1
00:00:01,110 --> 00:00:02,310
- Hello, everyone.

2
00:00:02,310 --> 00:00:03,750
We would love your feedback

3
00:00:03,750 --> 00:00:05,850
on "Conversations at the Perimeter."

4
00:00:05,850 --> 00:00:06,837
Let us know what you like

5
00:00:06,837 --> 00:00:08,790
and what you'd like to hear more of.

6
00:00:08,790 --> 00:00:12,720
Go to perimeterinstitute.ca/podcastsurvey

7
00:00:12,720 --> 00:00:14,070
to share your thoughts.

8
00:00:14,070 --> 00:00:14,903
Thanks so much.

9
00:00:16,343 --> 00:00:18,843
(light music)

10
00:00:24,180 --> 00:00:25,597
- Hey, everyone.

11
00:00:25,597 --> 00:00:27,420
And welcome back to
"Conversations at the Perimeter."

12
00:00:27,420 --> 00:00:29,550
I'm Colin here at Perimeter Institute,

13

00:00:29,550 --> 00:00:31,530
as always with Lauren.
- Hi.

14
00:00:31,530 --> 00:00:33,750
- And we are so glad to be bringing you

15
00:00:33,750 --> 00:00:36,570
the conversation that we
had with Shep Doelman.

16
00:00:36,570 --> 00:00:39,300
Shep is the leader of the
Event Horizon Telescope,

17
00:00:39,300 --> 00:00:42,630
or EH, a global
collaboration of scientists

18
00:00:42,630 --> 00:00:45,120
on every continent that gave us humanity's

19
00:00:45,120 --> 00:00:47,910
first ever glimpse of a black hole.

20
00:00:47,910 --> 00:00:50,880
- Now, chances are you've
already seen the images captured

21
00:00:50,880 --> 00:00:52,160
by the EHT.

22
00:00:52,160 --> 00:00:55,320
In 2019, the collaboration
unveiled an image

23
00:00:55,320 --> 00:00:58,890
of the super massive black
hole in the M87 Galaxy,

24
00:00:58,890 --> 00:01:02,190
and in 2022 they imaged
the black hole at the heart

25
00:01:02,190 --> 00:01:04,530
of our own Milky Way galaxy.

26
00:01:04,530 --> 00:01:07,260
Shep tells us how these
incredible discoveries were made

27
00:01:07,260 --> 00:01:09,480
through the collaboration
of hundreds of scientists

28
00:01:09,480 --> 00:01:11,850
around the world, half a dozen telescopes,

29
00:01:11,850 --> 00:01:14,880
and of course, incredible
amounts of ingenuity.

30
00:01:14,880 --> 00:01:17,460
- Yeah, it really is amazing
to hear Shep describe

31
00:01:17,460 --> 00:01:19,860
not only the power and the
mystery of black holes,

32
00:01:19,860 --> 00:01:22,710
but also the monumental global effort

33
00:01:22,710 --> 00:01:25,470
that went into seeing them
for the very first time.

34
00:01:25,470 --> 00:01:27,480
And Shep has such a sharp sense of humor

35
00:01:27,480 --> 00:01:28,980
and a knack for storytelling,

36
00:01:28,980 --> 00:01:31,620
this conversation just flew by for me.

37
00:01:31,620 --> 00:01:34,350
- Shep also assured us
that in black hole science,

38
00:01:34,350 --> 00:01:36,420
the best is yet to come.

39
00:01:36,420 --> 00:01:38,910
He tells us about the next generation EHT,

40
00:01:38,910 --> 00:01:41,280
which will expand the
earth-based telescope array

41
00:01:41,280 --> 00:01:44,070
to observe black holes in even more detail

42
00:01:44,070 --> 00:01:45,210
and future projects

43
00:01:45,210 --> 00:01:47,520
that will include space-based observations

44
00:01:47,520 --> 00:01:50,940
and even capturing movies
of black holes in action.

45
00:01:50,940 --> 00:01:53,850
It's a fascinating ride
and we felt so fortunate

46

00:01:53,850 --> 00:01:55,740
to be a part of this conversation.

47
00:01:55,740 --> 00:01:58,893
So, let's step inside the
perimeter with Shep Doelman.

48
00:02:00,870 --> 00:02:02,130
- Shep, thank you for being here

49
00:02:02,130 --> 00:02:04,050
at "Conversations at the Perimeter."

50
00:02:04,050 --> 00:02:05,160
- It's a pleasure to be here.

51
00:02:05,160 --> 00:02:07,470
- You and I have talked
a number of times before

52
00:02:07,470 --> 00:02:09,300
on Zoom calls where we each have

53
00:02:09,300 --> 00:02:12,570
just been a little a cube
on a tic-tac-toe board,

54
00:02:12,570 --> 00:02:15,000
but this is the first
time chatting in person

55
00:02:15,000 --> 00:02:17,670
and there's a question I've
always wanted to ask you.

56
00:02:17,670 --> 00:02:19,590
What's a black hole?

57
00:02:19,590 --> 00:02:21,120

- What is a black hole?

58
00:02:21,120 --> 00:02:22,860
So if you ask different people,

59
00:02:22,860 --> 00:02:24,300
they might have different viewpoints

60
00:02:24,300 --> 00:02:25,410
on what a black hole is.

61
00:02:25,410 --> 00:02:27,810
I mean, quantum physicists will want

62
00:02:27,810 --> 00:02:29,850
to dive into information theory.

63
00:02:29,850 --> 00:02:33,330
I'm an astronomer, so I live
kind of in the real world

64
00:02:33,330 --> 00:02:37,740
and my idea of a black hole
is that it's a condensation

65
00:02:37,740 --> 00:02:39,600
of matter that's so dense

66
00:02:39,600 --> 00:02:41,940
and in such a small region that it creates

67
00:02:41,940 --> 00:02:43,470
an event horizon around it.

68
00:02:43,470 --> 00:02:46,350
And that's a point where
light can't escape.

69

00:02:46,350 --> 00:02:48,150
Even if you travel at the speed of light,

70
00:02:48,150 --> 00:02:50,550
you can't escape the
gravity of that black hole.

71
00:02:50,550 --> 00:02:52,080
That for me is a black hole.

72
00:02:52,080 --> 00:02:54,930
And what's more, these
black holes we know exist

73
00:02:54,930 --> 00:02:55,830
in the universe.

74
00:02:55,830 --> 00:02:57,480
So, they're something we can study.

75
00:02:57,480 --> 00:02:59,100
And it's not just a theory,

76
00:02:59,100 --> 00:03:00,660
it's not just something
on a piece of paper.

77
00:03:00,660 --> 00:03:04,530
It's something we can see
with advanced instruments.

78
00:03:04,530 --> 00:03:05,363
- And you know what, Shep,

79
00:03:05,363 --> 00:03:06,790
today I was getting ready to come to work

80
00:03:06,790 --> 00:03:07,770
and I have to tell you,

81
00:03:07,770 --> 00:03:10,050
I was talking to my two
and a half year old son

82
00:03:10,050 --> 00:03:12,210
and I told him, "Guess what?

83
00:03:12,210 --> 00:03:14,850
Today I'm gonna talk to
someone named Shep Doelman

84
00:03:14,850 --> 00:03:17,250
and we're gonna talk about black holes."

85
00:03:17,250 --> 00:03:19,860
And he really loves
digging with his shovels.

86
00:03:19,860 --> 00:03:23,130
And he told me, "Mom,
I've seen a black hole

87
00:03:23,130 --> 00:03:25,140
when I was in the forest."

88
00:03:25,140 --> 00:03:29,280
So, you know, I think even
these really young kids,

89
00:03:29,280 --> 00:03:31,493
they have a picture come
to mind when they hear

90
00:03:31,493 --> 00:03:35,280
about a black hole, how much
of that picture that we have,

91
00:03:35,280 --> 00:03:36,750

as soon as we just hear that phrase,

92
00:03:36,750 --> 00:03:39,030
how much of that is really true?

93
00:03:39,030 --> 00:03:42,180
- Well, it is true in that
like when you dig a hole

94
00:03:42,180 --> 00:03:45,390
in the forest, maybe the one
that your son is thinking of,

95
00:03:45,390 --> 00:03:46,650
you can put things in it,

96
00:03:46,650 --> 00:03:48,390
you can forget about them, you know?

97
00:03:48,390 --> 00:03:50,250
So, we think of a hole as being something

98
00:03:50,250 --> 00:03:52,590
where you can store things

99
00:03:52,590 --> 00:03:55,170
or it's out of sight, out of mind.

100
00:03:55,170 --> 00:03:57,150
And a black hole really is like that.

101
00:03:57,150 --> 00:03:58,620
When things fall into the black hole,

102
00:03:58,620 --> 00:04:00,360
when they go through the event horizon,

103
00:04:00,360 --> 00:04:04,140

there's really no causal
connection left to our universe.

104
00:04:04,140 --> 00:04:05,580
They're gone forever.

105
00:04:05,580 --> 00:04:09,960
So, it's really a hole that you
can't withdraw anything from

106
00:04:09,960 --> 00:04:10,950
in the future.

107
00:04:10,950 --> 00:04:14,812
So in that sense, your
son has it exactly right.

108
00:04:14,812 --> 00:04:16,260
It's the universe's big pocket.

109
00:04:16,260 --> 00:04:18,000
It's something that you put something in,

110
00:04:18,000 --> 00:04:19,380
you can't take it out again.

111
00:04:19,380 --> 00:04:22,710
- Is there anything misleading
about what we might picture

112
00:04:22,710 --> 00:04:24,480
when we hear black hole?

113
00:04:24,480 --> 00:04:26,280
- I study black holes for a living.

114
00:04:26,280 --> 00:04:30,240
We observe them, but black
holes exist in literature.

115
00:04:30,240 --> 00:04:32,580
They exist in even music.

116
00:04:32,580 --> 00:04:33,990
They exist in art.

117
00:04:33,990 --> 00:04:37,680
So, a lot of the things that
we know about black holes come

118
00:04:37,680 --> 00:04:40,800
from the culture in which we live.

119
00:04:40,800 --> 00:04:43,560
So, it's perfectly fine
to think about black holes

120
00:04:43,560 --> 00:04:46,080
and interpret them in your daily life

121
00:04:46,080 --> 00:04:47,970
in a way that makes sense to you.

122
00:04:47,970 --> 00:04:50,190
And if you talk, again,
to a quantum physicist,

123
00:04:50,190 --> 00:04:51,540
they'll have a different
way of looking at it.

124
00:04:51,540 --> 00:04:53,310
If you talk to an astronomer like me,

125
00:04:53,310 --> 00:04:54,900
I'll be thinking about, you know,

126

00:04:54,900 --> 00:04:57,060
the hot gas that swirls
around the black hole

127
00:04:57,060 --> 00:05:00,570
that allows us to even see that
there's a black hole there.

128
00:05:00,570 --> 00:05:03,604
So, everyone can think about black holes

129
00:05:03,604 --> 00:05:05,070
in the way that they want to.

130
00:05:05,070 --> 00:05:08,760
When you get down to it,
there are some formulas,

131
00:05:08,760 --> 00:05:12,240
there are some equations,
there are some real world,

132
00:05:12,240 --> 00:05:15,000
telltale signatures of black holes.

133
00:05:15,000 --> 00:05:19,620
But I really enjoy the fact
that they have an existence

134
00:05:19,620 --> 00:05:23,340
beyond the theory,
beyond the observations.

135
00:05:23,340 --> 00:05:24,630
I embrace that.

136
00:05:24,630 --> 00:05:28,590
- How long was it before black holes moved

137

00:05:28,590 --> 00:05:31,110
from purely an idea, a theory,

138
00:05:31,110 --> 00:05:33,990
to something that you know is out there?

139
00:05:33,990 --> 00:05:36,300
- Black holes have a deep history.

140
00:05:36,300 --> 00:05:38,940
When we made our first
image of a black hole

141
00:05:38,940 --> 00:05:40,650
using the event horizon telescope

142
00:05:40,650 --> 00:05:42,360
that I'm sure we'll talk about,

143
00:05:42,360 --> 00:05:45,090
we felt a deep connection
with that history.

144
00:05:45,090 --> 00:05:47,293
I like to phrase it in
this way, that we have

145
00:05:47,293 --> 00:05:49,170
a 100 year handshake with Einstein,

146
00:05:49,170 --> 00:05:53,490
that we are living in an era
where if Einstein were here,

147
00:05:53,490 --> 00:05:55,170
he would be part of our team.

148
00:05:55,170 --> 00:05:58,710
There's a deep visceral

connection to all the people

149
00:05:58,710 --> 00:06:00,570
who came before us and studied this.

150
00:06:00,570 --> 00:06:02,130
And it begins with general relativity.

151
00:06:02,130 --> 00:06:06,570
It begins with Einstein in
1915 coming with this idea

152
00:06:06,570 --> 00:06:11,570
that gravity was different
than Newton had theorized.

153
00:06:11,790 --> 00:06:13,970
That there was a different
way of thinking about gravity.

154
00:06:13,970 --> 00:06:16,260
It was a deformation in space time,

155
00:06:16,260 --> 00:06:19,440
and things would move in
that deformed space time.

156
00:06:19,440 --> 00:06:20,400
And then the question is, well,

157
00:06:20,400 --> 00:06:23,430
how do you know that that's
the right new theory?

158
00:06:23,430 --> 00:06:24,480
Well, it explained things

159
00:06:24,480 --> 00:06:26,520
like the perihelion shift of mercury.

160
00:06:26,520 --> 00:06:28,530
When mercury orbits the sun,

161
00:06:28,530 --> 00:06:30,900
it changes its orientation a little bit,

162
00:06:30,900 --> 00:06:35,190
it gets a little kick that
general relativity predicts

163
00:06:35,190 --> 00:06:37,290
that Newton's gravity would not.

164
00:06:37,290 --> 00:06:38,940
So, it explained that right away.

165
00:06:38,940 --> 00:06:41,460
And then the next thing that happened

166
00:06:41,460 --> 00:06:44,490
was Karl Schwarzschild, in
the trenches of World War I,

167
00:06:44,490 --> 00:06:46,590
solves Einstein's equations

168
00:06:46,590 --> 00:06:49,260
and he comes up with this idea
of the Schwarzschild radius.

169
00:06:49,260 --> 00:06:51,840
This is where the event horizon is.

170
00:06:51,840 --> 00:06:55,410
And Einstein is so
tickled by this solution,

171

00:06:55,410 --> 00:06:58,200
by this scientist who's
serving in World War I.

172
00:06:58,200 --> 00:07:01,980
He presented to the Prussian
Academy of Sciences.

173
00:07:01,980 --> 00:07:03,750
And for many years,

174
00:07:03,750 --> 00:07:06,840
that was just a theoretical
mathematical oddity.

175
00:07:06,840 --> 00:07:09,660
No one really thought you
could make a black hole.

176
00:07:09,660 --> 00:07:12,060
And indeed Einstein went to his death,

177
00:07:12,060 --> 00:07:14,190
convinced that nature
would never allow you

178
00:07:14,190 --> 00:07:15,790
to make a black hole.

179
00:07:15,790 --> 00:07:16,830
There would be something
that would prevent it.

180
00:07:16,830 --> 00:07:19,590
Things would be orbiting
the black hole so fast that

181
00:07:19,590 --> 00:07:23,970
the centrifugal force
would prevent the collapse

182
00:07:23,970 --> 00:07:25,050
into a black hole.

183
00:07:25,050 --> 00:07:26,940
And now, of course, we
know that they do exist.

184
00:07:26,940 --> 00:07:30,160
There was work by Oppenheimer
and Snyder in the 30s

185
00:07:30,160 --> 00:07:33,180
that really showed you
could condense something

186
00:07:33,180 --> 00:07:35,100
beyond the event horizon.

187
00:07:35,100 --> 00:07:37,920
And astronomers began to get the inkling

188
00:07:37,920 --> 00:07:41,370
that there was something out
there looking at Cygnus X-1,

189
00:07:41,370 --> 00:07:43,740
a black hole that's
devouring another star.

190
00:07:43,740 --> 00:07:44,880
And the signature,

191
00:07:44,880 --> 00:07:47,730
the radiation signature from
that was such that it's hard

192
00:07:47,730 --> 00:07:50,790
to explain it unless you have a black hole

193
00:07:50,790 --> 00:07:52,710
that is devouring another star.

194
00:07:52,710 --> 00:07:55,710
And then the story got
even weirder in a sense

195
00:07:55,710 --> 00:07:58,830
because we began to see the
centers of galaxies glowing

196
00:07:58,830 --> 00:08:02,100
so brightly that only the conversion

197
00:08:02,100 --> 00:08:04,470
of gravitational potential energy,

198
00:08:04,470 --> 00:08:08,040
a matter falling in and turning
that into radiant energy,

199
00:08:08,040 --> 00:08:12,240
which a black hole can do,
was the only explanation.

200
00:08:12,240 --> 00:08:14,460
And all of a sudden you
could have black holes

201
00:08:14,460 --> 00:08:16,770
that were millions of
times the mass of our sun,

202
00:08:16,770 --> 00:08:19,050
billions of times the mass of our sun,

203
00:08:19,050 --> 00:08:20,880
at the centers of these galaxies.

204
00:08:20,880 --> 00:08:24,450
So, the evidence began
to become overwhelming,

205
00:08:24,450 --> 00:08:25,950
but we had never seen one,

206
00:08:25,950 --> 00:08:27,930
we didn't have the angular resolution,

207
00:08:27,930 --> 00:08:31,440
we didn't have the instrumentation
that would've allowed us

208
00:08:31,440 --> 00:08:33,000
to really see it.

209
00:08:33,000 --> 00:08:35,189
And that's what we've been working on

210
00:08:35,189 --> 00:08:36,360
for the past 20 years.

211
00:08:36,360 --> 00:08:39,840
So, from Einstein to
Schwarzschild, you know,

212
00:08:39,840 --> 00:08:42,180
all the way through like
thinking about quantum effects

213
00:08:42,180 --> 00:08:45,780
around black holes from
Stephen Hawking and Bekenstein,

214
00:08:45,780 --> 00:08:47,670
all the way through to
what we're doing now,

215
00:08:47,670 --> 00:08:49,800
which is observing black holes,

216
00:08:49,800 --> 00:08:52,320
it's been a wild ride
and it's hard to believe

217
00:08:52,320 --> 00:08:55,200
this has all happened in
such a short amount of time.

218
00:08:55,200 --> 00:08:56,280
- So, can you tell us a little bit

219
00:08:56,280 --> 00:08:59,820
about the event horizon
telescope and how it works,

220
00:08:59,820 --> 00:09:01,413
how it's achieved this?

221
00:09:01,413 --> 00:09:04,350
- This is just about my
favorite thing to talk about,

222
00:09:04,350 --> 00:09:07,890
but so when you think about
observing a black hole,

223
00:09:07,890 --> 00:09:09,960
it's totally counterintuitive.

224
00:09:09,960 --> 00:09:13,470
Something that's designed
by nature not to emit light,

225
00:09:13,470 --> 00:09:14,850
that swallows all the light.

226
00:09:14,850 --> 00:09:17,190
How do you go about viewing it?

227
00:09:17,190 --> 00:09:19,650
So, when you think about taking
a picture of a black hole,

228
00:09:19,650 --> 00:09:21,930
which is what we did with
the event horizon telescope,

229
00:09:21,930 --> 00:09:24,840
I wanna first talk about why they glow.

230
00:09:24,840 --> 00:09:27,420
So, all this matter is
falling into the black hole,

231
00:09:27,420 --> 00:09:29,010
let's say the center of a galaxy.

232
00:09:29,010 --> 00:09:33,450
And as it falls in, it encounters
this cosmic traffic jam.

233
00:09:33,450 --> 00:09:35,607
It's trying to get into
a very small space.

234
00:09:35,607 --> 00:09:37,440
And so it backs up,

235
00:09:37,440 --> 00:09:40,140
it collides with the
gas that came before it,

236
00:09:40,140 --> 00:09:43,170
and it soon heats up to

hundreds of billions of degrees.

237
00:09:43,170 --> 00:09:45,870
So, in a paradox of their own gravity,

238
00:09:45,870 --> 00:09:49,200
black holes glow extremely brightly,

239
00:09:49,200 --> 00:09:51,450
especially at the centers of galaxies

240
00:09:51,450 --> 00:09:53,400
where there's so much gas.

241
00:09:53,400 --> 00:09:57,540
So, we have this intense
flashlight illuminating

242
00:09:57,540 --> 00:10:00,690
from all directions, this event horizon,

243
00:10:00,690 --> 00:10:02,670
and the light gets bent around it.

244
00:10:02,670 --> 00:10:06,307
So in about 1916, Hilbert asked,

245
00:10:06,307 --> 00:10:09,210
"Well, how big would this ring of light be

246
00:10:09,210 --> 00:10:11,100
around the event horizon?"

247
00:10:11,100 --> 00:10:14,370
He came up with some clear formulas

248
00:10:14,370 --> 00:10:17,217
and Max von Laue in 1921 confirmed that.

249
00:10:17,217 --> 00:10:21,300
And then a bunch of simulations
were done in the 70s

250
00:10:21,300 --> 00:10:24,720
and then later in the 2000s that showed,

251
00:10:24,720 --> 00:10:28,830
given a super massive black
hole at the center of a galaxy,

252
00:10:28,830 --> 00:10:31,350
you would be able to
see this ring of light.

253
00:10:31,350 --> 00:10:34,020
And the dimensions of
that ring would tell you

254
00:10:34,020 --> 00:10:35,940
how massive the black hole,

255
00:10:35,940 --> 00:10:38,250
if Einstein's theory was correct.

256
00:10:38,250 --> 00:10:40,320
So, in one measurement
you could measure the mass

257
00:10:40,320 --> 00:10:43,680
of the black hole and
confirm Einstein's theories.

258
00:10:43,680 --> 00:10:44,940
And then we had to ask,

259
00:10:44,940 --> 00:10:47,100
well what wavelength of light

260
00:10:47,100 --> 00:10:49,380
is the right wavelength to look at?

261
00:10:49,380 --> 00:10:51,140
Because this thing can glow
at all different wavelengths,

262
00:10:51,140 --> 00:10:54,660
in the optical, in the x-ray, ultraviolet.

263
00:10:54,660 --> 00:10:56,970
And it turns out that you wanna
be able to see all the way

264
00:10:56,970 --> 00:10:58,320
to the event horizon.

265
00:10:58,320 --> 00:11:01,320
And in the optical you
probably can't do that.

266
00:11:01,320 --> 00:11:02,370
It's probably optically thick.

267
00:11:02,370 --> 00:11:05,897
You'd see like a cloud of emission outside

268
00:11:05,897 --> 00:11:07,440
of the event horizon.

269
00:11:07,440 --> 00:11:10,380
But with radio waves,
you can see all the way

270
00:11:10,380 --> 00:11:11,580
to the event horizon.

271

00:11:11,580 --> 00:11:13,170
So, now the event horizon telescope,

272
00:11:13,170 --> 00:11:16,380
so now we know what
wavelength to look at it in

273
00:11:16,380 --> 00:11:18,120
and we know that we can see this ring

274
00:11:18,120 --> 00:11:21,990
and we decided that we could
do this in the radio waves,

275
00:11:21,990 --> 00:11:24,630
but we needed a telescope
that was as big as the earth

276
00:11:24,630 --> 00:11:28,650
because the size of the
objects you can see on the sky

277
00:11:28,650 --> 00:11:30,600
is basically the wavelength of light

278
00:11:30,600 --> 00:11:31,830
at which you're observing,

279
00:11:31,830 --> 00:11:33,420
divided by the size of your telescope.

280
00:11:33,420 --> 00:11:34,650
A very simple formula.

281
00:11:34,650 --> 00:11:36,270
So, if you're looking in the radio,

282
00:11:36,270 --> 00:11:39,450
maybe a few millimeters of wavelength,

283
00:11:39,450 --> 00:11:42,540
you need to see the nearest
black hole, Sagittarius A star

284
00:11:42,540 --> 00:11:44,070
in the center of our galaxy,

285
00:11:44,070 --> 00:11:47,940
or M87 at the next distant galaxy.

286
00:11:47,940 --> 00:11:51,360
You need to have an angular resolution

287
00:11:51,360 --> 00:11:53,317
that's about 50 microarcseconds.

288
00:11:53,317 --> 00:11:55,800
Okay, and what does that mean?

289
00:11:55,800 --> 00:11:57,840
This is equivalent to
being able to read the date

290
00:11:57,840 --> 00:12:01,140
on a quarter if you're in Los Angeles

291
00:12:01,140 --> 00:12:03,570
and the quarter's in New
York, or equivalently,

292
00:12:03,570 --> 00:12:07,140
it's being able to see like
a tangerine on the moon.

293
00:12:07,140 --> 00:12:11,880
So, we had to devise a telescope that had

294

00:12:11,880 --> 00:12:15,450
the greatest resolving
power of anything ever done.

295
00:12:15,450 --> 00:12:18,240
And the way we did it
is we took telescopes

296
00:12:18,240 --> 00:12:20,190
on different sides of the earth,

297
00:12:20,190 --> 00:12:24,180
we recorded lights from the black hole,

298
00:12:24,180 --> 00:12:25,860
stored it on hard disks,

299
00:12:25,860 --> 00:12:29,640
and then brought those discs
together to a central facility

300
00:12:29,640 --> 00:12:33,000
and we played them back and we
were able to form a telescope

301
00:12:33,000 --> 00:12:36,420
as big as the distance
between the telescopes.

302
00:12:36,420 --> 00:12:38,310
So, by linking telescopes
across the earth,

303
00:12:38,310 --> 00:12:41,250
we made a telescope
the size of our planet.

304
00:12:41,250 --> 00:12:42,843
And when you think about it,

305
00:12:43,980 --> 00:12:46,410
what we're doing is pretty much the way

306
00:12:46,410 --> 00:12:48,240
an optical telescope works.

307
00:12:48,240 --> 00:12:51,540
An optical telescope is a perfect parabola

308
00:12:51,540 --> 00:12:53,520
and it's a highly reflective surface light

309
00:12:53,520 --> 00:12:55,713
from an object bounces off that.

310
00:12:56,870 --> 00:12:57,900
And it all comes to a focus

311
00:12:57,900 --> 00:13:00,150
and that's where you
put your camera, okay?

312
00:13:00,150 --> 00:13:04,320
And it's the shape of that
lens that gets all of the light

313
00:13:04,320 --> 00:13:07,800
to that one focus at the same time.

314
00:13:07,800 --> 00:13:09,750
And what we do with the
Event Horizon Telescope

315
00:13:09,750 --> 00:13:12,180
is we take these recordings of radio waves

316
00:13:12,180 --> 00:13:13,560
from the black hole,

317
00:13:13,560 --> 00:13:16,440
we bring them to a supercomputer
and we play them back

318
00:13:16,440 --> 00:13:18,210
and align them perfectly.

319
00:13:18,210 --> 00:13:21,990
So, we replicate what an
optical telescope does

320
00:13:21,990 --> 00:13:24,330
with its mirror in silicon.

321
00:13:24,330 --> 00:13:28,110
We delay the light and play it
back so it perfectly aligns.

322
00:13:28,110 --> 00:13:30,753
And that gives us this
earth-sized telescope.

323
00:13:31,860 --> 00:13:33,030
And even that's not enough,

324
00:13:33,030 --> 00:13:35,460
'cause you need many
telescopes around the globe.

325
00:13:35,460 --> 00:13:37,410
So, it's not just two telescopes,

326
00:13:37,410 --> 00:13:40,620
but in the first instance of
the Event Horizon Telescope,

327
00:13:40,620 --> 00:13:44,040
we took eight telescopes,

observed simultaneously,

328
00:13:44,040 --> 00:13:47,100
and that was just enough
to make the first image

329
00:13:47,100 --> 00:13:47,933
of a black hole.

330
00:13:48,990 --> 00:13:52,110
- It seems like an almost
impossible undertaking.

331
00:13:52,110 --> 00:13:53,880
How was this idea even conceived?

332
00:13:53,880 --> 00:13:56,430
Did you have a eureka
moment one night and wake up

333
00:13:56,430 --> 00:13:57,660
and think we could make a telescope

334
00:13:57,660 --> 00:13:58,910
the size of planet Earth?

335
00:14:00,146 --> 00:14:02,050
It's almost crazy.
- Yeah.

336
00:14:02,050 --> 00:14:04,110
It is like mind boggling
when you think about it.

337
00:14:04,110 --> 00:14:06,570
And I do pinch myself occasionally,

338
00:14:06,570 --> 00:14:09,180
not just because it was a

very interesting project,

339
00:14:09,180 --> 00:14:10,920
but because we got to do it.

340
00:14:10,920 --> 00:14:15,150
As with many ideas, this has
been burbling for a long time

341
00:14:15,150 --> 00:14:17,580
on the theory side, as I mentioned,

342
00:14:17,580 --> 00:14:20,970
back in the early parts
of the 20th century,

343
00:14:20,970 --> 00:14:23,250
people have been thinking
about how big a black hole

344
00:14:23,250 --> 00:14:25,080
might appear to be on the sky.

345
00:14:25,080 --> 00:14:27,720
And then there were many
simulations done in the 70s

346
00:14:27,720 --> 00:14:31,170
and the 2000s to show
what it might look like.

347
00:14:31,170 --> 00:14:34,920
And at the same time, this
idea of radio interferometry,

348
00:14:34,920 --> 00:14:39,030
of linking telescopes around
the globe, was in full flower.

349

00:14:39,030 --> 00:14:42,570
So, we had already begun to
look at longer wavelengths

350
00:14:42,570 --> 00:14:44,820
with less angular resolution on the sky,

351
00:14:44,820 --> 00:14:47,580
at galaxies, at stars.

352
00:14:47,580 --> 00:14:50,430
And we had come to understand
that this was a way

353
00:14:50,430 --> 00:14:53,730
of getting the most extreme
angular resolutions possible

354
00:14:53,730 --> 00:14:54,810
from our planet.

355
00:14:54,810 --> 00:14:57,720
What we did was we just
took it to the next level.

356
00:14:57,720 --> 00:15:01,170
We said, we can see all
the way to the heart

357
00:15:01,170 --> 00:15:03,660
of the black hole at short wavelengths,

358
00:15:03,660 --> 00:15:06,300
and we can make the electronics now work

359
00:15:06,300 --> 00:15:08,430
at these short wavelengths,

360
00:15:08,430 --> 00:15:11,010

which had been harder to do prior to

361
00:15:11,010 --> 00:15:12,570
the Event Horizon Telescope

362
00:15:12,570 --> 00:15:14,580
and everything will
converge and we'll be able

363
00:15:14,580 --> 00:15:17,490
to make this image of a black hole.

364
00:15:17,490 --> 00:15:21,210
So, it was really an
advancement of the technology

365
00:15:21,210 --> 00:15:22,980
with an idea that had already been around

366
00:15:22,980 --> 00:15:26,010
for a while that made this possible.

367
00:15:26,010 --> 00:15:28,500
- So, it really had to
happen when it happened

368
00:15:28,500 --> 00:15:32,140
because the technology hadn't
caught up with the ideas

369
00:15:33,532 --> 00:15:34,470
until fairly recently?

370
00:15:34,470 --> 00:15:38,130
- Yeah, it was really
technologically based,

371
00:15:38,130 --> 00:15:40,670
like a lot of the ideas

were there and it came

372
00:15:40,670 --> 00:15:42,360
at just the right time.

373
00:15:42,360 --> 00:15:44,820
And as with all things like this,

374
00:15:44,820 --> 00:15:48,600
you need a few crazy people who
are willing to champion this

375
00:15:48,600 --> 00:15:50,880
and risk their careers on it.

376
00:15:50,880 --> 00:15:53,970
So, one of the first
things we did was we said,

377
00:15:53,970 --> 00:15:56,250
even with this short wavelength,

378
00:15:56,250 --> 00:16:01,250
even with the Milky Way Galaxy,
there as a prime target,

379
00:16:01,440 --> 00:16:04,140
even with a few telescopes
around the globe,

380
00:16:04,140 --> 00:16:06,093
we're still short on sensitivity.

381
00:16:06,930 --> 00:16:09,450
Given the instrumentation that we had

382
00:16:09,450 --> 00:16:12,210
in the early 2000s, we
would not have been able

383
00:16:12,210 --> 00:16:14,540
to detect the super massive black hole

384
00:16:14,540 --> 00:16:16,710
at the center of the Milky Way Galaxy.

385
00:16:16,710 --> 00:16:21,240
So, we began to develop
this very wideband system.

386
00:16:21,240 --> 00:16:24,660
So, instead of just
recording a small sliver

387
00:16:24,660 --> 00:16:25,920
of the radio spectrum,

388
00:16:25,920 --> 00:16:30,450
we broadened that to
record many frequencies.

389
00:16:30,450 --> 00:16:34,050
And that took about four years to develop.

390
00:16:34,050 --> 00:16:35,610
But once we had that,

391
00:16:35,610 --> 00:16:38,250
the increase in sensitivity was dramatic.

392
00:16:38,250 --> 00:16:42,300
That proved to be the
enabling new capability.

393
00:16:42,300 --> 00:16:47,300
And then in 2007, we took
the systems to Hawaii,

394
00:16:47,670 --> 00:16:52,670
California, and Arizona and we
looked at Sagittarius A star.

395
00:16:52,710 --> 00:16:53,543
For the first time

396
00:16:53,543 --> 00:16:56,460
we discovered event
horizon scale structure

397
00:16:56,460 --> 00:16:57,420
around a black hole.

398
00:16:57,420 --> 00:16:59,250
So, we knew all of a sudden
that there was something

399
00:16:59,250 --> 00:17:03,210
really small and that we could
move towards real imaging.

400
00:17:03,210 --> 00:17:08,210
So it was that moment in
2007, 2008, when we realized

401
00:17:08,520 --> 00:17:11,580
that the Event Horizon
Telescope could succeed.

402
00:17:11,580 --> 00:17:13,800
We had the technology, we had the theory,

403
00:17:13,800 --> 00:17:16,530
but now we had the actual
measurement that there was

404
00:17:16,530 --> 00:17:18,270
something really small there.

405
00:17:18,270 --> 00:17:19,920
And that set us on the path.

406
00:17:19,920 --> 00:17:22,890
- And I'm curious too about the
number of telescopes needed.

407
00:17:22,890 --> 00:17:25,890
You said you had eight
to make that first image.

408
00:17:25,890 --> 00:17:28,620
So, with the technology
that you had at that time,

409
00:17:28,620 --> 00:17:30,990
how much would've changed
if you had had seven

410
00:17:30,990 --> 00:17:33,120
or if you had nine, how
much does this change?

411
00:17:33,120 --> 00:17:36,210
And also how much more
complicated does it become

412
00:17:36,210 --> 00:17:38,670
as you add more telescopes?

413
00:17:38,670 --> 00:17:40,230
- Yeah, what a great question.

414
00:17:40,230 --> 00:17:42,630
So, is eight telescopes enough?

415
00:17:42,630 --> 00:17:44,787
So, we did our first experiments

with three telescopes

416
00:17:44,787 --> 00:17:46,740
and we knew that wasn't enough.

417
00:17:46,740 --> 00:17:49,290
We could tell there was
something going on there.

418
00:17:49,290 --> 00:17:52,050
It was a great discovery
that put us on this path,

419
00:17:52,050 --> 00:17:55,560
but we couldn't make an image
and we decided to just get

420
00:17:55,560 --> 00:18:00,270
as many telescopes as we could
and that when we had enough,

421
00:18:00,270 --> 00:18:02,850
we'd be able to analyze the
data and then this image,

422
00:18:02,850 --> 00:18:04,650
if it was there, would emerge.

423
00:18:04,650 --> 00:18:07,230
But there really is a piece of the puzzle

424
00:18:07,230 --> 00:18:10,740
that set us at this level
of eight telescopes.

425
00:18:10,740 --> 00:18:13,170
I told you before that we
needed more sensitivity

426

00:18:13,170 --> 00:18:15,240
and we increased our
bandwidth and that was true.

427
00:18:15,240 --> 00:18:16,620
Without that extra bandwidth,

428
00:18:16,620 --> 00:18:18,150
this would not have been possible.

429
00:18:18,150 --> 00:18:18,983
But in addition,

430
00:18:18,983 --> 00:18:22,650
there was a new facility
that was just emerging called

431
00:18:22,650 --> 00:18:25,560
the Atacama Large Millimeter
Array, or ALMA, for short.

432
00:18:25,560 --> 00:18:28,260
And it was a new facility in Chile

433
00:18:28,260 --> 00:18:30,390
and it consisted of roughly 60 dishes,

434
00:18:30,390 --> 00:18:32,430
each 12 meters diameter.

435
00:18:32,430 --> 00:18:35,490
If we had recorded data
from one of those dishes,

436
00:18:35,490 --> 00:18:37,890
we might have been able to pull this off.

437
00:18:37,890 --> 00:18:41,970
But we realized that if we got

all those dishes in one area

438
00:18:41,970 --> 00:18:43,800
to act as a single dish,

439
00:18:43,800 --> 00:18:47,190
if we could add all the
signals from those 60 dishes,

440
00:18:47,190 --> 00:18:50,370
we would have effectively a gigantic dish.

441
00:18:50,370 --> 00:18:52,620
And that would increase our sensitivity,

442
00:18:52,620 --> 00:18:54,630
again by a factor of 10.

443
00:18:54,630 --> 00:18:58,950
So, we took our time and we
developed a whole system over

444
00:18:58,950 --> 00:19:01,260
about seven years to phase up

445
00:19:01,260 --> 00:19:04,050
or combine all of those
telescopes together.

446
00:19:04,050 --> 00:19:05,820
And while we were doing that,

447
00:19:05,820 --> 00:19:07,770
other telescopes were made ready.

448
00:19:07,770 --> 00:19:11,610
So when ALMA was ready,
we had seven other dishes

449
00:19:11,610 --> 00:19:14,910
and then we kicked off
our observations in 2017.

450
00:19:14,910 --> 00:19:16,230
we had amazing weather,

451
00:19:16,230 --> 00:19:18,870
I mean just absolutely fantastic weather.

452
00:19:18,870 --> 00:19:20,970
And it was a combination of having ALMA,

453
00:19:20,970 --> 00:19:22,530
having the wide bandwidths,

454
00:19:22,530 --> 00:19:26,520
having seven other dishes, and
having this amazing weather

455
00:19:26,520 --> 00:19:30,810
that put us at just the right
moment, just the right time.

456
00:19:30,810 --> 00:19:32,670
People say, "Were you lucky?"

457
00:19:32,670 --> 00:19:36,060
I think we were fortunate, but
fortune favors the prepared

458
00:19:36,060 --> 00:19:38,880
and we had spent almost two
decades preparing for this.

459
00:19:38,880 --> 00:19:40,620
So when the time was right,

460

00:19:40,620 --> 00:19:42,000
we had everything in place

461
00:19:42,000 --> 00:19:43,740
and then we were able to make the image.

462
00:19:43,740 --> 00:19:46,260
- I remember shortly after
I first started working here

463
00:19:46,260 --> 00:19:47,940
at Perimeter, this is
eight or nine years ago,

464
00:19:47,940 --> 00:19:49,860
I was talking to your
colleague, Avery Broderick,

465
00:19:49,860 --> 00:19:52,590
who works here, and we've
chatted with him on the podcast.

466
00:19:52,590 --> 00:19:54,990
And he told me, I actually thought he was

467
00:19:54,990 --> 00:19:56,940
a little bit out of his mind at the time.

468
00:19:56,940 --> 00:20:00,300
He said, "We're gonna take
the world's first image

469
00:20:00,300 --> 00:20:02,280
of a black hole, and mark my words,

470
00:20:02,280 --> 00:20:04,020
when we do it will be on the front page

471
00:20:04,020 --> 00:20:05,910

of the 'New York Times' above the fold."

472
00:20:05,910 --> 00:20:07,620
And I said, "Okay, Avery."

473
00:20:07,620 --> 00:20:10,920
Sure enough, in 2019 you
have a press conference.

474
00:20:10,920 --> 00:20:14,310
You issue the image of the M87 black hole.

475
00:20:14,310 --> 00:20:16,020
And not only the front page
of the "New York Times"

476
00:20:16,020 --> 00:20:19,500
above the fold, but all of
them, all the major newspapers,

477
00:20:19,500 --> 00:20:22,110
it seemed to be, had them
right on the front page.

478
00:20:22,110 --> 00:20:24,750
And I'm curious, A, I
should have trusted Avery,

479
00:20:24,750 --> 00:20:26,250
he knows this stuff better than I do,

480
00:20:26,250 --> 00:20:28,020
but also why do you think

481
00:20:28,020 --> 00:20:30,180
it captured people's imagination.

482
00:20:30,180 --> 00:20:33,510
There are breakthroughs in

science that get relegated

483
00:20:33,510 --> 00:20:38,510
to page C19, but this one
captured the world's imagination.

484
00:20:38,820 --> 00:20:39,966
- True.

485
00:20:39,966 --> 00:20:43,530
When we came down the morning
after this announcement

486
00:20:43,530 --> 00:20:48,530
on April 11th of 2019 and we
saw the "Wall Street Journal"

487
00:20:49,170 --> 00:20:51,840
and the "New York Times," "Boston Globe,"

488
00:20:51,840 --> 00:20:55,920
every major newspaper had
this picture above the fold,

489
00:20:55,920 --> 00:20:59,400
as you say, it really
rocked us back on our heels

490
00:20:59,400 --> 00:21:03,330
because we had been so
focused on getting this image.

491
00:21:03,330 --> 00:21:06,570
We'd been so focused on
some of the materials

492
00:21:06,570 --> 00:21:08,222
that would explain it to the public

493

00:21:08,222 --> 00:21:12,990
that we hadn't really thought
about where it would land.

494
00:21:12,990 --> 00:21:13,823
Right?

495
00:21:13,823 --> 00:21:15,060
Or I hadn't thought about
where it would land.

496
00:21:15,060 --> 00:21:19,200
I knew it was gonna be big,
but the visceral connection

497
00:21:19,200 --> 00:21:22,980
with the curious public,
and the curious public

498
00:21:22,980 --> 00:21:24,720
is they ask the best questions.

499
00:21:24,720 --> 00:21:26,670
Like they're really curious, right?

500
00:21:26,670 --> 00:21:29,880
And the connection was dramatic.

501
00:21:29,880 --> 00:21:31,650
So, we were surprised.

502
00:21:31,650 --> 00:21:33,000
I was surprised anyway.

503
00:21:33,000 --> 00:21:35,940
I mean you might have
predicted there'd be some play

504
00:21:35,940 --> 00:21:38,400

in the media, but you know,

505
00:21:38,400 --> 00:21:41,917
I got into cabs and I would say,

506
00:21:41,917 --> 00:21:44,490
"Hey, what do you think about
that black hole business?"

507
00:21:44,490 --> 00:21:46,590
Not letting them know that I
had anything to do with it.

508
00:21:46,590 --> 00:21:48,360
And they would say, "Oh
yeah, it's amazing."

509
00:21:48,360 --> 00:21:51,420
You know, and they would start
explaining how it was done,

510
00:21:51,420 --> 00:21:53,370
you know, and I would say, "Really?"

511
00:21:53,370 --> 00:21:54,810
And they were like, "Come on, get with it.

512
00:21:54,810 --> 00:21:57,067
I mean this interferometry
stuff, it's here, it's now."

513
00:21:57,067 --> 00:22:00,240
You know, so people were very invested

514
00:22:00,240 --> 00:22:02,610
in understanding the result,

515
00:22:02,610 --> 00:22:04,350
but your question was why?

516
00:22:04,350 --> 00:22:07,620
And I think it's due to
a few different factors.

517
00:22:07,620 --> 00:22:11,070
One is, people are always
interested in monsters

518
00:22:11,070 --> 00:22:13,590
and there's no bigger
monster than a black hole

519
00:22:13,590 --> 00:22:14,610
that sits at the center

520
00:22:14,610 --> 00:22:17,730
of a galaxy devouring
everything that comes near it.

521
00:22:17,730 --> 00:22:19,860
All throughout history, Greek mythology,

522
00:22:19,860 --> 00:22:20,970
there are these monsters

523
00:22:20,970 --> 00:22:22,800
and we're just fascinated with them.

524
00:22:22,800 --> 00:22:24,360
And to be able to see one

525
00:22:24,360 --> 00:22:26,220
that you've only heard about before

526
00:22:26,220 --> 00:22:29,610
and has been the subject of sci-fi movies,

527

00:22:29,610 --> 00:22:31,380
that captured everyone's imagination

528
00:22:31,380 --> 00:22:33,120
just to know that it was out there.

529
00:22:33,120 --> 00:22:34,650
That's the first thing.

530
00:22:34,650 --> 00:22:38,190
The second thing is,
black holes are unique

531
00:22:38,190 --> 00:22:41,550
in that once you fall into one,
you can never get out again.

532
00:22:41,550 --> 00:22:44,970
It's a knot that you can't
untie, that is scary.

533
00:22:44,970 --> 00:22:46,560
So in addition to being a monster,

534
00:22:46,560 --> 00:22:48,690
it's also especially scary.

535
00:22:48,690 --> 00:22:50,670
And to know that there's
really something out there

536
00:22:50,670 --> 00:22:53,340
that's a portal from our world

537
00:22:53,340 --> 00:22:55,830
to a place where you
can never return from,

538
00:22:55,830 --> 00:22:59,250

that captured people's imagination too.

539
00:22:59,250 --> 00:23:02,040
And then I think a really
important aspect of it

540
00:23:02,040 --> 00:23:04,170
was that we did it as a team.

541
00:23:04,170 --> 00:23:07,380
There was early work that put
all of this on solid footing,

542
00:23:07,380 --> 00:23:08,910
you know, on the theory side,

543
00:23:08,910 --> 00:23:12,360
also at the early experiments
that I told you about.

544
00:23:12,360 --> 00:23:17,010
But to make the image,
required connecting people

545
00:23:17,010 --> 00:23:20,310
from around the globe, you
know, sidestepping borders,

546
00:23:20,310 --> 00:23:23,823
all the things that normally
divide us as humans.

547
00:23:25,109 --> 00:23:27,990
We brought the best people
with the best expertise,

548
00:23:27,990 --> 00:23:29,280
no matter where they came from,

549

00:23:29,280 --> 00:23:31,470
we brought them together
to form this team.

550
00:23:31,470 --> 00:23:34,740
We used telescopes around the globe

551
00:23:34,740 --> 00:23:36,390
and then we used the earth itself,

552
00:23:36,390 --> 00:23:40,583
the geometry of our planet
as part of the telescope.

553
00:23:40,583 --> 00:23:43,650
I mean, you can't get
a more kumbaya moment

554
00:23:43,650 --> 00:23:45,180
than this, right?

555
00:23:45,180 --> 00:23:48,570
Everybody working together,
everybody contributing,

556
00:23:48,570 --> 00:23:53,570
the planet itself forming the
scaffolding of our telescope

557
00:23:54,270 --> 00:23:57,300
and then addressing one
of the greatest mysteries

558
00:23:57,300 --> 00:23:59,793
that we have ever really contemplated.

559
00:24:00,780 --> 00:24:02,850
And then coming with a success.

560

00:24:02,850 --> 00:24:07,850
All of that I think just gave
people a sense of wellbeing,

561
00:24:08,220 --> 00:24:10,260
of knowing that humans could pull together

562
00:24:10,260 --> 00:24:12,483
to do something truly extraordinary.

563
00:24:13,410 --> 00:24:15,780
And now that we're faced
with things like, you know,

564
00:24:15,780 --> 00:24:19,770
the pandemic and we're faced
with the climate change,

565
00:24:19,770 --> 00:24:22,680
and we're faced with
hunger, and all these things

566
00:24:22,680 --> 00:24:25,380
that we're gonna have to
deal with on a global basis,

567
00:24:25,380 --> 00:24:27,060
this is a beacon,

568
00:24:27,060 --> 00:24:31,800
this is an exemplar of how we
can come together as people

569
00:24:31,800 --> 00:24:34,350
to tackle the really big questions.

570
00:24:34,350 --> 00:24:36,750
- And your role on this very big team

571

00:24:36,750 --> 00:24:39,480
is the founding director of this project.

572
00:24:39,480 --> 00:24:41,733
How do you describe your role?

573
00:24:42,600 --> 00:24:45,900
- I led many of the early
experiments that showed this

574
00:24:45,900 --> 00:24:47,340
was gonna be possible.

575
00:24:47,340 --> 00:24:49,170
And that was with a small team.

576
00:24:49,170 --> 00:24:52,620
And that for me is probably
the thing I'm most proud of.

577
00:24:52,620 --> 00:24:54,540
The thing, you know,
these early experiments

578
00:24:54,540 --> 00:24:57,750
where we had no idea if
this was remotely possible

579
00:24:57,750 --> 00:25:01,740
and working with a small
group of colleagues

580
00:25:01,740 --> 00:25:03,900
and seeing for the first
time that there was

581
00:25:03,900 --> 00:25:07,500
this event horizon scale
structure, scientifically,

582
00:25:07,500 --> 00:25:11,940
that was the greatest moment
I have felt in my career.

583
00:25:11,940 --> 00:25:13,980
And that motivated me greatly.

584
00:25:13,980 --> 00:25:18,980
But, my role later grew to be
organizing this global effort

585
00:25:19,950 --> 00:25:24,420
and while in the early stages
I derived most satisfaction

586
00:25:24,420 --> 00:25:28,620
from the results, like looking
at a graph and seeing, yes,

587
00:25:28,620 --> 00:25:30,150
we've seen something that's only

588
00:25:30,150 --> 00:25:33,720
like 30 microarcseconds
across, it's like amazing.

589
00:25:33,720 --> 00:25:37,500
But later ,I began to
realize that I was deriving

590
00:25:37,500 --> 00:25:41,010
as much satisfaction from
organizing this effort,

591
00:25:41,010 --> 00:25:43,170
from putting this team together,

592
00:25:43,170 --> 00:25:45,690
from getting the theorists together,

593
00:25:45,690 --> 00:25:48,240
the instrumentalists together.

594
00:25:48,240 --> 00:25:50,640
And I view it a little
bit as herding cats.

595
00:25:50,640 --> 00:25:53,250
So, my role was really
to get everyone together,

596
00:25:53,250 --> 00:25:56,430
to focus us all with a common vision

597
00:25:56,430 --> 00:25:58,290
and see it through to the end.

598
00:25:58,290 --> 00:26:00,360
That was the most important part.

599
00:26:00,360 --> 00:26:03,210
- In 2019, that first
image that was released,

600
00:26:03,210 --> 00:26:05,850
that was the M87 black hole.

601
00:26:05,850 --> 00:26:08,640
Since then you've also unveiled an image

602
00:26:08,640 --> 00:26:11,370
of the Sagittarius A star black hole.

603
00:26:11,370 --> 00:26:12,810
Can you tell us about those two?

604
00:26:12,810 --> 00:26:15,003

Why those two and how are they different?

605
00:26:17,226 --> 00:26:18,059
How are they similar?

606
00:26:18,059 --> 00:26:19,950
How did you choose them?

607
00:26:19,950 --> 00:26:20,880
- Well, so you're asking

608
00:26:20,880 --> 00:26:24,775
how did we choose
Sagittarius A star and M87?

609
00:26:24,775 --> 00:26:25,950
And in a sense they chose us.

610
00:26:25,950 --> 00:26:28,440
We can't engineer the universe, right?

611
00:26:28,440 --> 00:26:30,150
We can engineer our telescopes,

612
00:26:30,150 --> 00:26:32,067
we can engineer our instrumentation,

613
00:26:32,067 --> 00:26:34,653
but we can't engineer the universe, right?

614
00:26:35,670 --> 00:26:38,610
It turns out that there are two sources.

615
00:26:38,610 --> 00:26:40,650
Sagittarius A star in the
center of the Milky Way

616
00:26:40,650 --> 00:26:43,320

and M87, 55 million light years away

617
00:26:43,320 --> 00:26:45,750
at the center of the Virgo A galaxy,

618
00:26:45,750 --> 00:26:50,190
that are massive enough and close enough

619
00:26:50,190 --> 00:26:52,320
that they present a ring of light,

620
00:26:52,320 --> 00:26:55,020
this lensed photon orbit
around the black hole

621
00:26:55,020 --> 00:26:57,060
that we can hope to image.

622
00:26:57,060 --> 00:27:00,540
So, we knew going into this
that Sagittarius A star

623
00:27:00,540 --> 00:27:02,100
was our primary target,

624
00:27:02,100 --> 00:27:05,490
and M87 whose mass was a
little bit less well-defined

625
00:27:05,490 --> 00:27:07,380
was likely our secondary target.

626
00:27:07,380 --> 00:27:09,690
And we observed both of them in 2017

627
00:27:09,690 --> 00:27:11,670
with the Event Horizon Telescope.

628

00:27:11,670 --> 00:27:13,230
Why are there only two?

629
00:27:13,230 --> 00:27:14,460
That's a mystery.

630
00:27:14,460 --> 00:27:15,960
Why aren't there more?

631
00:27:15,960 --> 00:27:16,980
That's a mystery.

632
00:27:16,980 --> 00:27:18,030
Are there others?

633
00:27:18,030 --> 00:27:21,720
Undoubtedly there are others
and new instrumentation

634
00:27:21,720 --> 00:27:23,400
that we're developing will likely bring

635
00:27:23,400 --> 00:27:26,520
other super massive black holes into range

636
00:27:26,520 --> 00:27:28,050
of our planet-sized telescopes.

637
00:27:28,050 --> 00:27:31,110
We'll be able to make
measurements of other galaxies

638
00:27:31,110 --> 00:27:32,400
and other black holes.

639
00:27:32,400 --> 00:27:34,920
But these two were special because we knew

640

00:27:34,920 --> 00:27:37,080
that we had a shot at imaging these two.

641
00:27:37,080 --> 00:27:37,920
And what I'd like to say

642
00:27:37,920 --> 00:27:41,340
is if I was on a desert
island with two black holes,

643
00:27:41,340 --> 00:27:43,680
these would be the ones I'd want, right?

644
00:27:43,680 --> 00:27:46,530
Because Sagittarius A
star is in our backyard.

645
00:27:46,530 --> 00:27:49,317
It's our own black hole.

646
00:27:49,317 --> 00:27:52,050
But what that means is
that it's very faint.

647
00:27:52,050 --> 00:27:54,240
It's eating very timidly.

648
00:27:54,240 --> 00:27:58,650
So, it glows with just
like a faint luminosity.

649
00:27:58,650 --> 00:28:01,440
And it's a kind of black hole
that is probably at the center

650
00:28:01,440 --> 00:28:03,060
of most galaxies out there.

651
00:28:03,060 --> 00:28:05,820

'Cause most galaxies are kind
of like the Milky Way Galaxy,

652
00:28:05,820 --> 00:28:09,330
small, non-descript, run-of-the-mill,

653
00:28:09,330 --> 00:28:11,910
working day black holes
that just go out there

654
00:28:11,910 --> 00:28:13,110
and do their thing.

655
00:28:13,110 --> 00:28:15,990
So, we're able to see Sagittarius A star

656
00:28:15,990 --> 00:28:17,760
because it's so close.

657
00:28:17,760 --> 00:28:19,800
So, it's one kind of black hole.

658
00:28:19,800 --> 00:28:22,110
M87 is a monster.

659
00:28:22,110 --> 00:28:27,110
M87 is so powerful that it
energizes a jet of material

660
00:28:28,770 --> 00:28:31,380
that likely leaves from
the north and south pole

661
00:28:31,380 --> 00:28:33,540
of this spinning black hole.

662
00:28:33,540 --> 00:28:37,410
And this jet is so powerful,
it pierces the entire galaxy.

663
00:28:37,410 --> 00:28:39,900
It goes for tens of
thousands of light years

664
00:28:39,900 --> 00:28:41,640
from the center of the galaxy.

665
00:28:41,640 --> 00:28:44,790
You would not wanna be in
the way of that jet, right?

666
00:28:44,790 --> 00:28:47,130
You wouldn't wanna live too
close to that black hole.

667
00:28:47,130 --> 00:28:48,180
- Why, what would happen?

668
00:28:48,180 --> 00:28:50,130
- It would create conditions that life

669
00:28:50,130 --> 00:28:51,870
would never have existed there, right?

670
00:28:51,870 --> 00:28:53,520
It would just like vaporize everything.

671
00:28:53,520 --> 00:28:57,420
So, what what I'm getting at
is that M87 is a different kind

672
00:28:57,420 --> 00:28:58,290
of black hole.

673
00:28:58,290 --> 00:29:00,810
It's a black hole that's
accreting enough matter

674
00:29:00,810 --> 00:29:02,730
that it glows very, very brightly.

675
00:29:02,730 --> 00:29:07,080
And so, it gives us a window
on a different kind of galaxy.

676
00:29:07,080 --> 00:29:09,930
So, what's really wonderful
about being able to look

677
00:29:09,930 --> 00:29:14,930
at Sagittarius A star and
M87 is it gives us an idea

678
00:29:15,090 --> 00:29:18,120
of how to study two different
kinds of black holes.

679
00:29:18,120 --> 00:29:19,830
One black hole that's faint,

680
00:29:19,830 --> 00:29:21,990
one black hole that's eating a lot,

681
00:29:21,990 --> 00:29:24,960
one black hole that's in
a large elliptical galaxy,

682
00:29:24,960 --> 00:29:27,990
that's M87, one that's in a spiral galaxy.

683
00:29:27,990 --> 00:29:31,170
So, it gives us two different
flavors of these black holes.

684
00:29:31,170 --> 00:29:33,120
And that's very interesting

685
00:29:33,120 --> 00:29:34,950
from an astronomical perspective.

686
00:29:34,950 --> 00:29:36,780
- When you describe the differences

687
00:29:36,780 --> 00:29:39,120
between M87 and and Sag A star,

688
00:29:39,120 --> 00:29:41,220
like how vast are these differences

689
00:29:41,220 --> 00:29:43,020
in terms of power and size?

690
00:29:43,020 --> 00:29:46,260
Can you give us a sort of a
more terrestrial comparison?

691
00:29:46,260 --> 00:29:49,890
- Well, one way of saying it
is a Sagittarius A star weighs

692
00:29:49,890 --> 00:29:53,040
about 4 million times what our sun does.

693
00:29:53,040 --> 00:29:56,040
So, you would think that if
there's a stellar phenomena,

694
00:29:56,040 --> 00:30:00,000
if there's a energetic phenomena
associated with a star,

695
00:30:00,000 --> 00:30:02,134
that you'd be looking at something

696
00:30:02,134 --> 00:30:03,660

that's 4 million times brighter,

697
00:30:03,660 --> 00:30:05,250
okay, if it scales with mass.

698
00:30:05,250 --> 00:30:08,220
But, it turns out that Sagittarius A star

699
00:30:08,220 --> 00:30:11,310
is surrounded by such a tenuous gas,

700
00:30:11,310 --> 00:30:14,940
such a thin vapor, that
even though it's accreting

701
00:30:14,940 --> 00:30:16,080
what's around it,

702
00:30:16,080 --> 00:30:18,450
it's insufficient to really glow beyond

703
00:30:18,450 --> 00:30:20,610
what a normal star would show.

704
00:30:20,610 --> 00:30:24,180
So, there are these stars where
the star is being devoured

705
00:30:24,180 --> 00:30:25,320
by a black hole.

706
00:30:25,320 --> 00:30:26,760
They're called X-ray binaries.

707
00:30:26,760 --> 00:30:27,630
So two stars,

708
00:30:27,630 --> 00:30:31,320

one of which has gone supernova,
is turned into a black hole

709
00:30:31,320 --> 00:30:33,243
and then is devouring this other star.

710
00:30:34,681 --> 00:30:37,680
Sagittarius A star doesn't
really emit more energy

711
00:30:37,680 --> 00:30:40,080
than one of those star pairs.

712
00:30:40,080 --> 00:30:41,670
That's really extraordinary.

713
00:30:41,670 --> 00:30:43,530
You have this behemoth,

714
00:30:43,530 --> 00:30:46,110
this 4 million solar mass black hole,

715
00:30:46,110 --> 00:30:48,870
and it's the most timid of giants.

716
00:30:48,870 --> 00:30:51,540
So in that sense, Sagittarius A star,

717
00:30:51,540 --> 00:30:56,130
the black hole there, is
very faint, very quiet.

718
00:30:56,130 --> 00:30:59,150
It represents a part of
the evolutionary life cycle

719
00:30:59,150 --> 00:31:00,630
of a super massive black hole

720
00:31:00,630 --> 00:31:03,690
in which it's just not perturbing

721
00:31:03,690 --> 00:31:05,190
what's around it too much.

722
00:31:05,190 --> 00:31:08,708
M87 on the other hand,
is devouring much more,

723
00:31:08,708 --> 00:31:12,240
probably a hundred thousand
times a greater rate

724
00:31:12,240 --> 00:31:15,000
than Sagittarius A star for its mass.

725
00:31:15,000 --> 00:31:18,390
And so, it is extremely luminous.

726
00:31:18,390 --> 00:31:21,990
It's probably billions
of times more luminous

727
00:31:21,990 --> 00:31:24,030
than Sagittarius A star.

728
00:31:24,030 --> 00:31:26,470
And it ejects this jet that goes

729
00:31:27,358 --> 00:31:28,530
for tens of thousand light years.

730
00:31:28,530 --> 00:31:30,630
So not only is it bright,

731
00:31:30,630 --> 00:31:34,800
but it's also dynamically

disrupting what's around it

732
00:31:34,800 --> 00:31:37,110
in a way that Sagittarius A star is not.

733
00:31:37,110 --> 00:31:39,210
So, they're very different
from that perspective,

734
00:31:39,210 --> 00:31:42,990
just in levels of energy
and in the phenomena

735
00:31:42,990 --> 00:31:44,490
that surrounds them.

736
00:31:44,490 --> 00:31:46,620
- And are any of these differences things

737
00:31:46,620 --> 00:31:50,430
that we can see when we
compare these images?

738
00:31:50,430 --> 00:31:53,460
- In a way, yes, and in a way, no.

739
00:31:53,460 --> 00:31:55,890
I hate when people do
that, like yes and no.

740
00:31:55,890 --> 00:31:59,280
So, when you get very
close to the black hole,

741
00:31:59,280 --> 00:32:01,410
even though there are some differences,

742
00:32:01,410 --> 00:32:03,810
Einstein's gravity

determines what you'll see.

743
00:32:03,810 --> 00:32:06,930
The space time around the
black hole is so warped

744
00:32:06,930 --> 00:32:09,030
that even though you have M87,

745
00:32:09,030 --> 00:32:12,480
which is accreting at a much
higher rate than Sag A star,

746
00:32:12,480 --> 00:32:14,850
you see the same ring of light.

747
00:32:14,850 --> 00:32:16,710
And when you look at Sagittarius A star,

748
00:32:16,710 --> 00:32:18,150
you see this ring of light,

749
00:32:18,150 --> 00:32:21,090
you're seeing the geometry
of space time and no matter

750
00:32:21,090 --> 00:32:24,840
how you light it up, whether
with a bright flashlight,

751
00:32:24,840 --> 00:32:27,870
which is M87, or a dim flashlight,

752
00:32:27,870 --> 00:32:29,100
which is Sagittarius A star,

753
00:32:29,100 --> 00:32:31,080
all the light gets bent into this ring

754
00:32:31,080 --> 00:32:33,150
and that's what captures your attention.

755
00:32:33,150 --> 00:32:37,050
If you look at things in
the time domain though.

756
00:32:37,050 --> 00:32:40,500
So, imagine we fast forward a few years,

757
00:32:40,500 --> 00:32:42,180
we're going to engineer something called

758
00:32:42,180 --> 00:32:45,210
the next generation
Event Horizon Telescope.

759
00:32:45,210 --> 00:32:48,870
And the goal is to make
movies of black holes,

760
00:32:48,870 --> 00:32:51,960
to capture the dynamics,
to capture the action

761
00:32:51,960 --> 00:32:53,220
around the event horizon.

762
00:32:53,220 --> 00:32:54,900
There you'll see something different.

763
00:32:54,900 --> 00:32:55,950
Sagittarius A star,

764
00:32:55,950 --> 00:32:59,640
because it's 4 million solar
masses entrains the matter

765

00:32:59,640 --> 00:33:02,910
around it to orbit about
every half an hour.

766
00:33:02,910 --> 00:33:04,350
So, every half an hour things

767
00:33:04,350 --> 00:33:05,790
will move around Sagittarius A star.

768
00:33:05,790 --> 00:33:07,470
So, during an evening of observing,

769
00:33:07,470 --> 00:33:09,420
you will see a change shape.

770
00:33:09,420 --> 00:33:11,850
It will shimmy while you're watching it.

771
00:33:11,850 --> 00:33:15,990
M87 is six and a half
billion solar masses.

772
00:33:15,990 --> 00:33:20,040
And the dynamical time scale
is related linearly with mass.

773
00:33:20,040 --> 00:33:24,270
So, the same orbit will
take three weeks for M87.

774
00:33:24,270 --> 00:33:25,650
So if you look at M87,

775
00:33:25,650 --> 00:33:29,040
it will not be changing moment to moment

776
00:33:29,040 --> 00:33:30,210
during a night of observing,

777
00:33:30,210 --> 00:33:32,910
while Sagittarius A star
will be madly spinning.

778
00:33:32,910 --> 00:33:36,240
- Even though M87 is the more
active, hungry of the two?

779
00:33:36,240 --> 00:33:40,200
- Even though on a larger
scale M87 is more luminous,

780
00:33:40,200 --> 00:33:44,160
it changes much more slowly
when you take a picture of it.

781
00:33:44,160 --> 00:33:46,860
So, when we moved to
taking motion pictures

782
00:33:46,860 --> 00:33:48,450
of black holes,

783
00:33:48,450 --> 00:33:51,990
then you will see the movies
for Sag A star and M87

784
00:33:51,990 --> 00:33:53,580
be completely different.

785
00:33:53,580 --> 00:33:56,550
- So, you've mentioned
the next generation EHT,

786
00:33:56,550 --> 00:33:57,383
what is that?

787
00:33:57,383 --> 00:33:59,790

How does it expand upon the original EHT?

788
00:33:59,790 --> 00:34:02,340
- So you ask yourself,
well how can we do better?

789
00:34:02,340 --> 00:34:05,130
The Earth is only so big, so
how do you take the next step?

790
00:34:05,130 --> 00:34:08,010
And, I would add that I think
it's the human condition

791
00:34:08,010 --> 00:34:09,330
to always be restless.

792
00:34:09,330 --> 00:34:10,830
And it's not just for scientists,

793
00:34:10,830 --> 00:34:13,740
we wanna do the next thing,
but also the curious public.

794
00:34:13,740 --> 00:34:15,630
After a while they start asking, okay,

795
00:34:15,630 --> 00:34:18,090
so you've made the image of
a black hole, what's next?

796
00:34:18,090 --> 00:34:18,923
When you think about it,

797
00:34:18,923 --> 00:34:21,570
people are really curious
about these things

798
00:34:21,570 --> 00:34:25,230

and they're not content with
what you've done just recently,

799
00:34:25,230 --> 00:34:26,580
what have you done for me lately?

800
00:34:26,580 --> 00:34:28,643
Yes, you imaged a black hole,
yawn, you know, what's next?

801
00:34:28,643 --> 00:34:31,572
(Lauren and Colin laughing)

802
00:34:31,572 --> 00:34:33,330
And I get that because
people are naturally curious,

803
00:34:33,330 --> 00:34:35,580
they push in the same
way that scientists do.

804
00:34:35,580 --> 00:34:38,171
So, if we're gonna take the next step,

805
00:34:38,171 --> 00:34:40,230
we do have to make movies of black holes

806
00:34:40,230 --> 00:34:43,260
because this will showcase the difference

807
00:34:43,260 --> 00:34:46,230
between M87 and Sagittarius A star.

808
00:34:46,230 --> 00:34:48,750
So, I'll give you just a
little bit of motivation.

809
00:34:48,750 --> 00:34:52,140
The size of the ring

around these black holes

810
00:34:52,140 --> 00:34:55,890
doesn't change much if the
black hole is not spinning

811
00:34:55,890 --> 00:34:59,730
or if it's spinning as
fast as it possibly can.

812
00:34:59,730 --> 00:35:02,400
These are very important
parameters for theorists

813
00:35:02,400 --> 00:35:05,100
and observers because if you
have a spinning black hole,

814
00:35:05,100 --> 00:35:07,050
then you can get these jets that erupt

815
00:35:07,050 --> 00:35:10,950
from the north and south pole
like the one we see for M87.

816
00:35:10,950 --> 00:35:14,280
And if it's not spinning,
as we suspect the black hole

817
00:35:14,280 --> 00:35:17,220
in the center of the Milky Way
is, you don't get these jets.

818
00:35:17,220 --> 00:35:18,870
And indeed around Sagittarius A star,

819
00:35:18,870 --> 00:35:22,230
we don't see these jets, not yet anyway.

820

00:35:22,230 --> 00:35:24,780
The motion of matter around the black hole

821
00:35:24,780 --> 00:35:27,390
is exquisitely sensitive to spin.

822
00:35:27,390 --> 00:35:28,740
So let me put it this way,

823
00:35:28,740 --> 00:35:31,080
if the black hole at the
center of our Milky Way Galaxy

824
00:35:31,080 --> 00:35:32,370
is not spinning,

825
00:35:32,370 --> 00:35:34,620
it'll take matter about half an hour

826
00:35:34,620 --> 00:35:36,060
to orbit the black hole.

827
00:35:36,060 --> 00:35:39,720
If it's spinning at its full potential,

828
00:35:39,720 --> 00:35:41,700
it would take four minutes.

829
00:35:41,700 --> 00:35:44,700
So, you'll be able to see
just by looking at a movie

830
00:35:44,700 --> 00:35:46,530
if the black hole is spinning or not.

831
00:35:46,530 --> 00:35:48,600
So, it gives you a whole new dimension

832

00:35:48,600 --> 00:35:51,870
into the fundamental
parameters of black holes.

833
00:35:51,870 --> 00:35:53,910
So now you ask, well
how do we make a movie?

834
00:35:53,910 --> 00:35:56,130
And the the answer is,

835
00:35:56,130 --> 00:36:00,270
you wanna be able to engineer
your Event Horizon Telescope

836
00:36:00,270 --> 00:36:03,090
so that from moment to moment you are able

837
00:36:03,090 --> 00:36:06,600
to make a snapshot image of
let's say Sagittarius A star

838
00:36:06,600 --> 00:36:09,060
and stitch those together into a movie.

839
00:36:09,060 --> 00:36:10,620
We were able to make the image

840
00:36:10,620 --> 00:36:13,410
of M87 pretty much immediately

841
00:36:13,410 --> 00:36:15,990
because it doesn't
change moment to moment.

842
00:36:15,990 --> 00:36:18,360
So, we were able to take
all the observations

843

00:36:18,360 --> 00:36:20,220
from a single night of observing

844
00:36:20,220 --> 00:36:22,770
as the earth turned and all the telescopes

845
00:36:22,770 --> 00:36:25,110
had different look
directions and they filled in

846
00:36:25,110 --> 00:36:26,970
this earth-sized virtual lens,

847
00:36:26,970 --> 00:36:29,730
we combined all that data
to make a still image.

848
00:36:29,730 --> 00:36:32,490
For Sagittarius A star
it's much more complicated

849
00:36:32,490 --> 00:36:34,590
because it's changing its appearance

850
00:36:34,590 --> 00:36:35,730
during a night of observing.

851
00:36:35,730 --> 00:36:39,180
So, there we need to make
a motion picture camera

852
00:36:39,180 --> 00:36:42,840
and we have determined
through a bunch of simulations

853
00:36:42,840 --> 00:36:45,480
that if we double the number of dishes,

854
00:36:45,480 --> 00:36:49,170

if we go from about 10 dishes
now to about 20 dishes,

855
00:36:49,170 --> 00:36:52,320
that will give us enough
coverage in this Earth-size lens

856
00:36:52,320 --> 00:36:56,010
so that every five minutes we'll
be able to make a new image

857
00:36:56,010 --> 00:36:57,240
and we'll stitch those together

858
00:36:57,240 --> 00:36:59,070
to make the first motion picture

859
00:36:59,070 --> 00:37:01,710
of the Sagittarius A star black hole.

860
00:37:01,710 --> 00:37:04,650
So, when we think about the
next generation instrument,

861
00:37:04,650 --> 00:37:07,890
we think of a few things,
adding more telescopes,

862
00:37:07,890 --> 00:37:08,820
that's the first.

863
00:37:08,820 --> 00:37:10,740
Broadening the bandwidth even further

864
00:37:10,740 --> 00:37:13,380
to make it more sensitive,
that's the second thing.

865
00:37:13,380 --> 00:37:16,350

And then observing at a higher frequency

866
00:37:16,350 --> 00:37:17,670
than we currently do.

867
00:37:17,670 --> 00:37:19,500
Right now, the Event
Horizon Telescope observes

868
00:37:19,500 --> 00:37:23,280
at 230 gigahertz which limits
our angular resolution.

869
00:37:23,280 --> 00:37:26,310
But by going to 345
gigahertz and recording

870
00:37:26,310 --> 00:37:29,760
that simultaneously with 230 gigahertz,

871
00:37:29,760 --> 00:37:32,370
this will give us more angular resolution,

872
00:37:32,370 --> 00:37:35,880
fill in the Earth-sized
virtual telescope even more

873
00:37:35,880 --> 00:37:37,050
and allow us to make movies.

874
00:37:37,050 --> 00:37:38,040
So it's those three things,

875
00:37:38,040 --> 00:37:42,003
more telescopes, more
bandwidth, and more frequencies,

876
00:37:43,329 --> 00:37:46,680
that will transform the EHT

into a motion picture camera.

877
00:37:46,680 --> 00:37:49,320
- And when you're adding
those 10 new telescopes,

878
00:37:49,320 --> 00:37:52,320
you have to choose 10 new
locations where they're gonna be.

879
00:37:52,320 --> 00:37:55,140
Can you tell us a bit about
that process of how you choose

880
00:37:55,140 --> 00:37:57,180
where to put the new telescopes?

881
00:37:57,180 --> 00:37:58,680
- So, it turns out that there are

882
00:37:58,680 --> 00:38:00,300
a couple of different factors.

883
00:38:00,300 --> 00:38:01,680
One is you can ask yourself,

884
00:38:01,680 --> 00:38:04,800
if I could put a telescope
anywhere on the planet,

885
00:38:04,800 --> 00:38:08,250
where is the place that
starts filling in the holes

886
00:38:08,250 --> 00:38:10,830
that I currently have in the
Earth-sized virtual lens?

887
00:38:10,830 --> 00:38:12,420

And you can think that there's
some places where you don't

888
00:38:12,420 --> 00:38:14,400
have a telescope now,
and if you put one there,

889
00:38:14,400 --> 00:38:16,950
you would immediately get sharper images.

890
00:38:16,950 --> 00:38:19,830
So, we go through many
simulations and we've identified

891
00:38:19,830 --> 00:38:21,750
some key sites around the globe

892
00:38:21,750 --> 00:38:26,100
that will be very important
to populate with telescopes.

893
00:38:26,100 --> 00:38:27,180
But then you have to ask yourself,

894
00:38:27,180 --> 00:38:29,700
well, I don't wanna put it
in the middle of nowhere

895
00:38:29,700 --> 00:38:32,940
because there's no power,
there's no communication,

896
00:38:32,940 --> 00:38:35,400
there are land rights
issues, et cetera, et cetera.

897
00:38:35,400 --> 00:38:38,850
So, there's a balance to
be struck between where you

898
00:38:38,850 --> 00:38:40,020
might be able to put a telescope,

899
00:38:40,020 --> 00:38:41,850
where there's already some infrastructure,

900
00:38:41,850 --> 00:38:45,570
and where the ideal place
for this new telescope is.

901
00:38:45,570 --> 00:38:47,430
So, we're playing that game now.

902
00:38:47,430 --> 00:38:50,730
We're going to sites in Mexico,
going to sites in Chile,

903
00:38:50,730 --> 00:38:52,980
going to sites in the
western United States.

904
00:38:52,980 --> 00:38:55,800
I just came back from
Tanzania where we're thinking

905
00:38:55,800 --> 00:38:58,440
about putting telescopes in that country

906
00:38:58,440 --> 00:39:00,420
because it fills in very nicely

907
00:39:00,420 --> 00:39:02,190
this Earth-sized virtual lens.

908
00:39:02,190 --> 00:39:06,480
And we're looking at local
universities that can help us.

909

00:39:06,480 --> 00:39:09,810
We're looking at local
infrastructure where we can use

910
00:39:09,810 --> 00:39:11,940
some of that for power and communications

911
00:39:11,940 --> 00:39:13,020
for these telescopes.

912
00:39:13,020 --> 00:39:15,720
And we've come with a two-phased approach.

913
00:39:15,720 --> 00:39:19,200
The first phase will be to
add about five new telescopes

914
00:39:19,200 --> 00:39:21,960
and that will allow us
to make movies of M87

915
00:39:21,960 --> 00:39:25,260
and then we'll add another
five or eight telescopes

916
00:39:25,260 --> 00:39:27,450
in phase two which will allow us

917
00:39:27,450 --> 00:39:29,940
to make movies of Sagittarius A star.

918
00:39:29,940 --> 00:39:32,700
And it's been a blast
going to different places

919
00:39:32,700 --> 00:39:35,850
around the globe and
surveying these new sites.

920

00:39:35,850 --> 00:39:39,150
You feel a little bit like an
explorer with your pith helmet

921
00:39:39,150 --> 00:39:41,880
and you know your
adventure pants, you know,

922
00:39:41,880 --> 00:39:44,580
going to these these far flung places.

923
00:39:44,580 --> 00:39:47,280
And it's a new dimension for us

924
00:39:47,280 --> 00:39:48,900
because with the Event Horizon Telescope,

925
00:39:48,900 --> 00:39:52,320
we used telescopes that
were already in place.

926
00:39:52,320 --> 00:39:57,090
We brought bespoke specialized
electronics to these sites

927
00:39:57,090 --> 00:39:58,500
so that together they could do something

928
00:39:58,500 --> 00:40:00,690
that no one telescope could do alone,

929
00:40:00,690 --> 00:40:02,640
but we used existing telescopes.

930
00:40:02,640 --> 00:40:05,160
Now we're thinking expansively,

931
00:40:05,160 --> 00:40:07,860
where do we put new

telescopes around the globe

932
00:40:07,860 --> 00:40:10,110
that don't have telescopes right now?

933
00:40:10,110 --> 00:40:12,720
And that is very interesting and exciting.

934
00:40:12,720 --> 00:40:13,800
- We've received some questions

935
00:40:13,800 --> 00:40:15,600
from elementary school students for you

936
00:40:15,600 --> 00:40:19,560
and Ria has a question about Sag A star.

937
00:40:19,560 --> 00:40:22,920
- Hi, my name is Ria and
I'm from grade seven.

938
00:40:22,920 --> 00:40:25,920
And will Sagittarius A
get bigger or smaller

939
00:40:25,920 --> 00:40:27,600
over the coming years

940
00:40:27,600 --> 00:40:30,783
and what would be the
consequences if it gets bigger?

941
00:40:31,680 --> 00:40:33,810
- Wow, Ria, that's a great question

942
00:40:33,810 --> 00:40:35,940
and it's a very intuitive question too

943

00:40:35,940 --> 00:40:39,720
because black holes digest
all the gas around them

944
00:40:39,720 --> 00:40:42,240
and they do grow because
nothing can ever escape

945
00:40:42,240 --> 00:40:43,073
from a black hole.

946
00:40:43,073 --> 00:40:45,750
It's always gaining weight,
it's never on a diet, right?

947
00:40:45,750 --> 00:40:46,620
When you think about that.

948
00:40:46,620 --> 00:40:49,410
But it turns out that
Sagittarius A star is in a phase

949
00:40:49,410 --> 00:40:52,770
right now where it's
eating very, very slowly.

950
00:40:52,770 --> 00:40:55,950
I think the way to say it is
that if Sagittarius A star

951
00:40:55,950 --> 00:40:57,060
was a person,

952
00:40:57,060 --> 00:40:59,970
the way it's eating is
equivalent to that person eating

953
00:40:59,970 --> 00:41:03,416
a grain of rice in a million years.

954
00:41:03,416 --> 00:41:04,249
- Oh my God.

955
00:41:04,249 --> 00:41:06,210
- That is the level of starvation.

956
00:41:06,210 --> 00:41:07,323
I may have that wrong.

957
00:41:08,190 --> 00:41:09,930
I know it's a grain of rice in a human

958
00:41:09,930 --> 00:41:12,210
for a very long amount of time.

959
00:41:12,210 --> 00:41:14,280
I think it's about a million years.

960
00:41:14,280 --> 00:41:18,000
It's not gaining weight
at an appreciable level.

961
00:41:18,000 --> 00:41:21,240
So, over the course of
like a human time scale,

962
00:41:21,240 --> 00:41:24,360
we won't see Sagittarius
A star grow at all.

963
00:41:24,360 --> 00:41:26,280
But if it were to grow,

964
00:41:26,280 --> 00:41:28,440
we would see the ring
of light surrounding it

965
00:41:28,440 --> 00:41:33,440

increase in size, we would
see the time it takes matter

966
00:41:33,570 --> 00:41:36,240
to orbit the black hole increase.

967
00:41:36,240 --> 00:41:38,250
So it would wouldn't take half an hour,

968
00:41:38,250 --> 00:41:40,590
it may take 40 minutes or an hour

969
00:41:40,590 --> 00:41:42,090
to orbit the black hole.

970
00:41:42,090 --> 00:41:43,380
If we're growing appreciably,

971
00:41:43,380 --> 00:41:46,410
we would see it with the
Event Horizon Telescope.

972
00:41:46,410 --> 00:41:50,040
Unfortunately, neither Sag A star nor M87

973
00:41:50,040 --> 00:41:53,130
really is growing fast
enough for humans to see it.

974
00:41:53,130 --> 00:41:55,500
Maybe a million years from now,

975
00:41:55,500 --> 00:41:58,830
our ancestors will say, "Hey,
Sagittarius A star has grown,"

976
00:41:58,830 --> 00:42:00,270
but we won't.

977
00:42:00,270 --> 00:42:04,800
- And talking about the NGEHT
and what may come after it,

978
00:42:04,800 --> 00:42:08,070
there's another question
from a student named Jackson.

979
00:42:08,070 --> 00:42:10,170
- Hi, my name is Jackson
and I'm in grade eight,

980
00:42:10,170 --> 00:42:11,160
and my question is,

981
00:42:11,160 --> 00:42:13,350
how detailed do you think
the images of black holes

982
00:42:13,350 --> 00:42:14,970
will be able to get?

983
00:42:14,970 --> 00:42:17,043
- Oh, what a great question, Jackson.

984
00:42:18,781 --> 00:42:20,820
And that's what consumes
us all the time, right?

985
00:42:20,820 --> 00:42:21,653
- Thought you'd like that one.

986
00:42:21,653 --> 00:42:24,000
- The only thing we
think about is how sharp

987
00:42:24,000 --> 00:42:25,230
can we make these images?

988
00:42:25,230 --> 00:42:27,180
So, lemme put it to you this way.

989
00:42:27,180 --> 00:42:30,030
We've seen this ring of light
and it's a little fuzzy,

990
00:42:30,030 --> 00:42:31,590
I'll be the first to admit that.

991
00:42:31,590 --> 00:42:32,820
But the reason it's fuzzy

992
00:42:32,820 --> 00:42:34,500
is not that we made a fuzzy picture,

993
00:42:34,500 --> 00:42:37,740
it's that we are at the absolute limit

994
00:42:37,740 --> 00:42:39,600
of what astronomers can do.

995
00:42:39,600 --> 00:42:41,670
We've seen this ring, it's a clear ring,

996
00:42:41,670 --> 00:42:42,900
but we're at the limit,

997
00:42:42,900 --> 00:42:45,600
but we're motivated to take
an even sharper picture

998
00:42:45,600 --> 00:42:48,450
because we think that that ring

999
00:42:48,450 --> 00:42:53,280
is actually a compilation of
an infinite number of rings.

1000
00:42:53,280 --> 00:42:58,170
We see some of the light gently
bent around the black hole,

1001
00:42:58,170 --> 00:43:00,360
that's what we call
the n equals zero ring.

1002
00:43:00,360 --> 00:43:03,030
But there's some light that does a U-turn

1003
00:43:03,030 --> 00:43:05,430
around the black hole and that creates

1004
00:43:05,430 --> 00:43:09,510
an even thinner sub-ring closer
to the actual photon orbit

1005
00:43:09,510 --> 00:43:11,490
and within that larger ring.

1006
00:43:11,490 --> 00:43:15,930
And then, there's some light
that does a full loop to loop

1007
00:43:15,930 --> 00:43:19,470
around the black hole, that
creates an even thinner ring.

1008
00:43:19,470 --> 00:43:20,310
And when you think about it,

1009
00:43:20,310 --> 00:43:24,120
there's an infinite nested
number of rings that go closer

1010
00:43:24,120 --> 00:43:26,220
and closer to the true photon orbit.

1011
00:43:26,220 --> 00:43:29,370
And if we could see past
the n equals zero ring.

1012
00:43:29,370 --> 00:43:30,900
This ring that we've already seen,

1013
00:43:30,900 --> 00:43:32,910
and we could resolve the very,

1014
00:43:32,910 --> 00:43:36,420
very thin ring just interior to that.

1015
00:43:36,420 --> 00:43:41,420
That ring so closely holds
to Einstein's equations

1016
00:43:41,550 --> 00:43:43,530
that we'll be able to, in a single stroke,

1017
00:43:43,530 --> 00:43:45,840
read off the spin of the black hole,

1018
00:43:45,840 --> 00:43:48,870
look for deviations from Einstein's theory

1019
00:43:48,870 --> 00:43:51,480
at a much deeper level than we can now.

1020
00:43:51,480 --> 00:43:54,330
So, we're actively focused
now on being able to see that

1021
00:43:54,330 --> 00:43:55,163
and we think that with

1022
00:43:55,163 --> 00:43:57,960

the Next Generation
Event Horizon Telescope,

1023
00:43:57,960 --> 00:44:01,440
we'll be able to see that first inner ring

1024
00:44:01,440 --> 00:44:06,420
and make our image of Sag
A star and M87 sharper

1025
00:44:06,420 --> 00:44:08,100
by many factors, right?

1026
00:44:08,100 --> 00:44:11,040
So, we're aiming at exactly
what Jackson is thinking about

1027
00:44:11,040 --> 00:44:15,210
and then we can think even
more expansively and ask,

1028
00:44:15,210 --> 00:44:18,000
can we make a telescope
larger than our planet?

1029
00:44:18,000 --> 00:44:21,000
And there we're thinking
about launching a satellite

1030
00:44:21,000 --> 00:44:22,500
so that the size of the telescope

1031
00:44:22,500 --> 00:44:25,860
would be about the distance
between telescopes on the Earth,

1032
00:44:25,860 --> 00:44:27,780
but the distance between
telescopes on the Earth

1033
00:44:27,780 --> 00:44:29,790
and a distant satellite.

1034
00:44:29,790 --> 00:44:33,870
And that will allow us to see
these infinite nested rings

1035
00:44:33,870 --> 00:44:37,770
using a different technique,
using space interferometry.

1036
00:44:37,770 --> 00:44:38,940
So, it's all very exciting.

1037
00:44:38,940 --> 00:44:41,528
- Is that the next, next generation EHT?

1038
00:44:41,528 --> 00:44:42,361
- Yeah, yeah.

1039
00:44:42,361 --> 00:44:44,160
Well, so we have different
names for these things.

1040
00:44:44,160 --> 00:44:46,830
The Next Generation EHT is on the Earth.

1041
00:44:46,830 --> 00:44:51,240
And then we have this event
horizon explorer concept,

1042
00:44:51,240 --> 00:44:52,680
which takes a satellite,

1043
00:44:52,680 --> 00:44:56,400
launches it into like a mid-Earth orbit

1044
00:44:56,400 --> 00:44:58,260

or a high-Earth orbit.

1045
00:44:58,260 --> 00:45:00,480
And that will give us the
anger resolution necessary

1046
00:45:00,480 --> 00:45:03,330
to begin to see these inner rings

1047
00:45:03,330 --> 00:45:05,640
with high degrees of clarity.

1048
00:45:05,640 --> 00:45:09,480
So, that's where we're going
probably after the next decade.

1049
00:45:09,480 --> 00:45:11,670
So, first will be the NGHT on the Earth,

1050
00:45:11,670 --> 00:45:13,830
then we'll be expanding into space.

1051
00:45:13,830 --> 00:45:16,380
So, if you thought that building
an Earth-sized telescope

1052
00:45:16,380 --> 00:45:19,290
was hard, just try launching
something into space

1053
00:45:19,290 --> 00:45:20,160
to do the same thing.

1054
00:45:20,160 --> 00:45:22,680
I mean everything is harder in space.

1055
00:45:22,680 --> 00:45:25,950
Launching the atomic
clocks that are necessary

1056
00:45:25,950 --> 00:45:27,420
is very, very difficult.

1057
00:45:27,420 --> 00:45:32,420
Getting the data back from
space is very, very difficult.

1058
00:45:32,610 --> 00:45:35,580
Knowing the precise orbit
is very, very difficult.

1059
00:45:35,580 --> 00:45:37,590
So, everything gets harder when you launch

1060
00:45:37,590 --> 00:45:39,030
a telescope into space.

1061
00:45:39,030 --> 00:45:41,820
But, we think we have a handle on a lot

1062
00:45:41,820 --> 00:45:43,380
of the fundamental concepts.

1063
00:45:43,380 --> 00:45:45,903
So, we think this really
is possible in the same way

1064
00:45:45,903 --> 00:45:48,000
that we thought the Event
Horizon Telescope was possible.

1065
00:45:48,000 --> 00:45:49,410
I wanna add one thing.

1066
00:45:49,410 --> 00:45:50,490
So, you asked before about

1067

00:45:50,490 --> 00:45:53,100
how the Event Horizon Telescope works,

1068
00:45:53,100 --> 00:45:56,880
and we do use telescopes at
different parts of the globe.

1069
00:45:56,880 --> 00:46:00,000
We record the light and
we combine that light

1070
00:46:00,000 --> 00:46:02,280
to create a telescope as
big as the Earth itself.

1071
00:46:02,280 --> 00:46:06,660
But, a key part of it is that
we have atomic clocks at each

1072
00:46:06,660 --> 00:46:09,720
of these locations because
when the radio waves come in

1073
00:46:09,720 --> 00:46:10,800
from the black hole,

1074
00:46:10,800 --> 00:46:13,710
you can think of them
as crests and troughs.

1075
00:46:13,710 --> 00:46:16,980
Troughs coming in from the
black hole, these radio waves.

1076
00:46:16,980 --> 00:46:20,160
We need to be able to
align the radio waves

1077
00:46:20,160 --> 00:46:22,410
that we record at one part of the earth,

1078
00:46:22,410 --> 00:46:24,870
exactly with the radio waves we record

1079
00:46:24,870 --> 00:46:26,250
at another part of the earth.

1080
00:46:26,250 --> 00:46:30,030
So, we need an atomic clock
so we can time tag all

1081
00:46:30,030 --> 00:46:32,880
the radio waves that we
get at both these locations

1082
00:46:32,880 --> 00:46:34,350
so we can line them up perfectly.

1083
00:46:34,350 --> 00:46:37,110
If we don't have a really
stable atomic clock

1084
00:46:37,110 --> 00:46:38,760
at both these locations,

1085
00:46:38,760 --> 00:46:41,070
then you can think of
it as like the waveforms

1086
00:46:41,070 --> 00:46:43,320
would be jittering back and forth.

1087
00:46:43,320 --> 00:46:44,153
If they're stable,

1088
00:46:44,153 --> 00:46:45,900
then we can line them up perfectly

1089

00:46:45,900 --> 00:46:49,500
and that's how you make this
Event Horizon Telescope work.

1090
00:46:49,500 --> 00:46:52,590
So, getting one of these
atomic clocks into space

1091
00:46:52,590 --> 00:46:55,080
and not disrupting it or not breaking it

1092
00:46:55,080 --> 00:46:56,703
during launch or something like that,

1093
00:46:56,703 --> 00:46:58,650
that is quite a challenge.

1094
00:46:58,650 --> 00:47:01,170
- There's just so many pieces
that clearly have to fall

1095
00:47:01,170 --> 00:47:03,900
into place to give us that
one image of a black hole.

1096
00:47:03,900 --> 00:47:04,733
And I'm just curious,

1097
00:47:04,733 --> 00:47:06,930
how many failed images did you see

1098
00:47:06,930 --> 00:47:08,700
that you might have expected?

1099
00:47:08,700 --> 00:47:10,800
I might see it today and
then it just didn't look

1100
00:47:10,800 --> 00:47:11,800

like what you expected?

1101
00:47:11,800 --> 00:47:15,450
- Well, I love that question
because in this business

1102
00:47:15,450 --> 00:47:17,130
you have to embrace failure.

1103
00:47:17,130 --> 00:47:19,020
Failure is your companion.

1104
00:47:19,020 --> 00:47:21,480
Failure is not a problem.

1105
00:47:21,480 --> 00:47:23,310
If you're not failing early on,

1106
00:47:23,310 --> 00:47:25,830
you're not really doing your job.

1107
00:47:25,830 --> 00:47:29,130
So first, I'll address your
question about the images,

1108
00:47:29,130 --> 00:47:32,040
but first I want to go back to 2006.

1109
00:47:32,040 --> 00:47:35,610
In 2006 we tried to
make our first detection

1110
00:47:35,610 --> 00:47:39,270
of event horizon scale structure
for Sagittarius A star.

1111
00:47:39,270 --> 00:47:43,380
And we went to Hawaii and we
put specialized instrumentation

1112
00:47:43,380 --> 00:47:45,240
on the Caltech Submillimeter Observatory,

1113
00:47:45,240 --> 00:47:48,421
which is a telescope on
the summit of Mauna Kea

1114
00:47:48,421 --> 00:47:49,410
on the big island of Hawaii.

1115
00:47:49,410 --> 00:47:52,600
And we also put this same
kind of instrumentation

1116
00:47:54,612 --> 00:47:56,670
on a telescope in Arizona, the SMT,

1117
00:47:56,670 --> 00:47:58,080
the Submillimeter Telescope.

1118
00:47:58,080 --> 00:47:59,370
And we failed.

1119
00:47:59,370 --> 00:48:01,680
Everything seemed like
it was working correctly.

1120
00:48:01,680 --> 00:48:05,070
All the instrumentation
seemed like it was going well,

1121
00:48:05,070 --> 00:48:08,070
but we didn't get any
detections, nothing worked.

1122
00:48:08,070 --> 00:48:10,800
Even when we steered the
telescope towards very,

1123
00:48:10,800 --> 00:48:14,220
very bright objects, we thought
for sure we would see it.

1124
00:48:14,220 --> 00:48:15,370
We didn't see anything.

1125
00:48:16,235 --> 00:48:18,600
And we spent months pouring over the data.

1126
00:48:18,600 --> 00:48:23,070
It turned out that a little
piece of metal had fallen into

1127
00:48:23,070 --> 00:48:28,070
the superconducting junction
of the telescope in Hawaii.

1128
00:48:28,440 --> 00:48:32,040
So, we were receiving the
radiation from the black hole,

1129
00:48:32,040 --> 00:48:35,040
but the wave form was
jittering back and forth

1130
00:48:35,040 --> 00:48:36,870
because that little piece of metal

1131
00:48:36,870 --> 00:48:40,410
was ruining all the phase of our waveform.

1132
00:48:40,410 --> 00:48:43,200
So, it was vibrating in there
and causing the whole waveform

1133
00:48:43,200 --> 00:48:44,640
to move back and forth.

1134
00:48:44,640 --> 00:48:45,990
We were doomed from the start.

1135
00:48:45,990 --> 00:48:47,730
And it was only afterwards,

1136
00:48:47,730 --> 00:48:50,460
like months later, that
we realized the problem.

1137
00:48:50,460 --> 00:48:54,240
And then we had to dust
ourselves off, pick ourselves up,

1138
00:48:54,240 --> 00:48:58,620
get our heads in the game again,
we were horribly, you know,

1139
00:48:58,620 --> 00:49:00,120
saddened by this.

1140
00:49:00,120 --> 00:49:02,970
And the next time we went
out, which was in 2007,

1141
00:49:02,970 --> 00:49:05,160
we added another dish in California

1142
00:49:05,160 --> 00:49:07,200
to make the whole array more robust.

1143
00:49:07,200 --> 00:49:09,870
We triple checked
everything 'cause we learned

1144
00:49:09,870 --> 00:49:13,620
from what had happened and
then we succeeded that year

1145
00:49:13,620 --> 00:49:16,170
in discovering horizon scale structure

1146
00:49:16,170 --> 00:49:17,730
around Sagittarius A star.

1147
00:49:17,730 --> 00:49:20,400
So, failure is important and
you have to be resilient,

1148
00:49:20,400 --> 00:49:21,660
but also learn from it.

1149
00:49:21,660 --> 00:49:25,980
On the images, for M87 in 2019,

1150
00:49:25,980 --> 00:49:29,460
we were very fortunate because
the signal was so strong

1151
00:49:29,460 --> 00:49:31,620
that you could even look at the raw data

1152
00:49:31,620 --> 00:49:35,670
and you could see there was
something that was ring-like.

1153
00:49:35,670 --> 00:49:39,540
I'll never forget, I was
at a dinner at a conference

1154
00:49:39,540 --> 00:49:42,450
and one of the postdocs
who was deeply involved

1155
00:49:42,450 --> 00:49:46,080
in the analysis of the data,
his name is Amachek Vilgas,

1156
00:49:46,080 --> 00:49:49,980
he came and he showed me
the freshly calibrated data

1157
00:49:49,980 --> 00:49:51,870
and I think there's
somewhere in the internet,

1158
00:49:51,870 --> 00:49:54,990
there's a picture of the
two of us just like looking

1159
00:49:54,990 --> 00:49:56,400
at this computer screen.

1160
00:49:56,400 --> 00:49:58,200
Like, oh my god, I
think I'm like pointing.

1161
00:49:58,200 --> 00:50:02,280
Like that's it, and
Amachek is beaming, right?

1162
00:50:02,280 --> 00:50:04,230
And that was the moment where we realized,

1163
00:50:04,230 --> 00:50:05,820
even though we didn't have an image,

1164
00:50:05,820 --> 00:50:08,640
that there was something so crystal clear

1165
00:50:08,640 --> 00:50:10,930
that we were seeing this ring of light

1166
00:50:11,846 --> 00:50:12,780
around the black hole.

1167
00:50:12,780 --> 00:50:15,570
So, for M87 we were lucky and fortunate.

1168
00:50:15,570 --> 00:50:18,120
Fortunate, not lucky,
that nature provided us

1169
00:50:18,120 --> 00:50:20,280
with this very, very clear signal

1170
00:50:20,280 --> 00:50:21,870
that we could see with the instrument.

1171
00:50:21,870 --> 00:50:24,300
So, there weren't too many false starts.

1172
00:50:24,300 --> 00:50:28,890
We did separate the team into
four separate imaging groups

1173
00:50:28,890 --> 00:50:32,250
because we wanted to make sure
that if we did see a ring,

1174
00:50:32,250 --> 00:50:34,170
there wasn't cross contamination.

1175
00:50:34,170 --> 00:50:36,007
So, we didn't want everyone
in one room and someone says,

1176
00:50:36,007 --> 00:50:37,507
"I think I see a ring" and
then someone else says,

1177
00:50:37,507 --> 00:50:39,450
"Oh, me too, I also see a ring."

1178

00:50:39,450 --> 00:50:42,030
And pretty soon everyone
says they're seeing a ring.

1179
00:50:42,030 --> 00:50:44,610
So, we kept four groups totally separate.

1180
00:50:44,610 --> 00:50:46,020
We gave them all the data,

1181
00:50:46,020 --> 00:50:47,760
but we didn't let them talk to each other.

1182
00:50:47,760 --> 00:50:50,580
And then in July of 2018,

1183
00:50:50,580 --> 00:50:51,910
we all came together

1184
00:50:52,978 --> 00:50:55,080
at the Smithsonian Astrophysical
Observatory in Cambridge

1185
00:50:55,080 --> 00:50:57,480
and each group showed their image

1186
00:50:57,480 --> 00:51:02,070
and you could see immediately
that we had four rings.

1187
00:51:02,070 --> 00:51:05,580
And that was the moment when
we all realized this signal

1188
00:51:05,580 --> 00:51:08,640
is so clear that even four
different teams that are working

1189
00:51:08,640 --> 00:51:11,430

with different algorithms,
different approaches,

1190
00:51:11,430 --> 00:51:13,440
all found the same structure.

1191
00:51:13,440 --> 00:51:15,660
That was when we realized
that we had a discovery

1192
00:51:15,660 --> 00:51:17,430
of great magnitude on our hands.

1193
00:51:17,430 --> 00:51:20,040
- What was the mood in
the room at that point?

1194
00:51:20,040 --> 00:51:20,890
- Pretty subdued.

1195
00:51:22,064 --> 00:51:24,423
No, no, it was like, we
were like going crazy.

1196
00:51:25,830 --> 00:51:30,830
It was absolutely a joyful celebration

1197
00:51:30,840 --> 00:51:32,808
and the fact that we had all done it

1198
00:51:32,808 --> 00:51:34,230
with different methods, right?

1199
00:51:34,230 --> 00:51:36,480
And we all got to the same point.

1200
00:51:36,480 --> 00:51:38,700
That was really something.

1201
00:51:38,700 --> 00:51:41,600
I like to think of that as
being like a beer stein moment.

1202
00:51:42,489 --> 00:51:44,910
Like, we were clinking our
beers, we were like drinking.

1203
00:51:44,910 --> 00:51:47,460
It was a moment of real comradery.

1204
00:51:47,460 --> 00:51:51,750
The champagne moment was
really unveiling the image

1205
00:51:51,750 --> 00:51:53,580
and it's a very important distinction

1206
00:51:53,580 --> 00:51:56,640
because even though we
had this great result

1207
00:51:56,640 --> 00:51:58,470
and we were convinced it was right,

1208
00:51:58,470 --> 00:52:02,400
we spent another six months
doing everything we could

1209
00:52:02,400 --> 00:52:04,170
to make that ring go away.

1210
00:52:04,170 --> 00:52:05,610
Because if you're going to come

1211
00:52:05,610 --> 00:52:07,470
with a great result like that,

1212

00:52:07,470 --> 00:52:09,360
you have to be your own worst critic.

1213
00:52:09,360 --> 00:52:13,200
So, we tried to model it with
two bright sources on the sky.

1214
00:52:13,200 --> 00:52:16,800
We tried to model it with a
filled disc with no shadow.

1215
00:52:16,800 --> 00:52:20,070
We tried to model it
with elliptical rings,

1216
00:52:20,070 --> 00:52:21,180
not circular rings.

1217
00:52:21,180 --> 00:52:25,020
We did everything we could
to fit the data in a way

1218
00:52:25,020 --> 00:52:28,980
that would not have
corroborated Einstein's theory.

1219
00:52:28,980 --> 00:52:31,320
And it was only after we
had ruled everything out

1220
00:52:31,320 --> 00:52:34,230
with high statistical significance,

1221
00:52:34,230 --> 00:52:37,890
then we realized that we had something

1222
00:52:37,890 --> 00:52:41,670
that all astronomers, all physicists,

1223

00:52:41,670 --> 00:52:43,800
everybody would look at and agree,

1224
00:52:43,800 --> 00:52:46,050
this is a very robust result.

1225
00:52:46,050 --> 00:52:49,620
It's an amazingly important
and indispensable part

1226
00:52:49,620 --> 00:52:51,420
of the scientific process,

1227
00:52:51,420 --> 00:52:52,770
being your own worst critic,

1228
00:52:52,770 --> 00:52:54,453
because you will fool yourself.

1229
00:52:55,519 --> 00:52:57,390
You are the easiest person to fool.

1230
00:52:57,390 --> 00:53:00,540
So, splitting us up into
teams, red teaming this

1231
00:53:00,540 --> 00:53:02,190
over the course of six months,

1232
00:53:02,190 --> 00:53:03,960
that's what gave us confidence.

1233
00:53:03,960 --> 00:53:07,020
And then I would say even then waiting

1234
00:53:07,020 --> 00:53:08,490
until we had Sag A star,

1235

00:53:08,490 --> 00:53:11,250
waiting until a completely
different object

1236
00:53:11,250 --> 00:53:13,440
in a different part of the sky,

1237
00:53:13,440 --> 00:53:17,310
different mass, also
showed this ring structure,

1238
00:53:17,310 --> 00:53:21,480
that now has beyond any doubt showed us

1239
00:53:21,480 --> 00:53:22,890
that the Event Horizon Telescope

1240
00:53:22,890 --> 00:53:26,790
has seen what Einstein
predicted 100 years ago.

1241
00:53:26,790 --> 00:53:29,880
- Is there any limit in
the Next Generation EHT,

1242
00:53:29,880 --> 00:53:32,250
or the Event Horizon Explorer?

1243
00:53:32,250 --> 00:53:35,790
Could you see other black
holes beside Sag A star and M87

1244
00:53:35,790 --> 00:53:39,630
or is there a limit to the
resolution that you can get?

1245
00:53:39,630 --> 00:53:42,540
- So, there are two ways we might increase

1246

00:53:42,540 --> 00:53:44,310
the number of sources

1247
00:53:44,310 --> 00:53:47,190
for which we can image the event horizon.

1248
00:53:47,190 --> 00:53:52,050
So, one is that we'll be able
to go deeper in sensitivity.

1249
00:53:52,050 --> 00:53:53,910
So, there are some sources out there,

1250
00:53:53,910 --> 00:53:56,640
we just need to find them
and they might even be as big

1251
00:53:56,640 --> 00:53:59,610
as Sagittarius A star, as big as M87,

1252
00:53:59,610 --> 00:54:01,710
but they're too faint
right now for us to see.

1253
00:54:01,710 --> 00:54:03,390
So, by increasing the bandwidth,

1254
00:54:03,390 --> 00:54:05,580
increasing the size of our telescopes,

1255
00:54:05,580 --> 00:54:07,410
we may be able to see those.

1256
00:54:07,410 --> 00:54:09,990
Okay, that's one area
that we're examining.

1257
00:54:09,990 --> 00:54:12,990
And with the Next Generation

Event Horizon telescope,

1258
00:54:12,990 --> 00:54:16,800
we are predicting that we
would see at least a few more

1259
00:54:16,800 --> 00:54:18,900
of these super massive black holes.

1260
00:54:18,900 --> 00:54:21,210
One of the postdocs working in our group,

1261
00:54:21,210 --> 00:54:22,890
or he was a postdoc,
now he's a staff member,

1262
00:54:22,890 --> 00:54:25,050
Dom Peche, has gone through

1263
00:54:25,050 --> 00:54:27,660
very detailed calculations showing

1264
00:54:27,660 --> 00:54:30,570
that we are likely to see
at least a few more with

1265
00:54:30,570 --> 00:54:32,820
the Next Generation
Event Horizon telescope.

1266
00:54:32,820 --> 00:54:36,840
The other possibility is
that we could increase

1267
00:54:36,840 --> 00:54:38,730
the angular resolution.

1268
00:54:38,730 --> 00:54:41,250
And we know there are

some sources right now

1269
00:54:41,250 --> 00:54:43,830
that we can see with the
EHT that are very bright,

1270
00:54:43,830 --> 00:54:45,390
that were sensitive enough to see already,

1271
00:54:45,390 --> 00:54:46,860
but we don't have the angular resolution

1272
00:54:46,860 --> 00:54:49,140
to see all the way to the event horizon.

1273
00:54:49,140 --> 00:54:51,330
And by going to higher frequencies,

1274
00:54:51,330 --> 00:54:56,330
let's say to 345 gigahertz,
maybe even 450, dare I say it,

1275
00:54:57,870 --> 00:55:00,660
690, we're dreaming, right?

1276
00:55:00,660 --> 00:55:02,820
If you did that, then even
from the surface of the planet,

1277
00:55:02,820 --> 00:55:04,980
you'd have enough angular resolution

1278
00:55:04,980 --> 00:55:07,890
to zoom in on some of the
sources we are already looking at

1279
00:55:07,890 --> 00:55:11,610
to potentially see these event
horizon scale structures.

1280
00:55:11,610 --> 00:55:14,790
So, we're coming at this from
a number of different angles,

1281
00:55:14,790 --> 00:55:17,643
from sensitivity, angular resolution,

1282
00:55:18,598 --> 00:55:19,710
on the planet, in space.

1283
00:55:19,710 --> 00:55:23,430
Everything is geared towards
giving us better images

1284
00:55:23,430 --> 00:55:25,950
of the sources we currently have

1285
00:55:25,950 --> 00:55:27,840
and increasing the number of sources

1286
00:55:27,840 --> 00:55:29,070
for which we can do this.

1287
00:55:29,070 --> 00:55:30,750
- You have mentioned that these projects

1288
00:55:30,750 --> 00:55:32,340
are huge team efforts,

1289
00:55:32,340 --> 00:55:34,140
and I know we have a lot of students

1290
00:55:34,140 --> 00:55:35,580
that listen to this podcast.

1291
00:55:35,580 --> 00:55:38,100
So, can you speak to

the role that students

1292
00:55:38,100 --> 00:55:40,230
and early career scientists play

1293
00:55:40,230 --> 00:55:43,050
in these big team collaborations?

1294
00:55:43,050 --> 00:55:47,013
- It is so important to talk about this.

1295
00:55:47,013 --> 00:55:50,520
This is not a bunch of experts
who have long been working

1296
00:55:50,520 --> 00:55:52,680
on this for their entire careers,

1297
00:55:52,680 --> 00:55:55,440
alone, bringing this result.

1298
00:55:55,440 --> 00:55:58,710
In fact, it's the early career people.

1299
00:55:58,710 --> 00:56:02,310
It's the undergraduate
students, the graduate students,

1300
00:56:02,310 --> 00:56:06,060
the postdocs, the early career scientists

1301
00:56:06,060 --> 00:56:07,410
who have put the energy

1302
00:56:07,410 --> 00:56:10,290
that's required into this
project to make it succeed.

1303

00:56:10,290 --> 00:56:11,580
And I would go so far as to say

1304
00:56:11,580 --> 00:56:13,740
that we would not have succeeded

1305
00:56:13,740 --> 00:56:16,110
if we had not created an environment

1306
00:56:16,110 --> 00:56:18,870
that made it comfortable for all

1307
00:56:18,870 --> 00:56:20,340
of these early career students

1308
00:56:20,340 --> 00:56:23,370
to dedicate a big portion
of their lives to this.

1309
00:56:23,370 --> 00:56:25,260
It's one thing to have this idea early on,

1310
00:56:25,260 --> 00:56:29,550
it's a completely different
notion to work 24/7

1311
00:56:29,550 --> 00:56:33,300
and to dedicate yourselves
as a young person to this.

1312
00:56:33,300 --> 00:56:35,850
It was the early career
astronomers that allowed us

1313
00:56:35,850 --> 00:56:37,320
to succeed in this.

1314
00:56:37,320 --> 00:56:40,500
So, to all the students out there,

1315
00:56:40,500 --> 00:56:42,510
to the early career people,

1316
00:56:42,510 --> 00:56:47,070
there is absolutely a place
for you to make substantial,

1317
00:56:47,070 --> 00:56:50,210
even formative contributions
to these kinds of projects.

1318
00:56:50,210 --> 00:56:51,810
So get involved,

1319
00:56:51,810 --> 00:56:54,630
find something that other
people aren't working on,

1320
00:56:54,630 --> 00:56:56,340
throw yourself into it.

1321
00:56:56,340 --> 00:56:58,800
It will always be of great value.

1322
00:56:58,800 --> 00:57:00,600
I can't stress that enough.

1323
00:57:00,600 --> 00:57:01,890
- Well, on the topic of students,

1324
00:57:01,890 --> 00:57:03,780
there's another question here.

1325
00:57:03,780 --> 00:57:08,550
This one's from Reba and it's
about general relativity,

1326

00:57:08,550 --> 00:57:11,820
which has come up earlier
and hoping we can talk

1327
00:57:11,820 --> 00:57:12,653
a bit more about it.

1328
00:57:12,653 --> 00:57:14,460
But Reba, take it away.

1329
00:57:14,460 --> 00:57:16,470
- Hi, my name is Reba from grade eight,

1330
00:57:16,470 --> 00:57:18,840
and does Einstein's theory of relativity

1331
00:57:18,840 --> 00:57:20,580
work near a black hole?

1332
00:57:20,580 --> 00:57:24,060
- Wow, so Reba, that is
exactly one of the questions

1333
00:57:24,060 --> 00:57:26,820
that we set out to answer with
the Event Horizon Telescope.

1334
00:57:26,820 --> 00:57:29,760
So, the answer is we don't know for sure.

1335
00:57:29,760 --> 00:57:31,380
With theories like this,

1336
00:57:31,380 --> 00:57:34,950
you can only make ever
better measurements.

1337
00:57:34,950 --> 00:57:37,170
And what I would say is that we know

1338
00:57:37,170 --> 00:57:40,230
that Einstein's theory has to break down.

1339
00:57:40,230 --> 00:57:41,340
I said it.

1340
00:57:41,340 --> 00:57:42,540
Okay?

1341
00:57:42,540 --> 00:57:46,620
The reason is that we do not
yet have a way of understanding

1342
00:57:46,620 --> 00:57:50,970
how the quantum world and
general relativity merge.

1343
00:57:50,970 --> 00:57:53,940
And we know that somewhere
inside the black hole,

1344
00:57:53,940 --> 00:57:57,060
this has to happen because
inside the black hole,

1345
00:57:57,060 --> 00:57:59,190
once you go through the event horizon,

1346
00:57:59,190 --> 00:58:02,610
things get so dense and
the gravity is so strong

1347
00:58:02,610 --> 00:58:05,700
that gravity and the quantum world merge.

1348
00:58:05,700 --> 00:58:06,533
Okay?

1349
00:58:06,533 --> 00:58:09,180
So, we know there has to be
a new theory that will emerge

1350
00:58:09,180 --> 00:58:10,710
inside the black hole.

1351
00:58:10,710 --> 00:58:13,770
We are testing for Einstein's theory,

1352
00:58:13,770 --> 00:58:16,050
we are testing the validity
of Einstein's theory

1353
00:58:16,050 --> 00:58:17,160
around the black hole.

1354
00:58:17,160 --> 00:58:19,740
Currently, all the measurements we've made

1355
00:58:19,740 --> 00:58:21,570
with the Event Horizon Telescope

1356
00:58:21,570 --> 00:58:23,400
are consistent with general relativity.

1357
00:58:23,400 --> 00:58:25,680
So, we have made these black holes,

1358
00:58:25,680 --> 00:58:27,360
these super massive black holes,

1359
00:58:27,360 --> 00:58:30,840
the most extreme
laboratories in the universe.

1360
00:58:30,840 --> 00:58:35,430
And we are testing Einstein's

theory in these laboratories.

1361
00:58:35,430 --> 00:58:38,760
So far, those theories are
passing all of our tests,

1362
00:58:38,760 --> 00:58:42,300
but as we get better
and better observations,

1363
00:58:42,300 --> 00:58:44,220
as we get more precision,

1364
00:58:44,220 --> 00:58:46,770
we'll be able to test it even more.

1365
00:58:46,770 --> 00:58:48,810
Now, whether or not we'll find

1366
00:58:48,810 --> 00:58:50,910
that Einstein's theory breaks down outside

1367
00:58:50,910 --> 00:58:53,160
the event horizon, which
is all we have access to,

1368
00:58:53,160 --> 00:58:54,390
that's an open question.

1369
00:58:54,390 --> 00:58:58,530
There are some theories that
modify Einstein's gravity

1370
00:58:58,530 --> 00:59:00,180
and we might be able to see some effects.

1371
00:59:00,180 --> 00:59:02,430
So that's what I impels us,

1372
00:59:02,430 --> 00:59:05,850
that's what motivates us to
make better and better images

1373
00:59:05,850 --> 00:59:07,260
using the Event Horizon Telescope

1374
00:59:07,260 --> 00:59:09,210
or the Event Horizon Explorer.

1375
00:59:09,210 --> 00:59:11,340
Reba, we're on the job.

1376
00:59:11,340 --> 00:59:12,330
That's what I can tell you.

1377
00:59:12,330 --> 00:59:15,090
We're moving in that
direction and we don't know

1378
00:59:15,090 --> 00:59:15,923
where we're going,

1379
00:59:15,923 --> 00:59:17,130
but we know that we're gonna get better

1380
00:59:17,130 --> 00:59:19,230
and better estimates.

1381
00:59:19,230 --> 00:59:22,110
- There's actually one more
student question that I'd love

1382
00:59:22,110 --> 00:59:24,030
to hear your response to.

1383
00:59:24,030 --> 00:59:26,193
This one is from Vera.

1384
00:59:27,240 --> 00:59:29,670
- Hi, my name is Vera from grade eight,

1385
00:59:29,670 --> 00:59:32,850
and I was wondering if we could
live inside of a black hole

1386
00:59:32,850 --> 00:59:34,413
or if it's even possible?

1387
00:59:35,280 --> 00:59:36,510
- Wow.

1388
00:59:36,510 --> 00:59:40,380
Okay, so that is also a
very interesting question.

1389
00:59:40,380 --> 00:59:42,480
Once you fall into the black hole,

1390
00:59:42,480 --> 00:59:44,580
something very interesting happens.

1391
00:59:44,580 --> 00:59:48,690
You know, the time axis
and the spatial axis flip.

1392
00:59:48,690 --> 00:59:52,080
So, there's no way you
can escape the black hole.

1393
00:59:52,080 --> 00:59:53,010
And in fact,

1394
00:59:53,010 --> 00:59:55,830
any path you're on moves you closer

1395

00:59:55,830 --> 00:59:57,450
to the center of the black hole.

1396
00:59:57,450 --> 00:59:58,950
So in a finite amount of time,

1397
00:59:58,950 --> 01:00:03,180
you will reach the center
and you will be ripped apart.

1398
01:00:03,180 --> 01:00:04,200
- Ah, okay.

1399
01:00:04,200 --> 01:00:07,020
- So, you could live inside a black hole

1400
01:00:07,020 --> 01:00:10,410
for a while probably, but
it wouldn't be forever.

1401
01:00:10,410 --> 01:00:11,700
As an example,

1402
01:00:11,700 --> 01:00:15,450
if you pass through the
event horizon of M87,

1403
01:00:15,450 --> 01:00:17,190
you wouldn't be ripped apart

1404
01:00:17,190 --> 01:00:18,840
because the differential gravity

1405
01:00:18,840 --> 01:00:22,140
between your feet and
your head is minuscule.

1406
01:00:22,140 --> 01:00:24,300
So, you would go through the event horizon

1407
01:00:24,300 --> 01:00:26,730
and you would still be, if
your friend went with you,

1408
01:00:26,730 --> 01:00:28,350
you'd be chatting with them,

1409
01:00:28,350 --> 01:00:30,810
you'd be able to have
a cup of tea, you know,

1410
01:00:30,810 --> 01:00:33,780
but you would be inexorably
falling to the center.

1411
01:00:33,780 --> 01:00:37,230
There's no way you could back
out at that point, right?

1412
01:00:37,230 --> 01:00:41,160
So you could have a little vacation maybe,

1413
01:00:41,160 --> 01:00:43,140
but you're not gonna be
spending a lot of time

1414
01:00:43,140 --> 01:00:46,500
before you zoom into the center
and truly are ripped apart.

1415
01:00:46,500 --> 01:00:47,370
- It's a one-way ticket.

1416
01:00:47,370 --> 01:00:48,600
- It's a one-way ticket.

1417
01:00:48,600 --> 01:00:51,720
Now, there are ways of

viewing the universe.

1418
01:00:51,720 --> 01:00:55,470
I mean, there are some
people and some formulations

1419
01:00:55,470 --> 01:00:58,560
that describe the Big Bang as a black hole

1420
01:00:58,560 --> 01:01:02,490
and that we are kind of
inside of a black hole.

1421
01:01:02,490 --> 01:01:05,280
So, there's a way in which we
could potentially be living

1422
01:01:05,280 --> 01:01:08,520
inside a space time that's
equivalent to a black hole,

1423
01:01:08,520 --> 01:01:10,320
that's more theoretical.

1424
01:01:10,320 --> 01:01:12,150
But, if you think about
just about falling into

1425
01:01:12,150 --> 01:01:14,880
a black hole, you'd have
only a finite amount

1426
01:01:14,880 --> 01:01:16,380
of time to enjoy yourself.

1427
01:01:16,380 --> 01:01:18,540
- And you wouldn't be able to
tell anybody what it was like.

1428

01:01:18,540 --> 01:01:21,090
- And you couldn't, yeah, no
postcards from that vacation.

1429
01:01:21,090 --> 01:01:21,930
- Right.

1430
01:01:21,930 --> 01:01:25,740
You spoke about the next
stages of the EHT and the NGEHT

1431
01:01:25,740 --> 01:01:29,160
as making movies of a black
hole instead of still images.

1432
01:01:29,160 --> 01:01:31,620
And I have to ask, when
you mentioned movies,

1433
01:01:31,620 --> 01:01:34,470
has Hollywood ever gotten
a black hole right?

1434
01:01:34,470 --> 01:01:35,303
- So first of all,

1435
01:01:35,303 --> 01:01:38,550
I love a good sci-fi movie
and really astronomers

1436
01:01:38,550 --> 01:01:39,960
and physicists I think love to see

1437
01:01:39,960 --> 01:01:42,000
what Hollywood's gonna come up with next

1438
01:01:42,000 --> 01:01:43,800
when they depict a black hole.

1439

01:01:43,800 --> 01:01:47,130
I guess the closest true
depiction of a black hole

1440
01:01:47,130 --> 01:01:49,080
came with "Interstellar"
because, of course,

1441
01:01:49,080 --> 01:01:53,058
they had Kip Thorne who's,
you know, won the Nobel Prize

1442
01:01:53,058 --> 01:01:57,060
for gravitational waves
consulting on that movie.

1443
01:01:57,060 --> 01:02:01,680
And they got it just about
right for a very particular kind

1444
01:02:01,680 --> 01:02:02,513
of black hole.

1445
01:02:02,513 --> 01:02:04,230
So, the kind of black hole they showed

1446
01:02:04,230 --> 01:02:08,040
in "Interstellar" has a thin
disc orbiting the black hole

1447
01:02:08,040 --> 01:02:11,280
and it's lens over the
top and on the bottom.

1448
01:02:11,280 --> 01:02:14,640
So, you wind up seeing
this kind of iconic ring

1449
01:02:14,640 --> 01:02:17,340
with a line drawn through it.

1450
01:02:17,340 --> 01:02:19,950
But when I talked to
Kip, I said, "You know,

1451
01:02:19,950 --> 01:02:21,210
that's not quite right."

1452
01:02:21,210 --> 01:02:22,470
And he said, "I know, right?"

1453
01:02:22,470 --> 01:02:26,070
So, Kip knows that there
was a problem with this

1454
01:02:26,070 --> 01:02:28,560
because when you're looking at it,

1455
01:02:28,560 --> 01:02:31,290
part of the emission should
be coming towards you

1456
01:02:31,290 --> 01:02:32,610
near the speed of light,

1457
01:02:32,610 --> 01:02:34,200
and part of it should
be going away from you.

1458
01:02:34,200 --> 01:02:36,390
So, that disc part of
it's coming towards you,

1459
01:02:36,390 --> 01:02:37,620
like this side is coming towards you,

1460
01:02:37,620 --> 01:02:39,270
this part is going away from you.

1461
01:02:39,270 --> 01:02:42,510
So, part of it should be much
brighter than the other part.

1462
01:02:42,510 --> 01:02:45,030
The part that's coming towards
you is Doppler boosted,

1463
01:02:45,030 --> 01:02:47,790
kind of in the same way that
a train whistle is higher

1464
01:02:47,790 --> 01:02:49,590
in pitch as it's coming towards you

1465
01:02:49,590 --> 01:02:52,200
and it's lower in pitch as
it's going away from you.

1466
01:02:52,200 --> 01:02:53,850
One side, the side
that's coming towards you

1467
01:02:53,850 --> 01:02:55,650
should be brighter around a black hole.

1468
01:02:55,650 --> 01:02:58,200
And the part going away
from you should be dimmer.

1469
01:02:58,200 --> 01:02:59,730
And in "Interstellar,"

1470
01:02:59,730 --> 01:03:02,070
they didn't do that because
I think they thought

1471
01:03:02,070 --> 01:03:05,430
that the public in the

theater would not be able

1472
01:03:05,430 --> 01:03:07,500
to appreciate why that was the case.

1473
01:03:07,500 --> 01:03:10,860
So, they made it uniformly
bright all around.

1474
01:03:10,860 --> 01:03:13,110
So, have they gotten
it right in Hollywood?

1475
01:03:13,110 --> 01:03:15,180
I think they've done
a lot of things right,

1476
01:03:15,180 --> 01:03:19,830
but sometimes just for cinema,
they cut a couple of corners.

1477
01:03:19,830 --> 01:03:22,590
- Was science fiction your
first introduction to the idea

1478
01:03:22,590 --> 01:03:25,230
of black holes, or was
science your introduction?

1479
01:03:25,230 --> 01:03:30,230
- Well, my first introduction
was my father Nels Doelman.

1480
01:03:30,570 --> 01:03:33,960
He was a high school science teacher.

1481
01:03:33,960 --> 01:03:36,180
I remember him telling
me about X-ray binaries,

1482
01:03:36,180 --> 01:03:38,010
like Cygnus X-1,

1483
01:03:38,010 --> 01:03:42,090
which was one of the first
possible black holes.

1484
01:03:42,090 --> 01:03:45,210
And he had some books
in the library at home

1485
01:03:45,210 --> 01:03:47,730
on general relativity.

1486
01:03:47,730 --> 01:03:50,130
And he's a very curious person,

1487
01:03:50,130 --> 01:03:52,020
and I had great conversations with him

1488
01:03:52,020 --> 01:03:55,257
and that got me thinking about black holes

1489
01:03:55,257 --> 01:03:57,540
and not really in an academic sense,

1490
01:03:57,540 --> 01:04:00,000
but just knowing they were
out there and understanding

1491
01:04:00,000 --> 01:04:01,750
that these kinds of things existed.

1492
01:04:02,827 --> 01:04:04,110
And that's a very nice memory.

1493
01:04:04,110 --> 01:04:07,290
And then thinking about

science fiction, of course,

1494
01:04:07,290 --> 01:04:09,270
then you start to think about, you know,

1495
01:04:09,270 --> 01:04:12,480
stories you've read and
stories about neutron stars,

1496
01:04:12,480 --> 01:04:13,620
about black holes.

1497
01:04:13,620 --> 01:04:16,620
I mean, there have been some
great failures, frankly,

1498
01:04:16,620 --> 01:04:19,500
there were some depictions
of black holes as portals

1499
01:04:19,500 --> 01:04:23,940
to like, hell, or things
like this, which got very,

1500
01:04:23,940 --> 01:04:26,760
very scary for me as a young kid.

1501
01:04:26,760 --> 01:04:28,590
And I think when things
go in that direction,

1502
01:04:28,590 --> 01:04:32,130
it gets problematic
because you can mix a lot

1503
01:04:32,130 --> 01:04:34,950
of different emotions with a black hole.

1504
01:04:34,950 --> 01:04:37,170

In truth, I think that's
part of their power.

1505
01:04:37,170 --> 01:04:41,070
I mean, you can imbue
them with like cultural,

1506
01:04:41,070 --> 01:04:43,560
even like religious meaning,

1507
01:04:43,560 --> 01:04:47,010
and that's because they are
such strange objects, right?

1508
01:04:47,010 --> 01:04:49,470
So, it's part of the whole package.

1509
01:04:49,470 --> 01:04:51,870
They're very powerful,

1510
01:04:51,870 --> 01:04:55,740
they're very meaningful and
you can ascribe to them a lot

1511
01:04:55,740 --> 01:04:58,020
of different attributes and that's part

1512
01:04:58,020 --> 01:05:00,360
of what makes them so compelling.

1513
01:05:00,360 --> 01:05:03,570
- So, on the topic of how you
went from someone interested

1514
01:05:03,570 --> 01:05:06,720
in some of these topics to
doing them for a career,

1515
01:05:06,720 --> 01:05:09,360

Avery Broderick told us that
we had to ask you of some

1516
01:05:09,360 --> 01:05:11,910
of your earlier experiences.

1517
01:05:11,910 --> 01:05:14,010
I think after you finished
your undergraduate degree,

1518
01:05:14,010 --> 01:05:15,750
you spent some time in Antarctica.

1519
01:05:15,750 --> 01:05:17,730
Could you tell us a little bit about this?

1520
01:05:17,730 --> 01:05:18,990
- Oh yeah, I did.

1521
01:05:18,990 --> 01:05:20,362
When was that?

1522
01:05:20,362 --> 01:05:23,460
So in 1986, I graduated
from undergraduate.

1523
01:05:23,460 --> 01:05:27,390
I went to Reed College
and studied physics there.

1524
01:05:27,390 --> 01:05:31,053
And I was a little bit
burned out at the time.

1525
01:05:31,903 --> 01:05:33,330
Many people leave undergraduate
and they're like, wow,

1526
01:05:33,330 --> 01:05:36,150

that was intense, and that's how I felt.

1527
01:05:36,150 --> 01:05:40,590
And I saw a poster when I was
thinking about what to do next

1528
01:05:40,590 --> 01:05:44,160
for a program where
people went to Antarctica

1529
01:05:44,160 --> 01:05:46,590
to look after all the experiments

1530
01:05:46,590 --> 01:05:48,780
that were set up there for astronomy.

1531
01:05:48,780 --> 01:05:50,670
And so, I applied for that
and I got the position

1532
01:05:50,670 --> 01:05:53,190
and I wound up going to
Antarctica for a year.

1533
01:05:53,190 --> 01:05:57,060
I lived at McMurdo Base on
the coast of Antarctica.

1534
01:05:57,060 --> 01:05:59,878
I also went to the South Pole
a few times to help set up

1535
01:05:59,878 --> 01:06:00,870
some equipment there.

1536
01:06:00,870 --> 01:06:03,630
And that gave me a really
interesting perspective

1537

01:06:03,630 --> 01:06:05,190
in a couple of ways.

1538
01:06:05,190 --> 01:06:09,810
It showed me that you could
do really interesting science

1539
01:06:09,810 --> 01:06:13,530
at remote sites in very
difficult circumstances

1540
01:06:13,530 --> 01:06:14,910
and what it took to do it.

1541
01:06:14,910 --> 01:06:19,020
And I kind of fell in love
with the swashbuckling aspect

1542
01:06:19,020 --> 01:06:23,970
of doing science, you know,
going to a difficult place,

1543
01:06:23,970 --> 01:06:25,020
making it work.

1544
01:06:25,020 --> 01:06:28,260
And that has colored my entire career.

1545
01:06:28,260 --> 01:06:31,290
It also taught me how to deal
with a lot of different people

1546
01:06:31,290 --> 01:06:34,560
because in Antarctica you
had this very interesting mix

1547
01:06:34,560 --> 01:06:39,270
of the Navy, which took care
of a lot of the construction

1548
01:06:39,270 --> 01:06:44,270
and the meteorology and some
of the day-to-day comforts

1549
01:06:44,670 --> 01:06:46,380
at the base at McMurdo.

1550
01:06:46,380 --> 01:06:49,470
You had the Air Force, which
was doing all the flights in.

1551
01:06:49,470 --> 01:06:51,777
You had construction workers

1552
01:06:51,777 --> 01:06:53,430
who were building new dormitories

1553
01:06:53,430 --> 01:06:56,610
and helping with
construction of laboratories.

1554
01:06:56,610 --> 01:06:59,220
And you also had the
scientists funded primarily

1555
01:06:59,220 --> 01:07:01,860
by the National Science
Foundation at those sites.

1556
01:07:01,860 --> 01:07:05,490
And I got my first taste of
seeing how different communities

1557
01:07:05,490 --> 01:07:08,850
work together and that
each community plays

1558
01:07:08,850 --> 01:07:10,140
a very vital role.

1559
01:07:10,140 --> 01:07:14,010
And you can't just be a scientist
in that remote location.

1560
01:07:14,010 --> 01:07:16,620
You can't just be someone
involved with construction.

1561
01:07:16,620 --> 01:07:18,750
You can't just be in the military.

1562
01:07:18,750 --> 01:07:21,000
You need to find a way for
everyone to work together

1563
01:07:21,000 --> 01:07:23,940
to make that base function.

1564
01:07:23,940 --> 01:07:26,940
And if you wanna do science
in that environment,

1565
01:07:26,940 --> 01:07:29,940
you need to work with a
lot of different people.

1566
01:07:29,940 --> 01:07:32,070
So in addition to
working in a remote site,

1567
01:07:32,070 --> 01:07:34,320
it also taught me how to deal with people.

1568
01:07:34,320 --> 01:07:37,110
And that has helped, as you might imagine.

1569
01:07:37,110 --> 01:07:39,180
- That's funny, to learn

how to deal with people,

1570
01:07:39,180 --> 01:07:43,320
you go to the continent that
has the fewest people on Earth,

1571
01:07:43,320 --> 01:07:46,530
but they're all working
toward a sort of common goal?

1572
01:07:46,530 --> 01:07:48,900
- Well, that's a very interesting point.

1573
01:07:48,900 --> 01:07:51,660
Often it is in these extreme environments

1574
01:07:51,660 --> 01:07:54,540
where people come together,
it's not an accident.

1575
01:07:54,540 --> 01:07:58,200
When you're just happy and you're content,

1576
01:07:58,200 --> 01:08:01,110
you make friends and you
are often with people

1577
01:08:01,110 --> 01:08:03,300
who believe the way you do.

1578
01:08:03,300 --> 01:08:05,880
You're often with people
who think the way you do.

1579
01:08:05,880 --> 01:08:06,750
Maybe even at work,

1580
01:08:06,750 --> 01:08:10,800
you're with people most of the

day who do the things you do.

1581
01:08:10,800 --> 01:08:13,560
But it's when you go
to a unique environment

1582
01:08:13,560 --> 01:08:16,590
and you are focused on a
very interesting mission

1583
01:08:16,590 --> 01:08:19,650
that requires many people come together,

1584
01:08:19,650 --> 01:08:23,700
that's where you really need
to broaden your perspective.

1585
01:08:23,700 --> 01:08:25,920
So it's in these extreme environments,

1586
01:08:25,920 --> 01:08:28,470
it's in these experiments

1587
01:08:28,470 --> 01:08:31,020
where you've gotta have
people coming together.

1588
01:08:31,020 --> 01:08:33,600
And coming back to something
that we talked about before,

1589
01:08:33,600 --> 01:08:35,970
if we're gonna address the big problems

1590
01:08:35,970 --> 01:08:38,430
that face us as humanity,

1591
01:08:38,430 --> 01:08:40,650
we're going to have to come together.

1592
01:08:40,650 --> 01:08:43,350
Solving a problem like climate change

1593
01:08:43,350 --> 01:08:44,850
is not gonna happen because a bunch

1594
01:08:44,850 --> 01:08:46,590
of scientists get together.

1595
01:08:46,590 --> 01:08:48,690
It's gonna happen because industry,

1596
01:08:48,690 --> 01:08:53,690
politics, science, the general
public, even like cultural,

1597
01:08:54,330 --> 01:08:57,090
religious leaders, all
come together and realize

1598
01:08:57,090 --> 01:09:00,000
this is a problem that faces everyone.

1599
01:09:00,000 --> 01:09:02,100
So it's in these extreme environments,

1600
01:09:02,100 --> 01:09:05,250
it's in these turning point problems

1601
01:09:05,250 --> 01:09:07,290
that face us as a planet.

1602
01:09:07,290 --> 01:09:09,690
This is where people
have to come together.

1603
01:09:09,690 --> 01:09:11,190

So, I don't think it's an accident.

1604
01:09:11,190 --> 01:09:14,670
I think it's almost by design
that we're thrown together

1605
01:09:14,670 --> 01:09:16,560
in these unique moments.

1606
01:09:16,560 --> 01:09:19,530
- And when we do face such
terrestrial challenges

1607
01:09:19,530 --> 01:09:22,140
of climate change and
politics and everything else,

1608
01:09:22,140 --> 01:09:25,500
why is it important for
us to look at black holes,

1609
01:09:25,500 --> 01:09:27,270
millions of light years away,

1610
01:09:27,270 --> 01:09:30,930
that won't necessarily
affect our day-to-day lives?

1611
01:09:30,930 --> 01:09:32,820
- So, it's a really interesting point.

1612
01:09:32,820 --> 01:09:34,770
We have so many things facing us now,

1613
01:09:34,770 --> 01:09:37,350
why pay attention to M87?

1614
01:09:37,350 --> 01:09:39,990
Why look at the center

of the Milky Way Galaxy?

1615
01:09:39,990 --> 01:09:43,410
The best answer I have is that you need

1616
01:09:43,410 --> 01:09:48,030
to play the long game in
any financial portfolio.

1617
01:09:48,030 --> 01:09:49,530
So, this will make sense
to people who are saving

1618
01:09:49,530 --> 01:09:51,540
for retirement and things like this.

1619
01:09:51,540 --> 01:09:54,420
You need to have your blue chip stocks,

1620
01:09:54,420 --> 01:09:56,910
which are going to do well over time.

1621
01:09:56,910 --> 01:10:01,410
You also wanna have some
more high risk element

1622
01:10:01,410 --> 01:10:02,310
of your portfolio.

1623
01:10:02,310 --> 01:10:05,520
Like any normal financial
manager will tell you this.

1624
01:10:05,520 --> 01:10:07,050
And it's the same thing with science.

1625
01:10:07,050 --> 01:10:09,120
It's the same thing with business.

1626
01:10:09,120 --> 01:10:11,400
It's the same thing with really humanity.

1627
01:10:11,400 --> 01:10:14,580
You need always to pay
attention to the here and now.

1628
01:10:14,580 --> 01:10:17,010
You need to pay attention
to what's in front of you.

1629
01:10:17,010 --> 01:10:19,470
Part of you needs to be
thinking about the future

1630
01:10:19,470 --> 01:10:23,790
and sometimes the far future
and investing in basic research

1631
01:10:23,790 --> 01:10:26,580
that doesn't necessarily pay off tomorrow

1632
01:10:26,580 --> 01:10:28,260
is never a bad idea.

1633
01:10:28,260 --> 01:10:31,800
It always pays off in
the long run, always.

1634
01:10:31,800 --> 01:10:33,510
And I think more than that,

1635
01:10:33,510 --> 01:10:35,400
it speaks to the human condition

1636
01:10:35,400 --> 01:10:39,270
because we're conditioned now
to think about the news cycle.

1637
01:10:39,270 --> 01:10:41,460
Every Tuesday something happens.

1638
01:10:41,460 --> 01:10:44,550
And if it's not this
Tuesday, you forget about it.

1639
01:10:44,550 --> 01:10:47,040
We are used to thinking about
the quarterly bottom line,

1640
01:10:47,040 --> 01:10:49,830
how is my company doing
and how will I report

1641
01:10:49,830 --> 01:10:51,090
to the shareholders?

1642
01:10:51,090 --> 01:10:53,640
We're thinking about
the next election cycle.

1643
01:10:53,640 --> 01:10:55,020
A couple of years down the road,

1644
01:10:55,020 --> 01:10:56,460
who will be leading the country

1645
01:10:56,460 --> 01:10:59,160
and what kind of politics
should we be dealing with?

1646
01:10:59,160 --> 01:11:03,900
Science and the pursuit of basic research

1647
01:11:03,900 --> 01:11:06,180
is the deep rudder in the water.

1648

01:11:06,180 --> 01:11:09,210
It is the long game that we play.

1649
01:11:09,210 --> 01:11:13,590
It is what connects us across
the centuries to the thinkers

1650
01:11:13,590 --> 01:11:14,910
that came before us.

1651
01:11:14,910 --> 01:11:17,250
It's really what defines humanity.

1652
01:11:17,250 --> 01:11:19,530
We are not what happens this week.

1653
01:11:19,530 --> 01:11:21,990
We are what happens over centuries.

1654
01:11:21,990 --> 01:11:24,060
We are what happens over millennia.

1655
01:11:24,060 --> 01:11:26,100
We are building the history

1656
01:11:26,100 --> 01:11:28,507
that people will look
back on later and say,

1657
01:11:28,507 --> 01:11:30,510
"These people were thinking

1658
01:11:30,510 --> 01:11:34,260
about the deepest
mysteries of the universe."

1659
01:11:34,260 --> 01:11:37,320
If you went back and talked
to Einstein and you could go

1660
01:11:37,320 --> 01:11:39,780
in a time machine and say, "Einstein,

1661
01:11:39,780 --> 01:11:42,990
100 years from now you'll
be able to use your phone.

1662
01:11:42,990 --> 01:11:45,000
And using a constellation of satellites,

1663
01:11:45,000 --> 01:11:47,190
you'll be able to pinpoint your location

1664
01:11:47,190 --> 01:11:50,370
on the earth using your theories."

1665
01:11:50,370 --> 01:11:51,990
As I like to say, he'd be very excited,

1666
01:11:51,990 --> 01:11:54,090
but of course he would
just say, "What's a phone?"

1667
01:11:54,090 --> 01:11:55,086
Right?

1668
01:11:55,086 --> 01:11:58,380
Because it's so far beyond his conception.

1669
01:11:58,380 --> 01:12:01,590
He didn't even know what
phones were back then, right?

1670
01:12:01,590 --> 01:12:04,530
So, he didn't realize that unless

1671
01:12:04,530 --> 01:12:07,740

you make general relativistic corrections

1672
01:12:07,740 --> 01:12:10,890
to the GPS system that we all rely on

1673
01:12:10,890 --> 01:12:13,920
to get us from point A
to point B in our cars,

1674
01:12:13,920 --> 01:12:17,040
if you don't make those
corrections, you're off by miles.

1675
01:12:17,040 --> 01:12:18,870
But, he never could have known that.

1676
01:12:18,870 --> 01:12:21,810
So, we are making the discoveries
today with basic research

1677
01:12:21,810 --> 01:12:23,010
that are not gonna pay off

1678
01:12:23,010 --> 01:12:25,620
until maybe 100 years from now.

1679
01:12:25,620 --> 01:12:28,020
But we'll look back and say, "Ah,

1680
01:12:28,020 --> 01:12:30,240
that was so important to think about."

1681
01:12:30,240 --> 01:12:31,980
And I will add one more thing.

1682
01:12:31,980 --> 01:12:34,830
If you only look at the things you know,

1683

01:12:34,830 --> 01:12:37,950
if you only try to make the ideas

1684
01:12:37,950 --> 01:12:40,140
that you currently understand better,

1685
01:12:40,140 --> 01:12:42,060
then you're doing engineering.

1686
01:12:42,060 --> 01:12:43,770
And engineering is amazing.

1687
01:12:43,770 --> 01:12:45,390
I consider myself to be an engineer.

1688
01:12:45,390 --> 01:12:49,200
In fact, my job title is
engineer and I love it.

1689
01:12:49,200 --> 01:12:52,950
But if you limit yourself to engineering

1690
01:12:52,950 --> 01:12:54,270
what you already know,

1691
01:12:54,270 --> 01:12:57,270
then you're missing out on the new ideas.

1692
01:12:57,270 --> 01:13:00,000
So, you need to be asking
these big questions.

1693
01:13:00,000 --> 01:13:02,610
You need to be looking
at M87 and Sag A star

1694
01:13:02,610 --> 01:13:04,980
because they will lead
you in the directions

1695
01:13:04,980 --> 01:13:08,010
that you have no idea about now.

1696
01:13:08,010 --> 01:13:09,600
And many of those will not pay off,

1697
01:13:09,600 --> 01:13:13,260
but the ones that do
will be truly new windows

1698
01:13:13,260 --> 01:13:14,310
on the universe.

1699
01:13:14,310 --> 01:13:17,340
And that's what humanity I
think should be focused on.

1700
01:13:17,340 --> 01:13:20,070
- Well, I think that's a
beautiful sentiment to wrap up on.

1701
01:13:20,070 --> 01:13:22,320
Shep, thank you so much
for this conversation.

1702
01:13:22,320 --> 01:13:23,250
- It was a real pleasure.

1703
01:13:23,250 --> 01:13:24,083
Thank you both.

1704
01:13:27,480 --> 01:13:30,000
- Thanks for stepping
inside the "Perimeter."

1705
01:13:30,000 --> 01:13:33,240
If you like what you hear,
please help us spread the word.

1706
01:13:33,240 --> 01:13:34,680
You can rate, review,

1707
01:13:34,680 --> 01:13:37,290
and subscribe to "Conversations
at the Perimeter"

1708
01:13:37,290 --> 01:13:39,660
wherever you get your podcasts.

1709
01:13:39,660 --> 01:13:41,820
Every review really helps us a lot

1710
01:13:41,820 --> 01:13:44,820
and it helps more science
enthusiasts find us.

1711
01:13:44,820 --> 01:13:47,073
Thank you for being part of the equation.