1
00:00:00,041 --> 00:00:01,709
(intricate instrumental music)

2
00:00:01,709 --> 00:00:04,745
- [Narrator] NASA's Jet
Propulsion Laboratory presents:

3
00:00:04,745 --> 00:00:08,349
the von Karman Lecture, a
series of talks by scientists

4
00:00:08,349 --> 00:00:11,185
and engineers who are
exploring our planet,

5
00:00:11,185 --> 00:00:14,756
our solar system, and
all that lies beyond.

6
00:00:27,368 --> 00:00:29,503
- Good evening,
ladies and gentlemen.

7
00:00:29,503 --> 00:00:30,504
How's everyone tonight?

8
00:00:30,504 --> 00:00:32,239
(applause)

9
00:00:32,239 --> 00:00:34,108
Thank you very much for
coming out on this rather

10
00:00:34,108 --> 00:00:36,377
soggy evening and
fighting the LA traffic.

11
00:00:36,377 --> 00:00:39,113
We're really grateful for

your attendance, for sure.

12
00:00:39,113 --> 00:00:40,714
So let's jump
right in, shall we?

13
00:00:40,714 --> 00:00:43,116
The Nuclear Spectroscopic
Telescope Array,

14
00:00:43,116 --> 00:00:46,654
or NuSTAR, which
launched in June of 2012,

15
00:00:46,654 --> 00:00:51,125
is the first telescope in
orbit to focus X-ray light.

16
00:00:51,125 --> 00:00:52,960
Compared to the
previous generation

17
00:00:52,960 --> 00:00:56,230
of non-focusing observatories,
working in this energy band,

18
00:00:56,230 --> 00:00:58,265
this change in technology
provides NuSTAR

19
00:00:58,265 --> 00:01:00,501
with a 10-times sharper images,

20
00:01:00,501 --> 00:01:03,738
and 100-times
improved sensitivity.

21
00:01:03,738 --> 00:01:05,873
High energy X-ray light
provides a unique probe

22
00:01:05,873 --> 00:01:08,876
of the most energetic
phenomena in the Universe.

23
00:01:08,876 --> 00:01:10,945
From flares on the
surface of the sun,

24
00:01:10,945 --> 00:01:13,847
to the explosions of stars,
to the extreme environments

25
00:01:13,847 --> 00:01:16,350
around neutron stars
and black holes.

26
00:01:16,350 --> 00:01:18,252
This talk will present some
of the recent highlights

27
00:01:18,252 --> 00:01:20,854
from the NuSTAR mission and
describe how they are changing

28
00:01:20,854 --> 00:01:23,157
our picture of the
extreme Universe.

29
00:01:23,157 --> 00:01:26,326
Tonight's guest earned his
AB in physics and Princeton,

30
00:01:26,326 --> 00:01:29,830
in 1991, and went on to
earn his PhD in astrophysics

31
00:01:29,830 --> 00:01:32,166
from UC Berkeley in 1999.

32
00:01:32,166 --> 00:01:34,335
He came straight
from Berkeley to JPL,

33
00:01:34,335 --> 00:01:37,304
initially as a post-doc, to
work with Peter Eisenhower,

34
00:01:37,304 --> 00:01:40,307
but switched to the Spitzer
Space Telescope science staff

35
00:01:40,307 --> 00:01:41,842
about 18 months later.

36
00:01:41,842 --> 00:01:44,111
Since then, he's
worked on WISE, Euclid,

37
00:01:44,111 --> 00:01:48,483
W-FIRST, a CubeSat,
the Habitable Exoplanet
Imaging Mission,

38
00:01:48,483 --> 00:01:51,252
and several other missions
and mission concepts.

39
00:01:51,252 --> 00:01:52,653
But his main job, currently,

40
00:01:52,653 --> 00:01:55,122
is as the NuSTAR
project scientist.

41
00:01:55,122 --> 00:01:56,857
Scientifically, his
main interests are

42

00:01:56,857 --> 00:02:00,394
observational cosmology, and
extra-galactic astrophysics.

43
00:02:00,394 --> 00:02:02,963
But he's had a sideline,
finding the most distant objects

44
00:02:02,963 --> 00:02:07,134
of various source
classes, including the
most distant object

45
00:02:07,134 --> 00:02:10,838
like, period, (laughing)
the most distant galaxy,

46
00:02:10,838 --> 00:02:14,441
the most distant radio galaxy,
the most distant quasar,

47
00:02:14,441 --> 00:02:16,410
the most distant galaxy cluster,

48
00:02:16,410 --> 00:02:18,512
and the most distant supernova.

49
00:02:18,512 --> 00:02:20,347
He's also very
interested in fields

50
00:02:20,347 --> 00:02:22,649
where infrared satellites
and X-ray satellites

51
00:02:22,649 --> 00:02:24,519
make important contributions.

52
00:02:24,519 --> 00:02:26,687
Specifically, distant

galaxy clusters

53
00:02:26,687 --> 00:02:29,256
and obscured black holes
are both well-served

54
00:02:29,256 --> 00:02:31,692
in observations in
those two wavelengths.

55
00:02:31,692 --> 00:02:34,962
As one might expect, he's a
very enthusiastic observer,

56
00:02:34,962 --> 00:02:38,632
having logged more than 500
nights at telescopes worldwide

57
00:02:38,632 --> 00:02:40,534
over the past 20 years.

58
00:02:40,534 --> 00:02:42,269
Ladies and gentlemen,
please help me welcome

59
00:02:42,269 --> 00:02:44,438
tonight's guest,
Dr. Daniel Stern.

60
00:02:44,438 --> 00:02:46,708
(applause)

61
00:02:50,277 --> 00:02:51,779
- Thank you.

62
00:02:51,779 --> 00:02:54,582
Thank you for braving the
weather and coming out for this.

63

00:02:54,582 --> 00:02:56,850
I'm excited to have the
opportunity to talk to you

64
00:02:56,850 --> 00:02:59,686
about some recent highlights
from the NuSTAR mission.

65
00:02:59,686 --> 00:03:03,056
Here is an artist's
conception of NuSTAR,

66
00:03:03,056 --> 00:03:04,992
and I'll talk about
spinning black holes,

67
00:03:04,992 --> 00:03:08,295
exploding stars, and
hyperluminous pulsars.

68
00:03:08,295 --> 00:03:10,765
And I list a couple other
missions that I'm involved in,

69
00:03:10,765 --> 00:03:14,768
if people have questions
afterwards about those.

70
00:03:14,768 --> 00:03:16,403
So, diving in a little bit.

71
00:03:16,403 --> 00:03:19,873
So, NuSTAR is the Nuclear
Spectroscopic Telescope Array.

72
00:03:19,873 --> 00:03:21,809
Our little tagline is:

73
00:03:21,809 --> 00:03:24,545
bringing the high-energy

Universe into focus.

74
00:03:24,545 --> 00:03:27,915
We were the, not quite
right in that tagline.

75
00:03:27,915 --> 00:03:31,252
We're not the first to
focus X-ray light, period.

76
00:03:31,252 --> 00:03:33,821
We're the first to focus
high-energy X-ray light.

77
00:03:33,821 --> 00:03:35,589
The more energetic X-rays.

78
00:03:35,589 --> 00:03:37,557
And we have a change in
technology that brought

79
00:03:37,557 --> 00:03:39,993
about a factor of 200
gain in sensitivity,

80
00:03:39,993 --> 00:03:42,696
compared to what
has flown before us.

81
00:03:42,696 --> 00:03:44,866
We're a NASA small
explorer mission

82
00:03:44,866 --> 00:03:47,802
that's a line of missions
that cost about 150 million.

83
00:03:47,802 --> 00:03:50,570
It's about as small as
NASA goes into space,

84
00:03:50,570 --> 00:03:53,340
typically, for, in astrophysics.

85
00:03:53,340 --> 00:03:55,843
About, you know, more
expensive than an indie film

86
00:03:55,843 --> 00:03:57,878
but less expensive
than a blockbuster.

87
00:03:57,878 --> 00:04:00,280
I think we've gotten
good value out of it.

88
00:04:00,280 --> 00:04:03,250
Giving into the LA context.

89
00:04:03,250 --> 00:04:05,886
We launched in June, 2012.

90
00:04:05,886 --> 00:04:08,589
We were initially designed
for a two-year mission,

91
00:04:08,589 --> 00:04:10,891
but everything's been
going swimmingly,

92
00:04:10,891 --> 00:04:14,061
and we then continued on
for continued funding,

93
00:04:14,061 --> 00:04:15,996
and so now we're a
couple years past that,

94
00:04:15,996 --> 00:04:19,800

in this extended mission,
since August, 2014.

95
00:04:19,800 --> 00:04:22,736
The principle investigator,
or PI, is Fiona Harrison,

96
00:04:22,736 --> 00:04:24,871
who's the Cal Tech
physics professor,

97
00:04:24,871 --> 00:04:26,774
and now the chair
of physics, math,

98
00:04:26,774 --> 00:04:29,377
and astronomy at Cal Tech.

99
00:04:29,377 --> 00:04:32,879
She, we were the first
mission that NASA selected

100
00:04:32,879 --> 00:04:36,283
with a female PI, which
is both very exciting

101
00:04:36,283 --> 00:04:38,819
and also kinda embarrassing,
because about 50 years

102
00:04:38,819 --> 00:04:42,056
into NASA's history,
before that had happened.

103
00:04:42,056 --> 00:04:45,492
Another mission selected
after us actually launched

104
00:04:45,492 --> 00:04:48,329
before us with a female

PI, so we weren't the first

105
00:04:48,329 --> 00:04:50,430
in orbit with a female PI.

106
00:04:50,430 --> 00:04:53,033
I'm the project scientist;
I'm a JPL employee.

107
00:04:53,033 --> 00:04:54,668
I spend a lot of
time at Cal Tech.

108
00:04:54,668 --> 00:04:57,204
And the NuSTAR mission's
been a really fun project.

109
00:04:57,204 --> 00:05:00,207
It's about 150 scientists
on the science team,

110
00:05:00,207 --> 00:05:01,709
around the world.

111
00:05:01,709 --> 00:05:04,611
We have the Italian Space
Agency has a big role in it.

112
00:05:04,611 --> 00:05:07,514
The Danish Technical
University in Copenhagen

113
00:05:07,514 --> 00:05:10,484
had a big role, and then
here's Columbia University,

114
00:05:10,484 --> 00:05:14,288
Berkeley, I guess, so
it's been a fun ride.

115
00:05:14,288 --> 00:05:16,224
With a nice, good team.

116
00:05:18,358 --> 00:05:21,662
I mentioned that we were
a NASA small explorer.

117
00:05:21,662 --> 00:05:24,631
Just to explain to you,
in the astrophysics,

118
00:05:24,631 --> 00:05:27,601
so everything that NASA studies
outside of our solar system

119
00:05:27,601 --> 00:05:30,671
counts as astrophysics,
and the smaller line

120
00:05:30,671 --> 00:05:32,205
of that are these explorers.

121
00:05:32,205 --> 00:05:34,174
We have the mid-sized explorers,

122
00:05:34,174 --> 00:05:35,876
and then the small explorers,

123
00:05:35,876 --> 00:05:37,944
and then sometimes these
mission of opportunities,

124
00:05:37,944 --> 00:05:40,481
which will often be NASA
building an instrument

125
00:05:40,481 --> 00:05:44,252
on a foreign instrument,
a foreign telescope.

126
00:05:45,619 --> 00:05:48,756
And so, there's NuSTAR,
one of the more recent

127
00:05:48,756 --> 00:05:51,892
small explorers, and then I
circled a couple other ones

128
00:05:51,892 --> 00:05:55,028
that came out of Pasadena
that you might have heard of.

129
00:05:55,028 --> 00:05:58,332
WISE and GALEX and ACE, and so
it's a really exciting line.

130
00:05:58,332 --> 00:06:01,135
It's had really
exciting discoveries.

131
00:06:01,135 --> 00:06:03,637
And these missions are
relatively small, for NASA.

132
00:06:03,637 --> 00:06:05,606
So it's a relatively small teams

133
00:06:05,606 --> 00:06:09,477
and relatively quick timelines,
from selection to launch.

134
00:06:09,477 --> 00:06:12,646
And in fact, by the
end of this month,

135
00:06:12,646 --> 00:06:14,180
or maybe by the
end of next month,

136
00:06:14,180 --> 00:06:17,051
the next SMEX will be selected.

137
00:06:17,051 --> 00:06:19,186
They do a multiple-stage
down-select.

138
00:06:19,186 --> 00:06:20,420
So at this point,

139
00:06:20,420 --> 00:06:22,789
there's three missions
competing for one slot.

140
00:06:22,789 --> 00:06:24,825
One of those three is
called SPIREX that comes

141
00:06:24,825 --> 00:06:26,894
out of Cal Tech and
JPL, so hopefully,

142
00:06:26,894 --> 00:06:29,130
maybe the next
week we'll find out

143
00:06:29,130 --> 00:06:32,199
that the next SMEX will be
coming out of JPL, as well.

144
00:06:32,199 --> 00:06:33,466
And you'll be able
to hear a talk

145
00:06:33,466 --> 00:06:36,604
about that in a couple of years.

146
00:06:36,604 --> 00:06:37,872
Our outline for the talk:

147
00:06:37,872 --> 00:06:39,506
I'll start off with a
little bit of overview

148
00:06:39,506 --> 00:06:41,008
of what the NuSTAR
mission is like.

149
00:06:41,008 --> 00:06:43,611
You know, the engineering
of it, the launch of it.

150
00:06:43,611 --> 00:06:45,946
And then I'll hit on those
three science topics,

151
00:06:45,946 --> 00:06:47,647
from the title of the talk.

152
00:06:47,647 --> 00:06:50,117
And here's the website, and
here's the artist's conception

153
00:06:50,117 --> 00:06:52,719
of what NuSTAR looks like.

154
00:06:52,719 --> 00:06:55,856
We work in the
high-energy X-ray regime.

155
00:06:55,856 --> 00:06:58,358
So this is the
same energy X-rays,

156
00:06:58,358 --> 00:07:01,428
or energy light, that
doctors and dentists use

157

00:07:01,428 --> 00:07:04,098
to study your body, that
airport security use

158
00:07:04,098 --> 00:07:06,800
to study your luggage; these
are very penetrating light.

159
00:07:06,800 --> 00:07:09,403
They're able to go
through material.

160
00:07:09,403 --> 00:07:11,705
We're not sending out
X-rays and then studying,

161
00:07:11,705 --> 00:07:14,208
you know, X-ray images,
the way doctors do.

162
00:07:14,208 --> 00:07:15,976
Instead, we study some
of the most energetic,

163
00:07:15,976 --> 00:07:19,947
powerful phenomena in the
Universe that create X-rays,

164
00:07:19,947 --> 00:07:23,117
like supernovae, the
sun, black holes,

165
00:07:24,518 --> 00:07:28,088
and use that to understand
the extreme Universe.

166
00:07:28,088 --> 00:07:31,458
We work in the high-energy,
or hard X-ray regime.

167

00:07:31,458 --> 00:07:32,959
I'll try not to use
the term "hard",

168
00:07:32,959 --> 00:07:35,562
but that's the technical term.

169
00:07:35,562 --> 00:07:38,232
We're the first
mission to focus X-rays

170
00:07:38,232 --> 00:07:40,534
in this high-energy
X-ray regime.

171
00:07:40,534 --> 00:07:42,269
There've been several
missions that have done this,

172
00:07:42,269 --> 00:07:44,772
similar things, in
the low-energy X-rays.

173
00:07:44,772 --> 00:07:48,308
I have a picture here of
Europe's XMM Newton Satellite.

174
00:07:48,308 --> 00:07:50,277
You might also have
heard of NASA's

175
00:07:50,277 --> 00:07:52,413
flagship Chandra
X-ray Observatory,

176
00:07:52,413 --> 00:07:54,648
that works in a
similar energy regime.

177
00:07:54,648 --> 00:07:57,018

Those missions launched
about 15 years ago

178
00:07:57,018 --> 00:07:59,486
and are continuing and
doing really exciting work

179
00:07:59,486 --> 00:08:01,421
in the lower-energy
X-rays, and we actually

180
00:08:01,421 --> 00:08:03,924
partner up a lot
with those missions.

181
00:08:03,924 --> 00:08:08,095
So we got a full X-ray study
of interesting objects.

182
00:08:10,297 --> 00:08:13,133
NuSTAR, I keep saying that
we're focusing optics,

183
00:08:13,133 --> 00:08:14,635
so I'll describe
that a little bit.

184
00:08:14,635 --> 00:08:17,972
We're the first focusing
X-ray satellite in orbit.

185
00:08:17,972 --> 00:08:21,708
Previous generations of X-ray
satellites use something

186
00:08:21,708 --> 00:08:23,777
called "coded aperture
optics", which are like

187
00:08:23,777 --> 00:08:26,246

a pinhole camera or, I
like to think of it as,

188
00:08:26,246 --> 00:08:29,750
kind of have a lead screen
with lots of holes in it,

189
00:08:29,750 --> 00:08:32,119
and then the satellites
looming across the sky,

190
00:08:32,119 --> 00:08:33,921
just rotating around,
and you watch how

191
00:08:33,921 --> 00:08:36,056
the shadow pattern
changes and you're able to

192
00:08:36,056 --> 00:08:39,793
figure out where the X-rays
are coming from in the sky.

193
00:08:39,793 --> 00:08:43,630
And so that sort of design,
this coded aperture optics,

194
00:08:43,630 --> 00:08:45,765
by nature, gets
you blurry images,

195
00:08:45,765 --> 00:08:47,301
you need really big detectors,

196
00:08:47,301 --> 00:08:49,803
you need this big
lead shielding thing,

197
00:08:49,803 --> 00:08:52,673
and so it ends up being

a very heavy satellite.

198
00:08:52,673 --> 00:08:55,309
I have a picture here of the
European INTEGRAL satellite,

199
00:08:55,309 --> 00:08:58,078
and NASA also has a
coded aperture satellite

200
00:08:58,078 --> 00:09:00,414
up in orbit right
now, called the BAT,

201
00:09:00,414 --> 00:09:04,551
the BAT Alert Telescope
on the Swift Satellite.

202
00:09:04,551 --> 00:09:06,620
Those sort of designs
are pretty heavy,

203
00:09:06,620 --> 00:09:09,756
and if you, if
you're a NASA person,

204
00:09:09,756 --> 00:09:11,792
you know heavy means expensive.

205
00:09:11,792 --> 00:09:13,460
Costs a lot to launch
things into space,

206
00:09:13,460 --> 00:09:16,863
so you try to make them
as light as possible.

207
00:09:16,863 --> 00:09:19,666
NuSTAR instead does
focusing optics.

208
00:09:19,666 --> 00:09:21,668
And X-ray focusing is
a little bit tricky,

209
00:09:21,668 --> 00:09:25,105
because if you had, like, your
usual antennas like we see

210
00:09:25,105 --> 00:09:27,540
here or like radio
dishes you see,

211
00:09:27,540 --> 00:09:29,777
or normal, optical telescopes,

212
00:09:29,777 --> 00:09:31,544
X-rays tend to like to go

213
00:09:31,544 --> 00:09:33,880
right into it and
penetrate through.

214
00:09:33,880 --> 00:09:35,682
And so when you wanna
focus X-ray light,

215
00:09:35,682 --> 00:09:37,951
you have to do grazing
incidence optics,

216
00:09:37,951 --> 00:09:40,053
so the X-rays come and
you kind of nudge them,

217
00:09:40,053 --> 00:09:42,823
almost like a rock on a lake.

218
00:09:42,823 --> 00:09:45,626

And so our design is something
called Walter One Optics,

219
00:09:45,626 --> 00:09:49,229
we have two bounces
to the X-rays,

220
00:09:49,229 --> 00:09:51,765
and then it sends them
down, focuses them on where

221
00:09:51,765 --> 00:09:53,900
we have our detectors.

222
00:09:53,900 --> 00:09:56,537
The optics end up, so, rather
than looking like a dish,

223
00:09:56,537 --> 00:09:59,939
it's a cylinder,
nudging the light in,

224
00:09:59,939 --> 00:10:03,344
and in fact, what we do
is we have 133 shells,

225
00:10:03,344 --> 00:10:06,546
concentric shells, almost
like Russian nesting dolls,

226
00:10:06,546 --> 00:10:08,448
that make up our optics.

227
00:10:08,448 --> 00:10:10,183
So our optics are about yay big,

228
00:10:10,183 --> 00:10:13,120
they weight about 50 kilograms.

229

00:10:13,120 --> 00:10:15,689
And they focus the light in.

230
00:10:15,689 --> 00:10:18,525
Here's a picture from a
Scientific American article

231
00:10:18,525 --> 00:10:20,260
about a year before we
launched, a year and a half

232
00:10:20,260 --> 00:10:22,095
before we launched,
where they took pictures

233
00:10:22,095 --> 00:10:23,931
of different parts of
NuSTAR being built.

234
00:10:23,931 --> 00:10:26,233
And this shows you the
top-end view of the optics,

235
00:10:26,233 --> 00:10:29,136
so you have these concentric
shells, 133 of them,

236
00:10:29,136 --> 00:10:31,738
with the little,
graphite spacers.

237
00:10:31,738 --> 00:10:34,407
This was a big effort
to build this thing.

238
00:10:34,407 --> 00:10:36,443
And we actually built,
we built three of them.

239
00:10:36,443 --> 00:10:39,880

We launched two of
them on the satellite.

240
00:10:41,314 --> 00:10:44,184
So this change in technology
buys NuSTAR a huge gain.

241
00:10:44,184 --> 00:10:47,421
We're about 10-times or
even more than 10-times

242
00:10:47,421 --> 00:10:50,791
sharper images, about 200-times
more sensitive images,

243
00:10:50,791 --> 00:10:53,593
and actually, because
we weigh so much less

244
00:10:53,593 --> 00:10:56,329
than the other design, we're
about a quarter of the cost

245
00:10:56,329 --> 00:10:59,032
of the INTEGRAL
satellite, for example.

246
00:10:59,032 --> 00:11:03,403
So this is just a game-changer
in high-energy astrophysics.

247
00:11:03,403 --> 00:11:06,840
Here's an example, showing
you what that change buys you.

248
00:11:06,840 --> 00:11:09,209
Here's an optical image
of a nearby galaxy,

249
00:11:09,209 --> 00:11:11,978

NGC 1365, it's a
barred-spiral galaxy.

250
00:11:11,978 --> 00:11:15,248
The pretty picture is a
ground-based, optical image.

251
00:11:15,248 --> 00:11:17,952
And then, what I'm showing
you here is the beam size,

252
00:11:17,952 --> 00:11:20,687
or essentially, the pixels
for some of the other

253
00:11:20,687 --> 00:11:22,789
high-energy satellites in orbit.

254
00:11:22,789 --> 00:11:25,225
So, INTEGRAL has this
big circle, here.

255
00:11:25,225 --> 00:11:28,562
Swift's pixels are about
the size of the full moon.

256
00:11:28,562 --> 00:11:31,264
Roughly about 20 arcminutes
versus 30 arcminutes,

257
00:11:31,264 --> 00:11:35,102
and the NuSTAR's beam size
is about the size of Mars.

258
00:11:35,102 --> 00:11:37,137
And so we get much,
much sharper images.

259
00:11:37,137 --> 00:11:39,606
We're able to, whereas

Swift and INTEGRAL

260
00:11:39,606 --> 00:11:43,209
might have said NGC 1365 has
a lot of high-energy X-rays

261
00:11:43,209 --> 00:11:45,078
coming out of it, with NuSTAR,

262
00:11:45,078 --> 00:11:46,980
we're actually able to map it.

263
00:11:46,980 --> 00:11:49,483
And so here's an example
of another nearby galaxy,

264
00:11:49,483 --> 00:11:53,653
IC 342, again, the background
image is an optical image,

265
00:11:53,653 --> 00:11:56,957
from the ground, of this
nearby spiral galaxy,

266
00:11:56,957 --> 00:12:00,160
the purple is the
NuSTAR image of it,

267
00:12:00,160 --> 00:12:01,895
and we actually
see three sources.

268
00:12:01,895 --> 00:12:04,198
You see two on the, two
bright buys in the outskirts,

269
00:12:04,198 --> 00:12:06,033
and there's actually a
little bit of high-energy

270
00:12:06,033 --> 00:12:08,635
X-ray light coming from
the center of the galaxy.

271
00:12:08,635 --> 00:12:10,437
And so, with Swift
or with INTEGRAL,

272
00:12:10,437 --> 00:12:12,639
all of the previous satellites
just would have seen

273
00:12:12,639 --> 00:12:14,408
there's X-rays coming from this,

274
00:12:14,408 --> 00:12:16,343
and they wouldn't have
know if it was one source,

275
00:12:16,343 --> 00:12:18,646
three sources, coming
from the center,

276
00:12:18,646 --> 00:12:21,114
from the outskirts, so
it's a total game-changer

277
00:12:21,114 --> 00:12:23,284
in what you're able to do.

278
00:12:24,618 --> 00:12:27,187
A little bit on the
technology that allowed it.

279
00:12:27,187 --> 00:12:30,523
So here's the
optics, I showed you.

280
00:12:30,523 --> 00:12:32,726

We have two of them, actually,

281
00:12:32,726 --> 00:12:34,795
just to get more
collecting area.

282
00:12:34,795 --> 00:12:36,330
Just a fun little story:

283
00:12:36,330 --> 00:12:38,632
they sit in something
called the "trashcan",

284
00:12:38,632 --> 00:12:40,834
or we called it the
trashcan before launch.

285
00:12:40,834 --> 00:12:42,669
Until the guys who
were building it said:

286
00:12:42,669 --> 00:12:44,571
can you stop calling
it the trashcan?

287
00:12:44,571 --> 00:12:46,506
(laughter)

288
00:12:46,506 --> 00:12:48,475
Yeah, so the optics are yay big.

289
00:12:48,475 --> 00:12:51,178
They focus the light
down on these detectors.

290
00:12:51,178 --> 00:12:53,012
We have two sets of
detectors, one for the optics.

291

00:12:53,012 --> 00:12:55,415
They're both pointing at
the same patch of sky.

292
00:12:55,415 --> 00:12:58,718
The detectors, whereas your
cellphones use a silicon

293
00:12:58,718 --> 00:13:02,089
detector to detect optical
light, for high-energy X-rays,

294
00:13:02,089 --> 00:13:03,524
you have to do a
little bit of change.

295
00:13:03,524 --> 00:13:06,125
It's cadmium-zinc-telluride
detectors.

296
00:13:06,125 --> 00:13:07,794
These detectors were all built

297
00:13:07,794 --> 00:13:09,996
at Cal Tech by Fiona
Harrison's group,

298
00:13:09,996 --> 00:13:11,397
which is one of
the world leaders

299
00:13:11,397 --> 00:13:13,066
in these high-energy detectors.

300
00:13:13,066 --> 00:13:16,970
And these were built
specifically for NuSTAR.

301
00:13:16,970 --> 00:13:19,306
Both the detectors

and the optics,

302
00:13:19,306 --> 00:13:22,275
we flew an earlier version
of NuSTAR on a balloon

303
00:13:22,275 --> 00:13:24,411
called the High-Energy
Focusing Telescope,

304
00:13:24,411 --> 00:13:27,047
or HEFT, which was really
a proof of technology,

305
00:13:27,047 --> 00:13:29,282
that the detectors
and the optics worked.

306
00:13:29,282 --> 00:13:31,718
It just, you know, flew
for a couple of hours,

307
00:13:31,718 --> 00:13:34,521
a couple of days, was able to
look at very bright objects,

308
00:13:34,521 --> 00:13:36,823
but this showed to
NASA that this worked,

309
00:13:36,823 --> 00:13:39,092
and then allowed
us to then propose,

310
00:13:39,092 --> 00:13:41,895
and get accepted as
a satellite mission.

311
00:13:41,895 --> 00:13:46,333
And really be able to

exploit this energy regime.

312
00:13:46,333 --> 00:13:49,102
And then finally, the third
key part of the technology

313
00:13:49,102 --> 00:13:53,239
is that these focusing,
high-energy X-ray optics

314
00:13:53,239 --> 00:13:54,841
have very long focal length.

315
00:13:54,841 --> 00:13:56,910
You need a really large
separation from your,

316
00:13:56,910 --> 00:13:59,446
essentially, your
lens and your film,

317
00:13:59,446 --> 00:14:02,015
or your, you know, your
lens and your detectors.

318
00:14:02,015 --> 00:14:05,285
For NuSTAR, this is
10 meters, 30 feet,

319
00:14:05,285 --> 00:14:08,388
or about the length
of a school bus.

320
00:14:08,388 --> 00:14:12,226
Chandra and XMM, those
flagship, lower-energy missions,

321
00:14:12,226 --> 00:14:16,296
had similar focal lengths
for their telescopes,

322
00:14:16,296 --> 00:14:18,865
but they were, you know,
billion-dollar class missions.

323
00:14:18,865 --> 00:14:23,002
They were able to launch on
a big rocket, fully-extended.

324
00:14:23,002 --> 00:14:25,205
For NuSTAR, we had to
extend after launch,

325
00:14:25,205 --> 00:14:28,075
because we had to go on a
little, cheap, less-expensive,

326
00:14:28,075 --> 00:14:29,276
(laughter)

327
00:14:29,276 --> 00:14:31,245
launch vehicle.

328
00:14:31,245 --> 00:14:33,547
And so, so we have
this extendable mast

329
00:14:33,547 --> 00:14:35,816
that was build in
Galleda, California.

330
00:14:35,816 --> 00:14:37,817
Pretty close to Santa
Barbara, by a company

331
00:14:37,817 --> 00:14:40,887
that specializes in
extendables in space.

332

00:14:40,887 --> 00:14:43,222
They have about,
more than 100 things,

333
00:14:43,222 --> 00:14:47,527
some in orbit, some on Mars,
with 100 percent success rate.

334
00:14:47,527 --> 00:14:49,562
The design for the one
on NuSTAR was based

335
00:14:49,562 --> 00:14:51,864
on something that launched
about 20 years ago,

336
00:14:51,864 --> 00:14:55,135
on the shuttle, called
the Shuttle Radar
Topography Mission.

337
00:14:55,135 --> 00:14:59,506
And so it was a very
similar design to that.

338
00:14:59,506 --> 00:15:01,541
And then here's just
a sense of scale.

339
00:15:01,541 --> 00:15:03,877
Here's a picture, towards
the end of the integration

340
00:15:03,877 --> 00:15:06,279
and testing of NuSTAR.

341
00:15:06,279 --> 00:15:09,116
So there's the two
optics modules,

342

00:15:10,483 --> 00:15:12,519
the mast is deployed in there,

343
00:15:12,519 --> 00:15:14,555
and there's a person, just
to give you a sense of scale.

344
00:15:14,555 --> 00:15:18,258
So, you know, we're a little
bit bigger than a person.

345
00:15:18,258 --> 00:15:21,128
Our launch was this
interesting launch called,

346
00:15:21,128 --> 00:15:24,197
the launch vehicle, called
the Pegasus Launch Vehicle.

347
00:15:24,197 --> 00:15:26,766
Here's a little video of it.

348
00:15:26,766 --> 00:15:28,701
This actually isn't our launch.

349
00:15:28,701 --> 00:15:32,372
We launched at night, and so
this is just archival footage

350
00:15:32,372 --> 00:15:35,409
of a launch, but essentially,
they use an L-1011,

351
00:15:35,409 --> 00:15:39,479
a Lockheed 1011 jumbo
jet as a first stage,

352
00:15:39,479 --> 00:15:42,716
takes the rocket
up to 30,000 feet,

353
00:15:42,716 --> 00:15:45,552
drops it for five
seconds, it ignites,

354
00:15:45,552 --> 00:15:48,488
and then takes
you up into space.

355
00:15:48,488 --> 00:15:50,157
And so this all
happened in June.

356
00:15:50,157 --> 00:15:52,392
The airplane took off
from the Kwajalein Atoll,

357
00:15:52,392 --> 00:15:55,528
in the Marshall Islands,
and since that point,

358
00:15:55,528 --> 00:15:57,698
NuSTAR has been
orbiting the Earth,

359
00:15:57,698 --> 00:16:00,766
basically over the
equator every 90 minutes

360
00:16:00,766 --> 00:16:03,670
and taking data the whole time.

361
00:16:03,670 --> 00:16:05,939
I heard on NPR this
morning, they launched a,

362
00:16:05,939 --> 00:16:08,007
they did another
Pegasus this morning,

363
00:16:08,007 --> 00:16:10,043
if you had heard, with
something studying,

364
00:16:10,043 --> 00:16:13,580
something called CYGNSS,
studying hurricanes.

365
00:16:13,580 --> 00:16:15,215
But there's beautiful
videos of that.

366
00:16:15,215 --> 00:16:17,317
I just was watching that.

367
00:16:18,818 --> 00:16:20,454
So we got into space.

368
00:16:20,454 --> 00:16:22,388
The first thing you do is
you deploy your solar panel,

369
00:16:22,388 --> 00:16:24,290
just to stay power-positive.

370
00:16:24,290 --> 00:16:27,261
Exercise that you're able to
move the spacecraft around,

371
00:16:27,261 --> 00:16:31,431
and then about a week
after launch, we deployed

372
00:16:31,431 --> 00:16:34,234
this extendable mast,
so that we could start

373
00:16:34,234 --> 00:16:36,269
focusing the X-ray light.

374
00:16:36,269 --> 00:16:37,771
And so this is the
artist's conception

375
00:16:37,771 --> 00:16:39,305
of what that looked like.

376
00:16:39,305 --> 00:16:42,074
There's our two optics modules.

377
00:16:42,074 --> 00:16:44,311
We have two detectors down here,

378
00:16:44,311 --> 00:16:46,512
and basically the launch
and then this were

379
00:16:46,512 --> 00:16:49,149
the two really scariest
parts of the mission.

380
00:16:49,149 --> 00:16:51,184
This took about 40 minutes.

381
00:16:51,184 --> 00:16:54,488
And just like the launch,
it went perfectly.

382
00:16:54,488 --> 00:16:57,658
And so, it just is
a very cute design,

383
00:16:58,825 --> 00:17:01,361
that very simple
and very compact,

384
00:17:02,562 --> 00:17:05,732
and then it extends

out by this 30 feet.

385
00:17:07,334 --> 00:17:10,170
And so, I'll just
let that finish.

386
00:17:11,605 --> 00:17:13,306
And so, we're orbiting the
Earth every 90 minutes,

387
00:17:13,306 --> 00:17:16,810
taking data; there's
the two optics units.

388
00:17:20,713 --> 00:17:24,451
So, with this very
successful launch,

389
00:17:24,451 --> 00:17:27,454
ant this great new technology,
we've been doing a range

390
00:17:27,454 --> 00:17:30,423
of really game-changing
observations.

391
00:17:30,423 --> 00:17:34,194
Talk about first: black
hole spin measurements.

392
00:17:34,194 --> 00:17:37,264
So, first off,
what's a black hole?

393
00:17:37,264 --> 00:17:40,967
I could give a whole, one-hour
lecture on black holes,

394
00:17:40,967 --> 00:17:42,903
do more than that even.

395
00:17:44,271 --> 00:17:46,273
We're not gonna do that
today, but just real briefly,

396
00:17:46,273 --> 00:17:49,409
black holes are these
sort of crazy things that,

397
00:17:49,409 --> 00:17:51,377
you know, if I take this
ball and I throw it up,

398
00:17:51,377 --> 00:17:53,246
it comes back down;
if I throw it higher,

399
00:17:53,246 --> 00:17:54,781
it takes longer to come down.

400
00:17:54,781 --> 00:17:58,718
If I threw it really hard,
it would go up into space,

401
00:17:58,718 --> 00:18:01,721
and reach, you know, escape
velocity and go out into space

402
00:18:01,721 --> 00:18:05,825
and escape the gravitational
pull of the Earth.

403
00:18:05,825 --> 00:18:09,129
So way back, actually,
back in the 1700s,

404
00:18:09,129 --> 00:18:11,998
Emanuel Kant kind of did
a thought experiment that,

405
00:18:11,998 --> 00:18:13,800
could you imagine if
you had something that,

406
00:18:13,800 --> 00:18:16,836
its escape speed was
the speed of light,

407
00:18:16,836 --> 00:18:19,572
then not even light would
be able to escape from it?

408
00:18:19,572 --> 00:18:21,941
And so Emanuel Kant actually
kind of came up with the idea

409
00:18:21,941 --> 00:18:24,577
that black holes might exist.

410
00:18:24,577 --> 00:18:26,546
And it was many centuries later,

411
00:18:26,546 --> 00:18:28,882
before you know, physics
started showing that,

412
00:18:28,882 --> 00:18:30,950
yeah, we do predict
they might happen,

413
00:18:30,950 --> 00:18:32,752
and that actually,
the first black holes

414
00:18:32,752 --> 00:18:35,555
were found by a Cal
Tech astronomer,

415
00:18:35,555 --> 00:18:38,925

Martin Schmidt, about
52, 53 years ago,

416
00:18:38,925 --> 00:18:42,495
using the Palomar
Telescope with 3C 273.

417
00:18:42,495 --> 00:18:46,933
So these are incredibly odd
objects in the Universe.

418
00:18:46,933 --> 00:18:48,835
Very heavy, very dense.

419
00:18:50,436 --> 00:18:52,873
And very fascinating objects.

420
00:18:54,307 --> 00:18:56,709
A couple of things that
we know about black holes,

421
00:18:56,709 --> 00:18:58,311
we know that there's
a big black hole

422
00:18:58,311 --> 00:19:01,314
in the center of
every large galaxy,

423
00:19:01,314 --> 00:19:05,251
weighing millions to billions
of times as much as the sun.

424
00:19:05,251 --> 00:19:06,753
We know that there are
smaller black holes,

425
00:19:06,753 --> 00:19:08,555
weighing a bit
more than the sun,

426
00:19:08,555 --> 00:19:11,124
near 10 or a couple of
10's of times as much

427
00:19:11,124 --> 00:19:13,626
as the sun, peppered
throughout galaxies.

428
00:19:13,626 --> 00:19:16,329
There's, you know,
thousands in our own galaxy,

429
00:19:16,329 --> 00:19:18,431
and we see them in
nearby galaxies.

430
00:19:18,431 --> 00:19:22,736
So astronomers, like,
all astronomers know
black holes exist

431
00:19:22,736 --> 00:19:25,137
and that there's
different types.

432
00:19:25,137 --> 00:19:27,874
Oddly, we don't know,
we only know of one,

433
00:19:27,874 --> 00:19:29,776
in this intermediate
range, between the small

434
00:19:29,776 --> 00:19:32,545
and the big, and
that's a big issue

435
00:19:32,545 --> 00:19:35,314
that I'll talk about

a little bit later.

436
00:19:35,314 --> 00:19:38,885
Highlighting some more
Southern California astronomy,

437
00:19:38,885 --> 00:19:43,823
one of the best studies of the
nearest big black hole to us

438
00:19:43,823 --> 00:19:46,592
comes out of Andrea
Ghez's group at UCLA.

439
00:19:46,592 --> 00:19:48,461
And they've been
using, for the last

440
00:19:48,461 --> 00:19:50,763
15, 20 years, very
advanced techniques

441
00:19:50,763 --> 00:19:53,466
on the biggest
ground-based telescopes,

442
00:19:53,466 --> 00:19:57,604
to watch stars moving in
the center of our galaxy.

443
00:19:57,604 --> 00:19:59,639
There's a couple dozen
stars that they've now

444
00:19:59,639 --> 00:20:02,542
been tracking for 20
years, and they find

445
00:20:02,542 --> 00:20:05,277
that they're all orbiting

around a single point.

446
00:20:05,277 --> 00:20:07,246
You can use just high
school level physics

447
00:20:07,246 --> 00:20:10,350
to figure out how much that
single point must weigh,

448
00:20:10,350 --> 00:20:12,919
and it's about four million
times as much as the sun.

449
00:20:12,919 --> 00:20:16,356
It's very dim; you see it
flaring every once in a while.

450
00:20:16,356 --> 00:20:18,324
And there's basically,
physics tells you

451
00:20:18,324 --> 00:20:20,960
that the only thing
that could be that heavy

452
00:20:20,960 --> 00:20:24,030
and that dense is a black hole.

453
00:20:24,030 --> 00:20:26,098
And so this is, you know,
one of the best-studied

454
00:20:26,098 --> 00:20:30,036
black holes, is that one in
the center of our own galaxy.

455
00:20:30,036 --> 00:20:32,138
Over the last 15 years,
we've come to appreciate

456
00:20:32,138 --> 00:20:35,008
that probably all big
galaxies have something

457
00:20:35,008 --> 00:20:37,276
that weighs millions
to billions of times

458
00:20:37,276 --> 00:20:39,579
as much as the sun,
at their center.

459
00:20:39,579 --> 00:20:41,915
And they, about one half
of one percent of the mass

460
00:20:41,915 --> 00:20:45,986
of a galaxy is in the
central, little black hole.

461
00:20:47,420 --> 00:20:50,423
Things that we don't know
about black holes is,

462
00:20:50,423 --> 00:20:52,959
there's really extreme
physics happening,

463
00:20:52,959 --> 00:20:54,694
right near the black hole.

464
00:20:54,694 --> 00:20:57,764
It's, space and time
is being torn apart,

465
00:20:57,764 --> 00:21:02,502
as you might have seen in
the Interstellar movie.

466
00:21:02,502 --> 00:21:04,905
The, really strong
magnetic fields,

467
00:21:04,905 --> 00:21:08,108
crazy high temperatures,
creating X-rays, for instance.

468
00:21:08,108 --> 00:21:09,575
And so there's a lot
of work going on,

469
00:21:09,575 --> 00:21:11,243
trying to understand
the detailed physics

470
00:21:11,243 --> 00:21:13,946
of what's going on
near black holes.

471
00:21:13,946 --> 00:21:16,349
The cosmic history
of how black holes

472
00:21:16,349 --> 00:21:20,520
form and grow over time is a
big area of study, right now.

473
00:21:21,954 --> 00:21:24,624
We see black holes weighing
a billion times as much

474
00:21:24,624 --> 00:21:28,428
as the sun, less than a billion
years after the Big Bang.

475
00:21:28,428 --> 00:21:31,831
And basically, theorists
say that shouldn't exist.

476
00:21:31,831 --> 00:21:35,100
They, that the models have
a really hard time creating

477
00:21:35,100 --> 00:21:37,170
things that big, that quickly,

478
00:21:37,170 --> 00:21:39,673
and then the
observers find them.

479
00:21:39,673 --> 00:21:42,241
And then the other thing is
we think that black holes

480
00:21:42,241 --> 00:21:45,311
are really important
in how galaxies form

481
00:21:45,311 --> 00:21:47,647
and evolve over time,
and that's a big area

482
00:21:47,647 --> 00:21:49,182
of study right now.

483
00:21:50,182 --> 00:21:52,452
So where does NuSTAR come in?

484
00:21:52,452 --> 00:21:56,122
So black holes, at some
level, are very simple things.

485
00:21:56,122 --> 00:21:58,558
They're really,
mathematically, very pure.

486
00:21:58,558 --> 00:22:03,129
There's only three parameters

that define a black hole:

487
00:22:03,129 --> 00:22:06,466
its mass, its spin,
and then its charge.

488
00:22:08,801 --> 00:22:10,903
But any astrophysical
black hole should

489
00:22:10,903 --> 00:22:13,239
essentially have zero charge,
so we really kind of think

490
00:22:13,239 --> 00:22:16,276
of just two parameters,
the mass and the spin.

491
00:22:16,276 --> 00:22:19,079
Masses, we've been measuring
for the last 20 years,

492
00:22:19,079 --> 00:22:21,380
like that study by Andrea
Ghez, you watch things

493
00:22:21,380 --> 00:22:23,950
orbiting the black hole, you
can figure out how big it is.

494
00:22:23,950 --> 00:22:27,086
The spin of the black hole
has been harder to measure.

495
00:22:27,086 --> 00:22:29,789
And that's where NuSTAR came in.

496
00:22:29,789 --> 00:22:31,491
Being able to measure
the spin tells you

497
00:22:31,491 --> 00:22:33,560
about the environment
around the black hole.

498
00:22:33,560 --> 00:22:35,695
A little bit about how
the black hole forms.

499
00:22:35,695 --> 00:22:39,099
But one of the big
issues is, before NuSTAR,

500
00:22:39,099 --> 00:22:41,434
there'd been this
longstanding debate

501
00:22:41,434 --> 00:22:43,536
in the high-energy
X-ray community

502
00:22:43,536 --> 00:22:45,972
about if you could even
measure how fast black holes

503
00:22:45,972 --> 00:22:48,207
are spinning, and if
you went to a conference

504
00:22:48,207 --> 00:22:51,044
before NuSTAR launched, somebody
would give a talk about,

505
00:22:51,044 --> 00:22:52,978
you know, we measure the
spin of this black hole

506
00:22:52,978 --> 00:22:55,048
to be blah-blah-blah,
and then the next person

507
00:22:55,048 --> 00:22:57,717
would come up and say:
you can't measure the spin

508
00:22:57,717 --> 00:23:00,153
of a black hole, here's
our model that tells you,

509
00:23:00,153 --> 00:23:02,355
we can take that same
data and tells you nothing

510
00:23:02,355 --> 00:23:04,523
about how fast the
black hole is spinning.

511
00:23:04,523 --> 00:23:06,659
So you have these two,
like, warring camps

512
00:23:06,659 --> 00:23:09,729
at conferences, and then
most of the community

513
00:23:09,729 --> 00:23:12,899
was just sitting on
the fence, unsure.

514
00:23:14,301 --> 00:23:18,838
And the way the people
who are thinking they were

515
00:23:18,838 --> 00:23:21,074
measuring the spin of the
black holes were doing it,

516
00:23:21,074 --> 00:23:24,043
is that one of the strongest
features that you see

517
00:23:24,043 --> 00:23:26,779
in the X-rays from a
black hole is a strong

518
00:23:26,779 --> 00:23:29,949
emission line of iron,
you get very hot iron,

519
00:23:29,949 --> 00:23:31,817
very close to the black hole,

520
00:23:31,817 --> 00:23:35,221
and so it basically
comes from the region

521
00:23:36,388 --> 00:23:39,359
closest to the black
hole, and that region

522
00:23:39,359 --> 00:23:41,294
closest to the black
hole, would depend

523
00:23:41,294 --> 00:23:44,063
on how fast the black
holes is spinning.

524
00:23:44,063 --> 00:23:47,133
If the black hole is
spinning very, very fast,

525
00:23:47,133 --> 00:23:50,503
the disc of material
around the black hole gets

526
00:23:50,503 --> 00:23:54,940
brought in very, very close to
the black hole, and so this,

527
00:23:54,940 --> 00:23:59,479
the iron, is moving at
incredibly fast speeds.

528
00:23:59,479 --> 00:24:02,282
It's so close to the black hole
that you have light bending

529
00:24:02,282 --> 00:24:05,417
going on, and the emission
line, this iron line,

530
00:24:05,417 --> 00:24:10,356
gets really spread out and has
this really extreme profile

531
00:24:10,356 --> 00:24:14,360
that's from light bending
and relativistic effects.

532
00:24:14,360 --> 00:24:16,028
In the middle, I have a picture

533
00:24:16,028 --> 00:24:18,231
of a black hole
that's not spinning.

534
00:24:18,231 --> 00:24:20,933
And then on the right, I have
a picture of a black hole

535
00:24:20,933 --> 00:24:22,869
that's spinning in
the opposite direction

536
00:24:22,869 --> 00:24:24,604
of the material around it.

537
00:24:24,604 --> 00:24:26,906

And in those cases, the
inner region is farther

538
00:24:26,906 --> 00:24:30,343
from the black hole, and
you get less extreme bending

539
00:24:30,343 --> 00:24:33,379
of the light from
this iron line.

540
00:24:33,379 --> 00:24:35,514
And so this is all from
Sky and Telescope article,

541
00:24:35,514 --> 00:24:38,384
prior to the NuSTAR
launch by a post-doc,

542
00:24:38,384 --> 00:24:41,253
Laura Brenneman, who's actually
part of the NuSTAR team.

543
00:24:41,253 --> 00:24:42,155
At Harvard.

544
00:24:43,589 --> 00:24:47,560
So that was one idea of
what's going on with how

545
00:24:47,560 --> 00:24:49,762
you're measuring the
spin of black holes.

546
00:24:49,762 --> 00:24:52,632
Other people said that we can
explain these weird shapes

547
00:24:52,632 --> 00:24:55,034
of the iron line by just

putting a lot of gas and dust

548
00:24:55,034 --> 00:24:57,703
in front of the black
hole, and you can get

549
00:24:57,703 --> 00:24:59,539
these weird shapes from that.

550
00:24:59,539 --> 00:25:01,207
So you kind of
had this one model

551
00:25:01,207 --> 00:25:03,676
where you had the
spinning black hole,

552
00:25:03,676 --> 00:25:06,012
and you had this
weird-shaped iron line,

553
00:25:06,012 --> 00:25:08,448
and then it predicts
that at higher energies,

554
00:25:08,448 --> 00:25:11,784
you get this bump, and
then this other model says

555
00:25:11,784 --> 00:25:15,054
that's just gas and dust,
in front of the black hole,

556
00:25:15,054 --> 00:25:17,590
that's giving that weird
shape, that looks basically the

557
00:25:17,590 --> 00:25:20,759
same in the lower-energy
X-rays that you could study,

558
00:25:20,759 --> 00:25:24,430
prior to NuSTAR, with
Chandra and XMM, but had very

559
00:25:24,430 --> 00:25:26,332
different predictions
of what you should see

560
00:25:26,332 --> 00:25:28,501
in the higher energies,
which were inaccessible.

561
00:25:28,501 --> 00:25:29,669
Before NuSTAR.

562
00:25:31,104 --> 00:25:33,239
And so one of our first
observations was, we went

563
00:25:33,239 --> 00:25:38,044
to NGC 1365, that barred-spiral
galaxy I showed early on.

564
00:25:38,044 --> 00:25:41,613
Here's the low-energy X-ray
data from the XMM satellite,

565
00:25:41,613 --> 00:25:43,149
with the two different models.

566
00:25:43,149 --> 00:25:46,452
One is the shape of this
feature over here is all due

567
00:25:46,452 --> 00:25:48,521
to the spin of the black
hole, and you predict

568

00:25:48,521 --> 00:25:51,090
that at higher energies, you
should get this big bump.

569
00:25:51,090 --> 00:25:53,693
The other model says this
weird shape is all from gas

570
00:25:53,693 --> 00:25:55,761
and dust, and you have
a very different shape

571
00:25:55,761 --> 00:25:57,730
predicted in the NuSTAR band.

572
00:25:57,730 --> 00:25:59,398
So one of the early
NuSTAR observations

573
00:25:59,398 --> 00:26:02,202
was this joint
observation, and bang.

574
00:26:02,202 --> 00:26:06,439
The NuSTAR observation
sat exactly on that model.

575
00:26:06,439 --> 00:26:08,374
And so, at this
point, almost everyone

576
00:26:08,374 --> 00:26:10,876
has dropped off the
fences, agreed that,

577
00:26:10,876 --> 00:26:14,747
you know, you are
able to measure the
spins of black holes.

578

00:26:14,747 --> 00:26:17,349
There's, I think, two
people, maybe three people

579
00:26:17,349 --> 00:26:19,619
left in that camp are
still fighting for that,

580
00:26:19,619 --> 00:26:22,021
but it seems very convincing,
and there's been a range

581
00:26:22,021 --> 00:26:24,691
of studies from, you know,
more than a dozen black holes,

582
00:26:24,691 --> 00:26:26,993
all supporting this, and
showing that we're really able

583
00:26:26,993 --> 00:26:29,629
to measure how fast the
black hole are spinning,

584
00:26:29,629 --> 00:26:32,097
which tells you how close
that material is coming

585
00:26:32,097 --> 00:26:34,367
to that black hole,
and coming, you know,

586
00:26:34,367 --> 00:26:36,836
just a few times the
Schwarzchild radius away

587
00:26:36,836 --> 00:26:40,039
from the black hole;
it's really extreme.

588

00:26:40,039 --> 00:26:44,377
And so just summarizing,
oh yeah, another thing,

589
00:26:44,377 --> 00:26:47,714
pardon, is that, with the
NuSTAR, with this extra data,

590
00:26:47,714 --> 00:26:50,783
you're able to get a better,
more precise measurement.

591
00:26:50,783 --> 00:26:53,152
So not only do you get
rid of this ambiguity,

592
00:26:53,152 --> 00:26:56,655
but you also get a more precise
measurement with NuSTAR.

593
00:26:56,655 --> 00:26:59,859
And so, what we found for
NGC 1365 is the black hole

594
00:26:59,859 --> 00:27:02,761
is spinning at at
least 84 percent

595
00:27:02,761 --> 00:27:05,864
of the maximal speed
allowed by relativity.

596
00:27:05,864 --> 00:27:08,701
It's a very robust measurement.

597
00:27:08,701 --> 00:27:12,171
The first, really,
robust measurement
of a black hole spin.

598

00:27:12,171 --> 00:27:14,640
At this point, we
have about a dozen

599
00:27:14,640 --> 00:27:17,276
that we've measured,
but most of these spins

600
00:27:17,276 --> 00:27:21,013
have been very high, and
that kind of fits with,

601
00:27:21,013 --> 00:27:24,984
we kind of have two ideas about
how black holes might grow.

602
00:27:24,984 --> 00:27:28,520
One is your little bits
of feeding all the time,

603
00:27:28,520 --> 00:27:30,723
and then in that case,
you know, some should be

604
00:27:30,723 --> 00:27:33,092
coming from this direction,
some from that direction.

605
00:27:33,092 --> 00:27:35,361
And then that result is
the black hole shouldn't

606
00:27:35,361 --> 00:27:36,995
be spinning that fast.

607
00:27:36,995 --> 00:27:39,732
Instead, if you imagine that
most of the feeding comes from

608
00:27:39,732 --> 00:27:43,769

large accretion events,
where a big bunch of material

609
00:27:43,769 --> 00:27:45,905
falls in on the black
hole, that will spin up

610
00:27:45,905 --> 00:27:48,140
the black hole almost
like a, you know,

611
00:27:48,140 --> 00:27:50,109
an ice-skater bringing
in their arms.

612
00:27:50,109 --> 00:27:52,277
It just, if it's all
coming in at once,

613
00:27:52,277 --> 00:27:54,613
it just starts spinning
up really close

614
00:27:54,613 --> 00:27:56,683
as it gets close
to the black hole.

615
00:27:56,683 --> 00:27:58,884
And so this seems like, the
fact that we're measuring

616
00:27:58,884 --> 00:28:01,354
high spins, generally,
might point to most

617
00:28:01,354 --> 00:28:03,322
of the black hole
growth is happening

618
00:28:03,322 --> 00:28:06,559

in this big accretion events.

619
00:28:06,559 --> 00:28:08,828
We're able to start studying
the immediate environment

620
00:28:08,828 --> 00:28:11,097
about the black holes,
and then the big thing is

621
00:28:11,097 --> 00:28:13,900
we resolved this 15-year
debate in the community.

622
00:28:13,900 --> 00:28:16,301
So that was the nice,
early result from NuSTAR,

623
00:28:16,301 --> 00:28:18,871
that was published in Nature.

624
00:28:18,871 --> 00:28:22,841
So that's the first big
science result from NuSTAR.

625
00:28:22,841 --> 00:28:27,013
The second one I wanna talk
about is supernova explosions.

626
00:28:28,981 --> 00:28:32,785
And just to emphasize,
again, just like black holes,

627
00:28:32,785 --> 00:28:35,588
we could give a whole
one-hour, one-day lecture

628
00:28:35,588 --> 00:28:38,557
about supernovae; they're
incredibly important things.

629
00:28:38,557 --> 00:28:41,360
Basically, the Universe
started mainly just hydrogen

630
00:28:41,360 --> 00:28:44,296
and helium, and then
stars burned that hydrogen

631
00:28:44,296 --> 00:28:46,999
and helium, or fused it
into heavier elements,

632
00:28:46,999 --> 00:28:49,868
and everything in our body,
like the carbon in our body,

633
00:28:49,868 --> 00:28:53,606
the silicon in our computers,
the platinum in our jewelry,

634
00:28:53,606 --> 00:28:56,441
all was formed in stars,
and then was spread out

635
00:28:56,441 --> 00:28:58,911
into the Universe in supernovae.

636
00:28:58,911 --> 00:29:01,747
And you might be a little
bit confused of how,

637
00:29:01,747 --> 00:29:04,016
how does that happen?

638
00:29:04,016 --> 00:29:06,853
As the stars,
living like our sun,

639

00:29:09,121 --> 00:29:12,625
you have gravity pushing in,
because the star is very heavy,

640
00:29:12,625 --> 00:29:15,194
and then it's burning
material that's pushing out,

641
00:29:15,194 --> 00:29:17,330
and those balance each other,
and we have this largely,

642
00:29:17,330 --> 00:29:21,834
you know, stable star in the
center of our solar system

643
00:29:21,834 --> 00:29:23,936
that's burning fuel.

644
00:29:23,936 --> 00:29:27,206
In about five billion years,
the sun will run out of fuel,

645
00:29:27,206 --> 00:29:30,776
you'll stop having stuff pushing
out, gravity will win out,

646
00:29:30,776 --> 00:29:32,945
and the star will collapse.

647
00:29:32,945 --> 00:29:36,015
For the biggest stars,
that collapse should,

648
00:29:36,015 --> 00:29:37,950
creates an explosion.

649
00:29:37,950 --> 00:29:41,453
And one way to think
of it is, you imagine

650
00:29:41,453 --> 00:29:44,490
that here's the heavy,
inner parts of the star,

651
00:29:44,490 --> 00:29:47,326
here's the lighter
atmosphere of the star.

652
00:29:47,326 --> 00:29:51,397
Usually, this heavier part's
being held up by the burning,

653
00:29:51,397 --> 00:29:55,033
the regions below it, but
as you run out of fuel,

654
00:29:55,033 --> 00:29:57,002
nothing's pushing on
this, and then gravity

655
00:29:57,002 --> 00:30:00,006
will make the heavy, inner
parts of the star fall in,

656
00:30:00,006 --> 00:30:02,608
the lighter atmosphere
will follow it,

657
00:30:02,608 --> 00:30:06,144
falling back in, but then
it will hit the bottom,

658
00:30:06,144 --> 00:30:08,581
and the outer parts will bounce

659
00:30:08,581 --> 00:30:11,684
off the heavier,
inner parts, so.

660
00:30:11,684 --> 00:30:13,386
This is it.

661
00:30:13,386 --> 00:30:15,655
(laughter)

662
00:30:17,122 --> 00:30:17,957
Oops.

663
00:30:19,358 --> 00:30:21,761
We're actually, I'm gonna do
one more, just 'cause it's fun.

664
00:30:21,761 --> 00:30:22,628
(laughter)

665
00:30:22,628 --> 00:30:23,563
Oh, thanks.

666
00:30:24,997 --> 00:30:25,832
Okay.

667
00:30:27,533 --> 00:30:29,802
(laughter)

668
00:30:33,406 --> 00:30:35,641
(applause)

669
00:30:39,879 --> 00:30:43,215
So, one little problem
in that though,

670
00:30:43,215 --> 00:30:47,587
is that theorists, trying
to create these supernova

671
00:30:47,587 --> 00:30:50,956
explosions on their computers,

over the last 20 years,

672
00:30:50,956 --> 00:30:53,058
can't get the
explosion to happen.

673
00:30:53,058 --> 00:30:55,361
You should get that
collapse, you should get

674
00:30:55,361 --> 00:30:58,130
that bounce back, but in
the computer simulations,

675
00:30:58,130 --> 00:31:01,300
after about, I don't
know, 100 milliseconds,

676
00:31:01,300 --> 00:31:06,072
the bounce back stalls, and
the star should stop exploding,

677
00:31:06,072 --> 00:31:08,407
so there's been a
slight embarrassment

678
00:31:08,407 --> 00:31:12,711
that the theorists say stars
shouldn't actually supernova.

679
00:31:12,711 --> 00:31:15,214
And then the observers are
saying, well, we see them.

680
00:31:15,214 --> 00:31:17,216
(laughter)

681
00:31:17,216 --> 00:31:19,785
And so, NuSTAR comes
in with a new way

682
00:31:19,785 --> 00:31:21,687
of studying the supernovae.

683
00:31:21,687 --> 00:31:23,589
This is a slightly
complicated slide,

684
00:31:23,589 --> 00:31:27,360
but basically, as a star
explodes, it creates

685
00:31:29,094 --> 00:31:31,330
a lot of very hot titanium.

686
00:31:32,564 --> 00:31:35,101
Titanium is an unstable element.

687
00:31:35,101 --> 00:31:37,136
It decays, it's a
radioactive element,

688
00:31:37,136 --> 00:31:40,072
it decays into calcium,
and as it decays,

689
00:31:40,072 --> 00:31:43,475
it creates high-energy
photons, X-ray light.

690
00:31:43,475 --> 00:31:46,145
You get two photons that
are in the NuSTAR band

691
00:31:46,145 --> 00:31:49,582
at 68 and 78
kiloelectronvolts, there.

692
00:31:49,582 --> 00:31:51,550

You know, that
high-energy X-ray light

693
00:31:51,550 --> 00:31:53,085
that NuSTAR can study.

694
00:31:53,085 --> 00:31:55,287
You got a couple other things
that are harder to study,

695
00:31:55,287 --> 00:31:58,457
like positrons and even
higher-energy photons.

696
00:31:58,457 --> 00:32:01,193
And so the key
thing, though, here,

697
00:32:01,193 --> 00:32:04,664
is that previous studies
that people have been doing

698
00:32:04,664 --> 00:32:08,868
of supernovae over the last
decades have been studying

699
00:32:10,102 --> 00:32:14,072
either hot iron, or hot
magnesium, or cold iron.

700
00:32:14,072 --> 00:32:16,642
They're measuring different
states of material

701
00:32:16,642 --> 00:32:18,277
that are dependent
on the temperature

702
00:32:18,277 --> 00:32:21,780
and the ionization

state of that material.

703
00:32:21,780 --> 00:32:24,016
NuSTAR comes in, and
we're the first ones able

704
00:32:24,016 --> 00:32:28,186
to study a radioactive element
created in the explosion.

705
00:32:28,186 --> 00:32:32,358
And so, all the titanium will
go through this decay rate,

706
00:32:32,358 --> 00:32:35,060
will create those
high-energy X-ray light,

707
00:32:35,060 --> 00:32:38,364
whereas the iron that had
been studied by Chandra,

708
00:32:38,364 --> 00:32:40,699
for example, had to be
a certain temperature

709
00:32:40,699 --> 00:32:43,402
and density of iron
to actually see it.

710
00:32:43,402 --> 00:32:45,070
It's not nearly as
good of a tracer.

711
00:32:45,070 --> 00:32:48,273
So this is like, DNA
evidence, and they were using,

712
00:32:48,273 --> 00:32:52,911
I don't know, fingerprints or

something not nearly as good

713
00:32:52,911 --> 00:32:56,148
for trying to understand
the supernova.

714
00:33:02,888 --> 00:33:04,790
Oh, and then the
other thing, pardon,

715
00:33:04,790 --> 00:33:07,859
is that this titanium also
gets formed in this region

716
00:33:07,859 --> 00:33:12,031
where in some models, the iron
falls back with the remnant,

717
00:33:13,799 --> 00:33:16,335
created by the supernova,
and then in other models,

718
00:33:16,335 --> 00:33:19,505
people had that titanium
gets thrown out.

719
00:33:19,505 --> 00:33:23,542
So this titanium line is
this very good diagnostic

720
00:33:23,542 --> 00:33:26,045
between all the different
theoretical models

721
00:33:26,045 --> 00:33:28,247
of what the explosion
should be like.

722
00:33:28,247 --> 00:33:30,816
So this was like,

kind of a holy grail

723
00:33:30,816 --> 00:33:33,685
to be able to study
the titanium emission

724
00:33:33,685 --> 00:33:36,288
from supernova remnants,
and that NuSTAR

725
00:33:36,288 --> 00:33:37,823
was the first one
really to step up

726
00:33:37,823 --> 00:33:39,992
and be able to do it well.

727
00:33:41,160 --> 00:33:42,961
Before we launched,
there was a range

728
00:33:42,961 --> 00:33:44,563
of models of what would happen.

729
00:33:44,563 --> 00:33:46,632
I said how the
models basically say

730
00:33:46,632 --> 00:33:49,502
the explosion should stall,
and so there were two different

731
00:33:49,502 --> 00:33:52,671
ideas out there of how
you might break the stall.

732
00:33:52,671 --> 00:33:54,039
Some people said, you know,

733

00:33:54,039 --> 00:33:55,708
the star should be
spinning quickly.

734
00:33:55,708 --> 00:33:57,209
When you have something
spinning quickly,

735
00:33:57,209 --> 00:33:58,577
you might get jets forming.

736
00:33:58,577 --> 00:34:00,379
That jet might break the stall.

737
00:34:00,379 --> 00:34:01,981
And so there were
some models where,

738
00:34:01,981 --> 00:34:03,815
you know, you might break
the stall from the jets.

739
00:34:03,815 --> 00:34:05,651
And they predicted
that the titanium

740
00:34:05,651 --> 00:34:09,721
should make this sort
of vertical structure,

741
00:34:09,721 --> 00:34:12,325
around the remnant of the star.

742
00:34:13,426 --> 00:34:15,327
Other people had models
where, basically,

743
00:34:15,327 --> 00:34:18,297
the stall, you get the
explosion would stall,

744
00:34:18,297 --> 00:34:20,332
and then they would say,
well, maybe there's some extra

745
00:34:20,332 --> 00:34:22,868
energy input, and they would
make up different reasons

746
00:34:22,868 --> 00:34:25,870
of how you would get it, but
that would break the stall.

747
00:34:25,870 --> 00:34:27,740
And those models would predict

748
00:34:27,740 --> 00:34:30,609
that you'd get this sort of
spherical explosion coming out,

749
00:34:30,609 --> 00:34:33,312
and so the titanium
should be in a ring.

750
00:34:33,312 --> 00:34:35,013
And so basically, the
theorists were very excited

751
00:34:35,013 --> 00:34:38,484
to see whether we would see
a line or a ring with NuSTAR.

752
00:34:38,484 --> 00:34:42,387
And that, here's just
a more colorful model,

753
00:34:42,387 --> 00:34:43,689
prior to the NuSTAR launch,

754

00:34:43,689 --> 00:34:46,992
of what you might
see with these jets.

755
00:34:46,992 --> 00:34:51,563
Motivating that, if you looked
at the silicon/magnesium

756
00:34:51,563 --> 00:34:53,699
in the lower-energy
X-rays, with Chandra,

757
00:34:53,699 --> 00:34:56,401
from the Cassiopeia
A supernova remnant,

758
00:34:56,401 --> 00:34:59,871
it's a nearby supernova
remnant in our galaxy,

759
00:34:59,871 --> 00:35:01,907
there's sort of this structure,

760
00:35:01,907 --> 00:35:04,376
this long structure, which
people would point to

761
00:35:04,376 --> 00:35:07,079
and say, oh, it must be the
jet that breaks the stall,

762
00:35:07,079 --> 00:35:09,248
and that's the physics
that's going on.

763
00:35:09,248 --> 00:35:11,484
If you looked at the iron,
though, from that same remnant

764
00:35:11,484 --> 00:35:13,585

it mainly made a ring,
and so people would point

765
00:35:13,585 --> 00:35:16,422
to that and say, oh,
it's probably mainly
this spherically,

766
00:35:16,422 --> 00:35:18,991
symmetric explosion
that's happening.

767
00:35:18,991 --> 00:35:20,493
And so, basically,
people thought we'd

768
00:35:20,493 --> 00:35:23,829
either see this, or
that with NuSTAR.

769
00:35:23,829 --> 00:35:26,665
And this is what we ended
up seeing with the titanium.

770
00:35:26,665 --> 00:35:30,302
We saw these bunches
of blue knots,

771
00:35:30,302 --> 00:35:32,971
unlike the ring or the line.

772
00:35:32,971 --> 00:35:35,640
And completely unexpected by us,

773
00:35:35,640 --> 00:35:38,810
completely unexpected by
what we put in the proposal

774
00:35:38,810 --> 00:35:42,981
when we, you know, wanted to

do NuSTAR in the early 2000s.

775
00:35:42,981 --> 00:35:44,950
We proposed the mission.

776
00:35:44,950 --> 00:35:48,587
However, it turned out
that, in the time that we

777
00:35:48,587 --> 00:35:50,489
were so busy building
those crazy optics

778
00:35:50,489 --> 00:35:52,958
and doing the extendable
mast, the theorists

779
00:35:52,958 --> 00:35:55,060
had taken a step forward
in their modeling,

780
00:35:55,060 --> 00:35:57,496
and finally gotten to do
three-dimensional models,

781
00:35:57,496 --> 00:35:59,631
putting in all the physics,
in a three-dimensional

782
00:35:59,631 --> 00:36:02,868
situation, and so actually,
even on the third floor

783
00:36:02,868 --> 00:36:06,205
of Cal Tech Astronomy,
there was models,

784
00:36:08,707 --> 00:36:12,177
trying to do this
three-dimensional version,

785
00:36:12,177 --> 00:36:13,979
and this is what their
models would show.

786
00:36:13,979 --> 00:36:17,416
You get that initial
collapse, that explosion out,

787
00:36:17,416 --> 00:36:21,687
you get the stall in the
explosion at 100 milliseconds,

788
00:36:21,687 --> 00:36:24,923
and that's just sitting
there for a while,

789
00:36:24,923 --> 00:36:27,592
and then in the 3D models, you
end up starting to get this

790
00:36:27,592 --> 00:36:31,229
sloshing that can happen,
that you didn't see

791
00:36:31,229 --> 00:36:34,667
in the two-dimensional
or one-dimensional
theoretical models

792
00:36:34,667 --> 00:36:38,837
and that basically breaks
the stall, almost like

793
00:36:38,837 --> 00:36:40,606
I like to think of like, when
you're blowing up a balloon,

794
00:36:40,606 --> 00:36:42,174
and you're blowing

it and it gets stuck,

795
00:36:42,174 --> 00:36:43,675
and it gets stuck,
and you keep blowing,

796
00:36:43,675 --> 00:36:46,711
and then eventually, part
of it gets expanded out,

797
00:36:46,711 --> 00:36:48,380
and it basically breaks that,

798
00:36:48,380 --> 00:36:50,783
and your balloon
gets much bigger.

799
00:36:50,783 --> 00:36:53,284
And so, in their
models, they were able

800
00:36:53,284 --> 00:36:57,422
to break the stall with
this sloshing pattern.

801
00:36:57,422 --> 00:37:00,158
And the predictions
of their models

802
00:37:00,158 --> 00:37:04,696
say that the titanium should
basically be in clumps,

803
00:37:04,696 --> 00:37:08,366
interior to the ring,
the symmetric iron ring,

804
00:37:08,366 --> 00:37:11,737
and basically fitting very
much what NuSTAR had seen.

805
00:37:11,737 --> 00:37:14,305
Here's the blue is
the NuSTAR titanium,

806
00:37:14,305 --> 00:37:17,242
in these clumps, the
red is the iron shell,

807
00:37:17,242 --> 00:37:19,310
and that green is a magnesium,

808
00:37:19,310 --> 00:37:22,314
that magnesium linear structure.

809
00:37:22,314 --> 00:37:27,019
And so basically, our
observations of the titanium

810
00:37:27,019 --> 00:37:30,722
fit in exactly with what the
theorists were predicting

811
00:37:30,722 --> 00:37:33,559
about, you know, just
in the months before

812
00:37:33,559 --> 00:37:35,861
we started making
these observations.

813
00:37:35,861 --> 00:37:38,130
And so it seems like
NuSTAR has solved

814
00:37:38,130 --> 00:37:40,399
this question of how
do stars explode,

815

00:37:40,399 --> 00:37:44,669
which is important for
everything around you.

816
00:37:44,669 --> 00:37:47,205
So that was another,
chalked up good,

817
00:37:47,205 --> 00:37:49,375
nice discovery from NuSTAR.

818
00:37:49,375 --> 00:37:51,709
And then finally,
the most recent one

819
00:37:51,709 --> 00:37:54,346
is ultraluminous X-ray sources.

820
00:37:54,346 --> 00:37:56,582
And so, I mentioned before,

821
00:37:57,916 --> 00:37:59,818
or I showed this picture before,

822
00:37:59,818 --> 00:38:02,554
of this nearby galaxy, IC 342.

823
00:38:02,554 --> 00:38:06,458
Most of the X-rays in this
galaxy are coming from two knots

824
00:38:06,458 --> 00:38:09,261
in the outer parts of
the disc of the galaxy.

825
00:38:09,261 --> 00:38:13,065
When you look at nearby
galaxies, it's rare,

826

00:38:13,065 --> 00:38:15,200
but not incredibly rare,
that you will see these

827
00:38:15,200 --> 00:38:17,035
really, really
bright X-ray sources,

828
00:38:17,035 --> 00:38:18,837
not at the center of the galaxy.

829
00:38:18,837 --> 00:38:20,239
At the center, we
think there's a billion

830
00:38:20,239 --> 00:38:21,907
or million solar
mass black hole,

831
00:38:21,907 --> 00:38:24,576
and if stuff's falling in on
it, it creates a lot of X-rays.

832
00:38:24,576 --> 00:38:26,712
No surprise if you
see a lot of X-rays

833
00:38:26,712 --> 00:38:29,180
coming from the
center of the galaxy.

834
00:38:29,180 --> 00:38:30,615
But these guys in the outskirts

835
00:38:30,615 --> 00:38:32,884
have been a bit of a mystery.

836
00:38:32,884 --> 00:38:35,420
There's two main ideas that
have been going on for them,

837
00:38:35,420 --> 00:38:38,090
prior to NuSTAR to explain them.

838
00:38:38,090 --> 00:38:40,692
One is that maybe they're
large black holes,

839
00:38:40,692 --> 00:38:42,761
bigger than the
sort of black holes

840
00:38:42,761 --> 00:38:44,529
that can get formed
in supernovae,

841
00:38:44,529 --> 00:38:46,298
that weigh you know,
a couple dozen times

842
00:38:46,298 --> 00:38:48,867
as much as the sun, not as
big as the guys in the center,

843
00:38:48,867 --> 00:38:52,604
so things weighing 1,000,
10,000-times as much as the sun.

844
00:38:52,604 --> 00:38:55,540
And as I said, there's only
one of those that's known.

845
00:38:55,540 --> 00:38:58,644
But the Universe has
to be full of them.

846
00:38:58,644 --> 00:38:59,944
And so it could be
something like that,

847
00:38:59,944 --> 00:39:02,180
just feeding at a typical rate.

848
00:39:02,180 --> 00:39:05,718
The other idea is maybe
they're more like those smaller

849
00:39:05,718 --> 00:39:08,053
black holes formed
when stars explode,

850
00:39:08,053 --> 00:39:10,856
but feeding at
incredibly high rates.

851
00:39:10,856 --> 00:39:13,058
Rates that can't be stable.

852
00:39:13,058 --> 00:39:15,193
We call it
Super-Eddington accretion.

853
00:39:15,193 --> 00:39:18,296
It's, in theory, it
should be possible,

854
00:39:18,296 --> 00:39:20,598
but it can't be a
stable scenario.

855
00:39:20,598 --> 00:39:23,768
But that was another idea
of what might be going on.

856
00:39:23,768 --> 00:39:25,337
And then maybe,
some people thought,

857
00:39:25,337 --> 00:39:27,205

maybe it's something else,
but it was pretty much

858
00:39:27,205 --> 00:39:30,475
one of those two is what
people were thinking.

859
00:39:30,475 --> 00:39:33,312
To put it a little bit in
context, here's the range

860
00:39:33,312 --> 00:39:37,649
of masses of very compact
objects in the Universe.

861
00:39:37,649 --> 00:39:41,086
At the high end, we see these
supermassive black holes

862
00:39:41,086 --> 00:39:43,421
at the centers of the
galaxies, weighing millions

863
00:39:43,421 --> 00:39:46,492
to billions of times
as much as the sun.

864
00:39:46,492 --> 00:39:49,928
We get stellar-mass black
holes, formed when stars explode

865
00:39:49,928 --> 00:39:52,498
that weigh a few 10-times
as much as the sun.

866
00:39:52,498 --> 00:39:54,599
There's this
intermediate mass range,

867
00:39:54,599 --> 00:39:57,669

which is, there's one object.

868
00:39:57,669 --> 00:40:01,140
And then into the lower end,
you can get neutron stars.

869
00:40:01,140 --> 00:40:03,541
So, really big stars
when they explode,

870
00:40:03,541 --> 00:40:05,611
leave this black hole remnant.

871
00:40:05,611 --> 00:40:08,313
Smaller black holes,
er, smaller stars,

872
00:40:08,313 --> 00:40:11,216
when they explode, can
leave a neutron star.

873
00:40:11,216 --> 00:40:14,686
And a neutron star is
basically a big atom.

874
00:40:14,686 --> 00:40:16,688
It's just protons and neutrons.

875
00:40:16,688 --> 00:40:19,124
It could be on the
periodic table.

876
00:40:19,124 --> 00:40:21,292
Relatively simple
physics tells you

877
00:40:21,292 --> 00:40:23,262
it's more neutrons than protons.

878

00:40:23,262 --> 00:40:26,397
But something like
the sun, if the sun

879
00:40:26,397 --> 00:40:29,501
were a neutron star, would be
about the size of Pasadena.

880
00:40:29,501 --> 00:40:32,972
About 10 kilometers in size,
so they're also very extreme,

881
00:40:32,972 --> 00:40:36,175
like black holes, but
they're made out of things

882
00:40:36,175 --> 00:40:37,909
that we understand:
protons, neutrons.

883
00:40:37,909 --> 00:40:40,312
You have electrons around them.

884
00:40:40,312 --> 00:40:44,483
So they're not nearly as
weird as the black holes.

885
00:40:45,950 --> 00:40:48,887
So, where did NuSTAR come in?

886
00:40:48,887 --> 00:40:52,458
So, we did a big study
of the Cigar Galaxy,

887
00:40:53,625 --> 00:40:56,060
also known as M82, and
this is just showing you

888
00:40:56,060 --> 00:40:57,896
a couple pictures of the M82.

889
00:40:57,896 --> 00:41:00,499
On the left-hand
side, I have a picture

890
00:41:00,499 --> 00:41:03,468
with Hubble Space Telescope
in the visible light,

891
00:41:03,468 --> 00:41:05,370
the sort of light that you
can see with your eyes.

892
00:41:05,370 --> 00:41:07,072
And there's sort
of this blue cigar

893
00:41:07,072 --> 00:41:12,010
with hydrogen gas coming
out, in the top and bottom.

894
00:41:12,010 --> 00:41:14,946
Chandra has also studied this
nearby, beautiful galaxy,

895
00:41:14,946 --> 00:41:18,016
and sees a very different
picture of this galaxy.

896
00:41:18,016 --> 00:41:19,984
This is, really
just beauty shots

897
00:41:19,984 --> 00:41:21,754
to show you that when you look
at different parts of light,

898
00:41:21,754 --> 00:41:24,490
you see very
different phenomena.

899
00:41:26,558 --> 00:41:30,396
In January, 2014, a
supernova went off in M82.

900
00:41:33,165 --> 00:41:35,266
It was, this is a
very nearby galaxy,

901
00:41:35,266 --> 00:41:36,935
so this is a bright supernova.

902
00:41:36,935 --> 00:41:39,471
In fact, it was so bright,
that it was found by

903
00:41:39,471 --> 00:41:43,909
a college astronomy class at
University College, London,

904
00:41:43,909 --> 00:41:47,846
on the rooftop in London,
doing their, like, star party.

905
00:41:47,846 --> 00:41:50,315
And one of the
students was like, hey,

906
00:41:50,315 --> 00:41:52,384
this isn't in my
picture in the book.

907
00:41:52,384 --> 00:41:55,887
And so they were the
discoverers of this supernova.

908
00:41:55,887 --> 00:41:59,191
It was the nearest
type 1A supernova,

909
00:41:59,191 --> 00:42:01,626
which is one of the subclasses,
but a very important

910
00:42:01,626 --> 00:42:03,595
subclass of supernova, so it was

911
00:42:03,595 --> 00:42:06,598
the nearest 1A in 150 years.

912
00:42:06,598 --> 00:42:09,500
So incredibly important
source for study.

913
00:42:09,500 --> 00:42:12,070
Basically, every
facility on the planet,

914
00:42:12,070 --> 00:42:14,205
and in space, went
and studied it.

915
00:42:14,205 --> 00:42:17,942
And this is a Hubble
image of that supernova.

916
00:42:17,942 --> 00:42:20,345
NuSTAR jumped on it as well.

917
00:42:20,345 --> 00:42:22,947
And we spent about a month
studying this supernova,

918
00:42:22,947 --> 00:42:24,950
because there was all
sorts of unique features

919
00:42:24,950 --> 00:42:27,352
for studying supernova, like

I talked about a minute ago,

920
00:42:27,352 --> 00:42:30,489
that NuSTAR has
unique access to.

921
00:42:30,489 --> 00:42:32,924
I'm not gonna talk about the
supernova anymore, though.

922
00:42:32,924 --> 00:42:34,358
We're still working on that.

923
00:42:34,358 --> 00:42:35,426
We have some exciting results,

924
00:42:35,426 --> 00:42:37,796
but we're still working on it.

925
00:42:37,796 --> 00:42:40,164
The big surprise in
this study, though,

926
00:42:40,164 --> 00:42:42,734
was that towards the
center of the galaxy,

927
00:42:42,734 --> 00:42:46,037
there are some, these
ultraluminous X-ray sources

928
00:42:46,037 --> 00:42:50,542
in M82, there's, astronomers
are very good at naming things,

929
00:42:50,542 --> 00:42:53,812
so there's M82 X-1
and M82 X-1 and X-2.

930

00:42:55,247 --> 00:42:57,682
Towards the center, they're
very bright X-ray sources.

931
00:42:57,682 --> 00:43:00,085
M82 X-1 is actually a candidate

932
00:43:00,085 --> 00:43:03,054
for this intermediate
mass black hole.

933
00:43:03,054 --> 00:43:04,989
Not one that everyone believes,

934
00:43:04,989 --> 00:43:06,925
but it's one of the
relatively good candidates

935
00:43:06,925 --> 00:43:08,093
for something like that.

936
00:43:08,093 --> 00:43:10,595
M82 X-2 wasn't nearly
as well-studied.

937
00:43:10,595 --> 00:43:14,399
The blue light, here,
is the Chandra image

938
00:43:14,399 --> 00:43:18,370
of the center of that galaxy,
and then the pink is NuSTAR.

939
00:43:18,370 --> 00:43:20,905
And so basically, NuSTAR
is seeing mainly X-rays

940
00:43:20,905 --> 00:43:23,808
coming from M82 X-2, so from the

941
00:43:23,808 --> 00:43:26,678
second ultraluminous
X-ray source.

942
00:43:26,678 --> 00:43:29,981
And so we spent about a
month staring at this galaxy.

943
00:43:29,981 --> 00:43:32,083
This is probably the
longest observation

944
00:43:32,083 --> 00:43:34,585
that NuSTAR has done
of a single object.

945
00:43:34,585 --> 00:43:37,321
Studying the supernova, but
as we were analyzing the data,

946
00:43:37,321 --> 00:43:40,458
we saw M82 X-2, so we
started looking at that.

947
00:43:40,458 --> 00:43:45,030
We did something else, and so
there's an Italian post-doc,

948
00:43:45,030 --> 00:43:48,700
Matteo Bacetti, who's
doing some timing analysis,

949
00:43:48,700 --> 00:43:52,437
and what he found was that,
not for the whole month,

950
00:43:52,437 --> 00:43:55,473
but for like, more than
a week of that month,

951
00:43:55,473 --> 00:43:59,878
M82 X-2 was pulsating; it
would get brighter and dimmer,

952
00:43:59,878 --> 00:44:01,412
brighter and dimmer.

953
00:44:01,412 --> 00:44:04,783
This is something that no
ultraluminous X-ray source

954
00:44:04,783 --> 00:44:07,285
had ever been seen to do.

955
00:44:07,285 --> 00:44:11,289
And what we think is happening
is that it's a pulsar.

956
00:44:11,289 --> 00:44:14,126
It's, basically, it's
like a lighthouse.

957
00:44:14,126 --> 00:44:16,961
You have a, black
holes can't do this,

958
00:44:16,961 --> 00:44:18,764
only neutron stars can do this,

959
00:44:18,764 --> 00:44:20,431
because black holes
don't have edges,

960
00:44:20,431 --> 00:44:22,500
and they're weird things
and they can't have charge,

961
00:44:22,500 --> 00:44:25,169
so only neutron

stars can do this,

962
00:44:25,169 --> 00:44:27,105
and it's essentially,
it's spinning.

963
00:44:27,105 --> 00:44:31,276
It's got, as it's spinning,
light's coming out of the edges.

964
00:44:32,443 --> 00:44:34,345
Pardon, along the spin
axis, and as that light

965
00:44:34,345 --> 00:44:36,982
points towards you,
it's like a lighthouse,

966
00:44:36,982 --> 00:44:39,050
where it gets
brighter and dimmer,

967
00:44:39,050 --> 00:44:41,086
brighter and dimmer.

968
00:44:41,086 --> 00:44:44,155
And so, M82 X-1 was
pulsating, I think,

969
00:44:44,155 --> 00:44:48,759
every 4.2 seconds, for about
a week of those observations,

970
00:44:48,759 --> 00:44:52,464
and immediately, we
knew like, that meant,

971
00:44:52,464 --> 00:44:54,665
it's not a black hole,
it's not a big black hole,

972
00:44:54,665 --> 00:44:57,102
it's not a small black
hole, it's a pulsar.

973
00:44:57,102 --> 00:45:00,405
And it's way brighter,
200-times brighter

974
00:45:00,405 --> 00:45:04,843
than any pulsar anyone
has ever seen before.

975
00:45:04,843 --> 00:45:06,477
It was a new class of object

976
00:45:06,477 --> 00:45:08,479
that hadn't even been dreamt of.

977
00:45:08,479 --> 00:45:10,348
You know, a new
denizen of the Universe

978
00:45:10,348 --> 00:45:13,784
that you know, had no idea
that these things existed.

979
00:45:13,784 --> 00:45:15,286
It was brighter and more distant

980
00:45:15,286 --> 00:45:18,223
than any pulsar that had
ever been seen before.

981
00:45:18,223 --> 00:45:22,761
Pulsars, or neutron
stars, have a fixed size.

982
00:45:22,761 --> 00:45:25,229

They can't get more massive
than a certain amount,

983
00:45:25,229 --> 00:45:26,965
or else they turn
into black holes.

984
00:45:26,965 --> 00:45:29,300
So this thing had to be
accreting at this extreme,

985
00:45:29,300 --> 00:45:33,472
Super-Eddington rate,
you know, 200-times the,

986
00:45:33,472 --> 00:45:35,940
essentially, the speed limit
of how fast you're allowed

987
00:45:35,940 --> 00:45:38,743
to accrete, this thing
had to be accreting at.

988
00:45:38,743 --> 00:45:42,247
Incredible surprise;
theorists confounded.

989
00:45:43,581 --> 00:45:45,149
And you know, so I've
observed I've been making fun

990
00:45:45,149 --> 00:45:47,051
of theorists a
couple times tonight,

991
00:45:47,051 --> 00:45:50,155
so for this, immediately
theorists starting
writing papers,

992

00:45:50,155 --> 00:45:52,157
you know, some groups said,
oh, we can explain it,

993
00:45:52,157 --> 00:45:53,892
the way you could get
this to happen is,

994
00:45:53,892 --> 00:45:56,728
it's gotta have super,
really high magnetic fields,

995
00:45:56,728 --> 00:45:58,697
and that's the way you
could get this happening.

996
00:45:58,697 --> 00:46:00,198
And then, you know, another
group somewhere else

997
00:46:00,198 --> 00:46:01,632
on the planet: oh,
we can explain it.

998
00:46:01,632 --> 00:46:02,834
The only way you could get it is

999
00:46:02,834 --> 00:46:04,169
it's got really low
magnetic fields.

1000
00:46:04,169 --> 00:46:07,205
And that's the way it's
able to accrete so fast.

1001
00:46:07,205 --> 00:46:10,675
Jury's out, we're still
trying to understand it.

1002
00:46:10,675 --> 00:46:13,077

This first one
was found in 2014,

1003
00:46:13,077 --> 00:46:16,114
and then for a long
time we're like,

1004
00:46:16,114 --> 00:46:17,782
is this the only one?

1005
00:46:17,782 --> 00:46:20,886
Maybe all ultraluminous
X-ray sources are pulsars.

1006
00:46:20,886 --> 00:46:22,420
We don't know.

1007
00:46:22,420 --> 00:46:24,389
You know, we've been doing
timing studies of a bunch.

1008
00:46:24,389 --> 00:46:26,491
And then it was a bit
like waiting for a bus

1009
00:46:26,491 --> 00:46:29,527
that, you know, for two
years or a year and a half,

1010
00:46:29,527 --> 00:46:31,462
we're waiting to see
if there are any more.

1011
00:46:31,462 --> 00:46:33,731
And then in a single
week, our group

1012
00:46:33,731 --> 00:46:38,036
and a group in Europe
simultaneously found two more,

1013
00:46:38,036 --> 00:46:40,205
using different data sets.

1014
00:46:41,372 --> 00:46:43,908
So now there's three of
these that are known.

1015
00:46:43,908 --> 00:46:45,710
And the other ones
are, in some ways,

1016
00:46:45,710 --> 00:46:47,612
better to study, because
there isn't another one,

1017
00:46:47,612 --> 00:46:50,015
another ultraluminous
source, right next door.

1018
00:46:50,015 --> 00:46:52,717
So it's, you know,
we're in the early days.

1019
00:46:52,717 --> 00:46:54,519
So there's all sorts of
studies we're trying to do

1020
00:46:54,519 --> 00:46:56,654
to both get more
information about them,

1021
00:46:56,654 --> 00:46:58,522
and then theorists
are trying to come up

1022
00:46:58,522 --> 00:47:01,759
with the models to explain them.

1023

00:47:01,759 --> 00:47:06,164
So, summary, NuSTAR is the
first focusing hard X-ray

1024
00:47:06,164 --> 00:47:09,034
satellite, or high-energy
X-ray satellite in orbit.

1025
00:47:09,034 --> 00:47:11,669
Very low backgrounds,
very compact detector.

1026
00:47:11,669 --> 00:47:14,272
200-times gain in sensitivity.

1027
00:47:14,272 --> 00:47:16,007
It's been a really fun ride.

1028
00:47:16,007 --> 00:47:19,778
We're up to more than
250 published papers

1029
00:47:19,778 --> 00:47:21,946
out of the NuSTAR
mission, at this point.

1030
00:47:21,946 --> 00:47:23,415
On a whole range of studies.

1031
00:47:23,415 --> 00:47:25,417
We've studied the sun,
we've studied black holes,

1032
00:47:25,417 --> 00:47:28,286
big black holes, small
black holes, neutron stars.

1033
00:47:28,286 --> 00:47:30,789
It's been a really
exciting ride.

1034
00:47:30,789 --> 00:47:34,726
And I'm glad to have taken
you over on part of it.

1035
00:47:34,726 --> 00:47:37,161
Here's technical details
for the X-ray astronomers.

1036
00:47:37,161 --> 00:47:39,364
And then as I was digging
through the slides,

1037
00:47:39,364 --> 00:47:43,701
I found, from the launch day,
a picture of Fiona's daughter

1038
00:47:43,701 --> 00:47:45,703
and then my kids and my wife.

1039
00:47:45,703 --> 00:47:49,607
And unfortunately, my
son's playing piano

1040
00:47:49,607 --> 00:47:51,977
at a school event that
I'm missing tonight,

1041
00:47:51,977 --> 00:47:55,547
but they'll be at
tomorrow's lecture.

1042
00:47:55,547 --> 00:47:58,316
And then, final, for
more information,

1043
00:47:58,316 --> 00:48:00,418
you can email me, or
here's some websites.

1044
00:48:00,418 --> 00:48:02,654
(applause)

1045
00:48:10,929 --> 00:48:12,497
Happy to take questions.

1046
00:48:12,497 --> 00:48:15,700
There's a mic over
there, that they prefer

1047
00:48:15,700 --> 00:48:18,470
if you go there
to ask questions.

1048
00:48:24,141 --> 00:48:25,910
- Is there any
limitation to how long

1049
00:48:25,910 --> 00:48:27,244
that it can stay
up there and work?

1050
00:48:27,244 --> 00:48:28,846
Is there a fuel or a
pointing or anything,

1051
00:48:28,846 --> 00:48:30,414
the cooling, anything like that?

1052
00:48:30,414 --> 00:48:31,917
- Yeah, so we, ah,

1053
00:48:34,519 --> 00:48:36,788
three ways we could
lose the mission.

1054
00:48:36,788 --> 00:48:38,690
One is it could break.

1055
00:48:38,690 --> 00:48:40,158
So far, things are
going very well.

1056
00:48:40,158 --> 00:48:42,794
We've lost like one
pixel in four years.

1057
00:48:42,794 --> 00:48:44,528
So that's going really well.

1058
00:48:44,528 --> 00:48:46,197
The lasers are slowly degrading,

1059
00:48:46,197 --> 00:48:48,800
but not at any level
that we're worried about.

1060
00:48:48,800 --> 00:48:51,569
The orbit decays slowly.

1061
00:48:51,569 --> 00:48:54,305
We drop about a
kilometer per year.

1062
00:48:54,305 --> 00:48:56,407
That goes with the solar cycle,

1063
00:48:56,407 --> 00:48:59,410
but we expect to get at
least 10 to 15 more years

1064
00:48:59,410 --> 00:49:02,046
before the orbit
brings us too far down.

1065
00:49:02,046 --> 00:49:03,415
And then when you get too low,

1066
00:49:03,415 --> 00:49:04,949
you hit the atmosphere,
and then you

1067
00:49:04,949 --> 00:49:07,618
rapidly crash into the ocean.

1068
00:49:07,618 --> 00:49:10,621
So that's probably
how the mission ends.

1069
00:49:10,621 --> 00:49:12,356
We could stop getting funding.

1070
00:49:12,356 --> 00:49:14,359
But hopefully we keep
writing good proposals,

1071
00:49:14,359 --> 00:49:18,863
and are able to motivate
NASA to keep funding us.

1072
00:49:18,863 --> 00:49:20,465
Yeah.

1073
00:49:20,465 --> 00:49:21,733
- Hi, I just had a question.

1074
00:49:21,733 --> 00:49:24,068
Has NuSTAR, at all,
gathered evidence

1075
00:49:24,068 --> 00:49:29,007
to kind of support answers for
the missing baryon problem?

1076
00:49:29,007 --> 00:49:30,441
- [Daniel] The missing
baryon problem?

1077
00:49:30,441 --> 00:49:31,376
- Yeah.

1078
00:49:31,376 --> 00:49:33,311
- Interesting question.

1079
00:49:34,512 --> 00:49:37,214
I do not think we have
done any work on that.

1080
00:49:37,214 --> 00:49:40,318
That's, ah, a lot of the
work to try to address

1081
00:49:40,318 --> 00:49:42,220
that tends to be in the
lower-energy X-rays,

1082
00:49:42,220 --> 00:49:46,124
or in the higher-energy
ultraviolet light.

1083
00:49:46,124 --> 00:49:47,992
- Right, yeah, I saw
your range was down

1084
00:49:47,992 --> 00:49:50,628
to about three KeV,
so I wasn't sure.

1085
00:49:50,628 --> 00:49:53,665
- [Daniel] Oh, missing
baryon or dark matter?

1086
00:49:53,665 --> 00:49:56,201
- Actually, well, you could
go with dark matter, too.

1087

00:49:56,201 --> 00:49:59,070
If you've seen any interesting
spikes around three KeV.

1088
00:49:59,070 --> 00:50:02,173
- So dark matter, again,
could be a whole lecture,

1089
00:50:02,173 --> 00:50:05,210
but a good fraction of
the Universe is not made

1090
00:50:05,210 --> 00:50:08,479
out of protons, electrons,
neutrons; things we're used to.

1091
00:50:08,479 --> 00:50:10,581
There's a weird thing
called dark matter,

1092
00:50:10,581 --> 00:50:12,617
and then there's an even
weirder thing called dark energy

1093
00:50:12,617 --> 00:50:14,786
that is actually
most of the Universe.

1094
00:50:14,786 --> 00:50:16,154
The stuff we're used to is

1095
00:50:16,154 --> 00:50:19,223
about four percent
of the Universe.

1096
00:50:19,223 --> 00:50:20,892
NuSTAR has done some studies,

1097
00:50:20,892 --> 00:50:24,429
has two papers now, out,

looking for evidence

1098
00:50:24,429 --> 00:50:28,033
of dark matter decay
in the NuSTAR band.

1099
00:50:28,033 --> 00:50:31,302
We've set stricter limits
than anyone has set before,

1100
00:50:31,302 --> 00:50:32,770
but haven't detected it.

1101
00:50:32,770 --> 00:50:34,171
That would have
been the whole talk

1102
00:50:34,171 --> 00:50:36,775
if we had found anything, yeah.

1103
00:50:43,782 --> 00:50:45,550
Questions, or?

1104
00:50:45,550 --> 00:50:47,485
If, I think we'll call it.

1105
00:50:47,485 --> 00:50:49,520
I will be here if
anybody wants to come up

1106
00:50:49,520 --> 00:50:51,589
and ask other questions,
but thank you for coming.

1107
00:50:51,589 --> 00:50:53,391
Thank you for braving the rain.

1108
00:50:53,391 --> 00:50:54,859
And thank you.