

1
00:00:00,030 --> 00:00:05,970
and tonight we have a lithograph this is

2
00:00:03,959 --> 00:00:10,919
a brand-new one of the Lagoon Nebula

3
00:00:05,969 --> 00:00:13,649
Messier 8 and thanks to a person on

4
00:00:10,919 --> 00:00:16,170
who wrote me and said hey can you share

5
00:00:13,650 --> 00:00:18,480
that with the online audience well I

6
00:00:16,170 --> 00:00:20,850
found it very hard to send paper through

7
00:00:18,480 --> 00:00:22,350
the internet unless you're wreckit-ralph

8
00:00:20,850 --> 00:00:24,810
you can't be traveling through the

9
00:00:22,350 --> 00:00:28,920
internet and bringing things around but

10
00:00:24,809 --> 00:00:31,018
I can share with you the URL of where

11
00:00:28,920 --> 00:00:34,170
these lithographs are posted on our

12
00:00:31,018 --> 00:00:37,519
amazing space so our G website so that

13
00:00:34,170 --> 00:00:40,500
URL amazing space to our G resource page

14
00:00:37,520 --> 00:00:43,710
548 will get you to the Lagoon Nebula

15
00:00:40,500 --> 00:00:45,899
and there is a PDF file of it and those

16
00:00:43,710 --> 00:00:48,420
of you on the webcast can look at it and

17
00:00:45,899 --> 00:00:50,489
you too can say oh and AH over the

18
00:00:48,420 --> 00:00:52,739
pretty picture and then turn over and

19
00:00:50,488 --> 00:00:57,808
read about what that pretty picture is

20
00:00:52,738 --> 00:01:00,869
really about okay tonight we have black

21
00:00:57,808 --> 00:01:02,669
holes and other dark matters which is

22
00:01:00,869 --> 00:01:04,679
the reason why I think this place is

23
00:01:02,670 --> 00:01:06,810
packed because once you put the term

24
00:01:04,680 --> 00:01:08,430
black holes in your talk everyone says

25
00:01:06,810 --> 00:01:12,900
oh we got to find out about this okay

26
00:01:08,430 --> 00:01:16,680
all right upcoming we have January 15

27
00:01:12,900 --> 00:01:20,130
now first Tuesday in January is New

28
00:01:16,680 --> 00:01:21,689
Year's Day second Tuesday in January is

29

00:01:20,129 --> 00:01:24,329
the American Astronomical Society

30
00:01:21,688 --> 00:01:26,309
meeting out in Seattle and I'll be out

31
00:01:24,329 --> 00:01:30,750
there and so a lot of other astronomers

32
00:01:26,310 --> 00:01:34,829
so we have postponed it yet again to the

33
00:01:30,750 --> 00:01:37,950
third Tuesday January 15th and it's

34
00:01:34,828 --> 00:01:40,199
really good because what this is what

35
00:01:37,950 --> 00:01:41,820
Scott will be talking about some new

36
00:01:40,200 --> 00:01:44,909
stuff will be announced at the double-a

37
00:01:41,819 --> 00:01:46,559
s meeting so you'll get some some really

38
00:01:44,909 --> 00:01:49,200
cool new stuff I'll be talking about

39
00:01:46,560 --> 00:01:50,728
initial exoplanet discoveries with Tess

40
00:01:49,200 --> 00:01:53,280
the transiting exoplanet survey

41
00:01:50,728 --> 00:01:54,420
satellite you're going to want to hear

42
00:01:53,280 --> 00:01:57,780
that because that's that's cool stuff

43
00:01:54,420 --> 00:01:58,978

about exoplanets February 5th back to

44

00:01:57,780 --> 00:02:01,290
the first Tuesday of the month

45

00:01:58,978 --> 00:02:04,920
am i immoral Martin will be talking

46

00:02:01,290 --> 00:02:07,920
about your place in the Stars and in

47

00:02:04,920 --> 00:02:10,830
March we have our familiar TBA showing

48

00:02:07,920 --> 00:02:13,840
up again which means I need to schedule

49

00:02:10,830 --> 00:02:17,590
somebody I might fill in this one myself

50

00:02:13,840 --> 00:02:20,080
with our visualization talk when that is

51

00:02:17,590 --> 00:02:22,780
decided it will be announced up here on

52

00:02:20,080 --> 00:02:24,340
our website if you go to your favorite

53

00:02:22,780 --> 00:02:26,739
search engine and search for Space

54

00:02:24,340 --> 00:02:28,360
Telescope public Hubble public talks

55

00:02:26,739 --> 00:02:30,909
you'll fly in this and we have our list

56

00:02:28,360 --> 00:02:34,090
of our upcoming links to our live and

57

00:02:30,909 --> 00:02:38,348
our archives as well as our email list

58
00:02:34,090 --> 00:02:39,939
server sign up that email will send you

59
00:02:38,348 --> 00:02:42,459
out announcements we send up by about

60
00:02:39,939 --> 00:02:46,509
two every month two or three a month so

61
00:02:42,459 --> 00:02:49,150
not not a huge crush on your inbox and

62
00:02:46,509 --> 00:02:50,709
we promise no spam if you have comments

63
00:02:49,150 --> 00:02:56,469
or questions you can send them to this

64
00:02:50,709 --> 00:02:59,199
email public lecture at STScI edu social

65
00:02:56,469 --> 00:03:01,539
media for the Hubble Space Telescope for

66
00:02:59,199 --> 00:03:03,310
the James Webb Space Telescope and for

67
00:03:01,539 --> 00:03:06,068
the Space Telescope Science Institute on

68
00:03:03,310 --> 00:03:08,650
Facebook Twitter YouTube and Instagram

69
00:03:06,068 --> 00:03:11,979
I myself dabble a little bit in Facebook

70
00:03:08,650 --> 00:03:15,760
Google+ and Twitter but not that much

71
00:03:11,979 --> 00:03:17,738
and tonight yes we have the observatory

72
00:03:15,759 --> 00:03:20,409
it's clear enough tonight that we will

73
00:03:17,739 --> 00:03:22,329
be doing observing it's nice and cool so

74
00:03:20,409 --> 00:03:24,879
hopefully the air is nice and still and

75
00:03:22,329 --> 00:03:25,810
you have some beautiful seeing it's one

76
00:03:24,879 --> 00:03:28,599
of the unfortunate things about

77
00:03:25,810 --> 00:03:34,180
astronomy that the best nights for

78
00:03:28,599 --> 00:03:34,750
seeing freezing cold okay so bring some

79
00:03:34,180 --> 00:03:38,340
hot chocolate

80
00:03:34,750 --> 00:03:41,680
so ireenie will be here at the end and

81
00:03:38,340 --> 00:03:43,870
take people across the street will

82
00:03:41,680 --> 00:03:46,329
probably gathered over here on this side

83
00:03:43,870 --> 00:03:49,060
of the room at the end if I forget to

84
00:03:46,329 --> 00:03:52,959
announce it remind me or I'm sure arena

85
00:03:49,060 --> 00:03:55,979
will remind me and now our news from the

86

00:03:52,959 --> 00:04:00,340
universe for December 2018

87
00:03:55,979 --> 00:04:03,369
our first story a stellar hazmat warning

88
00:04:00,340 --> 00:04:05,019
and I told you guys within the while we

89
00:04:03,370 --> 00:04:08,139
were vamping that osiris-rex was a

90
00:04:05,019 --> 00:04:09,759
tortured acronym hazmat is a slightly

91
00:04:08,139 --> 00:04:12,250
tortured acronym too and I'll get to

92
00:04:09,759 --> 00:04:15,009
that in a minute but let's start with

93
00:04:12,250 --> 00:04:16,930
the hertzsprung-russell diagram how do

94
00:04:15,009 --> 00:04:19,810
you take an astronomy 101 and know the

95
00:04:16,930 --> 00:04:21,340
hertzsprung-russell diagram how many are

96
00:04:19,810 --> 00:04:25,220
going oh my gosh is he gonna give a

97
00:04:21,339 --> 00:04:27,919
lecture now here alright okay class

98
00:04:25,220 --> 00:04:28,610
the hearts no I don't need you to

99
00:04:27,920 --> 00:04:31,129
understand the hertzsprung-russell

100
00:04:28,610 --> 00:04:33,889

diagram except to recognize that this is

101

00:04:31,129 --> 00:04:35,750

how astronomers organize all the various

102

00:04:33,889 --> 00:04:37,729

stars in the universe okay

103

00:04:35,750 --> 00:04:40,819

it's got temperature on one axis and

104

00:04:37,730 --> 00:04:43,069

luminosity on the y-axis and the

105

00:04:40,819 --> 00:04:45,379

important thing here is that the

106

00:04:43,069 --> 00:04:47,300

brightest stars the most luminous stars

107

00:04:45,379 --> 00:04:49,279

are up on the left and there's this

108

00:04:47,300 --> 00:04:51,199

diagonal track leading down to the lower

109

00:04:49,279 --> 00:04:56,029

right which we call the main sequence

110

00:04:51,199 --> 00:04:58,819

and the most luminous stars are few and

111

00:04:56,029 --> 00:05:01,009

far between whereas the least luminous

112

00:04:58,819 --> 00:05:04,399

stars the red dwarfs in the lower right

113

00:05:01,009 --> 00:05:06,289

are all over the place okay the meek

114

00:05:04,399 --> 00:05:09,049

have already inherited the cosmos

115
00:05:06,290 --> 00:05:12,319
because there are so many more red

116
00:05:09,050 --> 00:05:16,040
dwarfs than there are blue giant stars

117
00:05:12,319 --> 00:05:18,500
okay and so the red dwarf stars the ones

118
00:05:16,040 --> 00:05:20,660
in the lower right the the red ones the

119
00:05:18,500 --> 00:05:23,060
the low luminosity ones the low

120
00:05:20,660 --> 00:05:26,000
temperature ones they are actually

121
00:05:23,060 --> 00:05:29,660
extremely important because they are the

122
00:05:26,000 --> 00:05:31,310
most numerous stars in the universe so

123
00:05:29,660 --> 00:05:33,910
if you're going to be looking for

124
00:05:31,310 --> 00:05:37,939
planets and life in the universe

125
00:05:33,910 --> 00:05:40,040
they matter an awful lot okay another

126
00:05:37,939 --> 00:05:44,478
thing that matters about stars is that

127
00:05:40,040 --> 00:05:47,150
stars have energetic activity on them

128
00:05:44,478 --> 00:05:49,519
this is an ultraviolet light image of a

129
00:05:47,149 --> 00:05:51,349
solar prominence all right now many

130
00:05:49,519 --> 00:05:53,930
people mistake this and call this a

131
00:05:51,350 --> 00:05:55,580
solar flare it's not a solar flare it's

132
00:05:53,930 --> 00:05:58,430
a solar prominence and there's magnetic

133
00:05:55,579 --> 00:06:00,379
fields that are spewing all sorts of

134
00:05:58,430 --> 00:06:02,720
energy around on the surface of the Sun

135
00:06:00,379 --> 00:06:05,719
and there are things called solar flares

136
00:06:02,720 --> 00:06:08,360
they don't look like this they look like

137
00:06:05,720 --> 00:06:11,930
this and these are magnetic reconnection

138
00:06:08,360 --> 00:06:14,840
events that send out tremendous amounts

139
00:06:11,930 --> 00:06:16,459
of energy across our solar system we

140
00:06:14,839 --> 00:06:18,228
also have things called coronal mass

141
00:06:16,459 --> 00:06:20,659
ejections that send particles of high

142
00:06:18,228 --> 00:06:23,870
energies and we have what we call in our

143

00:06:20,660 --> 00:06:25,610
solar system space weather and a lot of

144
00:06:23,870 --> 00:06:28,399
some of our satellites are out there to

145
00:06:25,610 --> 00:06:30,740
monitor the space weather and you may

146
00:06:28,399 --> 00:06:32,149
have heard that sometimes when one of

147
00:06:30,740 --> 00:06:34,460
these coronal mass ejections or

148
00:06:32,149 --> 00:06:36,649
something is sent in the direction of

149
00:06:34,459 --> 00:06:37,930
Earth it hits our magnetic field and

150
00:06:36,649 --> 00:06:39,788
sometimes

151
00:06:37,930 --> 00:06:43,600
disrupt our communication satellites

152
00:06:39,788 --> 00:06:47,259
okay or if the astronauts are up in the

153
00:06:43,600 --> 00:06:49,539
and the space station they need to get

154
00:06:47,259 --> 00:06:51,360
inside and protect themselves okay when

155
00:06:49,538 --> 00:06:55,810
one of these solar storms commits

156
00:06:51,360 --> 00:06:58,569
however that's just for a Sun sized star

157
00:06:55,810 --> 00:07:02,139

and the Sun is a medium-sized star these

158

00:06:58,569 --> 00:07:06,089

small stars these red dwarf stars can

159

00:07:02,139 --> 00:07:10,269

have much more energetic activity and

160

00:07:06,089 --> 00:07:13,929

that is when we get to hazmat so this is

161

00:07:10,269 --> 00:07:16,598

a study habitable zones and m-dwarf

162

00:07:13,930 --> 00:07:20,259

activity over time can you see how you

163

00:07:16,598 --> 00:07:22,930

get hazmat out of that yeah okay

164

00:07:20,259 --> 00:07:26,110

but the acronym is actually appropriate

165

00:07:22,930 --> 00:07:28,750

because they're studying how volatile

166

00:07:26,110 --> 00:07:32,169

these M Dwarfs the red dwarf stars are

167

00:07:28,750 --> 00:07:34,478

and could they affect the planets

168

00:07:32,168 --> 00:07:36,758

forming around them and perhaps life

169

00:07:34,478 --> 00:07:38,800

forming on those planets and what's

170

00:07:36,759 --> 00:07:40,598

important is to take a look at stars at

171

00:07:38,800 --> 00:07:42,639

different ages this is the activity over

172
00:07:40,598 --> 00:07:44,918
time part of it okay looking at you know

173
00:07:42,639 --> 00:07:46,689
billion year old red dwarfs versus you

174
00:07:44,918 --> 00:07:48,639
know a few hundred million years old

175
00:07:46,689 --> 00:07:51,819
versus tens of millions of year old red

176
00:07:48,639 --> 00:07:53,829
dwarfs okay and what they found in this

177
00:07:51,819 --> 00:07:56,560
study and they basically these solar

178
00:07:53,829 --> 00:07:57,969
flares occur are easiest to see in

179
00:07:56,560 --> 00:08:00,728
ultraviolet so well that's why you need

180
00:07:57,970 --> 00:08:02,409
Hubble to do this because Hubble being

181
00:08:00,728 --> 00:08:04,870
above our atmosphere can see the

182
00:08:02,408 --> 00:08:08,259
ultraviolet light and they looked at a

183
00:08:04,870 --> 00:08:11,978
population of 40 million year old stars

184
00:08:08,259 --> 00:08:13,449
and a 40 million years old is old' for

185
00:08:11,978 --> 00:08:18,038
you and me but it's young for a star

186
00:08:13,449 --> 00:08:21,728
these are just born stars and the energy

187
00:08:18,038 --> 00:08:25,360
in the solar flares was one hundred to a

188
00:08:21,728 --> 00:08:27,668
thousand times stronger than it was for

189
00:08:25,360 --> 00:08:30,879
the billion year old stars the old stars

190
00:08:27,668 --> 00:08:34,468
so there's a lot more energy happening

191
00:08:30,879 --> 00:08:37,439
and this has interesting implementation

192
00:08:34,469 --> 00:08:42,240
implications for planets formation

193
00:08:37,440 --> 00:08:44,560
because at 40 million years that's when

194
00:08:42,240 --> 00:08:47,139
earth sized planets will be forming

195
00:08:44,559 --> 00:08:50,939
terrestrial planets will be forming so

196
00:08:47,139 --> 00:08:54,960
these impor stars the most new

197
00:08:50,940 --> 00:08:57,420
stars the universe have a energetic she

198
00:08:54,960 --> 00:09:00,180
appeared to be very energetic just at

199
00:08:57,419 --> 00:09:02,339
the time that planets are forming so if

200

00:09:00,179 --> 00:09:05,489
you want to form life on them

201
00:09:02,340 --> 00:09:08,330
could these m-dwarf act does could this

202
00:09:05,490 --> 00:09:11,759
end dwarf activity be effectively hasmat

203
00:09:08,330 --> 00:09:15,930
could they interfere with the formation

204
00:09:11,759 --> 00:09:19,049
of life on these planets and this is not

205
00:09:15,929 --> 00:09:21,359
a conclusive study in terms of that

206
00:09:19,049 --> 00:09:24,179
actually does or does not but it shows

207
00:09:21,360 --> 00:09:26,820
that we have to not only think about how

208
00:09:24,179 --> 00:09:29,370
we form these planets around a star but

209
00:09:26,820 --> 00:09:31,830
we also have to think about the activity

210
00:09:29,370 --> 00:09:34,110
of the star itself while those planets

211
00:09:31,830 --> 00:09:36,629
are forming so this is a interesting

212
00:09:34,110 --> 00:09:39,269
study that will I'm sure we followed up

213
00:09:36,629 --> 00:09:41,580
much further in the future trying to

214
00:09:39,269 --> 00:09:43,379

look and understand you know this whole

215

00:09:41,580 --> 00:09:47,570

process of plant information that you

216

00:09:43,379 --> 00:09:50,580

know we are still still you know just

217

00:09:47,570 --> 00:09:52,680

really you know if this is so exciting

218

00:09:50,580 --> 00:09:56,790

how much we're learning about this

219

00:09:52,679 --> 00:10:02,159

process as we go on alright our second

220

00:09:56,789 --> 00:10:03,959

story is the ghost of Cassiopeia this is

221

00:10:02,159 --> 00:10:06,600

the constellation of Cassiopeia and this

222

00:10:03,960 --> 00:10:08,940

beautiful image from Akira Fuji II it's

223

00:10:06,600 --> 00:10:12,210

that W you see in the center there okay

224

00:10:08,940 --> 00:10:14,040

and a Cassiopeia is a wonderful

225

00:10:12,210 --> 00:10:15,600

constellation for those of us in the

226

00:10:14,039 --> 00:10:18,329

northern hemisphere because it's

227

00:10:15,600 --> 00:10:20,550

circumpolar it's always around the North

228

00:10:18,330 --> 00:10:22,980

Pole and goes just circles around the

229

00:10:20,549 --> 00:10:24,809

North Pole so most of the times most

230

00:10:22,980 --> 00:10:28,050

times the year you can find Cassiopeia

231

00:10:24,809 --> 00:10:31,109

on the night sky and find that W and

232

00:10:28,049 --> 00:10:35,359

that Center star in the W is known as

233

00:10:31,110 --> 00:10:38,269

gamma Cassiopeia and gamma Cassiopeia is

234

00:10:35,360 --> 00:10:42,779

illuminating some of the gas around it

235

00:10:38,269 --> 00:10:46,588

that sort of the the faint red blotch on

236

00:10:42,779 --> 00:10:48,629

the left is called IC 59 and that bright

237

00:10:46,589 --> 00:10:53,010

one down bottom that looks sort of like

238

00:10:48,629 --> 00:10:54,179

a mountain that is IC 63 this is a

239

00:10:53,009 --> 00:10:56,490

wonderful image from the

240

00:10:54,179 --> 00:10:58,799

astrophotographer robert Gendler and you

241

00:10:56,490 --> 00:11:02,610

can see that the sort of the mountain in

242

00:10:58,799 --> 00:11:03,750

IC 63 is pointed toward gamma casts all

243
00:11:02,610 --> 00:11:04,528
right that shows that it's the

244
00:11:03,750 --> 00:11:06,178
ultraviolet

245
00:11:04,528 --> 00:11:08,578
the energy from gamma cos that's

246
00:11:06,178 --> 00:11:11,759
sculpting that gas that's blowing away

247
00:11:08,578 --> 00:11:12,928
the low-density gas and ionizing the gas

248
00:11:11,759 --> 00:11:17,009
to make it glow

249
00:11:12,928 --> 00:11:20,068
and Hubble does various pretty picture

250
00:11:17,009 --> 00:11:22,349
release images and when we did our

251
00:11:20,068 --> 00:11:24,058
pretty picture release image going

252
00:11:22,349 --> 00:11:25,649
through the various pretty pictures they

253
00:11:24,058 --> 00:11:28,348
thought that this looked like a ghost

254
00:11:25,649 --> 00:11:35,688
and so we released for Halloween a

255
00:11:28,349 --> 00:11:38,278
picture of the ghost of Cassiopeia I

256
00:11:35,688 --> 00:11:39,899
looks more like a hooded shroud or

257

00:11:38,278 --> 00:11:41,489
something like this but it it's really

258
00:11:39,899 --> 00:11:43,859
kind of cool so this is this is what

259
00:11:41,489 --> 00:11:45,689
they called the ghost of Cassiopeia not

260
00:11:43,859 --> 00:11:47,639
to be confused with the ghost nebula or

261
00:11:45,688 --> 00:11:48,718
the little ghost nebula or like three

262
00:11:47,639 --> 00:11:50,879
other things that are called ghost

263
00:11:48,719 --> 00:11:52,379
nebula type things but they nicknamed

264
00:11:50,879 --> 00:11:55,139
this the ghost of Cassiopeia

265
00:11:52,379 --> 00:11:59,788
we took this light invisible we also

266
00:11:55,139 --> 00:12:02,339
took a image in infrared light and to

267
00:11:59,788 --> 00:12:04,649
give it that really spooky feel we

268
00:12:02,339 --> 00:12:08,669
created an animated gif that goes back

269
00:12:04,649 --> 00:12:10,828
from visible to infrared and that was a

270
00:12:08,668 --> 00:12:14,609
sort of a Halloween pretty picture

271
00:12:10,828 --> 00:12:20,219

release the ghost of Cassiopeia and

272

00:12:14,609 --> 00:12:22,079

that's our news for this evening now we

273

00:12:20,220 --> 00:12:32,249

go to our main speaker of the night and

274

00:12:22,078 --> 00:12:34,138

our main speaker tonight is get there

275

00:12:32,249 --> 00:12:36,808

yes okay

276

00:12:34,139 --> 00:12:40,470

our speaker tonight is dr. Mark

277

00:12:36,808 --> 00:12:42,298

kamionkowski whom I had the extensive

278

00:12:40,470 --> 00:12:45,839

pleasure of working with up at Columbia

279

00:12:42,298 --> 00:12:47,428

University I was a postdoc working at

280

00:12:45,839 --> 00:12:49,139

Columbia half time at Columbia and half

281

00:12:47,428 --> 00:12:53,038

time at the American Natural History

282

00:12:49,139 --> 00:12:57,599

when Mark was up at Columbia he did his

283

00:12:53,038 --> 00:13:00,269

degree at Caltech and didn't Chicago

284

00:12:57,599 --> 00:13:02,239

right all right I thought I'd confirmed

285

00:13:00,269 --> 00:13:08,969

it was Caltech I'm wrong okay

286

00:13:02,239 --> 00:13:11,729
sorry at Chicago and then went to

287

00:13:08,969 --> 00:13:13,528
Columbia and after a few years he missed

288

00:13:11,729 --> 00:13:15,480
me so much he decided he'd come down to

289

00:13:13,528 --> 00:13:17,429
Johns Hopkins not quite

290

00:13:15,480 --> 00:13:18,509
who he came down he's in the department

291

00:13:17,429 --> 00:13:21,559
across the street at Johns Hopkins

292

00:13:18,509 --> 00:13:26,490
University he is one of the celebrated

293

00:13:21,559 --> 00:13:28,679
cosmologists and a real big expert on

294

00:13:26,490 --> 00:13:30,029
the Cosmic Microwave Background but he's

295

00:13:28,679 --> 00:13:32,399
not going to talk to you that about that

296

00:13:30,029 --> 00:13:34,740
tonight instead he's going to talk about

297

00:13:32,399 --> 00:13:36,899
cosmic ripples from black holes and the

298

00:13:34,740 --> 00:13:55,549
Big Bang ladies and gentlemen dr. Mark

299

00:13:36,899 --> 00:13:55,549
kamionkowski so okay is that good okay

300
00:13:56,600 --> 00:14:03,389
so today I'm going to talk to you about

301
00:14:00,419 --> 00:14:05,639
dark matter but the story is actually

302
00:14:03,389 --> 00:14:07,649
going to begin with them the discovery

303
00:14:05,639 --> 00:14:12,179
of gravitational waves from a binary

304
00:14:07,649 --> 00:14:15,809
black hole system two years ago and this

305
00:14:12,179 --> 00:14:20,699
is work that began in the cafeteria here

306
00:14:15,809 --> 00:14:22,259
in Asif Ron in January of 2016 the rumor

307
00:14:20,700 --> 00:14:24,360
started heating up in the astrophysics

308
00:14:22,259 --> 00:14:25,379
community that LIGO had detected

309
00:14:24,360 --> 00:14:26,700
something and there's gonna be an

310
00:14:25,379 --> 00:14:28,980
announcement it was going to be big and

311
00:14:26,700 --> 00:14:31,800
so I was sitting around the lunch table

312
00:14:28,980 --> 00:14:32,909
with some of my collaborators and we

313
00:14:31,799 --> 00:14:34,709
were thinking well we got to think of

314

00:14:32,909 --> 00:14:37,019
something interesting to say because

315
00:14:34,710 --> 00:14:39,540
this is gonna be big and we started

316
00:14:37,019 --> 00:14:42,090
brainstorming and we came up with that

317
00:14:39,539 --> 00:14:44,939
most ridiculous ideas you can possibly

318
00:14:42,090 --> 00:14:49,290
imagine and at some point we came up

319
00:14:44,940 --> 00:14:52,230
with an idea that was ridiculous but not

320
00:14:49,289 --> 00:14:55,379
completely ridiculous and so we decided

321
00:14:52,230 --> 00:14:58,110
to write a paper and in brief and what

322
00:14:55,379 --> 00:15:01,409
I'll tell you over the next 40 minutes

323
00:14:58,110 --> 00:15:03,240
is that we simply postulated that the

324
00:15:01,409 --> 00:15:05,789
black holes that they discovered might

325
00:15:03,240 --> 00:15:08,490
actually be the dark matter that we have

326
00:15:05,789 --> 00:15:11,399
for a long time known to exist in the

327
00:15:08,490 --> 00:15:14,970
universe but we have no idea what it is

328
00:15:11,399 --> 00:15:17,669

and it was a crazy idea but as I said

329

00:15:14,970 --> 00:15:20,399

not completely crazy there was an

330

00:15:17,669 --> 00:15:23,159

interesting coincidence that popped up

331

00:15:20,399 --> 00:15:25,199

when we considered this possibility and

332

00:15:23,159 --> 00:15:26,730

so we wrote this paper and a lot of

333

00:15:25,200 --> 00:15:30,110

people found it interesting it's got a

334

00:15:26,730 --> 00:15:30,110

lot of attention over the past two years

335

00:15:30,379 --> 00:15:34,708

do black holes like the ones that like

336

00:15:32,909 --> 00:15:37,439

oh detective make up the dark matter as

337

00:15:34,708 --> 00:15:39,388

I'll tell you we don't know two years

338

00:15:37,440 --> 00:15:41,760

ago I was fairly optimistic things have

339

00:15:39,389 --> 00:15:46,259

developed since then I'm a little less

340

00:15:41,759 --> 00:15:48,569

optimistic but the jury is still out so

341

00:15:46,259 --> 00:15:50,909

the title is cosmic ripples from the big

342

00:15:48,570 --> 00:15:52,410

from black holes in the Big Bang cosmic

343
00:15:50,909 --> 00:15:54,389
ripples refers to the gravitational

344
00:15:52,409 --> 00:15:55,620
waves I'll tell you about black holes

345
00:15:54,389 --> 00:16:01,049
were first two black holes in the Big

346
00:15:55,620 --> 00:16:02,549
Bang is the Big Bang please interrupt me

347
00:16:01,049 --> 00:16:04,319
if there are questions this is

348
00:16:02,549 --> 00:16:06,120
gravitational waves general relativity

349
00:16:04,320 --> 00:16:08,160
black holes dark matter it's not rocket

350
00:16:06,120 --> 00:16:13,828
science so everyone should be able to

351
00:16:08,159 --> 00:16:19,379
understand so the story begins February

352
00:16:13,828 --> 00:16:21,629
of 2016 there was a front-page article

353
00:16:19,379 --> 00:16:22,828
in The New York Times that pointed out

354
00:16:21,629 --> 00:16:24,750
the gravitational waves have been

355
00:16:22,828 --> 00:16:27,299
detected and it was a beautiful

356
00:16:24,750 --> 00:16:28,799
beautiful timing because I'm Albert

357
00:16:27,299 --> 00:16:31,588
Einstein realized that gravitational

358
00:16:28,799 --> 00:16:33,838
waves should exist almost a hundred

359
00:16:31,589 --> 00:16:35,850
years before we sort of put the

360
00:16:33,839 --> 00:16:38,819
finishing pieces of this theory of

361
00:16:35,850 --> 00:16:41,278
general relativity at the end of 2015

362
00:16:38,818 --> 00:16:43,708
and the gravitational wave signal was

363
00:16:41,278 --> 00:16:50,068
actually detected in September of 2015

364
00:16:43,708 --> 00:16:52,828
so very very nice coincidence this

365
00:16:50,068 --> 00:16:56,068
discovery was absolutely spectacular

366
00:16:52,828 --> 00:16:57,689
there's nobody in science who was so

367
00:16:56,068 --> 00:16:59,909
jaded as to say out and detected

368
00:16:57,690 --> 00:17:03,140
gravitational waves what's the big deal

369
00:16:59,909 --> 00:17:06,149
actually there is a story I have to say

370
00:17:03,139 --> 00:17:09,480
so this was a huge discovery and there

371

00:17:06,150 --> 00:17:11,189
was a press conference online that that

372
00:17:09,480 --> 00:17:14,400
NASA was brought I'm sorry that the NSF

373
00:17:11,189 --> 00:17:16,919
was broadcasting and some people in the

374
00:17:14,400 --> 00:17:19,319
physics department had set up a seminar

375
00:17:16,919 --> 00:17:20,730
room like this one so we could play it

376
00:17:19,318 --> 00:17:22,558
on video and everyone can come and watch

377
00:17:20,730 --> 00:17:24,929
and some people sort of got doughnuts

378
00:17:22,558 --> 00:17:27,629
and coffee and we're milling about

379
00:17:24,929 --> 00:17:29,400
before the thing started and there were

380
00:17:27,630 --> 00:17:31,230
two undergraduate students walking by

381
00:17:29,400 --> 00:17:33,210
and one of them was hard to say the

382
00:17:31,230 --> 00:17:34,860
other one what's going on here and the

383
00:17:33,210 --> 00:17:36,000
only goes I don't know that this covered

384
00:17:34,859 --> 00:17:39,439
gravitational waves or something like

385
00:17:36,000 --> 00:17:39,440

that other one goes whatever

386

00:17:41,069 --> 00:17:47,349

anyway it was one of the quickest Nobel

387

00:17:43,599 --> 00:17:49,089

Prizes ever awarded these people also

388

00:17:47,349 --> 00:17:50,769

received the Gruber prize that catalyzed

389

00:17:49,089 --> 00:17:53,798

the sharp rise in the breakthrough prize

390

00:17:50,769 --> 00:17:55,779

any possible scientific recognition or

391

00:17:53,798 --> 00:17:58,329

honor that is available immediately went

392

00:17:55,779 --> 00:18:03,759

to the team that discovered these

393

00:17:58,329 --> 00:18:08,439

gravitational waves and as I said this

394

00:18:03,759 --> 00:18:09,879

phenomenon was sort of predicted by

395

00:18:08,440 --> 00:18:12,580

Albert Einstein's theory of general

396

00:18:09,880 --> 00:18:16,330

relativity and this goes back 100 years

397

00:18:12,579 --> 00:18:18,639

to 1915 and the basic idea of general

398

00:18:16,329 --> 00:18:21,490

relativity is the following equation and

399

00:18:18,640 --> 00:18:24,640

I'm always told that I shouldn't show

400
00:18:21,490 --> 00:18:26,019
equations in popular talks but I like to

401
00:18:24,640 --> 00:18:28,000
show equations because I'm a theoretical

402
00:18:26,019 --> 00:18:30,369
physicist this is really all I have I'm

403
00:18:28,000 --> 00:18:32,079
not in the survey tional strong I don't

404
00:18:30,369 --> 00:18:34,058
have pretty pictures of nebula and

405
00:18:32,079 --> 00:18:42,369
things like that this is the best I can

406
00:18:34,058 --> 00:18:44,019
do we're really proud of it but the

407
00:18:42,369 --> 00:18:47,589
point of an equation is that there's an

408
00:18:44,019 --> 00:18:49,000
equal sign in the middle there's

409
00:18:47,589 --> 00:18:51,339
something on the left and there's

410
00:18:49,000 --> 00:18:52,779
something on the right and the thing on

411
00:18:51,339 --> 00:18:54,849
the left is supposed to be the same as a

412
00:18:52,779 --> 00:18:56,408
thing on the right so this is known as

413
00:18:54,849 --> 00:18:58,689
Einstein's equation nine Stein wrote

414
00:18:56,409 --> 00:19:00,520
this down and this encapsulate the

415
00:18:58,690 --> 00:19:01,808
theory of general relativity and simple

416
00:19:00,519 --> 00:19:03,940
and elegant because the thing on the

417
00:19:01,808 --> 00:19:05,079
left is a capital G with some Greek

418
00:19:03,940 --> 00:19:07,029
letters on there and the thing on the

419
00:19:05,079 --> 00:19:08,798
right is capital T and I remember I

420
00:19:07,029 --> 00:19:11,109
first learned this equation when I was a

421
00:19:08,798 --> 00:19:14,379
senior in college and I was taking a

422
00:19:11,109 --> 00:19:16,538
general relativity class and I passed by

423
00:19:14,380 --> 00:19:20,080
a professor I had for a quantum

424
00:19:16,538 --> 00:19:21,158
mechanics class and he said how's it

425
00:19:20,079 --> 00:19:22,359
going I was going great what are you

426
00:19:21,159 --> 00:19:23,860
taking I'm taking John Rolfe everies

427
00:19:22,359 --> 00:19:25,719
like what I think I said so simple and

428

00:19:23,859 --> 00:19:27,668
elegant you know G me nu equals team you

429
00:19:25,720 --> 00:19:32,110
know he goes yeah but what's G mu nu

430
00:19:27,669 --> 00:19:33,700
what's team you know yeah anyway this

431
00:19:32,109 --> 00:19:36,699
actually has a fairly simple

432
00:19:33,700 --> 00:19:37,150
interpretation G mu nu the thing on the

433
00:19:36,700 --> 00:19:39,909
left

434
00:19:37,150 --> 00:19:42,210
describes the curvature of space and

435
00:19:39,909 --> 00:19:44,320
space-time and the thing on the right

436
00:19:42,210 --> 00:19:47,740
describes the matter content of the

437
00:19:44,319 --> 00:19:49,928
universe and so this describes a picture

438
00:19:47,740 --> 00:19:52,569
that looks like this so according to

439
00:19:49,929 --> 00:19:57,490
general relativity space

440
00:19:52,569 --> 00:19:59,558
time can be bent and distorted and the

441
00:19:57,490 --> 00:20:02,079
distortion of space-time is given by the

442
00:19:59,558 --> 00:20:04,928

presence of massive objects so massive

443

00:20:02,079 --> 00:20:06,970

objects distort space-time and this

444

00:20:04,929 --> 00:20:12,250

equation tells you how that works

445

00:20:06,970 --> 00:20:14,589

the space-time curvature is related to

446

00:20:12,250 --> 00:20:16,869

the distribution of massive objects

447

00:20:14,589 --> 00:20:19,599

which is teeming of the matter content

448

00:20:16,869 --> 00:20:21,788

on the right hand side in words what

449

00:20:19,599 --> 00:20:23,199

this says is that space-time tells

450

00:20:21,788 --> 00:20:25,480

matter how to move and matter tells

451

00:20:23,200 --> 00:20:27,970

space-time how to move so the second

452

00:20:25,480 --> 00:20:30,009

thing I told you so matter tells the

453

00:20:27,970 --> 00:20:32,110

space-time how to curve and then the

454

00:20:30,009 --> 00:20:33,940

curvature of space-time tells you how

455

00:20:32,109 --> 00:20:37,028

objects move and I'll show you better

456

00:20:33,940 --> 00:20:39,159

pictures of this in a second but you

457
00:20:37,028 --> 00:20:40,869
know if someone was if a particle is

458
00:20:39,159 --> 00:20:42,370
gonna go along a straight line and this

459
00:20:40,869 --> 00:20:44,258
Crouch space-time it couldn't go along a

460
00:20:42,369 --> 00:20:46,628
straight line the trajectory is actually

461
00:20:44,259 --> 00:20:49,929
deflected if the space-time is curved if

462
00:20:46,628 --> 00:20:52,480
I take a very soft mattress and I put a

463
00:20:49,929 --> 00:20:54,129
very heavy bowling ball somewhere in the

464
00:20:52,480 --> 00:20:55,808
middle that sort of pushes that mattress

465
00:20:54,128 --> 00:20:58,058
down and then if I try to roll a

466
00:20:55,808 --> 00:20:59,980
ping-pong ball PLAs that bowling ball

467
00:20:58,058 --> 00:21:03,220
the trajectory of the ping-pong ball

468
00:20:59,980 --> 00:21:05,378
will be deflected by the curvature in

469
00:21:03,220 --> 00:21:09,069
the mattress so that's basically what

470
00:21:05,378 --> 00:21:10,569
general relativity tells us space-time

471
00:21:09,069 --> 00:21:13,058
tells matter how to move and matter

472
00:21:10,569 --> 00:21:15,928
tells space-time how to curve that's the

473
00:21:13,058 --> 00:21:19,569
essence of Einstein's equation this was

474
00:21:15,929 --> 00:21:22,450
an incredible mathematical insight back

475
00:21:19,569 --> 00:21:26,019
in 1915 there was absolutely nothing in

476
00:21:22,450 --> 00:21:29,080
any that existed in physics before this

477
00:21:26,019 --> 00:21:30,819
to foreshadow this or to build up to it

478
00:21:29,079 --> 00:21:31,240
it sort of came out of absolutely

479
00:21:30,819 --> 00:21:34,000
nowhere

480
00:21:31,240 --> 00:21:35,980
but it turns out that the theory is

481
00:21:34,000 --> 00:21:37,778
correct then Albert Einstein actually

482
00:21:35,980 --> 00:21:40,028
realized that theory was correct almost

483
00:21:37,778 --> 00:21:43,569
immediately because there was one

484
00:21:40,028 --> 00:21:45,460
anomaly in planetary dynamics in 1915

485

00:21:43,569 --> 00:21:47,769
which was the perihelion advance of

486
00:21:45,460 --> 00:21:49,840
mercury so it turns out that Mercury's

487
00:21:47,769 --> 00:21:51,730
orbit around the Sun like that of most

488
00:21:49,839 --> 00:21:54,459
planets is not perfectly around it's

489
00:21:51,730 --> 00:21:57,179
actually elongated according to Newton's

490
00:21:54,460 --> 00:22:00,250
laws if according to inverse square law

491
00:21:57,179 --> 00:22:02,919
from note that Isaac Newton derived we

492
00:22:00,250 --> 00:22:05,980
wrote down you know back in the early

493
00:22:02,919 --> 00:22:07,750
1700s late 1600s

494
00:22:05,980 --> 00:22:10,480
these ellipses should close in on

495
00:22:07,750 --> 00:22:12,369
themselves but what was found is that

496
00:22:10,480 --> 00:22:14,829
Mercury's orbit does not close in on

497
00:22:12,369 --> 00:22:16,808
itself it sort of processes the it sort

498
00:22:14,829 --> 00:22:18,849
of the rotates around in this direction

499
00:22:16,808 --> 00:22:20,529

over here and it's a very tiny and

500

00:22:18,849 --> 00:22:22,990

subtle effect but hasn't been measured

501

00:22:20,529 --> 00:22:25,389

quite well to be two degrees per century

502

00:22:22,990 --> 00:22:27,308

and Albert Einstein realized that these

503

00:22:25,390 --> 00:22:30,790

equations that he wrote down could

504

00:22:27,308 --> 00:22:33,099

account for this perihelion advance and

505

00:22:30,789 --> 00:22:34,210

so there's a story that he couldn't

506

00:22:33,099 --> 00:22:35,619

sleep that night because he was so

507

00:22:34,210 --> 00:22:37,150

excited that he actually realized that

508

00:22:35,619 --> 00:22:37,629

this ridiculous equation that came out

509

00:22:37,150 --> 00:22:40,660

of nowhere

510

00:22:37,630 --> 00:22:44,410

was actually correct we also know it's

511

00:22:40,660 --> 00:22:46,120

like correct because of the existence of

512

00:22:44,410 --> 00:22:48,910

gravitational lensing or the bending of

513

00:22:46,119 --> 00:22:53,729

light and this was verified by a famous

514
00:22:48,910 --> 00:22:56,950
expedition by Sir Arthur Eddington 1919

515
00:22:53,730 --> 00:22:58,839
so it turns out that the gravitational

516
00:22:56,950 --> 00:23:01,808
field of a massive object like the Sun

517
00:22:58,839 --> 00:23:04,509
will actually bend the trajectory of

518
00:23:01,808 --> 00:23:06,039
light so at you know if you send a light

519
00:23:04,509 --> 00:23:07,660
ray out you know where the light ray

520
00:23:06,039 --> 00:23:09,190
goes straight but if you send a near

521
00:23:07,660 --> 00:23:11,019
massive object the gravitational field

522
00:23:09,190 --> 00:23:13,240
of that massive object will actually

523
00:23:11,019 --> 00:23:14,589
bend the trajectory of light and this

524
00:23:13,240 --> 00:23:16,808
is something that's difficult to

525
00:23:14,589 --> 00:23:18,428
actually verify because the Sun is so

526
00:23:16,808 --> 00:23:20,950
bright that you can't see the stars

527
00:23:18,429 --> 00:23:22,900
behind it but if there's an eclipse

528
00:23:20,950 --> 00:23:24,970
if the moon passes in front of the Sun

529
00:23:22,900 --> 00:23:26,470
then for a brief period of time you can

530
00:23:24,970 --> 00:23:29,890
actually see the stars behind the Sun

531
00:23:26,470 --> 00:23:32,620
and so Eddington verified this that the

532
00:23:29,890 --> 00:23:38,890
this deflection of light during a solar

533
00:23:32,619 --> 00:23:40,959
eclipse in 1919 so I think I said 1916

534
00:23:38,890 --> 00:23:42,759
very shortly after the original theory

535
00:23:40,960 --> 00:23:45,279
was proposed Einstein realized that the

536
00:23:42,759 --> 00:23:48,849
theory predicts the existence of

537
00:23:45,279 --> 00:23:51,399
gravitational waves and here's a movie

538
00:23:48,849 --> 00:23:53,529
that I will show you and I'll show you

539
00:23:51,400 --> 00:23:55,330
another version later on and the basic

540
00:23:53,529 --> 00:23:57,789
idea is that there is a gravitational

541
00:23:55,329 --> 00:24:00,129
field due to a mass of objects so if I

542

00:23:57,789 --> 00:24:02,048
have one planted over here that gives me

543
00:24:00,130 --> 00:24:03,880
a gravitational field if there's a

544
00:24:02,048 --> 00:24:05,798
second planted over here that also has a

545
00:24:03,880 --> 00:24:07,450
gravitational field and the

546
00:24:05,798 --> 00:24:09,250
gravitational field due to the presence

547
00:24:07,450 --> 00:24:11,950
of two planets is going to be the sum of

548
00:24:09,250 --> 00:24:14,500
that from this one and the Sun the sum

549
00:24:11,950 --> 00:24:19,269
and the gravitational field from here

550
00:24:14,500 --> 00:24:21,069
now if I have a binary star system $5/2$

551
00:24:19,269 --> 00:24:23,829
stars that are gravitationally bound and

552
00:24:21,069 --> 00:24:26,649
spinning around each other or for

553
00:24:23,829 --> 00:24:28,449
example if I have a planet star system

554
00:24:26,650 --> 00:24:30,400
like the earth or the planet Jupiter

555
00:24:28,450 --> 00:24:32,279
spinning around the Sun I will have

556
00:24:30,400 --> 00:24:35,170

something that looks sort of like this

557

00:24:32,279 --> 00:24:37,059

now as those planets move around each

558

00:24:35,170 --> 00:24:38,410

other those stars or black holes or

559

00:24:37,059 --> 00:24:41,319

whatever the massive objects you have

560

00:24:38,410 --> 00:24:44,170

move around each other the gravitational

561

00:24:41,319 --> 00:24:49,450

field is going to change and so that's

562

00:24:44,170 --> 00:24:51,700

what we see over here so if I'm sitting

563

00:24:49,450 --> 00:24:55,269

over here the gravitational field that I

564

00:24:51,700 --> 00:24:57,100

see due to those two stars changes if

565

00:24:55,269 --> 00:24:58,809

you're looking at a pair of stars over

566

00:24:57,099 --> 00:25:00,069

here you'll see one gravitational field

567

00:24:58,809 --> 00:25:01,839

if you see them over here to see a

568

00:25:00,069 --> 00:25:03,579

different gravitational field and as

569

00:25:01,839 --> 00:25:06,309

they spin around you will see a time

570

00:25:03,579 --> 00:25:08,740

varying gravitational field that time

571
00:25:06,309 --> 00:25:10,869
varying gravitational field propagates

572
00:25:08,740 --> 00:25:16,359
outward as a set of ripples in

573
00:25:10,869 --> 00:25:19,509
space-time so something like this maybe

574
00:25:16,359 --> 00:25:22,629
non-intuitive originally but it

575
00:25:19,509 --> 00:25:26,109
shouldn't be too non-intuitive the

576
00:25:22,630 --> 00:25:31,090
surface of a pond if it still is very

577
00:25:26,109 --> 00:25:33,159
flat and peaceful and calm but it can

578
00:25:31,089 --> 00:25:35,980
bob up and down and if I drop something

579
00:25:33,160 --> 00:25:37,840
in the middle of this pond that

580
00:25:35,980 --> 00:25:41,140
disturbance will propagate out as a

581
00:25:37,839 --> 00:25:43,949
series of waves and suppose I have a toy

582
00:25:41,140 --> 00:25:47,680
boat sitting at the edge of the pond

583
00:25:43,950 --> 00:25:49,720
these waves will propagate out and the

584
00:25:47,680 --> 00:25:51,460
toy boat will be sitting there still but

585
00:25:49,720 --> 00:25:53,140
at some point the waves will pass by and

586
00:25:51,460 --> 00:25:57,579
that toy boat will start to bounce up

587
00:25:53,140 --> 00:26:01,870
and down so if I move the fluid over

588
00:25:57,579 --> 00:26:03,669
here somehow those waves propagate out

589
00:26:01,869 --> 00:26:07,149
and they are detected because they then

590
00:26:03,670 --> 00:26:12,039
induce motion in some test object like

591
00:26:07,150 --> 00:26:16,090
this toy boat a large distance if I have

592
00:26:12,039 --> 00:26:18,879
a tight string and I shake it and they

593
00:26:16,089 --> 00:26:20,769
disturb it on one end that disturbance

594
00:26:18,880 --> 00:26:23,350
will propagate out in this direction as

595
00:26:20,769 --> 00:26:26,769
a wave and suppose I have some beads on

596
00:26:23,349 --> 00:26:29,079
the string at the other end those beads

597
00:26:26,769 --> 00:26:32,609
will start to move up and down as the

598
00:26:29,079 --> 00:26:34,529
wave encounters them so again a

599

00:26:32,609 --> 00:26:37,289
string is a medium that can carry

600
00:26:34,529 --> 00:26:39,058
wave-like motions or carry waves and the

601
00:26:37,289 --> 00:26:40,678
way I induce those waves is by shaking

602
00:26:39,058 --> 00:26:42,450
the string up and down and the way I

603
00:26:40,679 --> 00:26:44,970
detect those waves is through the

604
00:26:42,450 --> 00:26:50,610
motions that those wave induce in a set

605
00:26:44,970 --> 00:26:53,789
of test masses the same thing is true

606
00:26:50,609 --> 00:26:57,539
for radio waves does anybody actually

607
00:26:53,789 --> 00:26:58,649
listen to the radio anymore okay back in

608
00:26:57,539 --> 00:27:00,298
the old days there was something in your

609
00:26:58,650 --> 00:27:04,048
car called the radio you could turn it

610
00:27:00,298 --> 00:27:06,298
on and the way the radio works is that

611
00:27:04,048 --> 00:27:08,668
there is a transmitter you see them for

612
00:27:06,298 --> 00:27:11,849
example in TV tower and roughly speaking

613
00:27:08,669 --> 00:27:14,759

there are a bunch of electrons and each

614

00:27:11,849 --> 00:27:16,379

electron when it Wiggles sends out

615

00:27:14,759 --> 00:27:18,419

electromagnetic wave and the way I

616

00:27:16,380 --> 00:27:21,150

detect that is that if I have an antenna

617

00:27:18,419 --> 00:27:24,299

like in my car the wave is it hits the

618

00:27:21,150 --> 00:27:28,019

antenna sets free electrons into motion

619

00:27:24,298 --> 00:27:33,418

and then you know your receiver detects

620

00:27:28,019 --> 00:27:37,259

and amplifies those motions there's one

621

00:27:33,419 --> 00:27:41,610

more example usually we think of the

622

00:27:37,259 --> 00:27:43,440

ground as rigid and fixed you don't

623

00:27:41,609 --> 00:27:48,149

think of the ground is shaking and

624

00:27:43,440 --> 00:27:49,890

moving around on California you do but

625

00:27:48,150 --> 00:27:51,630

you know here you generally think well

626

00:27:49,890 --> 00:27:52,980

the ground is fixed I can walk across

627

00:27:51,630 --> 00:27:55,080

it's not going to shake it's not going

628
00:27:52,980 --> 00:27:57,298
to move but you've all set been sitting

629
00:27:55,079 --> 00:28:00,029
at home at some time when a very heavy

630
00:27:57,298 --> 00:28:01,918
truck rolls by and on a bumpy road that

631
00:28:00,029 --> 00:28:04,139
heavy truck bounces up and down and you

632
00:28:01,919 --> 00:28:06,030
can feel the shaking in your house so

633
00:28:04,140 --> 00:28:08,429
although the ground is seems to be very

634
00:28:06,029 --> 00:28:10,200
rigid in fact it's not perfectly rigid

635
00:28:08,429 --> 00:28:12,200
and if you have something that's

636
00:28:10,200 --> 00:28:15,090
officially massive that starts shaking

637
00:28:12,200 --> 00:28:17,190
the ground will transmit waves and you

638
00:28:15,089 --> 00:28:19,439
will then feel them since the ground is

639
00:28:17,190 --> 00:28:21,120
so rigid that thing has to be really

640
00:28:19,440 --> 00:28:22,860
heavy to actually shake the ground and

641
00:28:21,119 --> 00:28:24,509
when the ground does shake it doesn't

642
00:28:22,859 --> 00:28:26,789
shrink a whole lot you feel a slight

643
00:28:24,509 --> 00:28:30,179
tremor but it's not a huge thing it

644
00:28:26,789 --> 00:28:32,970
turns out as Albert Einstein predicted

645
00:28:30,179 --> 00:28:34,650
and as we now know due to all these

646
00:28:32,970 --> 00:28:38,490
experimental verifications of general

647
00:28:34,650 --> 00:28:40,410
relativity that space-time which we

648
00:28:38,490 --> 00:28:44,130
always think of intuitively is being

649
00:28:40,410 --> 00:28:46,120
perfectly rigid you know every position

650
00:28:44,130 --> 00:28:49,000
in this room can be specified

651
00:28:46,119 --> 00:28:52,329
by three numbers a cart you know the

652
00:28:49,000 --> 00:28:54,038
numbers on a Cartesian grid the position

653
00:28:52,329 --> 00:28:55,298
in that direction the position in that

654
00:28:54,038 --> 00:28:57,538
direction and the position in that

655
00:28:55,298 --> 00:29:01,329
direction and we always in physics

656

00:28:57,538 --> 00:29:04,390
imagine a lattice that represents you

657
00:29:01,329 --> 00:29:09,129
know points in this direction x equals 1

658
00:29:04,390 --> 00:29:10,929
2 3 4 y equals 1 2 3 4 z equals 1 2 3 4

659
00:29:09,130 --> 00:29:12,370
and the location of anything or anybody

660
00:29:10,929 --> 00:29:15,330
in this room can be represented in terms

661
00:29:12,369 --> 00:29:17,528
of those three numbers so space in

662
00:29:15,329 --> 00:29:20,288
space-time we would always think of as

663
00:29:17,528 --> 00:29:22,808
being very rigid but as it turns out

664
00:29:20,288 --> 00:29:25,658
that space-time is extremely rigid but

665
00:29:22,808 --> 00:29:27,490
it's not perfectly rigid and if there

666
00:29:25,659 --> 00:29:29,049
are massive objects they can curve the

667
00:29:27,490 --> 00:29:31,089
space-time and if you shake those

668
00:29:29,048 --> 00:29:33,220
massive objects those will shake the

669
00:29:31,089 --> 00:29:36,250
space-time and if the space-time shakes

670
00:29:33,220 --> 00:29:41,640

we'll feel it things will start to move

671

00:29:36,250 --> 00:29:46,898

around so this was all pretty much

672

00:29:41,640 --> 00:29:51,190

theoretical expectation until a few

673

00:29:46,898 --> 00:29:59,009

years ago so in 1916 these gravitational

674

00:29:51,190 --> 00:30:01,630

waves were predicted waves carry energy

675

00:29:59,009 --> 00:30:03,849

when the truck drives by and starts

676

00:30:01,630 --> 00:30:05,620

shaking if you're sitting there and your

677

00:30:03,849 --> 00:30:08,439

chairs start shaking there's energy in

678

00:30:05,619 --> 00:30:11,109

that motion so how to get there well the

679

00:30:08,440 --> 00:30:14,288

medium the grounds carried the energy

680

00:30:11,109 --> 00:30:16,148

from the truck over to you so likewise

681

00:30:14,288 --> 00:30:20,048

gravitational waves can also carry

682

00:30:16,148 --> 00:30:27,038

energy they propagate at the speed of

683

00:30:20,048 --> 00:30:29,679

light they were detected indirectly back

684

00:30:27,038 --> 00:30:32,619

in 9th in the early 70s and it was a

685
00:30:29,679 --> 00:30:34,390
Nobel Prize award in 1993 there was a

686
00:30:32,619 --> 00:30:37,449
system of two neutron stars neutron

687
00:30:34,390 --> 00:30:40,720
stars are very dense remnants of stars

688
00:30:37,450 --> 00:30:42,880
each one weighs 1.4 times the mass of

689
00:30:40,720 --> 00:30:44,440
the Sun and there are several binary

690
00:30:42,880 --> 00:30:45,970
pulsar systems that we know about which

691
00:30:44,440 --> 00:30:49,179
are two neutron star spinning around

692
00:30:45,970 --> 00:30:50,769
each other and it was seen that in one

693
00:30:49,179 --> 00:30:52,929
particular system the two neutron stars

694
00:30:50,769 --> 00:30:56,440
were spinning around each other but they

695
00:30:52,929 --> 00:30:59,309
were spinning up the orbital period was

696
00:30:56,440 --> 00:31:01,830
shortening they were speeding up as they

697
00:30:59,308 --> 00:31:04,200
there seem to be speeding up which was

698
00:31:01,829 --> 00:31:09,689
interpreted as speeding up due to the

699
00:31:04,200 --> 00:31:11,970
emission of gravitational waves so the

700
00:31:09,690 --> 00:31:13,710
signal from these neutron stars gave us

701
00:31:11,970 --> 00:31:15,749
good evidence that the gravitational

702
00:31:13,710 --> 00:31:17,610
waves exist that they were being emitted

703
00:31:15,749 --> 00:31:19,528
from the spine or a neutron star system

704
00:31:17,609 --> 00:31:24,418
but no one are actually seen or detected

705
00:31:19,528 --> 00:31:26,429
a gravitational wave so how do we detect

706
00:31:24,419 --> 00:31:27,440
gravitational waves directly I told you

707
00:31:26,429 --> 00:31:32,159
already

708
00:31:27,440 --> 00:31:34,558
waves are detected by the motions they

709
00:31:32,159 --> 00:31:36,149
induce in some type of test masses radio

710
00:31:34,558 --> 00:31:39,658
waves are detected by the motions they

711
00:31:36,148 --> 00:31:41,308
induce an electrons the round waves are

712
00:31:39,659 --> 00:31:43,919
detected by the motions they induced in

713

00:31:41,308 --> 00:31:46,349
the chair that we're sitting on the toy

714
00:31:43,919 --> 00:31:49,950
boat is used to detect waves and

715
00:31:46,349 --> 00:31:52,859
otherwise still pond gravity effects

716
00:31:49,950 --> 00:31:54,929
masses and so the way do we detect

717
00:31:52,859 --> 00:31:56,908
gravitational waves is through the

718
00:31:54,929 --> 00:32:02,700
characteristic motions they induce in a

719
00:31:56,909 --> 00:32:08,269
set of freely falling test masses so the

720
00:32:02,700 --> 00:32:08,269
LIGO collaboration actually made a video

721
00:32:09,200 --> 00:32:13,919
this has scale in effect vastly

722
00:32:11,788 --> 00:32:20,099
exaggerated so I don't want to alarm

723
00:32:13,919 --> 00:32:22,200
anybody but they made a video of what it

724
00:32:20,099 --> 00:32:23,878
would look like if a very large

725
00:32:22,200 --> 00:32:26,429
amplitude gravitational wave were to

726
00:32:23,878 --> 00:32:32,699
pass through the earth and the video

727
00:32:26,429 --> 00:32:34,830

looks like this so this is a low

728

00:32:32,700 --> 00:32:36,990

amplitude gravitational wave and as

729

00:32:34,829 --> 00:32:39,678

we'll see the amplitude from a binary

730

00:32:36,990 --> 00:32:44,460

black hole mergers expected to increase

731

00:32:39,679 --> 00:32:46,019

and get faster so roughly speaking

732

00:32:44,460 --> 00:32:48,389

that's what's happening to the earth

733

00:32:46,019 --> 00:32:51,269

when a gravitational wave signal passes

734

00:32:48,388 --> 00:32:52,769

by the effect was greatly exaggerated

735

00:32:51,269 --> 00:32:58,769

they actually up to the effect is off

736

00:32:52,769 --> 00:33:02,548

one part in trillion trillion pretty

737

00:32:58,769 --> 00:33:04,788

small so in practice as I said the

738

00:33:02,548 --> 00:33:09,028

motions are getting extremely tiny and

739

00:33:04,788 --> 00:33:12,690

so what was done was something called

740

00:33:09,028 --> 00:33:16,170

laser interferometry and so

741

00:33:12,690 --> 00:33:17,640

what happens is the one of the

742
00:33:16,170 --> 00:33:18,900
characteristics of a gravitational wave

743
00:33:17,640 --> 00:33:22,350
is that if we have a gravitational wave

744
00:33:18,900 --> 00:33:27,240
propagating down but in a direction

745
00:33:22,349 --> 00:33:29,189
perpendicular to this plane the masses

746
00:33:27,240 --> 00:33:31,319
in this direction will get stretched out

747
00:33:29,190 --> 00:33:34,559
while the masses in this direction will

748
00:33:31,319 --> 00:33:37,649
get stretched inward and so what was

749
00:33:34,559 --> 00:33:40,109
people thought to do is to send a beam

750
00:33:37,650 --> 00:33:42,210
of light a laser signal through a

751
00:33:40,109 --> 00:33:44,189
half-silvered mirror that then splits

752
00:33:42,210 --> 00:33:46,829
the beam so that one beam goes towards

753
00:33:44,190 --> 00:33:48,750
this mirror over here and another beam

754
00:33:46,829 --> 00:33:50,189
goes toward this mirror over here the

755
00:33:48,750 --> 00:33:52,289
two beams then bounce back are

756
00:33:50,190 --> 00:33:58,259
recombined and then come back over here

757
00:33:52,289 --> 00:34:01,049
and since light is a wave when these two

758
00:33:58,259 --> 00:34:04,470
waves are recombined they can either add

759
00:34:01,049 --> 00:34:07,379
coherently or they can add destructively

760
00:34:04,470 --> 00:34:09,329
and if they add coherently the light

761
00:34:07,380 --> 00:34:11,190
signal that's received over here is

762
00:34:09,329 --> 00:34:13,710
stronger if they are destructively the

763
00:34:11,190 --> 00:34:15,539
light signal over here is weakened so

764
00:34:13,710 --> 00:34:20,099
again the LIGO people made a very nice

765
00:34:15,539 --> 00:34:21,659
movie of this which I can show you so

766
00:34:20,099 --> 00:34:24,210
there is the beam that gets split

767
00:34:21,659 --> 00:34:28,889
bounces back it comes back towards the

768
00:34:24,210 --> 00:34:30,900
detector and as these mirrors shake the

769
00:34:28,889 --> 00:34:35,009
light that's received in the detector is

770

00:34:30,900 --> 00:34:37,110
either brighter or weaker and the reason

771
00:34:35,010 --> 00:34:41,730
that happens is that each of these light

772
00:34:37,110 --> 00:34:43,769
rays is actually a wave and if the

773
00:34:41,730 --> 00:34:45,500
spacing between these two different arms

774
00:34:43,769 --> 00:34:49,530
is just right those two waves will add

775
00:34:45,500 --> 00:34:51,449
destructively and as the masses move

776
00:34:49,530 --> 00:34:54,269
around as the lengths in these two arms

777
00:34:51,449 --> 00:34:56,429
change what was otherwise the

778
00:34:54,269 --> 00:34:58,920
destructive interference might become a

779
00:34:56,429 --> 00:35:02,039
constructive interference and then the

780
00:34:58,920 --> 00:35:03,720
beam gets brighter so they have an

781
00:35:02,039 --> 00:35:07,409
interferometer that looks like this and

782
00:35:03,719 --> 00:35:13,529
what they look for is variable light

783
00:35:07,409 --> 00:35:15,029
brightness at that detector I am told

784
00:35:13,530 --> 00:35:17,670

that this is the most precise

785

00:35:15,030 --> 00:35:20,060

measurement ever made by a pretty wide

786

00:35:17,670 --> 00:35:22,309

stretch it was 40 years in the making

787

00:35:20,059 --> 00:35:26,000

from the time from the initial proposal

788

00:35:22,309 --> 00:35:29,690

so the detection was roughly 40 years

789

00:35:26,000 --> 00:35:32,659

technology development and science the

790

00:35:29,690 --> 00:35:34,429

detection was made by a collaboration an

791

00:35:32,659 --> 00:35:36,739

American collaboration LIGO they also

792

00:35:34,429 --> 00:35:39,079

used results from Burgo although they

793

00:35:36,739 --> 00:35:41,509

were not results which is a European

794

00:35:39,079 --> 00:35:43,279

collaboration there's a British German

795

00:35:41,510 --> 00:35:45,770

interferometer that's being built called

796

00:35:43,280 --> 00:35:48,410

Geo there's a Japanese interferometer

797

00:35:45,769 --> 00:35:50,509

being built Altima one in Australia and

798

00:35:48,409 --> 00:35:52,909

there's also one being built in India

799
00:35:50,510 --> 00:35:54,710
now but the original detection was by

800
00:35:52,909 --> 00:35:56,389
LIGO and in the future we're going to

801
00:35:54,710 --> 00:35:59,690
have networks of gravitational wave

802
00:35:56,389 --> 00:36:02,299
detectors all working together so LIGO

803
00:35:59,690 --> 00:36:04,579
stands for laser interferometer gravity

804
00:36:02,300 --> 00:36:06,500
wave observatory this is roughly

805
00:36:04,579 --> 00:36:08,960
speaking a billion dollars of taxpayer

806
00:36:06,500 --> 00:36:12,980
money very well spent it is the biggest

807
00:36:08,960 --> 00:36:14,840
NSF investment in single investment by a

808
00:36:12,980 --> 00:36:16,519
wide margin

809
00:36:14,840 --> 00:36:18,769
it's a us-led project it does have

810
00:36:16,519 --> 00:36:22,280
international collaboration they have

811
00:36:18,769 --> 00:36:24,349
two detectors one is in Washington State

812
00:36:22,280 --> 00:36:26,269
and the other one is in Louisiana and

813
00:36:24,349 --> 00:36:28,219
the reason they have two detectors is

814
00:36:26,269 --> 00:36:30,710
that if somebody told you they saw

815
00:36:28,219 --> 00:36:33,079
something go bump in the night you'd say

816
00:36:30,710 --> 00:36:35,470
what was that and see how if something

817
00:36:33,079 --> 00:36:38,719
went bump in the night Oh interesting

818
00:36:35,469 --> 00:36:41,179
but if somebody in Louisiana also says

819
00:36:38,719 --> 00:36:43,429
hey something went bump in the night and

820
00:36:41,179 --> 00:36:44,960
you say well what time did it help go

821
00:36:43,429 --> 00:36:49,699
bump in the night well it happened

822
00:36:44,960 --> 00:36:52,400
precisely at 12:03 a.m. plus sixteen

823
00:36:49,699 --> 00:36:55,549
point four eight seconds and then the

824
00:36:52,400 --> 00:36:58,250
people in Washington say oh wow we saw

825
00:36:55,550 --> 00:37:00,830
the exact same bump in the night so they

826
00:36:58,250 --> 00:37:02,000
used the simultaneity to reject spurious

827

00:37:00,829 --> 00:37:04,690
signals because things are always

828
00:37:02,000 --> 00:37:07,099
happening that shake those masses around

829
00:37:04,690 --> 00:37:10,639
the length of the arms are four

830
00:37:07,099 --> 00:37:15,259
kilometers and although there's four

831
00:37:10,639 --> 00:37:16,759
kilometers between these mirrors what

832
00:37:15,260 --> 00:37:18,560
they detect are motions that are a

833
00:37:16,760 --> 00:37:21,440
fraction of the size of an atomic

834
00:37:18,559 --> 00:37:23,929
nucleus so this is a picture of the

835
00:37:21,440 --> 00:37:27,500
Livingston Observatory from the sky four

836
00:37:23,929 --> 00:37:32,299
kilometers and four kilometers this is a

837
00:37:27,500 --> 00:37:34,519
another picture another picture and here

838
00:37:32,300 --> 00:37:37,130
is the Hanford Observatory there are

839
00:37:34,519 --> 00:37:38,119
more or less identical there are subtle

840
00:37:37,130 --> 00:37:39,829
differences but the more or less

841
00:37:38,119 --> 00:37:43,880

identical to four

842

00:37:39,829 --> 00:37:48,529

in her arms and the motion that they

843

00:37:43,880 --> 00:37:49,849

detect is illustrated by this movie in

844

00:37:48,530 --> 00:37:53,200

which the LIGO collaboration also

845

00:37:49,849 --> 00:37:55,639

provided so this is an atomic this is a

846

00:37:53,199 --> 00:37:59,299

that would let me start again what you

847

00:37:55,639 --> 00:38:04,909

started with was an electron spinning

848

00:37:59,300 --> 00:38:08,600

around let me go back because this is

849

00:38:04,909 --> 00:38:10,519

absolutely astounding this is a movie of

850

00:38:08,599 --> 00:38:17,389

an electron spinning around an atomic

851

00:38:10,519 --> 00:38:21,980

nucleus so that's pretty small so there

852

00:38:17,389 --> 00:38:25,309

is the atom and then we zoom in to the

853

00:38:21,980 --> 00:38:31,639

atomic nucleus which is composed of a

854

00:38:25,309 --> 00:38:34,279

couple of protons and neutrons and what

855

00:38:31,639 --> 00:38:45,469

they actually detect is a motion of that

856
00:38:34,280 --> 00:38:47,710
magnitude so that is incredible this is

857
00:38:45,469 --> 00:38:47,709
not easy

858
00:38:47,949 --> 00:38:54,679
so when I so I was a professor at

859
00:38:51,530 --> 00:38:56,480
Caltech for a while and my office was

860
00:38:54,679 --> 00:38:58,250
down the hall from the people working on

861
00:38:56,480 --> 00:38:59,659
this project and they're always like

862
00:38:58,250 --> 00:39:00,739
walking past my hall looking really busy

863
00:38:59,659 --> 00:39:02,779
because they were gonna detect

864
00:39:00,739 --> 00:39:03,709
gravitational waves and every time I saw

865
00:39:02,780 --> 00:39:05,180
them walking around this is what I

866
00:39:03,710 --> 00:39:09,740
thought this is fit a scene from his

867
00:39:05,179 --> 00:39:13,969
fits corrado which is a movie by a

868
00:39:09,739 --> 00:39:15,919
Verner Herzog about a man in 19th

869
00:39:13,969 --> 00:39:23,109
century Brazil who decides he wants to

870
00:39:15,920 --> 00:39:26,150
carry a boat over a mountain anyway on

871
00:39:23,110 --> 00:39:28,039
September 14th 2015 they had upgraded

872
00:39:26,150 --> 00:39:29,570
their detectors and before they're

873
00:39:28,039 --> 00:39:32,449
actually gonna start doing science runs

874
00:39:29,570 --> 00:39:33,860
they were doing some test runs so they

875
00:39:32,449 --> 00:39:35,239
turned the machine on just to do some

876
00:39:33,860 --> 00:39:39,440
tests to see if everything was working

877
00:39:35,239 --> 00:39:41,919
and this is what happened and there's a

878
00:39:39,440 --> 00:39:41,920
soundtrack

879
00:39:51,500 --> 00:39:57,900
so they're constantly measuring the

880
00:39:55,230 --> 00:40:00,690
separation of these mirrors with a very

881
00:39:57,900 --> 00:40:02,250
very small time resolution and the

882
00:40:00,690 --> 00:40:04,470
mirrors keep shaking around because when

883
00:40:02,250 --> 00:40:07,079
people drive by that shakes the ground

884

00:40:04,469 --> 00:40:09,119
and they when there's a lightning strike

885
00:40:07,079 --> 00:40:11,400
anywhere on the planet that shakes the

886
00:40:09,119 --> 00:40:14,159
things around so they're constantly see

887
00:40:11,400 --> 00:40:16,289
things in LIGO the custody see things in

888
00:40:14,159 --> 00:40:18,269
Livingston the number of things that

889
00:40:16,289 --> 00:40:20,849
affect the Hanford detector and the

890
00:40:18,269 --> 00:40:22,739
Livingston detector are pretty rare

891
00:40:20,849 --> 00:40:27,210
because they're several thousand miles

892
00:40:22,739 --> 00:40:29,189
away and what they saw though at the

893
00:40:27,210 --> 00:40:31,220
same time in both detectors is a very

894
00:40:29,190 --> 00:40:36,000
prominent signal that looked like that

895
00:40:31,219 --> 00:40:39,509
so here is another plot so this is the

896
00:40:36,000 --> 00:40:43,679
displacement of the mirrors as a

897
00:40:39,510 --> 00:40:45,960
function of time in the Hanford and you

898
00:40:43,679 --> 00:40:46,980

see that it goes up and down and up and

899

00:40:45,960 --> 00:40:51,059

down and up and down and up and down

900

00:40:46,980 --> 00:40:53,460

right faster faster and then stops and

901

00:40:51,059 --> 00:40:57,059

you see the exact same thing and the

902

00:40:53,460 --> 00:41:04,610

Livingston data goes up and down up and

903

00:40:57,059 --> 00:41:09,809

down up no it's big and then stops so

904

00:41:04,610 --> 00:41:13,440

this we are very very sure is the signal

905

00:41:09,809 --> 00:41:14,460

from a pair of black holes that are

906

00:41:13,440 --> 00:41:16,110

merging

907

00:41:14,460 --> 00:41:19,079

so another prediction of general

908

00:41:16,110 --> 00:41:22,130

relativity which was realized first by a

909

00:41:19,079 --> 00:41:24,509

guy named Karl Schwarzschild who was

910

00:41:22,130 --> 00:41:27,809

fighting in the trenches in World War

911

00:41:24,510 --> 00:41:30,360

one and figured this out while in the

912

00:41:27,809 --> 00:41:34,619

trenches and then passed away a few

913
00:41:30,360 --> 00:41:37,590
months later so Karl Schwarzschild

914
00:41:34,619 --> 00:41:39,480
figured out that the equations of

915
00:41:37,590 --> 00:41:41,900
general relativity allow for the

916
00:41:39,480 --> 00:41:44,699
existence of things called black holes

917
00:41:41,900 --> 00:41:47,160
these are the densest possible objects

918
00:41:44,699 --> 00:41:49,139
in nature and they are so strong that

919
00:41:47,159 --> 00:41:50,489
the grant they are so dense the

920
00:41:49,139 --> 00:41:53,489
gravitational field is so strong that

921
00:41:50,489 --> 00:41:56,159
not even light can escape so you know if

922
00:41:53,489 --> 00:41:58,139
I try to throw a ball in the air it goes

923
00:41:56,159 --> 00:41:59,609
up and it goes down but if I had a

924
00:41:58,139 --> 00:42:03,679
really good arm and I could throw the

925
00:41:59,610 --> 00:42:05,358
ball any velocity of 11 kilometers per

926
00:42:03,679 --> 00:42:08,808
second I shouldn't know what that is a

927
00:42:05,358 --> 00:42:11,420
miles per hour but I don't 11 kilometers

928
00:42:08,809 --> 00:42:12,619
per second the ball wouldn't return to

929
00:42:11,420 --> 00:42:14,088
Earth it would actually escape the

930
00:42:12,619 --> 00:42:19,880
gravitational pull of the earth and

931
00:42:14,088 --> 00:42:21,409
escape to infinity a black hole is an

932
00:42:19,880 --> 00:42:22,940
object that is so dense the

933
00:42:21,409 --> 00:42:25,338
gravitational field is so strong that

934
00:42:22,940 --> 00:42:26,990
the escape velocity from the surface is

935
00:42:25,338 --> 00:42:28,099
bigger than the speed of light and since

936
00:42:26,989 --> 00:42:30,348
nothing can travel faster than the speed

937
00:42:28,099 --> 00:42:35,930
of light nothing can escape from the

938
00:42:30,349 --> 00:42:40,400
black hole so we can take the equations

939
00:42:35,929 --> 00:42:42,078
of general relativity and set them up so

940
00:42:40,400 --> 00:42:44,630
that there's not just one black hole but

941

00:42:42,079 --> 00:42:48,109
two black holes that are in orbit about

942
00:42:44,630 --> 00:42:50,838
each other and if you do that what you

943
00:42:48,108 --> 00:42:53,690
find is that gravitational waves will be

944
00:42:50,838 --> 00:42:57,349
emitted as the gravitational waves are

945
00:42:53,690 --> 00:42:59,480
emitted those gravitational waves carry

946
00:42:57,349 --> 00:43:00,588
energy away and if they carry energy

947
00:42:59,480 --> 00:43:04,219
away that means there has to be less

948
00:43:00,588 --> 00:43:06,529
energy for the remaining system a Barn's

949
00:43:04,219 --> 00:43:09,108
system of two objects actually has a

950
00:43:06,530 --> 00:43:11,569
negative energy it has a gravitational

951
00:43:09,108 --> 00:43:13,068
binding or potential energy and as they

952
00:43:11,568 --> 00:43:15,558
get closer that becomes increasingly

953
00:43:13,068 --> 00:43:19,009
negative so the energy that's carried

954
00:43:15,559 --> 00:43:21,349
away is gravitational waves causes the

955
00:43:19,010 --> 00:43:24,230

remaining binary to become closer and

956

00:43:21,349 --> 00:43:25,940

closer and as that binary as the two

957

00:43:24,230 --> 00:43:27,289

stars become closer and closer they spin

958

00:43:25,940 --> 00:43:29,210

around faster and faster

959

00:43:27,289 --> 00:43:31,068

you know mercury gets around the Sun a

960

00:43:29,210 --> 00:43:32,119

lot more quickly does the earth and the

961

00:43:31,068 --> 00:43:36,710

earth gets around the Sun a lot more

962

00:43:32,119 --> 00:43:39,230

quickly than Pluto so likewise when two

963

00:43:36,710 --> 00:43:40,579

black holes get closer and closer they

964

00:43:39,230 --> 00:43:43,190

start to spin around each other faster

965

00:43:40,579 --> 00:43:45,349

and faster and when they do that the

966

00:43:43,190 --> 00:43:47,720

gravitational wave frequency increases

967

00:43:45,349 --> 00:43:50,930

and the power and gravitational waves

968

00:43:47,719 --> 00:43:54,219

increases and so that is what is seen

969

00:43:50,929 --> 00:43:56,868

here and this is actually a scientific

970
00:43:54,219 --> 00:43:59,629
simulation this is actually full

971
00:43:56,869 --> 00:44:03,048
solution of the numerical solution of

972
00:43:59,630 --> 00:44:05,329
the equations of general relativity so

973
00:44:03,048 --> 00:44:07,190
that is what they look like they get

974
00:44:05,329 --> 00:44:09,010
closer and closer here you see the

975
00:44:07,190 --> 00:44:12,380
gravitational waves being emitted as

976
00:44:09,010 --> 00:44:14,150
they get closer and closer the orbit

977
00:44:12,380 --> 00:44:15,500
will orbital period will decrease

978
00:44:14,150 --> 00:44:16,639
they'll start to spin up and the

979
00:44:15,500 --> 00:44:17,210
gravitational wave soon will get

980
00:44:16,639 --> 00:44:19,969
stronger

981
00:44:17,210 --> 00:44:21,829
stronger and so this is actually what it

982
00:44:19,969 --> 00:44:23,629
looks like when gravitational waves when

983
00:44:21,829 --> 00:44:26,900
two binary black to black holes merge

984
00:44:23,630 --> 00:44:28,160
and what's kind of interesting and I was

985
00:44:26,900 --> 00:44:30,110
surprised by when I first saw these

986
00:44:28,159 --> 00:44:32,089
numerical simulations is that when they

987
00:44:30,110 --> 00:44:33,559
finally merged it happens very quickly

988
00:44:32,090 --> 00:44:37,480
and there's a burst of gravitational

989
00:44:33,559 --> 00:44:39,889
waves emitted so it turns out that

990
00:44:37,480 --> 00:44:43,730
calculations such as the ones I just

991
00:44:39,889 --> 00:44:45,650
that I showed you here can allow you to

992
00:44:43,730 --> 00:44:48,800
predict a gravitational wave signal far

993
00:44:45,650 --> 00:44:57,019
away and that prediction turns out to be

994
00:44:48,800 --> 00:44:59,780
spot-on what was seen by LIGO not always

995
00:44:57,019 --> 00:45:03,199
it's spot-on but based on the properties

996
00:44:59,780 --> 00:45:05,210
of the signal you know the frequency how

997
00:45:03,199 --> 00:45:07,339
quickly the frequency increases the

998

00:45:05,210 --> 00:45:09,679
magnitude of the signal at the merger

999
00:45:07,340 --> 00:45:13,789
time and also the ring down and the

1000
00:45:09,679 --> 00:45:16,099
final period from all that information

1001
00:45:13,789 --> 00:45:18,710
we can actually infer that one of these

1002
00:45:16,099 --> 00:45:20,630
black holes had a mass of about 36 times

1003
00:45:18,710 --> 00:45:23,150
the mass of the Sun another was about 29

1004
00:45:20,630 --> 00:45:26,480
times the mass of the Sun the final

1005
00:45:23,150 --> 00:45:29,960
black hole had a mass of 62 and 62 minus

1006
00:45:26,480 --> 00:45:32,480
36 months 29 is three so they're

1007
00:45:29,960 --> 00:45:34,429
actually you know from just from now you

1008
00:45:32,480 --> 00:45:36,320
know special relativity Albert Einstein

1009
00:45:34,429 --> 00:45:38,629
e equals mc-squared

1010
00:45:36,320 --> 00:45:43,150
energy is equivalent to mass there were

1011
00:45:38,630 --> 00:45:45,680
three solar masses of energy released as

1012
00:45:43,150 --> 00:45:47,090

gravitational waves and we can also

1013

00:45:45,679 --> 00:45:49,759
infer the distance which is about

1014

00:45:47,090 --> 00:45:52,039
billion light years which is good

1015

00:45:49,760 --> 00:45:54,260
because things are because it feels a

1016

00:45:52,039 --> 00:45:57,500
lot closer than that movie they showed

1017

00:45:54,260 --> 00:46:03,470
you of the earth bouncing around might

1018

00:45:57,500 --> 00:46:04,969
have been a little more realistic this

1019

00:46:03,469 --> 00:46:06,230
is kind of a cute movie this is actually

1020

00:46:04,969 --> 00:46:11,539
another movie that they made that

1021

00:46:06,230 --> 00:46:14,990
illustrates what the sky would look like

1022

00:46:11,539 --> 00:46:19,250
if you were looking through a pair of

1023

00:46:14,989 --> 00:46:20,929
binary a binary black hole system so the

1024

00:46:19,250 --> 00:46:23,360
black hole's I told you to flecked the

1025

00:46:20,929 --> 00:46:24,469
light and so the image of the stars that

1026

00:46:23,360 --> 00:46:26,930
are behind the black hole's get

1027
00:46:24,469 --> 00:46:29,059
distorted and again this is a scientific

1028
00:46:26,929 --> 00:46:30,710
simulation of what it would look like if

1029
00:46:29,059 --> 00:46:38,329
we were a lot closer to the spine

1030
00:46:30,710 --> 00:46:40,460
black hole system so as they move around

1031
00:46:38,329 --> 00:46:42,529
the lensing pattern would change and

1032
00:46:40,460 --> 00:46:45,320
that is what the sky would look like as

1033
00:46:42,530 --> 00:46:48,980
these things spiral around each other

1034
00:46:45,320 --> 00:46:51,740
and then merge and the merger is pretty

1035
00:46:48,980 --> 00:46:54,230
happens very quickly and suddenly and

1036
00:46:51,739 --> 00:46:56,439
then there's a very brief ring down any

1037
00:46:54,230 --> 00:47:00,079
second now

1038
00:46:56,440 --> 00:47:09,559
so they're they merge and then there's

1039
00:47:00,079 --> 00:47:11,569
this final ring down anyway there's a

1040
00:47:09,559 --> 00:47:13,190
big question which is the question we

1041
00:47:11,570 --> 00:47:15,050
were wondering in the Aza front and then

1042
00:47:13,190 --> 00:47:20,780
the Space Telescope cafeteria over here

1043
00:47:15,050 --> 00:47:23,690
in January of 2016 in February where do

1044
00:47:20,780 --> 00:47:25,670
these black holes come from we detected

1045
00:47:23,690 --> 00:47:27,380
them we're very very sure that that was

1046
00:47:25,670 --> 00:47:29,349
a binary black hole system that we saw

1047
00:47:27,380 --> 00:47:31,608
with these gravitational wave events and

1048
00:47:29,349 --> 00:47:33,950
subsequent developments have given us

1049
00:47:31,608 --> 00:47:37,608
even more confidence but where do they

1050
00:47:33,949 --> 00:47:39,608
come from I told you that they can exist

1051
00:47:37,608 --> 00:47:41,838
within the context of general relativity

1052
00:47:39,608 --> 00:47:43,730
but they're there they're not just

1053
00:47:41,838 --> 00:47:45,739
mathematical constructions and you know

1054
00:47:43,730 --> 00:47:47,570
figments of theoretical imagination this

1055

00:47:45,739 --> 00:47:49,729
measurement shows that these black holes

1056
00:47:47,570 --> 00:47:53,990
actually exist and they weigh you know

1057
00:47:49,730 --> 00:47:56,480
30 times the mass of the Sun so the most

1058
00:47:53,989 --> 00:47:59,179
reasonable explanation and the one that

1059
00:47:56,480 --> 00:48:01,760
you know with 99% confidence is going to

1060
00:47:59,179 --> 00:48:04,549
be correct to some extent is that they

1061
00:48:01,760 --> 00:48:06,770
probably come from massive stars so this

1062
00:48:04,550 --> 00:48:10,369
is a very busy plot and I want you to

1063
00:48:06,769 --> 00:48:14,030
look at everything but basically there

1064
00:48:10,369 --> 00:48:15,559
are a lot of stars in the universe like

1065
00:48:14,030 --> 00:48:17,869
the Sun some of them are more massive

1066
00:48:15,559 --> 00:48:18,980
than the stars then the Sun like those

1067
00:48:17,869 --> 00:48:19,880
of you who are paying attention to the

1068
00:48:18,980 --> 00:48:22,369
details of the hertzprung-russell

1069
00:48:19,880 --> 00:48:23,960

diagram well remember that there were

1070

00:48:22,369 --> 00:48:26,450

blue giants which are extremely massive

1071

00:48:23,960 --> 00:48:31,220

and their red dwarfs which are very

1072

00:48:26,449 --> 00:48:34,579

low-mass so what we know is that stars

1073

00:48:31,219 --> 00:48:37,879

are powered by burning protons into

1074

00:48:34,579 --> 00:48:40,579

helium nuclei fission but there's only a

1075

00:48:37,880 --> 00:48:44,568

finite amount of fuel that a given star

1076

00:48:40,579 --> 00:48:47,828

has and when that fuel runs out the star

1077

00:48:44,568 --> 00:48:50,690

and it does not die an elegant death and

1078

00:48:47,829 --> 00:48:52,730

the way it dies and the remnant that it

1079

00:48:50,690 --> 00:48:55,760

leaves behind depends on its initial

1080

00:48:52,730 --> 00:48:59,030

mass so low mass stars like the Sun

1081

00:48:55,760 --> 00:49:01,400

we're pretty sure that when they use up

1082

00:48:59,030 --> 00:49:02,900

all their nuclear fuel they blow up into

1083

00:49:01,400 --> 00:49:05,059

a red giant for a brief period of time

1084
00:49:02,900 --> 00:49:06,380
they then blow off a lot of gas and they

1085
00:49:05,059 --> 00:49:12,050
leave behind something called a white

1086
00:49:06,380 --> 00:49:14,950
dwarf more massive stars though undergo

1087
00:49:12,050 --> 00:49:18,079
a similar evolution but when they

1088
00:49:14,949 --> 00:49:19,789
finally become a giant instead of just

1089
00:49:18,079 --> 00:49:21,920
blowing off a nebula leaving a white

1090
00:49:19,789 --> 00:49:25,699
dwarf they undergo this huge explosion

1091
00:49:21,920 --> 00:49:27,858
where their inner core's undergo

1092
00:49:25,699 --> 00:49:31,399
gravitational collapse and leave behind

1093
00:49:27,858 --> 00:49:32,869
either a neutron star or a black hole so

1094
00:49:31,400 --> 00:49:38,030
this is something that we're very very

1095
00:49:32,869 --> 00:49:41,780
sure about although the details we don't

1096
00:49:38,030 --> 00:49:43,819
have a lot of confidence in but we're

1097
00:49:41,780 --> 00:49:47,660
very very certain that neutron stars and

1098
00:49:43,818 --> 00:49:54,619
black holes are formed as the remnants

1099
00:49:47,659 --> 00:49:58,460
of massive stars now the issue that kind

1100
00:49:54,619 --> 00:50:00,559
of surprised us back in 2016

1101
00:49:58,460 --> 00:50:02,780
is that each of the black holes that

1102
00:50:00,559 --> 00:50:05,059
were detected in this original event had

1103
00:50:02,780 --> 00:50:07,400
a mass of 30 times the mass of the Sun

1104
00:50:05,059 --> 00:50:09,710
and the mass of the black hole that

1105
00:50:07,400 --> 00:50:11,930
remains is only a small fraction of the

1106
00:50:09,710 --> 00:50:13,579
mass of the original star because most

1107
00:50:11,929 --> 00:50:16,669
of the mass of the stars blown away in

1108
00:50:13,579 --> 00:50:18,079
this planetary nebula or supernova so

1109
00:50:16,670 --> 00:50:20,059
that means that a 30 solar mass black

1110
00:50:18,079 --> 00:50:22,640
hole would have had to come from a much

1111
00:50:20,059 --> 00:50:24,589
more massive star that's okay there are

1112

00:50:22,639 --> 00:50:27,048
many more much more massive stars in the

1113
00:50:24,588 --> 00:50:28,338
universe but if you're paying attention

1114
00:50:27,048 --> 00:50:30,139
when Frank was talking about the

1115
00:50:28,338 --> 00:50:34,279
hertzsprung-russell diagram he told you

1116
00:50:30,139 --> 00:50:37,400
that there are far more far far far more

1117
00:50:34,280 --> 00:50:39,980
low mass stars than there are high mass

1118
00:50:37,400 --> 00:50:42,289
stars and so it was kind of surprising

1119
00:50:39,980 --> 00:50:46,219
that the first black hole binary that

1120
00:50:42,289 --> 00:50:49,639
LIGO detected came from these very very

1121
00:50:46,219 --> 00:50:51,769
very rare supermassive stars we would

1122
00:50:49,639 --> 00:50:53,838
have thought we would see five or ten

1123
00:50:51,769 --> 00:50:55,900
solar mass black holes not 30 solar mass

1124
00:50:53,838 --> 00:50:58,869
black holes

1125
00:50:55,900 --> 00:51:00,940
and so that got us to thinking and I'm

1126
00:50:58,869 --> 00:51:02,680

not a gravitational wave astrophysicist

1127

00:51:00,940 --> 00:51:04,028

I'm not a stellar astrophysicist I'm not

1128

00:51:02,679 --> 00:51:08,980

a blackhole guy I'm not a neutron star

1129

00:51:04,028 --> 00:51:11,170

guy I'm a cosmologists and one of the

1130

00:51:08,980 --> 00:51:13,019

things that I get paid to do is think

1131

00:51:11,170 --> 00:51:14,889

about what the dark matter is

1132

00:51:13,018 --> 00:51:18,248

fortunately I don't get paid to actually

1133

00:51:14,889 --> 00:51:20,920

figure it out because that can only

1134

00:51:18,248 --> 00:51:27,759

happen once and once it happens we're

1135

00:51:20,920 --> 00:51:29,858

out of work so I think about what the

1136

00:51:27,759 --> 00:51:31,748

dark matter might be and so here are

1137

00:51:29,858 --> 00:51:33,219

black holes they're dark

1138

00:51:31,748 --> 00:51:36,608

they've been discovered they're out

1139

00:51:33,219 --> 00:51:43,358

there maybe there's the Dark Matter so

1140

00:51:36,608 --> 00:51:47,380

it's a silly idea so dark matter this is

1141
00:51:43,358 --> 00:51:49,989
a mystery that's been around for a good

1142
00:51:47,380 --> 00:51:51,249
fraction of a century and the reason we

1143
00:51:49,989 --> 00:51:53,889
believe in dark matter there are many

1144
00:51:51,248 --> 00:51:55,028
many lines of reasoning to tell us that

1145
00:51:53,889 --> 00:51:57,338
there's a lot of dark matter in the

1146
00:51:55,028 --> 00:51:59,679
universe but the simplest is perhaps

1147
00:51:57,338 --> 00:52:03,369
what we call galactic rotation curves so

1148
00:51:59,679 --> 00:52:05,588
there are a lot of galaxies like the

1149
00:52:03,369 --> 00:52:07,509
Milky Way which are a collection of a

1150
00:52:05,588 --> 00:52:09,788
gravitationally bound system of stars

1151
00:52:07,509 --> 00:52:11,650
and each star moves and the

1152
00:52:09,789 --> 00:52:15,640
gravitational potential due to every

1153
00:52:11,650 --> 00:52:19,108
other star and galaxies have some finite

1154
00:52:15,639 --> 00:52:21,190
extent they are ten what we call

1155
00:52:19,108 --> 00:52:22,869
kiloparsecs and the kiloparsec is

1156
00:52:21,190 --> 00:52:24,849
roughly 3,000 light years so here in

1157
00:52:22,869 --> 00:52:26,440
this diagram actually this is 10,000

1158
00:52:24,849 --> 00:52:28,900
light years this is a smallish galaxy

1159
00:52:26,440 --> 00:52:31,239
and then the star sort of peter out

1160
00:52:28,900 --> 00:52:33,130
there's not a whole lot out here but

1161
00:52:31,239 --> 00:52:36,068
occasionally you do find some star at

1162
00:52:33,130 --> 00:52:37,690
large distance or some gas cloud and you

1163
00:52:36,068 --> 00:52:39,429
can see these gas clouds spinning around

1164
00:52:37,690 --> 00:52:41,440
and you can measure the velocity which

1165
00:52:39,429 --> 00:52:44,608
they spin around and if you plot the

1166
00:52:41,440 --> 00:52:48,429
speed at which these gas clouds are

1167
00:52:44,608 --> 00:52:51,009
spinning around this galaxy it continues

1168
00:52:48,429 --> 00:52:53,710
to increase at large distances from the

1169

00:52:51,009 --> 00:52:55,329
galaxies and that is unusual because if

1170
00:52:53,710 --> 00:52:57,369
this was all the manner that we saw then

1171
00:52:55,329 --> 00:52:59,499
according to Newton's laws the velocity

1172
00:52:57,369 --> 00:53:02,019
should decrease right in the solar

1173
00:52:59,498 --> 00:53:05,288
system the Sun is a very very massive

1174
00:53:02,018 --> 00:53:06,699
object right in the middle and mercury

1175
00:53:05,289 --> 00:53:08,339
which is right next to the Sun spins

1176
00:53:06,699 --> 00:53:10,108
around really really quickly

1177
00:53:08,338 --> 00:53:12,538
but as you go further out the solar

1178
00:53:10,108 --> 00:53:14,478
system Pluto takes forever to get around

1179
00:53:12,539 --> 00:53:17,309
the Sun because Pluto is so far away so

1180
00:53:14,478 --> 00:53:20,068
if this was all that we all the matter

1181
00:53:17,309 --> 00:53:23,249
in the galaxy we would expected to see

1182
00:53:20,068 --> 00:53:25,259
these speeds become much smaller at

1183
00:53:23,248 --> 00:53:27,268

large distances from the galaxy but

1184

00:53:25,259 --> 00:53:30,869

instead they're seen to increase and

1185

00:53:27,268 --> 00:53:34,108

this along with many other lines of

1186

00:53:30,869 --> 00:53:37,140

reasoning and many other forms of

1187

00:53:34,108 --> 00:53:41,639

evidence suggests that there is a lot of

1188

00:53:37,139 --> 00:53:44,478

dark matter non luminous matter that

1189

00:53:41,639 --> 00:53:46,798

surrounds the luminous stuff that we see

1190

00:53:44,478 --> 00:53:48,478

we don't know what it is though we're

1191

00:53:46,798 --> 00:53:49,588

very very sure that it's there when we

1192

00:53:48,478 --> 00:53:52,199

have no idea what it is

1193

00:53:49,588 --> 00:53:54,179

all we know is that it's dark it does

1194

00:53:52,199 --> 00:53:58,798

not emit light and it does not absorb

1195

00:53:54,179 --> 00:54:00,719

light we know now precisely how much

1196

00:53:58,798 --> 00:54:02,309

there is I can tell you it within a few

1197

00:54:00,719 --> 00:54:04,099

percent how much dark matter there is

1198
00:54:02,309 --> 00:54:06,180
even though I can't tell you what it is

1199
00:54:04,099 --> 00:54:09,150
and we know how its distributing

1200
00:54:06,179 --> 00:54:11,399
galaxies and elsewhere in the universe I

1201
00:54:09,150 --> 00:54:13,528
told you it does not emit nor absorb

1202
00:54:11,400 --> 00:54:17,150
light so it can't be the same stuff that

1203
00:54:13,528 --> 00:54:19,710
were made out of it can't be it atoms

1204
00:54:17,150 --> 00:54:22,170
for many years we've speculated that's

1205
00:54:19,710 --> 00:54:23,429
perhaps some new elementary particle and

1206
00:54:22,170 --> 00:54:24,960
we've been trying really hard to find

1207
00:54:23,429 --> 00:54:29,009
this elementary particle but we have not

1208
00:54:24,960 --> 00:54:30,659
yet succeeded and so it's not

1209
00:54:29,009 --> 00:54:34,588
unreasonable to entertain other

1210
00:54:30,659 --> 00:54:37,920
possibilities and Stephen Hawking back

1211
00:54:34,588 --> 00:54:40,828
in 1974 and others thought maybe there

1212
00:54:37,920 --> 00:54:43,139
are primordial black holes maybe the Big

1213
00:54:40,829 --> 00:54:44,568
Bang when it produced the universe and

1214
00:54:43,139 --> 00:54:47,129
produced all the stuff in the universe

1215
00:54:44,568 --> 00:54:49,558
maybe it also produced a whole bunch of

1216
00:54:47,130 --> 00:54:53,489
black holes which survived to become the

1217
00:54:49,559 --> 00:54:55,349
dark matter today so we tried to figure

1218
00:54:53,489 --> 00:54:58,108
out and these are some my collaborators

1219
00:54:55,349 --> 00:54:59,849
so my work is always done with students

1220
00:54:58,108 --> 00:55:01,318
and postdocs and in this particular case

1221
00:54:59,849 --> 00:55:03,778
I'm also with Adam riess who's a

1222
00:55:01,318 --> 00:55:08,909
colleague who has a Nobel Prize which

1223
00:55:03,778 --> 00:55:11,039
helps with the credibility so these are

1224
00:55:08,909 --> 00:55:14,239
all postdocs and one graduate student

1225
00:55:11,039 --> 00:55:14,239
across the street

1226

00:55:14,849 --> 00:55:19,259
so this was the paper we wrote I don't

1227
00:55:17,670 --> 00:55:21,809
remember the exact title but it was more

1228
00:55:19,260 --> 00:55:23,430
or less did LIGO detect arc matter so

1229
00:55:21,809 --> 00:55:26,039
it's a crazy idea it's a speculative

1230
00:55:23,429 --> 00:55:27,929
idea but not completely crazy and this

1231
00:55:26,039 --> 00:55:29,579
is the coincident I told you about so we

1232
00:55:27,929 --> 00:55:32,879
know how much dark matter there is in

1233
00:55:29,579 --> 00:55:38,369
the Galactic halo so we know how much

1234
00:55:32,880 --> 00:55:40,470
stuff there is out here if all of that

1235
00:55:38,369 --> 00:55:43,739
dark matter is composed of 30 solar mass

1236
00:55:40,469 --> 00:55:45,839
objects but then I can tell you how many

1237
00:55:43,739 --> 00:55:48,569
of them there should be and what the

1238
00:55:45,840 --> 00:55:50,160
typical spacing should be we also know

1239
00:55:48,570 --> 00:55:52,980
how fast these things are moving around

1240
00:55:50,159 --> 00:55:54,989

these dark matter objects whatever they

1241

00:55:52,980 --> 00:55:56,670

are in a galaxy like the Milky Way

1242

00:55:54,989 --> 00:55:58,589

galaxy are actually spinning around and

1243

00:55:56,670 --> 00:56:03,720

a speed of several hundred kilometers

1244

00:55:58,590 --> 00:56:05,730

per second and we also know that two

1245

00:56:03,719 --> 00:56:08,609

black holes if they pass by each other

1246

00:56:05,730 --> 00:56:12,139

can actually form very briefly a Brown

1247

00:56:08,610 --> 00:56:14,280

system that then spirals in and merges

1248

00:56:12,139 --> 00:56:15,750

so roughly speaking I've got you know

1249

00:56:14,280 --> 00:56:17,910

two ping-pong balls passing by each

1250

00:56:15,750 --> 00:56:19,289

other a large separation they're not

1251

00:56:17,909 --> 00:56:22,199

gonna hit each other but if the two

1252

00:56:19,289 --> 00:56:24,840

ping-pong balls pass by each other with

1253

00:56:22,199 --> 00:56:26,399

a separation that's smaller than their

1254

00:56:24,840 --> 00:56:28,769

size they're gonna run into each other

1255
00:56:26,400 --> 00:56:33,450
same thing is true of automobiles which

1256
00:56:28,769 --> 00:56:35,190
is why we have lanes so we know roughly

1257
00:56:33,449 --> 00:56:38,069
speaking how big a 30 solar mass black

1258
00:56:35,190 --> 00:56:41,849
hole is and so it is very very

1259
00:56:38,070 --> 00:56:43,170
straightforward to estimate how often

1260
00:56:41,849 --> 00:56:45,989
these things should run into each other

1261
00:56:43,170 --> 00:56:49,740
and so we did this estimate we did this

1262
00:56:45,989 --> 00:56:52,949
calculation and some of these people are

1263
00:56:49,739 --> 00:56:54,299
actually very well equipped in terms of

1264
00:56:52,949 --> 00:56:57,329
the theoretical background to do the

1265
00:56:54,300 --> 00:57:00,150
calculation properly and so we did it

1266
00:56:57,329 --> 00:57:02,400
and it turns out that the rate at which

1267
00:57:00,150 --> 00:57:04,260
such black holes would merge if they

1268
00:57:02,400 --> 00:57:08,430
made up the dark matter in galactic

1269
00:57:04,260 --> 00:57:11,040
halos agreed surprisingly well with the

1270
00:57:08,429 --> 00:57:13,679
rates at which black holes merge that we

1271
00:57:11,039 --> 00:57:15,389
infer from the fact that LIGO saw one of

1272
00:57:13,679 --> 00:57:18,000
these events after two weeks of

1273
00:57:15,389 --> 00:57:20,190
observation and it was that coincidence

1274
00:57:18,000 --> 00:57:22,289
that led us to write the paper and it's

1275
00:57:20,190 --> 00:57:23,820
that coincidence that has been very

1276
00:57:22,289 --> 00:57:27,349
intriguing for a number of our

1277
00:57:23,820 --> 00:57:27,350
colleagues here and elsewhere

1278
00:57:27,480 --> 00:57:34,769
so I think that this paper that we wrote

1279
00:57:30,030 --> 00:57:39,090
is the most highly cited post LIGO LIGO

1280
00:57:34,769 --> 00:57:42,000
related paper so this is a hypothesis

1281
00:57:39,090 --> 00:57:43,559
but it's not the answer I don't know

1282
00:57:42,000 --> 00:57:47,250
that this is the Dark Matter - pretty

1283

00:57:43,559 --> 00:57:49,440
out-there hypothesis but scientists are

1284
00:57:47,250 --> 00:57:51,570
supposed to not only propose hypotheses

1285
00:57:49,440 --> 00:57:54,269
but try to come up with ways to test the

1286
00:57:51,570 --> 00:57:56,070
hypotheses and that has been a very

1287
00:57:54,269 --> 00:57:58,559
active area of investigation for our

1288
00:57:56,070 --> 00:58:00,570
group and others I will not tell you all

1289
00:57:58,559 --> 00:58:02,400
the things that people have proposed but

1290
00:58:00,570 --> 00:58:04,080
I'll tell you about one thing that we

1291
00:58:02,400 --> 00:58:10,559
suggested and that we're hoping will be

1292
00:58:04,079 --> 00:58:14,789
done soon so it turns out that there are

1293
00:58:10,559 --> 00:58:18,299
these things called fast radio bursts so

1294
00:58:14,789 --> 00:58:19,650
you've all seen James Bond movies and

1295
00:58:18,300 --> 00:58:21,810
there's the one James Bond movie where

1296
00:58:19,650 --> 00:58:24,769
he goes to the Arecibo space there osebo

1297
00:58:21,809 --> 00:58:26,549

telescope which is this huge radio dish

1298

00:58:24,769 --> 00:58:31,050

you know what I'm talking about

1299

00:58:26,550 --> 00:58:34,530

okay so radio telescopes like Arecibo

1300

00:58:31,050 --> 00:58:37,380

and a few others detect radio frequency

1301

00:58:34,530 --> 00:58:39,360

radiation from the sky and for a number

1302

00:58:37,380 --> 00:58:41,190

of years I don't remember exactly a lot

1303

00:58:39,360 --> 00:58:43,710

but for about the past 10 years it's

1304

00:58:41,190 --> 00:58:47,220

been noticed that occasionally there is

1305

00:58:43,710 --> 00:58:50,090

a very brief flash of radio frequency

1306

00:58:47,219 --> 00:58:52,799

radiation coming from the sky

1307

00:58:50,090 --> 00:58:55,500

so these flashes lasts less than one

1308

00:58:52,800 --> 00:58:56,789

thousandth of a second and for a long

1309

00:58:55,500 --> 00:58:59,000

time people wonder whether there was

1310

00:58:56,789 --> 00:59:01,289

some type of problem with the telescope

1311

00:58:59,000 --> 00:59:03,210

but a number of different telescopes

1312
00:59:01,289 --> 00:59:06,210
started to see these things they did a

1313
00:59:03,210 --> 00:59:07,710
number of tests and it's now very

1314
00:59:06,210 --> 00:59:09,929
certain that these are actually coming

1315
00:59:07,710 --> 00:59:11,789
from the sky and for a variety of

1316
00:59:09,929 --> 00:59:13,049
reasons we believe these to be coming

1317
00:59:11,789 --> 00:59:16,259
from there are good reasons to believe

1318
00:59:13,050 --> 00:59:18,330
these are coming from large distances so

1319
00:59:16,260 --> 00:59:20,160
suppose one of these fast radio bursts

1320
00:59:18,329 --> 00:59:22,980
goes off and we have no idea I should

1321
00:59:20,159 --> 00:59:24,179
say where they come from or a pretty

1322
00:59:22,980 --> 00:59:27,780
sure they're coming from outside the

1323
00:59:24,179 --> 00:59:29,669
Milky Way but we have no idea what the

1324
00:59:27,780 --> 00:59:31,410
source is most people think that has

1325
00:59:29,670 --> 00:59:33,150
something to do with phenomena and the

1326
00:59:31,409 --> 00:59:35,009
surfaces of neutron stars but we can't

1327
00:59:33,150 --> 00:59:37,470
be absolutely sure but we don't even

1328
00:59:35,010 --> 00:59:41,050
care for our purposes so I should also

1329
00:59:37,469 --> 00:59:42,429
tell you that as of now they're about 50

1330
00:59:41,050 --> 00:59:44,800
fast radio bursts that have been

1331
00:59:42,429 --> 00:59:47,169
detected about a year ago there were

1332
00:59:44,800 --> 00:59:49,090
about 25 that have been detected but

1333
00:59:47,170 --> 00:59:51,760
there is a new telescope that the

1334
00:59:49,090 --> 00:59:53,559
Canadians have built called chime which

1335
00:59:51,760 --> 00:59:55,840
stands for Canadian hydrogen intensity

1336
00:59:53,559 --> 00:59:57,909
mapping experiment and unlike the other

1337
00:59:55,840 --> 00:59:59,829
radio telescopes like Arecibo which

1338
00:59:57,909 --> 01:00:01,899
pointed a very small part of the sky on

1339
00:59:59,829 --> 01:00:03,819
this Canadian telescope points at a very

1340

01:00:01,900 --> 01:00:05,740
large fraction of the seas a very large

1341
01:00:03,820 --> 01:00:08,740
fraction in the sky and so they expect

1342
01:00:05,739 --> 01:00:10,689
to detect these fast radio bursts far

1343
01:00:08,739 --> 01:00:12,279
more frequently than the past and in

1344
01:00:10,690 --> 01:00:14,170
just a few months of observation they've

1345
01:00:12,280 --> 01:00:16,180
doubled the sample of fast radio bursts

1346
01:00:14,170 --> 01:00:19,240
already and they expect to see several

1347
01:00:16,179 --> 01:00:20,980
thousand more in the next few years so

1348
01:00:19,239 --> 01:00:23,049
suppose there's a fast radio bursts and

1349
01:00:20,980 --> 01:00:25,380
suppose the black hole's make up the

1350
01:00:23,050 --> 01:00:29,550
dark matter then there is some chance

1351
01:00:25,380 --> 01:00:32,800
that there will be such a black hole

1352
01:00:29,550 --> 01:00:36,160
along the line of sight to a given fast

1353
01:00:32,800 --> 01:00:39,100
radio bursts and if that's the case then

1354
01:00:36,159 --> 01:00:41,799

this massive object this black hole can

1355

01:00:39,099 --> 01:00:43,329

gravitationally lense the signal from

1356

01:00:41,800 --> 01:00:44,950

this fast radio bursts so the light from

1357

01:00:43,329 --> 01:00:49,299

this fast radio bursts these radio waves

1358

01:00:44,949 --> 01:00:52,049

can travel to us either along this

1359

01:00:49,300 --> 01:00:54,490

trajectory or along this trajectory and

1360

01:00:52,050 --> 01:00:56,530

it turns out that most generally these

1361

01:00:54,489 --> 01:01:01,629

two trajectories have slightly different

1362

01:00:56,530 --> 01:01:05,920

path lengths and the path lengths differ

1363

01:01:01,630 --> 01:01:09,190

by roughly a millisecond times the speed

1364

01:01:05,920 --> 01:01:11,050

of light or a few milliseconds time the

1365

01:01:09,190 --> 01:01:15,990

speed of light and so what we predict is

1366

01:01:11,050 --> 01:01:18,430

that instead of seeing one flash once

1367

01:01:15,989 --> 01:01:20,559

sub-millisecond flash which has been the

1368

01:01:18,429 --> 01:01:21,369

case for all the vast range of earths

1369
01:01:20,559 --> 01:01:23,739
that have been seen

1370
01:01:21,369 --> 01:01:26,409
if these black holes are out there

1371
01:01:23,739 --> 01:01:28,389
roughly one in a hundred of them will be

1372
01:01:26,409 --> 01:01:30,579
gravitationally lensed and after seeing

1373
01:01:28,389 --> 01:01:32,259
the original flash you'll see the

1374
01:01:30,579 --> 01:01:35,130
flashes arriving through a second

1375
01:01:32,260 --> 01:01:37,420
trajectory and so you'll see and that go

1376
01:01:35,130 --> 01:01:40,690
so these measurements are now being made

1377
01:01:37,420 --> 01:01:43,570
as I said they've seen 50 in a few years

1378
01:01:40,690 --> 01:01:46,119
they'll have maybe 5,000 and if black

1379
01:01:43,570 --> 01:01:48,490
holes make up the dark matter then they

1380
01:01:46,119 --> 01:01:50,980
will see several hundred within a few

1381
01:01:48,489 --> 01:01:52,779
years that have an echo that looks like

1382
01:01:50,980 --> 01:01:54,969
this so

1383
01:01:52,780 --> 01:01:56,140
this is one way to test the scenario

1384
01:01:54,969 --> 01:02:01,750
there are other ways to test the

1385
01:01:56,139 --> 01:02:05,440
scenario I won't discuss them all but I

1386
01:02:01,750 --> 01:02:07,000
think I will close there so the era of

1387
01:02:05,440 --> 01:02:08,679
gravitational wave astronomy is here

1388
01:02:07,000 --> 01:02:10,199
we're learning all about black holes

1389
01:02:08,679 --> 01:02:13,419
about general relativity

1390
01:02:10,199 --> 01:02:16,750
spacetime Wiggles around maybe we'll

1391
01:02:13,420 --> 01:02:18,880
also learn something about dark matter I

1392
01:02:16,750 --> 01:02:20,320
should say the jury is still out as to

1393
01:02:18,880 --> 01:02:25,180
whether prime order black holes can make

1394
01:02:20,320 --> 01:02:26,800
up the dark matter there's still some

1395
01:02:25,179 --> 01:02:28,299
debate within the Astrophysical

1396
01:02:26,800 --> 01:02:29,440
community about whether they can make up

1397

01:02:28,300 --> 01:02:32,410
the dark matter or whether current

1398
01:02:29,440 --> 01:02:33,700
observations already roll them out so

1399
01:02:32,409 --> 01:02:35,319
I'm not going to tell you I'm absolutely

1400
01:02:33,699 --> 01:02:37,239
certain that they can be the dark matter

1401
01:02:35,320 --> 01:02:37,960
but we are taking the idea very

1402
01:02:37,239 --> 01:02:40,569
seriously

1403
01:02:37,960 --> 01:02:42,460
either way it's a very exciting prospect

1404
01:02:40,570 --> 01:02:45,130
and many people are interested in in

1405
01:02:42,460 --> 01:02:48,769
trying to pursue further tests of this

1406
01:02:45,130 --> 01:02:51,869
scenario thank you very much

1407
01:02:48,769 --> 01:02:51,869
[Applause]

1408
01:02:55,889 --> 01:02:59,309
[Applause]

1409
01:03:05,509 --> 01:03:24,259
yes we are gonna have microphone here is

1410
01:03:07,489 --> 01:03:27,380
grant the bird at I2 that 2016

1411
01:03:24,259 --> 01:03:37,088

did you tell us more about bird there

1412

01:03:27,380 --> 01:03:40,640

was a bird was the Brit we had a Brit a

1413

01:03:37,088 --> 01:03:47,519

Frenchman and israeli-american

1414

01:03:40,639 --> 01:03:50,578

an Italian a Spaniard Greek and American

1415

01:03:47,519 --> 01:03:50,579

[Music]

1416

01:03:54,190 --> 01:03:59,409

so this is a sermon bird is the big one

1417

01:03:57,739 --> 01:04:05,420

with a glasses

1418

01:03:59,409 --> 01:04:17,958

he's uh so he was just the lead authors

1419

01:04:05,420 --> 01:04:19,369

of Simon's Simeon Simeon I'm a kind of

1420

01:04:17,958 --> 01:04:23,179

veteran you've seen a lot of these

1421

01:04:19,369 --> 01:04:25,940

lectures and this black black dark

1422

01:04:23,179 --> 01:04:30,909

matter compared to nothing where does

1423

01:04:25,940 --> 01:04:30,909

dark matter and and nothing begin

1424

01:04:34,289 --> 01:04:47,680

that's a tricky question I would say

1425

01:04:43,838 --> 01:04:49,869

that we don't actually know very

1426
01:04:47,679 --> 01:04:53,348
precisely but we know that in the center

1427
01:04:49,869 --> 01:04:57,309
of a galaxy there is a high density of

1428
01:04:53,349 --> 01:04:58,809
dark matter and the density of dark

1429
01:04:57,309 --> 01:05:01,030
matter which is going to be very big

1430
01:04:58,809 --> 01:05:04,510
over here decreases as you go further

1431
01:05:01,030 --> 01:05:06,369
out but sooner or later there's going to

1432
01:05:04,510 --> 01:05:08,799
be another galaxy over here that has its

1433
01:05:06,369 --> 01:05:10,180
own Dark Matter halo and so it's not

1434
01:05:08,798 --> 01:05:12,190
clear that there's anywhere in the

1435
01:05:10,179 --> 01:05:14,199
universe where there is no dark matter

1436
01:05:12,190 --> 01:05:16,059
but the density of dark matter is

1437
01:05:14,199 --> 01:05:20,318
probably going to be smallest in the

1438
01:05:16,059 --> 01:05:22,869
places between the galaxies is there a

1439
01:05:20,318 --> 01:05:27,130
place where there is that better is just

1440
01:05:22,869 --> 01:05:29,380
nothing well you have points I don't

1441
01:05:27,130 --> 01:05:31,180
think so I would say that there are

1442
01:05:29,380 --> 01:05:34,000
places where we the dark matter density

1443
01:05:31,179 --> 01:05:35,318
is small but I don't think there's any

1444
01:05:34,000 --> 01:05:36,789
place in the universe that we can point

1445
01:05:35,318 --> 01:05:49,480
to where we're pretty sure that there is

1446
01:05:36,789 --> 01:05:51,630
no dark matter yeah I see a basis for a

1447
01:05:49,480 --> 01:05:54,179
new disaster movie in the making here

1448
01:05:51,630 --> 01:05:56,289
[Laughter]

1449
01:05:54,179 --> 01:05:58,750
just just like the opposite you had

1450
01:05:56,289 --> 01:06:01,839
mention are implied that that of a solar

1451
01:05:58,750 --> 01:06:04,269
system was fairly close to emerging

1452
01:06:01,838 --> 01:06:06,009
block merging black holes that the

1453
01:06:04,269 --> 01:06:07,960
distortion would be considerably greater

1454

01:06:06,010 --> 01:06:13,180
would they be enough to actually care

1455
01:06:07,960 --> 01:06:14,650
apart a solar system I don't think so it

1456
01:06:13,179 --> 01:06:17,440
would have to be I we went through this

1457
01:06:14,650 --> 01:06:19,450
calculation once but when we're sitting

1458
01:06:17,440 --> 01:06:23,710
in the cafeteria and tossing around

1459
01:06:19,449 --> 01:06:26,500
crazy ideas the the probability that

1460
01:06:23,710 --> 01:06:29,858
this would happen is extremely extremely

1461
01:06:26,500 --> 01:06:31,838
small so the rate at which such things

1462
01:06:29,858 --> 01:06:35,528
occur as we infer from the LIGO

1463
01:06:31,838 --> 01:06:38,558
measurements is so small that it's

1464
01:06:35,528 --> 01:06:41,139
unlikely that there was ever such an

1465
01:06:38,559 --> 01:06:44,769
event even in our own galaxy over the

1466
01:06:41,139 --> 01:06:46,118
entire history of the universe so these

1467
01:06:44,769 --> 01:06:49,028
these events are so

1468
01:06:46,119 --> 01:06:52,660

err that a typical galaxy will go the

1469

01:06:49,028 --> 01:06:56,259

entire link you know the entire universe

1470

01:06:52,659 --> 01:06:57,818

without ever seeing such an event thank

1471

01:06:56,259 --> 01:06:59,409

you have to be relieved you don't have

1472

01:06:57,818 --> 01:07:00,690

to be very very close I think closer

1473

01:06:59,409 --> 01:07:23,739

than the nearest stars

1474

01:07:00,690 --> 01:07:27,568

so if black holes were in some way dark

1475

01:07:23,739 --> 01:07:30,159

matter how how would that relate to the

1476

01:07:27,568 --> 01:07:33,190

accelerating expansion of the universe

1477

01:07:30,159 --> 01:07:38,739

is there any connection that's a good

1478

01:07:33,190 --> 01:07:42,220

question and I have no idea so I was

1479

01:07:38,739 --> 01:07:43,719

just giving a I was giving a talk about

1480

01:07:42,219 --> 01:07:46,689

something related this morning to a

1481

01:07:43,719 --> 01:07:48,068

philosophy class oh there's a philosophy

1482

01:07:46,690 --> 01:07:49,929

of science class and they just wanted

1483
01:07:48,068 --> 01:07:53,498
somebody to talk about things that we do

1484
01:07:49,929 --> 01:07:55,568
in physics so there's the dark matter

1485
01:07:53,498 --> 01:07:58,988
problem and then there's the dark energy

1486
01:07:55,568 --> 01:08:03,759
problem and in science we are always

1487
01:07:58,989 --> 01:08:08,108
told to look for economic solutions and

1488
01:08:03,759 --> 01:08:10,269
so ideally we would have one theory or

1489
01:08:08,108 --> 01:08:13,389
model that can explain both dark matter

1490
01:08:10,268 --> 01:08:15,329
and dark energy and some theorists have

1491
01:08:13,389 --> 01:08:17,588
tried to do that but it turns out to be

1492
01:08:15,329 --> 01:08:18,250
far more difficult than you would

1493
01:08:17,588 --> 01:08:20,289
imagine

1494
01:08:18,250 --> 01:08:22,149
and what it really wants all these

1495
01:08:20,289 --> 01:08:24,488
solutions where they try to merge the

1496
01:08:22,149 --> 01:08:26,198
two they really wind up looking like a

1497
01:08:24,488 --> 01:08:27,698
solution for dark matter and a

1498
01:08:26,198 --> 01:08:30,719
completely different solution for dark

1499
01:08:27,698 --> 01:08:35,198
energy that are then glued together I

1500
01:08:30,719 --> 01:08:36,989
don't know but I don't think that I'll

1501
01:08:35,198 --> 01:08:39,358
be surprised if I were to be like

1502
01:08:36,988 --> 01:08:43,750
resurrected a hundred years from now and

1503
01:08:39,359 --> 01:08:45,699
learn that they actually the solution

1504
01:08:43,750 --> 01:08:49,298
for dark energy was related to the

1505
01:08:45,698 --> 01:08:50,250
solution for dark matter I can imagine

1506
01:08:49,298 --> 01:08:52,479
that a hundred years from now

1507
01:08:50,250 --> 01:08:55,899
cosmologists we were looking at back at

1508
01:08:52,479 --> 01:08:57,158
us and thinking oh that was so quaint

1509
01:08:55,899 --> 01:08:58,599
and silly they thought that was dark

1510
01:08:57,158 --> 01:09:00,319
matter those dark energy they didn't

1511

01:08:58,600 --> 01:09:03,329
understand that was just

1512
01:09:00,319 --> 01:09:05,189
but I have no idea what that is yeah

1513
01:09:03,329 --> 01:09:07,710
our current understanding has the the

1514
01:09:05,189 --> 01:09:09,809
dark matter localized around galaxies

1515
01:09:07,710 --> 01:09:13,050
etcetera whereas the dark energy is sort

1516
01:09:09,810 --> 01:09:15,060
of round all of space and so that that

1517
01:09:13,050 --> 01:09:16,800
to me you know has always been the

1518
01:09:15,060 --> 01:09:19,080
fundamental problem trying to combine

1519
01:09:16,800 --> 01:09:20,960
the two is that the distribution

1520
01:09:19,079 --> 01:09:24,000
function is totally different right I

1521
01:09:20,960 --> 01:09:28,140
agree and that's how I view it that's

1522
01:09:24,000 --> 01:09:31,560
how 99% of people like us view the

1523
01:09:28,140 --> 01:09:33,180
problem but I kind of think that

1524
01:09:31,560 --> 01:09:37,170
sometime in the future there's gonna be

1525
01:09:33,180 --> 01:09:38,760

like a solution that's you know of which

1526

01:09:37,170 --> 01:09:52,199

these are two different aspects

1527

01:09:38,760 --> 01:09:55,710

that's a nice hopeful thought thank you

1528

01:09:52,199 --> 01:09:59,880

um how closely closely related to

1529

01:09:55,710 --> 01:10:02,609

project Einstein is this as far as the

1530

01:09:59,880 --> 01:10:04,560

detection of gravitational waves how

1531

01:10:02,609 --> 01:10:07,710

closely related this is this to project

1532

01:10:04,560 --> 01:10:15,120

Einstein yes I don't think I know what

1533

01:10:07,710 --> 01:10:17,730

project Einstein is well it is one part

1534

01:10:15,119 --> 01:10:21,199

of it is a distributed processing

1535

01:10:17,729 --> 01:10:24,869

research project using blink

1536

01:10:21,199 --> 01:10:30,319

uh-huh okay taking data from the Arecibo

1537

01:10:24,869 --> 01:10:35,039

telescope and from the legos in

1538

01:10:30,319 --> 01:10:37,079

Louisiana and in Washington Policy and

1539

01:10:35,039 --> 01:10:41,689

they're looking for that for the

1540
01:10:37,079 --> 01:10:44,519
apparently if I understand correctly

1541
01:10:41,689 --> 01:10:48,559
looking at the locations of pulsars

1542
01:10:44,520 --> 01:10:50,940
where you could do interferometry use oh

1543
01:10:48,560 --> 01:10:54,630
okay that yeah okay now I know I know

1544
01:10:50,939 --> 01:11:01,879
what you're talking about that that's a

1545
01:10:54,630 --> 01:11:05,220
very very interesting set of projects so

1546
01:11:01,880 --> 01:11:07,770
there are pulsars which are spending

1547
01:11:05,220 --> 01:11:09,600
neutron stars that are located you know

1548
01:11:07,770 --> 01:11:11,010
ten thousand light years away and

1549
01:11:09,600 --> 01:11:12,990
there's a bunch of them spread

1550
01:11:11,010 --> 01:11:13,320
throughout the sky and what I showed you

1551
01:11:12,989 --> 01:11:15,029
was the

1552
01:11:13,319 --> 01:11:17,939
gravitational wave detector that they'd

1553
01:11:15,029 --> 01:11:21,118
built in Washington in Louisiana that

1554
01:11:17,939 --> 01:11:22,649
had two arms so there was a set of test

1555
01:11:21,118 --> 01:11:25,139
masses over here that were oscillating

1556
01:11:22,649 --> 01:11:28,710
like this another set like this so it's

1557
01:11:25,139 --> 01:11:30,630
been proposed to use pulsars for the

1558
01:11:28,710 --> 01:11:32,849
gravitational wave as gravitational wave

1559
01:11:30,630 --> 01:11:34,529
detectors so if I have you know if we're

1560
01:11:32,849 --> 01:11:37,800
on earth right here and there's one

1561
01:11:34,529 --> 01:11:39,689
pulsar over here and another pulsar over

1562
01:11:37,800 --> 01:11:43,380
here and the gravitational wave passes

1563
01:11:39,689 --> 01:11:45,118
by the Pulsar over here will oscillate

1564
01:11:43,380 --> 01:11:46,828
in this direction the Pulsar over here

1565
01:11:45,118 --> 01:11:49,348
lastly in this direction those two

1566
01:11:46,828 --> 01:11:53,729
oscillations will be out of phase and we

1567
01:11:49,349 --> 01:11:56,940
can detect that in principle and people

1568

01:11:53,729 --> 01:11:59,549
are trying to do this and the principle

1569
01:11:56,939 --> 01:12:01,348
is exactly the same as LIGO the

1570
01:11:59,550 --> 01:12:04,110
difference is that the arm lengths are

1571
01:12:01,349 --> 01:12:06,328
10,000 light years as opposed to for at

1572
01:12:04,109 --> 01:12:08,578
supposed a couple of miles and so the

1573
01:12:06,328 --> 01:12:11,309
wavelengths of the gravitational waves

1574
01:12:08,578 --> 01:12:18,710
that you can detect are bigger by about

1575
01:12:11,310 --> 01:12:22,619
a factor of a billion it's a it's a very

1576
01:12:18,710 --> 01:12:24,630
10 years ago even three years ago three

1577
01:12:22,618 --> 01:12:26,609
years ago I would have told I would have

1578
01:12:24,630 --> 01:12:28,529
put my money that those Paul start

1579
01:12:26,609 --> 01:12:33,420
timing arrays would detect gravitational

1580
01:12:28,529 --> 01:12:35,279
waves before Alia but they didn't but I

1581
01:12:33,420 --> 01:12:37,789
think they will I think we will see

1582
01:12:35,279 --> 01:12:40,259

something in the next few years

1583

01:12:37,789 --> 01:12:41,368

okay so mark there's a question from the

1584

01:12:40,260 --> 01:12:43,230

online audience that I'm sort of

1585

01:12:41,368 --> 01:12:45,328

summarizing from things is they want to

1586

01:12:43,229 --> 01:12:46,709

understand how many more gravitational

1587

01:12:45,328 --> 01:12:49,439

waves are out there you've got black

1588

01:12:46,710 --> 01:12:50,789

hole black hole mergers and obviously if

1589

01:12:49,439 --> 01:12:52,348

you had supermassive black hole

1590

01:12:50,789 --> 01:12:53,969

supermassive black hole murders you can

1591

01:12:52,349 --> 01:12:55,590

see along with that but you know the

1592

01:12:53,969 --> 01:12:58,020

neutron stars how many other different

1593

01:12:55,590 --> 01:13:01,409

types of events will these gravitational

1594

01:12:58,020 --> 01:13:03,780

wave detectors be able to see in the

1595

01:13:01,408 --> 01:13:07,229

near somewhat near future so their black

1596

01:13:03,779 --> 01:13:08,908

hole binary black hole mergers there was

1597
01:13:07,229 --> 01:13:11,399
a merger of it there's an event last

1598
01:13:08,908 --> 01:13:13,500
year there was either a binary neutron

1599
01:13:11,399 --> 01:13:15,658
star or a neutron star black hole we

1600
01:13:13,500 --> 01:13:16,590
don't know which but we do expect you

1601
01:13:15,658 --> 01:13:18,420
know over the next few years to see

1602
01:13:16,590 --> 01:13:21,210
neutron star neutron star mergers

1603
01:13:18,420 --> 01:13:23,099
neutron star or black hole murders we'll

1604
01:13:21,210 --> 01:13:26,930
see more black hole black hole mergers

1605
01:13:23,099 --> 01:13:30,409
there is a space-based gravitational

1606
01:13:26,930 --> 01:13:32,539
detector that we are considering the

1607
01:13:30,409 --> 01:13:35,840
European Space Agency's leading and NASA

1608
01:13:32,539 --> 01:13:37,640
is participating in if when that flies

1609
01:13:35,840 --> 01:13:39,500
that will detect or have sensitivity

1610
01:13:37,640 --> 01:13:41,660
detect mergers of supermassive black

1611
01:13:39,500 --> 01:13:44,479
holes black holes that each have a mass

1612
01:13:41,659 --> 01:13:47,750
of a billion times mass of a billion

1613
01:13:44,479 --> 01:13:50,629
times the mass of the Sun people have

1614
01:13:47,750 --> 01:13:52,340
also speculated that supernovae when a

1615
01:13:50,630 --> 01:13:54,260
star explodes and forms a neutron star

1616
01:13:52,340 --> 01:13:57,230
that there might be a gravitational wave

1617
01:13:54,260 --> 01:13:59,750
signal from that people have speculated

1618
01:13:57,229 --> 01:14:02,779
that some neutron stars might have

1619
01:13:59,750 --> 01:14:05,180
little mountains on them and those

1620
01:14:02,779 --> 01:14:06,349
mountains some the spending of a neutron

1621
01:14:05,180 --> 01:14:08,840
storm with the mountain might give you a

1622
01:14:06,350 --> 01:14:10,579
gravitational wave signal the

1623
01:14:08,840 --> 01:14:12,500
space-based observatories will also

1624
01:14:10,579 --> 01:14:15,409
detect gravitational waves from white

1625

01:14:12,500 --> 01:14:18,470
dwarf binaries so some of the you know

1626
01:14:15,409 --> 01:14:20,119
low mass stars at the end of their when

1627
01:14:18,470 --> 01:14:22,430
they sneeze up all the nuclear fuel turn

1628
01:14:20,119 --> 01:14:24,109
into white dwarfs so if I have a binary

1629
01:14:22,430 --> 01:14:26,150
star system that consists of two low

1630
01:14:24,109 --> 01:14:28,519
mass stars it will evolve to a white

1631
01:14:26,149 --> 01:14:30,079
dwarf binary and we actually know of a

1632
01:14:28,520 --> 01:14:32,450
number of white dwarf binary so there

1633
01:14:30,079 --> 01:14:37,309
are signals from those binaries that we

1634
01:14:32,449 --> 01:14:38,989
expect to see I'm sure there are other

1635
01:14:37,310 --> 01:14:41,240
things but those are the ones that them

1636
01:14:38,989 --> 01:14:43,219
we generally hear most about and the

1637
01:14:41,239 --> 01:14:45,109
most promising so really gravitational

1638
01:14:43,220 --> 01:14:46,909
waves just are studying the interactions

1639
01:14:45,109 --> 01:14:48,579

of dead stars with the light dwarfs and

1640

01:14:46,909 --> 01:14:50,689

the neutron stars and black holes so

1641

01:14:48,579 --> 01:14:52,489

stars got to give up their lives in

1642

01:14:50,689 --> 01:14:56,000

order for a gravitational wave astronomy

1643

01:14:52,489 --> 01:15:01,250

to work right exactly all right do we

1644

01:14:56,000 --> 01:15:03,739

have more questions up here there was a

1645

01:15:01,250 --> 01:15:07,130

famous inflammatory experiment in the

1646

01:15:03,739 --> 01:15:09,679

late 1800s Michelson Morley when people

1647

01:15:07,130 --> 01:15:11,569

were looking for the ether yep what

1648

01:15:09,680 --> 01:15:14,720

would have happened if this

1649

01:15:11,569 --> 01:15:17,869

interferometer LIGO had existed back

1650

01:15:14,720 --> 01:15:23,110

then and had gotten this reading back

1651

01:15:17,869 --> 01:15:26,359

then so it is exactly the same type of

1652

01:15:23,109 --> 01:15:27,710

interferometer that they use but as you

1653

01:15:26,359 --> 01:15:33,649

know trillions of times better

1654
01:15:27,710 --> 01:15:36,260
sensitivity have they seen that probably

1655
01:15:33,649 --> 01:15:37,639
would have blown their mind I actually

1656
01:15:36,260 --> 01:15:39,110
don't know what they probably thought it

1657
01:15:37,640 --> 01:15:40,239
was just noise because they only had one

1658
01:15:39,109 --> 01:15:43,809
detector

1659
01:15:40,238 --> 01:15:46,059
in Cleveland and had we had just if

1660
01:15:43,810 --> 01:15:47,260
there was only one detector I don't know

1661
01:15:46,060 --> 01:15:51,820
the we would have been as confident

1662
01:15:47,260 --> 01:15:54,670
there was a real signal but with Rago if

1663
01:15:51,819 --> 01:15:57,069
we'd had if we'd had this result then if

1664
01:15:54,670 --> 01:15:58,239
we had this result then I don't know

1665
01:15:57,069 --> 01:16:03,329
what people would have made of it

1666
01:15:58,238 --> 01:16:05,949
because there was no concept of a

1667
01:16:03,329 --> 01:16:10,899
space-time curvature there was no

1668
01:16:05,949 --> 01:16:12,939
concept of gravitational waves I have no

1669
01:16:10,899 --> 01:16:14,229
idea what the what they would have made

1670
01:16:12,939 --> 01:16:16,769
of it they were they were looking for

1671
01:16:14,229 --> 01:16:18,659
exactly this they did have some sense of

1672
01:16:16,770 --> 01:16:21,130
curvature they just didn't have

1673
01:16:18,659 --> 01:16:22,059
space-time the modern concept well they

1674
01:16:21,130 --> 01:16:23,980
were looking for something a little

1675
01:16:22,060 --> 01:16:25,780
different they were looking to see

1676
01:16:23,979 --> 01:16:28,089
whether there was a difference between

1677
01:16:25,779 --> 01:16:30,939
what happens when the interferometer is

1678
01:16:28,090 --> 01:16:33,250
in like orient in this direction versus

1679
01:16:30,939 --> 01:16:35,710
oriented in this direction whereas the

1680
01:16:33,250 --> 01:16:39,340
signal that they saw all takes place

1681
01:16:35,710 --> 01:16:41,670
with one orientation and the the the

1682

01:16:39,340 --> 01:16:43,750
interferometer just started to vibrate

1683
01:16:41,670 --> 01:16:46,750
Michelson Morley we're looking to see

1684
01:16:43,750 --> 01:16:50,289
whether the the the the arm lengths

1685
01:16:46,750 --> 01:16:54,039
would change if as the orientation of

1686
01:16:50,289 --> 01:16:55,719
the detector was changed but I have no

1687
01:16:54,039 --> 01:17:02,539
idea what they would have made of it had

1688
01:16:55,719 --> 01:17:05,180
they seen something I guess so

1689
01:17:02,539 --> 01:17:08,390
there's an e equals mc -squared waiting

1690
01:17:05,180 --> 01:17:12,560
out there that will equate dark energy

1691
01:17:08,390 --> 01:17:15,289
and dark matter well there is a you know

1692
01:17:12,560 --> 01:17:22,520
there is some energy density in the dark

1693
01:17:15,289 --> 01:17:24,319
energy so there is some equivalence

1694
01:17:22,520 --> 01:17:27,250
between the mass of the dark energy and

1695
01:17:24,319 --> 01:17:29,389
its energy but I don't think there's any

1696
01:17:27,250 --> 01:17:31,279

correspondence there's no obvious

1697

01:17:29,390 --> 01:17:35,470

correspondence between the density of

1698

01:17:31,279 --> 01:17:35,469

dark matter the density of dark energy

1699

01:17:38,829 --> 01:17:45,649

I'm really struck by the the declaration

1700

01:17:43,699 --> 01:17:49,760

that there's the loss of three solar

1701

01:17:45,649 --> 01:17:53,839

masses in the combination of those two

1702

01:17:49,760 --> 01:17:55,960

black holes and I've got a couple

1703

01:17:53,840 --> 01:17:58,489

questions on that the first is with

1704

01:17:55,960 --> 01:17:59,659

given that that's that's based upon the

1705

01:17:58,489 --> 01:18:01,250

energy coming out of the gravitational

1706

01:17:59,659 --> 01:18:03,619

waves so it doesn't have to necessarily

1707

01:18:01,250 --> 01:18:05,390

be two black holes I mean if it was the

1708

01:18:03,619 --> 01:18:07,729

black hole and really anything else that

1709

01:18:05,390 --> 01:18:10,310

would just be on a smaller scale correct

1710

01:18:07,729 --> 01:18:13,489

yes and then my question when that would

1711
01:18:10,310 --> 01:18:16,990
be brings to mind Hawking radiation and

1712
01:18:13,489 --> 01:18:20,269
the idea of black hole evaporation but

1713
01:18:16,989 --> 01:18:22,159
if there's three solar masses that are

1714
01:18:20,270 --> 01:18:23,330
getting pulled out based on

1715
01:18:22,159 --> 01:18:26,119
gravitational waves

1716
01:18:23,329 --> 01:18:27,769
I feel like Hawking radiation really

1717
01:18:26,119 --> 01:18:29,539
pales in comparison to whatever might

1718
01:18:27,770 --> 01:18:32,390
come out of just the gravitational

1719
01:18:29,539 --> 01:18:34,819
effects well it depends on the mass of

1720
01:18:32,390 --> 01:18:38,200
the black hole if for some reason there

1721
01:18:34,819 --> 01:18:43,039
were black holes that had a mass of a

1722
01:18:38,199 --> 01:18:45,859
thousand trillion grams a trillion

1723
01:18:43,039 --> 01:18:48,159
kilograms so if there was a black hole

1724
01:18:45,859 --> 01:18:52,399
down at a mass of a trillion kilograms

1725
01:18:48,159 --> 01:18:54,590
it would Hawking evaporate in less than

1726
01:18:52,399 --> 01:18:56,779
the age of the universe and the vast

1727
01:18:54,590 --> 01:18:58,970
majority that energy would be released

1728
01:18:56,779 --> 01:19:02,449
in a very short period of time now the

1729
01:18:58,970 --> 01:19:04,329
total energy is very small compared with

1730
01:19:02,449 --> 01:19:06,260
the total energy that's released in the

1731
01:19:04,329 --> 01:19:07,760
black holes that they've seen but those

1732
01:19:06,260 --> 01:19:10,489
but that's because those black holes are

1733
01:19:07,760 --> 01:19:11,050
so much more massive when when a black

1734
01:19:10,489 --> 01:19:13,760
hole

1735
01:19:11,050 --> 01:19:16,400
you know explodes by a Hawking

1736
01:19:13,760 --> 01:19:17,630
evaporation the entire rest mass energy

1737
01:19:16,399 --> 01:19:20,299
black hole as far as we know would be

1738
01:19:17,630 --> 01:19:24,829
released in radiation here it was just a

1739

01:19:20,300 --> 01:19:29,630
measly five percent okay but I should

1740
01:19:24,829 --> 01:19:32,840
say the the energy radiated that three

1741
01:19:29,630 --> 01:19:35,390
solar masses of energy was rated in one

1742
01:19:32,840 --> 01:19:40,850
millisecond and during that millisecond

1743
01:19:35,390 --> 01:19:43,310
this one system was more luminous than

1744
01:19:40,850 --> 01:19:44,270
the rest of the universe combined then

1745
01:19:43,310 --> 01:19:47,300
all the other stars in the universe

1746
01:19:44,270 --> 01:19:48,650
combined yeah there's a couple more

1747
01:19:47,300 --> 01:19:54,829
questions we had to this gentleman in

1748
01:19:48,649 --> 01:19:57,589
green here or like there there we go you

1749
01:19:54,829 --> 01:19:59,420
haven't talked about the speed of

1750
01:19:57,590 --> 01:20:00,230
gravitational waves at all do you think

1751
01:19:59,420 --> 01:20:03,159
about that

1752
01:20:00,229 --> 01:20:05,779
ah so general relativity predicts that

1753
01:20:03,159 --> 01:20:10,819

gravitational waves propagate at the

1754

01:20:05,779 --> 01:20:12,170

speed of light and we now know that that

1755

01:20:10,819 --> 01:20:18,130

prediction that prediction has been

1756

01:20:12,170 --> 01:20:23,000

verified because there was an event in

1757

01:20:18,130 --> 01:20:25,310

late in August of 2017 where there's a

1758

01:20:23,000 --> 01:20:27,229

gravitational wave signal seen from the

1759

01:20:25,310 --> 01:20:31,010

merger of either two neutron stars or

1760

01:20:27,229 --> 01:20:33,559

neutron star in a black hole and the

1761

01:20:31,010 --> 01:20:36,110

neutron star or neutron star merger

1762

01:20:33,560 --> 01:20:37,610

neutron star black hole merger some of

1763

01:20:36,109 --> 01:20:40,479

the material from the neutron star was

1764

01:20:37,609 --> 01:20:44,750

ripped out and there was a very visible

1765

01:20:40,479 --> 01:20:47,179

a very bright invisible explosion and so

1766

01:20:44,750 --> 01:20:49,489

this event was detected by a huge array

1767

01:20:47,180 --> 01:20:50,960

of telescopes simultaneously with the

1768
01:20:49,489 --> 01:20:54,260
ground with a gravitational wave

1769
01:20:50,960 --> 01:20:56,270
detection so we saw this one event in

1770
01:20:54,260 --> 01:20:58,489
gravitational waves and simultaneously

1771
01:20:56,270 --> 01:21:00,500
in electromagnetic waves and so from

1772
01:20:58,489 --> 01:21:03,439
that we know that they do propagate at

1773
01:21:00,500 --> 01:21:08,649
the speed of light so this this event

1774
01:21:03,439 --> 01:21:11,559
was astounding so the gravitational wave

1775
01:21:08,649 --> 01:21:13,939
observatory x' alerted the entire

1776
01:21:11,560 --> 01:21:15,950
astronomical community anybody who had a

1777
01:21:13,939 --> 01:21:18,049
telescope found out about this and

1778
01:21:15,949 --> 01:21:21,139
anybody who could pointed the telescope

1779
01:21:18,050 --> 01:21:25,250
at it and as it turns out one of nasa's

1780
01:21:21,140 --> 01:21:28,190
other one of nasa satellites the the

1781
01:21:25,250 --> 01:21:30,550
Fermi satellite detected

1782
01:21:28,189 --> 01:21:34,009
a gravitational wave burst

1783
01:21:30,550 --> 01:21:35,810
simultaneously and independently and

1784
01:21:34,010 --> 01:21:37,579
another you know telescopes like the

1785
01:21:35,810 --> 01:21:39,140
Hubble Space Telescope was as quickly as

1786
01:21:37,579 --> 01:21:40,909
possible pointed at that region of the

1787
01:21:39,140 --> 01:21:43,190
sky I'm all these ground-based

1788
01:21:40,909 --> 01:21:45,738
observatories radio telescopes all

1789
01:21:43,189 --> 01:21:47,750
observed that part of the sky and the

1790
01:21:45,738 --> 01:21:51,439
papers that resulted from this one event

1791
01:21:47,750 --> 01:21:54,319
I think one out of three astronomers in

1792
01:21:51,439 --> 01:21:56,539
the world and had a name on one of those

1793
01:21:54,319 --> 01:21:58,279
papers and I got a call from some

1794
01:21:56,539 --> 01:21:59,390
reporters and asked him how can you not

1795
01:21:58,279 --> 01:22:00,649
calling me about this because I'm not

1796

01:21:59,390 --> 01:22:02,000
really an expert on this kind of thing

1797
01:22:00,649 --> 01:22:03,198
and they said well you're the only

1798
01:22:02,000 --> 01:22:09,529
person we could think of it wasn't a

1799
01:22:03,198 --> 01:22:11,859
co-author on one of the papers there's

1800
01:22:09,529 --> 01:22:13,789
another astronomer in the room they were

1801
01:22:11,859 --> 01:22:19,819
yeah half the people in this building

1802
01:22:13,789 --> 01:22:22,039
were co-authors on one of the papers um

1803
01:22:19,819 --> 01:22:23,809
things have been moving around in our

1804
01:22:22,039 --> 01:22:26,180
solar system and bumping into each other

1805
01:22:23,810 --> 01:22:29,030
since time immemorial I mean supposedly

1806
01:22:26,180 --> 01:22:31,820
we were pelted by a mars-sized planet in

1807
01:22:29,029 --> 01:22:33,800
the past with what we can conceivably

1808
01:22:31,819 --> 01:22:37,988
build in the near future

1809
01:22:33,800 --> 01:22:37,989
how small of an event could be see

1810
01:22:38,529 --> 01:22:44,988

that's a good question

1811
01:22:41,529 --> 01:22:48,050
there are not nobody has really thought

1812
01:22:44,988 --> 01:22:49,039
of any other plausible Astrophysical

1813
01:22:48,050 --> 01:22:52,789
source that would produce a

1814
01:22:49,039 --> 01:22:56,390
gravitational wave signal involving an

1815
01:22:52,789 --> 01:23:00,350
object any less massive than a white

1816
01:22:56,390 --> 01:23:01,699
dwarf which the white dwarfs that exist

1817
01:23:00,350 --> 01:23:04,969
typically have a mass of about six

1818
01:23:01,698 --> 01:23:08,059
tenths the mass of the Sun the way that

1819
01:23:04,969 --> 01:23:10,880
the general relativity works the the

1820
01:23:08,060 --> 01:23:13,370
strength of the signal the gravitational

1821
01:23:10,880 --> 01:23:15,739
wave luminosity it greases very very

1822
01:23:13,369 --> 01:23:17,149
rapidly as you decrease the mass of the

1823
01:23:15,738 --> 01:23:20,149
system and also as you do as you

1824
01:23:17,149 --> 01:23:22,849
decrease the density so black holes are

1825
01:23:20,149 --> 01:23:25,069
the densest possible object and you know

1826
01:23:22,850 --> 01:23:29,060
those give us an observable signal if

1827
01:23:25,069 --> 01:23:31,819
there are very very massive but once you

1828
01:23:29,060 --> 01:23:36,070
go to something like a star an ordinary

1829
01:23:31,819 --> 01:23:39,198
star or a planet it's so diffuse that

1830
01:23:36,069 --> 01:23:41,899
the signals are conceivable signals are

1831
01:23:39,198 --> 01:23:43,729
way too weak to be detected

1832
01:23:41,899 --> 01:23:45,710
okay so I think we had one last question

1833
01:23:43,729 --> 01:23:48,229
over here and then we got to cut it off

1834
01:23:45,710 --> 01:23:51,590
a rainy is here to take people across

1835
01:23:48,229 --> 01:23:55,459
the street for the observing so catch

1836
01:23:51,590 --> 01:23:57,970
that does the expansion of space-time

1837
01:23:55,460 --> 01:24:01,430
affect the LIGO measurements and

1838
01:23:57,970 --> 01:24:06,490
interaction yes it does

1839
01:24:01,430 --> 01:24:06,490
and it is one of the problems we have so

1840
01:24:06,550 --> 01:24:11,150
so the expansion of space-time affects

1841
01:24:09,680 --> 01:24:14,420
the gravitational wave signal in that

1842
01:24:11,149 --> 01:24:17,359
the the binary black hole system is

1843
01:24:14,420 --> 01:24:20,119
moving away from us and so the

1844
01:24:17,359 --> 01:24:22,759
gravitational wave signal is Doppler

1845
01:24:20,119 --> 01:24:26,599
shifted or red shifted relative to what

1846
01:24:22,760 --> 01:24:28,010
it is when it is emitted and given the

1847
01:24:26,600 --> 01:24:30,560
equivalence principle and the way

1848
01:24:28,010 --> 01:24:32,420
general relativity works there's a

1849
01:24:30,560 --> 01:24:34,670
degeneracy between two black holes that

1850
01:24:32,420 --> 01:24:37,340
have say a mass of 30 solar masses that

1851
01:24:34,670 --> 01:24:40,130
are at some distance and two black holes

1852
01:24:37,340 --> 01:24:43,699
that have say a mass of 15 solar masses

1853

01:24:40,130 --> 01:24:47,989
that are at a closer distance but there

1854
01:24:43,699 --> 01:24:51,349
are ways to break that degeneracy okay

1855
01:24:47,989 --> 01:24:54,710
so I hope you have plenty to think about

1856
01:24:51,350 --> 01:24:56,829
from here this is the questions and the

1857
01:24:54,710 --> 01:25:00,520
comments online of to show that mark has

1858
01:24:56,829 --> 01:25:03,289
taken us new places here tonight ireenie

1859
01:25:00,520 --> 01:25:04,550
Lambrini says you want to be over here

1860
01:25:03,289 --> 01:25:05,960
to take people because you can go out

1861
01:25:04,550 --> 01:25:08,119
that door over there so if you would

1862
01:25:05,960 --> 01:25:10,399
like to go across the street to do the

1863
01:25:08,119 --> 01:25:14,180
observing or renew a joinery knee over

1864
01:25:10,399 --> 01:25:17,269
here our next talk is the third Thursday

1865
01:25:14,180 --> 01:25:19,900
January 15th and let's give mark one

1866
01:25:17,270 --> 01:25:19,900
more handle

1867
01:25:25,168 --> 01:25:40,050

so right let's Caltech and then yes I

1868

01:25:30,069 --> 01:25:40,049

got anything a lot before January 15th