



Ames Research Center

1  
00:00:01,666 --> 00:00:07,666  
[music playing]

2  
00:00:16,200 --> 00:00:21,166  
- Welcome to the  
NASA Ames 2016 Summer Series.

3  
00:00:22,466 --> 00:00:24,333  
Two questions:

4  
00:00:24,333 --> 00:00:29,333  
How does the microscopic world  
inform the macroscopic world

5  
00:00:29,333 --> 00:00:30,766  
and vice versa?

6  
00:00:30,766 --> 00:00:34,166  
What could we learn  
and how do they interact?

7  
00:00:34,166 --> 00:00:36,566  
Can we use quantum mechanics

8  
00:00:36,566 --> 00:00:40,266  
to advance  
real-world applications?

9  
00:00:41,666 --> 00:00:44,133  
Today's seminar entitled

10  
00:00:44,133 --> 00:00:47,533  
"Quantum Mechanics at  
Macroscopic Scales"

11  
00:00:47,533 --> 00:00:51,433  
will be given by  
Dr. Mark Kasevich.

12

00:00:51,433 --> 00:00:54,033

He is a Professor of Physics  
and Applied Physics

13

00:00:54,033 --> 00:00:57,700

at Stanford University.

14

00:00:57,700 --> 00:01:00,200

He received  
his Bachelor of Arts

15

00:01:00,200 --> 00:01:01,966

in Physics from Dartmouth,

16

00:01:01,966 --> 00:01:05,566

followed by a Master's  
in Physics and Philosophy

17

00:01:05,566 --> 00:01:09,066

from Oxford University  
as a Rhodes Scholar

18

00:01:09,066 --> 00:01:12,366

and then a PhD in  
Applied Physics from Stanford.

19

00:01:14,866 --> 00:01:18,066

His current research is centered  
on the development

20

00:01:18,066 --> 00:01:21,666

of quantum sensors of rotation  
and acceleration

21

00:01:21,666 --> 00:01:24,666

based on cold atoms.

22

00:01:26,833 --> 00:01:30,533

He has published

numerous publications

23

00:01:30,533 --> 00:01:33,266  
in really relevant journals,

24

00:01:33,266 --> 00:01:36,266  
including "Nature" and so on.

25

00:01:37,766 --> 00:01:39,900  
And in his spare time,

26

00:01:39,900 --> 00:01:42,966  
cofounded AOSense, Incorporated,

27

00:01:42,966 --> 00:01:45,300  
a developer and manufacturer

28

00:01:45,300 --> 00:01:47,900  
of innovative atom optic sensors

29

00:01:47,900 --> 00:01:52,000  
for precision navigation,  
time and frequency standards,

30

00:01:52,000 --> 00:01:54,533  
and gravity measurements,

31

00:01:54,533 --> 00:01:55,866  
and currently serves

32

00:01:55,866 --> 00:01:58,400  
as the company's consulting  
chief scientist.

33

00:01:58,400 --> 00:02:01,666  
Please join me in welcoming  
Dr. Mark Kasevich.

34

00:02:01,666 --> 00:02:03,666  
[applause]

35

00:02:03,666 --> 00:02:06,966  
- Thank you.

36

00:02:06,966 --> 00:02:08,200  
Thanks for the introduction.

37

00:02:08,200 --> 00:02:10,033  
It's great to be here  
this morning.

38

00:02:10,033 --> 00:02:12,700  
So I'm gonna tell you about  
experimental work

39

00:02:12,700 --> 00:02:15,866  
coming out of my laboratory  
at Stanford just up the road,

40

00:02:15,866 --> 00:02:17,966  
where we're trying to  
push the boundaries

41

00:02:17,966 --> 00:02:20,633  
of quantum mechanics,

42

00:02:20,633 --> 00:02:23,966  
to understand to what scales

43

00:02:23,966 --> 00:02:28,433  
we can accept that quantum  
mechanics will be true.

44

00:02:28,433 --> 00:02:31,633  
And when I say scales,  
I'll kind of orient you to the--

45

00:02:31,633 --> 00:02:34,200  
to my interest in that

46

00:02:34,200 --> 00:02:35,833  
as--as the talk goes on,

47

00:02:35,833 --> 00:02:38,800  
but I think it's no secret

48

00:02:38,800 --> 00:02:41,700  
that quantum mechanics...  
probably one of,

49

00:02:41,700 --> 00:02:44,700  
arguably, the most successful  
physical theory we have

50

00:02:44,700 --> 00:02:47,133  
that had its birth

51

00:02:47,133 --> 00:02:49,866  
in the early 20th century,

52

00:02:49,866 --> 00:02:52,100  
has left us puzzled.

53

00:02:52,100 --> 00:02:55,266  
And many of us who practice it  
have both--

54

00:02:55,266 --> 00:02:59,600  
by experiment  
and pencil and paper work,

55

00:02:59,600 --> 00:03:03,166  
find points where it just  
doesn't seem to make sense.

56

00:03:03,166 --> 00:03:06,266

And oftentimes that boundary  
becomes most puzzling

57

00:03:06,266 --> 00:03:09,700

when you ask, does quantum  
mechanics manifest

58

00:03:09,700 --> 00:03:13,200

over the distance scales and  
time scales of everyday life?

59

00:03:13,200 --> 00:03:17,533

Meters and seconds  
and large numbers of particles.

60

00:03:17,533 --> 00:03:20,266

And so I'm gonna tell you about  
experiments today

61

00:03:20,266 --> 00:03:23,033

where we're trying to find  
quantum systems

62

00:03:23,033 --> 00:03:24,966

that we can explore  
on meter scales

63

00:03:24,966 --> 00:03:27,000

and with large numbers  
of particles

64

00:03:27,000 --> 00:03:28,333

and so forth.

65

00:03:28,333 --> 00:03:31,100

Our dream would be to explore,  
you know,

66

00:03:31,100 --> 00:03:34,466

quantum mechanics of humans

being in two places at once,

67

00:03:34,466 --> 00:03:36,400

but we're nowhere near that.

68

00:03:36,400 --> 00:03:38,600

But what we have managed to do

69

00:03:38,600 --> 00:03:41,666

is to manipulate atoms

in such a way

70

00:03:41,666 --> 00:03:43,300

that they can exhibit

71

00:03:43,300 --> 00:03:47,166

surprising quantum mechanical  
attributes.

72

00:03:47,166 --> 00:03:50,133

So let me introduce you to  
the field that I'm in.

73

00:03:50,133 --> 00:03:52,600

I'm an atomic, molecular,  
and optical physicist,

74

00:03:52,600 --> 00:03:55,100

and back in the early '90s,

75

00:03:55,100 --> 00:03:56,833

there was some incredible work

76

00:03:56,833 --> 00:04:00,500

that came out of the Konstanz  
atomic physics group.

77

00:04:00,500 --> 00:04:04,033

And what they did, Jurgen Mlynek

and his colleagues did,

78

00:04:04,033 --> 00:04:05,466

is they did something

79

00:04:05,466 --> 00:04:07,966

analogous to the Young's  
double slit experiment

80

00:04:07,966 --> 00:04:10,900

but they used helium atoms.

81

00:04:10,900 --> 00:04:12,566

And the way  
this experiment worked

82

00:04:12,566 --> 00:04:15,066

is they--they took  
a beam of helium,

83

00:04:15,066 --> 00:04:18,966

which is at this part  
of the diagram,

84

00:04:18,966 --> 00:04:20,700

and they--  
they took these atoms

85

00:04:20,700 --> 00:04:22,800

and they fired them  
at a narrow slit.

86

00:04:22,800 --> 00:04:25,200

Now, if you're thinking  
classically,

87

00:04:25,200 --> 00:04:26,633

the atoms just  
go through the slit

88

00:04:26,633 --> 00:04:28,900

and the slit kind of defines  
an atomic beam.

89

00:04:28,900 --> 00:04:30,733

If you're thinking  
quantum mechanically

90

00:04:30,733 --> 00:04:33,333

and you're a believer in  
the de Broglie relationship,

91

00:04:33,333 --> 00:04:36,800

and namely that that atom could  
really be considered a wave

92

00:04:36,800 --> 00:04:38,600

whose wavelength  
is Planck's constant

93

00:04:38,600 --> 00:04:40,266

divided by its momentum,

94

00:04:40,266 --> 00:04:42,500

then you expect  
wavelike behavior.

95

00:04:42,500 --> 00:04:46,166

And by design, Mlynek's group  
made this slit narrow enough

96

00:04:46,166 --> 00:04:48,733

so that the helium atom waves

97

00:04:48,733 --> 00:04:51,200

diffracted into this  
coherent set of wave fronts

98

00:04:51,200 --> 00:04:54,066

much like you would see  
a beam of light diffract

99

00:04:54,066 --> 00:04:56,966  
as it propagates through a slit  
in a laboratory experiment

100

00:04:56,966 --> 00:04:59,666  
and such that it  
coherently illuminated

101

00:04:59,666 --> 00:05:02,400  
two more slits.

102

00:05:02,400 --> 00:05:04,700  
This location and that location.

103

00:05:04,700 --> 00:05:06,266  
Well, those two slits

104

00:05:06,266 --> 00:05:09,266  
now become sources for  
diffracted waves,

105

00:05:09,266 --> 00:05:11,633  
and those waves overlap

106

00:05:11,633 --> 00:05:13,433  
at a detection screen here.

107

00:05:13,433 --> 00:05:16,233  
Now, if they were  
water waves or light waves,

108

00:05:16,233 --> 00:05:18,366  
you would have  
no problem accepting

109

00:05:18,366 --> 00:05:20,400

that those waves would  
interfere constructively

110  
00:05:20,400 --> 00:05:21,833  
and destructively

111  
00:05:21,833 --> 00:05:23,933  
giving you maxima and minima  
in intensity.

112  
00:05:23,933 --> 00:05:25,866  
But these are atom waves

113  
00:05:25,866 --> 00:05:27,366  
and how do the atom waves  
interfere?

114  
00:05:27,366 --> 00:05:29,200  
How is that interference  
manifested?

115  
00:05:29,200 --> 00:05:31,433  
Well, it's manifested by  
the constructive

116  
00:05:31,433 --> 00:05:34,633  
and destructive interference  
of the atomic wave functions.

117  
00:05:34,633 --> 00:05:36,900  
And according to the rules  
of quantum mechanics,

118  
00:05:36,900 --> 00:05:38,900  
you add the wave functions  
before you square

119  
00:05:38,900 --> 00:05:41,033  
and then when you square you get  
those interference patterns

120

00:05:41,033 --> 00:05:42,600

that you calculate  
mathematically.

121

00:05:42,600 --> 00:05:44,466

But what it really means,

122

00:05:44,466 --> 00:05:46,900

again following  
the quantum paradigm,

123

00:05:46,900 --> 00:05:49,400

is that those ripples  
in the wave function

124

00:05:49,400 --> 00:05:51,666

correspond to ripples  
in the probability

125

00:05:51,666 --> 00:05:54,866

of detecting the atom at a given  
position along the screen.

126

00:05:54,866 --> 00:05:57,100

And so as they scanned  
their detector

127

00:05:57,100 --> 00:05:58,900

along this screen,

128

00:05:58,900 --> 00:06:01,800

they saw the following.

129

00:06:01,800 --> 00:06:03,633

This is  
the detector position,

130

00:06:03,633 --> 00:06:06,766

and this is the number of atoms  
that they detected

131

00:06:06,766 --> 00:06:08,633  
in five minutes.

132

00:06:08,633 --> 00:06:11,566  
They saw this beautiful  
oscillating pattern,

133

00:06:11,566 --> 00:06:13,400  
which is just  
the kind of picture

134

00:06:13,400 --> 00:06:16,666  
that you associate with the  
Young's double slit experiment.

135

00:06:16,666 --> 00:06:19,566  
And when they go back and use  
the Schrodinger equation

136

00:06:19,566 --> 00:06:22,933  
and so forth and calculate the  
periodicity of the oscillation,

137

00:06:22,933 --> 00:06:25,533  
what you would expect  
from the momentum of the atom

138

00:06:25,533 --> 00:06:27,233  
and Planck's constant  
and the mass of the atom,

139

00:06:27,233 --> 00:06:31,033  
turns out it lined up  
nearly perfectly

140

00:06:31,033 --> 00:06:32,400  
with this data,

141

00:06:32,400 --> 00:06:35,300  
demonstrating that  
we had reached a position

142

00:06:35,300 --> 00:06:36,533  
or they had reached a position

143

00:06:36,533 --> 00:06:38,833  
where they could  
coherently control

144

00:06:38,833 --> 00:06:40,400  
the--the center  
of mass wave function

145

00:06:40,400 --> 00:06:42,166  
of a beam of helium atoms.

146

00:06:42,166 --> 00:06:44,233  
Now, this wasn't a surprise  
to anybody.

147

00:06:44,233 --> 00:06:46,866  
I mean, if you believed  
what was written down

148

00:06:46,866 --> 00:06:48,800  
in the early 20th century,  
of course,

149

00:06:48,800 --> 00:06:51,900  
atoms, under certain  
circumstances, will interfere.

150

00:06:51,900 --> 00:06:53,466  
That's the law  
of quantum mechanics.

151

00:06:53,466 --> 00:06:56,000

Electrons interfere to give us  
the hydrogen spectrum

152

00:06:56,000 --> 00:06:58,066

and, you know, Davisson-Germer  
showed us diffraction

153

00:06:58,066 --> 00:06:59,433

from surfaces.

154

00:06:59,433 --> 00:07:01,100

So what's the big deal here?

155

00:07:01,100 --> 00:07:04,166

Well, the big deal was there  
were some notable physicists

156

00:07:04,166 --> 00:07:07,800

in the, oh,  
let's say mid-20th century

157

00:07:07,800 --> 00:07:09,500

who said, that's great,  
you know,

158

00:07:09,500 --> 00:07:12,066

quantum mechanics works just  
fine for those electrons,

159

00:07:12,066 --> 00:07:14,100

for magnetic spin,

160

00:07:14,100 --> 00:07:16,066

and everything we know about  
atomic structure,

161

00:07:16,066 --> 00:07:18,000

but ain't nobody  
ever gonna build

162

00:07:18,000 --> 00:07:19,933  
an interferometer for atoms.

163

00:07:19,933 --> 00:07:21,333  
Why?

164

00:07:21,333 --> 00:07:23,366  
Because, well, every time you  
build an interferometer,

165

00:07:23,366 --> 00:07:25,266  
one of your key  
engineering challenges

166

00:07:25,266 --> 00:07:27,833  
is to stabilize  
the relative paths

167

00:07:27,833 --> 00:07:29,966  
of the two interfering beams.

168

00:07:29,966 --> 00:07:32,466  
In other words,  
if I go back to this slide,

169

00:07:32,466 --> 00:07:35,166  
I have to make sure that  
the phase acquired by the wave

170

00:07:35,166 --> 00:07:36,333  
that goes through  
this slit

171

00:07:36,333 --> 00:07:37,933  
and hits  
the screen there

172

00:07:37,933 --> 00:07:39,833

is stable with respect  
to the phase

173

00:07:39,833 --> 00:07:41,433

that goes through  
that slit.

174

00:07:41,433 --> 00:07:44,300

And you could do some simple  
calculations for atoms

175

00:07:44,300 --> 00:07:46,166

and convince yourself that  
there's, you know,

176

00:07:46,166 --> 00:07:47,866

maybe you could build the slits,

177

00:07:47,866 --> 00:07:50,800

but there's no way  
you'd get stable phase.

178

00:07:50,800 --> 00:07:53,133

There'd always be some  
environmental perturbation

179

00:07:53,133 --> 00:07:55,733

which would shake one wave  
with respect to the next.

180

00:07:55,733 --> 00:07:57,500

So that pattern  
wouldn't be stable,

181

00:07:57,500 --> 00:07:59,166

those fringes would shake  
back and forth,

182

00:07:59,166 --> 00:08:01,533

and as you waited to see

the fringe emerge,

183

00:08:01,533 --> 00:08:02,900  
you would never see anything,

184

00:08:02,900 --> 00:08:05,700  
and that would look like  
just classical behavior.

185

00:08:05,700 --> 00:08:08,166  
And so what happened was

186

00:08:08,166 --> 00:08:10,633  
as technology since--  
in the kind of mid-20th century

187

00:08:10,633 --> 00:08:13,300  
to the early '90s,  
technology progressed

188

00:08:13,300 --> 00:08:15,266  
and we learned,  
the field learned,

189

00:08:15,266 --> 00:08:18,166  
how to control  
the environmental disturbances

190

00:08:18,166 --> 00:08:21,566  
on, in this case,  
the beam of helium atoms

191

00:08:21,566 --> 00:08:23,800  
so that you could have  
a stable phase.

192

00:08:23,800 --> 00:08:25,933  
And this was--this was  
the paradigmatic experiment

193

00:08:25,933 --> 00:08:29,233

that kind of started our field  
in the early '90s.

194

00:08:29,233 --> 00:08:31,933

So you could ask, well,  
technology has progressed

195

00:08:31,933 --> 00:08:34,033

yet again,  
so where are we?

196

00:08:34,033 --> 00:08:36,966

And I could take you through  
the entire 25 years,

197

00:08:36,966 --> 00:08:40,033

but I'll take you to a snapshot  
of our most recent data.

198

00:08:40,033 --> 00:08:41,333

Where are we today?

199

00:08:41,333 --> 00:08:43,966

How--how--how well  
can we control

200

00:08:43,966 --> 00:08:46,233

the trajectories of atoms,  
and can we see interference?

201

00:08:46,233 --> 00:08:49,533

And if so, over what types of  
distance scales

202

00:08:49,533 --> 00:08:51,066

and time scales?

203

00:08:51,066 --> 00:08:52,600

This distance scale here

204

00:08:52,600 --> 00:08:54,766  
is measured in  
millionths of a meter,

205

00:08:54,766 --> 00:08:57,433  
ten microns.

206

00:08:57,433 --> 00:08:59,500  
So here's some data  
that came out of my lab

207

00:08:59,500 --> 00:09:01,233  
last year.

208

00:09:01,233 --> 00:09:04,866  
And what I'm showing you is  
two ensembles of rubidium atoms.

209

00:09:04,866 --> 00:09:08,000  
I'll tell you how we make  
those atoms in--in a moment.

210

00:09:08,000 --> 00:09:09,833  
And these rubidium atoms--

211

00:09:09,833 --> 00:09:12,600  
this--this peak here has about  
10 to the 5 atoms,

212

00:09:12,600 --> 00:09:15,633  
and this peak here has about  
10 to the 5 atoms.

213

00:09:15,633 --> 00:09:17,200  
and they're separated  
by a distance

214

00:09:17,200 --> 00:09:18,933  
of more than a half a meter.

215  
00:09:18,933 --> 00:09:20,633  
Basically from here to there,  
that's--

216  
00:09:20,633 --> 00:09:22,700  
those atoms are separated.

217  
00:09:22,700 --> 00:09:26,000  
So it's not a big deal,  
but what is a big deal

218  
00:09:26,000 --> 00:09:29,333  
is that I claim  
each and every atom

219  
00:09:29,333 --> 00:09:31,733  
that is a member  
of this peak

220  
00:09:31,733 --> 00:09:33,700  
also has a partner  
in that peak.

221  
00:09:33,700 --> 00:09:37,833  
It's actually the same atom  
that's been coherently divided

222  
00:09:37,833 --> 00:09:40,333  
and put in both places  
at once.

223  
00:09:40,333 --> 00:09:42,166  
Now, according to  
laws of quantum mechanics,

224  
00:09:42,166 --> 00:09:43,566  
when I--when I look at a state

like this,

225

00:09:43,566 --> 00:09:45,800

I kill it,

226

00:09:45,800 --> 00:09:48,033

and I collapse the state so that  
the atom is either

227

00:09:48,033 --> 00:09:49,500

in the left peak  
or the right peak,

228

00:09:49,500 --> 00:09:51,433

which is what happened  
when I took this picture.

229

00:09:51,433 --> 00:09:53,600

But before I took that picture,

230

00:09:53,600 --> 00:09:56,733

I claim that I had  
this amazing state

231

00:09:56,733 --> 00:09:59,100

where each and every one

232

00:09:59,100 --> 00:10:02,033

of those  
10 to the 5 atoms was--

233

00:10:02,033 --> 00:10:05,200

the only way I could  
describe physically,

234

00:10:05,200 --> 00:10:07,066

you know, what it was,

235

00:10:07,066 --> 00:10:10,800

was--was an atom that was  
in this place and this place

236

00:10:10,800 --> 00:10:12,633  
at the same time.

237

00:10:12,633 --> 00:10:14,733  
The logical progression  
would be putting molecules

238

00:10:14,733 --> 00:10:16,133  
in two places at once

239

00:10:16,133 --> 00:10:19,100  
or human beings separated  
by a meter scale

240

00:10:19,100 --> 00:10:20,700  
and so on.

241

00:10:20,700 --> 00:10:23,333  
But an atom is,

242

00:10:23,333 --> 00:10:25,966  
I want to remind you, is  
a pretty complicated object

243

00:10:25,966 --> 00:10:29,333  
especially rubidium atom  
that has, you know,

244

00:10:29,333 --> 00:10:31,566  
a grab bag of nucleons

245

00:10:31,566 --> 00:10:33,833  
and a bunch of electrons  
all around it.

246

00:10:33,833 --> 00:10:36,100

It's not--it's not  
a fundamental particle,

247

00:10:36,100 --> 00:10:38,266

it's a--it's a big collection  
of fundamental particles.

248

00:10:38,266 --> 00:10:42,166

So obviously, my job now  
is to convince you

249

00:10:42,166 --> 00:10:44,733

that I've had atoms  
in two places at once.

250

00:10:44,733 --> 00:10:47,000

This picture alone cannot  
convince you of that.

251

00:10:47,000 --> 00:10:48,700

I might as well just put  
10 to the 5 on the left

252

00:10:48,700 --> 00:10:50,200

and 10 to the 5 on the right.

253

00:10:50,200 --> 00:10:53,800

How do I convince you that  
they're at two places at once?

254

00:10:53,800 --> 00:10:55,700

I have to do  
an interference experiment.

255

00:10:55,700 --> 00:10:57,100

I have to bring those clouds  
back together,

256

00:10:57,100 --> 00:10:58,900

and I have to overlap them

257

00:10:58,900 --> 00:11:01,200  
and I have to see them  
interfere as waves.

258

00:11:01,200 --> 00:11:04,033  
And so that's the data I'll show  
you in the next few slides.

259

00:11:04,033 --> 00:11:08,066  
So this is a picture  
of the apparatus,

260

00:11:08,066 --> 00:11:10,933  
and let me just walk you through  
the apparatus

261

00:11:10,933 --> 00:11:12,466  
before I show you  
some of the data.

262

00:11:12,466 --> 00:11:14,933  
So we like to joke in my group

263

00:11:14,933 --> 00:11:16,666  
that everything looks better  
in CAD.

264

00:11:16,666 --> 00:11:19,366  
So here's the CAD rendering  
of the apparatus,

265

00:11:19,366 --> 00:11:21,633  
which is in the pit  
in the basement

266

00:11:21,633 --> 00:11:23,566  
of the Varian physics building  
at Stanford,

267  
00:11:23,566 --> 00:11:26,333  
and it's about  
a ten-meter-deep pit.

268  
00:11:26,333 --> 00:11:29,000  
And what you see here is  
magnetic shielding

269  
00:11:29,000 --> 00:11:31,800  
that surrounds  
an ultrahigh vacuum system

270  
00:11:31,800 --> 00:11:34,200  
where we've basically  
pumped everything out

271  
00:11:34,200 --> 00:11:37,633  
in creating an environment that,  
if I have a rubidium atom

272  
00:11:37,633 --> 00:11:40,633  
of the appropriately  
conditioned state,

273  
00:11:40,633 --> 00:11:43,700  
it won't interact with  
or be collided with

274  
00:11:43,700 --> 00:11:46,700  
other gas elements  
in the vacuum system.

275  
00:11:46,700 --> 00:11:48,900  
And what we do is the following.

276  
00:11:48,900 --> 00:11:50,700  
We--at this location here,

277  
00:11:50,700 --> 00:11:52,033

which is at the bottom  
of that pit,

278

00:11:52,033 --> 00:11:53,633

we used some modern  
atomic physics techniques

279

00:11:53,633 --> 00:11:55,933

to create a cloud  
of ultracold,

280

00:11:55,933 --> 00:11:58,133

and I'll explain what  
ultracold means in a second,

281

00:11:58,133 --> 00:12:02,000

ultracold rubidium atoms,  
about a million of 'em.

282

00:12:02,000 --> 00:12:05,666

What we do is we take rubidium  
from a thermal atomic source,

283

00:12:05,666 --> 00:12:06,666

a chunk of metal.

284

00:12:06,666 --> 00:12:07,666

It gets heated up.

285

00:12:07,666 --> 00:12:09,166

You get a stream of atoms

286

00:12:09,166 --> 00:12:10,866

that are moving about  
200 meters a second.

287

00:12:10,866 --> 00:12:12,433

You capture them  
with laser light.

288

00:12:12,433 --> 00:12:14,666

The laser light is configured  
in such a way

289

00:12:14,666 --> 00:12:16,066

it cools them down  
to temperatures

290

00:12:16,066 --> 00:12:18,766

of--of millikelvin  
to microkelvin,

291

00:12:18,766 --> 00:12:21,933

and what we mean by that is that  
if I look at the kinetic energy

292

00:12:21,933 --> 00:12:23,800

or the velocity  
of one of those atoms,

293

00:12:23,800 --> 00:12:27,233

I measure it in units  
of centimeters per second.

294

00:12:27,233 --> 00:12:29,233

The way--this was something,  
a technique

295

00:12:29,233 --> 00:12:31,366

that was discovered  
by Steven Chu and others

296

00:12:31,366 --> 00:12:33,533

in the--in the '80s and '90s

297

00:12:33,533 --> 00:12:35,966

for which they received  
a Nobel Prize.

298

00:12:35,966 --> 00:12:38,033

After we cool the atoms  
that way,

299

00:12:38,033 --> 00:12:40,766

we further cool them in a--  
we--we--they're cold enough now

300

00:12:40,766 --> 00:12:42,733

that I can let them sit  
in a magnetic field

301

00:12:42,733 --> 00:12:44,933

and that magnetic field  
serves as a trap,

302

00:12:44,933 --> 00:12:47,166

and in that trap we can do

303

00:12:47,166 --> 00:12:49,300

a further so-called  
evaporative cooling step

304

00:12:49,300 --> 00:12:51,066

and bring them down  
to a state of matter

305

00:12:51,066 --> 00:12:53,000

known as  
a Bose-Einstein condensate.

306

00:12:53,000 --> 00:12:55,866

This was a technique developed  
by Carl Wieman

307

00:12:55,866 --> 00:12:57,633

and Eric Cornell  
and Wolfgang Ketterle

308

00:12:57,633 --> 00:12:59,866

in the late '90s, early 2000s,

309

00:12:59,866 --> 00:13:01,733

which also received  
a Nobel Prize.

310

00:13:01,733 --> 00:13:03,366

And the miracle of this is

311

00:13:03,366 --> 00:13:05,233

after you've done this  
evaporative cooling,

312

00:13:05,233 --> 00:13:07,666

which works just the same way  
as when you put your coffee cup

313

00:13:07,666 --> 00:13:09,500

on the counter  
and the hot stuff jumps out,

314

00:13:09,500 --> 00:13:10,900

leaving your coffee colder,

315

00:13:10,900 --> 00:13:12,633

here we put the atoms in a trap

316

00:13:12,633 --> 00:13:15,366

and the hot atoms jump out,  
leaving colder atoms behind.

317

00:13:15,366 --> 00:13:17,233

We end up with  
ensembles of atoms

318

00:13:17,233 --> 00:13:20,266

that have temperatures measured  
in nanokelvin,

319

00:13:20,266 --> 00:13:22,066  
and we further manipulate them  
so their temperature

320  
00:13:22,066 --> 00:13:24,333  
is just picokelvins,

321  
00:13:24,333 --> 00:13:27,266  
at which point their velocity  
spread is measured in,

322  
00:13:27,266 --> 00:13:30,000  
you know, units of hundreds  
of microns per second.

323  
00:13:30,000 --> 00:13:31,866  
That is, I have an atom,  
I prepare it this way,

324  
00:13:31,866 --> 00:13:34,900  
I let go of it,  
its velocity is defined

325  
00:13:34,900 --> 00:13:37,000  
to within 100 microns  
per second.

326  
00:13:37,000 --> 00:13:38,533  
Slower than an ant will crawl,

327  
00:13:38,533 --> 00:13:40,633  
which is kind of amazing  
when you consider that

328  
00:13:40,633 --> 00:13:42,300  
the atoms in this room  
are whipping around

329  
00:13:42,300 --> 00:13:44,066  
at a kilometer per second.

330

00:13:44,066 --> 00:13:45,866

Now, at these low velocities,

331

00:13:45,866 --> 00:13:48,933

per the de Broglie hypothesis  
or law,

332

00:13:48,933 --> 00:13:52,266

you expect wavelike behavior,

333

00:13:52,266 --> 00:13:53,666

because the velocity is low,

334

00:13:53,666 --> 00:13:55,433

the wavelength,  
the corresponding wavelength

335

00:13:55,433 --> 00:13:57,733

inversely proportional velocity  
is long.

336

00:13:57,733 --> 00:13:59,900

And that's the--  
getting them cold is key

337

00:13:59,900 --> 00:14:01,866

to observing  
these interference effects.

338

00:14:01,866 --> 00:14:03,766

So we've cooled them down here.

339

00:14:03,766 --> 00:14:05,466

That's at the bottom of the pit.

340

00:14:05,466 --> 00:14:07,600

And then we have a process  
whereby we launch them

341

00:14:07,600 --> 00:14:10,500  
up this ten-meter tower  
and they fall back down.

342

00:14:10,500 --> 00:14:12,466  
And so that process is--  
involves interactions

343

00:14:12,466 --> 00:14:14,366  
with beams of light,

344

00:14:14,366 --> 00:14:16,400  
and we basically  
turn on some lasers

345

00:14:16,400 --> 00:14:18,000  
in the appropriate way,

346

00:14:18,000 --> 00:14:20,566  
and we give the atoms  
a velocity kick

347

00:14:20,566 --> 00:14:22,666  
so that they're moving at about  
ten meters per second

348

00:14:22,666 --> 00:14:24,300  
with respect to the lab frame

349

00:14:24,300 --> 00:14:25,700  
and then we let go of them.

350

00:14:25,700 --> 00:14:27,333  
They still have that ultracold  
temperature now,

351

00:14:27,333 --> 00:14:28,766  
they're just

moving vertically,

352

00:14:28,766 --> 00:14:31,666

and they fly up this tube  
and fly back down that tube.

353

00:14:31,666 --> 00:14:33,166

It's like if you had  
a fistful of sand

354

00:14:33,166 --> 00:14:34,800

and you chucked it up.

355

00:14:34,800 --> 00:14:36,800

The sand would go up  
and would come back down

356

00:14:36,800 --> 00:14:39,600

and--but and the sand has got  
such a low velocity

357

00:14:39,600 --> 00:14:41,200

that it just kind of  
doesn't spread out.

358

00:14:41,200 --> 00:14:43,733

These atoms, the size of the  
clouds when they come back down

359

00:14:43,733 --> 00:14:45,666

to our detection region  
where we have the cameras

360

00:14:45,666 --> 00:14:50,333

to take pictures of them is,  
like, hundreds of microns.

361

00:14:50,333 --> 00:14:52,866

Let's see, I've got  
one more thing to explain

362

00:14:52,866 --> 00:14:55,333  
and that is I'm gonna make  
an interferometer for atoms,

363

00:14:55,333 --> 00:14:56,666  
so how do I make it?

364

00:14:56,666 --> 00:14:59,466  
Well, that's also done with  
light and mirrors.

365

00:14:59,466 --> 00:15:03,000  
And so we have a beam of--  
a bunch of laser beams

366

00:15:03,000 --> 00:15:04,133  
that start at this location.

367

00:15:04,133 --> 00:15:05,866  
We--we shine them down,

368

00:15:05,866 --> 00:15:08,333  
they hit the floor,  
they bounce back up,

369

00:15:08,333 --> 00:15:11,066  
and due to the way we configure  
the interaction,

370

00:15:11,066 --> 00:15:13,500  
and I'll explain this  
on a subsequent slide,

371

00:15:13,500 --> 00:15:17,166  
we precisely manipulate  
the atomic wave packets.

372

00:15:17,166 --> 00:15:19,066

We coherently divide them  
in two,

373

00:15:19,066 --> 00:15:21,666  
we add momentum to them,  
we take momentum away,

374

00:15:21,666 --> 00:15:23,766  
and we split them up  
and recombine them

375

00:15:23,766 --> 00:15:26,500  
all with pulses of light.

376

00:15:26,500 --> 00:15:30,166  
And this is the mirror here that  
that laser beam reflects off of.

377

00:15:30,166 --> 00:15:32,800  
That's the only really special  
part of this apparatus.

378

00:15:32,800 --> 00:15:35,866  
It has to be stable,  
pointing in the same direction

379

00:15:35,866 --> 00:15:38,000  
with respect to the stars.

380

00:15:38,000 --> 00:15:41,400  
Inertially it turns out in order  
to see the interference fringes.

381

00:15:41,400 --> 00:15:43,366  
And so what we actively do--  
we actually do

382

00:15:43,366 --> 00:15:45,900  
is we actively tip  
the angle of that mirror

383

00:15:45,900 --> 00:15:48,500

so that the beam kind of  
when it reflects off of it

384

00:15:48,500 --> 00:15:50,666

always points inertially,  
even though the Earth is--

385

00:15:50,666 --> 00:15:52,966

if the Earth is rotating, a  
laser beam would rotate with it,

386

00:15:52,966 --> 00:15:54,366

We have to make sure  
the laser beam,

387

00:15:54,366 --> 00:15:57,033

as the Earth rotates,  
stays pointed straight,

388

00:15:57,033 --> 00:15:59,066

and so there's  
a piezo stage there

389

00:15:59,066 --> 00:16:00,733

that makes sure that happens.

390

00:16:03,100 --> 00:16:05,700

how do--this is a little more  
experimental detail

391

00:16:05,700 --> 00:16:08,866

on how we coherently divide,  
redirect, and recombine atoms

392

00:16:08,866 --> 00:16:10,300

and make an interferometer,

393

00:16:10,300 --> 00:16:12,766

much as you would use  
beam splitters and mirrors

394

00:16:12,766 --> 00:16:15,433

and beam splitters to make  
an interferometer for light.

395

00:16:15,433 --> 00:16:18,733

And so what we do is,  
as I said,

396

00:16:18,733 --> 00:16:21,666

we shine on sequences of pulses  
to the atoms.

397

00:16:21,666 --> 00:16:25,533

Here's an example of one of  
our pulse sequences.

398

00:16:25,533 --> 00:16:27,433

Some of the data, I'll show you,  
we use sequences

399

00:16:27,433 --> 00:16:29,433

of hundreds of pulses.

400

00:16:29,433 --> 00:16:32,266

And each time the pulses  
irradiates the atom

401

00:16:32,266 --> 00:16:33,966

in the middle  
of the sequence here,

402

00:16:33,966 --> 00:16:36,766

what it does is  
it takes one of the--

403

00:16:36,766 --> 00:16:40,100

the--the wave packets,  
and I should back up a moment.

404

00:16:40,100 --> 00:16:43,733

This chart here plots  
the horizontal axis' time,

405

00:16:43,733 --> 00:16:45,800

the vertical axis'  
position.

406

00:16:45,800 --> 00:16:47,400

And what I'm plotting  
for you

407

00:16:47,400 --> 00:16:50,633

is the--the center  
of the wave packet,

408

00:16:50,633 --> 00:16:51,933

the probability  
distribution,

409

00:16:51,933 --> 00:16:53,966

which tells me  
where I find the atom.

410

00:16:53,966 --> 00:16:57,733

And the wave packet, of course,  
has some spatial distribution.

411

00:16:57,733 --> 00:17:00,400

It's about a millimeter wide--

412

00:17:00,400 --> 00:17:01,966

I'm sorry,  
hundreds of microns wide,

413

00:17:01,966 --> 00:17:03,933

but the center

of that wave packet

414

00:17:03,933 --> 00:17:07,200  
has a well-defined position  
in time--at a given time.

415

00:17:07,200 --> 00:17:08,933  
And that's what I'm--I'm--  
I'm plotting.

416

00:17:08,933 --> 00:17:10,900  
And because I'm building  
an interferometer,

417

00:17:10,900 --> 00:17:13,600  
a single atom can--is associated  
with two wave packets

418

00:17:13,600 --> 00:17:16,366  
as it's going through  
our apparatus.

419

00:17:16,366 --> 00:17:18,866  
So here comes the--the--  
the cloud of atoms,

420

00:17:18,866 --> 00:17:21,000  
and let me just think of one  
of the atoms in that cloud.

421

00:17:21,000 --> 00:17:23,133  
At time  $T$  equals zero,

422

00:17:23,133 --> 00:17:25,766  
it hits this pulse we know  
as a  $\pi$  over 2 pulse,

423

00:17:25,766 --> 00:17:28,833  
and what that pulse does is  
it exchanges momentum

424

00:17:28,833 --> 00:17:30,766  
between the photons  
in the laser beam

425

00:17:30,766 --> 00:17:33,533  
and the atoms in this  
Bose-Einstein condensed

426

00:17:33,533 --> 00:17:35,466  
flying cloud in such a way

427

00:17:35,466 --> 00:17:37,966  
that it puts the atom in  
a coherent super position

428

00:17:37,966 --> 00:17:39,766  
of its center of mass state

429

00:17:39,766 --> 00:17:41,800  
so that the atom has  
two wave packets,

430

00:17:41,800 --> 00:17:43,366  
one which has momentum.

431

00:17:43,366 --> 00:17:45,166  
We call this  
two-photon recoils,

432

00:17:45,166 --> 00:17:48,666  
because it absorbed and  
stimulated--emitted a photon,

433

00:17:48,666 --> 00:17:50,200  
and what that amounts to

434

00:17:50,200 --> 00:17:52,933  
is about a centimeter per second

velocity kick.

435

00:17:52,933 --> 00:17:54,766

And the other part  
of the wave packet,

436

00:17:54,766 --> 00:17:56,566

which was left behind  
in this interaction,

437

00:17:56,566 --> 00:17:58,533

which doesn't see  
that velocity kick.

438

00:17:58,533 --> 00:18:00,700

Well, the atomic physics details  
are--

439

00:18:00,700 --> 00:18:02,066

you know, I don't want  
to go into them here,

440

00:18:02,066 --> 00:18:03,966

but it's just  
standard application

441

00:18:03,966 --> 00:18:05,366

of the Schrodinger equation,

442

00:18:05,366 --> 00:18:07,366

which describes the interaction  
of a beam of light

443

00:18:07,366 --> 00:18:10,300

with a two-level atom.

444

00:18:10,300 --> 00:18:12,033

And so that's--  
that's our beam splitter,

445  
00:18:12,033 --> 00:18:14,033  
because this part  
of the atom there

446  
00:18:14,033 --> 00:18:16,633  
that has a different velocity,  
if I wait long enough,

447  
00:18:16,633 --> 00:18:17,933  
it drifts apart from the part

448  
00:18:17,933 --> 00:18:20,100  
that doesn't have  
that velocity kick.

449  
00:18:20,100 --> 00:18:23,133  
Now, we don't have--  
we only have so much time

450  
00:18:23,133 --> 00:18:24,500  
in which we can look at  
the atoms,

451  
00:18:24,500 --> 00:18:26,133  
so we want to give 'em a little  
bit more drift velocity

452  
00:18:26,133 --> 00:18:27,833  
that just two photon recoils,

453  
00:18:27,833 --> 00:18:30,300  
and so that's where all these  
other pulses come in.

454  
00:18:30,300 --> 00:18:32,000  
Every time  
I hit the atoms with--

455  
00:18:32,000 --> 00:18:34,133

wave packets  
with one of those pulses,

456  
00:18:34,133 --> 00:18:36,333  
I add,  
in the appropriate way,

457  
00:18:36,333 --> 00:18:38,866  
two photon recoils worth  
of momentum.

458  
00:18:38,866 --> 00:18:41,700  
And so if I'm plotting the  
position as a function of time,

459  
00:18:41,700 --> 00:18:43,866  
and here I've taken off--

460  
00:18:43,866 --> 00:18:46,600  
I've subtracted out the overall  
sag due to gravity.

461  
00:18:46,600 --> 00:18:49,133  
These atoms are flying up  
and they're coming down

462  
00:18:49,133 --> 00:18:52,000  
and I'm saying, forget about  
the gravitational part of it.

463  
00:18:52,000 --> 00:18:55,633  
Imagine you're flying with the--  
the mean of velocity

464  
00:18:55,633 --> 00:18:57,033  
as you--as you're going up  
and coming down.

465  
00:18:57,033 --> 00:18:59,733  
You just look at the relative

velocity of the wave packets.

466

00:18:59,733 --> 00:19:02,000

These wave packets  
drift apart

467

00:19:02,000 --> 00:19:03,600

and then we--  
we bang 'em again

468

00:19:03,600 --> 00:19:06,133

so that they come back together,  
and at this point, they overlap.

469

00:19:06,133 --> 00:19:07,933

They exit at this point.

470

00:19:07,933 --> 00:19:09,866

This is another  
beam splitter pulse.

471

00:19:09,866 --> 00:19:13,333

And we look to see interference  
between those two output paths,

472

00:19:13,333 --> 00:19:16,433

which is experimentally observed

473

00:19:16,433 --> 00:19:19,233

by detecting where the atoms are

474

00:19:19,233 --> 00:19:22,833

at this region of space by just  
flashing on a beam of light

475

00:19:22,833 --> 00:19:26,733

and taking a picture of 'em.

476

00:19:26,733 --> 00:19:28,600

This is about ten meters.

477

00:19:28,600 --> 00:19:31,566

This splitting here,  
that's at 54 centimeters.

478

00:19:31,566 --> 00:19:33,900

And now, what I want to  
show you is

479

00:19:33,900 --> 00:19:36,500

after they've been separated  
by the 54 centimeters,

480

00:19:36,500 --> 00:19:38,366

when they fall  
back down here,

481

00:19:38,366 --> 00:19:39,533

hit the final  
beam splitter,

482

00:19:39,533 --> 00:19:41,366

and then fall into  
the detection region,

483

00:19:41,366 --> 00:19:43,066

and when I take  
a picture,

484

00:19:43,066 --> 00:19:46,066

I actually see  
interference fringes.

485

00:19:47,933 --> 00:19:50,466

So this is our key data,

486

00:19:50,466 --> 00:19:54,200

and what I'm showing you  
is interference fringes,

487

00:19:54,200 --> 00:19:56,566  
which, when I say "fringes,"

488

00:19:56,566 --> 00:19:59,966  
what I'm talking about is  
probability of finding atoms

489

00:19:59,966 --> 00:20:02,633  
in one location  
or the other location

490

00:20:02,633 --> 00:20:04,100  
at my detection port,

491

00:20:04,100 --> 00:20:06,933  
and those two locations are  
this location and that location.

492

00:20:06,933 --> 00:20:09,333  
And I get excited

493

00:20:09,333 --> 00:20:13,733  
when I see that the--the atom's  
flopping between one location

494

00:20:13,733 --> 00:20:16,033  
and the next location.

495

00:20:16,033 --> 00:20:17,433  
The only way that's happening  
is--

496

00:20:17,433 --> 00:20:19,766  
the only way that can happen,  
I claim,

497

00:20:19,766 --> 00:20:22,133  
is if I consider the atoms

as waves

498

00:20:22,133 --> 00:20:24,366

and if these waves have gone  
through these two paths

499

00:20:24,366 --> 00:20:27,133

separated by a half a meter.

500

00:20:27,133 --> 00:20:28,366

When they come back together,

501

00:20:28,366 --> 00:20:30,866

if I separate them

by just 1.2 centimeters,

502

00:20:30,866 --> 00:20:33,666

I can find relative phases

between those waves

503

00:20:33,666 --> 00:20:36,566

where the addition of the wave

function is constructive

504

00:20:40,433 --> 00:20:38,100

and the atoms are there,

505

00:20:40,433 --> 00:20:42,333

and we can--you know, every--

anything in between also

506

00:20:42,333 --> 00:20:44,033

we're capable of detecting,

507

00:20:44,033 --> 00:20:46,066

but I'm just showing you

these two extremes.

508

00:20:46,066 --> 00:20:48,000

For fully constructive  
interference,

509  
00:20:48,000 --> 00:20:49,433  
all the atoms  
show up there.

510  
00:20:49,433 --> 00:20:52,500  
For fully destructive,  
all the atoms show up there.

511  
00:20:52,500 --> 00:20:55,100  
Now, it stands to reason, the  
further I separate them apart,

512  
00:20:55,100 --> 00:20:57,633  
the harder it is for me to get  
'em to all come back together.

513  
00:20:57,633 --> 00:21:00,733  
So when we separate them  
by a half a meter,

514  
00:21:00,733 --> 00:21:03,533  
we don't have what we call  
perfect contrast.

515  
00:21:03,533 --> 00:21:05,866  
We have somewhat  
imperfect contrast where--

516  
00:21:05,866 --> 00:21:07,933  
but we still see  
oscillations

517  
00:21:07,933 --> 00:21:10,400  
between the majority of the  
atoms being at that position

518  
00:21:10,400 --> 00:21:13,533

and the majority of the atoms  
being at that position.

519

00:21:13,533 --> 00:21:16,500

And for us, this is  
a smoking gun signature

520

00:21:16,500 --> 00:21:18,766

that these atoms  
had to be interfering

521

00:21:18,766 --> 00:21:20,600

as quantum mechanical particles.

522

00:21:20,600 --> 00:21:22,300

Now, you might say,

523

00:21:22,300 --> 00:21:24,800

shoot, you know,  
but quantum mechanics is true,

524

00:21:24,800 --> 00:21:26,766

so what's the big deal  
about a half meter

525

00:21:26,766 --> 00:21:28,666

versus a centimeter?

526

00:21:28,666 --> 00:21:31,133

And you know, also,  
what have other people done?

527

00:21:31,133 --> 00:21:34,033

So this data here  
for massive particles

528

00:21:34,033 --> 00:21:35,500

is--is the world record.

529

00:21:35,500 --> 00:21:37,566

We're about 100 times more  
spatially separated

530

00:21:37,566 --> 00:21:39,633

than anybody else has--  
has--has done

531

00:21:39,633 --> 00:21:41,766

in any other lab in the world.

532

00:21:41,766 --> 00:21:43,900

But you know, so those are  
kind of nice bragging rights

533

00:21:43,900 --> 00:21:46,166

that you use to maybe get  
your data into "Nature"

534

00:21:46,166 --> 00:21:47,533

or, you know,  
some other journal.

535

00:21:47,533 --> 00:21:50,566

But you know, you--  
as scientists, we want to know,

536

00:21:50,566 --> 00:21:52,766

is it--was it worth doing  
an experiment like that?

537

00:21:52,766 --> 00:21:54,500

And so that's--I kind of want  
to tell you that story

538

00:21:54,500 --> 00:21:57,100

a little bit  
on the subsequent slides.

539

00:21:57,100 --> 00:21:59,533

You might also be thinking,  
well, you know,

540  
00:21:59,533 --> 00:22:01,933  
I also know that light  
is comprised

541  
00:22:01,933 --> 00:22:03,500  
of a stream of photons,

542  
00:22:03,500 --> 00:22:05,900  
and a photon is  
a quantum mechanical object,

543  
00:22:05,900 --> 00:22:07,666  
and when I put a photon  
on the beam splitter

544  
00:22:07,666 --> 00:22:09,100  
and I separate it  
and recombine it,

545  
00:22:09,100 --> 00:22:11,966  
that photon flies over distances  
which are much larger

546  
00:22:11,966 --> 00:22:14,166  
than the 54 centimeters.

547  
00:22:14,166 --> 00:22:16,433  
And I would say,  
if you're thinking that,

548  
00:22:16,433 --> 00:22:19,033  
that is definitely, you know, a  
legitimate and interesting thing

549  
00:22:19,033 --> 00:22:21,633  
to--to think about, and it's--  
it's very interesting,

550

00:22:21,633 --> 00:22:23,000

in my view, to compare,  
you know,

551

00:22:23,000 --> 00:22:25,333

the quantum mechanics  
of photons,

552

00:22:25,333 --> 00:22:28,166

you know, massless relativistic  
particles,

553

00:22:28,166 --> 00:22:30,933

and those of massive particles,  
like atoms,

554

00:22:30,933 --> 00:22:33,933

and--and how quantum mechanics  
treats them in,

555

00:22:33,933 --> 00:22:35,666

you know, in terms of--

556

00:22:35,666 --> 00:22:39,666

of what the predictions  
ought to be.

557

00:22:39,666 --> 00:22:41,766

So what do we learn

558

00:22:41,766 --> 00:22:44,300

when we separate an atom  
by a half meter?

559

00:22:44,300 --> 00:22:47,633

Well, there's a lot of effort  
all across the world right now

560

00:22:47,633 --> 00:22:50,300

trying to figure out  
how macroscopic

561

00:22:50,300 --> 00:22:52,700

we can make a quantum system.

562

00:22:52,700 --> 00:22:55,766

And by macroscopic, how far  
apart can we separate it

563

00:22:55,766 --> 00:22:57,666

and recombine it?

564

00:22:57,666 --> 00:22:59,766

How massive can the particle be?

565

00:22:59,766 --> 00:23:01,433

You know, I showed you an atom.

566

00:23:01,433 --> 00:23:05,000

People are actually--in Vienna,  
they're interfering molecules,

567

00:23:05,000 --> 00:23:07,266

fairly substantial molecules,

568

00:23:07,266 --> 00:23:10,233

and one of the experiments  
they have on their docket

569

00:23:10,233 --> 00:23:12,633

is to interfere a virus,  
you know,

570

00:23:12,633 --> 00:23:14,800

so you can make something  
that's maybe alive,

571

00:23:14,800 --> 00:23:16,233  
separate it and recombine.

572  
00:23:16,233 --> 00:23:17,433  
They're doing those big stuff

573  
00:23:17,433 --> 00:23:19,200  
over much smaller  
distance scales,

574  
00:23:19,200 --> 00:23:21,966  
often measured in  
hundredths of nanometers.

575  
00:23:21,966 --> 00:23:24,033  
And also, over what time scale  
they're separated.

576  
00:23:24,033 --> 00:23:26,233  
There's all these different  
experiments happening,

577  
00:23:26,233 --> 00:23:29,233  
and you kind of want to have  
some way of comparing them all,

578  
00:23:29,233 --> 00:23:32,166  
you know, and--you know,  
some notion of how macroscopic,

579  
00:23:32,166 --> 00:23:35,066  
how big, the quantum state  
you're making really is.

580  
00:23:35,066 --> 00:23:37,133  
And so these theorists  
in Vienna,

581  
00:23:37,133 --> 00:23:39,266  
Nimmrichter and Hornberger,

in 2013

582

00:23:39,266 --> 00:23:41,900

did a really interesting set  
of theory work

583

00:23:41,900 --> 00:23:44,666

where they created the framework  
that allows us experimentalists

584

00:23:44,666 --> 00:23:46,800

to kind of compare  
the macroscopicity

585

00:23:46,800 --> 00:23:50,000

of one kind of quantum  
experiment with another.

586

00:23:50,000 --> 00:23:52,100

It might be that it's--  
it's more interesting

587

00:23:52,100 --> 00:23:53,966

from the point of view  
of fundamental test of theory

588

00:23:53,966 --> 00:23:56,533

to interfere a molecule  
over 100 nanometers

589

00:23:56,533 --> 00:23:59,100

than an atom  
over a half a meter.

590

00:23:59,100 --> 00:24:01,633

And their theory, by the way,  
only applies to

591

00:24:01,633 --> 00:24:03,866

massive particles,

not to photons.

592

00:24:03,866 --> 00:24:06,533

And so taken this way,

593

00:24:06,533 --> 00:24:09,366

I don't really have time to go  
into the axes on this plot.

594

00:24:09,366 --> 00:24:11,666

My point of showing this is  
just to kind of show you

595

00:24:11,666 --> 00:24:13,633

people are  
thinking about this.

596

00:24:13,633 --> 00:24:16,066

And our work, the stuff  
I just showed you,

597

00:24:16,066 --> 00:24:18,533

is--constrains  
quantum mechanics in a way

598

00:24:18,533 --> 00:24:20,066

shown by this green line

599

00:24:20,066 --> 00:24:22,866

and what it does for certain  
parameter ranges on that plot,

600

00:24:22,866 --> 00:24:25,600

which kind of tell you about the  
separation of the wave packets

601

00:24:25,600 --> 00:24:27,266

and so forth.

602

00:24:27,266 --> 00:24:29,433

We're setting the--  
kind of the--the--

603

00:24:29,433 --> 00:24:31,833

the most stringent limits  
on macroscopicity

604

00:24:31,833 --> 00:24:34,333

by many orders of magnitudes.

605

00:24:34,333 --> 00:24:36,600

So it turns out,  
it does seem like--

606

00:24:36,600 --> 00:24:39,766

it is interesting  
to be just exploring the...

607

00:24:41,200 --> 00:24:44,233

The interference patterns of  
atoms at these distance scales.

608

00:24:44,233 --> 00:24:46,366

Well, you might be asking,  
well, shoot,

609

00:24:46,366 --> 00:24:48,700

but what--what's the point?

610

00:24:48,700 --> 00:24:51,666

How--you know, what would happen  
if quantum mechanics was wrong?

611

00:24:51,666 --> 00:24:53,700

You know, how--how might  
quantum mechanics break down?

612

00:24:53,700 --> 00:24:55,666

A lot of people

thinking about that.

613

00:24:55,666 --> 00:24:58,933

There's a lot of  
kind of crazy theories

614

00:24:58,933 --> 00:25:01,466

that have been proposed  
for a long time.

615

00:25:01,466 --> 00:25:03,566

I want to tell you  
about one of them

616

00:25:03,566 --> 00:25:07,366

which resurfaced  
back just a few months ago

617

00:25:07,366 --> 00:25:11,100

and analyzed our data  
in the context of this theory.

618

00:25:11,100 --> 00:25:13,200

When you go--when we--  
when we do physics,

619

00:25:13,200 --> 00:25:15,466

when we do engineering, we make  
fundamental assumptions

620

00:25:15,466 --> 00:25:16,833

about space and time.

621

00:25:16,833 --> 00:25:20,066

Homogeneous, isotropic,  
time progresses uniformly.

622

00:25:20,066 --> 00:25:23,500

but when you look at, you know,  
a fine-grain scale,

623

00:25:23,500 --> 00:25:25,966

Planck scale,  
10 to the minus 34 meters,

624

00:25:25,966 --> 00:25:28,966

you start to think, well, maybe  
space really isn't homogeneous,

625

00:25:28,966 --> 00:25:30,166

maybe it's grainy.

626

00:25:30,166 --> 00:25:31,600

Maybe time isn't continuous.

627

00:25:31,600 --> 00:25:34,766

Maybe it ticks in a funny way  
on certain distance scales.

628

00:25:34,766 --> 00:25:38,600

And maybe quantum mechanics  
of massively separated objects

629

00:25:38,600 --> 00:25:42,733

might be sensitive to  
these kind of perturbations.

630

00:25:42,733 --> 00:25:45,733

It turns out we have to have  
extreme control

631

00:25:45,733 --> 00:25:48,800

over the paths of the atoms to  
get them to come back together

632

00:25:48,800 --> 00:25:50,400

and interfere constructively.

633

00:25:50,400 --> 00:25:52,966

And if the velocity of one of those wave packets changes

634

00:25:52,966 --> 00:25:54,500  
by nanometers per second,

635

00:25:54,500 --> 00:25:56,866  
that's enough to kind of wipe out the coherence.

636

00:25:56,866 --> 00:26:00,566  
And so we make this experiment by the fact that

637

00:26:00,566 --> 00:26:02,633  
we see those fringes make very good tests

638

00:26:02,633 --> 00:26:05,200  
of anything that's gonna go in there

639

00:26:05,200 --> 00:26:07,500  
and shake around the atoms as they're propagating.

640

00:26:07,500 --> 00:26:09,933  
And it may be very--the very nature of space-time itself

641

00:26:09,933 --> 00:26:11,200  
that's doing this.

642

00:26:11,200 --> 00:26:14,633  
This Ellis model imagines a gas of wormholes

643

00:26:14,633 --> 00:26:16,800  
that are flying through space,

644

00:26:16,800 --> 00:26:20,033

and this was taken seriously  
until the early '90s

645

00:26:20,033 --> 00:26:21,933

when some people  
shot this theory down.

646

00:26:21,933 --> 00:26:24,266

And these wormholes,  
according to this phenomenology,

647

00:26:24,266 --> 00:26:26,666

collide with the atoms  
and give small momentum kicks

648

00:26:26,666 --> 00:26:28,966

and ruin  
the interference pattern.

649

00:26:28,966 --> 00:26:31,633

And so there's a bunch of  
complicated math these guys did,

650

00:26:31,633 --> 00:26:33,700

and basically, you know,  
showed that the data

651

00:26:33,700 --> 00:26:36,433

I just showed you  
dramatically constrains

652

00:26:36,433 --> 00:26:37,933

these sort of wormhole theories.

653

00:26:37,933 --> 00:26:40,600

And to put these theories  
in context,

654

00:26:40,600 --> 00:26:42,966  
there's been a lot of thought  
about the quantum mechanics

655  
00:26:42,966 --> 00:26:45,000  
of black holes and things  
recently

656  
00:26:45,000 --> 00:26:46,633  
and over the past 20 years,

657  
00:26:46,633 --> 00:26:49,166  
and this was one of  
the early types of forays

658  
00:26:49,166 --> 00:26:51,166  
into quantum and gravity

659  
00:26:51,166 --> 00:26:52,866  
by people like Lenny Susskind

660  
00:26:52,866 --> 00:26:54,333  
when they were trying  
to figure out,

661  
00:26:54,333 --> 00:26:55,833  
and they still are trying  
to figure out,

662  
00:26:55,833 --> 00:26:57,933  
the quantum mechanics  
of black holes.

663  
00:26:59,633 --> 00:27:01,000  
I want to change gears  
a little bit.

664  
00:27:01,000 --> 00:27:03,333  
Oftentimes when you build  
an interferometer,

665

00:27:03,333 --> 00:27:05,000

you build it  
to measure something,

666

00:27:05,000 --> 00:27:07,433

not just to learn  
something about,

667

00:27:07,433 --> 00:27:09,033

you know, the structure  
of space and time,

668

00:27:09,033 --> 00:27:10,700

and that's kind of  
the reason why

669

00:27:10,700 --> 00:27:12,366

we're building these apparatus.

670

00:27:12,366 --> 00:27:14,566

By looking at  
the interference fringes,

671

00:27:14,566 --> 00:27:16,300

and assuming now  
the interference fringe

672

00:27:16,300 --> 00:27:17,766

is something stable,

673

00:27:17,766 --> 00:27:19,833

we can learn something  
about the relative paths

674

00:27:19,833 --> 00:27:22,166

that the two wave packets take.

675

00:27:22,166 --> 00:27:23,766

So what do we learn?

676

00:27:23,766 --> 00:27:26,933

Well, the theory for calculating

677

00:27:26,933 --> 00:27:28,533

the relative phase shifts

678

00:27:28,533 --> 00:27:30,300

between atom wave packets

679

00:27:30,300 --> 00:27:33,533

as they propagate through space  
and time is well-defined

680

00:27:33,533 --> 00:27:36,833

and it's been articulated since  
the beginning of this field,

681

00:27:36,833 --> 00:27:38,233

and it just involves, again,

682

00:27:38,233 --> 00:27:40,300

systematic application  
of the Schrodinger equation.

683

00:27:40,300 --> 00:27:44,166

And again, I'm not here to  
explain these equations to you,

684

00:27:44,166 --> 00:27:46,500

just to say that  
those equations exist

685

00:27:46,500 --> 00:27:48,700

and you can go in  
and actually calculate

686

00:27:48,700 --> 00:27:51,633

what the relative phase shifts  
for the two paths are.

687

00:27:51,633 --> 00:27:54,466

So you might ask me, well,  
what drives the relative phase

688

00:27:54,466 --> 00:27:55,900

of those two paths?

689

00:27:55,900 --> 00:27:58,166

Well, anything that changes  
the velocity of the two paths

690

00:27:58,166 --> 00:27:59,533

is gonna lead to a phase shift

691

00:27:59,533 --> 00:28:01,233

because of  
the de Broglie relationship.

692

00:28:01,233 --> 00:28:04,033

What changes the velocity?

693

00:28:04,033 --> 00:28:06,300

Well, how about the acceleration  
due to gravity?

694

00:28:06,300 --> 00:28:08,566

That's something that, as those  
atoms are flying through

695

00:28:08,566 --> 00:28:11,400

the apparatus, their velocity  
is changing with time.

696

00:28:11,400 --> 00:28:13,166

Their--their--their phase,

697

00:28:13,166 --> 00:28:15,300  
the wavelength is changing  
with time.

698  
00:28:15,300 --> 00:28:17,900  
That turns out to lead to  
a huge phase shift

699  
00:28:17,900 --> 00:28:19,466  
at the output  
of the interferometer.

700  
00:28:19,466 --> 00:28:21,366  
If the interferometer's  
rotating,

701  
00:28:21,366 --> 00:28:23,133  
there's another phase shift  
associated with that,

702  
00:28:23,133 --> 00:28:24,266  
the Coriolis effect.

703  
00:28:24,266 --> 00:28:26,766  
And there's a whole list  
of phase shifts

704  
00:28:26,766 --> 00:28:28,633  
that you can calculate  
along these lines.

705  
00:28:28,633 --> 00:28:31,100  
Bottom line is these--  
these devices

706  
00:28:31,100 --> 00:28:34,333  
are extremely sensitive  
to inertial forces,

707  
00:28:34,333 --> 00:28:36,733

rotations and accelerations.

708

00:28:36,733 --> 00:28:39,033

And that's why we--  
we use them--

709

00:28:39,033 --> 00:28:40,933

we build sensors with them.

710

00:28:40,933 --> 00:28:44,000

I'll show you a sensor  
in just a minute.

711

00:28:44,000 --> 00:28:47,400

This is one of those sensors,  
which is to say that--

712

00:28:47,400 --> 00:28:49,400

and I want to maybe go to  
this list first.

713

00:28:49,400 --> 00:28:51,933

When I do that calculation,

714

00:28:51,933 --> 00:28:55,066

you say, well, what do--what do  
those phase shifts look like?

715

00:28:55,066 --> 00:28:56,733

We--we--we call  
a table like this

716

00:28:56,733 --> 00:28:58,500

affectionately  
the term list.

717

00:28:58,500 --> 00:29:00,933

And what I'm--  
what I'm describing here

718

00:29:00,933 --> 00:29:04,100

is all the different ways  
that I can get relative phase

719

00:29:04,100 --> 00:29:05,666

at the output  
of the interferometer.

720

00:29:05,666 --> 00:29:07,933

And for the highly engineered  
sensors we build,

721

00:29:07,933 --> 00:29:09,666

these term lists  
have hundreds of terms,

722

00:29:09,666 --> 00:29:11,966

and I just put in  
a simplified one here

723

00:29:11,966 --> 00:29:15,066

to show you some of  
the most dramatic shifts.

724

00:29:15,066 --> 00:29:17,933

This "k" is the propagation  
vector of the laser beam

725

00:29:17,933 --> 00:29:19,700

that we used  
to bat around the atoms.

726

00:29:19,700 --> 00:29:21,533

"g" here is the acceleration  
due to gravity,

727

00:29:21,533 --> 00:29:24,166

and "T" is  
the time between--

728

00:29:24,166 --> 00:29:26,066

basically the time  
of flight

729

00:29:26,066 --> 00:29:28,900

between the first beam splitter  
and the exit beam splitter.

730

00:29:28,900 --> 00:29:31,566

And I'll just focus on  
this top term

731

00:29:31,566 --> 00:29:33,400

and point out  
something amazing

732

00:29:33,400 --> 00:29:35,266

that in that data  
I just showed you,

733

00:29:35,266 --> 00:29:37,833

as the atoms are flying through  
the interferometer,

734

00:29:37,833 --> 00:29:41,666

about  $10^{10}$  radians  
of phase evolve

735

00:29:41,666 --> 00:29:43,566

between one path and the other

736

00:29:43,566 --> 00:29:46,700

before the wave functions  
overlap.

737

00:29:46,700 --> 00:29:49,166

So if I measure the phase  
of the wave function precisely,

738

00:29:49,166 --> 00:29:52,733

I'm basically, and I can count  
which fringe I'm on,

739

00:29:52,733 --> 00:29:55,400

I basically have  
an awesome accelerometer,

740

00:29:55,400 --> 00:29:57,633

an awesome way  
of measuring accelerations,

741

00:29:57,633 --> 00:30:01,100

or if I'm on the Earth,  
the gravitational field.

742

00:30:01,100 --> 00:30:03,100

Let me just put  
an order of magnitude in there,

743

00:30:03,100 --> 00:30:04,333

10 to the 10 radians,

744

00:30:04,333 --> 00:30:06,266

and typically we can,  
on a single experiment,

745

00:30:06,266 --> 00:30:10,200

resolve a phase shift to about  
a 10 to the minus 3

746

00:30:10,200 --> 00:30:11,933

to 10 to the minus 2 radians.

747

00:30:11,933 --> 00:30:13,633

It says in a single shot

748

00:30:13,633 --> 00:30:16,166

we are, in principle,  
capable of revolve--

749

00:30:16,166 --> 00:30:18,733  
resolving accelerations  
at the 10 to the minus 12

750

00:30:18,733 --> 00:30:21,300  
of little "g" levels.

751

00:30:21,300 --> 00:30:23,333  
10 to the minus 12  
to 10 to the minus 13

752

00:30:23,333 --> 00:30:26,000  
in just a single realization.

753

00:30:26,000 --> 00:30:28,433  
How--and that's--that's--I mean,  
okay, that's a small number.

754

00:30:28,433 --> 00:30:29,533  
How small is it?

755

00:30:29,533 --> 00:30:31,400  
Well, the gravitational  
acceleration

756

00:30:31,400 --> 00:30:33,033  
of two of you guys sitting next  
to each other

757

00:30:33,033 --> 00:30:35,600  
is 10 to the minus 9  
of little "g."

758

00:30:35,600 --> 00:30:37,966  
So it means if somebody is  
drinking a cup of coffee

759

00:30:37,966 --> 00:30:39,433

next to you,

760

00:30:39,433 --> 00:30:41,066  
you know, their mass is changed  
by enough

761

00:30:41,066 --> 00:30:43,500  
that the gravitational  
interaction would be about

762

00:30:43,500 --> 00:30:45,700  
10 to the minus 11 of little "g"  
or something like that.

763

00:30:45,700 --> 00:30:47,833  
That still--and that  
would be detectible

764

00:30:47,833 --> 00:30:50,066  
with a sensor like this.

765

00:30:50,066 --> 00:30:51,933  
So it kind of makes you want  
to build these sensors,

766

00:30:51,933 --> 00:30:53,766  
maybe not on that  
grandiose scale.

767

00:30:53,766 --> 00:30:56,200  
And so this company, AOSense,

768

00:30:56,200 --> 00:30:57,566  
which is literally  
just down the road,

769

00:30:57,566 --> 00:31:00,300  
is building smaller versions  
of these sensors

770  
00:31:00,300 --> 00:31:02,800  
for real-world  
guidance navigation

771  
00:31:02,800 --> 00:31:04,400  
and control applications,

772  
00:31:04,400 --> 00:31:06,566  
and also geodetic applications,

773  
00:31:06,566 --> 00:31:08,400  
studying of  
the Earth's acceleration

774  
00:31:08,400 --> 00:31:09,766  
due to gravity and so forth.

775  
00:31:09,766 --> 00:31:11,766  
And in this can here

776  
00:31:11,766 --> 00:31:14,833  
is a much smaller  
atom interferometer

777  
00:31:14,833 --> 00:31:17,200  
that's measuring the  
acceleration due to gravity,

778  
00:31:17,200 --> 00:31:18,933  
and this is some data  
from that sensor.

779  
00:31:18,933 --> 00:31:21,300  
This is time  
in kiloseconds,

780  
00:31:21,300 --> 00:31:24,233  
and one of these oscillations  
is about--is about a day.

781

00:31:24,233 --> 00:31:27,800

And these variations in gravity  
are the well-known variations

782

00:31:27,800 --> 00:31:29,066

in acceleration due to gravity

783

00:31:29,066 --> 00:31:31,500

due to the motion  
of the Earth and the Moon.

784

00:31:31,500 --> 00:31:33,533

This is about 10 to the minus 7

785

00:31:33,533 --> 00:31:36,733

of the 9.8 meters per second  
squared of gravity.

786

00:31:36,733 --> 00:31:38,133

This is to point out that,

787

00:31:38,133 --> 00:31:40,133

yeah, these are  
really sensitive sensors

788

00:31:40,133 --> 00:31:42,466

and when you build them on  
these grandiose scales,

789

00:31:42,466 --> 00:31:44,566

they become extra sensitive.

790

00:31:45,900 --> 00:31:49,200

So what are we gonna use  
that extra sensitivity for?

791

00:31:49,200 --> 00:31:51,033

And this is data that's just

started rolling in

792

00:31:51,033 --> 00:31:52,433  
in the past month.

793

00:31:52,433 --> 00:31:54,833  
Well, one of the--  
I'm in a physics department

794

00:31:54,833 --> 00:31:58,866  
so what basic science  
might we do with this?

795

00:31:58,866 --> 00:32:02,433  
People are interested  
in answering at a precise level

796

00:32:02,433 --> 00:32:03,900  
the age-old question,

797

00:32:03,900 --> 00:32:05,833  
does the brick and the feather,

798

00:32:05,833 --> 00:32:07,500  
do they--do they fall  
at the same rate?

799

00:32:07,500 --> 00:32:09,300  
The Leaning Tower of Pisa  
experiment,

800

00:32:09,300 --> 00:32:11,966  
the Galileo experiment,  
in modern times,

801

00:32:11,966 --> 00:32:15,200  
you--it's known as equivalence  
principle measurement

802

00:32:15,200 --> 00:32:17,400  
and it's--the equivalence  
principle is a foundation

803  
00:32:17,400 --> 00:32:19,900  
for Einstein's theory  
of general relativity.

804  
00:32:19,900 --> 00:32:22,400  
And it's theoretically  
interesting,

805  
00:32:22,400 --> 00:32:24,300  
I'm told by  
my theory colleagues,

806  
00:32:24,300 --> 00:32:26,600  
to probe this principle

807  
00:32:26,600 --> 00:32:28,500  
at the part in 10 to the 15th

808  
00:32:28,500 --> 00:32:30,600  
to part in 10 to the 18 level.

809  
00:32:30,600 --> 00:32:34,200  
Which is to say as the objects  
are accelerating together

810  
00:32:34,200 --> 00:32:36,466  
at basically the acceleration  
due to gravity,

811  
00:32:36,466 --> 00:32:38,200  
there may be some  
spurious interaction

812  
00:32:38,200 --> 00:32:39,900  
due to particles  
we know nothing about

813

00:32:39,900 --> 00:32:43,166  
that make it so  
a rubidium 85 atom

814

00:32:43,166 --> 00:32:45,266  
accelerates at a slightly  
different rate

815

00:32:45,266 --> 00:32:46,966  
than a rubidium 87 atom

816

00:32:46,966 --> 00:32:49,900  
because they have different  
nuclear composition.

817

00:32:49,900 --> 00:32:52,033  
And so that's the experiment  
we're doing here.

818

00:32:52,033 --> 00:32:54,700  
We have two ensembles  
of Bose-Einstein condensed

819

00:32:54,700 --> 00:32:56,366  
laser-cooled atoms  
that have been launched

820

00:32:56,366 --> 00:32:58,600  
and subjected to  
a bunch of pulses

821

00:32:58,600 --> 00:33:00,933  
that are flying up and down  
this tube,

822

00:33:00,933 --> 00:33:03,266  
both opening up and closing  
interferometers,

823

00:33:03,266 --> 00:33:05,166

and then we measure  
simultaneously

824

00:33:05,166 --> 00:33:07,900

the phase shift  
from rubidium 85 and 87.

825

00:33:07,900 --> 00:33:09,766

By comparing the phase shifts,

826

00:33:09,766 --> 00:33:11,166

we make a comparative  
measurement

827

00:33:11,166 --> 00:33:12,866

of their acceleration  
due to gravity,

828

00:33:12,866 --> 00:33:14,566

and then we seek to understand

829

00:33:14,566 --> 00:33:16,766

whether the observed  
acceleration due to gravity

830

00:33:16,766 --> 00:33:19,066

is the same for one isotope  
or the other.

831

00:33:19,066 --> 00:33:22,066

Now, I don't have results to...

832

00:33:23,466 --> 00:33:24,833

You know, formally discuss,

833

00:33:24,833 --> 00:33:27,300

but I do have some  
preliminary data

834

00:33:27,300 --> 00:33:29,166  
to show you kind of what this--

835

00:33:29,166 --> 00:33:30,633  
these action shots look like now

836

00:33:30,633 --> 00:33:33,033  
when we're making a simultaneous  
measurement

837

00:33:33,033 --> 00:33:36,300  
of the co-acceleration  
of--of 87 and 85.

838

00:33:36,300 --> 00:33:39,100  
This is a picture  
in false color--

839

00:33:39,100 --> 00:33:40,700  
as my colleagues joke,

840

00:33:40,700 --> 00:33:42,766  
everything looks better  
in false color.

841

00:33:42,766 --> 00:33:44,466  
So in false color,

842

00:33:44,466 --> 00:33:47,033  
rubidium 87 in the upper part  
of the camera port,

843

00:33:47,033 --> 00:33:49,100  
rubidium 85  
in the lower part.

844

00:33:49,100 --> 00:33:51,733  
This is one output port

of the 87 interferometer.

845

00:33:51,733 --> 00:33:54,600

This is the other output port  
same for 85.

846

00:33:54,600 --> 00:33:57,166

And we introduce a phase--  
what we call a phase shear

847

00:33:57,166 --> 00:33:58,866

across the interfering waves

848

00:33:58,866 --> 00:34:01,200

so we can precisely measure  
the phase.

849

00:34:01,200 --> 00:34:03,266

This is like what happens  
if you misalign

850

00:34:03,266 --> 00:34:05,300

an optical max into  
interferometer,

851

00:34:05,300 --> 00:34:06,933

you see fringes.

852

00:34:06,933 --> 00:34:09,866

And basically,  
by comparing the phase of--

853

00:34:09,866 --> 00:34:11,933

of these--this is  
a lot of atoms,

854

00:34:11,933 --> 00:34:13,233

and this is a few atoms.

855

00:34:13,233 --> 00:34:14,933

By comparing the phase  
of those peaks

856

00:34:14,933 --> 00:34:16,166

to the phases  
of those peaks,

857

00:34:16,166 --> 00:34:18,066

we can measure  
their relative phase

858

00:34:18,066 --> 00:34:20,700

and then get a handle on  
the equivalence principle.

859

00:34:20,700 --> 00:34:22,633

The data I'm showing you here  
right now,

860

00:34:22,633 --> 00:34:25,733

we're--is good  
to about 12 digits,

861

00:34:25,733 --> 00:34:28,400

and we think that when we get  
this apparatus all tuned up,

862

00:34:28,400 --> 00:34:32,433

we're gonna have 14 digits  
of sensitivity or more.

863

00:34:32,433 --> 00:34:35,700

And at that level,  
our theoretical colleagues

864

00:34:35,700 --> 00:34:38,400

start getting interested  
in these results.

865

00:34:38,400 --> 00:34:40,400

Thanks.

866

00:34:40,400 --> 00:34:43,033

Let's see, so what's--

867

00:34:43,033 --> 00:34:45,500

You know, where do really interesting things happen?

868

00:34:45,500 --> 00:34:47,200

Well, people think the really interesting stuff

869

00:34:47,200 --> 00:34:48,566

is gonna be at 16 digits.

870

00:34:48,566 --> 00:34:50,866

The world record for equivalence principle right now is in

871

00:34:50,866 --> 00:34:53,500

the University of Washington gravity group,

872

00:34:53,500 --> 00:34:55,200

where they measure equivalence principle

873

00:34:55,200 --> 00:34:58,300

using torsion pendulum to 13 digits,

874

00:34:58,300 --> 00:35:00,700

and they're pushing into the 14-digit level.

875

00:35:00,700 --> 00:35:02,633

And so we're hoping to at least have a measurement

876

00:35:02,633 --> 00:35:04,700

that's competitive  
with what they're doing

877

00:35:04,700 --> 00:35:07,433

and complementary  
in the sense that we're using,

878

00:35:07,433 --> 00:35:09,933

you know, this completely  
quantum mechanical method

879

00:35:09,933 --> 00:35:11,733

for making the measurement.

880

00:35:14,133 --> 00:35:16,066

What else does equivalence  
principle measurement tell you?

881

00:35:16,066 --> 00:35:17,400

Well, you know,  
what's the impact

882

00:35:17,400 --> 00:35:20,800

of EP being true or false?

883

00:35:20,800 --> 00:35:23,066

And so here, there's a lot of  
recent theoretical work

884

00:35:23,066 --> 00:35:26,100

motivated by the fact--  
by cosmology

885

00:35:26,100 --> 00:35:29,000

of, basically,  
there's dark matter out there

886

00:35:29,000 --> 00:35:30,466  
and we don't know what it is

887  
00:35:30,466 --> 00:35:31,966  
and certain flavors  
of dark matter

888  
00:35:31,966 --> 00:35:34,833  
lead to equivalence principle  
violating interactions

889  
00:35:34,833 --> 00:35:36,433  
that we might see in our lab.

890  
00:35:36,433 --> 00:35:38,300  
And so this is a chart from one  
of my colleagues,

891  
00:35:38,300 --> 00:35:41,733  
Peter Graham, at Stanford,  
that shows the possible impact

892  
00:35:41,733 --> 00:35:43,800  
of the measurements  
we're doing right now

893  
00:35:43,800 --> 00:35:45,400  
on some of his favorite

894  
00:35:45,400 --> 00:35:47,866  
equivalence principle  
violating theories.

895  
00:35:47,866 --> 00:35:50,233  
And again, I'm not gonna explain  
the axes,

896  
00:35:50,233 --> 00:35:52,266  
just to say that  
this yellow region

897

00:35:52,266 --> 00:35:54,666

is what we know  
to be excluded right now,

898

00:35:54,666 --> 00:35:57,866

and the kind of data  
we're taking is--is--

899

00:35:57,866 --> 00:35:59,166

is gonna further  
push the bounds

900

00:35:59,166 --> 00:36:03,066

on the possible validity  
or lack of validity

901

00:36:03,066 --> 00:36:06,066

of these obscure theories  
about dark matter.

902

00:36:08,366 --> 00:36:11,133

I want to change gears to  
some more wholesome physics.

903

00:36:11,133 --> 00:36:13,500

So...

[laughs]

904

00:36:13,500 --> 00:36:16,333

You probably all have seen,  
in one form or another,

905

00:36:16,333 --> 00:36:18,733

this data, which is the--

906

00:36:18,733 --> 00:36:21,333

the unbelievable data

907

00:36:21,333 --> 00:36:24,766  
that was taken by  
the LIGO Collaboration when--

908  
00:36:24,766 --> 00:36:28,800  
for their first observation  
of gravitational radiation.

909  
00:36:28,800 --> 00:36:30,600  
What they did was  
they built two conventional

910  
00:36:30,600 --> 00:36:33,833  
optical interferometers at two  
regions in the United States.

911  
00:36:33,833 --> 00:36:38,100  
And the idea is that if...

912  
00:36:39,700 --> 00:36:42,100  
Black holes merge,  
spin and merge,

913  
00:36:42,100 --> 00:36:44,700  
at way far away,

914  
00:36:44,700 --> 00:36:47,633  
they give rise to perturbations,  
ripples in space-time,

915  
00:36:47,633 --> 00:36:49,900  
which propagate  
at the speed of light

916  
00:36:49,900 --> 00:36:53,066  
through space-time to us here  
on planet Earth

917  
00:36:53,066 --> 00:36:55,833  
and these space-time ripples

basically have

918

00:36:55,833 --> 00:36:59,366  
the--the effect of stretching  
and contracting space

919

00:36:59,366 --> 00:37:02,166  
as a function of time  
in such a way

920

00:37:02,166 --> 00:37:04,466  
that if you build one of these  
precision interferometers,

921

00:37:04,466 --> 00:37:06,433  
it can be observed.

922

00:37:06,433 --> 00:37:09,100  
And so just to take you--  
if you haven't seen this data,

923

00:37:09,100 --> 00:37:10,866  
take you through  
some of their signals.

924

00:37:10,866 --> 00:37:13,366  
This is the output of one  
of the interferometers

925

00:37:13,366 --> 00:37:15,200  
and this is the output of  
the other interferometer,

926

00:37:15,200 --> 00:37:17,133  
you know, that one there  
and that one there.

927

00:37:17,133 --> 00:37:20,433  
And when you see those fringes,  
when you see that shaking,

928

00:37:20,433 --> 00:37:24,200

that means that something came  
and changed the path length

929

00:37:24,200 --> 00:37:26,566

of one of the interferometer  
arms with respect to the other,

930

00:37:26,566 --> 00:37:28,700

that something being  
a gravitational wave,

931

00:37:28,700 --> 00:37:31,633

and in such a way  
that you can observe

932

00:37:31,633 --> 00:37:33,566

the cataclysmic event,

933

00:37:33,566 --> 00:37:37,733

which in this case  
was way far away,

934

00:37:37,733 --> 00:37:40,933

two black holes coalescing.

935

00:37:40,933 --> 00:37:43,533

And so I just explained

936

00:37:43,533 --> 00:37:45,133

that I'm building  
interferometers,

937

00:37:45,133 --> 00:37:46,700

and the interferometers  
I'm building

938

00:37:46,700 --> 00:37:48,900

I think are gonna be  
very sensitive.

939

00:37:48,900 --> 00:37:50,866

And so you might ask, you--

940

00:37:50,866 --> 00:37:53,433

could we see

gravitational radiation

941

00:37:53,433 --> 00:37:56,900

in a way that's similar to LIGO

942

00:37:56,900 --> 00:37:59,466

but now using atom interference?

943

00:37:59,466 --> 00:38:01,466

And if we could, what--

944

00:38:01,466 --> 00:38:03,300

why would you want to build

an instrument like that?

945

00:38:03,300 --> 00:38:05,066

And so I'll spend

just a few minutes

946

00:38:05,066 --> 00:38:06,900

kind of describing

our thinking on that.

947

00:38:06,900 --> 00:38:09,166

We haven't built anything that's

nearly as sensitive

948

00:38:09,166 --> 00:38:10,466

as this LIGO instrument,

949

00:38:10,466 --> 00:38:13,333

but we think that a space-based instrument holds promise

950

00:38:13,333 --> 00:38:17,000

for observing certain types of gravitational wave sources.

951

00:38:17,000 --> 00:38:19,833

And here my philosophy is the following:

952

00:38:19,833 --> 00:38:21,733

this was the breakthrough discovery

953

00:38:21,733 --> 00:38:24,633

that taught us that, you know, observing--the physics community

954

00:38:24,633 --> 00:38:26,966

and the astronomy community and the astrophysicist community,

955

00:38:26,966 --> 00:38:29,966

that observing gravitational waves

956

00:38:29,966 --> 00:38:31,500

is really interesting.

957

00:38:31,500 --> 00:38:33,266

And, you know, you go back in time, you say,

958

00:38:33,266 --> 00:38:35,133

well, we know that, you know, using telescopes

959

00:38:35,133 --> 00:38:37,433

to look at the cosmos

is also interesting.

960

00:38:37,433 --> 00:38:41,200

And right now, when you do  
optical astronomy,

961

00:38:41,200 --> 00:38:43,066

there are lots of different  
telescopes that you build

962

00:38:43,066 --> 00:38:45,000

depending on what you want  
to look at.

963

00:38:45,000 --> 00:38:48,133

So as gravitational wave  
astronomy progresses as a field,

964

00:38:48,133 --> 00:38:50,133

I think it stands to reason that  
there are gonna be

965

00:38:50,133 --> 00:38:53,400

a diversity of telescopes that  
you're gonna bring to the table

966

00:38:53,400 --> 00:38:54,966

for making interesting--

967

00:38:54,966 --> 00:38:57,833

scientifically interesting  
observation.

968

00:38:57,833 --> 00:39:00,166

So here's a--here's a plot

969

00:39:00,166 --> 00:39:02,500

generated by Sesana  
and colleagues

970  
00:39:02,500 --> 00:39:06,266  
that basically traces  
the evolution

971  
00:39:06,266 --> 00:39:10,300  
of the--the black hole merger  
that I just showed you

972  
00:39:10,300 --> 00:39:11,600  
through time.

973  
00:39:11,600 --> 00:39:15,166  
And what's happening  
in the LIGO signal

974  
00:39:15,166 --> 00:39:18,266  
is that the LIGO antenna  
only captures

975  
00:39:18,266 --> 00:39:20,300  
a transient signal for the--

976  
00:39:20,300 --> 00:39:21,900  
the very final moments  
of the merger.

977  
00:39:21,900 --> 00:39:23,433  
When those black holes  
are spinning really quick

978  
00:39:23,433 --> 00:39:24,766  
and then merge,

979  
00:39:24,766 --> 00:39:27,100  
that's when you see blips  
in the interferometer.

980  
00:39:27,100 --> 00:39:30,100  
Well, in this...

981  
00:39:31,666 --> 00:39:34,166  
Situation,  
those black holes

982  
00:39:34,166 --> 00:39:36,266  
are spinning slowly

983  
00:39:36,266 --> 00:39:38,733  
before they hit this  
cataclysmic event here

984  
00:39:38,733 --> 00:39:41,400  
for a long period  
of time.

985  
00:39:41,400 --> 00:39:46,000  
And it's interesting to go  
and look at these black holes

986  
00:39:46,000 --> 00:39:48,066  
in this region  
of parameter space

987  
00:39:48,066 --> 00:39:52,700  
before they finally hit  
their merger situation.

988  
00:39:52,700 --> 00:39:54,800  
How might you build an antenna

989  
00:39:54,800 --> 00:39:56,766  
that is capable of detecting

990  
00:39:56,766 --> 00:39:58,400  
these low frequency  
perturbations?

991  
00:39:58,400 --> 00:40:00,600

Well, the world has been  
thinking a lot about that,

992

00:40:00,600 --> 00:40:03,900  
and that's where I think  
our atom interferometer detector

993

00:40:03,900 --> 00:40:06,400  
may have something to say.

994

00:40:06,400 --> 00:40:08,300  
When I say the world's been  
thinking a lot about that,

995

00:40:08,300 --> 00:40:10,166  
there's a planned  
ESA mission,

996

00:40:10,166 --> 00:40:12,400  
and NASA may--

997

00:40:12,400 --> 00:40:14,400  
is looking like it will  
participate in that,

998

00:40:14,400 --> 00:40:16,700  
that is designed  
to detect

999

00:40:16,700 --> 00:40:18,966  
very low frequency  
gravitational waves.

1000

00:40:18,966 --> 00:40:21,000  
This is frequency  
and this is the--

1001

00:40:21,000 --> 00:40:24,066  
this axis here is the amplitude  
of the gravitational wave.

1002

00:40:24,066 --> 00:40:27,233

And you notice that  
this antenna, this telescope,

1003

00:40:27,233 --> 00:40:29,300

can see  
the very low frequencies.

1004

00:40:29,300 --> 00:40:31,600

LIGO can see  
the very high frequencies,

1005

00:40:31,600 --> 00:40:34,700

but maybe you want to see  
these intermediate frequencies.

1006

00:40:36,000 --> 00:40:39,166

So this is the antenna we  
propose to build with atoms.

1007

00:40:39,166 --> 00:40:41,133

And I'm showing you kind of  
a theory view

1008

00:40:41,133 --> 00:40:43,933

of something that we published  
in this paper

1009

00:40:43,933 --> 00:40:45,566

a number of years ago.

1010

00:40:45,566 --> 00:40:47,100

This is the space-time diagram

1011

00:40:47,100 --> 00:40:49,433

for the positions  
of wave packets

1012

00:40:49,433 --> 00:40:51,233  
at one region in space

1013  
00:40:51,233 --> 00:40:52,566  
and another region of space.

1014  
00:40:52,566 --> 00:40:55,033  
This is--  
this region of space now

1015  
00:40:55,033 --> 00:40:57,866  
I want to be separated  
by about a gigameter,

1016  
00:40:57,866 --> 00:40:58,866  
10 to the 9 meters,

1017  
00:40:58,866 --> 00:41:00,900  
such that if  
a gravitational wave

1018  
00:41:00,900 --> 00:41:04,066  
comes rolling through this--  
this intervening space,

1019  
00:41:04,066 --> 00:41:06,466  
that will lead to  
a relative phase shift

1020  
00:41:06,466 --> 00:41:08,533  
of this interferometer

1021  
00:41:08,533 --> 00:41:10,466  
with respect to  
that interferometer,

1022  
00:41:10,466 --> 00:41:12,000  
that I can observe  
very much like

1023

00:41:12,000 --> 00:41:14,800

the differential phase shift  
that we're observing right now

1024

00:41:14,800 --> 00:41:16,700

in our equivalence  
principle work.

1025

00:41:16,700 --> 00:41:18,700

The only difference is  
these interferometers now

1026

00:41:18,700 --> 00:41:20,333

are separated by  
a long distance

1027

00:41:20,333 --> 00:41:24,866

and I have to correlate the  
phases across that baseline.

1028

00:41:24,866 --> 00:41:27,200

It turns out this is  
a pretty good way

1029

00:41:27,200 --> 00:41:30,400

of detecting  
a gravitational wave.

1030

00:41:30,400 --> 00:41:32,100

If you're building instruments,

1031

00:41:32,100 --> 00:41:35,266

what we propose--are  
essentially proposing doing is

1032

00:41:35,266 --> 00:41:37,366

there's this LISA instrument,  
which is very good

1033

00:41:37,366 --> 00:41:39,500  
for the ultimate  
low frequencies.

1034  
00:41:39,500 --> 00:41:42,966  
We're proposing replacing  
a macroscopic proof mass,

1035  
00:41:42,966 --> 00:41:44,266  
which sits inside the satellite

1036  
00:41:44,266 --> 00:41:45,766  
and which has recently been  
verified

1037  
00:41:45,766 --> 00:41:47,733  
by the LISA Pathfinder  
collaboration,

1038  
00:41:47,733 --> 00:41:50,866  
spectacularly verified,  
with a cloud of atoms.

1039  
00:41:50,866 --> 00:41:52,533  
And due to the atomic physics  
processing,

1040  
00:41:52,533 --> 00:41:54,766  
it turns out we can  
build this antenna

1041  
00:41:54,766 --> 00:41:56,433  
with just two satellites.

1042  
00:41:56,433 --> 00:41:58,533  
The LISA configuration requires  
three satellites,

1043  
00:41:58,533 --> 00:42:00,200  
and from a system engineering

perspective,

1044

00:42:00,200 --> 00:42:03,466  
we think this may be favorable.

1045

00:42:03,466 --> 00:42:05,766  
And if you want to think  
more deeply about this,

1046

00:42:05,766 --> 00:42:07,900  
it turns out the atoms  
are serving as

1047

00:42:07,900 --> 00:42:11,233  
precision proof masses  
and position references

1048

00:42:11,233 --> 00:42:13,366  
and the lasers that we use  
to interrogate the atoms

1049

00:42:13,366 --> 00:42:15,966  
are providing  
a really excellent ruler

1050

00:42:15,966 --> 00:42:18,200  
by which we're--we're  
measuring the time evolution

1051

00:42:18,200 --> 00:42:19,933  
of the two distances

1052

00:42:19,933 --> 00:42:22,033  
as the gravitational wave  
comes through.

1053

00:42:22,033 --> 00:42:23,533  
And if you say,  
well, what--

1054

00:42:23,533 --> 00:42:25,833

how good  
is this telescope?

1055

00:42:25,833 --> 00:42:29,033

The telescope is--I characterize  
it by its frequency

1056

00:42:29,033 --> 00:42:31,666

and its strain response, how big  
of a wave it can measure.

1057

00:42:31,666 --> 00:42:34,133

This is what the LISA antenna  
can do,

1058

00:42:34,133 --> 00:42:36,700

and this is what we think the  
antennas that we are envisioning

1059

00:42:36,700 --> 00:42:37,833

can do.

1060

00:42:37,833 --> 00:42:39,833

And if you want to take that  
a step further,

1061

00:42:39,833 --> 00:42:41,800

there's some new ideas  
we have out there

1062

00:42:41,800 --> 00:42:44,266

where the LISA strain curve  
is sitting up here,

1063

00:42:44,266 --> 00:42:45,800

and what we want to do  
with atoms

1064

00:42:45,800 --> 00:42:48,700

is a couple of orders of  
magnitude better.

1065

00:42:48,700 --> 00:42:50,333

So this is not--this is probably

1066

00:42:50,333 --> 00:42:51,966

the generation of telescopes--

1067

00:42:51,966 --> 00:42:53,600

you know, two generations away.

1068

00:42:53,600 --> 00:42:55,166

LISA has to be built first,

1069

00:42:55,166 --> 00:42:57,866

but eventually, I hope that  
we'll be starting to build

1070

00:42:57,866 --> 00:42:59,900

these gravitational  
wave detectors

1071

00:42:59,900 --> 00:43:01,600

with these atom sensors.

1072

00:43:04,000 --> 00:43:05,766

More practical applications?

1073

00:43:05,766 --> 00:43:07,033

Well, I'm measuring--

1074

00:43:07,033 --> 00:43:08,700

when I build a gravitational  
wave detector,

1075

00:43:08,700 --> 00:43:10,666

I'm measuring perturbations

in space-time

1076

00:43:10,666 --> 00:43:12,700

due to gravity  
very precisely.

1077

00:43:12,700 --> 00:43:14,933

In that case, due to  
a gravitational wave.

1078

00:43:14,933 --> 00:43:17,466

If I have a satellite  
in low-Earth orbit,

1079

00:43:17,466 --> 00:43:19,333

I can do something more mundane.

1080

00:43:19,333 --> 00:43:21,633

I can look at the perturbations  
in the relative positions

1081

00:43:21,633 --> 00:43:23,800

between two clouds of atoms

1082

00:43:23,800 --> 00:43:28,400

this time separated by meters,  
not 10 to the 9 meters.

1083

00:43:28,400 --> 00:43:30,466

In the same way, by building  
two interferometers

1084

00:43:30,466 --> 00:43:32,666

and subtracting,  
and it turns out,

1085

00:43:32,666 --> 00:43:33,666

that makes a very good

1086

00:43:33,666 --> 00:43:35,466  
differential acceleration  
sensor,

1087  
00:43:35,466 --> 00:43:39,100  
which I can use to characterize  
the Earth's gravitational field

1088  
00:43:39,100 --> 00:43:41,600  
and perturbations in  
this gravitational field.

1089  
00:43:41,600 --> 00:43:43,433  
And this is considered  
interesting

1090  
00:43:43,433 --> 00:43:46,400  
because the perturbations  
in the gravitational field,

1091  
00:43:46,400 --> 00:43:47,833  
as observed from orbit,

1092  
00:43:47,833 --> 00:43:51,500  
tell you a lot about  
the mass distribution on Earth.

1093  
00:43:51,500 --> 00:43:53,166  
And we're interested in  
the mass distribution

1094  
00:43:53,166 --> 00:43:55,166  
because some of that mass  
is water,

1095  
00:43:55,166 --> 00:43:57,100  
and as we know,  
due to climate change,

1096  
00:43:57,100 --> 00:43:58,733

that water's moving around.

1097

00:43:58,733 --> 00:44:01,200

And so ice is melting  
in one place,

1098

00:44:01,200 --> 00:44:02,733

it's going someplace else,

1099

00:44:02,733 --> 00:44:04,833

and how can we figure out  
where it's going?

1100

00:44:04,833 --> 00:44:06,400

There's a guy at Goddard,

1101

00:44:06,400 --> 00:44:09,200

and there's some other people  
at JPL looking at this.

1102

00:44:09,200 --> 00:44:10,600

This is--  
this data here is from--

1103

00:44:10,600 --> 00:44:12,666

This analysis is from  
Scott Luthke's group

1104

00:44:12,666 --> 00:44:15,366

at Goddard of where  
they're actually looking at

1105

00:44:15,366 --> 00:44:17,700

the gravity gradient signals  
of--of water table.

1106

00:44:17,700 --> 00:44:20,266

And this is one of the maps  
they generate,

1107

00:44:20,266 --> 00:44:22,866

and, you know, they kind of show  
you the gravity contrast

1108

00:44:22,866 --> 00:44:25,700

from--from water  
as it's moving around.

1109

00:44:25,700 --> 00:44:27,533

And so we're, with NASA Goddard,

1110

00:44:27,533 --> 00:44:29,666

are building an instrument which  
would be a prototype

1111

00:44:29,666 --> 00:44:31,133

for one of these--  
thanks--

1112

00:44:31,133 --> 00:44:35,933

one of these space-based  
gravity gradiometers.

1113

00:44:35,933 --> 00:44:37,633

So I have--  
I have five minutes left,

1114

00:44:37,633 --> 00:44:40,666

and I want to,  
just in this last five minutes,

1115

00:44:40,666 --> 00:44:42,466

change gears a little bit.

1116

00:44:42,466 --> 00:44:45,500

I started the talk  
by telling you about a--

1117

00:44:45,500 --> 00:44:48,200

you know, a story about  
macroscopicity

1118

00:44:48,200 --> 00:44:51,433  
and quantum mechanics  
in terms of distance separation.

1119

00:44:51,433 --> 00:44:52,966  
I want to finish the talk by  
telling you

1120

00:44:52,966 --> 00:44:54,966  
a different type of  
macroscopicity.

1121

00:44:54,966 --> 00:44:57,766  
That is, how can we make states

1122

00:44:57,766 --> 00:45:00,300  
and manipulate states of--  
that are quantum mechanical

1123

00:45:00,300 --> 00:45:03,433  
but contain large ensembles  
of atoms?

1124

00:45:03,433 --> 00:45:04,833  
And the state I'm gonna  
tell you about

1125

00:45:04,833 --> 00:45:07,500  
is one where we have  
collections of atoms,

1126

00:45:07,500 --> 00:45:09,766  
thousands of atoms  
all glued together

1127

00:45:09,766 --> 00:45:11,466  
in a fundamentally

quantum mechanical way

1128

00:45:11,466 --> 00:45:14,933

that--so-called  
entangled states--

1129

00:45:14,933 --> 00:45:16,666

that are doing something  
very useful for us

1130

00:45:16,666 --> 00:45:18,833

in the context  
of interferometry.

1131

00:45:18,833 --> 00:45:21,933

And so my intro to  
this last subject is

1132

00:45:21,933 --> 00:45:24,733

let's talk about noise  
for a little bit.

1133

00:45:24,733 --> 00:45:27,333

When--when we go  
and build our interferometer

1134

00:45:27,333 --> 00:45:29,233

and look at  
an interference fringe,

1135

00:45:29,233 --> 00:45:30,633

we don't measure  
a perfect phase.

1136

00:45:30,633 --> 00:45:33,466

We always get a little noise  
on top of that fringe,

1137

00:45:33,466 --> 00:45:37,100

and I illustrate that

schematically here.

1138

00:45:37,100 --> 00:45:38,266

If I'm building  
an interferometer,

1139

00:45:38,266 --> 00:45:39,833

I don't care  
what interferometer it is,

1140

00:45:39,833 --> 00:45:41,200

I scan the phase,

1141

00:45:41,200 --> 00:45:43,633

I'm detecting some number of  
particles in an exit port,

1142

00:45:43,633 --> 00:45:46,466

and there's always some noise  
at a particular phase.

1143

00:45:46,466 --> 00:45:48,866

Here, I've frozen this--  
this cartoon

1144

00:45:48,866 --> 00:45:51,500

at this particular  
phase value

1145

00:45:51,500 --> 00:45:52,633

and plotted a distribution

1146

00:45:52,633 --> 00:45:55,400

of the number of particles  
that I detect,

1147

00:45:55,400 --> 00:45:56,866

photons or atoms,

1148

00:45:56,866 --> 00:45:58,900  
at an output port,  
and it fluctuates.

1149  
00:45:58,900 --> 00:46:00,600  
It fundamentally  
has to fluctuate

1150  
00:46:00,600 --> 00:46:03,066  
because what I'm doing is  
I'm collapsing wave packets

1151  
00:46:03,066 --> 00:46:06,100  
when those two interfering  
photons or atoms

1152  
00:46:06,100 --> 00:46:07,466  
come back together,

1153  
00:46:07,466 --> 00:46:09,600  
and it's a fundamentally  
statistical process.

1154  
00:46:09,600 --> 00:46:13,266  
Now, that collapse happens often  
in a way

1155  
00:46:13,266 --> 00:46:15,300  
where the statistics between  
one particle and the next

1156  
00:46:15,300 --> 00:46:17,300  
are completely uncorrelated,

1157  
00:46:17,300 --> 00:46:19,366  
and it gives us what's called  
shot noise.

1158  
00:46:19,366 --> 00:46:21,500  
And the--the--

the well-known theory

1159

00:46:21,500 --> 00:46:23,766

which predicts the amount of  
noise you expect to see

1160

00:46:23,766 --> 00:46:25,233

for the number of particles  
you have

1161

00:46:25,233 --> 00:46:28,033

coursing through  
your interferometer.

1162

00:46:28,033 --> 00:46:29,733

And to make a long story short,

1163

00:46:29,733 --> 00:46:32,500

using kind of laser  
and atomic physics techniques,

1164

00:46:32,500 --> 00:46:35,566

we are now manipulating  
that noise

1165

00:46:35,566 --> 00:46:38,333

in--in a fundamentally  
quantum mechanical way

1166

00:46:38,333 --> 00:46:40,700

to reduce the noise  
at the output port

1167

00:46:40,700 --> 00:46:41,766

of the interferometer.

1168

00:46:41,766 --> 00:46:46,566

And just to show you that  
in data,

1169

00:46:46,566 --> 00:46:48,933

this is the output port  
of an interferometer

1170

00:46:48,933 --> 00:46:52,266

which was tuned to operate  
exactly at the mid-phase point

1171

00:46:52,266 --> 00:46:54,500

that I showed you  
on the previous slide.

1172

00:46:54,500 --> 00:46:57,300

And if I use  
just regular atoms,

1173

00:46:57,300 --> 00:47:01,466

not fancily entangled  
or correlated with some tricks

1174

00:47:01,466 --> 00:47:03,200

I don't have time  
to tell you about,

1175

00:47:03,200 --> 00:47:05,733

if I measure the fluctuations,  
I get a distribution

1176

00:47:05,733 --> 00:47:07,666

shown here in blue.

1177

00:47:07,666 --> 00:47:09,000

And those fluctuations

1178

00:47:09,000 --> 00:47:12,000

for virtually every  
interferometric sensor

1179

00:47:12,000 --> 00:47:14,833

that's built today,  
those shot-noise fluctuations

1180  
00:47:14,833 --> 00:47:18,500  
fundamentally limit the  
sensitivity of that instrument.

1181  
00:47:18,500 --> 00:47:21,533  
Now, using  
quantum entanglement tricks,

1182  
00:47:21,533 --> 00:47:24,666  
we now have manipulated this--  
this ensemble of atoms

1183  
00:47:24,666 --> 00:47:28,633  
so that those fluctuations  
are ten times narrower.

1184  
00:47:28,633 --> 00:47:32,000  
And it stands to reason,  
if you're associating with

1185  
00:47:32,000 --> 00:47:34,666  
the mean position of that  
distribution of phase

1186  
00:47:34,666 --> 00:47:36,400  
and you care about  
measuring the phase,

1187  
00:47:36,400 --> 00:47:38,266  
having a narrower distribution

1188  
00:47:38,266 --> 00:47:40,900  
really helps you  
in your precision measurement.

1189  
00:47:40,900 --> 00:47:42,466  
And we demonstrate that

in this data

1190

00:47:42,466 --> 00:47:45,900  
by applying a tiny phase shift  
to this interferometer

1191

00:47:45,900 --> 00:47:47,366  
that shifts this distribution

1192

00:47:47,366 --> 00:47:49,600  
from an output of  
that number of atoms

1193

00:47:49,600 --> 00:47:51,066  
to this number of atoms.

1194

00:47:51,066 --> 00:47:53,700  
This is the number of atoms  
at the output port,

1195

00:47:53,700 --> 00:47:56,300  
and this is the probability of  
observing that number of atoms.

1196

00:47:56,300 --> 00:47:59,366  
This entanglement  
is really helping us.

1197

00:47:59,366 --> 00:48:01,833  
Now, this entanglement,  
this--this correlation

1198

00:48:01,833 --> 00:48:03,833  
of creating these  
correlated states of atoms,

1199

00:48:03,833 --> 00:48:06,966  
which again we do with  
lights and mirrors,

1200

00:48:06,966 --> 00:48:08,366

is doing something amazing

1201

00:48:08,366 --> 00:48:11,800

to a cloud of otherwise

10 to the 5 atoms,

1202

00:48:11,800 --> 00:48:13,966

which are noninteracting.

1203

00:48:13,966 --> 00:48:16,500

What it's doing is they're

making them fundamentally linked

1204

00:48:16,500 --> 00:48:19,033

in a quantum mechanical way so

that when I make a measurement,

1205

00:48:19,033 --> 00:48:21,500

I--if I--if I measure

an atom here,

1206

00:48:21,500 --> 00:48:23,733

somehow that affects

the wave function

1207

00:48:23,733 --> 00:48:26,166

of an atom over there

in--in--in such a way

1208

00:48:26,166 --> 00:48:28,666

that when I measure them all,

I can't--

1209

00:48:28,666 --> 00:48:31,866

they're correlated in such a way

that I can't have fluctuations

1210

00:48:31,866 --> 00:48:36,833

bigger than  
what we observe there.

1211  
00:48:36,833 --> 00:48:39,500  
I've been using this word  
"entanglement" a lot.

1212  
00:48:39,500 --> 00:48:41,300  
This is--I'll skip through this.

1213  
00:48:41,300 --> 00:48:42,833  
We do this with a cavity.

1214  
00:48:42,833 --> 00:48:46,266  
That's what the apparatus  
looks like.

1215  
00:48:49,166 --> 00:48:51,000  
We use this word  
entanglement a lot.

1216  
00:48:51,000 --> 00:48:52,400  
What do I mean by that?

1217  
00:48:52,400 --> 00:48:54,700  
Well, I mean when I try  
and write the wave function

1218  
00:48:54,700 --> 00:48:56,433  
for all those atoms,

1219  
00:48:56,433 --> 00:48:59,166  
and I--if you've had that  
quantum mechanics course,

1220  
00:48:59,166 --> 00:49:01,600  
you write--one particle you  
write its wave function down,

1221

00:49:01,600 --> 00:49:03,600  
and then in the Hilbert space  
you write the wave function

1222  
00:49:03,600 --> 00:49:05,500  
of the next atom down  
and the next atom down.

1223  
00:49:05,500 --> 00:49:07,800  
If they're uncorrelated  
straightforward,

1224  
00:49:07,800 --> 00:49:09,000  
you write the wave function

1225  
00:49:09,000 --> 00:49:10,933  
for all those  
10 to the 5 atoms down.

1226  
00:49:10,933 --> 00:49:13,133  
Once you do this, we call it  
a squeezing operation.

1227  
00:49:13,133 --> 00:49:14,866  
We're squeezing out the noise.

1228  
00:49:14,866 --> 00:49:17,500  
You have trouble writing down  
that wave function in such a way

1229  
00:49:17,500 --> 00:49:20,900  
that you can separate out the  
contributions from each atom

1230  
00:49:20,900 --> 00:49:22,500  
and factorize each atom  
independently.

1231  
00:49:22,500 --> 00:49:25,533  
In fact, for this data, this

analysis shown in this plot,

1232

00:49:25,533 --> 00:49:27,700

says that the wave functions  
for these atoms

1233

00:49:27,700 --> 00:49:29,733

are in--are correlated  
in such a way

1234

00:49:29,733 --> 00:49:33,566

that I can't think of the atoms  
in smaller groups than 1,000

1235

00:49:33,566 --> 00:49:35,266

independently.

1236

00:49:35,266 --> 00:49:36,800

They're--they're--they're  
correlated in clusters

1237

00:49:36,800 --> 00:49:38,333

of at least 1,000 atoms.

1238

00:49:38,333 --> 00:49:39,600

This is like a world record

1239

00:49:39,600 --> 00:49:41,666

for quantumness  
of ensembles of atoms.

1240

00:49:41,666 --> 00:49:43,966

And what's--what's interesting,

1241

00:49:43,966 --> 00:49:46,666

if you've read about quantum  
computers and things like that,

1242

00:49:46,666 --> 00:49:48,600

it's this very  
entanglement property

1243  
00:49:48,600 --> 00:49:51,400  
which is thought to be--  
gonna be useful

1244  
00:49:51,400 --> 00:49:53,200  
for speeding up computation.

1245  
00:49:53,200 --> 00:49:55,700  
Well, for building sensors,  
it's also useful.

1246  
00:49:55,700 --> 00:49:58,266  
And if by reliably  
entangling the particles,

1247  
00:49:58,266 --> 00:50:00,733  
I can dramatically reduce  
the sensor noise,

1248  
00:50:00,733 --> 00:50:02,566  
making a better sensor  
and actually making

1249  
00:50:02,566 --> 00:50:05,466  
these fancy ideas  
of quantum mechanics useful.

1250  
00:50:05,466 --> 00:50:08,133  
And so this work is  
demonstrating macroscopicity

1251  
00:50:08,133 --> 00:50:09,366  
in a different way.

1252  
00:50:09,366 --> 00:50:11,900  
I now have 1,000-atom  
quantum systems

1253

00:50:11,900 --> 00:50:14,466

truly behaving as quantum.

1254

00:50:14,466 --> 00:50:17,900

At that, I have to thank

the people in my research group

1255

00:50:17,900 --> 00:50:20,000

and my theory collaborations--  
collaborators,

1256

00:50:20,000 --> 00:50:21,966

and you guys

for your attention.

1257

00:50:21,966 --> 00:50:25,200

[applause]

1258

00:50:25,200 --> 00:50:27,300

- Thank you very much.

Thank you.

1259

00:50:29,000 --> 00:50:30,400

So we have time

for a few questions.

1260

00:50:30,400 --> 00:50:32,466

If you have a question,

please raise your hand,

1261

00:50:32,466 --> 00:50:35,900

wait for the microphone,

and ask one question only.

1262

00:50:35,900 --> 00:50:37,866

Thank you.

1263

00:50:45,033 --> 00:50:47,300

This, up front here.

1264

00:50:54,700 --> 00:50:56,733

- Thank you.

1265

00:50:56,733 --> 00:50:58,233

Thank you for  
interesting talk.

1266

00:50:58,233 --> 00:51:02,733

You mentioned this  
very sensitive accelerometer

1267

00:51:02,733 --> 00:51:08,133

based on atomic interferometry,

1268

00:51:08,133 --> 00:51:12,000

but they all required  
this cryogenic,

1269

00:51:12,000 --> 00:51:16,500

very low temperature  
sort of operation, right?

1270

00:51:16,500 --> 00:51:20,300

So you cannot make them  
very small.

1271

00:51:20,300 --> 00:51:22,566

They should be heavy.  
They should be bulky.

1272

00:51:22,566 --> 00:51:25,966

So how can you put something  
that big

1273

00:51:25,966 --> 00:51:28,033

to satellites or...

1274

00:51:28,033 --> 00:51:31,133

- Yeah, so when we say  
ultracold,

1275

00:51:31,133 --> 00:51:33,400

the only cryogen  
I'm using is laser light.

1276

00:51:33,400 --> 00:51:36,833

So I need  
a single-frequency laser

1277

00:51:36,833 --> 00:51:38,733

which is, you know,  
smaller than my--

1278

00:51:38,733 --> 00:51:40,166

the semiconductor laser  
flash

1279

00:51:40,166 --> 00:51:42,033

is smaller than my thumbnail,  
and it's the interaction

1280

00:51:42,033 --> 00:51:43,866

of the laser light  
with the atom cloud

1281

00:51:43,866 --> 00:51:45,700

that reduces their temperature.

1282

00:51:45,700 --> 00:51:49,033

And so the smallest sensors now

1283

00:51:49,033 --> 00:51:51,800

are approaching the size  
of my fist.

1284

00:51:51,800 --> 00:51:53,566

I showed you that--

that gravimeter,

1285

00:51:53,566 --> 00:51:56,300

which is about the size of  
a two-liter Coke bottle.

1286

00:51:56,300 --> 00:51:58,666

And as we, you know,

1287

00:51:58,666 --> 00:52:00,533

kind of start engineering these

1288

00:52:00,533 --> 00:52:04,400

and use--replace  
kind of bulk optics

1289

00:52:04,400 --> 00:52:07,166

with integrated photonics,  
which we're now manufacturing

1290

00:52:07,166 --> 00:52:09,433

with some partners  
in the valley,

1291

00:52:09,433 --> 00:52:13,166

and state-of-the-art  
semiconductor laser sources,

1292

00:52:13,166 --> 00:52:16,066

the size of these sensors  
is being crushed.

1293

00:52:16,066 --> 00:52:17,133

They're really becoming small.

1294

00:52:17,133 --> 00:52:19,266

In fact, there are some--

1295

00:52:19,266 --> 00:52:23,000

AOSense and my interest aren't  
in making them tiny, tiny, tiny,

1296  
00:52:23,000 --> 00:52:24,566  
like competing with  
MEMS sensors.

1297  
00:52:24,566 --> 00:52:28,400  
We want them to be big enough  
to be high performance.

1298  
00:52:28,400 --> 00:52:32,200  
But we have gyroscopes now that  
are about--about this big

1299  
00:52:32,200 --> 00:52:34,533  
that have performance figures  
of merit

1300  
00:52:34,533 --> 00:52:36,866  
that are really  
pretty extraordinary.

1301  
00:52:36,866 --> 00:52:41,400  
So it's all about, you know,  
engineering with optics,

1302  
00:52:41,400 --> 00:52:43,133  
and the--

1303  
00:52:43,133 --> 00:52:45,133  
that's--that's the main  
technical challenge.

1304  
00:52:45,133 --> 00:52:47,666  
There's a little bit  
of new engineering knowledge

1305  
00:52:47,666 --> 00:52:49,166  
that we have to gain,

1306

00:52:49,166 --> 00:52:51,000

figuring out how to make  
reliable sources of atoms

1307

00:52:51,000 --> 00:52:52,666

and all the rest.

1308

00:52:52,666 --> 00:52:55,900

Much of that draws on some work  
from the atomic clock community

1309

00:52:55,900 --> 00:52:58,233

in the--in the '50s.

1310

00:52:58,233 --> 00:53:00,100

Another way of answering  
your question is,

1311

00:53:00,100 --> 00:53:02,400

you're comfortable with going  
out and buying an optical--

1312

00:53:02,400 --> 00:53:05,000

I'm sorry, an atomic clock from,

1313

00:53:05,000 --> 00:53:06,966

used to be Hewlett-Packard

1314

00:53:06,966 --> 00:53:09,800

and now it's Microsemi,  
that's rack mounted.

1315

00:53:09,800 --> 00:53:12,200

That, you know,  
and has a beam of atoms in it

1316

00:53:12,200 --> 00:53:13,800

and it's interrogated,

1317

00:53:13,800 --> 00:53:15,833  
and kind of what we're doing  
is very similar.

1318

00:53:15,833 --> 00:53:17,766  
But we do not need  
liquid helium.

1319

00:53:17,766 --> 00:53:19,333  
[laughs]

1320

00:53:27,433 --> 00:53:29,900  
- If you can entangle  
1,000 atoms,

1321

00:53:29,900 --> 00:53:32,100  
any chance of using this

1322

00:53:32,100 --> 00:53:34,333  
in quantum computing  
in the near future?

1323

00:53:34,333 --> 00:53:35,500  
- For what?

1324

00:53:35,500 --> 00:53:37,433  
- Quantum computing.  
Quantum computer.

1325

00:53:37,433 --> 00:53:38,733  
- Oh, that's  
an interesting question.

1326

00:53:38,733 --> 00:53:40,466  
So what are the links between--

1327

00:53:40,466 --> 00:53:42,166  
the field I just discussed

1328

00:53:42,166 --> 00:53:44,833  
is receiving a great deal  
of interest right now,

1329

00:53:44,833 --> 00:53:46,566  
it's called quantum metrology,

1330

00:53:46,566 --> 00:53:50,066  
and that's using entanglement to  
improve performance of sensors,

1331

00:53:50,066 --> 00:53:52,900  
but we all sort of also want  
to build a quantum computer.

1332

00:53:52,900 --> 00:53:55,400  
And so what's the link between  
this kind of entanglement

1333

00:53:55,400 --> 00:53:58,433  
and the entanglement you need  
for quantum computation?

1334

00:53:58,433 --> 00:54:01,800  
Well, I view it as a baby step  
towards a quantum computer.

1335

00:54:01,800 --> 00:54:04,833  
So a quantum computer,  
you have to go in there

1336

00:54:04,833 --> 00:54:08,000  
and reliably entangle  
determine--

1337

00:54:08,000 --> 00:54:09,800  
almost deterministically,  
I should say,

1338

00:54:09,800 --> 00:54:12,333

the way functions of--  
of each and every atom

1339

00:54:12,333 --> 00:54:14,400

in a way that you--  
you sort of understand.

1340

00:54:14,400 --> 00:54:16,433

Here I have this grab bag  
of atoms

1341

00:54:16,433 --> 00:54:18,666

that are sort of magically  
being entangled

1342

00:54:18,666 --> 00:54:20,900

but in a way that I have even  
trouble writing down

1343

00:54:20,900 --> 00:54:22,400

what the wave function is.

1344

00:54:22,400 --> 00:54:23,733

So there's a big step between

1345

00:54:23,733 --> 00:54:25,733

what I've just demonstrated  
to you and--demonstrated

1346

00:54:25,733 --> 00:54:29,233

and the type of entanglement  
you need for a quantum computer.

1347

00:54:29,233 --> 00:54:32,200

Nonetheless, there are--

1348

00:54:32,200 --> 00:54:34,166

if you follow this field,

there's a lot of discussion

1349

00:54:34,166 --> 00:54:37,533  
about what makes a good qubit  
for a quantum computer,

1350

00:54:37,533 --> 00:54:40,200  
how you're gonna error-correct  
that qubit and so forth.

1351

00:54:40,200 --> 00:54:43,433  
And some of these  
cavity atom ideas

1352

00:54:43,433 --> 00:54:45,866  
are interesting players  
in that discussion,

1353

00:54:45,866 --> 00:54:47,600  
but it gets pretty technical  
and, you know,

1354

00:54:47,600 --> 00:54:50,300  
you have to talk about the gate  
fidelities and things like that,

1355

00:54:50,300 --> 00:54:54,000  
and it boils down to a bunch of  
technical details

1356

00:54:54,000 --> 00:54:55,466  
that maybe aren't, you know,

1357

00:54:55,466 --> 00:54:57,666  
they're surprising  
on first blush.

1358

00:54:57,666 --> 00:55:01,633  
So part of my program is  
to--to--to figure out

1359

00:55:01,633 --> 00:55:04,666

what role this type of  
entanglement might have

1360

00:55:04,666 --> 00:55:07,133

in quantum computation,  
and I say that.

1361

00:55:07,133 --> 00:55:09,800

I'm much more optimistic  
about other systems than that

1362

00:55:09,800 --> 00:55:11,466

for quantum computation.

1363

00:55:11,466 --> 00:55:13,733

Thank you.

1364

00:55:13,733 --> 00:55:15,433

- Okay, so please join me

1365

00:55:15,433 --> 00:55:18,066

in thanking Dr. Kasevich  
for an excellent talk.

1366

00:55:18,066 --> 00:55:19,266

Thank you.

- Thank you.

1367

00:55:19,266 --> 00:55:21,400

[applause]