1
00:00:00,733 --> 00:00:02,135
(rhythmic chiming music)

2
00:00:02,168 --> 00:00:03,870
- [Announcer] NASA's Jet
Propulsion Laboratory presents

3
00:00:04,737 --> 00:00:06,339
the von Kármán Lecture,

4
00:00:06,372 --> 00:00:09,142
a series of talks by
scientists and engineers

5
00:00:09,175 --> 00:00:12,545
who are exploring our
planet, our solar system

6
00:00:12,578 --> 00:00:14,681
and all that lies beyond.

7
00:00:26,759 --> 00:00:28,628
- Hey, good evening
ladies and gentlemen.

8
00:00:28,661 --> 00:00:29,929
How is everyone tonight?

9
00:00:29,962 --> 00:00:31,097
- Good
- Alright.

10
00:00:31,130 --> 00:00:32,365
(sparse applause)
- Oh, good.

11
00:00:32,398 --> 00:00:33,800
Thank you so much for
coming out to join us

12
00:00:33,833 --> 00:00:36,436
on this relatively soggy
California evening. (chuckling)

13
00:00:36,469 --> 00:00:37,737
So, shall we?

14
00:00:37,770 --> 00:00:40,173
Planets orbiting other
stars, or exoplanets,

15
00:00:40,206 --> 00:00:42,508
have become an important
field of astronomical study

16
00:00:42,541 --> 00:00:44,777
over the past 25 years.

17
00:00:44,810 --> 00:00:46,879
Recent findings from
NASA's Kepler Mission

18
00:00:46,912 --> 00:00:50,116
suggest that nearly every
star you see in the night sky

19
00:00:50,149 --> 00:00:52,852
probably has
exoplanets orbiting it.

20
00:00:52,885 --> 00:00:56,022
The number of confirmed
exoplanets is now a few thousand

21
00:00:56,055 --> 00:00:58,224
and their discoveries
have yielded terms

22

00:00:58,257 --> 00:01:00,393
that would have sounded
alien to astronomers

23
00:01:00,426 --> 00:01:02,128
before the 1990s:

24
00:01:02,161 --> 00:01:06,933
hot Jupiters, pulsar planets,
super-Earths, mini-Neptunes

25
00:01:06,966 --> 00:01:09,035
and circumbinary planets.

26
00:01:09,068 --> 00:01:12,672
Now, Trends are emerging
among exoplanet populations

27
00:01:12,705 --> 00:01:15,341
which put our own solar
system in context,

28
00:01:15,374 --> 00:01:17,710
noting most exoplanetary
systems appear

29
00:01:17,743 --> 00:01:20,213
to be very unlike our own.

30
00:01:20,246 --> 00:01:21,914
Tonight's guest will
present a brief history

31
00:01:21,947 --> 00:01:23,783
of exoplanet
discoveries, the story

32
00:01:23,816 --> 00:01:27,920
of the transiting super-Saturn
extrasolar ring system

33
00:01:27,953 --> 00:01:30,823
and summarize NASA's
ongoing and future plans

34
00:01:30,856 --> 00:01:34,894
to discover and characterize
strange new worlds.

35
00:01:34,927 --> 00:01:38,297
Tonight's guest has been the
Deputy Program Chief Scientist

36
00:01:38,330 --> 00:01:41,134
of the NASA Exoplanet
Exploration Program

37
00:01:41,167 --> 00:01:43,269
since August of 2016.

38
00:01:43,302 --> 00:01:46,339
His research interests focus
on astronomical observations

39
00:01:46,372 --> 00:01:48,841
related to the
formation and evolution

40
00:01:48,874 --> 00:01:50,943
of planetary systems and stars,

41
00:01:50,976 --> 00:01:53,179
and in particular, their ages.

42
00:01:53,212 --> 00:01:56,048
He graduated with a BS in
Astronomy and Astrophysics

43
00:01:56,081 --> 00:01:59,152

and Physics from
Penn State in 1998,

44
00:01:59,185 --> 00:02:00,453
a Master's degree in Physics

45
00:02:00,486 --> 00:02:02,321
from the University
of New South Wales

46
00:02:02,354 --> 00:02:04,624
Australian Defense Force Academy

47
00:02:04,657 --> 00:02:07,560
while a Fulbright
Fellow in 1999,

48
00:02:07,593 --> 00:02:09,495
and he received his
PhD in Astronomy

49
00:02:09,528 --> 00:02:12,832
from the University
of Arizona in 2004.

50
00:02:12,865 --> 00:02:16,102
After his PhD, he was a
Clay Postdoctoral Fellow

51
00:02:16,135 --> 00:02:18,971
at the Harvard Smithsonian
Center for Astrophysics.

52
00:02:19,004 --> 00:02:20,940
More recently, he was
a Professor of Physics

53
00:02:20,973 --> 00:02:23,142
and Astronomy at the
University of Rochester

54
00:02:23,175 --> 00:02:26,212
and a staff astronomer at
the Cerro Tololo Observatory

55
00:02:26,245 --> 00:02:27,613
in Chile.

56
00:02:27,646 --> 00:02:30,149
He has also been part of
several astronomical discoveries

57
00:02:30,182 --> 00:02:31,851
over the years
including the discovery

58
00:02:31,884 --> 00:02:34,954
of the first transiting
extrasolar ring system,

59
00:02:34,987 --> 00:02:38,791
the nearest historical fly-by
of a star to the solar system

60
00:02:38,824 --> 00:02:41,827
and the discoveries of
low-mass stellar companions

61
00:02:41,860 --> 00:02:45,731
to the bright stars Alcor,
Fomalhaut and Canopus.

62
00:02:45,764 --> 00:02:48,000
He has discovered several
nearby star clusters

63
00:02:48,033 --> 00:02:51,037
within hundreds of light-years'
distance to the Sun,

64
00:02:51,070 --> 00:02:54,707
and recently he was
co-discoverer of a comet.

65
00:02:54,740 --> 00:02:55,975
He is an active member

66
00:02:56,008 --> 00:02:57,710
of the International
Astronomical Union

67
00:02:57,743 --> 00:02:59,212
and he is currently the Chair

68
00:02:59,245 --> 00:03:03,349
of the newly-formed IAU
Working Group on Star Names.

69
00:03:03,382 --> 00:03:05,017
Ladies and gentlemen,
please help me welcome

70
00:03:05,050 --> 00:03:07,787
tonight's guest:
Dr. Eric Mamajek.

71
00:03:07,820 --> 00:03:10,990
(audience applauding)

72
00:03:17,930 --> 00:03:20,433
- Thank you, it is absolutely
wonderful to be here.

73
00:03:20,466 --> 00:03:23,769
As he mentioned, I just
got to JPL in August,

74
00:03:23,802 --> 00:03:25,671
so I'm relatively

new to California.

75
00:03:25,704 --> 00:03:29,675
So, apparently, things are
wetter than where I came from.

76
00:03:29,708 --> 00:03:33,946
We now inhabit a water world
in Southern California.

77
00:03:33,979 --> 00:03:35,448
So I'm gonna tell you

78
00:03:35,481 --> 00:03:38,184
about Exoplanets: A Quest
for Strange New Worlds.

79
00:03:38,217 --> 00:03:41,053
This is a topic that's obviously
near and dear to my heart

80
00:03:41,086 --> 00:03:43,456
so the first part of the talk

81
00:03:43,489 --> 00:03:44,690
will be a little
bit personal to me

82
00:03:44,723 --> 00:03:47,727
because as the discovers
have sort of unfolded

83
00:03:47,760 --> 00:03:50,429
over the last few
decades, they sort of fed

84
00:03:50,462 --> 00:03:53,099
into my interest in astronomy.

85

00:03:53,132 --> 00:03:54,800
So I've been sort of
watching this field

86
00:03:54,833 --> 00:03:56,836
since elementary school.

87
00:03:58,270 --> 00:04:00,940
So, this is one of my
favorite places on Earth.

88
00:04:00,973 --> 00:04:03,743
This is actually Cerro
Tololo Observatory in Chile.

89
00:04:03,776 --> 00:04:06,712
And this is a few
of the domes there.

90
00:04:06,745 --> 00:04:10,683
If you go out at night
when the Moon is not up,

91
00:04:12,017 --> 00:04:14,186
if there's some low
cloud that's blocking out

92
00:04:14,219 --> 00:04:16,689
some of the lights from a
few of the small towns nearby

93
00:04:16,722 --> 00:04:20,760
and the mines, you get a
really, really, really dark sky.

94
00:04:20,793 --> 00:04:23,162
It's so dark as
you're walking around,

95
00:04:23,195 --> 00:04:25,197

you can see your
shadow on the domes.

96
00:04:25,230 --> 00:04:28,467
And that shadow is not from the
Sun, it's not from the Moon,

97
00:04:28,500 --> 00:04:29,935
it's from the stars.

98
00:04:29,968 --> 00:04:32,705
There's nothing else
illuminating the sky.

99
00:04:32,738 --> 00:04:35,174
You only have to go outside
dark-adapted for a few minutes

100
00:04:35,207 --> 00:04:36,709
and you start
seeing this effect.

101
00:04:36,742 --> 00:04:38,411
It is literally the light,
the integrated light

102
00:04:38,444 --> 00:04:40,413
from billions of
stars in the galaxy

103
00:04:40,446 --> 00:04:44,850
that's projecting the light
that's producing your shadow.

104
00:04:44,883 --> 00:04:47,887
This was a really
neat place to work.

105
00:04:47,920 --> 00:04:50,523
And so every once in a

while when you're observing,

106
00:04:50,556 --> 00:04:52,325
you could take a little
break and walk outside

107
00:04:52,358 --> 00:04:53,826
and see the stars.

108
00:04:53,859 --> 00:04:57,997
And on a typical, outside
of light-pollution,

109
00:04:58,030 --> 00:04:59,498
you should be able to
see hundreds or thousands

110
00:04:59,531 --> 00:05:01,634
of stars in the night sky.

111
00:05:01,667 --> 00:05:03,869
We've got something like a
few hundred billion stars

112
00:05:03,902 --> 00:05:05,371
in our galaxy.

113
00:05:05,404 --> 00:05:06,572
There's probably hundreds
of billions of galaxies

114
00:05:06,605 --> 00:05:07,940
in our universe.

115
00:05:09,375 --> 00:05:13,713
And so you wonder, are there
other planets out there, okay?

116
00:05:13,746 --> 00:05:16,816

So, this is, you're
seeing on the left

117
00:05:16,849 --> 00:05:18,484
what our galaxy looks
like from Earth.

118
00:05:18,517 --> 00:05:21,087
You see lots of stars, you
see these inky dark regions

119
00:05:21,120 --> 00:05:22,421
among the stars.

120
00:05:22,454 --> 00:05:24,357
Those are dark molecular clouds

121
00:05:24,390 --> 00:05:25,858
and as I'll tell you later,

122
00:05:25,891 --> 00:05:28,527
that's actually where stars
are forming, in those clouds.

123
00:05:28,560 --> 00:05:30,162
We now, astronomers over
the last several decades

124
00:05:30,195 --> 00:05:31,430
have been able to
measure the distances

125
00:05:31,463 --> 00:05:33,032
to stars more precisely.

126
00:05:33,065 --> 00:05:35,668
We can measure the distances
to these clouds more precisely.

127

00:05:35,701 --> 00:05:38,838
And we can sort of deproject
the edge on Milky Way

128
00:05:38,871 --> 00:05:42,141
into the Milky Way's
actual appearance.

129
00:05:43,275 --> 00:05:44,477
Now, this is an
artist's conception

130
00:05:44,510 --> 00:05:47,947
but a really good
artist's conception.

131
00:05:47,980 --> 00:05:49,615
Most of the stuff we
have mapped out is just

132
00:05:49,648 --> 00:05:51,050
in this little
quadrant down here

133
00:05:51,083 --> 00:05:55,321
within a couple thousand
light-years of the Sun.

134
00:05:55,354 --> 00:05:58,524
Our Sun would be a
completely imperceptible dot

135
00:05:58,557 --> 00:06:01,160
right here between
to spiral arms, okay?

136
00:06:01,193 --> 00:06:02,628
So the galactic bulge is here,

137
00:06:02,661 --> 00:06:05,765

it's about 30,000
light-years away.

138
00:06:05,798 --> 00:06:07,066
And our Sun is moving
around the galaxy

139
00:06:07,099 --> 00:06:09,635
at about 200
kilometers per second.

140
00:06:09,668 --> 00:06:11,170
You don't feel it.

141
00:06:13,305 --> 00:06:18,110
So, we'd like to know, are
there other planets out there?

142
00:06:18,143 --> 00:06:20,112
This is the preface
to a great book

143
00:06:20,145 --> 00:06:22,248
that came out a few
years ago by Sara Seager,

144
00:06:22,281 --> 00:06:25,918
who's a regular visitor to
JPL and a professor at MIT.

145
00:06:25,951 --> 00:06:28,821
She edited this book
called Exoplanets.

146
00:06:28,854 --> 00:06:31,424
And she wrote, "This is a
unique time in human history.

147
00:06:31,457 --> 00:06:33,259
"For the first time, we're

on the technological brink

148
00:06:33,292 --> 00:06:35,327
"of being able to answer
questions that have been around

149
00:06:35,360 --> 00:06:36,562
"for thousands of years:

150
00:06:36,595 --> 00:06:38,397
"Are there other
planets like Earth?

151
00:06:38,430 --> 00:06:39,331
"Are they common?

152
00:06:39,364 --> 00:06:41,467
"Do they have signs of life?"

153
00:06:41,500 --> 00:06:43,436
These are really big questions

154
00:06:43,469 --> 00:06:46,906
and we're sort of slowly
unveiling the curtain

155
00:06:46,939 --> 00:06:48,741
and then finding these answers.

156
00:06:48,774 --> 00:06:50,643
And we're sort of at
a lucky generation

157
00:06:50,676 --> 00:06:53,179
to be able to see this unfurl.

158
00:06:54,980 --> 00:06:57,250
So, this is me, about 1980.

159
00:06:58,650 --> 00:07:01,554
I grew up on a horse farm in
Southwestern Pennsylvania.

160
00:07:01,587 --> 00:07:04,590
Skies were moderately dark.

161
00:07:04,623 --> 00:07:06,725
Very quickly I was
interested in things

162
00:07:06,758 --> 00:07:08,427
like geology and meteorology.

163
00:07:08,460 --> 00:07:10,796
I saw Mount St. Helens
the year after it blew up.

164
00:07:10,829 --> 00:07:12,331
I thought, this is crazy.

165
00:07:12,364 --> 00:07:14,333
How could the earth, you know,
how could a mountain explode?

166
00:07:14,366 --> 00:07:15,668
We didn't have those
in Pennsylvania,

167
00:07:15,701 --> 00:07:17,770
we had coal, limestone.

168
00:07:17,803 --> 00:07:19,438
It didn't explode.

169
00:07:19,471 --> 00:07:20,940
But it got you thinking
about the universe

170
00:07:20,973 --> 00:07:24,977
and physics and chemistry
and how the universe works.

171
00:07:25,010 --> 00:07:26,979
And it didn't take long
until I was interested

172
00:07:27,012 --> 00:07:28,614
in astronomy.

173
00:07:28,647 --> 00:07:31,350
But this also coincided
with pictures like this.

174
00:07:31,383 --> 00:07:32,918
I remember being
five or six years old

175
00:07:32,951 --> 00:07:35,654
and seeing the pictures
of this ringed planet

176
00:07:35,687 --> 00:07:37,089
and wondering what that was.

177
00:07:37,122 --> 00:07:38,757
And for a sort time, I thought
that must've been Earth.

178
00:07:38,790 --> 00:07:40,226
I thought I lived on
the ringed planet.

179
00:07:40,259 --> 00:07:42,094
And I was like, well, I
can't see the ring at night.

180
00:07:42,127 --> 00:07:45,197

But I saw these pictures
of Saturn so often

181
00:07:45,230 --> 00:07:47,233
that it made you wonder.

182
00:07:48,867 --> 00:07:53,472
And so I was sort of a
child of the Voyager era

183
00:07:53,505 --> 00:07:54,974
in the 1980s.

184
00:07:55,007 --> 00:07:58,043
You know, every few years, it
was all these great pictures

185
00:07:58,076 --> 00:08:01,013
coming from NASA from
these robotic space probes

186
00:08:01,046 --> 00:08:02,948
that were sent to the
outer solar system.

187
00:08:02,981 --> 00:08:04,383
The people in the
auditorium are sitting

188
00:08:04,416 --> 00:08:07,553
next to a model
of one right here.

189
00:08:07,586 --> 00:08:08,721
And the two probes
I'm talking about,

190
00:08:08,754 --> 00:08:10,789
of course, are Voyager
1 and Voyager 2.

191
00:08:10,822 --> 00:08:12,191
And they completed the
first reconnaissance

192
00:08:12,224 --> 00:08:13,726
of the outer solar system.

193
00:08:13,759 --> 00:08:16,529
Voyager 2 made it past all
four of the outer planets,

194
00:08:16,562 --> 00:08:18,797
Jupiter, Saturn,
Uranus and Neptune.

195
00:08:18,830 --> 00:08:21,634
And these are really interesting
worlds in themselves.

196
00:08:21,667 --> 00:08:25,004
Here's a picture of
Voyager 1 and Voyager 2.

197
00:08:25,037 --> 00:08:27,473
The Voyagers are now over
100 astronomical units

198
00:08:27,506 --> 00:08:30,843
away from the Sun, 100 times
the Earth-Sun distance.

199
00:08:30,876 --> 00:08:34,146
They're reaching the area where
the Sun's wispy atmosphere

200
00:08:34,179 --> 00:08:37,650
of ionized gas is sort
of melting into the gas

201
00:08:37,683 --> 00:08:38,884
from the rest of the galaxy.

202
00:08:38,917 --> 00:08:40,519
They've effectively
left the solar system.

203
00:08:40,552 --> 00:08:41,921
They haven't left
the Sun's gravity,

204
00:08:41,954 --> 00:08:45,791
but they've effectively
left the solar system.

205
00:08:47,025 --> 00:08:50,229
So Voyager was launched in 1977.

206
00:08:50,262 --> 00:08:52,631
And I knew, even in
elementary school,

207
00:08:52,664 --> 00:08:54,600
there was this interesting
place called JPL

208
00:08:54,633 --> 00:08:55,801
and there was these
interesting people

209
00:08:55,834 --> 00:08:57,303
at a place called,
you know, that worked

210
00:08:57,336 --> 00:09:01,173
for an entity called NASA
and they were explorers.

211
00:09:01,206 --> 00:09:03,742

And they wanted to study the
universe and study planets.

212
00:09:03,775 --> 00:09:07,880
And this sounded like a
really, really neat job.

213
00:09:07,913 --> 00:09:09,748
And it was an exciting time.

214
00:09:09,781 --> 00:09:11,417
The last few decades
have been very exciting,

215
00:09:11,450 --> 00:09:14,520
there's been a lot of very
interesting discoveries.

216
00:09:14,553 --> 00:09:17,056
And it's fun to be here at JPL

217
00:09:18,490 --> 00:09:20,326
and actually give
a talk on this.

218
00:09:20,359 --> 00:09:22,127
This is sort of our
classic, cartoon picture

219
00:09:22,160 --> 00:09:26,298
of the solar system with the
now-eight classic planets.

220
00:09:26,331 --> 00:09:28,133
And we were sort of
taught in the 1980s

221
00:09:28,166 --> 00:09:31,870
that we have these small
rocky planets on the interior.

222
00:09:31,903 --> 00:09:33,472
There's Earth, Mercury,
Venus, Earth, Mars,

223
00:09:33,505 --> 00:09:35,240
Jupiter, Saturn,
Uranus and Neptune.

224
00:09:35,273 --> 00:09:37,109
And the small, rocky planets
form on the inner part

225
00:09:37,142 --> 00:09:38,711
of the solar system.

226
00:09:38,744 --> 00:09:40,913
And then all of a sudden, out
past about two, three times

227
00:09:40,946 --> 00:09:43,916
the Earth-Sun distance, you
start getting these worlds

228
00:09:43,949 --> 00:09:45,851
that are dominated by the ices,

229
00:09:45,884 --> 00:09:47,820
things like water and
ammonia and methane.

230
00:09:47,853 --> 00:09:49,888
They're the so-called
astronomical ices,

231
00:09:49,921 --> 00:09:53,258
carbon, nitrogen and hydrogen
with hydrogens attached.

232

00:09:53,291 --> 00:09:55,427
And also, a lot of
hydrogen and helium.

233
00:09:55,460 --> 00:09:56,895
Jupiter and Saturn were
very much dominated

234
00:09:56,928 --> 00:09:58,430
by hydrogen and helium.

235
00:09:58,463 --> 00:09:59,999
And each of them have their
own little system of moons.

236
00:10:00,032 --> 00:10:01,734
All the moons were interesting,

237
00:10:01,767 --> 00:10:03,102
these small cratered worlds.

238
00:10:03,135 --> 00:10:04,803
Some of them had active geology.

239
00:10:04,836 --> 00:10:07,840
Couple of them have atmospheres.

240
00:10:07,873 --> 00:10:10,809
And so this was sort
our classic picture

241
00:10:10,842 --> 00:10:14,713
of the solar system
through about the 1980s.

242
00:10:14,746 --> 00:10:16,215
Shortly after, they
were finding the,

243

00:10:16,248 --> 00:10:19,585
there was discovery of the
Kuiper Belt out past Pluto.

244
00:10:19,618 --> 00:10:21,687
We now know there's
icy worlds out there.

245
00:10:21,720 --> 00:10:24,423
And there may even be another
planet, so-called Planet 9.

246
00:10:24,456 --> 00:10:25,824
It would not surprise me
if that was discovered

247
00:10:25,857 --> 00:10:27,292
in the next year or two.

248
00:10:27,325 --> 00:10:30,963
The dynamical evidence
looks pretty interesting.

249
00:10:30,996 --> 00:10:34,900
So one of the great, I would
say victories of physics

250
00:10:34,933 --> 00:10:38,037
and astronomical of
astronomy in the 20th century

251
00:10:38,070 --> 00:10:40,439
is this sort of
comprehensive picture

252
00:10:40,472 --> 00:10:43,142
of the formation, the
evolution and death of stars.

253
00:10:43,175 --> 00:10:45,277

We understand stellar
structure very well,

254
00:10:45,310 --> 00:10:47,479
the stellar atmospheres.

255
00:10:47,512 --> 00:10:49,648
If you could sort of
stand back and look

256
00:10:49,681 --> 00:10:52,184
at our galaxy over a time
scale of millions of years,

257
00:10:52,217 --> 00:10:54,920
billions of years, you would
see stars being formed,

258
00:10:54,953 --> 00:10:56,622
living their lives
and being snuffed out

259
00:10:56,655 --> 00:10:58,157
through various means.

260
00:10:58,190 --> 00:11:00,659
And this is just showing
the evolutionary pathways

261
00:11:00,692 --> 00:11:03,162
for small stars like the Sun.

262
00:11:04,362 --> 00:11:07,266
They're born in these
dark molecular clouds.

263
00:11:07,299 --> 00:11:09,368
I'll talk about this a
little bit more later.

264
00:11:09,401 --> 00:11:13,572
They collapse, basically
this is, why do stars form?

265
00:11:13,605 --> 00:11:16,241
Stars are forming
in the gas and dust

266
00:11:16,274 --> 00:11:17,176
floating around in the galaxy.

267
00:11:17,209 --> 00:11:18,811
It's where gravity wins out

268
00:11:18,844 --> 00:11:20,946
over gas-pressure and
magnetic-field pressure.

269
00:11:20,979 --> 00:11:23,048
It's a very inefficient
process, okay?

270
00:11:23,081 --> 00:11:24,950
Only a few percent of
mass in these clouds

271
00:11:24,983 --> 00:11:26,285
actually form stars.

272
00:11:26,318 --> 00:11:27,886
And then only a tiny
fraction of the mass

273
00:11:27,919 --> 00:11:29,988
that goes into forming
the, of the star,

274
00:11:30,021 --> 00:11:32,157
will end up forming the planets.

275
00:11:32,190 --> 00:11:33,459
So our Sun'll live
a nice happy life

276
00:11:33,492 --> 00:11:34,626
for about 10 billion years.

277
00:11:34,659 --> 00:11:36,128
We're about halfway through.

278
00:11:36,161 --> 00:11:38,030
At the end of its life,
it'll become a red giant.

279
00:11:38,063 --> 00:11:41,200
It'll exhaust its hydrogen
fuel and it'll furiously change

280
00:11:41,233 --> 00:11:42,768
its inner structure
to try to heat

281
00:11:42,801 --> 00:11:47,139
to higher temperatures to
burn other sources of fuel.

282
00:11:47,172 --> 00:11:48,507
It'll run out and eventually,

283
00:11:48,540 --> 00:11:49,842
it'll turn into a
planetary nebula.

284
00:11:49,875 --> 00:11:51,844
It'll blow off its outer layers.

285
00:11:51,877 --> 00:11:53,412
So this is is going on.

286
00:11:53,445 --> 00:11:55,681
This whole time scale here
is about 12 billion years.

287
00:11:55,714 --> 00:11:59,351
And for low-mass
stars in the galaxy,

288
00:11:59,384 --> 00:12:00,953
stars even down to
the mass of the Sun,

289
00:12:00,986 --> 00:12:03,288
some of them have had time
to go through this cycle.

290
00:12:03,321 --> 00:12:06,291
The massive stars, the
big, bright white-blue,

291
00:12:06,324 --> 00:12:09,394
blue-white stars you
see in the night sky,

292
00:12:09,427 --> 00:12:11,196
those live very short lives.

293
00:12:11,229 --> 00:12:12,564
These are stars that
are typically 10

294
00:12:12,597 --> 00:12:14,600
or tens of times
the mass of the Sun.

295
00:12:14,633 --> 00:12:16,935
They correspondingly
live very short lives.

296
00:12:16,968 --> 00:12:18,737
Maybe tens of millions of years.

297
00:12:18,770 --> 00:12:21,206
And they go through a much
more destructive phase

298
00:12:21,239 --> 00:12:23,242
at the end, they
actually explode.

299
00:12:23,275 --> 00:12:24,643
And depending on their
mass, they'll turn

300
00:12:24,676 --> 00:12:27,713
into either a neutron
star or a black hole.

301
00:12:27,746 --> 00:12:30,082
But what doesn't go into the
neutron star and black hole

302
00:12:30,115 --> 00:12:32,384
contains a lot of metals
and a lot of stuff

303
00:12:32,417 --> 00:12:34,787
that turns into planets
and turns into life.

304
00:12:34,820 --> 00:12:37,322
And this process is
constantly enriching the gas

305
00:12:37,355 --> 00:12:38,824
in our galaxy.

306
00:12:38,857 --> 00:12:42,361

Our galaxy is slowly getting
full of so-called metals.

307
00:12:43,728 --> 00:12:45,164
So there's the periodic
table of elements you're used

308
00:12:45,197 --> 00:12:48,534
to seeing, that you learned
in your chemistry class.

309
00:12:48,567 --> 00:12:51,570
Most of the normal
gas in the galaxy

310
00:12:52,904 --> 00:12:54,673
is hydrogen and helium, up here,

311
00:12:54,706 --> 00:12:56,975
elements number
one and number two.

312
00:12:57,008 --> 00:13:01,180
They're about 98% of the
amount of normal matter

313
00:13:02,547 --> 00:13:03,982
in the galaxy.

314
00:13:04,015 --> 00:13:05,984
We're excluding so-called
dark matter and dark energy.

315
00:13:06,017 --> 00:13:07,519
That's for another talk.

316
00:13:07,552 --> 00:13:10,255
All the rest of the other
elements are less than 2%.

317
00:13:10,288 --> 00:13:12,524
Okay, if you averaged
out over the galaxy.

318
00:13:12,557 --> 00:13:14,159
But those are pretty
important because they end up

319
00:13:14,192 --> 00:13:16,728
turning into planets
and turning into life.

320
00:13:16,761 --> 00:13:19,665
Now the astronomers, this is
the astronomer's H-R diagram.

321
00:13:19,698 --> 00:13:22,000
Hydrogen, helium, metals.

322
00:13:22,033 --> 00:13:25,137
Okay, all the other 90 plus,
I think we're up to 118,

323
00:13:25,170 --> 00:13:26,405
but most of those
are short-lived.

324
00:13:26,438 --> 00:13:29,208
But the other 90 or
so stable elements,

325
00:13:29,241 --> 00:13:31,076
the astronomers just
call them metals.

326
00:13:31,109 --> 00:13:32,978
And they tend to
track each other

327

00:13:33,011 --> 00:13:34,179
in terms of their
relative abundance

328
00:13:34,212 --> 00:13:35,781
with respect to each other.

329
00:13:35,814 --> 00:13:38,250
So we talk about the
metallicity of stars

330
00:13:38,283 --> 00:13:40,018
and the metallicity
of the galaxy.

331
00:13:40,051 --> 00:13:41,753
And the amount of
metals in the galaxy

332
00:13:41,786 --> 00:13:43,956
is slowly getting
higher over time

333
00:13:43,989 --> 00:13:45,724
because stars are
living it and dying

334
00:13:45,757 --> 00:13:48,027
and they're returning this,

335
00:13:48,860 --> 00:13:51,497
the products of the
nucleosynthesis

336
00:13:51,597 --> 00:13:52,731
in the stellar cores,

337
00:13:52,764 --> 00:13:54,900
returning it to the galaxy.

338
00:13:54,933 --> 00:13:56,201
Now what happens to that stuff,

339
00:13:56,234 --> 00:13:57,836
there's all of our metals.

340
00:13:57,869 --> 00:13:59,638
Well, here's a
typical nearby nebula,

341
00:13:59,671 --> 00:14:02,040
this is the Orion nebula.

342
00:14:02,073 --> 00:14:03,609
This is a very beautiful nebula

343
00:14:03,642 --> 00:14:05,644
about 1,000 light-years away.

344
00:14:05,677 --> 00:14:08,513
There's a few thousand stars
that are forming in this gas.

345
00:14:08,546 --> 00:14:10,282
And so what we're
seeing is baby stars,

346
00:14:10,315 --> 00:14:11,950
less than about a
million years old

347
00:14:11,983 --> 00:14:13,685
that are condensing
out of this gas.

348
00:14:13,718 --> 00:14:17,155
And the very most massive
ones have already turned on.

349
00:14:17,188 --> 00:14:18,657
They're already
burning their hydrogen.

350
00:14:18,690 --> 00:14:20,792
They're giving off a ton
of ultraviolet radiation

351
00:14:20,825 --> 00:14:22,661
and they're blowing
away the gas.

352
00:14:22,694 --> 00:14:25,397
Those high-mass stars are
actually destroying the nest

353
00:14:25,430 --> 00:14:28,333
that the stars are
forming out of.

354
00:14:28,366 --> 00:14:30,068
Well, if you zoom
in on that nebula,

355
00:14:30,101 --> 00:14:31,870
here's some Hubble
Space Telescope images.

356
00:14:31,903 --> 00:14:33,138
And this is amazing.

357
00:14:33,171 --> 00:14:35,340
What you're seeing is
baby pictures of suns.

358
00:14:35,373 --> 00:14:38,110
These are all little
stars forming.

359

00:14:38,143 --> 00:14:40,078
And you'll notice,
if you zoom in,

360
00:14:40,111 --> 00:14:42,514
they look like little blobs.

361
00:14:42,547 --> 00:14:44,049
And we know the
distance to Orion.

362
00:14:44,082 --> 00:14:48,287
And we can measure the angle
that covers these little blobs.

363
00:14:48,320 --> 00:14:50,589
And the size of these
blobs is only on the order

364
00:14:50,622 --> 00:14:54,126
of a few hundred times the
Earth-Sun distance, okay?

365
00:14:54,159 --> 00:14:58,830
So we're talking about solar
system scales, here okay?

366
00:14:58,863 --> 00:15:00,098
So these are so-called proplyds,

367
00:15:00,131 --> 00:15:01,199
or protoplanetary disks.

368
00:15:01,232 --> 00:15:02,434
And they're fascinating.

369
00:15:02,467 --> 00:15:04,303
You can see some of
these look very dark.

370
00:15:04,336 --> 00:15:06,905
What you're seeing is this
illuminated nebula behind it.

371
00:15:06,938 --> 00:15:09,641
And the gas and dust
that's forming in planets

372
00:15:09,674 --> 00:15:11,576
around these little stars
is actually blocking

373
00:15:11,609 --> 00:15:14,246
out the light behind it.

374
00:15:14,279 --> 00:15:15,714
There's hundreds of these.

375
00:15:15,747 --> 00:15:17,549
This is one star-formation
region in our galaxy.

376
00:15:17,582 --> 00:15:18,483
This is the Orion nebula.

377
00:15:18,516 --> 00:15:20,118
There's thousands of 'em, okay?

378
00:15:20,151 --> 00:15:21,954
This is going on right now.

379
00:15:21,987 --> 00:15:24,656
So, star-formation is going on,

380
00:15:24,689 --> 00:15:27,059
there's super-novi, we
see planetary nebula,

381

00:15:27,092 --> 00:15:29,261
we see evidence
of stellar death.

382
00:15:29,294 --> 00:15:33,031
So there's this sort of birth
and death of stars going on.

383
00:15:33,064 --> 00:15:35,167
And we see during stellar birth,

384
00:15:35,200 --> 00:15:38,470
we see the ingredients
for forming planets.

385
00:15:38,503 --> 00:15:39,671
Okay, so that's great.

386
00:15:39,704 --> 00:15:41,907
We've seen some disks
around baby stars,

387
00:15:41,940 --> 00:15:43,575
we know that there's
metals there,

388
00:15:43,608 --> 00:15:45,744
there's material
for forming planets

389
00:15:45,777 --> 00:15:47,679
including things you'll
find in your vitamins

390
00:15:47,712 --> 00:15:50,682
and in your food
that life likes.

391
00:15:50,715 --> 00:15:52,818
So, how do we discover

and characterize planets?

392
00:15:52,851 --> 00:15:54,286
Why are they so hard to find?

393
00:15:54,319 --> 00:15:56,188
Why did it take until
only a couple decades ago

394
00:15:56,221 --> 00:15:57,689
to find planets?

395
00:15:57,722 --> 00:16:01,126
Well, a few of the first
hints were actually teased

396
00:16:01,159 --> 00:16:03,495
out here in the 1980s.

397
00:16:03,528 --> 00:16:05,697
This is a satellite called IRAS

398
00:16:05,730 --> 00:16:08,500
that was launched in
1983 from Vandenberg.

399
00:16:08,533 --> 00:16:11,536
This satellite did an
infrared all-sky survey

400
00:16:11,569 --> 00:16:14,139
and it found a few surprises.

401
00:16:14,172 --> 00:16:15,407
So one of the things it found

402
00:16:15,440 --> 00:16:17,242
was that a handful
of the nearby stars

403
00:16:17,275 --> 00:16:19,478
actually had big
infrared excesses.

404
00:16:19,511 --> 00:16:22,214
These stars were giving
off way more infrared light

405
00:16:22,247 --> 00:16:23,415
than they should be, okay?

406
00:16:23,448 --> 00:16:25,617
So we know what the
distribution of energies

407
00:16:25,650 --> 00:16:28,954
are for stars and how much
light they should give out

408
00:16:28,987 --> 00:16:30,455
in the infrared.

409
00:16:30,488 --> 00:16:31,623
There was a certain class
of stars that was giving off

410
00:16:31,656 --> 00:16:33,191
way more infrared light.

411
00:16:33,224 --> 00:16:37,329
And it was actually a
group, here at JPL, in 1984

412
00:16:38,196 --> 00:16:40,032
and at University of Arizona,

413
00:16:40,065 --> 00:16:42,901
there was this great paper

by Smith and Richard Terrell,

414
00:16:42,934 --> 00:16:44,770
Brad Smith and Richard Terrell.

415
00:16:44,803 --> 00:16:47,439
And they actually went
to a telescope in Chile.

416
00:16:47,472 --> 00:16:49,541
And they decided to look
at one of these stars

417
00:16:49,574 --> 00:16:50,809
with a coronagraph.

418
00:16:50,842 --> 00:16:52,644
They blotted out the
light from the star.

419
00:16:52,677 --> 00:16:54,046
And they took a
deep image of it.

420
00:16:54,079 --> 00:16:56,882
And lo and behold,
they saw this stuff

421
00:16:56,915 --> 00:16:59,751
on both sides of
the stars, okay?

422
00:16:59,784 --> 00:17:02,087
This is actually, this
is what was responsible

423
00:17:02,120 --> 00:17:05,090
for the infrared light, but
this is ground-up dust grains

424
00:17:05,123 --> 00:17:07,225
orbiting this star,
Beta Pictoris,

425
00:17:07,258 --> 00:17:09,094
which we now know is
pretty young as a star.

426
00:17:09,127 --> 00:17:12,064
It's about 20 or 25
million years old.

427
00:17:12,097 --> 00:17:13,999
And this was sort of, this
was one of our first hints

428
00:17:14,032 --> 00:17:15,033
that there was planets there.

429
00:17:15,066 --> 00:17:16,234
Because if you see this dust,

430
00:17:16,267 --> 00:17:18,070
it should get blown
out by the star's light

431
00:17:18,103 --> 00:17:20,105
in a very short time,
maybe hundreds of thousands

432
00:17:20,138 --> 00:17:21,506
to millions of years.

433
00:17:21,539 --> 00:17:23,975
So there had to be some
population of things grinding up

434
00:17:24,008 --> 00:17:26,745
asteroids, comets, et

cetera that were creating,

435
00:17:26,778 --> 00:17:28,613
that were kicking up this dust.

436
00:17:28,646 --> 00:17:33,018
So this ended up being actually
nearby a baby solar system,

437
00:17:33,051 --> 00:17:34,486
so things were starting
to get interesting.

438
00:17:34,519 --> 00:17:36,488
I remember seeing this story
when I was in elementary school

439
00:17:36,521 --> 00:17:38,757
and that really sort
of made it clear

440
00:17:38,790 --> 00:17:40,959
that we were kinda
getting to the point

441
00:17:40,992 --> 00:17:43,295
where we're gonna start
finding these planets soon.

442
00:17:43,328 --> 00:17:45,197
So how do we find planets, okay?

443
00:17:45,230 --> 00:17:46,998
Well, you think you could
just take an image, right?

444
00:17:47,031 --> 00:17:49,067
You take your telescope,
you look at the star.

445
00:17:49,100 --> 00:17:52,070
If you squint hard enough
you may see a little dim dot

446
00:17:52,103 --> 00:17:53,472
next to the star.

447
00:17:53,505 --> 00:17:54,873
This is really tricky, okay?

448
00:17:54,906 --> 00:17:56,408
There's a few complications.

449
00:17:56,441 --> 00:17:59,811
One is the planets
themselves are only,

450
00:17:59,844 --> 00:18:01,413
a planet like Jupiter,

451
00:18:01,446 --> 00:18:04,249
is only about one-billionth
as bright as its star, okay?

452
00:18:04,282 --> 00:18:05,717
This is in the reflected light.

453
00:18:05,750 --> 00:18:08,019
So that planet is, the
star is giving off light,

454
00:18:08,052 --> 00:18:09,254
the light's hitting that planet

455
00:18:09,287 --> 00:18:11,690
and then that light's
being redirected to us.

456

00:18:11,723 --> 00:18:14,726
And the ratios about
one in a billion.

457
00:18:14,759 --> 00:18:18,463
It's even fainter for
a planet like Earth.

458
00:18:18,496 --> 00:18:19,998
Well, this is very challenging.

459
00:18:20,031 --> 00:18:21,933
The other problem is
that plants tend to be,

460
00:18:21,966 --> 00:18:23,668
if they're on the same
scale as our solar system,

461
00:18:23,701 --> 00:18:25,170
if they're several
astronomical units,

462
00:18:25,203 --> 00:18:28,473
the stars are so far away
that the angular separation

463
00:18:28,506 --> 00:18:30,442
is very, very tiny.

464
00:18:30,475 --> 00:18:33,445
So the star is right
up against the,

465
00:18:33,478 --> 00:18:35,614
sorry, the planet is
right up against the star

466
00:18:35,647 --> 00:18:37,949
and so you actually need to,

467
00:18:37,982 --> 00:18:40,218
you need to do something
to the star's light.

468
00:18:40,251 --> 00:18:41,686
Because the other problem is,

469
00:18:41,719 --> 00:18:44,022
we're on Earth, we're at
the bottom of an atmosphere

470
00:18:44,055 --> 00:18:46,458
and that atmosphere plays
with the light, right?

471
00:18:46,491 --> 00:18:47,659
The stars twinkle.

472
00:18:47,692 --> 00:18:49,027
The stars are twinkling 'cause

473
00:18:49,060 --> 00:18:50,762
there's these little
variations in the temperature

474
00:18:50,795 --> 00:18:53,198
and the humidity of the
air and the light waves

475
00:18:53,231 --> 00:18:54,633
that are going through
the atmosphere wiggle

476
00:18:54,666 --> 00:18:55,834
around a little bit.

477
00:18:55,867 --> 00:18:57,469
And so the blur out

the star's light

478
00:18:57,502 --> 00:18:59,604
and they will completely
swamp the poor planet.

479
00:18:59,637 --> 00:19:00,805
So you can't just
go to the telescope,

480
00:19:00,838 --> 00:19:02,207
look through it and
say, oh, I see a planet

481
00:19:02,240 --> 00:19:03,675
next to the star.

482
00:19:03,708 --> 00:19:05,844
You actually have to blot
out the star's light,

483
00:19:05,877 --> 00:19:08,813
or there's a few other tricks
I'll show you later, okay?

484
00:19:08,846 --> 00:19:12,584
So this is so-called
direct imaging.

485
00:19:12,617 --> 00:19:14,719
One of the ways to find planets

486
00:19:14,752 --> 00:19:16,755
that's been very
popular for decades

487
00:19:16,788 --> 00:19:19,224
and still has, unfortunately,

488

00:19:20,692 --> 00:19:22,561
it still shows promise but
has not borne much fruit,

489
00:19:22,594 --> 00:19:23,595
I'll put it that way,

490
00:19:23,628 --> 00:19:25,630
is so-called astrometry.

491
00:19:25,663 --> 00:19:27,866
And that is looking for
the wobbles of a star

492
00:19:27,899 --> 00:19:30,569
due to a planet
tugging on it, okay?

493
00:19:30,602 --> 00:19:33,905
So the planet itself is pulling
gravitationally on the star.

494
00:19:33,938 --> 00:19:35,674
We think of the planets
orbiting the Sun

495
00:19:35,707 --> 00:19:37,409
and the Sun is at the
center of the solar system.

496
00:19:37,442 --> 00:19:38,610
That's not quite true.

497
00:19:38,643 --> 00:19:40,845
There's something
called the Barycenter.

498
00:19:40,878 --> 00:19:43,882
Jupiter is the big
source of gravity

499
00:19:45,016 --> 00:19:48,587
that's tugging on the
Sun and the Sun actually

500
00:19:48,620 --> 00:19:50,255
moves around the inner
solar system a little bit

501
00:19:50,288 --> 00:19:52,824
on the time scale similar
to Jupiter's orbit.

502
00:19:52,857 --> 00:19:54,292
It's pretty gradual.

503
00:19:54,325 --> 00:19:56,228
It's on the order of hundreds
of thousands of kilometers

504
00:19:56,261 --> 00:19:58,463
but it's something and if
you're far enough away,

505
00:19:58,496 --> 00:20:00,465
you can measure the position
of the star accurately enough,

506
00:20:00,498 --> 00:20:02,400
you should be able to
tease out that signal.

507
00:20:02,433 --> 00:20:05,103
But it's very tough,
so this is just showing

508
00:20:05,136 --> 00:20:06,972
how you could use
multiple stars.

509
00:20:07,005 --> 00:20:08,773
If you could accurately
measure the angle

510
00:20:08,806 --> 00:20:11,309
between the star with the
planet and these other stars,

511
00:20:11,342 --> 00:20:13,345
over time, you might be
able to see the little bumps

512
00:20:13,378 --> 00:20:14,646
and wiggles of the
star's position

513
00:20:14,679 --> 00:20:17,616
and tease out
the planet.

514
00:20:17,649 --> 00:20:19,284
This is the, one of
the first techniques

515
00:20:19,317 --> 00:20:21,519
that ended up being
very fruitful.

516
00:20:21,552 --> 00:20:23,121
This is so-called
Doppler Spectroscopy

517
00:20:23,154 --> 00:20:24,489
or the Radial velocity method.

518
00:20:24,522 --> 00:20:25,924
So what are we doing?

519
00:20:25,957 --> 00:20:27,826

So, you've got your
planet orbiting the star,

520
00:20:27,859 --> 00:20:31,529
it's tugging on the star,
the star is moving around.

521
00:20:31,562 --> 00:20:33,832
And as it's moving around,
its velocity is changing.

522
00:20:33,865 --> 00:20:36,568
It's moving towards you, it's
moving away from you, okay?

523
00:20:36,601 --> 00:20:38,470
So the light is being
Doppler-shifted.

524
00:20:38,503 --> 00:20:40,238
It'll be blue-shifted if
its moving away from you.

525
00:20:40,271 --> 00:20:42,907
It's red-shifted if its
moving away from us.

526
00:20:42,940 --> 00:20:46,611
Now the planet is not that
massive compared to the star.

527
00:20:46,644 --> 00:20:49,347
It's a very, very
subtle signal, okay?

528
00:20:49,380 --> 00:20:51,783
If we're talking about
Jupiter pulling on the Sun,

529
00:20:51,816 --> 00:20:54,686

we're talking about a a
12-meter-per-second signal

530
00:20:54,719 --> 00:20:56,821
over 12 years, okay.

531
00:20:56,854 --> 00:20:58,156
12 meters per
second's about as fast

532
00:20:58,189 --> 00:21:02,227
as Usain Bolt goes
in ten seconds, okay?

533
00:21:02,260 --> 00:21:03,461
Very slow.

534
00:21:03,494 --> 00:21:04,729
If we're talking an
Earth-like planet,

535
00:21:04,762 --> 00:21:06,931
we're talking about ten
centimeters per second,

536
00:21:06,964 --> 00:21:10,635
which is how I would run
next to Usain Bolt, okay?

537
00:21:10,668 --> 00:21:12,070
Very, very slow signal, okay?

538
00:21:12,103 --> 00:21:13,605
So this is just sort
of generalizing.

539
00:21:13,638 --> 00:21:15,707
We don't see the colors
changing red and blue.

540
00:21:15,740 --> 00:21:17,042
When the things are moving
near the speed of light,

541
00:21:17,075 --> 00:21:17,976
you actually see a color shift.

542
00:21:18,009 --> 00:21:20,111
We see that with quasars.

543
00:21:20,144 --> 00:21:21,713
But this is a very
subtle signal.

544
00:21:21,746 --> 00:21:23,782
You're looking at the
spectrum of the star

545
00:21:23,815 --> 00:21:26,051
and the lines are
moving back and forth,

546
00:21:26,084 --> 00:21:28,420
very, very tiny amounts.

547
00:21:28,453 --> 00:21:30,221
So this is the so-called
Doppler spectrocity technique

548
00:21:30,254 --> 00:21:31,923
and there's been many
hundreds of planets found

549
00:21:31,956 --> 00:21:33,491
through this technique.

550
00:21:33,524 --> 00:21:35,026
The technique that's
been very fruitful

551
00:21:35,059 --> 00:21:36,227
for the last decade and a half

552
00:21:36,260 --> 00:21:38,196
is the so-called
transit method, okay?

553
00:21:38,229 --> 00:21:39,798
This is what happens
when a planet passes

554
00:21:39,831 --> 00:21:41,166
in front of its star.

555
00:21:41,199 --> 00:21:42,734
Now the trick is,
you need to measure

556
00:21:42,767 --> 00:21:45,637
how bright the star is
very accurately, okay?

557
00:21:45,670 --> 00:21:48,973
So here's time, here's
how bright the star is.

558
00:21:49,006 --> 00:21:50,241
If we got a star like the Sun,

559
00:21:50,274 --> 00:21:52,477
over time it only varies
at about the one part

560
00:21:52,510 --> 00:21:54,713
in a thousand level
over a long time,

561
00:21:54,746 --> 00:21:56,614

you might see some star-spots
appear here and there

562
00:21:56,647 --> 00:21:58,049
that make some little dips.

563
00:21:58,082 --> 00:22:00,452
But if you have a
Jupiter-sized planet pass

564
00:22:00,485 --> 00:22:04,089
in front of the Sun, you'd
get a dip of about 1%.

565
00:22:04,122 --> 00:22:05,623
Okay, now we're talkin'.

566
00:22:05,656 --> 00:22:07,726
We can measure 1% dip for a
lot of the brightest stars.

567
00:22:07,759 --> 00:22:09,227
If you get a planet like Earth,

568
00:22:09,260 --> 00:22:12,030
which is another factor
of 10 smaller than Jupiter

569
00:22:12,063 --> 00:22:14,999
and its area is another
factor of 100 smaller,

570
00:22:15,032 --> 00:22:17,736
we're looking for a signal
that's one part in 10,000.

571
00:22:17,769 --> 00:22:19,537
Hm, okay, that's getting tough.

572

00:22:19,570 --> 00:22:21,139
It's very difficult
to do from the ground.

573
00:22:21,172 --> 00:22:22,640
It's difficult to measure
the brightnesses of the stars

574
00:22:22,673 --> 00:22:24,142
that accurately from the ground

575
00:22:24,175 --> 00:22:25,877
but if you go to space, voila.

576
00:22:25,910 --> 00:22:27,946
Now we're talking about
discovering Earth-like planets.

577
00:22:27,979 --> 00:22:30,281
So I'll talk about the
Kepler Mission here in a bit.

578
00:22:30,314 --> 00:22:31,483
The Kepler Mission
has been responsible

579
00:22:31,516 --> 00:22:33,418
for finding most of the planets

580
00:22:33,451 --> 00:22:34,552
that have been discovered now.

581
00:22:34,585 --> 00:22:36,454
We're talking
thousands of planets.

582
00:22:36,487 --> 00:22:38,289
So this is a great technique.

583

00:22:38,322 --> 00:22:39,624
This is just another
movie showing

584
00:22:39,657 --> 00:22:40,759
differences in the sizes.

585
00:22:40,792 --> 00:22:42,660
So if you had large planet,

586
00:22:42,693 --> 00:22:44,162
let's say a
Jupiter-sized planet,

587
00:22:44,195 --> 00:22:48,633
and an Earth-sized planet,
you'll get different depths

588
00:22:48,666 --> 00:22:50,935
in the light curve, okay?

589
00:22:50,968 --> 00:22:53,905
So get roughly 1% signals
for a Jupiter-like planet

590
00:22:53,938 --> 00:22:55,440
and about a one part
in 10,000 signal

591
00:22:55,473 --> 00:22:57,576
for an Earth-like planet.

592
00:22:58,776 --> 00:23:01,279
Now, the other thing,
Kepler has been finding

593
00:23:01,312 --> 00:23:03,148
is multiple
planet-systems, okay?

594
00:23:03,181 --> 00:23:05,884
There's actually been
systems seen now,

595
00:23:05,917 --> 00:23:07,819
we have a great vantage point,

596
00:23:07,852 --> 00:23:09,554
we happened to see
multiple planets passing

597
00:23:09,587 --> 00:23:10,755
in front of the star.

598
00:23:10,788 --> 00:23:11,990
And if you're really
lucky, you start

599
00:23:12,023 --> 00:23:13,792
to see gravitational
perturbations.

600
00:23:13,825 --> 00:23:15,226
The planets are
pulling on each other.

601
00:23:15,259 --> 00:23:16,961
And we can actually
measure those masses.

602
00:23:16,994 --> 00:23:19,898
I'll show a plot later
in this talk exploiting

603
00:23:19,931 --> 00:23:22,167
that technique to
measure some masses.

604
00:23:22,200 --> 00:23:24,169

So Kepler has found
some very interesting

605
00:23:24,202 --> 00:23:25,403
multi-planet systems.

606
00:23:25,436 --> 00:23:28,072
And there's, these have
been very interesting

607
00:23:28,105 --> 00:23:31,543
because it's easier to get
the masses of those planets.

608
00:23:31,576 --> 00:23:34,012
This is another technique
called microlensing.

609
00:23:34,045 --> 00:23:36,848
This has been put to good use

610
00:23:36,881 --> 00:23:38,983
over about the last
decade and it's now

611
00:23:39,016 --> 00:23:42,654
gonna be a primary means
of finding planets for,

612
00:23:42,687 --> 00:23:43,655
one of the means
of finding planets

613
00:23:43,688 --> 00:23:46,357
for the upcoming WFIRST mission.

614
00:23:46,390 --> 00:23:49,627
So, you have your
telescope down here

615
00:23:49,660 --> 00:23:51,095
and let's say you have
a background star,

616
00:23:51,128 --> 00:23:52,597
but something passes
in front of it,

617
00:23:52,630 --> 00:23:54,999
let's say some mass, let's
say a star or a planet.

618
00:23:55,032 --> 00:23:59,204
As it passes in front, the
space-time is curved, okay?

619
00:24:00,304 --> 00:24:02,273
Light is not following
straight lines.

620
00:24:02,306 --> 00:24:04,642
You think a light beam is
gonna follow a straight line.

621
00:24:04,675 --> 00:24:06,044
The light is following
a straight line

622
00:24:06,077 --> 00:24:07,145
in four dimensions,

623
00:24:07,178 --> 00:24:10,181
oh, God, here we go,
we're going into Einstein.

624
00:24:10,214 --> 00:24:13,952
What, from our perspective
are three-dimensional beams

625

00:24:13,985 --> 00:24:17,021
passing through time,
from our perspective,

626
00:24:17,054 --> 00:24:19,491
that straight line looks curved.

627
00:24:19,524 --> 00:24:21,759
And the mass actually
acts like a lens.

628
00:24:21,792 --> 00:24:23,728
You'll actually get
the light from the star

629
00:24:23,761 --> 00:24:27,332
bend around around
that mass and focus.

630
00:24:27,365 --> 00:24:28,466
And what you get is
an enhancement

631
00:24:28,499 --> 00:24:29,700
in the amount
of light.

632
00:24:29,734 --> 00:24:32,103
So this is time and then this
is the brightness of the star.

633
00:24:32,136 --> 00:24:34,606
So you'll get these
characteristic curves

634
00:24:34,639 --> 00:24:36,407
and if this thing
that's passing in front

635
00:24:36,440 --> 00:24:38,409

has a planet, you get
an extra little curve

636
00:24:38,442 --> 00:24:39,911
on top of it, okay?

637
00:24:39,944 --> 00:24:42,080
So may get this curve and then
you get another little one.

638
00:24:42,113 --> 00:24:44,516
And this technique so
far has been sensitive

639
00:24:44,549 --> 00:24:45,984
to very small planets.

640
00:24:46,017 --> 00:24:49,287
We're talking things down
well below the size of Earth.

641
00:24:49,320 --> 00:24:51,256
Now, the trick is, this
doesn't happen all the time.

642
00:24:51,289 --> 00:24:52,757
You need these two
stars to line up.

643
00:24:52,790 --> 00:24:54,526
So you need to look at
many, many, many thousands

644
00:24:54,559 --> 00:24:56,528
of stars or millions of stars.

645
00:24:56,561 --> 00:24:58,029
And so WFIRST is
gonna be surveying

646
00:24:58,062 --> 00:24:59,531
the center of our galaxy.

647
00:24:59,564 --> 00:25:00,732
I showed you that
picture at the beginning,

648
00:25:00,765 --> 00:25:02,834
of our, the center
of our galaxy.

649
00:25:02,867 --> 00:25:05,103
Some of the richest star
fields in the galaxy,

650
00:25:05,136 --> 00:25:06,638
and then if you start
looking at a lot of these,

651
00:25:06,671 --> 00:25:10,842
statistically, you'll start
picking these events up.

652
00:25:12,009 --> 00:25:15,113
So, I showed you that
there was the detection

653
00:25:15,146 --> 00:25:17,582
of that dust around
Beta Pictorus in 1983.

654
00:25:17,615 --> 00:25:18,883
With the IRAS satellite,
things started

655
00:25:18,916 --> 00:25:20,785
to get interesting around 1989.

656
00:25:20,818 --> 00:25:23,054

This is the star HD 114762.

657
00:25:24,388 --> 00:25:27,125
These are our lovely
stellar designations, okay?

658
00:25:27,158 --> 00:25:30,328
Stellar designations are
the phone-number names.

659
00:25:30,361 --> 00:25:33,998
This was a giant planet,
orbiting in about 80 days,

660
00:25:34,031 --> 00:25:36,034
roughly at about the
same distance Mercury is

661
00:25:36,067 --> 00:25:37,769
from its star, but this planet's

662
00:25:37,802 --> 00:25:40,405
about 11 times
bigger than Jupiter.

663
00:25:40,438 --> 00:25:41,873
We don't know the
inclination of this system,

664
00:25:41,906 --> 00:25:43,141
we don't know how tilted it is

665
00:25:43,174 --> 00:25:45,310
because it didn't pass
in front of its star.

666
00:25:45,343 --> 00:25:49,013
But around 1989, this
star was being used

667
00:25:49,046 --> 00:25:50,481
as a standard.

668
00:25:50,514 --> 00:25:51,983
When they were measuring the
velocities of other stars

669
00:25:52,016 --> 00:25:55,086
they kept coming back to
this one as a useful ruler

670
00:25:55,119 --> 00:25:56,588
of how fast a star was moving.

671
00:25:56,621 --> 00:25:59,157
And they noticed that this,
this standard star itself

672
00:25:59,190 --> 00:25:59,991
was moving at the

673
00:26:00,024 --> 00:26:02,026
hundreds-of-meters-a-second
level.

674
00:26:02,059 --> 00:26:03,728
So there was this
nice paper Dave Latham

675
00:26:03,761 --> 00:26:06,497
from Harvard Smithsonian
Center for Astrophysics.

676
00:26:06,530 --> 00:26:08,399
And they said, "Well, this
could be a failed star,

677
00:26:08,432 --> 00:26:09,634
"it could be a planet."

678
00:26:09,667 --> 00:26:11,302
And back in these days,
it was a little voodoo

679
00:26:11,335 --> 00:26:14,506
to start saying you
detected a planet.

680
00:26:16,374 --> 00:26:18,276
But as we look back now, this
could be the first planet

681
00:26:18,309 --> 00:26:21,879
that was actually
detected, this one is real.

682
00:26:21,912 --> 00:26:24,182
Things got really
interesting around 1992.

683
00:26:24,215 --> 00:26:26,317
This was 25 years
ago, this week.

684
00:26:26,350 --> 00:26:27,552
Hard to believe.

685
00:26:27,585 --> 00:26:29,621
January, 1992, there
was the discovery

686
00:26:29,654 --> 00:26:33,024
of three planets
around a pulsar.

687
00:26:33,057 --> 00:26:34,325
So what's a pulsar?

688

00:26:34,358 --> 00:26:36,160
This is the remnant
of a massive star

689
00:26:36,193 --> 00:26:37,428
that's undergone a supernova

690
00:26:37,461 --> 00:26:40,765
and all that's left
is this huge mass

691
00:26:40,798 --> 00:26:43,201
about the mass of
our Sun, but packed

692
00:26:43,234 --> 00:26:45,503
into about 10 kilometers, okay?

693
00:26:45,536 --> 00:26:48,806
So, roughly the
size of Pasadena,

694
00:26:48,839 --> 00:26:51,409
but with as much mass
as our Sun, okay?

695
00:26:51,442 --> 00:26:54,512
It would not be a very
nice place to live, okay?

696
00:26:54,545 --> 00:26:56,948
The whole thing is
made of neutrons, okay?

697
00:26:56,981 --> 00:26:59,617
There's so much pressure there

698
00:26:59,650 --> 00:27:01,185
the protons and
electrons themselves

699
00:27:01,218 --> 00:27:03,621
have actually fused
into neutrons.

700
00:27:03,654 --> 00:27:05,890
So it's essentially
a gigantic nucleus.

701
00:27:05,923 --> 00:27:07,592
Well, it has a
huge magnetic field

702
00:27:07,625 --> 00:27:10,361
and it spins rapidly and it
gives off these radio waves.

703
00:27:10,394 --> 00:27:11,295
And those radio waves
can be picked up

704
00:27:11,328 --> 00:27:13,031
by astronomers on Earth.

705
00:27:13,064 --> 00:27:17,168
And lo and behold, this
new pulsar called B1257+12,

706
00:27:17,201 --> 00:27:20,705
also known as Lich, now,
it has a new IU name.

707
00:27:20,738 --> 00:27:22,974
This object was
moving back and forth.

708
00:27:23,007 --> 00:27:25,109
The timing of the radio
signals was changing

709
00:27:25,142 --> 00:27:27,145
and it was fairly complex
because lo and behold,

710
00:27:27,178 --> 00:27:29,247
was three bodies pulling on it.

711
00:27:29,280 --> 00:27:33,051
So, these two outer ones,
and I can't remember

712
00:27:33,084 --> 00:27:34,419
the original letter.

713
00:27:34,452 --> 00:27:36,621
There's letter designations
B, C, D for these.

714
00:27:36,654 --> 00:27:38,189
I like the, there's
the new IU names,

715
00:27:38,222 --> 00:27:39,357
these are easier
to remember now.

716
00:27:39,390 --> 00:27:41,292
Poltergeist and
Draugr, these two are

717
00:27:41,325 --> 00:27:43,561
about three times the
mass of the Earth.

718
00:27:43,594 --> 00:27:45,196
Phobetor is very small.

719
00:27:45,229 --> 00:27:48,099
It's on the order of the

size of Mercury or such.

720
00:27:48,132 --> 00:27:49,534
And these were
very tiny planets.

721
00:27:49,567 --> 00:27:51,235
There was no other effect
they could think of

722
00:27:51,268 --> 00:27:53,171
that could
replicate this

723
00:27:53,204 --> 00:27:55,606
variation in
the pulsar's signals.

724
00:27:55,639 --> 00:27:57,642
So this was really the
first rock-solid evidence

725
00:27:57,675 --> 00:28:00,912
I would say of
extrasolar planets.

726
00:28:00,945 --> 00:28:04,248
And again, that was 25
years ago this week.

727
00:28:04,281 --> 00:28:07,786
Around 1995, things
got interesting again.

728
00:28:09,386 --> 00:28:12,724
This was the
discovery of 51 Peg b.

729
00:28:12,757 --> 00:28:14,058
This was a Hot Jupiter.

730
00:28:14,091 --> 00:28:16,461
This was a very
unexpected signal.

731
00:28:16,494 --> 00:28:18,830
51 Peg is very sun-like star.

732
00:28:18,863 --> 00:28:22,800
It's a yellow, main-sequence
star like the Sun.

733
00:28:22,833 --> 00:28:25,303
Sort of middle-aged
and lo and behold,

734
00:28:25,336 --> 00:28:27,705
the star was moving
back and forth

735
00:28:27,738 --> 00:28:29,207
at about the
100-meter-per-second level

736
00:28:29,240 --> 00:28:30,508
in its orbit.

737
00:28:30,541 --> 00:28:33,044
And what you need to do,
what you need to explain that

738
00:28:33,077 --> 00:28:37,448
is a half-Jupiter-mass planet
on a four-day period, okay?

739
00:28:37,481 --> 00:28:39,784
Nobody was expecting
this before 1995

740

00:28:39,817 --> 00:28:41,786
because as you saw
from our solar system,

741
00:28:41,819 --> 00:28:43,254
we had an example
of one solar system.

742
00:28:43,287 --> 00:28:44,922
We don't have any giant
planets within a few

743
00:28:44,955 --> 00:28:46,591
astronomical units of the Sun.

744
00:28:46,624 --> 00:28:49,727
They're, you need
ices to form those.

745
00:28:49,760 --> 00:28:52,697
So, why would you have
a giant plant so close?

746
00:28:52,730 --> 00:28:54,232
But it was there and it
was quickly confirmed

747
00:28:54,265 --> 00:28:56,835
by another group in California.

748
00:28:58,002 --> 00:28:59,871
So, right away we
were starting to see

749
00:28:59,904 --> 00:29:02,173
some very strange objects, okay?

750
00:29:02,206 --> 00:29:04,675
The first one I showed
you was 10 Jupiter masses.

751
00:29:04,708 --> 00:29:06,611
This was really
pushing the boundaries

752
00:29:06,644 --> 00:29:08,379
of what you might
consider a planet.

753
00:29:08,412 --> 00:29:11,749
The second example was
planets around a dead star,

754
00:29:11,782 --> 00:29:12,950
pulsar planets.

755
00:29:12,983 --> 00:29:14,919
And then the next
example was a Jupiter

756
00:29:14,952 --> 00:29:16,420
orbiting its star in a few days.

757
00:29:16,453 --> 00:29:17,789
Okay, we're nowhere
near finding anything

758
00:29:17,822 --> 00:29:20,725
like our solar
system yet, by 1995.

759
00:29:21,859 --> 00:29:23,327
I'm gonna skip a lot of history,

760
00:29:23,360 --> 00:29:25,530
which is gonna make a lot of
exoplanet astronomers mad.

761
00:29:25,563 --> 00:29:27,698

I'll apologize if I've
left out your planets.

762
00:29:27,731 --> 00:29:28,933
There's a few
thousand of them now

763
00:29:28,966 --> 00:29:30,401
and all your missions
and all your telescopes.

764
00:29:30,434 --> 00:29:32,336
So, we're gonna skip
through to what I think

765
00:29:32,369 --> 00:29:35,907
is a few interesting
cases, here.

766
00:29:35,940 --> 00:29:39,878
And just to show you some
interesting examples.

767
00:29:41,245 --> 00:29:44,248
So, the Kepler Mission
launched in 2009.

768
00:29:44,281 --> 00:29:46,684
I'll show you a few
plots from that mission.

769
00:29:46,717 --> 00:29:49,287
And one of the surprises was
a circumbinary planet, okay?

770
00:29:49,320 --> 00:29:52,490
Could a planet
actually form out here,

771
00:29:53,457 --> 00:29:56,127

outside the orbits of its stars?

772
00:29:58,195 --> 00:30:00,364
And the answer seems to be yes.

773
00:30:00,397 --> 00:30:02,867
And they're finding
many examples of these.

774
00:30:02,900 --> 00:30:04,769
And they're roughly, they
tend to be on the order

775
00:30:04,802 --> 00:30:06,370
of a factor of five further away

776
00:30:06,403 --> 00:30:09,373
that the separations
between the two stars.

777
00:30:09,406 --> 00:30:12,009
As we look at young stars,
we do see examples of pairs

778
00:30:12,042 --> 00:30:14,378
of young stars that actually
have a disk of material

779
00:30:14,411 --> 00:30:15,613
orbiting both.

780
00:30:15,646 --> 00:30:18,249
We see circumbinary
disks of gas and dust

781
00:30:18,282 --> 00:30:21,953
that probably formed
these planets.

782

00:30:21,986 --> 00:30:23,788
So, I'll be the first
astronomer whose given one

783
00:30:23,821 --> 00:30:26,290
of these talks that
does not mention

784
00:30:26,323 --> 00:30:29,160
a certain movie about
a certain person

785
00:30:29,193 --> 00:30:33,865
that was bulls-eyeing womp
rats on their desert planet

786
00:30:33,898 --> 00:30:34,832
that had two stars.

787
00:30:34,865 --> 00:30:37,568
I'm not gonna mention it.

788
00:30:37,601 --> 00:30:41,205
Kepler also found,
has found so far,

789
00:30:41,238 --> 00:30:43,541
small, rocky planets
in the habitable zones

790
00:30:43,574 --> 00:30:44,842
of their stars.

791
00:30:44,875 --> 00:30:46,344
So what do we mean
by habitable zone?

792
00:30:46,377 --> 00:30:48,913
You can start many an
argument defining exactly

793
00:30:48,946 --> 00:30:52,149
what the habitable zone means.

794
00:30:52,182 --> 00:30:55,286
It's the range of
orbital separations

795
00:30:56,720 --> 00:30:59,457
orbiting a star where you could
plausibly have liquid water

796
00:30:59,490 --> 00:31:00,958
on the surface of the planet.

797
00:31:00,991 --> 00:31:05,029
Liquid water seems to be the
main environmental constraint

798
00:31:05,062 --> 00:31:06,430
for life, at least
on our planet.

799
00:31:06,463 --> 00:31:07,899
You need water.

800
00:31:07,932 --> 00:31:10,368
And so, if you move
a planet too close,

801
00:31:10,401 --> 00:31:12,169
if you took Earth and
you moved it a bit closer

802
00:31:12,202 --> 00:31:15,706
to the Sun, you initiate a
runaway greenhouse effect.

803
00:31:15,739 --> 00:31:17,909

You'd actually boil
off the oceans.

804
00:31:17,942 --> 00:31:20,511
If you moved the
Earth too far away,

805
00:31:20,544 --> 00:31:21,879
the Earth starts
to get very cold,

806
00:31:21,912 --> 00:31:23,247
you actually start
freezing out carbon dioxide

807
00:31:23,280 --> 00:31:25,416
up in the atmosphere and
you start forming clouds

808
00:31:25,449 --> 00:31:27,151
that act like a big mirror
and you get a runaway

809
00:31:27,184 --> 00:31:29,086
which actually makes
the planet colder.

810
00:31:29,119 --> 00:31:30,888
So there's sort
of a narrow range

811
00:31:30,921 --> 00:31:32,590
of orbital separations
where a planet

812
00:31:32,623 --> 00:31:35,159
can have liquid water.

813
00:31:35,192 --> 00:31:36,427
And so this is just

a little gallery

814
00:31:36,460 --> 00:31:39,864
of the planets so far,
out of the 2,000 plus

815
00:31:39,897 --> 00:31:42,133
that Kepler has found
that happen to be

816
00:31:42,166 --> 00:31:43,834
in the habitable
zones of their stars.

817
00:31:43,867 --> 00:31:45,403
These are the different
types of stars.

818
00:31:45,436 --> 00:31:47,571
M stars, these are the
so-called red dwarfs.

819
00:31:47,604 --> 00:31:49,840
These are the most common
types of stars in the galaxy.

820
00:31:49,873 --> 00:31:52,343
About 3/4 of the stars in
the galaxy are M dwarfs,

821
00:31:52,376 --> 00:31:55,913
including the next star after
the Sun, Proxima Centauri.

822
00:31:55,946 --> 00:31:57,315
K stars are a
little bit smaller,

823
00:31:57,348 --> 00:31:58,849
typically about half

the mass of the Sun.

824
00:31:58,882 --> 00:32:01,886
And then these are the G
stars like our Sun, okay?

825
00:32:01,919 --> 00:32:03,721
So we have been finding a lot
of these habitable planets

826
00:32:03,754 --> 00:32:06,724
around the M stars and K stars.

827
00:32:06,757 --> 00:32:08,326
It's been a little bit
tougher for the G stars

828
00:32:08,359 --> 00:32:12,730
because you have to trace
the planets further out,

829
00:32:12,763 --> 00:32:14,632
to periods closer to a year

830
00:32:14,665 --> 00:32:17,168
and Kepler had a
limited lifetime

831
00:32:17,201 --> 00:32:19,236
for detecting planets
passing in front of a star.

832
00:32:19,269 --> 00:32:22,139
So this is not indicating
that there's fewer planets

833
00:32:22,172 --> 00:32:24,742
around the G stars, simply
that our current techniques

834
00:32:24,775 --> 00:32:27,044
are more sensitive to
the very close-in planets

835
00:32:27,077 --> 00:32:29,580
around these lower-mass stars.

836
00:32:31,015 --> 00:32:32,450
This was one of my favorites.

837
00:32:32,483 --> 00:32:36,554
This was in one of the first
directly-imaged planets

838
00:32:36,587 --> 00:32:38,556
called Fomalhaut b.

839
00:32:38,589 --> 00:32:41,492
This is a bright
nearby southern star.

840
00:32:41,525 --> 00:32:45,863
It's Alpha Piscis Austrini
in the southern fish.

841
00:32:45,896 --> 00:32:47,732
This is the brightest star
in that constellation.

842
00:32:47,765 --> 00:32:50,501
It has a big disk of
material around it.

843
00:32:50,534 --> 00:32:51,802
I was telling you
about the IRAS Mission

844
00:32:51,835 --> 00:32:53,337
in the early '80s.

845
00:32:53,370 --> 00:32:55,239
This is one of the first big
infrared excesses detected

846
00:32:55,272 --> 00:32:56,474
with that satellite.

847
00:32:56,507 --> 00:32:58,275
There's a lot of
dust in that system.

848
00:32:58,308 --> 00:33:01,813
And back in 2009, Paul
Kalas and colleagues

849
00:33:03,414 --> 00:33:05,249
were looking at
images of Fomalhaut

850
00:33:05,282 --> 00:33:06,751
with a coronagraph in place.

851
00:33:06,784 --> 00:33:08,452
So they're blotting out
the bright star, here.

852
00:33:08,485 --> 00:33:10,187
Fomalhaut's, you know, probably

853
00:33:10,220 --> 00:33:12,823
in the top 10 or 20
brightest stars in the sky.

854
00:33:12,856 --> 00:33:14,458
They had to blot out
the light with Hubble

855
00:33:14,491 --> 00:33:15,760

and see all the faint structure.

856
00:33:15,793 --> 00:33:18,195
And lo and behold, there
was a little dot moving.

857
00:33:18,228 --> 00:33:21,499
And this appears to be a
planet orbiting the star.

858
00:33:21,532 --> 00:33:23,000
What's weird about this thing

859
00:33:23,033 --> 00:33:25,469
is that the colors of it
look like reflected light

860
00:33:25,502 --> 00:33:26,971
from the star.

861
00:33:27,004 --> 00:33:29,373
So what we may be seeing
here is not a Jupiter,

862
00:33:29,406 --> 00:33:30,708
or maybe even not
even a Neptune,

863
00:33:30,741 --> 00:33:32,243
we may be seeing reflected light

864
00:33:32,276 --> 00:33:35,513
from icy particles,
something like Saturn's rings

865
00:33:35,546 --> 00:33:38,716
or a cloud of material
orbiting the star.

866

00:33:38,749 --> 00:33:41,252
So the nature of this object's
a little bit nebulous,

867
00:33:41,285 --> 00:33:42,853
but it's been very interesting.

868
00:33:42,886 --> 00:33:44,422
But we could be
seeing a tiny planet

869
00:33:44,455 --> 00:33:47,124
with a ring system around it.

870
00:33:47,157 --> 00:33:48,359
So speaking of rings,
I wanted to tell you

871
00:33:48,392 --> 00:33:52,630
about one of projects
I've worked on recently.

872
00:33:52,663 --> 00:33:55,066
This is a object, I won't give
you the full phone number,

873
00:33:55,099 --> 00:33:56,600
'cause it's horrible.

874
00:33:56,633 --> 00:33:57,568
This one has one of those
horrible astronomical names

875
00:33:57,601 --> 00:33:59,804
with about 15 digits in it.

876
00:33:59,837 --> 00:34:02,139
We shortened it to J-1407.

877

00:34:02,172 --> 00:34:03,407
This was a nearby young star,

878
00:34:03,440 --> 00:34:04,875
a few hundred light-years away.

879
00:34:04,908 --> 00:34:06,811
It's similar to the
Sun, but it's only

880
00:34:06,844 --> 00:34:10,214
about 15 million years
old, very young star.

881
00:34:10,247 --> 00:34:12,016
And we were looking through data

882
00:34:12,049 --> 00:34:14,652
from a robotic telescope
that was monitoring

883
00:34:14,685 --> 00:34:18,055
the brightnesses of thousands
of stars looking for planets.

884
00:34:18,088 --> 00:34:19,924
And when we were looking
through the data,

885
00:34:19,957 --> 00:34:21,959
one of the young stars
that we were studying,

886
00:34:21,992 --> 00:34:24,528
back on 2007, so this is time,

887
00:34:24,561 --> 00:34:27,398
this is April and May of 2007,

888

00:34:27,431 --> 00:34:29,233
and this is the brightness
of the star, okay?

889
00:34:29,266 --> 00:34:32,837
One is its average brightness
over a few-year period.

890
00:34:32,870 --> 00:34:35,439
And the star rotates really
rapidly every three days

891
00:34:35,472 --> 00:34:37,541
and it has star-spots and
so in the course of a day

892
00:34:37,574 --> 00:34:38,776
it'll go do-do-do-do-do-do,
you know,

893
00:34:38,809 --> 00:34:41,579
it'll vary by about
two or three percent.

894
00:34:41,612 --> 00:34:43,247
And then all of a
sudden in April and May,

895
00:34:43,280 --> 00:34:44,648
over about 2007,

896
00:34:44,681 --> 00:34:48,252
the star started behaving
very badly, okay?

897
00:34:48,285 --> 00:34:49,420
We started seeing dimming

898
00:34:49,453 --> 00:34:51,522
at the tens of

percent level, okay?

899
00:34:51,555 --> 00:34:54,592
That should scream
that there's something

900
00:34:54,625 --> 00:34:55,826
very interesting going on.

901
00:34:55,859 --> 00:34:59,029
You just don't see
stars turn off, okay?

902
00:34:59,062 --> 00:35:03,234
At its dimmest point, the
star had dimmed 95%, okay?

903
00:35:04,201 --> 00:35:05,769
This really got our attention.

904
00:35:05,802 --> 00:35:08,873
The shape of the variations
was even more interesting

905
00:35:08,906 --> 00:35:10,741
because it looked like
you had to be passing

906
00:35:10,774 --> 00:35:12,143
some structure in
front of the star

907
00:35:12,176 --> 00:35:14,011
that it might be symmetric.

908
00:35:14,044 --> 00:35:17,581
So we first saw this
in December 2010

909

00:35:17,614 --> 00:35:19,116
at University of Rochester.

910
00:35:19,149 --> 00:35:20,551
My graduate student,
Mark Picho and I,

911
00:35:20,584 --> 00:35:23,554
I remember in December
2010, looking at this plot,

912
00:35:23,587 --> 00:35:25,923
trying to figure out what
the heck to make of it.

913
00:35:25,956 --> 00:35:29,260
And the first thing
that came to mind

914
00:35:29,293 --> 00:35:32,029
was how the rings of
Uranus were discovered.

915
00:35:32,062 --> 00:35:34,965
So Uranus has these very
faint rings around it.

916
00:35:34,998 --> 00:35:37,935
The Kuiper Airborne
Observatory was used in 1977

917
00:35:37,968 --> 00:35:41,605
to observe Uranus and Uranus
passed in front of a star

918
00:35:41,638 --> 00:35:43,140
and the star blinked off.

919
00:35:43,173 --> 00:35:45,309
And they detected

the rings of Uranus.

920
00:35:45,342 --> 00:35:47,044
And I thought, could
this be like that?

921
00:35:47,077 --> 00:35:48,846
But these rings would have
to be absolutely huge,

922
00:35:48,879 --> 00:35:50,314
very massive.

923
00:35:50,347 --> 00:35:52,816
The bottom is just a zoom-in
of some of the structure.

924
00:35:52,849 --> 00:35:57,121
Each little clump of points
here is one night of data, okay?

925
00:35:57,154 --> 00:35:59,256
This is a real telescope,
a real robotic telescope

926
00:35:59,289 --> 00:36:01,325
from the ground, so you
have to worry about things

927
00:36:01,358 --> 00:36:04,995
like clouds and power-outages
and things that.

928
00:36:05,028 --> 00:36:06,830
And so there's lots of
gaps in the data, okay?

929
00:36:06,863 --> 00:36:09,333
We only have data covering
about 20% of the time here.

930
00:36:09,366 --> 00:36:11,535
But even during after the
gaps, you'll see the star

931
00:36:11,568 --> 00:36:14,271
has still dimmed tens
of percent, okay?

932
00:36:14,304 --> 00:36:17,007
So we tried to piece together
the story of this star.

933
00:36:17,040 --> 00:36:18,809
And you'll notice by the
way, if you look at it,

934
00:36:18,842 --> 00:36:22,680
there's sort of this big
inner dip over a couple weeks

935
00:36:22,713 --> 00:36:25,349
and then you see these
little dips on the side.

936
00:36:25,382 --> 00:36:27,117
And even in the course of
a night, the variation,

937
00:36:27,150 --> 00:36:29,353
it can vary by tens of percent.

938
00:36:29,386 --> 00:36:30,854
This is a really bizarre object.

939
00:36:30,887 --> 00:36:33,390
It took us about a
year to analyze this

940

00:36:33,423 --> 00:36:35,059
and come out with a
paper that even had

941
00:36:35,092 --> 00:36:39,463
a plausible first attempt at
what we thought this thing was.

942
00:36:39,496 --> 00:36:40,698
This is not that first attempt,

943
00:36:40,731 --> 00:36:42,399
this is about our
third attempt, okay?

944
00:36:42,432 --> 00:36:44,635
This is a movie from about 2015.

945
00:36:44,668 --> 00:36:48,539
This is the time, this is
the brightness of the star.

946
00:36:48,572 --> 00:36:50,307
The orange line
is a model trying

947
00:36:50,340 --> 00:36:52,343
to fit those yellow data points.

948
00:36:52,376 --> 00:36:53,978
The yellow data are
the actual measurements

949
00:36:54,011 --> 00:36:55,212
of the star's brightness.

950
00:36:55,245 --> 00:36:57,281
It's not perfect, okay?

951

00:36:57,314 --> 00:36:58,649
It does a reasonable job.

952
00:36:58,682 --> 00:37:00,951
It probably fits
about 90% of the data.

953
00:37:00,984 --> 00:37:04,054
And at top, this is our
model of a huge ring system

954
00:37:04,087 --> 00:37:07,758
around a companion we call
J-1407 little b, okay?

955
00:37:07,791 --> 00:37:09,326
We're not sure
exactly what this is.

956
00:37:09,359 --> 00:37:11,061
It's probably a giant planet.

957
00:37:11,094 --> 00:37:13,931
It could be a failed star
called a brown dwarf.

958
00:37:13,964 --> 00:37:16,200
I'll talk a little
bit about those later.

959
00:37:16,233 --> 00:37:17,501
Right now, we
think it's probably

960
00:37:17,534 --> 00:37:19,937
less than tens of times
the mass of Jupiter.

961
00:37:19,970 --> 00:37:22,172
The whole system, this

whole system of rings

962
00:37:22,205 --> 00:37:25,676
you could fit well inside
the orbit of Mercury, okay?

963
00:37:25,709 --> 00:37:29,146
But it's much bigger than
Saturn's rings, okay?

964
00:37:29,179 --> 00:37:30,814
The whole system is
about 200 times bigger

965
00:37:30,847 --> 00:37:32,049
than Saturn's rings.

966
00:37:32,082 --> 00:37:33,584
This is a totally
different beast.

967
00:37:33,617 --> 00:37:36,053
This is not like
Saturn's systems.

968
00:37:36,086 --> 00:37:38,589
Saturn has a ring system,

969
00:37:38,622 --> 00:37:40,324
covers a few hundred
thousand kilometers,

970
00:37:40,357 --> 00:37:43,060
very icy particles and
they exist in a region

971
00:37:43,093 --> 00:37:45,396
where the tidal forces of Saturn

972

00:37:45,429 --> 00:37:47,698
would shred the material
apart in case it tried

973
00:37:47,731 --> 00:37:49,333
to form a moon.

974
00:37:49,366 --> 00:37:50,734
It'll say, no big
moons here, okay?

975
00:37:50,767 --> 00:37:53,070
Gravity will tear
these objects apart.

976
00:37:53,103 --> 00:37:55,339
This system's about
200 times larger.

977
00:37:55,372 --> 00:37:57,141
And so what we think
we might be seeing

978
00:37:57,174 --> 00:37:58,609
is the material that would go

979
00:37:58,642 --> 00:38:01,812
into forming a system of
moons around a giant planet

980
00:38:01,845 --> 00:38:03,347
or little planets
around a brown dwarf.

981
00:38:03,380 --> 00:38:04,782
I don't even know what,
there's no word yet

982
00:38:04,815 --> 00:38:06,517
for, I guess satellite.

983
00:38:06,550 --> 00:38:08,786
You would say a satellite
around a brown dwarf.

984
00:38:08,819 --> 00:38:10,821
The other interesting
thing is we see these gaps.

985
00:38:10,854 --> 00:38:11,889
We've seen disks before.

986
00:38:11,922 --> 00:38:13,490
We see disks around young stars.

987
00:38:13,523 --> 00:38:16,560
They can be huge, tens of
times the Earth-Sun distance.

988
00:38:16,593 --> 00:38:19,229
We don't see too much
structure in them.

989
00:38:19,262 --> 00:38:20,597
There's a lot of
structure in this.

990
00:38:20,630 --> 00:38:23,000
To explain these dips,
these big variations

991
00:38:23,033 --> 00:38:24,335
at the tens-of-percent level,

992
00:38:24,368 --> 00:38:27,104
there has to be
gaps in the disk.

993
00:38:27,137 --> 00:38:29,473

Well, if there's gaps,
why is there dust

994
00:38:29,506 --> 00:38:32,543
preferentially in some lanes
and not in other lanes, okay?

995
00:38:32,576 --> 00:38:34,945
So, especially this one,
this one really stood out.

996
00:38:34,978 --> 00:38:36,180
We put ring-gap.

997
00:38:36,213 --> 00:38:38,182
We could be seeing
moon formation.

998
00:38:38,215 --> 00:38:41,051
This could be the
first indirect evidence

999
00:38:41,084 --> 00:38:43,721
of exo-moons
orbiting exoplanets,

1000
00:38:43,754 --> 00:38:45,422
orbiting other stars.

1001
00:38:45,455 --> 00:38:47,024
We haven't seen any moons, yet.

1002
00:38:47,057 --> 00:38:48,525
All we've got is this disk.

1003
00:38:48,558 --> 00:38:50,227
But something has
gotta be clearing out

1004

00:38:50,260 --> 00:38:53,097
these lanes in this disk.

1005
00:38:53,130 --> 00:38:55,099
We've gone looking for
more objects like this.

1006
00:38:55,132 --> 00:38:57,768
We keep finding, we've
found a few disks.

1007
00:38:57,801 --> 00:39:01,372
We have a system that'll
be coming out next year

1008
00:39:01,405 --> 00:39:03,874
that is somewhat analogous,
but we haven't found one

1009
00:39:03,907 --> 00:39:08,045
whose structure is as
rich as this system.

1010
00:39:08,078 --> 00:39:11,448
By the way, so my
co-author, Matt Kenworthy

1011
00:39:11,481 --> 00:39:12,649
at University of Leiden had

1012
00:39:12,682 --> 00:39:14,518
this cheeky graphic
he came up with.

1013
00:39:14,551 --> 00:39:16,320
If you replaced
Saturn in our system

1014
00:39:16,353 --> 00:39:18,722
with this set of rings, this

is what it would look like

1015
00:39:18,755 --> 00:39:19,990
during the day.

1016
00:39:21,358 --> 00:39:23,660
It would be picking off
about 1% of the stars' light.

1017
00:39:23,693 --> 00:39:24,928
It would be like a huge mirror.

1018
00:39:24,961 --> 00:39:26,163
There is the moon.

1019
00:39:26,196 --> 00:39:27,998
So how'd you like to
come out during the day

1020
00:39:28,031 --> 00:39:29,633
and see that thing?

1021
00:39:31,835 --> 00:39:35,205
It was a slow news
day in January 2015.

1022
00:39:35,238 --> 00:39:39,176
2015 was such a nice
year, compared to 2016.

1023
00:39:39,209 --> 00:39:42,212
And so for a few hours on CNN,

1024
00:39:42,245 --> 00:39:45,783
this was not fake news,
this was real news.

1025
00:39:45,816 --> 00:39:47,851
This beautiful graphic

was done by Ron Miller

1026
00:39:47,884 --> 00:39:48,986
at Black Cat Studios.

1027
00:39:49,019 --> 00:39:49,920
He's done a lot of space art.

1028
00:39:49,953 --> 00:39:51,789
And I wanted to mention that.

1029
00:39:51,822 --> 00:39:54,725
But he had this beautiful
artwork that went with it.

1030
00:39:54,758 --> 00:39:56,427
I'm doing an experiment
with a student

1031
00:39:56,460 --> 00:39:59,329
at University of Rochester to
build a robotic observatory.

1032
00:39:59,362 --> 00:40:00,964
He's building it, I'm here.

1033
00:40:00,997 --> 00:40:01,932
Hi, Sam.

1034
00:40:01,965 --> 00:40:03,100
(audience chuckling)

1035
00:40:03,133 --> 00:40:04,268
We're hoping to
build this experiment

1036
00:40:04,301 --> 00:40:07,438
to put in Australia in 2017,

1037
00:40:07,471 --> 00:40:10,207
and we wanna watch
a nearby exoplanet

1038
00:40:10,240 --> 00:40:11,341
called Beta Pictoris b.

1039
00:40:11,374 --> 00:40:13,444
I showed you that disk system.

1040
00:40:13,477 --> 00:40:16,079
There's a little planet
they discovered in 2009.

1041
00:40:16,112 --> 00:40:18,816
And this is a movie of
the images of that planet

1042
00:40:18,849 --> 00:40:21,885
over the last, over
about 2013 to 2015.

1043
00:40:21,918 --> 00:40:23,253
And as you see, it's
gonna come very close

1044
00:40:23,286 --> 00:40:25,189
to its star in 2017.

1045
00:40:25,222 --> 00:40:26,690
It's not gonna pass
exactly in front of it,

1046
00:40:26,723 --> 00:40:28,158
but it's gonna
come pretty close.

1047
00:40:28,191 --> 00:40:30,027
So we wanna probe the

region near the planet

1048
00:40:30,060 --> 00:40:33,063
to see if there's any evidence
of a moon-forming disk

1049
00:40:33,096 --> 00:40:34,498
like J-1407.

1050
00:40:34,531 --> 00:40:36,700
This system's only a little
bit older than J-1407.

1051
00:40:36,733 --> 00:40:38,402
We're talkin' about
20 million years.

1052
00:40:38,435 --> 00:40:40,003
So we could be, if we're lucky,

1053
00:40:40,036 --> 00:40:41,705
we may catch a
snapshot of a disk

1054
00:40:41,738 --> 00:40:44,274
passing in front of
a star and maybe see

1055
00:40:44,307 --> 00:40:47,344
if we can catch
moon-formation in action.

1056
00:40:47,377 --> 00:40:49,947
So I now work at
JPL, I'm now working

1057
00:40:49,980 --> 00:40:52,950
with the NASA Exoplanet
Exploration Program.

1058
00:40:52,983 --> 00:40:57,187
Its purpose is described in
the 2014 NASA Science Plan.

1059
00:40:57,220 --> 00:40:59,356
We are here to discover
planets around other stars,

1060
00:40:59,389 --> 00:41:01,625
characterize their properties,
identify candidates

1061
00:41:01,658 --> 00:41:03,660
that could harbor life.

1062
00:41:03,693 --> 00:41:05,529
So we're supporting
various space missions

1063
00:41:05,562 --> 00:41:08,399
and some ground-based
efforts too,

1064
00:41:09,733 --> 00:41:14,371
at achieving discovering
planets and characterizing them.

1065
00:41:14,404 --> 00:41:16,073
This is just a little snapshot
of some of the activities

1066
00:41:16,106 --> 00:41:19,476
that the Exoplanet
Exploration Program does.

1067
00:41:19,509 --> 00:41:21,645
A few of the missions
here that're managed

1068

00:41:21,678 --> 00:41:23,981
are the Kepler and
now K2 Mission.

1069
00:41:24,014 --> 00:41:26,049
Kepler is the the
mission that's finding

1070
00:41:26,082 --> 00:41:28,752
all these transiting planets.

1071
00:41:28,785 --> 00:41:33,657
It has transitioned now, a
couple of the gyros are dead.

1072
00:41:33,690 --> 00:41:35,259
They're in a phase now
where they can only observe

1073
00:41:35,292 --> 00:41:36,960
certain parts of the sky
and they now call this

1074
00:41:36,993 --> 00:41:39,062
the K2 Mission, but
it's still finding

1075
00:41:39,095 --> 00:41:41,365
many dozens of planets.

1076
00:41:41,398 --> 00:41:43,033
This is the WFIRST Mission
I'll talk a little bit

1077
00:41:43,066 --> 00:41:45,168
about here in a few minutes.

1078
00:41:45,201 --> 00:41:46,770
There's development
of a starshade.

1079
00:41:46,803 --> 00:41:48,405
I'll show you the
animation of the starshade.

1080
00:41:48,438 --> 00:41:49,706
And then there's lots
of other activities,

1081
00:41:49,739 --> 00:41:53,443
including some efforts
to characterize disks

1082
00:41:53,476 --> 00:41:55,879
around nearby stars and measure

1083
00:41:55,912 --> 00:42:00,050
their radial velocities in
support of these missions.

1084
00:42:01,017 --> 00:42:02,920
Let me click on this.

1085
00:42:02,953 --> 00:42:04,454
And fortunately,
the sound is off.

1086
00:42:04,487 --> 00:42:07,090
I wanna thank Dan Fabrycky
at University of Chicago.

1087
00:42:07,123 --> 00:42:10,227
This is the classic
Kepler Orrery.

1088
00:42:10,260 --> 00:42:13,564
These are the multi-planet
systems that Kepler found.

1089

00:42:13,597 --> 00:42:15,933
Every one of these
is a solar system.

1090
00:42:15,966 --> 00:42:17,935
And this is only showing
the planets that we can see,

1091
00:42:17,968 --> 00:42:21,438
that happen to be along
the line-of-sight, okay?

1092
00:42:21,471 --> 00:42:23,407
They're sorted by size,
so you get some things

1093
00:42:23,440 --> 00:42:25,108
that are probably
Jupiter-sized, here,

1094
00:42:25,141 --> 00:42:27,477
all the way down to
very tiny things,

1095
00:42:27,510 --> 00:42:31,048
approaching maybe half
the size of the Earth.

1096
00:42:31,081 --> 00:42:33,784
Some of these are three-,
four-, five-planet systems

1097
00:42:33,817 --> 00:42:35,385
and there's a lot of these.

1098
00:42:35,418 --> 00:42:37,387
And we can now start
to measure masses

1099
00:42:37,420 --> 00:42:40,290

because these planets are
tugging on each other.

1100
00:42:40,323 --> 00:42:41,725
I think it was
supposed to zoom in.

1101
00:42:41,758 --> 00:42:42,760
There we go.

1102
00:42:44,227 --> 00:42:47,698
And they're sorted by the
size of the orbits, okay?

1103
00:42:47,731 --> 00:42:48,999
But it's amazing.

1104
00:42:49,032 --> 00:42:50,534
And these are very
close-in systems,

1105
00:42:50,567 --> 00:42:52,736
so pretty much none of these
are like our solar system.

1106
00:42:52,769 --> 00:42:53,870
These are the systems
that have planets

1107
00:42:53,903 --> 00:42:55,505
very, very close to their star.

1108
00:42:55,538 --> 00:42:58,008
Most of these planets
are closer to the star

1109
00:42:58,041 --> 00:42:59,944
than Mercury and Venus.

1110

00:43:01,144 --> 00:43:02,379
Okay, so that's dizzying,

1111
00:43:02,412 --> 00:43:03,714
turn away if it's
hurting your eyes.

1112
00:43:03,747 --> 00:43:05,482
(audience chuckling)

1113
00:43:05,515 --> 00:43:07,584
So the Kepler Mission
was launched in 2009.

1114
00:43:07,617 --> 00:43:09,886
This has been a
phenomenally-successful mission.

1115
00:43:09,919 --> 00:43:12,522
And again, it's in this
so-called K2 phase now,

1116
00:43:12,555 --> 00:43:14,825
where it's using a
limited amount of fuel

1117
00:43:14,858 --> 00:43:16,893
to look at different
fields along the ecliptic,

1118
00:43:16,926 --> 00:43:19,630
along the path where the Earth,

1119
00:43:19,663 --> 00:43:22,532
in the Earth's orbital plane.

1120
00:43:22,565 --> 00:43:25,669
And also, very soon,
the TESS Mission

1121
00:43:27,037 --> 00:43:28,739
being developed at Goddard
Space Flight Center.

1122
00:43:28,772 --> 00:43:31,441
It's gonna be similar to
Kepler, but it's gonna look,

1123
00:43:31,474 --> 00:43:32,976
it's going to image
the whole sky.

1124
00:43:33,009 --> 00:43:35,145
Kepler basically looked
at one region of the sky

1125
00:43:35,178 --> 00:43:37,648
and stared at 100,000 stars

1126
00:43:37,681 --> 00:43:41,018
and discovered about
5,000 candidates

1127
00:43:41,051 --> 00:43:45,722
and we have about 2,000 of those
that are confirmed planets.

1128
00:43:45,755 --> 00:43:47,157
So from the Kepler
and K2 Mission,

1129
00:43:47,190 --> 00:43:49,326
this is showing the
sizes of the planets

1130
00:43:49,359 --> 00:43:50,894
that have been discovered
along with the temperature

1131

00:43:50,927 --> 00:43:52,162
of the host star.

1132
00:43:52,195 --> 00:43:54,364
Our Sun is around
5800 Kelvin, here.

1133
00:43:54,397 --> 00:43:56,700
So these are the yellow stars,
these are the orange stars,

1134
00:43:56,733 --> 00:43:58,035
these are the red stars.

1135
00:43:58,068 --> 00:43:59,703
We're starting to find
a lot of planets now

1136
00:43:59,736 --> 00:44:02,472
that are similar in
size to the Earth, okay?

1137
00:44:02,505 --> 00:44:05,075
So the Earth's size
is a one on here,

1138
00:44:05,108 --> 00:44:08,145
Uranus and Neptune are
around a four on here.

1139
00:44:08,178 --> 00:44:09,946
And you'll notice a lot of
these things are intermediate

1140
00:44:09,979 --> 00:44:14,518
in size between the Earth
and Uranus and Neptune.

1141
00:44:14,551 --> 00:44:16,953
This is one of the interesting

results from Kepler,

1142
00:44:16,986 --> 00:44:20,624
is most of the
planets we're finding,

1143
00:44:20,657 --> 00:44:22,659
there's no counterpart
in our solar system.

1144
00:44:22,692 --> 00:44:23,894
There's planets
intermediate in size

1145
00:44:23,927 --> 00:44:26,630
between Earth and Venus
and Uranus and Neptune

1146
00:44:26,663 --> 00:44:29,733
and they seem to be
very, very common.

1147
00:44:29,766 --> 00:44:32,769
This was a plot form 2015
showing the distribution

1148
00:44:32,802 --> 00:44:33,970
of planets.

1149
00:44:34,003 --> 00:44:35,372
These are the big
Jupiter-like planets.

1150
00:44:35,405 --> 00:44:38,275
Here's the Neptune-sized
planets, two to six Earth radii.

1151
00:44:38,308 --> 00:44:39,910
These are so-called
super-Earths,

1152
00:44:39,943 --> 00:44:41,478
1.25 to two Earth radii.

1153
00:44:41,511 --> 00:44:44,614
These definitions you'll see
vary a little bit over time.

1154
00:44:44,647 --> 00:44:47,851
And these are Earth-size
and smaller, okay?

1155
00:44:47,884 --> 00:44:49,286
Now this could be
a little bit biased

1156
00:44:49,319 --> 00:44:50,987
because these smaller planets
are harder to pick out.

1157
00:44:51,020 --> 00:44:52,923
They cover a smaller area.

1158
00:44:52,956 --> 00:44:56,526
If you de-bias this plot,
if you take into account

1159
00:44:56,559 --> 00:44:58,895
that it's harder to find
the smaller planets,

1160
00:44:58,928 --> 00:45:01,231
you start to get a
distribution like this.

1161
00:45:01,264 --> 00:45:03,166
And we still have this excess.

1162
00:45:03,199 --> 00:45:05,535

There's lots of little
so-called mini-Neptunes

1163
00:45:05,568 --> 00:45:08,872
and super-Earths, for
lack of better terms here.

1164
00:45:08,905 --> 00:45:11,808
And we're seeing a
lot of Earths, also,

1165
00:45:11,841 --> 00:45:15,746
compared to the number
of these gas giants

1166
00:45:15,779 --> 00:45:17,180
and things intermediate
between the size

1167
00:45:17,213 --> 00:45:19,149
of Neptune and Jupiter.

1168
00:45:21,351 --> 00:45:24,554
Coincidentally, the
hypothesized Planet 9

1169
00:45:24,587 --> 00:45:26,990
you may have heard about
that they're looking for,

1170
00:45:27,023 --> 00:45:29,092
the dynamical
estimates, if it's real

1171
00:45:29,125 --> 00:45:31,528
are something on the order
of five to 10 Earth-masses.

1172
00:45:31,561 --> 00:45:33,897
And so that would actually

be intermediate in size

1173
00:45:33,930 --> 00:45:35,098
between Earth and Neptune.

1174
00:45:35,131 --> 00:45:37,467
So if there is a Planet
9, it could be part

1175
00:45:37,500 --> 00:45:40,537
of this class of planets
that so far we have not seen

1176
00:45:40,570 --> 00:45:42,072
up close in our solar system.

1177
00:45:42,105 --> 00:45:46,009
But they're very, very
common around nearby stars.

1178
00:45:46,042 --> 00:45:49,679
This was a recent plot
that was put together

1179
00:45:49,712 --> 00:45:53,884
on showing the masses and
the radii of these exoplanets

1180
00:45:55,185 --> 00:45:56,553
and I've plotted Earth on here.

1181
00:45:56,586 --> 00:45:58,922
One Earth-mass,
one Earth-radius.

1182
00:45:58,955 --> 00:46:02,893
Here's Neptune, 17
Earth-masses, four Earth-radii.

1183

00:46:02,926 --> 00:46:04,561
And here's a lot of these
things that are intermediate

1184
00:46:04,594 --> 00:46:06,029
between the Earth and Neptune.

1185
00:46:06,062 --> 00:46:06,963
We're seeing a lot of the
so-called super-Earths

1186
00:46:06,996 --> 00:46:08,265
and mini-Neptunes.

1187
00:46:08,298 --> 00:46:10,667
These are gas giants
up here, okay?

1188
00:46:10,700 --> 00:46:12,302
So Jupiter, if you
could plot on here,

1189
00:46:12,335 --> 00:46:15,705
Jupiter is about
300 Earth-masses

1190
00:46:15,738 --> 00:46:17,974
and about 10 or 11 Earth-radii.

1191
00:46:18,007 --> 00:46:21,111
So Jupiter's up
here, Neptune, Earth.

1192
00:46:22,512 --> 00:46:25,148
So we're finding a lot of these
things that're intermediate.

1193
00:46:25,181 --> 00:46:27,083
These lines are showing,

1194
00:46:27,116 --> 00:46:28,985
what if you made a
planet out of pure iron?

1195
00:46:29,018 --> 00:46:31,288
Okay, astrophysically, we
don't think that's gonna exist,

1196
00:46:31,321 --> 00:46:32,756
at least far out.

1197
00:46:32,789 --> 00:46:34,925
Maybe close in we might
get things similar to that.

1198
00:46:34,958 --> 00:46:36,493
Things that are
dominated by rock.

1199
00:46:36,526 --> 00:46:37,961
Things that are
dominated by ice.

1200
00:46:37,994 --> 00:46:39,729
And when we mean ice, we
mean the astrophysical ices,

1201
00:46:39,762 --> 00:46:43,099
things like water,
ammonia and methane.

1202
00:46:43,132 --> 00:46:44,835
And if you get bigger
than this line,

1203
00:46:44,868 --> 00:46:46,937
you have to start adding
hydrogen and helium, okay?

1204

00:46:46,970 --> 00:46:48,772
So Uranus and Neptune are
good examples of that.

1205
00:46:48,805 --> 00:46:50,073
Uranus and Neptune have
sort of a sprinkling

1206
00:46:50,106 --> 00:46:51,708
of hydrogen and helium,
but they're probably

1207
00:46:51,741 --> 00:46:54,845
mostly dominated
by ice and rock.

1208
00:46:54,878 --> 00:46:57,113
Earth has a big iron-nickel core

1209
00:46:57,146 --> 00:47:00,350
and a big silicate
mantle and crust

1210
00:47:00,383 --> 00:47:01,885
and just a little
thin veneer of water

1211
00:47:01,918 --> 00:47:04,955
that covers most of the planet.

1212
00:47:04,988 --> 00:47:06,556
But we're finding a
lot of these things

1213
00:47:06,589 --> 00:47:07,757
intermediate in size.

1214
00:47:07,790 --> 00:47:09,092
And you'll notice,
you start running out

1215
00:47:09,125 --> 00:47:10,560
of the rocky planets
once you get up to

1216
00:47:10,593 --> 00:47:12,062
about 10 Earth-radii.

1217
00:47:12,095 --> 00:47:14,197
They all start
getting big, okay?

1218
00:47:14,230 --> 00:47:15,799
And for the big fluffy planets,

1219
00:47:15,832 --> 00:47:18,235
you start losing these
big, large-radii planets

1220
00:47:18,268 --> 00:47:20,337
right around two Earth-radii.

1221
00:47:20,370 --> 00:47:22,806
These things could be
considered gas dwarfs.

1222
00:47:22,839 --> 00:47:24,040
There're things not that
much bigger than Earth

1223
00:47:24,073 --> 00:47:26,276
that are dominated by gas.

1224
00:47:26,309 --> 00:47:28,245
But you may also get things
about 10 times the mass

1225
00:47:28,278 --> 00:47:31,081
of the Earth that are

mostly rock, okay?

1226
00:47:31,114 --> 00:47:33,016
So this intermediate
region's very interesting.

1227
00:47:33,049 --> 00:47:35,385
We're seeing a huge
variety of the densities

1228
00:47:35,418 --> 00:47:36,953
of these planets and
that's gonna translate

1229
00:47:36,986 --> 00:47:40,557
into a huge variety
in their compositions.

1230
00:47:40,590 --> 00:47:42,025
This is the WFIRST Mission.

1231
00:47:42,058 --> 00:47:45,295
This is a project
being formulated now.

1232
00:47:46,396 --> 00:47:48,598
There's work on
developing a coronagraph

1233
00:47:48,631 --> 00:47:50,300
for this instrument, here.

1234
00:47:50,333 --> 00:47:52,636
The coronagraph is the
instrument for blotting out

1235
00:47:52,669 --> 00:47:54,204
the lights of stars.

1236

00:47:54,237 --> 00:47:56,172
This was a very
interesting mission concept

1237
00:47:56,205 --> 00:48:00,310
that the so-called 2010
Astronomical Decadal Survey

1238
00:48:01,978 --> 00:48:03,113
came up with.

1239
00:48:03,146 --> 00:48:04,047
The astronomical
community comes together

1240
00:48:04,080 --> 00:48:07,217
about every decade and comes up

1241
00:48:07,250 --> 00:48:08,785
with recommendations
on missions.

1242
00:48:08,818 --> 00:48:10,053
And this was a very
interesting case

1243
00:48:10,086 --> 00:48:12,088
because it can study
extrasolar planets,

1244
00:48:12,121 --> 00:48:13,990
dark energy and dark matter.

1245
00:48:14,023 --> 00:48:15,759
So it satisfies the
people that study galaxies

1246
00:48:15,792 --> 00:48:19,162
and cosmology and it studies
the people that study planets.

1247
00:48:19,195 --> 00:48:21,164
And it's actually formulated
to work on planets

1248
00:48:21,197 --> 00:48:22,632
in two different regimes.

1249
00:48:22,665 --> 00:48:24,100
It's gonna have a coronagraph
for blotting out the light

1250
00:48:24,133 --> 00:48:26,536
of nearby stars and
it's also gonna image

1251
00:48:26,569 --> 00:48:28,138
near the galactic
center and look

1252
00:48:28,171 --> 00:48:30,340
at many thousands and
thousands of stars

1253
00:48:30,373 --> 00:48:33,009
to look for
microlensing candidates.

1254
00:48:33,042 --> 00:48:34,778
In case a star with a
planet passes in front,

1255
00:48:34,811 --> 00:48:36,746
it'll see an enhancement
in brightness.

1256
00:48:36,779 --> 00:48:39,182
So what that
project is gonna do,

1257
00:48:39,215 --> 00:48:41,184
this is showing the
orbital separation,

1258
00:48:41,217 --> 00:48:43,286
semimajor axis in
astronomical units,

1259
00:48:43,319 --> 00:48:46,490
so the Earth is one,
here's the Earth.

1260
00:48:47,690 --> 00:48:50,126
And this is the planet
mass and Earth-masses.

1261
00:48:50,159 --> 00:48:53,029
Now Kepler, Kepler in
this shaded region,

1262
00:48:53,062 --> 00:48:55,632
these are the planets that
pass in front of the stars.

1263
00:48:55,665 --> 00:48:56,800
So you're very
sensitive to the planets

1264
00:48:56,833 --> 00:48:58,001
that are very close to the star

1265
00:48:58,034 --> 00:48:59,536
but you tend not
to find the ones

1266
00:48:59,569 --> 00:49:01,938
that are further away,
just 'cause geometrically,

1267

00:49:01,971 --> 00:49:05,675
it's much more rare to see
the distant planets line up.

1268
00:49:05,708 --> 00:49:08,111
So WFIRST is gonna help us
sample the outer region.

1269
00:49:08,144 --> 00:49:10,080
This is the realm of the
Jupiter-, Saturn-, Uranus-

1270
00:49:10,113 --> 00:49:11,348
and Neptune-type planets.

1271
00:49:11,381 --> 00:49:14,317
And even things down to
Earth-size and smaller.

1272
00:49:14,350 --> 00:49:18,088
So we're gonna get a statistical
survey of this region,

1273
00:49:18,121 --> 00:49:18,888
this sort of
one-to-10

1274
00:49:18,921 --> 00:49:21,191
astronomical-unit region

1275
00:49:22,091 --> 00:49:23,160
using WFIRST.

1276
00:49:25,228 --> 00:49:27,130
This is an interesting
plot and I apologize,

1277
00:49:27,163 --> 00:49:30,166
'cause I, this one's
gonna get a little messy

1278
00:49:30,199 --> 00:49:32,102
but this is showing
the distribution of

1279
00:49:32,135 --> 00:49:34,871
masses of objects.

1280
00:49:34,904 --> 00:49:36,606
We've got stars over here.

1281
00:49:36,639 --> 00:49:40,210
And this is their density,
how many per cubic parsec.

1282
00:49:40,243 --> 00:49:43,113
Parsecs are astronomer's ruler,

1283
00:49:43,146 --> 00:49:44,948
it's about three and
a quarter light-years.

1284
00:49:44,981 --> 00:49:48,385
So it's basically the number
of stars per density, okay?

1285
00:49:48,418 --> 00:49:50,654
So, this is one solar mass.

1286
00:49:51,854 --> 00:49:53,189
There's the Sun.

1287
00:49:53,222 --> 00:49:54,991
And this is not fitting
all the data we have

1288
00:49:55,024 --> 00:49:56,593
but the distribution of stars,

1289
00:49:56,626 --> 00:49:58,495
it increases as you
get to lower masses

1290
00:49:58,528 --> 00:49:59,763
and then it decreases.

1291
00:49:59,796 --> 00:50:01,664
And recently, we've
been finding things

1292
00:50:01,697 --> 00:50:04,334
floating around in space
that are very low-mass.

1293
00:50:04,367 --> 00:50:07,170
This is 10 to the
minus three Sun-masses.

1294
00:50:07,203 --> 00:50:09,305
That is roughly a Jupiter, okay?

1295
00:50:09,338 --> 00:50:11,608
So things the size
of our Sun are here.

1296
00:50:11,641 --> 00:50:13,676
Things the size of
Jupiter are here.

1297
00:50:13,709 --> 00:50:15,145
Okay, so here's the stars.

1298
00:50:15,178 --> 00:50:17,113
Okay, we've been studying
stars for a long time.

1299
00:50:17,146 --> 00:50:19,949
This is the mass

function of the stars.

1300
00:50:19,982 --> 00:50:22,252
It peaks around a couple
tenths of a solar-mass.

1301
00:50:22,285 --> 00:50:24,421
We tons of these
little dim red dwarfs

1302
00:50:24,454 --> 00:50:26,122
in the solar neighborhood.

1303
00:50:26,155 --> 00:50:27,924
The mechanism for forming stars,

1304
00:50:27,957 --> 00:50:30,126
for collapsing gas in
the inner-stellar medium

1305
00:50:30,159 --> 00:50:32,395
seems to prefer
forming red dwarfs.

1306
00:50:32,428 --> 00:50:34,497
Our Sun is actually
kind of a massive star,

1307
00:50:34,530 --> 00:50:35,799
it's at one solar-mass.

1308
00:50:35,832 --> 00:50:37,200
And you tend not to
see things bigger

1309
00:50:37,233 --> 00:50:38,902
than about 150 times
the mass of the Sun.

1310

00:50:38,935 --> 00:50:42,072
Those are very, very
massive short-lived stars.

1311
00:50:42,105 --> 00:50:44,074
As you go below about a
tenth of the solar-mass,

1312
00:50:44,107 --> 00:50:46,509
you get so-called
brown dwarfs, okay?

1313
00:50:46,542 --> 00:50:49,746
There's a limit below which
the hydrogen in the core

1314
00:50:49,779 --> 00:50:51,614
can't fuse, the
temperatures are too low.

1315
00:50:51,647 --> 00:50:52,882
And these things
aren't really stars.

1316
00:50:52,915 --> 00:50:54,717
They're kinda the
failed stars, okay?

1317
00:50:54,750 --> 00:50:56,686
So the last 20 years,
we've been finding more

1318
00:50:56,719 --> 00:50:58,688
and more of these failed stars

1319
00:50:58,721 --> 00:51:00,256
but there's been
a surprise, okay?

1320
00:51:00,289 --> 00:51:01,825

So this is from about a
tenth of the solar-mass

1321
00:51:01,858 --> 00:51:03,693
down to about a hundredth
of a solar-mass.

1322
00:51:03,726 --> 00:51:05,295
This is about 10 Jupiters.

1323
00:51:05,328 --> 00:51:07,163
Recently, we've been starting

1324
00:51:07,196 --> 00:51:09,732
to see very, very low-mass
things in the field.

1325
00:51:09,765 --> 00:51:10,667
And now we're starting to put

1326
00:51:10,700 --> 00:51:12,102
some estimates on their density.

1327
00:51:12,135 --> 00:51:14,404
By the way, I'm sorry, there's
the hydrogen burn limit.

1328
00:51:14,437 --> 00:51:16,206
Now, when I squint,
this is a paper

1329
00:51:16,239 --> 00:51:18,274
that just came out by Jonathan
Gagné I'm co-author on.

1330
00:51:18,307 --> 00:51:20,577
If I squint and I look at this,

1331
00:51:20,610 --> 00:51:22,946

you could just about
fit a line through here.

1332
00:51:22,979 --> 00:51:24,948
I wouldn't place any bets on it.

1333
00:51:24,981 --> 00:51:27,650
The line I've picked is
actually the mass function

1334
00:51:27,683 --> 00:51:30,820
for planets orbiting
stars, okay?

1335
00:51:30,853 --> 00:51:33,656
It goes roughly as the mass
to the minus one power.

1336
00:51:33,689 --> 00:51:35,225
You have many fewer
massive planets

1337
00:51:35,258 --> 00:51:37,293
than you do low-mass planets.

1338
00:51:37,326 --> 00:51:41,264
If you fit that
function through here,

1339
00:51:41,297 --> 00:51:43,566
these could be planets
that are floating in space

1340
00:51:43,599 --> 00:51:45,435
that are not orbiting a star.

1341
00:51:45,468 --> 00:51:47,437
These could be the
so-called rogue planets.

1342
00:51:47,470 --> 00:51:49,372
And I think I'm
starting to see data

1343
00:51:49,405 --> 00:51:51,141
from a few different
surveys now that I think

1344
00:51:51,174 --> 00:51:53,710
there's a convincing
case to made,

1345
00:51:53,743 --> 00:51:55,545
that there's a
separate population.

1346
00:51:55,578 --> 00:51:58,615
These things fundamentally
formed different from stars.

1347
00:51:58,648 --> 00:52:03,019
The physics of gas and dust
on the scales of light-years,

1348
00:52:03,052 --> 00:52:04,687
and gravity winning
out over gas-pressure

1349
00:52:04,720 --> 00:52:07,490
and magnetic-field
pressure, that forms stars

1350
00:52:07,523 --> 00:52:09,959
and the brown dwarf
population, okay?

1351
00:52:09,992 --> 00:52:11,227
But below that,
there seems to be

1352
00:52:11,260 --> 00:52:13,196
this whole different population.

1353
00:52:13,229 --> 00:52:15,932
And these could be planets
that have been stripped

1354
00:52:15,965 --> 00:52:19,102
from their stars and
just roaming in space.

1355
00:52:19,135 --> 00:52:21,171
So we keep talkin' about,
you know, Alpha Centauri

1356
00:52:21,204 --> 00:52:23,773
as the nearest
destination in space.

1357
00:52:23,806 --> 00:52:26,042
We could very well find
things that are on the order

1358
00:52:26,075 --> 00:52:29,579
of the sizes of Jupiters or
Saturns or Neptunes floating.

1359
00:52:29,612 --> 00:52:31,915
There could be many more
targets, just not stars,

1360
00:52:31,948 --> 00:52:34,017
between us and Alpha Centauri

1361
00:52:34,050 --> 00:52:37,086
and these would be dimly
glowing in the infrared.

1362
00:52:37,119 --> 00:52:40,223

So there's our rogue planet.

1363
00:52:40,256 --> 00:52:41,724
The James Webb Space Telescope

1364
00:52:41,757 --> 00:52:43,660
is gonna be launching in 2019.

1365
00:52:43,693 --> 00:52:44,594
This is gonna be the successor

1366
00:52:44,627 --> 00:52:46,196
to the Hubble Space Telescope.

1367
00:52:46,229 --> 00:52:48,464
It's gonna be studying
planets that pass

1368
00:52:48,497 --> 00:52:49,966
in front of their stars.

1369
00:52:49,999 --> 00:52:52,535
Some of the missions like
Kepler and TESS and K2

1370
00:52:52,568 --> 00:52:56,239
are feeding targets
into the plans for JWST.

1371
00:52:56,272 --> 00:52:58,441
What we want is
nearby bright stars

1372
00:52:58,474 --> 00:53:00,310
that have planets
passing in front of them

1373
00:53:00,343 --> 00:53:03,279
and we can measure the

spectra of those planets.

1374
00:53:03,312 --> 00:53:04,681
And so there'll be
some interesting

1375
00:53:04,714 --> 00:53:07,150
extrasolar planetary
science coming out of JWST.

1376
00:53:07,183 --> 00:53:10,520
But beyond JWST, what
we really wanna see

1377
00:53:10,553 --> 00:53:14,958
is the small pale dots, the
pale blue dots next to stars.

1378
00:53:14,991 --> 00:53:17,360
And so this is one of the
concepts that's being worked on.

1379
00:53:17,393 --> 00:53:18,561
And in fact, here at JPL,

1380
00:53:18,594 --> 00:53:20,496
there's a so-called
starshade, okay?

1381
00:53:20,529 --> 00:53:23,900
The idea of a starshade
is you launch a telescope

1382
00:53:23,933 --> 00:53:26,703
and then you launce a
separate spacecraft, okay?

1383
00:53:26,736 --> 00:53:29,272
And the model they have is
about 34 meters in size,

1384
00:53:29,305 --> 00:53:30,506
pretty big.

1385
00:53:30,539 --> 00:53:33,009
But you can wrap it
up inside of a rocket

1386
00:53:33,042 --> 00:53:35,111
and let it unfurl in space.

1387
00:53:35,144 --> 00:53:37,513
And this starshade, you
would put between what star

1388
00:53:37,546 --> 00:53:39,716
you wanted to look at
and your telescope.

1389
00:53:39,749 --> 00:53:42,585
And so the starshade would
essentially form a little shadow

1390
00:53:42,618 --> 00:53:44,687
and you have to keep your
spacecraft in that shadow

1391
00:53:44,720 --> 00:53:46,990
and then look for the
dim little planets

1392
00:53:47,023 --> 00:53:50,693
whose light is not passing
through the starshade, okay?

1393
00:53:50,726 --> 00:53:52,228
Lots of technical challenges,

1394
00:53:52,261 --> 00:53:55,932

but there's a path ahead and
there's currently proposals

1395
00:53:55,965 --> 00:53:58,535
now to construct the starshade.

1396
00:53:59,468 --> 00:54:00,570
And there's actually a demo

1397
00:54:00,603 --> 00:54:03,473
in one of the
buildings here at JPL.

1398
00:54:03,506 --> 00:54:04,907
So this is what it
would look like.

1399
00:54:04,940 --> 00:54:06,376
This is an earlier concept
where the starshade

1400
00:54:06,409 --> 00:54:08,578
would actually launch
with a telescope.

1401
00:54:08,611 --> 00:54:11,347
One of the proposals
on the table now

1402
00:54:11,380 --> 00:54:15,018
that's being considered is you
launch the WFIRST spacecraft

1403
00:54:15,051 --> 00:54:17,120
in the mid-2020s and
then a few years later,

1404
00:54:17,153 --> 00:54:20,123
you would launch a
separate starshade mission

1405
00:54:20,156 --> 00:54:24,127
and the starshade would
move about 80,000 kilometers

1406
00:54:24,160 --> 00:54:25,762
away from the spacecraft.

1407
00:54:25,795 --> 00:54:27,230
Right here, they show like
they're close together.

1408
00:54:27,263 --> 00:54:29,966
They won't be close together.

1409
00:54:29,999 --> 00:54:32,702
And the starshade
has its own fuel.

1410
00:54:32,735 --> 00:54:36,406
And so it would sort of
park in front of a star,

1411
00:54:36,439 --> 00:54:39,909
WFIRST would look at it or
whatever future mission comes up

1412
00:54:39,942 --> 00:54:44,213
and you would study the
planets, the faint planets.

1413
00:54:44,246 --> 00:54:46,049
And basically if you
wanna get down to things

1414
00:54:46,082 --> 00:54:47,350
that are about
the size of Earth,

1415

00:54:47,383 --> 00:54:49,285
this is really the next
step you have to take.

1416
00:54:49,318 --> 00:54:52,455
Right now, we're not, this
is gonna be a ways ahead

1417
00:54:52,488 --> 00:54:53,556
of the 2020s.

1418
00:54:54,857 --> 00:54:57,694
I'll show a few slides
on Proxima Centauri b,

1419
00:54:57,727 --> 00:54:59,362
'cause you've probably heard
about this in the media.

1420
00:54:59,395 --> 00:55:01,631
So Proxima Centauri's the
nearest star to the Sun.

1421
00:55:01,664 --> 00:55:03,232
It's about four
light-years away.

1422
00:55:03,265 --> 00:55:06,836
And it was a great discovery,
middle of last year.

1423
00:55:06,869 --> 00:55:08,971
And this was a
ground-based discovery.

1424
00:55:09,004 --> 00:55:10,406
There were some
astronomers in Europe

1425
00:55:10,439 --> 00:55:13,509

that used a ground-based
telescope with a spectrograph.

1426
00:55:13,542 --> 00:55:14,677
And they were
measuring the motions

1427
00:55:14,710 --> 00:55:16,179
of Proxima Centauri
very closely.

1428
00:55:16,212 --> 00:55:17,680
And what they decided to
do was observe it night

1429
00:55:17,713 --> 00:55:19,015
after night, after night,
after night, after night

1430
00:55:19,048 --> 00:55:20,416
for months, okay?

1431
00:55:20,449 --> 00:55:21,784
They took a lot of
telescope time to do this.

1432
00:55:21,817 --> 00:55:23,286
It was worth it, okay?

1433
00:55:23,319 --> 00:55:25,621
So what they found on the
velocity signal of the star

1434
00:55:25,654 --> 00:55:27,724
was this little 11-day ripple

1435
00:55:27,757 --> 00:55:29,726
at the
one-meter-per-second level.

1436
00:55:29,759 --> 00:55:31,327
Okay, this is one
meter per second.

1437
00:55:31,360 --> 00:55:33,996
Actually, I'm not allowed
to walk over the rug here.

1438
00:55:34,029 --> 00:55:35,131
One meter per second.

1439
00:55:35,164 --> 00:55:36,766
This is an Earth-sized
planet tugging

1440
00:55:36,799 --> 00:55:40,970
on a little star about a
tenth of the size of our Sun.

1441
00:55:41,003 --> 00:55:43,406
So, this is the art
for Proxima Centauri b.

1442
00:55:43,439 --> 00:55:46,442
This is Proxima Centauri,
the little faint star.

1443
00:55:46,475 --> 00:55:47,844
It's actually a triple system.

1444
00:55:47,877 --> 00:55:50,179
Our nearest stellar
neighbor is a triple, okay?

1445
00:55:50,212 --> 00:55:52,482
Our Sun is a little bit of
an oddball as a single star.

1446
00:55:52,515 --> 00:55:55,885

Lots of stars come in doubles,
triples, quadruples and up.

1447
00:55:55,918 --> 00:55:58,121
So the art here
actually shows this.

1448
00:55:58,154 --> 00:56:00,490
There's two sun-like
stars very far away,

1449
00:56:00,523 --> 00:56:03,025
about 10,000 astronomical
units away from the star.

1450
00:56:03,058 --> 00:56:05,361
And then here's the
little red-dwarf star

1451
00:56:05,394 --> 00:56:07,797
of Proxima Centauri.

1452
00:56:07,830 --> 00:56:08,798
So these are the designations,

1453
00:56:08,831 --> 00:56:10,233
Alpha Centauri A, B and C

1454
00:56:10,266 --> 00:56:13,403
and then the so-called proper
names, Rigel Kentaurus.

1455
00:56:13,436 --> 00:56:15,271
This was the foot
of the centaur,

1456
00:56:15,304 --> 00:56:16,639
Proxima Centauri
was the nickname

1457
00:56:16,672 --> 00:56:19,976
for the dim red dwarf
discovered about 100 years ago.

1458
00:56:20,009 --> 00:56:21,878
This is just showing a
comparison of the size

1459
00:56:21,911 --> 00:56:23,479
of those stars
compared to the Sun.

1460
00:56:23,512 --> 00:56:25,915
Alpha Centauri A is a little
bit bigger than the Sun.

1461
00:56:25,948 --> 00:56:28,117
Alpha Centauri B is a little
bit smaller than the Sun.

1462
00:56:28,150 --> 00:56:31,421
Proxima Centauri's about a
tenth the size of the Sun.

1463
00:56:31,454 --> 00:56:32,555
And there could be planets

1464
00:56:32,588 --> 00:56:35,225
around Alpha Centauri
A and B, too.

1465
00:56:36,425 --> 00:56:39,362
There was a purported
planet a few years ago

1466
00:56:39,395 --> 00:56:42,765
around Alpha Centauri B,
so far that seems to have

1467

00:56:42,798 --> 00:56:43,966
not been confirmed.

1468
00:56:43,999 --> 00:56:46,936
But so far Proxima
Centauri b looks good.

1469
00:56:46,969 --> 00:56:48,771
This was showing a
comparison of the Sun

1470
00:56:48,804 --> 00:56:50,006
and Mercury's orbit.

1471
00:56:50,039 --> 00:56:53,376
Okay, our innermost
planet along with,

1472
00:56:53,409 --> 00:56:56,579
on this side, Proxima
Centauri, dim little red dwarf.

1473
00:56:56,612 --> 00:56:58,948
If you can see, its
luminosity's very tiny.

1474
00:56:58,981 --> 00:57:01,651
It's about .0015
times the energy

1475
00:57:02,852 --> 00:57:04,353
that the Sun is putting out.

1476
00:57:04,386 --> 00:57:06,823
This is the habitable
zone for Proxima Centauri

1477
00:57:06,856 --> 00:57:09,192
and lo and behold,
Proxima Centauri b,

1478
00:57:09,225 --> 00:57:10,693
it orbits its star in 11 days,

1479
00:57:10,726 --> 00:57:12,895
but this star is so dim
that if you wanna look

1480
00:57:12,928 --> 00:57:14,163
for a place that
has liquid water,

1481
00:57:14,196 --> 00:57:16,699
you have to move this
close to the star, okay?

1482
00:57:16,732 --> 00:57:18,434
You're campin' real
close to the fire

1483
00:57:18,467 --> 00:57:19,902
to keep that water liquid.

1484
00:57:19,935 --> 00:57:24,006
Now we don't know, this planet
is probably a rocky planet

1485
00:57:24,039 --> 00:57:25,374
based on its mass.

1486
00:57:25,407 --> 00:57:26,943
We don't have an
estimate of the radii,

1487
00:57:26,976 --> 00:57:28,344
we don't have an
estimate of the,

1488
00:57:28,377 --> 00:57:30,179

we haven't seen the
atmosphere or anything yet.

1489
00:57:30,212 --> 00:57:35,151
So right now, there's a
bit of speculation on that.

1490
00:57:35,184 --> 00:57:37,253
By the way, eventually,
these planets'll need names.

1491
00:57:37,286 --> 00:57:41,324
Eventually your kids and
your grandkids and beyond,

1492
00:57:41,357 --> 00:57:42,592
some of these objects are
gonna be so interesting

1493
00:57:42,625 --> 00:57:43,993
that they may have
their own proper names.

1494
00:57:44,026 --> 00:57:46,429
You think of the planets
in our own solar system.

1495
00:57:46,462 --> 00:57:47,597
So this is the first attempt

1496
00:57:47,630 --> 00:57:49,532
the International
Astronomical Union did.

1497
00:57:49,565 --> 00:57:51,701
Last year, there was a contest
opened up to the public

1498
00:57:51,734 --> 00:57:54,571
called the Name

Exoworlds Contest.

1499
00:57:55,971 --> 00:57:57,507
And so there was a few
dozen of these exoplanets

1500
00:57:57,540 --> 00:57:59,675
were actually named and you
saw a few of those in the talk.

1501
00:57:59,708 --> 00:58:00,943
And so some of these are like,

1502
00:58:00,976 --> 00:58:02,144
there's a very
nice example here.

1503
00:58:02,177 --> 00:58:04,747
The mu Aire system is
known as Cervantes,

1504
00:58:04,780 --> 00:58:07,183
Quijote, Dulcinea,
Rocinante, Sancho.

1505
00:58:07,216 --> 00:58:08,851
So some of them have
interesting themes

1506
00:58:08,884 --> 00:58:11,187
based on characters from books.

1507
00:58:11,220 --> 00:58:13,689
The contest was, there was
entries from all over the world.

1508
00:58:13,722 --> 00:58:16,425
You had to be in an astronomical
organization to apply, so,

1509
00:58:16,458 --> 00:58:19,295
but there was classrooms
and amateur astronomy clubs

1510
00:58:19,328 --> 00:58:20,530
that contributed.

1511
00:58:20,563 --> 00:58:23,232
And so there was a
lot of great entries

1512
00:58:23,265 --> 00:58:24,734
and so these are the
ones that won out.

1513
00:58:24,767 --> 00:58:27,837
There was 600,000 votes from
all over the world for these.

1514
00:58:27,870 --> 00:58:31,240
So this was the first
attempt of the IAU at this

1515
00:58:31,273 --> 00:58:35,578
but I suspect we'll be doing
more of this in the future.

1516
00:58:35,611 --> 00:58:37,246
I just wanted to
look back at Earth.

1517
00:58:37,279 --> 00:58:39,782
There's this great
picture the Voyagers took,

1518
00:58:39,815 --> 00:58:41,851
Voyager 1 took in 1991.

1519
00:58:41,884 --> 00:58:44,320

This was the Earth
as seen from tens

1520
00:58:44,353 --> 00:58:47,690
of astronomical units
away from the Sun.

1521
00:58:49,358 --> 00:58:50,159
Oops.

1522
00:58:51,293 --> 00:58:52,762
Oh, it didn't show
the other one.

1523
00:58:52,795 --> 00:58:53,963
Okay, I have another one,
there was a picture that

1524
00:58:53,996 --> 00:58:55,965
was just taken this
week from Mars.

1525
00:58:55,998 --> 00:58:57,466
From one of the Mars orbiters.

1526
00:58:57,499 --> 00:59:00,069
It shows the Earth and the
Moon as seen from Mars.

1527
00:59:00,102 --> 00:59:01,537
But at the end of the day,

1528
00:59:01,570 --> 00:59:04,106
we'd like to also understand
the Earth in the context

1529
00:59:04,139 --> 00:59:05,608
of the other planets.

1530

00:59:05,641 --> 00:59:08,010
We only have one Earth, we
can't run the experiment

1531
00:59:08,043 --> 00:59:11,647
of forming the Earth
and we probably

1532
00:59:11,680 --> 00:59:13,182
shouldn't be tweaking too much

1533
00:59:13,215 --> 00:59:14,550
with the chemistry of the
atmosphere and the oceans.

1534
00:59:14,583 --> 00:59:15,818
Just a suggestion.

1535
00:59:15,851 --> 00:59:18,387
I like the Earth the way it is.

1536
00:59:18,420 --> 00:59:21,357
But we get to see all
the different examples

1537
00:59:21,390 --> 00:59:23,492
of how physics and
chemistry comes together

1538
00:59:23,525 --> 00:59:24,860
to form other planets.

1539
00:59:24,893 --> 00:59:26,462
So this is sort of
a, it's January,

1540
00:59:26,495 --> 00:59:28,998
this is the state of
the galaxy report.

1541
00:59:29,031 --> 00:59:31,267
This is, I'm gonna
give you a few results.

1542
00:59:31,300 --> 00:59:32,501
These are basically
extrapolating

1543
00:59:32,534 --> 00:59:34,236
from what we know now, okay?

1544
00:59:34,269 --> 00:59:36,973
We don't have a complete
census of all these objects.

1545
00:59:37,006 --> 00:59:38,474
This is just from what
we've been able to gather

1546
00:59:38,507 --> 00:59:40,376
from some of these systems.

1547
00:59:40,409 --> 00:59:42,445
First off, exoplanets
are ubiquitous, okay?

1548
00:59:42,478 --> 00:59:45,047
Nearly every star you see in
the night sky has planets.

1549
00:59:45,080 --> 00:59:46,248
This is amazing, okay?

1550
00:59:46,281 --> 00:59:47,183
This is one of
the terms that was

1551
00:59:47,216 --> 00:59:48,451
in the so-called Drake equation.

1552
00:59:48,484 --> 00:59:49,685
How common are planets?

1553
00:59:49,718 --> 00:59:52,855
We now know planets
are very, very common.

1554
00:59:52,888 --> 00:59:55,091
Sun-like planets, sorry,
Sun-like stars typically

1555
00:59:55,124 --> 00:59:57,126
have five or more planets.

1556
00:59:57,159 --> 00:59:58,661
There could be even more.

1557
00:59:58,694 --> 01:00:00,663
This is only down to the size
of about half an Earth, okay?

1558
01:00:00,696 --> 01:00:02,798
So most of those stars
not only have planets,

1559
01:00:02,831 --> 01:00:05,401
they probably have
several planets.

1560
01:00:05,434 --> 01:00:07,069
The super-Earths
and mini-Neptunes,

1561
01:00:07,102 --> 01:00:08,304
these things sort
of intermediate

1562
01:00:08,337 --> 01:00:09,772

between the size of
the Earth and Neptune,

1563
01:00:09,805 --> 01:00:13,242
they seem to be more common
than the rocky planets.

1564
01:00:13,275 --> 01:00:14,477
They especially
seem to be common

1565
01:00:14,510 --> 01:00:17,013
around the very
lowest-mass stars.

1566
01:00:18,113 --> 01:00:19,048
That may be a hint
why the aliens

1567
01:00:19,081 --> 01:00:21,751
haven't got here, yet, alright?

1568
01:00:21,784 --> 01:00:23,386
The planets, if there's
a lot of these planets

1569
01:00:23,419 --> 01:00:25,154
that have these big
gaseous envelopes,

1570
01:00:25,187 --> 01:00:27,790
they may not be conducive
for forming life.

1571
01:00:27,823 --> 01:00:31,227
But anyway, so those
intermediate-sized planets

1572
01:00:31,260 --> 01:00:32,695
seem to be very common.

1573
01:00:32,728 --> 01:00:34,997
Planets form over a wide
range of stellar properties.

1574
01:00:35,030 --> 01:00:36,532
It seems like everywhere we go

1575
01:00:36,565 --> 01:00:39,268
in parameter space is a
function of stellar mass,

1576
01:00:39,301 --> 01:00:40,536
luminosity, age.

1577
01:00:40,569 --> 01:00:43,205
We see planets around
very youngest stars.

1578
01:00:43,238 --> 01:00:45,041
The oldest planetary
system we've seen so far

1579
01:00:45,074 --> 01:00:46,942
is 11 billion years old, okay?

1580
01:00:46,975 --> 01:00:48,577
The universe is 13
billion years old.

1581
01:00:48,610 --> 01:00:50,913
This is one of the,

1582
01:00:50,946 --> 01:00:53,549
we've seen a system with
a full set of planets

1583
01:00:53,582 --> 01:00:56,652
that formed less than 2 billion

years after the Big Bang.

1584
01:00:56,685 --> 01:00:58,688
We see the planets as a variety,

1585
01:00:58,721 --> 01:01:00,122
varying by chemical composition

1586
01:01:00,155 --> 01:01:01,357
around the very metal-rich stars

1587
01:01:01,390 --> 01:01:02,825
and around the very
metal-poor stars.

1588
01:01:02,858 --> 01:01:05,628
We're starting to see some
trends like the planets that,

1589
01:01:05,661 --> 01:01:08,197
the stars that have more metals
seem to form more Jupiters.

1590
01:01:08,230 --> 01:01:09,965
So that might be telling us
something about the conditions

1591
01:01:09,998 --> 01:01:11,267
for forming planets.

1592
01:01:11,300 --> 01:01:13,102
And also the
multiplicity of the star.

1593
01:01:13,135 --> 01:01:14,537
We see planets around
one-star systems,

1594
01:01:14,570 --> 01:01:16,806

two-star systems,
triples quadruples,

1595
01:01:16,839 --> 01:01:19,909
so the planets are
very resilient.

1596
01:01:19,942 --> 01:01:21,444
The incidents of the exo-Earths.

1597
01:01:21,477 --> 01:01:22,945
This is still being worked on.

1598
01:01:22,978 --> 01:01:25,181
If we called the so-called
exo-Earths rocky planets,

1599
01:01:25,214 --> 01:01:27,116
rock-dominated planets
between about half the size

1600
01:01:27,149 --> 01:01:29,819
of the Earth and 1.5 times
the size of the Earth.

1601
01:01:29,852 --> 01:01:30,653
I picked that
upper limit

1602
01:01:30,686 --> 01:01:32,922
because if you
go bigger than that

1603
01:01:32,955 --> 01:01:34,256
it looks like the
planets start

1604
01:01:34,289 --> 01:01:37,226
to get very thick
gaseous envelopes

1605
01:01:38,127 --> 01:01:39,328
and they become less Earth-like.

1606
01:01:39,361 --> 01:01:42,965
If you go much below
about Earth-mass

1607
01:01:42,998 --> 01:01:45,268
in size, you start to have,

1608
01:01:46,168 --> 01:01:47,803
the lower gravity starts to,

1609
01:01:47,836 --> 01:01:49,238
you start to lose atmosphere.

1610
01:01:49,271 --> 01:01:50,606
It would turn into
something more like Mars.

1611
01:01:50,639 --> 01:01:52,108
So, we're sort of
looking at things

1612
01:01:52,141 --> 01:01:54,310
within about half the
size of the Earth in size

1613
01:01:54,343 --> 01:01:55,578
and orbiting in their
habitable zones.

1614
01:01:55,611 --> 01:01:56,946
So how many are there?

1615
01:01:56,979 --> 01:01:58,581
This is still being debated.

1616
01:01:58,614 --> 01:02:01,450
There's still, people
are still taking the data

1617
01:02:01,483 --> 01:02:04,053
and trying to
statistically combine it.

1618
01:02:04,086 --> 01:02:05,721
And the answers
are coming up over,

1619
01:02:05,754 --> 01:02:06,655
there's a bit of a range, here,

1620
01:02:06,688 --> 01:02:08,257
by about a factor of 10 or so.

1621
01:02:08,290 --> 01:02:11,393
But the answer's probably
something like a half, okay?

1622
01:02:11,426 --> 01:02:14,230
There's probably about half
a planet per Sun-like star

1623
01:02:14,263 --> 01:02:15,698
where you've got a rocky planet.

1624
01:02:15,731 --> 01:02:19,702
That's not to say that's the
incidence of planets with life.

1625
01:02:19,735 --> 01:02:20,636
There's a lot of things that

1626
01:02:20,669 --> 01:02:22,171
can go wrong with those planets.

1627
01:02:22,204 --> 01:02:24,373
They may have the right size,
they may be in the right place

1628
01:02:24,406 --> 01:02:27,042
but there may be
other conditions

1629
01:02:27,075 --> 01:02:29,211
that preclude life on them.

1630
01:02:29,244 --> 01:02:31,580
I wanted to show this plot
I had made several years ago

1631
01:02:31,613 --> 01:02:33,382
and I just updated it last Fall.

1632
01:02:33,415 --> 01:02:36,919
This is kinda the
Moore's Law for planets.

1633
01:02:36,952 --> 01:02:39,388
This is showing the
year going back to 1989

1634
01:02:39,421 --> 01:02:41,490
and this is the number of
planets but its logarithmic.

1635
01:02:41,523 --> 01:02:43,893
It goes one, 10, 100, 1,000.

1636
01:02:43,926 --> 01:02:46,228
And the remarkable thing is
over the last three decades,

1637
01:02:46,261 --> 01:02:48,764
this doubling time

hasn't varied that much.

1638
01:02:48,797 --> 01:02:51,567
About every 27 months the
number of exoplanets doubles.

1639
01:02:51,600 --> 01:02:52,768
And actually if you
look at the missions

1640
01:02:52,801 --> 01:02:54,036
that are coming
ahead, we'll probably

1641
01:02:54,069 --> 01:02:55,871
be discovering tens of
thousands of planets

1642
01:02:55,904 --> 01:02:57,873
with those missions
and this trend looks

1643
01:02:57,906 --> 01:03:01,911
like it'll continue at least
well through the 2020s.

1644
01:03:01,944 --> 01:03:05,281
So there is a characteristic
doubling time scale.

1645
01:03:05,314 --> 01:03:07,116
The interesting thing is
once you start finding these,

1646
01:03:07,149 --> 01:03:08,918
now you're gonna
start finding planets

1647
01:03:08,951 --> 01:03:10,853
that are more and

more similar to Earth.

1648
01:03:10,886 --> 01:03:12,655
You're starting to find
things that are within

1649
01:03:12,688 --> 01:03:15,224
a small parameter-range of
the characteristics of Earth.

1650
01:03:15,257 --> 01:03:17,426
And hopefully, we'll be able
to get the spectra of those.

1651
01:03:17,459 --> 01:03:20,763
So, I'm gonna put this slide up,

1652
01:03:20,796 --> 01:03:23,365
these are a few links to
the Exoplanets Program:

1653
01:03:23,398 --> 01:03:25,501
exoplanets.nasa.gov.

1654
01:03:25,534 --> 01:03:28,504
We have the NASA
Exoplanet Archive down

1655
01:03:28,537 --> 01:03:32,708
at the Caltech campus at the
so-called MechSci Institute.

1656
01:03:34,076 --> 01:03:36,278
This is a shout-out to the
Kepler and K2 Exoplanet Mission.

1657
01:03:36,311 --> 01:03:38,914
They have a lot of great
graphics from that mission.

1658
01:03:38,947 --> 01:03:40,449
And I'm gonna show
a little example

1659
01:03:40,482 --> 01:03:43,352
for a minute or two here of
the so-called NASA Eyes app.

1660
01:03:43,385 --> 01:03:45,421
This is an app you can
download that lets you fly

1661
01:03:45,454 --> 01:03:47,556
around the galaxy and
visit the exoplanets.

1662
01:03:47,589 --> 01:03:51,427
So, I'm going to switch
the screen to Eyes on,

1663
01:03:56,732 --> 01:03:58,601
whoops, Eyes on Exoplanets.

1664
01:03:58,634 --> 01:04:02,538
And I have to move my computer
without destroying it.

1665
01:04:02,571 --> 01:04:05,341
And now, we're gonna
fly around the galaxy.

1666
01:04:05,374 --> 01:04:08,711
So this is, this is
the NASA's Eyes app.

1667
01:04:09,878 --> 01:04:12,248
And you can rotate
around the galaxy.

1668

01:04:12,281 --> 01:04:15,050
So these highlighted
stars all have exoplanets.

1669
01:04:15,083 --> 01:04:17,152
The Sun is at the center
of this distribution.

1670
01:04:17,185 --> 01:04:19,889
And you see this big plume
of objects our there.

1671
01:04:19,922 --> 01:04:21,490
That's the Kepler field.

1672
01:04:21,523 --> 01:04:24,159
The Kepler Mission stared
at 100 square degrees of sky

1673
01:04:24,192 --> 01:04:26,695
for a few years and discovered
thousands of planets

1674
01:04:26,728 --> 01:04:28,097
in one direction.

1675
01:04:28,130 --> 01:04:29,832
So all those results I
showed you from that mission,

1676
01:04:29,865 --> 01:04:32,167
it was just from that
tiny patch of sky

1677
01:04:32,200 --> 01:04:35,504
in the constellations
Cygnus and Lyra, okay?

1678
01:04:35,537 --> 01:04:38,807
The TESS Mission is

gonna map the whole sky

1679
01:04:38,840 --> 01:04:40,843
and there'll be
thousands more exoplanets

1680
01:04:40,876 --> 01:04:42,311
to be found.

1681
01:04:42,344 --> 01:04:46,782
And I wanted to show this
has a little animation.

1682
01:04:46,815 --> 01:04:48,617
This'll fly us to
Proxima Centauri

1683
01:04:48,650 --> 01:04:51,053
in the nearest
exoplanetary system.

1684
01:04:51,086 --> 01:04:53,789
So if you look hard enough,
you'll see the Sun flying by.

1685
01:04:53,822 --> 01:04:57,026
We're zooming in to
Proxima Centauri, the star,

1686
01:04:57,059 --> 01:04:58,093
and then this is
the little planet

1687
01:04:58,126 --> 01:05:00,396
that was discovered in 2016.

1688
01:05:01,830 --> 01:05:06,268
And we can, you can sort
of change the orientation.

1689
01:05:06,301 --> 01:05:07,937
It tells you about the planet,

1690
01:05:07,970 --> 01:05:10,673
tells you the mass of the star,

1691
01:05:10,706 --> 01:05:12,875
how many planets
are in this system.

1692
01:05:12,908 --> 01:05:15,144
And you can get
information about these.

1693
01:05:15,177 --> 01:05:16,345
And so there's a nice app here,

1694
01:05:16,378 --> 01:05:19,848
you can go visit the
planetary systems.

1695
01:05:19,881 --> 01:05:22,484
And with that, I'll thank
you very much for your time

1696
01:05:22,517 --> 01:05:23,986
and I'll open up to questions.

1697
01:05:24,019 --> 01:05:27,189
(audience applauding)

1698
01:05:35,063 --> 01:05:37,599
So there's a microphone
in the center of the room.

1699
01:05:37,632 --> 01:05:38,867
So I ask if you, if
you ask a question

1700
01:05:38,900 --> 01:05:41,070
please use the microphone.

1701
01:05:48,810 --> 01:05:50,212
- Can I go?
- Yep.

1702
01:05:50,245 --> 01:05:53,048
- Hi, great
presentation, thank you.

1703
01:05:53,081 --> 01:05:55,384
I had a question
about Hot Jupiters.

1704
01:05:55,417 --> 01:05:57,119
I was wondering
how it's possible

1705
01:05:57,152 --> 01:06:00,756
that they form around
Sun-like planets.

1706
01:06:00,789 --> 01:06:02,191
- That's a very good question.

1707
01:06:02,224 --> 01:06:04,226
So, as soon as they were
discovered about 20 years ago,

1708
01:06:04,259 --> 01:06:07,329
the theorists went to work
trying to explain how they form.

1709
01:06:07,362 --> 01:06:10,332
There's a couple
different ideas.

1710
01:06:10,365 --> 01:06:13,369

One of them, I would say
the idea that probably

1711
01:06:13,402 --> 01:06:16,005
has the most merit is
that there are Jupiters

1712
01:06:16,038 --> 01:06:20,376
that form far out, just
like our Jupiter did

1713
01:06:20,409 --> 01:06:21,910
but they were able to,

1714
01:06:21,943 --> 01:06:23,212
they had gravitational
interaction with

1715
01:06:23,245 --> 01:06:25,247
their inner disk,

1716
01:06:25,280 --> 01:06:27,716
there was a torque between
the disk and the planet.

1717
01:06:27,749 --> 01:06:31,921
And the planet can actually
slowly change its trajectory.

1718
01:06:33,088 --> 01:06:35,524
But, you can tweak
the initial conditions

1719
01:06:35,557 --> 01:06:37,926
on these experiments and
you may get a Jupiter

1720
01:06:37,959 --> 01:06:40,029
that travels all the way
in and runs into the star.

1721
01:06:40,062 --> 01:06:42,264
You may get ones that
move in and then stop.

1722
01:06:42,297 --> 01:06:43,966
You may get ones that
don't move at all.

1723
01:06:43,999 --> 01:06:47,803
And so there seems to a
range of stopping points.

1724
01:06:47,836 --> 01:06:50,305
It's possible that
our Jupiter moved in,

1725
01:06:50,338 --> 01:06:52,641
cleared out, there really
isn't that much matter

1726
01:06:52,674 --> 01:06:55,844
in the inner part of our solar
system compared to Jupiter.

1727
01:06:55,877 --> 01:06:57,546
In fact, Jupiter's
existence itself may be

1728
01:06:57,579 --> 01:07:01,150
why there's so little
mass in the inner planets.

1729
01:07:01,183 --> 01:07:02,751
There's a model
called the Grand Tack

1730
01:07:02,784 --> 01:07:05,087
where Jupiter and Saturn
and the other planets,

1731
01:07:05,120 --> 01:07:07,122
the outer planets were
migrating a little bit

1732
01:07:07,155 --> 01:07:11,427
and Jupiter may have swept out
some of the region near us.

1733
01:07:11,460 --> 01:07:15,731
It's conceivable the planets
could have formed in situ.

1734
01:07:15,764 --> 01:07:17,666
It's a little hard to
believe because we think

1735
01:07:17,699 --> 01:07:20,969
that if you have ice, ice
sticks together a lot better

1736
01:07:21,002 --> 01:07:23,739
than rock, especially hot rock.

1737
01:07:23,772 --> 01:07:27,376
And so the conditions for
these planets accreting

1738
01:07:27,409 --> 01:07:29,878
out of that disk, it
can go much, much faster

1739
01:07:29,911 --> 01:07:31,547
if you have a lot of ice.

1740
01:07:31,580 --> 01:07:33,048
And so you need to be
a couple times further

1741

01:07:33,081 --> 01:07:35,851
the nearest Sun-distance
where water becomes an ice

1742
01:07:35,884 --> 01:07:38,087
and carbon monoxide,
carbon dioxide,

1743
01:07:38,120 --> 01:07:40,189
these things are very
good at forming ices

1744
01:07:40,222 --> 01:07:41,690
that stick together.

1745
01:07:41,723 --> 01:07:43,659
So, but there's been some
planets where they think

1746
01:07:43,692 --> 01:07:46,528
they may have a
large rocky core.

1747
01:07:46,561 --> 01:07:48,597
You may need tens of
Earth-masses to form these

1748
01:07:48,630 --> 01:07:50,632
along with a hydrogen-,
helium-rich envelope.

1749
01:07:50,665 --> 01:07:54,236
So, we may be seeing, there
may be a variety of mechanisms.

1750
01:07:54,269 --> 01:07:55,938
The other hint is some of
the hot-Jupiter systems

1751
01:07:55,971 --> 01:07:57,706

have stellar companions.

1752
01:07:57,739 --> 01:08:01,210
Those stellar companions
could have altered the orbits

1753
01:08:01,243 --> 01:08:02,678
of those Jupiters.

1754
01:08:02,711 --> 01:08:05,247
And if they were sent in on
sort of comet-like orbits,

1755
01:08:05,280 --> 01:08:07,015
the torques from the star itself

1756
01:08:07,048 --> 01:08:10,586
would actually circularize
them and bring them

1757
01:08:10,619 --> 01:08:11,987
closer to the star.

1758
01:08:12,020 --> 01:08:14,323
So, there may be a few
different physical mechanisms.

1759
01:08:14,356 --> 01:08:15,858
- Thank you.
- Yep.

1760
01:08:18,460 --> 01:08:20,095
- It was probably a really
good reason for this,

1761
01:08:20,128 --> 01:08:24,099
but why does the starshade
have to be so big

1762

01:08:24,132 --> 01:08:26,301
and far away rather than smaller

1763
01:08:26,334 --> 01:08:29,238
and just closer to the lens?

1764
01:08:29,271 --> 01:08:31,106
- I think the answer is the,

1765
01:08:31,139 --> 01:08:32,608
so you need the,

1766
01:08:32,641 --> 01:08:34,143
the position of the
starshade with respect

1767
01:08:34,176 --> 01:08:35,777
to the spacecraft,
you need to get

1768
01:08:35,810 --> 01:08:37,179
within a couple meters, right?

1769
01:08:37,212 --> 01:08:38,447
It has to be very, very,

1770
01:08:38,480 --> 01:08:40,382
basically about as
much wiggle-room

1771
01:08:40,415 --> 01:08:42,818
as I have on this
rug up here, okay?

1772
01:08:42,851 --> 01:08:44,186
And this is one of the
technical challenges,

1773
01:08:44,219 --> 01:08:46,155

is keeping the orientation
of the starshade

1774
01:08:46,188 --> 01:08:47,789
and the spacecraft so close.

1775
01:08:47,822 --> 01:08:49,458
- [Audience Member] I guess
it has to be big enough

1776
01:08:49,491 --> 01:08:50,659
to create a shadow, also?

1777
01:08:50,692 --> 01:08:52,327
- Yeah, you have to,
you want the spacecraft

1778
01:08:52,360 --> 01:08:57,065
to be in the shadow that
the starshade is creating.

1779
01:08:57,098 --> 01:09:00,335
So it's not purely
the geometric size.

1780
01:09:00,368 --> 01:09:04,273
There's some other
optical complications

1781
01:09:04,306 --> 01:09:06,074
that you have to
take into account.

1782
01:09:06,107 --> 01:09:08,010
But the model they're
working with now,

1783
01:09:08,043 --> 01:09:10,546
we're talking tens
of meters in size.

1784
01:09:10,579 --> 01:09:11,413
- [Audience Member]
Cool, thank you.

1785
01:09:11,446 --> 01:09:12,281
- Mm-hm.

1786
01:09:16,785 --> 01:09:18,420
- Then, as a follow-up
question to that,

1787
01:09:18,453 --> 01:09:22,357
is the starshade, is it the
same idea as a coronagraph?

1788
01:09:22,390 --> 01:09:25,494
Is it the same thing and as
kind of a follow-up to that,

1789
01:09:25,527 --> 01:09:29,731
is that how much, how well
does it blot out the light?

1790
01:09:29,764 --> 01:09:32,734
How, like, what planets,
how far would those planets

1791
01:09:32,767 --> 01:09:35,737
be away from the star such
that we could see them?

1792
01:09:35,770 --> 01:09:36,972
- That's a great question.

1793
01:09:37,005 --> 01:09:39,441
So, if I had some more
time, I would've talked

1794

01:09:39,474 --> 01:09:40,642
a little bit more
about the coronagraph.

1795
01:09:40,675 --> 01:09:42,077
So the coronagraphs
are essentially little,

1796
01:09:42,110 --> 01:09:45,781
miniature starshades you have
inside of your telescope.

1797
01:09:45,814 --> 01:09:50,152
You can blot out the star
within your telescope.

1798
01:09:50,185 --> 01:09:52,121
And you have to create,

1799
01:09:54,889 --> 01:09:56,291
you have to make them
in certain shapes

1800
01:09:56,324 --> 01:09:59,161
that have to be very
precisely machined.

1801
01:09:59,194 --> 01:10:00,596
How dark can they get?

1802
01:10:00,629 --> 01:10:02,698
I think the answer for
the internal coronagraph

1803
01:10:02,731 --> 01:10:05,601
in WFIRST, I think
now's 10 to the minus--

1804
01:10:05,634 --> 01:10:07,269
- Nine.

- Nine?

1805
01:10:07,302 --> 01:10:11,373
Yeah, so, something on the
order of a part in a billion.

1806
01:10:11,406 --> 01:10:13,942
So, you're getting
down to seeing things

1807
01:10:13,975 --> 01:10:15,911
like Jupiter around
the nearby stars.

1808
01:10:15,944 --> 01:10:17,079
The other thing to
consider is the so-called

1809
01:10:17,112 --> 01:10:18,513
inner-working angle.

1810
01:10:18,546 --> 01:10:20,716
And so for the set-ups
that we're taking about,

1811
01:10:20,749 --> 01:10:23,118
for the telescopes that
we're talking about,

1812
01:10:23,151 --> 01:10:24,553
the inner-working
angle's on the order of

1813
01:10:24,586 --> 01:10:26,188
a tenth of an arcsecond.

1814
01:10:26,221 --> 01:10:30,926
So something like one over few
ten-thousandths of a degree.

1815
01:10:30,959 --> 01:10:34,329
And so if you wanna
see, you know,

1816
01:10:34,362 --> 01:10:36,198
planets like Jupiter,
Neptune, et cetera,

1817
01:10:36,231 --> 01:10:38,200
you'd have to look around
just the nearby stars.

1818
01:10:38,233 --> 01:10:39,835
If you move the
star too far away,

1819
01:10:39,868 --> 01:10:43,005
that angular separation
gets too small.

1820
01:10:43,038 --> 01:10:44,206
- And then, a follow-up to that,

1821
01:10:44,239 --> 01:10:46,341
is does the starshade,
would that move

1822
01:10:46,374 --> 01:10:48,677
so that you could look
at multiple stars?

1823
01:10:48,710 --> 01:10:50,212
- Yes.

1824
01:10:50,245 --> 01:10:51,246
Yeah, I think people would
scream if it only looked

1825
01:10:51,279 --> 01:10:52,514

at one star.

1826
01:10:52,547 --> 01:10:53,482
- [Audience Member]
I would think so.

1827
01:10:53,515 --> 01:10:54,716
- The idea is the starshade,

1828
01:10:54,749 --> 01:10:55,951
so you would launch
your telescope,

1829
01:10:55,984 --> 01:10:58,553
your telescope would
observe the star

1830
01:10:58,586 --> 01:11:00,889
for days or weeks on end,

1831
01:11:00,922 --> 01:11:02,190
but you need to
integrate all that signal

1832
01:11:02,223 --> 01:11:04,526
to get the faint light
from the planets.

1833
01:11:04,559 --> 01:11:06,895
And then the starshade
would, has some fuel,

1834
01:11:06,928 --> 01:11:08,630
and it would move to
its next orientation.

1835
01:11:08,663 --> 01:11:09,798
And it may take days or weeks

1836

01:11:09,831 --> 01:11:11,667
to get to that next orientation.

1837
01:11:11,700 --> 01:11:15,170
In the meantime, you
have a space telescope

1838
01:11:15,203 --> 01:11:17,105
which can do other things.

1839
01:11:17,138 --> 01:11:18,740
It can look for
microlensing events

1840
01:11:18,773 --> 01:11:21,109
or study dark energy
and galactic structure.

1841
01:11:21,142 --> 01:11:23,245
There's lots of other
astrophysics you can do

1842
01:11:23,278 --> 01:11:24,680
in the down time.

1843
01:11:25,914 --> 01:11:27,316
Not really down time, but,

1844
01:11:27,349 --> 01:11:30,319
in between observing
the exo-Earths, okay?

1845
01:11:30,352 --> 01:11:31,953
- One more question.

1846
01:11:31,986 --> 01:11:35,157
So with respect to
circumbinary stars,

1847

01:11:38,426 --> 01:11:40,696
have we found any
planets that orbit

1848
01:11:40,729 --> 01:11:44,866
within the boundary of two, of
a binary system or are they--

1849
01:11:44,899 --> 01:11:46,501
- Yes.
- all on the outside?

1850
01:11:46,534 --> 01:11:49,037
- Alpha Centauri's
a perfect example.

1851
01:11:49,070 --> 01:11:51,573
That's an Earth-sized planet
orbiting a little red dwarf.

1852
01:11:51,606 --> 01:11:53,508
If you go 10,000
astronomical units away,

1853
01:11:53,541 --> 01:11:56,144
you've got two Sun-like
stars orbiting each other,

1854
01:11:56,177 --> 01:11:57,713
Alpha Centauri A and
B go around each other

1855
01:11:57,746 --> 01:11:59,614
about every 80 years.

1856
01:11:59,647 --> 01:12:00,549
And they, themselves,

1857
01:12:00,582 --> 01:12:03,152
there's dynamically-stable zones

1858
01:12:04,886 --> 01:12:08,824
around each of those about
the size of Mars' orbit

1859
01:12:08,857 --> 01:12:10,092
where there could be planets.

1860
01:12:10,125 --> 01:12:12,894
So all three bodies
could have planets.

1861
01:12:12,927 --> 01:12:13,929
- Thank you.

1862
01:12:16,598 --> 01:12:17,966
- It looks like we have some,

1863
01:12:17,999 --> 01:12:19,167
whoops, sorry.

1864
01:12:19,200 --> 01:12:22,270
We have some questions
from the internet.

1865
01:12:22,303 --> 01:12:24,039
It is known what the
effect of dark matter

1866
01:12:24,072 --> 01:12:26,208
is on gravitational
lensing if any.

1867
01:12:26,241 --> 01:12:29,211
Okay, so when we're
talking about dark matter,

1868
01:12:29,244 --> 01:12:31,113
the dark matter seems

to be distributed

1869
01:12:31,146 --> 01:12:32,347
on very large scales.

1870
01:12:32,380 --> 01:12:34,750
We're talking
thousands-of-light-years scales.

1871
01:12:34,783 --> 01:12:37,018
The dark matter is
probably everywhere

1872
01:12:37,051 --> 01:12:38,787
but it's very, very low-density

1873
01:12:38,820 --> 01:12:40,055
and particle physicists
have not been able

1874
01:12:40,088 --> 01:12:41,523
to detect it, yet.

1875
01:12:41,556 --> 01:12:43,558
But we don't think its having
an influence on the scale

1876
01:12:43,591 --> 01:12:46,828
of planetary systems,
on those scales.

1877
01:12:46,861 --> 01:12:48,563
Where we really need to
worry about dark matter

1878
01:12:48,596 --> 01:12:50,298
if you will, is on
the scales of galaxies

1879

01:12:50,331 --> 01:12:51,767
and galaxy-clusters.

1880
01:12:51,800 --> 01:12:54,169
And that's where it
seems like we're missing,

1881
01:12:54,202 --> 01:12:57,706
we're missing much of the
matter in the universe.

1882
01:12:57,739 --> 01:12:59,141
The next question is:

1883
01:12:59,174 --> 01:13:01,076
how can information be
discerned about any one planet

1884
01:13:01,109 --> 01:13:03,044
using the wobble
method where there

1885
01:13:03,077 --> 01:13:05,947
are likely multiple planets
causing their star to wobble?

1886
01:13:05,980 --> 01:13:08,216
That's a great question.

1887
01:13:08,249 --> 01:13:10,619
You need to watch
them for a long time.

1888
01:13:10,652 --> 01:13:12,621
If you were watching,

1889
01:13:12,654 --> 01:13:14,956
if you're our Sun, if
you were an astronomer

1890
01:13:14,989 --> 01:13:15,891
who was tens of light-years away

1891
01:13:15,924 --> 01:13:17,426
and you're watching our Sun,

1892
01:13:17,459 --> 01:13:19,227
Jupiter is tugging on our Sun,

1893
01:13:19,260 --> 01:13:20,629
Jupiter has a 12-year period.

1894
01:13:20,662 --> 01:13:22,097
Saturn's a pretty big planet.

1895
01:13:22,130 --> 01:13:25,066
It has a 30-year period,
so it's tugging on the Sun.

1896
01:13:25,099 --> 01:13:26,835
And then the Earth
and the Venus,

1897
01:13:26,868 --> 01:13:28,870
Earth and Venus are
both tugging on the Sun.

1898
01:13:28,903 --> 01:13:31,206
And so you actually get a
fairly-complicated pattern

1899
01:13:31,239 --> 01:13:34,843
and you need to monitor
them over many years, okay?

1900
01:13:34,876 --> 01:13:36,445
And this is, you know,

1901

01:13:36,478 --> 01:13:39,981
teasing out the signals
over very long time-scales,

1902
01:13:40,014 --> 01:13:42,384
this is technically challenging.

1903
01:13:42,417 --> 01:13:43,618
We're used to thinking
of these missions

1904
01:13:43,651 --> 01:13:46,321
in terms of years,
but we may need to,

1905
01:13:46,354 --> 01:13:48,223
you know, to properly
characterize the masses

1906
01:13:48,256 --> 01:13:49,825
of the planets further out,

1907
01:13:49,858 --> 01:13:54,062
we may need missions
that last decades, so.

1908
01:13:54,095 --> 01:13:56,164
You need to do, you need
to do computer modeling

1909
01:13:56,197 --> 01:13:59,434
and try different
solutions until you get one

1910
01:13:59,467 --> 01:14:02,004
that statistically looks right.

1911
01:14:03,638 --> 01:14:04,540
Yes?

1912
01:14:07,041 --> 01:14:08,477
- Yeah, I just
wanted to say that

1913
01:14:08,510 --> 01:14:11,246
if you go to that top link,

1914
01:14:11,279 --> 01:14:13,615
the website, exoplanets.nasa.gov

1915
01:14:13,648 --> 01:14:16,618
there is a lot of good
things to read there

1916
01:14:16,651 --> 01:14:20,222
and some good videos that
will help you understand

1917
01:14:20,255 --> 01:14:21,823
the coronagraph
and the starshade

1918
01:14:21,856 --> 01:14:25,260
and what the strengths and
difficulties are for each.

1919
01:14:25,293 --> 01:14:26,461
- Yes.

1920
01:14:26,494 --> 01:14:28,864
Barely scratch the
surface with graphics

1921
01:14:28,897 --> 01:14:32,200
for the coronagraph
and the starshade,

1922
01:14:32,233 --> 01:14:34,069
so I definitely

encourage you to go

1923
01:14:34,102 --> 01:14:36,004
to exoplanets.nasa.gov.

1924
01:14:38,106 --> 01:14:39,775
Any other questions?

1925
01:14:42,644 --> 01:14:44,846
- My question is
how will we know

1926
01:14:44,879 --> 01:14:49,050
when we've found a planet
that may have life on it?

1927
01:14:49,083 --> 01:14:51,119
What are you looking for?

1928
01:14:51,152 --> 01:14:53,255
- That is a great
question (laughing)

1929
01:14:53,288 --> 01:14:54,556
and is a whole talk in itself.

1930
01:14:54,589 --> 01:14:56,958
There's the so-called
biosignatures.

1931
01:14:56,991 --> 01:14:58,927
I mean, we're obviously
looking for planets

1932
01:14:58,960 --> 01:15:01,963
similar to Earth that
would have, you know,

1933
01:15:01,996 --> 01:15:05,734

features like oxygen,
you know, some CO2,

1934
01:15:05,767 --> 01:15:07,969
maybe see methane.

1935
01:15:08,002 --> 01:15:10,005
There's a lot of discussion now.

1936
01:15:10,038 --> 01:15:11,973
What are the unique
chemical signatures

1937
01:15:12,006 --> 01:15:13,508
that you would
see in a spectrum?

1938
01:15:13,541 --> 01:15:16,444
Because what we're
finding is there may be

1939
01:15:16,477 --> 01:15:20,882
abiotic reasons for having
oxygen-rich atmospheres

1940
01:15:20,915 --> 01:15:24,853
that may not require,
you know, photosynthesis.

1941
01:15:26,621 --> 01:15:29,658
So, right now, people
are studying how do you,

1942
01:15:29,691 --> 01:15:31,893
what chemical signatures
do you look for

1943
01:15:31,926 --> 01:15:33,262
that are unique?

1944
01:15:34,629 --> 01:15:37,098
You'd look for chemicals
that are out of equilibriums.

1945
01:15:37,131 --> 01:15:39,834
If you start seeing
oxygen, CO2, methane

1946
01:15:39,867 --> 01:15:41,536
in certain abundances,
you might ask,

1947
01:15:41,569 --> 01:15:43,271
well why is there so
much methane there.

1948
01:15:43,304 --> 01:15:44,739
Oh, there's cows there, right?

1949
01:15:44,772 --> 01:15:46,341
(audience chuckling)

1950
01:15:46,374 --> 01:15:50,312
So, you know, if we look
at a planet like Mars,

1951
01:15:51,646 --> 01:15:54,849
you see CO2, and
Venus, you see CO2.

1952
01:15:54,882 --> 01:15:56,918
You would would
know that there's

1953
01:15:56,951 --> 01:15:59,321
a very strong greenhouse
effect in Venus' atmosphere

1954
01:15:59,354 --> 01:16:02,591

from the depths of the
carbon dioxide feature.

1955
01:16:02,624 --> 01:16:04,492
We have some CO2, little bit,

1956
01:16:04,525 --> 01:16:07,462
just enough to
warm up the planet

1957
01:16:07,495 --> 01:16:10,298
on the order of 14 Celsius.

1958
01:16:10,331 --> 01:16:11,766
You know, there's
different things

1959
01:16:11,799 --> 01:16:13,168
you'll be able to tell from
the chemical signatures.

1960
01:16:13,201 --> 01:16:16,171
So that's a whole
talk in itself.

1961
01:16:16,204 --> 01:16:19,808
And we've, some of
the larger planets,

1962
01:16:19,841 --> 01:16:20,842
some of the larger
transiting planets,

1963
01:16:20,875 --> 01:16:22,277
people may be able to tease out

1964
01:16:22,310 --> 01:16:26,481
the chemistry and see
evidence of certain molecules.

1965
01:16:28,082 --> 01:16:30,151
A few of the
directly-imaged planets,

1966
01:16:30,184 --> 01:16:32,520
the giant planets,
they're also seeing

1967
01:16:32,553 --> 01:16:37,292
things like methane and
hydrogen in the atmospheres.

1968
01:16:37,325 --> 01:16:39,828
- [Audience Member] Thank you.

1969
01:16:43,665 --> 01:16:47,102
- In addition to the, sort
of the unusual-mass planets

1970
01:16:47,135 --> 01:16:49,671
that we don't really see based
on the solar system model

1971
01:16:49,704 --> 01:16:54,209
that we have, have we seen
any super-dynamic systems

1972
01:16:54,242 --> 01:16:56,945
where there's multiple
orbital planes,

1973
01:16:56,978 --> 01:16:58,747
so you have one planet
over here, you know,

1974
01:16:58,780 --> 01:17:01,416
several on one angle, you know,

1975
01:17:01,449 --> 01:17:03,518

and very eccentric
comet light orbits

1976
01:17:03,551 --> 01:17:05,553
or is it all very sort of
conventional, what we see here?

1977
01:17:05,586 --> 01:17:07,555
- Ah, so that's been one
of the other surprises.

1978
01:17:07,588 --> 01:17:08,823
We look at our own solar system,

1979
01:17:08,856 --> 01:17:11,059
the planet orbits tend
to be fairly circular.

1980
01:17:11,092 --> 01:17:12,293
There's a few exceptions.

1981
01:17:12,326 --> 01:17:13,995
You know, Mercury's
is a little eccentric.

1982
01:17:14,028 --> 01:17:17,399
But most of the
planets like Earth's,

1983
01:17:17,432 --> 01:17:20,201
Earth's orbit is
circular to about 2%.

1984
01:17:20,234 --> 01:17:21,403
Most of the planets
in the solar system,

1985
01:17:21,436 --> 01:17:23,905
their orbits are
circular to about 5%.

1986
01:17:23,938 --> 01:17:26,608
A lot of the systems
we're seeing,

1987
01:17:26,641 --> 01:17:28,076
a lot of the ones
that Kepler's seeing

1988
01:17:28,109 --> 01:17:29,577
that are very close in
tend to be very circular.

1989
01:17:29,610 --> 01:17:31,046
But there are ones on
very eccentric orbits.

1990
01:17:31,079 --> 01:17:31,913
A lot of the

1991
01:17:31,947 --> 01:17:34,049
Doppler-spectroscopy-detected
systems,

1992
01:17:34,082 --> 01:17:35,917
some of them are on
very eccentric orbits.

1993
01:17:35,950 --> 01:17:39,621
They've seen Jupiter-like
planets on comet-like orbits.

1994
01:17:39,654 --> 01:17:42,724
They've also detected
planets orbiting very close

1995
01:17:42,757 --> 01:17:45,126
to their star going
the opposite way

1996
01:17:45,159 --> 01:17:47,095
of the star's rotation.

1997
01:17:48,029 --> 01:17:49,330
Bah, how do you do that?

1998
01:17:49,363 --> 01:17:51,132
(laughing) You know,
they've had to,

1999
01:17:51,165 --> 01:17:53,001
you know, that's a
whole can of worms

2000
01:17:53,034 --> 01:17:54,703
in terms of dynamical
simulations.

2001
01:17:54,736 --> 01:17:56,204
You must've had a very complex,

2002
01:17:56,237 --> 01:17:59,407
it must've been multiple
planets, some collisions.

2003
01:17:59,440 --> 01:18:03,545
You know, how do you get a
system where one of the planets

2004
01:18:04,579 --> 01:18:06,781
is going the wrong way?

2005
01:18:06,814 --> 01:18:09,784
And at a very steep angle
with respect to its star?

2006
01:18:09,817 --> 01:18:12,821
So, they're not all
nice and circular

2007
01:18:12,854 --> 01:18:14,289
like our solar system.

2008
01:18:14,322 --> 01:18:15,523
And that's actually
an open question,

2009
01:18:15,556 --> 01:18:18,359
is just how unique
is our solar system

2010
01:18:18,392 --> 01:18:20,495
in terms of the dynamics?

2011
01:18:21,729 --> 01:18:22,564
- Thanks.

2012
01:18:27,235 --> 01:18:30,238
- Another question with
respect to the orbits.

2013
01:18:30,271 --> 01:18:32,640
I guess for us to be able
to detect the planets,

2014
01:18:32,673 --> 01:18:35,243
they have to cross
the line between us

2015
01:18:35,276 --> 01:18:37,212
and their sun?
- Yep.

2016
01:18:37,245 --> 01:18:39,314
- And so how much
of a coincidence

2017
01:18:39,347 --> 01:18:43,518

is that that there are orbits
that have that property

2018
01:18:45,753 --> 01:18:47,789
and how often are they
completely misaligned

2019
01:18:47,822 --> 01:18:50,125
such that they never
cross that line?

2020
01:18:50,158 --> 01:18:52,127
- Well, most of them are not
passing in front of the star

2021
01:18:52,160 --> 01:18:54,596
so we have to be, you know,

2022
01:18:54,629 --> 01:18:56,030
with missions like
Kepler, literally,

2023
01:18:56,063 --> 01:18:57,632
you're looking at
over 100,000 stars

2024
01:18:57,665 --> 01:18:59,367
and we're only seeing a few
thousand where the planets

2025
01:18:59,400 --> 01:19:00,969
are passing in
front of the star.

2026
01:19:01,002 --> 01:19:03,037
So, statistically, you
have to take into account

2027
01:19:03,070 --> 01:19:04,906
that it's less likely that

you would see the planets

2028
01:19:04,939 --> 01:19:07,008
pass in front of the star
as you get further away.

2029
01:19:07,041 --> 01:19:08,476
There's just a lot more,

2030
01:19:08,509 --> 01:19:12,847
if you started varying the
orientations of the orbits,

2031
01:19:12,880 --> 01:19:16,551
you know, 99.99% of the
time, you're not gonna see it

2032
01:19:16,584 --> 01:19:17,986
passing in front of the star.

2033
01:19:18,019 --> 01:19:19,420
So this is one of the
reasons the Kepler Mission's

2034
01:19:19,453 --> 01:19:21,189
been so sensitive to the planets

2035
01:19:21,222 --> 01:19:23,591
that are very close in.

2036
01:19:23,624 --> 01:19:27,328
So, its, you know, those
are the ones we can see.

2037
01:19:27,361 --> 01:19:28,496
What we're doing is we're,

2038
01:19:28,529 --> 01:19:30,031
based off of those statistic,

2039
01:19:30,064 --> 01:19:31,633
we're trying to figure out what
the distribution looks like

2040
01:19:31,666 --> 01:19:33,335
for all the planets,

2041
01:19:35,469 --> 01:19:38,273
taking into account the
ones that we can't see.

2042
01:19:38,306 --> 01:19:39,774
One of the frustrating aspects

2043
01:19:39,807 --> 01:19:41,309
of the planet-detection
techniques

2044
01:19:41,342 --> 01:19:44,145
is they all probe slightly
different parameter space.

2045
01:19:44,178 --> 01:19:45,780
Like the transit method,
you're very sensitive

2046
01:19:45,813 --> 01:19:48,249
to planets very close in
and you get the radii.

2047
01:19:48,282 --> 01:19:49,784
And occasionally,
you can get the mass

2048
01:19:49,817 --> 01:19:51,886
if the planets are
tugging on each other.

2049

01:19:51,919 --> 01:19:53,588
With radial velocity,
it's tougher

2050
01:19:53,621 --> 01:19:54,823
to get the low-mass planets,

2051
01:19:54,856 --> 01:19:56,324
but you can detect the
planets further out.

2052
01:19:56,357 --> 01:19:58,760
Microlensing, you're
very sensitive to bigger,

2053
01:19:58,793 --> 01:20:00,128
or to planets at a
wide range of masses

2054
01:20:00,161 --> 01:20:03,431
but mostly very far
away from their star.

2055
01:20:03,464 --> 01:20:05,099
They all cover different
parameter spaces

2056
01:20:05,132 --> 01:20:06,501
and so we're trying
to piece together

2057
01:20:06,534 --> 01:20:10,539
what the distribution of
planetary properties is

2058
01:20:11,973 --> 01:20:14,542
building off the strengths of
these different techniques.

2059
01:20:14,575 --> 01:20:18,747

But no single technique's gonna
give you the whole answer.

2060
01:20:23,417 --> 01:20:24,719
Any other questions?

2061
01:20:24,752 --> 01:20:26,855
Okay, I'll take one more.

2062
01:20:29,557 --> 01:20:30,725
- Hello, I'd like
to keep it short.

2063
01:20:30,758 --> 01:20:32,126
I just had a question.

2064
01:20:32,159 --> 01:20:34,863
You vaguely touched on Planet 9?

2065
01:20:34,896 --> 01:20:39,067
And I guess digesting data to
see if it really was a planet

2066
01:20:40,101 --> 01:20:41,336
or just debris.

2067
01:20:42,770 --> 01:20:45,340
Do you think you'd be
able to give us a heads-up

2068
01:20:45,373 --> 01:20:49,544
on a timeline, possibly or when
we would know more about it?

2069
01:20:50,912 --> 01:20:51,713
- (laughing) There's
other people down the road

2070
01:20:51,746 --> 01:20:53,582

to talk to about that.

2071
01:20:54,982 --> 01:20:58,052
I would say what
looks interesting

2072
01:20:58,085 --> 01:21:01,523
is that we're finding
there's a whole belt

2073
01:21:02,657 --> 01:21:04,259
of objects out past
Neptune's orbit,

2074
01:21:04,292 --> 01:21:06,294
the so-called Kuiper Belt.

2075
01:21:06,327 --> 01:21:08,062
Over the past two
and a half decades,

2076
01:21:08,095 --> 01:21:09,731
been finding more
and more objects out

2077
01:21:09,764 --> 01:21:11,132
past Neptune's orbit.

2078
01:21:11,165 --> 01:21:12,567
Pluto and a few of
the dwarf planets

2079
01:21:12,600 --> 01:21:13,735
just tend to be
the biggest ones,

2080
01:21:13,768 --> 01:21:15,637
Eris, Makemake, Haumea.

2081

01:21:15,670 --> 01:21:18,306
There's thousands of these
big objects out there.

2082
01:21:18,339 --> 01:21:20,608
And as you go further out,

2083
01:21:20,641 --> 01:21:22,977
out, sort of 40, 50
astronomical units,

2084
01:21:23,010 --> 01:21:24,612
you're starting to see
a little bit of clumping

2085
01:21:24,645 --> 01:21:26,214
in the orbital
properties of some

2086
01:21:26,247 --> 01:21:28,616
of the very, very
distant objects.

2087
01:21:28,649 --> 01:21:31,686
And it looks a little,
it's interesting.

2088
01:21:31,719 --> 01:21:33,021
There's not many of them,

2089
01:21:33,054 --> 01:21:34,822
but their properties are
starting to clump up.

2090
01:21:34,855 --> 01:21:36,057
Why would they be clumped up?

2091
01:21:36,090 --> 01:21:38,326
It's almost like there's
preferred orbits.

2092
01:21:38,359 --> 01:21:41,129
Now, this is for a very
low number of objects,

2093
01:21:41,162 --> 01:21:42,697
but over time, they've
been finding more

2094
01:21:42,730 --> 01:21:44,299
of these objects, very far out.

2095
01:21:44,332 --> 01:21:47,068
Things on orbital-time
scales of thousands of years.

2096
01:21:47,101 --> 01:21:48,369
These spend most of their time

2097
01:21:48,402 --> 01:21:50,004
hundreds to thousands
of astronomical units

2098
01:21:50,037 --> 01:21:51,539
away from the Sun.

2099
01:21:51,572 --> 01:21:53,975
We can only catch them
when they're very close.

2100
01:21:54,008 --> 01:21:56,210
Very close, out past
Pluto, you know?

2101
01:21:56,243 --> 01:21:59,247
40, 50 astronomical units out.

2102
01:21:59,280 --> 01:22:01,049
That's when they're bright

enough that we can see them

2103
01:22:01,082 --> 01:22:02,717
with our telescopes.

2104
01:22:02,750 --> 01:22:05,186
They're very dim,
they're very slow-moving.

2105
01:22:05,219 --> 01:22:07,288
And so, it's only been
the last few years

2106
01:22:07,321 --> 01:22:08,923
they've been able to piece
together a few of these

2107
01:22:08,956 --> 01:22:10,058
and they're starting to say,

2108
01:22:10,091 --> 01:22:11,592
hm, there's some
interesting properties.

2109
01:22:11,625 --> 01:22:13,328
You know, that the orbits
are starting to clump up.

2110
01:22:13,361 --> 01:22:15,563
Well, what would produce a
clumping up of those properties?

2111
01:22:15,596 --> 01:22:18,299
And so, you know, I'm starting,

2112
01:22:18,332 --> 01:22:19,834
I was skeptical initially,

2113
01:22:19,867 --> 01:22:21,135

I'm starting to take it a
little bit more seriously

2114
01:22:21,168 --> 01:22:24,305
when there's results
from multiple teams

2115
01:22:24,338 --> 01:22:25,673
that are working
on the dynamics.

2116
01:22:25,706 --> 01:22:27,208
They're doing simulations
and are starting

2117
01:22:27,241 --> 01:22:29,310
to come to some
similar constraints.

2118
01:22:29,343 --> 01:22:33,481
And so, I think what the
hypothesis at this point

2119
01:22:33,514 --> 01:22:35,383
is you're talking about
an object that's probably

2120
01:22:35,416 --> 01:22:38,152
about 600 astronomical
units away from the Sun,

2121
01:22:38,185 --> 01:22:40,521
probably something like
five or 10 Earth-masses,

2122
01:22:40,554 --> 01:22:41,689
maybe something intermediate
between the Earth

2123
01:22:41,722 --> 01:22:43,391

and Neptune in size.

2124
01:22:44,525 --> 01:22:46,427
Am I 100% sure
they're gonna find it?

2125
01:22:46,460 --> 01:22:48,062
No. (chuckling)

2126
01:22:48,095 --> 01:22:49,664
We've been burned
too many times.

2127
01:22:49,697 --> 01:22:54,435
But it's, when I see multiple
teams doing these simulations

2128
01:22:54,468 --> 01:22:57,405
and coming to
similar conclusions

2129
01:22:57,438 --> 01:22:58,639
and starting to say,

2130
01:22:58,672 --> 01:23:00,475
it's probably in that
region of the sky.

2131
01:23:00,508 --> 01:23:01,943
You know, then they'll
actually show a plot

2132
01:23:01,976 --> 01:23:03,378
and they'll say, it's probably
in this banana-shaped region

2133
01:23:03,411 --> 01:23:04,812
of the sky and we
think we know the mass

2134
01:23:04,845 --> 01:23:08,049
and we think we know the
radius and the orbital period.

2135
01:23:08,082 --> 01:23:09,917
Then, I start to
take that seriously.

2136
01:23:09,950 --> 01:23:11,652
The reason it hasn't
been discovered yet,

2137
01:23:11,685 --> 01:23:15,123
if it is real, is
because the region of sky

2138
01:23:15,156 --> 01:23:17,425
where it is is
probably, is very big.

2139
01:23:17,458 --> 01:23:20,061
And it's probably so faint,
even if it's something the size

2140
01:23:20,094 --> 01:23:22,063
of Neptune and it's
600 times further away

2141
01:23:22,096 --> 01:23:23,364
than the Earth-Sun distance,

2142
01:23:23,397 --> 01:23:24,899
we're talking about
something that's about,

2143
01:23:24,932 --> 01:23:27,668
in magnitude parlance,
24th, 25th magnitude.

2144

01:23:27,701 --> 01:23:30,004
This is just many, many
factors of 10 dimmer

2145
01:23:30,037 --> 01:23:32,173
than most the things
you're used to looking at

2146
01:23:32,206 --> 01:23:33,408
with a telescope.

2147
01:23:33,441 --> 01:23:34,942
So it takes up a lot
of telescope time,

2148
01:23:34,975 --> 01:23:36,077
you need wide-field images

2149
01:23:36,110 --> 01:23:37,311
and they need to be deep.

2150
01:23:37,344 --> 01:23:38,379
And that means a lot
of time on telescopes

2151
01:23:38,412 --> 01:23:39,347
and you have to
convince astronomers

2152
01:23:39,380 --> 01:23:40,448
to give you that time

2153
01:23:40,481 --> 01:23:42,484
to carry out that study.

2154
01:23:43,684 --> 01:23:47,088
But now that there's
been multiple teams,

2155

01:23:47,121 --> 01:23:48,556
there's multiple teams searching

2156
01:23:48,589 --> 01:23:50,858
and there's multiple teams
coming to similar conclusions

2157
01:23:50,891 --> 01:23:52,760
about where on the
sky it might be.

2158
01:23:52,793 --> 01:23:54,429
I would not be, I
would not be shocked

2159
01:23:54,462 --> 01:23:56,731
if next week there
was an announcement

2160
01:23:56,764 --> 01:24:00,468
but it could be in a few
years, it may disappear.

2161
01:24:00,501 --> 01:24:01,702
Maybe there's some
observational bias

2162
01:24:01,735 --> 01:24:04,305
we hadn't thought of in
the orbital properties

2163
01:24:04,338 --> 01:24:08,576
of these very distant objects
that may be effecting the,

2164
01:24:09,844 --> 01:24:11,779
that may be allowing
astronomers just to find ones

2165
01:24:11,812 --> 01:24:13,247

that have certain properties.

2166
01:24:13,280 --> 01:24:17,085
But my money now is they're
probably gonna find one.

2167
01:24:18,619 --> 01:24:22,657
And it's probably gonna be
something smaller than Neptune.

2168
01:24:22,690 --> 01:24:23,925
- [Audience Member] Thank you.

2169
01:24:23,958 --> 01:24:26,260
- And when they do, we
need to build a probe

2170
01:24:26,293 --> 01:24:28,563
and send it there
as fast as we can.

2171
01:24:28,596 --> 01:24:31,766
And along the way, we can
take pictures of exoplanets.

2172
01:24:31,799 --> 01:24:34,402
So, okay, that may not go
over well with some people

2173
01:24:34,435 --> 01:24:36,637
but we should definitely
build a probe to Planet 9.

2174
01:24:36,670 --> 01:24:39,674
Send a probe to Planet
9 if it's discovered.

2175
01:24:39,707 --> 01:24:41,109
- [Audience Member] Thank you.

2176
01:24:41,142 --> 01:24:42,844
- Okay, I think we'll close
up the questions there.

2177
01:24:42,877 --> 01:24:44,045
And thank you very
much for your time,

2178
01:24:44,078 --> 01:24:45,012
I hope you enjoyed the talk.

2179
01:24:45,045 --> 01:24:48,216
(audience applauding)