WEBVTT

1
00:00:03.750 --> 00:00:05.970
Jason Hogan: Okay, so hopefully you can see my slides.

2
00:00:11.250 --> 00:00:12.090
Jason Hogan: Yeah okay so

3
00:00:13.469 --> 00:00:25.860
Jason Hogan: I'm here to tell you about some as, as mentioned some some some fairly new ideas are for for detecting gravitational waves. And so, so I'll tell you about this technique using an admin from a tree.

4
00:00:26.280 --> 00:00:37.590
Jason Hogan: And a little bit how Adam interferometer his work and and sort of what the idea is that we have vision for a future detector based on this technology that could have some interesting science implications. So

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00:00:39.060 --> 00:00:43.950
Jason Hogan: Maybe just a word on this, on this image here that you're looking at. So this is some data from an Adam interferometer

6
00:00:44.430 --> 00:00:55.200
Jason Hogan: From one of our labs at Stanford and and what you see here on these, these two sort of clouds there. So this is basically looking at Adam and Adam interference pattern or matter. We've interference pattern.

7
00:00:55.560 --> 00:01:03.360
Jason Hogan: And you see these fringes that. So these are the minimum and maximum you see here on the on these two clouds as the result of constructive and destructive inner interference.

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00:01:03.660 --> 00:01:09.750
Jason Hogan: Of matter waves. And by looking at where these minima are on these two clouds, where the peaks and the troughs are

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00:01:10.470 --> 00:01:20.070
Jason Hogan: That that can allow us to measure very small forces that that the atoms field during the, during, during, during an admin frommer and essentially, let us look for

10
00:01:20.430 --> 00:01:35.490

Jason Hogan: A variety of interesting science signals, including potentially gravitational waves. And so just to mention a little bit about that breath here before sort of focusing mostly on gravitational waves in this talk. So there's sort of a variety of

11
00:01:36.990 --> 00:01:52.710
Jason Hogan: I guess generally fundamental questions that we think there's something interesting. You can say, or potentially studying with this technology with atomic sensing and so I mentioned a couple of these today in passing. So in addition to gravitational waves.

12
00:01:54.120 --> 00:02:02.790
Jason Hogan: Essentially, you can use these these instruments to test gravity and study the things like the equivalent principal and more generic test of general relativity

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00:02:03.840 --> 00:02:14.250
Jason Hogan: You can look for tests of quantum mechanics as all described, we can manipulate Adam We functions in sort of interesting ways into the sort of macroscopic

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00:02:14.640 --> 00:02:19.380
Jason Hogan: Regime. So what I mean by that, if you see this image down in the bottom right. This is some data.

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00:02:19.680 --> 00:02:27.930
Jason Hogan: Taken from the same experiment as that on the on the first slide. And so you see a sort of a spike in the foreground. Another spike in the background. And this is sort of an image.

16
00:02:28.200 --> 00:02:41.310
Jason Hogan: Of an atom, an atom that's in a superposition are really an ensemble atoms in a superposition with a macroscopic separation in this case of over half a meter between these two halves of the atoms wave function. And so that's sort of getting into this

17
00:02:42.360 --> 00:02:50.880
Jason Hogan: Some fairly large spatial regime and LSE if quantum mechanics is behaving the way we expect on those tunneling skills.

18
00:02:51.840 --> 00:02:59.730
Jason Hogan: And I'll say a little bit also about the prospects for for dark matter detection using this technology, in particular the gravitational wave

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00:03:00.210 --> 00:03:16.950
Jason Hogan: Detector concept that all describe it turns out in doubles as a as a search for dark matter, which is kind of great for have a two for one instrument. And so, but anyway, just wanted to mention a little bit about the breadth of what we can do and this is maybe even an incomplete list.

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00:03:18.090 --> 00:03:25.350
Jason Hogan: OK, so now mainly focusing on gravitational waves for the rest of the talk, mostly. So this is the gravitational wave

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00:03:26.430 --> 00:03:33.810
Jason Hogan: Spectrum, more or less, or big chunk of it. So you see the strain versus frequency of gravitational waves.

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00:03:34.680 --> 00:03:41.520
Jason Hogan: And just to sort of calibrate you there's a couple of detectors drawn on here that are familiar so

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00:03:41.910 --> 00:03:50.730
Jason Hogan: In the higher frequency range we have advanced Lego and detector. So that's sort of in the above 10 Hertz two kilo hertz range sort of over here.

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00:03:51.450 --> 00:03:58.590
Jason Hogan: Which is where all the exciting developments have been happening in terms of detecting the first signals and sort of in the middle of this chart here.

25
00:03:59.040 --> 00:04:08.310
Jason Hogan: Is as a spacecraft original a protector, such as Lisa, which are best served in the middle. Hertz range below, like maybe a 10th of a hertz.

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00:04:08.880 --> 00:04:13.140
Jason Hogan: And then a very low frequencies we have a pulse our timing your rate instrument.

27
00:04:13.830 --> 00:04:26.010
Jason Hogan: And so I guess what I want to focus on is sort of what I consider a sort of salient gap between these two space basic ground based detectors, sort of in this range here, which I've labeled the mid band.

28
00:04:26.370 --> 00:04:33.810

Jason Hogan: From about fraction of a hurts to a few hurts, maybe going down to its lowest point of three Hertz. A 4.1 hurts.

29
00:04:34.380 --> 00:04:41.610
Jason Hogan: Where there's not great coverage from either sort of the Lego Virgo detector and and Lisa

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00:04:42.000 --> 00:04:55.230
Jason Hogan: And it turns out that this is where we think the adamant prefer a metric approach that all scribe could do a really great job of looking for gravitational waves and maybe fill this gap, basically in the future. So I guess.

31
00:04:56.130 --> 00:05:08.520
Jason Hogan: Well, I have to tell you how that would work. But maybe before we do that, say a little bit about why we might care. Is there anything interesting science wise in this band between a fraction of a hurts and a few hurts.

32
00:05:10.260 --> 00:05:19.080
Jason Hogan: And so there's actually a lot of really interesting sources in the mid band gravitational wave spectrum. Turns out, and maybe just as a general point

33
00:05:19.650 --> 00:05:29.010
Jason Hogan: You know, it's always good to keep an open mind about any new band that hasn't been explored and it's been the case. Historically, and the optical every time we look for electromagnetic waves.

34
00:05:29.280 --> 00:05:40.320
Jason Hogan: We look in different frequency ranges. We tend to find things we don't expect. So that's just a general reason for looking as broadly as you as you can and trying to fill any gaps in your ability to detect these signals.

35
00:05:41.010 --> 00:05:44.970
Jason Hogan: But it turns out there are actually a lot of known sources as well. So in particular,

36
00:05:45.720 --> 00:06:03.330
Jason Hogan: There are the sort of compact binary sources that we think about with respect to Lego such as a black hole binaries a neutron star binaries etc that will show up in the mid band and the key idea here is the

37

00:06:04.410 --> 00:06:10.980
Jason Hogan: Something something sort of important about how the sources that make it into the Lego band evolve in time. So if you have

38
00:06:11.520 --> 00:06:25.650
Jason Hogan: For example, a black hole binary that Legos able to see it really starts to see it above about 10 her too. So like I said, that's when Lego sensitivity kicks in. And so that's a, you know, multiple maybe 10 solar mass each

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00:06:26.310 --> 00:06:35.010
Jason Hogan: Binary pair of black holes orbiting at 10 Hertz that system is very much near the end of its life. It's about to inspire and coalesce

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00:06:35.970 --> 00:06:47.850
Jason Hogan: And that's what legacies that last final burst, but such a source would have started off its life with a much lower orbital frequency would have been further apart and it takes

41
00:06:48.870 --> 00:06:58.890
Jason Hogan: A very long time for it to, you know, evolve towards the Lego band and the process of moving, excuse me, as the process of slowly losing energy by gravitational waves and

42
00:07:00.780 --> 00:07:07.020
Jason Hogan: increasing its frequency of orbit and moving towards the Lego bad as it does that it would sweep through

43
00:07:07.260 --> 00:07:14.370
Jason Hogan: This mid band. So starting at much lower frequencies, it would come through the mid band and then eventually, it would be detected in the Lego ban and so

44
00:07:14.880 --> 00:07:26.100
Jason Hogan: So it's sort of interesting is that you can detect in principle the same sources that Lego has been seeing or many of the same sources. The Lego has been seeing you can detect them in the mid band with some kind of mid band detector.

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00:07:26.820 --> 00:07:33.510
Jason Hogan: This goes for any technology, even though I'm focusing on Adam interferometry, I think this is a general point that we should keep in mind.

46
00:07:33.810 --> 00:07:45.510

Jason Hogan: That there's these signals are coming through there and that in turn gives you a great way to predict and do multi messenger astronomy, essentially. And so what I have on here is

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00:07:46.260 --> 00:07:55.200
Jason Hogan: Parameter estimation and and sky localization. So I really want to focus on Sky localization basically figuring out where an event is

48
00:07:55.890 --> 00:08:01.980
Jason Hogan: And so like already can do this really well you using the two Lego detectors, they look at the time delay.

49
00:08:02.730 --> 00:08:09.900
Jason Hogan: Or an excuse me, and I should saying, you know, more and more detectors coming online. So, including Virgo as well and other detectors as the, as are added to the network.

50
00:08:10.650 --> 00:08:19.920
Jason Hogan: You look at the time to live arrival of the signal of these different detectors and that can be used to back out where this guy, the source must be I'm just using the speed of light delay.

51
00:08:21.450 --> 00:08:24.870
Jason Hogan: The exciting thing would be is that you could predict

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00:08:26.100 --> 00:08:42.060
Jason Hogan: Where an event would be before it reached the Lego band before the actual merger event. And so the dream scenario in my mind at least, would be to use a detector in the mid band to localize a source to figure out where in the sky sources.

53
00:08:43.260 --> 00:08:49.830
Jason Hogan: Good enough that you could point optical telescopes electromagnetic telescopes in that in that patch of sky.

54
00:08:50.280 --> 00:08:57.450
Jason Hogan: Before the inspire has occurred. And so then when it finally does reach the Lego band and Lego detects the coalescence

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00:08:57.780 --> 00:09:05.550
Jason Hogan: You would be able to watch at the same time the electromagnetic analogs of that in spiral and that would be, I think, really, really exciting multiple astrophysics.

56
00:09:05.940 --> 00:09:10.800
Jason Hogan: Already we've seen how how exciting this can be by looking at the neutron star in spirals.

57
00:09:11.550 --> 00:09:18.930
Jason Hogan: That likewise detected. Although, in that case, it's really after the fact, or inspire others would detect and then you have to rapidly trying to determine where was

58
00:09:19.140 --> 00:09:25.110
Jason Hogan: And then point the telescopes there to see the after aftermath. But in principle you could see it at certain real time.

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00:09:25.770 --> 00:09:36.660
Jason Hogan: And so it turns out that the mid band is, in fact, arguably, the optimal frequency range to do this determination to figure out where in the sky, an event.

60
00:09:37.140 --> 00:09:45.510
Jason Hogan: Is it is going to be. And the reason for that is twofold. So basically, the ability to localize depends on on two parameters.

61
00:09:46.380 --> 00:09:54.330
Jason Hogan: The wavelength of the of the of the gravitational waves. So the shorter the wavelength that the better you can figure out where it is. I think that's somewhat intuitive.

62
00:09:55.080 --> 00:10:00.030
Jason Hogan: But the other parameter that's relevant is the spacing between the detector. So in the case of Lego

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00:10:00.270 --> 00:10:06.060
Jason Hogan: And Virgo and sort of on the order of the size of the Earth. You know me thousands of kilometers is the maximum delay.

64
00:10:06.270 --> 00:10:13.770
Jason Hogan: That you can use and that sort of them that you know you important factor for determining that the localization, the ratio of the wavelength to that separation is sort of the figure of merit.

65
00:10:14.670 --> 00:10:18.750
Jason Hogan: But it turns out that you can do better than that. And the idea here is that

66
00:10:19.500 --> 00:10:28.080
Jason Hogan: If you have a source of gravitational waves that persists for rather than just a few seconds, like in the Lego band, but for many weeks or even months.

67
00:10:28.530 --> 00:10:34.260
Jason Hogan: Then you can use the fact that the, the earth is orbiting the Sun to get an increase letter arm.

68
00:10:34.620 --> 00:10:41.700
Jason Hogan: And so when you imagine is a detector, either on the earth, or maybe in orbit around the Earth for space based version of this, this concept.

69
00:10:42.210 --> 00:10:50.640
Jason Hogan: And if you detect the same signal in, you know, six months apart then essentially you essentially have two detectors that are separated by

70
00:10:51.390 --> 00:10:58.680
Jason Hogan: You know, the, the earth son separation and astronomical unit. So it's very large spacing that you're effectively able to synthesize

71
00:10:59.400 --> 00:11:07.290
Jason Hogan: A very large, you know, set up detectors by comparing them in time, like that. And so that gives a big improvement. And so what you want is

72
00:11:07.650 --> 00:11:19.050
Jason Hogan: To optimize localization. You want to thank short wavelengths, but also sources that persist, a long time so you can orbit the sun. And so the mid band is where these two sort of optimize basically

73
00:11:19.590 --> 00:11:26.310
Jason Hogan: The mid band is higher frequency than you would get for Lisa, which is, you know, in the lower frequency range. That means the wavelengths are a little bit shorter.

74
00:11:26.760 --> 00:11:35.130
Jason Hogan: Course Lego the waves or even shorter, and that would be, in principle, better for that but but then the separation can't be as good because the sources. Don't let live long enough.

75
00:11:35.400 --> 00:11:40.650
Jason Hogan: To have the Earth orbit the Sun very much in the case of Lego. So they're limited by the separation, the physical separation between

76
00:11:41.010 --> 00:11:50.520
Jason Hogan: The detectors. And so the mid band is kind of the sweet spot between those two events. And so we think that in principle with such a detector, it will be possible to get better than a square degree.

77
00:11:50.850 --> 00:12:01.320
Jason Hogan: Of sky localization, which is kind of what you want to for many optical detectors to be able to reliably point in the direction where it's going to be so. So this is sort of focusing in on this.

78
00:12:01.770 --> 00:12:10.410
Jason Hogan: Thing. It's really interesting physics. And once again, a general point about mid band detection. So let me let me shift gears and talk now about the technology.

79
00:12:11.460 --> 00:12:20.460
Jason Hogan: That we're proposing to develop for a future detector in this band. And so it's you know it's generally speaking, an atomic sensor.

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00:12:20.880 --> 00:12:27.300
Jason Hogan: So I've got here atomic interferometry and clocks, which are which are closely related tools and just to kind of prime you here.

81
00:12:27.720 --> 00:12:41.430
Jason Hogan: So atomic clocks are really good their best, the best atomic clocks in the world now lose less than one seconds in 2018 seconds. They've a fractal fractal frequency stability of better than 10 to the minus

82
00:12:43.080 --> 00:12:57.450
Jason Hogan: 18. And so, so that means that you know you lose back basically a second in the lifetime of the universe. So the, so the motivation is with that kind of tiny precision, maybe we can do some extra in physics, and I'll show you how many we can do that.

83
00:12:58.980 --> 00:13:11.430
Jason Hogan: So the, the principle that all describe the concept is generally we're calling me just, which I'll describe what that means

later. So this added her from her approach. It uses the same physics as as these optical lattice box that has such such great timing precision.

84
00:13:13.050 --> 00:13:14.790
Jason Hogan: animator for amateurs, which is that sort of the

85
00:13:15.210 --> 00:13:24.420
Jason Hogan: Right, I got a little graph, you're showing that the strontium barium strontium is the atom of choice for some of the best blocks in the world is a very narrow along the transition here. I'll say more about that.

86
00:13:25.260 --> 00:13:34.350
Jason Hogan: Adam interferometry, which I'll describe briefly is a way to essentially realize excellent inertial references which is another thing you need for gravitational a protection protectors.

87
00:13:34.770 --> 00:13:40.320
Jason Hogan: And then finally we're going to be using the concept. So combining Adam and from which is with this idea of the gradiometer

88
00:13:40.770 --> 00:13:51.330
Jason Hogan: Which is basically to Adam interferometer separated by some large baseline, which will serve as the as the baseline for the gravitational wave detector in this case and interrogating them with common

89
00:13:51.900 --> 00:13:57.390
Jason Hogan: With a common laser to to eliminate sources of technical noise. So that's kind of a big picture of the technology.

90
00:13:58.140 --> 00:14:02.310
Jason Hogan: And I'll dive into, particularly the admin or from a tree right now and a little more detail so

91
00:14:02.940 --> 00:14:14.700
Jason Hogan: For those of you that are unfamiliar with Adam interferometry, this is a brief intro by way of analogy with optical interferometry, so this is a at the top here is an optical mock sender interferometer

92
00:14:15.510 --> 00:14:23.610
Jason Hogan: So we have lights incident on a beam splitter which divides like two pounds. You can bring it around smears, and then that gets the two paths to cross.

93
00:14:24.180 --> 00:14:33.030
Jason Hogan: But those two paths do not interfere unless you add a beam splitter second beam splitter here. So that's what I've got. And then now you can essentially measure

94
00:14:33.690 --> 00:14:37.470
Jason Hogan: You can you can stay as interferometer by looking at how much light and each of these two output ports.

95
00:14:37.800 --> 00:14:46.740
Jason Hogan: And the amount the ratio of the light between those two ports depends on on the face difference between these two arms, you know, the optical path like difference. And so, so

96
00:14:47.310 --> 00:14:58.980
Jason Hogan: I guess that's one thing you can do is just look at the intensity. Another thing you can do is you can actually look spatially at the interference pattern at one of the ports. And that's what you see here, and you might see something like these circular light fringes.

97
00:15:00.090 --> 00:15:04.170
Jason Hogan: Which you can use also to study the the interference pattern between these two paths.

98
00:15:04.740 --> 00:15:11.190
Jason Hogan: So that's what I learned from it or we can do actually turns out the same thing with Adam. So rather than using language. We've matter waves to

99
00:15:11.790 --> 00:15:18.120
Jason Hogan: To build interferometer and this is the same kind of mock center geometry where you have to pass, but in this case we have an atom.

100
00:15:18.420 --> 00:15:23.430
Jason Hogan: Atom is going to be split somehow I say how that works in a second. We want to send the atom along the upper path.

101
00:15:23.820 --> 00:15:30.630
Jason Hogan: And a lower path using some kind of beam splitter some kind of mirrors. Some Adam optics. Basically, we need to redirect the path of the atom.

102
00:15:30.930 --> 00:15:39.150

Jason Hogan: And ultimately, once again, we need a second beam splitter to interfere. The two arms, just like we did with lights and then and then in this case the

103
00:15:39.450 --> 00:15:48.420
Jason Hogan: What happens with an admin or founders, we look at rather than rather than intensity of light at these two outputs. What we study is how many outcomes. We get a really the probability of detecting an atom.

104
00:15:48.990 --> 00:15:57.630
Jason Hogan: Based on its way function squared. And each of these two ports and by just counting how many items. Again, those directions. It tells us about the phase shift of this advert for her.

105
00:15:58.380 --> 00:16:08.100
Jason Hogan: And finally, to complete the analogy, we have this this picture here. So, Madam interference patterns spatially so this would be at one of the ports, you can get a similar thing to the circular fringes.

106
00:16:08.520 --> 00:16:13.050
Jason Hogan: Were here you see these nodes. These black lines and the red and blue.

107
00:16:13.980 --> 00:16:21.870
Jason Hogan: Stripes indicate the fringes, and they're different colors are anti correlated. So you see more items in the blue region when they're less atoms in the red region.

108
00:16:22.110 --> 00:16:30.840
Jason Hogan: And so this is a fringe pattern, very much like what I showed them on the front slide, we can look at the phase of this interferometer by studying either these fringes are looking at the intensity ratio.

109
00:16:31.170 --> 00:16:39.690
Jason Hogan: For the item number ratio between sports and that phase shift it turns out is going to encode all the physics that we're interested in for in this case graduate detection.

110
00:16:40.590 --> 00:16:49.260
Jason Hogan: So a word on on Adam optics. So, how we realized the beam splitters and mirrors of a matter we have interferometer we use to fundamental process.

111

00:16:49.830 --> 00:16:59.220
Jason Hogan: Matter Adam light interactions. So one is light absorption. So the idea here is if we send in a photon with which has momentum a spark a

112
00:16:59.910 --> 00:17:03.600
Jason Hogan: To an atom. So this is a little cartoon of an atom, a two level item.

113
00:17:04.410 --> 00:17:09.480
Jason Hogan: With these two lines of the levels and then the blue.is to indicate that the atoms in the ground state initially

114
00:17:09.840 --> 00:17:15.750
Jason Hogan: And so if this photon is on resonance. The outer can absorb that photon and it'll transition into the red excited state.

115
00:17:16.200 --> 00:17:24.180
Jason Hogan: But in addition, the key point here is that there's momentum, especially with that that light pulse. And so if the animals orbs that photon and has to be

116
00:17:24.630 --> 00:17:27.750
Jason Hogan: You know, to conserve I met someone has to be moving with some velocity, which we call

117
00:17:28.140 --> 00:17:34.470
Jason Hogan: The require velocity a spark a over em, the mass of the atom. And so that's essentially we can push the atom around with the pulse of light.

118
00:17:34.740 --> 00:17:41.160
Jason Hogan: And then mechanical motion is essentially how we realize the beam splitter. We can split atoms, by giving them a little kicks.

119
00:17:41.610 --> 00:17:47.370
Jason Hogan: So that's processed one and process to sort of the reverse of that if we haven't added that's in the excited state. The red excited state here.

120
00:17:47.610 --> 00:17:51.510
Jason Hogan: Moving to the right, let's say, and we bring in another photon, this time.

121

00:17:51.750 --> 00:18:01.440
Jason Hogan: That can cause the stimulated admission, where the atom gives us energy admits this photon into the beam and returns to the ground state at rest. So these are complementary process and by

122
00:18:01.800 --> 00:18:14.400
Jason Hogan: Using our controlling our laser pulse duration intensity. It turns out we have deterministic control over where we lie on on this Robbie oscillation curve. So what that means is

123
00:18:14.910 --> 00:18:23.400
Jason Hogan: You see here the probability of finding an atom in one of these two states, the red or the blue state as a function of time. And so initially

124
00:18:23.670 --> 00:18:32.370
Jason Hogan: Hundred percent the address in the ground state zeros and the excited state as we leave the leaves are on for more time, there's this Robbie oscillation, which is the population starts to

125
00:18:33.540 --> 00:18:42.360
Jason Hogan: Turn into a superposition of these two states. And if we choose the time appropriately so called pi over to pulse duration, then the animal beanie.

126
00:18:43.020 --> 00:18:56.970
Jason Hogan: superposition state one and stage two and therefore, half the atom will be moving a little bit different philosophy than the other half. And so we call that a beam splitter once again we can choose that duration and be sure that we're in this superposition state every time.

127
00:18:58.890 --> 00:19:06.240
Jason Hogan: If we want to we want to implement a mirror, we leave the light on for twice as long, and make a pipe holes and that basically takes out of that we're in the ground state and flips them.

128
00:19:06.750 --> 00:19:17.040
Jason Hogan: To the, to the excited state with 100% probability nominally. So that's the atom optics and so we can combine these two make a mock center interferometer so we started off with an atom.

129
00:19:17.520 --> 00:19:23.760
Jason Hogan: Over here on the left side is the same cartoon again. But now I'll walk through and the quantum mechanics of these, uh, these beams flares and mirrors.

130
00:19:24.180 --> 00:19:31.020
Jason Hogan: So the first the first pulse. The beam splitter pulse we call the pirate to pulse and that puts us once again in a superposition

131
00:19:31.320 --> 00:19:35.730
Jason Hogan: Of the two states in here I'm just noting that we've absorbed momentum ah parquet

132
00:19:36.000 --> 00:19:46.050
Jason Hogan: In the red state that's excited absorb light. And so that's moving at a higher velocity. And as a result in on this FaceTime diagram. So this is the time on the horizontal axis position running vertically

133
00:19:46.560 --> 00:20:01.350
Jason Hogan: You can see that the atom was in path was initially at rest, which is sitting here at a fixed position now half of the atom that's the red line is moving with a different slope has a higher velocity by the recall velocity. So that's, we get this mechanical splitting between the two halves.

134
00:20:02.520 --> 00:20:13.590
Jason Hogan: And then the other half is still in stay P which is a rest. In this example, we can evolve some fears delta phi between these two arms and that delta phi is where all the physics is encoded that we want to study.

135
00:20:14.430 --> 00:20:20.250
Jason Hogan: So at some after some time t, where those splitting has reached the biggest point. We're gonna let it get

136
00:20:20.580 --> 00:20:28.230
Jason Hogan: We want to bring the two halves back together. So we use a mirror pulse or pie pulse which takes the slow Adam arm and makes it fast and takes the fast.

137
00:20:28.740 --> 00:20:36.900
Jason Hogan: Mr makes it slow. And now we basically got to this point here and the two halves of the Adam Adams we function will start to converge.

138
00:20:37.620 --> 00:20:46.950
Jason Hogan: As we wait an equal amount of time, they'll eventually overlap and reach this point and to make them interfere. We do a final beam splitter pulse. Another pirate to false.

139
00:20:47.250 --> 00:20:59.640
Jason Hogan: And that essentially takes each arm and splits it into two extra amplitude components which can then add constructively and destructively in a way that depends sensitively on delta phi, the total phase shift of this interferometer

140
00:21:01.110 --> 00:21:10.650
Jason Hogan: And then the measurement is is going to be over here where we look at how many atoms are in each of those two states we basically make a projection measurement onto which one of these two momentum states or

141
00:21:11.970 --> 00:21:18.090
Jason Hogan: Excited and ground state tended are correlated with this momentum. So we can also look at the internal state of the item.

142
00:21:18.510 --> 00:21:26.640
Jason Hogan: And if I if I showed me that probability. It's just going to be, for example, cosine square of delta phi for finding an atom in the initial ground state with them. It's a peek.

143
00:21:27.480 --> 00:21:34.410
Jason Hogan: And this little animation down here shows what we would see sort of a CCD image of the output ports.

144
00:21:34.740 --> 00:21:45.690
Jason Hogan: Of the interferometer so you see some to blogs comfy little mountains that are going back and forth. Those are the two alpha ports image sort of at this time here, where they're separated enough to see the two. There's two of them.

145
00:21:46.170 --> 00:21:53.880
Jason Hogan: And depending on the phase of the interferometer which is being scammed here you see the number of atoms. The two ports swinging back and forth, and so

146
00:21:54.150 --> 00:22:02.370
Jason Hogan: The way the data analysis works is we look at an image we see how many atoms are in each of these two locations and use that to infer delta phi, the face.

147
00:22:04.080 --> 00:22:05.610
Jason Hogan: Okay, so

148

00:22:06.990 --> 00:22:13.110
Jason Hogan: We we do these experiments typically on on on the ground. So there's gravity and so the paths are actually curved

149
00:22:13.440 --> 00:22:22.590
Jason Hogan: Like parabolas due to the acceleration of gravity. So this is the same space and background some time just height of the atom. Same idea, but now that the pastor of our parabolic

150
00:22:23.040 --> 00:22:34.230
Jason Hogan: And so typically, I'll talk about one dimensional Adam interferometer is that is atoms that are launched vertically upwards and fall right back down along the same direction. So, in principle, there only moving

151
00:22:34.800 --> 00:22:41.430
Jason Hogan: In the only the height is varying and time and they'll move in the other dimensions. This cartoon is kind of separate a little bit so you can see

152
00:22:42.420 --> 00:22:48.150
Jason Hogan: Just for visualization purposes. So we start with an atom cloud that's this blue dot. And we launched it upward

153
00:22:48.390 --> 00:22:56.010
Jason Hogan: On on a vertical trajectory and then it falls back down. And in that process. We use these red arrows to do the splitting. So the pirate two poles happens here.

154
00:22:56.430 --> 00:23:07.680
Jason Hogan: And and that causes half of the atom to go to a higher elevation than the other half because of the momentum difference. So, so these two little dots here at the top correspond to point B and C on this diagram.

155
00:23:08.430 --> 00:23:14.700
Jason Hogan: So that distance here between B and C. And we call the wave packet separation. So it's how big the two halves of the atom are split

156
00:23:15.090 --> 00:23:19.020
Jason Hogan: At the maximum point of the interferometer and it turns out that's an important

157
00:23:19.350 --> 00:23:27.450

Jason Hogan: Factor for determining the sensitivity of this of this device. So this is the so called mock center or three poles admin or frommer sequence that I'm

158
00:23:27.780 --> 00:23:34.980
Jason Hogan: Describing it turns out it's, it's an accelerometer it sensitive, the acceleration that the Anopheles particular due to gravity.

159
00:23:35.730 --> 00:23:47.400
Jason Hogan: Or any other local acceleration and the sensitivity to accelerations depends on two parameters really depends on the space time area and close it depends on this separation between points B and C. The way fights operation.

160
00:23:47.700 --> 00:23:57.360
Jason Hogan: And the overall duration and time of the interferometer. And so if we're interested in studying gravitational waves, we need to we need to maximize the sensitivity of these of these sensors.

161
00:23:58.020 --> 00:24:05.820
Jason Hogan: By really pushing these two parameters we want really long time and really long with large weight packet separation. So I wanted to give you a little bit of

162
00:24:07.290 --> 00:24:12.420
Jason Hogan: Some, some experimental results showing sort of efforts in that direction.

163
00:24:13.050 --> 00:24:21.600
Jason Hogan: So this is a 10 meter scale Adam interferometer very much like what I like the cartoon I just showed up on the previous slide, but but realizing it in a 10 meter.

164
00:24:21.870 --> 00:24:35.730
Jason Hogan: form factor. So there's a long time to drop so you can maximize the freefall time. So the way this works. You can see there's a the apparatus is installed in a pit here. This is in one of the labs in various on campus.

165
00:24:37.110 --> 00:24:45.300
Jason Hogan: The experiment itself has a source of atoms at the bottom of this pit is a basically laser cooling and we can make bose-einstein condensates type

166
00:24:45.570 --> 00:24:55.080

Jason Hogan: Out of clouds with this, with this with the source that we launched the atoms vertically into what we call the interferometer region. And that's a Magnetically shielded ultra high vacuum chamber.

167
00:24:55.440 --> 00:25:02.970
Jason Hogan: Which sort of pristine environment for doing the actual sensing and that's where we do the interferometry, and then we detect the items as they fall back down.

168
00:25:03.720 --> 00:25:15.210
Jason Hogan: And so this very long so 10 meter scale device allows you to drop out ins for multiple seconds and have sort of the time record breaking performance actually think this still is potentially the record for

169
00:25:16.530 --> 00:25:27.660
Jason Hogan: For for drop time of interferometer. So, uh, so, so this is the some early results from that machine. So here the key parameter is that is the duration to t.

170
00:25:28.260 --> 00:25:33.510
Jason Hogan: between the first and the last post was 2.3 seconds because we have this very long time.

171
00:25:34.230 --> 00:25:36.510
Jason Hogan: And so that lets you really increase your sensitivity.

172
00:25:36.780 --> 00:25:45.780
Jason Hogan: And so just to show what the, what the data looks like in this case. So at the output ports of the interferometer we got these two parts. Part one and Part two, we want to look at the number of atoms in each one.

173
00:25:46.110 --> 00:25:58.470
Jason Hogan: And when you see down here is a series of shots series of bad and interferometer experiments with different delta phi. So, different phase shift. So in this one on the left here most of the items are in part one, very few are important.

174
00:25:59.070 --> 00:26:05.940
Jason Hogan: Too, and that indicates the phases near zero. But if the phase is closer to pi, then you'll see more items important to than Part one

175
00:26:06.810 --> 00:26:09.180

Jason Hogan: So once again, we look at these pictures and in further phase.

176
00:26:10.170 --> 00:26:17.340
Jason Hogan: A key thing that I'll point out here is in addition to a long time the separate the wheat packets separation between the two halves of the atom, it's actually

177
00:26:17.640 --> 00:26:22.890
Jason Hogan: Pretty microscopic in this in this set of experiments. So you can see an image of that off to the right.

178
00:26:23.280 --> 00:26:33.870
Jason Hogan: So, so this is a an image taken at the midpoint and at this at this time capital T, where the atom is maximally separated and and it's a take this image is really a

179
00:26:34.470 --> 00:26:43.890
Jason Hogan: Is a destructive measurements. It's a projection of the wave function to figure out if you think about the way to think about this is we have an ensemble of atoms running through this interferometer

180
00:26:44.430 --> 00:26:54.300
Jason Hogan: But each atom is in this superposition state of being in these two different locations. And so if you make a measurement of where the atoms are by taking a picture of them each Adam will collapse.

181
00:26:54.900 --> 00:27:00.360
Jason Hogan: Into one of the two locations and then what you see here is then the statistics of

182
00:27:00.660 --> 00:27:08.160
Jason Hogan: Of the probability distributions. You'll see about half of the cloud lens and each of these two ports. So if you make that measurement you aren't able to build an out of it from it or

183
00:27:08.400 --> 00:27:20.700
Jason Hogan: Anymore. You've, you've you've you've gotten which way information you will not see interference at the end. So we usually don't take this picture we usually need to maintain ignorance about which are the item is on. So that will see interference.

184
00:27:21.450 --> 00:27:29.280

Jason Hogan: And but if we do take it, it's a nice way to sort of get a diagnostic for how how big these made the interference. So this case it was separated by about 1.4 centimeters.

185
00:27:29.580 --> 00:27:37.650
Jason Hogan: Between the two halves of the atom, which is, you know, getting to be pretty reasonably sized that to happen to imagine an atom in two places at once, separated by over a centimeter

186
00:27:38.070 --> 00:27:50.430
Jason Hogan: But it turns out we can do better than that. And so we can increase the separation even larger distances by rather than increasing just the time also increasing the momentum transfer. And so, so here

187
00:27:51.030 --> 00:27:57.900
Jason Hogan: Is another follow up experiment to that were in the same apparatus, we increase the amount of separation. Bye bye. Bye.

188
00:27:58.200 --> 00:28:08.040
Jason Hogan: Bye large factor. So it turns out for technical reasons, each laser full transfers to HP arcade. It's a two photon transition with Ron and brag transitions which are two photon processes.

189
00:28:09.690 --> 00:28:13.950
Jason Hogan: And in these in these experiments with rubidium Adams that I'm showing you data from

190
00:28:14.250 --> 00:28:20.550
Jason Hogan: And so if you do multiple pulses, rather than just a single pi over to Paul so you can follow us the pirate to

191
00:28:20.820 --> 00:28:28.320
Jason Hogan: beam splitter, Paul. So you can follow up with additional pulses that transfer more momentum to one of the two arms. So that's kind of what this cartoon is showing here.

192
00:28:28.500 --> 00:28:36.180
Jason Hogan: So there's the initial beam splitter that happens at t equals zero. But if you zoom in here we get we're going to apply another, subsequent laser pulse.

193
00:28:36.600 --> 00:28:43.950
Jason Hogan: Which will take the arm is moving it to each bar k and and transfer it to forage bar k. So, basically,

194
00:28:44.430 --> 00:28:51.570
Jason Hogan: We can absorb to our photons of momentum with that second pulse while leaving this this this initial arm still at zero h bar. Okay.

195
00:28:52.470 --> 00:28:59.400
Jason Hogan: And so what we've done here is we've added these little gray zones in this whole sequence. This is showing what when the pulses happened versus time.

196
00:28:59.670 --> 00:29:11.430
Jason Hogan: So addition to the pirate to pi pi over to that we usually do we add a sort of a pulse train here, which increases the momentum to one of the two arms. In this case we pushed it up to 98 spark a of momentum.

197
00:29:11.910 --> 00:29:18.600
Jason Hogan: So that this this upper arm is moving really fast and that gets a larger separation at this midpoint, which I've circled here in yellow.

198
00:29:18.990 --> 00:29:24.420
Jason Hogan: And so if we take a similar picture at this time, what we get is this image of the bottom here, which is

199
00:29:24.690 --> 00:29:30.810
Jason Hogan: It's kind of hard to see, actually, because the address so far separate that they look small but there's a little spike on the left and on the right.

200
00:29:31.350 --> 00:29:37.170
Jason Hogan: You can see here, this little rainbow colored spike. That's the atom on ensemble and it's the interpretation here is that

201
00:29:37.530 --> 00:29:45.840
Jason Hogan: Each out of it, either in this location or on the left or on the right, either of those two locations, before we make the projected measurement at this point.

202
00:29:46.260 --> 00:29:52.800
Jason Hogan: And the key thing is we have these two, the two halves. The way function are separated by 54 centimeters in this result so

203
00:29:53.340 --> 00:30:01.770

Jason Hogan: Really, I was a human scale quantum superposition state. And so, you know, you can, you can, and once again the motivations that is the sensitivity is increasing.

204
00:30:02.160 --> 00:30:08.850
Jason Hogan: The scale linearly with the momentum transfer. So we can get a much bigger sensitive much bigger space time area, much more sensitive device.

205
00:30:09.150 --> 00:30:14.940
Jason Hogan: But it's also, I think, interesting, just from the point of view of demonstrating quantum mechanics in this sort of new

206
00:30:15.900 --> 00:30:23.220
Jason Hogan: Macroscopic link scale and and you won't be surprised to hear that even though the atoms are separated by such a large distance

207
00:30:23.460 --> 00:30:27.240
Jason Hogan: Quantum Mechanics behaves exactly the way we expect we can still see robust

208
00:30:27.480 --> 00:30:35.580
Jason Hogan: Constructive and destructive interference at the end of the sequence to measure face ships and so we want to use this kind of idea. These large, we call this generally

209
00:30:35.820 --> 00:30:41.520
Jason Hogan: Large ones and transfer or lmt large mentioned transfer Adam optics to increase our sensitivity.

210
00:30:42.390 --> 00:30:55.740
Jason Hogan: Okay, so, so that's my sort of intro to Adam interferometry, and the technology that goes into making these devices sensitive. Now I want to drill down a little bit more and talk about how an admin from it, or can be used to detect gravitational waves.

211
00:30:56.850 --> 00:31:03.960
Jason Hogan: So, so this is sort of a generic gravitational wave source here showing off on the left, maybe some compact binary

212
00:31:05.010 --> 00:31:13.080
Jason Hogan: Causing ripples and spacetime to propagate over large distances to some detector and so that detector. I'm going to conceptualize as

213
00:31:13.620 --> 00:31:22.140
Jason Hogan: Basically to inertial references. So these black blobs here are supposed to represent some some some some some test mass some gravitational test mass

214
00:31:22.440 --> 00:31:35.970
Jason Hogan: That is, is isolated. We can imagine it floating in space with no non gravitational forces acting on it. Ideally, and it's sort of sitting there, following its geodesic. And what happens is as the gravitational wave comes by.

215
00:31:36.570 --> 00:31:46.800
Jason Hogan: The experimental or the observable that you have is that the physical distance between these two for the following test masses will oscillate. So to the distance

216
00:31:47.160 --> 00:31:54.930
Jason Hogan: Here, if it's nominally L if Ellison, the baseline between these two test masses, you'll pick up in a military components of the baseline.

217
00:31:55.380 --> 00:31:56.190
Jason Hogan: To that distance

218
00:31:56.640 --> 00:31:59.700
Jason Hogan: Excuse me, proportional to the strain age of the gravitational wave

219
00:31:59.880 --> 00:32:11.940
Jason Hogan: And oscillating at frequency omega of the of the source. And so to detect a gravitational wave, it comes down to how know essentially making this distance measurement measuring the distance and looking for this oscillation

220
00:32:12.240 --> 00:32:17.850
Jason Hogan: And that's, that's how life at work so so Lego has if we just focus on one arm of Lego, for example.

221
00:32:18.060 --> 00:32:29.070
Jason Hogan: It realizes exactly this concept. So the test masses in case of Lego are these mirrors that they have suspended from these these pendulums, so that there is what as good as possible.

222
00:32:29.760 --> 00:32:34.740

Jason Hogan: Isolated from but from from ground vibrations and things like that. So these test masters are nominally following

223
00:32:35.610 --> 00:32:43.740
Jason Hogan: A freefall path along the degree of freedom you care about and then to measure the distance between them. That's going to modulate by the gravitational wave

224
00:32:44.370 --> 00:32:49.170
Jason Hogan: They use light so they essentially are used for measuring the lake travel time between these two mirrors.

225
00:32:49.860 --> 00:32:57.420
Jason Hogan: And and then that if that that like travel time is modulating you would infer that the physical distance between these tests masses is being affected by gravitational

226
00:32:57.870 --> 00:33:03.780
Jason Hogan: Now, now of course Lego is shaped like an L. There's actually two arms that are kind of like identical copies

227
00:33:04.440 --> 00:33:11.400
Jason Hogan: But I want to emphasize that one arm is a principal enough right you you can detect this oscillation. If you have a perfect setup. Ideally,

228
00:33:12.360 --> 00:33:18.720
Jason Hogan: The reason you know, or at least the motivation for having to the case of Lego is that to measure that distance using light.

229
00:33:19.560 --> 00:33:28.710
Jason Hogan: You basically need a perfect laser or at least we need to be really good if there's any noise on the laser that can actually masquerade as fluctuation in the path length and so

230
00:33:29.190 --> 00:33:39.930
Jason Hogan: You would be swamped by that. And so to get around that. Likewise, is very clever trick where they split this noisy laser and send it along to pass at right angles and then

231
00:33:40.650 --> 00:33:48.270
Jason Hogan: When they look at the detector this this is this Michael some geometry basically makes a differential measurement between the length of one arm versus only for the other arm.

232
00:33:48.600 --> 00:33:55.710
Jason Hogan: And in that differential measurement, the lasers imperfections. The noise and the laser is largely canceled suppressed as a common mode.

233
00:33:56.280 --> 00:34:06.630
Jason Hogan: And since the gravitational wave acts differently on these two arms, it's a it's a quarter polar expectation and it makes one on longer will make the other arm shorter the signal gets increased by a factor of two.

234
00:34:07.050 --> 00:34:19.860
Jason Hogan: But the key thing here is that this is a mechanism for suppressing the noise of the laser. And so, so with that in mind, I want to describe an admin from it and it's based on just essentially one arm rather than two.

235
00:34:20.610 --> 00:34:30.840
Jason Hogan: So we see Adam interferometer approach all described in principle, one could realize this and and that's not because we have better lasers than like Legos lessons are actually really great

236
00:34:31.440 --> 00:34:43.830
Jason Hogan: It's because that with the atom interferometer turns out there's there's another mechanism, we can use to suppress the lasers noise and that allows us to do that with just one arm. And so that has some I think advantages for

237
00:34:44.160 --> 00:34:49.620
Jason Hogan: The construction of these devices in particular, few imagine space based versions of gravitational wave detector.

238
00:34:50.820 --> 00:35:00.630
Jason Hogan: Lisa is uses three satellites in order to realize essentially to non parallel arms with an atom based approach. You could, in principle, have a single arms. Only you only need two spacecraft

239
00:35:01.140 --> 00:35:12.630
Jason Hogan: So sort of an interesting maybe advantage to this, we can use the atom degrees of freedom to cancel this noise with just one arm. Okay, so, so. All right, so, so this is then not not coming to

240
00:35:14.070 --> 00:35:20.700
Jason Hogan: The what we call me just me just concept which is the matter wave atomic gradiometer interfere metric sensor.

241
00:35:21.150 --> 00:35:25.950
Jason Hogan: So this is the the admin centric approach for gravitational wave detections that I've been discussing fan, so

242
00:35:26.490 --> 00:35:34.500
Jason Hogan: So if we want to realize the the the the the ideal measurement. I just described with to inertial test masses and we measure the distance between them by

243
00:35:35.010 --> 00:35:50.040
Jason Hogan: The flow delayed flight time that the time it takes light to travel and so both of those two requirements will be a both those two roles will be played by Adam. So in this case, so instead of mirrors. We're going to use atoms as the initial reference. So the atoms are going to be

244
00:35:51.090 --> 00:36:00.000
Jason Hogan: These freely falling out and clouds are can be excellent inertial references there neutrals. They don't get impacted very much by non gravitational forces.

245
00:36:00.840 --> 00:36:13.710
Jason Hogan: So that's, that's one of the reasons why these items could potentially be good at this and then admins can also be really good clocks. As I said at the beginning. So we can use the clock aspect of an atom, the fact that we can use it to measure.

246
00:36:15.150 --> 00:36:22.740
Jason Hogan: To measure time we can use that to measure the light travel time between these two. And there's references the to the to

247
00:36:23.430 --> 00:36:40.680
Jason Hogan: Adam initial references really precisely. So we're going to leverage the, the really good performance of atomic clocks to measure the light travel time in between the two test message. So I figured I would give a kind of a sort of a little Animation showing how we imagined it. So, so

248
00:36:41.730 --> 00:36:51.660
Jason Hogan: We need 200 references which I'm calling atomic clock. So just imagine we have an add on at these two locations. And so these are our test masses, they're separated by some baseline.

249
00:36:51.930 --> 00:36:58.710

Jason Hogan: And I'm going to tell you how we could imagine using an atomic clock to realize a gravitational wave detector. So

250
00:36:59.280 --> 00:37:08.790
Jason Hogan: For this I'm assuming the atoms are once again to level systems with the ground state and excited state with some splitting omega a and we're just going to run simultaneous

251
00:37:09.270 --> 00:37:14.940
Jason Hogan: Clock measurements and these two locations and and I can show you how the how we can measure the light travel time

252
00:37:15.540 --> 00:37:24.450
Jason Hogan: It's going to be moderated by the gravitational way. Okay, so to start an atomic clock you apply a laser polls. We're going to send the user pulls from the left. So you'll see it go across.

253
00:37:25.020 --> 00:37:32.400
Jason Hogan: So the pulse travels from left to right and when it hits each atom, it's, it's a pirate to pole. So it's going to put the atom in the super position.

254
00:37:32.760 --> 00:37:38.100
Jason Hogan: Of the ground in the excited state. And so after that first pools travels across the baseline, it will

255
00:37:38.400 --> 00:37:46.140
Jason Hogan: Both, both the items will be in the superposition state. Now I want to emphasize that it takes some time for the light to cross the baseline because it's separated by

256
00:37:46.380 --> 00:37:51.870
Jason Hogan: Not only a large distance, the bigger the separation, the more sensitive the gravitational effect. So imagine many kilometers.

257
00:37:52.260 --> 00:38:04.020
Jason Hogan: So the two atoms get put in a superposition state at slightly different initial times, but once they're in the state. They're going to evolve in a similar way. So in particular, as time evolves these clocks are going to tick. Right. And what that

258
00:38:04.860 --> 00:38:15.900
Jason Hogan: Means physically is the excited state. It will evolve at a higher higher energy, so it will accumulate phase at a faster rate due to

quantum mechanics. So, it involves phase that array proportional to this energy splitting will make a

259
00:38:16.740 --> 00:38:20.580
Jason Hogan: Um, so, after some time. We want to stop the clock. We have, we apply a second laser pulse.

260
00:38:21.450 --> 00:38:27.930
Jason Hogan: Which travels across the baseline once again and stops the clock. And so at the moment when that second pulse hits

261
00:38:28.410 --> 00:38:34.470
Jason Hogan: Some phase Omega eight times t or t is the time between these pulses at so much face each clock will evolve.

262
00:38:35.220 --> 00:38:40.470
Jason Hogan: Now it's really important that even though the left and the right clock restarted at slightly delayed time

263
00:38:41.280 --> 00:38:53.640
Jason Hogan: 11 O'CLOCK IN THE RIGHT, WE STARTED later, it also was stopped at a later time, because the light travel time, you have to, you have to wait. Each for each of the first and the second pulse for that. So even though their time to lead the phase is

264
00:38:54.090 --> 00:38:58.230
Jason Hogan: For these two clocks and so there's no signal in this case. And so it's boring.

265
00:38:58.770 --> 00:39:07.980
Jason Hogan: But what if gravitational waves were to come by. In the meantime, in between these two and the gravitational wave. His presence than what we could say is that space time is stretching

266
00:39:08.760 --> 00:39:17.490
Jason Hogan: During between these two pulses and so gravitational wave, you know, it's let's say it shows up here. That means that the distance between these clocks gets a little bit bigger.

267
00:39:19.110 --> 00:39:30.180
Jason Hogan: For the at the time when we played the second poll. So it takes longer for the light to travel this long the slightly longer baseline. And so the four o'clock or the second clock here on the right will evolve a little bit more time delta t.

268
00:39:30.750 --> 00:39:39.360
Jason Hogan: Proportional to the extra baseline each strain to grab that attends L and that that will cause a phase shift of this clock with respect to backlog so

269
00:39:40.350 --> 00:39:47.640
Jason Hogan: The the the experiment. That is to say, is to measure the phases of each of these two clocks and subtract them and look at any slightly

270
00:39:47.850 --> 00:39:57.780
Jason Hogan: Different phase, it would arise due to a little bit extra like travel time. So this is a measurement of the light travel time and how it changed between the first and the second pulse due to a gravitational wave

271
00:39:58.680 --> 00:40:05.550
Jason Hogan: Now in practice that's that's sort of an atomic clock for the experts in the audience that's that's a, that's a Ramsey sequence pirating Piper to

272
00:40:06.570 --> 00:40:17.640
Jason Hogan: The. It turns out that there may be better or where we think that it's actually helpful to do more than just to laser pulses, but rather implement this sort of mock sender.

273
00:40:18.270 --> 00:40:24.090
Jason Hogan: Geometry which which which I've shown here on this diagram to the raid the sort of diamond shape and then from mentors that I've been describing

274
00:40:24.390 --> 00:40:33.600
Jason Hogan: And so this is, you know, a spacetime diagram of the sort of three pulse version that we expect will be more practical. So we've got here time running vertically

275
00:40:34.230 --> 00:40:42.600
Jason Hogan: The two atoms obsession, x one, x two, separated by nominally large baseline. And we've made some mock center out of it for our mentors in each of these two locations.

276
00:40:43.110 --> 00:40:55.350
Jason Hogan: I don't want to dive too much into the details of the sequence you see like going back and forth. I can. I'm happy to answer

questions about that. So if people are interested, but for now I'll just, I'll point out that the sort of

277
00:40:56.640 --> 00:41:05.220
Jason Hogan: This approach is using these these three these three ideas I described before, right. So, so the the we were using the fact that the atoms are clocks in the following way. So,

278
00:41:05.730 --> 00:41:14.220
Jason Hogan: The transition that we want to use to drive these atomic transitions is shown here. It's the strontium clock transitions use and lattice clocks and so

279
00:41:14.880 --> 00:41:24.360
Jason Hogan: When the when the pulse is traveling across the baseline part of the animals in this red excited state. And it's accumulating phase because it's

280
00:41:25.110 --> 00:41:27.600
Jason Hogan: It's in the higher energy state and we're basically then getting

281
00:41:28.050 --> 00:41:37.740
Jason Hogan: We're building into this interferometer aphasia, it depends on how long it takes the light to go between the two. The two atoms. So we're using the clock aspect to measure the travel time

282
00:41:38.580 --> 00:41:45.780
Jason Hogan: The atoms are excellent inertial test masses there. The following their geodesics. So then, so they're they're playing that role as well. And then finally, we have a Grady armor.

283
00:41:46.020 --> 00:41:53.190
Jason Hogan: Because we're measuring the differential phase between these 200 parameters and that critically is how we suppress the laser noise that I described on

284
00:41:53.760 --> 00:42:03.450
Jason Hogan: You know, a few slides ago. So each of these laser pulses that are shown as the squiggly lines going back and forth. Each of those laser pulses is not ideal, and has noise on it, but

285
00:42:03.780 --> 00:42:09.600
Jason Hogan: As you can see, if you track one of these pulses traveling across the baseline interacts with both adults.

286
00:42:09.900 --> 00:42:18.480
Jason Hogan: And so whatever noise is on the laser is going to be imprinted on the atoms wave function, but it will be done in a symmetric way both of the of the items will get the same phase.

287
00:42:18.840 --> 00:42:25.260
Jason Hogan: And so in the grading owner and this which is a difference phase difference between these two such as such laser post noise.

288
00:42:25.590 --> 00:42:31.260
Jason Hogan: Will be suppressing the common mode. And so that's the way that this single baseline grab it out of interferometer

289
00:42:31.980 --> 00:42:38.700
Jason Hogan: Or gravitational a protector. That's how it can suppress LASER NOISE by taking the differential measurement. These two clowns.

290
00:42:39.660 --> 00:42:48.330
Jason Hogan: Okay, so how well do we think we can do so. So this is once again stream versus frequency. You can see the Lego detector.

291
00:42:48.810 --> 00:43:02.280
Jason Hogan: Above 10 Hertz here. Lisa lower frequencies and in the mid band. We have some some some projected sensitivity cars, what you could do with with the majors configuration, both in space and for a terrestrial kilometers scale instrument.

292
00:43:03.660 --> 00:43:08.910
Jason Hogan: And so and so, these, these are curves that are these, these are what we think we could achieve sort of in the long term.

293
00:43:09.330 --> 00:43:13.290
Jason Hogan: With technology development. This is not what we can do with the state of the art but

294
00:43:13.860 --> 00:43:19.290
Jason Hogan: We think that there's a straight. We think that there's a technology development path to get the admin for amateurs to this level of sensitivity.

295
00:43:19.860 --> 00:43:23.790
Jason Hogan: And when you can see as a few examples sources. So these red lines, for example.

296
00:43:24.480 --> 00:43:34.170
Jason Hogan: Are some of the early binary black holes that like I was able to see. And the reason is current his current sweeping up because the the sources actually are.

297
00:43:35.070 --> 00:43:39.870
Jason Hogan: They show up at a lower frequencies earlier in their lifetime. And so you can see these dots indicate like when

298
00:43:40.560 --> 00:43:56.070
Jason Hogan: You know, sort of 10 years ago. One year ago a 10th of a year and months ago when the surfaces would have been at these different frequencies. And so the idea is you see it sweeping through the major spam. And so you could see these sources before they reach the Lego band and principal

299
00:43:57.750 --> 00:44:07.680
Jason Hogan: Okay so kilometer scale is what you need. It turns out to get this little sensitivity and sort of similar and scale to Lego and then you know in space, you know,

300
00:44:08.130 --> 00:44:19.980
Jason Hogan: This this sensitivity curve here assumes slowly tend to the seven meters which is colors and it shorter than Lisa, but still a very large baseline. So, you know, Lisa's tend to the nine meters.

301
00:44:21.360 --> 00:44:26.250
Jason Hogan: Nominally so so so these are really large baseline separations between the two Adam class.

302
00:44:26.550 --> 00:44:31.890
Jason Hogan: And we haven't done that before. So we've done experiments that I showed you with sort of a 10 meter scale machine.

303
00:44:32.190 --> 00:44:39.600
Jason Hogan: And so it's a sort of bridge the gap between where we are now technology was in these sort of kilometers steel instruments or larger.

304
00:44:40.320 --> 00:44:50.760
Jason Hogan: How can we, how do we do that. And so that's where this demonstration experiment that it's kicking off now is hopefully playing a role. So, so there's a new project fairly new project now.

305
00:44:51.360 --> 00:45:04.200
Jason Hogan: That we call me just 100 which is a 100 meter scale demonstration detector. That's how it's designed to bridge this gap. And this is going to be located at formula in an existing 100 meter deep

306
00:45:04.620 --> 00:45:15.150
Jason Hogan: Chef that they have here as part of a neutrino experiment. And so you can see a sort of a cross section of the elevation here fairly lab, there's a, there's this vertical hole in the ground, which is perfect for making a really big out of there from

307
00:45:16.020 --> 00:45:25.170
Jason Hogan: Which you can see sort of a CAD model that here. So we've got a vertical vacuum tube, they're going to run along the length of this this brown shaft, all the way down.

308
00:45:25.560 --> 00:45:38.100
Jason Hogan: And we want to put sources of cold Adams on on either end to realize this is me just configuration with Adams on each end and then we're going to send laser pulses up and down this 100 meter to to measure the light travel time

309
00:45:39.240 --> 00:45:47.400
Jason Hogan: So, so once again, as I said, there's an intermediate step it won't be able to detect gravitational waves, per se, unless there's something really unusual that we don't expect

310
00:45:48.660 --> 00:45:54.720
Jason Hogan: So it's likely technology demonstration of gravitational wave detectors, but it turns out, as all a lot describe

311
00:45:55.410 --> 00:46:04.380
Jason Hogan: It can be used to do some other physics. So at this same detector geometry turns out to be sensitive to certain models of dark matter as all we have time to say a little bit about

312
00:46:04.800 --> 00:46:19.350
Jason Hogan: And and and you know, given this large drop time we think we can push the quantum superposition states to even more large distances. Then I showed you some maybe multiple meters of splitting between the islands, which is kind of, I think, an interesting technology to push

313
00:46:20.640 --> 00:46:25.470
Jason Hogan: So this. So this is kind of the goals of a major. These are different science things I alluded to.

314
00:46:26.340 --> 00:46:32.100
Jason Hogan: It's a big collaboration international in scope with universities and national labs in the US and in the UK.

315
00:46:32.850 --> 00:46:44.820
Jason Hogan: And, you know, we're in the design and construction phase sort of right now and hoping to have this put together in the next couple of years. And so I'll show you a little bit about the details of the design and

316
00:46:45.330 --> 00:46:51.780
Jason Hogan: You can see the site here is this is looking down what this 100 meter shaft and you can see there's

317
00:46:52.650 --> 00:47:01.620
Jason Hogan: A little link at the bottom here, which is the bottom of the shaft. There's some some tips and tools running down which are just, you know, you can do it, things like that for for for the existing shaft

318
00:47:02.430 --> 00:47:07.080
Jason Hogan: There's little blank spot in the wall here. We're gonna put her out of it from there and read it all the way down to the bottom.

319
00:47:08.280 --> 00:47:18.450
Jason Hogan: So you can see that once again here at each of actually at the top and the bottom and it turns out in the middle. We're going to put sources of strontium atoms we want to put out of the three different heights.

320
00:47:19.290 --> 00:47:24.630
Jason Hogan: It turns out, and so that's a little cartoon of the CAD model of our source.

321
00:47:25.440 --> 00:47:35.490
Jason Hogan: And then at the bottom, we have a mirror which were which we use to us. We can send light from the top. So the high power lasers come in here and they get sent down and then we bounce them off of here at the bottom.

322
00:47:35.970 --> 00:47:44.880
Jason Hogan: Off of this retro affliction mirror, and that gives us late propagating either up or down. We need light for both directions to realize some of these more advanced large amount of transfer

323
00:47:46.440 --> 00:47:58.170
Jason Hogan: Adam optics and this mirror. You can see it's on tilt stage. So we can do we can compensate for Earth's rotation and things like that. So there's just to show some of the design. I'm happy to answer questions about any of this. I'm going to go quickly.

324
00:47:59.550 --> 00:48:05.460
Jason Hogan: So a bit more detail of the atom services. So you can see CAD model of one of the sources. So there's sort of

325
00:48:06.000 --> 00:48:09.990
Jason Hogan: An oven and 2D Mark chambers, the spacing cools the items into a beam.

326
00:48:10.440 --> 00:48:21.270
Jason Hogan: That gets sent down into a small tube into our, our 3D cooling chamber where we do laser cooling and evaporated cooling and you can see some of the laser beams shown schematically after the ends or cool in the middle.

327
00:48:21.630 --> 00:48:27.540
Jason Hogan: We drag them out to the side towards the hundred meter chamber which is not showing would be just off to the right here.

328
00:48:27.900 --> 00:48:32.580
Jason Hogan: And so that's kind of what that looks like. And there's once again and be three of these, one of the top on the bottom one in the middle.

329
00:48:33.240 --> 00:48:41.880
Jason Hogan: And then when we want to do detection, we have this chambers of in line with the hundred meter vacuum chamber with a couple of lenses and vacuum and this blue.is one of the item class.

330
00:48:42.420 --> 00:48:47.670
Jason Hogan: We want to measure and we have a camera outside that we can use to image that out of cloud and look at the interference pattern.

331
00:48:48.420 --> 00:48:57.420
Jason Hogan: So let's get this all cat models, but just to show the design process is underway. Okay, so I promised I would say something about dark matter and the remaining few minutes. I think I'll try to get to that.

332

00:48:58.560 --> 00:49:03.270
Jason Hogan: So this is a sort of that diagram I showed before, so busy diagram with all these

333
00:49:03.720 --> 00:49:09.000
Jason Hogan: squiggly lines going back and forth. So let me say a little bit more about what this means. So this is supposed to be the majors configuration.

334
00:49:09.210 --> 00:49:18.900
Jason Hogan: This is the gradiometer. So we've got an admin or from Iran on the left out or from on the right, and once again position is on the horizontal axis here. So these are separated by some large baseline.

335
00:49:19.170 --> 00:49:28.350
Jason Hogan: And we're using laser pulses showed a squiggly lines to realize these Adam optics and splitting the atom into these these these diamond shaped at mach center and for others.

336
00:49:28.860 --> 00:49:33.480
Jason Hogan: And the key thing I want to point out is that the phase shift in the center for these frommer's is showing up.

337
00:49:33.690 --> 00:49:40.920
Jason Hogan: Due to the time you Adam spends in this red dashed excited state that when the item is in the excited state. It's accumulating phase at the higher rate.

338
00:49:41.220 --> 00:49:48.000
Jason Hogan: And that's essentially how we're measuring the light travel time, right. So we send a post to the, to the left from left to right and then from right to left.

339
00:49:48.330 --> 00:49:56.520
Jason Hogan: And this Adam will spend some large amount of time in the excited state which will basically be proportional to how long it took the light to go back and forth.

340
00:49:56.760 --> 00:50:05.310
Jason Hogan: So the phase shift that you evolve in that segment, for example, is this is the splitting omega and between the levels times to oversee which is the back and forth like travel time

341
00:50:06.780 --> 00:50:08.700
grzegorz madejski: Yes, five minutes or so.

342
00:50:08.970 --> 00:50:15.030
Jason Hogan: Five minutes. Yeah, okay, no problem. Yeah, that sounds good. So I'll wrap up, maybe a little early. But I think we'll be able to get to most of

343
00:50:15.600 --> 00:50:16.230
Jason Hogan: Our things

344
00:50:16.410 --> 00:50:18.210
Jason Hogan: Yeah, so, so let me just

345
00:50:19.020 --> 00:50:30.870
Jason Hogan: Finish this so so the fee shift here proportional to the energy splitting of the atom and the baseline is out. And so basically this phase shift, which is our observable. It can vary in two ways. I've talked to you a lot about the gravitational wave

346
00:50:31.950 --> 00:50:37.500
Jason Hogan: Causing the baseline L to fluctuate. So we can see fluctuations, don't lie on the baseline that that would be gravitational wave

347
00:50:37.860 --> 00:50:47.100
Jason Hogan: But if the energy splitting omega a fluctuates, we could see that as well. And in so in the case of and that's how we how we could see

348
00:50:47.580 --> 00:50:52.950
Jason Hogan: Certain dark matter singles is looking for changes in the energy splitting of the atom. So how does that work and

349
00:50:53.610 --> 00:50:58.470
Jason Hogan: So this is a just I'll go through this quickly. I think you heard the story before. Probably so.

350
00:50:59.460 --> 00:51:08.700
Jason Hogan: When I say dark matter. I'm thinking not have sort of traditional WIMPs sort of particle like dark matter, but rather than sort of so called ultra light, dark matter sort of field like dark matter.

351
00:51:09.270 --> 00:51:18.000
Jason Hogan: So you can think accion still autonomy or accion like particles, things like that where the particles have very little mass. So like you know 10 to the minus

352
00:51:18.540 --> 00:51:26.790
Jason Hogan: 15 eaten them is at the very, very low mass per particle and and sort of long debris, the wavelengths that they overlap and accepted field like

353
00:51:27.150 --> 00:51:36.240
Jason Hogan: And so this is a chart from from the upcoming year and report that shows the space versus the for example accion mass or dark matter bass.

354
00:51:36.960 --> 00:51:45.300
Jason Hogan: And it's a variety of different technologies that can be used in different mass ranges and at the lowest frequency range or admin frommer's and that's what

355
00:51:45.750 --> 00:51:53.130
Jason Hogan: You know, I'll show you how that how that works. So if we imagine, for example, a scale or a couple fields. This is a ski a five field five

356
00:51:53.580 --> 00:52:03.750
Jason Hogan: Which is the dark proposed Dark Matter of field has some few field of evolution. Let's say it can couple to the standard model, for example, via the electronic photon.

357
00:52:04.590 --> 00:52:11.550
Jason Hogan: And and if the field has some ample to which is due to the fact that there is dark matter and proportional to the dark matter density

358
00:52:12.570 --> 00:52:22.110
Jason Hogan: This field will oscillate at a frequency characteristic of it's constant. It's complex frequency so characters admits mass and find things and so that field. If it's coupled to stuff.

359
00:52:22.620 --> 00:52:32.430
Jason Hogan: Can affect fundamental constants, like the electron mass or the find structure constant those little constants constants are would determine the energy splitting of the atom. So

360
00:52:32.670 --> 00:52:39.870
Jason Hogan: This dark matter field causes an energy shift then therefore have to the atom, an energy shift is going to oscillate it a wiggle in time.

361
00:52:40.110 --> 00:52:45.690
Jason Hogan: To to the time evolution of this dark matter field. So, so the characteristics signal will be an oscillating energy splitting.

362
00:52:46.140 --> 00:52:53.010
Jason Hogan: And so that we can look for in a similar way that I described with this may just configuration. So here's how we can do with me just 100

363
00:52:53.700 --> 00:53:00.930
Jason Hogan: For two examples. This is the scale or dark matter. I was telling you about versus the mass of the particle. The mass of the proposal and particle

364
00:53:01.590 --> 00:53:08.190
Jason Hogan: There's a couple into the electron mass in this case. And you can see the red line is what we think they do with me. Just a couple of order of magnitude.

365
00:53:08.550 --> 00:53:24.900
Jason Hogan: Beyond current limits and then this is another example of a b minus l vector coupled dark matter candidate, which we can look for and with another configuration of majors. So I kind of have to skip over some of the details.

366
00:53:26.130 --> 00:53:30.480
Jason Hogan: I'll just mention briefly as I start to wind. Wind up here, down here, finish up here.

367
00:53:31.770 --> 00:53:38.730
Jason Hogan: We can run the instrument into writing, writing different modes with these three different sources. So you can see this is the major 100 and submit once again.

368
00:53:39.090 --> 00:53:45.600
Jason Hogan: So since we have Adam sources at the top of the middle of the bottom we sort of can drop one from the top and one for the middle and get sort of

369
00:53:45.840 --> 00:53:52.590
Jason Hogan: A 50 meter baseline. And we can let both Adams fall for about 15 meters. So that's sort of a long drop Long Baseline

370

00:53:52.890 --> 00:54:03.630
Jason Hogan: We can also have some of the 100 meter baseline where the atoms fall for a shorter distance I need Jen and then we can also use all three at once, which is interesting for settings certain noise sources and gravitational wave

371
00:54:04.740 --> 00:54:13.200
Jason Hogan: The shock of gravitational wave detectors, such as gravity gradient noise do to local vibrate vibration of the earth. We can potentially measure and subtract that was such a configuration.

372
00:54:13.560 --> 00:54:16.800
Jason Hogan: And then we also can use two different kinds of animals. So to isotopes.

373
00:54:17.220 --> 00:54:26.670
Jason Hogan: Which I'm calling the dark matter mode here which we can use to search for that, for example, that that be myself. Couple of vector by looking at differential accelerations that violate the equivalence principle in that case.

374
00:54:27.360 --> 00:54:36.990
Jason Hogan: Okay, so I think I'm going to have to skip over the last thing I was going to cover just I'll say a few words of it and then people are can certainly ask questions if you have it.

375
00:54:37.710 --> 00:54:42.930
Jason Hogan: I really just wanted to point out some of the progress happening at Stanford in my lab to develop the

376
00:54:43.530 --> 00:54:47.550
Jason Hogan: strontium Adam sources and admin or from a tree that's necessary for me just

377
00:54:48.120 --> 00:54:55.530
Jason Hogan: So all of the data that I showed you for large amount of transfer and long, long duration and frommer's was done using rubidium Adams.

378
00:54:55.860 --> 00:55:05.940
Jason Hogan: And for me, just, we're going to be using strontium Adams, because those are the items that are really good clocks. And so we've had to transfer a lot of technology from rubidium to strontium and turns out there's some differences that are important.

379

00:55:06.360 --> 00:55:15.420
Jason Hogan: And so we built up as astronomy anonymous sources and we're building a 10 meter scale mock up of majors to test out the large Baseline Interferometry

380
00:55:16.920 --> 00:55:25.170
Jason Hogan: And so, uh, let's see. So, so this is the strontium I'll and I'll end with with it with a note on this. This is the strontium level structure.

381
00:55:26.400 --> 00:55:38.400
Jason Hogan: So we want to do. Adam interferometry on this clock transition which is here to this triple p zero state that I mentioned before this transition used by all the best clocks in the world as a lifetime of 150 seconds.

382
00:55:39.180 --> 00:55:49.110
Jason Hogan: And it's at 698 nanometers, but no one had really done this sort of large amount of transfer Adam interferometry on that transition before and we wanted to demonstrate that that was possible.

383
00:55:49.440 --> 00:55:57.000
Jason Hogan: And so, so we ended up actually to for practical reasons trying it up first on a nearby transition which is at a slightly

384
00:55:57.570 --> 00:56:05.520
Jason Hogan: Shorter shorter shorter wavelength 698 nanometers to the triple P one state and that that actually has a much shorter lifetime and only 22 microseconds.

385
00:56:06.000 --> 00:56:14.310
Jason Hogan: Which is not good for this application, but it turns out to be good enough to test the basic concept of this large amount of transfer physics and so

386
00:56:14.820 --> 00:56:20.160
Jason Hogan: All, as I said, I won't have time to go through all this. I just want to basically say that we were able to implement

387
00:56:20.550 --> 00:56:32.880
Jason Hogan: A large momentum transfer out of interferometer. You can see the splitting between the two arms is increased by many auxiliary pipe pulses and it works really well it using the six at night in transition as a demonstrator and so

388

00:56:34.020 --> 00:56:44.730
Jason Hogan: Basically we're able to get beyond state of the art performance. So we wrote a match and then exceed best that have attended with their video Adams using the Astronomy mountains. So pushing up to 140 over 148 spark a

389
00:56:45.150 --> 00:56:51.660
Jason Hogan: momentum transfer and and that's what this contrast plus shine. What's, what's gonna have time to really go through it and then I'll I guess.

390
00:56:52.470 --> 00:56:58.050
Jason Hogan: We also made a gradiometer, which is what we want to make from ages. We have where we had to he's out of interferometer separated by

391
00:56:58.260 --> 00:57:05.760
Jason Hogan: In this case, a very small baseline just for proof of concept. But once again, if anyone's interested in the details of this, I'd be happy to elaborate, but I think I ought to

392
00:57:06.330 --> 00:57:18.240
Jason Hogan: Wrap up now since I ran a little over. So just in summary, I'll, I'll just, you know, give you high points here once again. So maybe 100 is designed as a bit bad detector. Grab a detector prototype.

393
00:57:18.810 --> 00:57:23.640
Jason Hogan: It will have enough sensitivity to do to look for new physics in the dark matter range.

394
00:57:24.390 --> 00:57:38.100
Jason Hogan: And will push quantum mechanics into the sort of even larger macroscopic separations in space and time, and we're hoping we're in the design process. Now we're hoping for construction and conditioning in the 2021 to 2022 timeframe.

395
00:57:38.820 --> 00:57:47.820
Jason Hogan: And then the stuff that I didn't really get to spend as much time on unfortunately is the the the under from share with astronomy mountains in my lab, which has shown already

396
00:57:48.930 --> 00:57:55.290
Jason Hogan: Great performance proof of concept work for these larger and transcribe it for amateurs and there were hoping to push even further.

397

00:57:55.920 --> 00:58:04.050
Jason Hogan: To separate the atoms by up to 1000 each bar k which is getting to be the direction you need to go to get a sensitive enough to ultimately detect

398
00:58:04.560 --> 00:58:13.650
Jason Hogan: Gravitational waves. So with that, I will wrap up projects running a little bit over and just emphasize the team at Stanford, my group that's doing astronomy from tree.

399
00:58:14.400 --> 00:58:29.310
Jason Hogan: And are many collaborators and all these institutions participating me just 100 and and of course our funding support for that project so great. So that's I think that's where I should wrap up. Thanks everybody. And I'm happy to take any questions.

400
00:58:30.510 --> 00:58:44.910
grzegorz madejski: Thank you very much. Jason for very nice and clear talk at this point we're going to transfer over to us to doc was going to be a continuing asking questions from the from those gases emitted from the, from the indigo page. So go ahead, take it over soon.

401
00:58:46.230 --> 00:58:54.690
dong su: Okay, thanks. Jason. So let's start with maybe a basic question on page nine. There's a question on

402
00:58:57.300 --> 00:59:00.540
dong su: How, how do you control the absorption and

403
00:59:02.460 --> 00:59:08.370
dong su: Assimilation the mission really the mission happens and the one the light shine on

404
00:59:10.740 --> 00:59:14.700
Jason Hogan: Yeah. So how do we control this process.

405
00:59:15.960 --> 00:59:16.470
dong su: Happens.

406
00:59:17.010 --> 00:59:17.640
Jason Hogan: Right, yeah.

407
00:59:17.700 --> 00:59:19.530
Jason Hogan: So that's this one here, I think.

408
00:59:19.560 --> 00:59:20.040
So,

409
00:59:21.510 --> 00:59:22.830
Jason Hogan: Yeah, so the

410
00:59:23.580 --> 00:59:27.390
Jason Hogan: When the light is turned on and in the atom is is coupled to it.

411
00:59:28.920 --> 00:59:29.370
Jason Hogan: The

412
00:59:30.420 --> 00:59:42.330
Jason Hogan: The state of the atom evolves as shown here. So we start off at t equals zero here and the additives initially prepared in the ground state. So that would be why

413
00:59:42.720 --> 00:59:49.890
Jason Hogan: We have 100% of the probability is in this blue state and there's zero probability of finding the item and state to if you just turn on a light.

414
00:59:50.760 --> 01:00:02.520
Jason Hogan: The coupling between the atom in the light will result in Ronnie oscillations, which is what these oscillations are shown here are called and basically the, the state of the item is

415
01:00:03.870 --> 01:00:04.590
Jason Hogan: is evolving.

416
01:00:05.880 --> 01:00:12.540
Jason Hogan: In the presence of the light. Basically you have one way to think about it is, this is sort of a diabetic process so

417
01:00:12.660 --> 01:00:21.030
Jason Hogan: The animals initially in and I can state right it's in the ground, students, it's sitting there and nothing's happening. But as soon as you turn on the line, if you if you impulsively turn on a light interaction.

418
01:00:21.360 --> 01:00:31.290

Jason Hogan: You've changed the Hamiltonian of the system and the atom is no longer in an eigen stage of the Hamiltonian of the combined Hamiltonian of the atom, plus the light

419
01:00:31.740 --> 01:00:38.580
Jason Hogan: And so as a result, the state is in some some some superposition of I can say since the new Hamiltonian and it will therefore

420
01:00:38.820 --> 01:00:45.330
Jason Hogan: Evolve and time and that's what Robbie oscillations can be thought of as if you like, that's sort of one clinics description of it. We're physically

421
01:00:46.020 --> 01:00:51.060
Jason Hogan: You know, the, the, the light starts to interact with the atom and starts to starts to evolve the states.

422
01:00:51.990 --> 01:01:06.420
Jason Hogan: From from, you know, from from being in the ground sense of the ascendancy but that process take some time. And the key thing is that even though you know so. So the process you know that we've looked at evolution is is deterministic following these curves that I've shown here, it's

423
01:01:07.560 --> 01:01:15.030
Jason Hogan: Just classic to level evolution. And so all we have to do to control you know where we are in this curve is control.

424
01:01:15.780 --> 01:01:24.480
Jason Hogan: The time of this pulse rate. So if we stop the pulse at a certain time, then the wave function will have evolved to that point on this, on this Robbie isolation curve and so

425
01:01:25.290 --> 01:01:32.820
Jason Hogan: At this at this pirate to time, we're in a superposition state one state to sort of which, which is what we want for a beam splitter so

426
01:01:33.480 --> 01:01:39.420
Jason Hogan: So that's that that's sort of the story. I guess maybe an important caveat that I'm leaving out is that

427
01:01:39.990 --> 01:01:45.810

Jason Hogan: You this won't work. If there is spontaneous submissions. Right. So this is all assuming that everything is ideal.

428
01:01:46.470 --> 01:01:58.170
Jason Hogan: If they're spontaneous submission, then that could be sort of incoherent process, which would mean we don't we aren't able to control the state of the item. And so for example if this excited state decays.

429
01:01:59.340 --> 01:02:09.000
Jason Hogan: It has a lifetime. That's significantly small enough, then, then the state will not evolve in this way. Right. As soon as you get some population excited state. It will start to decay.

430
01:02:09.450 --> 01:02:16.110
Jason Hogan: And so this this diagram assumes that spontaneous mission is negligible. And that's the little we need to work in, in order for this physics to work out.

431
01:02:16.410 --> 01:02:21.900
Jason Hogan: And so we realized that in two different ways. So in the case of the clock atoms. So using the strontium Adams.

432
01:02:22.470 --> 01:02:30.240
Jason Hogan: It's a two level system where the excited state has 150 second lifetime, but that's that's why that level and that that transition is so valuable for

433
01:02:30.510 --> 01:02:38.760
Jason Hogan: For making a good clock is that essentially as a really high IQ and that transition. You can you could be an exciting day for a really long time without to King

434
01:02:39.330 --> 01:02:45.930
Jason Hogan: So that's so that basically spontaneous mission is not an issue. We can just do these these a very coherent evolution of the way from

435
01:02:46.560 --> 01:02:51.720
Jason Hogan: The other way we control that, and in some cases of atoms like like video which don't have such a long life stage.

436
01:02:52.050 --> 01:03:07.170
Jason Hogan: Is we do a two photon process where we make sure that we go from the state that stable up through an intermediate state and back to

another state of state and so as long as we're far to tune from the excited state that has spontaneous mission. We can suppress that last mechanism.

437
01:03:09.120 --> 01:03:13.200
dong su: Okay, thanks. So the next question for page 19

438
01:03:15.510 --> 01:03:19.020
dong su: You you actually mentioned something is that excellent

439
01:03:20.040 --> 01:03:21.060
dong su: Well, the question here is,

440
01:03:22.350 --> 01:03:25.140
dong su: What is not a good initial test math.

441
01:03:26.850 --> 01:03:35.040
Jason Hogan: Yeah, I guess, you know, I guess that you know that that that's a little bit of a loose statement for sure but I, what I mean is that neutral atoms are

442
01:03:35.910 --> 01:03:42.540
Jason Hogan: There unusual. Right. They don't interact strongly with electromagnetic fields that that's the basic it that's sort of one reason why it has to be a good test that's

443
01:03:43.260 --> 01:03:54.030
Jason Hogan: Another reason is we when we make it will get atoms all atoms are the same, right. Every strontium Adam is the same as every other so we have this sort of, we don't have to manufacturer

444
01:03:55.380 --> 01:04:02.070
Jason Hogan: Sort of an artifact and try to make it equivalent right we can be sure that every story about astronomy mountains and these two locations on the same

445
01:04:03.090 --> 01:04:11.970
Jason Hogan: And so, yeah, but I guess so. It's like that's a couple of reasons insensitivity to interaction with non gravitational fields is the key takeaway there.

446
01:04:12.960 --> 01:04:17.490
Jason Hogan: Another thing is that I should have mentioned. And so that's why it's a great question.

447
01:04:18.870 --> 01:04:23.550
Jason Hogan: The atoms in these experiments. If it's not clear, you know, they're in freefall were able to, we take

448
01:04:23.850 --> 01:04:28.740
Jason Hogan: These, these positives and prepare them we cool look and then we drop them they're falling in a vacuum chamber.

449
01:04:29.100 --> 01:04:39.000
Jason Hogan: And so in that case they are experiencing or they're falling normally some geodesic, to the extent these non gravitational forces are negligible. They're just subject to

450
01:04:39.780 --> 01:04:44.790
Jason Hogan: The effects of gravity so that that's a key feature of good testaments

451
01:04:45.120 --> 01:04:53.160
Jason Hogan: And so you can do that with things that are not out of course. And so we, let's look at Lego, for example. So LEGO has realized excellent initial test masses.

452
01:04:53.460 --> 01:05:03.780
Jason Hogan: But the way that they did that is by suspending them off of, you know, very sophisticated isolation stage. So they have pendulums hanging from other pendulums basically

453
01:05:04.560 --> 01:05:15.780
Jason Hogan: That the decouple the acceleration of the test mass from the vibration of the ground. So even though the ground is shaking like if you just have a test mess sitting on the ground. That's not a good interval

454
01:05:16.080 --> 01:05:20.430
Jason Hogan: Massive because it's really just measuring the vibration of the ground. It's going to be coupled to that.

455
01:05:20.760 --> 01:05:25.770
Jason Hogan: But like, oh, has gotten around that by suspending it off of a pendulum, so that when the ground shakes.

456
01:05:25.950 --> 01:05:36.480
Jason Hogan: There's a suppression of the vibration of their initial test message so so you can realize a good initial test mass with isolation

from vibration and then the key thing here is that the free the following items are

457
01:05:36.990 --> 01:05:43.380
Jason Hogan: They're dropping. So they aren't they don't have any coupling at all, at least you know they don't have any direct couple of socialization. Be careful.

458
01:05:44.490 --> 01:05:52.200
Jason Hogan: And so there's no need for sort of these this pendulum isolation stages, like you would have with Lego and it would be the equivalent of Lego droppings.

459
01:05:52.200 --> 01:06:00.060
Jason Hogan: Mirrors which they obviously can't do right that the they have to hold them against gravity. But with the items we can make our, our test message.

460
01:06:00.540 --> 01:06:11.820
Jason Hogan: Over and over again with by collecting more atoms and then launching them and then just getting rid of them and making new test messages so so that's, I think that's the other the other key differences. The isolation that you can get with a freely falling object.

461
01:06:12.450 --> 01:06:19.260
Jason Hogan: Is can be can be quite good and you don't have to do, you're not limited by and don't have to make sophisticated isolation system.

462
01:06:20.850 --> 01:06:29.040
dong su: Okay, thanks. So maybe next question is how would you do or what the prospect do sky location with this technology.

463
01:06:31.050 --> 01:06:43.440
Jason Hogan: Okay, yeah. So the idea is to have let's say one. Let's imagine we have one detector on the earth, we can be in orbit around the Earth to but that that's that doesn't really affect this argument, too.

464
01:06:43.440 --> 01:06:52.230
Jason Hogan: Much so you know it, like, Oh, we have two or more detectors that we use to measure the delay, but this can be done with one detector in principle.

465
01:06:52.500 --> 01:07:01.980

Jason Hogan: And the way it works is you detect the event over a long time. So in this cartoon here we're imagining that the sources persisting long enough that

466
01:07:02.250 --> 01:07:10.410
Jason Hogan: The detector would would would would measure gravitational wave in January and the same gravitational wave source would be measured in July and the

467
01:07:11.700 --> 01:07:22.050
Jason Hogan: By by basically fitting the the data that you collected have that large duration, you have to account for the fact that the position with respect to the source is changing as the Earth moves around the sun.

468
01:07:22.440 --> 01:07:28.980
Jason Hogan: So you know this, the source has to be in, you know, just as with any of these local Asian measurements. You have to be

469
01:07:29.160 --> 01:07:36.540
Jason Hogan: In a location where it makes a difference. So you if there are certain locations that you're blind to like you're directly if the sources directly above the sun.

470
01:07:36.900 --> 01:07:46.410
Jason Hogan: Then it's the gender. It doesn't matter where you are, but if the sources for example in the plane of the Earth's orbit. Then as you move around the sun. You're getting closer and further from the source.

471
01:07:46.620 --> 01:07:56.520
Jason Hogan: And the arrival time will change that will effectively change the phase of the gravitational wave signal. And so you can think of it as like essentially a fit you look at this data coming in at the sutra times and you have to find

472
01:07:56.850 --> 01:08:10.590
Jason Hogan: What you can find a model parameter which is the localization. You know the position to in the sky that fits the data over the full orbit in this case. And so, yes, you're looking for something that maximize that variation. And so a large baseline.

473
01:08:11.970 --> 01:08:17.400
Jason Hogan: Is helpful. So it's a yeah so that's, I guess that's what I would say for that. So you

474
01:08:17.490 --> 01:08:18.360

dong su: Have one detector.

475
01:08:18.570 --> 01:08:19.320
Jason Hogan: You can measure

476
01:08:19.440 --> 01:08:21.060
Jason Hogan: The signal at different times and then

477
01:08:21.210 --> 01:08:27.000
Jason Hogan: correlate them and it's essentially synthesizing a large aperture with with one detector.

478
01:08:28.710 --> 01:08:34.620
Jason Hogan: Is also gives you polarization information. By the way, the fact that the detector is reorienting every time the Earth orbits.

479
01:08:34.920 --> 01:08:41.640
Jason Hogan: Or every time the the the recession say we've given him the Earth spins. If you're a detector is that a fixed location, the detector.

480
01:08:41.910 --> 01:08:51.840
Jason Hogan: It's it's angles changing with respect to the source which gives you different projection onto the gravitational wave polarization. So even though this a single base lie detector. Seems like you wouldn't be able to measure, you know, whether it's a

481
01:08:52.650 --> 01:09:04.260
Jason Hogan: Which polarization of repetition. When you have if the detector is spinning around you get polarization information from that. So, so you can get a lot of information with sources that last longer than the sources, we're used to thinking about and like

482
01:09:06.450 --> 01:09:12.450
dong su: Okay, well, maybe later question here is, why do you need on page 22

483
01:09:13.680 --> 01:09:17.250
dong su: Hey, Frank. Why do you need three items forces for the magic.

484
01:09:18.300 --> 01:09:30.510
Jason Hogan: Yeah, so, so you don't. That's a good question. So, so actually, I'll go to this one. So, so the we have to realize the scheme we need a source of the bottom and a source of the top. And that's a

485
01:09:31.830 --> 01:09:40.320
Jason Hogan: Realize this may just configuration of have a large gradient. But the reason for the source of the middle is interesting. So I've got on the sensitivity curve here this dashed orange line which is

486
01:09:40.770 --> 01:09:51.360
Jason Hogan: An example of a really important background that can show up and gravitational wave detectors cause Gigi and sensor gravity gradient noise, sometimes called New Newtonian noise and this

487
01:09:51.870 --> 01:10:02.160
Jason Hogan: This noise source spoils the fun of the argument that I gave before, right. So this idea of these test message being decoupled from vibration works for direct coupled noise but

488
01:10:02.220 --> 01:10:15.450
Jason Hogan: There's an annoying. Another effect, which is the fact that if, if the earth near the detector is shaking do the sizing noise. The atoms are not directly affected because they're in freefall. But the shaking Earth.

489
01:10:15.480 --> 01:10:17.730
Jason Hogan: Is sourcing a gravitational field.

490
01:10:18.150 --> 01:10:22.530
Jason Hogan: The just the local Newtonian gravitational field of the mass of the of the nearby stuff.

491
01:10:22.920 --> 01:10:24.120
Jason Hogan: And if that is shaking

492
01:10:24.360 --> 01:10:31.530
Jason Hogan: It can couple to the atoms gravitationally so you can see a time varying gravitational acceleration due to the seismic noise and that's

493
01:10:32.430 --> 01:10:38.190
Jason Hogan: You can't feel that. And so it would limit a terrestrial detector. So this is actually one of the reasons why.

494
01:10:38.640 --> 01:10:42.300
Jason Hogan: It makes sense to go into space for very low frequency detectors, because

495
01:10:42.480 --> 01:10:52.440
Jason Hogan: Gravity greedy noise gets really bad at low frequencies. And you can see here, it starts to limit pretty much any terrestrial detector. And so you want to get away from the earth going to space for the very lowest frequency very low frequencies.

496
01:10:53.520 --> 01:11:02.010
Jason Hogan: But there might be a way to do a little bit better than what this curve here would suggest, which is somewhat pessimistic. And the idea is to measure the noise.

497
01:11:02.310 --> 01:11:03.540
Jason Hogan: Due to the ground.

498
01:11:04.080 --> 01:11:15.750
Jason Hogan: With the inner firm or itself. And so the big difference between gravity gradient noise so called Newtonian noise and a gravitational wave signal is the spatial dependence. Right. Gravitational waves are planar expectations because they

499
01:11:15.750 --> 01:11:21.210
Jason Hogan: Come from a really large far far distance away. And so it's been playing with excitation. So it's linear across the baseline.

500
01:11:21.960 --> 01:11:33.330
Jason Hogan: In its effect, but local Newtonian perturbations, you know, their source, bye bye bye masses. There's someone here near near the testers. The Graduate field falls off like one of our R squared.

501
01:11:33.780 --> 01:11:36.270
Jason Hogan: And so there could be a variation in

502
01:11:36.330 --> 01:11:39.510
Jason Hogan: That single do grab the gradient noise across baseline itself.

503
01:11:39.900 --> 01:11:45.510
Jason Hogan: And so the idea of putting a third Adam starts in the middle here is to try to measure the curvature of the signal. Right.

504
01:11:45.780 --> 01:11:59.670
Jason Hogan: We're look we're seeing time during patients across this baseline. And if there are correlated linearly across the baseline, the

mass one spirit of gravitational wave a local source would have potentially spatial variation. And so by

505
01:11:59.700 --> 01:12:04.560
Jason Hogan: Measuring that the curvature or higher order derivatives, maybe with more than three. So we imagine

506
01:12:04.740 --> 01:12:13.410
Jason Hogan: Three or more. You could initially measure and subtract this background and maybe push the slightly lower frequencies. And so we envision, maybe even 10 sources.

507
01:12:13.860 --> 01:12:17.790
Jason Hogan: In a full scale instrument to measure grab the gradient noise but

508
01:12:17.820 --> 01:12:22.320
Jason Hogan: For me just 100 we want to add a third source to at least do a proof of principle of this concept.

509
01:12:22.560 --> 01:12:27.510
Jason Hogan: And try to do some courage, your measurements of the local vibrational. So we've already made measurements of the local sizable

510
01:12:27.570 --> 01:12:34.770
Jason Hogan: Space ENvironment, we have predictions of the effective strain due to that and it would be really interesting to see if we could measure that a curvature and potentially

511
01:12:35.370 --> 01:12:37.740
Jason Hogan: You know, decide whether it's something you can suppress

512
01:12:40.620 --> 01:12:43.950
dong su: Okay, so let me switch to a different

513
01:12:45.060 --> 01:12:46.020
dong su: Passion here the

514
01:12:47.250 --> 01:12:53.310
dong su: What kind of sources with the Midas 100 expect to detect the cover of the mid range frequency so

515
01:12:54.690 --> 01:12:58.080

dong su: I'll defer other type of fourth of you would cover compared to the other techniques.

516
01:12:59.070 --> 01:13:03.960
Jason Hogan: Right, so, so let me just re emphasize that major 100 with me just 100 is a demonstrator and we

517
01:13:03.960 --> 01:13:06.210
Jason Hogan: Don't expect to the tech gravitational waves.

518
01:13:06.270 --> 01:13:13.440
Jason Hogan: Because it's only 100 meter baseline. And we're using it as a way to sort of develop the technical the detector technology.

519
01:13:13.800 --> 01:13:18.540
Jason Hogan: It's very much in the spirit of what we what was done with with Lego is

520
01:13:18.720 --> 01:13:23.940
Jason Hogan: The large laser and from there they weren't kilometer scale wasn't the first step right there was a preliminary step.

521
01:13:23.940 --> 01:13:24.210
Jason Hogan: Where

522
01:13:24.420 --> 01:13:30.750
Jason Hogan: Things were skilled up beyond the tabletop to understand how to build large text. We're kind of at that stage right now.

523
01:13:31.200 --> 01:13:35.280
Jason Hogan: So, so it's not designed. We don't expect to see sources like I've shown on this plot.

524
01:13:36.150 --> 01:13:43.890
Jason Hogan: That said in the frequency range of interest, the kinds of sources that you wouldn't be able to see with a more sense and protector include the kind of sources that

525
01:13:44.160 --> 01:13:52.860
Jason Hogan: The Lego has already seen black hole binaries do trust neutron star binaries potentially other sources that don't make it up to Legos rain. So, any, any inspire that would would

526

01:13:52.920 --> 01:14:05.160
Jason Hogan: Terminate before reaching the highest frequencies. These may include white dwarf binaries, in particular for the space based detector. I've got here and there are a number of signals of interest.

527
01:14:05.310 --> 01:14:08.100
Jason Hogan: In this band. I'll just say a word about this so

528
01:14:09.060 --> 01:14:14.280
Jason Hogan: The cosmic gravitational wave background so so called to cast the gravitational waves which

529
01:14:15.450 --> 01:14:24.420
Jason Hogan: Are expected to arise, for example, due to the early universe or inflationary evolution, causing source of gravitational waves. Those kinds of sources.

530
01:14:24.900 --> 01:14:31.920
Jason Hogan: Would be broadband. But there's there's some so argument that the mid band ranch might be a good place to look for them for various reasons.

531
01:14:32.640 --> 01:14:41.610
Jason Hogan: And those are really, really weak and hard to detect. But, and we would expect to happen with the sensitive Chris I'm showing here, but we've done some thinking about

532
01:14:42.180 --> 01:14:47.850
Jason Hogan: About loosens the classic sources and other sort of beyond, beyond primordial also

533
01:14:48.270 --> 01:14:59.490
Jason Hogan: You know, other novel sources of sarcastic graduates that would show up in a nice way. In the mid band, including do to face transitions in the or the universe or next next of cosmic strings, for example, and some of those

534
01:15:00.000 --> 01:15:03.030
Jason Hogan: Can you can do better in the mid band and you could maybe even

535
01:15:03.600 --> 01:15:14.790
Jason Hogan: Lisa, simply because and Lisa. There's so many signals you have so many white dwarfs, for example, that it tends to be difficult to resolve all the signals and it might be difficult to see.

536
01:15:15.270 --> 01:15:21.570
Jason Hogan: Some of these novels to Catholic sources. Can you just have this fantastic background due to white dwarfs and so

537
01:15:21.810 --> 01:15:23.580
Jason Hogan: You know, it's a speculation, but

538
01:15:23.760 --> 01:15:32.820
Jason Hogan: It may be that in the mid band that those issues are somewhat mitigated. And you can look for some of these cosmological signals but but there's a there's a variety of

539
01:15:32.880 --> 01:15:36.030
Jason Hogan: astrophysical and cosmological sources that we think are really interesting in the mid band.

540
01:15:36.330 --> 01:15:44.910
Jason Hogan: And I would argue that some detector, you know, have some texture technology. I think should be developed in this range to sort of fill out the spectrum as much as possible.

541
01:15:48.000 --> 01:15:50.490
dong su: Okay, so maybe one last one is

542
01:15:51.840 --> 01:15:58.830
dong su: On page 21 say hello magic 100 mitigate the effects of gravitational gradient with them.

543
01:16:00.480 --> 01:16:10.860
Jason Hogan: So Gretchen radiant. I think so. I think I'll that's basically what I was saying with this gravitation gradient noise suppression so that so so the answer. That is the same. I gave before it's this

544
01:16:11.850 --> 01:16:23.970
Jason Hogan: The third Adam source that we're adding is really designed to try to measure that gravity gradient noise in situ with the atoms. And yeah, it's, it's a, it's a, you know, this is a demonstrator so

545
01:16:23.970 --> 01:16:26.400
Jason Hogan: The question is whether or not that works and how well it works.

546
01:16:26.760 --> 01:16:28.800
Jason Hogan: And once again, we don't expect to

547
01:16:29.910 --> 01:16:31.710
Jason Hogan: To detect gravitational waves with this instrument.

548
01:16:32.520 --> 01:16:37.860
Jason Hogan: Even if you know we were sensitive enough this is maybe this might not be the best sites, you know, could be a fairly noisy sites.

549
01:16:38.820 --> 01:16:45.180
Jason Hogan: In a fairly lab that for full scale and smack you want to think very carefully about choosing a low noise environment because

550
01:16:45.600 --> 01:16:56.640
Jason Hogan: Even though the atoms are in freefall. Like I said, the gravitational coupling is gonna put a limit at low frequencies. So it's so we're will be doing exploratory work on image 100 to study gravity gradient noise.

551
01:16:57.720 --> 01:17:03.810
Jason Hogan: I hope, I hope that that question was not distinct that I'm not missing something. But I think that that was what I was saying before,

552
01:17:05.160 --> 01:17:09.720
dong su: Right, okay, maybe a great law me one last question after the very first one I miss

553
01:17:10.140 --> 01:17:10.830
Jason Hogan: You, oh, actually.

554
01:17:11.430 --> 01:17:23.730
dong su: The, the, the, the, the range, you're covering, but there are also people spotting that there is a gap between the between the PDA and the space race.

555
01:17:24.030 --> 01:17:24.450
Yeah.

556
01:17:25.680 --> 01:17:30.390
dong su: The possible techniques to cover that gap as well or some other techniques.

557
01:17:31.260 --> 01:17:34.020
Jason Hogan: So I, I can't really speak to that, I think,

558
01:17:34.200 --> 01:17:45.630
Jason Hogan: That's a good point. I think it's worth investigation. I, I want to say that that I've heard of some efforts in that area. But I don't want to be specific, because I I couldn't do it justice, but

559
01:17:46.350 --> 01:17:52.020
Jason Hogan: I think that's a good point. I think similar argument could be made to what I made in the mid band is that in general is it's important to

560
01:17:52.020 --> 01:17:52.980
Jason Hogan: Look in as many

561
01:17:54.840 --> 01:18:04.260
Jason Hogan: As many regions as possible. I mean, I know for example of work looking to look above Lego like is interesting to look above 10 kilohertz other other any sources there.

562
01:18:05.190 --> 01:18:15.630
Jason Hogan: And in the in the low frequency range. I think that there's probably, you know, straightforward arguments for sources that are going to span the gap between these two detector geometry.

563
01:18:16.680 --> 01:18:20.670
Jason Hogan: Detectors I'm sure that is well known, so what, but I don't have specific ideas.

564
01:18:21.330 --> 01:18:25.260
Jason Hogan: For how to build such detector. So it says that's a good question. I think. Yeah.

565
01:18:25.830 --> 01:18:26.430
Jason Hogan: We're

566
01:18:26.490 --> 01:18:26.910
Looking into

567
01:18:28.650 --> 01:18:32.220
dong su: Probably all the time. So I think that's probably great

568
01:18:32.310 --> 01:18:37.740
Jason Hogan: Well thank thanks everybody for the great questions and for your attention. I appreciate the opportunity to speak to all

569
01:18:37.920 --> 01:18:46.200
grzegorz madejski: Well, we thank you, Jason for taking the time and then providing such a nice presentation here. So thank you again and we're going to stop recording now and

570
01:18:47.100 --> 01:18:52.950
grzegorz madejski: Hopefully if you have a chance, come and listen to some other talks in the series since they're really great. Excellent. So thanks again.