1
00:00:00,562 --> 00:00:03,229
(twinkly music)

2
00:00:08,490 --> 00:00:11,680
- Hi everyone and welcome
to this very special episode

3
00:00:11,680 --> 00:00:14,170
of "Conversations at the Perimeter".

4
00:00:14,170 --> 00:00:16,230
- Today we're talking to Avery Broderick.

5
00:00:16,230 --> 00:00:18,320
He's a researcher here
at Perimeter Institute

6
00:00:18,320 --> 00:00:19,900
and at the University of Waterloo

7
00:00:19,900 --> 00:00:22,640
and he's one of the world's
leading experts on black holes.

8
00:00:22,640 --> 00:00:25,770
He's part of the Event Horizon
Telescope Collaboration

9
00:00:25,770 --> 00:00:28,470
who've just come out
with a big announcement.

10
00:00:28,470 --> 00:00:30,020
- We don't want to give any spoilers here.

11
00:00:30,020 --> 00:00:33,193
So let's move into our
conversation with Avery.

12
00:00:37,420 --> 00:00:39,620
- Avery, thank you so much for being here.

13
00:00:39,620 --> 00:00:40,590
- My pleasure.

14
00:00:40,590 --> 00:00:42,240
- We're so excited to talk to you.

15
00:00:42,240 --> 00:00:44,370
Personally I think that black holes

16
00:00:44,370 --> 00:00:47,310
are the most fascinating,
amazing things in the universe

17
00:00:47,310 --> 00:00:50,620
and you're my favorite person
to explain black holes.

18
00:00:50,620 --> 00:00:53,240
You're the source of all of
my knowledge of black holes.

19
00:00:53,240 --> 00:00:56,550
So I'm hoping you can tell
us the news that has come out

20
00:00:56,550 --> 00:00:58,830
about black holes and the
Event Horizon Telescope

21
00:00:58,830 --> 00:01:00,290
that you're involved with.

22
00:01:00,290 --> 00:01:02,050
What's new, what's
happening with black holes?

23
00:01:02,050 --> 00:01:03,800
- First Colin let me say,

24
00:01:03,800 --> 00:01:06,170
you're my favorite person
in the universe now too

25
00:01:06,170 --> 00:01:08,250
because you love the same thing I love.

26
00:01:08,250 --> 00:01:09,250
I shouldn't say that,

27
00:01:09,250 --> 00:01:10,437
because of course my favorite people

28
00:01:10,437 --> 00:01:13,200
are my family that support us
and make this all possible.

29
00:01:13,200 --> 00:01:14,600
You're my favorite PR person.

30
00:01:14,600 --> 00:01:16,290
- I'll take it.
- Favorite podcaster.

31
00:01:16,290 --> 00:01:17,356
- All right.

32
00:01:17,356 --> 00:01:18,540
- So.
- What?

33
00:01:18,540 --> 00:01:20,070
- Sorry Lauren.
- Tied for first.

34

00:01:20,070 --> 00:01:21,900
Tied for favorite podcaster.
- Yes, yes.

35
00:01:21,900 --> 00:01:23,260
Well she could be favorite in a minute,

36
00:01:23,260 --> 00:01:24,560
depends on how she starts her question.

37
00:01:24,560 --> 00:01:26,010
- All right.
- The news now

38
00:01:26,010 --> 00:01:28,070
is that Horizon Telescope

39
00:01:28,070 --> 00:01:31,460
has now released the image
of the second black hole

40
00:01:31,460 --> 00:01:33,033
that it has observed.

41
00:01:33,033 --> 00:01:33,920
And this black hole is the one

42
00:01:33,920 --> 00:01:36,310
at the center of our very own galaxy.

43
00:01:36,310 --> 00:01:38,510
All right, so this is near and dear to us

44
00:01:38,510 --> 00:01:41,550
and it looks very much
like the first image

45
00:01:41,550 --> 00:01:43,230
that we released three years ago.

46
00:01:43,230 --> 00:01:45,870
It's a fire donut on the sky okay?

47
00:01:45,870 --> 00:01:50,870
But it's an important and I
think striking confirmation

48
00:01:51,230 --> 00:01:54,520
that the first image was not
unique, it was not special.

49
00:01:54,520 --> 00:01:56,030
We didn't get lucky.

50
00:01:56,030 --> 00:01:59,300
That in fact imaging the event horizons

51
00:01:59,300 --> 00:02:01,870
of black holes is a going concern.

52
00:02:01,870 --> 00:02:03,520
We now have done it with two objects

53
00:02:03,520 --> 00:02:06,470
and it looks the way that Einstein

54
00:02:06,470 --> 00:02:08,870
and many others afterwards predicted.

55
00:02:08,870 --> 00:02:10,650
- And you mentioned the
first one a few years ago.

56
00:02:10,650 --> 00:02:11,730
Can you tell us about that one

57
00:02:11,730 --> 00:02:13,760

and you said they look similar

58
00:02:13,760 --> 00:02:17,130
but they also have differences,
significant differences in.

59
00:02:17,130 --> 00:02:17,963
- Absolutely.

60
00:02:17,963 --> 00:02:19,960
Yeah so what we released three years ago

61
00:02:19,960 --> 00:02:24,110
was an image of the six and
a half billion solar mass.

62
00:02:24,110 --> 00:02:26,630
So it's not just the mass of the sun

63
00:02:26,630 --> 00:02:29,430
which dwarves of course the
mass of any terrestrial object

64
00:02:29,430 --> 00:02:31,930
but of the sun and six and a half billion

65
00:02:31,930 --> 00:02:33,490
of its closet friends.

66
00:02:33,490 --> 00:02:36,380
Almost the mass of a galaxy.

67
00:02:36,380 --> 00:02:38,690
All collected into one point in space

68
00:02:38,690 --> 00:02:43,360
out in the giant elliptical
galaxy, Messier 87.

69
00:02:43,360 --> 00:02:46,360
54 million light years away right?

70
00:02:46,360 --> 00:02:49,337
So it's an enormous distance away

71
00:02:49,337 --> 00:02:53,660
and the photons that left M87
left, departed the black hole,

72
00:02:53,660 --> 00:02:55,990
the dinosaurs had just gone extinct.

73
00:02:55,990 --> 00:02:58,600
Mammals had not yet
become ascendant right?

74
00:02:58,600 --> 00:03:00,090
- That's cool.
- It's an incredible,

75
00:03:00,090 --> 00:03:01,110
incredible distance.

76
00:03:01,110 --> 00:03:03,660
Mind-boggling scales.

77
00:03:03,660 --> 00:03:05,180
The one that we just saw today,

78
00:03:05,180 --> 00:03:07,400
the one that we just released today.

79
00:03:07,400 --> 00:03:09,960
It came from the same observation route

80
00:03:09,960 --> 00:03:12,790
but it's the black hole at

the center of our galaxy.

81
00:03:12,790 --> 00:03:14,540
Okay, so it's still a long distance away.

82
00:03:14,540 --> 00:03:17,900
If you wanted to get into
your car and drive there,

83
00:03:17,900 --> 00:03:20,130
it would take you about as long.

84
00:03:20,130 --> 00:03:22,200
Essentially an infinite amount of time.

85
00:03:22,200 --> 00:03:23,810
I don't know what gas
mileage your car gets

86
00:03:23,810 --> 00:03:26,890
but it's, I guess unless you're Elon Musk.

87
00:03:26,890 --> 00:03:29,100
- If your car went the speed
of light just to clarify

88
00:03:29,100 --> 00:03:30,885
you could get there in
how many million years?

89
00:03:30,885 --> 00:03:32,930
- It would take 24,000.
- 24,000 that's a lot, okay.

90
00:03:32,930 --> 00:03:34,040
- 24,000 years.

91
00:03:34,040 --> 00:03:37,400
So that means that the

light that left Sag A*,

92
00:03:37,400 --> 00:03:38,390
that's the name we give the black hole

93
00:03:38,390 --> 00:03:39,930
at the center of our galaxy.

94
00:03:39,930 --> 00:03:41,860
Left in the late Stone Age.

95
00:03:41,860 --> 00:03:43,380
Not only were there humans

96
00:03:43,380 --> 00:03:47,430
but they were well on their way
to becoming what we are now.

97
00:03:47,430 --> 00:03:51,080
So it really drives home how
much closer this new beast is.

98
00:03:51,080 --> 00:03:54,660
It's closer but it's also
1500 times less massive.

99
00:03:54,660 --> 00:03:57,503
More typical, not this
really extreme kind of thing

100
00:03:57,503 --> 00:03:59,520
that M87 was.

101
00:03:59,520 --> 00:04:00,510
It's our black hole.

102
00:04:00,510 --> 00:04:03,340
So I think a lot of us
feel an affinity for it

103
00:04:03,340 --> 00:04:04,863
and it means that it changes.

104
00:04:05,700 --> 00:04:09,900
M87 is the stately old
lion, just sitting there.

105
00:04:09,900 --> 00:04:12,900
Letting take its photograph every night.

106
00:04:12,900 --> 00:04:14,580
Sag A* is the puppy

107
00:04:14,580 --> 00:04:17,440
that's constantly moving
around, wagging its tail,

108
00:04:17,440 --> 00:04:18,610
won't stay still.

109
00:04:18,610 --> 00:04:21,644
On minutes, maybe hours time scale.

110
00:04:21,644 --> 00:04:22,950
Because that's a
completely different face.

111
00:04:22,950 --> 00:04:25,470
And that's a massive difference right?

112
00:04:25,470 --> 00:04:27,650
Different time scale that
it takes to image it.

113
00:04:27,650 --> 00:04:30,360
Different time scale that
things are changing on.

114
00:04:30,360 --> 00:04:31,550
- How do you do this?

115
00:04:31,550 --> 00:04:33,670
How do we image black holes?

116
00:04:33,670 --> 00:04:34,960
- With great difficulty

117
00:04:34,960 --> 00:04:37,200
and with a global group
of extraordinary people

118
00:04:37,200 --> 00:04:39,480
who all come together
for this one purpose.

119
00:04:39,480 --> 00:04:42,390
The imaging of M87, the imaging of Sag A*

120
00:04:42,390 --> 00:04:45,850
begins with telescopes at
far corners of the earth.

121
00:04:45,850 --> 00:04:49,820
Each planning and executing
coordinated observing campaigns.

122
00:04:49,820 --> 00:04:52,820
Collecting these subtle
photons from the universe.

123
00:04:52,820 --> 00:04:56,920
Recording them on literally
tons of hard drives.

124
00:04:56,920 --> 00:04:59,380
That then gets shipped
back to a central facility

125
00:04:59,380 --> 00:05:03,040
where we try to piece
together what is effectively

126
00:05:03,040 --> 00:05:05,070
an earth-sized telescope.

127
00:05:05,070 --> 00:05:07,740
So then once we have these
little bits of information

128
00:05:07,740 --> 00:05:09,840
pieced together in an
earth-sized telescope,

129
00:05:09,840 --> 00:05:12,800
then we can complete the
process of forming an image

130
00:05:12,800 --> 00:05:14,510
in a large supercomputer.

131
00:05:14,510 --> 00:05:17,320
And that involves effectively
implementing something

132
00:05:17,320 --> 00:05:19,540
like an inverse Fourier transformer.

133
00:05:19,540 --> 00:05:21,130
Unmixing little bits of information

134
00:05:21,130 --> 00:05:22,710
from each of these around the globe.

135
00:05:22,710 --> 00:05:24,140
- So it's some difficulty.

136
00:05:24,140 --> 00:05:25,290
- A little bit, yes.

137
00:05:25,290 --> 00:05:26,147
Yeah yeah, yeah.

138
00:05:26,147 --> 00:05:27,930
- And it's a really involved procedure

139
00:05:27,930 --> 00:05:30,560
but at the end of the day
you're getting this one image

140
00:05:30,560 --> 00:05:31,510
that we can look at.

141
00:05:31,510 --> 00:05:33,960
As you said, it looked like a fire donut.

142
00:05:33,960 --> 00:05:36,510
What are we seeing when
we look at that image?

143
00:05:36,510 --> 00:05:40,640
- The fire in the fire donut
is the luminous hot plasma

144
00:05:40,640 --> 00:05:43,800
that has rushed headlong
towards an inexorable fate

145
00:05:43,800 --> 00:05:45,640
crossing the event horizon.

146
00:05:45,640 --> 00:05:47,800
Out of the visible universe.

147
00:05:47,800 --> 00:05:49,410

Black holes are a nice place to look

148
00:05:49,410 --> 00:05:51,730
but if you linger too
long, you're in trouble

149
00:05:51,730 --> 00:05:53,800
and that plasma is lingering too long.

150
00:05:53,800 --> 00:05:56,070
But by virtue of having fallen down

151
00:05:56,070 --> 00:05:57,320
deep into the potential well

152
00:05:57,320 --> 00:05:59,041
presented by the black hole

153
00:05:59,041 --> 00:06:01,440
that has heated up to
enormous temperatures,

154
00:06:01,440 --> 00:06:02,940
billions of degrees

155
00:06:02,940 --> 00:06:05,440
and that's producing the fire that we see.

156
00:06:05,440 --> 00:06:08,330
That's what we would call
synchrotron emission.

157
00:06:08,330 --> 00:06:10,010
It's an emission mechanism that happens

158
00:06:10,010 --> 00:06:11,760
when you have very energetic electrons,

159

00:06:11,760 --> 00:06:14,930
very hot electrons zipping
around magnetic fields.

160
00:06:14,930 --> 00:06:16,475
The hole in the donut,

161
00:06:16,475 --> 00:06:17,540
which is of course the defining feature.

162
00:06:17,540 --> 00:06:18,960
That's the black hole.

163
00:06:18,960 --> 00:06:20,960
That's the gravitational bending of light

164
00:06:20,960 --> 00:06:22,430
around the central black hole.

165
00:06:22,430 --> 00:06:24,459
It leaves behind a shadow.

166
00:06:24,459 --> 00:06:25,292
And that's the defining feature.

167
00:06:25,292 --> 00:06:26,520
We talk about the Event Horizon Telescope.

168
00:06:26,520 --> 00:06:28,520
That's what we were built to observe.

169
00:06:28,520 --> 00:06:31,230
- I always thought black
holes were by definition,

170
00:06:31,230 --> 00:06:34,250
impossible to see,
impossible to photograph

171
00:06:34,250 --> 00:06:37,200
and the idea that the
icing around the donut

172
00:06:37,200 --> 00:06:39,070
and my initial perception would be,

173
00:06:39,070 --> 00:06:41,000
well everything falls in
and you can't see anything.

174
00:06:41,000 --> 00:06:43,410
So what are we seeing light

175
00:06:43,410 --> 00:06:47,660
that has just barely escaped
from this pit of gravity?

176
00:06:47,660 --> 00:06:49,960
- Yeah, so the darkness of black holes.

177
00:06:49,960 --> 00:06:51,870
That's an isolated black hole statement.

178
00:06:51,870 --> 00:06:54,670
Right, black holes are
definitely the perfect prison.

179
00:06:54,670 --> 00:06:56,500
Nothing escapes, even light.

180
00:06:56,500 --> 00:06:58,370
But black holes plus the stuff,

181
00:06:58,370 --> 00:06:59,640
that's the icing right?

182
00:06:59,640 --> 00:07:02,740

That they are the most luminous
objects in the universe.

183
00:07:02,740 --> 00:07:06,190
What we're seeing is
emitted far enough out

184
00:07:06,190 --> 00:07:08,623
that it's not quite so dire.

185
00:07:09,469 --> 00:07:10,642
A non-trivial fraction of the light

186
00:07:10,642 --> 00:07:13,290
is captured and absorbed by the black hole

187
00:07:13,290 --> 00:07:15,220
depending on where exactly
we're talking about.

188
00:07:15,220 --> 00:07:17,930
It can be as high as 50%, maybe less.

189
00:07:17,930 --> 00:07:19,400
So I don't know, what kind of odds

190
00:07:19,400 --> 00:07:21,012
do you want to give our photon?

191
00:07:21,012 --> 00:07:23,360
- Not great.
- Not great, yeah, yeah.

192
00:07:23,360 --> 00:07:25,310
So yeah, it's an extreme environment

193
00:07:25,310 --> 00:07:27,760
but it's not right up against the horizon.

194
00:07:27,760 --> 00:07:29,510
- Yeah, I want to go
back to this word horizon

195
00:07:29,510 --> 00:07:30,660
'cause you've said it a few times

196
00:07:30,660 --> 00:07:33,610
and it's even in the name of
the Event Horizon Telescope.

197
00:07:33,610 --> 00:07:37,080
What's the event horizon and
where is that on the image?

198
00:07:37,080 --> 00:07:39,960
- The event horizon is mathematically

199
00:07:39,960 --> 00:07:41,460
that point of no return.

200
00:07:41,460 --> 00:07:44,680
The surface in space that
separates those things

201
00:07:44,680 --> 00:07:47,730
that can reach out to infinity
and those things that can't.

202
00:07:47,730 --> 00:07:50,530
A good definition might be event horizon

203
00:07:50,530 --> 00:07:52,950
is that line you cross
when people stop responding

204
00:07:52,950 --> 00:07:54,610
to your tweets.

205
00:07:54,610 --> 00:07:57,673
That puts it in a very contemporary frame.

206
00:07:58,560 --> 00:08:01,790
In the image, the reason
why we see a dark shadow

207
00:08:01,790 --> 00:08:04,830
is because light can't traverse
through the black hole.

208
00:08:04,830 --> 00:08:07,120
The light that tries to
traverse through the black hole

209
00:08:07,120 --> 00:08:09,040
would cross that event horizon.

210
00:08:09,040 --> 00:08:10,880
Then that's captured forevermore

211
00:08:10,880 --> 00:08:12,490
and that's what leaves this deficit

212
00:08:12,490 --> 00:08:15,110
that you can see from any vantage point.

213
00:08:15,110 --> 00:08:16,500
It's kind of a funny idea

214
00:08:16,500 --> 00:08:18,030
that no matter what
direction you're looking

215
00:08:18,030 --> 00:08:18,940
at the black hole at,

216
00:08:18,940 --> 00:08:21,560

it casts the same shadow
on the surrounding material

217
00:08:21,560 --> 00:08:23,440
and it's because the light can't propagate

218
00:08:23,440 --> 00:08:26,427
through this event horizon
and come back to it.

219
00:08:26,427 --> 00:08:28,610
So that we shadow we see
is literally the image

220
00:08:28,610 --> 00:08:29,700
of the event horizon.

221
00:08:29,700 --> 00:08:31,650
Or the absence of image from

222
00:08:31,650 --> 00:08:32,760
the event horizon.
- Right.

223
00:08:32,760 --> 00:08:35,252
- I remember one of the first
times I ever spoke to you,

224
00:08:35,252 --> 00:08:36,110
this was about eight years ago.

225
00:08:36,110 --> 00:08:37,687
You said, "You know
we're working on getting

226
00:08:37,687 --> 00:08:39,307
"the first image of a black hole

227
00:08:39,307 --> 00:08:41,897

"and mark my words, when we
do, it'll be on the front page

228
00:08:41,897 --> 00:08:44,270
"of the New York Times, above the fold."

229
00:08:44,270 --> 00:08:46,500
And then you announced
it and the next day,

230
00:08:46,500 --> 00:08:47,900
I remember I picked you up at the airport

231
00:08:47,900 --> 00:08:50,690
and I looked at the newsstand
and there's the black hole

232
00:08:50,690 --> 00:08:52,890
on the front page of the New
York Times above the fold

233
00:08:52,890 --> 00:08:55,200
and I thought, "Well he got
that prediction correct."

234
00:08:55,200 --> 00:08:57,880
And if the predictions of the
black hole itself are correct,

235
00:08:57,880 --> 00:09:00,990
why do you think there's
such a public fascination?

236
00:09:00,990 --> 00:09:03,970
It's, New York Times above
the fold is prime real estate

237
00:09:03,970 --> 00:09:06,520
for an object that's impossibly far away

238
00:09:06,520 --> 00:09:08,623
for us to ever experience.

239
00:09:08,623 --> 00:09:09,456
- Now this is one of the great joys

240
00:09:09,456 --> 00:09:10,289
of working on black holes.

241
00:09:10,289 --> 00:09:13,400
I think it connects with
people on a deep level.

242
00:09:13,400 --> 00:09:14,850
I think most people,

243
00:09:14,850 --> 00:09:18,200
they may not have a
mathematically exact concept

244
00:09:18,200 --> 00:09:19,330
of what a black hole is.

245
00:09:19,330 --> 00:09:20,670
But black holes have penetrated

246
00:09:20,670 --> 00:09:23,550
the public consciousness
so well that most people

247
00:09:23,550 --> 00:09:25,670
have a reasonable conceptual idea,

248
00:09:25,670 --> 00:09:28,930
that perfect prison from
which nothing escapes.

249
00:09:28,930 --> 00:09:32,350

Maybe they see them in movies,
black holes don't suck.

250
00:09:32,350 --> 00:09:34,540
But beyond that, you
know they're not Hoovers

251
00:09:34,540 --> 00:09:36,000
sucking up the universe.

252
00:09:36,000 --> 00:09:37,457
But the idea of a thing that you go into

253
00:09:37,457 --> 00:09:38,330
and you don't come out.

254
00:09:38,330 --> 00:09:42,830
It also ends up being a useful reference,

255
00:09:42,830 --> 00:09:44,780
many things that people experience right?

256
00:09:44,780 --> 00:09:46,180
I mean there's a real mystery.

257
00:09:46,180 --> 00:09:48,680
What happens on the other
side of that event horizon

258
00:09:48,680 --> 00:09:49,937
and how would you know?

259
00:09:49,937 --> 00:09:52,910
You can't send an undergraduate
across the event horizon

260
00:09:52,910 --> 00:09:54,710
and then report back to you right?

261
00:09:54,710 --> 00:09:56,970
They cross the event
horizon and it's a mystery.

262
00:09:56,970 --> 00:09:58,760
That's an obvious metaphor

263
00:09:58,760 --> 00:09:59,593
for a lot of things.
- There's also ethical reasons

264
00:09:59,593 --> 00:10:02,220
why you shouldn't send an
undergraduate to the black hole.

265
00:10:02,220 --> 00:10:05,350
- Undoubtedly yes, yes, yes and practical.

266
00:10:05,350 --> 00:10:06,520
It's very, very expensive.

267
00:10:06,520 --> 00:10:08,913
You would at least send
a graduate student.

268
00:10:08,913 --> 00:10:10,800
It's a metaphor for changes in life

269
00:10:10,800 --> 00:10:12,850
that you can't see the other side of.

270
00:10:12,850 --> 00:10:15,060
So people in a visceral
sense connect with it

271
00:10:15,060 --> 00:10:16,690
and it's visual.

272

00:10:16,690 --> 00:10:17,523
You know a large part of your brain

273
00:10:17,523 --> 00:10:18,870
is focused on visual processing.

274
00:10:18,870 --> 00:10:21,270
So this is a profound science result

275
00:10:21,270 --> 00:10:23,661
that talks about these
kind of extreme objects

276
00:10:23,661 --> 00:10:24,910
that people already kind of get.

277
00:10:24,910 --> 00:10:26,540
And it's presented to them in a format

278
00:10:26,540 --> 00:10:27,810
that they can easily absorb.

279
00:10:27,810 --> 00:10:29,430
I think that's why this ends up

280
00:10:29,430 --> 00:10:33,680
being a really exciting
prospect for public engagement.

281
00:10:33,680 --> 00:10:34,520
- Yeah.
- And as you said,

282
00:10:34,520 --> 00:10:36,720
it relies on a global collaboration.

283
00:10:36,720 --> 00:10:39,580
Can you talk a little bit
about that collaboration?

284
00:10:39,580 --> 00:10:43,060
How many people, where the
different telescopes are located.

285
00:10:43,060 --> 00:10:45,080
- Maybe your role in that collaboration,

286
00:10:45,080 --> 00:10:46,450
which piece of the puzzle are you?

287
00:10:46,450 --> 00:10:50,350
- Right so the collaboration
is more than 400 people.

288
00:10:50,350 --> 00:10:53,120
They are on six of the seven continents.

289
00:10:53,120 --> 00:10:56,881
We managed to get onto
Antarctica before Australia.

290
00:10:56,881 --> 00:10:59,640
There's not enough tall
mountains in Australia.

291
00:10:59,640 --> 00:11:01,880
We'll have to find a solution for that.

292
00:11:01,880 --> 00:11:04,310
These are people who range from engineers

293
00:11:04,310 --> 00:11:08,490
who design and build hardware,
put steel on the ground.

294
00:11:08,490 --> 00:11:11,420
All the way to people like me, theorists

295
00:11:11,420 --> 00:11:14,950
who try to make sense of what we see.

296
00:11:14,950 --> 00:11:19,090
So my role in all of this
has been trying to determine

297
00:11:19,090 --> 00:11:22,000
what does it mean that we
see this particular brand

298
00:11:22,000 --> 00:11:23,030
of fire donut.

299
00:11:23,030 --> 00:11:24,380
You know is it a French cruller?

300
00:11:24,380 --> 00:11:26,177
Is it a Boston cream?

301
00:11:26,177 --> 00:11:27,830
And what does that mean for black holes

302
00:11:27,830 --> 00:11:30,250
and how they impact the galaxy?

303
00:11:30,250 --> 00:11:33,430
The telescopes are at the
highest stria sites on earth.

304
00:11:33,430 --> 00:11:34,640
It's absolutely critical

305
00:11:34,640 --> 00:11:38,610
because we are looking at
millimeter wavelength photons.

306
00:11:38,610 --> 00:11:43,530

These are about 10 times
smaller than the size of photons

307
00:11:43,530 --> 00:11:46,020
that are bouncing around your microwaves.

308
00:11:46,020 --> 00:11:47,790
A few times smaller than your microwaves.

309
00:11:47,790 --> 00:11:49,890
The reason why we use microwave ovens

310
00:11:49,890 --> 00:11:53,410
is because those photons
are absorbed well by water.

311
00:11:53,410 --> 00:11:55,380
If you put a steak in the microwave

312
00:11:55,380 --> 00:11:58,270
and it comes out even looking
like you boiled a steak,

313
00:11:58,270 --> 00:11:59,970
that's 'cause that's what you did.

314
00:12:00,829 --> 00:12:01,662
You heated up all the water,

315
00:12:01,662 --> 00:12:03,030
then you cooked the
steak with the hot water

316
00:12:03,030 --> 00:12:04,110
inside the steak.

317
00:12:04,110 --> 00:12:06,410
So that's slightly tragic
because we have these photons

318
00:12:06,410 --> 00:12:09,890
that came from the late Stone Age,

319
00:12:09,890 --> 00:12:11,180
from the center of our galaxy

320
00:12:11,180 --> 00:12:13,480
or just after the end of the dinosaurs.

321
00:12:13,480 --> 00:12:17,430
From M87 they've traversed
the universe to come to us

322
00:12:17,430 --> 00:12:19,350
and in that last moment of their journey,

323
00:12:19,350 --> 00:12:20,950
they slam into our upper atmosphere

324
00:12:20,950 --> 00:12:22,855
and get absorbed by water right?

325
00:12:22,855 --> 00:12:25,370
I mean it's sort of a
brutal Game of Thrones type.

326
00:12:25,370 --> 00:12:26,970
- That long journey.
- Game of Thrones for photons.

327
00:12:26,970 --> 00:12:29,780
- And then just shy of reaching us, they.

328
00:12:29,780 --> 00:12:31,160
- No payoff.

329
00:12:31,160 --> 00:12:32,470

So we try to help those photons

330
00:12:32,470 --> 00:12:34,230
by getting above as much
of the water as we can.

331
00:12:34,230 --> 00:12:36,380
So you have to be in
those highest locations

332
00:12:36,380 --> 00:12:38,800
and try to choose the places
that don't have lots of water.

333
00:12:38,800 --> 00:12:40,550
So South Pole's a good example.

334
00:12:40,550 --> 00:12:41,920
First it's pretty high and second,

335
00:12:41,920 --> 00:12:44,830
the water has precipitated
out, it's all frozen out.

336
00:12:44,830 --> 00:12:47,040
Chile, the Atacama Plain.

337
00:12:47,040 --> 00:12:48,940
Alma's built on a high plateau,

338
00:12:48,940 --> 00:12:51,300
that's in the middle of a desert.

339
00:12:51,300 --> 00:12:53,420
Montecito in Hawaii

340
00:12:53,420 --> 00:12:55,740
is a mountain that protrudes up very high

341
00:12:55,740 --> 00:12:58,560
and it's in a very stable
thermal environment.

342
00:12:58,560 --> 00:13:00,190
So all of these places high and dry

343
00:13:00,190 --> 00:13:03,470
help us get to these photons
before the water vapor does.

344
00:13:03,470 --> 00:13:05,760
- THE EHT has been
described by you and others

345
00:13:05,760 --> 00:13:07,710
as an earth-sized telescope.

346
00:13:07,710 --> 00:13:09,610
Can you explain what you mean by that?

347
00:13:10,680 --> 00:13:12,600
- All astronomical observations

348
00:13:12,600 --> 00:13:16,670
must fundamentally contend
with the wave nature of light.

349
00:13:16,670 --> 00:13:18,260
It's unfortunately not an option.

350
00:13:18,260 --> 00:13:19,993
Light's a wave and that means

351
00:13:19,993 --> 00:13:22,530
that when we see small structures,

352
00:13:22,530 --> 00:13:26,260

they get blurred out by
something called diffraction.

353
00:13:26,260 --> 00:13:29,500
You experience diffraction
and as I get older,

354
00:13:29,500 --> 00:13:31,367
I might see it a little
worse than I did before

355
00:13:31,367 --> 00:13:34,470
but you experience diffraction
every time you drive at night

356
00:13:34,470 --> 00:13:35,763
and you look out into the distance

357
00:13:35,763 --> 00:13:38,860
and you see the streetlights.

358
00:13:38,860 --> 00:13:41,540
You'll notice they all
look like little stars,

359
00:13:41,540 --> 00:13:42,680
not stars in the sky.

360
00:13:42,680 --> 00:13:46,610
Multipointed star bursts.
- Star bursts.

361
00:13:46,610 --> 00:13:47,443
- Yes, thank you.

362
00:13:47,443 --> 00:13:49,710
And if you look closely you'll notice

363
00:13:49,710 --> 00:13:52,510

that every street light
looks like the same star

364
00:13:52,510 --> 00:13:55,880
and if you turn your head,
the star moves with your head.

365
00:13:55,880 --> 00:13:57,530
It's always oriented the same way

366
00:13:58,397 --> 00:13:59,860
and the because the star
is not in the light,

367
00:13:59,860 --> 00:14:00,890
it's in your eye.

368
00:14:00,890 --> 00:14:03,730
You're looking at diffraction
spikes through your pupil.

369
00:14:03,730 --> 00:14:07,387
You see this in movies when
you see the diffraction spikes

370
00:14:07,387 --> 00:14:08,360
on the camera.

371
00:14:08,360 --> 00:14:11,810
You can tell how many sides
their pupil on the camera has.

372
00:14:11,810 --> 00:14:14,640
Or how many sides they thought
the pupil on the camera

373
00:14:14,640 --> 00:14:16,960
would have when they do
it all in post processing

374
00:14:16,960 --> 00:14:18,220
and add lens flare and things.

375
00:14:18,220 --> 00:14:19,310
- The JJ Abrams shot.

376
00:14:19,310 --> 00:14:20,693
- That's right.

377
00:14:20,693 --> 00:14:22,810
And so the same thing happens
to astronomical instruments.

378
00:14:22,810 --> 00:14:26,020
Your ability to resolve
something goes down

379
00:14:26,020 --> 00:14:27,850
as your telescope gets bigger.

380
00:14:27,850 --> 00:14:29,020
Let me turn that around.

381
00:14:29,020 --> 00:14:31,160
The smallest thing you
resolve gets smaller

382
00:14:31,160 --> 00:14:32,940
as your telescope gets bigger.

383
00:14:32,940 --> 00:14:33,773
- Okay.
- Bigger telescope,

384
00:14:33,773 --> 00:14:35,540
you can see smaller objects.

385
00:14:35,540 --> 00:14:38,340

At millimeter wavelengths
which is where microwaves

386
00:14:38,340 --> 00:14:40,340
that the EHT observes.

387
00:14:40,340 --> 00:14:43,110
We really do need a
telescope that is the size

388
00:14:43,110 --> 00:14:43,960
of the planet.

389
00:14:43,960 --> 00:14:46,440
The 10,000 kilometer diameter telescope.

390
00:14:46,440 --> 00:14:49,550
That's an unpopular thing to
build in people's backyards.

391
00:14:49,550 --> 00:14:52,440
They somehow object if
you completely cover

392
00:14:52,440 --> 00:14:54,260
their entire yard in shade.

393
00:14:54,260 --> 00:14:56,180
The solution is that it turns out

394
00:14:56,180 --> 00:14:58,330
you don't need a whole telescope.

395
00:14:58,330 --> 00:15:00,340
You just need to fill in enough of it

396
00:15:00,340 --> 00:15:03,160
to spread out across
that 10,000 kilometers

397
00:15:03,160 --> 00:15:05,010
and the Event Horizon Telescope uses

398
00:15:05,010 --> 00:15:08,350
this very clever technique
where we have telescopes

399
00:15:08,350 --> 00:15:10,600
that are spaced around the world

400
00:15:10,600 --> 00:15:11,900
and they're in each filling in.

401
00:15:11,900 --> 00:15:14,050
In fact, it's each pair
of them are filling in

402
00:15:14,050 --> 00:15:16,810
a little point on this mirror.

403
00:15:16,810 --> 00:15:20,630
The strategy is one, more
telescopes is better.

404
00:15:20,630 --> 00:15:24,320
We get more points on the
mirror and two, patience

405
00:15:24,320 --> 00:15:26,530
as the earth rotates underneath the sky

406
00:15:26,530 --> 00:15:27,570
and as the earth rotates,

407
00:15:27,570 --> 00:15:29,160
those telescopes are
at different locations

408
00:15:29,160 --> 00:15:31,210
and they're filling in a
different part of the mirror.

409
00:15:31,210 --> 00:15:33,430
So when we say we have
an earth-sized telescope,

410
00:15:33,430 --> 00:15:35,150
we mean that very literally.

411
00:15:35,150 --> 00:15:40,050
So we really do effectively
construct a sparsely-sampled

412
00:15:40,050 --> 00:15:44,173
but nevertheless,
earth-sized primary mirror

413
00:15:44,173 --> 00:15:45,780
but it's also a computational telescope

414
00:15:45,780 --> 00:15:48,010
because that process has to be completed

415
00:15:48,010 --> 00:15:49,760
in large computers after the fact

416
00:15:49,760 --> 00:15:53,000
which is effectively
propagating the photons

417
00:15:53,000 --> 00:15:55,320
from the mirror where normally
you would have the mirror.

418
00:15:55,320 --> 00:15:56,710
You've flecked your photons off the mirror

419
00:15:56,710 --> 00:15:58,770
up to your primary focus

420
00:15:58,770 --> 00:16:00,350
and then you'd make your image there.

421
00:16:00,350 --> 00:16:03,480
We reflect, we'll redetect
the photons on the mirror

422
00:16:03,480 --> 00:16:04,387
and then on a computer and say,

423
00:16:04,387 --> 00:16:07,127
"Well, this photon would have done this

424
00:16:07,127 --> 00:16:08,670
"up to our primary focus."

425
00:16:08,670 --> 00:16:10,043
And then we make images.

426
00:16:11,010 --> 00:16:13,490
- So all of these telescopes that existed

427
00:16:13,490 --> 00:16:14,530
for other purposes,

428
00:16:14,530 --> 00:16:17,100
they were built for
other astronomical uses,

429
00:16:17,100 --> 00:16:19,190
you've sort of hijacked
isn't the right word.

430
00:16:19,190 --> 00:16:20,210
Piggybacked?

431
00:16:20,210 --> 00:16:21,043
Capitalized.

432
00:16:21,043 --> 00:16:21,876
- Borrowed.
- What's the good word?

433
00:16:21,876 --> 00:16:25,060
Borrowed, made the most of.
- Leverage

434
00:16:25,060 --> 00:16:26,562
- Leverage, there's the word

435
00:16:26,562 --> 00:16:27,395
I was working for.
- Leverage, leverage yeah.

436
00:16:27,395 --> 00:16:30,210
- So these telescopes
weren't built themselves

437
00:16:30,210 --> 00:16:31,910
for black hole hunting is that right?

438
00:16:31,910 --> 00:16:32,743
- That's right.

439
00:16:32,743 --> 00:16:35,510
In fact one of the largest
telescopes in the world,

440
00:16:35,510 --> 00:16:39,703
if not the largest had Atacama
Large Millimeter Array.

441
00:16:39,703 --> 00:16:41,750
It's this telescope in the Chilean desert.

442
00:16:41,750 --> 00:16:42,650
Canada is a partner.

443
00:16:42,650 --> 00:16:46,130
It's so big that it couldn't
be made with a single region.

444
00:16:46,130 --> 00:16:48,250
So you got Europe, it's got North America

445
00:16:48,250 --> 00:16:51,420
and it's got the Asian partners.

446
00:16:51,420 --> 00:16:53,830
And they all came together
and they built this

447
00:16:53,830 --> 00:16:56,450
one enormous radio telescope.

448
00:16:56,450 --> 00:16:57,920
Two billion dollars.

449
00:16:57,920 --> 00:16:59,410
This was not the thing they built it for.

450
00:16:59,410 --> 00:17:00,850
They built it for a whole host of things.

451
00:17:00,850 --> 00:17:03,320
Finding birth places of planets.

452
00:17:03,320 --> 00:17:05,930
The disks around young
stars where planets form.

453
00:17:05,930 --> 00:17:07,350

One of the first images it produced

454
00:17:07,350 --> 00:17:08,710
shows these beautiful rings

455
00:17:08,710 --> 00:17:12,290
where you can see the planets
are forming inside of the gas

456
00:17:12,290 --> 00:17:14,580
and dust disk around a young star.

457
00:17:14,580 --> 00:17:17,014
Understanding how stars form.

458
00:17:17,014 --> 00:17:19,340
Understanding the formation
and evolution of galaxies

459
00:17:19,340 --> 00:17:20,690
and any number of other things.

460
00:17:20,690 --> 00:17:22,960
I'm shortchanging Alma by a long shot.

461
00:17:22,960 --> 00:17:24,193
Then there's a whole
bunch of other telescopes

462
00:17:24,193 --> 00:17:26,760
that were built for very similar purposes.

463
00:17:26,760 --> 00:17:29,282
None of which by themselves

464
00:17:29,282 --> 00:17:31,570
could even hope to do the
experiment that we're doing.

465
00:17:31,570 --> 00:17:33,750
But what the Event Horizon
Telescope really did

466
00:17:33,750 --> 00:17:37,550
was provide the secret sauce
or the clever application

467
00:17:37,550 --> 00:17:39,341
that connects them all.

468
00:17:39,341 --> 00:17:41,070
And it's a good example
of how you can have

469
00:17:41,070 --> 00:17:44,820
a lot of excellent pieces
but until you assemble them,

470
00:17:44,820 --> 00:17:46,220
maybe there's something you're missing.

471
00:17:46,220 --> 00:17:47,760
All right, the EHT is really,

472
00:17:47,760 --> 00:17:50,060
allows these telescopes
together to be far more

473
00:17:50,060 --> 00:17:51,720
than the sum of their parts.

474
00:17:51,720 --> 00:17:52,930
- How did you even conceive,

475
00:17:52,930 --> 00:17:55,220
you or your colleagues think of.

476

00:17:55,220 --> 00:17:56,870
Maybe if we connect these telescopes,

477
00:17:56,870 --> 00:17:59,290
we could resolve this mysterious object.

478
00:17:59,290 --> 00:18:01,630
Where did this idea come
from, to built the EHT?

479
00:18:01,630 --> 00:18:05,250
- To be fair, this technique,
radio interferometry

480
00:18:05,250 --> 00:18:07,330
is a venerable technique.

481
00:18:07,330 --> 00:18:09,780
I mentioned Alma, I went on
and on about Alma a moment ago.

482
00:18:09,780 --> 00:18:12,010
It actually uses radio interferometry.

483
00:18:12,010 --> 00:18:16,180
It's 64 individual dishes
that all connect up

484
00:18:16,180 --> 00:18:18,560
to form one effective telescope

485
00:18:18,560 --> 00:18:20,830
that's maybe 10 kilometers across.

486
00:18:20,830 --> 00:18:22,520
100 kilometers across sometime.

487
00:18:22,520 --> 00:18:24,430
They move the dishes around.

488
00:18:24,430 --> 00:18:25,490
The idea of using telescopes

489
00:18:25,490 --> 00:18:29,010
separated by earth-sized
distances also is not new.

490
00:18:29,010 --> 00:18:32,600
People have been doing that
for almost half a century.

491
00:18:32,600 --> 00:18:35,050
The Very Long Baseline Array,

492
00:18:35,050 --> 00:18:37,720
so the technique is very
long baseline interferometry

493
00:18:37,720 --> 00:18:41,360
and there's a dedicated
array that does this.

494
00:18:41,360 --> 00:18:44,433
Very Long Baseline Array
at much longer wavelengths.

495
00:18:45,350 --> 00:18:47,750
Seven millimeters is really pushing it

496
00:18:47,750 --> 00:18:50,720
and then they go all the way
out to a meter wavelength.

497
00:18:50,720 --> 00:18:53,860
So the VLBA has been
doing this for 30 years.

498
00:18:53,860 --> 00:18:56,980

What's new in the EHT is
pushing that technique

499
00:18:56,980 --> 00:18:58,030
down to one mil.

500
00:18:58,030 --> 00:19:00,090
It is expensive to make the earth bigger.

501
00:19:00,090 --> 00:19:03,000
You can do it at the price
of launching rockets.

502
00:19:03,000 --> 00:19:04,890
It's difficult otherwise
to make the earth bigger

503
00:19:04,890 --> 00:19:06,800
but if you want to improve the resolution,

504
00:19:06,800 --> 00:19:08,590
the other thing you can do is observe

505
00:19:08,590 --> 00:19:10,200
at shorter and shorter wavelengths.

506
00:19:10,200 --> 00:19:11,580
Higher and higher frequencies.

507
00:19:11,580 --> 00:19:14,540
Bluer and bluer color and
the Event Horizon Telescope

508
00:19:14,540 --> 00:19:17,910
really is the clever
element of figuring out

509
00:19:17,910 --> 00:19:20,300
how to make that technique

which is very challenging,

510
00:19:20,300 --> 00:19:22,810
very significant
tolerances at each station,

511
00:19:22,810 --> 00:19:25,340
work on this heterogeneous
array of telescopes

512
00:19:25,340 --> 00:19:26,950
that were otherwise already built

513
00:19:26,950 --> 00:19:28,680
to do the millimeter science,

514
00:19:28,680 --> 00:19:31,280
in part for the reasons why
I talked about microwaves.

515
00:19:31,280 --> 00:19:32,600
Because looking at water is interesting

516
00:19:32,600 --> 00:19:35,107
and it's not just water that
shows up in a microwave right?

517
00:19:35,107 --> 00:19:38,360
- And these are features of
the technique in general.

518
00:19:38,360 --> 00:19:41,410
Did you have to modify or
improve any of the techniques

519
00:19:41,410 --> 00:19:46,090
when you went from studying
M87 to studying Sag A*?

520

00:19:46,090 --> 00:19:48,890
- The observational
side of it is the same.

521
00:19:48,890 --> 00:19:50,720
In fact it's the same observing route.

522
00:19:50,720 --> 00:19:54,440
Detecting those subtle radio photons,

523
00:19:54,440 --> 00:19:56,630
that was effectively identical.

524
00:19:56,630 --> 00:19:59,840
But because Sag A* is that frenetic puppy

525
00:19:59,840 --> 00:20:01,720
and constantly changing,

526
00:20:01,720 --> 00:20:03,330
that means that if we are patient

527
00:20:03,330 --> 00:20:04,850
as we have to be to make an image

528
00:20:04,850 --> 00:20:06,800
'cause we do have to fill in that mirror.

529
00:20:06,800 --> 00:20:09,000
Remember that mirror is
just a couple points.

530
00:20:09,000 --> 00:20:10,560
I mean you can imagine
what it would be like

531
00:20:10,560 --> 00:20:13,610
trying to get ready in the
morning and all you have

532
00:20:13,610 --> 00:20:15,520
are 15 points on your mirror.

533
00:20:15,520 --> 00:20:17,800
Maybe 15 little dime-sized pieces.

534
00:20:17,800 --> 00:20:20,970
Some of us might be able to
do that but most of us won't.

535
00:20:20,970 --> 00:20:22,710
The patience part fills that in.

536
00:20:22,710 --> 00:20:24,943
Is absolutely critical and that's the part

537
00:20:24,943 --> 00:20:26,910
that is a real problem for Sag A*

538
00:20:26,910 --> 00:20:29,850
because as we are patient,
Sag A*'s changing.

539
00:20:29,850 --> 00:20:32,210
So it's really like we're
leaving the shutter open,

540
00:20:32,210 --> 00:20:34,637
trying to get that photo in dim light

541
00:20:34,637 --> 00:20:37,740
and the puppy is not standing still.

542
00:20:37,740 --> 00:20:39,500
In fact we're chasing it around.

543
00:20:39,500 --> 00:20:42,040

The M87 required a whole new set of tools

544
00:20:42,040 --> 00:20:46,498
to operate in a challenging
data environment.

545
00:20:46,498 --> 00:20:49,160
The Event Horizon Telescope,
as wonderful as it is

546
00:20:49,160 --> 00:20:52,220
is still just barely capable
of doing what we ask.

547
00:20:52,220 --> 00:20:54,840
I mean it's really a
groundbreaking instrument

548
00:20:54,840 --> 00:20:56,741
which also means that you're the first

549
00:20:56,741 --> 00:20:57,574
to find all the difficulties.

550
00:20:57,574 --> 00:20:59,070
All the problems.

551
00:20:59,070 --> 00:21:01,000
We don't have enough telescopes,

552
00:21:01,000 --> 00:21:03,230
we always want more telescopes.

553
00:21:03,230 --> 00:21:04,920
We don't have enough
pieces of that mirror,

554
00:21:04,920 --> 00:21:06,010
we always want more.

555
00:21:06,010 --> 00:21:08,060
There are some calibration challenges

556
00:21:08,060 --> 00:21:11,130
that we hadn't anticipated
that we had to overcome.

557
00:21:11,130 --> 00:21:14,520
We had to rewrite most of
the data processing software.

558
00:21:14,520 --> 00:21:17,060
There are packages that
people use for the VLBA

559
00:21:17,060 --> 00:21:19,470
or for these other instruments
and they just did not work

560
00:21:19,470 --> 00:21:20,690
for EHT.

561
00:21:20,690 --> 00:21:21,950
But then on top of that

562
00:21:21,950 --> 00:21:25,840
we had to relax this patience assumption.

563
00:21:25,840 --> 00:21:28,850
We could just stare it,
leave the shutter open

564
00:21:28,850 --> 00:21:29,930
and make a picture.

565
00:21:29,930 --> 00:21:31,820
And that required I think a revolution

566
00:21:31,820 --> 00:21:35,430
in how we think about making
these sorts of pictures.

567
00:21:35,430 --> 00:21:36,980
That's what took us the three years.

568
00:21:36,980 --> 00:21:41,160
We had to develop the
analysis techniques necessary

569
00:21:41,160 --> 00:21:43,420
to allow us to be patient.

570
00:21:43,420 --> 00:21:44,840
- These images that you come up with,

571
00:21:44,840 --> 00:21:48,160
they take years of effort
from many different people.

572
00:21:48,160 --> 00:21:51,640
How do you choose which black
hole you're gonna focus on?

573
00:21:51,640 --> 00:21:53,193
What factors do you consider?

574
00:21:54,240 --> 00:21:56,323
- Unfortunately that's easy.

575
00:21:57,176 --> 00:21:59,980
- Sounds like the one easy thing.

576
00:21:59,980 --> 00:22:01,710
So far.
- Yeah, yeah.

577

00:22:01,710 --> 00:22:03,530
You observe the black holes you have,

578
00:22:03,530 --> 00:22:05,490
not the black holes you wish you had.

579
00:22:05,490 --> 00:22:07,890
As this groundbreaking experiment

580
00:22:07,890 --> 00:22:10,890
and being confined to
earth-sized baselines,

581
00:22:10,890 --> 00:22:13,660
earth-sized mirrors,
there's only two black holes

582
00:22:13,660 --> 00:22:17,460
that exhibit a shadow
that we could resolve

583
00:22:17,460 --> 00:22:18,460
that we are aware of.

584
00:22:18,460 --> 00:22:22,070
And those are the black holes in M87

585
00:22:22,070 --> 00:22:24,360
and the black hole at
the center of our galaxy.

586
00:22:24,360 --> 00:22:26,550
The one at the center of our
galaxy because it's so close.

587
00:22:26,550 --> 00:22:30,220
It's very typical in many
ways but it's right next door.

588

00:22:30,220 --> 00:22:32,710
And the one in M87
because it's much further

589
00:22:32,710 --> 00:22:36,340
but it's also much larger
and those two, that's it.

590
00:22:36,340 --> 00:22:40,220
Then after that, the next
one is three times smaller.

591
00:22:40,220 --> 00:22:42,000
So just barely on the cusp.

592
00:22:42,000 --> 00:22:44,175
Of course we do look at other objects.

593
00:22:44,175 --> 00:22:45,440
There's a lot of interesting
science to be done.

594
00:22:45,440 --> 00:22:47,570
To be looking at mostly accreting,

595
00:22:47,570 --> 00:22:49,550
it turns out accreting black holes

596
00:22:49,550 --> 00:22:51,730
but those are the only two horizon,

597
00:22:51,730 --> 00:22:53,610
what we call horizon science targets.

598
00:22:53,610 --> 00:22:55,830
Targets where we can
resolve the fire donut,

599
00:22:55,830 --> 00:22:57,350

resolve the shadow.

600
00:22:57,350 --> 00:22:59,190
- I have to ask you about the fire donut.

601
00:22:59,190 --> 00:23:00,270
Why you're calling

602
00:23:00,270 --> 00:23:01,367
it a fire donut.
- Yeah, yep.

603
00:23:01,367 --> 00:23:03,760
One of the members of the EHT,

604
00:23:03,760 --> 00:23:07,510
just before the first
announcement put our M87 picture

605
00:23:07,510 --> 00:23:08,870
into a Google image search.

606
00:23:08,870 --> 00:23:11,410
Just to find out what Google
thought this might look like.

607
00:23:11,410 --> 00:23:13,320
I think actually there
were some predictions,

608
00:23:13,320 --> 00:23:14,450
that's not the fun ones though.

609
00:23:14,450 --> 00:23:17,610
The fun one is they came up with fire,

610
00:23:17,610 --> 00:23:19,770
rings of fire and donuts.

611
00:23:19,770 --> 00:23:22,070
Also because it's a little bit fuzzy.

612
00:23:22,070 --> 00:23:24,000
I know we have this picture of very sharp,

613
00:23:24,000 --> 00:23:26,500
ring-like structures from these beautiful

614
00:23:26,500 --> 00:23:29,870
and numerical simulations
that run on supercomputers.

615
00:23:29,870 --> 00:23:31,290
But we're just pushing the envelope,

616
00:23:31,290 --> 00:23:32,580
we're just at the boundary.

617
00:23:32,580 --> 00:23:34,810
The resolution we have is what we show

618
00:23:34,810 --> 00:23:36,950
and that kind of smears it out into this.

619
00:23:36,950 --> 00:23:38,410
Looks kind of like a French cruller.

620
00:23:38,410 --> 00:23:39,520
- You said to us the other day though

621
00:23:39,520 --> 00:23:41,040
that these two black
holes that you have now

622
00:23:41,040 --> 00:23:42,470
are kind of like an odd couple

623
00:23:42,470 --> 00:23:44,810
and if you had to choose just two,

624
00:23:44,810 --> 00:23:47,240
there are two pretty good black holes

625
00:23:47,240 --> 00:23:49,140
to have at your disposal now.

626
00:23:49,140 --> 00:23:50,750
Can you explain why that is?

627
00:23:50,750 --> 00:23:53,130
- There's the movers and
shakers in the universe

628
00:23:53,130 --> 00:23:55,310
and then there's everybody else.

629
00:23:55,310 --> 00:23:57,610
Black holes are the
engines of the universe.

630
00:23:57,610 --> 00:23:59,090
Pumping out huge amounts of energy

631
00:23:59,090 --> 00:24:00,530
but that's only a subset.

632
00:24:00,530 --> 00:24:03,280
M87 is one of these very,

633
00:24:03,280 --> 00:24:05,190
certainly historically
powerful black holes.

634
00:24:05,190 --> 00:24:07,840
It sits at an enormous galaxy,

635
00:24:07,840 --> 00:24:09,630
in an enormous galaxy cluster.

636
00:24:09,630 --> 00:24:12,481
It's thousands of galaxies
all orbiting each other.

637
00:24:12,481 --> 00:24:15,120
It's not just that it sits
in a galaxy that's 100 times

638
00:24:15,120 --> 00:24:16,910
more massive than our own

639
00:24:16,910 --> 00:24:19,100
and it's down at the
center of all of that.

640
00:24:19,100 --> 00:24:23,240
Benefiting from all that
commotion, driving gas down to it.

641
00:24:23,240 --> 00:24:26,900
And while these days it's on
something of A*vation diet,

642
00:24:26,900 --> 00:24:28,600
certainly historically it wasn't.

643
00:24:28,600 --> 00:24:30,540
That's how it got to be six
and a half billion times

644
00:24:30,540 --> 00:24:32,690
the mass of the sun.

645
00:24:32,690 --> 00:24:34,840
And it powers a powerful outflow.

646
00:24:34,840 --> 00:24:36,360
Powers what we call a jet.

647
00:24:36,360 --> 00:24:38,760
These are light-speed emanation.

648
00:24:38,760 --> 00:24:41,040
Right, remember black
hole's perfect prison.

649
00:24:41,040 --> 00:24:43,610
This is exactly the opposite
of what you would expect.

650
00:24:43,610 --> 00:24:45,330
Stuff going out, not in.

651
00:24:45,330 --> 00:24:46,660
And that stuff is being launched

652
00:24:46,660 --> 00:24:48,080
right near the event horizon

653
00:24:48,080 --> 00:24:51,120
and we think we understand
something about how that work.

654
00:24:51,120 --> 00:24:54,050
One of the goals of the EHT
is really to nail that down.

655
00:24:54,050 --> 00:24:55,200
So that's M87.

656
00:24:55,200 --> 00:24:58,040
Launching these counterintuitive,

657

00:24:58,040 --> 00:25:00,130
paradoxical light speed outflows,

658
00:25:00,130 --> 00:25:02,490
center of all the commotion.

659
00:25:02,490 --> 00:25:03,980
The one at the center of our galaxy

660
00:25:03,980 --> 00:25:05,570
is the black hole next door.

661
00:25:05,570 --> 00:25:08,580
It's really this typical
average black hole.

662
00:25:08,580 --> 00:25:11,450
Our galaxy is kind of a
typical average galaxy.

663
00:25:11,450 --> 00:25:12,550
It's ours, so we like it.

664
00:25:12,550 --> 00:25:14,573
But it's not terribly unique.

665
00:25:15,631 --> 00:25:17,490
Out of four million solar masses,

666
00:25:17,490 --> 00:25:20,280
our black hole is really
similar to all the other ones.

667
00:25:20,280 --> 00:25:22,830
We only see it because
we're so close to it.

668
00:25:22,830 --> 00:25:27,800
It's on starvation diet and

were it a couple galaxies away

669
00:25:27,800 --> 00:25:29,050
we would not be able to see it.

670
00:25:29,050 --> 00:25:32,000
So it is as different
as you could imagine,

671
00:25:32,000 --> 00:25:34,750
one of these enormous behemoths,

672
00:25:34,750 --> 00:25:37,060
these super massive monsters

673
00:25:37,060 --> 00:25:38,950
at the centers of galaxies it could be.

674
00:25:38,950 --> 00:25:41,460
We have one power jet, it's enormous.

675
00:25:41,460 --> 00:25:43,390
At the center of all the commotion

676
00:25:43,390 --> 00:25:45,050
and then we have another
one that's kind of typical

677
00:25:45,050 --> 00:25:46,320
of everything else.

678
00:25:46,320 --> 00:25:50,200
Not really growing very much,
not feasting on very much gas.

679
00:25:50,200 --> 00:25:52,850
Hardly observable, almost shy.

680

00:25:52,850 --> 00:25:54,808
And it is the comparison then

681
00:25:54,808 --> 00:25:55,710
that allows you to ask questions

682
00:25:55,710 --> 00:25:58,470
like why is our black hole
little and that one big?

683
00:25:58,470 --> 00:25:59,900
You know I'm not complaining right?

684
00:25:59,900 --> 00:26:02,131
I don't want to live next to M87,

685
00:26:02,131 --> 00:26:03,250
that would probably be dangerous.

686
00:26:03,250 --> 00:26:06,080
What makes a black hole produce
those light speed outflow?

687
00:26:06,080 --> 00:26:07,960
What allows a black
hole to grow very fast?

688
00:26:07,960 --> 00:26:11,163
What determines how bright
they are, how big they are?

689
00:26:12,060 --> 00:26:13,577
- You've said, these are your words.

690
00:26:13,577 --> 00:26:16,367
"There is a monster, a
super massive fire donut

691
00:26:16,367 --> 00:26:19,510

"behaving like an unruly
puppy in our neighborhood."

692
00:26:19,510 --> 00:26:22,810
Should we be scared, this
all sounds very scary.

693
00:26:22,810 --> 00:26:24,490
- It's the astronomical neighborhood.

694
00:26:24,490 --> 00:26:25,760
- Not right next door.

695
00:26:25,760 --> 00:26:26,809
- Not right next door.

696
00:26:26,809 --> 00:26:28,650
There's 24,000 light years

697
00:26:28,650 --> 00:26:31,420
is a comfortable distance for now.

698
00:26:31,420 --> 00:26:33,008
Remember black holes don't suck.

699
00:26:33,008 --> 00:26:34,630
It's a great line for a sixth grade class.

700
00:26:34,630 --> 00:26:36,570
The black hole at the
center of our galaxy,

701
00:26:36,570 --> 00:26:39,330
even at four million
times the mass of the sun

702
00:26:39,330 --> 00:26:43,590
is only massive enough to
rule the gravity in its area.

703
00:26:43,590 --> 00:26:46,020
Rule the dynamics and
material in its area.

704
00:26:46,020 --> 00:26:47,460
Where a distance that's kind of typical

705
00:26:47,460 --> 00:26:49,097
is the distance between
stars where we are.

706
00:26:49,097 --> 00:26:52,370
Now it has almost no more
authority than the sun.

707
00:26:52,370 --> 00:26:56,100
The sun is ruling the area
around in our vicinity

708
00:26:56,100 --> 00:26:57,540
of about that distance as well.

709
00:26:57,540 --> 00:26:58,780
Now there's a lot more stuff there

710
00:26:58,780 --> 00:26:59,900
so it's a little bit more impressive.

711
00:26:59,900 --> 00:27:02,850
It has a larger retinue
of more interesting things

712
00:27:02,850 --> 00:27:04,330
but nevertheless it's relatively small.

713
00:27:04,330 --> 00:27:08,017
Because the mass of the
galaxy is 10 billion times

714
00:27:08,017 --> 00:27:08,850
that of the sun.

715
00:27:08,850 --> 00:27:10,250
At four million with an M.

716
00:27:10,250 --> 00:27:13,500
So 10 billion with a B,
that's still a tiny fraction

717
00:27:13,500 --> 00:27:15,270
of the galaxy which is
part of the magic trick.

718
00:27:15,270 --> 00:27:18,550
How do black holes achieve
such enormous energy output

719
00:27:18,550 --> 00:27:20,240
while being such a tiny
fraction of the mass

720
00:27:20,240 --> 00:27:21,840
of their host galaxy?

721
00:27:21,840 --> 00:27:23,040
It's not gonna suck us up.

722
00:27:23,040 --> 00:27:24,280
We're not gonna fall into it.

723
00:27:24,280 --> 00:27:26,420
At least not in any time scale

724
00:27:26,420 --> 00:27:29,400
that is even astronomically conceivable.

725

00:27:29,400 --> 00:27:31,750
Long before that the sun will have grown

726
00:27:31,750 --> 00:27:34,962
into a supergiant, envelop the earth.

727
00:27:34,962 --> 00:27:36,574
Had gone out.
- Oh great.

728
00:27:36,574 --> 00:27:37,407
What a relief.
- Yeah, yeah.

729
00:27:37,407 --> 00:27:38,340
I mean like there's other things.

730
00:27:38,340 --> 00:27:40,952
I'm not saying don't be worried,
I'm just saying that's not.

731
00:27:40,952 --> 00:27:43,040
But that doesn't mean that it's safe.

732
00:27:43,040 --> 00:27:43,873
That's because

733
00:27:43,873 --> 00:27:46,420
if it ever decides to go
off the starvation diet,

734
00:27:46,420 --> 00:27:48,580
it can suddenly start producing

735
00:27:48,580 --> 00:27:50,849
a lot of high energy emission.

736
00:27:50,849 --> 00:27:51,682
A lot of x-rays,

737
00:27:51,682 --> 00:27:54,880
a lot of ultraviolet
and a lot of gamma rays

738
00:27:54,880 --> 00:27:57,480
and we know that a million
years ago it was doing that.

739
00:27:57,480 --> 00:28:00,620
There are these giant bubbles of hot stuff

740
00:28:00,620 --> 00:28:03,780
above and below the plane
of the Milky Way Galaxy

741
00:28:03,780 --> 00:28:06,280
and it's believed that that is caused by

742
00:28:06,280 --> 00:28:09,950
a episode of energetic behavior.

743
00:28:09,950 --> 00:28:13,620
An episode of rapid accretion
which suddenly produced

744
00:28:13,620 --> 00:28:16,530
a lot of energy, produced
jets like we see in M87.

745
00:28:16,530 --> 00:28:17,840
Those light speed outflows.

746
00:28:17,840 --> 00:28:19,660
- But we haven't seen in Sag A*?

747
00:28:19,660 --> 00:28:21,730
Not any evidence in
the past million years.

748
00:28:21,730 --> 00:28:24,870
In fact everything you see
looks like the luminosity

749
00:28:24,870 --> 00:28:27,170
is dropping exponentially,
dropping like a rock.

750
00:28:27,170 --> 00:28:29,090
So now is the time to do this.

751
00:28:29,090 --> 00:28:30,580
Million years from now, it might not be.

752
00:28:30,580 --> 00:28:32,550
If it ever did that
again, you know who knows?

753
00:28:32,550 --> 00:28:33,960
We might all get irradiated.

754
00:28:33,960 --> 00:28:36,090
You know, living next to
an active galactic nucleus

755
00:28:36,090 --> 00:28:37,090
is a little danger.

756
00:28:37,090 --> 00:28:39,340
- You did say, you gave us
an analogy the other day

757
00:28:39,340 --> 00:28:40,840
of it's like living in the plain

758
00:28:40,840 --> 00:28:42,460
next to a cosmic volcano.

759
00:28:42,460 --> 00:28:44,880
It's dormant.
- Yeah yeah yeah.

760
00:28:44,880 --> 00:28:45,713
- But it may not always stay dormant.

761
00:28:45,713 --> 00:28:46,710
- That's right, it might
be beautiful at night

762
00:28:46,710 --> 00:28:48,120
as long as it's not erupting.

763
00:28:48,120 --> 00:28:49,560
- You make these nice analogies

764
00:28:49,560 --> 00:28:51,660
to the type of diet that
the black hole is on.

765
00:28:51,660 --> 00:28:53,710
Whether it's starving or feasting.

766
00:28:53,710 --> 00:28:57,670
Does this effect how
difficult it is to measure it?

767
00:28:57,670 --> 00:29:01,520
- Yes, there's a sweet spot
between starved and feasting

768
00:29:01,520 --> 00:29:02,660
that we have to hit.

769
00:29:02,660 --> 00:29:06,220
If it's feasting, it's
bright and that sounds good.

770
00:29:06,220 --> 00:29:07,580
It's easier to see bright objects.

771
00:29:07,580 --> 00:29:10,540
I mean these things are,
these things are so dim

772
00:29:10,540 --> 00:29:12,870
astronomers have a special unit.

773
00:29:12,870 --> 00:29:14,840
Because it just gets really cumbersome

774
00:29:14,840 --> 00:29:18,080
to carry around 10 to the
minus 26 all the time.

775
00:29:18,080 --> 00:29:20,285
It doesn't matter what
unit you're talking about.

776
00:29:20,285 --> 00:29:21,570
It's 10 to the minus 26 something.

777
00:29:21,570 --> 00:29:25,770
So it's 10 to the minus 26
watts per second per Hertz.

778
00:29:25,770 --> 00:29:27,790
We all used to have
hundred watt light bulb.

779
00:29:27,790 --> 00:29:29,420
Now we all have 15 watt.

780
00:29:29,420 --> 00:29:31,600
10 to the minus 26 watt,

781

00:29:31,600 --> 00:29:32,890
that's what astronomers are measuring,

782
00:29:32,890 --> 00:29:34,500
it's really incredible.

783
00:29:34,500 --> 00:29:36,620
And that's a bright source.

784
00:29:36,620 --> 00:29:37,523
We call that a Jansky.

785
00:29:37,523 --> 00:29:39,680
A Jansky source is a pretty rare source.

786
00:29:39,680 --> 00:29:42,680
Sag A* is three Janskys,
two and a half Janskys.

787
00:29:42,680 --> 00:29:44,770
If we're rapidly creating,
that'd be brighter,

788
00:29:44,770 --> 00:29:45,780
it's easier to see.

789
00:29:45,780 --> 00:29:48,230
On the other hand, at some point,

790
00:29:48,230 --> 00:29:49,660
you know what we mean by rapid accretion

791
00:29:49,660 --> 00:29:53,380
is that gas is rushing headlong
down towards the black hole

792
00:29:53,380 --> 00:29:56,360
and more accretion means more gas.

793
00:29:56,360 --> 00:29:58,900
You put too much gas, it becomes opaque

794
00:29:58,900 --> 00:30:00,270
and then you can't see the shadow.

795
00:30:00,270 --> 00:30:01,610
You know the big bright ball

796
00:30:01,610 --> 00:30:03,340
at the center of the galaxy telescope.

797
00:30:03,340 --> 00:30:05,530
The Event Horizon Telescope,
we have a sweet spot.

798
00:30:05,530 --> 00:30:07,390
It has to be accreting enough.

799
00:30:07,390 --> 00:30:10,240
It has to be feasting
enough that it's bright

800
00:30:10,240 --> 00:30:12,720
and there are some galaxies that aren't.

801
00:30:12,720 --> 00:30:14,660
M31, the Andromeda Galaxy.

802
00:30:14,660 --> 00:30:16,400
All right, so you can see
that in the night sky.

803
00:30:16,400 --> 00:30:18,680
The black hole at the center
of that one is a little too dim

804
00:30:18,680 --> 00:30:21,760

and then on the flip side it
can't be feasting too much.

805
00:30:21,760 --> 00:30:23,560
It has to be starving a little bit

806
00:30:23,560 --> 00:30:25,870
or else we won't be
able to see through the,

807
00:30:25,870 --> 00:30:27,290
the material around it
to get that horizon.

808
00:30:27,290 --> 00:30:28,660
- Is there a spot on the night sky

809
00:30:28,660 --> 00:30:30,407
where we could go out and look and say,

810
00:30:30,407 --> 00:30:32,627
"Sagittarius A* is roughly there

811
00:30:32,627 --> 00:30:34,560
"in the Sagittarius constellation."?

812
00:30:34,560 --> 00:30:38,050
- Yeah, that's why it's
Sagittarius A*, that's right.

813
00:30:38,050 --> 00:30:40,760
So the center of our galaxy is located

814
00:30:40,760 --> 00:30:43,312
in the constellation Sagittarius.

815
00:30:43,312 --> 00:30:44,470
It's a teapot.

816
00:30:44,470 --> 00:30:45,690
From the northern hemisphere,

817
00:30:45,690 --> 00:30:49,160
you're really right on
the, right on the limb.

818
00:30:49,160 --> 00:30:49,993
I've never been able to,

819
00:30:49,993 --> 00:30:51,580
actually in my backyard to see it.

820
00:30:51,580 --> 00:30:54,090
Because the light pollution and trees

821
00:30:54,090 --> 00:30:57,070
and so it's always been
a sore spot for me.

822
00:30:57,070 --> 00:30:59,480
At some point I'm gonna get
into the southern hemisphere.

823
00:30:59,480 --> 00:31:02,380
The only time that I was
in the southern hemisphere,

824
00:31:02,380 --> 00:31:05,000
I was in Australia and
they had brush fires.

825
00:31:05,000 --> 00:31:06,240
But you couldn't see anything.

826
00:31:06,240 --> 00:31:07,982
- Yeah.
- I was really bummed

827
00:31:07,982 --> 00:31:10,430
and I'm a theorist so I didn't
even I was at the wrong.

828
00:31:10,430 --> 00:31:13,870
I asked some of my observing colleagues.

829
00:31:13,870 --> 00:31:15,610
Okay, so where would I have looked?

830
00:31:15,610 --> 00:31:16,850
They kind of looked up at the sky

831
00:31:16,850 --> 00:31:17,967
and they thought for a
second and they said,

832
00:31:17,967 --> 00:31:22,350
"Well, at around noon look at the sun."

833
00:31:22,350 --> 00:31:23,560
That was also the wrong time of year.

834
00:31:23,560 --> 00:31:24,967
So that wasn't gonna happen.

835
00:31:24,967 --> 00:31:28,095
- Sounds like bad advice.
- Yeah, yeah.

836
00:31:28,095 --> 00:31:29,350
- The high noon, stare at the sun.

837
00:31:30,250 --> 00:31:31,931
- Yeah exactly.

838
00:31:31,931 --> 00:31:33,150
It's in the constellation Sagittarius

839
00:31:33,150 --> 00:31:34,700
and this is where the name comes from.

840
00:31:34,700 --> 00:31:38,343
Right, so the brightest
radio source in Sagittarius

841
00:31:38,343 --> 00:31:39,280
is above Sagittarius A.

842
00:31:39,280 --> 00:31:41,710
And it's a point source
which means until now

843
00:31:41,710 --> 00:31:43,910
it wasn't resolvable as a structure.

844
00:31:43,910 --> 00:31:45,980
It was just a single spot of light

845
00:31:45,980 --> 00:31:47,690
so that become a star.

846
00:31:47,690 --> 00:31:49,643
- Is this black ball in
the center of our galaxy,

847
00:31:49,643 --> 00:31:53,080
does it effect the shape or
the structure or the motion?

848
00:31:53,080 --> 00:31:54,100
Or anything

849
00:31:54,100 --> 00:31:55,720
of the galaxy surrounding it?
- Yeah.

850
00:31:55,720 --> 00:31:57,500
No, only the,

851
00:31:57,500 --> 00:32:00,470
only the dynamics of the
stars right around it.

852
00:32:00,470 --> 00:32:02,290
So these are the stars that Andrea Ghez

853
00:32:02,290 --> 00:32:05,590
and Reinhard Genzel won
a Nobel Prize in 2020

854
00:32:05,590 --> 00:32:07,920
for watching for decades.

855
00:32:07,920 --> 00:32:10,470
They watched them orbit the
black hole and from that,

856
00:32:10,470 --> 00:32:11,940
measure its mass.

857
00:32:11,940 --> 00:32:13,200
It's only those stars really

858
00:32:13,200 --> 00:32:15,520
that are being dramatically affected.

859
00:32:15,520 --> 00:32:17,893
This is a deep question because we do know

860
00:32:17,893 --> 00:32:21,316
that big galaxies, M87's a big galaxy.

861
00:32:21,316 --> 00:32:22,149
It has a big black hole.

862
00:32:22,149 --> 00:32:23,820
Small galaxies have small black hole.

863
00:32:23,820 --> 00:32:24,960
Why is that?

864
00:32:24,960 --> 00:32:26,800
It's certainly a correlation
that people observe,

865
00:32:26,800 --> 00:32:28,610
it doesn't sound that unreasonable.

866
00:32:28,610 --> 00:32:32,030
That whatever allows a
big galaxy to accumulate

867
00:32:32,030 --> 00:32:34,657
all the gas and all the mass
that produces all the stars

868
00:32:34,657 --> 00:32:37,630
and you see in it also will accumulate

869
00:32:37,630 --> 00:32:39,980
stuff at the center
which forms a black hole.

870
00:32:39,980 --> 00:32:41,410
That might make sense.

871
00:32:41,410 --> 00:32:44,020
On the other hand, we know
that's not the whole story

872
00:32:44,020 --> 00:32:46,850
because we do know that
black holes like M87

873
00:32:46,850 --> 00:32:48,810
are producing those light speed outflows,

874
00:32:48,810 --> 00:32:51,543
they can outshine their
galaxies by factors of 100.

875
00:32:52,432 --> 00:32:54,390
And they're producing
prodigious amounts of energy.

876
00:32:54,390 --> 00:32:56,000
It's mind boggling

877
00:32:56,000 --> 00:32:57,850
and that energy's not
just coming out as light.

878
00:32:57,850 --> 00:32:59,330
It's not just coming out as radio waves.

879
00:32:59,330 --> 00:33:02,560
It's also coming out as
kinetic energy in outflows.

880
00:33:02,560 --> 00:33:04,300
It's pushing material out.

881
00:33:04,300 --> 00:33:06,300
It's a giant snowplow.
- Actual stuff, matter.

882
00:33:06,300 --> 00:33:07,720
- That's right, actual matter

883
00:33:07,720 --> 00:33:10,530
and you can watch that process happen.

884
00:33:10,530 --> 00:33:13,870
By this, what we call
feedback, gas falls down

885
00:33:13,870 --> 00:33:16,370
into the center of the galaxy.

886
00:33:16,370 --> 00:33:17,780
It feeds the black hole

887
00:33:17,780 --> 00:33:20,340
which then enters this very active state.

888
00:33:20,340 --> 00:33:22,230
Starts pushing all this stuff around.

889
00:33:22,230 --> 00:33:24,170
It's kind of like an unruly baby.

890
00:33:24,170 --> 00:33:26,270
It's throwing everything against the wall.

891
00:33:26,270 --> 00:33:30,050
You can limit how fast more
gas can rain into the galaxy

892
00:33:30,050 --> 00:33:31,020
and so that black hole,

893
00:33:31,020 --> 00:33:34,150
even though it can only
effect the dynamics

894
00:33:34,150 --> 00:33:36,780
of the things right around its environment

895
00:33:36,780 --> 00:33:40,610
and spread that influence out

to the sides of the galaxy,

896
00:33:40,610 --> 00:33:42,663
out to beyond the sides of the galaxy,

897
00:33:42,663 --> 00:33:43,520
the sides of clusters.

898
00:33:43,520 --> 00:33:46,520
The largest examples of
these jets that we see

899
00:33:46,520 --> 00:33:48,840
extend many times the distance.

900
00:33:48,840 --> 00:33:51,290
Intergalactic impact, all from that point.

901
00:33:51,290 --> 00:33:53,830
That most compact thing
you could think of,

902
00:33:53,830 --> 00:33:55,830
down deep at the center.

903
00:33:55,830 --> 00:33:58,330
- And you have said a few
times that you're a theorist

904
00:33:58,330 --> 00:34:01,540
and so while this
collaboration requires people

905
00:34:01,540 --> 00:34:02,870
with a lot of different expertise,

906
00:34:02,870 --> 00:34:05,010
you focus on theoretical analysis.

907
00:34:05,010 --> 00:34:07,700
Can you tell us a little bit
about the specific questions

908
00:34:07,700 --> 00:34:10,657
or topics that you focus on studying?

909
00:34:10,657 --> 00:34:13,230
- You know, 20 years ago
I started thinking about

910
00:34:13,230 --> 00:34:15,120
trying to explain the phenomenology

911
00:34:15,120 --> 00:34:17,540
of some of these, some of these objects.

912
00:34:17,540 --> 00:34:19,490
Some of these accreting black holes

913
00:34:19,490 --> 00:34:22,890
and understand what it is that
resulted in the distribution

914
00:34:22,890 --> 00:34:24,250
of light that we see.

915
00:34:24,250 --> 00:34:26,620
The polarmetric properties that we see.

916
00:34:26,620 --> 00:34:28,610
Variability properties that we see

917
00:34:28,610 --> 00:34:30,850
and that was inextricably tied up

918
00:34:30,850 --> 00:34:33,870
with what's happening

down at the Event Horizon.

919
00:34:33,870 --> 00:34:35,390
So how these black holes grow.

920
00:34:35,390 --> 00:34:37,750
How they launch those outflows.

921
00:34:37,750 --> 00:34:41,430
And that led me right away
to be trying to make models

922
00:34:41,430 --> 00:34:45,750
of what that plasma,
that astrophysical bluff

923
00:34:45,750 --> 00:34:47,700
around the black hole that is so important

924
00:34:47,700 --> 00:34:49,550
for the astronomers, for us.

925
00:34:49,550 --> 00:34:52,460
Making numerical prediction,
explicit predictions.

926
00:34:52,460 --> 00:34:53,440
What that looked like.

927
00:34:53,440 --> 00:34:56,380
And then I did a thing which
is dangerous for a theorist

928
00:34:56,380 --> 00:34:58,670
as I thought maybe we
can answer this question

929
00:34:58,670 --> 00:35:01,270
on timescales that matter for my career.

930
00:35:01,270 --> 00:35:05,453
I have a, kind of a rule
of thumb I try to follow.

931
00:35:05,453 --> 00:35:07,240
I try to make predictions
that can be proven

932
00:35:07,240 --> 00:35:10,149
or disproven in about 10 years.

933
00:35:10,149 --> 00:35:12,530
I think my going timescale
is about 15 years,

934
00:35:12,530 --> 00:35:15,069
so that's pretty good
for an astrophysicist.

935
00:35:15,069 --> 00:35:17,209
It's within a factor of
two, so I'm satisfied.

936
00:35:17,209 --> 00:35:18,042
- Considering you're looking at light

937
00:35:18,042 --> 00:35:19,580
that is started in this direction

938
00:35:19,580 --> 00:35:20,647
when the dinosaurs were around.

939
00:35:20,647 --> 00:35:22,740
- Out at M87, no.
- Yeah.

940
00:35:22,740 --> 00:35:24,930
- Right, no that's right, that's right.

941
00:35:24,930 --> 00:35:27,440
So originally I'm building these models,

942
00:35:27,440 --> 00:35:30,670
trying to ascertain what
is the right observation

943
00:35:30,670 --> 00:35:33,030
that's going to allow me to distinguish

944
00:35:33,030 --> 00:35:36,090
between different ways
black holes can grow

945
00:35:36,090 --> 00:35:38,040
and different ways they
can launch outflows

946
00:35:38,040 --> 00:35:42,160
and how that affects their
otherwise observed properties

947
00:35:42,160 --> 00:35:46,700
and how that, how that
relates to how gravity works.

948
00:35:46,700 --> 00:35:47,553
Right, I mean black holes

949
00:35:47,553 --> 00:35:49,960
that we've talked about them
as very astronomical objects

950
00:35:49,960 --> 00:35:52,180
but they're also you know,

951
00:35:52,180 --> 00:35:55,730
this kind of perfect mix of

traits for general relativity.

952
00:35:55,730 --> 00:35:57,570
Extremely simple solutions

953
00:35:57,570 --> 00:36:00,220
to Einstein's equations
on the one hand and yet,

954
00:36:00,220 --> 00:36:03,283
completely counterintuitive physics.

955
00:36:03,283 --> 00:36:04,470
Extreme physics in every other sense.

956
00:36:04,470 --> 00:36:06,003
It's all non-linear gravity.

957
00:36:07,220 --> 00:36:09,298
My uncle once asked me,

958
00:36:09,298 --> 00:36:12,727
"Avery if you found that general
relativity was not right,

959
00:36:12,727 --> 00:36:14,180
"would you report that?"

960
00:36:14,180 --> 00:36:17,010
And I had to explain to him
that we're all theorists,

961
00:36:17,010 --> 00:36:19,360
we're all raging egomaniacs.

962
00:36:19,360 --> 00:36:20,570
The one thing we want to do

963

00:36:20,570 --> 00:36:22,280
is knock Einstein off the pedestal

964
00:36:22,280 --> 00:36:23,760
so we can climb onto it.

965
00:36:23,760 --> 00:36:25,190
That's what we're all hoping to find.

966
00:36:25,190 --> 00:36:29,220
Some inkling, some hint which
you may already have seen

967
00:36:29,220 --> 00:36:31,343
that there's something not kosher

968
00:36:31,343 --> 00:36:32,840
in the theory of general relativity,

969
00:36:32,840 --> 00:36:33,820
something not quite right

970
00:36:33,820 --> 00:36:35,740
that we have to fix up.

971
00:36:35,740 --> 00:36:37,030
We have theoretical reasons for thinking

972
00:36:37,030 --> 00:36:38,929
that has to be the case

973
00:36:38,929 --> 00:36:41,480
but observationally it's
been quite difficult

974
00:36:41,480 --> 00:36:43,880
and the place you might
look, naturalist look

975
00:36:43,880 --> 00:36:45,520
would be right around black hole.

976
00:36:45,520 --> 00:36:47,790
Since that time I've really gotten into

977
00:36:47,790 --> 00:36:49,590
actually trying to make those tests work.

978
00:36:49,590 --> 00:36:52,230
So this is where I come into
the Event Horizon Telescope.

979
00:36:52,230 --> 00:36:53,880
My job is not to come up with the ideas

980
00:36:53,880 --> 00:36:55,560
that motivate the telescope.

981
00:36:55,560 --> 00:36:56,480
We did that.

982
00:36:56,480 --> 00:36:57,410
We're working on ideas

983
00:36:57,410 --> 00:36:59,620
for the next telescope but we did that

984
00:36:59,620 --> 00:37:01,730
and now we're working
on trying to test them.

985
00:37:01,730 --> 00:37:05,140
And trying to bring those
theoretical concepts into contact,

986
00:37:05,140 --> 00:37:08,203
direct contact with the

underlying observation.

987
00:37:09,237 --> 00:37:11,320
What prediction do we make
for the fire donuts right?

988
00:37:11,320 --> 00:37:13,630
So for M87 one of them was,

989
00:37:13,630 --> 00:37:15,170
it should be bright in the south,

990
00:37:15,170 --> 00:37:18,423
not bright in the west and
that was a little weird.

991
00:37:18,423 --> 00:37:20,454
That sounds like a very boring prediction

992
00:37:20,454 --> 00:37:24,450
but the reason is because light
speed emanation goes west.

993
00:37:24,450 --> 00:37:26,430
It's about 10 degrees northwest.

994
00:37:26,430 --> 00:37:28,130
So you'd have thought that
if there was a bright side

995
00:37:28,130 --> 00:37:29,607
to the black hole,

996
00:37:29,607 --> 00:37:30,950
it's in the direction
of the emanation but no.

997
00:37:30,950 --> 00:37:33,210
It's not, because the material is rotating

998
00:37:33,210 --> 00:37:37,301
very rapidly and we see the
side that's coming towards it.

999
00:37:37,301 --> 00:37:38,320
It's a searchlight effect.

1000
00:37:38,320 --> 00:37:41,696
When I say wrap, it's rotating
at half the speed of light.

1001
00:37:41,696 --> 00:37:42,529
And there's a search light effect.

1002
00:37:42,529 --> 00:37:44,380
The mission gets beamed in
the direction that it's moving

1003
00:37:44,380 --> 00:37:47,174
and so we see it, the
side coming towards us

1004
00:37:47,174 --> 00:37:48,010
and that's the south.

1005
00:37:48,010 --> 00:37:49,750
So that the jet as a whole,

1006
00:37:49,750 --> 00:37:51,450
it's all spiraling around in a jet

1007
00:37:51,450 --> 00:37:53,360
is going towards the east.

1008
00:37:53,360 --> 00:37:55,120
And that's not true
further out in the jet.

1009
00:37:55,120 --> 00:37:56,990
As the jet gets wider

1010
00:37:56,990 --> 00:37:58,570
and it's just anger moenum constipation.

1011
00:37:58,570 --> 00:38:00,640
It's just the figure
skater expanding her arms,

1012
00:38:00,640 --> 00:38:01,640
slowing down.

1013
00:38:01,640 --> 00:38:02,473
But at the black hole

1014
00:38:02,473 --> 00:38:05,470
the arms are all tucked in
nice and tight and we see it,

1015
00:38:05,470 --> 00:38:06,640
we see it rise in the south.

1016
00:38:06,640 --> 00:38:09,130
So that's the kind of
prediction that we made.

1017
00:38:09,130 --> 00:38:12,040
For Sag A* we have predictions about

1018
00:38:12,040 --> 00:38:13,173
how much it can vary.

1019
00:38:14,077 --> 00:38:15,120
So how frenetic is the puppy right?

1020
00:38:15,120 --> 00:38:16,420
It's not enough to say frenetic puppy,

1021
00:38:16,420 --> 00:38:19,320
we want to know did
this puppy just wake up?

1022
00:38:19,320 --> 00:38:20,620
Is he tired?

1023
00:38:20,620 --> 00:38:22,220
Has he received a little bit of training?

1024
00:38:22,220 --> 00:38:23,350
Is it a high strung puppy?

1025
00:38:23,350 --> 00:38:25,019
Is it a chill puppy?

1026
00:38:25,019 --> 00:38:25,852
It was like these are,

1027
00:38:25,852 --> 00:38:28,414
we have a quantification of all of that

1028
00:38:28,414 --> 00:38:30,700
and it turns out that the large scale

1029
00:38:30,700 --> 00:38:32,400
numerical simulations that we have

1030
00:38:32,400 --> 00:38:34,720
that give us purchase on that question

1031
00:38:34,720 --> 00:38:36,697
are a little bit too variable.

1032
00:38:36,697 --> 00:38:38,002
So there's a mystery.

1033
00:38:38,002 --> 00:38:38,835
We don't really know,

1034
00:38:38,835 --> 00:38:41,302
it's like are those really applicable?

1035
00:38:41,302 --> 00:38:42,290
Was there an ingredient we just missed?

1036
00:38:42,290 --> 00:38:45,300
Did we forget to put the
baking soda in or something?

1037
00:38:45,300 --> 00:38:47,360
We'll find out right?

1038
00:38:47,360 --> 00:38:49,890
This is, just leave something
exciting to think about

1039
00:38:49,890 --> 00:38:52,180
and try to develop going forward.

1040
00:38:52,180 --> 00:38:53,310
But building out those direct tests,

1041
00:38:53,310 --> 00:38:55,120
direct contact with the data

1042
00:38:55,120 --> 00:38:57,903
is where we've been focused
for the past five years.

1043
00:38:59,191 --> 00:39:00,953
- The Sagittarius A*, the
black hole in our Milky Way.

1044
00:39:00,953 --> 00:39:02,760

How did it come to be there?

1045
00:39:02,760 --> 00:39:03,743
How was it formed?

1046
00:39:04,603 --> 00:39:06,178
Why is there a black hole there?

1047
00:39:06,178 --> 00:39:08,089
That was a brilliant
question, I don't know.

1048
00:39:08,089 --> 00:39:09,300
So there's two kinds of black holes

1049
00:39:09,300 --> 00:39:10,800
that we observed in the universe.

1050
00:39:10,800 --> 00:39:13,091
We'll have the things like
we've been talking about

1051
00:39:13,091 --> 00:39:14,687
that we call super massive.

1052
00:39:14,687 --> 00:39:16,690
We think every galaxy
has one at its heart.

1053
00:39:16,690 --> 00:39:18,040
Sometimes you'll see two

1054
00:39:18,040 --> 00:39:20,100
and we think that's because the galaxies,

1055
00:39:20,100 --> 00:39:22,240
we do see galaxies run into each other,

1056

00:39:22,240 --> 00:39:23,810
merging galaxies.

1057
00:39:23,810 --> 00:39:26,090
They'll ultimately settle down and combine

1058
00:39:26,090 --> 00:39:27,860
and distribute and when that happens,

1059
00:39:27,860 --> 00:39:30,743
the two will merge and become one.

1060
00:39:31,791 --> 00:39:32,780
One of these big ones for gas.

1061
00:39:32,780 --> 00:39:36,509
The other kind of black hole
that we see in the universe,

1062
00:39:36,509 --> 00:39:38,052
that doesn't mean there aren't other ones.

1063
00:39:38,052 --> 00:39:40,445
These are the two that we
have direct evidence for

1064
00:39:40,445 --> 00:39:42,290
are what we call stellar mass black holes

1065
00:39:42,290 --> 00:39:44,963
which is also inconveniently SMBH.

1066
00:39:46,421 --> 00:39:48,140
The stellar mass black
holes are the end products

1067
00:39:48,140 --> 00:39:51,660
of every star over about 30 solar mass.

1068
00:39:51,660 --> 00:39:54,920
So a star that grows
beyond 30 solar masses

1069
00:39:54,920 --> 00:39:59,799
during its formation has
a, a unique sentence.

1070
00:39:59,799 --> 00:40:01,090
Right, there's nothing it's gonna do

1071
00:40:01,090 --> 00:40:02,560
that's gonna stop it from forming

1072
00:40:02,560 --> 00:40:04,510
one of these stellar mass black holes.

1073
00:40:04,510 --> 00:40:07,070
Now we know that vary massed stars

1074
00:40:07,070 --> 00:40:09,284
live only a very short time.

1075
00:40:09,284 --> 00:40:10,540
They live only about a million years.

1076
00:40:10,540 --> 00:40:12,397
So when you generate a massive star,

1077
00:40:12,397 --> 00:40:14,760
it, as far as astronomers are concerned,

1078
00:40:14,760 --> 00:40:17,337
the universe is concerned,
in the blink of an eye

1079
00:40:17,337 --> 00:40:19,810
you've now made a stellar mass black hole.

1080
00:40:19,810 --> 00:40:21,000
One of these things that's 10,

1081
00:40:21,000 --> 00:40:23,572
maybe 30 times the mass of the sun.

1082
00:40:23,572 --> 00:40:25,245
There is some heavy one.

1083
00:40:25,245 --> 00:40:26,080
- Which we haven't seen directly.

1084
00:40:26,080 --> 00:40:28,340
- We haven't imaged them but LIGO,

1085
00:40:28,340 --> 00:40:31,120
so this is gravitation wave experiment

1086
00:40:31,120 --> 00:40:33,020
where they're looking not at light,

1087
00:40:33,020 --> 00:40:35,260
not at the subtle ripples in
the electric magnetic fields

1088
00:40:35,260 --> 00:40:37,060
that we pick up.

1089
00:40:37,060 --> 00:40:39,463
But subtle ripples in
the gravitational field.

1090
00:40:39,463 --> 00:40:42,380
A subtle jiggling due to
ripples in space time.

1091
00:40:42,380 --> 00:40:44,080

They are seeing the merger

1092
00:40:44,080 --> 00:40:46,283
of these stellar mass black holes.

1093
00:40:47,124 --> 00:40:47,957
So we know they're there.

1094
00:40:47,957 --> 00:40:49,080
We do see them.
- The famous LIGO discovery

1095
00:40:49,080 --> 00:40:52,546
was two black holes eventually
slamming in to one another.

1096
00:40:52,546 --> 00:40:53,966
- That's right, exactly.
- Right.

1097
00:40:53,966 --> 00:40:55,290
- So LIGO's you know, very inefficient.

1098
00:40:55,290 --> 00:40:57,810
Every time they find two, they lose one.

1099
00:40:57,810 --> 00:40:59,470
EHT is very environmentally
friendly right?

1100
00:40:59,470 --> 00:41:02,689
We see one black hole at
a time and we leave it be.

1101
00:41:02,689 --> 00:41:04,420
So that's a very exciting dynamical event.

1102
00:41:04,420 --> 00:41:06,650
Unfortunately, I can't

give you a formation story.

1103
00:41:06,650 --> 00:41:09,417
You asked where do these super
mass black holes come from?

1104
00:41:09,417 --> 00:41:10,250
I can't give you the formation story

1105
00:41:10,250 --> 00:41:11,849
for the ones at the
center of the galaxies.

1106
00:41:11,849 --> 00:41:13,610
I know that if I have to wait

1107
00:41:13,610 --> 00:41:16,890
for one of these stars to form.

1108
00:41:16,890 --> 00:41:18,440
Right, these stars don't
just automatically form

1109
00:41:18,440 --> 00:41:20,929
in the universe out of nothing right?

1110
00:41:20,929 --> 00:41:22,410
The first stars are very different

1111
00:41:22,410 --> 00:41:24,740
from the stars you see right now.

1112
00:41:24,740 --> 00:41:25,780
Stars you see right now

1113
00:41:25,780 --> 00:41:29,540
have all kinds of heavy elements
in them that were created

1114
00:41:29,540 --> 00:41:31,580
in the furnace of earlier stars.

1115
00:41:31,580 --> 00:41:33,641
The first stars don't have that.

1116
00:41:33,641 --> 00:41:35,550
First stars are made out of
just what the universe had

1117
00:41:35,550 --> 00:41:36,550
at the beginning.

1118
00:41:36,550 --> 00:41:37,960
So they look very different.

1119
00:41:37,960 --> 00:41:39,180
The James Webb Space Telescope,

1120
00:41:39,180 --> 00:41:41,070
one of the things that it's designed to do

1121
00:41:41,070 --> 00:41:43,120
is go see those and tell us about them.

1122
00:41:43,120 --> 00:41:44,830
If you wait for those to form

1123
00:41:44,830 --> 00:41:47,460
and then create a stellar mass black hole

1124
00:41:47,460 --> 00:41:50,186
and then start growing.

1125
00:41:50,186 --> 00:41:52,252
You put them in a very advantageous place.

1126

00:41:52,252 --> 00:41:53,224
You let them gobble up

1127
00:41:53,224 --> 00:41:55,400
all the gas they can get their hands on

1128
00:41:55,400 --> 00:41:57,961
and there's a limit to how much
they can get their hands on.

1129
00:41:57,961 --> 00:41:58,794
First you can only grab

1130
00:41:58,794 --> 00:42:00,860
what you can gravitationally
access and second,

1131
00:42:00,860 --> 00:42:03,770
if you start trying to eat
too much, it gets in the way.

1132
00:42:03,770 --> 00:42:06,610
At some point you start
shining too brightly

1133
00:42:06,610 --> 00:42:08,680
and the light that you're putting out,

1134
00:42:08,680 --> 00:42:10,520
the electromagnetic radiation you put out

1135
00:42:10,520 --> 00:42:12,380
starts pushing back on the flow.

1136
00:42:12,380 --> 00:42:13,920
- Right.
- It becomes self-regulating.

1137
00:42:13,920 --> 00:42:16,230

Just look at a hot dog
eating contest right?

1138
00:42:16,230 --> 00:42:19,090
At some point, at some points
you can't go any faster

1139
00:42:19,090 --> 00:42:21,410
and that fundamentally
limits how fast they can grow

1140
00:42:21,410 --> 00:42:24,304
and if you put in that limit,

1141
00:42:24,304 --> 00:42:25,137
we call that the Eddington limit.

1142
00:42:25,137 --> 00:42:27,620
After Sir Arthur Eddington
who first identified it.

1143
00:42:27,620 --> 00:42:30,519
If you say they're growing
at the Eddington limit,

1144
00:42:30,519 --> 00:42:31,352
at that maximum rate,

1145
00:42:31,352 --> 00:42:36,180
they can't get to the sizes
that we see some quasars at

1146
00:42:37,188 --> 00:42:38,281
in the universe.

1147
00:42:38,281 --> 00:42:40,062
So we know there are these
super massive black holes

1148

00:42:40,062 --> 00:42:42,120
floating around earlier
than you could make

1149
00:42:42,120 --> 00:42:43,723
from a stellar mass black hole.

1150
00:42:44,642 --> 00:42:45,475
So now, how do you do it?

1151
00:42:45,475 --> 00:42:46,870
I don't know, it's a great question.

1152
00:42:46,870 --> 00:42:49,350
- Is that part of what EHT
is hoping to figure out?

1153
00:42:49,350 --> 00:42:50,940
How these things come to be?

1154
00:42:50,940 --> 00:42:52,910
If there was a way to circumvent

1155
00:42:52,910 --> 00:42:55,700
Sir Arthur Eddington's
limit, that would be one way.

1156
00:42:55,700 --> 00:42:56,910
Not just looking at the gravity,

1157
00:42:56,910 --> 00:43:00,710
but not the essential
gravity, at some sense,

1158
00:43:00,710 --> 00:43:02,260
the gravitational stage

1159
00:43:02,260 --> 00:43:04,860
on which all of the

astrophysical dramas play out.

1160
00:43:04,860 --> 00:43:07,410
But instead looking at
those astrophysical dramas,

1161
00:43:07,410 --> 00:43:09,760
we try to determine

1162
00:43:09,760 --> 00:43:12,160
how does accretion onto black holes work?

1163
00:43:12,160 --> 00:43:14,290
Is it really subject to the assumptions

1164
00:43:14,290 --> 00:43:16,500
that go into the Eddington limit?

1165
00:43:16,500 --> 00:43:19,970
Could you exceed it by
orders of magnitude?

1166
00:43:19,970 --> 00:43:22,493
If you can, then we
can solve that problem.

1167
00:43:23,459 --> 00:43:26,060
The other thing is is of
course there's a future

1168
00:43:26,060 --> 00:43:27,263
beyond the EHT.

1169
00:43:28,222 --> 00:43:29,055
You know there's a near future

1170
00:43:29,055 --> 00:43:31,880
but then there's a far
future which is the one,

1171
00:43:31,880 --> 00:43:33,859
I get excited about both.

1172
00:43:33,859 --> 00:43:35,653
They're both wonderful but you know,

1173
00:43:35,653 --> 00:43:38,161
the one I dream about is
the far future of course.

1174
00:43:38,161 --> 00:43:40,340
The EHT in space that we have.

1175
00:43:40,340 --> 00:43:42,720
We've made the earth 100 times bigger

1176
00:43:42,720 --> 00:43:46,145
by virtue of putting satellites
out there with radio dishes.

1177
00:43:46,145 --> 00:43:47,990
This is something that you
could actually talk about doing.

1178
00:43:47,990 --> 00:43:50,974
This is, this is a
project that's accessible,

1179
00:43:50,974 --> 00:43:54,390
at least technologically,
just about accessible today.

1180
00:43:54,390 --> 00:43:56,320
So this is something we
could be thinking about

1181
00:43:56,320 --> 00:43:58,750
50 years from now, timeline's very,

1182
00:43:58,750 --> 00:44:00,143
always very long for that.

1183
00:44:01,290 --> 00:44:03,540
And if you built an instrument like that,

1184
00:44:03,540 --> 00:44:06,370
we could see every M87 in the universe.

1185
00:44:06,370 --> 00:44:09,930
So that would have the
resolution necessary to see M87

1186
00:44:09,930 --> 00:44:12,100
all the way to the edge of the universe

1187
00:44:12,100 --> 00:44:15,274
which is a remarkable, a remarkable thing.

1188
00:44:15,274 --> 00:44:16,860
Now maybe they're not
all bright enough to see

1189
00:44:16,860 --> 00:44:18,830
but that means that you're
really talking about

1190
00:44:18,830 --> 00:44:20,110
looking at black holes

1191
00:44:20,110 --> 00:44:21,907
and their evolution across cosmic time

1192
00:44:21,907 --> 00:44:23,930
and this gets to exactly this question.

1193
00:44:23,930 --> 00:44:26,330

How did they grow, how
did they get to be so big?

1194
00:44:26,330 --> 00:44:29,990
- Is M87 one of the biggest we know of?

1195
00:44:29,990 --> 00:44:33,450
Are there other M87s floating
around or is it an anomaly?

1196
00:44:33,450 --> 00:44:36,470
- There are other similarly-sized
objects in the universe

1197
00:44:36,470 --> 00:44:38,690
but they are anomalies.

1198
00:44:38,690 --> 00:44:41,860
10 billion solar masses
is about the limit.

1199
00:44:41,860 --> 00:44:44,270
There's a category of
ultra massive black holes

1200
00:44:44,270 --> 00:44:48,411
which are defined as bigger
than 10 billion right?

1201
00:44:48,411 --> 00:44:50,917
So I mean we're getting
into the superlative game.

1202
00:44:50,917 --> 00:44:51,750
- This is where the mind reels

1203
00:44:51,750 --> 00:44:54,180
because these numbers are just impossible

1204

00:44:54,180 --> 00:44:55,430
for me to comprehend.

1205
00:44:55,430 --> 00:44:57,450
I think impossible for most people.

1206
00:44:57,450 --> 00:44:59,640
How do you wrap your head
around these distances

1207
00:44:59,640 --> 00:45:01,661
and sizes and scale?

1208
00:45:01,661 --> 00:45:02,820
- We don't, they're numbers.

1209
00:45:02,820 --> 00:45:04,602
- You shut up and you calculate?

1210
00:45:04,602 --> 00:45:05,435
- You just write them down.

1211
00:45:05,435 --> 00:45:07,350
That's a really great question.

1212
00:45:07,350 --> 00:45:10,420
How do you internalize
or connect these things

1213
00:45:10,420 --> 00:45:13,166
to a terrestrial scale?

1214
00:45:13,166 --> 00:45:15,566
And it really is not, I
think it's not possible.

1215
00:45:16,427 --> 00:45:18,568
You say M87 is bigger than Sag A*

1216
00:45:18,568 --> 00:45:20,460
so you get the, and similar things right.

1217
00:45:20,460 --> 00:45:23,820
How many 10 billion, how many one billion?

1218
00:45:23,820 --> 00:45:25,320
Do that kind of game right?

1219
00:45:25,320 --> 00:45:27,564
But what does it mean to be a 10 billion?

1220
00:45:27,564 --> 00:45:28,610
That's one I don't know.

1221
00:45:28,610 --> 00:45:29,443
It's physically enormous.

1222
00:45:29,443 --> 00:45:32,172
- To add another number to this.

1223
00:45:32,172 --> 00:45:34,410
Do theorists have estimates
for how many black holes

1224
00:45:34,410 --> 00:45:36,630
there are in the whole universe?

1225
00:45:36,630 --> 00:45:38,695
- One per galaxy right?

1226
00:45:38,695 --> 00:45:40,270
If I put my Carl Sagan hat on,

1227
00:45:40,270 --> 00:45:42,730
that's billions upon billions.

1228

00:45:42,730 --> 00:45:45,490
In our galaxy, remember I said before

1229
00:45:45,490 --> 00:45:47,523
that every 30 solar mass black hole,

1230
00:45:49,256 --> 00:45:50,410
I'm sorry 30 solar mass
star makes a black hole

1231
00:45:50,410 --> 00:45:51,530
and there is a certain number

1232
00:45:51,530 --> 00:45:53,777
of 30 solar mass stars you make

1233
00:45:53,777 --> 00:45:58,200
for every solar mass star,
every star like the sun.

1234
00:45:58,200 --> 00:46:00,720
And stars like the sun don't
die in a million years right?

1235
00:46:00,720 --> 00:46:02,530
They last 10 billion years.

1236
00:46:02,530 --> 00:46:05,710
Every solar-type star in the galaxy about,

1237
00:46:05,710 --> 00:46:08,160
is still sticking around.

1238
00:46:08,160 --> 00:46:08,993
Maybe some have gone.

1239
00:46:08,993 --> 00:46:12,080
It's still of the young
with it generation.

1240
00:46:12,080 --> 00:46:13,510
Every half solar mass star

1241
00:46:13,510 --> 00:46:16,224
in the universe still exists right?

1242
00:46:16,224 --> 00:46:17,630
They have not run out of fuel yet.

1243
00:46:17,630 --> 00:46:20,020
So you can just look at the
number of solar mass stars,

1244
00:46:20,020 --> 00:46:21,614
number of half solar mass stars

1245
00:46:21,614 --> 00:46:23,720
and you can estimate how
many 30 solar mass stars

1246
00:46:23,720 --> 00:46:24,740
must there have been.

1247
00:46:24,740 --> 00:46:26,420
And remember, they fly by
in the blink of an eye.

1248
00:46:26,420 --> 00:46:29,960
10,000 times brighter,
10,000 times shorter lives.

1249
00:46:29,960 --> 00:46:32,580
Candlelight burns 10,000 times as bright,

1250
00:46:32,580 --> 00:46:35,560
burns 10,000 shorter lives right?

1251

00:46:35,560 --> 00:46:39,060
As long, 10,000ths okay.

1252
00:46:39,060 --> 00:46:40,820
So these are short-lived,

1253
00:46:40,820 --> 00:46:43,248
so they're almost instantly transferred.

1254
00:46:43,248 --> 00:46:44,370
So we can estimate how many

1255
00:46:44,370 --> 00:46:46,420
of these stellar mass black
holes there are in the Milky Way

1256
00:46:46,420 --> 00:46:48,590
and the answer is millions.

1257
00:46:48,590 --> 00:46:51,480
So we talked earlier,
is Sag A* gonna get us?

1258
00:46:51,480 --> 00:46:54,690
No, but I've started calling
the closest black hole.

1259
00:46:54,690 --> 00:46:56,610
We don't know what it is right?

1260
00:46:56,610 --> 00:46:58,224
It was the closet known black hole

1261
00:46:58,224 --> 00:46:59,470
and you'll hear about that
every now and then in the news.

1262
00:46:59,470 --> 00:47:02,160
The closest black hole

called proxima opie,

1263
00:47:02,160 --> 00:47:06,550
it's probably something like
20, 30 light years away.

1264
00:47:06,550 --> 00:47:08,600
You could send a mission to it

1265
00:47:08,600 --> 00:47:09,830
if you knew where to send it.

1266
00:47:09,830 --> 00:47:12,682
Again, people think about
going to the nearest stars.

1267
00:47:12,682 --> 00:47:14,360
You see all these science fiction movies

1268
00:47:14,360 --> 00:47:17,290
going to the nearest habitable planet,

1269
00:47:17,290 --> 00:47:20,003
maybe we'll stop at the
nearest black hole on the way.

1270
00:47:20,003 --> 00:47:22,053
We just have to figure out where it is.

1271
00:47:22,945 --> 00:47:25,830
This comes back to black holes
being so difficult to see.

1272
00:47:25,830 --> 00:47:27,768
Hardly know where they were.

1273
00:47:27,768 --> 00:47:29,070
And so we have something
that's right next to us.

1274
00:47:29,070 --> 00:47:30,203
No idea where it is.

1275
00:47:31,730 --> 00:47:33,500
- Avery, you have a very
cool job and I'm curious,

1276
00:47:33,500 --> 00:47:35,550
how did you get into black hole research?

1277
00:47:36,964 --> 00:47:40,260
- First like many people,
I love science fiction.

1278
00:47:40,260 --> 00:47:42,090
Love Star Trek.

1279
00:47:42,090 --> 00:47:45,320
Just watched original
Star Trek all the time

1280
00:47:45,320 --> 00:47:47,500
and the thing that I
loved about Star Trek,

1281
00:47:47,500 --> 00:47:50,720
aside from the kind of
sciencey stuff and the phasers,

1282
00:47:50,720 --> 00:47:53,390
and of course now we all have
communicators and the like.

1283
00:47:53,390 --> 00:47:55,460
They stopped flipping awhile ago.

1284
00:47:55,460 --> 00:47:57,180
One of the things that

I really liked about it

1285
00:47:57,180 --> 00:47:58,500
was the exploration.

1286
00:47:58,500 --> 00:48:00,440
Every episode goes someplace new.

1287
00:48:00,440 --> 00:48:05,390
See something never seen before
and so that motivated me,

1288
00:48:05,390 --> 00:48:08,400
being scientifically or
mathematically inclined

1289
00:48:08,400 --> 00:48:11,330
to seek out a job where I
get to travel the universe

1290
00:48:11,330 --> 00:48:14,290
and Starfleet didn't exist.

1291
00:48:14,290 --> 00:48:16,870
Couldn't go on a starship.

1292
00:48:16,870 --> 00:48:20,143
I guess you could go now,
Musk is making starship.

1293
00:48:21,388 --> 00:48:22,326
- Can you afford it?

1294
00:48:22,326 --> 00:48:23,334
- Can you afford it?

1295
00:48:23,334 --> 00:48:25,330
No, it's getting cheaper every day.

1296
00:48:25,330 --> 00:48:28,510
There was no Starfleet
to join to go you know,

1297
00:48:28,510 --> 00:48:31,690
investigate or explore the universe.

1298
00:48:31,690 --> 00:48:33,610
So instead I found a job

1299
00:48:33,610 --> 00:48:36,410
where I could explore
the universe in computers

1300
00:48:36,410 --> 00:48:38,880
and on blackboards and in my mind.

1301
00:48:38,880 --> 00:48:41,196
That's what astronomy really is right?

1302
00:48:41,196 --> 00:48:43,470
It's a way to go and see the most extreme,

1303
00:48:43,470 --> 00:48:47,150
the most unusual
environments in the universe

1304
00:48:47,150 --> 00:48:48,623
and try to understand them.

1305
00:48:49,690 --> 00:48:52,550
After becoming enamored with that,

1306
00:48:52,550 --> 00:48:55,400
you know my path is pretty similar.

1307
00:48:55,400 --> 00:48:58,060
I went to university,

majored in math and physics.

1308
00:48:58,060 --> 00:49:00,610
Couldn't get enough and so never left.

1309
00:49:00,610 --> 00:49:02,210
- Does it feel like
you're getting to do that?

1310
00:49:02,210 --> 00:49:05,109
You're getting to explore the universe

1311
00:49:05,109 --> 00:49:07,460
with this research and others?

1312
00:49:07,460 --> 00:49:10,740
- Absolutely, I couldn't
have done it any better

1313
00:49:10,740 --> 00:49:15,740
than able to put images of
black holes up on a view screen.

1314
00:49:15,970 --> 00:49:18,520
It's basically an episode
right out of "Star Trek".

1315
00:49:19,540 --> 00:49:21,613
- Do you know what you
want to explore next?

1316
00:49:23,020 --> 00:49:24,330
- That's a great question.

1317
00:49:24,330 --> 00:49:29,113
We have had our heads down the
grinding wheel for so long,

1318
00:49:29,113 --> 00:49:29,990

I don't think much about it.

1319
00:49:29,990 --> 00:49:31,230
But what to look for next?

1320
00:49:31,230 --> 00:49:36,230
Really this era of resolving
Event Horizons has just begun

1321
00:49:37,520 --> 00:49:41,230
and we are now in a very
special, a special period

1322
00:49:41,230 --> 00:49:44,630
where it's not just the
Event Horizon telescope

1323
00:49:44,630 --> 00:49:46,490
but we also have LIGO.

1324
00:49:46,490 --> 00:49:48,450
We also have neutrino experiments

1325
00:49:48,450 --> 00:49:49,890
that are looking at the universe.

1326
00:49:49,890 --> 00:49:53,100
Not in terms of the kinetic waves

1327
00:49:53,100 --> 00:49:54,320
or gravitational waves.

1328
00:49:54,320 --> 00:49:56,120
But neutrinos as particles.

1329
00:49:56,120 --> 00:49:59,110
We have the CTA, the
Cherenkov Telescope Array

1330
00:49:59,110 --> 00:50:01,840
looking at the universe
in high energy gamma rays.

1331
00:50:01,840 --> 00:50:04,010
Again, a very different way to look at it.

1332
00:50:04,010 --> 00:50:07,873
And all of these are focused
predominately on black holed.

1333
00:50:08,800 --> 00:50:12,350
We are at the era where
the theoretical musings

1334
00:50:12,350 --> 00:50:15,940
of Schwarzschild and Kerr and Einstein,

1335
00:50:15,940 --> 00:50:17,290
you know when they
thought about the things

1336
00:50:17,290 --> 00:50:21,930
that nobody could ever possibly
see, that's being seen.

1337
00:50:21,930 --> 00:50:24,450
Black hole science has
gone from being theoretical

1338
00:50:24,450 --> 00:50:27,820
to being empirical over the past 10 years

1339
00:50:27,820 --> 00:50:29,598
and we're just at the beginning.

1340
00:50:29,598 --> 00:50:34,300
You know the things that
occupy my future time

1341
00:50:34,300 --> 00:50:36,060
in as much as I find it,

1342
00:50:36,060 --> 00:50:38,770
are really thinking about how to move from

1343
00:50:38,770 --> 00:50:41,130
making that first image to you know,

1344
00:50:41,130 --> 00:50:43,700
doing something akin to
black hole meteorology.

1345
00:50:43,700 --> 00:50:46,160
We don't want to see a picture.

1346
00:50:46,160 --> 00:50:48,770
I want to see beautiful
high resolution movies.

1347
00:50:48,770 --> 00:50:51,020
I want to see magnetic flux tubes.

1348
00:50:51,020 --> 00:50:54,370
Little magnetic vortices zipping around.

1349
00:50:54,370 --> 00:50:56,650
I want to see flares popping off

1350
00:50:56,650 --> 00:50:59,990
that look like solar flares or
solar coronal mass ejections.

1351
00:50:59,990 --> 00:51:02,790
Sudden snapping of magnetic field lines,

1352
00:51:02,790 --> 00:51:04,830

huge amounts of energy going off

1353
00:51:04,830 --> 00:51:05,990
right around the Event Horizon.

1354
00:51:05,990 --> 00:51:09,290
Tracking all of these things in real time.

1355
00:51:09,290 --> 00:51:12,330
And then understanding
how that all interplays

1356
00:51:12,330 --> 00:51:14,660
with the gravity of black hole.

1357
00:51:14,660 --> 00:51:18,550
The future in this context
is higher resolution,

1358
00:51:18,550 --> 00:51:21,670
higher cadence, higher sensitivity.

1359
00:51:21,670 --> 00:51:24,690
It's our Olympics of black hole science.

1360
00:51:24,690 --> 00:51:26,433
Was it stronger, faster, higher?

1361
00:51:27,620 --> 00:51:29,230
So yeah, that's my future and right,

1362
00:51:29,230 --> 00:51:31,040
there's ways to do that.

1363
00:51:31,040 --> 00:51:34,370
We've talked about the next
generation EHT, the NGHT.

1364

00:51:34,370 --> 00:51:37,760
This is not an evolution of
the Event Horizon Telescope

1365
00:51:37,760 --> 00:51:39,950
but a revolution of the
Event Horizon Telescope

1366
00:51:39,950 --> 00:51:43,420
where we add 10 or more new dishes

1367
00:51:43,420 --> 00:51:48,310
that are dedicated to doing
this sort of millimeter VLVI.

1368
00:51:48,310 --> 00:51:49,760
This sort of

1369
00:51:49,760 --> 00:51:50,593
earth-side telescope.
- On top of

1370
00:51:50,593 --> 00:51:51,426
the existing telescopes already?

1371
00:51:51,426 --> 00:51:52,780
- On top of the existing ones.
- Wow.

1372
00:51:52,780 --> 00:51:54,910
- Right, and every telescope you add

1373
00:51:54,910 --> 00:51:57,080
is not just one piece better

1374
00:51:57,080 --> 00:52:00,540
because it's really the
number of pairs of telescopes.

1375

00:52:00,540 --> 00:52:03,360
The way we fill in that
mirror goes as the square

1376
00:52:03,360 --> 00:52:04,380
of the number of the telescopes.

1377
00:52:04,380 --> 00:52:08,060
So the difference between 20 and eight

1378
00:52:08,060 --> 00:52:09,650
is not the difference.

1379
00:52:09,650 --> 00:52:11,070
Is not 12 right?

1380
00:52:11,070 --> 00:52:13,980
It's 400 versus 64.

1381
00:52:13,980 --> 00:52:17,060
So that's going to allow
us to start mapping out

1382
00:52:17,060 --> 00:52:20,860
that black hole meteorology
to very large distances

1383
00:52:20,860 --> 00:52:22,260
away from the black hole.

1384
00:52:22,260 --> 00:52:25,690
So how do you connect the
environment to the horizon?

1385
00:52:25,690 --> 00:52:29,190
And then there's that
space fantasy almost right?

1386
00:52:29,190 --> 00:52:31,580

1387
00:52:31,580 --> 00:52:33,390
which we have to start doing now

1388
00:52:33,390 --> 00:52:34,503
if it's going to happen.

1389
00:52:34,503 --> 00:52:37,100
That just opens up the entire universe

1390
00:52:37,100 --> 00:52:37,940
to this sort of thing.

1391
00:52:37,940 --> 00:52:41,770
Now we're not talking
about two, maybe 10 targets

1392
00:52:41,770 --> 00:52:42,760
if we really push it.

1393
00:52:42,760 --> 00:52:44,860
We're talking about million.

1394
00:52:44,860 --> 00:52:46,940
That would be an
extraordinary change right?

1395
00:52:46,940 --> 00:52:50,250
So then we would go from
theoretical black hole science

1396
00:52:50,250 --> 00:52:54,130
to empirical black hole
science to surveys right?

1397
00:52:54,130 --> 00:52:55,800
Having so much data,

1398
00:52:55,800 --> 00:52:56,700
who knows what you're gonna do

1399
00:52:56,700 --> 00:52:59,240
with all of what you're gonna find.

1400
00:52:59,240 --> 00:53:00,290
- I'm curious.

1401
00:53:00,290 --> 00:53:02,070
When you look at these
images that you get.

1402
00:53:02,070 --> 00:53:06,860
I remember in 2019, with the M87 image,

1403
00:53:06,860 --> 00:53:09,815
when you sort of had the image
you came up to me and said,

1404
00:53:09,815 --> 00:53:10,648
"Colin, you want to see something?"

1405
00:53:10,648 --> 00:53:12,257
And you showed me on your
phone and I was like,

1406
00:53:12,257 --> 00:53:13,090
"That's incredible."

1407
00:53:13,090 --> 00:53:16,830
I'm one of the first people
on earth to see this image

1408
00:53:16,830 --> 00:53:19,280
but you were probably
among the very, very first

1409

00:53:19,280 --> 00:53:21,560
and with the Sag A* too.

1410
00:53:21,560 --> 00:53:25,200
You've now been the first,
among the first people on earth

1411
00:53:25,200 --> 00:53:26,033
to see something.

1412
00:53:26,033 --> 00:53:26,866
What's that like for you?

1413
00:53:26,866 --> 00:53:29,441
And do you, are you able
to look at that data

1414
00:53:29,441 --> 00:53:32,900
and the fire donut and sort
of let your imagination

1415
00:53:32,900 --> 00:53:35,730
take you to the place itself?

1416
00:53:35,730 --> 00:53:38,370
- So often those first
imaging experiments,

1417
00:53:38,370 --> 00:53:40,320
you're just trying to get
everything to work right.

1418
00:53:40,320 --> 00:53:41,930
So there's a sense of elation

1419
00:53:41,930 --> 00:53:43,940
which doesn't necessarily
come from the importance

1420

00:53:43,940 --> 00:53:44,773
of the moment.

1421
00:53:44,773 --> 00:53:48,960
But oh thank God it, it
finally did what I asked.

1422
00:53:48,960 --> 00:53:51,620
We actually produced
some of the first images

1423
00:53:51,620 --> 00:53:54,470
of Sag A* at a workshop
right here at Perimeter

1424
00:53:54,470 --> 00:53:59,010
and shortly after M87 in August 2019,

1425
00:53:59,010 --> 00:54:02,066
we had a workshop to
identify the main challenge

1426
00:54:02,066 --> 00:54:04,550
and begin game planning out

1427
00:54:04,550 --> 00:54:07,243
how we were going to solve all of them

1428
00:54:07,243 --> 00:54:08,300
and it turned out that many of those,

1429
00:54:08,300 --> 00:54:11,288
I think all of those gave lights

1430
00:54:11,288 --> 00:54:12,430
of what we ended up following.

1431
00:54:12,430 --> 00:54:16,350
So that was a momentous

meaning and there we did see,

1432
00:54:16,350 --> 00:54:17,790
we didn't share.

1433
00:54:17,790 --> 00:54:20,206
So we kind of sequestered the groups.

1434
00:54:20,206 --> 00:54:23,800
Each analysis team is
trying to make their,

1435
00:54:23,800 --> 00:54:26,340
their particular image with
their particular method

1436
00:54:26,340 --> 00:54:28,810
and we have a method that we use.

1437
00:54:28,810 --> 00:54:30,540
But everybody was producing images

1438
00:54:30,540 --> 00:54:32,820
and you kind of knew that we
were getting something good

1439
00:54:32,820 --> 00:54:36,140
because everyone was smiling
a lot and yeah, yeah.

1440
00:54:36,140 --> 00:54:37,210
We've produced the first image

1441
00:54:37,210 --> 00:54:39,830
and it looks about like what
we thought it should look like.

1442
00:54:39,830 --> 00:54:42,290
There was a lot of happiness in that room.

1443
00:54:42,290 --> 00:54:44,870
Did we feel the weight of history?

1444
00:54:44,870 --> 00:54:48,270
Thinking oh we've seen this
thing for the first time?

1445
00:54:48,270 --> 00:54:50,229
I'm not sure I'd go that far.

1446
00:54:50,229 --> 00:54:51,210
- That was just me.
- But we do now.

1447
00:54:51,210 --> 00:54:52,920
We do look back on it and we think,

1448
00:54:52,920 --> 00:54:54,730
you know it's a very special thing.

1449
00:54:54,730 --> 00:54:58,930
M87 was seen by half the
human beings on planet earth.

1450
00:54:58,930 --> 00:55:00,860
We're talking about Sag A* today,

1451
00:55:00,860 --> 00:55:02,950
it was just released but I imagine that

1452
00:55:02,950 --> 00:55:04,920
it will also be seen by a similar number

1453
00:55:04,920 --> 00:55:06,880
and there's few cultural phenomena

1454
00:55:06,880 --> 00:55:09,510

that transcend at that level.

1455
00:55:09,510 --> 00:55:12,786
It's an amazing privilege
to be part of that.

1456
00:55:12,786 --> 00:55:13,619
- Well Avery,

1457
00:55:13,619 --> 00:55:16,990
thank you so much for just
spending this time with us

1458
00:55:16,990 --> 00:55:19,103
and once again helping
us understand black holes

1459
00:55:19,103 --> 00:55:20,120
and the EHT.

1460
00:55:20,120 --> 00:55:22,500
It's like I said, it's one
of my favorite subjects.

1461
00:55:22,500 --> 00:55:23,333
- Well my pleasure

1462
00:55:23,333 --> 00:55:25,435
and thank you for having
me Lauren and Colin.

1463
00:55:25,435 --> 00:55:28,018
(upbeat music)

1464
00:55:29,370 --> 00:55:31,010
- Thanks so much for listening.

1465
00:55:31,010 --> 00:55:31,960
Be sure to subscribe

1466
00:55:31,960 --> 00:55:34,410
so you don't miss any
of our conversations.

1467
00:55:34,410 --> 00:55:36,720
We've interviewed so
many brilliant scientists

1468
00:55:36,720 --> 00:55:39,620
whose research spans from
the quantum to the cosmos

1469
00:55:39,620 --> 00:55:42,090
and we can't wait for you to hear more

1470
00:55:42,090 --> 00:55:43,240
and if you like what you hear,

1471
00:55:43,240 --> 00:55:44,880
please rate and review our show

1472
00:55:44,880 --> 00:55:47,340
on your preferred podcast platform.

1473
00:55:47,340 --> 00:55:49,200
Great science is for everyone.

1474
00:55:49,200 --> 00:55:51,030
So please, help us spread the word

1475
00:55:51,030 --> 00:55:53,130
and thanks for being part of the equation.