1
00:00:01,534 --> 00:00:02,935
(bright, inquisitive music)

2
00:00:02,968 --> 00:00:05,638
- [Narrator] NASA's Jet
Propulsion Laboratory presents

3
00:00:05,671 --> 00:00:09,375
the von Karman lecture, a
series of talks by scientists

4
00:00:09,408 --> 00:00:12,678
and engineers who are
exploring our planet,

5
00:00:12,711 --> 00:00:16,282
our Solar System, and
all that lies beyond.

6
00:00:28,260 --> 00:00:29,962
- Hey, good evening,
ladies and gentlemen.

7
00:00:29,995 --> 00:00:31,030
How's everyone tonight?

8
00:00:31,063 --> 00:00:32,165
(audience murmurs)

9
00:00:32,198 --> 00:00:33,132
Good, very good.

10
00:00:33,165 --> 00:00:34,534
Well, thanks for coming out;

11
00:00:34,567 --> 00:00:36,969
as always, we greatly
appreciate your attendance here.

12
00:00:37,002 --> 00:00:40,807
The Cold Atom Laboratory, or
CAL, is a multi-user facility

13
00:00:40,840 --> 00:00:44,577
for the study of
ultra-cold quantum gases.

14
00:00:44,610 --> 00:00:48,448
Scheduled to launch in 2017,
CAL will then be installed

15
00:00:48,481 --> 00:00:50,383
by astronauts into
the Destiny module

16
00:00:50,416 --> 00:00:52,285
of the International
Space Station.

17
00:00:52,318 --> 00:00:55,354
Facilitated by the microgravity
environment of the ISS,

18
00:00:55,387 --> 00:00:58,558
CAL will achieve temperatures
a billion times colder

19
00:00:58,591 --> 00:01:01,260
than the vacuum of
space, making the ISS

20
00:01:01,293 --> 00:01:05,364
the home to the coldest
spot in the known universe.

21
00:01:05,397 --> 00:01:08,234
It will explore the nature
of gravity and dark energy,

22
00:01:08,267 --> 00:01:11,938
giving scientists access to
an unexplored quantum realm.

23
00:01:11,971 --> 00:01:13,840
Tonight, we have both
the project manager

24
00:01:13,873 --> 00:01:16,209
and project scientist
to tell us all about

25
00:01:16,242 --> 00:01:18,344
this amazing new facility.

26
00:01:18,377 --> 00:01:19,912
Ladies first.

27
00:01:19,945 --> 00:01:22,548
Dr. Anita Sengupta has been a
member of the technical staff

28
00:01:22,581 --> 00:01:24,784
at JPL since 2001.

29
00:01:24,817 --> 00:01:28,020
She started out working on,
and testing, and improving,

30
00:01:28,053 --> 00:01:30,189
the ion propulsion
systems for Deep Space 1

31
00:01:30,222 --> 00:01:31,858
and Dawn missions.

32
00:01:31,891 --> 00:01:34,060
After that, she led the
supersonic qualification

33
00:01:34,093 --> 00:01:36,129
of the MSL parachute that landed

34
00:01:36,162 --> 00:01:38,598
the Curiosity rover on Mars.

35
00:01:38,631 --> 00:01:41,300
Her next roles were the
development of mission concepts

36
00:01:41,333 --> 00:01:44,270
for a Venus lander, a Mars
sample-return mission,

37
00:01:44,303 --> 00:01:46,305
and a Mars ascent vehicle.

38
00:01:46,338 --> 00:01:48,307
For the past five years,
she has led the development

39
00:01:48,340 --> 00:01:51,944
of the Cold Atom Laboratory
mission as the project manager.

40
00:01:51,977 --> 00:01:55,581
She earned her MS and PhD in
aerospace engineering from USC,

41
00:01:55,614 --> 00:01:57,316
where she is also a
research professor

42
00:01:57,349 --> 00:01:59,252
and teaches spacecraft design.

43
00:01:59,285 --> 00:02:02,388
In her spare time, she is a

pilot with Cal Tech Flying Club,

44
00:02:02,421 --> 00:02:06,792
a sport motorcyclist, public
speaker, and world traveler.

45
00:02:06,825 --> 00:02:08,828
Dr. Robert Thompson is
the project scientist

46
00:02:08,861 --> 00:02:11,097
of the Cold Atom Lab,
and the developer

47
00:02:11,130 --> 00:02:13,332
of its conceptual design.

48
00:02:13,365 --> 00:02:14,600
Raised in Savannah, Georgia,

49
00:02:14,633 --> 00:02:16,536
he received his BS
from Georgia Tech

50
00:02:16,569 --> 00:02:19,205
and a PhD from the University
of Texas at Austin.

51
00:02:19,238 --> 00:02:21,040
He worked two years as a postdoc

52
00:02:21,073 --> 00:02:23,876
at the National Institute of
Technology with Bill Phillips,

53
00:02:23,909 --> 00:02:26,679
a 1997 Nobel
Laureate in physics.

54

00:02:28,080 --> 00:02:30,183
He's been in the quantum
science and technology group

55
00:02:30,216 --> 00:02:32,318
at JPL for nearly 20 years,

56
00:02:32,351 --> 00:02:34,287
spending much of that
time developing technology

57
00:02:34,320 --> 00:02:37,323
for future space-based,
cold-atom missions.

58
00:02:37,356 --> 00:02:39,725
With all his spare
time, he teaches courses

59
00:02:39,758 --> 00:02:41,827
about the science
of sustainability

60
00:02:41,860 --> 00:02:43,963
and the future of
science and technology

61
00:02:43,996 --> 00:02:47,333
at the Art Center College of
Design right here in Pasadena.

62
00:02:47,366 --> 00:02:48,634
Ladies and gentlemen,
please help welcome

63
00:02:48,667 --> 00:02:51,003
our guests tonight,
Dr. Anita Sengupta

64
00:02:51,036 --> 00:02:52,004

and Dr. Robert Thompson.

65
00:02:52,037 --> 00:02:55,041
(audience applauds)

66
00:03:01,280 --> 00:03:03,549
- Well thanks everyone for
coming to hear us speak tonight.

67
00:03:03,582 --> 00:03:05,651
We've got about an
hour presentation
that we're gonna split

68
00:03:05,684 --> 00:03:08,054
between Rob and myself,

69
00:03:08,087 --> 00:03:10,256
and Rob, do you want
to say to introduce?

70
00:03:11,490 --> 00:03:12,291
- Oh.

71
00:03:12,324 --> 00:03:13,125
(both chuckle)

72
00:03:13,158 --> 00:03:14,727
Yeah, welcome,

73
00:03:14,760 --> 00:03:18,932
and this experiment has
been very exciting for us,

74
00:03:20,899 --> 00:03:23,169
I see a lot of people who
are putting it together

75
00:03:23,202 --> 00:03:26,039

here in the crowd,
so welcome, and

76
00:03:28,907 --> 00:03:32,011
let's talk about NASA's
coolest mission ever.

77
00:03:32,044 --> 00:03:34,313
(audience titters)

78
00:03:34,346 --> 00:03:36,582
- We're going to do a brief
overview of the mission,

79
00:03:36,615 --> 00:03:38,184
for those of you who
aren't familiar with it,

80
00:03:38,217 --> 00:03:40,553
and for those of you online,
participating in the webcast,

81
00:03:40,586 --> 00:03:43,022
I'll talk a little bit how
we're using the Space Station

82
00:03:43,055 --> 00:03:44,690
to facilitate this experiment.

83
00:03:44,723 --> 00:03:47,760
Rob's gonna talk about the
science that CAL will do

84
00:03:47,793 --> 00:03:50,863
and the science in general
of low-temperature physics.

85
00:03:50,896 --> 00:03:53,165
I'll talk a little bit about
the implementation operations

86
00:03:53,198 --> 00:03:54,834
that the CAL mission
has been going through

87
00:03:54,867 --> 00:03:56,636
for the last past five
years, then we'll wrap up

88
00:03:56,669 --> 00:04:00,106
with some lessons
learned and do Q&A.

89
00:04:00,139 --> 00:04:02,341
So, we're your
presenters this evening,

90
00:04:02,374 --> 00:04:04,543
and some of you know
us, but obviously

91
00:04:04,576 --> 00:04:07,146
Rob is the atomic physicist,
project scientist,

92
00:04:07,179 --> 00:04:10,516
and I have been the project
manager for the past five years,

93
00:04:10,549 --> 00:04:11,984
and I am a rocket
scientist by training.

94
00:04:12,017 --> 00:04:14,020
The obvious difference
is that I'm very short,

95
00:04:14,053 --> 00:04:15,755
Rob is very tall,
(audience laughs)

96
00:04:15,788 --> 00:04:16,922
(Anita laughs)

97
00:04:16,955 --> 00:04:18,658
and we both look really
good in hair nets,

98
00:04:18,691 --> 00:04:19,859
you'll see tons of
hair net pictures

99
00:04:19,892 --> 00:04:22,061
throughout this
entire presentation.

100
00:04:22,094 --> 00:04:25,064
Now, we're gonna give
you a short mission video

101
00:04:25,097 --> 00:04:26,265
that we've come up with

102
00:04:26,298 --> 00:04:28,934
for education/public-outreach
purposes,

103
00:04:28,967 --> 00:04:31,203
and we'll go to
YouTube to play it.

104
00:04:31,236 --> 00:04:33,506
Hopefully, you'll enjoy it.

105
00:04:36,442 --> 00:04:38,010
(deep, evocative music)

106
00:04:38,043 --> 00:04:39,211
There are many things

that we actually

107
00:04:39,244 --> 00:04:41,781
don't understand about matter.

108
00:04:41,814 --> 00:04:45,651
One thing, for example,
would be gravity.

109
00:04:45,684 --> 00:04:47,820
We know that gravity exists,
we can observe gravity,

110
00:04:47,853 --> 00:04:52,458
but people don't understand
the quantum nature of gravity.

111
00:04:52,491 --> 00:04:53,859
- We have a very good
theory of gravity,

112
00:04:53,892 --> 00:04:56,862
it's Albert Einstein's
General Theory of Relativity.

113
00:04:56,895 --> 00:04:59,432
The unfortunate thing
is it's not compatible

114
00:04:59,465 --> 00:05:03,035
with the very good theory that
we have of quantum mechanics,

115
00:05:03,068 --> 00:05:07,240
of subatomic particles and
atoms and molecules and so on.

116
00:05:08,841 --> 00:05:12,445
Those two theories, they're
not compatible, they conflict.

117
00:05:14,646 --> 00:05:18,818
- Roughly 68% of the
universe is dark energy.

118
00:05:21,120 --> 00:05:24,123
About 27% makes up dark matter.

119
00:05:25,224 --> 00:05:28,227
So all we know is less than 5%.

120
00:05:29,661 --> 00:05:33,333
95% of what surrounds us
continues to be a mystery.

121
00:05:35,367 --> 00:05:38,003
- The way a Bose-Einstein
condensate expands

122
00:05:38,036 --> 00:05:40,339
thermodynamically could
potentially represent

123
00:05:40,372 --> 00:05:44,277
how the universe expanded
when it first formed.

124
00:05:45,644 --> 00:05:49,915
- A Bose-Einstein condensate
is a unique, man-made,

125
00:05:49,948 --> 00:05:53,252
quantum state of matter
which we can only obtain

126
00:05:53,285 --> 00:05:56,822
at the coldest temperatures
and very high densities.

127

00:05:56,855 --> 00:06:00,760
It is actually a macroscopic
ensemble of atoms

128
00:06:02,227 --> 00:06:05,297
that you can view with a camera

129
00:06:05,330 --> 00:06:09,502
and these wispy clouds of atoms
behave in very strange ways.

130
00:06:11,069 --> 00:06:14,874
They're no longer
distinguishable as an
individual particle.

131
00:06:14,907 --> 00:06:17,710
You really have to
describe it more like

132
00:06:17,743 --> 00:06:20,747
atoms acting
collectively as a wave.

133
00:06:22,681 --> 00:06:25,017
- [Dr. Sengupta] What we're
trying to do is to understand

134
00:06:25,050 --> 00:06:27,386
the fundamental
nature of matter,

135
00:06:27,419 --> 00:06:29,288
by basically continuing
the quest to get it

136
00:06:29,321 --> 00:06:32,158
to colder and
colder temperatures.

137

00:06:33,659 --> 00:06:36,028
- It's not just lower
temperatures but
it's also the fact

138
00:06:36,061 --> 00:06:38,731
that we want to study atoms
and we want to look at them

139
00:06:38,764 --> 00:06:40,833
for really long periods of time,

140
00:06:40,866 --> 00:06:44,971
and that is really only
possible in microgravity.

141
00:06:46,171 --> 00:06:48,207
On the Earth, you're
limited by gravity.

142
00:06:48,240 --> 00:06:49,508
We have a limited amount of time

143
00:06:49,541 --> 00:06:51,310
once you let go of the
atoms or weaken them

144
00:06:51,343 --> 00:06:54,113
that they will fall
out of your trap

145
00:06:54,146 --> 00:06:57,716
and run into the limits
of your experiment.

146
00:06:57,749 --> 00:07:00,686
So when we get to a
microgravity environment,

147
00:07:00,719 --> 00:07:04,824

we can get to these long
interrogation times in space.

148
00:07:06,225 --> 00:07:07,827
- We're going to be getting
to a temperature regime

149
00:07:07,860 --> 00:07:09,595
which no one has
ever seen before,

150
00:07:09,628 --> 00:07:11,730
so it's essentially the
unknown, what we're gonna find,

151
00:07:11,763 --> 00:07:15,701
in terms of how matter's gonna
behave at those temperatures.

152
00:07:15,734 --> 00:07:18,304
- [Jim] The Cold Atom
Laboratory is a journey

153
00:07:18,337 --> 00:07:22,341
to try to understand and
to explore the unknown.

154
00:07:30,949 --> 00:07:35,120
- So that's our video.
(audience applauds)

155
00:07:38,190 --> 00:07:39,792
Okay, so now I'm gonna
talk a little bit

156
00:07:39,825 --> 00:07:41,227
about the CAL mission timeline

157
00:07:41,260 --> 00:07:42,895
and the CAL mission overview.

158
00:07:42,928 --> 00:07:44,830
So, Rob and I actually worked
together on the proposal

159
00:07:44,863 --> 00:07:48,133
back in, roughly, April
of 2012, which is almost

160
00:07:48,166 --> 00:07:50,503
five years ago to the day.

161
00:07:50,536 --> 00:07:53,205
During the period
of September of 2012

162
00:07:53,238 --> 00:07:54,974
'til about, I would say, 2016,

163
00:07:55,007 --> 00:07:58,244
we were in the detailed
design-fabrication phase;

164
00:07:58,277 --> 00:07:59,578
now, the mission is currently

165
00:07:59,611 --> 00:08:01,480
in the
hardware-integration phase,

166
00:08:01,513 --> 00:08:03,415
getting ready for its
launch operations.

167
00:08:03,448 --> 00:08:05,217
The overall profile of
how the mission works

168
00:08:05,250 --> 00:08:07,353

is that once the
instrument is completed

169
00:08:07,386 --> 00:08:10,222
in terms of being built
and tested and assembled,

170
00:08:10,255 --> 00:08:13,659
it will be launched in a
pressurized cargo vehicle.

171
00:08:13,692 --> 00:08:14,827
There's different ways to get up

172
00:08:14,860 --> 00:08:16,295
to the International
Space Station.

173
00:08:16,328 --> 00:08:18,264
If you go inside of a
pressurized cargo vehicle,

174
00:08:18,297 --> 00:08:20,399
your payload will
actually always see

175
00:08:20,432 --> 00:08:22,234
a "short-sleeves
environment", that means

176
00:08:22,267 --> 00:08:26,038
both in terms of pressure
as well as temperatures.

177
00:08:26,071 --> 00:08:27,439
You don't see these
sort of extremes

178
00:08:27,472 --> 00:08:28,574
of the vacuum environment

that you might see

179
00:08:28,607 --> 00:08:29,775
during a typical launch.

180
00:08:29,808 --> 00:08:31,043
Our mission is
scheduled to go up

181
00:08:31,076 --> 00:08:33,712
on a SpaceX pressurized
launch vehicle.

182
00:08:33,745 --> 00:08:35,681
So basically, the pressurized
vehicles allow payloads

183
00:08:35,714 --> 00:08:38,617
such as ours or
such as life-science
payloads, like rats,

184
00:08:38,650 --> 00:08:39,818
to go up there and
not get damaged

185
00:08:39,851 --> 00:08:41,387
as they ride up
to Space Station.

186
00:08:41,420 --> 00:08:42,888
We'll talk a little bit
more about that later.

187
00:08:42,921 --> 00:08:46,258
So after we get launched
on the Falcon vehicle,

188
00:08:46,291 --> 00:08:47,660
in the pressurized

cargo vehicle,

189
00:08:47,693 --> 00:08:49,428
we dock with the
International Space Station,

190
00:08:49,461 --> 00:08:51,897
we dock via an airlock; the
astronauts then take us out

191
00:08:51,930 --> 00:08:54,233
of the Dragon capsule
and then install us

192
00:08:54,266 --> 00:08:55,968
into something called
an EXPRESS rack,

193
00:08:56,001 --> 00:08:57,736
which is a standardized
interface for payloads

194
00:08:57,769 --> 00:09:00,239
for Space Station; we'll talk
about that a little bit later.

195
00:09:00,272 --> 00:09:03,442
One of the advantages of CAL
is that it's actually operated

196
00:09:03,475 --> 00:09:05,377
entirely remotely
from the ground.

197
00:09:05,410 --> 00:09:07,446
So once the astronauts
install the payload

198
00:09:07,479 --> 00:09:09,014
into what is called

an EXPRESS rack,

199
00:09:09,047 --> 00:09:10,983
we're able to operate
the payload from JPL

200
00:09:11,016 --> 00:09:12,818
and do all of our science
experiments remotely,

201
00:09:12,851 --> 00:09:14,453
and that minimizes
the amount of time

202
00:09:14,486 --> 00:09:16,922
that the crew is required
to interact with you,

203
00:09:16,955 --> 00:09:19,525
which is a good thing, because
crew time is at a premium.

204
00:09:19,558 --> 00:09:21,160
And in terms of how we
communicate with the payload,

205
00:09:21,193 --> 00:09:23,329
the Space Station
communicates to TDRSS,

206
00:09:23,362 --> 00:09:25,798
which then communicates
down to NASA Marshall,

207
00:09:25,831 --> 00:09:28,667
which then communicates to
JPL, so it's a relatively fast,

208
00:09:28,700 --> 00:09:31,937
almost real-time data link

between JPL, NASA Marshall,

209
00:09:31,970 --> 00:09:34,307
TDRSS, to the Space Station.

210
00:09:36,642 --> 00:09:38,611
So the ride to Space Station
is also slightly different

211
00:09:38,644 --> 00:09:40,512
than the typical free-flying
spacecraft missions

212
00:09:40,545 --> 00:09:42,047
that JPL does.

213
00:09:42,080 --> 00:09:44,016
We go inside of a pressurized
vehicle that you can see here,

214
00:09:44,049 --> 00:09:46,785
and payloads are
basically launched in bags

215
00:09:46,818 --> 00:09:48,887
surrounded by foam,
and so what that means

216
00:09:48,920 --> 00:09:50,589
is that the traditional
launch vehicle environment

217
00:09:50,622 --> 00:09:53,025
which can be very harsh
on sensitive components

218
00:09:53,058 --> 00:09:55,060
is somewhat mitigated
by the use of foam

219
00:09:55,093 --> 00:09:56,462
inside of these bags.

220
00:09:56,495 --> 00:09:58,664
Once the bags are installed
inside of the hatch,

221
00:09:58,697 --> 00:10:00,633
they're actually strapped
into the interior

222
00:10:00,666 --> 00:10:03,769
of the cabin here, and this
is how CAL will be installed,

223
00:10:03,802 --> 00:10:05,838
basically, into the
pressurized cargo vehicle,

224
00:10:05,871 --> 00:10:07,640
they're sort of strapped
down, winched down.

225
00:10:07,673 --> 00:10:11,143
At that point, the
launch occurs, we go
up to Space Station,

226
00:10:11,176 --> 00:10:13,779
we dock with an airlock,
and all this time,

227
00:10:13,812 --> 00:10:15,981
the payload only
sees, essentially,

228
00:10:16,014 --> 00:10:17,549
a short-sleeves
environment, which keeps it

229
00:10:17,582 --> 00:10:19,952
in a more safe condition than
a traditional launch vehicle.

230
00:10:19,985 --> 00:10:22,254
The astronauts take us out
of this bag, out of the foam,

231
00:10:22,287 --> 00:10:26,425
and install us into an EXPRESS
rack, that you can see here.

232
00:10:26,458 --> 00:10:28,727
So, where are we going
to be on Space Station?

233
00:10:28,760 --> 00:10:31,063
Our payload is an interior
payload, so it goes

234
00:10:31,096 --> 00:10:33,365
inside the habitable
volume of Space Station,

235
00:10:33,398 --> 00:10:34,733
and there's many
different modules

236
00:10:34,766 --> 00:10:36,168
of the International
Space Station;

237
00:10:36,201 --> 00:10:37,836
it's quite a large
assembly, almost the size

238
00:10:37,869 --> 00:10:39,972
of a football
field, but our goal,

239
00:10:40,005 --> 00:10:41,306
what Rob's gonna talk
about a little bit later

240
00:10:41,339 --> 00:10:43,042
in terms of the science
that we're trying to do,

241
00:10:43,075 --> 00:10:45,811
is we want to minimize our
exposure to vibrations.

242
00:10:45,844 --> 00:10:47,813
We want to minimize our
exposure to accelerations,

243
00:10:47,846 --> 00:10:49,148
because the atom
cloud that we create

244
00:10:49,181 --> 00:10:50,683
is very sensitive to that.

245
00:10:50,716 --> 00:10:52,718
So as a result, we want to be
close to the center of mass

246
00:10:52,751 --> 00:10:54,486
of the Space Station, so
we actually want to go

247
00:10:54,519 --> 00:10:56,455
inside the US module
of Space Station,

248
00:10:56,488 --> 00:10:59,124
where the accelerations and
the vibrations are a minimum,

249

00:10:59,157 --> 00:11:01,126
so we can get the
best science possible,

250
00:11:01,159 --> 00:11:02,828
to the coldest
temperatures possible.

251
00:11:02,861 --> 00:11:05,731
What we also wanna do
is we want to be aligned

252
00:11:05,764 --> 00:11:07,332
with the gravity vector,
'cause some of the science

253
00:11:07,365 --> 00:11:08,801
that we're gonna
be doing is related

254
00:11:08,834 --> 00:11:10,769
to gravitational science,
which means that we either have

255
00:11:10,802 --> 00:11:14,239
to be in the port or starboard
location on Space Station.

256
00:11:14,272 --> 00:11:15,741
Now, on Space Station,
since you're in

257
00:11:15,774 --> 00:11:17,743
a zero-gravity environment,
there really is no ceiling

258
00:11:17,776 --> 00:11:19,812
or floor, but there
is an orientation

259

00:11:19,845 --> 00:11:22,114
relative to where the gravity
vector is, so that defines,

260
00:11:22,147 --> 00:11:24,483
basically, which EXPRESS
racks we can go inside of.

261
00:11:24,516 --> 00:11:28,053
We are able to make use of
a very convenient feature

262
00:11:28,086 --> 00:11:30,322
that Space Station has
for the interior payloads,

263
00:11:30,355 --> 00:11:32,024
which is water
cooling, that allows us

264
00:11:32,057 --> 00:11:34,159
to keep our system cold,
because we actually generate

265
00:11:34,192 --> 00:11:35,694
a lot of heat during
the course of making

266
00:11:35,727 --> 00:11:38,330
the Bose-Einstein condensates,
and we are able to occupy

267
00:11:38,363 --> 00:11:39,932
a relatively large
volume of space;

268
00:11:39,965 --> 00:11:42,568
I'll talk about that later,
but we roughly occupy the size

269

00:11:42,601 --> 00:11:46,004
of something the standard
Earth-sized ice chest would be.

270
00:11:46,037 --> 00:11:48,240
We do operate the payload
remotely from the ground,

271
00:11:48,273 --> 00:11:49,742
which is called
sequence control,

272
00:11:49,775 --> 00:11:52,211
which once again minimizes
crew involvement and crew time,

273
00:11:52,244 --> 00:11:54,313
which is at a premium,
but we are very sensitive

274
00:11:54,346 --> 00:11:57,049
to all kinds of fields: electric
fields, magnetic fields,

275
00:11:57,082 --> 00:11:58,584
and gravitational fields.

276
00:11:58,617 --> 00:12:00,686
We want to be in a
location where we have

277
00:12:00,719 --> 00:12:03,989
a series of payload neighbors
which minimize noise

278
00:12:04,022 --> 00:12:06,258
and magnetic interaction.

279
00:12:06,291 --> 00:12:08,127
So, based off of that,

this is a little bit

280
00:12:08,160 --> 00:12:09,628
of audience participation.

281
00:12:09,661 --> 00:12:11,697
I want you to give me your
input by a show of hands

282
00:12:11,730 --> 00:12:14,266
as who would be CAL's
favorite space neighbor

283
00:12:14,299 --> 00:12:15,934
onboard the International
Space Station.

284
00:12:15,967 --> 00:12:18,070
So by a show of hands,
would we want to be near

285
00:12:18,103 --> 00:12:21,640
a Sunita Williams on
the running machine?

286
00:12:21,673 --> 00:12:22,875
No? (chuckles)

287
00:12:22,908 --> 00:12:25,144
What about a space rat
going around in a wheel?

288
00:12:25,177 --> 00:12:26,145
No? (chuckles)

289
00:12:26,178 --> 00:12:27,613
Lettuce?

290
00:12:27,646 --> 00:12:29,281

Yes, so the lettuce
is the selection.

291
00:12:29,314 --> 00:12:31,083
The reason for that is because
the lettuce doesn't generate

292
00:12:31,116 --> 00:12:32,951
any vibrations, the
lettuce doesn't generate

293
00:12:32,984 --> 00:12:35,521
any magnetic field,
and the other way

294
00:12:35,554 --> 00:12:37,122
that we get around
Sunita Williams

295
00:12:37,155 --> 00:12:39,391
and other astronauts exercising
is that we only operate

296
00:12:39,424 --> 00:12:40,893
during the crew sleep period.

297
00:12:40,926 --> 00:12:44,496
So when they're not exercising,
generating extra vibrations

298
00:12:44,529 --> 00:12:46,498
which we would feel
inside the EXPRESS rack,

299
00:12:46,531 --> 00:12:48,133
we actually operate
CAL, which means that

300
00:12:48,166 --> 00:12:50,669
because the Space Station

is operated on Houston time,

301
00:12:50,702 --> 00:12:53,138
the mission operators for
CAL will have to be operating

302
00:12:53,171 --> 00:12:55,207
during sleep time in
Houston to be able

303
00:12:55,240 --> 00:12:57,109
to minimize vibrations
to the payload.

304
00:12:57,142 --> 00:12:58,944
Although the rat
is cute, I think,

305
00:12:58,977 --> 00:13:00,512
in this particular
situation (chuckles).

306
00:13:00,545 --> 00:13:02,748
So if you were going up into
space, what would you need?

307
00:13:02,781 --> 00:13:06,585
You would need air, water,
power, and data, right?

308
00:13:06,618 --> 00:13:08,020
That makes sense if
you're going into space.

309
00:13:08,053 --> 00:13:09,788
So our payload needs
the exact same thing,

310
00:13:09,821 --> 00:13:11,623
and fortunately for

us, the EXPRESS rack,

311
00:13:11,656 --> 00:13:13,759
which is the standardized
interface for Space Station,

312
00:13:13,792 --> 00:13:15,561
provides just that.

313
00:13:15,594 --> 00:13:18,864
It provides 28-volt constant
power to our payload,

314
00:13:18,897 --> 00:13:20,332
which actually keeps
our pump going,

315
00:13:20,365 --> 00:13:22,467
so we can maintain really
low vacuum pressures;

316
00:13:22,500 --> 00:13:24,603
it provides air
cooling, cooled air

317
00:13:24,636 --> 00:13:26,872
which goes into the
interior cavity here,

318
00:13:26,905 --> 00:13:28,373
which provides
additional cooling;

319
00:13:28,406 --> 00:13:31,610
we also have access to
a water-cooling loop,

320
00:13:31,643 --> 00:13:33,645
which actually allows
cold water to flow

321
00:13:33,678 --> 00:13:35,247
through heat exchangers
that all of our

322
00:13:35,280 --> 00:13:36,982
electronics equipment
is attached to,

323
00:13:37,015 --> 00:13:39,484
which allows us to cool it;

324
00:13:39,517 --> 00:13:41,220
we don't make use of the
vacuum supply on board,

325
00:13:41,253 --> 00:13:43,689
'cause we have our own pump,
but we also do have connection

326
00:13:43,722 --> 00:13:45,824
to Ethernet, not because
we're using Facebook

327
00:13:45,857 --> 00:13:47,693
but because we're
trying to connect

328
00:13:47,726 --> 00:13:49,328
and login to our payload.

329
00:13:49,361 --> 00:13:51,230
Basically, we're able to
login to the CAL payload

330
00:13:51,263 --> 00:13:53,332
from the ground here at
JPL and communicate with it

331

00:13:53,365 --> 00:13:55,701
back and forth, both to
uplink data and commands

332
00:13:55,734 --> 00:13:58,804
as well as to to downlink data
from the science instrument,

333
00:13:58,837 --> 00:14:02,241
which is our science
data product.

334
00:14:02,274 --> 00:14:03,709
So, what do we do?

335
00:14:03,742 --> 00:14:05,344
We go inside an EXPRESS
rack, so this is showing you

336
00:14:05,377 --> 00:14:08,513
the interior of the US
module in Space Station,

337
00:14:08,546 --> 00:14:11,083
and each side here represents
a different location

338
00:14:11,116 --> 00:14:12,784
of EXPRESS racks,
so this basically is

339
00:14:12,817 --> 00:14:13,919
an EXPRESS rack region.

340
00:14:13,952 --> 00:14:15,854
They're constantly
being used for payloads

341
00:14:15,887 --> 00:14:18,457
for different reasons,

so CAL will be integrated

342
00:14:18,490 --> 00:14:20,292
when other payloads
come out, CAL can go in

343
00:14:20,325 --> 00:14:21,793
and we can operate it.

344
00:14:21,826 --> 00:14:23,295
So we're gonna make use of
that water-cooling loop,

345
00:14:23,328 --> 00:14:26,231
we're gonna make use of air
cooling to also keep us cool,

346
00:14:26,264 --> 00:14:29,735
constant 28-volt power, and
then access to Ethernet,

347
00:14:29,768 --> 00:14:31,904
which allows us to
communicate with Earth,

348
00:14:31,937 --> 00:14:34,206
and then from Earth back
up to Space Station.

349
00:14:34,239 --> 00:14:36,808
That's the way you make use
of this interior laboratory

350
00:14:36,841 --> 00:14:39,044
on Space Station, and
what's so nice about this

351
00:14:39,077 --> 00:14:42,147
is that it's standardized,
so we know what the interface

352
00:14:42,180 --> 00:14:44,082
is going to be ahead of
time, we designed the system

353
00:14:44,115 --> 00:14:47,319
to interface with it, and that
is how CAL was built to be,

354
00:14:47,352 --> 00:14:49,721
specifically
tailored to make use

355
00:14:49,754 --> 00:14:51,189
of the International
Space Station.

356
00:14:51,222 --> 00:14:52,591
The reason why this is different

357
00:14:52,624 --> 00:14:54,593
from some of other JPL's
free-flying spacecraft missions

358
00:14:54,626 --> 00:14:56,929
is that we don't have to
generate our own power.

359
00:14:56,962 --> 00:14:58,997
We don't need solar rays,
because the Space Station

360
00:14:59,030 --> 00:15:00,265
already has them.

361
00:15:00,298 --> 00:15:02,401
We don't have to have
our own cooling system

362

00:15:02,434 --> 00:15:04,503
with the use of
radiators, for example,

363
00:15:04,536 --> 00:15:05,971
because we have access
to the water cooling

364
00:15:06,004 --> 00:15:07,406
and the air cooling.

365
00:15:07,439 --> 00:15:09,441
That's what makes Space
Station a laboratory in space,

366
00:15:09,474 --> 00:15:12,644
and specifically to understand
microgravity science

367
00:15:12,677 --> 00:15:15,948
that Rob is gonna talk
about in a lot more detail.

368
00:15:15,981 --> 00:15:19,151
So the other advantage of
using the Space Station,

369
00:15:19,184 --> 00:15:20,519
and Rob's gonna
talk about it more

370
00:15:20,552 --> 00:15:22,554
from a science perspective,
is that it allows us

371
00:15:22,587 --> 00:15:25,490
to come up with an instrument
that can actually be repaired

372
00:15:25,523 --> 00:15:26,992

and upgraded on orbit.

373
00:15:27,025 --> 00:15:29,561
That means that you can make
it last for a really long time,

374
00:15:29,594 --> 00:15:31,563
because the crew can come
in there and do repairs,

375
00:15:31,596 --> 00:15:33,632
but you can also
upgrade it to give you

376
00:15:33,665 --> 00:15:35,367
additional science
capability on time.

377
00:15:35,400 --> 00:15:38,737
So what we did here is we came
up with a modular approach,

378
00:15:38,770 --> 00:15:40,872
so this is different from how
systems are normally built

379
00:15:40,905 --> 00:15:43,241
at JPL, so that a human
being could go in there

380
00:15:43,274 --> 00:15:45,711
and disassemble the
instrument on orbit,

381
00:15:45,744 --> 00:15:48,447
take components of it out,
replace individual boxes,

382
00:15:48,480 --> 00:15:50,649
putting them back on

again, and make it work

383
00:15:50,682 --> 00:15:53,085
without ever having any
involvement from here at JPL

384
00:15:53,118 --> 00:15:54,686
or the experts at JPL.

385
00:15:54,719 --> 00:15:56,388
That was an engineering
challenge for us,

386
00:15:56,421 --> 00:15:58,957
to be able to come up with
this plug-and-play approach.

387
00:15:58,990 --> 00:16:01,059
You can see here how
the system looks like

388
00:16:01,092 --> 00:16:04,096
in this plug-and-play fashion,
where all hardware is mounted

389
00:16:04,129 --> 00:16:05,797
on individual
heat-exchanger plates,

390
00:16:05,830 --> 00:16:08,934
and then either lasers or
electronics are in each one

391
00:16:08,967 --> 00:16:10,769
of those heat-exchanger
plates, so that the astronauts

392
00:16:10,802 --> 00:16:13,405
have to be trained on how to
disconnect all the connections,

393
00:16:13,438 --> 00:16:16,775
whether they be fiber-optic
connections, water, or power

394
00:16:16,808 --> 00:16:19,077
or data connections, and
how to reconnect them again.

395
00:16:19,110 --> 00:16:21,980
And so what we did to
facilitate that is that we built

396
00:16:22,013 --> 00:16:25,917
a 3-d model, and we
actually used 3-d printing,

397
00:16:25,950 --> 00:16:27,386
which was a great use for it.

398
00:16:27,419 --> 00:16:29,388
So instead of building a
full engineering version,

399
00:16:29,421 --> 00:16:31,056
we did it at
relatively low cost,

400
00:16:31,089 --> 00:16:32,958
where we actually would
print each component

401
00:16:32,991 --> 00:16:35,427
with a 3-d printer with
the correct hole pattern

402
00:16:35,460 --> 00:16:36,728
so that we could
train the astronauts

403
00:16:36,761 --> 00:16:37,963
on how to put it together.

404
00:16:37,996 --> 00:16:40,365
And so we have this
up in our ORU lab,

405
00:16:40,398 --> 00:16:42,267
it's called Orbit
Replacement Unit lab

406
00:16:42,300 --> 00:16:44,636
up in Building 238 if you
wanna come take a look at it,

407
00:16:44,669 --> 00:16:46,772
so this is actually what
the CAL payload looks like.

408
00:16:46,805 --> 00:16:49,708
There's a quad locker here
and a single locker up here.

409
00:16:49,741 --> 00:16:53,145
We have had several
astronauts come out

410
00:16:53,178 --> 00:16:55,514
over the course of the past
three years to work with us,

411
00:16:55,547 --> 00:16:58,150
both to teach us how
to design an instrument

412
00:16:58,183 --> 00:17:00,085
that astronauts can
interact with on orbit

413

00:17:00,118 --> 00:17:02,120
and easily disassemble
on orbit, and also for us

414
00:17:02,153 --> 00:17:04,990
to teach them how to do the
repairs and do the assembly

415
00:17:05,023 --> 00:17:06,958
and do the disassembly on orbit.

416
00:17:06,991 --> 00:17:09,561
Our first time, we had
astronaut Mike Barrett come out,

417
00:17:09,594 --> 00:17:12,497
this was at a much earlier
stage in the CAL design process,

418
00:17:12,530 --> 00:17:15,567
and he basically taught us
about which kind of connections

419
00:17:15,600 --> 00:17:16,968
were easy for them to
do, which ones are hard,

420
00:17:17,001 --> 00:17:19,071
which were gonna require
special training,

421
00:17:19,104 --> 00:17:20,739
and then something that you
probably wouldn't think about

422
00:17:20,772 --> 00:17:23,809
necessarily is the range of
different potential astronauts.

423
00:17:23,842 --> 00:17:25,710

You may have some astronauts
with very big hands,

424
00:17:25,743 --> 00:17:28,080
like Mike Barrett had; you
may have some astronauts

425
00:17:28,113 --> 00:17:29,081
with really really small hands,

426
00:17:29,114 --> 00:17:30,582
like I have really small hands.

427
00:17:30,615 --> 00:17:33,218
So each connector has to be
thought with that in mind,

428
00:17:33,251 --> 00:17:34,653
so somebody can
actually go in there

429
00:17:34,686 --> 00:17:36,788
and unscrew them and
then re-torque them

430
00:17:36,821 --> 00:17:38,356
to make them strong again.

431
00:17:38,389 --> 00:17:40,559
This was a more recent
crew training that we had

432
00:17:40,592 --> 00:17:42,961
with astronaut Tom
Marshburn and John Cassada.

433
00:17:42,994 --> 00:17:45,097
This was just January
a few months ago,

434
00:17:45,130 --> 00:17:47,499
and here, this is essentially
the final configuration

435
00:17:47,532 --> 00:17:49,534
of the instrument, and now
we're actually developing

436
00:17:49,567 --> 00:17:52,370
the procedures, whilst
recording videos,

437
00:17:52,403 --> 00:17:54,706
so that the astronaut
crew can do these repairs

438
00:17:54,739 --> 00:17:56,575
when the time comes
for them to do,

439
00:17:56,608 --> 00:17:58,009
which will maybe
be one or two years

440
00:17:58,042 --> 00:18:00,178
into the on-orbit mission.

441
00:18:00,211 --> 00:18:03,014
We also do it to make
estimates of how much time

442
00:18:03,047 --> 00:18:04,349
it takes to do these.

443
00:18:04,382 --> 00:18:06,218
There's different stages
that they'll have to do,

444
00:18:06,251 --> 00:18:08,186

the initial installation,
which is relatively easy

445
00:18:08,219 --> 00:18:10,722
in terms of there's hex
bolts that you connect,

446
00:18:10,755 --> 00:18:12,924
the quad locker to
the EXPRESS rack,

447
00:18:12,957 --> 00:18:15,227
but later on, when we do
installations of lasers,

448
00:18:15,260 --> 00:18:16,995
that actually turns out to
be a much more extensive

449
00:18:17,028 --> 00:18:20,532
day to two-day-long
repair period.

450
00:18:20,565 --> 00:18:22,634
So it is complicated,
that is what they told us.

451
00:18:22,667 --> 00:18:24,569
In terms of the different
types of payloads

452
00:18:24,602 --> 00:18:26,138
that are in Space
Station, CAL is probably

453
00:18:26,171 --> 00:18:28,940
in the 80th to 90th percentile
in terms of complexity,

454
00:18:28,973 --> 00:18:31,143

because of the number of
electrical connections,

455
00:18:31,176 --> 00:18:33,378
fiber optic connections,
water connections,

456
00:18:33,411 --> 00:18:35,180
and data connections.

457
00:18:36,347 --> 00:18:38,683
One other thing which
is unique about CAL

458
00:18:38,716 --> 00:18:41,753
is the type of risk
classification that it has.

459
00:18:41,786 --> 00:18:43,622
Those of you who already
work at JPL and NASA

460
00:18:43,655 --> 00:18:46,958
know there is Class
A, B, C, D missions;

461
00:18:46,991 --> 00:18:49,528
Class A/B missions are missions
like the Curiosity rover,

462
00:18:49,561 --> 00:18:51,730
very expensive, multi-billion
dollar missions,

463
00:18:51,763 --> 00:18:53,899
one-way trip, it's gotta work,

464
00:18:53,932 --> 00:18:57,169
and then Class C missions are
a little bit less expensive,

465
00:18:57,202 --> 00:18:59,004
and then Class D
missions are typically

466
00:18:59,037 --> 00:19:01,339
much cheaper missions, let's
say CubeSat-type missions,

467
00:19:01,372 --> 00:19:03,041
where it's okay for the thing

468
00:19:03,074 --> 00:19:04,943
not necessarily to
work downstream.

469
00:19:04,976 --> 00:19:08,046
So even though CAL has to
work, we were able to adopt

470
00:19:08,079 --> 00:19:11,283
a Class D mission architecture,
because we have the ability

471
00:19:11,316 --> 00:19:13,652
to do repairs on orbit, and
because we have the ability,

472
00:19:13,685 --> 00:19:16,221
if we really needed to, to
bring the entire instrument down

473
00:19:16,254 --> 00:19:17,222
and repair it on the ground.

474
00:19:17,255 --> 00:19:18,890
So that allowed us to do things

475
00:19:18,923 --> 00:19:21,126

a little bit more
cost-effectively and
time-effectively,

476
00:19:21,159 --> 00:19:22,627
and one of the ways
that we do that

477
00:19:22,660 --> 00:19:24,696
is with the use of
commercial hardware,

478
00:19:24,729 --> 00:19:27,766
but of course,
commercial hardware does
have its challenges,

479
00:19:27,799 --> 00:19:30,235
for example, using Windows,
we're all used to using Windows

480
00:19:30,268 --> 00:19:31,770
and crashes that you might have.

481
00:19:31,803 --> 00:19:34,005
So our operating system
actually does operate

482
00:19:34,038 --> 00:19:36,174
off of Windows, so
we do have a concern,

483
00:19:36,207 --> 00:19:37,676
but we have the ability
to reboot the system

484
00:19:37,709 --> 00:19:39,911
and even potentially do a
hard reboot from the ground

485

00:19:39,944 --> 00:19:42,314
if we need to, but the reason
why using commercial hardware

486
00:19:42,347 --> 00:19:45,817
is good is that the
development-time cost
associated with it

487
00:19:45,850 --> 00:19:48,553
has already been captured,
essentially, by somebody else,

488
00:19:48,586 --> 00:19:50,255
and you're buying a
part off the shelf.

489
00:19:50,288 --> 00:19:52,057
So we have, to the
maximum extent possible,

490
00:19:52,090 --> 00:19:55,427
used commercial hardware
in the design of CAL.

491
00:19:55,460 --> 00:19:58,096
We also are allowed
to accept more risk,

492
00:19:58,129 --> 00:20:01,066
and this means technical
risk, it means schedule risk,

493
00:20:01,099 --> 00:20:03,568
and it means cost risk, and
so it's always a trading game

494
00:20:03,601 --> 00:20:05,003
as to how much is acceptable.

495

00:20:05,036 --> 00:20:07,305
So if you can accept zero
risk, your mission's gonna cost

496
00:20:07,338 --> 00:20:08,573
a lot more money.

497
00:20:08,606 --> 00:20:09,808
If you can accept a lot of risk,

498
00:20:09,841 --> 00:20:11,276
your mission is going
to be a lot cheaper,

499
00:20:11,309 --> 00:20:12,744
but there is chances when
things don't go right

500
00:20:12,777 --> 00:20:14,613
that you'll have to spend
more money and spend more time

501
00:20:14,646 --> 00:20:16,114
to fix them, and
that's something that
we have experienced

502
00:20:16,147 --> 00:20:17,582
over the years.

503
00:20:17,615 --> 00:20:20,552
But it's a gamble, you
can think of it that way,

504
00:20:20,585 --> 00:20:24,089
but it's a way to make the
mission more cost-effective,

505
00:20:24,122 --> 00:20:26,091
basically for NASA.

506
00:20:26,124 --> 00:20:27,993
The difficulty, of
course, is that we have

507
00:20:28,026 --> 00:20:29,828
a very low budget,
which means that we have

508
00:20:29,861 --> 00:20:31,463
a really small cookie jar
that we have to work with

509
00:20:31,496 --> 00:20:32,731
and we have to be really careful

510
00:20:32,764 --> 00:20:35,400
with how we spend the
money, and it also means

511
00:20:35,433 --> 00:20:37,535
that you have a very small
team, and what that really means

512
00:20:37,568 --> 00:20:39,237
is that each and every
member of the team

513
00:20:39,270 --> 00:20:41,973
has had to wear multiple
hats, play multiple roles.

514
00:20:42,006 --> 00:20:44,042
So how do you find
the skill mix,

515
00:20:44,075 --> 00:20:45,844
from a management perspective,
of somebody who can do

516
00:20:45,877 --> 00:20:48,546
scientific work,
engineering work,

517
00:20:48,579 --> 00:20:51,149
integration and test work,
as well as programmatic?

518
00:20:51,182 --> 00:20:52,917
It's actually very difficult,
so whoever is working

519
00:20:52,950 --> 00:20:55,420
on a project like this actually
has to have the ability

520
00:20:55,453 --> 00:20:57,589
to grow into many
different aspects

521
00:20:57,622 --> 00:20:59,024
that they wouldn't
have to begin with.

522
00:20:59,057 --> 00:21:01,159
So part of the past five-year
journey for all of us

523
00:21:01,192 --> 00:21:02,927
is adopting a lot of
roles and adopting

524
00:21:02,960 --> 00:21:04,929
a lot of capabilities that
we didn't start off with,

525
00:21:04,962 --> 00:21:06,564
but I think we had a
great team of people

526
00:21:06,597 --> 00:21:09,100
which has gotten us
to this point today.

527
00:21:09,133 --> 00:21:11,636
The other issue with Class
D is that when you use

528
00:21:11,669 --> 00:21:13,405
commercial hardware,
you're working with

529
00:21:13,438 --> 00:21:15,740
a capability-driven design,
and what that means is

530
00:21:15,773 --> 00:21:18,743
the box that you bought
can only do what it can do,

531
00:21:18,776 --> 00:21:20,445
and so if it doesn't
meet the specifications

532
00:21:20,478 --> 00:21:21,913
that it says it should,

533
00:21:21,946 --> 00:21:24,616
I'm buying a computer
which has this much memory

534
00:21:24,649 --> 00:21:26,751
and this much hard-drive
space, that's the capability

535
00:21:26,784 --> 00:21:28,219
you have to work within it.

536
00:21:28,252 --> 00:21:30,655

So we had to do a lot of trades
as the engineering community

537
00:21:30,688 --> 00:21:32,691
to make sure that we can fit
within those constraints,

538
00:21:32,724 --> 00:21:34,726
having had to use
commercial hardware,

539
00:21:34,759 --> 00:21:37,128
and of course, the interfaces
associated with Space Station,

540
00:21:37,161 --> 00:21:39,297
which we couldn't go beyond.

541
00:21:39,330 --> 00:21:41,032
So this is the final
on-orbit configuration,

542
00:21:41,065 --> 00:21:42,434
we'll talk a little
bit more about the guts

543
00:21:42,467 --> 00:21:43,802
of the instrument
after the science talk

544
00:21:43,835 --> 00:21:45,737
that Rob's gonna go
through, but you can see

545
00:21:45,770 --> 00:21:47,272
this is an entire EXPRESS rack.

546
00:21:47,305 --> 00:21:51,576
We occupy four lockers
here, one locker here.

547
00:21:51,609 --> 00:21:54,412
Each one of these locker spaces
could be a separate payload

548
00:21:54,445 --> 00:21:56,715
but because we're a very
large, complicated instrument,

549
00:21:56,748 --> 00:21:59,951
we actually had to occupy
a total of five lockers.

550
00:21:59,984 --> 00:22:02,087
So we call this the
science instrument,

551
00:22:02,120 --> 00:22:03,922
which is where most of
the science is going on,

552
00:22:03,955 --> 00:22:06,024
where our vacuum system is, and
we'll talk a little bit more

553
00:22:06,057 --> 00:22:07,992
about the guts of that later
on in the presentation,

554
00:22:08,025 --> 00:22:10,061
and then we have the
power electronics locker,

555
00:22:10,094 --> 00:22:13,164
which houses a lot of our
power distribution electronics.

556
00:22:13,197 --> 00:22:15,200
So we can see we are a
relatively big payload,

557
00:22:15,233 --> 00:22:17,836
but we needed that,
and compared to what

558
00:22:17,869 --> 00:22:20,472
we started off with, which
is an entire laboratory,

559
00:22:20,505 --> 00:22:22,540
condensing into
the size of a box

560
00:22:22,573 --> 00:22:24,809
is actually quite a challenge.

561
00:22:24,842 --> 00:22:27,679
Rob's gonna take
it over from here.

562
00:22:27,712 --> 00:22:30,716
(audience applauds)

563
00:22:34,118 --> 00:22:35,453
- Thanks Anita.

564
00:22:35,486 --> 00:22:38,156
(clears throat)

565
00:22:39,023 --> 00:22:41,459
I'm going to talk a little bit

566
00:22:41,492 --> 00:22:44,462
about the science
background for CAL.

567
00:22:44,495 --> 00:22:49,300
There's a number of grand
themes that play out in science

568
00:22:49,333 --> 00:22:50,836
over many decades.

569
00:22:52,036 --> 00:22:53,838
For example, for
several centuries,

570
00:22:53,871 --> 00:22:56,674
astronomers have been building
ever-bigger telescopes

571
00:22:56,707 --> 00:23:00,045
to look further and
further back in time

572
00:23:02,480 --> 00:23:05,550
and deeper and deeper
out into the universe.

573
00:23:05,583 --> 00:23:08,219
Physicists for much of past
century have been building

574
00:23:08,252 --> 00:23:10,522
larger and larger
particle accelerators

575
00:23:10,555 --> 00:23:12,724
to reach higher and
higher intensities

576
00:23:12,757 --> 00:23:15,026
and to look, again,
deeper and deeper

577
00:23:15,059 --> 00:23:16,594
into the heart of matter.

578

00:23:16,627 --> 00:23:20,732
I'm gonna talk to you about
another of the great themes

579
00:23:20,765 --> 00:23:25,069
of physics: the quest for
ever-colder temperatures,

580
00:23:25,102 --> 00:23:27,739
and especially I'm going to
talk about the Cold Atom Lab,

581
00:23:27,772 --> 00:23:31,777
which represents the
latest step in that journey

582
00:23:32,610 --> 00:23:34,446
towards absolute zero.

583
00:23:36,314 --> 00:23:37,882
One of the early
pioneers in this field

584
00:23:37,915 --> 00:23:42,654
is the 19th-century Scottish
scientist Sir James Dewar.

585
00:23:42,687 --> 00:23:44,222
He invented the
famous Dewar flask

586
00:23:44,255 --> 00:23:47,158
and he developed
technologies to reach lower

587
00:23:47,191 --> 00:23:50,061
and lower temperatures,
culminating in the ability

588
00:23:50,094 --> 00:23:54,466

to liquefy hydrogen
at temperatures about
20 degrees Kelvin,

589
00:23:54,499 --> 00:23:57,202
20 degrees above absolute zero.

590
00:23:57,235 --> 00:24:01,773
As an aside, physicists
in particular like to talk

591
00:24:01,806 --> 00:24:05,977
in Kelvin, that's how we
like to measure temperature.

592
00:24:08,579 --> 00:24:10,849
It's referenced to absolute
zero, so zero in Kelvin

593
00:24:10,882 --> 00:24:14,619
is absolute zero, compared
to zero in Celsius

594
00:24:15,686 --> 00:24:18,557
which is the freezing
point of water.

595
00:24:21,092 --> 00:24:23,461
The magnitude of
each degree Kelvin

596
00:24:23,494 --> 00:24:26,097
and degree Celsius is the same.

597
00:24:27,265 --> 00:24:31,603
Anyhow, after Sir James
Dewar's breakthroughs,

598
00:24:31,636 --> 00:24:36,140
following that, there was

breakthroughs by Heike Onnes

599
00:24:36,173 --> 00:24:37,876
of the Netherlands, who
was the first person

600
00:24:37,909 --> 00:24:40,245
to liquefy helium,
and soon after,

601
00:24:40,278 --> 00:24:43,114
he discovered superconductivity,

602
00:24:43,147 --> 00:24:46,684
the ability in certain
metals for currents to flow

603
00:24:46,717 --> 00:24:50,421
within the total
absence of resistance.

604
00:24:50,454 --> 00:24:54,826
A few years later, during
the infancy of the science

605
00:24:54,859 --> 00:24:57,996
of quantum mechanics, Bose
and Einstein developed

606
00:24:58,029 --> 00:25:00,031
the theory of the
Bose-Einstein condensate,

607
00:25:00,064 --> 00:25:04,236
which we're gonna spend much
of the lecture talking about.

608
00:25:06,237 --> 00:25:10,175
This theory told how
certain types of particles

609
00:25:12,443 --> 00:25:15,213
would behave at temperatures
very, very close

610
00:25:15,246 --> 00:25:16,648
to absolute zero.

611
00:25:19,784 --> 00:25:22,387
When it first came out, this
theory, not too many people

612
00:25:22,420 --> 00:25:24,856
believed it really corresponded
to anything physical,

613
00:25:24,889 --> 00:25:26,958
even Einstein didn't
really believe it.

614
00:25:26,991 --> 00:25:30,395
But as people started
discovering the laws
of superfluidity

615
00:25:30,428 --> 00:25:33,731
and superconductivity,
they realized it related

616
00:25:33,764 --> 00:25:37,502
to these investigations
by Bose and Einstein.

617
00:25:38,703 --> 00:25:41,606
In the 1980s, techniques
were made to cool atoms

618
00:25:41,639 --> 00:25:43,207
with lasers and
reach temperatures

619
00:25:43,240 --> 00:25:46,511
of a millionth of a degree
above absolute zero,

620
00:25:46,544 --> 00:25:48,947
and that rose a lot of
excitement in the field

621
00:25:48,980 --> 00:25:52,150
that possibly we
could finally observe

622
00:25:53,884 --> 00:25:56,454
this predicted state of matter.

623
00:25:58,122 --> 00:26:00,592
But it took another 10
years before Eric Cornell

624
00:26:00,625 --> 00:26:02,727
and Carl Wiemann at the
University of Colorado

625
00:26:02,760 --> 00:26:04,495
developed a new
set of techniques

626
00:26:04,528 --> 00:26:09,500
that allowed them to finally
observe this condensate.

627
00:26:09,533 --> 00:26:12,737
At the time, I was a
postdoc, I had just started

628
00:26:12,770 --> 00:26:16,942
a little earlier than that
in the lab of Bill Phillips,

629
00:26:18,309 --> 00:26:22,013
and as soon as this result
came out, everybody in our lab,

630
00:26:23,314 --> 00:26:25,450
or at least a large
fraction of us,

631
00:26:25,483 --> 00:26:27,018
sorta stopped what we were doing

632
00:26:27,051 --> 00:26:31,055
and we started trying to
make condensate machines.

633
00:26:31,088 --> 00:26:33,558
Not just our lab but many
labs around the world

634
00:26:33,591 --> 00:26:37,762
joined into this rush, and
that excitement has not let up.

635
00:26:39,296 --> 00:26:43,001
After 20 years,
this has provided an
extremely diverse area

636
00:26:46,170 --> 00:26:48,339
of physics, and we'll
learn a little bit

637
00:26:48,372 --> 00:26:53,111
about some of that diversity
as I go on in the talk.

638
00:26:53,144 --> 00:26:55,313
Sir James Dewar, of
course, there's no way

639
00:26:55,346 --> 00:26:57,715
he could have predicted
all these exciting things

640
00:26:57,748 --> 00:26:59,784
that would have come
from this journey

641
00:26:59,817 --> 00:27:03,488
towards absolute zero, and
as we take the next step,

642
00:27:03,521 --> 00:27:07,959
go a little bit closer, little
bit cooler temperatures,

643
00:27:07,992 --> 00:27:10,795
we have to expect that,
possibly, Nature will have

644
00:27:10,828 --> 00:27:13,999
some sort of surprises
for us as well.

645
00:27:16,100 --> 00:27:18,670
Now I should state, Sir
James Dewar's contributions

646
00:27:18,703 --> 00:27:22,374
are very important, of
course, but in truth,

647
00:27:24,008 --> 00:27:26,744
if the truth be told,
he's actually not even

648
00:27:26,777 --> 00:27:30,115
the greatest inventor
named James Dewar.

649
00:27:31,248 --> 00:27:33,851
That honor goes to
the American inventor,

650
00:27:33,884 --> 00:27:37,288
James Alexander Dewar,
who developed the Twinkie.

651
00:27:37,321 --> 00:27:40,225
(audience laughs)

652
00:27:42,326 --> 00:27:44,696
So what is a
Bose-Einstein condensate?

653
00:27:44,729 --> 00:27:48,366
To understand what a
Bose-Einstein condensate is,

654
00:27:48,399 --> 00:27:52,237
we have to recall a few
facts from the science

655
00:27:53,370 --> 00:27:54,972
of quantum mechanics,
that's the science

656
00:27:55,005 --> 00:27:58,543
of very small objects:
atoms and molecules

657
00:27:58,576 --> 00:28:00,578
and subatomic particles.

658
00:28:02,046 --> 00:28:04,449
Quantum mechanics teaches
us that all matter has

659
00:28:04,482 --> 00:28:08,019

both a wave and a
particle nature.

660
00:28:08,052 --> 00:28:12,924
Associated with any quantum
object, there's a wave function,

661
00:28:12,957 --> 00:28:15,893
and the wavelength associated
with that wave function

662
00:28:15,926 --> 00:28:19,630
is inversely proportionate to
the momentum of that particle,

663
00:28:19,663 --> 00:28:24,435
and hence inversely proportional
to how fast it's moving.

664
00:28:24,468 --> 00:28:27,538
And that wave describes
the probability

665
00:28:27,571 --> 00:28:30,141
of finding that particle
in a particular location,

666
00:28:30,174 --> 00:28:32,010
in a particular state.

667
00:28:33,410 --> 00:28:36,714
At high temperatures, atoms
behave pretty much as particles.

668
00:28:36,747 --> 00:28:40,818
If you have a gas of
molecules at room temperature,

669
00:28:40,851 --> 00:28:43,788
they're shooting around

like bullets being fired

670
00:28:43,821 --> 00:28:47,992
out of a high-velocity rifle,
and that classical behavior,

671
00:28:49,126 --> 00:28:50,962
you can think of them
as billiard balls,

672
00:28:50,995 --> 00:28:54,799
their wavelengths are so short
that we don't have to worry

673
00:28:54,832 --> 00:28:56,667
about quantum mechanics
and we can just

674
00:28:56,700 --> 00:28:58,136
think of them
completely classically.

675
00:28:58,169 --> 00:29:00,037
As we reach colder temperatures,

676
00:29:00,070 --> 00:29:02,473
as we reach the types of
temperatures that we can reach

677
00:29:02,506 --> 00:29:06,110
with laser cooling, we start
to see that quantum nature;

678
00:29:06,143 --> 00:29:08,212
the wavelengths get
bigger and bigger

679
00:29:08,245 --> 00:29:11,015
and it becomes more pronounced.

680
00:29:11,048 --> 00:29:13,217
And there's a transition
that occurs at temperatures

681
00:29:13,250 --> 00:29:17,822
of a few tens of nanoKelvin
where the wavelengths

682
00:29:17,855 --> 00:29:20,892
of neighboring atoms
starts to overlap.

683
00:29:20,925 --> 00:29:22,693
Now, remember that
wavelength of that atom

684
00:29:22,726 --> 00:29:25,129
tells the probability
of finding the atom

685
00:29:25,162 --> 00:29:26,597
in a particular location.

686
00:29:26,630 --> 00:29:30,334
As soon as those wavelengths
overlap, you can't tell

687
00:29:30,367 --> 00:29:34,672
which atom is which anymore,
and you have to treat

688
00:29:34,705 --> 00:29:37,842
all these atoms are identical,
and that was the insight

689
00:29:37,875 --> 00:29:41,212
that Bose and Einstein
had come up with.

690

00:29:42,479 --> 00:29:45,116
So when you reach that point,

691
00:29:45,149 --> 00:29:48,286
the atoms undergo
a phase transition.

692
00:29:48,319 --> 00:29:51,455
A phase transition is,
you're all familiar

693
00:29:51,488 --> 00:29:54,959
with the transition from
liquid water to ice,

694
00:29:54,992 --> 00:29:58,196
that's a type of phase
transition, one state of matter

695
00:29:58,229 --> 00:30:00,231
to another state of matter.

696
00:30:00,264 --> 00:30:03,701
In a Bose-Einstein condensation,
that's a phase transition,

697
00:30:03,734 --> 00:30:07,906
a purely quantum
phase transition, in
which you transition

698
00:30:09,273 --> 00:30:12,143
into a state where a
large faction of the atoms

699
00:30:12,176 --> 00:30:16,247
are in the lowest possible
energy level available

700
00:30:18,048 --> 00:30:20,251

to the state, and
all of those atoms,

701
00:30:20,284 --> 00:30:22,787
their waves are
perfectly in phase

702
00:30:22,820 --> 00:30:25,557
and coordinated
with one another.

703
00:30:29,126 --> 00:30:32,763
That process of making
BECs is now done routinely

704
00:30:32,796 --> 00:30:36,500
in hundreds if not thousands
of labs around the world,

705
00:30:36,533 --> 00:30:40,504
and many people are reaching
these types of temperatures.

706
00:30:40,537 --> 00:30:42,240
Going into microgravity,
as we'll see,

707
00:30:42,273 --> 00:30:45,710
allows us to reach a new
regime of temperatures

708
00:30:45,743 --> 00:30:49,013
that ultimately might get
as low as a picoKelvin,

709
00:30:49,046 --> 00:30:53,517
that's a trillionth of a
degree above absolute zero.

710
00:30:53,550 --> 00:30:55,753

Temperatures like that,
the wavelength becomes

711
00:30:55,786 --> 00:30:58,022
on the order of
about a millimeter.

712
00:30:58,055 --> 00:31:01,459
That's just an astonishing
thing, that a quantum wavelength

713
00:31:01,492 --> 00:31:03,461
could be that big.

714
00:31:03,494 --> 00:31:06,631
The one thing that
people tend to know

715
00:31:06,664 --> 00:31:08,866
about quantum mechanics
is that it's the science

716
00:31:08,899 --> 00:31:11,335
of very small things,
tiny things like atoms,

717
00:31:11,368 --> 00:31:13,237
but at these temperatures,

718
00:31:13,270 --> 00:31:16,541
these objects can
actually be extended.

719
00:31:17,841 --> 00:31:19,243
This is the observation

720
00:31:19,276 --> 00:31:22,046
of our first
Bose-Einstein condensate

721
00:31:22,079 --> 00:31:24,515
in a prototype of
the CAL apparatus

722
00:31:24,548 --> 00:31:28,119
in our Ground
Testbed up the hill,

723
00:31:28,152 --> 00:31:31,022
and this is a series of
pictures that we take.

724
00:31:31,055 --> 00:31:34,358
We shine a light on the atoms
and we look at the shadow

725
00:31:34,391 --> 00:31:38,729
cast by the atoms, and we
can measure a density profile

726
00:31:38,762 --> 00:31:41,299
of the atoms, and this is
three different measurements

727
00:31:41,332 --> 00:31:44,569
as we lower the
temperature bit by bit,

728
00:31:45,869 --> 00:31:48,306
and you see as you go
through this transition,

729
00:31:48,339 --> 00:31:50,641
as you pass this
critical temperature,

730
00:31:50,674 --> 00:31:53,444
you very suddenly see
this spike shoot up

731
00:31:53,477 --> 00:31:57,649
of nearly stationary atoms
in the center of the cloud.

732
00:32:00,684 --> 00:32:02,586
So how do we get there?

733
00:32:02,619 --> 00:32:05,589
What are the techniques
that we use to achieve

734
00:32:05,622 --> 00:32:07,625
these cold temperatures?

735
00:32:09,259 --> 00:32:11,128
We actually have
a whole sequence;

736
00:32:11,161 --> 00:32:14,332
there's a series of different
techniques that we use,

737
00:32:14,365 --> 00:32:18,536
and we start with a technique
called laser cooling.

738
00:32:20,571 --> 00:32:23,240
This might surprise most people.

739
00:32:23,273 --> 00:32:25,609
We think of lasers as
things that we can cut with

740
00:32:25,642 --> 00:32:29,013
or that we can weld with,
even do nuclear fusion

741
00:32:29,046 --> 00:32:30,648
with lasers, right?

742
00:32:30,681 --> 00:32:33,785
So how can lasers
make things colder?

743
00:32:35,119 --> 00:32:37,021
To understand how that
works, we need to understand

744
00:32:37,054 --> 00:32:38,556
three basic facts.

745
00:32:39,990 --> 00:32:41,859
The first is that we can
push on things with light.

746
00:32:41,892 --> 00:32:45,663
Light carries momentum,
so you can imagine things

747
00:32:45,696 --> 00:32:49,200
like solar sails to
zip around the galaxy,

748
00:32:52,803 --> 00:32:54,972
and this is the same types
of forces that produce

749
00:32:55,005 --> 00:32:57,508
the beautiful tails on comets.

750
00:32:58,876 --> 00:33:00,411
So light can push on
objects, it carries momentum

751
00:33:00,444 --> 00:33:03,381
and it can push on things.

752
00:33:03,414 --> 00:33:07,218

And then the next fact is
that atoms are very particular

753
00:33:07,251 --> 00:33:11,022
in terms of the colors of
light that they absorb.

754
00:33:11,055 --> 00:33:13,324
This is the spectra of
rubidium; the very first spectra

755
00:33:13,357 --> 00:33:17,161
was actually taken by Robert
Bunsen of Bunsen-burner fame,

756
00:33:17,194 --> 00:33:21,366
he's the person that first
discovered rubidium, I believe.

757
00:33:22,733 --> 00:33:26,237
Rubidium, if you try to
shine light on rubidium,

758
00:33:26,270 --> 00:33:29,306
it'll only absorb in
these very sharp lines.

759
00:33:29,339 --> 00:33:32,209
If you actually change the
wavelength of the light

760
00:33:32,242 --> 00:33:36,414
that's impinging on a rubidium
atom by a part in a million,

761
00:33:37,748 --> 00:33:39,984
it'll go from strongly absorbent
to just barely absorbent

762
00:33:40,017 --> 00:33:43,020

at all, almost totally
not interacting.

763
00:33:43,053 --> 00:33:45,923
So that's the second fact
that we need to recall,

764
00:33:45,956 --> 00:33:49,861
is that the colors of
light absorbed by an atom

765
00:33:52,229 --> 00:33:54,298
is only very sharp lines.

766
00:33:58,035 --> 00:34:00,738
And then the third thing
we need to remember

767
00:34:00,771 --> 00:34:04,041
is that that color absorbed
depends on the motion

768
00:34:04,074 --> 00:34:07,344
of the atom, because
of the Doppler Effect.

769
00:34:07,377 --> 00:34:10,648
We're all probably
familiar with the fact

770
00:34:10,681 --> 00:34:13,818
that if you listen
to an ambulance siren

771
00:34:13,851 --> 00:34:16,387
as it's moving towards you,
compared to when it's moving

772
00:34:16,420 --> 00:34:19,090
away from you, it

sounds different.

773
00:34:19,123 --> 00:34:21,826
The reason it sounds
different is, when it's moving

774
00:34:21,859 --> 00:34:24,929
towards you, those
wavelengths are compressed,

775
00:34:24,962 --> 00:34:26,397
they're a little bit shorter.

776
00:34:26,430 --> 00:34:29,934
When it moves away from you,
those wavelengths are stretched

777
00:34:29,967 --> 00:34:31,902
and they're a little bit longer.

778
00:34:31,935 --> 00:34:36,640
Likewise, with light
that's absorbed by an atom,

779
00:34:36,673 --> 00:34:40,044
if the atom is moving
towards the source,

780
00:34:40,077 --> 00:34:42,613
it'll strongly absorb light
with a slightly shorter

781
00:34:42,646 --> 00:34:46,417
wavelength, what's called
blue-shifted light,

782
00:34:47,885 --> 00:34:49,954
and if it's moving
away from a source,

783
00:34:49,987 --> 00:34:52,156
that light will be red-shifted,

784
00:34:52,189 --> 00:34:55,826
the wavelength absorbed by
the atoms will be longer.

785
00:34:55,859 --> 00:34:56,994
So we can put all those together

786
00:34:57,027 --> 00:34:59,964
and then understand
laser cooling.

787
00:34:59,997 --> 00:35:02,566
When we want to cool
atoms with lasers,

788
00:35:02,599 --> 00:35:06,771
we have a pair of lasers
pointing on a gas of atoms,

789
00:35:08,639 --> 00:35:11,575
and we tune both of those
lasers so they're a little bit

790
00:35:11,608 --> 00:35:15,213
to the red, a little
bit longer wavelength,

791
00:35:16,313 --> 00:35:18,883
than those atoms
really want to absorb.

792
00:35:18,916 --> 00:35:21,418
So they're a little bit more
red-colored than the color

793
00:35:21,451 --> 00:35:23,687

the atoms really
want to absorb at.

794
00:35:23,720 --> 00:35:25,523
So if an atom's just
sitting at rest,

795
00:35:25,556 --> 00:35:29,727
it barely feels the force
from either of those atoms.

796
00:35:30,861 --> 00:35:32,763
But if the atom
happens to be moving

797
00:35:32,796 --> 00:35:36,968
towards one of these lasers,
because of the Doppler shift,

798
00:35:38,368 --> 00:35:41,272
it will see that light
shifted towards the light

799
00:35:41,305 --> 00:35:44,608
that it wants to absorb at,
so it'll more strongly absorb

800
00:35:44,641 --> 00:35:46,143
from this laser beam.

801
00:35:46,176 --> 00:35:50,081
That'll provide a force on the
atom which will slow it down.

802
00:35:51,882 --> 00:35:56,720
We could extend this into
three dimensions very easily,

803
00:35:56,753 --> 00:36:00,090
with six beams coming from

all different directions,

804
00:36:00,123 --> 00:36:03,227
and this proves just
amazingly effective,

805
00:36:03,260 --> 00:36:06,463
more than one could
possibly hope for,

806
00:36:06,496 --> 00:36:09,099
and the most amazing thing
about this, probably,

807
00:36:09,132 --> 00:36:11,902
is the fact that we can
achieve these temperatures

808
00:36:11,935 --> 00:36:15,673
as cold as a few millionths of
a degree above absolute zero

809
00:36:15,706 --> 00:36:18,776
in an amazingly routine manner.

810
00:36:18,809 --> 00:36:20,711
In thousands of labs
around the world,

811
00:36:20,744 --> 00:36:22,213
scientists can
walk into that lab

812
00:36:22,246 --> 00:36:24,782
and literally, it's
almost a flick of a switch

813
00:36:24,815 --> 00:36:29,053
and you have a sample of atoms
a few millionths of a degree

814
00:36:29,086 --> 00:36:30,755
above absolute zero.

815
00:36:32,089 --> 00:36:32,924
Now,

816
00:36:34,324 --> 00:36:36,360
I said at the beginning,
most people, when they think

817
00:36:36,393 --> 00:36:38,596
about shining lasers at things,
this is not just laymen,

818
00:36:38,629 --> 00:36:41,065
but scientists, when
you tell them that,

819
00:36:41,098 --> 00:36:43,100
if they're not in this
field, would imagine

820
00:36:43,133 --> 00:36:44,802
that things would get hotter.

821
00:36:44,835 --> 00:36:47,304
And it's true, it
actually is true,

822
00:36:47,337 --> 00:36:50,407
there is a heating mechanism,
and to actually figure out

823
00:36:50,440 --> 00:36:52,509
the temperature, where we get
this millionths of a degree

824
00:36:52,542 --> 00:36:56,380

above absolute zero, we have
to balance heating effect

825
00:36:56,413 --> 00:36:59,216
from the lasers with this
very powerful cooling effect,

826
00:36:59,249 --> 00:37:01,986
and that leads to
temperatures in this range.

827
00:37:02,019 --> 00:37:06,257
If you want to get colder, we
have to turn the lasers off.

828
00:37:08,358 --> 00:37:10,094
So the way we do that
is we use a technique

829
00:37:10,127 --> 00:37:12,396
called evaporative cooling.

830
00:37:13,530 --> 00:37:16,567
We put the atoms
into a magnetic trap

831
00:37:16,600 --> 00:37:19,403
in certain so we can
prepare the atoms in a state

832
00:37:19,436 --> 00:37:21,372
where they act like
a little bar magnet,

833
00:37:21,405 --> 00:37:24,976
so they have a north
side and a south side,

834
00:37:26,443 --> 00:37:28,612
and they can be pushed

around with magnetic fields,

835
00:37:28,645 --> 00:37:30,447
and if you can set up
your magnetic field

836
00:37:30,480 --> 00:37:33,450
so that there's a
minimum in that field,

837
00:37:33,483 --> 00:37:34,752
the atoms will be trapped there

838
00:37:34,785 --> 00:37:37,021
and they'll be attracted
to that minimum.

839
00:37:37,054 --> 00:37:39,990
In CAL, we produce those fields

840
00:37:40,023 --> 00:37:41,659
with something
called an atom chip.

841
00:37:41,692 --> 00:37:46,497
It's a piece of silicon and
it's got wires printed on it,

842
00:37:46,530 --> 00:37:50,634
just little metal wires,
and we run currents

843
00:37:50,667 --> 00:37:54,705
through those wires and that
produces a magnetic field

844
00:37:54,738 --> 00:37:57,541
that we can use
to trap the atoms.

845
00:37:58,809 --> 00:38:02,112
Inside that magnetic
trap, the atoms,

846
00:38:02,145 --> 00:38:04,581
it's like they
were inside a cup,

847
00:38:04,614 --> 00:38:07,985
and the cold atoms are
bouncing around the bottom,

848
00:38:08,018 --> 00:38:12,189
the hot atoms make it up
higher and higher up the walls.

849
00:38:14,458 --> 00:38:15,959
The cold ones are down
here, the hot ones bounce up

850
00:38:15,992 --> 00:38:19,930
like this, and we can
selectively pull off

851
00:38:19,963 --> 00:38:24,001
just those hottest atoms
by shining radio frequency

852
00:38:24,034 --> 00:38:27,137
or microwave frequencies
if we tune it

853
00:38:27,170 --> 00:38:29,506
to just the right frequency,
we can just pull off

854
00:38:29,539 --> 00:38:31,241
just these hot atoms.

855

00:38:31,274 --> 00:38:33,877
The rest of the atoms will
cool down and equilibrate

856
00:38:33,910 --> 00:38:36,147
at much lower temperatures.

857
00:38:37,481 --> 00:38:39,616
It's something like
blowing on a cup of coffee;

858
00:38:39,649 --> 00:38:41,051
when you blow on
a cup of coffee,

859
00:38:41,084 --> 00:38:44,221
you're helping the hottest
atoms to escape from the liquid

860
00:38:44,254 --> 00:38:48,426
and that brings down the whole
temperature of the coffee.

861
00:38:51,595 --> 00:38:54,365
So how do we
measure temperature?

862
00:38:55,532 --> 00:38:57,234
There's several actual
methods that we can use

863
00:38:57,267 --> 00:38:59,436
to measure temperature
and we can compare them

864
00:38:59,469 --> 00:39:01,338
to make sure that we're
getting everything right,

865
00:39:01,371 --> 00:39:03,107

but the simplest way
to measure temperature

866
00:39:03,140 --> 00:39:05,943
is simply to turn off
our magnetic fields

867
00:39:05,976 --> 00:39:08,278
and release those atoms, so
the atoms will sit in there

868
00:39:08,311 --> 00:39:10,681
in a cup and we finish cooling
them and they're pretty cold,

869
00:39:10,714 --> 00:39:12,316
and we want to see
how cold they are,

870
00:39:12,349 --> 00:39:16,620
we can just, very quickly,
turn off that magnetic field.

871
00:39:16,653 --> 00:39:20,825
When we do so, that cloud
of atoms starts to expand

872
00:39:22,225 --> 00:39:25,529
and the hottest atoms move
the furthest and the fastest,

873
00:39:25,562 --> 00:39:27,598
and the cold ones
are left behind.

874
00:39:27,631 --> 00:39:29,066
We can just wait a little while

875
00:39:29,099 --> 00:39:32,369
and then we take a quick

snapshot of what's going on

876
00:39:32,402 --> 00:39:36,273
with the atoms, and just by
measuring the size of this cloud

877
00:39:36,306 --> 00:39:38,442
we can tell the difference
between a hot cloud

878
00:39:38,475 --> 00:39:39,877
and a cold cloud.

879
00:39:41,511 --> 00:39:45,215
Again, these images are taken
by shining light on the atoms

880
00:39:45,248 --> 00:39:49,153
and looking at the shadow
cast by those atoms

881
00:39:49,186 --> 00:39:50,187
on a camera.

882
00:39:52,923 --> 00:39:55,559
(clears throat)

883
00:39:55,592 --> 00:39:57,895
This evaporative cooling
technique is used in many labs

884
00:39:57,928 --> 00:40:00,964
around the world; we want
to be the coldest spot

885
00:40:00,997 --> 00:40:04,201
in the universe or close to it,

886
00:40:04,234 --> 00:40:08,406

and so we use some
other techniques that
fall into the realm

887
00:40:09,573 --> 00:40:11,575
of what I call advanced cooling

888
00:40:11,608 --> 00:40:13,477
to get even colder temperatures,

889
00:40:13,510 --> 00:40:14,945
and the first one
I'm gonna talk about

890
00:40:14,978 --> 00:40:17,014
is something that goes
by the rather exotic name

891
00:40:17,047 --> 00:40:18,849
of delta-kick cooling.

892
00:40:20,217 --> 00:40:22,920
It's actually more like a
freeze ray, so I like to call it

893
00:40:22,953 --> 00:40:27,124
a freeze ray, but what we do
is we just let go of our atoms

894
00:40:28,525 --> 00:40:31,428
and they expand just like
we were gonna measure

895
00:40:31,461 --> 00:40:33,764
their temperature,
and the hottest atoms,

896
00:40:33,797 --> 00:40:35,799
after a little while,
have moved the furthest,

897
00:40:35,832 --> 00:40:39,069
and the cold atoms
are left behind.

898
00:40:39,102 --> 00:40:42,239
We can then snap on
another magnetic potential

899
00:40:42,272 --> 00:40:46,444
for just an instant, and if
we turn that magnetic field

900
00:40:47,944 --> 00:40:51,648
to just the right strength
and in the right position,

901
00:40:51,681 --> 00:40:54,518
we can provide
each of these atoms

902
00:40:55,652 --> 00:40:58,188
a little bit of a kick,
such that the atoms

903
00:40:58,221 --> 00:41:02,025
that are far away over
here and the hottest ones

904
00:41:02,058 --> 00:41:04,595
receive the biggest kick and
the atoms that are left behind

905
00:41:04,628 --> 00:41:06,597
receive a much
smaller kick, and so

906
00:41:06,630 --> 00:41:09,967
they're all instantly
frozen into space.

907
00:41:11,167 --> 00:41:12,536
Another technique
that we can use

908
00:41:12,569 --> 00:41:15,539
is a technique called
adiabatic cooling.

909
00:41:15,572 --> 00:41:19,009
We just let that cup,
that magnetic trap,

910
00:41:20,544 --> 00:41:23,313
we just get it weaker
and weaker and weaker,

911
00:41:23,346 --> 00:41:26,550
and if we do that slowly
enough, as that gas expands,

912
00:41:26,583 --> 00:41:28,886
it cools down; this is
similar to when you spray

913
00:41:28,919 --> 00:41:32,890
an aerosol can and the
aerosol can gets colder

914
00:41:32,923 --> 00:41:34,191
as you do that.

915
00:41:36,126 --> 00:41:38,128
This, again, can be
done on the ground,

916
00:41:38,161 --> 00:41:42,132
and we do it fairly
routinely to try to lower

917
00:41:42,165 --> 00:41:44,601
our temperatures that we
see, but you're limited

918
00:41:44,634 --> 00:41:46,737
in how well you can
do it on the ground.

919
00:41:46,770 --> 00:41:51,008
On the ground, you always have
to support against gravity,

920
00:41:51,041 --> 00:41:53,143
you have to hold the
thing up against gravity,

921
00:41:53,176 --> 00:41:56,113
so that limits how weak
you can make those traps,

922
00:41:56,146 --> 00:42:00,484
and that limits how well
you can use this technique.

923
00:42:00,517 --> 00:42:03,854
We have a number of
PIs on this project,

924
00:42:05,288 --> 00:42:09,226
these external folks that are
doing science investigations.

925
00:42:09,259 --> 00:42:12,129
The first one I'm gonna
mention is Cass Sackett

926
00:42:12,162 --> 00:42:15,532
because he is actually
helping us, trying to research

927
00:42:15,565 --> 00:42:19,737
the ultimate limits of this
adiabatic cooling technique.

928
00:42:22,906 --> 00:42:24,575
So we combine all
these techniques

929
00:42:24,608 --> 00:42:28,011
into all these different
stages of cooling,

930
00:42:28,044 --> 00:42:30,948
different types of techniques
into the Cold Atom Lab,

931
00:42:30,981 --> 00:42:33,584
and you've seen pictures
of it that Anita showed.

932
00:42:33,617 --> 00:42:36,053
It's a mini-lab in
space; the idea is that

933
00:42:36,086 --> 00:42:39,289
we give researchers a
large suite of tools,

934
00:42:39,322 --> 00:42:42,593
many of the same tools that
they use in their own labs

935
00:42:42,626 --> 00:42:46,797
on Earth, and we try to put
those into this facility.

936
00:42:50,100 --> 00:42:53,070
We have, for example,
the ability to trap

937
00:42:53,103 --> 00:42:57,608
two different species of
atoms, rubidium and potassium,

938
00:42:57,641 --> 00:43:01,011
and two of the different
potassium isotopes as well.

939
00:43:01,044 --> 00:43:03,180
We have the ability
to look at atoms

940
00:43:03,213 --> 00:43:07,384
from two different directions,
with high and low resolution.

941
00:43:10,086 --> 00:43:11,555
We can prepare a
variety of states,

942
00:43:11,588 --> 00:43:13,991
and we have ability to actually
tune their interactions,

943
00:43:14,024 --> 00:43:17,060
and we'll talk more
about that in a bit.

944
00:43:17,093 --> 00:43:20,597
But the basic idea is to give
scientists a versatile set

945
00:43:20,630 --> 00:43:23,266
of tools that they can
carry out just a wide range

946
00:43:23,299 --> 00:43:25,235
of very different experiments.

947

00:43:25,268 --> 00:43:26,770
As we talk about some
of the experiments

948
00:43:26,803 --> 00:43:30,741
our PIs are gonna do, you'll
get a sense of the breadth,

949
00:43:30,774 --> 00:43:33,744
both of the field and
what we're able to do

950
00:43:33,777 --> 00:43:35,713
with the Cold Atom Lab.

951
00:43:37,847 --> 00:43:41,184
Why do we do this
in microgravity?

952
00:43:41,217 --> 00:43:43,821
The dream of atomic physics is,

953
00:43:44,988 --> 00:43:47,591
for a century it's
been this way,

954
00:43:47,624 --> 00:43:50,627
we want to create a sample
of atoms and we want to just

955
00:43:50,660 --> 00:43:55,432
have them sit there, motionless,
while we look at them

956
00:43:55,465 --> 00:43:57,367
for as long as we want to.

957
00:43:57,400 --> 00:43:59,770
So we want them completely
unconfined, we don't want

958
00:43:59,803 --> 00:44:02,906
any magnetic fields or
light-wave fields on them,

959
00:44:02,939 --> 00:44:06,143
those would also disturb
them a little bit.

960
00:44:06,176 --> 00:44:08,912
We don't want them bouncing
into walls and things like that,

961
00:44:08,945 --> 00:44:13,117
we just want them to just
sit there, just stay put,

962
00:44:18,321 --> 00:44:22,926
and we want to look at them
for very long periods of time.

963
00:44:22,959 --> 00:44:24,161
If you try to do this on Earth,

964
00:44:24,194 --> 00:44:26,163
you can get pretty cold
temperatures on Earth,

965
00:44:26,196 --> 00:44:28,598
but if you try to
just let the atoms go,

966
00:44:28,631 --> 00:44:31,334
they'll go plop to the
bottom of your vacuum chamber

967
00:44:31,367 --> 00:44:34,271
and you'll get a fraction
of a second, typically,

968
00:44:34,304 --> 00:44:37,974
as your time to look at them,
unless people make tricks

969
00:44:38,007 --> 00:44:39,242
to get a little bit longer time,

970
00:44:39,275 --> 00:44:41,812
but you're fundamentally
limited in how much time

971
00:44:41,845 --> 00:44:43,580
you can look at them.

972
00:44:46,616 --> 00:44:50,620
In CAL, in microgravity, these
atoms should just hang around

973
00:44:50,653 --> 00:44:54,925
for, we hope, something
like five seconds.

974
00:44:54,958 --> 00:44:58,228
One of the ideas behind CAL
is that it could be improved,

975
00:44:58,261 --> 00:45:00,430
we'll have follow-on missions,

976
00:45:00,463 --> 00:45:03,400
and these things can
be improved upon.

977
00:45:03,433 --> 00:45:07,604
Ultimately, the limits could
be hundreds of seconds.

978
00:45:10,807 --> 00:45:13,844
I started thinking about CAL

979
00:45:13,877 --> 00:45:18,048
back as soon as I came to
JPL, just a couple years

980
00:45:19,516 --> 00:45:23,186
after being a postdoc,
and I've been working on

981
00:45:23,219 --> 00:45:26,656
almost my whole career, even
right from the beginning,

982
00:45:26,689 --> 00:45:29,493
even before the Space Station
had been put together,

983
00:45:29,526 --> 00:45:32,629
just a couple years after
BEC had been discovered,

984
00:45:32,662 --> 00:45:34,531
I was trying to pitch this idea

985
00:45:34,564 --> 00:45:38,001
that we could have
this BEC lab up there.

986
00:45:39,769 --> 00:45:41,204
So this project, me
and my colleagues

987
00:45:41,237 --> 00:45:44,574
have been developing a
lot of that technology.

988
00:45:44,607 --> 00:45:48,045
Our effort got off
strong for a few years

989
00:45:49,813 --> 00:45:54,785
and because of issues with
the Space Station program,

990
00:45:54,818 --> 00:45:58,455
we stopped doing this type
of research for a while.

991
00:45:58,488 --> 00:46:01,958
The Europeans, in
particular German groups,

992
00:46:01,991 --> 00:46:05,428
have continued this and have
had a very steady, long,

993
00:46:05,461 --> 00:46:07,931
and very successful
program actually preparing

994
00:46:07,964 --> 00:46:10,967
Bose condensates and studying
them in microgravity,

995
00:46:11,000 --> 00:46:13,303
first in drop-tower
experiments where they had

996
00:46:13,336 --> 00:46:16,907
these 200-meter towers and
they drop a whole apparatus

997
00:46:16,940 --> 00:46:19,342
to get a few seconds
of microgravity,

998
00:46:19,375 --> 00:46:22,546
and also in sounding rocket
experiments, where they can get

999
00:46:22,579 --> 00:46:25,248
hundreds of seconds
of microgravity.

1000
00:46:25,281 --> 00:46:27,517
The goal in CAL, though,
is to just be up there

1001
00:46:27,550 --> 00:46:30,520
and have hours upon hours,
that you can tweak things

1002
00:46:30,553 --> 00:46:32,322
and fiddle with things
and get them just right

1003
00:46:32,355 --> 00:46:36,193
and have much longer
duration of microgravity.

1004
00:46:38,761 --> 00:46:39,996
(coughs)

1005
00:46:40,029 --> 00:46:43,801
One of the technologies,
and it's the killer app

1006
00:46:45,134 --> 00:46:48,238
for ultra-cold atoms in
space, is a technique

1007
00:46:48,271 --> 00:46:50,640
called atom interferometry.

1008
00:46:50,673 --> 00:46:53,777
Some of our most
sensitive measurements

1009
00:46:53,810 --> 00:46:56,313

are made with light
interferometers;

1010
00:46:56,346 --> 00:46:59,316
probably the most famous
is the LIGO detector,

1011
00:46:59,349 --> 00:47:03,520
that's Laser Interferometry
Gravitational Observatory,

1012
00:47:05,521 --> 00:47:07,057
and there's two of
these, one in Washington

1013
00:47:07,090 --> 00:47:11,195
and one in Louisiana, and
last year they observed

1014
00:47:13,062 --> 00:47:15,732
the first signal of
a gravitational wave

1015
00:47:15,765 --> 00:47:18,769
formed by two
combining black holes.

1016
00:47:20,603 --> 00:47:23,540
These types of interferometers
use physical beam splitters

1017
00:47:23,573 --> 00:47:25,609
and mirrors to
interfere beams of light

1018
00:47:25,642 --> 00:47:29,212
to make these exquisitely
sensitive measurements.

1019
00:47:29,245 --> 00:47:32,515

An atom interferometer,
that's the opposite.

1020
00:47:32,548 --> 00:47:37,220
We actually use beams of light
to split up atomic waves,

1021
00:47:37,253 --> 00:47:40,290
and then other beams to reflect
them, and we combine them.

1022
00:47:40,323 --> 00:47:43,994
So we have atoms coming
into this apparatus,

1023
00:47:44,861 --> 00:47:47,697
we shine on a laser beam.

1024
00:47:47,730 --> 00:47:50,433
When we shine that laser beam,
we can arrange its strength

1025
00:47:50,466 --> 00:47:53,970
so that the atom had a 50%
chance of going this way

1026
00:47:54,003 --> 00:47:56,439
and a 50% chance
of going that way.

1027
00:47:56,472 --> 00:47:59,009
Quantum mechanics says if you
haven't made a measurement,

1028
00:47:59,042 --> 00:48:02,279
you have to assume it's
in both at the same time.

1029
00:48:02,312 --> 00:48:04,481
So the atom's actually

physically in two
different places

1030
00:48:04,514 --> 00:48:06,316
at exactly the same time.

1031
00:48:06,349 --> 00:48:08,752
That's a little mind boggling
if you think of atoms

1032
00:48:08,785 --> 00:48:12,289
as particles; it's not so
strange if you think of an atom

1033
00:48:12,322 --> 00:48:13,757
as a wave though, right?

1034
00:48:13,790 --> 00:48:15,458
You look at the beach
and you see a wave coming

1035
00:48:15,491 --> 00:48:17,861
into the beach, it's spread out,

1036
00:48:17,894 --> 00:48:20,797
and if you have a wall that
juts out into the ocean,

1037
00:48:20,830 --> 00:48:23,333
half of the wave can go on
one side, half of the wave

1038
00:48:23,366 --> 00:48:28,204
can go on the other side,
that's not such a big deal.

1039
00:48:28,237 --> 00:48:30,006
The thing to wrap
your head around is

1040
00:48:30,039 --> 00:48:32,175
how can something be a wave and
a particle at the same time,

1041
00:48:32,208 --> 00:48:36,646
how can these things actually
be in two places at once?

1042
00:48:36,679 --> 00:48:39,549
We then recombine these waves,

1043
00:48:39,582 --> 00:48:41,651
and when they recombine,
they interfere.

1044
00:48:41,684 --> 00:48:46,289
This is a very ubiquitous
process with any type

1045
00:48:46,322 --> 00:48:51,261
of wave phenomenon, that
when you combine two waves,

1046
00:48:51,294 --> 00:48:53,964
they will either
cancel each other out

1047
00:48:53,997 --> 00:48:56,766
or they will enhance each
other by what's called

1048
00:48:56,799 --> 00:48:58,868
constructive or
destructive interference.

1049
00:48:58,901 --> 00:49:01,338
So they produce fringes, and
by monitoring these fringes,

1050

00:49:01,371 --> 00:49:03,573
we can make these very
sensitive measurements.

1051
00:49:03,606 --> 00:49:07,711
Already on the ground, we
get measurements of things

1052
00:49:07,744 --> 00:49:11,614
like accelerations and
rotations and gravity

1053
00:49:11,647 --> 00:49:13,850
that are as good as you can make

1054
00:49:13,883 --> 00:49:17,487
with almost any other
means of making them,

1055
00:49:18,888 --> 00:49:21,524
but the fantastic thing is how
much better these things get

1056
00:49:21,557 --> 00:49:23,326
when we go into space.

1057
00:49:23,359 --> 00:49:26,730
When we go into space, we
get to look to the atoms

1058
00:49:26,763 --> 00:49:28,231
for much longer.

1059
00:49:28,264 --> 00:49:30,667
So on Earth, the way we do
these experiments typically

1060
00:49:30,700 --> 00:49:32,369
is we toss the atoms in the air

1061
00:49:32,402 --> 00:49:34,337
and they have about
a half a second or so

1062
00:49:34,370 --> 00:49:36,272
that we can use
an interferometer,

1063
00:49:36,305 --> 00:49:39,075
we have one of
those here at JPL.

1064
00:49:42,145 --> 00:49:45,815
In space though, in CAL, we
can get a couple of seconds,

1065
00:49:45,848 --> 00:49:48,351
but in future missions,
we might even get

1066
00:49:48,384 --> 00:49:49,853
hundreds of seconds.

1067
00:49:49,886 --> 00:49:51,755
For some types of
measurements, for example,

1068
00:49:51,788 --> 00:49:54,224
for gravity or an
acceleration measurement,

1069
00:49:54,257 --> 00:49:58,128
the sensitivity of that
measurement goes as the square

1070
00:49:58,161 --> 00:50:00,096
of the amount of time that
you have to look at it.

1071

00:50:00,129 --> 00:50:02,899
So you have this
huge possibility

1072
00:50:04,067 --> 00:50:06,903
of making incredible
types of measurements.

1073
00:50:06,936 --> 00:50:11,008
These types of instruments
will yield, basically,

1074
00:50:13,309 --> 00:50:17,981
a new generation of exquisitely
sensitive quantum sensors.

1075
00:50:18,014 --> 00:50:19,482
They can be used for
things like testing

1076
00:50:19,515 --> 00:50:22,218
fundamental physics, some
of the fundamental ideas

1077
00:50:22,251 --> 00:50:23,853
of Einstein and
some of the ideas

1078
00:50:23,886 --> 00:50:27,023
behind things like dark energy,
but they can also be used

1079
00:50:27,056 --> 00:50:29,159
for real-world applications.

1080
00:50:29,192 --> 00:50:31,561
We can use them to
monitor Earth's gravity,

1081
00:50:31,594 --> 00:50:35,198

so JPL has a mission now
called the Grace mission

1082
00:50:35,231 --> 00:50:38,701
that monitors Earth's gravity
using a pair of satellites

1083
00:50:38,734 --> 00:50:40,770
that orbit around the Earth.

1084
00:50:40,803 --> 00:50:44,474
That can measure things, that
can weigh the ice sheets.

1085
00:50:44,507 --> 00:50:46,443
We have a follow-on
mission that's gonna go on

1086
00:50:46,476 --> 00:50:50,213
called Grace Follow-on, but
in the future, we might use

1087
00:50:50,246 --> 00:50:53,450
these types of sensors, with
a little bit more development,

1088
00:50:53,483 --> 00:50:57,821
these might be very competitive
or significantly improved

1089
00:50:57,854 --> 00:50:59,889
over what we can measure.

1090
00:50:59,922 --> 00:51:03,226
That allows you to make
very important measurements

1091
00:51:03,259 --> 00:51:06,830
relating to climate, but
we might also fly these

1092
00:51:06,863 --> 00:51:09,165
around some planet
and look for resources

1093
00:51:09,198 --> 00:51:11,768
that future astronauts
might want to use,

1094
00:51:11,801 --> 00:51:15,004
or we might search for
oceans under Europa

1095
00:51:15,037 --> 00:51:19,042
and all kinds of
interesting possibilities.

1096
00:51:19,075 --> 00:51:22,145
And that brings up
to the basic idea,

1097
00:51:23,312 --> 00:51:26,249
various applications
of absolute zero.

1098
00:51:26,282 --> 00:51:30,053
One of my favorites has
always been the atom laser.

1099
00:51:30,086 --> 00:51:34,090
An atom laser is a source
of coherent matter waves,

1100
00:51:34,123 --> 00:51:38,295
just like a laser is a source
of coherent light waves,

1101
00:51:39,695 --> 00:51:43,299
and these were discovered,
and have been observed

1102
00:51:43,332 --> 00:51:46,603
on the ground, this is
one that we observed

1103
00:51:46,636 --> 00:51:48,972
something like 10 years ago.

1104
00:51:50,840 --> 00:51:53,810
Another scientist was the
first, had observed them

1105
00:51:53,843 --> 00:51:57,514
significantly longer
before that, but these,

1106
00:52:00,283 --> 00:52:02,519
they don't do that
much on the ground,

1107
00:52:02,552 --> 00:52:04,921
because they're very strongly
perturbed by gravity.

1108
00:52:04,954 --> 00:52:08,558
In space, we might imagine a
whole world of applications

1109
00:52:08,591 --> 00:52:11,327
for them in atom
optics and things like

1110
00:52:11,360 --> 00:52:13,630
matter-wave holography.

1111
00:52:13,663 --> 00:52:16,699
Probably one of the killer
applications for them

1112

00:52:16,732 --> 00:52:20,904
would be as a source for an
atom interferometer, though.

1113
00:52:22,838 --> 00:52:26,843
I now want to turn to
some of the CAL science,

1114
00:52:26,876 --> 00:52:28,244
some of the science
investigations

1115
00:52:28,277 --> 00:52:29,946
by our principal investigators.

1116
00:52:29,979 --> 00:52:33,449
We put this facility together
with all these standard tools

1117
00:52:33,482 --> 00:52:37,253
and then we invited scientists
to come up with proposals

1118
00:52:37,286 --> 00:52:39,923
of how to do it, and
we were very impressed

1119
00:52:39,956 --> 00:52:43,560
with the quality of the
proposals, the quality

1120
00:52:43,593 --> 00:52:47,197
of the science, and
really, CAL has probably

1121
00:52:47,230 --> 00:52:49,332
one of the most
prestigious science teams

1122
00:52:49,365 --> 00:52:52,802

that NASA's put together
for any mission.

1123
00:52:54,237 --> 00:52:57,774
This is a study of few-body
physics in microgravity.

1124
00:52:57,807 --> 00:53:00,009
It's led by Eric Cornell,
he's one of those people

1125
00:53:00,042 --> 00:53:04,047
on the team that made the
first Bose condensate.

1126
00:53:05,514 --> 00:53:08,985
Peter Engels works with him,
does a lot of the heavy lifting

1127
00:53:09,018 --> 00:53:11,287
on this particular project.

1128
00:53:11,320 --> 00:53:14,357
Debbie Jin started with this
project, we were very honored

1129
00:53:14,390 --> 00:53:15,925
to have her.

1130
00:53:15,958 --> 00:53:19,629
She's a very prominent
scientist, really
a leading expert

1131
00:53:19,662 --> 00:53:21,431
in the world on
cooling potassium

1132
00:53:21,464 --> 00:53:26,402
and she was the first person

to make a fermionic condensate

1133
00:53:26,435 --> 00:53:29,039
and she was a MacArthur Fellow.

1134
00:53:30,940 --> 00:53:32,742
Tragically, she died last year

1135
00:53:32,775 --> 00:53:35,612
and we're all very
sad about that.

1136
00:53:36,879 --> 00:53:40,116
This experiment searches
for universal features

1137
00:53:40,149 --> 00:53:43,519
in the way a few bodies,
three, four, five,

1138
00:53:43,552 --> 00:53:47,724
come together and collide,
and it looks for bound states

1139
00:53:48,958 --> 00:53:51,060
between those molecules.

1140
00:53:51,093 --> 00:53:54,897
Because it's universal,
you get the same behavior

1141
00:53:54,930 --> 00:53:59,102
with gases of potassium as
you would with a gas of, say,

1142
00:53:59,135 --> 00:54:02,205
strontium or something like
that, or even in some cases,

1143

00:54:02,238 --> 00:54:07,143
you could see universal behavior
between how atoms behave

1144
00:54:07,176 --> 00:54:11,047
and things like neutrons
and quarks behave.

1145
00:54:11,080 --> 00:54:14,751
What's very profound about
these types of experiments,

1146
00:54:14,784 --> 00:54:19,455
they can give us some insight
into how complexity arises

1147
00:54:19,488 --> 00:54:20,824
in the universe.

1148
00:54:22,591 --> 00:54:26,529
If we listen to our
particle physicist friends,

1149
00:54:27,930 --> 00:54:32,235
they are convinced that the
universe is very simple.

1150
00:54:32,268 --> 00:54:34,837
There's just a few
fundamental particles

1151
00:54:34,870 --> 00:54:38,041
and they obey just
a few simple rules,

1152
00:54:39,475 --> 00:54:41,344
and they also tell us that the
only thing that ever happens

1153
00:54:41,377 --> 00:54:44,380

in the universe is these
fundamental particles

1154
00:54:44,413 --> 00:54:47,150
bounce off of each
other as they collide.

1155
00:54:47,183 --> 00:54:49,485
So how can you get from
that simple physics

1156
00:54:49,518 --> 00:54:51,721
that we believe; we
don't know for sure,

1157
00:54:51,754 --> 00:54:53,856
'cause we don't yet have
that final theory of physics,

1158
00:54:53,889 --> 00:54:56,459
but one of the
driving principles of
theoretical physics

1159
00:54:56,492 --> 00:54:59,962
is that physics is
simple, and we always look

1160
00:54:59,995 --> 00:55:02,665
for these simple solutions.

1161
00:55:02,698 --> 00:55:06,102
So what could lead
to all the complexity

1162
00:55:07,103 --> 00:55:08,338
that we see around us?

1163
00:55:08,371 --> 00:55:12,041
Galaxies and forests

and trees and symphonies

1164
00:55:12,074 --> 00:55:15,111
and things like that, how
could that kinda complexity

1165
00:55:15,144 --> 00:55:17,914
arise from very simple
underlying physics,

1166
00:55:17,947 --> 00:55:20,883
and we can get an insight into
that by looking at this realm

1167
00:55:20,916 --> 00:55:24,420
of few-body physics, with
three, four, five atoms

1168
00:55:24,453 --> 00:55:25,688
and then try to work our way up

1169
00:55:25,721 --> 00:55:28,625
to understand more
complex systems.

1170
00:55:29,825 --> 00:55:32,228
Another team, and
this team features

1171
00:55:32,261 --> 00:55:35,131
two other Nobel Laureates:
Wolfgang Ketterle,

1172
00:55:35,164 --> 00:55:39,102
who, independent of Eric
Cornell and Carl Wiemann,

1173
00:55:39,135 --> 00:55:42,438
developed one of the very first
Bose-condensate apparatuses

1174
00:55:42,471 --> 00:55:45,608
and did a number of
landmark studies with them,

1175
00:55:45,641 --> 00:55:47,343
and Bill Phillips, who
is one of the pioneers

1176
00:55:47,376 --> 00:55:51,214
of laser cooling, are both
working with Nick Bigelow,

1177
00:55:51,247 --> 00:55:53,483
who is heading a fairly
large consortium,

1178
00:55:53,516 --> 00:55:56,018
lots of different, very
prominent scientists,

1179
00:55:56,051 --> 00:55:58,688
and in particular,
Holger Mueller is doing

1180
00:55:58,721 --> 00:56:02,258
most of the thinking about
this one particular experiment.

1181
00:56:02,291 --> 00:56:04,961
He has a number of ideas
of how to test Einstein

1182
00:56:04,994 --> 00:56:08,197
using atom
interferometers in space,

1183
00:56:08,230 --> 00:56:11,568
and one of the ideas
is to just look at,

1184
00:56:12,768 --> 00:56:15,171
kinda repeat Galileo's
famous, we don't know

1185
00:56:15,204 --> 00:56:17,073
if he actually did
it or not, experiment

1186
00:56:17,106 --> 00:56:20,676
where he drops two balls made
out of different material

1187
00:56:20,709 --> 00:56:22,345
off of the Leaning Tower of Pisa

1188
00:56:22,378 --> 00:56:25,882
and shows that they
fall at the same rate.

1189
00:56:27,049 --> 00:56:29,852
And the idea is, can we
drop a potassium atom

1190
00:56:29,885 --> 00:56:31,921
and a rubidium atom,
we're gonna drop them

1191
00:56:31,954 --> 00:56:35,191
up on the Space Station,
and they'll fall

1192
00:56:35,224 --> 00:56:38,961
for a couple of seconds, and
during that time in orbit,

1193
00:56:38,994 --> 00:56:41,431
they'll go about eight
miles around the Earth,

1194
00:56:41,464 --> 00:56:43,433
and at the end of that,
we can measure them

1195
00:56:43,466 --> 00:56:47,270
to within a fraction of
the wavelength of light,

1196
00:56:47,303 --> 00:56:51,507
about 100 nanometers or so,
with an atom interferometer.

1197
00:56:51,540 --> 00:56:53,443
The importance of this
is Einstein's theory

1198
00:56:53,476 --> 00:56:57,113
is predicated on gravity
acting on all particles

1199
00:56:57,146 --> 00:56:58,548
exactly the same.

1200
00:57:00,416 --> 00:57:03,419
And so, if we can see
a difference, that
might point the way

1201
00:57:03,452 --> 00:57:06,289
to some theories
beyond Einstein.

1202
00:57:09,024 --> 00:57:13,196
Jason Williams of JPL has
really a nice study planned

1203
00:57:15,865 --> 00:57:18,768
of what we call halo molecules.

1204

00:57:18,801 --> 00:57:22,205
One of the really interesting
things about ultra-cold atoms

1205
00:57:22,238 --> 00:57:25,942
is that we have techniques
to very precisely control

1206
00:57:25,975 --> 00:57:30,079
how strongly they interact;
so if you just look at atoms

1207
00:57:30,112 --> 00:57:33,683
in an ordinary gas, they
may repel each other,

1208
00:57:33,716 --> 00:57:36,285
they may be attracted to
each other by a little bit

1209
00:57:36,318 --> 00:57:38,955
or stronger, but with
these types of systems,

1210
00:57:38,988 --> 00:57:40,490
we can actually control that.

1211
00:57:40,523 --> 00:57:43,292
We can make them attract very
strongly, we can make them

1212
00:57:43,325 --> 00:57:47,129
attract very weakly,
we can make them repel

1213
00:57:47,162 --> 00:57:49,398
very strongly or very weakly.

1214
00:57:49,431 --> 00:57:52,468
By making the interactions

very, very low,

1215
00:57:52,501 --> 00:57:55,338
we can actually observe
what we call halo molecules,

1216
00:57:55,371 --> 00:57:58,341
and these are the most
weakly bound of any kind

1217
00:57:58,374 --> 00:57:59,976
of diatomic molecules.

1218
00:58:00,009 --> 00:58:02,178
They can be on the
order of a micron,

1219
00:58:02,211 --> 00:58:04,380
which is an
astonishingly large size,

1220
00:58:04,413 --> 00:58:07,116
compared to typical
molecules that we see,

1221
00:58:07,149 --> 00:58:11,187
and Jason has a number of ideas
of things that you can study

1222
00:58:11,220 --> 00:58:14,057
with this very
interesting system.

1223
00:58:15,524 --> 00:58:18,694
We have another team
that is trying to study,

1224
00:58:18,727 --> 00:58:22,031
led by Nathan Lundblad
of Bates College,

1225
00:58:22,064 --> 00:58:24,867
which is trying to study
bubble quantum states.

1226
00:58:24,900 --> 00:58:29,138
These are spherical quantum
states, so hollow bubbles,

1227
00:58:29,171 --> 00:58:33,476
condensate spreading
around that type of trap.

1228
00:58:33,509 --> 00:58:37,647
We know how to produce
a potential that
would make a bubble,

1229
00:58:37,680 --> 00:58:40,483
but if we try to do that on
Earth, this is what we find.

1230
00:58:40,516 --> 00:58:42,919
This is actual data that
we took in our testbed

1231
00:58:42,952 --> 00:58:45,388
trying to use parameters that

1232
00:58:46,555 --> 00:58:50,860
represented what Nathan
was interested in doing,

1233
00:58:50,893 --> 00:58:54,997
and what you see, you have
this circular potential

1234
00:58:55,030 --> 00:58:57,967
but all the atoms sit
down at the bottom,

1235
00:58:58,000 --> 00:59:01,370
so it's not terribly
interesting.

1236
00:59:01,403 --> 00:59:05,642
In microgravity, they were
spread out over an ellipsoid.

1237
00:59:07,409 --> 00:59:10,746
And it's a very complex
system, lots of possibilities

1238
00:59:10,779 --> 00:59:14,717
of study and interactions,
excitations and maybe

1239
00:59:14,750 --> 00:59:17,453
putting in multiple
atoms and watching them,

1240
00:59:17,486 --> 00:59:19,388
how they interfere
and things like that.

1241
00:59:19,421 --> 00:59:22,758
It would be a very rich set
of physics from this state

1242
00:59:22,791 --> 00:59:26,362
which can only be
observed in microgravity.

1243
00:59:29,164 --> 00:59:32,101
But as Anita pointed
out, we designed CAL

1244
00:59:32,134 --> 00:59:35,038
to be repairable
by the astronauts,

1245
00:59:36,372 --> 00:59:39,609
and it's also upgradable,
so we can bring in

1246
00:59:39,642 --> 00:59:42,345
new technologies,
new types of lasers,

1247
00:59:42,378 --> 00:59:45,581
we can bring in a
whole new vacuum system

1248
00:59:45,614 --> 00:59:47,783
with new geometries
for our magnetic traps

1249
00:59:47,816 --> 00:59:51,220
and new ways to aim
lasers into that trap

1250
00:59:52,388 --> 00:59:55,091
or put other types
of systems in it.

1251
00:59:55,124 --> 00:59:58,728
So it really leads to
a limitless potential

1252
00:59:59,862 --> 01:00:02,565
for possible future
investigations.

1253
01:00:04,333 --> 01:00:07,803
And with that, I will turn
it back over to Anita.

1254
01:00:07,836 --> 01:00:10,840
(audience applauds)

1255
01:00:15,210 --> 01:00:16,379
- So I'm gonna wrap it up now;

1256
01:00:16,412 --> 01:00:17,813
we're showing you
some more fun pictures

1257
01:00:17,846 --> 01:00:20,349
of the hardware we developed
and the build process,

1258
01:00:20,382 --> 01:00:23,252
but first I wanted to start
off with the real challenge

1259
01:00:23,285 --> 01:00:25,488
for our overall
engineering implementation

1260
01:00:25,521 --> 01:00:28,057
was to be able to condense
something which takes the size

1261
01:00:28,090 --> 01:00:30,126
of an entire laboratory, and
I'm sure you've all worked

1262
01:00:30,159 --> 01:00:32,728
or seen laboratories, and to
condense it into something

1263
01:00:32,761 --> 01:00:35,264
the size of a box
around this big.

1264
01:00:35,297 --> 01:00:38,300
So, our Ground Testbed,
which is up the hill

1265

01:00:38,333 --> 01:00:41,504
in Building 298 at JPL,
basically is that laboratory.

1266
01:00:41,537 --> 01:00:44,473
You can see this entire one
side of the room is electronics,

1267
01:00:44,506 --> 01:00:48,244
lasers, optics, computer
system, and on the other side

1268
01:00:48,277 --> 01:00:51,280
of the lab is where we
have the vacuum system

1269
01:00:51,313 --> 01:00:53,416
that actually makes it with
some free-space optics.

1270
01:00:53,449 --> 01:00:55,584
All of that had to be
condensed, so we had to make

1271
01:00:55,617 --> 01:00:58,587
specific engineering decisions
and technology choices

1272
01:00:58,620 --> 01:01:00,990
to facilitate being able
to fit in that small space

1273
01:01:01,023 --> 01:01:03,492
so that we could go
inside of Space Station.

1274
01:01:03,525 --> 01:01:05,961
The large way that we
did that is by the use

1275

01:01:05,994 --> 01:01:08,698
of the atom-chip-based
vacuum system

1276
01:01:08,731 --> 01:01:11,901
that Rob already spoke about,
and the use of fiber optics,

1277
01:01:11,934 --> 01:01:14,203
because by using fiber
optics, you eliminate the need

1278
01:01:14,236 --> 01:01:16,439
to have free-space optics,
which allows you to condense

1279
01:01:16,472 --> 01:01:18,307
into a smaller volume.

1280
01:01:18,340 --> 01:01:19,809
I'll talk about this in
a little bit more detail.

1281
01:01:19,842 --> 01:01:22,845
So, just to go through some
of the enabling technologies.

1282
01:01:22,878 --> 01:01:25,047
The first one is the use
of our atom-chip-based

1283
01:01:25,080 --> 01:01:27,516
vacuum system here, so you
can see the the system,

1284
01:01:27,549 --> 01:01:29,652
it consists of basically
two glass cells,

1285
01:01:29,685 --> 01:01:31,187

these are under
ultra-high vacuum,

1286
01:01:31,220 --> 01:01:34,023
and then a metallic structure
that goes around it,

1287
01:01:34,056 --> 01:01:35,858
and the laser light
is basically shined

1288
01:01:35,891 --> 01:01:38,861
into the lower glass cell
for the 2-d MOT region

1289
01:01:38,894 --> 01:01:42,465
and to the upper glass cell
for the 3-d MOT region.

1290
01:01:42,498 --> 01:01:44,233
The challenge of this, of
course, for anyone here

1291
01:01:44,266 --> 01:01:46,869
who has a mechanical background,
is that glass, obviously,

1292
01:01:46,902 --> 01:01:48,471
is a very sensitive structure.

1293
01:01:48,504 --> 01:01:50,573
If the glass breaks, number
one, you lose your vacuum,

1294
01:01:50,606 --> 01:01:52,608
and then number two, you don't
want to have pieces of glass

1295
01:01:52,641 --> 01:01:54,577
floating around on Space

Station, so we had to make sure

1296
01:01:54,610 --> 01:01:57,046
that we had a robust enough
design so that we could handle

1297
01:01:57,079 --> 01:01:59,348
the launch loads going
up to Space Station

1298
01:01:59,381 --> 01:02:00,950
as well as the
handling associated

1299
01:02:00,983 --> 01:02:02,685
with assembling
the vacuum system

1300
01:02:02,718 --> 01:02:04,186
to the final configuration.

1301
01:02:04,219 --> 01:02:07,389
So what you can see here is the
buildup of the vacuum system

1302
01:02:07,422 --> 01:02:10,559
inside something called
an optical bench.

1303
01:02:10,592 --> 01:02:13,195
The bulk of our system is
an optomechanical assembly,

1304
01:02:13,228 --> 01:02:15,531
so we had to have a way
to route the laser light

1305
01:02:15,564 --> 01:02:17,166
which is coming through
these fiber optics

1306
01:02:17,199 --> 01:02:20,836
specifically into locations in
the 2-d MOT region down here

1307
01:02:20,869 --> 01:02:24,206
and the 3-d MOT region down
there, and if those laser beams

1308
01:02:24,239 --> 01:02:26,709
are not perfectly aligned,
basically within fractions

1309
01:02:26,742 --> 01:02:29,111
of a millimeter, you're not
able to do the laser coolings,

1310
01:02:29,144 --> 01:02:30,846
so you have to come
up with a very rigid

1311
01:02:30,879 --> 01:02:33,282
mechanical structure on
an optomechanical bench

1312
01:02:33,315 --> 01:02:35,084
to make sure that
never shifts over time,

1313
01:02:35,117 --> 01:02:37,553
either due to the initial
exposure to launch loads

1314
01:02:37,586 --> 01:02:40,689
or over time due to creep,
as it sits there in orbit

1315
01:02:40,722 --> 01:02:43,025
for many, many years on end.

1316
01:02:43,058 --> 01:02:44,727
So this is the system
we came up with,

1317
01:02:44,760 --> 01:02:46,862
this is in its partially
assembled state,

1318
01:02:46,895 --> 01:02:48,731
but tucked inside of here
is the vacuum system,

1319
01:02:48,764 --> 01:02:51,901
so once it goes in,
it doesn't come out.

1320
01:02:51,934 --> 01:02:54,837
The other enabling technology
was the use of external-cavity

1321
01:02:54,870 --> 01:02:57,540
diode lasers which had
fiber-optic outputs.

1322
01:02:57,573 --> 01:03:00,709
These were essentially
commercially available lasers,

1323
01:03:00,742 --> 01:03:03,145
we had to customize them a bit
from a packaging perspective,

1324
01:03:03,178 --> 01:03:05,347
but we're able to
put all six lasers

1325
01:03:05,380 --> 01:03:08,284
on a single heat-exchanger
plate, so we have three

1326
01:03:08,317 --> 01:03:10,486
for rubidium, three for
potassium, and the fiber optics

1327
01:03:10,519 --> 01:03:13,722
get routed and go into
the assembly you see here,

1328
01:03:13,755 --> 01:03:16,892
which gives you the laser
cooling in the lower region

1329
01:03:16,925 --> 01:03:18,327
and in the upper region.

1330
01:03:18,360 --> 01:03:20,496
So those were two key pieces
of enabling technology

1331
01:03:20,529 --> 01:03:22,364
to fit in this small,
constrained space

1332
01:03:22,397 --> 01:03:24,433
to be able to go
on Space Station.

1333
01:03:24,466 --> 01:03:26,836
The other piece of technology
that we had to develop

1334
01:03:26,869 --> 01:03:29,839
custom to JPL was our
electronics, and essentially,

1335
01:03:29,872 --> 01:03:32,141
low-noise, current
driver assemblies.

1336

01:03:32,174 --> 01:03:34,577
Normally, electronics
that we would use

1337
01:03:34,610 --> 01:03:37,079
to control these lasers
basically are about this big

1338
01:03:37,112 --> 01:03:38,681
for just one of them,
so you can imagine

1339
01:03:38,714 --> 01:03:40,850
having to have that times
a total of six lasers,

1340
01:03:40,883 --> 01:03:42,952
times another two
tapered amplifiers,

1341
01:03:42,985 --> 01:03:45,788
you've already blown
your volume allocation,

1342
01:03:45,821 --> 01:03:47,723
so we get to come up with
our own uniquely-designed

1343
01:03:47,756 --> 01:03:49,959
current driver electronics,
and they basically fit

1344
01:03:49,992 --> 01:03:52,161
inside the region of
a tiny little box,

1345
01:03:52,194 --> 01:03:54,096
and so that was a large
engineering challenge

1346

01:03:54,129 --> 01:03:55,998
to be able to give us the
performance that we needed

1347
01:03:56,031 --> 01:03:58,367
in the space that we needed,
with the power levels

1348
01:03:58,400 --> 01:03:59,635
that we needed.

1349
01:04:00,836 --> 01:04:02,504
This is gonna show
you the buildup;

1350
01:04:02,537 --> 01:04:05,441
I do like to show this
for people who are,

1351
01:04:05,474 --> 01:04:06,642
I guess there's not a lot
of kids in the audience

1352
01:04:06,675 --> 01:04:08,177
but from an engineering
perspective,

1353
01:04:08,210 --> 01:04:09,879
first you have to come up
with a conceptual design,

1354
01:04:09,912 --> 01:04:12,481
then you come up with
engineering requirements,

1355
01:04:12,514 --> 01:04:14,016
and then you come up
with a detailed design.

1356
01:04:14,049 --> 01:04:17,786

So what you can see here is a
CAD model of our vacuum system

1357
01:04:17,819 --> 01:04:19,521
embedded inside this
mechanical structure

1358
01:04:19,554 --> 01:04:21,557
with a magnetic shield
that goes around it.

1359
01:04:21,590 --> 01:04:23,192
So this is the design
that we came up with,

1360
01:04:23,225 --> 01:04:25,427
you analyze this design to
make sure that it can handle

1361
01:04:25,460 --> 01:04:27,696
all of the spacecraft
environments that
you're gonna see,

1362
01:04:27,729 --> 01:04:29,498
and it's gonna give you the
performance that you need,

1363
01:04:29,531 --> 01:04:31,333
and then you go off and
you actually build it.

1364
01:04:31,366 --> 01:04:33,535
So you can see a partial
build state here,

1365
01:04:33,568 --> 01:04:35,671
the vacuum system is
tucked inside of here.

1366

01:04:35,704 --> 01:04:38,173
This is the optomechanical
bench that you see around.

1367
01:04:38,206 --> 01:04:40,442
These copper-looking
pieces are actually

1368
01:04:40,475 --> 01:04:43,746
copper conductive straps, so
that you can cool the system,

1369
01:04:43,779 --> 01:04:45,848
it actually gets very,
very hot, and so you have

1370
01:04:45,881 --> 01:04:47,416
a water cooling loop
that goes around here

1371
01:04:47,449 --> 01:04:50,119
throwing cold water through
it from Space Station,

1372
01:04:50,152 --> 01:04:53,389
which then all the heat from
inside of here gets conducted

1373
01:04:53,422 --> 01:04:55,758
through these copper straps
into this water cooling loop,

1374
01:04:55,791 --> 01:04:57,293
so that's how we're
able to keep something

1375
01:04:57,326 --> 01:04:59,695
which is generating a lot of
heat, inside of a tight box

1376

01:04:59,728 --> 01:05:01,397
so it doesn't get too hot.

1377
01:05:01,430 --> 01:05:03,399
This is the engineering
challenge of being able

1378
01:05:03,432 --> 01:05:05,935
to get the heat out and get
the performance that you need.

1379
01:05:05,968 --> 01:05:08,237
And then also, as we're
going around in orbit

1380
01:05:08,270 --> 01:05:11,307
on Space Station, we're
going around the Earth,

1381
01:05:11,340 --> 01:05:14,009
and so when you're in a
laboratory environment on Earth,

1382
01:05:14,042 --> 01:05:16,011
the magnetic field is
essentially always the same,

1383
01:05:16,044 --> 01:05:17,746
but when you're going
around in orbit of the Earth

1384
01:05:17,779 --> 01:05:20,549
on Space Station, the magnetic
field is constantly changing,

1385
01:05:20,582 --> 01:05:22,818
and so we have to have
a way to dampen out

1386
01:05:22,851 --> 01:05:24,820

the changing magnetic field,
so we developed something

1387
01:05:24,853 --> 01:05:26,322
called a magnetic shield.

1388
01:05:26,355 --> 01:05:28,557
For those of you who are Star
Trek fans, it's shields up,

1389
01:05:28,590 --> 01:05:30,092
but our shields are always up,

1390
01:05:30,125 --> 01:05:32,061
and we're, of course, just
damping out small changes

1391
01:05:32,094 --> 01:05:34,330
in the magnetic field as
opposed to photon torpedoes,

1392
01:05:34,363 --> 01:05:36,932
but we used a technology
called MuShield

1393
01:05:36,965 --> 01:05:39,768
which basically took it
down by almost two orders

1394
01:05:39,801 --> 01:05:42,938
of magnitude, so that now
we're no longer having to see

1395
01:05:42,971 --> 01:05:47,509
these large fluctuations
in the magnetic field

1396
01:05:47,542 --> 01:05:49,311
as we go around the
Earth every 90 minutes.

1397
01:05:49,344 --> 01:05:51,146
And so this is the final
configuration you can see here,

1398
01:05:51,179 --> 01:05:53,716
assembled, ready for integration

1399
01:05:53,749 --> 01:05:56,318
into the overall quad
locker structure.

1400
01:05:56,351 --> 01:05:57,886
The second part
of the instrument

1401
01:05:57,919 --> 01:05:59,621
is called the
science instrument.

1402
01:05:59,654 --> 01:06:02,024
This is the quad locker,
you can see it here

1403
01:06:02,057 --> 01:06:04,126
at the design stage;
all of this, of course,

1404
01:06:04,159 --> 01:06:05,694
done in CAD originally.

1405
01:06:05,727 --> 01:06:08,597
This is where you see
the science module,

1406
01:06:08,630 --> 01:06:10,833
which is that
magnetically-shielded
vacuum assembly,

1407
01:06:10,866 --> 01:06:14,003
and then these are
electronics, this is called

1408
01:06:14,036 --> 01:06:15,804
a laser frequency lock
assembly, this is a plate

1409
01:06:15,837 --> 01:06:18,407
where all of the lasers and
the tapered amplifiers were on,

1410
01:06:18,440 --> 01:06:20,209
and then another set of
current driver electronics.

1411
01:06:20,242 --> 01:06:22,111
All of this gets tucked away

1412
01:06:22,144 --> 01:06:24,079
into this pretty
tightly-constrained space,

1413
01:06:24,112 --> 01:06:25,948
all of the electrical
connections are made,

1414
01:06:25,981 --> 01:06:28,083
the water connections
are made here and here,

1415
01:06:28,116 --> 01:06:30,285
the fiber-optic connections
are made between the lasers

1416
01:06:30,318 --> 01:06:32,554
and the science module,
and this is the system

1417

01:06:32,587 --> 01:06:34,023
that gets designed.

1418
01:06:34,056 --> 01:06:36,191
In terms of how does it get
installed into the EXPRESS rack,

1419
01:06:36,224 --> 01:06:37,359
it's pretty simple.

1420
01:06:37,392 --> 01:06:38,827
We had these two
little rails up here,

1421
01:06:38,860 --> 01:06:40,629
a hex bolt goes all
the way through,

1422
01:06:40,662 --> 01:06:42,564
the astronauts screw it
in in these two locations,

1423
01:06:42,597 --> 01:06:44,633
and you're done, because when
you're in a microgravity,

1424
01:06:44,666 --> 01:06:46,668
zero-gravity environment,
you don't have to worry

1425
01:06:46,701 --> 01:06:49,505
about this heavy, 200-kilogram
box hulking around,

1426
01:06:49,538 --> 01:06:51,607
it's essentially in
free-fall, floating around,

1427
01:06:51,640 --> 01:06:53,042
so it's pretty easy to install.

1428
01:06:53,075 --> 01:06:55,177
The worst loading experiences
are either on the ground

1429
01:06:55,210 --> 01:06:57,046
or during the ride up
in the launch vehicle.

1430
01:06:57,079 --> 01:06:58,814
So here, you can see the
final flight configuration

1431
01:06:58,847 --> 01:07:00,916
in our clean room at JPL.

1432
01:07:02,084 --> 01:07:03,685
What you don't see here
is the science module,

1433
01:07:03,718 --> 01:07:05,354
because that's still sitting
in a different clean room

1434
01:07:05,387 --> 01:07:07,022
right now, but you
can see installed here

1435
01:07:07,055 --> 01:07:10,159
our flight computer,
the common-mode filter,

1436
01:07:10,192 --> 01:07:11,593
which is another
piece of electronics,

1437
01:07:11,626 --> 01:07:14,096
and the lasers that
would go right over here,

1438
01:07:14,129 --> 01:07:16,598
and up here is our
power-electronics locker,

1439
01:07:16,631 --> 01:07:18,600
so I'll show you one
more picture of that.

1440
01:07:18,633 --> 01:07:20,402
This was the detailed design

1441
01:07:20,435 --> 01:07:22,571
of what the power-electronics
locker would look like.

1442
01:07:22,604 --> 01:07:24,807
You can see the top
cover is removed here.

1443
01:07:24,840 --> 01:07:26,775
Once again, all of our
equipment is designed

1444
01:07:26,808 --> 01:07:28,844
for the astronauts to be
able to disassemble on orbit

1445
01:07:28,877 --> 01:07:30,379
and take out the
different boxes.

1446
01:07:30,412 --> 01:07:32,681
So this is the design and
this is the actual build.

1447
01:07:32,714 --> 01:07:34,716
This was during the
intermediate build process

1448

01:07:34,749 --> 01:07:36,552
and this is the final
configuration here,

1449
01:07:36,585 --> 01:07:38,587
and you can see it's
got a nice paint job

1450
01:07:38,620 --> 01:07:41,090
so that it fits in
with everything else
on Space Station.

1451
01:07:41,123 --> 01:07:44,159
It takes a long time to go
from the original design

1452
01:07:44,192 --> 01:07:46,095
all the way to the
fully-integrated system,

1453
01:07:46,128 --> 01:07:49,264
which, on our order, was
around five years in total.

1454
01:07:49,297 --> 01:07:50,866
So then we're in the
integration-and-test phase.

1455
01:07:50,899 --> 01:07:53,435
We had a really nice
article released recently

1456
01:07:53,468 --> 01:07:56,138
by the Pasadena Star, so we
got a bunch of fun pictures

1457
01:07:56,171 --> 01:07:57,573
if you want to see them,
I think I've included

1458
01:07:57,606 --> 01:07:58,874
a lot of these in
the presentations.

1459
01:07:58,907 --> 01:08:01,009
So, the final phase of
any spacecraft mission

1460
01:08:01,042 --> 01:08:03,378
is integration and
test, where you take

1461
01:08:03,411 --> 01:08:05,347
all your flight hardware,
you put it together,

1462
01:08:05,380 --> 01:08:06,882
you plug it in, and
you start testing it

1463
01:08:06,915 --> 01:08:08,917
and get your system-level
testing and performance,

1464
01:08:08,950 --> 01:08:10,586
so that's the stage the
mission is in right now

1465
01:08:10,619 --> 01:08:12,654
where things are being
integrated in our clean room

1466
01:08:12,687 --> 01:08:14,823
and we're going through and
testing out all the interfaces

1467
01:08:14,856 --> 01:08:18,327
between the different equipment:
software, electronics,

1468
01:08:18,360 --> 01:08:20,429
lasers, vacuum system.

1469
01:08:20,462 --> 01:08:22,064
For us, that's what it is.

1470
01:08:22,097 --> 01:08:24,299
We did take this one
picture which I liked,

1471
01:08:24,332 --> 01:08:27,002
which is the shot for our new
album cover, Ice Ice Baby,

1472
01:08:27,035 --> 01:08:28,303
I hope you get that.
(audience chuckles)

1473
01:08:28,336 --> 01:08:31,173
If you're too young, you
won't get that (laughs).

1474
01:08:31,206 --> 01:08:33,609
So, our mission timeline.

1475
01:08:33,642 --> 01:08:36,311
Our plan is to go on
SpaceX, so what that means

1476
01:08:36,344 --> 01:08:39,314
is that we deliver basically
16 days before launch,

1477
01:08:39,347 --> 01:08:41,950
we want to hold on to the
payload for as long as possible,

1478
01:08:41,983 --> 01:08:43,285
basically so that

we can keep it safe

1479
01:08:43,318 --> 01:08:45,721
and also so that we
can keep the power on.

1480
01:08:45,754 --> 01:08:48,357
The way we maintain our vacuum
is with something called

1481
01:08:48,390 --> 01:08:51,026
an ion pump, so it's not a
traditional mechanical pump.

1482
01:08:51,059 --> 01:08:52,661
It's basically a
cathode and an anode,

1483
01:08:52,694 --> 01:08:54,796
high voltage between
it, and whatever atoms

1484
01:08:54,829 --> 01:08:56,465
are still floating
around there get ionized

1485
01:08:56,498 --> 01:08:57,733
and they stick to the plates.

1486
01:08:57,766 --> 01:08:59,201
So we want to keep
the power going on

1487
01:08:59,234 --> 01:09:00,502
for as long as possible,
'cause it keeps

1488
01:09:00,535 --> 01:09:01,737
our vacuum level really low.

1489
01:09:01,770 --> 01:09:03,238
We're able to turn
it over pretty late,

1490
01:09:03,271 --> 01:09:04,973
which is 16 days before launch.

1491
01:09:05,006 --> 01:09:07,176
It gets turned over, it
gets put inside of something

1492
01:09:07,209 --> 01:09:10,045
called a clam shell, which is
basically a big piece of foam,

1493
01:09:10,078 --> 01:09:11,513
all tucked in so
that it's protected

1494
01:09:11,546 --> 01:09:13,649
from the really nasty
vibrations of the launch.

1495
01:09:13,682 --> 01:09:15,551
It's then installed
into the Dragon capsule

1496
01:09:15,584 --> 01:09:18,353
which takes around 13 days,
where they strap it in

1497
01:09:18,386 --> 01:09:20,689
with the straps that
I showed you early.

1498
01:09:20,722 --> 01:09:22,858
You always have to account
for potential launch delays,

1499

01:09:22,891 --> 01:09:24,493
so we put two days in for that.

1500
01:09:24,526 --> 01:09:26,628
It takes about five days,
going up on the rocket,

1501
01:09:26,661 --> 01:09:27,896
to get to Space Station.

1502
01:09:27,929 --> 01:09:30,999
We then dock, berth,
it should be taken out

1503
01:09:31,032 --> 01:09:34,369
in about one day's time,
and the install we estimate

1504
01:09:34,402 --> 01:09:35,837
to take around two days.

1505
01:09:35,870 --> 01:09:37,773
And at that point, the
power on the express rack

1506
01:09:37,806 --> 01:09:39,875
is turned on and then we
start communicating with it

1507
01:09:39,908 --> 01:09:41,910
and we start doing our
science from the ground,

1508
01:09:41,943 --> 01:09:43,378
which starts off with
initial calibrations

1509
01:09:43,411 --> 01:09:46,014
and then all the science
investigations which follow.

1510
01:09:46,047 --> 01:09:48,750
So, we add all that up,
it adds up to 26 days

1511
01:09:48,783 --> 01:09:51,053
and this means we have
26 days with no power,

1512
01:09:51,086 --> 01:09:53,655
no ability to communicate
with it, but we think we have

1513
01:09:53,688 --> 01:09:56,258
plenty of margin on that,
so it should be okay.

1514
01:09:56,291 --> 01:09:58,527
So, how are we going
to do operations?

1515
01:09:58,560 --> 01:10:01,997
The operations are all remote,
we have out laboratory here

1516
01:10:02,030 --> 01:10:03,498
called our Ground Testbed.

1517
01:10:03,531 --> 01:10:05,033
Also, the testbed
is where we generate

1518
01:10:05,066 --> 01:10:07,069
our flight software
sequences, we test them out

1519
01:10:07,102 --> 01:10:08,437
in a laboratory
environment first,

1520
01:10:08,470 --> 01:10:09,972
to make sure that they'll work,

1521
01:10:10,005 --> 01:10:11,506
then we transfer them over
to the operations center.

1522
01:10:11,539 --> 01:10:15,210
We're gonna be in
Building 264, first floor,

1523
01:10:15,243 --> 01:10:17,312
Earth Science Mission
Operation Center.

1524
01:10:17,345 --> 01:10:20,315
They're uploaded to
CAL via Ethernet,

1525
01:10:20,348 --> 01:10:24,253
it's called KuIP services, and
then the data comes back down

1526
01:10:24,286 --> 01:10:27,389
in the form of images, which
are reduced by the scientists

1527
01:10:27,422 --> 01:10:29,591
and they're able to collect
the science data off of them

1528
01:10:29,624 --> 01:10:31,360
to continue doing
our experiments.

1529
01:10:31,393 --> 01:10:33,996
That data is then sent
to the individual PIs

1530

01:10:34,029 --> 01:10:37,633
who then will go off and
process them further.

1531
01:10:37,666 --> 01:10:40,202
So in terms of the overall
operation phases for CAL,

1532
01:10:40,235 --> 01:10:42,404
we start off with the
initial installation,

1533
01:10:42,437 --> 01:10:45,140
this is done by the
crew, really does consist

1534
01:10:45,173 --> 01:10:46,675
of unpacking it
from the clam shell,

1535
01:10:46,708 --> 01:10:49,945
installing that
science instrument,

1536
01:10:49,978 --> 01:10:51,546
installing the
power-electronics locker,

1537
01:10:51,579 --> 01:10:53,548
making fiber-optic connections
between the two of them,

1538
01:10:53,581 --> 01:10:55,717
making the water connections
to the express rack,

1539
01:10:55,750 --> 01:10:58,787
making the power connection to
the 28-volt DC power supply,

1540

01:10:58,820 --> 01:11:00,889
and then it's
essentially good to go.

1541
01:11:00,922 --> 01:11:03,659
We have an initial checkout
phase, where we wanna make sure

1542
01:11:03,692 --> 01:11:05,594
that we can communicate,
uplink commands

1543
01:11:05,627 --> 01:11:08,263
to the instrument and then
receive the data via downlink

1544
01:11:08,296 --> 01:11:10,232
via the KuIP
services connection.

1545
01:11:10,265 --> 01:11:11,700
We're gonna take about six weeks

1546
01:11:11,733 --> 01:11:13,068
to do that initial checking.

1547
01:11:13,101 --> 01:11:15,337
Then we're gonna do
validation, which is where Rob

1548
01:11:15,370 --> 01:11:17,906
and his team are going
to be going through,

1549
01:11:17,939 --> 01:11:20,575
testing out all the capabilities
of the instrument on orbit

1550
01:11:20,608 --> 01:11:22,644
to make sure everything's

working, and to calibrate,

1551
01:11:22,677 --> 01:11:25,113
to understand how things
are gonna perform,

1552
01:11:25,146 --> 01:11:27,849
because the environment in
Space Station is gonna be

1553
01:11:27,882 --> 01:11:29,418
very different from the
environment on the ground

1554
01:11:29,451 --> 01:11:30,752
in two fundamental ways.

1555
01:11:30,785 --> 01:11:33,555
One, on the ground, we
have one g, up in orbit,

1556
01:11:33,588 --> 01:11:35,590
we're gonna have
essentially zero gravity,

1557
01:11:35,623 --> 01:11:37,359
so things are gonna
behave very differently.

1558
01:11:37,392 --> 01:11:39,628
The cloud my normally
have been in one location

1559
01:11:39,661 --> 01:11:41,563
which means they're gonna
have to tweak magnetic fields,

1560
01:11:41,596 --> 01:11:42,964
that all needs to be calibrated

1561
01:11:42,997 --> 01:11:46,635
into the operational sequence
once we get up there.

1562
01:11:46,668 --> 01:11:48,704
Of course, the magnetic
field is gonna be different,

1563
01:11:48,737 --> 01:11:50,872
which also affects the way
they're going to generate

1564
01:11:50,905 --> 01:11:53,108
the sequences, and the
thermal environment

1565
01:11:53,141 --> 01:11:54,810
is gonna be very different,
because when you're in

1566
01:11:54,843 --> 01:11:56,511
a microgravity
environment, you don't have

1567
01:11:56,544 --> 01:11:58,480
natural convection, so you
basically have hot spots,

1568
01:11:58,513 --> 01:12:00,649
so you have to be
able to move stuff,

1569
01:12:00,682 --> 01:12:02,117
either you have to be
able to force conduction

1570
01:12:02,150 --> 01:12:05,520
by using fans or the
water cooling loop,

1571
01:12:05,553 --> 01:12:07,189
but it's gonna change
our thermal environment.

1572
01:12:07,222 --> 01:12:10,592
So at JPL, we have a mantra
which we call test as you fly,

1573
01:12:10,625 --> 01:12:12,961
but sometimes you have
test as you fly exceptions,

1574
01:12:12,994 --> 01:12:15,063
so for us, our
exceptions are gravity,

1575
01:12:15,096 --> 01:12:17,532
and then the thermal environment
associated with that,

1576
01:12:17,565 --> 01:12:19,468
and then the change
in the magnetic field

1577
01:12:19,501 --> 01:12:21,403
that we see between here
on Earth and what we'll see

1578
01:12:21,436 --> 01:12:24,406
varying as we go around
on orbit on Space Station.

1579
01:12:24,439 --> 01:12:26,641
Then we shift over to the
science operations phase,

1580
01:12:26,674 --> 01:12:28,877
and we have almost three
years of science operations

1581
01:12:28,910 --> 01:12:30,879
to go through our five PI teams,

1582
01:12:30,912 --> 01:12:34,349
and we'll probably do
times where they operate

1583
01:12:34,382 --> 01:12:38,220
for a month or two and
then another teams comes in

1584
01:12:38,253 --> 01:12:39,888
and another team comes in
and make it recycle back,

1585
01:12:39,921 --> 01:12:41,823
but we've got plenty of
margin in the system.

1586
01:12:41,856 --> 01:12:44,159
Now, in all of this,
we're going to be reading

1587
01:12:44,192 --> 01:12:45,961
the telemetry that comes
back from the instrument,

1588
01:12:45,994 --> 01:12:48,096
so if something shows us
that one of the lasers

1589
01:12:48,129 --> 01:12:49,731
is starting to
degrade, for example,

1590
01:12:49,764 --> 01:12:52,200
we do have the ability to have
the astronauts go in there

1591

01:12:52,233 --> 01:12:54,269
and replace the laser.

1592
01:12:54,302 --> 01:12:56,638
This is the reason why it's
an advantage to be able

1593
01:12:56,671 --> 01:12:58,440
to be on Space Station
where you have the ability

1594
01:12:58,473 --> 01:12:59,875
to do these repairs,
and we're actually

1595
01:12:59,908 --> 01:13:01,543
flying up spare parts.

1596
01:13:01,576 --> 01:13:03,345
So even though we have
the primary instrument

1597
01:13:03,378 --> 01:13:05,380
that gets shipped
up in a clam shell,

1598
01:13:05,413 --> 01:13:08,450
we also have a bag of spare
parts, which is extra lasers,

1599
01:13:08,483 --> 01:13:11,486
extra tapered amplifiers,
and extra computer parts.

1600
01:13:11,519 --> 01:13:14,423
So the radiation environment
in low-Earth orbit

1601
01:13:14,456 --> 01:13:16,258
where Space Station

is is pretty benign,

1602
01:13:16,291 --> 01:13:18,093
but you do still have
the chance of getting

1603
01:13:18,126 --> 01:13:20,429
high-energy particles that
could potentially come and hit

1604
01:13:20,462 --> 01:13:22,264
an electronics card that
you're worried about,

1605
01:13:22,297 --> 01:13:23,965
so we also have spare
parts that we can shift out

1606
01:13:23,998 --> 01:13:25,967
those electronics
cards if we need to,

1607
01:13:26,000 --> 01:13:29,805
and the astronauts will
do that for us as well.

1608
01:13:29,838 --> 01:13:32,207
So, this one, we probably
won't go through,

1609
01:13:32,240 --> 01:13:34,242
this is the details of
what the science operations

1610
01:13:34,275 --> 01:13:37,345
look like, a day in the
life of operating CAL,

1611
01:13:37,378 --> 01:13:40,615
and so I think we wanted sum

up with our lessons learned

1612
01:13:40,648 --> 01:13:42,951
from the mission overall,
the past five years.

1613
01:13:42,984 --> 01:13:44,786
You want to engage the
science community early

1614
01:13:44,819 --> 01:13:46,555
so you can understand
what they need,

1615
01:13:46,588 --> 01:13:48,824
how they want to operate it,
what capabilities they need

1616
01:13:48,857 --> 01:13:50,859
to be able to do it.

1617
01:13:50,892 --> 01:13:53,228
You really want to
understand how do translate

1618
01:13:53,261 --> 01:13:55,730
science requirements into
engineering requirements

1619
01:13:55,763 --> 01:13:57,966
to give you sufficient margin
on the engineering side

1620
01:13:57,999 --> 01:13:59,501
to give you the
science that you need.

1621
01:13:59,534 --> 01:14:01,369
That's very difficult to
do when you've never done

1622
01:14:01,402 --> 01:14:03,839
something like this before, so
CAL's the first of its kind,

1623
01:14:03,872 --> 01:14:07,776
going from very complex
science requirements

1624
01:14:07,809 --> 01:14:10,045
to very complex
engineering requirements.

1625
01:14:10,078 --> 01:14:12,113
If you are going to
use new technology,

1626
01:14:12,146 --> 01:14:14,616
you want to test it early,
so that you can find

1627
01:14:14,649 --> 01:14:16,485
any kinks in the
system and fix them.

1628
01:14:16,518 --> 01:14:17,953
That, of course, suggests
you have enough schedule

1629
01:14:17,986 --> 01:14:19,287
to do it, it can always
be a little tricky

1630
01:14:19,320 --> 01:14:20,722
for Class D missions.

1631
01:14:20,755 --> 01:14:23,325
Use of commercial
hardware is convenient

1632
01:14:23,358 --> 01:14:25,460
because it already exists,
but it's also very difficult,

1633
01:14:25,493 --> 01:14:27,896
because sometimes, commercial
hardware doesn't meet

1634
01:14:27,929 --> 01:14:30,198
its specification value,
and then you're limited

1635
01:14:30,231 --> 01:14:33,301
to the actual capability of
that commercial hardware.

1636
01:14:33,334 --> 01:14:35,103
And there's also a
lot of variability;

1637
01:14:35,136 --> 01:14:38,273
so I'm sure you've all
bought TVs over time,

1638
01:14:38,306 --> 01:14:40,709
one TV comes out of the
box, fries the next day,

1639
01:14:40,742 --> 01:14:42,878
another TV lasts for 15 years.

1640
01:14:42,911 --> 01:14:44,312
So that's one of
the risks associated

1641
01:14:44,345 --> 01:14:46,882
with using commercial
technology.

1642

01:14:46,915 --> 01:14:50,285
You also wanna understand your
ISS interfaces really well,

1643
01:14:50,318 --> 01:14:51,720
so that comes to
systems engineering,

1644
01:14:51,753 --> 01:14:53,421
which is in the
discipline of engineering

1645
01:14:53,454 --> 01:14:55,790
that the space
community has to use.

1646
01:14:55,823 --> 01:14:58,527
It basically tells you how do
you interface with hardware

1647
01:14:58,560 --> 01:15:01,830
from a mechanical perspective,
thermal perspective,

1648
01:15:01,863 --> 01:15:04,266
pretty much in every way.

1649
01:15:04,299 --> 01:15:06,034
Now, the unique thing
about operating something

1650
01:15:06,067 --> 01:15:07,402
inside of Space Station
is understanding

1651
01:15:07,435 --> 01:15:09,938
the safety requirements
working with the crew,

1652
01:15:09,971 --> 01:15:11,873

it imposes a whole new
set of requirements

1653
01:15:11,906 --> 01:15:14,042
which most missions at JPL
don't have to deal with.

1654
01:15:14,075 --> 01:15:16,411
Things such as touch
temperature, the thing can't get

1655
01:15:16,444 --> 01:15:18,446
too hot so the astronauts
don't injure their hands;

1656
01:15:18,479 --> 01:15:20,549
how sharp are the edges, so
the astronauts don't injure

1657
01:15:20,582 --> 01:15:23,685
their skin or their
fingers; ways that fasteners

1658
01:15:23,718 --> 01:15:25,820
have to have some kind of
tether associated with them

1659
01:15:25,853 --> 01:15:27,355
or have to be captive fasteners

1660
01:15:27,388 --> 01:15:29,224
so they can't go float around,
'cause you don't want someone

1661
01:15:29,257 --> 01:15:30,659
to accidentally
swallow something.

1662
01:15:30,692 --> 01:15:34,229
So it actually brings about

a whole other paradigm

1663
01:15:34,262 --> 01:15:37,265
of doing engineering when
people are involved in space

1664
01:15:37,298 --> 01:15:39,234
as opposed to
free-flying spacecraft.

1665
01:15:39,267 --> 01:15:41,469
And ultimately, it really
does take a village,

1666
01:15:41,502 --> 01:15:43,438
and this goes for
every mission at JPL,

1667
01:15:43,471 --> 01:15:45,674
a diversity of technical
backgrounds and capabilities

1668
01:15:45,707 --> 01:15:48,743
to be able to pull
off engineering such
complicated systems,

1669
01:15:48,776 --> 01:15:50,312
but if everyone's
interested in it

1670
01:15:50,345 --> 01:15:51,646
and loves what they're
doing, it ends up

1671
01:15:51,679 --> 01:15:53,448
working out quite well.

1672
01:15:53,481 --> 01:15:55,650
So I think that wraps it

up, we're gonna do Q&A now,

1673
01:15:55,683 --> 01:15:57,886
and so we've got some
fun pictures of the team.

1674
01:15:57,919 --> 01:15:59,654
This is the engineering
team listed here

1675
01:15:59,687 --> 01:16:01,389
and I think at least
seven of them are

1676
01:16:01,422 --> 01:16:02,857
in the audience
right now (chuckles).

1677
01:16:02,890 --> 01:16:04,459
So thank you very much.

1678
01:16:04,492 --> 01:16:07,563
(audience applauds)

1679
01:16:16,237 --> 01:16:17,439
So how do we take questions?

1680
01:16:17,472 --> 01:16:18,640
- Yeah, if there
are any questions,

1681
01:16:18,673 --> 01:16:21,543
please step up to
one of the mics here.

1682
01:16:27,115 --> 01:16:30,619
- Everyone's too
afraid (laughs).

1683

01:16:30,652 --> 01:16:31,987
- [Audience Member]
Yes, can you tell me,

1684
01:16:32,020 --> 01:16:34,255
roughly what kind of
quantities of the materials

1685
01:16:34,288 --> 01:16:37,459
like the potassium
are you using?

1686
01:16:37,492 --> 01:16:39,728
Is it micrograms or pounds?

1687
01:16:40,862 --> 01:16:42,864
- Yeah, a fraction of a,

1688
01:16:44,465 --> 01:16:46,201
I think it's what,
100 micrograms or
something like that

1689
01:16:46,234 --> 01:16:48,269
that comes inside a dispenser.

1690
01:16:48,302 --> 01:16:49,504
- [Audience Member]
Is that something

1691
01:16:49,537 --> 01:16:53,008
that can be added
later from the crew?

1692
01:16:53,041 --> 01:16:57,646
- That's one of the few things
that could actually run out.

1693
01:16:57,679 --> 01:17:01,416
These systems usually last

for three or four years,

1694
01:17:01,449 --> 01:17:03,852
so we think we'll last the
three years with the amount

1695
01:17:03,885 --> 01:17:05,553
that we have.

1696
01:17:05,586 --> 01:17:07,255
That is what we call a
consumable, it is something

1697
01:17:07,288 --> 01:17:08,857
that would run out.

1698
01:17:10,058 --> 01:17:11,259
If it ran out, we
would have to replace

1699
01:17:11,292 --> 01:17:12,794
the whole vacuum system.

1700
01:17:12,827 --> 01:17:16,231
- [Audience Member]
I see. Thank you.

1701
01:17:16,264 --> 01:17:17,298
- Hello.

1702
01:17:17,331 --> 01:17:19,101
Using the pico scale,

1703
01:17:23,871 --> 01:17:27,542
in effect, does CAL
fluctuate in temperature

1704
01:17:30,545 --> 01:17:34,716
from the time it's launched to

the time it reaches the ISS?

1705
01:17:40,021 --> 01:17:43,758
- One of the amazing things
about this technology,

1706
01:17:43,791 --> 01:17:45,894
the atom chip that
we're talking about,

1707
01:17:45,927 --> 01:17:48,830
is this cold sample that's
at these temperatures,

1708
01:17:48,863 --> 01:17:51,600
nanoKelvin or
below, is held just

1709
01:17:54,602 --> 01:17:57,839
100 microns, which is
the width of a hair

1710
01:17:57,872 --> 01:18:00,508
below the size of
that atom chip,

1711
01:18:00,541 --> 01:18:03,778
and the rest of the apparatus
is all room temperature.

1712
01:18:03,811 --> 01:18:07,348
And it might change
a little bit,

1713
01:18:07,381 --> 01:18:10,085
get warmer or colder
through different cycles,

1714
01:18:10,118 --> 01:18:14,422
but the atoms are isolated

from that and don't see that.

1715
01:18:14,455 --> 01:18:16,424
- If that does occur
though, is there any way

1716
01:18:16,457 --> 01:18:18,794
to possibly fix the problem?

1717
01:18:21,262 --> 01:18:22,464
- I would say from a
thermal perspective,

1718
01:18:22,497 --> 01:18:23,732
the most difficult
thermal environment

1719
01:18:23,765 --> 01:18:25,300
would be when it's
actually operating.

1720
01:18:25,333 --> 01:18:27,135
So when it's non-operational,
it isn't really dissipating

1721
01:18:27,168 --> 01:18:29,971
any heat, so the most
extreme thermal environment

1722
01:18:30,004 --> 01:18:32,207
will be when it's operating.

1723
01:18:32,240 --> 01:18:34,743
- [Audience Member] Thank you.

1724
01:18:35,877 --> 01:18:38,012
- Great talk, thank you so much.

1725
01:18:38,045 --> 01:18:40,448

Is it okay to ask
three questions?

1726
01:18:40,481 --> 01:18:41,449
(audience chuckles)

1727
01:18:41,482 --> 01:18:42,617
- [Dr. Thompson] That's fine.

1728
01:18:42,650 --> 01:18:44,586
- First one, is there
any possibility,

1729
01:18:44,619 --> 01:18:47,122
assuming the current
draw's really minimal,

1730
01:18:47,155 --> 01:18:49,691
is there any possibility of
using an external capacitor

1731
01:18:49,724 --> 01:18:53,361
to maintain charge on the
plates during the 29 days

1732
01:18:53,394 --> 01:18:55,731
where it's being integrated?

1733
01:18:57,832 --> 01:18:59,801
- We did do a trade,
actually, to use a battery

1734
01:18:59,834 --> 01:19:02,403
to keep that going, and
we decided that that added

1735
01:19:02,436 --> 01:19:04,372
so much cost and
complexity that it's easier

1736
01:19:04,405 --> 01:19:07,075
just to not use it, but you
could actually use a battery

1737
01:19:07,108 --> 01:19:09,944
to keep it charged up, but
we're pretty insensitive

1738
01:19:09,977 --> 01:19:12,781
to the 26 days in terms of
vacuum pressure changing.

1739
01:19:12,814 --> 01:19:15,750
- Yeah, it's not a huge risk.

1740
01:19:15,783 --> 01:19:18,419
If your pressure gets too
high, it just takes a while,

1741
01:19:18,452 --> 01:19:22,624
you lose time to pull it back
down to pressure that we need.

1742
01:19:23,524 --> 01:19:24,993
- Cool.

1743
01:19:25,026 --> 01:19:27,162
Second question, can you
comment a little bit about

1744
01:19:27,195 --> 01:19:30,999
what are the underlying
principles for quantum bubbles

1745
01:19:31,032 --> 01:19:34,102
to assume a elliptical
cross-section,

1746
01:19:35,536 --> 01:19:37,539

as opposed to spherical?

1747
01:19:42,310 --> 01:19:44,212
- We bake this trap

1748
01:19:44,245 --> 01:19:46,148
that has this geometry.

1749
01:19:51,485 --> 01:19:53,154
We would actually like
to make them spherical,

1750
01:19:53,187 --> 01:19:55,156
we'd like to make
them equal strengths

1751
01:19:55,189 --> 01:19:56,791
in all the different
directions, but that's actually

1752
01:19:56,824 --> 01:19:58,993
fairly difficult
with our system,

1753
01:19:59,026 --> 01:20:02,864
they tend to be more
football-shaped, I guess.

1754
01:20:04,298 --> 01:20:07,101
- And then third question,
can you comment a little bit

1755
01:20:07,134 --> 01:20:11,306
about when you get to intended
operating temperature,

1756
01:20:12,506 --> 01:20:15,310
you indicated that the
summation wavelengths

1757
01:20:15,343 --> 01:20:18,546
are on the order
of a millimeter.

1758
01:20:18,579 --> 01:20:21,983
How does laser tuning
work as you proceed

1759
01:20:23,684 --> 01:20:26,855
down the wavelength
dimension changes?

1760
01:20:29,557 --> 01:20:32,694
- We've turned the
laser cooling off

1761
01:20:32,727 --> 01:20:35,563
at a point of temperatures
of millionths of a degree,

1762
01:20:35,596 --> 01:20:39,201
so those last stages
just have the magnetic

1763
01:20:43,437 --> 01:20:44,940
trapping involved.

1764
01:20:49,343 --> 01:20:50,912
And that wavelength
really tells us something

1765
01:20:50,945 --> 01:20:53,181
about the probability
of finding an atom

1766
01:20:53,214 --> 01:20:56,351
in a particular
location, I guess.

1767

01:20:56,384 --> 01:20:57,385
- Thank you.

1768
01:20:59,987 --> 01:21:01,155
- Hi.

1769
01:21:01,188 --> 01:21:03,958
You mentioned earlier
how you were using

1770
01:21:03,991 --> 01:21:07,929
Windows operating system
to run the software

1771
01:21:07,962 --> 01:21:09,397
on this machine.

1772
01:21:09,430 --> 01:21:11,332
I was just curious if
you could expand on that,

1773
01:21:11,365 --> 01:21:13,768
like what kind of
Windows are you using,

1774
01:21:13,801 --> 01:21:17,238
as a very customized
version, I'm assuming?

1775
01:21:17,271 --> 01:21:20,208
- We actually use a lot of
National Instruments hardware,

1776
01:21:20,241 --> 01:21:21,676
so the computer that we're using

1777
01:21:21,709 --> 01:21:24,612
is a National
Instruments PXI chassis,

1778
01:21:24,645 --> 01:21:26,814
and we run LabVIEW off of it,
and so LabVIEW has to operate

1779
01:21:26,847 --> 01:21:28,883
off of Windows.

1780
01:21:28,916 --> 01:21:30,084
Is it Windows NT? I forget.

1781
01:21:30,117 --> 01:21:32,787
Is it Windows 98 or NT?

1782
01:21:32,820 --> 01:21:34,822
- Windows RT, I think.

1783
01:21:34,855 --> 01:21:38,226
- So because we're using
LabVIEW, we have to use Windows

1784
01:21:38,259 --> 01:21:39,894
to run it, so we
don't have a choice.

1785
01:21:39,927 --> 01:21:41,930
So we're using commercial
software as well.

1786
01:21:41,963 --> 01:21:42,931
- [Audience Member] Oh, okay.

1787
01:21:42,964 --> 01:21:43,798
Thank you.

1788
01:21:45,766 --> 01:21:49,604
- How do you actually measure
these low temperatures?

1789

01:21:49,637 --> 01:21:53,808
- Really, it's this idea of
just releasing the atoms,

1790
01:21:54,875 --> 01:21:56,511
and so, what is temperature?

1791
01:21:56,544 --> 01:22:00,949
It's just the average
random motion of molecules

1792
01:22:00,982 --> 01:22:04,653
or atoms, and so if we
just let the atoms go,

1793
01:22:06,487 --> 01:22:10,024
the hot ones will move
faster and further

1794
01:22:10,057 --> 01:22:13,027
than the cold ones, and so
just by measuring the size

1795
01:22:13,060 --> 01:22:17,232
of the cloud, we can measure
what its temperature is.

1796
01:22:20,501 --> 01:22:22,337
- Hi, just had another question.

1797
01:22:22,370 --> 01:22:24,672
Do you believe if CAL
is successful enough

1798
01:22:24,705 --> 01:22:28,776
that it would aid
in explanations to
strange phenomena

1799
01:22:28,809 --> 01:22:31,379

such as the Boomerang
Nebula, which is currently

1800
01:22:31,412 --> 01:22:34,916
the coldest place
in the universe?

1801
01:22:34,949 --> 01:22:38,286
- Yeah, so there's lots of
claims to the coldest place

1802
01:22:38,319 --> 01:22:41,956
in the universe,
and that's, I think,

1803
01:22:41,989 --> 01:22:44,459
one of the coldest
naturally-occurring ones.

1804
01:22:44,492 --> 01:22:48,663
I don't actually think that
we would provide any insights

1805
01:22:50,031 --> 01:22:51,700
into that situation.

1806
01:22:56,103 --> 01:22:57,472
- What do you hope to discover?

1807
01:22:57,505 --> 01:22:59,774
Any reasonable expectation?

1808
01:23:02,143 --> 01:23:03,945
(audience chuckles)

1809
01:23:03,978 --> 01:23:07,749
- Well, we've talked
about these steps

1810

01:23:07,782 --> 01:23:10,952
of systems that we
can make and probe.

1811
01:23:15,790 --> 01:23:17,759
Ultimately, these
types of experiments,

1812
01:23:17,792 --> 01:23:21,129
and it might not be CAL,
but some follow-on to CAL,

1813
01:23:21,162 --> 01:23:24,332
I think can push
Einstein to the limit

1814
01:23:25,666 --> 01:23:28,136
as well as he can be tested.

1815
01:23:28,169 --> 01:23:30,204
It's not clear that it'll
be good enough to find

1816
01:23:30,237 --> 01:23:33,908
that he's wrong, so as
we said in the video,

1817
01:23:35,876 --> 01:23:38,913
the General Theory
of Relativity, it's
a very good theory,

1818
01:23:38,946 --> 01:23:42,684
it stands up to every
test that we put it to,

1819
01:23:43,717 --> 01:23:46,287
but it's not compatible
with our ideas

1820

01:23:46,320 --> 01:23:48,790
about how quantum mechanics
work, the science,

1821
01:23:48,823 --> 01:23:51,759
and that, again, that
survives every test

1822
01:23:51,792 --> 01:23:53,861
that we can put that to.

1823
01:23:53,894 --> 01:23:57,732
They don't usually, even
though they're in conflict,

1824
01:23:57,765 --> 01:24:01,936
you don't normally, on
everyday, Earth-like scales,

1825
01:24:01,969 --> 01:24:03,738
they don't come into conflict,

1826
01:24:03,771 --> 01:24:06,441
because one is only there
for really small things

1827
01:24:06,474 --> 01:24:09,877
and one is more on
the scale of galaxies

1828
01:24:09,910 --> 01:24:12,713
and planets moving around
and things like that.

1829
01:24:12,746 --> 01:24:15,616
So it's hard to do an
experiment that shows

1830
01:24:15,649 --> 01:24:18,153
where they come into conflict.

1831
01:24:19,487 --> 01:24:23,358
But that is perhaps the biggest
impact that we could have.

1832
01:24:27,328 --> 01:24:30,498
I don't think the CAL
experiments in this generation

1833
01:24:30,531 --> 01:24:33,434
are gonna overthrow
Einstein's theory of gravity,

1834
01:24:33,467 --> 01:24:35,636
though I think they will
be very interesting,

1835
01:24:35,669 --> 01:24:40,541
they could be textbook examples
of why Einstein still seems

1836
01:24:40,574 --> 01:24:45,012
to be right, people would
be very interested in.

1837
01:24:45,045 --> 01:24:46,914
But a follow-on experiment
might actually be able

1838
01:24:46,947 --> 01:24:49,183
to see something someday.

1839
01:24:49,216 --> 01:24:50,284
- Another aspect of CAL is

1840
01:24:50,317 --> 01:24:51,986
a technology
demonstration mission.

1841

01:24:52,019 --> 01:24:54,288
So it's the first time that
we're doing laser cooling

1842
01:24:54,321 --> 01:24:56,023
in space, it's the first
time we're doing most of this

1843
01:24:56,056 --> 01:24:58,126
in space, so the missions
that will follow,

1844
01:24:58,159 --> 01:25:00,461
this facilitates them.

1845
01:25:00,494 --> 01:25:02,697
- You spoke of the
Doppelganger effect

1846
01:25:02,730 --> 01:25:05,600
and I was wondering if
there's any relation

1847
01:25:05,633 --> 01:25:07,802
to the red light effect...

1848
01:25:09,336 --> 01:25:10,805
- [Dr. Thompson]
In astronomy, yep.

1849
01:25:10,838 --> 01:25:15,042
- To the Big Bang Theory, and
I've heard reasonable doubt

1850
01:25:15,075 --> 01:25:18,579
to the Big bang Theory
and the red-light shift,

1851
01:25:18,612 --> 01:25:19,780
I wonder if there's any relation

1852
01:25:19,813 --> 01:25:22,817
between quantum
physics and physics.

1853
01:25:24,385 --> 01:25:27,622
- (chuckles) Sure.

1854
01:25:27,655 --> 01:25:29,624
The physics behind the
Doppler shifts that we see

1855
01:25:29,657 --> 01:25:33,794
in astronomy is very similar
to the physics that we see

1856
01:25:33,827 --> 01:25:36,331
in Doppler shifts in our labs.

1857
01:25:38,265 --> 01:25:42,437
That's pretty well understood,
it's why we believe

1858
01:25:43,804 --> 01:25:47,242
those measurements
coming from astronomy.

1859
01:25:48,609 --> 01:25:52,346
One of the things astronomers
see is that the universe

1860
01:25:52,379 --> 01:25:54,448
seems to be accelerating
and seems to be expanding

1861
01:25:54,481 --> 01:25:57,485
faster than they
thought, and that's

1862

01:25:58,352 --> 01:26:01,055
not well understood at all.

1863
01:26:01,088 --> 01:26:03,991
It's a theory of dark energy,
and we have, actually,

1864
01:26:04,024 --> 01:26:07,061
one of those teams, the
team with Holger Mueller,

1865
01:26:07,094 --> 01:26:10,231
that's doing the test of
equivalence principle,

1866
01:26:10,264 --> 01:26:14,435
dropping the rubidium and
potassium atoms together,

1867
01:26:16,303 --> 01:26:20,375
they will also do some
measurements that can test

1868
01:26:22,009 --> 01:26:24,245
one of the theories
of dark energy

1869
01:26:24,278 --> 01:26:26,847
and might be able to
give some insight,

1870
01:26:26,880 --> 01:26:31,586
or more likely, to rule
it out as a possibility.

1871
01:26:31,619 --> 01:26:34,622
- Excellent
presentation, thank you.

1872
01:26:36,857 --> 01:26:38,626

- Hope you didn't dodge
two more questions.

1873
01:26:38,659 --> 01:26:40,127
(audience chuckles)
- Sure.

1874
01:26:40,160 --> 01:26:42,363
- [Dr. Sengupta] We do have
to cut it off by 8:30 though.

1875
01:26:42,396 --> 01:26:46,067
- First one had to do on
test subject selection.

1876
01:26:46,100 --> 01:26:49,036
Why weren't noble gases with
full valence shells used

1877
01:26:49,069 --> 01:26:50,504
as opposed to--

1878
01:26:50,537 --> 01:26:52,974
- Yeah, that's a good question.

1879
01:26:53,007 --> 01:26:57,178
Rubidium is kinda the
workhorse; so at this point,

1880
01:26:58,212 --> 01:27:00,548
groups around the world have

1881
01:27:02,950 --> 01:27:04,819
Bose-condensed a number
of different species,

1882
01:27:04,852 --> 01:27:08,022
I forget whether it's up
to 13 or 14 or something,

1883
01:27:08,055 --> 01:27:10,992
including some of
the noble gases.

1884
01:27:11,025 --> 01:27:13,595
Helium has been Bose-condensed,

1885
01:27:15,796 --> 01:27:17,365
hydrogen has been
Bose-condensed,

1886
01:27:17,398 --> 01:27:20,768
but the easiest one, it
turns out to be rubidium,

1887
01:27:20,801 --> 01:27:24,572
so that's the workhorse,
and then potassium is chosen

1888
01:27:24,605 --> 01:27:28,743
as the second one because its
wavelength is fairly close

1889
01:27:28,776 --> 01:27:31,112
to the rubidium one, so you can
use a lot of the same optics

1890
01:27:31,145 --> 01:27:33,514
and things like that.

1891
01:27:33,547 --> 01:27:36,550
- And then, partially related
to that, when you get down

1892
01:27:36,583 --> 01:27:40,421
to the picoKelvin levels,
and at the dimension

1893
01:27:42,056 --> 01:27:46,227

that you're dealing with in
terms of individual atoms,

1894
01:27:47,628 --> 01:27:51,565
you mention that light was
used to pass through the cloud

1895
01:27:51,598 --> 01:27:54,268
to determine its presence.

1896
01:27:54,301 --> 01:27:55,870
Isn't that a massive
perturbation for it,

1897
01:27:55,903 --> 01:27:57,138
and how do you--

1898
01:27:57,171 --> 01:27:58,572
- Oh yes, it is a
huge perturbation;

1899
01:27:58,605 --> 01:28:01,142
in fact, it completely
destroys the condensate.

1900
01:28:01,175 --> 01:28:04,545
I didn't really mention
that, but when we go through

1901
01:28:04,578 --> 01:28:07,248
those steps of laser cooling
and evaporative cooling

1902
01:28:07,281 --> 01:28:10,117
and then we make
that condensate,

1903
01:28:10,150 --> 01:28:12,386
typically, we can
only measure it once,

1904
01:28:12,419 --> 01:28:14,155
and that measurement
actually destroys it.

1905
01:28:14,188 --> 01:28:15,489
There's some tricks
that we can play

1906
01:28:15,522 --> 01:28:18,759
that we can move some of
the atoms into a state

1907
01:28:18,792 --> 01:28:21,529
that's invisible to our
laser beam that might let us

1908
01:28:21,562 --> 01:28:24,332
look at it, take a
couple of pictures of it,

1909
01:28:24,365 --> 01:28:26,233
but basically, those
pictures are destructive

1910
01:28:26,266 --> 01:28:28,202
and they destroy the condensate.

1911
01:28:28,235 --> 01:28:30,237
So you need the system
to be very reproducible

1912
01:28:30,270 --> 01:28:32,840
and you take your data
by doing the experiment

1913
01:28:32,873 --> 01:28:35,309
hundreds of times and building
up your statistics that way.

1914
01:28:35,342 --> 01:28:37,845
- [Audience Member] Thank you.

1915
01:28:39,279 --> 01:28:40,781
- I have two questions also.

1916
01:28:40,814 --> 01:28:42,750
First of all, I think you
mentioned it was something

1917
01:28:42,783 --> 01:28:45,286
like millions or
billions of times colder

1918
01:28:45,319 --> 01:28:48,222
than anything
previously constructed,

1919
01:28:48,255 --> 01:28:49,990
and I'm wondering,
since you're talking

1920
01:28:50,023 --> 01:28:52,226
about a small fraction of a
degree, how do you measure

1921
01:28:52,259 --> 01:28:54,528
millions or billions
of times colder?

1922
01:28:54,561 --> 01:28:57,298
Is it by the movement
of subatomic particles,

1923
01:28:57,331 --> 01:28:59,500
or how are you doing that?

1924
01:29:01,902 --> 01:29:04,438
- Because we can look at

them for a fairly long time;

1925
01:29:04,471 --> 01:29:06,107
actually, one of the
reasons when we make

1926
01:29:06,140 --> 01:29:08,142
these cold temperatures,

1927
01:29:12,346 --> 01:29:13,981
one of the advantages
of microgravity

1928
01:29:14,014 --> 01:29:15,783
is that we can wait long enough

1929
01:29:15,816 --> 01:29:18,419
to actually see the gas expand,

1930
01:29:18,452 --> 01:29:20,087
and they're expanding
pretty slowly

1931
01:29:20,120 --> 01:29:22,690
when times you get
to 100 picoKelvin.

1932
01:29:22,723 --> 01:29:25,893
You have to wait a fraction
of a second for the cloud

1933
01:29:25,926 --> 01:29:28,629
to get a tiny bit bigger,
to show that you've done it

1934
01:29:28,662 --> 01:29:30,498
to that extent.

1935
01:29:30,531 --> 01:29:32,400

- So it is the speed of the
particles that you're measuring

1936
01:29:32,433 --> 01:29:35,169
when you're saying millions
or billions of times colder?

1937
01:29:35,202 --> 01:29:36,871
The relative speeds?

1938
01:29:39,306 --> 01:29:42,209
- It's millions of
times colder than space,

1939
01:29:42,242 --> 01:29:45,179
or than than we
started with, I guess,

1940
01:29:45,212 --> 01:29:47,481
a billion of times colder.

1941
01:29:47,514 --> 01:29:49,016
- Okay.

1942
01:29:49,049 --> 01:29:52,319
The other question, I did
get something on my email

1943
01:29:52,352 --> 01:29:55,556
that referred to a
Bose-Einstein condensate,

1944
01:29:55,589 --> 01:29:58,159
if we could somehow swirl
it around like you would

1945
01:29:58,192 --> 01:30:01,228
water in a glass, that
because of the zero friction,

1946
01:30:01,261 --> 01:30:05,099
it would continue forever,
it wouldn't slow down.

1947
01:30:05,132 --> 01:30:07,168
Well, does this mean that
if you were to do that

1948
01:30:07,201 --> 01:30:10,471
that you would have constructed
a perpetual-motion machine

1949
01:30:10,504 --> 01:30:12,440
as long as you didn't
take energy out of it,

1950
01:30:12,473 --> 01:30:15,543
or would simply observing it
somehow be taking energy away

1951
01:30:15,576 --> 01:30:17,044
from the system?

1952
01:30:17,077 --> 01:30:19,613
- Yeah, so people have made
these little quantum vortices,

1953
01:30:19,646 --> 01:30:23,017
little tornadoes,
mini quantum tornadoes

1954
01:30:23,050 --> 01:30:27,021
inside these condensates,
and they've observed them,

1955
01:30:27,054 --> 01:30:30,324
and they flow pretty
much frictionless.

1956

01:30:31,358 --> 01:30:33,427
But the difference is,

1957
01:30:33,460 --> 01:30:35,596
you can approach
perfectly frictionless,

1958
01:30:35,629 --> 01:30:37,665
but you can only
get close to it,

1959
01:30:37,698 --> 01:30:39,200
you can't get perfectly there.

1960
01:30:39,233 --> 01:30:41,502
So it's not quite a
perpetual-motion machine,

1961
01:30:41,535 --> 01:30:43,471
it would eventually
have some mechanism

1962
01:30:43,504 --> 01:30:44,738
that would dissipate it--

1963
01:30:44,771 --> 01:30:46,540
- What's the piece de
resistance, so to speak?

1964
01:30:46,573 --> 01:30:47,908
- What actually stops it?

1965
01:30:47,941 --> 01:30:49,510
I actually don't know.

1966
01:30:49,543 --> 01:30:52,246
The clouds themselves usually
have a limited lifetime,

1967

01:30:52,279 --> 01:30:54,281
so our clouds are
limited by the vacuum

1968
01:30:54,314 --> 01:30:56,884
that they're found in,
but if you could somehow

1969
01:30:56,917 --> 01:31:00,755
get rid of those, in
principle, they should...

1970
01:31:02,256 --> 01:31:03,390
- So it is
theoretically possible

1971
01:31:03,423 --> 01:31:05,125
to have a
perpetual-motion machine

1972
01:31:05,158 --> 01:31:06,460
as long as you're
just observing it

1973
01:31:06,493 --> 01:31:07,895
and not trying to
take energy away?

1974
01:31:07,928 --> 01:31:10,164
- I think it's still not,
(audience chuckles)

1975
01:31:10,197 --> 01:31:14,201
but you can make, perhaps,
pretty close to one

1976
01:31:14,234 --> 01:31:16,370
with a perfect system
with no dissipation.

1977

01:31:16,403 --> 01:31:17,404
- [Audience Member] I figured
there was a catch there.

1978
01:31:17,437 --> 01:31:18,806
Thank you.

1979
01:31:18,839 --> 01:31:21,108
- We'll try and answer
them pretty quickly.

1980
01:31:21,141 --> 01:31:23,744
So the first one is, how much
power does the system use?

1981
01:31:23,777 --> 01:31:26,514
Each express rack actually
has the ability to give you

1982
01:31:26,547 --> 01:31:29,116
2,000 watts of power;
we've been given permission

1983
01:31:29,149 --> 01:31:31,752
to use up to 1,500 watts but
we'll probably use something

1984
01:31:31,785 --> 01:31:34,822
just about under 1,000 watts.

1985
01:31:34,855 --> 01:31:37,291
- Another question is,
are the lasers used

1986
01:31:37,324 --> 01:31:40,294
to position the atoms
as well as to cool them?

1987
01:31:40,327 --> 01:31:41,862
And they are, to some extent.

1988
01:31:41,895 --> 01:31:44,365
We actually have
a couple of stages

1989
01:31:44,398 --> 01:31:46,934
just of the laser cooling, I
didn't really talk about it,

1990
01:31:46,967 --> 01:31:49,703
but we start with a source
of atoms at room temperature

1991
01:31:49,736 --> 01:31:53,307
and we use a set of
lasers that are set up,

1992
01:31:54,775 --> 01:31:58,946
four different lasers, so
they come into two directions,

1993
01:32:00,180 --> 01:32:01,715
and that makes a beam of
atoms that actually does

1994
01:32:01,748 --> 01:32:05,486
transport the atoms from the
region where we produce them

1995
01:32:05,519 --> 01:32:07,955
where our source is where
the vacuum's not that great,

1996
01:32:07,988 --> 01:32:10,024
to a region where the
vacuum is really good,

1997
01:32:10,057 --> 01:32:12,459
and then we capture
them with other lasers.

1998
01:32:12,492 --> 01:32:15,896
So to some extent, we do use
the lasers to position them,

1999
01:32:15,929 --> 01:32:17,264
but for the most part,
when we're trying

2000
01:32:17,297 --> 01:32:19,199
to position the atoms
and move them around,

2001
01:32:19,232 --> 01:32:23,237
we're using magnetic
fields to push on them.

2002
01:32:23,270 --> 01:32:24,438
You can, though, in
other experiments,

2003
01:32:24,471 --> 01:32:27,308
do that with lasers
in some cases.

2004
01:32:29,176 --> 01:32:33,347
- Do I understand
that temperature is
relative to motion?

2005
01:32:34,548 --> 01:32:36,917
In other words,
the colder it is,

2006
01:32:36,950 --> 01:32:39,386
the slower?
- Yeah, yes.

2007
01:32:39,419 --> 01:32:42,189
- Well, if you get

things real cold,

2008
01:32:42,222 --> 01:32:45,893
you can make matter
just disappear.

2009
01:32:45,926 --> 01:32:46,994
- Well, no...

2010
01:32:49,496 --> 01:32:51,832
It'll get slower and slower.

2011
01:32:53,333 --> 01:32:55,903
Quantum mechanics actually
doesn't let it go all the way

2012
01:32:55,936 --> 01:32:57,705
to not moving at all.

2013
01:32:58,905 --> 01:33:02,176
Heisenberg finally
has his say and says

2014
01:33:02,209 --> 01:33:06,113
you can't get something
completely cooled down

2015
01:33:07,481 --> 01:33:09,350
so it's not moving at
all, because if you did,

2016
01:33:09,383 --> 01:33:12,252
you would be able to know
both how fast it's moving,

2017
01:33:12,285 --> 01:33:14,955
like zero, and
exactly where it was,

2018

01:33:14,988 --> 01:33:17,591
and you can't measure those
things both at the same time,

2019
01:33:17,624 --> 01:33:18,859
according to Heisenberg.

2020
01:33:18,892 --> 01:33:20,461
So there's always still
a little bit of motion.

2021
01:33:20,494 --> 01:33:22,596
- Isn't there situations
where matter will disappear

2022
01:33:22,629 --> 01:33:25,366
and then all of
a sudden, appear?

2023
01:33:26,767 --> 01:33:29,336
- Quantum mechanics allows
that in certain circumstances

2024
01:33:29,369 --> 01:33:33,007
when it interacts with
things like antimatter

2025
01:33:33,040 --> 01:33:35,175
or falls into a black hole,

2026
01:33:35,208 --> 01:33:38,178
but not under these
kind of situations.

2027
01:33:38,211 --> 01:33:39,413
- Yeah.

2028
01:33:39,446 --> 01:33:41,816
Well, when things
get really hot,

2029
01:33:43,617 --> 01:33:46,887
would it solidify
the particle or what?

2030
01:33:49,656 --> 01:33:51,291
- Well, that's an
interesting question.

2031
01:33:51,324 --> 01:33:55,162
The transition to a
Bose-Einstein condensation

2032
01:33:57,531 --> 01:34:00,868
is actually
thermodynamically forbidden.

2033
01:34:02,035 --> 01:34:03,637
According to the rules
of thermodynamics,

2034
01:34:03,670 --> 01:34:07,841
you shouldn't be able
to; the stable state

2035
01:34:07,874 --> 01:34:09,777
at these really cold
temperatures is just

2036
01:34:09,810 --> 01:34:11,645
a big chunk of
rubidium at the bottom

2037
01:34:11,678 --> 01:34:13,247
of your vacuum chamber.

2038
01:34:13,280 --> 01:34:16,017
It should be a
cold, solid metal.

2039
01:34:18,018 --> 01:34:22,189
But the time scale for that
to happen is very long,

2040
01:34:23,623 --> 01:34:26,894
and that only happens when
three atoms have to bounce

2041
01:34:26,927 --> 01:34:30,798
in together to form molecules
to trigger that process.

2042
01:34:30,831 --> 01:34:34,902
So yeah, eventually, if
you wait long enough,

2043
01:34:34,935 --> 01:34:39,106
you would lose atoms due to
processes that make molecules

2044
01:34:42,275 --> 01:34:45,379
and they fall out of your trap.

2045
01:34:45,412 --> 01:34:46,380
- Okay.

2046
01:34:46,413 --> 01:34:47,381
Thank you.

2047
01:34:47,414 --> 01:34:48,348
- Thanks, everyone.

2048
01:34:48,381 --> 01:34:51,385
(audience applauds)

2049
01:34:58,058 --> 01:34:59,460
- [Dr. Thompson] Anyone
who has any follow-up