PUBLIC LECTURE SERIES

Black Holes and Gravitational Waves

Featuring Guest Speaker:

Emanuele Berti

1
00:00:09,470 --> 00:00:01,939
microphone is it working yes it's

2
00:00:14,930 --> 00:00:09,480
working I'll set this up and we are

3
00:00:16,670 --> 00:00:14,940
ready good evening ladies and gentlemen

4
00:00:19,460 --> 00:00:16,680
and welcome to the Space Telescope

5
00:00:20,990 --> 00:00:19,470
public lecture series I'm your host dr.

6
00:00:23,630 --> 00:00:21,000
Frank summers from the office of public

7
00:00:26,960 --> 00:00:23,640
outreach and it is my pleasure to

8
00:00:29,240 --> 00:00:26,970
welcome you here tonight as you came in

9
00:00:32,269 --> 00:00:29,250
hopefully you grabbed one of these this

10
00:00:35,330 --> 00:00:32,279
is our lithograph for this evening

11
00:00:39,830 --> 00:00:35,340
this is Saturn as it appeared in

12
00:00:41,119 --> 00:00:39,840
Hubble's image taken in 2018 and if you

13
00:00:43,639 --> 00:00:41,129

want to know what's special about this

14
00:00:46,910 --> 00:00:43,649
image flip over on the back and you will

15
00:00:49,720 --> 00:00:46,920
find a few hundred words about it one of

16
00:00:54,950 --> 00:00:49,730
the interesting features in this image

17
00:00:55,580 --> 00:00:54,960
whoops is right here you see that storm

18
00:00:58,340 --> 00:00:55,590
here

19
00:01:01,130 --> 00:00:58,350
all right storms on Saturn are not as

20
00:01:03,799 --> 00:01:01,140
prevalent as they are on Jupiter there

21
00:01:08,030 --> 00:01:03,809
was a storm in the northern latitudes of

22
00:01:10,670 --> 00:01:08,040
of Saturn in 2018 and on the back we

23
00:01:12,770 --> 00:01:10,680
actually show you a series of several

24
00:01:15,740 --> 00:01:12,780
other storms here in northern latitudes

25
00:01:18,109 --> 00:01:15,750
mid latitudes and southern latitudes

26
00:01:21,410 --> 00:01:18,119
across the years that Hubble has been

27
00:01:23,149 --> 00:01:21,420
observing satyr so if you didn't get one

28
00:01:26,719 --> 00:01:23,159
on the way in please grab one on the way

29
00:01:30,499 --> 00:01:26,729
out now is a pause for the cause please

30
00:01:32,450 --> 00:01:30,509
silence your phones all right reach in

31
00:01:34,190 --> 00:01:32,460
check them put them on airplane mode or

32
00:01:37,010 --> 00:01:34,200
silent and whatever you can thank you

33
00:01:39,679 --> 00:01:37,020
because you will not want to disrupt the

34
00:01:42,469 --> 00:01:39,689
talk we have tonight our talk is black

35
00:01:44,719 --> 00:01:42,479
holes and gravitational waves from

36
00:01:48,139 --> 00:01:44,729
Emanuel Ax Betty from across the street

37
00:01:49,700 --> 00:01:48,149
in Johns Hopkins University coming up we

38
00:01:52,730 --> 00:01:49,710

have in November

39
00:01:54,649 --> 00:01:52,740
Sara Kendra who it works for the

40
00:01:57,410 --> 00:01:54,659
European Space Agency but does it so

41
00:02:00,139 --> 00:01:57,420
right here in our building she did not

42
00:02:02,780 --> 00:02:00,149
give me an actual title yet but she told

43
00:02:06,709 --> 00:02:02,790
me her topic was optical infrared

44
00:02:08,960 --> 00:02:06,719
telescopes okay so she's a great she

45
00:02:10,279 --> 00:02:08,970
really is a wonderful speaker you're

46
00:02:13,190 --> 00:02:10,289
gonna want to hear what she has to say

47
00:02:13,730 --> 00:02:13,200
no matter what actual topic she uses

48
00:02:14,780 --> 00:02:13,740
guess

49
00:02:17,810 --> 00:02:14,790
you're definitely gonna want to hear it

50
00:02:20,180 --> 00:02:17,820
she says in December surge Diedrich

51
00:02:22,760 --> 00:02:20,190
we'll be talking about red and brown

52
00:02:25,370 --> 00:02:22,770
dwarf our smallest and closest

53
00:02:27,230 --> 00:02:25,380
substellar neighbors what happened we

54
00:02:28,700 --> 00:02:27,240
always talk about the really big things

55
00:02:31,790 --> 00:02:28,710
in the universe we're gonna talk about

56
00:02:33,800 --> 00:02:31,800
some of the tiniest stars and sub stars

57
00:02:37,070 --> 00:02:33,810
in the universe this is gonna be a lot

58
00:02:39,200 --> 00:02:37,080
of fun and in January I do not have a

59
00:02:42,710 --> 00:02:39,210
speaker yet because I sort of reserved

60
00:02:45,920 --> 00:02:42,720
this date for a possible special talk we

61
00:02:49,550 --> 00:02:45,930
will be noting that will do it On

62
00:02:51,380 --> 00:02:49,560
January 14th okay will we will delay it

63
00:02:54,440 --> 00:02:51,390

a week because the first week of January

64
00:02:56,210 --> 00:02:54,450
a lot of people in this building will be

65
00:02:59,720 --> 00:02:56,220
at the American Astronomical Society

66
00:03:01,790 --> 00:02:59,730
meeting so that it's always best for us

67
00:03:03,800 --> 00:03:01,800
to delay it a week in January so we can

68
00:03:07,040 --> 00:03:03,810
make sure we have a great speaker for

69
00:03:11,690 --> 00:03:07,050
you then when that is set up it will be

70
00:03:15,680 --> 00:03:11,700
on our website and we have a new short

71
00:03:16,460 --> 00:03:15,690
link for it it is WWSD SEI tu edu slash

72
00:03:19,220 --> 00:03:16,470
public

73
00:03:22,310 --> 00:03:19,230
- lectures that will get you to our

74
00:03:26,480 --> 00:03:22,320
public lecture series page where we have

75
00:03:28,520 --> 00:03:26,490
links for the webcasts right here

76
00:03:31,880 --> 00:03:28,530
both on YouTube and in the webcast

77
00:03:33,560 --> 00:03:31,890
archives as well as our email you can

78
00:03:36,530 --> 00:03:33,570
sign up for our e-mail by putting in

79
00:03:40,010 --> 00:03:36,540
your email address there we also have

80
00:03:42,290 --> 00:03:40,020
the lists of the upcoming talks as well

81
00:03:44,960 --> 00:03:42,300
as a complete list of all the previous

82
00:03:47,870 --> 00:03:44,970
talks and for each of the previous talks

83
00:03:51,380 --> 00:03:47,880
we have our details of it as well as

84
00:03:56,390 --> 00:03:51,390
links to the STScI webcast up here and

85
00:03:59,140 --> 00:03:56,400
the YouTube webcast down here new fancy

86
00:04:04,850 --> 00:03:59,150
hopefully easy to navigate for you

87
00:04:07,250 --> 00:04:04,860
alright our email please if you just use

88
00:04:10,400 --> 00:04:07,260

the website to sign up if you don't like

89
00:04:11,810 --> 00:04:10,410
using websites to sign up you can write

90
00:04:13,670 --> 00:04:11,820
it down on a piece of paper and hand it

91
00:04:16,550 --> 00:04:13,680
to me and I will make sure you get

92
00:04:19,340 --> 00:04:16,560
signed up if you would like to ask ad

93
00:04:22,150 --> 00:04:19,350
send us a comment or ask questions you

94
00:04:26,360 --> 00:04:22,160
can send them to public lecture at stsci

95
00:04:27,470 --> 00:04:26,370
edu for social media we are available on

96
00:04:30,020 --> 00:04:27,480
Facebook Twitter

97
00:04:32,090 --> 00:04:30,030
YouTube and Instagram not just for

98
00:04:34,160 --> 00:04:32,100
Hubble not just for the James Webb Space

99
00:04:35,870 --> 00:04:34,170
Telescope but also for the Space

100
00:04:39,020 --> 00:04:35,880
Telescope Science Institute you've got

101
00:04:41,180 --> 00:04:39,030
your panoply of social media channels

102
00:04:43,700 --> 00:04:41,190
there if you would like to hear what I

103
00:04:45,590 --> 00:04:43,710
think you can follow me on Facebook or

104
00:04:48,200 --> 00:04:45,600
Twitter

105
00:04:50,450 --> 00:04:48,210
the observatory the weather does look

106
00:04:52,160 --> 00:04:50,460
like it is permitting tonight so the

107
00:04:54,020 --> 00:04:52,170
Maryland spacecraft Sartori let me know

108
00:04:56,360 --> 00:04:54,030
that they will be doing observing

109
00:04:59,870 --> 00:04:56,370
afterwards so if you would like to go up

110
00:05:03,020 --> 00:04:59,880
and look through the Maryland Space

111
00:05:05,030 --> 00:05:03,030
Grant Observatory telescope will collect

112
00:05:06,560 --> 00:05:05,040
down here after the talk if I forget

113
00:05:08,530 --> 00:05:06,570

about it somebody please remind me

114
00:05:11,690 --> 00:05:08,540
hopefully the part of the person from

115
00:05:14,000 --> 00:05:11,700
aerospace grant will be here okay if you

116
00:05:16,760 --> 00:05:14,010
cannot make it tonight they also have

117
00:05:18,980 --> 00:05:16,770
open houses on Friday evenings and this

118
00:05:21,590 --> 00:05:18,990
webpage right here shows you the

119
00:05:24,110 --> 00:05:21,600
observatory status check it on Friday

120
00:05:25,820 --> 00:05:24,120
afternoon / evening and it will tell you

121
00:05:28,550 --> 00:05:25,830
whether or not they're going to be doing

122
00:05:31,580 --> 00:05:28,560
observing that Friday evening all right

123
00:05:36,250 --> 00:05:31,590
and now our news from the universe for

124
00:05:39,920 --> 00:05:36,260
October 20 19 hour first story tonight

125
00:05:43,970 --> 00:05:39,930
blue stragglers and the kinetic age of

126
00:05:45,620 --> 00:05:43,980
globular clusters ah okay so first of

127
00:05:46,610 --> 00:05:45,630
all let's start let's parse all that

128
00:05:48,110 --> 00:05:46,620
because that's a lot a lot to put

129
00:05:50,690 --> 00:05:48,120
together first of all let's start with

130
00:05:53,330 --> 00:05:50,700
globular clusters this is the globular

131
00:05:55,490 --> 00:05:53,340
star cluster 47 to Connie or as we call

132
00:05:58,970 --> 00:05:55,500
it 47 tuck you know we you know like

133
00:06:01,430 --> 00:05:58,980
fire tuck but 47 talk here this is a

134
00:06:03,710 --> 00:06:01,440
ground-based image and you can see that

135
00:06:05,270 --> 00:06:03,720
it's you know really kind of clouded out

136
00:06:07,100 --> 00:06:05,280
in the center a lot of things will go

137
00:06:09,110 --> 00:06:07,110
out it's very crowded in the center of

138
00:06:10,880 --> 00:06:09,120

these globular clusters and the stars

139
00:06:13,460 --> 00:06:10,890
all mixed together and they're very hard

140
00:06:15,830 --> 00:06:13,470
to see who are you gonna call to fix

141
00:06:18,110 --> 00:06:15,840
that of course you're gonna call Hubble

142
00:06:20,180 --> 00:06:18,120
when Hubble looks at the center of that

143
00:06:23,330 --> 00:06:20,190
globular cluster it can see the

144
00:06:25,700 --> 00:06:23,340
individual stars and when it looked at

145
00:06:28,970 --> 00:06:25,710
the individual stars inside 47 tuck it

146
00:06:32,210 --> 00:06:28,980
found some blue stars that it didn't

147
00:06:35,810 --> 00:06:32,220
expect to see because globular clusters

148
00:06:38,270 --> 00:06:35,820
are old stars old stars are orange and

149
00:06:41,660 --> 00:06:38,280
red and yellow at the best Kay

150
00:06:44,690 --> 00:06:41,670
not blue old really old stars are not

151
00:06:48,379 --> 00:06:44,700
blue only young stars are blue but yet

152
00:06:51,170 --> 00:06:48,389
we found some extra blue stars nicknamed

153
00:06:53,030 --> 00:06:51,180
blue stragglers as in they shoulda

154
00:06:56,120 --> 00:06:53,040
should be old and yellow by now but

155
00:06:59,300 --> 00:06:56,130
they're still blue so where do these

156
00:07:01,760 --> 00:06:59,310
blue stragglers come from well the first

157
00:07:04,190 --> 00:07:01,770
hypothesis the first idea was that they

158
00:07:06,470 --> 00:07:04,200
came from collisions you take two old

159
00:07:08,540 --> 00:07:06,480
stars smash them together

160
00:07:11,150 --> 00:07:08,550
the hydrogen mixes throughout you get

161
00:07:13,490 --> 00:07:11,160
some new nuclear fusion going on and you

162
00:07:15,290 --> 00:07:13,500
can get yourself a blue star and that's

163
00:07:16,909 --> 00:07:15,300

how I first learned that all blue Suraj

164
00:07:19,400 --> 00:07:16,919
little star or straggler stars are

165
00:07:21,470 --> 00:07:19,410
collisions between stars and you only

166
00:07:23,510 --> 00:07:21,480
see them in globular clusters because

167
00:07:24,920 --> 00:07:23,520
the density of stars in globular

168
00:07:27,800 --> 00:07:24,930
clusters is so great you can actually

169
00:07:29,030 --> 00:07:27,810
get these collisions well we worked on

170
00:07:30,980 --> 00:07:29,040
it and worked on and then they figured

171
00:07:32,960 --> 00:07:30,990
out well actually you can do an

172
00:07:35,810 --> 00:07:32,970
accretion method you can actually have

173
00:07:38,360 --> 00:07:35,820
one star steal the atmosphere from the

174
00:07:40,400 --> 00:07:38,370
other star add more in get some fresh

175
00:07:43,730 --> 00:07:40,410
hydrogen get some fresh nuclear fusion

176
00:07:46,610 --> 00:07:43,740
and get the blue blue star again so but

177
00:07:47,900 --> 00:07:46,620
you can get these blue stars okay the

178
00:07:51,050 --> 00:07:47,910
important point about these blue

179
00:07:54,080 --> 00:07:51,060
stragglers is that they are blue they're

180
00:07:57,409 --> 00:07:54,090
very bright okay and they're very

181
00:07:59,690 --> 00:07:57,419
luminous okay so they are easy to find

182
00:08:01,070 --> 00:07:59,700
inside globular clusters when you have a

183
00:08:04,940 --> 00:08:01,080
Hubble Space Telescope

184
00:08:09,260 --> 00:08:04,950
now the dynamics there's a second point

185
00:08:11,450 --> 00:08:09,270
this kinematic age when a globular

186
00:08:12,920 --> 00:08:11,460
cluster orbits all these stars orbiting

187
00:08:14,990 --> 00:08:12,930
around each other you think this is a

188
00:08:17,029 --> 00:08:15,000

great gravitational laboratory with the

189
00:08:18,950 --> 00:08:17,039
Stars moving all over the place but

190
00:08:21,469 --> 00:08:18,960
there's an effect inside these globular

191
00:08:25,100 --> 00:08:21,479
clusters called dynamical friction in

192
00:08:28,640 --> 00:08:25,110
which the more massive stars tend to

193
00:08:30,230 --> 00:08:28,650
settle toward the center while the less

194
00:08:33,200 --> 00:08:30,240
massive stars gets thrown out towards

195
00:08:35,990 --> 00:08:33,210
the periphery so more massive stars

196
00:08:39,560 --> 00:08:36,000
toward the center these blue stragglers

197
00:08:42,020 --> 00:08:39,570
are more massive stars they should

198
00:08:44,720 --> 00:08:42,030
congregate toward the center we could

199
00:08:47,690 --> 00:08:44,730
use them to measure the dynamical age

200
00:08:51,110 --> 00:08:47,700
how dynamically evolved these globular

201
00:08:52,160 --> 00:08:51,120
clusters are right so here's how they

202
00:08:54,920 --> 00:08:52,170
designed

203
00:08:57,650 --> 00:08:54,930
method to test this they used the Large

204
00:08:59,780 --> 00:08:57,660
Magellanic Cloud which is about 160,000

205
00:09:01,910 --> 00:08:59,790
light years away and they found a

206
00:09:04,220 --> 00:09:01,920
selection of globular clusters that are

207
00:09:07,220 --> 00:09:04,230
all basically born about the same time

208
00:09:09,230 --> 00:09:07,230
so these globular clusters are at the

209
00:09:11,420 --> 00:09:09,240
same distance and they're the same

210
00:09:13,640 --> 00:09:11,430
chronological age they're about the same

211
00:09:16,160 --> 00:09:13,650
age the difference between these

212
00:09:19,550 --> 00:09:16,170
globular clusters is their mass their

213
00:09:22,010 --> 00:09:19,560

size right and so here is one of these

214
00:09:24,140 --> 00:09:22,020
globular clusters this is a globular

215
00:09:26,330 --> 00:09:24,150
cluster in the Large Magellanic Cloud

216
00:09:28,880 --> 00:09:26,340
this is not in our galaxy this is in a

217
00:09:31,940 --> 00:09:28,890
satellite galaxy and this is how cool

218
00:09:34,820 --> 00:09:31,950
Hubble can Hubble's resolution can see

219
00:09:36,920 --> 00:09:34,830
such great detail and so with a

220
00:09:39,530 --> 00:09:36,930
selection of these globular clusters

221
00:09:41,960 --> 00:09:39,540
they measured the blue stragglers and

222
00:09:44,180 --> 00:09:41,970
the concentration toward the center of

223
00:09:46,670 --> 00:09:44,190
these blue stragglers in each of these

224
00:09:49,250 --> 00:09:46,680
globular clusters and for the first time

225
00:09:52,220 --> 00:09:49,260
they confirmed what's probably an

226
00:09:54,500 --> 00:09:52,230
expected result but that in the more

227
00:09:57,680 --> 00:09:54,510
massive clusters the blue stragglers

228
00:10:00,050 --> 00:09:57,690
were more concentrated they showed that

229
00:10:01,730 --> 00:10:00,060
you can use the concentration of the

230
00:10:04,520 --> 00:10:01,740
blue stragglers toward the center of God

231
00:10:07,310 --> 00:10:04,530
go up a cluster as a measure of its

232
00:10:09,470 --> 00:10:07,320
dynamical age or its kinetic age of the

233
00:10:11,630 --> 00:10:09,480
globular cluster different from its

234
00:10:14,180 --> 00:10:11,640
chronological age how old the stars are

235
00:10:16,430 --> 00:10:14,190
that dot how much dynamics evolution has

236
00:10:19,340 --> 00:10:16,440
gone on inside the cluster can be shown

237
00:10:21,800 --> 00:10:19,350
by these blue stragglers in the core of

238
00:10:24,260 --> 00:10:21,810

a globular cluster and that was kind of

239
00:10:27,980 --> 00:10:24,270
cool in terms of understanding these

240
00:10:31,010 --> 00:10:27,990
very very large stellar systems our

241
00:10:32,990 --> 00:10:31,020
second story for you tonight which is by

242
00:10:36,590 --> 00:10:33,000
the way it related to the litho that

243
00:10:39,710 --> 00:10:36,600
you've got Saturn's 2019 yearbook

244
00:10:42,710 --> 00:10:39,720
picture how many of you were here last

245
00:10:44,240 --> 00:10:42,720
month okay if you were it since you were

246
00:10:47,330 --> 00:10:44,250
here you remember what we talked about

247
00:10:49,490 --> 00:10:47,340
we talked about Jupiter and the opal the

248
00:10:51,950 --> 00:10:49,500
outer planets atmospheres Legacy Program

249
00:10:55,040 --> 00:10:51,960
getting a gorgeous image of Jupiter for

250
00:10:57,440 --> 00:10:55,050
2019 well if it's the outer planets

251
00:11:01,970 --> 00:10:57,450
program if you get Jupiter you've got to

252
00:11:04,640 --> 00:11:01,980
get Saturn boom there is the Opel image

253
00:11:06,560 --> 00:11:04,650
for 2019 of Saturn all right

254
00:11:08,480 --> 00:11:06,570
gorgeous images of the outer planets

255
00:11:11,900 --> 00:11:08,490
that they take in order to study

256
00:11:18,220 --> 00:11:11,910
year-over-year the history of the outer

257
00:11:20,810 --> 00:11:18,230
planets atmospheres now let me grab this

258
00:11:23,950 --> 00:11:20,820
reason I gave you this here tonight is

259
00:11:27,590 --> 00:11:23,960
now this was the 2018 image of Saturn

260
00:11:30,800 --> 00:11:27,600
this is the 2019 image of Saturn what

261
00:11:39,610 --> 00:11:30,810
can we see that changed okay well here's

262
00:11:42,590 --> 00:11:39,620
the 2018 and back to the 2019 2018 2019

263
00:11:49,040 --> 00:11:42,600

go back to the 2018 what I pointed out

264
00:11:51,710 --> 00:11:49,050
earlier this storm up here right that is

265
00:11:54,830 --> 00:11:51,720
gone in 2019 okay so this storm is not

266
00:11:58,160 --> 00:11:54,840
very long-lasting you'll also notice the

267
00:12:00,740 --> 00:11:58,170
tilt of the Rings okay if you look at

268
00:12:04,000 --> 00:12:00,750
the top of Jupiter it sort of touches

269
00:12:06,950 --> 00:12:04,010
the Rings here but if I go back to 2018

270
00:12:07,330 --> 00:12:06,960
you can see the tilt of the Rings all

271
00:12:11,060 --> 00:12:07,340
right

272
00:12:14,150 --> 00:12:11,070
Saturn like Earth is has an axial tilt

273
00:12:16,220 --> 00:12:14,160
and that axial tilt stays constant as it

274
00:12:18,680 --> 00:12:16,230
orbits around the Sun but since its

275
00:12:22,130 --> 00:12:18,690
moved a bit in its orbit our view of it

276
00:12:25,040 --> 00:12:22,140
changes and they or the perspective that

277
00:12:27,470 --> 00:12:25,050
we see for a changes and now we can see

278
00:12:33,310 --> 00:12:27,480
less of the Rings in 2019 than we could

279
00:12:36,530 --> 00:12:33,320
in 2018 all right so this is yet another

280
00:12:41,480 --> 00:12:36,540
image in the Opel Legacy Program here in

281
00:12:43,940 --> 00:12:41,490
2019 and I have a really cool fun fact

282
00:12:47,270 --> 00:12:43,950
for you because Hubble has been looking

283
00:12:52,450 --> 00:12:47,280
at Saturn throughout its entire history

284
00:12:55,490 --> 00:12:52,460
and Hubble is 29 years over 29 years old

285
00:12:58,150 --> 00:12:55,500
matter of fact what Hubble is almost

286
00:13:01,130 --> 00:12:58,160
twenty nine point four five years old

287
00:13:02,090 --> 00:13:01,140
which is a very important number yes he

288
00:13:04,130 --> 00:13:02,100

knows what I'm talking about

289
00:13:08,090 --> 00:13:04,140
here's your fun fact I'm gonna leave you

290
00:13:10,550 --> 00:13:08,100
with on Tuesday October 8th 2019 next

291
00:13:14,990 --> 00:13:10,560
Tuesday Saturn will have completed

292
00:13:18,910 --> 00:13:15,000
exactly one orbit around the Sun since

293
00:13:22,900 --> 00:13:18,920
the launch of Hubble on April 24th 9th

294
00:13:26,540 --> 00:13:22,910
in all the years that Hubble has been up

295
00:13:29,870 --> 00:13:26,550
Saturn has made only one orbit around

296
00:13:32,750 --> 00:13:29,880
the Sun it has a twenty nine point four

297
00:13:34,540 --> 00:13:32,760
five earth year orbit which is ten

298
00:13:39,019 --> 00:13:34,550
thousand seven hundred and fifty nine

299
00:13:40,430 --> 00:13:39,029
days so while Hubble has been up for

300
00:13:44,000 --> 00:13:40,440
almost 30 years

301
00:13:47,180 --> 00:13:44,010
Saturn has only had one rotation around

302
00:13:49,550 --> 00:13:47,190
the Sun that's a fun fact all right

303
00:13:52,970 --> 00:13:49,560
that is our news from the universe floor

304
00:13:57,199 --> 00:13:52,980
and we go to our featured speaker our

305
00:13:59,990 --> 00:13:57,209
featured speaker tonight is let's see

306
00:14:02,389 --> 00:14:00,000
what's his Emmanuel Bertie from the

307
00:14:07,670 --> 00:14:02,399
Johns Hopkins University

308
00:14:10,129 --> 00:14:07,680
he has a storied past which number are

309
00:14:13,250 --> 00:14:10,139
you on this are you four on this circle

310
00:14:16,370 --> 00:14:13,260
for great there we go

311
00:14:19,610 --> 00:14:16,380
here's a storied past having yet gotten

312
00:14:22,519 --> 00:14:19,620
his master's in his PhD in Italy then

313
00:14:25,220 --> 00:14:22,529

having worked in Greece then he moved to

314
00:14:26,840 --> 00:14:25,230
Paris and after the cosmopolitan in

315
00:14:33,439 --> 00:14:26,850
Paris he which of the great city of st.

316
00:14:36,559 --> 00:14:33,449
Louis let's say Louis for the Jet

317
00:14:38,059 --> 00:14:36,569
Propulsion Laboratory in Pasadena and

318
00:14:39,590 --> 00:14:38,069
then went to the University of

319
00:14:43,280 --> 00:14:39,600
Mississippi where he actually stayed for

320
00:14:45,740 --> 00:14:43,290
nine years before last summer coming

321
00:14:48,319 --> 00:14:45,750
here to joins a faculty at Johns Hopkins

322
00:14:55,760 --> 00:14:48,329
University so ladies and gentlemen

323
00:15:00,930 --> 00:14:58,770
thank you Frank and great memory I have

324
00:15:02,840 --> 00:15:00,940
been to so many places I don't remember

325
00:15:07,230 --> 00:15:02,850
myself

326
00:15:10,740 --> 00:15:07,240
okay so it's great to see so many people

327
00:15:12,900 --> 00:15:10,750
here tonight and to see so much interest

328
00:15:16,380 --> 00:15:12,910
in science what I'm going to talk about

329
00:15:18,510 --> 00:15:16,390
tonight are the very big guys and so I'm

330
00:15:21,870 --> 00:15:18,520
gonna be talking about black holes big

331
00:15:24,660 --> 00:15:21,880
and small actually and I will start by

332
00:15:27,690 --> 00:15:24,670
describing what black holes are what the

333
00:15:30,960 --> 00:15:27,700
history of the black hole idea is and

334
00:15:33,540 --> 00:15:30,970
then I will tell you about new ways that

335
00:15:36,540 --> 00:15:33,550
we have for looking at black holes and

336
00:15:39,450 --> 00:15:36,550
these colors are coming in by the day

337
00:15:42,540 --> 00:15:39,460
quite literally with the construction of

338
00:15:44,940 --> 00:15:42,550

gravitational wave detectors and the

339
00:15:47,070 --> 00:15:44,950
first detections just started about four

340
00:15:49,410 --> 00:15:47,080
years ago and it's a very exciting time

341
00:15:52,230 --> 00:15:49,420
to be alive so what are black holes

342
00:15:54,300 --> 00:15:52,240
these are an artist's impression of two

343
00:15:56,640 --> 00:15:54,310
black holes surrounded by accretion

344
00:15:59,250 --> 00:15:56,650
disks coming together and merging this

345
00:16:00,720 --> 00:15:59,260
is the kind of cataclysmic event that we

346
00:16:04,080 --> 00:16:00,730
are observing with gravitational wave

347
00:16:07,200 --> 00:16:04,090
detectors by now black holes are pretty

348
00:16:10,590 --> 00:16:07,210
much accepted by astronomers as one of

349
00:16:13,440 --> 00:16:10,600
the many inhabitants of the universe but

350
00:16:15,800 --> 00:16:13,450
there was a time when this was not so

351
00:16:18,180 --> 00:16:15,810
and I will start from the very beginning

352
00:16:19,710 --> 00:16:18,190
actually if I wanted to start from the

353
00:16:22,980 --> 00:16:19,720
very beginning I should go back to a guy

354
00:16:24,900 --> 00:16:22,990
called Reverend Mitchell who conceived

355
00:16:27,720 --> 00:16:24,910
of the idea black holes in Newtonian

356
00:16:29,640 --> 00:16:27,730
gravity but you know you only want

357
00:16:32,160 --> 00:16:29,650
Einstein gravity to describe black holes

358
00:16:34,430 --> 00:16:32,170
for what they really are and so we had

359
00:16:38,460 --> 00:16:34,440
to start with Einstein who in November

360
00:16:41,940 --> 00:16:38,470
1915 after ten years of struggling to

361
00:16:43,830 --> 00:16:41,950
put together Newtonian gravity with

362
00:16:46,350 --> 00:16:43,840
special relativity came up with what we

363
00:16:48,750 --> 00:16:46,360

now call the general theory of

364
00:16:50,610 --> 00:16:48,760
relativity so he wrote down is very

365
00:16:52,860 --> 00:16:50,620
complicated field equations he presented

366
00:16:57,240 --> 00:16:52,870
them to the Prussian Academy of Science

367
00:16:58,950 --> 00:16:57,250
in November 1915 and he thought they

368
00:17:01,470 --> 00:16:58,960
would be very very hard to find the

369
00:17:05,190 --> 00:17:01,480
solution to these equations what I

370
00:17:08,010 --> 00:17:05,200
didn't expect is that a German

371
00:17:10,740 --> 00:17:08,020
mathematician kashfar chilled

372
00:17:12,450 --> 00:17:10,750
we'll find a solution to the field

373
00:17:14,730 --> 00:17:12,460
equations and their conditions of very

374
00:17:16,410 --> 00:17:14,740
high symmetry so this german

375
00:17:18,600 --> 00:17:16,420
mathematician looked for solutions that

376
00:17:21,150 --> 00:17:18,610
do not depend on time and that are

377
00:17:23,070 --> 00:17:21,160
perfectly spherically symmetric so you

378
00:17:26,550 --> 00:17:23,080
know it's a mathematical solution it is

379
00:17:28,410 --> 00:17:26,560
really this he found it while he was

380
00:17:31,740 --> 00:17:28,420
fighting for the German army during

381
00:17:33,600 --> 00:17:31,750
World War one and at the same time he

382
00:17:37,740 --> 00:17:33,610
contracted a terrible disease and in

383
00:17:39,120 --> 00:17:37,750
fact he died on the front this solution

384
00:17:40,890 --> 00:17:39,130
was pretty much a mathematical curiosity

385
00:17:42,270 --> 00:17:40,900
at the very beginning and Einstein

386
00:17:44,240 --> 00:17:42,280
himself did not believe that he

387
00:17:46,980 --> 00:17:44,250
described anything of physical reality

388
00:17:48,890 --> 00:17:46,990

for two reasons one was a mathematical

389
00:17:51,390 --> 00:17:48,900
misunderstanding there was an apparent

390
00:17:53,460 --> 00:17:51,400
singularity in the equations that

391
00:17:55,200 --> 00:17:53,470
describe the solution a singularity is a

392
00:17:57,810 --> 00:17:55,210
point where this ocean goes to infinity

393
00:17:59,400 --> 00:17:57,820
so at first sight if you look at the

394
00:18:02,490 --> 00:17:59,410
solution looks like it's very badly

395
00:18:04,650 --> 00:18:02,500
behaved at some finite radius and so

396
00:18:06,950 --> 00:18:04,660
people thought yeah you know whatever

397
00:18:09,210 --> 00:18:06,960
it's mathematics it doesn't mean much

398
00:18:12,750 --> 00:18:09,220
but then there was another solution

399
00:18:14,370 --> 00:18:12,760
another singularity inside and that

400
00:18:18,510 --> 00:18:14,380
that's a different story I would get

401
00:18:20,160 --> 00:18:18,520
back to a little bit later so okay

402
00:18:21,600 --> 00:18:20,170
there's some mathematical solution of

403
00:18:26,340 --> 00:18:21,610
the field equations but no one really

404
00:18:28,650 --> 00:18:26,350
cares until 1930 were when an Indian

405
00:18:30,030 --> 00:18:28,660
student a very gifted Indian student by

406
00:18:33,060 --> 00:18:30,040
the name of Subrahmanyan Chandrasekhar

407
00:18:36,450 --> 00:18:33,070
wins a scholarship to go to Cambridge

408
00:18:38,100 --> 00:18:36,460
and study astrophysics there so at the

409
00:18:39,810 --> 00:18:38,110
time you didn't have airplane so this

410
00:18:41,810 --> 00:18:39,820
guy gets on a boat and he travels for

411
00:18:44,520 --> 00:18:41,820
about a month to go from India to

412
00:18:46,200 --> 00:18:44,530
Cambridge and on the boat he's he's

413
00:18:48,600 --> 00:18:46,210

doing math he's doing body well he knows

414
00:18:50,310 --> 00:18:48,610
how to do and he's tinkering with ideas

415
00:18:52,140 --> 00:18:50,320
coming from quantum mechanics that at

416
00:18:54,900 --> 00:18:52,150
the time was a brand-new theory and

417
00:18:57,330 --> 00:18:54,910
special relativity and he understands

418
00:19:02,010 --> 00:18:57,340
that certain stars they're called white

419
00:19:05,000 --> 00:19:02,020
dwarfs must collapse gravitationally if

420
00:19:08,430 --> 00:19:05,010
they are more massive than a certain

421
00:19:10,440 --> 00:19:08,440
mass which is 1.4 times the mass of the

422
00:19:13,380 --> 00:19:10,450
Sun what we now call the Chandrasekhar

423
00:19:15,690 --> 00:19:13,390
mass so he gets to Cambridge and he

424
00:19:19,320 --> 00:19:15,700
talks to Sir Arthur Eddington where the

425
00:19:21,550 --> 00:19:19,330
time was the British Royal astronomer so

426
00:19:25,360 --> 00:19:21,560
he was the world leading authority

427
00:19:27,760 --> 00:19:25,370
in astronomy and Eddington in public

428
00:19:30,120 --> 00:19:27,770
ridicules his discovery and he calls it

429
00:19:32,590 --> 00:19:30,130
a stellar buffoonery and and

430
00:19:35,850 --> 00:19:32,600
Chandrasekhar was a young kid at the

431
00:19:38,560 --> 00:19:35,860
time is completely shattered by the

432
00:19:39,840 --> 00:19:38,570
reaction but yet internally decides to

433
00:19:42,460 --> 00:19:39,850
leave and he goes to the United States

434
00:19:44,590 --> 00:19:42,470
he moves so Chicago becomes a professor

435
00:19:46,840 --> 00:19:44,600
in Chicago he works for many many years

436
00:19:50,560 --> 00:19:46,850
makes a lot of discoveries right seven

437
00:19:52,420 --> 00:19:50,570
books and in 1983 gets a Nobel Prize for

438
00:19:53,650 --> 00:19:52,430

what we now understand was the discovery

439
00:19:59,350 --> 00:19:53,660
that these stars when there are two

440
00:20:03,040 --> 00:19:59,360
massive must collapse okay then in 1939

441
00:20:06,280 --> 00:20:03,050
something else happens in 1939 of course

442
00:20:08,500 --> 00:20:06,290
the second world war begins and at that

443
00:20:10,450 --> 00:20:08,510
time there is another very brilliant

444
00:20:12,250 --> 00:20:10,460
physicist in the US who goes by the name

445
00:20:13,990 --> 00:20:12,260
of Robert Oppenheimer and I'm pretty

446
00:20:14,710 --> 00:20:14,000
sure that several of you had heard that

447
00:20:17,340 --> 00:20:14,720
name before

448
00:20:20,320 --> 00:20:17,350
I was working with a student Snyder on

449
00:20:22,480 --> 00:20:20,330
this idea of collapse and basically

450
00:20:25,210 --> 00:20:22,490
understands in a paper that is now

451
00:20:27,490 --> 00:20:25,220
famous by the time went unnoticed that

452
00:20:29,650 --> 00:20:27,500
stars can collapse and form what we now

453
00:20:32,080 --> 00:20:29,660
call black holes but this idea goes

454
00:20:33,700 --> 00:20:32,090
dormant because because of history

455
00:20:36,580 --> 00:20:33,710
Oppenheimer basically has to stop

456
00:20:38,830 --> 00:20:36,590
working on fancy astrophysics and he

457
00:20:40,090 --> 00:20:38,840
goes to Los Alamos puts together a group

458
00:20:44,050 --> 00:20:40,100
of brilliant people and builds the

459
00:20:46,540 --> 00:20:44,060
atomic bomb right at the same time

460
00:20:48,450 --> 00:20:46,550
there's another guy who's a main actor

461
00:20:52,360 --> 00:20:48,460
in the story was called John wheeler

462
00:20:54,220 --> 00:20:52,370
John Wheeler went to Denmark where he

463
00:20:56,710 --> 00:20:54,230

studied with new spore I was recently

464
00:20:59,170 --> 00:20:56,720
there visiting the newest Bohr Institute

465
00:21:00,460 --> 00:20:59,180
of the Copenhagen and there's some nice

466
00:21:02,740 --> 00:21:00,470
pictures of John wheeler

467
00:21:06,190 --> 00:21:02,750
you see him here he had a very special

468
00:21:08,140 --> 00:21:06,200
style when he lectured and used to draw

469
00:21:09,970 --> 00:21:08,150
a lot of diagrams on the board and then

470
00:21:11,950 --> 00:21:09,980
go through the diagrams one by one

471
00:21:16,360 --> 00:21:11,960
during his talks it was a very

472
00:21:18,550 --> 00:21:16,370
fascinating speaker wheeler was a

473
00:21:22,330 --> 00:21:18,560
nuclear physicist by training so he

474
00:21:24,820 --> 00:21:22,340
studies with Niels Bohr and then tragedy

475
00:21:27,730 --> 00:21:24,830
happens his brother dies in my native

476
00:21:29,830 --> 00:21:27,740
Italy while fighting in World War two

477
00:21:31,870 --> 00:21:29,840
and at the point he decides I really

478
00:21:34,740 --> 00:21:31,880
wants to get involved in the Manhattan

479
00:21:37,020 --> 00:21:34,750
Project si joins Oppenheimer

480
00:21:40,460 --> 00:21:37,030
works on the atomic bomb you know that

481
00:21:43,320 --> 00:21:40,470
particular story ends the war ends in

482
00:21:46,140 --> 00:21:43,330
1950 wheeler decides to get together

483
00:21:48,000 --> 00:21:46,150
with many brilliant students one of them

484
00:21:51,000 --> 00:21:48,010
is this guy keeps all of the Nobel Prize

485
00:21:52,620 --> 00:21:51,010
just a couple of years ago and he

486
00:21:54,570 --> 00:21:52,630
returns to the problem gravitational

487
00:21:58,740 --> 00:21:54,580
collapse that Oppenheimer had attacked

488
00:22:00,870 --> 00:21:58,750

back in the 1930s and with this group of

489
00:22:03,750 --> 00:22:00,880
students he understands gravitational

490
00:22:05,580 --> 00:22:03,760
collapse much better and in 1973 he

491
00:22:08,910 --> 00:22:05,590
writes his book called gravitation that

492
00:22:10,560 --> 00:22:08,920
is like a thousand pages thick and I

493
00:22:15,390 --> 00:22:10,570
have two copies of the book in my office

494
00:22:17,750 --> 00:22:15,400
and that's how revered it is and it's

495
00:22:23,040 --> 00:22:17,760
the Bible for everything gravitation

496
00:22:25,050 --> 00:22:23,050
okay then the 1960s in the 1960s there's

497
00:22:27,870 --> 00:22:25,060
a couple of crucial developments one is

498
00:22:31,560 --> 00:22:27,880
that once again a mathematician springs

499
00:22:33,570 --> 00:22:31,570
to action these guys call Eroica and I

500
00:22:35,670 --> 00:22:33,580
told you that the solution that shot you

501
00:22:37,770 --> 00:22:35,680
that found was very symmetric it was

502
00:22:39,840 --> 00:22:37,780
perfectly spherical and we know that

503
00:22:42,600 --> 00:22:39,850
stars rotate so you know if a star

504
00:22:44,580 --> 00:22:42,610
collapses it cannot form an object that

505
00:22:48,180 --> 00:22:44,590
is not rotating because of conservation

506
00:22:51,240 --> 00:22:48,190
of angular momentum and this guy car

507
00:22:54,780 --> 00:22:51,250
finds a solution that is what we call

508
00:22:57,270 --> 00:22:54,790
now a black hole and it's rotating so

509
00:22:59,580 --> 00:22:57,280
that's the mathematical progress and by

510
00:23:01,620 --> 00:22:59,590
coincidence in 1963 there's an

511
00:23:04,710 --> 00:23:01,630
astronomer a Caltech called Martin

512
00:23:07,290 --> 00:23:04,720
Schmidt who discovers an object that is

513
00:23:11,480 --> 00:23:07,300

extremely bright very far away

514
00:23:15,630 --> 00:23:11,490
located at a redshift of 0.15 and

515
00:23:19,200 --> 00:23:15,640
changes it changes very on a timescale

516
00:23:22,550 --> 00:23:19,210
that is very short so he calls the

517
00:23:25,650 --> 00:23:22,560
because this object a quasar quasi star

518
00:23:28,530 --> 00:23:25,660
this object has to be very bright very

519
00:23:30,480 --> 00:23:28,540
compact and each outshines even the

520
00:23:31,860 --> 00:23:30,490
brightest galaxies now we understand

521
00:23:34,890 --> 00:23:31,870
that that object was the first

522
00:23:38,040 --> 00:23:34,900
supermassive black hole so in the 60s

523
00:23:40,710 --> 00:23:38,050
and 70s many other things happen one of

524
00:23:42,780 --> 00:23:40,720
them is developments that involved the

525
00:23:45,780 --> 00:23:42,790
Space Telescope that will tell you about

526
00:23:48,300 --> 00:23:45,790
in a minute and keep Thorne wheeler

527
00:23:50,340 --> 00:23:48,310
student gets together with them

528
00:23:52,290 --> 00:23:50,350
bunch of very brilliant students and

529
00:23:53,970 --> 00:23:52,300
they try to understand whether these

530
00:23:56,250 --> 00:23:53,980
black hole solutions are stable or not

531
00:23:58,590 --> 00:23:56,260
there are still purely mathematical

532
00:24:00,630 --> 00:23:58,600
solutions so people want to understand

533
00:24:02,070 --> 00:24:00,640
if they make sense at all and they try

534
00:24:03,360 --> 00:24:02,080
to understand if they're stable and they

535
00:24:05,400 --> 00:24:03,370
had to do a lot of math and the math

536
00:24:09,840 --> 00:24:05,410
turns out right and these objects are

537
00:24:11,580 --> 00:24:09,850
stable okay all right not only they are

538
00:24:14,850 --> 00:24:11,590

stable they are very fascinating and

539
00:24:16,980 --> 00:24:14,860
they're very fascinating because to

540
00:24:18,690 --> 00:24:16,990
British mathematicians one of them is

541
00:24:22,260 --> 00:24:18,700
Roger Penrose and the other one is

542
00:24:23,670 --> 00:24:22,270
Stephen Hawking they discovered that the

543
00:24:26,550 --> 00:24:23,680
gravitational collapses I spoke about

544
00:24:29,550 --> 00:24:26,560
before is a very generic feature and

545
00:24:32,640 --> 00:24:29,560
whenever it happens within the theory of

546
00:24:34,680 --> 00:24:32,650
general relativity it inevitably leads

547
00:24:37,590 --> 00:24:34,690
to the formation of singularities now

548
00:24:39,000 --> 00:24:37,600
this is not the fake mathematical

549
00:24:41,610 --> 00:24:39,010
singularity I was talking about before

550
00:24:46,320 --> 00:24:41,620
it's a real singularity so black holes

551
00:24:48,240 --> 00:24:46,330
are sort of like the time reversal what

552
00:24:50,180 --> 00:24:48,250
happens in the birth of the universe at

553
00:24:52,890 --> 00:24:50,190
the birth of the universe there's a

554
00:24:55,070 --> 00:24:52,900
singularity or you know a point at which

555
00:24:58,410 --> 00:24:55,080
we don't know what the laws of physics

556
00:25:00,300 --> 00:24:58,420
look like and everything expands out of

557
00:25:02,880 --> 00:25:00,310
the singularity gravitational collapse

558
00:25:03,930 --> 00:25:02,890
is basically the same film in Reverse

559
00:25:08,760 --> 00:25:03,940
right

560
00:25:11,010 --> 00:25:08,770
and so Hawking in particular understands

561
00:25:12,750 --> 00:25:11,020
this fact and you also understand

562
00:25:14,760 --> 00:25:12,760
something else that if you try to

563
00:25:17,610 --> 00:25:14,770

combine quantum mechanics with black

564
00:25:21,270 --> 00:25:17,620
holes then black holes are not quite as

565
00:25:23,340 --> 00:25:21,280
black as their picture to be because

566
00:25:25,830 --> 00:25:23,350
they can radiate now we call the Hawking

567
00:25:28,350 --> 00:25:25,840
radiation we think that holds clues to

568
00:25:31,970 --> 00:25:28,360
the nature of quantum gravity that we

569
00:25:34,680 --> 00:25:31,980
don't understand yet so all you know

570
00:25:36,420 --> 00:25:34,690
black holes are mathematical solutions

571
00:25:38,790 --> 00:25:36,430
of the Einstein equations they do not

572
00:25:40,830 --> 00:25:38,800
involve matter they're very pretty

573
00:25:42,800 --> 00:25:40,840
mathematical constructs that I can write

574
00:25:45,240 --> 00:25:42,810
down in two lines on a piece of paper

575
00:25:47,010 --> 00:25:45,250
but they are extremely fascinating

576
00:25:50,010 --> 00:25:47,020
because as Chandra said and Chandra

577
00:25:53,400 --> 00:25:50,020
someone was had a very active scientific

578
00:25:55,980 --> 00:25:53,410
life in all of that scientific like life

579
00:25:58,440 --> 00:25:55,990
extending over 45 years the most

580
00:25:59,880 --> 00:25:58,450
shattering experience for him had been

581
00:26:01,720 --> 00:25:59,890
the realization that an exact solution

582
00:26:04,810 --> 00:26:01,730
of Einstein's equations disco

583
00:26:06,910 --> 00:26:04,820
by row occur provides the absolutely

584
00:26:08,890 --> 00:26:06,920
exact representation of untold numbers

585
00:26:11,140 --> 00:26:08,900
of massive black holes that populate the

586
00:26:12,610 --> 00:26:11,150
universe the shattering before the

587
00:26:14,260 --> 00:26:12,620
beautiful this incredible factor a

588
00:26:16,660 --> 00:26:14,270

discovery motivated by a search after

589
00:26:19,180 --> 00:26:16,670
the beautiful in mathematics should find

590
00:26:21,070 --> 00:26:19,190
its exact replica in nature persuades me

591
00:26:23,170 --> 00:26:21,080
to say that beauty is that which the

592
00:26:26,410 --> 00:26:23,180
human mind responds at its deepest and

593
00:26:28,360 --> 00:26:26,420
most profound it's mind-boggling for

594
00:26:30,910 --> 00:26:28,370
someone like me who does physics for a

595
00:26:32,500 --> 00:26:30,920
living that you can write down simple

596
00:26:35,230 --> 00:26:32,510
equations and solve them and the

597
00:26:38,710 --> 00:26:35,240
universe works that way you know it's

598
00:26:40,660 --> 00:26:38,720
it's really amazing so what are how how

599
00:26:44,680 --> 00:26:40,670
do these black holes get there in the

600
00:26:47,890 --> 00:26:44,690
universe in several ways we think but

601
00:26:50,380 --> 00:26:47,900
the most the most likely way is through

602
00:26:53,560 --> 00:26:50,390
the collapse of stars so what you have

603
00:26:56,290 --> 00:26:53,570
are stars you guys probably come here

604
00:26:58,480 --> 00:26:56,300
after you know how stars work stars work

605
00:27:01,990 --> 00:26:58,490
through a balance of gravity and

606
00:27:04,750 --> 00:27:02,000
pressure forces gravity pulls stuff in

607
00:27:07,090 --> 00:27:04,760
when stuff gets compressed it becomes

608
00:27:09,910 --> 00:27:07,100
hot it becomes hot there are nuclear

609
00:27:13,240 --> 00:27:09,920
reactions those nuclear reactions burn

610
00:27:16,240 --> 00:27:13,250
typically two hydrogen atoms into helium

611
00:27:18,910 --> 00:27:16,250
and release some energy and that energy

612
00:27:22,690 --> 00:27:18,920
generates pressure that pushes outwards

613
00:27:25,000 --> 00:27:22,700

okay so you have nuclear reactions you

614
00:27:29,380 --> 00:27:25,010
burn nuclear fuel you push outwards

615
00:27:31,660 --> 00:27:29,390
gravity pushes inwards and when stuff

616
00:27:33,340 --> 00:27:31,670
becomes more and more compact there are

617
00:27:35,890 --> 00:27:33,350
other nuclear reactions that come into

618
00:27:38,800 --> 00:27:35,900
play so hydrogen thebirds into helium

619
00:27:42,820 --> 00:27:38,810
and then carbon and the neon oxygen

620
00:27:46,360 --> 00:27:42,830
silica and ira and that's it and that's

621
00:27:48,760 --> 00:27:46,370
it because iron out of all nuclear

622
00:27:51,400 --> 00:27:48,770
elements is the one that has the lowest

623
00:27:53,140 --> 00:27:51,410
binding energy per nucleon we say so

624
00:27:55,630 --> 00:27:53,150
it's the most stable of all nuclear

625
00:28:00,820 --> 00:27:55,640
elements you cannot make anything that

626
00:28:03,730 --> 00:28:00,830
is more stable than iron okay so when

627
00:28:06,730 --> 00:28:03,740
you run out of fuel what happens gravity

628
00:28:10,810 --> 00:28:06,740
wins and when gravity wins all of this

629
00:28:13,060 --> 00:28:10,820
stuff collapses and the star dies and it

630
00:28:15,930 --> 00:28:13,070
makes a big splash and produces what we

631
00:28:19,600 --> 00:28:15,940
call a supernova the first super

632
00:28:23,770 --> 00:28:19,610
was observed by chinese astronomers back

633
00:28:25,270 --> 00:28:23,780
in 1054 and what they saw was they were

634
00:28:28,030 --> 00:28:25,280
looking at the sky that were keeping

635
00:28:30,220 --> 00:28:28,040
very careful record of everything that

636
00:28:32,440 --> 00:28:30,230
they saw and in their journals they

637
00:28:34,960 --> 00:28:32,450
wrote down that a star suddenly appeared

638
00:28:38,050 --> 00:28:34,970

in the sky it was there for about 23

639
00:28:40,600 --> 00:28:38,060
days and then it disappeared

640
00:28:43,150 --> 00:28:40,610
so didn't know what it went where it

641
00:28:46,360 --> 00:28:43,160
went and now we understand that this was

642
00:28:49,870 --> 00:28:46,370
a supernova and what was left behind was

643
00:28:51,700 --> 00:28:49,880
what we now call a neutron star what are

644
00:28:53,530 --> 00:28:51,710
all of these crazy things I'm talking

645
00:28:54,220 --> 00:28:53,540
about white dwarfs neutron stars black

646
00:28:59,710 --> 00:28:54,230
holes

647
00:29:01,330 --> 00:28:59,720
I like zombie movies and I hope you like

648
00:29:01,960 --> 00:29:01,340
this movie - it's brilliant it's

649
00:29:04,000 --> 00:29:01,970
brilliant

650
00:29:05,620 --> 00:29:04,010
this is the Night of the Living Dead if

651
00:29:07,180 --> 00:29:05,630
you haven't seen it I highly recommend

652
00:29:10,690 --> 00:29:07,190
it

653
00:29:13,690 --> 00:29:10,700
and what what these objects are they're

654
00:29:16,240 --> 00:29:13,700
zombies they are stars who died and come

655
00:29:18,700 --> 00:29:16,250
back to life okay how do they come back

656
00:29:21,460 --> 00:29:18,710
to life there are several different ways

657
00:29:24,280 --> 00:29:21,470
that stars can come back to life when a

658
00:29:26,050 --> 00:29:24,290
star is small smaller than about three

659
00:29:27,640 --> 00:29:26,060
solar masses take these numbers with a

660
00:29:30,010 --> 00:29:27,650
grain of salt because no one really

661
00:29:33,900 --> 00:29:30,020
knows let's say smaller than about three

662
00:29:36,280 --> 00:29:33,910
solar masses then a star like our Sun

663
00:29:39,430 --> 00:29:36,290

after it burns its nuclear fuel it

664
00:29:41,710 --> 00:29:39,440
expands it becomes a red giant then it

665
00:29:44,770 --> 00:29:41,720
collapses eventually and it forms a

666
00:29:46,990 --> 00:29:44,780
white dwarf if the mass of the star is

667
00:29:49,830 --> 00:29:47,000
higher how much higher between about

668
00:29:53,170 --> 00:29:49,840
three and ten solar masses about okay

669
00:29:54,790 --> 00:29:53,180
then when the star collapses he forms

670
00:29:58,030 --> 00:29:54,800
what we call a neutron star but if the

671
00:30:01,150 --> 00:29:58,040
star is really really massive more than

672
00:30:03,280 --> 00:30:01,160
about ten solar masses then there is

673
00:30:05,770 --> 00:30:03,290
nothing to keep it from collapsing and

674
00:30:07,360 --> 00:30:05,780
it produces a black hole what keeps a

675
00:30:10,630 --> 00:30:07,370
white dwarf together is quantum

676
00:30:12,640 --> 00:30:10,640
mechanics it's the uncertainty principle

677
00:30:15,070 --> 00:30:12,650
it's actually the power exclusion

678
00:30:16,270 --> 00:30:15,080
principle between electrons so electrons

679
00:30:18,310 --> 00:30:16,280
don't want to be together and they push

680
00:30:20,170 --> 00:30:18,320
outward what keeps a neutron star

681
00:30:23,020 --> 00:30:20,180
together is the same idea but for

682
00:30:24,520 --> 00:30:23,030
neutrons and what keeps a black hole

683
00:30:28,100 --> 00:30:24,530
together is nothing a black hole is just

684
00:30:31,789 --> 00:30:28,110
stuff that keeps collapsing okay

685
00:30:34,720 --> 00:30:31,799
so if you imagine picturing gravity as

686
00:30:37,250 --> 00:30:34,730
the bending in the fabric of space-time

687
00:30:41,570 --> 00:30:37,260
what you can imagine is that you have a

688
00:30:44,870 --> 00:30:41,580

large sheet and the sheet is only mildly

689
00:30:47,960 --> 00:30:44,880
bent by the Sun it's much more bent

690
00:30:49,789 --> 00:30:47,970
around a white dwarf and extremely bent

691
00:30:51,019 --> 00:30:49,799
around the black hole and the way to

692
00:30:53,750 --> 00:30:51,029
understand the gravitational collapse

693
00:30:56,570 --> 00:30:53,760
that I was talking about before a very

694
00:30:58,370 --> 00:30:56,580
useful analogy comes from a book that

695
00:31:01,730 --> 00:30:58,380
Kip Thorne wrote which is called black

696
00:31:04,820 --> 00:31:01,740
holes time warps black holes and time

697
00:31:08,029 --> 00:31:04,830
warps I think Einstein is outrageous

698
00:31:10,159 --> 00:31:08,039
legacy and and well this is what he

699
00:31:12,409 --> 00:31:10,169
calls the parable of the ends so imagine

700
00:31:14,419 --> 00:31:12,419
that you have a bunch of ants living on

701
00:31:17,570 --> 00:31:14,429
a membrane like the one that I was

702
00:31:18,529 --> 00:31:17,580
talking about before and one of these

703
00:31:20,960 --> 00:31:18,539
ants is a loner

704
00:31:23,779 --> 00:31:20,970
she's an astronomer she decides to stay

705
00:31:26,299 --> 00:31:23,789
at the side of the membrane because she

706
00:31:28,279 --> 00:31:26,309
doesn't like partying but the other the

707
00:31:30,769 --> 00:31:28,289
others the other hands they decide to

708
00:31:33,620 --> 00:31:30,779
congregate at the center and has some

709
00:31:35,299 --> 00:31:33,630
drinks so they go to a center and the

710
00:31:39,500 --> 00:31:35,309
membrane under the weight of the ants

711
00:31:41,810 --> 00:31:39,510
starts collapsing okay now these ants

712
00:31:44,509 --> 00:31:41,820
decide to communicate with the loner by

713
00:31:46,490 --> 00:31:44,519

sending little balls okay and they send

714
00:31:48,799 --> 00:31:46,500
little balls every one second let's say

715
00:31:50,870 --> 00:31:48,809
so they send a ball and they send the

716
00:31:52,820 --> 00:31:50,880
ball and they send a ball but at the

717
00:31:54,649 --> 00:31:52,830
same time as they're sending balls they

718
00:31:57,169 --> 00:31:54,659
keep falling because the membrane is

719
00:31:59,509 --> 00:31:57,179
collapsing down and at some point the

720
00:32:02,149 --> 00:31:59,519
speed at which the membrane is falling

721
00:32:04,370 --> 00:32:02,159
down is faster than the speed of the

722
00:32:08,629 --> 00:32:04,380
balls that they're throwing out so in

723
00:32:11,000 --> 00:32:08,639
this analogy the balls are light and the

724
00:32:12,830 --> 00:32:11,010
fact that the the ants are congregating

725
00:32:14,450 --> 00:32:12,840
at the center and collapsing is matter

726
00:32:17,240 --> 00:32:14,460
in a star that is collapse into a black

727
00:32:18,919 --> 00:32:17,250
hole and at some point as you can

728
00:32:21,019 --> 00:32:18,929
imagine there's a horizon there's a

729
00:32:22,789 --> 00:32:21,029
point beyond which these balls will

730
00:32:25,100 --> 00:32:22,799
never get to the astronomer any more and

731
00:32:27,680 --> 00:32:25,110
he will think that these ends are frozen

732
00:32:30,139 --> 00:32:27,690
at the point and in fact initially

733
00:32:31,759 --> 00:32:30,149
people thought of black holes as frozen

734
00:32:35,240 --> 00:32:31,769
stars that's what they were called in

735
00:32:37,220 --> 00:32:35,250
Russian books before John Wheeler and

736
00:32:40,159 --> 00:32:37,230
the gang came over and started calling

737
00:32:41,879 --> 00:32:40,169
them black holes so these exactly what

738
00:32:43,259 --> 00:32:41,889

happens during gravitational collapse

739
00:32:45,450 --> 00:32:43,269
from the point of view of the ants

740
00:32:48,659 --> 00:32:45,460
nothing wrong happen they just fell in

741
00:32:53,369 --> 00:32:48,669
and they got trapped they'll die but you

742
00:32:54,810 --> 00:32:53,379
know whether that's life so so you

743
00:32:56,909 --> 00:32:54,820
cannot see a black hole because by

744
00:32:59,340 --> 00:32:56,919
definition not even light can get out so

745
00:33:02,100 --> 00:32:59,350
how do we see black holes the way we see

746
00:33:04,049 --> 00:33:02,110
black holes is through gas that is

747
00:33:06,989 --> 00:33:04,059
accreting on to the black hole and

748
00:33:09,359 --> 00:33:06,999
that's because physics tells us the

749
00:33:11,700 --> 00:33:09,369
neutron stars can never be more massive

750
00:33:14,639 --> 00:33:11,710
than about three solar masses there's

751
00:33:15,899 --> 00:33:14,649
just no way that regular matter can keep

752
00:33:18,090 --> 00:33:15,909
them together if they are more massive

753
00:33:19,560 --> 00:33:18,100
than that so you watch gas that is

754
00:33:21,960 --> 00:33:19,570
falling onto something that is very

755
00:33:23,310 --> 00:33:21,970
compact and if it's very compact and

756
00:33:26,820 --> 00:33:23,320
it's more massive than three solar

757
00:33:28,739 --> 00:33:26,830
masses then you can be pretty certain

758
00:33:32,999 --> 00:33:28,749
it's a block oh this is the way the

759
00:33:35,099 --> 00:33:33,009
first black hole was observed in 1964 by

760
00:33:37,619 --> 00:33:35,109
this guy riccardo giacconi who comes

761
00:33:40,979 --> 00:33:37,629
like me from Italy and got the Nobel

762
00:33:42,599 --> 00:33:40,989
Prize unlike me and he was here and he

763
00:33:45,769 --> 00:33:42,609

played a major role in the development

764
00:33:47,970 --> 00:33:45,779
of the space telescope as you all know

765
00:33:50,249 --> 00:33:47,980
and Jack O'Neill went on and he

766
00:33:53,909 --> 00:33:50,259
basically created a whole new way of

767
00:33:57,749 --> 00:33:53,919
looking at astronomical objects through

768
00:34:00,389 --> 00:33:57,759
x-rays there's a second way that we can

769
00:34:02,700 --> 00:34:00,399
look at black holes and I'll show you a

770
00:34:04,440 --> 00:34:02,710
neat movie here this is now the black

771
00:34:08,129 --> 00:34:04,450
hole that is born from the collapse of

772
00:34:10,200 --> 00:34:08,139
stars this is what the monster that

773
00:34:13,530 --> 00:34:10,210
lives at the center of our own Milky Way

774
00:34:16,200 --> 00:34:13,540
it's called Sagittarius a star and the

775
00:34:20,700 --> 00:34:16,210
way we see it is through the motion of

776
00:34:23,339 --> 00:34:20,710
stars that are very close to that

777
00:34:25,740 --> 00:34:23,349
central object this white dot is only

778
00:34:30,750 --> 00:34:25,750
there to guide the eye it's not really

779
00:34:32,220 --> 00:34:30,760
there and what we observe over time you

780
00:34:34,849 --> 00:34:32,230
can see the date of the observations

781
00:34:37,829 --> 00:34:34,859
over here are perfect ellipses around

782
00:34:40,530 --> 00:34:37,839
something that we don't see now from the

783
00:34:42,149 --> 00:34:40,540
shape of those ellipses you can tell the

784
00:34:44,399 --> 00:34:42,159
mass of the big guy that they're

785
00:34:46,319 --> 00:34:44,409
orbiting around and because these stars

786
00:34:49,680 --> 00:34:46,329
are so close you can also tell that that

787
00:34:51,539 --> 00:34:49,690
object has to be very very compact so

788
00:34:53,730 --> 00:34:51,549

compact that the only reasonable

789
00:34:55,080 --> 00:34:53,740
explanation is that it's a black hole

790
00:34:57,210 --> 00:34:55,090
we can measure the mass of the black

791
00:35:00,420 --> 00:34:57,220
hole now very accurately and it's four

792
00:35:02,520 --> 00:35:00,430
million solar masses how they get there

793
00:35:03,870 --> 00:35:02,530
we don't really know and we want to find

794
00:35:08,730 --> 00:35:03,880
out and he'll tell you some ideas that

795
00:35:10,560 --> 00:35:08,740
we have to find out now everything that

796
00:35:13,290 --> 00:35:10,570
we have seen in astronomy so far we have

797
00:35:14,970 --> 00:35:13,300
seen it through electromagnetic waves

798
00:35:17,280 --> 00:35:14,980
electromagnetic waves are basically

799
00:35:20,100 --> 00:35:17,290
light of different frequencies right and

800
00:35:23,970 --> 00:35:20,110
I find this image really fascinating

801
00:35:24,810 --> 00:35:23,980
these Andromeda m31 which is very very

802
00:35:27,750 --> 00:35:24,820
close by

803
00:35:30,780 --> 00:35:27,760
as far as astronomical distances go and

804
00:35:32,730 --> 00:35:30,790
you can see it in the visible this is

805
00:35:35,430 --> 00:35:32,740
what you could see if you had a very

806
00:35:36,810 --> 00:35:35,440
powerful optical telescope but you can

807
00:35:38,400 --> 00:35:36,820
also see that if you look at it in

808
00:35:40,740 --> 00:35:38,410
different wave bands it looks very very

809
00:35:42,510 --> 00:35:40,750
different you're seeing very different

810
00:35:44,580 --> 00:35:42,520
physics and very different phenomenon

811
00:35:48,109 --> 00:35:44,590
going on for example here what you see

812
00:35:50,970 --> 00:35:48,119
are dust lanes what you see appear is

813
00:35:52,230 --> 00:35:50,980

what the galaxy looks like in x-rays and

814
00:35:55,740 --> 00:35:52,240
you can see that there's a lot going on

815
00:35:57,030 --> 00:35:55,750
at the center and we now know that so

816
00:35:58,530 --> 00:35:57,040
much is going on at the center because

817
00:36:00,390 --> 00:35:58,540
there's a massive black hole there but

818
00:36:02,700 --> 00:36:00,400
you also see a lot of stuff going on out

819
00:36:04,200 --> 00:36:02,710
here and those are supernova explosions

820
00:36:05,910 --> 00:36:04,210
and stuff like that very violent

821
00:36:08,070 --> 00:36:05,920
phenomena that you will never see in the

822
00:36:10,950 --> 00:36:08,080
optical and what if I'm most fascinating

823
00:36:16,790 --> 00:36:10,960
is the radio observation can any of you

824
00:36:21,270 --> 00:36:16,800
tell me what those red dots are you know

825
00:36:23,820 --> 00:36:21,280
so those are quasars those are other

826
00:36:26,700 --> 00:36:23,830
black holes that are behind a galaxy but

827
00:36:29,099 --> 00:36:26,710
they're so bright that they outshine the

828
00:36:30,450 --> 00:36:29,109
galaxy like I told you before so you see

829
00:36:34,590 --> 00:36:30,460
many many black holes in the picture

830
00:36:37,650 --> 00:36:34,600
there okay now to explain a little more

831
00:36:38,970 --> 00:36:37,660
about how black holes work I have to

832
00:36:41,250 --> 00:36:38,980
introduce a little bit of general

833
00:36:42,990 --> 00:36:41,260
relativity and I need to explain how

834
00:36:45,180 --> 00:36:43,000
general relativity is different from

835
00:36:46,410 --> 00:36:45,190
Newtonian gravity Newtonian gravity is a

836
00:36:49,109 --> 00:36:46,420
perfectly good theory

837
00:36:51,620 --> 00:36:49,119
I just spent about a month over the

838
00:36:54,420 --> 00:36:51,630

street there at the physics department

839
00:36:56,760 --> 00:36:54,430
teaching only Newtonian gravity it's

840
00:36:58,020 --> 00:36:56,770
super beautiful and explains everything

841
00:37:00,120 --> 00:36:58,030
that you need to know about gravity in

842
00:37:02,740 --> 00:37:00,130
the solar system except maybe one thing

843
00:37:07,990 --> 00:37:02,750
but that's kind of not

844
00:37:10,090 --> 00:37:08,000
and it Newtonian gravity works in the

845
00:37:12,130 --> 00:37:10,100
way that I bet most of you know it tells

846
00:37:15,040 --> 00:37:12,140
you that two objects attract each other

847
00:37:16,630 --> 00:37:15,050
with the force law that is proportional

848
00:37:18,580 --> 00:37:16,640
to the masses of the two objects and

849
00:37:19,390 --> 00:37:18,590
inversely proportional to the square of

850
00:37:23,490 --> 00:37:19,400
the distance

851
00:37:27,760 --> 00:37:23,500
now that force law is very beautiful

852
00:37:30,490 --> 00:37:27,770
pretty accurate but is wrong and and

853
00:37:32,110 --> 00:37:30,500
it's wrong because it tells you that the

854
00:37:35,950 --> 00:37:32,120
interaction between two masses

855
00:37:37,660 --> 00:37:35,960
propagates at infinite speed and because

856
00:37:39,430 --> 00:37:37,670
of special relativity we know that

857
00:37:42,790 --> 00:37:39,440
nothing can propagate faster than the

858
00:37:44,560 --> 00:37:42,800
speed of light so when Einstein

859
00:37:46,330 --> 00:37:44,570
discovered special relativity spent

860
00:37:50,050 --> 00:37:46,340
about ten years thinking long and hard

861
00:37:53,230 --> 00:37:50,060
about how to fix Newtonian gravity so

862
00:37:54,910 --> 00:37:53,240
that it wouldn't clash with special

863
00:37:57,670 --> 00:37:54,920

relativity and he came up with this

864
00:38:01,480 --> 00:37:57,680
crazy idea that gravity is not a force

865
00:38:03,520 --> 00:38:01,490
at all so gravity is the natural state

866
00:38:05,140 --> 00:38:03,530
of motion of objects the only reason I'm

867
00:38:08,110 --> 00:38:05,150
not falling through the floor

868
00:38:10,210 --> 00:38:08,120
is that the floor is pushing up on me if

869
00:38:11,980 --> 00:38:10,220
there were no forces from the floor

870
00:38:14,200 --> 00:38:11,990
pushing upon me I would be happily

871
00:38:16,810 --> 00:38:14,210
falling and that's the natural state of

872
00:38:21,850 --> 00:38:16,820
all things they just fall all the time

873
00:38:24,640 --> 00:38:21,860
okay so this is summarized by another

874
00:38:27,370 --> 00:38:24,650
famous phrase by John Wheeler which says

875
00:38:32,250 --> 00:38:27,380
that space time tells matter how to move

876
00:38:34,810 --> 00:38:32,260
and mass tells space-time how to curve

877
00:38:36,550 --> 00:38:34,820
how do we know that Einstein was right

878
00:38:38,620 --> 00:38:36,560
and Newton was wrong the first time we

879
00:38:40,870 --> 00:38:38,630
found out was exactly 100 years ago

880
00:38:42,880 --> 00:38:40,880
there was a very famous expedition led

881
00:38:44,350 --> 00:38:42,890
by Eddington the same Addington that I

882
00:38:46,390 --> 00:38:44,360
was talking about before the Royal

883
00:38:50,500 --> 00:38:46,400
astronomer the one who ridiculed

884
00:38:54,460 --> 00:38:50,510
Chandrasekhar who knew that there would

885
00:38:56,980 --> 00:38:54,470
be a complete solar eclipse and the new

886
00:39:01,270 --> 00:38:56,990
word that solar eclipse will happen so

887
00:39:04,450 --> 00:39:01,280
he set up an expedition he himself went

888
00:39:06,400 --> 00:39:04,460

to a small island close to Africa the

889
00:39:09,520 --> 00:39:06,410
island of principle and he sent other

890
00:39:11,650 --> 00:39:09,530
astronomers to sobral in Brazil in the

891
00:39:14,440 --> 00:39:11,660
Amazon region of Brazil and they

892
00:39:16,710 --> 00:39:14,450
observed what happened during the solar

893
00:39:18,910 --> 00:39:16,720
eclipse why were they interested in this

894
00:39:21,700 --> 00:39:18,920
because one of the predictions of

895
00:39:26,920 --> 00:39:21,710
Einstein's relativity is that every mass

896
00:39:28,870 --> 00:39:26,930
must bend light okay so they knew that

897
00:39:31,960 --> 00:39:28,880
if they would look at the spot where the

898
00:39:34,420 --> 00:39:31,970
Sun was because the Sun was there and

899
00:39:36,520 --> 00:39:34,430
because it was dark they could look at

900
00:39:38,970 --> 00:39:36,530
the positions the positions of the stars

901
00:39:41,020 --> 00:39:38,980
behind the Sun and measured how

902
00:39:45,010 --> 00:39:41,030
deflected they were because they were

903
00:39:47,290 --> 00:39:45,020
behind the Sun and mutant predicts a

904
00:39:50,500 --> 00:39:47,300
certain deflection Einstein predicts

905
00:39:51,790 --> 00:39:50,510
actly twice as much so they went and

906
00:39:54,160 --> 00:39:51,800
they looked at the position of all of

907
00:39:55,930 --> 00:39:54,170
these stars during the full Eclipse they

908
00:39:57,370 --> 00:39:55,940
had two different observations in two

909
00:39:59,110 --> 00:39:57,380
different places just to make sure that

910
00:40:01,240 --> 00:39:59,120
they got things right and they found

911
00:40:04,330 --> 00:40:01,250
that Einstein was right and Newton was

912
00:40:06,580 --> 00:40:04,340
wrong and then the next day newspapers

913
00:40:08,890 --> 00:40:06,590

never trust the newspapers they came out

914
00:40:12,040 --> 00:40:08,900
with things like lights all askew in the

915
00:40:14,670 --> 00:40:12,050
heavens many science more or less agog

916
00:40:18,220 --> 00:40:14,680
over results of eclipses observations

917
00:40:20,890 --> 00:40:18,230
Einstein triumphs stars not where they

918
00:40:26,220 --> 00:40:20,900
sing or were calculated to be but nobody

919
00:40:29,080 --> 00:40:26,230
need worry don't worry don't worry now

920
00:40:31,570 --> 00:40:29,090
we have seen that light bending in a

921
00:40:32,950 --> 00:40:31,580
much more spectacular way and I'm sure

922
00:40:35,710 --> 00:40:32,960
all of you have seen this picture

923
00:40:38,050 --> 00:40:35,720
this is the same light bending but it's

924
00:40:40,000 --> 00:40:38,060
the much more extreme bending that

925
00:40:41,710 --> 00:40:40,010
happens around the black hole now if I

926
00:40:43,810 --> 00:40:41,720
were living around the black hole I

927
00:40:46,710 --> 00:40:43,820
could see the back of my head and

928
00:40:50,200 --> 00:40:46,720
discover a ball that became over time

929
00:40:51,910 --> 00:40:50,210
because light can form the gravity

930
00:40:53,710 --> 00:40:51,920
around the black hole is so strong the

931
00:40:56,710 --> 00:40:53,720
lobby's gravity can go around in circles

932
00:40:58,720 --> 00:40:56,720
and those circles are called light rings

933
00:41:00,790 --> 00:40:58,730
and this is pretty much what you're

934
00:41:03,970 --> 00:41:00,800
seeing here okay this is a light ring

935
00:41:05,230 --> 00:41:03,980
it's beautiful but is still an

936
00:41:09,370 --> 00:41:05,240
observation in the electromagnetic

937
00:41:11,290 --> 00:41:09,380
spectrum what what is why am i here

938
00:41:13,060 --> 00:41:11,300

tonight to tell you that there's a new

939
00:41:14,800 --> 00:41:13,070
way to look at black holes that is

940
00:41:15,820 --> 00:41:14,810
completely different and it's based on

941
00:41:20,020 --> 00:41:15,830
gravitational waves

942
00:41:22,380 --> 00:41:20,030
they are very different from

943
00:41:26,260 --> 00:41:22,390
electromagnetic waves to begin with

944
00:41:28,480 --> 00:41:26,270
everything that you look at in your

945
00:41:31,240 --> 00:41:28,490
daily life can be described by electron

946
00:41:33,760 --> 00:41:31,250
maduk phenomena and if you look at the

947
00:41:35,859 --> 00:41:33,770
typical wavelengths of those phenomena

948
00:41:38,109 --> 00:41:35,869
you know stuff that you see with your

949
00:41:40,270 --> 00:41:38,119
own eyes is in the optical it's over

950
00:41:42,430 --> 00:41:40,280
here it's a pretty limited band then you

951
00:41:45,970 --> 00:41:42,440
have the gammas the x-ray ultraviolet

952
00:41:47,710 --> 00:41:45,980
infrared the radio down here all of

953
00:41:51,460 --> 00:41:47,720
those beautiful images of Andromeda I've

954
00:41:53,710 --> 00:41:51,470
shown you before and that's one sense

955
00:41:57,390 --> 00:41:53,720
right one sense that we had to look at

956
00:42:01,660 --> 00:41:57,400
the universe gravitational waves are

957
00:42:03,730 --> 00:42:01,670
bending in space-time and they propagate

958
00:42:06,520 --> 00:42:03,740
at frequencies that are very different

959
00:42:09,460 --> 00:42:06,530
in fact if we had to understand them in

960
00:42:11,770 --> 00:42:09,470
terms of senses they are their

961
00:42:14,290 --> 00:42:11,780
frequencies are so low that they are

962
00:42:17,170 --> 00:42:14,300
more similar to sound waves sound waves

963
00:42:20,109 --> 00:42:17,180

are compression rarefaction of the air

964
00:42:21,400 --> 00:42:20,119
that we pick up with our years and they

965
00:42:22,810 --> 00:42:21,410
have frequencies that are very low

966
00:42:24,609 --> 00:42:22,820
compared to all of the electromagnetic

967
00:42:26,560 --> 00:42:24,619
spectrum now I'm not saying the

968
00:42:28,240 --> 00:42:26,570
gravitational waves are sound but you

969
00:42:29,680 --> 00:42:28,250
can think of them as a completely

970
00:42:31,750 --> 00:42:29,690
different sense that you have to look at

971
00:42:37,240 --> 00:42:31,760
the universe that is more like hearing

972
00:42:40,090 --> 00:42:37,250
than it is like seeing okay and what are

973
00:42:41,710 --> 00:42:40,100
they so gravitational waves you can

974
00:42:47,290 --> 00:42:41,720
understand them pretty much as tidal

975
00:42:49,930 --> 00:42:47,300
gravity so you know when the moon goes

976
00:42:54,370 --> 00:42:49,940
around the earth it exerts tides and

977
00:42:57,820 --> 00:42:54,380
those stars produce you know the effects

978
00:42:59,560 --> 00:42:57,830
that you see on oceans for example if

979
00:43:02,920 --> 00:42:59,570
you imagine that a gravitational wave

980
00:43:05,220 --> 00:43:02,930
goes through me in this direction so you

981
00:43:07,900 --> 00:43:05,230
are sending a gravitational wave my way

982
00:43:10,540 --> 00:43:07,910
what the gravitational wave does as it

983
00:43:12,810 --> 00:43:10,550
passes through me is it makes me thinner

984
00:43:15,910 --> 00:43:12,820
and taller and a little bit heavier and

985
00:43:18,099 --> 00:43:15,920
shorter and fatter and I will be sadder

986
00:43:21,460 --> 00:43:18,109
and it does so every time it goes

987
00:43:23,410 --> 00:43:21,470
through okay so by how much

988
00:43:26,740 --> 00:43:23,420

not very much happier not very much

989
00:43:29,020 --> 00:43:26,750
sadder because the typical displacement

990
00:43:30,640 --> 00:43:29,030
so if you imagine that you had a

991
00:43:33,310 --> 00:43:30,650
gravitational wave generator that you

992
00:43:35,740 --> 00:43:33,320
could put in this room well the best you

993
00:43:39,760 --> 00:43:35,750
can do to generate gravitational waves

994
00:43:42,070 --> 00:43:39,770
is say take one ton of stuff and make it

995
00:43:44,170 --> 00:43:42,080
spin as fast as you can

996
00:43:45,970 --> 00:43:44,180
if you look at the typical deformation

997
00:43:48,520 --> 00:43:45,980
that the gravitational wave would

998
00:43:50,800 --> 00:43:48,530
produce on me it's one part in 10 to the

999
00:43:54,190 --> 00:43:50,810
39 okay

1000
00:43:56,050 --> 00:43:54,200
not very much happier so there's no hope

1001
00:43:58,900 --> 00:43:56,060
that we can generate gravitational waves

1002
00:44:01,600 --> 00:43:58,910
on on earth and detect them but if you

1003
00:44:03,460 --> 00:44:01,610
start talking about massive black holes

1004
00:44:05,440 --> 00:44:03,470
in the universe moving at speeds close

1005
00:44:07,630 --> 00:44:05,450
to the speed of light you get a number

1006
00:44:10,840 --> 00:44:07,640
that is still ridiculously small it's

1007
00:44:13,120 --> 00:44:10,850
about 10 to the minus 21 that that is

1008
00:44:15,220 --> 00:44:13,130
still ridiculously small so if I want to

1009
00:44:17,740 --> 00:44:15,230
build a detector on earth I need to make

1010
00:44:21,070 --> 00:44:17,750
it as big as I can because I want to

1011
00:44:23,650 --> 00:44:21,080
make it long because that that number is

1012
00:44:26,170 --> 00:44:23,660
the Delta L over L it's the fractional

1013
00:44:28,510 --> 00:44:26,180

displacement as the weight goes by and

1014
00:44:31,150 --> 00:44:28,520
even if I build a detector that is like

1015
00:44:32,590 --> 00:44:31,160
1 kilo meter long that fractional

1016
00:44:37,110 --> 00:44:32,600
deviation is still going to be much

1017
00:44:39,430 --> 00:44:37,120
smaller than the nucleus of an atom so

1018
00:44:41,470 --> 00:44:39,440
about 20 years ago when I started

1019
00:44:43,090 --> 00:44:41,480
studying this stuff the other physics

1020
00:44:45,070 --> 00:44:43,100
students in my department were making

1021
00:44:48,190 --> 00:44:45,080
fun of me they're like you understand

1022
00:44:51,100 --> 00:44:48,200
how crazy all of this is and they were

1023
00:44:53,320 --> 00:44:51,110
right so it took about 20 years to

1024
00:44:55,870 --> 00:44:53,330
actually get there but eventually we got

1025
00:44:57,280 --> 00:44:55,880
there and the way we got there is by

1026
00:44:59,170 --> 00:44:57,290
building what is called a laser

1027
00:45:03,340 --> 00:44:59,180
interferometer and the idea here is that

1028
00:45:05,590 --> 00:45:03,350
you basically have a long pipe where you

1029
00:45:08,050 --> 00:45:05,600
make vacuum you make the best vacuum you

1030
00:45:12,160 --> 00:45:08,060
can make then you shine a laser here

1031
00:45:14,260 --> 00:45:12,170
these this laser is split into two

1032
00:45:16,600 --> 00:45:14,270
arrays at something called the beam

1033
00:45:18,790 --> 00:45:16,610
splitter these a semi-transparent mirror

1034
00:45:21,040 --> 00:45:18,800
so some of the laser goes up some of the

1035
00:45:22,870 --> 00:45:21,050
laser goes this way and then you put two

1036
00:45:25,810 --> 00:45:22,880
big mirrors at the end of each arm and

1037
00:45:28,180 --> 00:45:25,820
those mirrors reflect the light back now

1038
00:45:31,900 --> 00:45:28,190

if there is no gravitational wave

1039
00:45:34,090 --> 00:45:31,910
passing by there's a photo detector here

1040
00:45:37,270 --> 00:45:34,100
and it sees that the light coming from

1041
00:45:39,700 --> 00:45:37,280
the two arms interferes destructively

1042
00:45:40,990 --> 00:45:39,710
and so you see black you don't see

1043
00:45:43,900 --> 00:45:41,000
anything okay

1044
00:45:46,480 --> 00:45:43,910
but if there is even a tiny displacement

1045
00:45:49,060 --> 00:45:46,490
in each of those arms then you don't see

1046
00:45:51,790 --> 00:45:49,070
black anymore an interferometer is a

1047
00:45:54,880 --> 00:45:51,800
very very precise way of detecting even

1048
00:45:55,990 --> 00:45:54,890
the tiniest vibrations this was Ray

1049
00:45:57,640 --> 00:45:56,000
wisest idea

1050
00:45:59,740 --> 00:45:57,650
and the one for which you got the Nobel

1051
00:46:03,940 --> 00:45:59,750
Prize now how big do you need to make

1052
00:46:05,710 --> 00:46:03,950
those pipes this big so this thing is

1053
00:46:07,290 --> 00:46:05,720
close to Mississippi where I used to be

1054
00:46:10,030 --> 00:46:07,300
it is actually in Livingston Louisiana

1055
00:46:10,839 --> 00:46:10,040
it's beautiful except that there's a lot

1056
00:46:14,920 --> 00:46:10,849
of crocodiles

1057
00:46:18,820 --> 00:46:14,930
Olivia goes over there it's a nice place

1058
00:46:21,280 --> 00:46:18,830
I took pictures over there and the the

1059
00:46:23,320 --> 00:46:21,290
beam splitter and the photo detector are

1060
00:46:25,870 --> 00:46:23,330
housed in this white building over here

1061
00:46:27,940 --> 00:46:25,880
the light goes all the way down almost

1062
00:46:30,490 --> 00:46:27,950
you see almost all the way to the

1063
00:46:33,250 --> 00:46:30,500

horizon and you cannot fit this in a

1064
00:46:35,200 --> 00:46:33,260
single picture so you know the other arm

1065
00:46:38,080 --> 00:46:35,210
keeps going over there somewhere over

1066
00:46:39,550 --> 00:46:38,090
there and these the one in Livingston

1067
00:46:45,609 --> 00:46:39,560
Louisiana there's another one that they

1068
00:46:47,680 --> 00:46:45,619
built in Hanford and in well used to be

1069
00:46:49,420 --> 00:46:47,690
a nuclear site and then there's another

1070
00:46:50,530 --> 00:46:49,430
one that they built in Italy you can

1071
00:46:52,030 --> 00:46:50,540
tell that the scenery is pretty

1072
00:46:54,040 --> 00:46:52,040
different is close to where I was born

1073
00:46:57,280 --> 00:46:54,050
it's called Villalobos bill it's an

1074
00:46:59,950 --> 00:46:57,290
Italian French collaboration with other

1075
00:47:03,130 --> 00:46:59,960
contributions so ok so what happened

1076
00:47:04,839 --> 00:47:03,140
these things turned on actually the tool

1077
00:47:11,250 --> 00:47:04,849
I goes turned on the Italians are slower

1078
00:47:13,540 --> 00:47:11,260
and what happened is that in 2015 I

1079
00:47:16,240 --> 00:47:13,550
started hearing rumors that something

1080
00:47:18,849 --> 00:47:16,250
happened ok I'm not part of the LIGO

1081
00:47:24,520 --> 00:47:18,859
collaboration but I know many people and

1082
00:47:26,349 --> 00:47:24,530
and then around February I got an email

1083
00:47:27,700 --> 00:47:26,359
from one of the editors of Physical

1084
00:47:31,150 --> 00:47:27,710
Review Letters that is one of the main

1085
00:47:33,460 --> 00:47:31,160
physics journals telling me we got the

1086
00:47:35,050 --> 00:47:33,470
paper that is a pretty big discovery

1087
00:47:37,420 --> 00:47:35,060
would you like to write a popular

1088
00:47:40,150 --> 00:47:37,430

article to explain what happens of

1089
00:47:41,589 --> 00:47:40,160
course I heard something and I didn't

1090
00:47:43,960 --> 00:47:41,599
sleep for a few days until I actually

1091
00:47:47,470 --> 00:47:43,970
got my hands on the paper and there are

1092
00:47:50,410 --> 00:47:47,480
this thing here and and and this is what

1093
00:47:53,920 --> 00:47:50,420
they saw so what you see here is two

1094
00:47:56,020 --> 00:47:53,930
black holes coming together as they come

1095
00:47:57,790 --> 00:47:56,030
together they spiral faster and faster

1096
00:48:01,200 --> 00:47:57,800
because they're producing gravitational

1097
00:48:04,060 --> 00:48:01,210
waves the signal is a maximum and then

1098
00:48:05,650 --> 00:48:04,070
these two black holes merge they form a

1099
00:48:08,079 --> 00:48:05,660
single black hole and that black hole

1100
00:48:08,600 --> 00:48:08,089
wants to become a simple rotating black

1101
00:48:11,990 --> 00:48:08,610
hole of the

1102
00:48:14,660 --> 00:48:12,000
the cur wrote down in one line on math

1103
00:48:17,720 --> 00:48:14,670
and when it does so it trains down we

1104
00:48:19,400 --> 00:48:17,730
call it ring down because it's it's the

1105
00:48:23,600 --> 00:48:19,410
same thing that happens when you hit a

1106
00:48:26,810 --> 00:48:23,610
bell with a hammer it wants to vibrate

1107
00:48:28,580 --> 00:48:26,820
away all of the deformations and it does

1108
00:48:30,380 --> 00:48:28,590
it by producing a sound and then it

1109
00:48:36,220 --> 00:48:30,390
becomes the belt that used to be before

1110
00:48:39,140 --> 00:48:36,230
by ringing them okay and here I'm gonna

1111
00:48:41,000 --> 00:48:39,150
make you hear the sound that those two

1112
00:48:43,490 --> 00:48:41,010
black holes made when they merge

1113
00:48:45,800 --> 00:48:43,500

together you're gonna hear it twice the

1114
00:48:48,560 --> 00:48:45,810
first is the actual sound if you take

1115
00:48:49,940 --> 00:48:48,570
the gravitational waves and you sonar

1116
00:48:52,700 --> 00:48:49,950
eyes then that's what you would actually

1117
00:48:55,670 --> 00:48:52,710
hear and it sounds like a pop sound well

1118
00:48:58,130 --> 00:48:55,680
you'll hear it and then they slightly

1119
00:49:00,050 --> 00:48:58,140
change the frequency so that you hear

1120
00:49:15,650 --> 00:49:00,060
the initial part of the signal a little

1121
00:49:20,720 --> 00:49:15,660
better so I'll play so the thud that you

1122
00:49:24,110 --> 00:49:20,730
hear that's the this ring down signal

1123
00:49:26,000 --> 00:49:24,120
and then they expanded the frequency

1124
00:49:29,150 --> 00:49:26,010
band so that you can hear it better you

1125
00:49:31,970 --> 00:49:29,160
can hear what we call it chirp it sounds

1126
00:49:35,090 --> 00:49:31,980
like a wash more than not sharp but it's

1127
00:49:36,860 --> 00:49:35,100
pretty much the same way that birds make

1128
00:49:38,590 --> 00:49:36,870
sound it's a sound of increasing

1129
00:49:41,120 --> 00:49:38,600
frequency and increasing the amplitude

1130
00:49:42,830 --> 00:49:41,130
so it's the same kind of sound it

1131
00:49:45,050 --> 00:49:42,840
depends on the frequency which you play

1132
00:49:48,710 --> 00:49:45,060
but it's pretty much the same thing that

1133
00:49:52,310 --> 00:49:48,720
birds do black holes sing right okay so

1134
00:49:54,290 --> 00:49:52,320
this thing is published they put in

1135
00:49:55,730 --> 00:49:54,300
nominations for the Nobel Prize a little

1136
00:49:57,110 --> 00:49:55,740
too late so they don't get it the first

1137
00:50:00,380 --> 00:49:57,120
year around they get it the next year

1138
00:50:02,150 --> 00:50:00,390

because this was such a big deal and the

1139
00:50:06,290 --> 00:50:02,160
people got the Nobel Prize already wise

1140
00:50:08,120 --> 00:50:06,300
who basically invented the idea behind

1141
00:50:10,640 --> 00:50:08,130
the interferometers kept thorn

1142
00:50:12,620 --> 00:50:10,650
denominated many many times and very

1143
00:50:15,110 --> 00:50:12,630
bearish who basically put together the

1144
00:50:17,000 --> 00:50:15,120
collaboration made it work as a particle

1145
00:50:20,510 --> 00:50:17,010
physics experiment a thousand people

1146
00:50:22,970 --> 00:50:20,520
worked on this so what happened

1147
00:50:25,339 --> 00:50:22,980
afterwards what happen is that

1148
00:50:27,890 --> 00:50:25,349
besides those two detectors notice that

1149
00:50:31,730 --> 00:50:27,900
they turn down on September 12 two days

1150
00:50:33,680 --> 00:50:31,740
later they detected something so all of

1151
00:50:35,900 --> 00:50:33,690
a sudden we became just sensitive enough

1152
00:50:37,910 --> 00:50:35,910
that we could see these things and we

1153
00:50:40,400 --> 00:50:37,920
knew at that point we knew that we would

1154
00:50:43,069 --> 00:50:40,410
see more okay in fact we have seen many

1155
00:50:43,910 --> 00:50:43,079
more the detectors were operational for

1156
00:50:46,910 --> 00:50:43,920
a little while

1157
00:50:48,859 --> 00:50:46,920
you see from December until January then

1158
00:50:52,730 --> 00:50:48,869
they turned on for an upgrade and then

1159
00:50:55,970 --> 00:50:52,740
they started taking data again and they

1160
00:50:59,329 --> 00:50:55,980
saw a total of 10 binary black hole

1161
00:51:02,660 --> 00:50:59,339
mergers and one neutron star merger one

1162
00:51:05,089 --> 00:51:02,670
merger of two neutron stars and you can

1163
00:51:08,239 --> 00:51:05,099

go now and look at these events as they

1164
00:51:09,890 --> 00:51:08,249
are being observed day by day if you go

1165
00:51:12,620 --> 00:51:09,900
to that website at the bottom because

1166
00:51:15,049 --> 00:51:12,630
it's open science now every time one of

1167
00:51:17,150 --> 00:51:15,059
these things happens an alert is sent

1168
00:51:19,730 --> 00:51:17,160
out to astronomers who can go and look

1169
00:51:22,779 --> 00:51:19,740
for electromagnetic radiation produced

1170
00:51:25,460 --> 00:51:22,789
when these cataclysmic events happen

1171
00:51:28,309 --> 00:51:25,470
this is the catalogue of the 10 events

1172
00:51:29,839 --> 00:51:28,319
which are public and published there's

1173
00:51:31,489 --> 00:51:29,849
10 black holes and then there is one

1174
00:51:33,739 --> 00:51:31,499
that is much longer that's the merger of

1175
00:51:35,390 --> 00:51:33,749
two neutron stars why was that so

1176
00:51:39,079 --> 00:51:35,400
relevant I will explain it in a minute

1177
00:51:41,509 --> 00:51:39,089
so think again about the way that a

1178
00:51:43,279 --> 00:51:41,519
gravitational wave works it goes through

1179
00:51:44,720 --> 00:51:43,289
me and it makes me a little taller and

1180
00:51:46,729 --> 00:51:44,730
then a little further and a little

1181
00:51:49,339 --> 00:51:46,739
taller and a little fatter now I built a

1182
00:51:52,220 --> 00:51:49,349
detector which is two arms so if a

1183
00:51:55,130 --> 00:51:52,230
gravitational wave comes in and it hits

1184
00:51:57,799 --> 00:51:55,140
the detector face on from above or below

1185
00:52:00,710 --> 00:51:57,809
it's gonna stretch and squeeze both of

1186
00:52:03,140 --> 00:52:00,720
the arms right but if he comes from the

1187
00:52:05,839 --> 00:52:03,150
side it's gonna stretch and squeeze only

1188
00:52:07,279 --> 00:52:05,849

one of the arms so you would expect that

1189
00:52:10,569 --> 00:52:07,289
these detectors are going to be a little

1190
00:52:13,640 --> 00:52:10,579
more sensitive see a little further up

1191
00:52:15,680 --> 00:52:13,650
or further out in the universe if the

1192
00:52:17,420 --> 00:52:15,690
waves come from above or below and

1193
00:52:22,130 --> 00:52:17,430
they're going to be less sensitive if

1194
00:52:25,130 --> 00:52:22,140
the waves come from the side right so

1195
00:52:27,529 --> 00:52:25,140
this is pictured in in this peanut here

1196
00:52:29,180 --> 00:52:27,539
this is the sensitivity of the detector

1197
00:52:31,460 --> 00:52:29,190
to gravitational waves at different

1198
00:52:34,519 --> 00:52:31,470
positions in the sky it's more sensitive

1199
00:52:35,680 --> 00:52:34,529
up and down and less sensitive on the

1200
00:52:38,770 --> 00:52:35,690
sides

1201
00:52:40,420 --> 00:52:38,780
okay so what this tells you is that a

1202
00:52:42,130 --> 00:52:40,430
single gravitational wave detector is

1203
00:52:42,609 --> 00:52:42,140
not very good at locating things in the

1204
00:52:45,030 --> 00:52:42,619
sky

1205
00:52:47,410 --> 00:52:45,040
it's basically an omnidirectional

1206
00:52:49,599 --> 00:52:47,420
detector so if I want to know where

1207
00:52:52,240 --> 00:52:49,609
these waves are coming from and it at

1208
00:52:55,210 --> 00:52:52,250
least two detectors why use if I have

1209
00:52:57,099 --> 00:52:55,220
two detectors I can tell from the time

1210
00:53:00,849 --> 00:52:57,109
that the waves arrive at one detector

1211
00:53:04,660 --> 00:53:00,859
and the other that these waves travel at

1212
00:53:06,190 --> 00:53:04,670
the speed of light so I construct two

1213
00:53:08,349 --> 00:53:06,200

spheres that travel at the speed of

1214
00:53:10,960 --> 00:53:08,359
light around those two detectors and two

1215
00:53:12,940 --> 00:53:10,970
spheres intersect in a circle so if I

1216
00:53:17,829 --> 00:53:12,950
had two detectors I can locate the

1217
00:53:19,540 --> 00:53:17,839
source in the sky on a ring okay it gets

1218
00:53:21,520 --> 00:53:19,550
even better if I have three detectors

1219
00:53:23,050 --> 00:53:21,530
because if I have three detectors now I

1220
00:53:26,559 --> 00:53:23,060
can take the intersection of two rings

1221
00:53:28,690 --> 00:53:26,569
and I have two points in the sky so we

1222
00:53:31,809 --> 00:53:28,700
two detectors you locate the source on a

1223
00:53:33,700 --> 00:53:31,819
ring by time of arrival with three

1224
00:53:36,730 --> 00:53:33,710
detectors you can tell that it's either

1225
00:53:40,270 --> 00:53:36,740
at this point or the point opposite in

1226
00:53:42,010 --> 00:53:40,280
the sky so these exactly what happened

1227
00:53:43,720 --> 00:53:42,020
with the Barry neutron star they have

1228
00:53:46,809 --> 00:53:43,730
three detectors because the detection

1229
00:53:49,809 --> 00:53:46,819
happened in August when the Italian

1230
00:53:53,530 --> 00:53:49,819
detector finally woke up so the two lie

1231
00:53:55,900 --> 00:53:53,540
goes saw a signal the Italian detector

1232
00:53:58,750 --> 00:53:55,910
unlucky that we are didn't see anything

1233
00:54:01,240 --> 00:53:58,760
but it didn't see anything because the

1234
00:54:03,099 --> 00:54:01,250
waves unfortunately for the Italians

1235
00:54:06,280 --> 00:54:03,109
were produced in the blind spot of the

1236
00:54:08,290 --> 00:54:06,290
Italian detector so we knew because it

1237
00:54:10,750 --> 00:54:08,300
didn't see them that it had to be in a

1238
00:54:14,650 --> 00:54:10,760

certain location in the sky and from

1239
00:54:17,050 --> 00:54:14,660
that we could locate the position within

1240
00:54:18,970 --> 00:54:17,060
almost two points they don't quite look

1241
00:54:20,650 --> 00:54:18,980
like points okay there's experimental

1242
00:54:23,980 --> 00:54:20,660
error but then something miraculous

1243
00:54:26,500 --> 00:54:23,990
happened that at the same time Fermi an

1244
00:54:30,700 --> 00:54:26,510
observatory to look for gamma-ray bursts

1245
00:54:33,190 --> 00:54:30,710
observe the gamma-ray burst just a

1246
00:54:35,740 --> 00:54:33,200
little delayed from the gravitational

1247
00:54:37,599 --> 00:54:35,750
wave signal and by combining these two

1248
00:54:40,720 --> 00:54:37,609
things we could locate the source in the

1249
00:54:43,180 --> 00:54:40,730
sky into a very tiny region and at that

1250
00:54:45,609 --> 00:54:43,190
point the hunt was on every single

1251
00:54:47,740 --> 00:54:45,619
astronomer on earth more than 3000

1252
00:54:49,060 --> 00:54:47,750
astronomers pointed everything they had

1253
00:54:51,700 --> 00:54:49,070
at the spot in the sky

1254
00:54:54,010 --> 00:54:51,710
and so they started seeing fireworks

1255
00:54:58,060 --> 00:54:54,020
they saw optical they saw everything

1256
00:54:58,690 --> 00:54:58,070
they saw everything okay that was

1257
00:55:00,670 --> 00:54:58,700
amazing

1258
00:55:02,350 --> 00:55:00,680
it never happened again we were super

1259
00:55:04,240 --> 00:55:02,360
lucky there's people who say that the

1260
00:55:05,800 --> 00:55:04,250
alien LIGO stands for lucky because the

1261
00:55:07,150 --> 00:55:05,810
first binary black hole that we saw was

1262
00:55:09,130 --> 00:55:07,160
super loud and it happened two days

1263
00:55:11,320 --> 00:55:09,140

after they turned it on and the first

1264
00:55:15,550 --> 00:55:11,330
binary neutron star we located in the

1265
00:55:17,500 --> 00:55:15,560
sky super precisely now we can use these

1266
00:55:19,180 --> 00:55:17,510
observations to do cosmology that's

1267
00:55:21,280 --> 00:55:19,190
amazing that I had too much time to

1268
00:55:22,990 --> 00:55:21,290
explain it maybe you heard in previous

1269
00:55:25,450 --> 00:55:23,000
talks that there is attention in

1270
00:55:26,950 --> 00:55:25,460
cosmology now between measurements that

1271
00:55:29,140 --> 00:55:26,960
are made with the microwave background

1272
00:55:32,410 --> 00:55:29,150
radiation cosmic microwave background

1273
00:55:34,510 --> 00:55:32,420
and measurements are made locally by

1274
00:55:37,240 --> 00:55:34,520
people like Adam riess who work here

1275
00:55:39,250 --> 00:55:37,250
they get different numbers for the

1276
00:55:41,890 --> 00:55:39,260
expansion rate as measured by a continue

1277
00:55:43,840 --> 00:55:41,900
is called the Hubble constant okay and

1278
00:55:46,420 --> 00:55:43,850
gravitational waves are not quite

1279
00:55:49,150 --> 00:55:46,430
precise enough to say who is right

1280
00:55:51,220 --> 00:55:49,160
because the measurement of the Hubble

1281
00:55:52,930 --> 00:55:51,230
constant that they make has errors that

1282
00:55:55,300 --> 00:55:52,940
are large enough that they're compatible

1283
00:55:56,830 --> 00:55:55,310
with both measurements but we hope that

1284
00:56:00,730 --> 00:55:56,840
in the near future they will help us

1285
00:56:03,130 --> 00:56:00,740
understand how the universe expands what

1286
00:56:07,660 --> 00:56:03,140
else happened these detectors went on

1287
00:56:09,970 --> 00:56:07,670
again in April of 2019 I don't know why

1288
00:56:13,330 --> 00:56:09,980

they chose April 1st it's a very bad

1289
00:56:15,760 --> 00:56:13,340
date and after they turned on they

1290
00:56:18,310 --> 00:56:15,770
started recording events on a very

1291
00:56:20,500 --> 00:56:18,320
regular basis so regular that my slides

1292
00:56:22,180 --> 00:56:20,510
are always outdated so I don't know if

1293
00:56:26,080 --> 00:56:22,190
some of you came here early

1294
00:56:29,470 --> 00:56:26,090
I had 28 here I had to write 31 because

1295
00:56:31,150 --> 00:56:29,480
I gave a similar talk like last week for

1296
00:56:33,610 --> 00:56:31,160
high school in Italy and there were less

1297
00:56:35,110 --> 00:56:33,620
you know they keep coming they keep

1298
00:56:37,240 --> 00:56:35,120
coming it's super exciting every morning

1299
00:56:39,070 --> 00:56:37,250
I have an app on my phone and I look at

1300
00:56:39,670 --> 00:56:39,080
the app and it tells me there is a new

1301
00:56:41,680 --> 00:56:39,680
event today

1302
00:56:44,380 --> 00:56:41,690
great it's a very black hole it's a

1303
00:56:45,760 --> 00:56:44,390
binary neutron star you know so what are

1304
00:56:47,740 --> 00:56:45,770
we doing now we're building more

1305
00:56:49,360 --> 00:56:47,750
detectors because the more detectors we

1306
00:56:51,910 --> 00:56:49,370
have the better we can localize sources

1307
00:56:53,650 --> 00:56:51,920
in the sky so now we have to Lagos we

1308
00:56:55,540 --> 00:56:53,660
have been going Italy this is a

1309
00:56:57,850 --> 00:56:55,550
prototype that is not sensitive enough

1310
00:56:59,410 --> 00:56:57,860
to see things there's a new detector the

1311
00:57:02,260 --> 00:56:59,420
Japanese were super fast

1312
00:57:03,370 --> 00:57:02,270
they built a detector underground in the

1313
00:57:07,780 --> 00:57:03,380

Kamioka mine

1314
00:57:10,180 --> 00:57:07,790
it's called Kagura and these this is

1315
00:57:12,490 --> 00:57:10,190
gonna start taking data before the end

1316
00:57:16,690 --> 00:57:12,500
of all three the third observational run

1317
00:57:18,160 --> 00:57:16,700
and the Indians are also rushing to

1318
00:57:21,610 --> 00:57:18,170
build their own detectors they're gonna

1319
00:57:23,290 --> 00:57:21,620
get a like oh all the way from the

1320
00:57:25,990 --> 00:57:23,300
US and they have a site where they

1321
00:57:29,140 --> 00:57:26,000
started making this giant vacuum holes

1322
00:57:31,030 --> 00:57:29,150
and what's gonna happen when I go India

1323
00:57:33,010 --> 00:57:31,040
goes online is that we're gonna have a

1324
00:57:34,900 --> 00:57:33,020
network that is spread throughout the

1325
00:57:37,090 --> 00:57:34,910
earth that's the way that they took that

1326
00:57:40,150 --> 00:57:37,100
picture of the supermassive black hole

1327
00:57:41,440 --> 00:57:40,160
by having very many observatories all

1328
00:57:42,430 --> 00:57:41,450
around the earth and we're trying to do

1329
00:57:44,200 --> 00:57:42,440
the same with gravitational wave

1330
00:57:45,850 --> 00:57:44,210
detector so we can locate the sources in

1331
00:57:48,610 --> 00:57:45,860
the sky better and go after the

1332
00:57:51,310 --> 00:57:48,620
electromagnetic counterparts and like I

1333
00:57:55,210 --> 00:57:51,320
said you can go online you see I stopped

1334
00:57:58,420 --> 00:57:55,220
I took a screenshot of this website on a

1335
00:58:00,130 --> 00:57:58,430
1909 24 but now there are more they keep

1336
00:58:02,470 --> 00:58:00,140
coming there's more and more events and

1337
00:58:05,440 --> 00:58:02,480
you can go online and you can you can

1338
00:58:06,610 --> 00:58:05,450

see what's happening by yourselves how

1339
00:58:14,440 --> 00:58:06,620
much time do I have

1340
00:58:15,790 --> 00:58:14,450
I can I can five ten minutes okay I want

1341
00:58:17,880 --> 00:58:15,800
to tell you something about what we

1342
00:58:22,290 --> 00:58:17,890
understood from these first detections

1343
00:58:25,780 --> 00:58:22,300
first of all we understood we we can now

1344
00:58:29,080 --> 00:58:25,790
pin down more precisely how often these

1345
00:58:31,690 --> 00:58:29,090
objects merging the universe we have a

1346
00:58:34,450 --> 00:58:31,700
pretty good idea now of how often black

1347
00:58:36,460 --> 00:58:34,460
holes merge we have a not so good idea

1348
00:58:37,960 --> 00:58:36,470
how often neutron stars marriage but

1349
00:58:39,010 --> 00:58:37,970
that's getting better and at the end of

1350
00:58:42,430 --> 00:58:39,020
all three they're gonna have a much

1351
00:58:44,920 --> 00:58:42,440
better measurement of the rate at the

1352
00:58:46,570 --> 00:58:44,930
end of the first two observing runs we

1353
00:58:48,910 --> 00:58:46,580
had not observed a neutron star black

1354
00:58:51,010 --> 00:58:48,920
hole so we could only place upper limits

1355
00:58:54,100 --> 00:58:51,020
on how often they emerge in the universe

1356
00:58:56,650 --> 00:58:54,110
but now the rumor is that they have seen

1357
00:58:59,470 --> 00:58:56,660
some and so by the end of a three we

1358
00:59:01,150 --> 00:58:59,480
will know more or less how often black

1359
00:59:04,210 --> 00:59:01,160
holes merge with neutron stars in the

1360
00:59:07,360 --> 00:59:04,220
universe there is also some evidence

1361
00:59:09,820 --> 00:59:07,370
that the rate at which things merge in

1362
00:59:11,710 --> 00:59:09,830
the universe changes with the age of the

1363
00:59:14,260 --> 00:59:11,720

universe and that makes sense because

1364
00:59:16,150 --> 00:59:14,270
these things are made out of stars so

1365
00:59:17,260 --> 00:59:16,160
more or less they should follow the star

1366
00:59:19,240 --> 00:59:17,270
formation

1367
00:59:22,060 --> 00:59:19,250
the more stars you form the more black

1368
00:59:24,700 --> 00:59:22,070
holes you form so we expect that the

1369
00:59:27,880 --> 00:59:24,710
black coal merger rate should peak at

1370
00:59:29,650 --> 00:59:27,890
some distance and then go down because

1371
00:59:33,880 --> 00:59:29,660
when the universe was very old we were

1372
00:59:35,740 --> 00:59:33,890
not making stars right the other thing

1373
00:59:37,240 --> 00:59:35,750
that we understood is that the masses of

1374
00:59:38,710 --> 00:59:37,250
these guys that we are observing are

1375
00:59:40,960 --> 00:59:38,720
very different from the masses we

1376
00:59:42,910 --> 00:59:40,970
estimated before if you remember I told

1377
00:59:45,130 --> 00:59:42,920
you that to estimate black hole masses

1378
00:59:48,730 --> 00:59:45,140
we looked at gas falling onto black

1379
00:59:50,650 --> 00:59:48,740
holes and from the orbit of the gas we

1380
00:59:54,580 --> 00:59:50,660
can tell how massive the black holes are

1381
00:59:58,180 --> 00:59:54,590
and those are the purple dots that you

1382
01:00:00,100 --> 00:59:58,190
see here now you can see that all of the

1383
01:00:02,710 --> 01:00:00,110
black holes the LIGO saw seem to be more

1384
01:00:06,250 --> 01:00:02,720
massive than that so one question is how

1385
01:00:07,840 --> 01:00:06,260
do you make them right most people now

1386
01:00:10,030 --> 01:00:07,850
believe that these black holes were

1387
01:00:12,700 --> 01:00:10,040
formed when the universe was a little

1388
01:00:15,430 --> 01:00:12,710

bit older and the mr. metal D City was

1389
01:00:17,320 --> 01:00:15,440
lower and the reason is that the

1390
01:00:20,770 --> 01:00:17,330
metallicity is the fractional heavy

1391
01:00:22,480 --> 01:00:20,780
metals that you have in a star heavy for

1392
01:00:25,750 --> 01:00:22,490
an astronomer is everything heavier than

1393
01:00:27,790 --> 01:00:25,760
helium so anything that is not hydrogen

1394
01:00:31,270 --> 01:00:27,800
or helium astronomers here call it a

1395
01:00:37,390 --> 01:00:31,280
metal don't let medo me but you know so

1396
01:00:41,950 --> 01:00:37,400
if a star has more metals then winds are

1397
01:00:44,410 --> 01:00:41,960
not as efficient at blowing stuff out

1398
01:00:46,900 --> 01:00:44,420
when a supernova happens and so more

1399
01:00:49,900 --> 01:00:46,910
mass falls in and so the black holes

1400
01:00:52,390 --> 01:00:49,910
that you form are more massive and so we

1401
01:00:53,980 --> 01:00:52,400
think that's what happened but there are

1402
01:00:55,870 --> 01:00:53,990
other people that believe that these

1403
01:00:59,890 --> 01:00:55,880
black holes are so massive because they

1404
01:01:01,450 --> 01:00:59,900
are formed in clusters of the kind that

1405
01:01:03,250 --> 01:01:01,460
Frank was talking about before my talk

1406
01:01:04,920 --> 01:01:03,260
so there could be very dense

1407
01:01:08,200 --> 01:01:04,930
environments where these black holes

1408
01:01:10,540 --> 01:01:08,210
through dynamical friction that he was

1409
01:01:12,040 --> 01:01:10,550
talking about fall toward the center if

1410
01:01:14,380 --> 01:01:12,050
you have many black holes and they're

1411
01:01:16,660 --> 01:01:14,390
close to each other they can bind and

1412
01:01:18,580 --> 01:01:16,670
when they bind they can merge and so

1413
01:01:20,730 --> 01:01:18,590

maybe what's happening is that these

1414
01:01:24,070 --> 01:01:20,740
black holes are not first-generation

1415
01:01:26,290 --> 01:01:24,080
they are not born from a star they're

1416
01:01:28,590 --> 01:01:26,300
not zombies of the kind that was talking

1417
01:01:30,850 --> 01:01:28,600
about before but they are zombies

1418
01:01:34,720 --> 01:01:30,860
merging with each other so

1419
01:01:37,180 --> 01:01:34,730
they are second-generation mergers okay

1420
01:01:39,430 --> 01:01:37,190
so the masses I already said it

1421
01:01:41,200 --> 01:01:39,440
one thing that is fascinating is that we

1422
01:01:43,750 --> 01:01:41,210
don't see black holes more massive at

1423
01:01:46,570 --> 01:01:43,760
least so far I hear rumors than maybe

1424
01:01:48,480 --> 01:01:46,580
this is gonna change but we haven't seen

1425
01:01:51,850 --> 01:01:48,490
any black holes more massive than about

1426
01:01:54,520 --> 01:01:51,860
40 50 solar masses and that's very

1427
01:01:57,520 --> 01:01:54,530
interesting because there is something

1428
01:02:01,470 --> 01:01:57,530
in astrophysics called pair-instability

1429
01:02:06,310 --> 01:02:01,480
supernova so when a supernova happens

1430
01:02:08,950 --> 01:02:06,320
you can have collisions between gamma

1431
01:02:12,730 --> 01:02:08,960
rays and nuclei that produce electrons

1432
01:02:15,610 --> 01:02:12,740
and protons now those are pairs electron

1433
01:02:18,940 --> 01:02:15,620
proton pairs when that happens there's a

1434
01:02:21,520 --> 01:02:18,950
sudden drop in pressure in the stuff

1435
01:02:24,370 --> 01:02:21,530
that is contained within your supernova

1436
01:02:27,820 --> 01:02:24,380
and so the material suddenly collapses

1437
01:02:31,930 --> 01:02:27,830
toward the center and you have a big

1438
01:02:34,750 --> 01:02:31,940

blowout of stuff and nothing ends up

1439
01:02:36,550 --> 01:02:34,760
collapsing into the black hole for this

1440
01:02:38,830 --> 01:02:36,560
to happen you need to have stars that

1441
01:02:42,880 --> 01:02:38,840
are more massive than about 130 solar

1442
01:02:45,460 --> 01:02:42,890
masses so this tells you that the

1443
01:02:48,340 --> 01:02:45,470
remnant of that supernova explosion

1444
01:02:50,980 --> 01:02:48,350
cannot be more massive than about 50

1445
01:02:53,590 --> 01:02:50,990
solar masses lo and behold all of the

1446
01:02:56,950 --> 01:02:53,600
first observations tell you that the

1447
01:03:00,010 --> 01:02:56,960
pre-merger black holes do not seem to be

1448
01:03:01,840 --> 01:03:00,020
more massive than 50 so maybe we're

1449
01:03:04,420 --> 01:03:01,850
understanding that this parent Zubaydah

1450
01:03:05,980 --> 01:03:04,430
supernova actually happens but if we see

1451
01:03:08,410 --> 01:03:05,990
black holes are more massive than that

1452
01:03:10,960 --> 01:03:08,420
then astronomers will have to scratch

1453
01:03:12,400 --> 01:03:10,970
their heads again and find ways to make

1454
01:03:15,900 --> 01:03:12,410
black holes there are more massive than

1455
01:03:19,000 --> 01:03:15,910
50 okay and I'm sure that they will

1456
01:03:21,460 --> 01:03:19,010
assure that they will okay this is ideas

1457
01:03:24,970 --> 01:03:21,470
that I already spoke about let me tell

1458
01:03:26,760 --> 01:03:24,980
you something a little fancier well one

1459
01:03:29,920 --> 01:03:26,770
thing that we really want to see is

1460
01:03:31,720 --> 01:03:29,930
spins for reasons that I don't want to

1461
01:03:34,540 --> 01:03:31,730
explain right now you can ask me later

1462
01:03:36,310 --> 01:03:34,550
another thing that we want to understand

1463
01:03:38,620 --> 01:03:36,320

is whether the stuff we are seeing are

1464
01:03:40,720 --> 01:03:38,630
actually black holes and one way that we

1465
01:03:43,390 --> 01:03:40,730
can do it is through what we call black

1466
01:03:44,590 --> 01:03:43,400
hole spectroscopy I told you many times

1467
01:03:46,690 --> 01:03:44,600
already this black holes are

1468
01:03:49,030 --> 01:03:46,700
very simple we can think of them as the

1469
01:03:52,000 --> 01:03:49,040
atoms of gravity now

1470
01:03:55,240 --> 01:03:52,010
ordinary atoms have spectral lines right

1471
01:03:56,530 --> 01:03:55,250
and the way that we identify elements in

1472
01:03:59,320 --> 01:03:56,540
the universe is by looking at the

1473
01:04:02,230 --> 01:03:59,330
spectral lines now the black holes are

1474
01:04:04,300 --> 01:04:02,240
produced through these violent mergers

1475
01:04:06,370 --> 01:04:04,310
if they are the black holes of general

1476
01:04:08,800 --> 01:04:06,380
relativity they also have gravitational

1477
01:04:11,470 --> 01:04:08,810
spectral lines and we can compute them

1478
01:04:13,150 --> 01:04:11,480
all and because black holes are so

1479
01:04:15,340 --> 01:04:13,160
simple all of those spectral lines

1480
01:04:20,590 --> 01:04:15,350
depend only on the mass and the spin of

1481
01:04:22,980 --> 01:04:20,600
the black hole so likewise in things

1482
01:04:26,740 --> 01:04:22,990
that seem to be very compatible with

1483
01:04:29,230 --> 01:04:26,750
general relativity but it was not quite

1484
01:04:30,460 --> 01:04:29,240
precise enough to measure the frequency

1485
01:04:32,530 --> 01:04:30,470
of the stuff at the end over here

1486
01:04:35,320 --> 01:04:32,540
because as you can see there's a lot of

1487
01:04:36,880 --> 01:04:35,330
noise here what we see is perfectly

1488
01:04:39,310 --> 01:04:36,890

compatible with the predictions of

1489
01:04:41,080 --> 01:04:39,320
general relativity but as our detectors

1490
01:04:43,270 --> 01:04:41,090
become more and more precise we will be

1491
01:04:45,070 --> 01:04:43,280
able to measure those frequencies and do

1492
01:04:49,230 --> 01:04:45,080
spectroscopy gravitation spectroscopy

1493
01:04:52,270 --> 01:04:49,240
will because let me skip to what's next

1494
01:04:54,700 --> 01:04:52,280
what's next are more sensitive detectors

1495
01:04:58,180 --> 01:04:54,710
on earth and detectors that can look at

1496
01:05:00,010 --> 01:04:58,190
other way bands just like radio

1497
01:05:01,690 --> 01:05:00,020
astronomy is looking at the other bands

1498
01:05:02,920 --> 01:05:01,700
in the electromagnetic spectrum we want

1499
01:05:05,110 --> 01:05:02,930
to look at the other bands in the

1500
01:05:08,890 --> 01:05:05,120
gravitational wave spectrum so what

1501
01:05:11,530 --> 01:05:08,900
we're doing now is the Europeans

1502
01:05:13,990 --> 01:05:11,540
together with NASA are planning to put

1503
01:05:16,690 --> 01:05:14,000
one interferometer of the kind that I

1504
01:05:17,890 --> 01:05:16,700
was talking about before in space this

1505
01:05:20,260 --> 01:05:17,900
is the reason I moved to the United

1506
01:05:22,120 --> 01:05:20,270
States that's why I went from Paris to

1507
01:05:26,320 --> 01:05:22,130
st. Louis and I was perfectly happy to

1508
01:05:31,570 --> 01:05:26,330
do it and so the idea that led me over

1509
01:05:33,460 --> 01:05:31,580
here was we are gonna take three

1510
01:05:34,900 --> 01:05:33,470
satellites we're gonna launch them in

1511
01:05:37,630 --> 01:05:34,910
space that will make an equilateral

1512
01:05:39,730 --> 01:05:37,640
triangle is equilateral triangle will

1513
01:05:41,860 --> 01:05:39,740

trail the earth in its orbit around the

1514
01:05:44,800 --> 01:05:41,870
Sun sounds like science fiction right

1515
01:05:46,570 --> 01:05:44,810
but that's what the other students told

1516
01:05:49,480 --> 01:05:46,580
me when I spoke to them about like when

1517
01:05:50,800 --> 01:05:49,490
it happened so we're gonna put three

1518
01:05:52,780 --> 01:05:50,810
satellites in orbit

1519
01:05:56,140 --> 01:05:52,790
they will cartwheel behind the earth

1520
01:05:58,420 --> 01:05:56,150
going around the Sun and there's a

1521
01:06:01,539 --> 01:05:58,430
gravitational wave passes by it will

1522
01:06:03,430 --> 01:06:01,549
stretch and squeeze the triangle so

1523
01:06:06,099 --> 01:06:03,440
we're gonna shoot lasers in between the

1524
01:06:08,140 --> 01:06:06,109
different satellites measure the arrival

1525
01:06:09,700 --> 01:06:08,150
times and if a gravitational wave passes

1526
01:06:11,950 --> 01:06:09,710
by bingo

1527
01:06:14,140 --> 01:06:11,960
the distance between the satellites has

1528
01:06:17,620 --> 01:06:14,150
to change okay that's the idea

1529
01:06:19,420 --> 01:06:17,630
now with those things you can see not

1530
01:06:21,490 --> 01:06:19,430
stellar-mass black holes merging but

1531
01:06:22,750 --> 01:06:21,500
supermassive black holes merging stuff

1532
01:06:25,150 --> 01:06:22,760
like the one at the center of our own

1533
01:06:27,339 --> 01:06:25,160
galaxy we think that those black holes

1534
01:06:28,690 --> 01:06:27,349
got there because galaxies like to merge

1535
01:06:30,910 --> 01:06:28,700
with each other throughout the history

1536
01:06:33,279 --> 01:06:30,920
of the universe and so by measuring out

1537
01:06:35,140 --> 01:06:33,289
those massive black holes merge we can

1538
01:06:38,019 --> 01:06:35,150

tell how the galaxies came together and

1539
01:06:40,779 --> 01:06:38,029
that's the real the real goal that's why

1540
01:06:45,579 --> 01:06:40,789
I moved to the US I like Italy but you

1541
01:06:48,400 --> 01:06:45,589
know now I go back for holidays so there

1542
01:06:51,039 --> 01:06:48,410
was a prototype mission that launched in

1543
01:06:52,000 --> 01:06:51,049
December 2015 the showed that we can

1544
01:06:54,930 --> 01:06:52,010
actually do this

1545
01:06:57,010 --> 01:06:54,940
that means feasible these are technical

1546
01:06:59,589 --> 01:06:57,020
details that can tell you about later

1547
01:07:02,519 --> 01:06:59,599
and we're gonna do spectroscopy in space

1548
01:07:06,609 --> 01:07:02,529
and there's even a hope that we could

1549
01:07:08,470 --> 01:07:06,619
detect dark matter around black holes in

1550
01:07:10,450 --> 01:07:08,480
this way I want to leave you with one

1551
01:07:14,200 --> 01:07:10,460
plot that was made so I came to the

1552
01:07:16,870 --> 01:07:14,210
United States I went to JPL Caltech and

1553
01:07:20,559 --> 01:07:16,880
I met an aerospace engineer over there

1554
01:07:25,690 --> 01:07:20,569
who is now my wife and the guy who was

1555
01:07:28,589 --> 01:07:25,700
my witness at the the wedding is this

1556
01:07:31,180 --> 01:07:28,599
guy Steve Brasco who made this movie and

1557
01:07:35,289 --> 01:07:31,190
that's that's a long winded way to say

1558
01:07:37,420 --> 01:07:35,299
that a friend of mine made this so so

1559
01:07:39,130 --> 01:07:37,430
what you see in this movie is a stellar

1560
01:07:40,779 --> 01:07:39,140
mass black hole that falls into a

1561
01:07:42,609 --> 01:07:40,789
massive black hole this is one of the

1562
01:07:45,700 --> 01:07:42,619
things that we want to target with Lisa

1563
01:07:48,309 --> 01:07:45,710

and why is it fascinating what you're

1564
01:07:49,930 --> 01:07:48,319
gonna see here is the orbit that the

1565
01:07:51,609 --> 01:07:49,940
small black hole makes around the big

1566
01:07:53,529 --> 01:07:51,619
black hole and you will hear the

1567
01:07:56,109 --> 01:07:53,539
gravitational waves at the same time and

1568
01:07:59,289 --> 01:07:56,119
they will sound much more interesting

1569
01:08:02,230 --> 01:07:59,299
than the whoop that we heard before so

1570
01:08:04,510 --> 01:08:02,240
let me play it notice also that this

1571
01:08:08,319 --> 01:08:04,520
object is falling in so my friend that

1572
01:08:30,510 --> 01:08:08,329
to zoom in with the camera as the object

1573
01:09:20,430 --> 01:09:14,440
[Music]

1574
01:09:23,770 --> 01:09:20,440
[Applause]

1575
01:09:26,440 --> 01:09:23,780
the applause is for Steve okay

1576
01:09:28,600 --> 01:09:26,450
now you understand that there's a lot of

1577
01:09:30,550 --> 01:09:28,610
structure in those gravity waves and you

1578
01:09:32,530 --> 01:09:30,560
can tell very precisely from those

1579
01:09:34,690 --> 01:09:32,540
gravitational waves what the center of

1580
01:09:37,540 --> 01:09:34,700
the cone looks like in fact one of the

1581
01:09:39,190 --> 01:09:37,550
ideas that were pursuing now is that if

1582
01:09:42,160 --> 01:09:39,200
there is dark matter around that black

1583
01:09:45,070 --> 01:09:42,170
hole by measuring those waves you could

1584
01:09:47,530 --> 01:09:45,080
tell what kind of dark matter could be

1585
01:09:49,270 --> 01:09:47,540
around a black hole okay that's just a

1586
01:09:52,480 --> 01:09:49,280
sketch I wanna leave you with a couple

1587
01:09:54,790 --> 01:09:52,490
of suggestions for reading one is this

1588
01:09:56,770 --> 01:09:54,800

beautiful book by Kip on the history of

1589
01:09:58,840 --> 01:09:56,780
gravitational waves you will see that he

1590
01:10:00,640 --> 01:09:58,850
is the optimist to push many of us to

1591
01:10:02,980 --> 01:10:00,650
work in this field because there is a

1592
01:10:04,840 --> 01:10:02,990
book from the 90s and he said we're

1593
01:10:07,230 --> 01:10:04,850
gonna see them within 10 years that's

1594
01:10:10,870 --> 01:10:07,240
when I was a student he was lying to me

1595
01:10:12,790 --> 01:10:10,880
and the one over here is the

1596
01:10:16,020 --> 01:10:12,800
autobiography of John Wheeler that is

1597
01:10:22,360 --> 01:10:16,030
really fascinating reading that's all

1598
01:10:29,700 --> 01:10:26,780
[Applause]

1599
01:10:32,090 --> 01:10:29,710
okay I'm sure we have a bunch of

1600
01:10:34,260 --> 01:10:32,100
questions we had many of them online

1601
01:10:48,000 --> 01:10:34,270
who's got the first question for our

1602
01:10:52,370 --> 01:10:48,010
speaker I try in the back go catch okay

1603
01:10:56,580 --> 01:10:52,380
so I was gonna ask what is quantum foam

1604
01:11:01,140 --> 01:10:56,590
you know I always get that question so

1605
01:11:05,640 --> 01:11:01,150
quantum foam John Wheeler had a thing

1606
01:11:07,040 --> 01:11:05,650
for names he named a lot of things black

1607
01:11:09,720 --> 01:11:07,050
hole comes from him

1608
01:11:12,540 --> 01:11:09,730
Gian is something else that comes from

1609
01:11:18,750 --> 01:11:12,550
him at Gianni's mass without mass at

1610
01:11:20,730 --> 01:11:18,760
some point so I told you before that one

1611
01:11:24,390 --> 01:11:20,740
of the disturbing predictions of general

1612
01:11:26,820 --> 01:11:24,400
relativity according to Penrose is that

1613
01:11:29,490 --> 01:11:26,830

if you make stuff collapse it will

1614
01:11:31,410 --> 01:11:29,500
create a singularity at the center we

1615
01:11:33,060 --> 01:11:31,420
don't like singularities we don't like

1616
01:11:36,060 --> 01:11:33,070
singular it means that the equations are

1617
01:11:39,210 --> 01:11:36,070
going bad we think that just like

1618
01:11:41,780 --> 01:11:39,220
Newton's theory was incomplete so so

1619
01:11:45,330 --> 01:11:41,790
general relativity is incomplete and

1620
01:11:47,460 --> 01:11:45,340
what happens is that when the curvature

1621
01:11:50,070 --> 01:11:47,470
of space-time becomes very large but not

1622
01:11:52,530 --> 01:11:50,080
quite infinite there have to be some

1623
01:11:54,870 --> 01:11:52,540
quantum Corrections that come in now

1624
01:11:58,460 --> 01:11:54,880
there are some theories like loop

1625
01:12:01,230 --> 01:11:58,470
quantum gravity or string theory that

1626
01:12:03,900 --> 01:12:01,240
make the same prediction such as general

1627
01:12:06,150 --> 01:12:03,910
relativity for relatively low curvatures

1628
01:12:08,790 --> 01:12:06,160
and they make different predictions when

1629
01:12:11,850 --> 01:12:08,800
the curvatures become we say Planckian

1630
01:12:14,580 --> 01:12:11,860
close to the maximum curvature that we

1631
01:12:17,490 --> 01:12:14,590
can expect and so the way that we

1632
01:12:20,610 --> 01:12:17,500
learned like to think about this in this

1633
01:12:22,890 --> 01:12:20,620
visionary ways that they the topology of

1634
01:12:26,430 --> 01:12:22,900
space-time the way that the sheet of

1635
01:12:29,160 --> 01:12:26,440
space-time bends becomes for me when you

1636
01:12:31,110 --> 01:12:29,170
get close to that singularity and so you

1637
01:12:33,570 --> 01:12:31,120
could have the effects in space-time

1638
01:12:36,210 --> 01:12:33,580

that produce things like wormholes and

1639
01:12:39,480 --> 01:12:36,220
all of this is a lot of blahblah

1640
01:12:41,220 --> 01:12:39,490
and and I can do it here but we don't

1641
01:12:44,010 --> 01:12:41,230
really know what happens okay that's the

1642
01:12:47,730 --> 01:12:44,020
truth that's the honest truth okay I

1643
01:12:49,140 --> 01:12:47,740
have a question from online first they

1644
01:12:50,550 --> 01:12:49,150
were a little confused by when you were

1645
01:12:53,370 --> 01:12:50,560
talking about needing space

1646
01:12:56,430 --> 01:12:53,380
observatories to see supermassive black

1647
01:12:58,380 --> 01:12:56,440
holes wouldn't they're basically it says

1648
01:13:00,480 --> 01:12:58,390
something like I'm assuming the size of

1649
01:13:02,550 --> 01:13:00,490
the black hole determines the strength

1650
01:13:04,500 --> 01:13:02,560
size the gravitational wave that is

1651
01:13:07,140 --> 01:13:04,510
right so why would you need bigger

1652
01:13:07,860 --> 01:13:07,150
things to see the bigger ones you need

1653
01:13:10,440 --> 01:13:07,870
bigger

1654
01:13:12,770 --> 01:13:10,450
you need big detectors okay so first of

1655
01:13:15,240 --> 01:13:12,780
all the size of the detector is

1656
01:13:17,220 --> 01:13:15,250
basically proportional to the wavelength

1657
01:13:20,010 --> 01:13:17,230
for the gravitational waves that you see

1658
01:13:21,810 --> 01:13:20,020
so the longer the detector the longer

1659
01:13:24,450 --> 01:13:21,820
the wavelength the smaller the frequency

1660
01:13:27,360 --> 01:13:24,460
so if you want to see small frequencies

1661
01:13:30,210 --> 01:13:27,370
you need to build very big detectors why

1662
01:13:33,240 --> 01:13:30,220
can you not do it on earth so you can

1663
01:13:35,760 --> 01:13:33,250

build bigger detectors on earth in fact

1664
01:13:38,520 --> 01:13:35,770
one of the ideas here in the u.s. to

1665
01:13:41,490 --> 01:13:38,530
build a better Lego is to make it

1666
01:13:43,830 --> 01:13:41,500
instead of 4 kilometers 3 miles and

1667
01:13:45,810 --> 01:13:43,840
sorry I'm in the US instead of 4

1668
01:13:48,840 --> 01:13:45,820
kilometers you wanna make it 40

1669
01:13:50,490 --> 01:13:48,850
kilometers okay what's the problem that

1670
01:13:52,400 --> 01:13:50,500
if you want to make something that is 40

1671
01:14:00,540 --> 01:13:52,410
kilometer long you better start digging

1672
01:14:03,150 --> 01:14:00,550
because the earth is not flat so you

1673
01:14:07,080 --> 01:14:03,160
need a lot of big in whatever those

1674
01:14:09,470 --> 01:14:07,090
people say and besides there's another

1675
01:14:12,540 --> 01:14:09,480
problem that is more serious the earth

1676
01:14:16,680 --> 01:14:12,550
there's earthquakes unfortunately and

1677
01:14:19,860 --> 01:14:16,690
their seismic motion now the these

1678
01:14:22,740 --> 01:14:19,870
detectors now are so sensitive that the

1679
01:14:24,390 --> 01:14:22,750
main limitation comes from the

1680
01:14:26,520 --> 01:14:24,400
uncertainty principle that's how

1681
01:14:28,920 --> 01:14:26,530
sensitive they are okay quantum

1682
01:14:31,910 --> 01:14:28,930
mechanics of the movement of the mirrors

1683
01:14:35,790 --> 01:14:31,920
is what we have to take into account now

1684
01:14:38,880 --> 01:14:35,800
at low frequencies there's no way that

1685
01:14:41,070 --> 01:14:38,890
you can beat seismic noise the noise

1686
01:14:43,380 --> 01:14:41,080
that is caused by the fact that the

1687
01:14:45,870 --> 01:14:43,390
earth is shaking so there are some ideas

1688
01:14:48,490 --> 01:14:45,880

to improve on that build another ground

1689
01:14:50,740 --> 01:14:48,500
you have to dig a lot

1690
01:14:52,720 --> 01:14:50,750
and in any case you cannot make them

1691
01:14:56,620 --> 01:14:52,730
sensitive the frequencies below let's

1692
01:14:58,030 --> 01:14:56,630
say maybe one Hertz or so so if you want

1693
01:15:00,630 --> 01:14:58,040
to build something that is sensitive

1694
01:15:03,180 --> 01:15:00,640
below one Hertz you need to go to space

1695
01:15:06,520 --> 01:15:03,190
because there's no earthquakes in space

1696
01:15:10,930 --> 01:15:06,530
so you build satellites and you make

1697
01:15:13,650 --> 01:15:10,940
them as large as you want what's the

1698
01:15:19,240 --> 01:15:13,660
consensus on primordial black holes Oh

1699
01:15:21,730 --> 01:15:19,250
is there a consensus I have a lot of

1700
01:15:25,270 --> 01:15:21,740
friends on the other side of the street

1701
01:15:28,390 --> 01:15:25,280
that were compromised like holes it

1702
01:15:30,220 --> 01:15:28,400
they're very fascinating so they are

1703
01:15:32,290 --> 01:15:30,230
interesting because they could be very

1704
01:15:37,020 --> 01:15:32,300
very small and so Hawking evaporation

1705
01:15:40,660 --> 01:15:37,030
could happen on shorter time scales they

1706
01:15:44,560 --> 01:15:40,670
could and probably were formed in the

1707
01:15:46,720 --> 01:15:44,570
early universe the question is do they

1708
01:15:48,940 --> 01:15:46,730
make a fraction of the dark matter can

1709
01:15:51,130 --> 01:15:48,950
we see them when the first detection

1710
01:15:54,370 --> 01:15:51,140
happened people like Mark kamionkowski

1711
01:15:57,220 --> 01:15:54,380
and his students over there got really

1712
01:16:01,270 --> 01:15:57,230
excited because like I told you before

1713
01:16:03,580 --> 01:16:01,280

it's very hard to well it's not so hard

1714
01:16:06,760 --> 01:16:03,590
we also published papers on that but it

1715
01:16:08,740 --> 01:16:06,770
it was kind of unexpected that the black

1716
01:16:13,120 --> 01:16:08,750
holes the LIGO saw were as massive as

1717
01:16:15,430 --> 01:16:13,130
they were and so at the time one of the

1718
01:16:17,680 --> 01:16:15,440
windows for primordial black holes that

1719
01:16:20,470 --> 01:16:17,690
was not ruled out by experiments was

1720
01:16:22,900 --> 01:16:20,480
exactly around there 30 solar masses or

1721
01:16:27,700 --> 01:16:22,910
so and so they published this paper

1722
01:16:30,280 --> 01:16:27,710
saying oh maybe LIGO has not seen black

1723
01:16:31,840 --> 01:16:30,290
holes that were made by dying stars they

1724
01:16:34,090 --> 01:16:31,850
were not that zombies I was talking

1725
01:16:36,790 --> 01:16:34,100
about before they were primordial black

1726
01:16:39,670 --> 01:16:36,800
holes that were formed from fluctuations

1727
01:16:42,580 --> 01:16:39,680
in the early universe and I think if you

1728
01:16:48,070 --> 01:16:42,590
talk with mark now you will say yeah

1729
01:16:49,090 --> 01:16:48,080
maybe no maybe not but you know it will

1730
01:16:51,910 --> 01:16:49,100
keep looking

1731
01:16:53,050 --> 01:16:51,920
them they will tell us a lot of

1732
01:16:58,540 --> 01:16:53,060
interesting things about the early

1733
01:17:04,970 --> 01:17:01,640
come on wait for the microphone son like

1734
01:17:08,260 --> 01:17:04,980
when you have the triangle out in space

1735
01:17:12,800 --> 01:17:08,270
how would that be affected by solo women

1736
01:17:15,919 --> 01:17:12,810
so that's a very good question so you

1737
01:17:18,680 --> 01:17:15,929
have to shield all possible disturbances

1738
01:17:20,330 --> 01:17:18,690

okay and like that that gives me an

1739
01:17:24,350 --> 01:17:20,340
excuse to go back to one of the things

1740
01:17:27,620 --> 01:17:24,360
that I do that you see here so that's a

1741
01:17:31,700 --> 01:17:27,630
very valid concern anything out there is

1742
01:17:34,820 --> 01:17:31,710
going to push on whatever is inside that

1743
01:17:36,140 --> 01:17:34,830
satellite in particular cosmic rays you

1744
01:17:39,919 --> 01:17:36,150
know there's all sorts of things that

1745
01:17:43,580 --> 01:17:39,929
can push on it so this experiment was

1746
01:17:46,790 --> 01:17:43,590
looked at with some suspicion I think I

1747
01:17:49,669 --> 01:17:46,800
can confidently say for a while because

1748
01:17:53,990 --> 01:17:49,679
you have to show that you can keep stuff

1749
01:17:56,180 --> 01:17:54,000
in freefall to a very very high accuracy

1750
01:17:58,760 --> 01:17:56,190
if you want to carry out the experiment

1751
01:18:01,430 --> 01:17:58,770
that I was talking about so basically

1752
01:18:03,620 --> 01:18:01,440
this satellite is falling freely like

1753
01:18:05,570 --> 01:18:03,630
everything does happily in the universe

1754
01:18:08,030 --> 01:18:05,580
when there's no ground to keep them up

1755
01:18:10,100 --> 01:18:08,040
and you want to make sure that it's

1756
01:18:11,990 --> 01:18:10,110
falling freely to a very high accuracy

1757
01:18:13,879 --> 01:18:12,000
and so you want to keep down the

1758
01:18:17,149 --> 01:18:13,889
acceleration noise that's what it's

1759
01:18:20,180 --> 01:18:17,159
called so basically what you do is you

1760
01:18:23,260 --> 01:18:20,190
build a test mass that is what you want

1761
01:18:26,950 --> 01:18:23,270
to make sure is falling freely as

1762
01:18:30,169 --> 01:18:26,960
accurately as you need and you shield it

1763
01:18:33,169 --> 01:18:30,179

okay you shield it from everything else

1764
01:18:35,660 --> 01:18:33,179
and so when anything passes by say a

1765
01:18:39,140 --> 01:18:35,670
cosmic ray it's the shield around that

1766
01:18:42,560 --> 01:18:39,150
mass you have sensors that push back so

1767
01:18:44,149 --> 01:18:42,570
that that mass keeps freely falling and

1768
01:18:47,000 --> 01:18:44,159
you want to demonstrate that you can do

1769
01:18:49,430 --> 01:18:47,010
it as precisely as you need this is what

1770
01:18:51,110 --> 01:18:49,440
that experiment did and that experiment

1771
01:18:54,560 --> 01:18:51,120
was launched the day my daughter was

1772
01:18:55,820 --> 01:18:54,570
born and and so I told my wife all about

1773
01:19:04,610 --> 01:18:55,830
we call her Lisa and she said you're

1774
01:19:06,890 --> 01:19:04,620
insane you don't use an actual shield

1775
01:19:09,340 --> 01:19:06,900
what you do is you have sensors that

1776
01:19:11,929 --> 01:19:09,350
measure the disturbance on the outer

1777
01:19:13,819 --> 01:19:11,939
shield and you push back

1778
01:19:16,219 --> 01:19:13,829
and you had to do this very very

1779
01:19:19,909 --> 01:19:16,229
accurately I'm not an experimentalist

1780
01:19:23,739 --> 01:19:19,919
don't ask me these things in uncertainty

1781
01:19:26,270 --> 01:19:23,749
how strong the solar wind right right

1782
01:19:28,250 --> 01:19:26,280
another another reason why this thing is

1783
01:19:30,770 --> 01:19:28,260
trailing behind the earth is that the

1784
01:19:32,629 --> 01:19:30,780
earth is sweeping stuff away so you

1785
01:19:37,959 --> 01:19:32,639
build it and it's following the earth

1786
01:19:54,979 --> 01:19:49,640
right over here is around black holes

1787
01:19:57,469 --> 01:19:54,989
the accretion disks form when black

1788
01:20:00,709 --> 01:19:57,479

holes so you want to know why black

1789
01:20:04,189 --> 01:20:00,719
holes are accretion disks okay

1790
01:20:07,209 --> 01:20:04,199
there's various different ways that

1791
01:20:11,029 --> 01:20:07,219
black holes can have accretion disks

1792
01:20:12,830 --> 01:20:11,039
many stars in the universe very large

1793
01:20:16,189 --> 01:20:12,840
fraction of the stars in the universe in

1794
01:20:20,839 --> 01:20:16,199
fact are in binaries okay so imagine

1795
01:20:25,399 --> 01:20:20,849
that you have two stars one star becomes

1796
01:20:27,859 --> 01:20:25,409
old runs out of fuel collapses forints a

1797
01:20:31,069 --> 01:20:27,869
black hole the other star is over there

1798
01:20:34,850 --> 01:20:31,079
the other star keeps expanding when the

1799
01:20:37,609 --> 01:20:34,860
star expands he starts transferring mass

1800
01:20:40,879 --> 01:20:37,619
to the companion that's an accretion

1801
01:20:43,580 --> 01:20:40,889
disk for you so this is one way that a

1802
01:20:45,290 --> 01:20:43,590
black hole can eat from another star it

1803
01:20:47,120 --> 01:20:45,300
can a create matter from the star that

1804
01:20:50,089 --> 01:20:47,130
is now becoming old okay

1805
01:20:51,979 --> 01:20:50,099
in fact that process can become very

1806
01:20:53,750 --> 01:20:51,989
complicated and can create what is

1807
01:20:55,060 --> 01:20:53,760
called a common envelope I will not go

1808
01:20:57,469 --> 01:20:55,070
there

1809
01:20:59,750 --> 01:20:57,479
supermassive black holes can eat in

1810
01:21:03,049 --> 01:20:59,760
other ways because were massive black

1811
01:21:05,239 --> 01:21:03,059
holes are typically at the active center

1812
01:21:07,489 --> 01:21:05,249
of galaxies and there's a lot of stuff

1813
01:21:09,199 --> 01:21:07,499

going on there because that's where

1814
01:21:12,890 --> 01:21:09,209
gravity is the strongest and a lot of

1815
01:21:15,140 --> 01:21:12,900
gas falls in so each of the black holes

1816
01:21:17,659 --> 01:21:15,150
in a galaxy is expected to have a lot of

1817
01:21:19,989 --> 01:21:17,669
gas around it and then one of the things

1818
01:21:22,790 --> 01:21:19,999
that we want to understand with Lisa is

1819
01:21:24,139 --> 01:21:22,800
maybe when galaxies come together each

1820
01:21:25,270 --> 01:21:24,149
of these black holes is gonna have an

1821
01:21:26,620 --> 01:21:25,280
accretion disk around

1822
01:21:28,810 --> 01:21:26,630
because it's at the center of its own

1823
01:21:30,790 --> 01:21:28,820
galaxy eating stuff and when they come

1824
01:21:32,890 --> 01:21:30,800
together they could keep those accretion

1825
01:21:34,570 --> 01:21:32,900
disks so what happens to the two

1826
01:21:37,120 --> 01:21:34,580
accretion disks as the two black holes

1827
01:21:39,130 --> 01:21:37,130
come together and that's gonna be

1828
01:21:41,170 --> 01:21:39,140
interesting because the black holes that

1829
01:21:42,880 --> 01:21:41,180
we are seeing with LIGO we think there's

1830
01:21:45,580 --> 01:21:42,890
going to be very little gas left around

1831
01:21:47,140 --> 01:21:45,590
them and when they merge astronomers

1832
01:21:50,590 --> 01:21:47,150
don't get very excited because they do

1833
01:21:51,700 --> 01:21:50,600
not expect fireworks to happen but with

1834
01:21:54,790 --> 01:21:51,710
the black holes that we're gonna see

1835
01:21:56,890 --> 01:21:54,800
with Lisa there's hope that we're gonna

1836
01:21:58,870 --> 01:21:56,900
see electromagnetic fireworks after the

1837
01:22:01,330 --> 01:21:58,880
marriage so you'll have this gigantic

1838
01:22:04,480 --> 01:22:01,340

splash of gravitational waves and then

1839
01:22:09,040 --> 01:22:04,490
fireworks that follow and that's gonna

1840
01:22:10,600 --> 01:22:09,050
be fun if I live to see it all right

1841
01:22:19,840 --> 01:22:10,610
well if there are no more questions

1842
01:22:22,990 --> 01:22:19,850
let's thank our speaker again okay so

1843
01:22:26,170 --> 01:22:23,000
next month November 4th sense

1844
01:22:27,940 --> 01:22:26,180
Sarah Kendra and do we have the Maryland

1845
01:22:30,460 --> 01:22:27,950
space Cranham servitor yes we have the

1846
01:22:31,900 --> 01:22:30,470
Maryland space man Observatory coming

1847
01:22:33,430 --> 01:22:31,910
down here if you would like to go across

1848
01:22:36,400 --> 01:22:33,440
the street and look through the

1849
01:22:39,130 --> 01:22:36,410
telescope please join this gentleman