

PUBLIC LECTURE SERIES

# Black Holes and Other Dark Matters

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Featuring Guest Speaker:  
**Marc Kamionkowski**

1  
00:00:05,960 --> 00:00:03,949  
and tonight we have a lithograph this is

2  
00:00:10,910 --> 00:00:05,970  
a brand-new one of the Lagoon Nebula

3  
00:00:13,640 --> 00:00:10,920  
Messier 8 and thanks to a a person on

4  
00:00:16,160 --> 00:00:13,650  
who wrote me and said hey can you share

5  
00:00:18,470 --> 00:00:16,170  
that with the online audience well I

6  
00:00:20,840 --> 00:00:18,480  
found it very hard to send paper through

7  
00:00:22,340 --> 00:00:20,850  
the internet unless you're wreckit-ralph

8  
00:00:24,800 --> 00:00:22,350  
you can't be traveling through the

9  
00:00:28,910 --> 00:00:24,810  
internet and bringing things around but

10  
00:00:31,009 --> 00:00:28,920  
I can share with you the URL of where

11  
00:00:34,160 --> 00:00:31,019  
these lithographs are posted on our

12  
00:00:37,510 --> 00:00:34,170  
amazing space so our G website so that

13  
00:00:40,490 --> 00:00:37,520

URL amazing space to our G resource page

14

00:00:43,700 --> 00:00:40,500

548 will get you to the Lagoon Nebula

15

00:00:45,889 --> 00:00:43,710

and there is a PDF file of it and those

16

00:00:48,410 --> 00:00:45,899

of you on the webcast can look at it and

17

00:00:50,479 --> 00:00:48,420

you too can say oh and AH over the

18

00:00:52,729 --> 00:00:50,489

pretty picture and then turn over and

19

00:00:57,799 --> 00:00:52,739

read about what that pretty picture is

20

00:01:00,860 --> 00:00:57,809

really about okay tonight we have black

21

00:01:02,660 --> 00:01:00,870

holes and other dark matters which is

22

00:01:04,670 --> 00:01:02,670

the reason why I think this place is

23

00:01:06,800 --> 00:01:04,680

packed because once you put the term

24

00:01:08,420 --> 00:01:06,810

black holes in your talk everyone says

25

00:01:12,890 --> 00:01:08,430

oh we got to find out about this okay

26  
00:01:16,670 --> 00:01:12,900  
all right upcoming we have January 15

27  
00:01:20,120 --> 00:01:16,680  
now first Tuesday in January is New

28  
00:01:21,679 --> 00:01:20,130  
Year's Day second Tuesday in January is

29  
00:01:24,320 --> 00:01:21,689  
the American Astronomical Society

30  
00:01:26,300 --> 00:01:24,330  
meeting out in Seattle and I'll be out

31  
00:01:30,740 --> 00:01:26,310  
there and so a lot of other astronomers

32  
00:01:34,819 --> 00:01:30,750  
so we have postponed it yet again to the

33  
00:01:37,940 --> 00:01:34,829  
third Tuesday January 15th and it's

34  
00:01:40,190 --> 00:01:37,950  
really good because what this is what

35  
00:01:41,810 --> 00:01:40,200  
Scott will be talking about some new

36  
00:01:44,899 --> 00:01:41,820  
stuff will be announced at the double-a

37  
00:01:46,550 --> 00:01:44,909  
s meeting so you'll get some some really

38  
00:01:49,190 --> 00:01:46,560

cool new stuff I'll be talking about

39

00:01:50,719 --> 00:01:49,200

initial exoplanet discoveries with Tess

40

00:01:53,270 --> 00:01:50,729

the transiting exoplanet survey

41

00:01:54,410 --> 00:01:53,280

satellite you're going to want to hear

42

00:01:57,770 --> 00:01:54,420

that because that's that's cool stuff

43

00:01:58,969 --> 00:01:57,780

about exoplanets February 5th back to

44

00:02:01,280 --> 00:01:58,979

the first Tuesday of the month

45

00:02:04,910 --> 00:02:01,290

am i immoral Martin will be talking

46

00:02:07,910 --> 00:02:04,920

about your place in the Stars and in

47

00:02:10,820 --> 00:02:07,920

March we have our familiar TBA showing

48

00:02:13,830 --> 00:02:10,830

up again which means I need to schedule

49

00:02:17,580 --> 00:02:13,840

somebody I might fill in this one myself

50

00:02:20,070 --> 00:02:17,590

with our visualization talk when that is

51  
00:02:22,770 --> 00:02:20,080  
decided it will be announced up here on

52  
00:02:24,330 --> 00:02:22,780  
our website if you go to your favorite

53  
00:02:26,729 --> 00:02:24,340  
search engine and search for Space

54  
00:02:28,350 --> 00:02:26,739  
Telescope public Hubble public talks

55  
00:02:30,900 --> 00:02:28,360  
you'll fly in this and we have our list

56  
00:02:34,080 --> 00:02:30,910  
of our upcoming links to our live and

57  
00:02:38,339 --> 00:02:34,090  
our archives as well as our email list

58  
00:02:39,930 --> 00:02:38,349  
server sign up that email will send you

59  
00:02:42,449 --> 00:02:39,940  
out announcements we send up by about

60  
00:02:46,500 --> 00:02:42,459  
two every month two or three a month so

61  
00:02:49,140 --> 00:02:46,510  
not not a huge crush on your inbox and

62  
00:02:50,699 --> 00:02:49,150  
we promise no spam if you have comments

63  
00:02:56,460 --> 00:02:50,709

or questions you can send them to this

64

00:02:59,190 --> 00:02:56,470

email public lecture at STScl edu social

65

00:03:01,530 --> 00:02:59,200

media for the Hubble Space Telescope for

66

00:03:03,300 --> 00:03:01,540

the James Webb Space Telescope and for

67

00:03:06,059 --> 00:03:03,310

the Space Telescope Science Institute on

68

00:03:08,640 --> 00:03:06,069

Facebook Twitter YouTube and Instagram

69

00:03:11,970 --> 00:03:08,650

I myself dabble a little bit in Facebook

70

00:03:15,750 --> 00:03:11,980

Google+ and Twitter but not that much

71

00:03:17,729 --> 00:03:15,760

and tonight yes we have the observatory

72

00:03:20,400 --> 00:03:17,739

it's clear enough tonight that we will

73

00:03:22,319 --> 00:03:20,410

be doing observing it's nice and cool so

74

00:03:24,870 --> 00:03:22,329

hopefully the air is nice and still and

75

00:03:25,800 --> 00:03:24,880

you have some beautiful seeing it's one

76

00:03:28,590 --> 00:03:25,810

of the unfortunate things about

77

00:03:34,170 --> 00:03:28,600

astronomy that the best nights for

78

00:03:34,740 --> 00:03:34,180

seeing freezing cold okay so bring some

79

00:03:38,330 --> 00:03:34,750

hot chocolate

80

00:03:41,670 --> 00:03:38,340

so ireenie will be here at the end and

81

00:03:43,860 --> 00:03:41,680

take people across the street will

82

00:03:46,319 --> 00:03:43,870

probably gathered over here on this side

83

00:03:49,050 --> 00:03:46,329

of the room at the end if I forget to

84

00:03:52,949 --> 00:03:49,060

announce it remind me or I'm sure arena

85

00:03:55,970 --> 00:03:52,959

will remind me and now our news from the

86

00:04:00,330 --> 00:03:55,980

universe for December 2018

87

00:04:03,360 --> 00:04:00,340

our first story a stellar hazmat warning

88

00:04:05,009 --> 00:04:03,370

and I told you guys within the while we

89

00:04:08,129 --> 00:04:05,019

were vamping that osiris-rex was a

90

00:04:09,750 --> 00:04:08,139

tortured acronym hazmat is a slightly

91

00:04:12,240 --> 00:04:09,760

tortured acronym too and I'll get to

92

00:04:15,000 --> 00:04:12,250

that in a minute but let's start with

93

00:04:16,920 --> 00:04:15,010

the hertzsprung-russell diagram how do

94

00:04:19,800 --> 00:04:16,930

you take an astronomy 101 and know the

95

00:04:21,330 --> 00:04:19,810

hertzsprung-russell diagram how many are

96

00:04:25,210 --> 00:04:21,340

going oh my gosh is he gonna give a

97

00:04:27,910 --> 00:04:25,220

lecture now here alright okay class

98

00:04:28,600 --> 00:04:27,920

the hearts no I don't need you to

99

00:04:31,120 --> 00:04:28,610

understand the hertzsprung-russell

100

00:04:33,880 --> 00:04:31,130

diagram except to recognize that this is

101  
00:04:35,740 --> 00:04:33,890  
how astronomers organize all the various

102  
00:04:37,720 --> 00:04:35,750  
stars in the universe okay

103  
00:04:40,810 --> 00:04:37,730  
it's got temperature on one axis and

104  
00:04:43,060 --> 00:04:40,820  
luminosity on the y-axis and the

105  
00:04:45,370 --> 00:04:43,070  
important thing here is that the

106  
00:04:47,290 --> 00:04:45,380  
brightest stars the most luminous stars

107  
00:04:49,270 --> 00:04:47,300  
are up on the left and there's this

108  
00:04:51,190 --> 00:04:49,280  
diagonal track leading down to the lower

109  
00:04:56,020 --> 00:04:51,200  
right which we call the main sequence

110  
00:04:58,810 --> 00:04:56,030  
and the most luminous stars are few and

111  
00:05:01,000 --> 00:04:58,820  
far between whereas the least luminous

112  
00:05:04,390 --> 00:05:01,010  
stars the red dwarfs in the lower right

113  
00:05:06,280 --> 00:05:04,400

are all over the place okay the meek

114

00:05:09,040 --> 00:05:06,290

have already inherited the cosmos

115

00:05:12,310 --> 00:05:09,050

because there are so many more red

116

00:05:16,030 --> 00:05:12,320

dwarfs than there are blue giant stars

117

00:05:18,490 --> 00:05:16,040

okay and so the red dwarf stars the ones

118

00:05:20,650 --> 00:05:18,500

in the lower right the the red ones the

119

00:05:23,050 --> 00:05:20,660

the low luminosity ones the low

120

00:05:25,990 --> 00:05:23,060

temperature ones they are actually

121

00:05:29,650 --> 00:05:26,000

extremely important because they are the

122

00:05:31,300 --> 00:05:29,660

most numerous stars in the universe so

123

00:05:33,900 --> 00:05:31,310

if you're going to be looking for

124

00:05:37,930 --> 00:05:33,910

planets and life in the universe

125

00:05:40,030 --> 00:05:37,940

they matter an awful lot okay another

126

00:05:44,469 --> 00:05:40,040

thing that matters about stars is that

127

00:05:47,140 --> 00:05:44,479

stars have energetic activity on them

128

00:05:49,510 --> 00:05:47,150

this is an ultraviolet light image of a

129

00:05:51,340 --> 00:05:49,520

solar prominence all right now many

130

00:05:53,920 --> 00:05:51,350

people mistake this and call this a

131

00:05:55,570 --> 00:05:53,930

solar flare it's not a solar flare it's

132

00:05:58,420 --> 00:05:55,580

a solar prominence and there's magnetic

133

00:06:00,370 --> 00:05:58,430

fields that are spewing all sorts of

134

00:06:02,710 --> 00:06:00,380

energy around on the surface of the Sun

135

00:06:05,710 --> 00:06:02,720

and there are things called solar flares

136

00:06:08,350 --> 00:06:05,720

they don't look like this they look like

137

00:06:11,920 --> 00:06:08,360

this and these are magnetic reconnection

138

00:06:14,830 --> 00:06:11,930

events that send out tremendous amounts

139

00:06:16,450 --> 00:06:14,840

of energy across our solar system we

140

00:06:18,219 --> 00:06:16,460

also have things called coronal mass

141

00:06:20,650 --> 00:06:18,229

ejections that send particles of high

142

00:06:23,860 --> 00:06:20,660

energies and we have what we call in our

143

00:06:25,600 --> 00:06:23,870

solar system space weather and a lot of

144

00:06:28,390 --> 00:06:25,610

some of our satellites are out there to

145

00:06:30,730 --> 00:06:28,400

monitor the space weather and you may

146

00:06:32,140 --> 00:06:30,740

have heard that sometimes when one of

147

00:06:34,450 --> 00:06:32,150

these coronal mass ejections or

148

00:06:36,640 --> 00:06:34,460

something is sent in the direction of

149

00:06:37,920 --> 00:06:36,650

Earth it hits our magnetic field and

150

00:06:39,779 --> 00:06:37,930

sometimes

151

00:06:43,590 --> 00:06:39,789

disrupt our communication satellites

152

00:06:47,249 --> 00:06:43,600

okay or if the astronauts are up in the

153

00:06:49,529 --> 00:06:47,259

and the space station they need to get

154

00:06:51,350 --> 00:06:49,539

inside and protect themselves okay when

155

00:06:55,800 --> 00:06:51,360

one of these solar storms commits

156

00:06:58,560 --> 00:06:55,810

however that's just for a Sun sized star

157

00:07:02,129 --> 00:06:58,570

and the Sun is a medium-sized star these

158

00:07:06,080 --> 00:07:02,139

small stars these red dwarf stars can

159

00:07:10,260 --> 00:07:06,090

have much more energetic activity and

160

00:07:13,920 --> 00:07:10,270

that is when we get to hazmat so this is

161

00:07:16,589 --> 00:07:13,930

a study habitable zones and m-dwarf

162

00:07:20,249 --> 00:07:16,599

activity over time can you see how you

163

00:07:22,920 --> 00:07:20,259

get hazmat out of that yeah okay

164

00:07:26,100 --> 00:07:22,930

but the acronym is actually appropriate

165

00:07:28,740 --> 00:07:26,110

because they're studying how volatile

166

00:07:32,159 --> 00:07:28,750

these M Dwarfs the red dwarf stars are

167

00:07:34,469 --> 00:07:32,169

and could they affect the planets

168

00:07:36,749 --> 00:07:34,479

forming around them and perhaps life

169

00:07:38,790 --> 00:07:36,759

forming on those planets and what's

170

00:07:40,589 --> 00:07:38,800

important is to take a look at stars at

171

00:07:42,629 --> 00:07:40,599

different ages this is the activity over

172

00:07:44,909 --> 00:07:42,639

time part of it okay looking at you know

173

00:07:46,680 --> 00:07:44,919

billion year old red dwarfs versus you

174

00:07:48,629 --> 00:07:46,690

know a few hundred million years old

175

00:07:51,810 --> 00:07:48,639

versus tens of millions of year old red

176

00:07:53,820 --> 00:07:51,820

dwarfs okay and what they found in this

177

00:07:56,550 --> 00:07:53,830

study and they basically these solar

178

00:07:57,960 --> 00:07:56,560

flares occur are easiest to see in

179

00:08:00,719 --> 00:07:57,970

ultraviolet so well that's why you need

180

00:08:02,399 --> 00:08:00,729

Hubble to do this because Hubble being

181

00:08:04,860 --> 00:08:02,409

above our atmosphere can see the

182

00:08:08,249 --> 00:08:04,870

ultraviolet light and they looked at a

183

00:08:11,969 --> 00:08:08,259

population of 40 million year old stars

184

00:08:13,439 --> 00:08:11,979

and a 40 million years old is old' for

185

00:08:18,029 --> 00:08:13,449

you and me but it's young for a star

186

00:08:21,719 --> 00:08:18,039

these are just born stars and the energy

187

00:08:25,350 --> 00:08:21,729

in the solar flares was one hundred to a

188

00:08:27,659 --> 00:08:25,360

thousand times stronger than it was for

189

00:08:30,870 --> 00:08:27,669

the billion year old stars the old stars

190

00:08:34,459 --> 00:08:30,880

so there's a lot more energy happening

191

00:08:37,430 --> 00:08:34,469

and this has interesting implementation

192

00:08:42,230 --> 00:08:37,440

implications for planets formation

193

00:08:44,550 --> 00:08:42,240

because at 40 million years that's when

194

00:08:47,130 --> 00:08:44,560

earth sized planets will be forming

195

00:08:50,930 --> 00:08:47,140

terrestrial planets will be forming so

196

00:08:54,950 --> 00:08:50,940

these impor stars the most new

197

00:08:57,410 --> 00:08:54,960

stars the universe have a energetic she

198

00:09:00,170 --> 00:08:57,420

appeared to be very energetic just at

199

00:09:02,330 --> 00:09:00,180

the time that planets are forming so if

200

00:09:05,480 --> 00:09:02,340

you want to form life on them

201  
00:09:08,320 --> 00:09:05,490  
could these m-dwarf act does could this

202  
00:09:11,750 --> 00:09:08,330  
end dwarf activity be effectively hasmat

203  
00:09:15,920 --> 00:09:11,760  
could they interfere with the formation

204  
00:09:19,040 --> 00:09:15,930  
of life on these planets and this is not

205  
00:09:21,350 --> 00:09:19,050  
a conclusive study in terms of that

206  
00:09:24,170 --> 00:09:21,360  
actually does or does not but it shows

207  
00:09:26,810 --> 00:09:24,180  
that we have to not only think about how

208  
00:09:29,360 --> 00:09:26,820  
we form these planets around a star but

209  
00:09:31,820 --> 00:09:29,370  
we also have to think about the activity

210  
00:09:34,100 --> 00:09:31,830  
of the star itself while those planets

211  
00:09:36,620 --> 00:09:34,110  
are forming so this is a interesting

212  
00:09:39,260 --> 00:09:36,630  
study that will I'm sure we followed up

213  
00:09:41,570 --> 00:09:39,270

much further in the future trying to

214

00:09:43,370 --> 00:09:41,580

look and understand you know this whole

215

00:09:47,560 --> 00:09:43,380

process of plant information that you

216

00:09:50,570 --> 00:09:47,570

know we are still still you know just

217

00:09:52,670 --> 00:09:50,580

really you know if this is so exciting

218

00:09:56,780 --> 00:09:52,680

how much we're learning about this

219

00:10:02,150 --> 00:09:56,790

process as we go on alright our second

220

00:10:03,950 --> 00:10:02,160

story is the ghost of Cassiopeia this is

221

00:10:06,590 --> 00:10:03,960

the constellation of Cassiopeia and this

222

00:10:08,930 --> 00:10:06,600

beautiful image from Akira Fuji II it's

223

00:10:12,200 --> 00:10:08,940

that W you see in the center there okay

224

00:10:14,030 --> 00:10:12,210

and a Cassiopeia is a wonderful

225

00:10:15,590 --> 00:10:14,040

constellation for those of us in the

226

00:10:18,320 --> 00:10:15,600

northern hemisphere because it's

227

00:10:20,540 --> 00:10:18,330

circumpolar it's always around the North

228

00:10:22,970 --> 00:10:20,550

Pole and goes just circles around the

229

00:10:24,800 --> 00:10:22,980

North Pole so most of the times most

230

00:10:28,040 --> 00:10:24,810

times the year you can find Cassiopeia

231

00:10:31,100 --> 00:10:28,050

on the night sky and find that W and

232

00:10:35,350 --> 00:10:31,110

that Center star in the W is known as

233

00:10:38,260 --> 00:10:35,360

gamma Cassiopeia and gamma Cassiopeia is

234

00:10:42,770 --> 00:10:38,270

illuminating some of the gas around it

235

00:10:46,579 --> 00:10:42,780

that sort of the the faint red blotch on

236

00:10:48,620 --> 00:10:46,589

the left is called IC 59 and that bright

237

00:10:53,000 --> 00:10:48,630

one down bottom that looks sort of like

238

00:10:54,170 --> 00:10:53,010

a mountain that is IC 63 this is a

239

00:10:56,480 --> 00:10:54,180

wonderful image from the

240

00:10:58,790 --> 00:10:56,490

astrophotographer robert Gendler and you

241

00:11:02,600 --> 00:10:58,800

can see that the sort of the mountain in

242

00:11:03,740 --> 00:11:02,610

IC 63 is pointed toward gamma casts all

243

00:11:04,519 --> 00:11:03,750

right that shows that it's the

244

00:11:06,169 --> 00:11:04,529

ultraviolet

245

00:11:08,569 --> 00:11:06,179

the energy from gamma cos that's

246

00:11:11,749 --> 00:11:08,579

sculpting that gas that's blowing away

247

00:11:12,919 --> 00:11:11,759

the low-density gas and ionizing the gas

248

00:11:16,999 --> 00:11:12,929

to make it glow

249

00:11:20,059 --> 00:11:17,009

and Hubble does various pretty picture

250

00:11:22,339 --> 00:11:20,069

release images and when we did our

251  
00:11:24,049 --> 00:11:22,349  
pretty picture release image going

252  
00:11:25,639 --> 00:11:24,059  
through the various pretty pictures they

253  
00:11:28,339 --> 00:11:25,649  
thought that this looked like a ghost

254  
00:11:35,679 --> 00:11:28,349  
and so we released for Halloween a

255  
00:11:38,269 --> 00:11:35,689  
picture of the ghost of Cassiopeia I

256  
00:11:39,889 --> 00:11:38,279  
looks more like a hooded shroud or

257  
00:11:41,479 --> 00:11:39,899  
something like this but it it's really

258  
00:11:43,849 --> 00:11:41,489  
kind of cool so this is this is what

259  
00:11:45,679 --> 00:11:43,859  
they called the ghost of Cassiopeia not

260  
00:11:47,629 --> 00:11:45,689  
to be confused with the ghost nebula or

261  
00:11:48,709 --> 00:11:47,639  
the little ghost nebula or like three

262  
00:11:50,869 --> 00:11:48,719  
other things that are called ghost

263  
00:11:52,369 --> 00:11:50,879

nebula type things but they nicknamed

264

00:11:55,129 --> 00:11:52,379

this the ghost of Cassiopeia

265

00:11:59,779 --> 00:11:55,139

we took this light invisible we also

266

00:12:02,329 --> 00:11:59,789

took a image in infrared light and to

267

00:12:04,639 --> 00:12:02,339

give it that really spooky feel we

268

00:12:08,659 --> 00:12:04,649

created an animated gif that goes back

269

00:12:10,819 --> 00:12:08,669

from visible to infrared and that was a

270

00:12:14,599 --> 00:12:10,829

sort of a Halloween pretty picture

271

00:12:20,210 --> 00:12:14,609

release the ghost of Cassiopeia and

272

00:12:22,069 --> 00:12:20,220

that's our news for this evening now we

273

00:12:32,239 --> 00:12:22,079

go to our main speaker of the night and

274

00:12:34,129 --> 00:12:32,249

our main speaker tonight is get there

275

00:12:36,799 --> 00:12:34,139

yes okay

276

00:12:40,460 --> 00:12:36,809

our speaker tonight is dr. Mark

277

00:12:42,289 --> 00:12:40,470

kamionkowski whom I had the extensive

278

00:12:45,829 --> 00:12:42,299

pleasure of working with up at Columbia

279

00:12:47,419 --> 00:12:45,839

University I was a postdoc working at

280

00:12:49,129 --> 00:12:47,429

Columbia half time at Columbia and half

281

00:12:53,029 --> 00:12:49,139

time at the American Natural History

282

00:12:57,589 --> 00:12:53,039

when Mark was up at Columbia he did his

283

00:13:00,259 --> 00:12:57,599

degree at Caltech and didn't Chicago

284

00:13:02,229 --> 00:13:00,269

right all right I thought I'd confirmed

285

00:13:08,959 --> 00:13:02,239

it was Caltech I'm wrong okay

286

00:13:11,719 --> 00:13:08,969

sorry at Chicago and then went to

287

00:13:13,519 --> 00:13:11,729

Columbia and after a few years he missed

288

00:13:15,470 --> 00:13:13,529

me so much he decided he'd come down to

289

00:13:17,420 --> 00:13:15,480

Johns Hopkins not quite

290

00:13:18,500 --> 00:13:17,430

who he came down he's in the department

291

00:13:21,550 --> 00:13:18,510

across the street at Johns Hopkins

292

00:13:26,480 --> 00:13:21,560

University he is one of the celebrated

293

00:13:28,670 --> 00:13:26,490

cosmologists and a real big expert on

294

00:13:30,020 --> 00:13:28,680

the Cosmic Microwave Background but he's

295

00:13:32,390 --> 00:13:30,030

not going to talk to you that about that

296

00:13:34,730 --> 00:13:32,400

tonight instead he's going to talk about

297

00:13:36,890 --> 00:13:34,740

cosmic ripples from black holes and the

298

00:13:56,590 --> 00:13:36,900

Big Bang ladies and gentlemen dr. Mark

299

00:14:03,380 --> 00:14:00,410

so today I'm going to talk to you about

300

00:14:05,630 --> 00:14:03,390

dark matter but the story is actually

301  
00:14:07,640 --> 00:14:05,640  
going to begin with them the discovery

302  
00:14:12,170 --> 00:14:07,650  
of gravitational waves from a binary

303  
00:14:15,800 --> 00:14:12,180  
black hole system two years ago and this

304  
00:14:20,690 --> 00:14:15,810  
is work that began in the cafeteria here

305  
00:14:22,250 --> 00:14:20,700  
in Asif Ron in January of 2016 the rumor

306  
00:14:24,350 --> 00:14:22,260  
started heating up in the astrophysics

307  
00:14:25,370 --> 00:14:24,360  
community that LIGO had detected

308  
00:14:26,690 --> 00:14:25,380  
something and there's gonna be an

309  
00:14:28,970 --> 00:14:26,700  
announcement it was going to be big and

310  
00:14:31,790 --> 00:14:28,980  
so I was sitting around the lunch table

311  
00:14:32,900 --> 00:14:31,800  
with some of my collaborators and we

312  
00:14:34,700 --> 00:14:32,910  
were thinking well we got to think of

313  
00:14:37,010 --> 00:14:34,710

something interesting to say because

314

00:14:39,530 --> 00:14:37,020

this is gonna be big and we started

315

00:14:42,080 --> 00:14:39,540

brainstorming and we came up with that

316

00:14:44,930 --> 00:14:42,090

most ridiculous ideas you can possibly

317

00:14:49,280 --> 00:14:44,940

imagine and at some point we came up

318

00:14:52,220 --> 00:14:49,290

with an idea that was ridiculous but not

319

00:14:55,370 --> 00:14:52,230

completely ridiculous and so we decided

320

00:14:58,100 --> 00:14:55,380

to write a paper and in brief and what

321

00:15:01,400 --> 00:14:58,110

I'll tell you over the next 40 minutes

322

00:15:03,230 --> 00:15:01,410

is that we simply postulated that the

323

00:15:05,780 --> 00:15:03,240

black holes that they discovered might

324

00:15:08,480 --> 00:15:05,790

actually be the dark matter that we have

325

00:15:11,390 --> 00:15:08,490

for a long time known to exist in the

326

00:15:14,960 --> 00:15:11,400

universe but we have no idea what it is

327

00:15:17,660 --> 00:15:14,970

and it was a crazy idea but as I said

328

00:15:20,390 --> 00:15:17,670

not completely crazy there was an

329

00:15:23,150 --> 00:15:20,400

interesting coincidence that popped up

330

00:15:25,190 --> 00:15:23,160

when we considered this possibility and

331

00:15:26,720 --> 00:15:25,200

so we wrote this paper and a lot of

332

00:15:30,370 --> 00:15:26,730

people found it interesting it's got a

333

00:15:34,699 --> 00:15:32,900

do black holes like the ones that like

334

00:15:37,430 --> 00:15:34,709

oh detective make up the dark matter as

335

00:15:39,379 --> 00:15:37,440

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

336

00:15:41,750 --> 00:15:39,389

ago I was fairly optimistic things have

337

00:15:46,250 --> 00:15:41,760

developed since then I'm a little less

338

00:15:48,560 --> 00:15:46,260

optimistic but the jury is still out so

339

00:15:50,900 --> 00:15:48,570

the title is cosmic ripples from the big

340

00:15:52,400 --> 00:15:50,910

from black holes in the Big Bang cosmic

341

00:15:54,379 --> 00:15:52,410

ripples refers to the gravitational

342

00:15:55,610 --> 00:15:54,389

waves I'll tell you about black holes

343

00:16:01,040 --> 00:15:55,620

were first two black holes in the Big

344

00:16:02,540 --> 00:16:01,050

Bang is the Big Bang please interrupt me

345

00:16:04,310 --> 00:16:02,550

if there are questions this is

346

00:16:06,110 --> 00:16:04,320

gravitational waves general relativity

347

00:16:08,150 --> 00:16:06,120

black holes dark matter it's not rocket

348

00:16:13,819 --> 00:16:08,160

science so everyone should be able to

349

00:16:19,370 --> 00:16:13,829

understand so the story begins February

350

00:16:21,620 --> 00:16:19,380

of 2016 there was a front-page article

351  
00:16:22,819 --> 00:16:21,630  
in The New York Times that pointed out

352  
00:16:24,740 --> 00:16:22,829  
the gravitational waves have been

353  
00:16:27,290 --> 00:16:24,750  
detected and it was a beautiful

354  
00:16:28,790 --> 00:16:27,300  
beautiful timing because I'm Albert

355  
00:16:31,579 --> 00:16:28,800  
Einstein realized that gravitational

356  
00:16:33,829 --> 00:16:31,589  
waves should exist almost a hundred

357  
00:16:35,840 --> 00:16:33,839  
years before we sort of put the

358  
00:16:38,809 --> 00:16:35,850  
finishing pieces of this theory of

359  
00:16:41,269 --> 00:16:38,819  
general relativity at the end of 2015

360  
00:16:43,699 --> 00:16:41,279  
and the gravitational wave signal was

361  
00:16:50,059 --> 00:16:43,709  
actually detected in September of 2015

362  
00:16:52,819 --> 00:16:50,069  
so very very nice coincidence this

363  
00:16:56,059 --> 00:16:52,829

discovery was absolutely spectacular

364

00:16:57,680 --> 00:16:56,069

there's nobody in science who was so

365

00:16:59,900 --> 00:16:57,690

jaded as to say out and detected

366

00:17:03,130 --> 00:16:59,910

gravitational waves what's the big deal

367

00:17:06,140 --> 00:17:03,140

actually there is a story I have to say

368

00:17:09,470 --> 00:17:06,150

so this was a huge discovery and there

369

00:17:11,179 --> 00:17:09,480

was a press conference online that that

370

00:17:14,390 --> 00:17:11,189

NASA was brought I'm sorry that the NSF

371

00:17:16,909 --> 00:17:14,400

was broadcasting and some people in the

372

00:17:19,309 --> 00:17:16,919

physics department had set up a seminar

373

00:17:20,720 --> 00:17:19,319

room like this one so we could play it

374

00:17:22,549 --> 00:17:20,730

on video and everyone can come and watch

375

00:17:24,919 --> 00:17:22,559

and some people sort of got doughnuts

376

00:17:27,620 --> 00:17:24,929

and coffee and we're milling about

377

00:17:29,390 --> 00:17:27,630

before the thing started and there were

378

00:17:31,220 --> 00:17:29,400

two undergraduate students walking by

379

00:17:33,200 --> 00:17:31,230

and one of them was hard to say the

380

00:17:34,850 --> 00:17:33,210

other one what's going on here and the

381

00:17:35,990 --> 00:17:34,860

only goes I don't know that this covered

382

00:17:41,060 --> 00:17:36,000

gravitational waves or something like

383

00:17:47,340 --> 00:17:43,590

anyway it was one of the quickest Nobel

384

00:17:49,080 --> 00:17:47,350

Prizes ever awarded these people also

385

00:17:50,760 --> 00:17:49,090

received the Gruber prize that catalyzed

386

00:17:53,789 --> 00:17:50,770

the sharp rise in the breakthrough prize

387

00:17:55,770 --> 00:17:53,799

any possible scientific recognition or

388

00:17:58,320 --> 00:17:55,780

honor that is available immediately went

389

00:18:03,750 --> 00:17:58,330

to the team that discovered these

390

00:18:08,430 --> 00:18:03,760

gravitational waves and as I said this

391

00:18:09,870 --> 00:18:08,440

phenomenon was sort of predicted by

392

00:18:12,570 --> 00:18:09,880

Albert Einstein's theory of general

393

00:18:16,320 --> 00:18:12,580

relativity and this goes back 100 years

394

00:18:18,630 --> 00:18:16,330

to 1915 and the basic idea of general

395

00:18:21,480 --> 00:18:18,640

relativity is the following equation and

396

00:18:24,630 --> 00:18:21,490

I'm always told that I shouldn't show

397

00:18:26,010 --> 00:18:24,640

equations in popular talks but I like to

398

00:18:27,990 --> 00:18:26,020

show equations because I'm a theoretical

399

00:18:30,360 --> 00:18:28,000

physicist this is really all I have I'm

400

00:18:32,070 --> 00:18:30,370

not in the survey tional strong I don't

401  
00:18:34,049 --> 00:18:32,080  
have pretty pictures of nebula and

402  
00:18:42,360 --> 00:18:34,059  
things like that this is the best I can

403  
00:18:44,010 --> 00:18:42,370  
do we're really proud of it but the

404  
00:18:47,580 --> 00:18:44,020  
point of an equation is that there's an

405  
00:18:48,990 --> 00:18:47,590  
equal sign in the middle there's

406  
00:18:51,330 --> 00:18:49,000  
something on the left and there's

407  
00:18:52,770 --> 00:18:51,340  
something on the right and the thing on

408  
00:18:54,840 --> 00:18:52,780  
the left is supposed to be the same as a

409  
00:18:56,399 --> 00:18:54,850  
thing on the right so this is known as

410  
00:18:58,680 --> 00:18:56,409  
Einstein's equation nine Stein wrote

411  
00:19:00,510 --> 00:18:58,690  
this down and this encapsulate the

412  
00:19:01,799 --> 00:19:00,520  
theory of general relativity and simple

413  
00:19:03,930 --> 00:19:01,809

and elegant because the thing on the

414

00:19:05,070 --> 00:19:03,940

left is a capital G with some Greek

415

00:19:07,020 --> 00:19:05,080

letters on there and the thing on the

416

00:19:08,789 --> 00:19:07,030

right is capital T and I remember I

417

00:19:11,100 --> 00:19:08,799

first learned this equation when I was a

418

00:19:14,370 --> 00:19:11,110

senior in college and I was taking a

419

00:19:16,529 --> 00:19:14,380

general relativity class and I passed by

420

00:19:20,070 --> 00:19:16,539

a professor I had for a quantum

421

00:19:21,149 --> 00:19:20,080

mechanics class and he said how's it

422

00:19:22,350 --> 00:19:21,159

going I was going great what are you

423

00:19:23,850 --> 00:19:22,360

taking I'm taking John Rolfe everies

424

00:19:25,710 --> 00:19:23,860

like what I think I said so simple and

425

00:19:27,659 --> 00:19:25,720

elegant you know G me nu equals team you

426

00:19:32,100 --> 00:19:27,669

know he goes yeah but what's G mu nu

427

00:19:33,690 --> 00:19:32,110

what's team you know yeah anyway this

428

00:19:36,690 --> 00:19:33,700

actually has a fairly simple

429

00:19:37,140 --> 00:19:36,700

interpretation G mu nu the thing on the

430

00:19:39,899 --> 00:19:37,150

left

431

00:19:42,200 --> 00:19:39,909

describes the curvature of space and

432

00:19:44,310 --> 00:19:42,210

space-time and the thing on the right

433

00:19:47,730 --> 00:19:44,320

describes the matter content of the

434

00:19:49,919 --> 00:19:47,740

universe and so this describes a picture

435

00:19:52,560 --> 00:19:49,929

that looks like this so according to

436

00:19:57,480 --> 00:19:52,570

general relativity space

437

00:19:59,549 --> 00:19:57,490

time can be bent and distorted and the

438

00:20:02,070 --> 00:19:59,559

distortion of space-time is given by the

439

00:20:04,919 --> 00:20:02,080

presence of massive objects so massive

440

00:20:06,960 --> 00:20:04,929

objects distort space-time and this

441

00:20:12,240 --> 00:20:06,970

equation tells you how that works

442

00:20:14,580 --> 00:20:12,250

the space-time curvature is related to

443

00:20:16,860 --> 00:20:14,590

the distribution of massive objects

444

00:20:19,590 --> 00:20:16,870

which is teeming of the matter content

445

00:20:21,779 --> 00:20:19,600

on the right hand side in words what

446

00:20:23,190 --> 00:20:21,789

this says is that space-time tells

447

00:20:25,470 --> 00:20:23,200

matter how to move and matter tells

448

00:20:27,960 --> 00:20:25,480

space-time how to move so the second

449

00:20:29,999 --> 00:20:27,970

thing I told you so matter tells the

450

00:20:32,100 --> 00:20:30,009

space-time how to curve and then the

451  
00:20:33,930 --> 00:20:32,110  
curvature of space-time tells you how

452  
00:20:37,019 --> 00:20:33,940  
objects move and I'll show you better

453  
00:20:39,149 --> 00:20:37,029  
pictures of this in a second but you

454  
00:20:40,860 --> 00:20:39,159  
know if someone was if a particle is

455  
00:20:42,360 --> 00:20:40,870  
gonna go along a straight line and this

456  
00:20:44,249 --> 00:20:42,370  
Crouch space-time it couldn't go along a

457  
00:20:46,619 --> 00:20:44,259  
straight line the trajectory is actually

458  
00:20:49,919 --> 00:20:46,629  
deflected if the space-time is curved if

459  
00:20:52,470 --> 00:20:49,929  
I take a very soft mattress and I put a

460  
00:20:54,119 --> 00:20:52,480  
very heavy bowling ball somewhere in the

461  
00:20:55,799 --> 00:20:54,129  
middle that sort of pushes that mattress

462  
00:20:58,049 --> 00:20:55,809  
down and then if I try to roll a

463  
00:20:59,970 --> 00:20:58,059

ping-pong ball PLAs that bowling ball

464

00:21:03,210 --> 00:20:59,980

the trajectory of the ping-pong ball

465

00:21:05,369 --> 00:21:03,220

will be deflected by the curvature in

466

00:21:09,060 --> 00:21:05,379

the mattress so that's basically what

467

00:21:10,560 --> 00:21:09,070

general relativity tells us space-time

468

00:21:13,049 --> 00:21:10,570

tells matter how to move and matter

469

00:21:15,919 --> 00:21:13,059

tells space-time how to curve that's the

470

00:21:19,560 --> 00:21:15,929

essence of Einstein's equation this was

471

00:21:22,440 --> 00:21:19,570

an incredible mathematical insight back

472

00:21:26,009 --> 00:21:22,450

in 1915 there was absolutely nothing in

473

00:21:29,070 --> 00:21:26,019

any that existed in physics before this

474

00:21:30,810 --> 00:21:29,080

to foreshadow this or to build up to it

475

00:21:31,230 --> 00:21:30,820

it sort of came out of absolutely

476

00:21:33,990 --> 00:21:31,240

nowhere

477

00:21:35,970 --> 00:21:34,000

but it turns out that the theory is

478

00:21:37,769 --> 00:21:35,980

correct then Albert Einstein actually

479

00:21:40,019 --> 00:21:37,779

realized that theory was correct almost

480

00:21:43,560 --> 00:21:40,029

immediately because there was one

481

00:21:45,450 --> 00:21:43,570

anomaly in planetary dynamics in 1915

482

00:21:47,759 --> 00:21:45,460

which was the perihelion advance of

483

00:21:49,830 --> 00:21:47,769

mercury so it turns out that Mercury's

484

00:21:51,720 --> 00:21:49,840

orbit around the Sun like that of most

485

00:21:54,450 --> 00:21:51,730

planets is not perfectly around it's

486

00:21:57,169 --> 00:21:54,460

actually elongated according to Newton's

487

00:22:00,240 --> 00:21:57,179

laws if according to inverse square law

488

00:22:02,909 --> 00:22:00,250

from note that Isaac Newton derived we

489

00:22:05,970 --> 00:22:02,919

wrote down you know back in the early

490

00:22:07,740 --> 00:22:05,980

1700s late 1600s

491

00:22:10,470 --> 00:22:07,750

these ellipses should close in on

492

00:22:12,360 --> 00:22:10,480

themselves but what was found is that

493

00:22:14,820 --> 00:22:12,370

Mercury's orbit does not close in on

494

00:22:16,799 --> 00:22:14,830

itself it sort of processes the it sort

495

00:22:18,840 --> 00:22:16,809

of the rotates around in this direction

496

00:22:20,520 --> 00:22:18,850

over here and it's a very tiny and

497

00:22:22,980 --> 00:22:20,530

subtle effect but hasn't been measured

498

00:22:25,380 --> 00:22:22,990

quite well to be two degrees per century

499

00:22:27,299 --> 00:22:25,390

and Albert Einstein realized that these

500

00:22:30,780 --> 00:22:27,309

equations that he wrote down could

501  
00:22:33,090 --> 00:22:30,790  
account for this perihelion advance and

502  
00:22:34,200 --> 00:22:33,100  
so there's a story that he couldn't

503  
00:22:35,610 --> 00:22:34,210  
sleep that night because he was so

504  
00:22:37,140 --> 00:22:35,620  
excited that he actually realized that

505  
00:22:37,620 --> 00:22:37,150  
this ridiculous equation that came out

506  
00:22:40,650 --> 00:22:37,630  
of nowhere

507  
00:22:44,400 --> 00:22:40,660  
was actually correct we also know it's

508  
00:22:46,110 --> 00:22:44,410  
like correct because of the existence of

509  
00:22:48,900 --> 00:22:46,120  
gravitational lensing or the bending of

510  
00:22:53,720 --> 00:22:48,910  
light and this was verified by a famous

511  
00:22:56,940 --> 00:22:53,730  
expedition by Sir Arthur Eddington 1919

512  
00:22:58,830 --> 00:22:56,950  
so it turns out that the gravitational

513  
00:23:01,799 --> 00:22:58,840

field of a massive object like the Sun

514

00:23:04,500 --> 00:23:01,809

will actually bend the trajectory of

515

00:23:06,030 --> 00:23:04,510

light so at you know if you send a light

516

00:23:07,650 --> 00:23:06,040

ray out mil know where the light ray

517

00:23:09,180 --> 00:23:07,660

goes straight but if you send a near

518

00:23:11,010 --> 00:23:09,190

massive object the gravitational field

519

00:23:13,230 --> 00:23:11,020

of that massive object will actually

520

00:23:14,580 --> 00:23:13,240

blend the trajectory of light and this

521

00:23:16,799 --> 00:23:14,590

is something that's difficult to

522

00:23:18,419 --> 00:23:16,809

actually verify because the Sun is so

523

00:23:20,940 --> 00:23:18,429

bright that you can't see the stars

524

00:23:22,890 --> 00:23:20,950

behind it but if there's an eclipse

525

00:23:24,960 --> 00:23:22,900

if the moon passes in front of the Sun

526

00:23:26,460 --> 00:23:24,970

then for a brief period of time you can

527

00:23:29,880 --> 00:23:26,470

actually see the stars behind the Sun

528

00:23:32,610 --> 00:23:29,890

and so Eddington verified this that the

529

00:23:38,880 --> 00:23:32,620

this deflection of light during a solar

530

00:23:40,950 --> 00:23:38,890

eclipse in 1919 so I think I said 1916

531

00:23:42,750 --> 00:23:40,960

very shortly after the original theory

532

00:23:45,270 --> 00:23:42,760

was proposed Einstein realized that the

533

00:23:48,840 --> 00:23:45,280

theory predicts the existence of

534

00:23:51,390 --> 00:23:48,850

gravitational waves and here's a movie

535

00:23:53,520 --> 00:23:51,400

that I will show you and I'll show you

536

00:23:55,320 --> 00:23:53,530

another version later on and the basic

537

00:23:57,780 --> 00:23:55,330

idea is that there is a gravitational

538

00:24:00,120 --> 00:23:57,790

field due to a mass of objects so if I

539

00:24:02,039 --> 00:24:00,130

have one planted over here that gives me

540

00:24:03,870 --> 00:24:02,049

a gravitational field if there's a

541

00:24:05,789 --> 00:24:03,880

second planted over here that also has a

542

00:24:07,440 --> 00:24:05,799

gravitational field and the

543

00:24:09,240 --> 00:24:07,450

gravitational field due to the presence

544

00:24:11,940 --> 00:24:09,250

of two planets is going to be the sum of

545

00:24:14,490 --> 00:24:11,950

that from this one and the Sun the sum

546

00:24:19,260 --> 00:24:14,500

and the gravitational field from here

547

00:24:21,060 --> 00:24:19,270

now if I have a binary star system  $5/2$

548

00:24:23,820 --> 00:24:21,070

stars that are gravitationally bound and

549

00:24:26,640 --> 00:24:23,830

spinning around each other or for

550

00:24:28,440 --> 00:24:26,650

example if I have a planet star system

551  
00:24:30,390 --> 00:24:28,450  
like the earth or the planet Jupiter

552  
00:24:32,270 --> 00:24:30,400  
spinning around the Sun I will have

553  
00:24:35,160 --> 00:24:32,280  
something that looks sort of like this

554  
00:24:37,050 --> 00:24:35,170  
now as those planets move around each

555  
00:24:38,400 --> 00:24:37,060  
other those stars or black holes or

556  
00:24:41,310 --> 00:24:38,410  
whatever the massive objects you have

557  
00:24:44,160 --> 00:24:41,320  
move around each other the gravitational

558  
00:24:49,440 --> 00:24:44,170  
field is going to change and so that's

559  
00:24:51,690 --> 00:24:49,450  
what we see over here so if I'm sitting

560  
00:24:55,260 --> 00:24:51,700  
over here the gravitational field that I

561  
00:24:57,090 --> 00:24:55,270  
see due to those two stars changes if

562  
00:24:58,800 --> 00:24:57,100  
you're looking at a pair of stars over

563  
00:25:00,060 --> 00:24:58,810

here you'll see one gravitational field

564

00:25:01,830 --> 00:25:00,070

if you see them over here to see a

565

00:25:03,570 --> 00:25:01,840

different gravitational field and as

566

00:25:06,300 --> 00:25:03,580

they spin around you will see a time

567

00:25:08,730 --> 00:25:06,310

varying gravitational field that time

568

00:25:10,860 --> 00:25:08,740

varying gravitational field propagates

569

00:25:16,350 --> 00:25:10,870

outward as a set of ripples in

570

00:25:19,500 --> 00:25:16,360

space-time so something like this maybe

571

00:25:22,620 --> 00:25:19,510

non-intuitive originally but it

572

00:25:26,100 --> 00:25:22,630

shouldn't be too non-intuitive the

573

00:25:31,080 --> 00:25:26,110

surface of a pond if it still is very

574

00:25:33,150 --> 00:25:31,090

flat and peaceful and calm but it can

575

00:25:35,970 --> 00:25:33,160

bob up and down and if I drop something

576

00:25:37,830 --> 00:25:35,980

in the middle of this pond that

577

00:25:41,130 --> 00:25:37,840

disturbance will propagate out as a

578

00:25:43,940 --> 00:25:41,140

series of waves and suppose I have a toy

579

00:25:47,670 --> 00:25:43,950

boat sitting at the edge of the pond

580

00:25:49,710 --> 00:25:47,680

these waves will propagate out and the

581

00:25:51,450 --> 00:25:49,720

toy boat will be sitting there still but

582

00:25:53,130 --> 00:25:51,460

at some point the waves will pass by and

583

00:25:57,570 --> 00:25:53,140

that toy boat will start to bounce up

584

00:26:01,860 --> 00:25:57,580

and down so if I move the fluid over

585

00:26:03,660 --> 00:26:01,870

here somehow those waves propagate out

586

00:26:07,140 --> 00:26:03,670

and they are detected because they then

587

00:26:12,030 --> 00:26:07,150

induce motion in some test object like

588

00:26:16,080 --> 00:26:12,040

this toy boat a large distance if I have

589

00:26:18,870 --> 00:26:16,090

a tight string and I shake it and they

590

00:26:20,760 --> 00:26:18,880

disturb it on one end that disturbance

591

00:26:23,340 --> 00:26:20,770

will propagate out in this direction as

592

00:26:26,760 --> 00:26:23,350

a wave and suppose I have some beads on

593

00:26:29,070 --> 00:26:26,770

the string at the other end those beads

594

00:26:32,600 --> 00:26:29,080

will start to move up and down as the

595

00:26:34,520 --> 00:26:32,610

wave encounters them so again a

596

00:26:37,280 --> 00:26:34,530

string is a medium that can carry

597

00:26:39,049 --> 00:26:37,290

wave-like motions or carry waves and the

598

00:26:40,669 --> 00:26:39,059

way I induce those waves is by shaking

599

00:26:42,440 --> 00:26:40,679

the string up and down and the way I

600

00:26:44,960 --> 00:26:42,450

detect those waves is through the

601  
00:26:50,600 --> 00:26:44,970  
motions that those wave induce in a set

602  
00:26:53,780 --> 00:26:50,610  
of test masses the same thing is true

603  
00:26:57,530 --> 00:26:53,790  
for radio waves does anybody actually

604  
00:26:58,640 --> 00:26:57,540  
listen to the radio anymore okay back in

605  
00:27:00,289 --> 00:26:58,650  
the old days there was something in your

606  
00:27:04,039 --> 00:27:00,299  
car called the radio you could turn it

607  
00:27:06,289 --> 00:27:04,049  
on and the way the radio works is that

608  
00:27:08,659 --> 00:27:06,299  
there is a transmitter you see them for

609  
00:27:11,840 --> 00:27:08,669  
example in TV tower and roughly speaking

610  
00:27:14,750 --> 00:27:11,850  
there are a bunch of electrons and each

611  
00:27:16,370 --> 00:27:14,760  
electron when it Wiggles sends out

612  
00:27:18,409 --> 00:27:16,380  
electromagnetic wave and the way I

613  
00:27:21,140 --> 00:27:18,419

detect that is that if I have an antenna

614

00:27:24,289 --> 00:27:21,150

like in my car the wave is it hits the

615

00:27:28,010 --> 00:27:24,299

antenna sets free electrons into motion

616

00:27:33,409 --> 00:27:28,020

and then you know your receiver detects

617

00:27:37,250 --> 00:27:33,419

and amplifies those motions there's one

618

00:27:41,600 --> 00:27:37,260

more example usually we think of the

619

00:27:43,430 --> 00:27:41,610

ground as rigid and fixed you don't

620

00:27:48,140 --> 00:27:43,440

think of the ground is shaking and

621

00:27:49,880 --> 00:27:48,150

moving around on California you do but

622

00:27:51,620 --> 00:27:49,890

you know here you generally think well

623

00:27:52,970 --> 00:27:51,630

the ground is fixed I can walk across

624

00:27:55,070 --> 00:27:52,980

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

625

00:27:57,289 --> 00:27:55,080

to move but you've all set been sitting

626

00:28:00,020 --> 00:27:57,299

at home at some time when a very heavy

627

00:28:01,909 --> 00:28:00,030

truck rolls by and on a bumpy road that

628

00:28:04,130 --> 00:28:01,919

heavy truck bounces up and down and you

629

00:28:06,020 --> 00:28:04,140

can feel the shaking in your house so

630

00:28:08,419 --> 00:28:06,030

although the ground is seems to be very

631

00:28:10,190 --> 00:28:08,429

rigid in fact it's not perfectly rigid

632

00:28:12,190 --> 00:28:10,200

and if you have something that's

633

00:28:15,080 --> 00:28:12,200

officially massive that starts shaking

634

00:28:17,180 --> 00:28:15,090

the ground will transmit waves and you

635

00:28:19,430 --> 00:28:17,190

will then feel them since the ground is

636

00:28:21,110 --> 00:28:19,440

so rigid that thing has to be really

637

00:28:22,850 --> 00:28:21,120

heavy to actually shake the ground and

638

00:28:24,500 --> 00:28:22,860

when the ground does shake it doesn't

639

00:28:26,780 --> 00:28:24,510

shrink a whole lot you feel a slight

640

00:28:30,169 --> 00:28:26,790

tremor but it's not a huge thing it

641

00:28:32,960 --> 00:28:30,179

turns out as Albert Einstein predicted

642

00:28:34,640 --> 00:28:32,970

and as we now know due to all these

643

00:28:38,480 --> 00:28:34,650

experimental verifications of general

644

00:28:40,400 --> 00:28:38,490

relativity that space-time which we

645

00:28:44,120 --> 00:28:40,410

always think of intuitively is being

646

00:28:46,110 --> 00:28:44,130

perfectly rigid you know every position

647

00:28:48,990 --> 00:28:46,120

in this room can be specified

648

00:28:52,320 --> 00:28:49,000

by three numbers a cart you know the

649

00:28:54,029 --> 00:28:52,330

numbers on a Cartesian grid the position

650

00:28:55,289 --> 00:28:54,039

in that direction the position in that

651  
00:28:57,529 --> 00:28:55,299  
direction and the position in that

652  
00:29:01,320 --> 00:28:57,539  
direction and we always in physics

653  
00:29:04,380 --> 00:29:01,330  
imagine a lattice that represents you

654  
00:29:09,120 --> 00:29:04,390  
know points in this direction  $x$  equals 1

655  
00:29:10,919 --> 00:29:09,130  
2 3 4  $y$  equals 1 2 3 4  $z$  equals 1 2 3 4

656  
00:29:12,360 --> 00:29:10,929  
and the location of anything or anybody

657  
00:29:15,320 --> 00:29:12,370  
in this room can be represented in terms

658  
00:29:17,519 --> 00:29:15,330  
of those three numbers so space in

659  
00:29:20,279 --> 00:29:17,529  
space-time we would always think of as

660  
00:29:22,799 --> 00:29:20,289  
being very rigid but as it turns out

661  
00:29:25,649 --> 00:29:22,809  
that space-time is extremely rigid but

662  
00:29:27,480 --> 00:29:25,659  
it's not perfectly rigid and if there

663  
00:29:29,039 --> 00:29:27,490

are massive objects they can curve the

664

00:29:31,080 --> 00:29:29,049

space-time and if you shake those

665

00:29:33,210 --> 00:29:31,090

massive objects those will shake the

666

00:29:36,240 --> 00:29:33,220

space-time and if the space-time shakes

667

00:29:41,630 --> 00:29:36,250

we'll feel it things will start to move

668

00:29:46,889 --> 00:29:41,640

around so this was all pretty much

669

00:29:51,180 --> 00:29:46,899

theoretical expectation until a few

670

00:29:59,000 --> 00:29:51,190

years ago so in 1916 these gravitational

671

00:30:01,620 --> 00:29:59,010

waves were predicted waves carry energy

672

00:30:03,840 --> 00:30:01,630

when the truck drives by and starts

673

00:30:05,610 --> 00:30:03,850

shaking if you're sitting there and your

674

00:30:08,430 --> 00:30:05,620

chairs start shaking there's energy in

675

00:30:11,100 --> 00:30:08,440

that motion so how to get there well the

676  
00:30:14,279 --> 00:30:11,110  
medium the grounds carried the energy

677  
00:30:16,139 --> 00:30:14,289  
from the truck over to you so likewise

678  
00:30:20,039 --> 00:30:16,149  
gravitational waves can also carry

679  
00:30:27,029 --> 00:30:20,049  
energy they propagate at the speed of

680  
00:30:29,669 --> 00:30:27,039  
light they were detected indirectly back

681  
00:30:32,610 --> 00:30:29,679  
in 9th in the early 70s and it was a

682  
00:30:34,380 --> 00:30:32,620  
Nobel Prize award in 1993 there was a

683  
00:30:37,440 --> 00:30:34,390  
system of two neutron stars neutron

684  
00:30:40,710 --> 00:30:37,450  
stars are very dense remnants of stars

685  
00:30:42,870 --> 00:30:40,720  
each one weighs 1.4 times the mass of

686  
00:30:44,430 --> 00:30:42,880  
the Sun and there are several binary

687  
00:30:45,960 --> 00:30:44,440  
pulsar systems that we know about which

688  
00:30:49,169 --> 00:30:45,970

are two neutron star spinning around

689

00:30:50,760 --> 00:30:49,179

each other and it was seen that in one

690

00:30:52,919 --> 00:30:50,770

particular system the two neutron stars

691

00:30:56,430 --> 00:30:52,929

were spinning around each other but they

692

00:30:59,299 --> 00:30:56,440

were spinning up the orbital period was

693

00:31:01,820 --> 00:30:59,309

shortening they were speeding up as they

694

00:31:04,190 --> 00:31:01,830

there seem to be speeding up which was

695

00:31:09,680 --> 00:31:04,200

interpreted as speeding up due to the

696

00:31:11,960 --> 00:31:09,690

emission of gravitational waves so the

697

00:31:13,700 --> 00:31:11,970

signal from these neutron stars gave us

698

00:31:15,739 --> 00:31:13,710

good evidence that the gravitational

699

00:31:17,600 --> 00:31:15,749

waves exist that they were being emitted

700

00:31:19,519 --> 00:31:17,610

from the spine or a neutron star system

701  
00:31:24,409 --> 00:31:19,529  
but no one are actually seen or detected

702  
00:31:26,419 --> 00:31:24,419  
a gravitational wave so how do we detect

703  
00:31:27,430 --> 00:31:26,429  
gravitational waves directly I told you

704  
00:31:32,149 --> 00:31:27,440  
already

705  
00:31:34,549 --> 00:31:32,159  
waves are detected by the motions they

706  
00:31:36,139 --> 00:31:34,559  
induce in some type of test masses radio

707  
00:31:39,649 --> 00:31:36,149  
waves are detected by the motions they

708  
00:31:41,299 --> 00:31:39,659  
induce an electrons the round waves are

709  
00:31:43,909 --> 00:31:41,309  
detected by the motions they induced in

710  
00:31:46,340 --> 00:31:43,919  
the chair that we're sitting on the toy

711  
00:31:49,940 --> 00:31:46,350  
boat is used to detect waves and

712  
00:31:52,850 --> 00:31:49,950  
otherwise still pond gravity effects

713  
00:31:54,919 --> 00:31:52,860

masses and so the way do we detect

714

00:31:56,899 --> 00:31:54,929

gravitational waves is through the

715

00:32:02,690 --> 00:31:56,909

characteristic motions they induce in a

716

00:32:09,190 --> 00:32:02,700

set of freely falling test masses so the

717

00:32:13,909 --> 00:32:11,779

this has scale in effect vastly

718

00:32:20,090 --> 00:32:13,919

exaggerated so I don't want to alarm

719

00:32:22,190 --> 00:32:20,100

anybody but they made a video of what it

720

00:32:23,869 --> 00:32:22,200

would look like if a very large

721

00:32:26,419 --> 00:32:23,879

amplitude gravitational wave were to

722

00:32:32,690 --> 00:32:26,429

pass through the earth and the video

723

00:32:34,820 --> 00:32:32,700

looks like this so this is a low

724

00:32:36,980 --> 00:32:34,830

amplitude gravitational wave and as

725

00:32:39,669 --> 00:32:36,990

we'll see the amplitude from a binary

726  
00:32:44,450 --> 00:32:39,679  
black hole mergers expected to increase

727  
00:32:46,009 --> 00:32:44,460  
and get faster so roughly speaking

728  
00:32:48,379 --> 00:32:46,019  
that's what's happening to the earth

729  
00:32:51,259 --> 00:32:48,389  
when a gravitational wave signal passes

730  
00:32:52,759 --> 00:32:51,269  
by the effect was greatly exaggerated

731  
00:32:58,759 --> 00:32:52,769  
they actually up to the effect is off

732  
00:33:02,539 --> 00:32:58,769  
one part in trillion trillion pretty

733  
00:33:04,779 --> 00:33:02,549  
small so in practice as I said the

734  
00:33:09,019 --> 00:33:04,789  
motions are getting extremely tiny and

735  
00:33:12,680 --> 00:33:09,029  
so what was done was something called

736  
00:33:16,160 --> 00:33:12,690  
laser interferometry and so

737  
00:33:17,630 --> 00:33:16,170  
what happens is the one of the

738  
00:33:18,890 --> 00:33:17,640

characteristics of a gravitational wave

739

00:33:22,340 --> 00:33:18,900

is that if we have a gravitational wave

740

00:33:27,230 --> 00:33:22,350

propagating down but in a direction

741

00:33:29,180 --> 00:33:27,240

perpendicular to this plane the masses

742

00:33:31,310 --> 00:33:29,190

in this direction will get stretched out

743

00:33:34,550 --> 00:33:31,320

while the masses in this direction will

744

00:33:37,640 --> 00:33:34,560

get stretched inward and so what was

745

00:33:40,100 --> 00:33:37,650

people thought to do is to send a beam

746

00:33:42,200 --> 00:33:40,110

of light a laser signal through a

747

00:33:44,180 --> 00:33:42,210

half-silvered mirror that then splits

748

00:33:46,820 --> 00:33:44,190

the beam so that one beam goes towards

749

00:33:48,740 --> 00:33:46,830

this mirror over here and another beam

750

00:33:50,180 --> 00:33:48,750

goes toward this mirror over here the

751  
00:33:52,280 --> 00:33:50,190  
two beams then bounce back are

752  
00:33:58,250 --> 00:33:52,290  
recombined and then come back over here

753  
00:34:01,040 --> 00:33:58,260  
and since light is a wave when these two

754  
00:34:04,460 --> 00:34:01,050  
waves are recombined they can either add

755  
00:34:07,370 --> 00:34:04,470  
coherently or they can add destructively

756  
00:34:09,320 --> 00:34:07,380  
and if they add coherently the light

757  
00:34:11,180 --> 00:34:09,330  
signal that's received over here is

758  
00:34:13,700 --> 00:34:11,190  
stronger if they are destructively the

759  
00:34:15,530 --> 00:34:13,710  
light signal over here is weakened so

760  
00:34:20,090 --> 00:34:15,540  
again the LIGO people made a very nice

761  
00:34:21,650 --> 00:34:20,100  
movie of this which I can show you so

762  
00:34:24,200 --> 00:34:21,660  
there is the beam that gets split

763  
00:34:28,880 --> 00:34:24,210

bounces back it comes back towards the

764

00:34:30,890 --> 00:34:28,890

detector and as these mirrors shake the

765

00:34:35,000 --> 00:34:30,900

light that's received in the detector is

766

00:34:37,100 --> 00:34:35,010

either brighter or weaker and the reason

767

00:34:41,720 --> 00:34:37,110

that happens is that each of these light

768

00:34:43,760 --> 00:34:41,730

rays is actually a wave and if the

769

00:34:45,490 --> 00:34:43,770

spacing between these two different arms

770

00:34:49,520 --> 00:34:45,500

is just right those two waves will add

771

00:34:51,440 --> 00:34:49,530

destructively and as the masses move

772

00:34:54,260 --> 00:34:51,450

around as the lengths in these two arms

773

00:34:56,420 --> 00:34:54,270

change what was otherwise the

774

00:34:58,910 --> 00:34:56,430

destructive interference might become a

775

00:35:02,030 --> 00:34:58,920

constructive interference and then the

776

00:35:03,710 --> 00:35:02,040

beam gets brighter so they have an

777

00:35:07,400 --> 00:35:03,720

interferometer that looks like this and

778

00:35:13,520 --> 00:35:07,410

what they look for is variable light

779

00:35:15,020 --> 00:35:13,530

brightness at that detector I am told

780

00:35:17,660 --> 00:35:15,030

that this is the most precise

781

00:35:20,050 --> 00:35:17,670

measurement ever made by a pretty wide

782

00:35:22,300 --> 00:35:20,060

stretch it was 40 years in the making

783

00:35:25,990 --> 00:35:22,310

from the time from the initial proposal

784

00:35:29,680 --> 00:35:26,000

so the detection was roughly 40 years

785

00:35:32,650 --> 00:35:29,690

technology development and science the

786

00:35:34,420 --> 00:35:32,660

detection was made by a collaboration an

787

00:35:36,730 --> 00:35:34,430

American collaboration LIGO they also

788

00:35:39,070 --> 00:35:36,740

used results from Burgo although they

789

00:35:41,500 --> 00:35:39,080

were not results which is a European

790

00:35:43,270 --> 00:35:41,510

collaboration there's a British German

791

00:35:45,760 --> 00:35:43,280

interferometer that's being built called

792

00:35:48,400 --> 00:35:45,770

Geo there's a Japanese interferometer

793

00:35:50,500 --> 00:35:48,410

being built Altima one in Australia and

794

00:35:52,900 --> 00:35:50,510

there's also one being built in India

795

00:35:54,700 --> 00:35:52,910

now but the original detection was by

796

00:35:56,380 --> 00:35:54,710

LIGO and in the future we're going to

797

00:35:59,680 --> 00:35:56,390

have networks of gravitational wave

798

00:36:02,290 --> 00:35:59,690

detectors all working together so LIGO

799

00:36:04,570 --> 00:36:02,300

stands for laser interferometer gravity

800

00:36:06,490 --> 00:36:04,580

wave observatory this is roughly

801  
00:36:08,950 --> 00:36:06,500  
speaking a billion dollars of taxpayer

802  
00:36:12,970 --> 00:36:08,960  
money very well spent it is the biggest

803  
00:36:14,830 --> 00:36:12,980  
NSF investment in single investment by a

804  
00:36:16,510 --> 00:36:14,840  
wide margin

805  
00:36:18,760 --> 00:36:16,520  
it's a us-led project it does have

806  
00:36:22,270 --> 00:36:18,770  
international collaboration they have

807  
00:36:24,340 --> 00:36:22,280  
two detectors one is in Washington State

808  
00:36:26,260 --> 00:36:24,350  
and the other one is in Louisiana and

809  
00:36:28,210 --> 00:36:26,270  
the reason they have two detectors is

810  
00:36:30,700 --> 00:36:28,220  
that if somebody told you they saw

811  
00:36:33,070 --> 00:36:30,710  
something go bump in the night you'd say

812  
00:36:35,460 --> 00:36:33,080  
what was that and see how if something

813  
00:36:38,710 --> 00:36:35,470

went bump in the night Oh interesting

814

00:36:41,170 --> 00:36:38,720

but if somebody in Louisiana also says

815

00:36:43,420 --> 00:36:41,180

hey something went bump in the night and

816

00:36:44,950 --> 00:36:43,430

you say well what time did it help go

817

00:36:49,690 --> 00:36:44,960

bump in the night well it happened

818

00:36:52,390 --> 00:36:49,700

precisely at 12:03 a.m. plus sixteen

819

00:36:55,540 --> 00:36:52,400

point four eight seconds and then the

820

00:36:58,240 --> 00:36:55,550

people in Washington say oh wow we saw

821

00:37:00,820 --> 00:36:58,250

the exact same bump in the night so they

822

00:37:01,990 --> 00:37:00,830

used the simultaneity to reject spurious

823

00:37:04,680 --> 00:37:02,000

signals because things are always

824

00:37:07,090 --> 00:37:04,690

happening that shake those masses around

825

00:37:10,630 --> 00:37:07,100

the length of the arms are four

826

00:37:15,250 --> 00:37:10,640

kilometers and although there's four

827

00:37:16,750 --> 00:37:15,260

kilometers between these mirrors what

828

00:37:18,550 --> 00:37:16,760

they detect are motions that are a

829

00:37:21,430 --> 00:37:18,560

fraction of the size of an atomic

830

00:37:23,920 --> 00:37:21,440

nucleus so this is a picture of the

831

00:37:27,490 --> 00:37:23,930

Livingston Observatory from the sky four

832

00:37:32,290 --> 00:37:27,500

kilometers and four kilometers this is a

833

00:37:34,510 --> 00:37:32,300

another picture another picture and here

834

00:37:37,120 --> 00:37:34,520

is the Hanford Observatory there are

835

00:37:38,110 --> 00:37:37,130

more or less identical there are subtle

836

00:37:39,820 --> 00:37:38,120

differences but the more or less

837

00:37:43,870 --> 00:37:39,830

identical to four

838

00:37:48,520 --> 00:37:43,880

in her arms and the motion that they

839

00:37:49,840 --> 00:37:48,530

detect is illustrated by this movie in

840

00:37:53,190 --> 00:37:49,850

which the LIGO collaboration also

841

00:37:55,630 --> 00:37:53,200

provided so this is an atomic this is a

842

00:37:59,290 --> 00:37:55,640

that would let me start again what you

843

00:38:04,900 --> 00:37:59,300

started with was an electron spinning

844

00:38:08,590 --> 00:38:04,910

around let me go back because this is

845

00:38:10,510 --> 00:38:08,600

absolutely astounding this is a movie of

846

00:38:17,380 --> 00:38:10,520

an electron spinning around an atomic

847

00:38:21,970 --> 00:38:17,390

nucleus so that's pretty small so there

848

00:38:25,300 --> 00:38:21,980

is the atom and then we zoom in to the

849

00:38:31,630 --> 00:38:25,310

atomic nucleus which is composed of a

850

00:38:34,270 --> 00:38:31,640

couple of protons and neutrons and what

851  
00:38:45,460 --> 00:38:34,280  
they actually detect is a motion of that

852  
00:38:47,940 --> 00:38:45,470  
magnitude so that is incredible this is

853  
00:38:54,670 --> 00:38:51,520  
so when I so I was a professor at

854  
00:38:56,470 --> 00:38:54,680  
Caltech for a while and my office was

855  
00:38:58,240 --> 00:38:56,480  
down the hall from the people working on

856  
00:38:59,650 --> 00:38:58,250  
this project and they're always like

857  
00:39:00,730 --> 00:38:59,660  
walking past my hall looking really busy

858  
00:39:02,770 --> 00:39:00,740  
because they were gonna detect

859  
00:39:03,700 --> 00:39:02,780  
gravitational waves and every time I saw

860  
00:39:05,170 --> 00:39:03,710  
them walking around this is what I

861  
00:39:09,730 --> 00:39:05,180  
thought this is fit a scene from his

862  
00:39:13,960 --> 00:39:09,740  
fits corrado which is a movie by a

863  
00:39:15,910 --> 00:39:13,970

Verner Herzog about a man in 19th

864

00:39:23,100 --> 00:39:15,920

century Brazil who decides he wants to

865

00:39:26,140 --> 00:39:23,110

carry a boat over a mountain anyway on

866

00:39:28,030 --> 00:39:26,150

September 14th 2015 they had upgraded

867

00:39:29,560 --> 00:39:28,040

their detectors and before they're

868

00:39:32,440 --> 00:39:29,570

actually gonna start doing science runs

869

00:39:33,850 --> 00:39:32,450

they were doing some test runs so they

870

00:39:35,230 --> 00:39:33,860

turned the machine on just to do some

871

00:39:39,430 --> 00:39:35,240

tests to see if everything was working

872

00:39:51,490 --> 00:39:39,440

and this is what happened and there's a

873

00:39:57,890 --> 00:39:55,220

so they're constantly measuring the

874

00:40:00,680 --> 00:39:57,900

separation of these mirrors with a very

875

00:40:02,240 --> 00:40:00,690

very small time resolution and the

876

00:40:04,460 --> 00:40:02,250

mirrors keep shaking around because when

877

00:40:07,070 --> 00:40:04,470

people drive by that shakes the ground

878

00:40:09,110 --> 00:40:07,080

and they when there's a lightning strike

879

00:40:11,390 --> 00:40:09,120

anywhere on the planet that shakes the

880

00:40:14,150 --> 00:40:11,400

things around so they're constantly see

881

00:40:16,280 --> 00:40:14,160

things in LIGO the custody see things in

882

00:40:18,260 --> 00:40:16,290

Livingston the number of things that

883

00:40:20,840 --> 00:40:18,270

affect the Hanford detector and the

884

00:40:22,730 --> 00:40:20,850

Livingston detector are pretty rare

885

00:40:27,200 --> 00:40:22,740

because they're several thousand miles

886

00:40:29,180 --> 00:40:27,210

away and what they saw though at the

887

00:40:31,210 --> 00:40:29,190

same time in both detectors is a very

888

00:40:35,990 --> 00:40:31,220

prominent signal that looked like that

889

00:40:39,500 --> 00:40:36,000

so here is another plot so this is the

890

00:40:43,670 --> 00:40:39,510

displacement of the mirrors as a

891

00:40:45,950 --> 00:40:43,680

function of time in the Hanford and you

892

00:40:46,970 --> 00:40:45,960

see that it goes up and down and up and

893

00:40:51,050 --> 00:40:46,980

down and up and down and up and down

894

00:40:53,450 --> 00:40:51,060

right faster faster and then stops and

895

00:40:57,050 --> 00:40:53,460

you see the exact same thing and the

896

00:41:04,600 --> 00:40:57,060

Livingston data goes up and down up and

897

00:41:09,800 --> 00:41:04,610

down up no it's big and then stops so

898

00:41:13,430 --> 00:41:09,810

this we are very very sure is the signal

899

00:41:14,450 --> 00:41:13,440

from a pair of black holes that are

900

00:41:16,100 --> 00:41:14,460

merging

901  
00:41:19,070 --> 00:41:16,110  
so another prediction of general

902  
00:41:22,120 --> 00:41:19,080  
relativity which was realized first by a

903  
00:41:24,500 --> 00:41:22,130  
guy named Karl Schwarzschild who was

904  
00:41:27,800 --> 00:41:24,510  
fighting in the trenches in World War

905  
00:41:30,350 --> 00:41:27,810  
one and figured this out while in the

906  
00:41:34,610 --> 00:41:30,360  
trenches and then passed away a few

907  
00:41:37,580 --> 00:41:34,620  
months later so Karl Schwarzschild

908  
00:41:39,470 --> 00:41:37,590  
figured out that the equations of

909  
00:41:41,890 --> 00:41:39,480  
general relativity allow for the

910  
00:41:44,690 --> 00:41:41,900  
existence of things called black holes

911  
00:41:47,150 --> 00:41:44,700  
these are the densest possible objects

912  
00:41:49,130 --> 00:41:47,160  
in nature and they are so strong that

913  
00:41:50,480 --> 00:41:49,140

the grant they are so dense the

914

00:41:53,480 --> 00:41:50,490

gravitational field is so strong that

915

00:41:56,150 --> 00:41:53,490

not even light can escape so you know if

916

00:41:58,130 --> 00:41:56,160

I try to throw a ball in the air it goes

917

00:41:59,600 --> 00:41:58,140

up and it goes down but if I had a

918

00:42:03,670 --> 00:41:59,610

really good arm and I could throw the

919

00:42:05,349 --> 00:42:03,680

ball any velocity of 11 kilometers per

920

00:42:08,799 --> 00:42:05,359

second I shouldn't know what that is a

921

00:42:11,410 --> 00:42:08,809

miles per hour but I don't 11 kilometers

922

00:42:12,609 --> 00:42:11,420

per second the ball wouldn't return to

923

00:42:14,079 --> 00:42:12,619

Earth it would actually escape the

924

00:42:19,870 --> 00:42:14,089

gravitational pull of the earth and

925

00:42:21,400 --> 00:42:19,880

escape to infinity a black hole is an

926

00:42:22,930 --> 00:42:21,410

object that is so dense the

927

00:42:25,329 --> 00:42:22,940

gravitational field is so strong that

928

00:42:26,980 --> 00:42:25,339

the escape velocity from the surface is

929

00:42:28,089 --> 00:42:26,990

bigger than the speed of light and since

930

00:42:30,339 --> 00:42:28,099

nothing can travel faster than the speed

931

00:42:35,920 --> 00:42:30,349

of light nothing can escape from the

932

00:42:40,390 --> 00:42:35,930

black hole so we can take the equations

933

00:42:42,069 --> 00:42:40,400

of general relativity and set them up so

934

00:42:44,620 --> 00:42:42,079

that there's not just one black hole but

935

00:42:48,099 --> 00:42:44,630

two black holes that are in orbit about

936

00:42:50,829 --> 00:42:48,109

each other and if you do that what you

937

00:42:53,680 --> 00:42:50,839

find is that gravitational waves will be

938

00:42:57,339 --> 00:42:53,690

emitted as the gravitational waves are

939

00:42:59,470 --> 00:42:57,349

emitted those gravitational waves carry

940

00:43:00,579 --> 00:42:59,480

energy away and if they carry energy

941

00:43:04,210 --> 00:43:00,589

away that means there has to be less

942

00:43:06,520 --> 00:43:04,220

energy for the remaining system a Barn's

943

00:43:09,099 --> 00:43:06,530

system of two objects actually has a

944

00:43:11,559 --> 00:43:09,109

negative energy it has a gravitational

945

00:43:13,059 --> 00:43:11,569

binding or potential energy and as they

946

00:43:15,549 --> 00:43:13,069

get closer that becomes increasingly

947

00:43:19,000 --> 00:43:15,559

negative so the energy that's carried

948

00:43:21,339 --> 00:43:19,010

away is gravitational waves causes the

949

00:43:24,220 --> 00:43:21,349

remaining binary to become closer and

950

00:43:25,930 --> 00:43:24,230

closer and as that binary as the two

951  
00:43:27,280 --> 00:43:25,940  
stars become closer and closer they spin

952  
00:43:29,200 --> 00:43:27,290  
around faster and faster

953  
00:43:31,059 --> 00:43:29,210  
you know mercury gets around the Sun a

954  
00:43:32,109 --> 00:43:31,069  
lot more quickly does the earth and the

955  
00:43:36,700 --> 00:43:32,119  
earth gets around the Sun a lot more

956  
00:43:39,220 --> 00:43:36,710  
quickly than Pluto so likewise when two

957  
00:43:40,569 --> 00:43:39,230  
black holes get closer and closer they

958  
00:43:43,180 --> 00:43:40,579  
start to spin around each other faster

959  
00:43:45,339 --> 00:43:43,190  
and faster and when they do that the

960  
00:43:47,710 --> 00:43:45,349  
gravitational wave frequency increases

961  
00:43:50,920 --> 00:43:47,720  
and the power and gravitational waves

962  
00:43:54,210 --> 00:43:50,930  
increases and so that is what is seen

963  
00:43:56,859 --> 00:43:54,220

here and this is actually a scientific

964

00:43:59,620 --> 00:43:56,869

simulation this is actually full

965

00:44:03,039 --> 00:43:59,630

solution of the numerical solution of

966

00:44:05,319 --> 00:44:03,049

the equations of general relativity so

967

00:44:07,180 --> 00:44:05,329

that is what they look like they get

968

00:44:09,000 --> 00:44:07,190

closer and closer here you see the

969

00:44:12,370 --> 00:44:09,010

gravitational waves being emitted as

970

00:44:14,140 --> 00:44:12,380

they get closer and closer the orbit

971

00:44:15,490 --> 00:44:14,150

will orbital period will decrease

972

00:44:16,630 --> 00:44:15,500

they'll start to spin up and the

973

00:44:17,200 --> 00:44:16,640

gravitational wave soon will get

974

00:44:21,820 --> 00:44:17,210

stronger

975

00:44:23,620 --> 00:44:21,830

looks like when gravitational waves when

976

00:44:26,890 --> 00:44:23,630

two binary black to black holes merge

977

00:44:28,150 --> 00:44:26,900

and what's kind of interesting and I was

978

00:44:30,100 --> 00:44:28,160

surprised by when I first saw these

979

00:44:32,080 --> 00:44:30,110

numerical simulations is that when they

980

00:44:33,550 --> 00:44:32,090

finally merged it happens very quickly

981

00:44:37,470 --> 00:44:33,560

and there's a burst of gravitational

982

00:44:39,880 --> 00:44:37,480

waves emitted so it turns out that

983

00:44:43,720 --> 00:44:39,890

calculations such as the ones I just

984

00:44:45,640 --> 00:44:43,730

that I showed you here can allow you to

985

00:44:48,790 --> 00:44:45,650

predict a gravitational wave signal far

986

00:44:57,010 --> 00:44:48,800

away and that prediction turns out to be

987

00:44:59,770 --> 00:44:57,020

spot-on what was seen by LIGO not always

988

00:45:03,190 --> 00:44:59,780

it's spot-on but based on the properties

989

00:45:05,200 --> 00:45:03,200

of the signal you know the frequency how

990

00:45:07,330 --> 00:45:05,210

quickly the frequency increases the

991

00:45:09,670 --> 00:45:07,340

magnitude of the signal at the merger

992

00:45:13,780 --> 00:45:09,680

time and also the ring down and the

993

00:45:16,090 --> 00:45:13,790

final period from all that information

994

00:45:18,700 --> 00:45:16,100

we can actually infer that one of these

995

00:45:20,620 --> 00:45:18,710

black holes had a mass of about 36 times

996

00:45:23,140 --> 00:45:20,630

the mass of the Sun another was about 29

997

00:45:26,470 --> 00:45:23,150

times the mass of the Sun the final

998

00:45:29,950 --> 00:45:26,480

black hole had a mass of 62 and 62 minus

999

00:45:32,470 --> 00:45:29,960

36 months 29 is three so they're

1000

00:45:34,420 --> 00:45:32,480

actually you know from just from now you

1001  
00:45:36,310 --> 00:45:34,430  
know special relativity Albert Einstein

1002  
00:45:38,620 --> 00:45:36,320  
e equals mc-squared

1003  
00:45:43,140 --> 00:45:38,630  
energy is equivalent to mass there were

1004  
00:45:45,670 --> 00:45:43,150  
three solar masses of energy released as

1005  
00:45:47,080 --> 00:45:45,680  
gravitational waves and we can also

1006  
00:45:49,750 --> 00:45:47,090  
infer the distance which is about

1007  
00:45:52,030 --> 00:45:49,760  
billion light years which is good

1008  
00:45:54,250 --> 00:45:52,040  
because things are because it feels a

1009  
00:45:57,490 --> 00:45:54,260  
lot closer than that movie they showed

1010  
00:46:03,460 --> 00:45:57,500  
you of the earth bouncing around might

1011  
00:46:04,960 --> 00:46:03,470  
have been a little more realistic this

1012  
00:46:06,220 --> 00:46:04,970  
is kind of a cute movie this is actually

1013  
00:46:11,530 --> 00:46:06,230

another movie that they made that

1014

00:46:14,980 --> 00:46:11,540

illustrates what the sky would look like

1015

00:46:19,240 --> 00:46:14,990

if you were looking through a pair of

1016

00:46:20,920 --> 00:46:19,250

binary a binary black hole system so the

1017

00:46:23,350 --> 00:46:20,930

black hole's I told you to flecked the

1018

00:46:24,460 --> 00:46:23,360

light and so the image of the stars that

1019

00:46:26,920 --> 00:46:24,470

are behind the black hole's get

1020

00:46:29,050 --> 00:46:26,930

distorted and again this is a scientific

1021

00:46:30,700 --> 00:46:29,060

simulation of what it would look like if

1022

00:46:38,320 --> 00:46:30,710

we were a lot closer to the spine

1023

00:46:40,450 --> 00:46:38,330

black hole system so as they move around

1024

00:46:42,520 --> 00:46:40,460

the lensing pattern would change and

1025

00:46:45,310 --> 00:46:42,530

that is what the sky would look like as

1026

00:46:48,970 --> 00:46:45,320

these things spiral around each other

1027

00:46:51,730 --> 00:46:48,980

and then merge and the merger is pretty

1028

00:46:54,220 --> 00:46:51,740

happens very quickly and suddenly and

1029

00:46:56,430 --> 00:46:54,230

then there's a very brief ring down any

1030

00:47:00,070 --> 00:46:56,440

second now

1031

00:47:09,550 --> 00:47:00,080

so they're they merge and then there's

1032

00:47:11,560 --> 00:47:09,560

this final ring down anyway there's a

1033

00:47:13,180 --> 00:47:11,570

big question which is the question we

1034

00:47:15,040 --> 00:47:13,190

were wondering in the Aza front and then

1035

00:47:20,770 --> 00:47:15,050

the Space Telescope cafeteria over here

1036

00:47:23,680 --> 00:47:20,780

in January of 2016 in February where do

1037

00:47:25,660 --> 00:47:23,690

these black holes come from we detected

1038

00:47:27,370 --> 00:47:25,670

them we're very very sure that that was

1039

00:47:29,339 --> 00:47:27,380

a binary black hole system that we saw

1040

00:47:31,599 --> 00:47:29,349

with these gravitational wave events and

1041

00:47:33,940 --> 00:47:31,609

subsequent developments have given us

1042

00:47:37,599 --> 00:47:33,950

even more confidence but where do they

1043

00:47:39,599 --> 00:47:37,609

come from I told you that they can exist

1044

00:47:41,829 --> 00:47:39,609

within the context of general relativity

1045

00:47:43,720 --> 00:47:41,839

but they're there they're not just

1046

00:47:45,730 --> 00:47:43,730

mathematical constructions and you know

1047

00:47:47,560 --> 00:47:45,740

figments of theoretical imagination this

1048

00:47:49,720 --> 00:47:47,570

measurement shows that these black holes

1049

00:47:53,980 --> 00:47:49,730

actually exist and they weigh you know

1050

00:47:56,470 --> 00:47:53,990

30 times the mass of the Sun so the most

1051  
00:47:59,170 --> 00:47:56,480  
reasonable explanation and the one that

1052  
00:48:01,750 --> 00:47:59,180  
you know with 99% confidence is going to

1053  
00:48:04,540 --> 00:48:01,760  
be correct to some extent is that they

1054  
00:48:06,760 --> 00:48:04,550  
probably come from massive stars so this

1055  
00:48:10,359 --> 00:48:06,770  
is a very busy plot and I want you to

1056  
00:48:14,020 --> 00:48:10,369  
look at everything but basically there

1057  
00:48:15,550 --> 00:48:14,030  
are a lot of stars in the universe like

1058  
00:48:17,859 --> 00:48:15,560  
the Sun some of them are more massive

1059  
00:48:18,970 --> 00:48:17,869  
than the stars then the Sun like those

1060  
00:48:19,870 --> 00:48:18,980  
of you who are paying attention to the

1061  
00:48:22,359 --> 00:48:19,880  
details of the hertzsprung-russell

1062  
00:48:23,950 --> 00:48:22,369  
diagram well remember that there were

1063  
00:48:26,440 --> 00:48:23,960

blue giants which are extremely massive

1064

00:48:31,210 --> 00:48:26,450

and their red dwarfs which are very

1065

00:48:34,570 --> 00:48:31,220

low-mass so what we know is that stars

1066

00:48:37,870 --> 00:48:34,580

are powered by burning protons into

1067

00:48:40,570 --> 00:48:37,880

helium nuclei fission but there's only a

1068

00:48:44,559 --> 00:48:40,580

finite amount of fuel that a given star

1069

00:48:47,819 --> 00:48:44,569

has and when that fuel runs out the star

1070

00:48:50,680 --> 00:48:47,829

and it does not die an elegant death and

1071

00:48:52,720 --> 00:48:50,690

the way it dies and the remnant that it

1072

00:48:55,750 --> 00:48:52,730

leaves behind depends on its initial

1073

00:48:59,020 --> 00:48:55,760

mass so low mass stars like the Sun

1074

00:49:01,390 --> 00:48:59,030

we're pretty sure that when they use up

1075

00:49:02,890 --> 00:49:01,400

all their nuclear fuel they blow up into

1076

00:49:05,049 --> 00:49:02,900

a red giant for a brief period of time

1077

00:49:06,370 --> 00:49:05,059

they then blow off a lot of gas and they

1078

00:49:12,040 --> 00:49:06,380

leave behind something called a white

1079

00:49:14,940 --> 00:49:12,050

dwarf more massive stars though undergo

1080

00:49:18,069 --> 00:49:14,950

a similar evolution but when they

1081

00:49:19,780 --> 00:49:18,079

finally become a giant instead of just

1082

00:49:21,910 --> 00:49:19,790

blowing off a nebula leaving a white

1083

00:49:25,690 --> 00:49:21,920

dwarf they undergo this huge explosion

1084

00:49:27,849 --> 00:49:25,700

where their inner core's undergo

1085

00:49:31,390 --> 00:49:27,859

gravitational collapse and leave behind

1086

00:49:32,859 --> 00:49:31,400

either a neutron star or a black hole so

1087

00:49:38,020 --> 00:49:32,869

this is something that we're very very

1088

00:49:41,770 --> 00:49:38,030

sure about although the details we don't

1089

00:49:43,809 --> 00:49:41,780

have a lot of confidence in but we're

1090

00:49:47,650 --> 00:49:43,819

very very certain that neutron stars and

1091

00:49:54,609 --> 00:49:47,660

black holes are formed as the remnants

1092

00:49:58,450 --> 00:49:54,619

of massive stars now the issue that kind

1093

00:50:00,549 --> 00:49:58,460

of surprised us back in 2016

1094

00:50:02,770 --> 00:50:00,559

is that each of the black holes that

1095

00:50:05,049 --> 00:50:02,780

were detected in this original event had

1096

00:50:07,390 --> 00:50:05,059

a mass of 30 times the mass of the Sun

1097

00:50:09,700 --> 00:50:07,400

and the mass of the black hole that

1098

00:50:11,920 --> 00:50:09,710

remains is only a small fraction of the

1099

00:50:13,569 --> 00:50:11,930

mass of the original star because most

1100

00:50:16,660 --> 00:50:13,579

of the mass of the stars blown away in

1101

00:50:18,069 --> 00:50:16,670

this planetary nebula or supernova so

1102

00:50:20,049 --> 00:50:18,079

that means that a 30 solar mass black

1103

00:50:22,630 --> 00:50:20,059

hole would have had to come from a much

1104

00:50:24,579 --> 00:50:22,640

more massive star that's okay there are

1105

00:50:27,039 --> 00:50:24,589

many more much more massive stars in the

1106

00:50:28,329 --> 00:50:27,049

universe but if you're paying attention

1107

00:50:30,130 --> 00:50:28,339

when Frank was talking about the

1108

00:50:34,270 --> 00:50:30,140

hertzsprung-russell diagram he told you

1109

00:50:37,390 --> 00:50:34,280

that there are far more far far far more

1110

00:50:39,970 --> 00:50:37,400

low mass stars than there are high mass

1111

00:50:42,280 --> 00:50:39,980

stars and so it was kind of surprising

1112

00:50:46,210 --> 00:50:42,290

that the first black hole binary that

1113

00:50:49,630 --> 00:50:46,220

LIGO detected came from these very very

1114

00:50:51,760 --> 00:50:49,640

very rare supermassive stars we would

1115

00:50:53,829 --> 00:50:51,770

have thought we would see five or ten

1116

00:50:55,890 --> 00:50:53,839

solar mass black holes not 30 solar mass

1117

00:50:58,859 --> 00:50:55,900

black holes

1118

00:51:00,930 --> 00:50:58,869

and so that got us to thinking and I'm

1119

00:51:02,670 --> 00:51:00,940

not a gravitational wave astrophysicist

1120

00:51:04,019 --> 00:51:02,680

I'm not a stellar astrophysicist I'm not

1121

00:51:08,970 --> 00:51:04,029

a blackhole guy I'm not a neutron star

1122

00:51:11,160 --> 00:51:08,980

guy I'm a cosmologists and one of the

1123

00:51:13,009 --> 00:51:11,170

things that I get paid to do is think

1124

00:51:14,880 --> 00:51:13,019

about what the dark matter is

1125

00:51:18,239 --> 00:51:14,890

fortunately I don't get paid to actually

1126

00:51:20,910 --> 00:51:18,249

figure it out because that can only

1127

00:51:27,749 --> 00:51:20,920

happen once and once it happens we're

1128

00:51:29,849 --> 00:51:27,759

out of work so I think about what the

1129

00:51:31,739 --> 00:51:29,859

dark matter might be and so here are

1130

00:51:33,210 --> 00:51:31,749

black holes they're dark

1131

00:51:36,599 --> 00:51:33,220

they've been discovered they're out

1132

00:51:43,349 --> 00:51:36,609

there maybe there's the Dark Matter so

1133

00:51:47,370 --> 00:51:43,359

it's a silly idea so dark matter this is

1134

00:51:49,980 --> 00:51:47,380

a mystery that's been around for a good

1135

00:51:51,239 --> 00:51:49,990

fraction of a century and the reason we

1136

00:51:53,880 --> 00:51:51,249

believe in dark matter there are many

1137

00:51:55,019 --> 00:51:53,890

many lines of reasoning to tell us that

1138

00:51:57,329 --> 00:51:55,029

there's a lot of dark matter in the

1139

00:51:59,670 --> 00:51:57,339

universe but the simplest is perhaps

1140

00:52:03,359 --> 00:51:59,680

what we call galactic rotation curves so

1141

00:52:05,579 --> 00:52:03,369

there are a lot of galaxies like the

1142

00:52:07,499 --> 00:52:05,589

Milky Way which are a collection of a

1143

00:52:09,779 --> 00:52:07,509

gravitationally bound system of stars

1144

00:52:11,640 --> 00:52:09,789

and each star moves and the

1145

00:52:15,630 --> 00:52:11,650

gravitational potential due to every

1146

00:52:19,099 --> 00:52:15,640

other star and galaxies have some finite

1147

00:52:21,180 --> 00:52:19,109

extent they are ten what we call

1148

00:52:22,859 --> 00:52:21,190

kiloparsecs and the kiloparsec is

1149

00:52:24,839 --> 00:52:22,869

roughly 3,000 light years so here in

1150

00:52:26,430 --> 00:52:24,849

this diagram actually this is 10,000

1151  
00:52:28,890 --> 00:52:26,440  
light years this is a smallish galaxy

1152  
00:52:31,229 --> 00:52:28,900  
and then the star sort of peter out

1153  
00:52:33,120 --> 00:52:31,239  
there's not a whole lot out here but

1154  
00:52:36,059 --> 00:52:33,130  
occasionally you do find some star at

1155  
00:52:37,680 --> 00:52:36,069  
large distance or some gas cloud and you

1156  
00:52:39,420 --> 00:52:37,690  
can see these gas clouds spinning around

1157  
00:52:41,430 --> 00:52:39,430  
and you can measure the velocity which

1158  
00:52:44,599 --> 00:52:41,440  
they spin around and if you plot the

1159  
00:52:48,420 --> 00:52:44,609  
speed at which these gas clouds are

1160  
00:52:50,999 --> 00:52:48,430  
spinning around this galaxy it continues

1161  
00:52:53,700 --> 00:52:51,009  
to increase at large distances from the

1162  
00:52:55,319 --> 00:52:53,710  
galaxies and that is unusual because if

1163  
00:52:57,359 --> 00:52:55,329

this was all the manner that we saw then

1164

00:52:59,489 --> 00:52:57,369

according to Newton's laws the velocity

1165

00:53:02,009 --> 00:52:59,499

should decrease right in the solar

1166

00:53:05,279 --> 00:53:02,019

system the Sun is a very very massive

1167

00:53:06,690 --> 00:53:05,289

object right in the middle and mercury

1168

00:53:08,329 --> 00:53:06,700

which is right next to the Sun spins

1169

00:53:10,099 --> 00:53:08,339

around really really quickly

1170

00:53:12,529 --> 00:53:10,109

but as you go further out the solar

1171

00:53:14,469 --> 00:53:12,539

system Pluto takes forever to get around

1172

00:53:17,299 --> 00:53:14,479

the Sun because Pluto is so far away so

1173

00:53:20,059 --> 00:53:17,309

if this was all that we all the matter

1174

00:53:23,239 --> 00:53:20,069

in the galaxy we would expected to see

1175

00:53:25,249 --> 00:53:23,249

these speeds become much smaller at

1176

00:53:27,259 --> 00:53:25,259

large distances from the galaxy but

1177

00:53:30,859 --> 00:53:27,269

instead they're seen to increase and

1178

00:53:34,099 --> 00:53:30,869

this along with many other lines of

1179

00:53:37,130 --> 00:53:34,109

reasoning and many other forms of

1180

00:53:41,630 --> 00:53:37,140

evidence suggests that there is a lot of

1181

00:53:44,469 --> 00:53:41,640

dark matter non luminous matter that

1182

00:53:46,789 --> 00:53:44,479

surrounds the luminous stuff that we see

1183

00:53:48,469 --> 00:53:46,799

we don't know what it is though we're

1184

00:53:49,579 --> 00:53:48,479

very very sure that it's there when we

1185

00:53:52,190 --> 00:53:49,589

have no idea what it is

1186

00:53:54,170 --> 00:53:52,200

all we know is that it's dark it does

1187

00:53:58,789 --> 00:53:54,180

not emit light and it does not absorb

1188

00:54:00,709 --> 00:53:58,799

light we know now precisely how much

1189

00:54:02,299 --> 00:54:00,719

there is I can tell you it within a few

1190

00:54:04,089 --> 00:54:02,309

percent how much dark matter there is

1191

00:54:06,170 --> 00:54:04,099

even though I can't tell you what it is

1192

00:54:09,140 --> 00:54:06,180

and we know how its distributing

1193

00:54:11,390 --> 00:54:09,150

galaxies and elsewhere in the universe I

1194

00:54:13,519 --> 00:54:11,400

told you it does not emit nor absorb

1195

00:54:17,140 --> 00:54:13,529

light so it can't be the same stuff that

1196

00:54:19,700 --> 00:54:17,150

were made out of it can't be it atoms

1197

00:54:22,160 --> 00:54:19,710

for many years we've speculated that's

1198

00:54:23,420 --> 00:54:22,170

perhaps some new elementary particle and

1199

00:54:24,950 --> 00:54:23,430

we've been trying really hard to find

1200

00:54:28,999 --> 00:54:24,960

this elementary particle but we have not

1201

00:54:30,650 --> 00:54:29,009

yet succeeded and so it's not

1202

00:54:34,579 --> 00:54:30,660

unreasonable to entertain other

1203

00:54:37,910 --> 00:54:34,589

possibilities and Stephen Hawking back

1204

00:54:40,819 --> 00:54:37,920

in 1974 and others thought maybe there

1205

00:54:43,130 --> 00:54:40,829

are primordial black holes maybe the Big

1206

00:54:44,559 --> 00:54:43,140

Bang when it produced the universe and

1207

00:54:47,120 --> 00:54:44,569

produced all the stuff in the universe

1208

00:54:49,549 --> 00:54:47,130

maybe it also produced a whole bunch of

1209

00:54:53,479 --> 00:54:49,559

black holes which survived to become the

1210

00:54:55,339 --> 00:54:53,489

dark matter today so we tried to figure

1211

00:54:58,099 --> 00:54:55,349

out and these are some my collaborators

1212

00:54:59,839 --> 00:54:58,109

so my work is always done with students

1213

00:55:01,309 --> 00:54:59,849

and postdocs and in this particular case

1214

00:55:03,769 --> 00:55:01,319

I'm also with Adam Riess who's a

1215

00:55:08,900 --> 00:55:03,779

colleague who has a Nobel Prize which

1216

00:55:11,029 --> 00:55:08,910

helps with the credibility so these are

1217

00:55:14,840 --> 00:55:11,039

all postdocs and one graduate student

1218

00:55:19,250 --> 00:55:17,660

so this was the paper we wrote I don't

1219

00:55:21,800 --> 00:55:19,260

remember the exact title but it was more

1220

00:55:23,420 --> 00:55:21,810

or less did LIGO detect dark matter so

1221

00:55:26,030 --> 00:55:23,430

it's a crazy idea it's a speculative

1222

00:55:27,920 --> 00:55:26,040

idea but not completely crazy and this

1223

00:55:29,570 --> 00:55:27,930

is the coincident I told you about so we

1224

00:55:32,870 --> 00:55:29,580

know how much dark matter there is in

1225

00:55:38,360 --> 00:55:32,880

the Galactic halo so we know how much

1226

00:55:40,460 --> 00:55:38,370

stuff there is out here if all of that

1227

00:55:43,730 --> 00:55:40,470

dark matter is composed of 30 solar mass

1228

00:55:45,830 --> 00:55:43,740

objects but then I can tell you how many

1229

00:55:48,560 --> 00:55:45,840

of them there should be and what the

1230

00:55:50,150 --> 00:55:48,570

typical spacing should be we also know

1231

00:55:52,970 --> 00:55:50,160

how fast these things are moving around

1232

00:55:54,980 --> 00:55:52,980

these dark matter objects whatever they

1233

00:55:56,660 --> 00:55:54,990

are in a galaxy like the Milky Way

1234

00:55:58,580 --> 00:55:56,670

galaxy are actually spinning around and

1235

00:56:03,710 --> 00:55:58,590

a speed of several hundred kilometers

1236

00:56:05,720 --> 00:56:03,720

per second and we also know that two

1237

00:56:08,600 --> 00:56:05,730

black holes if they pass by each other

1238

00:56:12,130 --> 00:56:08,610

can actually form very briefly a Brown

1239

00:56:14,270 --> 00:56:12,140

system that then spirals in and merges

1240

00:56:15,740 --> 00:56:14,280

so roughly speaking I've got you know

1241

00:56:17,900 --> 00:56:15,750

two ping-pong balls passing by each

1242

00:56:19,280 --> 00:56:17,910

other a large separation they're not

1243

00:56:22,190 --> 00:56:19,290

gonna hit each other but if the two

1244

00:56:24,830 --> 00:56:22,200

ping-pong balls pass by each other with

1245

00:56:26,390 --> 00:56:24,840

a separation that's smaller than their

1246

00:56:28,760 --> 00:56:26,400

size they're gonna run into each other

1247

00:56:33,440 --> 00:56:28,770

same thing is true of automobiles which

1248

00:56:35,180 --> 00:56:33,450

is why we have lanes so we know roughly

1249

00:56:38,060 --> 00:56:35,190

speaking how big a 30 solar mass black

1250

00:56:41,840 --> 00:56:38,070

hole is and so it is very very

1251

00:56:43,160 --> 00:56:41,850

straightforward to estimate how often

1252

00:56:45,980 --> 00:56:43,170

these things should run into each other

1253

00:56:49,730 --> 00:56:45,990

and so we did this estimate we did this

1254

00:56:52,940 --> 00:56:49,740

calculation and some of these people are

1255

00:56:54,290 --> 00:56:52,950

actually very well equipped in terms of

1256

00:56:57,320 --> 00:56:54,300

the theoretical background to do the

1257

00:57:00,140 --> 00:56:57,330

calculation properly and so we did it

1258

00:57:02,390 --> 00:57:00,150

and it turns out that the rate at which

1259

00:57:04,250 --> 00:57:02,400

such black holes would merge if they

1260

00:57:08,420 --> 00:57:04,260

made up the dark matter in galactic

1261

00:57:11,030 --> 00:57:08,430

halos agreed surprisingly well with the

1262

00:57:13,670 --> 00:57:11,040

rates at which black holes merge that we

1263

00:57:15,380 --> 00:57:13,680

infer from the fact that LIGO saw one of

1264

00:57:17,990 --> 00:57:15,390

these events after two weeks of

1265

00:57:20,180 --> 00:57:18,000

observation and it was that coincidence

1266

00:57:22,280 --> 00:57:20,190

that led us to write the paper and it's

1267

00:57:23,810 --> 00:57:22,290

that coincidence that has been very

1268

00:57:27,470 --> 00:57:23,820

intriguing for a number of our

1269

00:57:34,760 --> 00:57:30,020

so I think that this paper that we wrote

1270

00:57:39,080 --> 00:57:34,770

is the most highly cited post LIGO LIGO

1271

00:57:41,990 --> 00:57:39,090

related paper so this is a hypothesis

1272

00:57:43,550 --> 00:57:42,000

but it's not the answer I don't know

1273

00:57:47,240 --> 00:57:43,560

that this is the Dark Matter - pretty

1274

00:57:49,430 --> 00:57:47,250

out-there hypothesis but scientists are

1275

00:57:51,560 --> 00:57:49,440

supposed to not only propose hypotheses

1276

00:57:54,260 --> 00:57:51,570

but try to come up with ways to test the

1277

00:57:56,060 --> 00:57:54,270

hypotheses and that has been a very

1278

00:57:58,550 --> 00:57:56,070

active area of investigation for our

1279

00:58:00,560 --> 00:57:58,560

group and others I will not tell you all

1280

00:58:02,390 --> 00:58:00,570

the things that people have proposed but

1281

00:58:04,070 --> 00:58:02,400

I'll tell you about one thing that we

1282

00:58:10,550 --> 00:58:04,080

suggested and that we're hoping will be

1283

00:58:14,780 --> 00:58:10,560

done soon so it turns out that there are

1284

00:58:18,290 --> 00:58:14,790

these things called fast radio bursts so

1285

00:58:19,640 --> 00:58:18,300

you've all seen James Bond movies and

1286

00:58:21,800 --> 00:58:19,650

there's the one James Bond movie where

1287

00:58:24,760 --> 00:58:21,810

he goes to the Arecibo space there osebo

1288

00:58:26,540 --> 00:58:24,770

telescope which is this huge radio dish

1289

00:58:31,040 --> 00:58:26,550

you know what I'm talking about

1290

00:58:34,520 --> 00:58:31,050

okay so radio telescopes like Arecibo

1291

00:58:37,370 --> 00:58:34,530

and a few others detect radio frequency

1292

00:58:39,350 --> 00:58:37,380

radiation from the sky and for a number

1293

00:58:41,180 --> 00:58:39,360

of years I don't remember exactly a lot

1294

00:58:43,700 --> 00:58:41,190

but for about the past 10 years it's

1295

00:58:47,210 --> 00:58:43,710

been noticed that occasionally there is

1296

00:58:50,080 --> 00:58:47,220

a very brief flash of radio frequency

1297

00:58:52,790 --> 00:58:50,090

radiation coming from the sky

1298

00:58:55,490 --> 00:58:52,800

so these flashes lasts less than one

1299

00:58:56,780 --> 00:58:55,500

thousandth of a second and for a long

1300

00:58:58,990 --> 00:58:56,790

time people wonder whether there was

1301  
00:59:01,280 --> 00:58:59,000  
some type of problem with the telescope

1302  
00:59:03,200 --> 00:59:01,290  
but a number of different telescopes

1303  
00:59:06,200 --> 00:59:03,210  
started to see these things they did a

1304  
00:59:07,700 --> 00:59:06,210  
number of tests and it's now very

1305  
00:59:09,920 --> 00:59:07,710  
certain that these are actually coming

1306  
00:59:11,780 --> 00:59:09,930  
from the sky and for a variety of

1307  
00:59:13,040 --> 00:59:11,790  
reasons we believe these to be coming

1308  
00:59:16,250 --> 00:59:13,050  
from there are good reasons to believe

1309  
00:59:18,320 --> 00:59:16,260  
these are coming from large distances so

1310  
00:59:20,150 --> 00:59:18,330  
suppose one of these fast radio bursts

1311  
00:59:22,970 --> 00:59:20,160  
goes off and we have no idea I should

1312  
00:59:24,170 --> 00:59:22,980  
say where they come from or a pretty

1313  
00:59:27,770 --> 00:59:24,180

sure they're coming from outside the

1314

00:59:29,660 --> 00:59:27,780

Milky Way but we have no idea what the

1315

00:59:31,400 --> 00:59:29,670

source is most people think that has

1316

00:59:33,140 --> 00:59:31,410

something to do with phenomena and the

1317

00:59:35,000 --> 00:59:33,150

surfaces of neutron stars but we can't

1318

00:59:37,460 --> 00:59:35,010

be absolutely sure but we don't even

1319

00:59:41,040 --> 00:59:37,470

care for our purposes so I should also

1320

00:59:42,420 --> 00:59:41,050

tell you that as of now they're about 50

1321

00:59:44,790 --> 00:59:42,430

fast radio bursts that have been

1322

00:59:47,160 --> 00:59:44,800

detected about a year ago there were

1323

00:59:49,080 --> 00:59:47,170

about 25 that have been detected but

1324

00:59:51,750 --> 00:59:49,090

there is a new telescope that the

1325

00:59:53,550 --> 00:59:51,760

Canadians have built called chyme which

1326  
00:59:55,830 --> 00:59:53,560  
stands for Canadian hydrogen intensity

1327  
00:59:57,900 --> 00:59:55,840  
mapping experiment and unlike the other

1328  
00:59:59,820 --> 00:59:57,910  
radio telescopes like Arecibo which

1329  
01:00:01,890 --> 00:59:59,830  
pointed a very small part of the sky on

1330  
01:00:03,810 --> 01:00:01,900  
this Canadian telescope points at a very

1331  
01:00:05,730 --> 01:00:03,820  
large fraction of the seas a very large

1332  
01:00:08,730 --> 01:00:05,740  
fraction in the sky and so they expect

1333  
01:00:10,680 --> 01:00:08,740  
to detect these fast radio bursts far

1334  
01:00:12,270 --> 01:00:10,690  
more frequently than the past and in

1335  
01:00:14,160 --> 01:00:12,280  
just a few months of observation they've

1336  
01:00:16,170 --> 01:00:14,170  
doubled the sample of fast radio bursts

1337  
01:00:19,230 --> 01:00:16,180  
already and they expect to see several

1338  
01:00:20,970 --> 01:00:19,240

thousand more in the next few years so

1339

01:00:23,040 --> 01:00:20,980

suppose there's a fast radio bursts and

1340

01:00:25,370 --> 01:00:23,050

suppose the black hole's make up the

1341

01:00:29,540 --> 01:00:25,380

dark matter then there is some chance

1342

01:00:32,790 --> 01:00:29,550

that there will be such a black hole

1343

01:00:36,150 --> 01:00:32,800

along the line of sight to a given fast

1344

01:00:39,090 --> 01:00:36,160

radio bursts and if that's the case then

1345

01:00:41,790 --> 01:00:39,100

this massive object this black hole can

1346

01:00:43,320 --> 01:00:41,800

gravitationally lends the signal from

1347

01:00:44,940 --> 01:00:43,330

this fast radio bursts so the light from

1348

01:00:49,290 --> 01:00:44,950

this fast radio bursts these radio waves

1349

01:00:52,040 --> 01:00:49,300

can travel to us either along this

1350

01:00:54,480 --> 01:00:52,050

trajectory or along this trajectory and

1351

01:00:56,520 --> 01:00:54,490

it turns out that most generally these

1352

01:01:01,620 --> 01:00:56,530

two trajectories have slightly different

1353

01:01:05,910 --> 01:01:01,630

path lengths and the path lengths differ

1354

01:01:09,180 --> 01:01:05,920

by roughly a millisecond times the speed

1355

01:01:11,040 --> 01:01:09,190

of light or a few milliseconds time the

1356

01:01:15,980 --> 01:01:11,050

speed of light and so what we predict is

1357

01:01:18,420 --> 01:01:15,990

that instead of seeing one flash once

1358

01:01:20,550 --> 01:01:18,430

sub-millisecond flash which has been the

1359

01:01:21,360 --> 01:01:20,560

case for all the vast rate of earths

1360

01:01:23,730 --> 01:01:21,370

that have been seen

1361

01:01:26,400 --> 01:01:23,740

if these black holes are out there

1362

01:01:28,380 --> 01:01:26,410

roughly one in a hundred of them will be

1363

01:01:30,570 --> 01:01:28,390

gravitationally lensed and after seeing

1364

01:01:32,250 --> 01:01:30,580

the original flash you'll see the

1365

01:01:35,120 --> 01:01:32,260

flashes arriving through a second

1366

01:01:37,410 --> 01:01:35,130

trajectory and so you'll see and that go

1367

01:01:40,680 --> 01:01:37,420

so these measurements are now being made

1368

01:01:43,560 --> 01:01:40,690

as I said they've seen 50 in a few years

1369

01:01:46,110 --> 01:01:43,570

they'll have maybe 5,000 and if black

1370

01:01:48,480 --> 01:01:46,120

holes make up the dark matter then they

1371

01:01:50,970 --> 01:01:48,490

will see several hundred within a few

1372

01:01:52,770 --> 01:01:50,980

years that have an echo that looks like

1373

01:01:54,960 --> 01:01:52,780

this so

1374

01:01:56,130 --> 01:01:54,970

this is one way to test the scenario

1375

01:02:01,740 --> 01:01:56,140

there are other ways to test the

1376

01:02:05,430 --> 01:02:01,750

scenario I won't discuss them all but I

1377

01:02:06,990 --> 01:02:05,440

think I will close there so the era of

1378

01:02:08,670 --> 01:02:07,000

gravitational wave astronomy is here

1379

01:02:10,190 --> 01:02:08,680

we're learning all about black holes

1380

01:02:13,410 --> 01:02:10,200

about general relativity

1381

01:02:16,740 --> 01:02:13,420

spacetime Wiggles around maybe we'll

1382

01:02:18,870 --> 01:02:16,750

also learn something about dark matter I

1383

01:02:20,310 --> 01:02:18,880

should say the jury is still out as to

1384

01:02:25,170 --> 01:02:20,320

whether prime order black holes can make

1385

01:02:26,790 --> 01:02:25,180

up the dark matter there's still some

1386

01:02:28,290 --> 01:02:26,800

debate within the Astrophysical

1387

01:02:29,430 --> 01:02:28,300

community about whether they can make up

1388

01:02:32,400 --> 01:02:29,440

the dark matter or whether current

1389

01:02:33,690 --> 01:02:32,410

observations already roll them out so

1390

01:02:35,310 --> 01:02:33,700

I'm not going to tell you I'm absolutely

1391

01:02:37,230 --> 01:02:35,320

certain that they can be the dark matter

1392

01:02:37,950 --> 01:02:37,240

but we are taking the idea very

1393

01:02:40,560 --> 01:02:37,960

seriously

1394

01:02:42,450 --> 01:02:40,570

either way it's a very exciting prospect

1395

01:02:45,120 --> 01:02:42,460

and many people are interested in in

1396

01:02:48,760 --> 01:02:45,130

trying to pursue further tests of this

1397

01:02:55,880 --> 01:02:48,770

scenario thank you very much

1398

01:02:55,890 --> 01:03:05,499

[Applause]

1399

01:03:24,249 --> 01:03:07,479

yes we are gonna have microphone here is

1400

01:03:27,370 --> 01:03:24,259

grant the bird at I2 that 2016

1401

01:03:37,079 --> 01:03:27,380

did you tell us more about bird there

1402

01:03:40,630 --> 01:03:37,089

was a bird was the Brit we had a Brit a

1403

01:03:47,510 --> 01:03:40,640

Frenchman and israeli-american

1404

01:03:54,180 --> 01:03:47,520

an Italian a Spaniard Greek and American

1405

01:03:59,400 --> 01:03:57,729

so this is a sermon bird is the big one

1406

01:04:05,410 --> 01:03:59,410

with a glasses

1407

01:04:17,949 --> 01:04:05,420

he's uh so he was just the lead authors

1408

01:04:19,359 --> 01:04:17,959

of Simon's Simeon Simeon I'm a kind of

1409

01:04:23,170 --> 01:04:19,369

veteran you've seen a lot of these

1410

01:04:25,930 --> 01:04:23,180

lectures and this black black dark

1411

01:04:34,279 --> 01:04:25,940

matter compared to nothing where does

1412

01:04:47,670 --> 01:04:43,829

that's a tricky question I would say

1413

01:04:49,859 --> 01:04:47,680

that we don't actually know very

1414

01:04:53,339 --> 01:04:49,869

precisely but we know that in the center

1415

01:04:57,299 --> 01:04:53,349

of a galaxy there is a high density of

1416

01:04:58,799 --> 01:04:57,309

dark matter and the density of dark

1417

01:05:01,020 --> 01:04:58,809

matter which is going to be very big

1418

01:05:04,500 --> 01:05:01,030

over here decreases as you go further

1419

01:05:06,359 --> 01:05:04,510

out but sooner or later there's going to

1420

01:05:08,789 --> 01:05:06,369

be another galaxy over here that has its

1421

01:05:10,170 --> 01:05:08,799

own Dark Matter halo and so it's not

1422

01:05:12,180 --> 01:05:10,180

clear that there's anywhere in the

1423

01:05:14,190 --> 01:05:12,190

universe where there is no dark matter

1424

01:05:16,049 --> 01:05:14,200

but the density of dark matter is

1425

01:05:20,309 --> 01:05:16,059

probably going to be smallest in the

1426

01:05:22,859 --> 01:05:20,319

places between the galaxies is there a

1427

01:05:27,120 --> 01:05:22,869

place where there is that better is just

1428

01:05:29,370 --> 01:05:27,130

nothing well you have points I don't

1429

01:05:31,170 --> 01:05:29,380

think so I would say that there are

1430

01:05:33,990 --> 01:05:31,180

places where we the dark matter density

1431

01:05:35,309 --> 01:05:34,000

is small but I don't think there's any

1432

01:05:36,779 --> 01:05:35,319

place in the universe that we can point

1433

01:05:49,470 --> 01:05:36,789

to where we're pretty sure that there is

1434

01:05:51,620 --> 01:05:49,480

no dark matter yeah I see a basis for a

1435

01:05:54,170 --> 01:05:51,630

new disaster movie in the making here

1436

01:05:56,279 --> 01:05:54,180

[Laughter]

1437

01:05:58,740 --> 01:05:56,289

just just like the opposite you had

1438

01:06:01,829 --> 01:05:58,750

mention are implied that that of a solar

1439

01:06:04,260 --> 01:06:01,839

system was fairly close to emerging

1440

01:06:06,000 --> 01:06:04,270

block merging black holes that the

1441

01:06:07,950 --> 01:06:06,010

distortion would be considerably greater

1442

01:06:13,170 --> 01:06:07,960

would they be enough to actually care

1443

01:06:14,640 --> 01:06:13,180

apart a solar system I don't think so it

1444

01:06:17,430 --> 01:06:14,650

would have to be I we went through this

1445

01:06:19,440 --> 01:06:17,440

calculation once but when we're sitting

1446

01:06:23,700 --> 01:06:19,450

in the cafeteria and tossing around

1447

01:06:26,490 --> 01:06:23,710

crazy ideas the the probability that

1448

01:06:29,849 --> 01:06:26,500

this would happen is extremely extremely

1449

01:06:31,829 --> 01:06:29,859

small so the rate at which such things

1450

01:06:35,519 --> 01:06:31,839

occur as we infer from the LIGO

1451

01:06:38,549 --> 01:06:35,529

measurements is so small that it's

1452

01:06:41,130 --> 01:06:38,559

unlikely that there was ever such an

1453

01:06:44,760 --> 01:06:41,140

event even in our own galaxy over the

1454

01:06:46,109 --> 01:06:44,770

entire history of the universe so these

1455

01:06:49,019 --> 01:06:46,119

these events are so

1456

01:06:52,650 --> 01:06:49,029

err that a typical galaxy will go the

1457

01:06:56,249 --> 01:06:52,660

entire link you know the entire universe

1458

01:06:57,809 --> 01:06:56,259

without ever seeing such an event thank

1459

01:06:59,400 --> 01:06:57,819

you have to be relieved you don't have

1460

01:07:00,680 --> 01:06:59,410

to be very very close I think closer

1461

01:07:23,730 --> 01:07:00,690

than the nearest stars

1462

01:07:27,559 --> 01:07:23,740

so if black holes were in some way dark

1463

01:07:30,150 --> 01:07:27,569

matter how how would that relate to the

1464

01:07:33,180 --> 01:07:30,160

accelerating expansion of the universe

1465

01:07:38,730 --> 01:07:33,190

is there any connection that's a good

1466

01:07:42,210 --> 01:07:38,740

question and I have no idea so I was

1467

01:07:43,710 --> 01:07:42,220

just giving a I was giving a talk about

1468

01:07:46,680 --> 01:07:43,720

something related this morning to a

1469

01:07:48,059 --> 01:07:46,690

philosophy class oh there's a philosophy

1470

01:07:49,920 --> 01:07:48,069

of science class and they just wanted

1471

01:07:53,489 --> 01:07:49,930

somebody to talk about things that we do

1472

01:07:55,559 --> 01:07:53,499

in physics so there's the dark matter

1473

01:07:58,979 --> 01:07:55,569

problem and then there's the dark energy

1474

01:08:03,749 --> 01:07:58,989

problem and in science we are always

1475

01:08:08,099 --> 01:08:03,759

told to look for economic solutions and

1476

01:08:10,259 --> 01:08:08,109

so ideally we would have one theory or

1477

01:08:13,380 --> 01:08:10,269

model that can explain both dark matter

1478

01:08:15,320 --> 01:08:13,390

and dark energy and some theorists have

1479

01:08:17,579 --> 01:08:15,330

tried to do that but it turns out to be

1480

01:08:18,240 --> 01:08:17,589

far more difficult than you would

1481

01:08:20,280 --> 01:08:18,250

imagine

1482

01:08:22,140 --> 01:08:20,290

and what it really wants all these

1483

01:08:24,479 --> 01:08:22,150

solutions where they try to merge the

1484

01:08:26,189 --> 01:08:24,489

two they really wind up looking like a

1485

01:08:27,689 --> 01:08:26,199

solution for dark matter and a

1486

01:08:30,709 --> 01:08:27,699

completely different solution for dark

1487

01:08:35,189 --> 01:08:30,719

energy that are then glued together I

1488

01:08:36,979 --> 01:08:35,199

don't know but I don't think that I'll

1489

01:08:39,349 --> 01:08:36,989

be surprised if I were to be like

1490

01:08:43,740 --> 01:08:39,359

resurrected a hundred years from now and

1491

01:08:45,689 --> 01:08:43,750

learn that they actually the solution

1492

01:08:49,289 --> 01:08:45,699

for dark energy was related to the

1493

01:08:50,240 --> 01:08:49,299

solution for dark matter I can imagine

1494

01:08:52,470 --> 01:08:50,250

that a hundred years from now

1495

01:08:55,890 --> 01:08:52,480

cosmologists we were looking at back at

1496

01:08:57,149 --> 01:08:55,900

us and thinking oh that was so quaint

1497

01:08:58,590 --> 01:08:57,159

and silly they thought that was dark

1498

01:09:00,310 --> 01:08:58,600

matter those dark energy they didn't

1499

01:09:03,320 --> 01:09:00,320

understand that was just

1500

01:09:05,180 --> 01:09:03,330

but I have no idea what that is yeah

1501

01:09:07,700 --> 01:09:05,190

our current understanding has the the

1502

01:09:09,800 --> 01:09:07,710

dark matter localized around galaxies

1503

01:09:13,040 --> 01:09:09,810

etcetera whereas the dark energy is sort

1504

01:09:15,050 --> 01:09:13,050

of round all of space and so that that

1505

01:09:16,790 --> 01:09:15,060

to me you know has always been the

1506

01:09:19,070 --> 01:09:16,800

fundamental problem trying to combine

1507

01:09:20,950 --> 01:09:19,080

the two is that the distribution

1508

01:09:23,990 --> 01:09:20,960

function is totally different right I

1509

01:09:28,130 --> 01:09:24,000

agree and that's how I view it that's

1510

01:09:31,550 --> 01:09:28,140

how 99% of people like us view the

1511

01:09:33,170 --> 01:09:31,560

problem but I kind of think that

1512

01:09:37,160 --> 01:09:33,180

sometime in the future there's gonna be

1513

01:09:38,750 --> 01:09:37,170

like a solution that's you know of which

1514

01:09:52,190 --> 01:09:38,760

these are two different aspects

1515

01:09:55,700 --> 01:09:52,200

that's a nice hopeful thought thank you

1516

01:09:59,870 --> 01:09:55,710

um how closely closely related to

1517

01:10:02,600 --> 01:09:59,880

project Einstein is this as far as the

1518

01:10:04,550 --> 01:10:02,610

detection of gravitational waves how

1519

01:10:07,700 --> 01:10:04,560

closely related this is this to project

1520

01:10:15,110 --> 01:10:07,710

Einstein yes I don't think I know what

1521

01:10:17,720 --> 01:10:15,120

project Einstein is well it is one part

1522

01:10:21,190 --> 01:10:17,730

of it is a distributed processing

1523

01:10:24,860 --> 01:10:21,200

research project using blink

1524

01:10:30,310 --> 01:10:24,870

uh-huh okay taking data from the Arecibo

1525

01:10:35,030 --> 01:10:30,320

telescope and from the legos in

1526

01:10:37,070 --> 01:10:35,040

Louisiana and in Washington Policy and

1527

01:10:41,680 --> 01:10:37,080

they're looking for that for the

1528

01:10:44,510 --> 01:10:41,690

apparently if I understand correctly

1529

01:10:48,550 --> 01:10:44,520

looking at the locations of pulsars

1530

01:10:50,930 --> 01:10:48,560

where you could do interferometry use oh

1531

01:10:54,620 --> 01:10:50,940

okay that yeah okay now I know I know

1532

01:11:01,870 --> 01:10:54,630

what you're talking about that that's a

1533

01:11:05,210 --> 01:11:01,880

very very interesting set of projects so

1534

01:11:07,760 --> 01:11:05,220

there are pulsars which are spending

1535

01:11:09,590 --> 01:11:07,770

neutron stars that are located you know

1536

01:11:11,000 --> 01:11:09,600

ten thousand light years away and

1537

01:11:12,980 --> 01:11:11,010

there's a bunch of them spread

1538

01:11:13,310 --> 01:11:12,990

throughout the sky and what I showed you

1539

01:11:15,020 --> 01:11:13,320

was the

1540

01:11:17,930 --> 01:11:15,030

gravitational wave detector that they'd

1541

01:11:21,109 --> 01:11:17,940

built in Washington in Louisiana that

1542

01:11:22,640 --> 01:11:21,119

had two arms so there was a set of test

1543

01:11:25,129 --> 01:11:22,650

masses over here that were oscillating

1544

01:11:28,700 --> 01:11:25,139

like this another set like this so it's

1545

01:11:30,620 --> 01:11:28,710

been proposed to use pulsars for the

1546

01:11:32,839 --> 01:11:30,630

gravitational wave as gravitational wave

1547

01:11:34,520 --> 01:11:32,849

detectors so if I have you know if we're

1548

01:11:37,790 --> 01:11:34,530

on earth right here and there's one

1549

01:11:39,680 --> 01:11:37,800

pulsar over here and another pulsar over

1550

01:11:43,370 --> 01:11:39,690

here and the gravitational wave passes

1551  
01:11:45,109 --> 01:11:43,380  
by the Pulsar over here will oscillate

1552  
01:11:46,819 --> 01:11:45,119  
in this direction the Pulsar over here

1553  
01:11:49,339 --> 01:11:46,829  
lastly in this direction those two

1554  
01:11:53,720 --> 01:11:49,349  
oscillations will be out of phase and we

1555  
01:11:56,930 --> 01:11:53,730  
can detect that in principle and people

1556  
01:11:59,540 --> 01:11:56,940  
are trying to do this and the principle

1557  
01:12:01,339 --> 01:11:59,550  
is exactly the same as LIGO the

1558  
01:12:04,100 --> 01:12:01,349  
difference is that the arm lengths are

1559  
01:12:06,319 --> 01:12:04,110  
10,000 light years as opposed to for at

1560  
01:12:08,569 --> 01:12:06,329  
supposed a couple of miles and so the

1561  
01:12:11,300 --> 01:12:08,579  
wavelengths of the gravitational waves

1562  
01:12:18,700 --> 01:12:11,310  
that you can detect are bigger by about

1563  
01:12:22,609 --> 01:12:18,710

a factor of a billion it's a it's a very

1564

01:12:24,620 --> 01:12:22,619

10 years ago even three years ago three

1565

01:12:26,600 --> 01:12:24,630

years ago I would have told I would have

1566

01:12:28,520 --> 01:12:26,610

put my money that those Paul start

1567

01:12:33,410 --> 01:12:28,530

timing arrays would detect gravitational

1568

01:12:35,270 --> 01:12:33,420

waves before Alaia but they didn't but I

1569

01:12:37,780 --> 01:12:35,280

think they will I think we will see

1570

01:12:40,250 --> 01:12:37,790

something in the next few years

1571

01:12:41,359 --> 01:12:40,260

okay so mark there's a question from the

1572

01:12:43,220 --> 01:12:41,369

online audience that I'm sort of

1573

01:12:45,319 --> 01:12:43,230

summarizing from things is they want to

1574

01:12:46,700 --> 01:12:45,329

understand how many more gravitational

1575

01:12:49,430 --> 01:12:46,710

waves are out there you've got black

1576

01:12:50,780 --> 01:12:49,440

hole black hole mergers and obviously if

1577

01:12:52,339 --> 01:12:50,790

you had supermassive black hole

1578

01:12:53,959 --> 01:12:52,349

supermassive black hole murders you can

1579

01:12:55,580 --> 01:12:53,969

see along with that but you know the

1580

01:12:58,010 --> 01:12:55,590

neutron stars how many other different

1581

01:13:01,399 --> 01:12:58,020

types of events will these gravitational

1582

01:13:03,770 --> 01:13:01,409

wave detectors be able to see in the

1583

01:13:07,220 --> 01:13:03,780

near somewhat near future so their black

1584

01:13:08,899 --> 01:13:07,230

hole binary black hole mergers there was

1585

01:13:11,390 --> 01:13:08,909

a merger of it there's an event last

1586

01:13:13,490 --> 01:13:11,400

year there was either a binary neutron

1587

01:13:15,649 --> 01:13:13,500

star or a neutron star black hole we

1588

01:13:16,580 --> 01:13:15,659

don't know which but we do expect you

1589

01:13:18,410 --> 01:13:16,590

know over the next few years to see

1590

01:13:21,200 --> 01:13:18,420

neutron star neutron star mergers

1591

01:13:23,089 --> 01:13:21,210

neutron star or black hole murders we'll

1592

01:13:26,920 --> 01:13:23,099

see more black hole black hole mergers

1593

01:13:30,400 --> 01:13:26,930

there is a space-based gravitational

1594

01:13:32,530 --> 01:13:30,410

detector that we are considering the

1595

01:13:35,830 --> 01:13:32,540

European Space Agency's leading and NASA

1596

01:13:37,630 --> 01:13:35,840

is participating in if when that flies

1597

01:13:39,490 --> 01:13:37,640

that will detect or have sensitivity

1598

01:13:41,650 --> 01:13:39,500

detect mergers of supermassive black

1599

01:13:44,470 --> 01:13:41,660

holes black holes that each have a mass

1600

01:13:47,740 --> 01:13:44,480

of a billion times mass of a billion

1601  
01:13:50,620 --> 01:13:47,750  
times the mass of the Sun people have

1602  
01:13:52,330 --> 01:13:50,630  
also speculated that supernovae when a

1603  
01:13:54,250 --> 01:13:52,340  
star explodes and forms a neutron star

1604  
01:13:57,220 --> 01:13:54,260  
that there might be a gravitational wave

1605  
01:13:59,740 --> 01:13:57,230  
signal from that people have speculated

1606  
01:14:02,770 --> 01:13:59,750  
that some neutron stars might have

1607  
01:14:05,170 --> 01:14:02,780  
little mountains on them and those

1608  
01:14:06,340 --> 01:14:05,180  
mountains some the spending of a neutron

1609  
01:14:08,830 --> 01:14:06,350  
storm with the mountain might give you a

1610  
01:14:10,570 --> 01:14:08,840  
gravitational wave signal the

1611  
01:14:12,490 --> 01:14:10,580  
space-based observatories will also

1612  
01:14:15,400 --> 01:14:12,500  
detect gravitational waves from white

1613  
01:14:18,460 --> 01:14:15,410

dwarf binaries so some of the you know

1614

01:14:20,110 --> 01:14:18,470

low mass stars at the end of their when

1615

01:14:22,420 --> 01:14:20,120

they sneeze up all the nuclear fuel turn

1616

01:14:24,100 --> 01:14:22,430

into white dwarfs so if I have a binary

1617

01:14:26,140 --> 01:14:24,110

star system that consists of two low

1618

01:14:28,510 --> 01:14:26,150

mass stars it will evolve to a white

1619

01:14:30,070 --> 01:14:28,520

dwarf binary and we actually know of a

1620

01:14:32,440 --> 01:14:30,080

number of white dwarf binary so there

1621

01:14:37,300 --> 01:14:32,450

are signals from those binaries that we

1622

01:14:38,980 --> 01:14:37,310

expect to see I'm sure there are other

1623

01:14:41,230 --> 01:14:38,990

things but those are the ones that them

1624

01:14:43,210 --> 01:14:41,240

we generally hear most about and the

1625

01:14:45,100 --> 01:14:43,220

most promising so really gravitational

1626  
01:14:46,900 --> 01:14:45,110  
waves just are studying the interactions

1627  
01:14:48,570 --> 01:14:46,910  
of dead stars with the light dwarfs and

1628  
01:14:50,680 --> 01:14:48,580  
the neutron stars and black holes so

1629  
01:14:52,480 --> 01:14:50,690  
stars got to give up their lives in

1630  
01:14:55,990 --> 01:14:52,490  
order for a gravitational wave astronomy

1631  
01:15:01,240 --> 01:14:56,000  
to work right exactly all right do we

1632  
01:15:03,730 --> 01:15:01,250  
have more questions up here there was a

1633  
01:15:07,120 --> 01:15:03,740  
famous inflammatory experiment in the

1634  
01:15:09,670 --> 01:15:07,130  
late 1800s Michelson Morley when people

1635  
01:15:11,560 --> 01:15:09,680  
were looking for the ether yep what

1636  
01:15:14,710 --> 01:15:11,570  
would have happened if this

1637  
01:15:17,860 --> 01:15:14,720  
interferometer LIGO had existed back

1638  
01:15:23,100 --> 01:15:17,870

then and had gotten this reading back

1639

01:15:26,350 --> 01:15:23,110

then so it is exactly the same type of

1640

01:15:27,700 --> 01:15:26,360

interferometer that they use but as you

1641

01:15:33,640 --> 01:15:27,710

know trillions of times better

1642

01:15:36,250 --> 01:15:33,650

sensitivity have they seen that probably

1643

01:15:37,630 --> 01:15:36,260

would have blown their mind I actually

1644

01:15:39,100 --> 01:15:37,640

don't know what they probably thought it

1645

01:15:40,229 --> 01:15:39,110

was just noise because they only had one

1646

01:15:43,800 --> 01:15:40,239

detector

1647

01:15:46,050 --> 01:15:43,810

in Cleveland and had we had just if

1648

01:15:47,250 --> 01:15:46,060

there was only one detector I don't know

1649

01:15:51,810 --> 01:15:47,260

the we would have been as confident

1650

01:15:54,660 --> 01:15:51,820

there was a real signal but with Rago if

1651  
01:15:57,060 --> 01:15:54,670  
we'd had if we'd had this result then if

1652  
01:15:58,229 --> 01:15:57,070  
we had this result then I don't know

1653  
01:16:03,320 --> 01:15:58,239  
what people would have made of it

1654  
01:16:05,940 --> 01:16:03,330  
because there was no concept of a

1655  
01:16:10,890 --> 01:16:05,950  
space-time curvature there was no

1656  
01:16:12,930 --> 01:16:10,900  
concept of gravitational waves I have no

1657  
01:16:14,220 --> 01:16:12,940  
idea what the what they would have made

1658  
01:16:16,760 --> 01:16:14,230  
of it they were they were looking for

1659  
01:16:18,650 --> 01:16:16,770  
exactly this they did have some sense of

1660  
01:16:21,120 --> 01:16:18,660  
curvature they just didn't have

1661  
01:16:22,050 --> 01:16:21,130  
space-time the modern concept well they

1662  
01:16:23,970 --> 01:16:22,060  
were looking for something a little

1663  
01:16:25,770 --> 01:16:23,980

different they were looking to see

1664

01:16:28,080 --> 01:16:25,780

whether there was a difference between

1665

01:16:30,930 --> 01:16:28,090

what happens when the interferometer is

1666

01:16:33,240 --> 01:16:30,940

in like orient in this direction versus

1667

01:16:35,700 --> 01:16:33,250

oriented in this direction whereas the

1668

01:16:39,330 --> 01:16:35,710

signal that they saw all takes place

1669

01:16:41,660 --> 01:16:39,340

with one orientation and the the the

1670

01:16:43,740 --> 01:16:41,670

interferometer just started to vibrate

1671

01:16:46,740 --> 01:16:43,750

Michelson Morley we're looking to see

1672

01:16:50,280 --> 01:16:46,750

whether the the the the arm lengths

1673

01:16:54,030 --> 01:16:50,290

would change if as the orientation of

1674

01:16:55,709 --> 01:16:54,040

the detector was changed but I have no

1675

01:17:02,530 --> 01:16:55,719

idea what they would have made of it had

1676

01:17:05,170 --> 01:17:02,540

they seen something I guess so

1677

01:17:08,380 --> 01:17:05,180

there's an e equals mc-squared waiting

1678

01:17:12,550 --> 01:17:08,390

out there that will equate dark energy

1679

01:17:15,280 --> 01:17:12,560

and dark matter well there is a you know

1680

01:17:22,510 --> 01:17:15,290

there is some energy density in the dark

1681

01:17:24,310 --> 01:17:22,520

energy so there is some equivalence

1682

01:17:27,240 --> 01:17:24,320

between the mass of the dark energy and

1683

01:17:29,380 --> 01:17:27,250

its energy but I don't think there's any

1684

01:17:31,270 --> 01:17:29,390

correspondence there's no obvious

1685

01:17:38,820 --> 01:17:31,280

correspondence between the density of

1686

01:17:45,640 --> 01:17:43,690

I'm really struck by the the declaration

1687

01:17:49,750 --> 01:17:45,650

that there's the loss of three solar

1688

01:17:53,830 --> 01:17:49,760

masses in the combination of those two

1689

01:17:55,950 --> 01:17:53,840

black holes and I've got a couple

1690

01:17:58,480 --> 01:17:55,960

questions on that the first is with

1691

01:17:59,650 --> 01:17:58,490

given that that's that's based upon the

1692

01:18:01,240 --> 01:17:59,660

energy coming out of the gravitational

1693

01:18:03,610 --> 01:18:01,250

waves so it doesn't have to necessarily

1694

01:18:05,380 --> 01:18:03,620

be two black holes I mean if it was the

1695

01:18:07,720 --> 01:18:05,390

black hole and really anything else that

1696

01:18:10,300 --> 01:18:07,730

would just be on a smaller scale correct

1697

01:18:13,480 --> 01:18:10,310

yes and then my question when that would

1698

01:18:16,980 --> 01:18:13,490

be brings to mind Hawking radiation and

1699

01:18:20,260 --> 01:18:16,990

the idea of black hole evaporation but

1700

01:18:22,150 --> 01:18:20,270

if there's three solar masses that are

1701

01:18:23,320 --> 01:18:22,160

getting pulled out based on

1702

01:18:26,110 --> 01:18:23,330

gravitational waves

1703

01:18:27,760 --> 01:18:26,120

I feel like Hawking radiation really

1704

01:18:29,530 --> 01:18:27,770

pales in comparison to whatever might

1705

01:18:32,380 --> 01:18:29,540

come out of just the gravitational

1706

01:18:34,810 --> 01:18:32,390

effects well it depends on the mass of

1707

01:18:38,190 --> 01:18:34,820

the black hole if for some reason there

1708

01:18:43,030 --> 01:18:38,200

were black holes that had a mass of a

1709

01:18:45,850 --> 01:18:43,040

thousand trillion grams a trillion

1710

01:18:48,150 --> 01:18:45,860

kilograms so if there was a black hole

1711

01:18:52,390 --> 01:18:48,160

down at a mass of a trillion kilograms

1712

01:18:54,580 --> 01:18:52,400

it would Hawking evaporate in less than

1713

01:18:56,770 --> 01:18:54,590

the age of the universe and the vast

1714

01:18:58,960 --> 01:18:56,780

majority that energy would be released

1715

01:19:02,440 --> 01:18:58,970

in a very short period of time now the

1716

01:19:04,320 --> 01:19:02,450

total energy is very small compared with

1717

01:19:06,250 --> 01:19:04,330

the total energy that's released in the

1718

01:19:07,750 --> 01:19:06,260

black holes that they've seen but those

1719

01:19:10,480 --> 01:19:07,760

but that's because those black holes are

1720

01:19:11,040 --> 01:19:10,490

so much more massive when when a black

1721

01:19:13,750 --> 01:19:11,050

hole

1722

01:19:16,390 --> 01:19:13,760

you know explodes by a Hawking

1723

01:19:17,620 --> 01:19:16,400

evaporation the entire rest mass energy

1724

01:19:20,290 --> 01:19:17,630

black hole as far as we know would be

1725

01:19:24,820 --> 01:19:20,300

released in radiation here it was just a

1726

01:19:29,620 --> 01:19:24,830

measly five percent okay but I should

1727

01:19:32,830 --> 01:19:29,630

say the the energy radiated that three

1728

01:19:35,380 --> 01:19:32,840

solar masses of energy was rated in one

1729

01:19:40,840 --> 01:19:35,390

millisecond and during that millisecond

1730

01:19:43,300 --> 01:19:40,850

this one system was more luminous than

1731

01:19:44,260 --> 01:19:43,310

the rest of the universe combined then

1732

01:19:47,290 --> 01:19:44,270

all the other stars in the universe

1733

01:19:48,640 --> 01:19:47,300

combined yeah there's a couple more

1734

01:19:54,820 --> 01:19:48,650

questions we had to this gentleman in

1735

01:19:57,580 --> 01:19:54,830

green here or like there there we go you

1736

01:19:59,410 --> 01:19:57,590

haven't talked about the speed of

1737

01:20:00,220 --> 01:19:59,420

gravitational waves at all do you think

1738

01:20:03,150 --> 01:20:00,230

about that

1739

01:20:05,770 --> 01:20:03,160

ah so general relativity predicts that

1740

01:20:10,810 --> 01:20:05,780

gravitational waves propagate at the

1741

01:20:12,160 --> 01:20:10,820

speed of light and we now know that that

1742

01:20:18,120 --> 01:20:12,170

prediction that prediction has been

1743

01:20:22,990 --> 01:20:18,130

verified because there was an event in

1744

01:20:25,300 --> 01:20:23,000

late in August of 2017 where there's a

1745

01:20:27,220 --> 01:20:25,310

gravitational wave signal seen from the

1746

01:20:31,000 --> 01:20:27,230

merger of either two neutron stars or

1747

01:20:33,550 --> 01:20:31,010

neutron star in a black hole and the

1748

01:20:36,100 --> 01:20:33,560

neutron star or neutron star merger

1749

01:20:37,600 --> 01:20:36,110

neutron star black hole merger some of

1750

01:20:40,470 --> 01:20:37,610

the material from the neutron star was

1751  
01:20:44,740 --> 01:20:40,480  
ripped out and there was a very visible

1752  
01:20:47,170 --> 01:20:44,750  
a very bright invisible explosion and so

1753  
01:20:49,480 --> 01:20:47,180  
this event was detected by a huge array

1754  
01:20:50,950 --> 01:20:49,490  
of telescopes simultaneously with the

1755  
01:20:54,250 --> 01:20:50,960  
ground with a gravitational wave

1756  
01:20:56,260 --> 01:20:54,260  
detection so we saw this one event in

1757  
01:20:58,480 --> 01:20:56,270  
gravitational waves and simultaneously

1758  
01:21:00,490 --> 01:20:58,490  
in electromagnetic waves and so from

1759  
01:21:03,430 --> 01:21:00,500  
that we know that they do propagate at

1760  
01:21:08,640 --> 01:21:03,440  
the speed of light so this this event

1761  
01:21:11,550 --> 01:21:08,650  
was astounding so the gravitational wave

1762  
01:21:13,930 --> 01:21:11,560  
observatory x' alerted the entire

1763  
01:21:15,940 --> 01:21:13,940

astronomical community anybody who had a

1764

01:21:18,040 --> 01:21:15,950

telescope found out about this and

1765

01:21:21,130 --> 01:21:18,050

anybody who could pointed the telescope

1766

01:21:25,240 --> 01:21:21,140

at it and as it turns out one of nasa's

1767

01:21:28,180 --> 01:21:25,250

other one of nasa satellites the the

1768

01:21:30,540 --> 01:21:28,190

Fermi satellite detected

1769

01:21:34,000 --> 01:21:30,550

a gravitational wave burst

1770

01:21:35,800 --> 01:21:34,010

simultaneously and independently and

1771

01:21:37,570 --> 01:21:35,810

another you know telescopes like the

1772

01:21:39,130 --> 01:21:37,580

Hubble Space Telescope was as quickly as

1773

01:21:40,900 --> 01:21:39,140

possible pointed at that region of the

1774

01:21:43,180 --> 01:21:40,910

sky I'm all these ground-based

1775

01:21:45,729 --> 01:21:43,190

observatories radio telescopes all

1776

01:21:47,740 --> 01:21:45,739

observed that part of the sky and the

1777

01:21:51,430 --> 01:21:47,750

papers that resulted from this one event

1778

01:21:54,310 --> 01:21:51,440

I think one out of three astronomers in

1779

01:21:56,530 --> 01:21:54,320

the world and had a name on one of those

1780

01:21:58,270 --> 01:21:56,540

papers and I got a call from some

1781

01:21:59,380 --> 01:21:58,280

reporters and asked him how can you not

1782

01:22:00,640 --> 01:21:59,390

calling me about this because I'm not

1783

01:22:01,990 --> 01:22:00,650

really an expert on this kind of thing

1784

01:22:03,189 --> 01:22:02,000

and they said well you're the only

1785

01:22:09,520 --> 01:22:03,199

person we could think of it wasn't a

1786

01:22:11,850 --> 01:22:09,530

co-author on one of the papers there's

1787

01:22:13,780 --> 01:22:11,860

another astronomer in the room they were

1788

01:22:19,810 --> 01:22:13,790

yeah half the people in this building

1789

01:22:22,030 --> 01:22:19,820

were co-authors on one of the papers um

1790

01:22:23,800 --> 01:22:22,040

things have been moving around in our

1791

01:22:26,170 --> 01:22:23,810

solar system and bumping into each other

1792

01:22:29,020 --> 01:22:26,180

since time immemorial I mean supposedly

1793

01:22:31,810 --> 01:22:29,030

we were pelted by a mars-sized planet in

1794

01:22:33,790 --> 01:22:31,820

the past with what we can conceivably

1795

01:22:38,520 --> 01:22:33,800

build in the near future

1796

01:22:44,979 --> 01:22:41,520

that's a good question

1797

01:22:48,040 --> 01:22:44,989

there are not nobody has really thought

1798

01:22:49,030 --> 01:22:48,050

of any other plausible Astrophysical

1799

01:22:52,780 --> 01:22:49,040

source that would produce a

1800

01:22:56,380 --> 01:22:52,790

gravitational wave signal involving an

1801  
01:23:00,340 --> 01:22:56,390  
object any less massive than a white

1802  
01:23:01,689 --> 01:23:00,350  
dwarf which the white dwarfs that exist

1803  
01:23:04,959 --> 01:23:01,699  
typically have a mass of about six

1804  
01:23:08,050 --> 01:23:04,969  
tenths the mass of the Sun the way that

1805  
01:23:10,870 --> 01:23:08,060  
the general relativity works the the

1806  
01:23:13,360 --> 01:23:10,880  
strength of the signal the gravitational

1807  
01:23:15,729 --> 01:23:13,370  
wave luminosity it greases very very

1808  
01:23:17,140 --> 01:23:15,739  
rapidly as you decrease the mass of the

1809  
01:23:20,140 --> 01:23:17,150  
system and also as you do as you

1810  
01:23:22,840 --> 01:23:20,150  
decrease the density so black holes are

1811  
01:23:25,060 --> 01:23:22,850  
the densest possible object and you know

1812  
01:23:29,050 --> 01:23:25,070  
those give us an observable signal if

1813  
01:23:31,810 --> 01:23:29,060

there are very very massive but once you

1814

01:23:36,060 --> 01:23:31,820

go to something like a star an ordinary

1815

01:23:39,189 --> 01:23:36,070

star or a planet it's so diffuse that

1816

01:23:41,890 --> 01:23:39,199

the signals are conceivable signals are

1817

01:23:43,720 --> 01:23:41,900

way too weak to be detected

1818

01:23:45,700 --> 01:23:43,730

okay so I think we had one last question

1819

01:23:48,220 --> 01:23:45,710

over here and then we got to cut it off

1820

01:23:51,580 --> 01:23:48,230

a rainy is here to take people across

1821

01:23:55,450 --> 01:23:51,590

the street for the observing so catch

1822

01:23:57,960 --> 01:23:55,460

that does the expansion of space-time

1823

01:24:01,420 --> 01:23:57,970

affect the LIGO measurements and

1824

01:24:06,540 --> 01:24:01,430

interaction yes it does

1825

01:24:11,140 --> 01:24:09,670

so the expansion of space-time affects

1826

01:24:14,410 --> 01:24:11,150

the gravitational wave signal in that

1827

01:24:17,350 --> 01:24:14,420

the the binary black hole system is

1828

01:24:20,110 --> 01:24:17,360

moving away from us and so the

1829

01:24:22,750 --> 01:24:20,120

gravitational wave signal is Doppler

1830

01:24:26,590 --> 01:24:22,760

shifted or red shifted relative to what

1831

01:24:28,000 --> 01:24:26,600

it is when it is emitted and given the

1832

01:24:30,550 --> 01:24:28,010

equivalence principle and the way

1833

01:24:32,410 --> 01:24:30,560

general relativity works there's a

1834

01:24:34,660 --> 01:24:32,420

degeneracy between two black holes that

1835

01:24:37,330 --> 01:24:34,670

have say a mass of 30 solar masses that

1836

01:24:40,120 --> 01:24:37,340

are at some distance and two black holes

1837

01:24:43,690 --> 01:24:40,130

that have say a mass of 15 solar masses

1838

01:24:47,980 --> 01:24:43,700

that are at a closer distance but there

1839

01:24:51,340 --> 01:24:47,990

are ways to break that degeneracy okay

1840

01:24:54,700 --> 01:24:51,350

so I hope you have plenty to think about

1841

01:24:56,820 --> 01:24:54,710

from here this is the questions and the

1842

01:25:00,510 --> 01:24:56,830

comments online of to show that mark has

1843

01:25:03,280 --> 01:25:00,520

taken us new places here tonight ireenie

1844

01:25:04,540 --> 01:25:03,290

Lambrini says you want to be over here

1845

01:25:05,950 --> 01:25:04,550

to take people because you can go out

1846

01:25:08,110 --> 01:25:05,960

that door over there so if you would

1847

01:25:10,390 --> 01:25:08,120

like to go across the street to do the

1848

01:25:14,170 --> 01:25:10,400

observing or renew a joinery knee over

1849

01:25:17,260 --> 01:25:14,180

here our next talk is the third Thursday

1850

01:25:25,159 --> 01:25:17,270

January 15th and let's give mark one

