1
00:00:00,319 --> 00:00:04,069
(gentle upbeat music begins)

2
00:00:08,820 --> 00:00:10,530
- Hello everyone and welcome back

3
00:00:10,530 --> 00:00:12,690
to Conversations at the Perimeter.

4
00:00:12,690 --> 00:00:15,240
I'm Lauren and I'm here
as always with Colin.

5
00:00:15,240 --> 00:00:16,073
- Hello.

6
00:00:16,073 --> 00:00:18,420
- In this episode we're
sharing our conversation

7
00:00:18,420 --> 00:00:20,130
with Savas Dimopoulos.

8
00:00:20,130 --> 00:00:21,630
Savas is a faculty member

9
00:00:21,630 --> 00:00:24,120
at Stanford University in California,

10
00:00:24,120 --> 00:00:26,940
and he's the Coril Holdings
Archimedes Visiting Chair,

11
00:00:26,940 --> 00:00:28,920
here at Perimeter Institute.

12
00:00:28,920 --> 00:00:30,720
He's a renowned particle physicist

13
00:00:30,720 --> 00:00:33,510
whose career spans over four decades.

14
00:00:33,510 --> 00:00:35,483
- So I've been wanting
to have Savas as a guest

15
00:00:35,483 --> 00:00:38,430
on this podcast ever since
we first launched it.

16
00:00:38,430 --> 00:00:40,440
So I was thrilled that
we made this happen.

17
00:00:40,440 --> 00:00:42,780
I first met Savas nearly 10 years ago

18
00:00:42,780 --> 00:00:44,880
during one of his annual
visits to Perimeter,

19
00:00:44,880 --> 00:00:48,390
and I was immediately struck
by his kindness and his wisdom,

20
00:00:48,390 --> 00:00:51,390
and really by his undiminished
passion after all these years

21
00:00:51,390 --> 00:00:55,110
for exploring the most puzzling
mysteries in the universe.

22
00:00:55,110 --> 00:00:56,220
- In this conversation,

23
00:00:56,220 --> 00:00:59,760

he shares his thoughts on
fundamental, huge, open questions

24
00:00:59,760 --> 00:01:02,190
like, why is gravity so weak?

25
00:01:02,190 --> 00:01:03,960
- Why is the universe so big?

26
00:01:03,960 --> 00:01:05,910
- And is there a multiverse?

27
00:01:05,910 --> 00:01:08,490
And he also talks about
how he remains motivated

28
00:01:08,490 --> 00:01:11,580
to search for answers
to such huge puzzles.

29
00:01:11,580 --> 00:01:14,760
- Savas was also one of the
scientists featured prominently

30
00:01:14,760 --> 00:01:18,960
in the award-winning 2013
documentary, Particle Fever,

31
00:01:18,960 --> 00:01:21,990
about the hunt for the
Higgs boson at the LHC,

32
00:01:21,990 --> 00:01:24,510
CERN's Large Hadron Collider.

33
00:01:24,510 --> 00:01:27,270
Savas tells us some
history of collider physics

34

00:01:27,270 --> 00:01:30,450
and he explains how a renaissance
in small-scale experiments

35
00:01:30,450 --> 00:01:32,580
could reshape how physics is done

36
00:01:32,580 --> 00:01:34,920
in the generation between the LHC

37
00:01:34,920 --> 00:01:37,080
and the next big super-collider.

38
00:01:37,080 --> 00:01:39,150
We were fascinated by this conversation

39
00:01:39,150 --> 00:01:41,190
and we're pretty sure
that you will be too.

40
00:01:41,190 --> 00:01:45,242
So let's step inside the
Perimeter with Savas Demopolis.

41
00:01:45,242 --> 00:01:48,990
(gentle upbeat music fades)

42
00:01:48,990 --> 00:01:51,120
Savas, thank you so much for joining us.

43
00:01:51,120 --> 00:01:52,620
I've been looking forward
to chatting with you

44
00:01:52,620 --> 00:01:54,060
for a long time now.

45
00:01:54,060 --> 00:01:55,140
- My pleasure.

46
00:01:55,140 --> 00:01:57,690
- It's been a bit of a break
for you coming to Perimeter

47
00:01:57,690 --> 00:02:00,600
because of the pandemic, but
we're glad to have you back.

48
00:02:00,600 --> 00:02:04,710
And I was looking at your
Stanford webpage the other day,

49
00:02:04,710 --> 00:02:07,890
and it says that your job
is to search for answers

50
00:02:07,890 --> 00:02:10,290
to the biggest mysteries in the universe.

51
00:02:10,290 --> 00:02:12,120
That's about the biggest job description.

52
00:02:12,120 --> 00:02:14,220
Can you tell us what does that mean?

53
00:02:14,220 --> 00:02:15,510
What do you do for a living?

54
00:02:15,510 --> 00:02:18,060
- I assure you, the
job description is big,

55
00:02:18,060 --> 00:02:22,500
but it is not matched by
salary. (both laughing)

56
00:02:22,500 --> 00:02:25,110
- It would have to be

an astronomical salary.

57
00:02:25,110 --> 00:02:27,300
- It would have, but I'm happy,

58
00:02:27,300 --> 00:02:31,320
because my main reward is
that I'm given the time

59
00:02:31,320 --> 00:02:34,170
to just think about the universe,

60
00:02:34,170 --> 00:02:37,230
and that's the reward enough for me.

61
00:02:37,230 --> 00:02:39,570
- So what are the big
questions about the universe

62
00:02:39,570 --> 00:02:41,130
that are driving you these days?

63
00:02:41,130 --> 00:02:43,170
- Yeah, so there are several,

64
00:02:43,170 --> 00:02:46,890
but I want to give you some big principles

65
00:02:46,890 --> 00:02:49,710
that guide the questions
that we are asking.

66
00:02:49,710 --> 00:02:53,340
One of the big principles is
what's called, "Naturalness."

67
00:02:53,340 --> 00:02:58,110
And the idea of naturalness,
actually, is in all of science.

68
00:02:58,110 --> 00:03:00,450
In the case of physics,

69
00:03:00,450 --> 00:03:03,870
naturalness has to do
with trying to understand

70
00:03:03,870 --> 00:03:05,970
very large numbers.

71
00:03:05,970 --> 00:03:09,810
For example, if you take
the size of the universe

72
00:03:09,810 --> 00:03:13,470
and you compare it with the
size of an atomic nucleus,

73
00:03:13,470 --> 00:03:17,130
you get an enormous number, 10 to the 40,

74
00:03:17,130 --> 00:03:21,480
which is 1 with 40 decimals next to it.

75
00:03:21,480 --> 00:03:25,417
With such enormous numbers
it's natural to ask,

76
00:03:25,417 --> 00:03:29,637
"How come the fundamental
particles of the theory

77
00:03:29,637 --> 00:03:31,830
are so much smaller than the universe?"

78
00:03:31,830 --> 00:03:34,620
Or conversion, "Why is
the universe so big?"

79
00:03:34,620 --> 00:03:36,810
You can ask it in many different ways,

80
00:03:36,810 --> 00:03:39,270
but one of the ways it's asked,

81
00:03:39,270 --> 00:03:42,210
it's called a, "Cosmological
constant problem."

82
00:03:42,210 --> 00:03:46,560
Another question is,
"Why is gravity so weak?"

83
00:03:46,560 --> 00:03:51,060
So for example, what I mean
by the weakness of gravity,

84
00:03:51,060 --> 00:03:54,060
when I lift this glass of water,

85
00:03:54,060 --> 00:03:59,060
the electrical forces from
my fingers to the glass

86
00:03:59,550 --> 00:04:03,780
are large enough to
compensate or to overcome

87
00:04:03,780 --> 00:04:07,786
the gravitational attraction
of the entire planet Earth.

88
00:04:07,786 --> 00:04:09,660
And if you think about it,
- Hmm.

89
00:04:09,660 --> 00:04:10,710

this is amazing.

90
00:04:10,710 --> 00:04:13,200
The entire planet Earth is enormous

91
00:04:13,200 --> 00:04:15,090
compared to my fingers,
- Mm-hmm (affirmative).

92
00:04:15,090 --> 00:04:18,190
yet I'm able to overcome the gravity

93
00:04:19,097 --> 00:04:23,130
of the earth with the electrical
forces, or atomic forces,

94
00:04:23,130 --> 00:04:27,030
that my fingers exert on on the glass.

95
00:04:27,030 --> 00:04:29,080
So the only reason why this is possible

96
00:04:30,390 --> 00:04:35,390
is because the intrinsic
strength of electrical forces,

97
00:04:35,400 --> 00:04:39,300
or atomic forces, is far, far bigger

98
00:04:39,300 --> 00:04:41,250
than the strength of gravity.

99
00:04:41,250 --> 00:04:44,910
It's, again, it's about
40 orders of magnitude,

100
00:04:44,910 --> 00:04:47,910
1 with 40 zeros bigger.

101
00:04:47,910 --> 00:04:50,667
That is called, "The hierarchy problem."

102
00:04:51,818 --> 00:04:53,160
And these questions,

103
00:04:53,160 --> 00:04:56,880
the enormity of the universe
and the weakness of gravity

104
00:04:56,880 --> 00:05:00,660
have been driving, in some
ways, theoretical thinking

105
00:05:00,660 --> 00:05:03,750
for the last 40 some years.

106
00:05:03,750 --> 00:05:08,400
And much of the theoretical
community in my field,

107
00:05:08,400 --> 00:05:11,040
which is called, "High energy physics,"

108
00:05:11,040 --> 00:05:14,250
has been driven by these questions.

109
00:05:14,250 --> 00:05:16,380
Now, one of these questions,

110
00:05:16,380 --> 00:05:20,010
the so-called, 'hierarchy problem,'

111
00:05:20,010 --> 00:05:23,310
has had some possible answers.

112
00:05:23,310 --> 00:05:26,190
And much of what many people did,

113
00:05:26,190 --> 00:05:28,740
including myself, over the last 40 years,

114
00:05:28,740 --> 00:05:31,530
was to search for
answers to this question,

115
00:05:31,530 --> 00:05:33,180
the weakness of gravity.

116
00:05:33,180 --> 00:05:36,810
Why is gravity so much
weaker than electricity?

117
00:05:36,810 --> 00:05:39,090
Or why is gravity so much weaker

118
00:05:39,090 --> 00:05:41,610
than all the other forces of nature?

119
00:05:41,610 --> 00:05:43,440
To answer these questions,

120
00:05:43,440 --> 00:05:47,310
we came up with theoretical ideas.

121
00:05:47,310 --> 00:05:51,090
There is three or four,
depending on how you count,

122
00:05:51,090 --> 00:05:56,090
but the simplest one to describe
in words and with pictures

123
00:05:56,610 --> 00:05:59,163
is the idea of large extra dimensions,

124

00:06:00,007 --> 00:06:02,740
which was proposed back in 1998

125
00:06:04,132 --> 00:06:06,540
by myself and a couple of collaborators,

126
00:06:06,540 --> 00:06:08,333
Nima Arkani-Hamed and Gia Dvali.

127
00:06:09,900 --> 00:06:14,610
The basic idea of that
framework is that gravity,

128
00:06:14,610 --> 00:06:17,760
in contrast to the other forces of nature,

129
00:06:17,760 --> 00:06:19,983
lives in more than three dimensions.

130
00:06:21,210 --> 00:06:22,800
As a result,

131
00:06:22,800 --> 00:06:27,060
it spreads inside a space
bigger than three dimensions,

132
00:06:27,060 --> 00:06:30,660
maybe four, maybe five, maybe
six, et cetera, dimensions.

133
00:06:30,660 --> 00:06:33,870
And in so doing, it dilutes its strength.

134
00:06:33,870 --> 00:06:36,120
It spreads itself thin in a sense.

135
00:06:36,120 --> 00:06:38,850
- So gravity's having an
influence in the dimensions,

136
00:06:38,850 --> 00:06:41,070
we might not experience ourselves?

137
00:06:41,070 --> 00:06:43,830
- Exactly right, at least not directly.

138
00:06:43,830 --> 00:06:46,590
The picture there can
be described as follow:

139
00:06:46,590 --> 00:06:48,603
Imagine the surface of this table

140
00:06:48,603 --> 00:06:51,270
that represents our universe.

141
00:06:51,270 --> 00:06:52,200
By our universe,

142
00:06:52,200 --> 00:06:55,770
I mean the three-dimensional
space of our universe, okay?

143
00:06:55,770 --> 00:06:58,860
So clearly this is not a precise...

144
00:06:58,860 --> 00:07:01,110
The surface of the table
has two dimensions.

145
00:07:01,110 --> 00:07:04,260
Our universe has three
dimensions, but nevertheless,

146
00:07:04,260 --> 00:07:06,693
imagine the surface
represents our universe.

147
00:07:07,885 --> 00:07:12,885
So all ordinary forces, which
is electricity, magnetism,

148
00:07:13,320 --> 00:07:15,720
the so-called, 'strong interactions,'

149
00:07:15,720 --> 00:07:18,630
which keep an atomic nucleus together,

150
00:07:18,630 --> 00:07:19,980
or the 'weak interactions,'

151
00:07:19,980 --> 00:07:22,830
which are responsible for radioactivity,

152
00:07:22,830 --> 00:07:25,080
all of the other forces of nature

153
00:07:25,080 --> 00:07:26,967
stay in this three-dimensional space,

154
00:07:26,967 --> 00:07:29,640
and are confined to this table.

155
00:07:29,640 --> 00:07:34,640
Whereas gravity can spread
also perpendicular to the table

156
00:07:34,770 --> 00:07:39,180
in these extra dimensions that
we usually call, 'height.'

157
00:07:39,180 --> 00:07:42,750
So because gravity spreads
in more dimensions,

158
00:07:42,750 --> 00:07:45,000

it dilutes its intrinsic strength.

159
00:07:45,000 --> 00:07:47,700
It's like when a river which moves,

160
00:07:47,700 --> 00:07:50,550
let's say in one direction,
in one dimension,

161
00:07:50,550 --> 00:07:53,520
spreads itself into several tributaries,

162
00:07:53,520 --> 00:07:55,380
it loses its strength.
- Hmm (affirmative).

163
00:07:55,380 --> 00:07:57,330
- So it is with gravity

164
00:07:57,330 --> 00:08:01,890
that this extra dimensional
space dilutes its strength.

165
00:08:01,890 --> 00:08:06,890
And this idea received
tremendous attention,

166
00:08:06,990 --> 00:08:10,568
both theoretically and observationally.

167
00:08:10,568 --> 00:08:13,027
The big experiment that we call,

168
00:08:13,027 --> 00:08:17,160
"The Large Hadron
Collider," at CERN in Geneva

169
00:08:17,160 --> 00:08:21,510
is looking for signature

of these theories.

170
00:08:21,510 --> 00:08:24,960
And I can describe to you a couple of ways

171
00:08:24,960 --> 00:08:29,310
you can look for this that
follow from this picture

172
00:08:29,310 --> 00:08:33,540
of the table representing our
three-dimensional universe

173
00:08:33,540 --> 00:08:35,400
and the vertical directions,
- Mm-hmm (affirmative).

174
00:08:35,400 --> 00:08:36,420
the extra dimension.

175
00:08:36,420 --> 00:08:41,010
So one test is the following
of this hypothesis:

176
00:08:41,010 --> 00:08:44,040
Imagine the surface, which
represents our universe,

177
00:08:44,040 --> 00:08:46,380
is like a pool table.

178
00:08:46,380 --> 00:08:48,060
The surface of the pool table

179
00:08:48,060 --> 00:08:51,570
represents our three dimensions.

180
00:08:51,570 --> 00:08:54,180
Billiard balls on the pool table

181
00:08:54,180 --> 00:08:56,550
represent elementary particles,

182
00:08:56,550 --> 00:09:00,210
like the proton or the
electron, et cetera.

183
00:09:00,210 --> 00:09:03,570
Now, normally when we
play with billiard balls,

184
00:09:03,570 --> 00:09:06,660
the billiard balls collide
and when they collide,

185
00:09:06,660 --> 00:09:09,270
of course, they still
stay in two dimensions,

186
00:09:09,270 --> 00:09:11,433
they stay in ordinary space,

187
00:09:12,270 --> 00:09:17,040
but the sound that the collision creates

188
00:09:17,040 --> 00:09:19,260
propagate also in the third dimension,

189
00:09:19,260 --> 00:09:22,170
inside the space of the extra dimensions.

190
00:09:22,170 --> 00:09:27,170
So even if we were not looking
at the extra dimensions,

191
00:09:27,600 --> 00:09:30,190
just by listening to the sound

192
00:09:31,680 --> 00:09:35,340
that the collision of the
billiard balls produces,

193
00:09:35,340 --> 00:09:38,760
we could infer about, well, what happened,

194
00:09:38,760 --> 00:09:41,970
the collision and the
fact that some sound or,

195
00:09:41,970 --> 00:09:44,700
was emitted inside the third dimension.

196
00:09:44,700 --> 00:09:46,590
So we could infer about the presence

197
00:09:46,590 --> 00:09:48,540
of the extra dimensions.

198
00:09:48,540 --> 00:09:52,470
So LHC is looking for the analog of that.

199
00:09:52,470 --> 00:09:54,450
You collide to elementary particles,

200
00:09:54,450 --> 00:09:56,340
which in that case is protons.

201
00:09:56,340 --> 00:09:58,080
And if there are extra dimension,

202
00:09:58,080 --> 00:10:02,460
some of the energy of this
collision may manifest itself

203
00:10:02,460 --> 00:10:06,150
by particles that come

into the extra dimensions.

204
00:10:06,150 --> 00:10:10,350
So some of the energy that was
in our universe, if you wish,

205
00:10:10,350 --> 00:10:13,890
in our, what we thought was
three-dimensional universe,

206
00:10:13,890 --> 00:10:17,040
will be missing before
the collision and after.

207
00:10:17,040 --> 00:10:20,430
Some of the energy has been carried out

208
00:10:20,430 --> 00:10:24,570
in a new space that we
are normally not aware of.

209
00:10:24,570 --> 00:10:27,120
This is called, "The
missing energy signature."

210
00:10:27,120 --> 00:10:30,510
You collide two particles
or two billiard balls,

211
00:10:30,510 --> 00:10:31,890
and there is some energy missing

212
00:10:31,890 --> 00:10:34,920
because it went to new
particles or to the sound waves

213
00:10:34,920 --> 00:10:36,960
in the case of the billiard ball.

214

00:10:36,960 --> 00:10:40,290
And by looking very
carefully at energy imbalance

215
00:10:40,290 --> 00:10:43,050
before the collision
and after the collision,

216
00:10:43,050 --> 00:10:47,910
you can look for the
space of extra dimensions.

217
00:10:47,910 --> 00:10:48,990
- Can you say a little bit more

218
00:10:48,990 --> 00:10:52,260
about where the seed of this
idea comes from because,

219
00:10:52,260 --> 00:10:54,750
as you're saying, there are
some experimental signatures

220
00:10:54,750 --> 00:10:55,710
that you can look for,

221
00:10:55,710 --> 00:10:58,620
but is that something that you
come up with after the fact?

222
00:10:58,620 --> 00:11:02,010
Or is it these experimental
signatures that inspired you

223
00:11:02,010 --> 00:11:04,620
to look for a theory in higher dimensions

224
00:11:04,620 --> 00:11:05,610
in the first place?

225
00:11:05,610 --> 00:11:07,410
- Well, that's a very interesting question

226
00:11:07,410 --> 00:11:08,550
because in some sense,

227
00:11:08,550 --> 00:11:13,440
for the case of extra dimensions,
both played their role.

228
00:11:13,440 --> 00:11:15,930
Historically, I was made aware

229
00:11:15,930 --> 00:11:19,480
by talking to some of my
experimental colleagues at Stanford

230
00:11:21,155 --> 00:11:23,830
that gravity has been tested

231
00:11:25,186 --> 00:11:27,780
to only distances of about,

232
00:11:27,780 --> 00:11:29,820
back then it was about a centimeter.

233
00:11:29,820 --> 00:11:32,550
This means, Newton's law of gravitation

234
00:11:32,550 --> 00:11:35,040
that the force between two particles

235
00:11:35,040 --> 00:11:37,590
was like the inverse square law.

236
00:11:37,590 --> 00:11:39,870
Had only been tested down to a distance

237
00:11:39,870 --> 00:11:42,060
of a little less than a centimeter,

238
00:11:42,060 --> 00:11:44,550
and this was back in 1990.

239
00:11:44,550 --> 00:11:46,590
So I was astonished to hear that

240
00:11:46,590 --> 00:11:49,830
because when I was an undergraduate,

241
00:11:49,830 --> 00:11:51,543
in my lab, we tested Newton's law

242
00:11:51,543 --> 00:11:55,800
to a distance which was
maybe 15, 20 centimeters,

243
00:11:55,800 --> 00:11:59,250
not much larger than
the 1 centimeter or so.

244
00:11:59,250 --> 00:12:04,023
The original measurement was
done 200 years ago. How come?

245
00:12:04,860 --> 00:12:09,240
So that immediately planted
to me the seed of an idea

246
00:12:09,240 --> 00:12:13,920
that I should be brave
about creating theories

247
00:12:13,920 --> 00:12:18,240
where the law of gravity is different,

248

00:12:18,240 --> 00:12:20,250
distances below a centimeter.

249
00:12:20,250 --> 00:12:23,040
Newton's, what's called,
"Inverse square law,"

250
00:12:23,040 --> 00:12:26,220
is not obey that shorter distances.

251
00:12:26,220 --> 00:12:29,280
So that sort of opened the door for me

252
00:12:29,280 --> 00:12:32,130
that I could contemplate such possibility

253
00:12:32,130 --> 00:12:34,440
without immediately being disproven

254
00:12:34,440 --> 00:12:37,080
by non-experimental facts.

255
00:12:37,080 --> 00:12:39,750
The other thing theory also played a role,

256
00:12:39,750 --> 00:12:43,920
in the sense that I was
looking for an explanation

257
00:12:43,920 --> 00:12:45,780
of the weakness of gravity.

258
00:12:45,780 --> 00:12:48,270
However, for several years,

259
00:12:48,270 --> 00:12:50,823
I didn't make the connection
between those two.

260
00:12:51,840 --> 00:12:55,500
In fact, I wrote papers
proposing new particles

261
00:12:55,500 --> 00:13:00,500
that would cause deviations
from Newton's law of attraction,

262
00:13:01,890 --> 00:13:06,060
but without any reference
to extra dimensions.

263
00:13:06,060 --> 00:13:08,520
And then finally, after a few years,

264
00:13:08,520 --> 00:13:12,990
my colleagues and I started
making the connection

265
00:13:12,990 --> 00:13:13,823
and that's how

266
00:13:13,823 --> 00:13:16,860
the theory of large extra
dimensions was proposed.

267
00:13:16,860 --> 00:13:20,220
In fact, your question also is related

268
00:13:20,220 --> 00:13:24,660
to the second test of
these theories, namely,

269
00:13:24,660 --> 00:13:29,040
you can study Newton's law
at very short distances.

270
00:13:29,040 --> 00:13:33,210
So when I started talking

about this possibility in 1990,

271
00:13:33,210 --> 00:13:36,150
several of these in
particular colleagues of mine

272
00:13:36,150 --> 00:13:40,380
at Stanford were inspired,
experimental colleagues,

273
00:13:40,380 --> 00:13:43,890
and we started talking about
them testing Newton's law.

274
00:13:43,890 --> 00:13:47,700
We spoke for a long time,
maybe a couple of years,

275
00:13:47,700 --> 00:13:50,160
with a friend of mine, Aharon Kapitulnik.

276
00:13:50,160 --> 00:13:51,690
And we have good friends,

277
00:13:51,690 --> 00:13:54,660
we have dinners together and
we drink good wine together.

278
00:13:54,660 --> 00:13:59,610
So it was at that setting
that we started talking about

279
00:13:59,610 --> 00:14:02,520
these very wild and speculative ideas,

280
00:14:02,520 --> 00:14:04,080
and he decided to test them.

281
00:14:04,080 --> 00:14:08,100

And he and several other
people around the world

282
00:14:08,100 --> 00:14:10,470
started looking and today,

283
00:14:10,470 --> 00:14:14,370
the force of gravity that
Newton say inverse square law

284
00:14:14,370 --> 00:14:16,140
has been tested,

285
00:14:16,140 --> 00:14:19,380
done with distance of
about a hundred microns.

286
00:14:19,380 --> 00:14:23,250
So far smaller than a centimeter,
which used to be the case.

287
00:14:23,250 --> 00:14:25,710
And now there is enormous amount of effort

288
00:14:25,710 --> 00:14:28,950
to test it at shorter
and shorter distances.

289
00:14:28,950 --> 00:14:31,950
Now, what does this have to
do with extra dimensions?

290
00:14:31,950 --> 00:14:34,440
Well, if there is extra dimensions,

291
00:14:34,440 --> 00:14:37,890
the so-called, 'inverse
square law,' will be modified.

292

00:14:37,890 --> 00:14:41,100
For example, if instead of
three spatial dimensions

293
00:14:41,100 --> 00:14:42,390
you have a fourth,

294
00:14:42,390 --> 00:14:45,510
the inverse square law will
become the inverse cube law.

295
00:14:45,510 --> 00:14:47,280
And if it's two dimensions,

296
00:14:47,280 --> 00:14:51,150
it'll be the inverse fourth
power law, et cetera.

297
00:14:51,150 --> 00:14:54,570
So that's what these
experimentalists are looking for.

298
00:14:54,570 --> 00:14:57,690
A deviation from one over distance square

299
00:14:57,690 --> 00:15:00,480
to one over distance cube
or fourth, et cetera.

300
00:15:00,480 --> 00:15:03,810
And clearly, no such
deviation has been seen,

301
00:15:03,810 --> 00:15:08,310
but people are looking at shorter
and shorter distances now.

302
00:15:08,310 --> 00:15:11,580
And in fact there was
a very nice workshop,

303
00:15:11,580 --> 00:15:14,760
or actually it was a school last week,

304
00:15:14,760 --> 00:15:18,090
where many of these top experimentalists

305
00:15:18,090 --> 00:15:22,650
were giving lectures to
students from all over the world

306
00:15:22,650 --> 00:15:23,670
and to each other.

307
00:15:23,670 --> 00:15:27,150
Actually there were many
professors, experiment and theory,

308
00:15:27,150 --> 00:15:28,620
about the new frontiers,

309
00:15:28,620 --> 00:15:31,470
how to look for such new dimensions.

310
00:15:31,470 --> 00:15:33,930
And this is a very nice story

311
00:15:33,930 --> 00:15:37,560
because it shows you
how a theoretical idea

312
00:15:37,560 --> 00:15:41,400
that can be described
without too much mathematics

313
00:15:41,400 --> 00:15:44,730
can in fact connect with experiment.

314

00:15:44,730 --> 00:15:49,020
Now, part of the reason for
that is 30, 40 years ago,

315
00:15:49,020 --> 00:15:52,980
it would be incredible for
anyone to propose looking for

316
00:15:52,980 --> 00:15:57,980
such small forces at, let's
say, below a hundred microns.

317
00:15:58,020 --> 00:15:59,820
Such new forces has been looked for

318
00:15:59,820 --> 00:16:02,040
down to distance of 40 microns.

319
00:16:02,040 --> 00:16:03,030
To give you an idea,

320
00:16:03,030 --> 00:16:08,030
a hundred microns is smaller
than the width of human hair.

321
00:16:08,040 --> 00:16:13,040
So it's incredible that you
can even conduct an experiment,

322
00:16:13,530 --> 00:16:16,920
let alone a precise experiment
that will measure the force

323
00:16:16,920 --> 00:16:21,920
between two not visible
particles to such a precision.

324
00:16:22,170 --> 00:16:25,140
And so why was this possible?

325
00:16:25,140 --> 00:16:28,410
Definitely it was impossible 50 years ago.

326
00:16:28,410 --> 00:16:30,690
Microtechnology. In other words,

327
00:16:30,690 --> 00:16:33,810
there has been a driving force in part

328
00:16:33,810 --> 00:16:35,670
because of application

329
00:16:35,670 --> 00:16:40,080
to manipulate things at
extremely short distances.

330
00:16:40,080 --> 00:16:42,630
And over the last several decades,

331
00:16:42,630 --> 00:16:45,660
experimental physicists have
been at the forefront of this

332
00:16:45,660 --> 00:16:48,150
manipulation of the very small.

333
00:16:48,150 --> 00:16:49,590
When they started doing that,

334
00:16:49,590 --> 00:16:51,750
their objective was not to test gravity.

335
00:16:51,750 --> 00:16:54,450
I don't think there would be
enough money (Colin laughing)

336
00:16:54,450 --> 00:16:59,450
funding such an effort from the

physics of 40, 50 years ago.

337
00:17:00,330 --> 00:17:03,000
Usually, physicists like to emphasize

338
00:17:03,000 --> 00:17:06,570
how physics makes our lives better.

339
00:17:06,570 --> 00:17:09,960
We have all of technology, electricity,

340
00:17:09,960 --> 00:17:12,990
and how useful quantum mechanics has been,

341
00:17:12,990 --> 00:17:14,550
lasers, et cetera.

342
00:17:14,550 --> 00:17:16,380
But there is also, of course, the converse

343
00:17:16,380 --> 00:17:20,190
where technology allows
physics to progress,

344
00:17:20,190 --> 00:17:22,410
and these things go hand in hand.

345
00:17:22,410 --> 00:17:26,310
So when I started to
think about this in 1990s

346
00:17:26,310 --> 00:17:30,480
and started talking to my
good experimental friends,

347
00:17:30,480 --> 00:17:32,820
partly motivator for social reasons

348

00:17:32,820 --> 00:17:36,450
to have a good time on
the weekends, et cetera.

349
00:17:36,450 --> 00:17:39,480
Then I realized, "Oh my god,
these people are amazing!"

350
00:17:39,480 --> 00:17:40,380
I couldn't believe it.

351
00:17:40,380 --> 00:17:42,870
They can look at a hundred microns

352
00:17:42,870 --> 00:17:45,630
smaller than the width of a human hair.

353
00:17:45,630 --> 00:17:46,980
Yeah, just by all means do it.

354
00:17:46,980 --> 00:17:50,010
So they went from a centimeter,
which you can visualize,

355
00:17:50,010 --> 00:17:52,080
to extremely small distances

356
00:17:52,080 --> 00:17:54,780
and they'll be progressing further.

357
00:17:54,780 --> 00:17:59,780
I actually think this paradigm
sort of summarizes much of,

358
00:17:59,850 --> 00:18:01,800
I mean this is sort of
at the highest level,

359
00:18:01,800 --> 00:18:03,240

summarizes though,

360
00:18:03,240 --> 00:18:07,110
the interplay between
theoretical ideas and technology

361
00:18:07,110 --> 00:18:10,950
and experimental progress
and the back and forth.

362
00:18:10,950 --> 00:18:12,240
- You mentioned a few minutes ago,

363
00:18:12,240 --> 00:18:13,563
the term, 'naturalness.'
- Yes.

364
00:18:13,563 --> 00:18:16,290
- It's not one that I've
come across very often.

365
00:18:16,290 --> 00:18:19,080
Can you explain how that sort
of fits into this picture?

366
00:18:19,080 --> 00:18:21,990
- Yeah, so the way it
fits into the picture,

367
00:18:21,990 --> 00:18:25,890
I can explain in the context
of the hierarchy problem.

368
00:18:25,890 --> 00:18:26,910
So let's back up.

369
00:18:26,910 --> 00:18:31,740
So the hierarchy problem was
the problem of understanding

370
00:18:31,740 --> 00:18:34,860
why gravity is so weak.

371
00:18:34,860 --> 00:18:36,750
So the connection is,

372
00:18:36,750 --> 00:18:39,840
if there are extra dimensions of space

373
00:18:39,840 --> 00:18:44,100
in which all elementary
particles that we know of,

374
00:18:44,100 --> 00:18:44,933
electrons, protons, all the forces,

375
00:18:44,933 --> 00:18:49,470
the other forces we know,
electricity, magnetism, et cetera,

376
00:18:49,470 --> 00:18:51,840
are constrained to this
three-dimensional space.

377
00:18:51,840 --> 00:18:55,110
This three-dimensional
space we call our universe.

378
00:18:55,110 --> 00:18:57,420
Now if gravity is not constrained

379
00:18:57,420 --> 00:18:58,800
to this three-dimensional place,

380
00:18:58,800 --> 00:19:02,040
but it spreads into the extra dimensions,

381
00:19:02,040 --> 00:19:05,460

then it'll dilute its strength
and it'll become weaker.

382
00:19:05,460 --> 00:19:07,050
Now how weak? Well,

383
00:19:07,050 --> 00:19:09,960
it depends on the size
of the extra dimensions.

384
00:19:09,960 --> 00:19:12,270
The bigger the size of
the extra dimensions

385
00:19:12,270 --> 00:19:14,610
or the more extra dimensions you have,

386
00:19:14,610 --> 00:19:18,870
the more rapidly you dilute
the strength of gravity.

387
00:19:18,870 --> 00:19:21,870
So in fact, you can infer

388
00:19:21,870 --> 00:19:24,840
some relation between the
size of the extra dimensions

389
00:19:24,840 --> 00:19:27,300
and the weakness of gravity.

390
00:19:27,300 --> 00:19:28,620
So that's the connection.

391
00:19:28,620 --> 00:19:33,300
The gravity is weak because
there is a large amount of space

392
00:19:33,300 --> 00:19:34,890

in extra dimensions

393
00:19:34,890 --> 00:19:37,230
inside which gravity dilutes its strength.

394
00:19:37,230 --> 00:19:38,063
- Okay.

395
00:19:38,063 --> 00:19:40,073
- That's the connection.

396
00:19:40,073 --> 00:19:42,810
So what used to be, and you know,

397
00:19:42,810 --> 00:19:46,200
40 decimals now translates to

398
00:19:46,200 --> 00:19:49,950
how many extra dimensions you
have and how big they are.

399
00:19:49,950 --> 00:19:51,780
They cannot be ultra small,

400
00:19:51,780 --> 00:19:55,680
but they can be even
as small as 10 microns,

401
00:19:55,680 --> 00:19:56,910
a hundred microns,

402
00:19:56,910 --> 00:20:01,440
and still explain the dilution
or the weakness of gravity.

403
00:20:01,440 --> 00:20:05,640
So naturalness came because
you transcribe the problem,

404
00:20:05,640 --> 00:20:08,640
which look like a 40
decimal problem to some

405
00:20:08,640 --> 00:20:12,330
geometric problem that
you can imagine solving.

406
00:20:12,330 --> 00:20:15,840
So that's an example of an
approach to the natural.

407
00:20:15,840 --> 00:20:18,720
Now there are, I don't want
to get, because I'm not,

408
00:20:18,720 --> 00:20:21,480
it's not my field, but in
other fields, for example,

409
00:20:21,480 --> 00:20:23,880
in biology, in some sense,

410
00:20:23,880 --> 00:20:28,650
Darwin's theory made many
of the biological wonders.

411
00:20:28,650 --> 00:20:32,490
So what seems unimaginably
complicated, like a human being,

412
00:20:32,490 --> 00:20:37,490
where millions of things
have to work synchronously,

413
00:20:37,890 --> 00:20:42,030
very precisely, can think, the
heart, the mind, everything,

414

00:20:42,030 --> 00:20:44,520
this become a natural consequence

415
00:20:44,520 --> 00:20:47,220
of what's called, "Evolution."
- Mm-hmm (affirmative).

416
00:20:47,220 --> 00:20:50,460
- Now not everybody buys
that, but scientifically,

417
00:20:50,460 --> 00:20:54,150
I think there is no question
that that's a valid theory.

418
00:20:54,150 --> 00:20:55,650
So that's another example

419
00:20:55,650 --> 00:20:58,140
where you take an incredible mystery,

420
00:20:58,140 --> 00:21:00,960
you look at it from a
different perspective

421
00:21:00,960 --> 00:21:03,420
where this mystery looks more natural.

422
00:21:03,420 --> 00:21:04,740
- Mm-hmm (affirmative).
- In physics,

423
00:21:04,740 --> 00:21:07,500
it usually has to do with
explaining big numbers.

424
00:21:07,500 --> 00:21:12,480
Numbers that are about are
like 1 or 10 or a 10th,

425
00:21:12,480 --> 00:21:13,920
we feel, "Oh, okay,

426
00:21:13,920 --> 00:21:18,270
well such and such is about as
big as such and such, okay."

427
00:21:18,270 --> 00:21:21,900
But when you have
disparities of many, many,

428
00:21:21,900 --> 00:21:25,320
many orders of magnitude,
they beg for an explanation.

429
00:21:25,320 --> 00:21:28,050
And the other example of this,

430
00:21:28,050 --> 00:21:30,930
is the enormity of the universe,

431
00:21:30,930 --> 00:21:33,780
or the so-called, 'cosmological
constant problem.'

432
00:21:33,780 --> 00:21:35,880
- That's a question I've been dying to ask

433
00:21:35,880 --> 00:21:37,530
a physicist is,
- Yes, please.

434
00:21:37,530 --> 00:21:39,063
why is the universe so big?

435
00:21:39,900 --> 00:21:41,700
- So the universe, why it's so big...

436

00:21:41,700 --> 00:21:45,240
First of all, how big it is,
as we were saying before,

437
00:21:45,240 --> 00:21:48,810
if you compare it to the
size of anatomic nucleus,

438
00:21:48,810 --> 00:21:52,290
it's again, about 40 orders
of magnitude bigger than

439
00:21:52,290 --> 00:21:56,040
the size of anatomic nucleus.
- Mm-hmm (affirmative).

440
00:21:56,040 --> 00:21:57,690
Again, it begs for a mystery.

441
00:21:57,690 --> 00:22:01,470
You start, if you wish, with
a theory that has nuclei

442
00:22:01,470 --> 00:22:05,066
and electrons and atoms
and all of a sudden,

443
00:22:05,066 --> 00:22:08,340
you have this enormous universe
that supposedly follows

444
00:22:08,340 --> 00:22:12,270
from the same equations
that have this tiny nuclei,

445
00:22:12,270 --> 00:22:14,070
et cetera. How can this be?

446
00:22:14,070 --> 00:22:16,710
This problem has many, many facets

447
00:22:16,710 --> 00:22:19,350
and I cannot do justice to it.

448
00:22:19,350 --> 00:22:20,670
I'll just tell you that

449
00:22:20,670 --> 00:22:22,530
there is no solution to this problem.

450
00:22:22,530 --> 00:22:26,730
At least there is no solution
within the usual framework

451
00:22:26,730 --> 00:22:29,100
that science proceeds,

452
00:22:29,100 --> 00:22:32,820
where you write down the
laws of nature which means,

453
00:22:32,820 --> 00:22:37,820
some equations that dictate
how the universe works.

454
00:22:38,190 --> 00:22:39,877
And then you can derive that,

455
00:22:39,877 --> 00:22:43,110
"Oh, therefore, the universe is large."

456
00:22:43,110 --> 00:22:46,230
There is no mathematical theory of this.

457
00:22:46,230 --> 00:22:50,280
There is a very controversial
approach to this problem,

458

00:22:50,280 --> 00:22:55,280
which was proposed back in
1987 by more than one person,

459
00:22:56,220 --> 00:22:59,407
but in particular, a very
well known physicist called,

460
00:22:59,407 --> 00:23:03,120
"Steven Weinberg," who just
passed over a year ago.

461
00:23:03,120 --> 00:23:07,117
The basic idea there is
embedded in what's called,

462
00:23:07,117 --> 00:23:09,510
"The idea of the multiverse."

463
00:23:09,510 --> 00:23:12,060
But before I take you back
to what's the multiverse,

464
00:23:12,060 --> 00:23:14,490
I want to draw an analog.

465
00:23:14,490 --> 00:23:19,320
And this goes back again to
some ancient Greek physicist

466
00:23:19,320 --> 00:23:20,370
called, "Aristochos."

467
00:23:21,270 --> 00:23:25,500
Aristochos was one of the
first people that believed

468
00:23:25,500 --> 00:23:27,873
there were many, many solar systems.

469
00:23:28,770 --> 00:23:31,890
That was not a very popular idea,

470
00:23:31,890 --> 00:23:35,610
either at the time of
Aristochos or even in 1600,

471
00:23:35,610 --> 00:23:40,440
when what we call,
"Modern science," emerged.

472
00:23:40,440 --> 00:23:42,720
Most people, even by 1600,

473
00:23:42,720 --> 00:23:45,960
believe that there was
only one solar system.

474
00:23:45,960 --> 00:23:47,520
That was it.

475
00:23:47,520 --> 00:23:51,300
So then, in the context of
these many mysteries up here,

476
00:23:51,300 --> 00:23:53,790
if you believe there is one solar system,

477
00:23:53,790 --> 00:23:57,270
it looks amazing that that solar system,

478
00:23:57,270 --> 00:24:00,300
in particular, the
planet Earth and the sun,

479
00:24:00,300 --> 00:24:03,240
the distance between
the earth and the sun,

480
00:24:03,240 --> 00:24:07,440
were made just perfectly
to allow the conditions

481
00:24:07,440 --> 00:24:10,500
on earth to be friendly to our existence.

482
00:24:10,500 --> 00:24:12,870
For example, if we were
a few percent closer,

483
00:24:12,870 --> 00:24:16,230
a few percent further than the sun,

484
00:24:16,230 --> 00:24:18,450
the earth would either boil or freeze

485
00:24:18,450 --> 00:24:20,220
and we wouldn't be around.

486
00:24:20,220 --> 00:24:22,590
The chemical compounds
that we see on earth

487
00:24:22,590 --> 00:24:25,170
are just exactly what we need

488
00:24:25,170 --> 00:24:27,780
to exist and to flourish, et cetera.

489
00:24:27,780 --> 00:24:31,020
So it looks like, again,
there is some, you know,

490
00:24:31,020 --> 00:24:33,813
higher intelligence that
really cares for us. Ah,

491

00:24:34,931 --> 00:24:36,312
- Like turning a knob until they...

492
00:24:36,312 --> 00:24:37,687
- Turning a knob.
- Just right.

493
00:24:37,687 --> 00:24:39,900
- Exactly right. Oh, okay.

494
00:24:39,900 --> 00:24:42,315
Oh, we don't have Savas,
so let me go back.

495
00:24:42,315 --> 00:24:44,160
(all laughing)

496
00:24:44,160 --> 00:24:48,213
So it looks like a miracle in many ways,

497
00:24:49,050 --> 00:24:53,103
considering how much
it takes to have life.

498
00:24:53,970 --> 00:24:55,860
And this point of view is very popular.

499
00:24:55,860 --> 00:24:59,550
It was obviously also
popular with the church.

500
00:24:59,550 --> 00:25:01,740
There is some deity that really cares.

501
00:25:01,740 --> 00:25:03,690
That's why everything was made perfectly

502
00:25:03,690 --> 00:25:05,283
for our existence, et cetera.

503
00:25:06,150 --> 00:25:11,150
Then in 1600, there was a
priest called, "Giordano Bruno,"

504
00:25:12,930 --> 00:25:17,930
from Italy, who really believed
in our Aristochos's ideas,

505
00:25:18,270 --> 00:25:21,990
and he started discussing them in public.

506
00:25:21,990 --> 00:25:26,990
And eventually, he was burnt
at the stake for his beliefs.

507
00:25:27,000 --> 00:25:29,520
He was burned at the stake in 600.

508
00:25:29,520 --> 00:25:33,203
Galileo was almost burned
at the stake around 1630s.

509
00:25:34,770 --> 00:25:39,330
Galileo died in 1642 and
Newton was born in 1642.

510
00:25:39,330 --> 00:25:40,980
So that was really the beginning

511
00:25:40,980 --> 00:25:43,890
of the renaissance of science.

512
00:25:43,890 --> 00:25:47,365
And so many ideas in many ways
they went back to Aristochos.

513
00:25:47,365 --> 00:25:48,780
Aristochos who actually could argue

514
00:25:48,780 --> 00:25:51,420
that the lights that we see in the sky

515
00:25:51,420 --> 00:25:53,700
are actually solar systems,

516
00:25:53,700 --> 00:25:55,410
and because they're so far

517
00:25:55,410 --> 00:25:57,240
you can't tell that they're moving,

518
00:25:57,240 --> 00:25:58,710
but they're moving, et cetera.

519
00:25:58,710 --> 00:26:00,648
So they started going back,

520
00:26:00,648 --> 00:26:03,420
and then Galileo, of course, invented,

521
00:26:03,420 --> 00:26:05,580
or co-invented, the telescope.

522
00:26:05,580 --> 00:26:08,310
And people started looking at planets,

523
00:26:08,310 --> 00:26:10,560
which had moons around them.

524
00:26:10,560 --> 00:26:12,300
And then they said, "Okay,

525
00:26:12,300 --> 00:26:15,030
it looks like things like our solar system

526

00:26:15,030 --> 00:26:17,400
actually are probably out there,"

527
00:26:17,400 --> 00:26:21,540
and they started making
observations, so modern science.

528
00:26:21,540 --> 00:26:23,820
And now, of course, if you ask anybody yet

529
00:26:23,820 --> 00:26:26,580
now, of course, there
is many solar systems.

530
00:26:26,580 --> 00:26:29,760
In fact, if you take
the number of galaxies,

531
00:26:29,760 --> 00:26:34,760
there is about a hundred billion galaxies,

532
00:26:34,800 --> 00:26:38,280
and each one has about
a hundred billion stars,

533
00:26:38,280 --> 00:26:40,800
10 to the 22 stars, again,

534
00:26:40,800 --> 00:26:44,910
and 1 with 22 zeros,
stars in the universe.

535
00:26:44,910 --> 00:26:49,650
And most stars have
planets. We are not unique.

536
00:26:49,650 --> 00:26:52,560
So the chance is that when
you have such a huge number

537
00:26:52,560 --> 00:26:56,220
of stars that senses that in some of them

538
00:26:56,220 --> 00:26:59,730
there are friendly conditions

539
00:26:59,730 --> 00:27:02,550
that allow life like our own,

540
00:27:02,550 --> 00:27:05,250
or maybe quite different than our own,

541
00:27:05,250 --> 00:27:07,950
to exist is extremely likely.

542
00:27:07,950 --> 00:27:09,210
It hasn't been proven

543
00:27:09,210 --> 00:27:12,120
because we haven't made an observation.

544
00:27:12,120 --> 00:27:13,380
It hasn't been proven yet,

545
00:27:13,380 --> 00:27:17,190
but I think most scientists
believe that it's very likely

546
00:27:17,190 --> 00:27:20,940
that conditions similar to
our own or even different,

547
00:27:20,940 --> 00:27:23,250
has allowed the evolution of intelligence

548
00:27:23,250 --> 00:27:25,560
and life in other places.
- Mm-hmm (affirmative).

549
00:27:25,560 --> 00:27:29,730
- So notice what happened
that what used to be unnatural

550
00:27:29,730 --> 00:27:32,700
or required great care,

551
00:27:32,700 --> 00:27:36,210
namely the occurrence
of life in the universe,

552
00:27:36,210 --> 00:27:39,600
is by changing your
perspective and, of course,

553
00:27:39,600 --> 00:27:41,394
encouraged by observations,

554
00:27:41,394 --> 00:27:46,350
it became something not just
palatable but very likely.

555
00:27:46,350 --> 00:27:50,260
So that's an example of
how a change of perspective

556
00:27:51,450 --> 00:27:53,760
converts something that looks miraculous

557
00:27:53,760 --> 00:27:56,220
to something that looks natural.

558
00:27:56,220 --> 00:27:59,850
- That's all within our
own known Universe, right?

559
00:27:59,850 --> 00:28:00,683
- Exactly.

- Okay.

560
00:28:00,683 --> 00:28:02,850
- So now we are taking the next step.

561
00:28:02,850 --> 00:28:04,050
- Okay.

562
00:28:04,050 --> 00:28:08,070
- So we go back to, why
is our universe so large?

563
00:28:08,070 --> 00:28:11,850
Now this is correlated with, as I said,

564
00:28:11,850 --> 00:28:14,520
what's called a, "Cosmological
constant problem."

565
00:28:14,520 --> 00:28:17,520
The cosmological constant is essentially

566
00:28:17,520 --> 00:28:22,520
the energy density that is in
the vacuum of the universe.

567
00:28:22,740 --> 00:28:27,120
This is an energy density
that we are not aware of,

568
00:28:27,120 --> 00:28:29,370
but in principle it's there.

569
00:28:29,370 --> 00:28:30,870
And in fact, if it was there,

570
00:28:30,870 --> 00:28:33,270
there are measurable consequences.

571
00:28:33,270 --> 00:28:35,550
The energy of the vacuum...

572
00:28:35,550 --> 00:28:37,429
If you ask any theorist,

573
00:28:37,429 --> 00:28:41,250
what would you think the
energy of the vacuum is?

574
00:28:41,250 --> 00:28:43,680
They would pull out pencil
and paper and say, "Oh,

575
00:28:43,680 --> 00:28:46,200
it's probably this number."

576
00:28:46,200 --> 00:28:48,690
And the number that they would get

577
00:28:48,690 --> 00:28:52,110
is 120 orders of magnitude

578
00:28:52,110 --> 00:28:54,870
larger than what it actually is.

579
00:28:54,870 --> 00:28:57,720
And what it actually is, is not zero.

580
00:28:57,720 --> 00:29:01,650
Has been measured back in
the 90s, very precisely,

581
00:29:01,650 --> 00:29:04,500
by astrophysicists and cosmologists

582
00:29:04,500 --> 00:29:08,670
because it has consequences

on how the universe expands

583
00:29:08,670 --> 00:29:11,790
or if it expands or
contracts, how rapidly.

584
00:29:11,790 --> 00:29:14,340
So with cosmological observation,

585
00:29:14,340 --> 00:29:18,990
looking at how far away
objects like supernovas

586
00:29:18,990 --> 00:29:23,550
recede from us, how rapidly
they move away from us,

587
00:29:23,550 --> 00:29:26,247
you can tell if there was
cosmological constant or not.

588
00:29:26,247 --> 00:29:30,660
And it's 120 orders of magnitude smaller

589
00:29:30,660 --> 00:29:32,010
than it should have been

590
00:29:32,010 --> 00:29:36,330
by just taking what you know
in your theory and computing.

591
00:29:36,330 --> 00:29:40,590
So very much like, and
very closely related to,

592
00:29:40,590 --> 00:29:43,220
the fact that the size of the universe

593
00:29:43,220 --> 00:29:46,410

is 40 orders of magnitude bigger

594
00:29:46,410 --> 00:29:48,750
than the size of an atomic nucleus.

595
00:29:48,750 --> 00:29:52,140
So they're very closely
connected problems.

596
00:29:52,140 --> 00:29:54,510
And finally, a few physicists,

597
00:29:54,510 --> 00:29:57,877
and together with Steven Weinberg said,

598
00:29:57,877 --> 00:30:00,330
"There is many, many universes."

599
00:30:00,330 --> 00:30:02,400
All of these universes
have different value

600
00:30:02,400 --> 00:30:04,410
of the cosmological constant.

601
00:30:04,410 --> 00:30:06,810
Some are big, some are small, et cetera.

602
00:30:06,810 --> 00:30:09,900
When you have cosmological constant,

603
00:30:09,900 --> 00:30:12,840
that affects how the universe expands.

604
00:30:12,840 --> 00:30:15,690
So if you have too much,
it expands very rapidly.

605

00:30:15,690 --> 00:30:17,853
So if you have small enough,

606
00:30:19,005 --> 00:30:20,950
then it expands slowly enough

607
00:30:22,021 --> 00:30:25,380
to allow for galaxies to form.

608
00:30:25,380 --> 00:30:28,440
Our planetary system belongs to a galaxy,

609
00:30:28,440 --> 00:30:31,470
and stars and their
planets are in galaxies.

610
00:30:31,470 --> 00:30:34,110
So galaxies are very important

611
00:30:34,110 --> 00:30:38,410
because they're relatively
dense structures

612
00:30:39,520 --> 00:30:42,390
that allow stars to form.

613
00:30:42,390 --> 00:30:43,770
And stars are important

614
00:30:43,770 --> 00:30:46,020
because there are planets around stars

615
00:30:46,020 --> 00:30:48,420
and that's where life forms.

616
00:30:48,420 --> 00:30:50,550
Life benefits from having

617

00:30:50,550 --> 00:30:53,760
the heat of the stars provide energy,

618
00:30:53,760 --> 00:30:55,230
so it's important for life.

619
00:30:55,230 --> 00:30:58,740
Galaxies are important for life
because we live on planets.

620
00:30:58,740 --> 00:31:00,300
Planets are near the sun.

621
00:31:00,300 --> 00:31:01,230
They draw energy,

622
00:31:01,230 --> 00:31:05,430
and stars like our own
sun belong to galaxies.

623
00:31:05,430 --> 00:31:10,430
So if the cosmological constant
was any bigger than it is,

624
00:31:11,010 --> 00:31:13,020
then galaxies wouldn't form.

625
00:31:13,020 --> 00:31:16,560
So we wouldn't have stars
and we wouldn't have planets,

626
00:31:16,560 --> 00:31:19,200
we wouldn't have life.

627
00:31:19,200 --> 00:31:21,150
So to do that,

628
00:31:21,150 --> 00:31:23,370
Weinberg had to postulate the existence

629
00:31:23,370 --> 00:31:26,760
of many, many, many, many
universes. (chuckling)

630
00:31:26,760 --> 00:31:27,720
And again,

631
00:31:27,720 --> 00:31:32,310
the number of these universes
is enormous that you need,

632
00:31:32,310 --> 00:31:36,120
because the cosmological
constant is so much smaller

633
00:31:36,120 --> 00:31:37,530
than its natural value,

634
00:31:37,530 --> 00:31:41,580
which would've been 120
orders of magnitude bigger.

635
00:31:41,580 --> 00:31:45,270
So this was the proposal in '87.

636
00:31:45,270 --> 00:31:50,070
And in fact, using this
idea, he derived a prediction

637
00:31:50,070 --> 00:31:54,930
for how big the cosmological
constant should be,

638
00:31:54,930 --> 00:31:56,820
because if it's any bigger than that,

639
00:31:56,820 --> 00:31:59,160
galaxies cannot form,

640
00:31:59,160 --> 00:32:02,010
but there is no reason
why it should be smaller

641
00:32:02,010 --> 00:32:06,510
than the maximum it could be
to allow for our existence.

642
00:32:06,510 --> 00:32:08,697
So he made the prediction in '87

643
00:32:08,697 --> 00:32:11,490
and the prediction sure
enough was confirmed

644
00:32:11,490 --> 00:32:14,700
within a factor of an order of magnitude,

645
00:32:14,700 --> 00:32:18,870
which is not considering
the range of the prediction

646
00:32:18,870 --> 00:32:21,180
that it predicts a quantity

647
00:32:21,180 --> 00:32:24,270
that is off by 120 orders of magnitude.

648
00:32:24,270 --> 00:32:27,060
But it did something within a factor of 10

649
00:32:27,060 --> 00:32:30,900
and it turned out to be what
the cosmological constant.

650
00:32:30,900 --> 00:32:34,470
So it looks like our universe is tuned.

651
00:32:34,470 --> 00:32:39,120
It doesn't have as big a
cosmological constant as it could

652
00:32:39,120 --> 00:32:40,440
because it would be crazy.

653
00:32:40,440 --> 00:32:43,020
The universe would be
expanding at an enormous speed.

654
00:32:43,020 --> 00:32:45,930
We wouldn't, not even atoms would form,

655
00:32:45,930 --> 00:32:48,960
let alone galaxies and stars, et cetera.

656
00:32:48,960 --> 00:32:50,943
So it's not as big as it could be.

657
00:32:50,943 --> 00:32:54,030
It's smaller and smaller
and smaller, far smaller.

658
00:32:54,030 --> 00:32:56,610
It's 120 orders of magnitude smaller,

659
00:32:56,610 --> 00:32:57,690
but that's when you stop.

660
00:32:57,690 --> 00:33:00,180
The moment it's 120
orders magnitude smaller,

661
00:33:00,180 --> 00:33:02,190
you form life and that's you stop.

662
00:33:02,190 --> 00:33:06,120

So in fact, he proposed it
as a way to test his theory

663
00:33:06,120 --> 00:33:09,960
just about 10 years before it was tested,

664
00:33:09,960 --> 00:33:13,950
because the idea was
exceedingly unpopular in 1987.

665
00:33:13,950 --> 00:33:17,103
In fact, I remember
'cause I was visiting him.

666
00:33:18,059 --> 00:33:20,704
It was October 19th, 1987,

667
00:33:20,704 --> 00:33:22,290
'cause the same day I was visiting him,

668
00:33:22,290 --> 00:33:24,660
there was a big stock market crash.

669
00:33:24,660 --> 00:33:27,330
And I was giving a talk
(both laughing)

670
00:33:27,330 --> 00:33:30,600
at the University of Texas where he was.

671
00:33:30,600 --> 00:33:34,230
So he showed me his theory and I said,

672
00:33:34,230 --> 00:33:37,350
of course, I was very polite,
"Oh interesting," et cetera.

673
00:33:37,350 --> 00:33:41,119
But I said, "Oh, the old

man has completely lost it."

674
00:33:41,119 --> 00:33:42,840
(all chuckling)

675
00:33:42,840 --> 00:33:44,880
My definition of old back then,

676
00:33:44,880 --> 00:33:46,503
I think he was like 56 or 50.

677
00:33:49,170 --> 00:33:52,260
Yeah, he was in fact, yeah, 55 back then.

678
00:33:52,260 --> 00:33:56,040
Old by my then standards and
I think he was ultra young.

679
00:33:56,040 --> 00:33:58,567
But he tells me this thing,

680
00:33:58,567 --> 00:34:01,020
"Many universe in my head is spinning."

681
00:34:01,020 --> 00:34:03,090
And I say, "Oh, I understand."

682
00:34:03,090 --> 00:34:05,520
He's about to die pretty soon.

683
00:34:05,520 --> 00:34:09,510
He wants this big questions
answered. (laughing)

684
00:34:09,510 --> 00:34:13,770
And what can you do? Yes, sleep a lot.

685
00:34:13,770 --> 00:34:16,327

And I wasn't alone, I
think everybody thought,

686
00:34:16,327 --> 00:34:19,890
"Hey, Weinberg has lost it."
(chuckling)

687
00:34:19,890 --> 00:34:24,270
He was viewed until the
end of his life as a major,

688
00:34:24,270 --> 00:34:28,320
if not thee major physicist of his time.

689
00:34:28,320 --> 00:34:30,870
So he seems to have been right,

690
00:34:30,870 --> 00:34:33,390
at least with the numerical prediction.

691
00:34:33,390 --> 00:34:38,390
Whether the multiverse exists
is exceedingly controversial

692
00:34:39,120 --> 00:34:40,140
for several reasons.

693
00:34:40,140 --> 00:34:43,590
One is, the number of
universes you need to explain

694
00:34:43,590 --> 00:34:46,230
this cosmological constant is enormous.

695
00:34:46,230 --> 00:34:48,270
Now we are talking about really enormous,

696
00:34:48,270 --> 00:34:52,470
like 10 to the 120, 10 to

the hundred 30 universes,

697
00:34:52,470 --> 00:34:54,329
you know, one with the hundred 20.

698
00:34:54,329 --> 00:34:57,180
This is sort of the
minimum number you need

699
00:34:57,180 --> 00:34:59,310
to begin to explain the cosmology.

700
00:34:59,310 --> 00:35:01,650
- This sounds like the
opposite of naturalness.

701
00:35:01,650 --> 00:35:05,287
- Exactly, so in a sense the complaint is,

702
00:35:05,287 --> 00:35:07,440
"My God, you transcribe the problem

703
00:35:07,440 --> 00:35:09,630
to a different large number,

704
00:35:09,630 --> 00:35:12,960
and unless you have a sort of theory,

705
00:35:12,960 --> 00:35:15,540
how are so many universes created,

706
00:35:15,540 --> 00:35:18,570
you haven't made progress.
It's a great point.

707
00:35:18,570 --> 00:35:20,610
That's one of the reasons.

708

00:35:20,610 --> 00:35:22,710
And then the controversy get even stronger

709
00:35:22,710 --> 00:35:25,890
because there is a very
speculative, again,

710
00:35:25,890 --> 00:35:28,710
controversial theory
called, "String theory,"

711
00:35:28,710 --> 00:35:30,210
which turns out,

712
00:35:30,210 --> 00:35:34,200
it can predict the existence
of so many universes.

713
00:35:34,200 --> 00:35:36,960
However, it's already
a controversial theory,

714
00:35:36,960 --> 00:35:38,340
the fact that...

715
00:35:38,340 --> 00:35:40,710
So it's very much an open question

716
00:35:40,710 --> 00:35:43,290
and the question in the end in science

717
00:35:43,290 --> 00:35:47,830
are not decided by conversation
or writing down formula

718
00:35:49,068 --> 00:35:53,310
or the prestige of the
person who made the proposal

719

00:35:53,310 --> 00:35:56,040
and whether they have
a Nobel Prize or not.

720
00:35:56,040 --> 00:35:57,510
This don't count for anything.

721
00:35:57,510 --> 00:35:59,883
It has to be experiment in the end.

722
00:36:00,764 --> 00:36:03,210
The one piece of experimental evidence

723
00:36:03,210 --> 00:36:06,543
for Weinberg's multiverse was,

724
00:36:07,410 --> 00:36:09,870
of course, the fact that
the cosmological constant

725
00:36:09,870 --> 00:36:12,660
was measured to be what he had predicted.

726
00:36:12,660 --> 00:36:14,760
But you need more than that in science,

727
00:36:14,760 --> 00:36:17,340
especially with such big ideas.

728
00:36:17,340 --> 00:36:22,340
So there are some proposals
on how to test this idea.

729
00:36:22,950 --> 00:36:25,260
One is called, "Split supersymmetry,"

730
00:36:25,260 --> 00:36:27,990
that I was involved with.

731
00:36:27,990 --> 00:36:31,440
However, even if you
see split supersymmetry,

732
00:36:31,440 --> 00:36:34,920
I don't think it'll be enough
to prove the multiverse.

733
00:36:34,920 --> 00:36:36,120
You need many more data.

734
00:36:36,120 --> 00:36:38,460
And the problem is the idea,

735
00:36:38,460 --> 00:36:40,590
it's not obvious what to go and measure.

736
00:36:40,590 --> 00:36:45,590
For example, when Aristochos
and Giordano Bruno, et cetera,

737
00:36:46,200 --> 00:36:50,790
postulated the many
solar systems hypothesis,

738
00:36:50,790 --> 00:36:52,980
multi solar systems,

739
00:36:52,980 --> 00:36:56,140
eventually there was a
discovery of the telescope

740
00:36:57,580 --> 00:37:02,490
which allowed you to begin
this path towards discovering

741
00:37:02,490 --> 00:37:04,680
that there is much more
in the universe out there.

742
00:37:04,680 --> 00:37:07,620
Those sort of blinking lights
are not there for decor.

743
00:37:07,620 --> 00:37:09,600
In fact, they're a world
like us. (Colin chuckling)

744
00:37:09,600 --> 00:37:14,220
Many of them are whole galaxies
so they have 10 to 11 stars.

745
00:37:14,220 --> 00:37:18,450
But there was a way to
progress through experiment,

746
00:37:18,450 --> 00:37:19,350
through observation.

747
00:37:19,350 --> 00:37:22,980
And there is no clear
path through experiment,

748
00:37:22,980 --> 00:37:27,510
through observation to
prove the multiverse so far.

749
00:37:27,510 --> 00:37:30,990
So I think it'll remain controversial for,

750
00:37:30,990 --> 00:37:32,493
I would say maybe,

751
00:37:34,078 --> 00:37:38,880
decades if I'm optimistic
if not more than a century,

752
00:37:38,880 --> 00:37:41,070

which is a very long time scale.

753
00:37:41,070 --> 00:37:43,530
But maybe I'll be proven wrong.

754
00:37:43,530 --> 00:37:44,820
There are other predictions.

755
00:37:44,820 --> 00:37:47,700
There is another idea which
is called, "The axiverse."

756
00:37:47,700 --> 00:37:49,110
I don't want to get into it.

757
00:37:49,110 --> 00:37:52,320
There are other predictions
of having many universes.

758
00:37:52,320 --> 00:37:53,790
- Mm-hmm (affirmative).
- In particular,

759
00:37:53,790 --> 00:37:55,790
the axiverse is the idea that

760
00:37:55,790 --> 00:37:57,480
if there are many universes,

761
00:37:57,480 --> 00:38:00,180
there's also many
particles in our universe,

762
00:38:00,180 --> 00:38:05,180
that again, the conference
that we had last week here

763
00:38:05,190 --> 00:38:07,920
touched upon how you

can go out to discover

764
00:38:07,920 --> 00:38:09,360
this many particles.

765
00:38:09,360 --> 00:38:12,840
So if you see many particles,
you see split supersymmetry,

766
00:38:12,840 --> 00:38:15,600
maybe people will start believing.

767
00:38:15,600 --> 00:38:18,090
I'll be convert very rapidly

768
00:38:18,090 --> 00:38:21,810
because I'm psychologically
prepared for wild ideas.

769
00:38:21,810 --> 00:38:24,210
And that's why I worked on trying to find,

770
00:38:24,210 --> 00:38:26,610
I mean I was involved both
with split supersymmetry

771
00:38:26,610 --> 00:38:30,540
and the axiverse ideas
because I still want to see

772
00:38:30,540 --> 00:38:35,530
how you could test the existence
of many universes and...

773
00:38:35,530 --> 00:38:37,680
- So I really love this
point you've raised

774
00:38:37,680 --> 00:38:41,010

a couple of times about
how the types of questions

775
00:38:41,010 --> 00:38:44,250
we can hope to answer in our theories

776
00:38:44,250 --> 00:38:46,920
really depends on the
technology that we have.

777
00:38:46,920 --> 00:38:49,230
And when I read about your work online,

778
00:38:49,230 --> 00:38:50,880
I've seen the line a few times

779
00:38:50,880 --> 00:38:54,690
that your career in particle
physics spans four decades.

780
00:38:54,690 --> 00:38:57,060
So I would assume that
the types of questions

781
00:38:57,060 --> 00:38:58,380
that you've been able to answer

782
00:38:58,380 --> 00:39:00,150
have evolved a lot throughout your career.

783
00:39:00,150 --> 00:39:02,190
So can you tell us a little bit about this

784
00:39:02,190 --> 00:39:05,550
and how the types of questions
you've been able to study

785
00:39:05,550 --> 00:39:07,530
have changed with technology?

786
00:39:07,530 --> 00:39:09,150
- Yes, yes.

787
00:39:09,150 --> 00:39:14,150
I was trained in the late
70s as a particle physicist.

788
00:39:14,790 --> 00:39:16,710
Again, to give you a perspective,

789
00:39:16,710 --> 00:39:20,310
I'll sort of zoom out to tell you what,

790
00:39:20,310 --> 00:39:22,890
how particle physics started.

791
00:39:22,890 --> 00:39:26,700
So a key day in the history of science,

792
00:39:26,700 --> 00:39:29,100
a key year is 1945.

793
00:39:29,100 --> 00:39:34,100
That's when the public and
politicians and everybody

794
00:39:34,140 --> 00:39:38,310
realized that actually
science has consequences.

795
00:39:38,310 --> 00:39:42,840
It can be used in a bad or in good ways,

796
00:39:42,840 --> 00:39:45,240
but knowledge allows you to do things.

797
00:39:45,240 --> 00:39:48,660

So they started funding
the science very heavily

798
00:39:48,660 --> 00:39:53,660
and that led immediately to
what we call, "Big science."

799
00:39:55,770 --> 00:39:58,350
Big science means, for example,

800
00:39:58,350 --> 00:40:00,600
what are called, "Colliders."

801
00:40:00,600 --> 00:40:05,600
Colliders are, essentially, you
take two beams of particles,

802
00:40:07,170 --> 00:40:09,270
one from the left and one from the right,

803
00:40:09,270 --> 00:40:13,050
and you collide them and
you see what comes out.

804
00:40:13,050 --> 00:40:15,150
And the more the energy, the more,

805
00:40:15,150 --> 00:40:18,480
the faster the particles
go towards each other,

806
00:40:18,480 --> 00:40:22,920
the more energy you have
to produce new particles.

807
00:40:22,920 --> 00:40:25,830
By new, I mean, things that
we are not familiar with,

808

00:40:25,830 --> 00:40:29,670
like the electron or the
proton are familiar particles.

809
00:40:29,670 --> 00:40:31,230
We know them from...

810
00:40:31,230 --> 00:40:36,230
Because we are made out
of nuclei and electrons.

811
00:40:36,330 --> 00:40:39,630
New particles, I mean,
things that live for a very,

812
00:40:39,630 --> 00:40:41,010
the briefest amount of time.

813
00:40:41,010 --> 00:40:44,190
You create them and then they
decay into other particles,

814
00:40:44,190 --> 00:40:45,420
familiar particles.

815
00:40:45,420 --> 00:40:48,240
- Are these collisions that
happen in nature as well

816
00:40:48,240 --> 00:40:51,240
or are you creating things
that only exist in the lab?

817
00:40:51,240 --> 00:40:54,150
- They can happen both
in nature and the lab.

818
00:40:54,150 --> 00:40:58,140
In nature, they happen very far away from,

819
00:40:58,140 --> 00:41:00,933
you need very violent conditions.

820
00:41:00,933 --> 00:41:04,860
Or they happen in what
are called, "Cosmic rays,"

821
00:41:04,860 --> 00:41:06,240
very energetic particles

822
00:41:06,240 --> 00:41:08,910
that have been accelerated
somewhere in the universe.

823
00:41:08,910 --> 00:41:10,320
And they come towards us,

824
00:41:10,320 --> 00:41:15,320
not by intelligent life, but
by astrophysical processes.

825
00:41:15,330 --> 00:41:17,340
But we study them on earth

826
00:41:17,340 --> 00:41:19,680
because you need a lot of collisions

827
00:41:19,680 --> 00:41:21,737
to be able to study what you predict.

828
00:41:21,737 --> 00:41:25,020
And in the universe,
definitely in our location,

829
00:41:25,020 --> 00:41:26,880
there is not a lot of collisions.

830
00:41:26,880 --> 00:41:29,187

You have an occasional
cosmic ray come and hit,

831
00:41:29,187 --> 00:41:31,620
but it'll hit something in the atmosphere.

832
00:41:31,620 --> 00:41:35,820
You won't know it, but they
can happen also naturally.

833
00:41:35,820 --> 00:41:39,450
So you have these collisions,
you study the decay,

834
00:41:39,450 --> 00:41:43,170
the product of these collisions
and that's how you find out,

835
00:41:43,170 --> 00:41:45,600
in some sense, new particles.

836
00:41:45,600 --> 00:41:48,990
Sometimes you find out what
something is made out of.

837
00:41:48,990 --> 00:41:52,440
If you collide nuclei or
an electron, a nucleus,

838
00:41:52,440 --> 00:41:54,960
you find out what's inside the nucleus.

839
00:41:54,960 --> 00:41:59,400
Sometimes you produce a new
particle that was not inside,

840
00:41:59,400 --> 00:42:01,710
but the energy that you produced

841

00:42:01,710 --> 00:42:04,800
allowed you to create
new particles, et cetera.

842
00:42:04,800 --> 00:42:06,300
That's called, "The colliders."

843
00:42:06,300 --> 00:42:09,540
Colliders are very big projects.

844
00:42:09,540 --> 00:42:11,700
An example is a certain collider,

845
00:42:11,700 --> 00:42:16,263
the most recent one in the
Large Hadron Collider at CERN.

846
00:42:17,357 --> 00:42:22,357
And they involve hundreds of
people now working for decades.

847
00:42:24,000 --> 00:42:27,180
It started out working for years now.

848
00:42:27,180 --> 00:42:30,240
The colliders have been
getting bigger and bigger.

849
00:42:30,240 --> 00:42:34,500
To give you an idea, the
Large Hadron Collider at CERN

850
00:42:34,500 --> 00:42:39,150
has a circumference of
26 or so kilometers.

851
00:42:39,150 --> 00:42:41,910
It's about a couple of
hundred meters underground

852
00:42:41,910 --> 00:42:43,770
and it involves magnets

853
00:42:43,770 --> 00:42:47,370
going all around these 26 kilometers.

854
00:42:47,370 --> 00:42:49,770
And these magnets are very important

855
00:42:49,770 --> 00:42:53,160
because they navigate the
protons that are accelerated

856
00:42:53,160 --> 00:42:55,140
to go on a very precise trajectories.

857
00:42:55,140 --> 00:42:56,514
Again, within microns,

858
00:42:56,514 --> 00:42:59,040
things have to be exactly where they are

859
00:42:59,040 --> 00:43:00,840
within tiny, tiny distance

860
00:43:00,840 --> 00:43:02,280
or else they will miss each other,

861
00:43:02,280 --> 00:43:03,780
they won't collide.

862
00:43:03,780 --> 00:43:06,450
So half the protons go clockwise,

863
00:43:06,450 --> 00:43:08,700
the other half counterclockwise

864

00:43:08,700 --> 00:43:11,790
and then magnets navigate
them and eventually,

865
00:43:11,790 --> 00:43:15,300
they collide in four different spots

866
00:43:15,300 --> 00:43:17,670
where you have detectors.

867
00:43:17,670 --> 00:43:20,880
They are huge, like a 5-story building

868
00:43:20,880 --> 00:43:25,500
that are instrumented with
very sophisticated machines,

869
00:43:25,500 --> 00:43:27,630
versions of the human eye.

870
00:43:27,630 --> 00:43:29,490
You can see what happens.

871
00:43:29,490 --> 00:43:32,040
You can see what particles you produced.

872
00:43:32,040 --> 00:43:36,120
And just like the eye has to
go to connect to the brain,

873
00:43:36,120 --> 00:43:38,430
so there is then cables
that take these events,

874
00:43:38,430 --> 00:43:39,990
they analyze them, computers.

875
00:43:39,990 --> 00:43:42,210
And then they tell you,

"Okay, you produced it."

876
00:43:42,210 --> 00:43:44,580
It's beyond my imagination

877
00:43:44,580 --> 00:43:49,560
that humans have been able to
do such complicated things.

878
00:43:49,560 --> 00:43:54,560
It all started with the
willingness to support science

879
00:43:54,990 --> 00:43:58,440
that was started in 1945.

880
00:43:58,440 --> 00:43:59,273
In the beginning,

881
00:43:59,273 --> 00:44:03,360
colliders would take a
few months to a few years

882
00:44:03,360 --> 00:44:07,020
to be built, only a fraction
of the cost that they are now.

883
00:44:07,020 --> 00:44:08,430
Now they have reached the point,

884
00:44:08,430 --> 00:44:10,410
for example, the Large Hadron Collider

885
00:44:10,410 --> 00:44:13,830
is about a billion per year to run,

886
00:44:13,830 --> 00:44:16,740
and so it was like 10 billion to build.

887
00:44:16,740 --> 00:44:21,120
It's a big project and the
money is not the main problem.

888
00:44:21,120 --> 00:44:25,770
The problem is that it takes
time and expertise to build it,

889
00:44:25,770 --> 00:44:29,850
to have 27 kilometers worth of magnets.

890
00:44:29,850 --> 00:44:31,560
These are huge magnets,

891
00:44:31,560 --> 00:44:35,160
where it is they have to be
ultra cold and they have...

892
00:44:35,160 --> 00:44:38,640
It's a miracle that you can
have control to this level.

893
00:44:38,640 --> 00:44:40,620
It's even, as a European, for me,

894
00:44:40,620 --> 00:44:41,940
it's even more of a miracle.

895
00:44:41,940 --> 00:44:44,760
It was created, in a sense,

896
00:44:44,760 --> 00:44:47,580
as a result of the Second World War,

897
00:44:47,580 --> 00:44:52,290
where European countries
were fighting each other.

898

00:44:52,290 --> 00:44:53,730
At least that's how it started.

899
00:44:53,730 --> 00:44:56,220
And then the same European countries

900
00:44:56,220 --> 00:45:01,220
collaborated at this spectacularly
precise accomplishment.

901
00:45:02,160 --> 00:45:06,540
One of the great accomplishments
of, I think, humans

902
00:45:06,540 --> 00:45:07,770
to create this machine.

903
00:45:07,770 --> 00:45:10,050
Work so well and we've
learned so much from it

904
00:45:10,050 --> 00:45:11,580
and all the predecessors.

905
00:45:11,580 --> 00:45:14,412
LHC is only the last example,

906
00:45:14,412 --> 00:45:17,940
and there have been tens of colliders,

907
00:45:17,940 --> 00:45:20,580
you know, various sizes,
et cetera, since then.

908
00:45:20,580 --> 00:45:25,580
So we've been on this large
science road over 70 years.

909
00:45:26,040 --> 00:45:29,640

Now we've reached the point
where the next collider,

910
00:45:29,640 --> 00:45:34,323
the next upgrade that will take
us to even bigger energies,

911
00:45:36,517 --> 00:45:41,280
may take, if we are lucky,
20 to 30 years to build.

912
00:45:41,280 --> 00:45:42,690
- And why is it that long?

913
00:45:42,690 --> 00:45:45,570
Is that because of the technology
needed or the investment?

914
00:45:45,570 --> 00:45:47,130
- Or how big it has to be?

915
00:45:47,130 --> 00:45:49,110
- I think all of the above.
- Hmm (affirmative).

916
00:45:49,110 --> 00:45:50,280
- Plus it takes time.

917
00:45:50,280 --> 00:45:54,427
Even if Bezos gives you
all his money saying,

918
00:45:54,427 --> 00:45:56,820
"Okay go build it,"
(chuckling)

919
00:45:56,820 --> 00:46:00,120
the money would be plenty in his case.

920

00:46:00,120 --> 00:46:02,310
However, it would still take a long time

921
00:46:02,310 --> 00:46:04,740
to assemble the people.

922
00:46:04,740 --> 00:46:07,800
And then the technology,
even if the technology exists

923
00:46:07,800 --> 00:46:09,990
because the technology does exist.

924
00:46:09,990 --> 00:46:14,880
If you make it long enough,
you can have enough magnets

925
00:46:14,880 --> 00:46:19,440
and enough to accelerate
particles to very high energies,

926
00:46:19,440 --> 00:46:21,270
the next energy frontier.

927
00:46:21,270 --> 00:46:24,690
10 times bigger energy than the LHC.

928
00:46:24,690 --> 00:46:29,690
So the technology exists,
but the time it would take,

929
00:46:30,090 --> 00:46:34,230
I would guess at least 15
years, probably much more.

930
00:46:34,230 --> 00:46:35,430
Even with all the money,

931
00:46:35,430 --> 00:46:37,830

I think it would take couple of decades.

932
00:46:37,830 --> 00:46:40,740
- Well this comes across in
the movie, Particle Fever,

933
00:46:40,740 --> 00:46:42,060
the documentary that you're in,

934
00:46:42,060 --> 00:46:44,700
which is largely set at
the Large Hadron Collider.

935
00:46:44,700 --> 00:46:46,230
'Cause you personally had to wait

936
00:46:46,230 --> 00:46:47,700
how many years of your career

937
00:46:47,700 --> 00:46:51,390
for that to to be completed
and be brought online?

938
00:46:51,390 --> 00:46:52,680
That was a long wait for...

939
00:46:52,680 --> 00:46:54,630
- That was a long wait. By the way,

940
00:46:54,630 --> 00:46:57,180
I didn't think it was going
to be a long wait (chuckling)

941
00:46:57,180 --> 00:46:58,500
when I started.

942
00:46:58,500 --> 00:47:01,320
You know, humans tend to
be optimistic by nature.

943
00:47:01,320 --> 00:47:03,510
That's why we've evolved
so well. (Colin laughing)

944
00:47:03,510 --> 00:47:07,260
I can tell you, anecdotally, in 1983,

945
00:47:07,260 --> 00:47:10,507
there was the first study
group of what was then called,

946
00:47:10,507 --> 00:47:12,690
"The Superconducting Super Collider,"

947
00:47:12,690 --> 00:47:15,180
which was a very similar collider.

948
00:47:15,180 --> 00:47:17,580
Actually would have
higher energy than the LHC

949
00:47:17,580 --> 00:47:21,420
that was going to be
built in the US, the SSC,

950
00:47:21,420 --> 00:47:23,910
Superconducting Super Collider.

951
00:47:23,910 --> 00:47:27,943
And the date that was discussed

952
00:47:27,943 --> 00:47:31,260
was well by 1990 we should be running.

953
00:47:31,260 --> 00:47:33,030
This was the first study.

954

00:47:33,030 --> 00:47:35,430
So it took much longer and it wasn't even,

955
00:47:35,430 --> 00:47:40,380
the SSC was canceled in
'93 for political reasons.

956
00:47:40,380 --> 00:47:44,400
The moment a site was chosen,
which was Texas, to build it,

957
00:47:44,400 --> 00:47:48,810
then a support from the rest
of the states diminished.

958
00:47:48,810 --> 00:47:50,340
And in the end it was not built,

959
00:47:50,340 --> 00:47:52,110
which is really a shame

960
00:47:52,110 --> 00:47:55,080
because it would be
very good for the world

961
00:47:55,080 --> 00:47:57,870
to have two colliders
in the same competition

962
00:47:57,870 --> 00:48:00,570
and at any rate, so it took much longer.

963
00:48:00,570 --> 00:48:04,510
So I didn't think it would take from '83

964
00:48:05,748 --> 00:48:09,450
until 2008 when it first started.

965
00:48:09,450 --> 00:48:14,450

So this time scale, it seems
like it was getting longer.

966
00:48:16,381 --> 00:48:19,080
I anticipated this in the 90s.

967
00:48:19,080 --> 00:48:23,160
That's why I started thinking
about small-scale experiments.

968
00:48:23,160 --> 00:48:26,077
I didn't anticipate
exactly dates, but I said,

969
00:48:26,077 --> 00:48:29,310
"Well there is a lot of
technology happening,

970
00:48:29,310 --> 00:48:31,230
so what can we do with it?"

971
00:48:31,230 --> 00:48:33,990
Because I was learning
these things from my friends

972
00:48:33,990 --> 00:48:37,140
that I have dinners and
wine tasting, et cetera.

973
00:48:37,140 --> 00:48:41,250
So I could see that there
was a whole other field

974
00:48:41,250 --> 00:48:43,200
of experimentation.

975
00:48:43,200 --> 00:48:45,990
So that inspired me to
start thinking about this.

976
00:48:45,990 --> 00:48:50,520
And now it's a major
part of what's happening.

977
00:48:50,520 --> 00:48:54,330
Because the next collider
will take so many decades,

978
00:48:54,330 --> 00:48:56,280
many people have started doing it,

979
00:48:56,280 --> 00:48:58,710
especially in the last five years.

980
00:48:58,710 --> 00:49:03,710
There has been what is called,
"The golden age of small,

981
00:49:04,050 --> 00:49:07,350
doing fundamental physics
with small-scale experiments."

982
00:49:07,350 --> 00:49:09,000
- So you don't have to wait three decades

983
00:49:09,000 --> 00:49:10,650
for a collider to be built?
- You don't have...

984
00:49:10,650 --> 00:49:15,030
- I think colliders are
still very important.

985
00:49:15,030 --> 00:49:17,610
You are not looking for
exactly the same physics

986
00:49:17,610 --> 00:49:22,080
if you do small-scale,

high precision experiments

987
00:49:22,080 --> 00:49:23,880
and collider experiments.

988
00:49:23,880 --> 00:49:26,970
Collider experiments, eventually
you produce new particles.

989
00:49:26,970 --> 00:49:28,410
When you produce them,

990
00:49:28,410 --> 00:49:30,540
even though they live for very short time,

991
00:49:30,540 --> 00:49:32,220
you can study them.

992
00:49:32,220 --> 00:49:34,950
You can see what are their decay products

993
00:49:34,950 --> 00:49:36,900
and from there you learn a lot.

994
00:49:36,900 --> 00:49:38,610
You learn all there is to know

995
00:49:38,610 --> 00:49:41,850
about their fundamental
properties, their mask,

996
00:49:41,850 --> 00:49:44,880
their electric charts, and
what's called, 'their spin,'

997
00:49:44,880 --> 00:49:47,130
and how they couple to other particles.

998

00:49:47,130 --> 00:49:49,170
You learn a lot in detail.

999
00:49:49,170 --> 00:49:52,050
And the moment you've produced a particle,

1000
00:49:52,050 --> 00:49:56,340
the signature of that is fairly clean.

1001
00:49:56,340 --> 00:49:57,840
With small-scale experiments,

1002
00:49:57,840 --> 00:49:59,550
the discoveries are more indirect.

1003
00:49:59,550 --> 00:50:01,260
You see a new effect,

1004
00:50:01,260 --> 00:50:03,630
and then you have to
infer from that effect

1005
00:50:03,630 --> 00:50:05,670
what it is that produced this effect.

1006
00:50:05,670 --> 00:50:08,310
And it could be the same particle

1007
00:50:08,310 --> 00:50:12,060
that you would have
discovered in a collider,

1008
00:50:12,060 --> 00:50:13,980
but you'll see it more indirectly.

1009
00:50:13,980 --> 00:50:17,400
So usually it takes more than
one small-scale experiment

1010
00:50:17,400 --> 00:50:19,850
to study, let's say the same particle

1011
00:50:19,850 --> 00:50:21,720
or the same phenomenon.

1012
00:50:21,720 --> 00:50:25,200
Nevertheless, I think
these are complimentary.

1013
00:50:25,200 --> 00:50:28,650
So there is a lot that can be done

1014
00:50:28,650 --> 00:50:32,160
thanks to the amazing
technological developments

1015
00:50:32,160 --> 00:50:36,120
for what's can be called,
"The high precision frontier."

1016
00:50:36,120 --> 00:50:38,580
So there is a lot that can be done

1017
00:50:38,580 --> 00:50:42,510
and now it is a golden era
for this many experimentalists

1018
00:50:42,510 --> 00:50:44,910
have turned their attention to this.

1019
00:50:44,910 --> 00:50:45,900
Many of these people,

1020
00:50:45,900 --> 00:50:49,140
what they were doing for
technological purposes,

1021

00:50:49,140 --> 00:50:52,800
and now they're doing it to
make major new discoveries

1022
00:50:52,800 --> 00:50:55,740
about the laws of nature new.

1023
00:50:55,740 --> 00:50:58,113
So it's very exciting.

1024
00:50:58,980 --> 00:51:02,220
- I remember in that
documentary, Particle Fever,

1025
00:51:02,220 --> 00:51:05,280
which is largely about the
search for and discovery

1026
00:51:05,280 --> 00:51:08,160
of the Higgs boson, sort
of the most famous outcome

1027
00:51:08,160 --> 00:51:09,420
of the Large Hadron Collider.

1028
00:51:09,420 --> 00:51:11,910
I've always wanted to ask you, that movie,

1029
00:51:11,910 --> 00:51:13,830
it shows people packing an auditorium

1030
00:51:13,830 --> 00:51:16,110
for the big announcement
of the Higgs boson

1031
00:51:16,110 --> 00:51:18,540
and you couldn't get past
security, they locked you out.

1032

00:51:18,540 --> 00:51:19,470
What happened?

1033
00:51:19,470 --> 00:51:21,518
- I was late.
(all laughing)

1034
00:51:21,518 --> 00:51:23,430
So what happened was,

1035
00:51:23,430 --> 00:51:27,640
I had several students and
posts docs that went there early

1036
00:51:28,650 --> 00:51:30,630
and they kept a seat.

1037
00:51:30,630 --> 00:51:32,760
In fact, they showed in Particle Fever,

1038
00:51:32,760 --> 00:51:35,910
the empty seat for me.
(all laughing)

1039
00:51:35,910 --> 00:51:39,390
But even though there
was a seat available,

1040
00:51:39,390 --> 00:51:43,020
I couldn't go in because
there was a big backlog

1041
00:51:43,020 --> 00:51:44,700
and they didn't...

1042
00:51:44,700 --> 00:51:49,003
Anyway, so I had to watch
it from a TV outside.

1043

00:51:49,003 --> 00:51:52,590
- Yeah. But you were
there at the LHC at CERN

1044
00:51:52,590 --> 00:51:54,600
when the discovery was announced.

1045
00:51:54,600 --> 00:51:56,850
How did that feel for
you for that milestone?

1046
00:51:56,850 --> 00:51:58,890
- Oh, it felt fanta...

1047
00:51:58,890 --> 00:52:03,540
You know, it's like when
something amazing happens,

1048
00:52:03,540 --> 00:52:06,450
you feel that you live in a dream.

1049
00:52:06,450 --> 00:52:08,340
That's how it was.

1050
00:52:08,340 --> 00:52:11,760
That was, by the way, December of 2011.

1051
00:52:11,760 --> 00:52:14,340
That actual first announcement,

1052
00:52:14,340 --> 00:52:16,710
that was the incident that was shown.

1053
00:52:16,710 --> 00:52:20,760
July 4th, 2012 was the
official announcement.

1054
00:52:20,760 --> 00:52:23,100
And at the time of the

official announcement,

1055
00:52:23,100 --> 00:52:26,700
I was actually in Santorini on vacation

1056
00:52:26,700 --> 00:52:29,670
looking at the announcement

1057
00:52:29,670 --> 00:52:33,720
and some beautiful views of the sea.

1058
00:52:33,720 --> 00:52:34,560
- That sounds nice.

1059
00:52:34,560 --> 00:52:36,300
It's better than being
locked out by security.

1060
00:52:36,300 --> 00:52:38,550
- Exactly, but the first...

1061
00:52:38,550 --> 00:52:41,880
I'm glad I was there though
for the first announcement.

1062
00:52:41,880 --> 00:52:45,060
- Mm-hmm (affirmative).
- And it was amazing.

1063
00:52:45,060 --> 00:52:46,740
It was amazing.

1064
00:52:46,740 --> 00:52:50,100
Scientists are like humans.
(both laughing)

1065
00:52:50,100 --> 00:52:54,030
So the moment you dream
of something, it happens.

1066
00:52:54,030 --> 00:52:57,000
You accomplish and say,
"Okay, what's next?"

1067
00:52:57,000 --> 00:53:01,740
Very soon, you get used to
now we are looking forward

1068
00:53:01,740 --> 00:53:04,800
to seeing what may be beyond
what's called, "New physics,"

1069
00:53:04,800 --> 00:53:08,850
beyond what we call, "The
standard model," now.

1070
00:53:08,850 --> 00:53:11,700
With the discovery of the Higgs,

1071
00:53:11,700 --> 00:53:14,730
marks the end of what we
call the standard model

1072
00:53:14,730 --> 00:53:19,500
and we are now on a path
to discover new particles.

1073
00:53:19,500 --> 00:53:21,900
That's what we are looking forward to.

1074
00:53:21,900 --> 00:53:23,670
- We have a student question submitted

1075
00:53:23,670 --> 00:53:26,880
that's about the standard
model, by Felicity.

1076
00:53:26,880 --> 00:53:28,020

And maybe we could play that for you?

1077
00:53:28,020 --> 00:53:28,853
- Yeah, sure.

1078
00:53:30,060 --> 00:53:33,090
- Hello Savas, I'm
Felicity in grade eight.

1079
00:53:33,090 --> 00:53:34,590
What are the discrepancies

1080
00:53:34,590 --> 00:53:36,720
in the standard model for physics,

1081
00:53:36,720 --> 00:53:39,000
and what makes them as such?

1082
00:53:39,000 --> 00:53:43,710
- Okay, that's an interesting
question bec... (chuckling)

1083
00:53:43,710 --> 00:53:45,780
the word 'discrepancies'

1084
00:53:45,780 --> 00:53:48,750
suggest that there is something wrong

1085
00:53:48,750 --> 00:53:52,380
with the standard model,
that something doesn't work.

1086
00:53:52,380 --> 00:53:55,020
That 'by doesn't work,'
I mean it's contradicted.

1087
00:53:55,020 --> 00:53:57,720
The standard model makes a prediction

1088
00:53:57,720 --> 00:54:02,490
that when you do experiment
X, you'll find A,

1089
00:54:02,490 --> 00:54:07,020
but you don't find A, when
you do it, you find B.

1090
00:54:07,020 --> 00:54:10,410
So there is no discrepancy
of the standard model

1091
00:54:10,410 --> 00:54:13,680
in that sense. If there was,

1092
00:54:13,680 --> 00:54:16,560
it wouldn't be the standard
model of particle physics.

1093
00:54:16,560 --> 00:54:20,370
It would be a theory
that has some problems.

1094
00:54:20,370 --> 00:54:23,130
So there is no real discrepancy.

1095
00:54:23,130 --> 00:54:27,090
What I described to you,
the hierarchy problem,

1096
00:54:27,090 --> 00:54:29,100
the cosmological constant problem,

1097
00:54:29,100 --> 00:54:33,600
are not logical contradictions
with the standard model.

1098
00:54:33,600 --> 00:54:35,550
In a sense, they're a static criteria,

1099
00:54:35,550 --> 00:54:37,320
that in the same theory,

1100
00:54:37,320 --> 00:54:42,030
you have two numbers that differ
by 40 orders of magnitude.

1101
00:54:42,030 --> 00:54:43,350
There must be a reason for it.

1102
00:54:43,350 --> 00:54:46,470
The standard model is
not fundamental enough

1103
00:54:46,470 --> 00:54:49,200
to address these questions of,

1104
00:54:49,200 --> 00:54:53,520
why is the universe so much
bigger than an atomic nucleus,

1105
00:54:53,520 --> 00:54:57,600
or why is gravity so much
weaker than the other forces.

1106
00:54:57,600 --> 00:55:00,840
It is, essentially, the
naturalness criteria

1107
00:55:00,840 --> 00:55:02,433
and aesthetic criteria.

1108
00:55:03,330 --> 00:55:06,037
- I remember once, you
saying something like,

1109
00:55:06,037 --> 00:55:08,070
"The biggest mystery is that

1110
00:55:08,070 --> 00:55:11,097
the universe is
comprehensible to us at all."

1111
00:55:12,840 --> 00:55:16,080
- That is, in a sense, a meta question.

1112
00:55:16,080 --> 00:55:19,290
It's almost in the realm of philosophy.

1113
00:55:19,290 --> 00:55:23,400
Indeed, several big
philosophers and physicists

1114
00:55:23,400 --> 00:55:27,120
have said the same thing in different ways

1115
00:55:27,120 --> 00:55:29,380
that the most, (I forgot,
maybe it was Einstein),

1116
00:55:31,050 --> 00:55:34,470
who said that, "The most
incomprehensible thing

1117
00:55:34,470 --> 00:55:37,140
about the universe is
that it's comprehensible."

1118
00:55:37,140 --> 00:55:39,090
The fact that there is a
language for the universe,

1119
00:55:39,090 --> 00:55:41,190
which is called, "Mathematics."

1120
00:55:41,190 --> 00:55:45,960
The fact that the universe

obeys mathematical laws

1121
00:55:45,960 --> 00:55:48,847
is just astonishing, what's called,

1122
00:55:48,847 --> 00:55:52,110
"The unreasonable
effectiveness of mathematics."

1123
00:55:52,110 --> 00:55:53,400
In mathematics,

1124
00:55:53,400 --> 00:55:57,540
you can ask a question and
no matter how hard it is,

1125
00:55:57,540 --> 00:56:01,110
if it's within the realm
of mathematics and physics,

1126
00:56:01,110 --> 00:56:04,140
and it may involve millions of steps,

1127
00:56:04,140 --> 00:56:06,600
but you arrive at something that's true.

1128
00:56:06,600 --> 00:56:08,670
Now it's very rare you start,

1129
00:56:08,670 --> 00:56:10,560
you have a starting point, some question,

1130
00:56:10,560 --> 00:56:14,100
and then a million steps later

1131
00:56:14,100 --> 00:56:16,680
you arrive at a conclusion
that's still true.

1132
00:56:16,680 --> 00:56:18,840
Because a million steps is a lot of steps

1133
00:56:18,840 --> 00:56:20,580
and all it takes is few missteps

1134
00:56:20,580 --> 00:56:22,560
to be led to the wrong direction,

1135
00:56:22,560 --> 00:56:24,750
and mathematics that doesn't do that

1136
00:56:24,750 --> 00:56:26,463
if you ask the right question.

1137
00:56:27,690 --> 00:56:30,690
I think it was Pythagoras

1138
00:56:30,690 --> 00:56:34,140
who said that, "O Theós geometreí,"

1139
00:56:34,140 --> 00:56:38,070
which means in English,
(chuckling)

1140
00:56:38,070 --> 00:56:41,220
that, "God geometrizes everything."

1141
00:56:41,220 --> 00:56:42,990
By geometry, he meant mathematics,

1142
00:56:42,990 --> 00:56:45,830
that God speaks the
language of mathematics,

1143
00:56:45,830 --> 00:56:48,060
if you want to paraphrase.
- Mm-hmm (affirmative).

1144
00:56:48,060 --> 00:56:50,430
That's an incredible mystery.

1145
00:56:50,430 --> 00:56:53,460
And the fact that mathematics
is a precise language,

1146
00:56:53,460 --> 00:56:56,010
like one plus one equal two,

1147
00:56:56,010 --> 00:56:58,860
there is no if, but, approximate.

1148
00:56:58,860 --> 00:57:01,830
Well, it's a matter of
opinion, (Colin laughing)

1149
00:57:01,830 --> 00:57:03,103
and there is left wingers and right.

1150
00:57:03,103 --> 00:57:04,680
- Now that's fake news.

1151
00:57:04,680 --> 00:57:06,720
- Yeah, fake news. There is no...

1152
00:57:06,720 --> 00:57:09,810
And, of course, that's an
exceedingly simple example,

1153
00:57:09,810 --> 00:57:12,690
but with math you can have
very complicated examples

1154
00:57:12,690 --> 00:57:14,820
that describe what happens

1155

00:57:14,820 --> 00:57:18,630
in a complicated situation in nature.

1156
00:57:18,630 --> 00:57:22,500
You know, how the sun works
and creates energy for us.

1157
00:57:22,500 --> 00:57:25,950
And there is trillions of steps and to do,

1158
00:57:25,950 --> 00:57:28,740
but before you figure
out how the sun works,

1159
00:57:28,740 --> 00:57:30,840
how come it produces all this energy?

1160
00:57:30,840 --> 00:57:32,580
What will it do next?

1161
00:57:32,580 --> 00:57:35,990
Or the loss of gravity,
you don't have to go...

1162
00:57:36,870 --> 00:57:39,810
Newton told us, gave us equations,

1163
00:57:39,810 --> 00:57:41,970
you can use these equations to predict

1164
00:57:41,970 --> 00:57:45,360
where any planet will be
at any point in the future,

1165
00:57:45,360 --> 00:57:47,880
and where it has been
any point in the past,

1166
00:57:47,880 --> 00:57:51,300

10 billion years ago or
10 billion years from now.

1167
00:57:51,300 --> 00:57:53,550
And you can tell exactly,

1168
00:57:53,550 --> 00:57:56,760
if you'll have an eclipse
and what it'll be.

1169
00:57:56,760 --> 00:57:59,970
So this power of extrapolation

1170
00:57:59,970 --> 00:58:03,450
gives a new meaning to
the concept of truth

1171
00:58:03,450 --> 00:58:05,820
that, "Oh my God, this is real true.

1172
00:58:05,820 --> 00:58:08,439
There is no fake stuff."

1173
00:58:08,439 --> 00:58:10,860
It's amazing that such a thing exists,

1174
00:58:10,860 --> 00:58:14,550
and in fact, it's what
drove me into physics,

1175
00:58:14,550 --> 00:58:17,160
what I told you about Newton's equations.

1176
00:58:17,160 --> 00:58:21,090
When I was, I think I was 13 years old,

1177
00:58:21,090 --> 00:58:25,488
one of my classmates back
in Greece told me that,

1178
00:58:25,488 --> 00:58:27,777
"There is these equations that
do exactly what I told you.

1179
00:58:27,777 --> 00:58:31,440
You can predict the position
and speed of a planet

1180
00:58:31,440 --> 00:58:33,420
any point in the future

1181
00:58:33,420 --> 00:58:35,220
if you know it today or any point."

1182
00:58:35,220 --> 00:58:37,920
I said, "Impossible. No way."

1183
00:58:37,920 --> 00:58:41,010
It's so complicated. There
are all these other planets

1184
00:58:41,010 --> 00:58:45,450
and there is so much
happening at the same time.

1185
00:58:45,450 --> 00:58:48,180
And that's when I said,
"I want to do this.

1186
00:58:48,180 --> 00:58:49,290
What is it called?"

1187
00:58:49,290 --> 00:58:51,240
I know, I knew it was called, "Physics,"

1188
00:58:51,240 --> 00:58:52,740
because...
- Mm-hmm (affirmative).

1189
00:58:52,740 --> 00:58:54,780
- And this comes up in the movie also.

1190
00:58:54,780 --> 00:58:57,360
I was interested in the concept of truth.

1191
00:58:57,360 --> 00:59:02,360
When I went to Greece for
the first time, I was age 12.

1192
00:59:02,700 --> 00:59:04,620
I was born in Constantinople,

1193
00:59:04,620 --> 00:59:08,460
but then my family was expelled
because they were Greeks

1194
00:59:08,460 --> 00:59:11,040
to go to Greece and we went there.

1195
00:59:11,040 --> 00:59:13,500
And all of a sudden,
it was a free country.

1196
00:59:13,500 --> 00:59:15,120
There was left and right,

1197
00:59:15,120 --> 00:59:19,207
and I would hear a speech by
the left leaning politicians.

1198
00:59:19,207 --> 00:59:20,730
"Well that makes perfect sense."

1199
00:59:20,730 --> 00:59:22,650
Then I would go to the same topic,

1200

00:59:22,650 --> 00:59:24,030
a speech from the right leaning.

1201
00:59:24,030 --> 00:59:25,680
I said, "Oh that makes sense too,

1202
00:59:25,680 --> 00:59:27,450
but they are opposite conclusions."

1203
00:59:27,450 --> 00:59:29,010
So I was confused.

1204
00:59:29,010 --> 00:59:31,500
What does it mean to be true?

1205
00:59:31,500 --> 00:59:36,500
And then I realized that with
language you can play games,

1206
00:59:36,750 --> 00:59:41,130
whereas with mathematics,
it's such a precise language

1207
00:59:41,130 --> 00:59:43,110
that you don't play games.

1208
00:59:43,110 --> 00:59:44,730
If you ask a precise question,

1209
00:59:44,730 --> 00:59:46,530
you get a precise answer.

1210
00:59:46,530 --> 00:59:48,480
So I said, "I want to do that."

1211
00:59:48,480 --> 00:59:52,500
And then I was, for about
a year, I was wondering,

1212
00:59:52,500 --> 00:59:54,477
if I should do mathematics or physics.

1213
00:59:54,477 --> 00:59:58,200
And it was that comment
by my classmate that,

1214
00:59:58,200 --> 01:00:00,960
because you can predict precisely

1215
01:00:00,960 --> 01:00:03,090
what will happen in the future.

1216
01:00:03,090 --> 01:00:04,050
And then I realized

1217
01:00:04,050 --> 01:00:06,930
that physics has an
advantage over mathematics.

1218
01:00:06,930 --> 01:00:10,590
That in physics it's not just the logic

1219
01:00:10,590 --> 01:00:13,500
and what two or three
mathematicians think,

1220
01:00:13,500 --> 01:00:15,480
or a million mathematicians think.

1221
01:00:15,480 --> 01:00:18,240
It is nature that goes
and tests your theory

1222
01:00:18,240 --> 01:00:21,330
to see if it's actually
realized in nature or not.

1223

01:00:21,330 --> 01:00:25,050
So that gives an additional foundation

1224
01:00:25,050 --> 01:00:26,400
to the concept of truth.

1225
01:00:26,400 --> 01:00:27,690
And I said, "Ah, no."

1226
01:00:27,690 --> 01:00:28,860
In math, there is truth.

1227
01:00:28,860 --> 01:00:30,240
In physics, it's super true

1228
01:00:30,240 --> 01:00:32,790
because even nature agrees with you.

1229
01:00:32,790 --> 01:00:36,060
The truth does not depend on
the eloquence of the speaker.

1230
01:00:36,060 --> 01:00:41,060
And in fact, nature can answer
what the truth is in physics.

1231
01:00:41,940 --> 01:00:45,090
So those were very
attractive ideas for me.

1232
01:00:45,090 --> 01:00:48,900
So I decided to spend my life on it.

1233
01:00:48,900 --> 01:00:50,820
I'm glad I did.

1234
01:00:50,820 --> 01:00:53,550
- So you decided at that stage
to spend your life on this

1235
01:00:53,550 --> 01:00:55,140
and you haven't looked back since?

1236
01:00:55,140 --> 01:00:57,780
- No, for sure, I haven't looked back.

1237
01:00:57,780 --> 01:01:02,347
It's very funny because many
of my relatives would tell me,

1238
01:01:02,347 --> 01:01:05,610
"You know, with your brain
you can make a lot of money."

1239
01:01:05,610 --> 01:01:07,350
Said, "I know. I don't want money.

1240
01:01:07,350 --> 01:01:11,070
I want time to do what I enjoy doing."

1241
01:01:11,070 --> 01:01:14,275
And they thought I was a bit strange.

1242
01:01:14,275 --> 01:01:15,750
True.
(all laughing)

1243
01:01:15,750 --> 01:01:17,220
- But you're still
enjoying what you're doing?

1244
01:01:17,220 --> 01:01:19,590
- I'm still enjoying, yeah.

1245
01:01:19,590 --> 01:01:23,650
Yeah, there is this childlike curiosity

1246

01:01:24,758 --> 01:01:27,210
and joy that you discover.

1247
01:01:27,210 --> 01:01:28,140
You know how children,

1248
01:01:28,140 --> 01:01:30,780
they're excited because
they discover new things.

1249
01:01:30,780 --> 01:01:33,990
And in science, there's so
many interesting questions

1250
01:01:33,990 --> 01:01:37,200
that even now, there's
interesting questions.

1251
01:01:37,200 --> 01:01:39,660
When you understand something,

1252
01:01:39,660 --> 01:01:41,670
you get the joy of understanding.

1253
01:01:41,670 --> 01:01:43,920
You see connections and...

1254
01:01:43,920 --> 01:01:44,790
- Well, Savas,

1255
01:01:44,790 --> 01:01:46,920
we're delighted that you
still enjoy your work,

1256
01:01:46,920 --> 01:01:49,830
and we're very excited that
you stopped to chat with us.

1257
01:01:49,830 --> 01:01:51,180

This has just been fascinating.

1258
01:01:51,180 --> 01:01:52,013
- Thank you.
(gentle upbeat music begins)

1259
01:01:52,013 --> 01:01:53,553
It has been a pleasure for me too.

1260
01:01:57,060 --> 01:01:58,620
- Thanks so much for listening.

1261
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