WEBVTT

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00:00:03.060 --> 00:00:09.330
Kent Irwin: Different one to thank the organizers for the invitation. It's a great pleasure to be there and not see everyone but I'll have faith that you're out there.

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00:00:10.110 --> 00:00:16.080
Kent Irwin: So this talk is going to be a little bit different than most of the talks at the SSI because it's more instrumentation and technology oriented.

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00:00:16.920 --> 00:00:20.580
Kent Irwin: superconducting teachers are actually having, you know, growing and strong impact.

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00:00:20.910 --> 00:00:25.980
Kent Irwin: On particle physics, you know, very, notably in the area of like exploring the weekly coupled universe.

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00:00:26.220 --> 00:00:37.410
Kent Irwin: But there's a lot of other talks that are actually going to be expanding on all the main science areas. So this talk will be providing some background for things like dark matter searches and C and D measurements for

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00:00:38.130 --> 00:00:48.360
Kent Irwin: invisible particles and things like that, and I'll be filling in more of the technical details more of the historical basis of doing this sort of sensitivity and I've actually

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00:00:49.920 --> 00:01:00.030
Kent Irwin: Addressed two things I think that I was actually invited to speak on this transition of sensors, depending on how time goes, I will also go past them to talk about kind of

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00:01:00.810 --> 00:01:12.840
Kent Irwin: Quantum sensors that are evolving out of some of that same technology basis. I do, however, find that when I do doom zoom talks I end up going significantly slower. So I don't know if I'll get to the to the quantum sensor part

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00:01:15.150 --> 00:01:23.220
Kent Irwin: If I can get there we go. So let me just mentioned a little bit about some of the other talks during SSI that are going to

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00:01:23.700 --> 00:01:27.660
Kent Irwin: Build it some level upon it, but the basis of the sensitive detection technology.

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00:01:28.380 --> 00:01:34.800
Kent Irwin: Transition to just first 10. Oh, that's what I'll be talking about initially our direct detectors and all describe what that means.

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00:01:35.130 --> 00:01:44.580
Kent Irwin: And I would point you towards zetia just talk coming later on, almost invisible is in the CB and also Jody Cooley's talk talking about direct dark matter searches.

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00:01:45.360 --> 00:02:00.210
Kent Irwin: Two yeses are both important tools in those areas and then moving on towards quantum coherence superconducting centers, I would point you to the discussion of accion and accion like particle searches and Yun Pala currency will be talking about that.

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00:02:02.640 --> 00:02:12.810
Kent Irwin: Okay, so let's start by talking about kind of the distinction. First there's you can broadly speak or separate detection into two categories.

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00:02:13.290 --> 00:02:25.590
Kent Irwin: They have different names depending on what sub community you're in, but one set of of names would be direct detectors and coherent detectors coherent detectors are basically like amplifiers that measure a waveform.

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00:02:26.130 --> 00:02:34.290
Kent Irwin: Whereas direct detectors measure energy deposited or power deposited and the technologies are very, very

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00:02:34.290 --> 00:02:39.630
Kent Irwin: Different and the implications for sensitive measurement and noise are very different.

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00:02:40.230 --> 00:02:48.870

Kent Irwin: So I'm going to be starting this talk by talking about superconducting transition its sensors which are no mature mature technology.

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00:02:49.170 --> 00:02:57.450
Kent Irwin: Which is having strong impact on a number of different areas in particle physics in the search for these weekend or actions.

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00:02:58.260 --> 00:03:02.340
Kent Irwin: And there's a variety of different types of superconducting detectors that are doing that.

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00:03:02.790 --> 00:03:09.450
Kent Irwin: The superconducting tradition is is really the most mature as the one that's the most deployed and it's being, you know,

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00:03:09.750 --> 00:03:16.410
Kent Irwin: Baseline for things like cosmic microwave background experiments at CNBC H4 so I'll focus on that as well as its history.

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00:03:16.650 --> 00:03:28.590
Kent Irwin: But I would also just mentioned that there's a variety of other superconducting detector technologies that you've categories direct detectors that Mr energy or power. These include superconducting tunnel junctions.

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00:03:29.070 --> 00:03:41.610
Kent Irwin: Microwave kinetic conductors detectors nano wires, etc. In contrast, coherent detectors, as I said, amplify a waveform like a field effect transistor is a type of coherent detector.

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00:03:42.120 --> 00:03:46.140
Kent Irwin: And it measures both amplitude and phase because it actually mentioned a sine wave.

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00:03:46.650 --> 00:03:55.230
Kent Irwin: And the fact that you're doing that has great advantages you automatically get things like spectroscopy frequency information and some disadvantages.

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00:03:55.620 --> 00:04:01.410
Kent Irwin: When you start talking about quantum mechanics. There's we'll get to towards the end when you measure both the amplitude

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00:04:01.770 --> 00:04:11.400
Kent Irwin: And phase of a signal of electromagnetic signal quantum mechanics insists that there's some additional noise added to the measurements called quantum noise.

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00:04:11.730 --> 00:04:21.090
Kent Irwin: And that is because just like position and momentum don't commute for a particle, you can't measure both perfectly well because they are in different basis sets.

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00:04:21.750 --> 00:04:29.850
Kent Irwin: The same sort of thing that amplitude and phase, you cannot measure at the same time they're both not perfectly defined in the same quantum state.

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00:04:30.120 --> 00:04:36.090
Kent Irwin: And this means you've got an additional half a photon, or maybe one photon after you amplify it of noise.

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00:04:36.990 --> 00:04:42.660
Kent Irwin: However, we'll get we'll get to that part of it later. We're going to focus on the directors, they don't have that sort of noise.

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00:04:43.050 --> 00:04:49.590
Kent Irwin: But they're actually you broadly applicable over a very wide range of electromagnetic signals, where you might not even

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00:04:49.800 --> 00:04:57.840
Kent Irwin: Want to consider using coherent detectors. For instance, if you're measuring x ray signals you typically wouldn't think about measuring the amplitude and phase.

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00:04:58.080 --> 00:05:07.590
Kent Irwin: You can do some of those measurements which is very difficult typically just measure the energy. So I've got here at the bottom, a graph of the electromagnetic spectrum.

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00:05:08.700 --> 00:05:18.510
Kent Irwin: Focusing on the higher frequencies which is where you typically see the direct detectors and lower frequencies, you often see coherent detectors that I'll come back to

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00:05:19.080 --> 00:05:29.310

Kent Irwin: And the higher frequencies, you can actually put the axes based on either energy like an electron volts at the top or wavelength and meters, the size of the photons.

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00:05:29.790 --> 00:05:35.970
Kent Irwin: Or frequency and the visible spectrum is in the middle there. The rainbow. And one thing to note

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00:05:36.510 --> 00:05:48.030
Kent Irwin: Is that you can kind of think of the universe as being quantum mechanical in its very nature at some frequencies and not others. I'm not talking about the physics, everything's quantum mechanics and physics.

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00:05:48.420 --> 00:05:55.950
Kent Irwin: But typically, you can you can think about whether a phenomenon is described by individual quanta or whether you've got so many

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00:05:56.190 --> 00:06:02.460
Kent Irwin: Of those individual quanta that you just think of it as a wave. And you can think of is classically, and that'll be accurate enough

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00:06:02.910 --> 00:06:08.940
Kent Irwin: And we do know that the universe is filled with background radiation from the cosmic microwave background.

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00:06:09.720 --> 00:06:20.010
Kent Irwin: You've all heard of that. And there will be some more discussions about that later in this in this workshop and universe itself is putting out thermal radiation at a temperature of about three Kelvin.

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00:06:20.490 --> 00:06:25.830
Kent Irwin: And that is a high enough temperature that when you get up above 100 gigahertz.

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00:06:26.100 --> 00:06:38.790
Kent Irwin: You've got many, many photons in any patch of space of the size of wavelength many photons in any energy level. And so you can really think of the the signal as being a classical signal.

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00:06:39.150 --> 00:06:46.950
Kent Irwin: And a direct detectors are natural thing to use. So let's go in and kind of delve into one particular type of direct detector.

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00:06:47.910 --> 00:06:53.730
Kent Irwin: Which is having actually a lot of use. But first, I mentioned that a superconductor largely

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00:06:54.330 --> 00:07:02.580
Kent Irwin: Are actually now being deployed more and more all across the spectrum of direct detection down the submillimeter and millimeter for cosmology and astronomy.

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00:07:02.940 --> 00:07:15.360
Kent Irwin: There are single optical detectors and near IR detectors that are based on superconductors that are being used for both quantum information applications and for cosmology astronomy and even some

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00:07:15.930 --> 00:07:23.880
Kent Irwin: Dark Matter candidate searches x ray centers for materials and astronomy and gamma ray so super intransigent are having more and more impact.

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00:07:24.390 --> 00:07:35.460
Kent Irwin: The, the grandfather of all superconducting sensors is what I'm going to be speaking about, which is the superconducting transition and sensor and I call it just the grandfather in the sense that is certainly the oldest

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00:07:36.600 --> 00:07:50.280
Kent Irwin: And in fact, use the idea of using a superconducting transition as a sensor goes all the way back to 1938 even though this this sort of work body of work was largely forgotten for a number of decades.

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00:07:50.700 --> 00:08:03.060
Kent Irwin: And it was actually suggested initially by a Johns Hopkins professor named Donald hatch Andrews and the chemistry department and he had the idea that actually, if you take a superconducting film.

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00:08:03.930 --> 00:08:15.690
Kent Irwin: There's a certain very narrow temperature range where it makes an extraordinarily good thermometer and that's simply because what a superconductor is is just a metal

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00:08:16.230 --> 00:08:25.890
Kent Irwin: That has the right materials characteristics so that a certain temperature it will it when you get down below that temperature it will lose all electrical resistance.

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00:08:26.130 --> 00:08:39.750
Kent Irwin: Above that temperature, it acts like a normal metal, you've got electron scattering of rents but below that temperature, the electrons pair into cooper pairs. And they propagate without scattering and this is one of the few fundamental

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00:08:40.260 --> 00:08:52.410
Kent Irwin: Fundamentally zero parameters that you get in the universe or this this resistance can be so low that you wouldn't measure a scattering event over the lifetime of the universe. It's a very, very, very, very hard zero

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00:08:52.950 --> 00:08:57.990
Kent Irwin: But if we look here on the left, this is a plot of the resistive transition

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00:08:58.260 --> 00:09:15.690
Kent Irwin: Of a typical superconducting film that's been it's been designed to have a transition temperature at about a 10th of a degree Kelvin, a 10th of a degree above absolute zero. And as you see it goes from a really hard zero in this particular case at about 95.8

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00:09:16.800 --> 00:09:32.160
Kent Irwin: To its normal value some resistance. Just, just that you'd get from normal materials properties at 96.2 so over some fraction of a degree Milla Kelvin. It goes from hard zero resistance to

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00:09:32.670 --> 00:09:41.850
Kent Irwin: Prior resistance, you can actually measure and what Donald Enders realized back in 1938 was it if you could just buy us it right in that tiny region.

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00:09:42.240 --> 00:09:48.420
Kent Irwin: Its resistance is a very, very strong function of temperature. And so anything that you can convert

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00:09:48.720 --> 00:09:57.900
Kent Irwin: To a temperature, you can measure with extraordinary precision that was his idea he had very big ideas. He was very much ahead of his time. That's a photograph of him right here.

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00:09:58.110 --> 00:10:10.920
Kent Irwin: He not only measured the first did the first color imagery with these devices where he measured the heat deposited by individual

alpha particles, but he built sensors that would measure infrared radiation even

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00:10:11.700 --> 00:10:26.370
Kent Irwin: Infrared radiation that with the thermal infrared radiation and he took what actually, I believe, was the first real time video rates infrared image using a Ts. That's actually a photograph of Silla scope trace

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00:10:26.790 --> 00:10:38.520
Kent Irwin: And he synchronized and the Silla scope couple to just to superconducting film looking out into the room and that is actually an image of Donald Andrews with his hands up in the air like this.

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00:10:38.790 --> 00:10:49.110
Kent Irwin: As he had mechanically rostered a superconducting films optics. So it was looking at him picking up the thermal infrared signal from him in the dark with the lights out

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00:10:49.410 --> 00:10:58.500
Kent Irwin: And so you could actually wave his arms and you get a real time video rate, night vision and it's got to be the first one that was ever done that was done back in 1945

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00:10:59.130 --> 00:11:09.090
Kent Irwin: So he was a very ambitious man. He had great goals with two yeses. He actually wanted to put a tradition in center and every car to look for wildlife. That was kind of run out of the dark

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00:11:09.390 --> 00:11:16.830
Kent Irwin: It never worked was way ahead of his time and that technology completely faded away after he passed for a number of decades.

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00:11:18.300 --> 00:11:26.340
Kent Irwin: And there was actually a real issue. While he really did nail that these devices were extraordinarily sensitive

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00:11:26.790 --> 00:11:32.280
Kent Irwin: And so it could be great thermometers and in anything you could convert to heat you could measure very well.

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00:11:33.090 --> 00:11:39.180
Kent Irwin: There were issues with stability that were prevented them practically disseminating and being practical used broadly.

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00:11:39.960 --> 00:11:49.350
Kent Irwin: Now let me just mentioned a bit about the a thermal sensor which is called a bolometer if it's measuring power or a calorie perimeter. If it's measuring energy

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00:11:49.920 --> 00:12:05.610
Kent Irwin: Is an extraordinarily sensitive type of sensor because almost anything can be converted to heat it can be hard to manipulate different forms of energy. But if you're trying to convert it to heat the second law of thermodynamics is your friend. And you can typically do it quite efficiently.

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00:12:06.720 --> 00:12:16.200
Kent Irwin: So they were just wide transition as sensors are really useful over this broad range of the spectrum but but but Donald Leonard's did what the natural thing you would do.

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00:12:16.800 --> 00:12:26.310
Kent Irwin: You know, this is very early on, he 38 you had a very limited choice of amplifiers. And what he did is he, he applied a constant bias current as you see in this very simple electrical circuit.

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00:12:26.760 --> 00:12:38.430
Kent Irwin: Through a transition in sensor and then read it out with an amplifier and the sensitivity was great. It was limited at some level by the noise of the follow on amplifier we have much better amplifiers now.

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00:12:38.820 --> 00:12:47.070
Kent Irwin: But the temperature over which TS works is very narrow and the problem wasn't these devices were intrinsically firmly unstable.

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00:12:47.520 --> 00:12:58.890
Kent Irwin: Because as an energy is to pod pod deposited like from an infrared signal or a CNBC signal or an X ray pulse that makes the temperature of the TS go up.

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00:12:59.490 --> 00:13:05.340
Kent Irwin: And when the temperature of a TS goes up, the resistance goes up. And that's what that gives you a voltage pulse. You can measure

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00:13:06.060 --> 00:13:09.420
Kent Irwin: But as the voltage goes up. If you've got a constant current

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00:13:09.810 --> 00:13:22.950

Kent Irwin: That means the jewel power also goes up your card dissipation I squared R increases. So, tip temperature inputs feedback in a positive feedback loop to make the jewel power go up.

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00:13:23.190 --> 00:13:28.860
Kent Irwin: These are intrinsically unstable devices, you have to bias them very carefully and even more difficult.

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00:13:29.760 --> 00:13:36.360
Kent Irwin: Need the bigger difficulty is you really couldn't figure out a way to have multiple devices operating at the same temperature

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00:13:36.840 --> 00:13:43.530
Kent Irwin: Because each TS will have slightly different transition temperatures because of material properties very narrow transition

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00:13:43.740 --> 00:13:53.010
Kent Irwin: Of small variation. If you put them to Ts as at the same bias temperature one will be honest transition. The other won't. And then you have this thermal runaway prop problem.

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00:13:53.430 --> 00:14:02.670
Kent Irwin: So the use of tea. Yes. Is never really took off after Donner liners until the early 1990s and

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00:14:03.300 --> 00:14:10.260
Kent Irwin: Then recent developments that occurred actually was when I was a grad student working with plus Cabrera on the cryogenic dark matter search experiment.

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00:14:10.740 --> 00:14:21.060
Kent Irwin: We figured out a new way to operate these devices that really meet them practical and intrinsically stable and led to this exponential growth in their use that's gone. That's happened over the last

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00:14:21.420 --> 00:14:26.340
Kent Irwin: 20 years or so, to the point where they're a very powerful tool for particle physics now.

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00:14:28.620 --> 00:14:37.200
Kent Irwin: It's a very simple idea. There's nothing, nothing, you know, remarkable about this, you can understand it very quickly if one of the problems is thermal runaway

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00:14:37.800 --> 00:14:42.720
Kent Irwin: The problem is just that if you current bias device and its resistance goes up its power goes up.

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00:14:43.320 --> 00:14:50.670
Kent Irwin: But the very, very simple trick is you just voltage bias. This device, you put a constant voltage across it instead of a constant current

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00:14:51.270 --> 00:15:03.960
Kent Irwin: Then the jewel power is now V squirt over our instead of I squared R. And now if the resistance goes up the jewel power goes down there intrinsically self stabilizing devices.

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00:15:04.590 --> 00:15:10.800
Kent Irwin: So that's great. But now you have to be able to measure the current instead of the voltage to the current amplifier.

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00:15:11.430 --> 00:15:23.040
Kent Irwin: But there's also another important thing that you get for free. Once you get into this intrinsically self temperature regulating state where this negative feedback is making them stable.

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00:15:23.370 --> 00:15:33.120
Kent Irwin: And that is suddenly you can make bigger race and you can make bigger raised with relative ease because if you have a silicon wafer with many TS has across it.

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00:15:33.630 --> 00:15:44.070
Kent Irwin: It doesn't matter that they've got different transitioning temperatures, because even if you bias them all the same temperature because they're intrinsically self regulating temperature

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00:15:44.550 --> 00:15:48.600
Kent Irwin: Each of them will pull exactly the jewel power they need to stay in their transition

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00:15:49.140 --> 00:16:03.210
Kent Irwin: So imagine you start by having an array of many, many TSS that are biased across a wafer and you put it right at right above the transition temperature you apply your voltage bias. And then you start cooling your bath temperature down

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00:16:03.750 --> 00:16:10.050

Kent Irwin: As individual TSS start going superconducting their resistance or drop and the jewel power will go up.

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00:16:10.410 --> 00:16:18.600
Kent Irwin: And the resistance can never drop to zero because the Napoleon financial power. So each device will pull exactly the jewel parent needs to stay in the transition

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00:16:19.110 --> 00:16:28.050
Kent Irwin: So that means that you can now have some variation of materials properties their self regulating and now you can make bigger razor devices and they'll all be sensitive at the same time.

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00:16:29.670 --> 00:16:39.150
Kent Irwin: Okay. So as I mentioned before, you also need a current amplifier and fats are not current amplifiers, the great amplifiers, but they do not amplify current

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00:16:40.740 --> 00:16:48.180
Kent Irwin: So the great thing is, even though in 1838 we didn't have very sensitive current amplifiers in the 1960s. That all changed.

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00:16:48.540 --> 00:16:59.040
Kent Irwin: And superconducting amplifiers became available that are extraordinarily sensitive and these are devices called squids superconducting quantum interference devices.

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00:16:59.370 --> 00:17:08.700
Kent Irwin: And what they do is they if you if you bias. A Ts, like you see in this diagram and the right as a variable resistor with a voltage bias on the left.

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00:17:09.180 --> 00:17:18.780
Kent Irwin: But you have the current passing through an inductive loop, which is the inductor besides that circle that inductive Lupul transducers that current into a magnetic field.

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00:17:19.260 --> 00:17:32.880
Kent Irwin: And the magnetic field can then be coupled to this new and 1960s kind of superconducting quantum amplifier that actually measures that magnetic field and can do so it very, very close to quantum mechanical limits and we'll see how that works.

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00:17:34.050 --> 00:17:43.260

Kent Irwin: OK, so the basic physics breakthrough that made this possible on the device is still had to be invented. But the basic physics breakthrough was made by Brian Josephson

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00:17:43.530 --> 00:17:56.760
Kent Irwin: In the early 1960s, when he was a graduate student, and he developed a theory or he understood from the the superconductors. In addition to having individual electrons pair so they don't scatter

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00:17:57.120 --> 00:18:03.660
Kent Irwin: They actually exhibit a macroscopic quantum face, and he was able to derive as part of his graduate work.

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00:18:04.200 --> 00:18:10.980
Kent Irwin: The relations of what will happen when you have to superconductors separated by a gap, like an insulator.

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00:18:11.430 --> 00:18:22.980
Kent Irwin: And you have some of the superconducting wave function that macroscopic quantum wave function of all that all the electrons in the left hand side, or in tunnels through to the superconductor on the right.

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00:18:23.310 --> 00:18:34.950
Kent Irwin: That these wave functions will will link with each other and you actually have a what's called a justice and current that then passes across that superconductor gap from one to the other.

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00:18:35.280 --> 00:18:47.700
Kent Irwin: And what brand justice and showed is that the amount of current that flows is Sonia solely dependent on the difference in quantum face from one superconductor to the other.

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00:18:48.450 --> 00:18:59.370
Kent Irwin: And so that the current flowing is equal to some critical current value times the sign of the difference in face. Does that mean fundamentally amazing it's a it's a very early practical quantum circuit.

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00:19:00.600 --> 00:19:07.020
Kent Irwin: But he already, but there's actually more more exciting things that happen when, instead of having one junction, you have to

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00:19:07.590 --> 00:19:16.890
Kent Irwin: When you have to that form a loop then you end up forming a kind of interferometer because you have to sign you solely dependent

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00:19:17.400 --> 00:19:28.230
Kent Irwin: Changes in phase that are kind of like two different optical slits and there's something else that can modulate the quantum phase in a superconductor. And that is an applied medic magnetic field.

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00:19:28.800 --> 00:19:38.700
Kent Irwin: And it turns out that putting a magnetic flux through that loop will change the phase so that the the the macroscopic quantum wave function in one

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00:19:39.330 --> 00:19:49.320
Kent Irwin: Justice direction to the other are a little out of phase mathematically it's a lot just like a to slit optical interferometer where if you have two slits and you have

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00:19:49.980 --> 00:19:59.430
Kent Irwin: A coherent light going through both if you go off at a little bit of an angle one slit will be at a slightly different phase than the other. So depending on which angle you look at

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00:19:59.670 --> 00:20:11.550
Kent Irwin: You'll have see either constructive interference from the two slits or destructive interference. Well, the same thing happens here except an angle. It's instead of angle, what you have is magnetic flux

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00:20:11.910 --> 00:20:28.050
Kent Irwin: That determines whether the interaction between these two junctions is destructive or constructive and then a remarkable thing happened within two years after Brian came up with this theory as a graduate student.

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00:20:29.130 --> 00:20:36.120
Kent Irwin: There were some people that developed a practical device that was able to use this as a magnetic amplifier.

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00:20:36.690 --> 00:20:48.030
Kent Irwin: And the world was a kinder and gentler world at the time or large corporations did fundamental research, the inventor of the DC squid turns out to be the Ford Motor Company.

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00:20:48.930 --> 00:20:56.250
Kent Irwin: The food that some researchers, including Arnold silver at the Ford Motor Company, we're making superconducting tunnel junctions.

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00:20:56.550 --> 00:21:09.120
Kent Irwin: And found that if they make two junctions next to each other with a little loop that the current that flowed through it was dependent on how much magnetic flux. There was in a periodic way.

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00:21:09.540 --> 00:21:17.640
Kent Irwin: That's actually providing additional evidence of that justice and was right, and also making a nearly quantum mechanically limited amplifier.

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00:21:18.090 --> 00:21:32.520
Kent Irwin: Because now you see if you try and reduce the current to magnetic flux that changes how much current can flow through this device, this device that Ford queen to name for the superconducting quantum interference device or the squid.

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00:21:34.200 --> 00:21:39.840
Kent Irwin: Okay, so that, so the great thing here is here's these devices. These superconducting amplifiers.

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00:21:40.140 --> 00:21:50.880
Kent Irwin: That are great nearly quantum mechanical current amplifiers. Now they've gotten used to do all sorts of interesting experiments squids are also used to probe magnetic fields in like human brains and things like that.

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00:21:51.150 --> 00:21:58.170
Kent Irwin: But they're difficult devices to use because they're cold. You have to cool them down to where they're superconducting just a few degrees Kelvin.

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00:21:59.100 --> 00:22:05.520
Kent Irwin: But they're not difficult to use with Ts is because he is, is there always cold. In fact, it's a match made in heaven.

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00:22:05.940 --> 00:22:17.220
Kent Irwin: And the combination of those two technologies made this wonderfully powerful easily fabricated scalable technology that has led to the technological impact we have today.

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00:22:17.790 --> 00:22:24.870
Kent Irwin: And I just wanted to mention that, as I said before, it was part of the cryogenic dark matter search program that these

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00:22:25.440 --> 00:22:33.480

Kent Irwin: This pairing of the squid and a voltage bias TS was done. And still, even as today that the

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00:22:34.050 --> 00:22:48.870
Kent Irwin: Super CMS project is using superconducting transition and sensors with the squids that were invented by forward in order to look for dark matter, and I would point you towards God Cooley's talks I think for dark matter experiments.

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00:22:49.920 --> 00:22:55.890
Kent Irwin: Okay, so that gives you some background. But as I said before, you know, these are thermal sensors.

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00:22:56.310 --> 00:23:05.160
Kent Irwin: But transition and sensors and because the thermal sensors. If you can figure out how to do something like measure the heat that might be deposited by dark matter.

144
00:23:05.760 --> 00:23:15.480
Kent Irwin: You can measure anything that can be converted to heat and in fact transition. It centers, very quickly got a spread to be used over large other fractions of the

145
00:23:16.050 --> 00:23:28.020
Kent Irwin: Magnetic electromagnetic spectrum. I mean, after I left as a graduate student in 1995 from Stanford. I actually went for 20 years to the National Institute of Standards and Technology Laboratory in Boulder, Colorado.

146
00:23:28.470 --> 00:23:43.050
Kent Irwin: And actually, while I was there, we developed applications far across the electromagnetic spectrum, all the way from gamma rays on the right hand side that you see here where you're actually just absorbing gamma rays in a tin foil measuring heat deposited in a Ts.

147
00:23:44.070 --> 00:23:54.780
Kent Irwin: For soft X rays. That's a business film to do absorption for optical detection. We measure individual single photons with a TS still have some work of seeing when they would name it missed

148
00:23:55.050 --> 00:24:01.410
Kent Irwin: But you can also measure seven millimeter and millimeter and C and B and all the way down to Cosmic Microwave Background.

149
00:24:01.680 --> 00:24:07.050

Kent Irwin: And all of these are important. And I should say that my group and this is doing this, but in fact us. And there's many different groups.

150
00:24:07.260 --> 00:24:19.380
Kent Irwin: At Berkeley and NASA Goddard Space Flight Center and many other institutions that makes superconducting transition and centers and some companies are getting in the game as well to have applications across the spectrum.

151
00:24:21.300 --> 00:24:23.490
Kent Irwin: Okay. So I want to show you a little bit of history here.

152
00:24:24.630 --> 00:24:35.100
Kent Irwin: One particularly exciting area of application for the particle physics community is in the measurement of cosmic radiation kind of record background radiation, but also submillimeter radiation.

153
00:24:35.610 --> 00:24:49.320
Kent Irwin: And here's some photographs of some of the first devices that were actually developed for measuring in in this submillimeter millimeter wavelength range. This is actually the first photograph in the top left of the first

154
00:24:50.010 --> 00:25:04.590
Kent Irwin: Eight pixel TS bolometer array that was actually put on the sky to measure submillimeter signals that was the Celtic submillimeter Observatory in 2001 and I'm always very proud of this. Because that's the last device. I personally fabricated in the FAB.

155
00:25:05.940 --> 00:25:09.570
Kent Irwin: People don't believe that. I can do that, but actually did. That's actually eight individual pixels.

156
00:25:10.800 --> 00:25:18.300
Kent Irwin: These are actually squares of silicon with an absorbing film on them. And then there's a little superconducting transition and sensor.

157
00:25:18.810 --> 00:25:32.730
Kent Irwin: If you see the two doctrine. Each one of these squares. Each one of those is a Ts and some superconducting wires come through these suspended legs, you get these little squares of silicon or about a millimeter and size and they're suspended by little silicon legs.

158
00:25:33.780 --> 00:25:39.270

Kent Irwin: And there's another technology, which I'm going to be moving on to talk about now, which was used to read it out.

159
00:25:39.510 --> 00:25:51.180
Kent Irwin: And we talked about the idea that the squids with this match made in heaven that made it possible to to amplify and read out two yeses, but the state of the art is now moving towards millions of TSS

160
00:25:51.480 --> 00:26:01.890
Kent Irwin: And you can't have millions of wires coming up from 100 mil Kelvin up to room temperature. Do a measurement. So you have to have some cold cryogenic multiplexes

161
00:26:02.280 --> 00:26:09.990
Kent Irwin: What I'll be talking about next is one of the ways you do that with a squid multiplex are here in the right that's a time division multiplication will discuss

162
00:26:10.470 --> 00:26:25.710
Kent Irwin: And to give you some contrast. This is actually a modern a more modern TS array that's a CNBC bolometer array that was developed for actual fabricated at NIST, and this is the outcome of cosmology telescope in in the

163
00:26:26.910 --> 00:26:31.290
Kent Irwin: Article plateau and chill a. It's one of the predecessors to the CMT stage for experiment.

164
00:26:32.040 --> 00:26:45.360
Kent Irwin: And then now these are much more complicated circuits where you see on the left, there's a few two yeses. But there's an antenna that measures two different polarization. There's built in filters, all sorts of other devices. It's a very established technology now.

165
00:26:46.440 --> 00:26:56.790
Kent Irwin: Okay, so I would have mentioned a little bit about how these are thermometers. So obviously you can measure a power signal by just seeing how much it heats up a constant temperature

166
00:26:57.300 --> 00:27:02.820
Kent Irwin: I also want to mention as you go up to higher frequencies, especially and the photons get larger.

167
00:27:03.120 --> 00:27:12.840

Kent Irwin: You can use these devices also to measure single photons. You can not only count them, but you can intrinsically do spectroscopy, which is something that calorie meters intrinsically can do

168
00:27:13.620 --> 00:27:23.670
Kent Irwin: But this is like a cartoon to get this idea. These devices are using x ray spectroscopy. In fact, there are devices installed at the Stanford Synchrotron Radiation Laboratory at slack.

169
00:27:24.210 --> 00:27:28.140
Kent Irwin: On two different beam lines that use 240 pixels of these devices.

170
00:27:28.650 --> 00:27:40.980
Kent Irwin: And the basic idea here is that when a a photon like an X ray comes in and is converted to heat the temperature goes up an impulse. So the idea is if you're measuring the TS resistance which is the temperature on the Y axis.

171
00:27:41.580 --> 00:27:52.350
Kent Irwin: When an X ray arrives. Suddenly, the temperature goes up, and then you have that pixel connected to a heat bath. So the heat then relaxes back and you go back down to the

172
00:27:53.250 --> 00:28:01.890
Kent Irwin: Question temperature. So, you have account. So you're counting photons, but also the higher the frequency of the photon, the more energy per photon.

173
00:28:02.220 --> 00:28:11.880
Kent Irwin: The larger the pulse will be so you can use these devices to do x ray spectroscopy and now there is a European satellite mission called the Athena.

174
00:28:12.630 --> 00:28:28.680
Kent Irwin: X ray satellite in the US is actually creating a TS array with squid multi flexors. That will be put on that European satellite to do x ray spectroscopy and this is like a flagship missions. So these devices really have arrived.

175
00:28:30.150 --> 00:28:34.560
Kent Irwin: Okay. So as I said, the other part of the coin. I can already see since I'm already

176
00:28:35.040 --> 00:28:39.780

Kent Irwin: Halfway in that I'm going to probably do the multiplication and not get to the quantum stuff. That's what I anticipated.

177
00:28:40.230 --> 00:28:45.630
Kent Irwin: But that's what I was invited to talk about anyway. So I think there's nothing lost there. Okay. So as I said,

178
00:28:46.200 --> 00:28:58.560
Kent Irwin: The other thing you need to have big impact with these types of sensors is not only that they're very sensitive that they're very stable that you can buy as many of them at the same time, and they have a good amplifier to read them out.

179
00:28:58.980 --> 00:29:06.930
Kent Irwin: But that amplifier. You can't have wires from every apples are going to room temperature when you're having 10s of thousands of pixels or even up towards a million.

180
00:29:07.260 --> 00:29:13.320
Kent Irwin: You just cannot build a refrigerator with millions of wires going from room temperature down to a 10th of a Kelvin.

181
00:29:13.680 --> 00:29:23.160
Kent Irwin: So you need to have some way to comply many signals on one wire. And this is just a simple cartoon. We're going to get much more into the details here. How do you do that technologically

182
00:29:23.550 --> 00:29:33.150
Kent Irwin: And now there are mature techniques mature superconducting integrated circuits that can take large arrays and have few wires carrying out all the signal.

183
00:29:33.630 --> 00:29:44.040
Kent Irwin: And one simple way to do it would be called time division multiplexes were supposed to have three Ts is just a cartoon to give you the idea. We'll get into the actual architecture in a bit.

184
00:29:44.730 --> 00:29:54.120
Kent Irwin: Three two yeses each couple to one of these squid amplifiers that were invented by Ford and but then you turn on those squids, one at a time.

185
00:29:54.900 --> 00:30:01.560

Kent Irwin: So for instance, I've heard this is actually not how it's done. But this is a conceptual thing. Suppose you had three squids each is looking at one tea. Yes.

186
00:30:01.890 --> 00:30:10.980
Kent Irwin: But you only close the switch to look one at one, then you look at next. Then you look at the next then on one wire, what you'll end up having isn't interleaved data stream.

187
00:30:11.310 --> 00:30:18.840
Kent Irwin: Or you switch back and forth in this case between two Ts is red and blue. And when an X ray post, for instance, it's one, the temperature will go up.

188
00:30:19.260 --> 00:30:28.170
Kent Irwin: Whereas the other one won't. And by looking at this interleaved data stream at room temperature, you can then break it up into two to two sets of data again.

189
00:30:28.410 --> 00:30:37.380
Kent Irwin: And extract the two pixels. So this is a way where one wire can carry signals for many detectors. It's a very old idea to do time division multiplication.

190
00:30:37.920 --> 00:30:44.820
Kent Irwin: But the ability to do it practically with a with a Ts and superconducting Electronics has been enabling

191
00:30:45.450 --> 00:30:55.650
Kent Irwin: Okay. And in fact, there's many different ways you can do this. And basically what you need to do is you need to have an orthogonal basis set either in time, you can basically have the these

192
00:30:56.190 --> 00:31:01.950
Kent Irwin: square waves or these step functions or you turn on one squid, then you turn on another

193
00:31:02.430 --> 00:31:14.970
Kent Irwin: These, these functions where once goods on than the other ones on orthogonal functions. And essentially what you're doing is you're multiplying these two different orthogonal functions by the input then coding it. That's what you do with time.

194
00:31:15.480 --> 00:31:19.950

Kent Irwin: But that's not the only orthogonal function another obvious one is frequency

195
00:31:20.310 --> 00:31:26.160
Kent Irwin: So frequency division multiplexes is another way to do that in this case where you take the signal from to Ts is

196
00:31:26.430 --> 00:31:36.060
Kent Irwin: And you modulate it at two different frequencies, then you can just dump them on the same wire. And then when you get to temperature, you can take a Fourier transform to extract the two different pixels.

197
00:31:36.420 --> 00:31:43.050
Kent Irwin: And frequency division multiplication has been developed in for a number of different ways. Berkeley and also

198
00:31:43.710 --> 00:31:55.440
Kent Irwin: The Space Research Organization at the Netherlands were two of the pioneers that developed way used to bias TS at AC frequencies, both of bucks and D multiplex in this case this is both

199
00:31:56.160 --> 00:32:08.040
Kent Irwin: I have photographs of devices, both that were fabricated by the business builder group time division multiplexes here and then a squid amplifier to reach out reach out AC frequency division multiplex

200
00:32:09.060 --> 00:32:13.320
Kent Irwin: So, but the question is fundamentally how far is this technology going to be able to go

201
00:32:14.190 --> 00:32:34.620
Kent Irwin: Can you really do megapixel arrays. And so what I'd like to spend a few slides, thinking about how much multiplication, can you do. And really, that's an information theory question with one wire. How many multiplex pixels, can you fit on obviously this is a very mature information theory.

202
00:32:35.700 --> 00:32:39.870
Kent Irwin: Region part of information theory for things like cell phones, which are obviously multiplex

203
00:32:40.110 --> 00:32:48.030

Kent Irwin: But how do you do it in a fundamental way with the available superconducting wires and available AMP amplifiers. So let's do a little bit of math here.

204
00:32:48.270 --> 00:32:59.490
Kent Irwin: To see how much information there is on each Ts and how much information you can carry out of a squid or another kind of amplifier. So that if you do multiplex thing.

205
00:32:59.760 --> 00:33:07.770
Kent Irwin: What sort of multiple factors can you get, how many pixels. Can you have in each one. And so the the theory that lets you analyze this is called the

206
00:33:08.430 --> 00:33:12.780
Kent Irwin: Well, there's a couple of them the necklace chain and sampling theorem and the Shannon Hartley theorem.

207
00:33:13.680 --> 00:33:23.430
Kent Irwin: And first of all, the, the Nick was Shannon sampling theorem says that to fully characterize a signal that has a certain bandwidth be like a megahertz or a kilo hertz.

208
00:33:23.790 --> 00:33:34.230
Kent Irwin: You can do this with time samples, but you have to sample at least the Nyquil straight, which means that the highest frequency, the sine wave associated with the highest frequency of the signal.

209
00:33:34.440 --> 00:33:41.130
Kent Irwin: You have to be able to sample that sine wave at least twice during a period in order to be able to reconstruct the signal.

210
00:33:41.760 --> 00:33:50.280
Kent Irwin: And what this tells you is that if you have data being taken at a certain sample rate, you need a certain bandwidth to be able to carry that data.

211
00:33:50.700 --> 00:33:59.760
Kent Irwin: Or if you flip it around. If you have a certain bandwidth signal. They need to sample at a certain Nyquil straight in order to be able to reconstruct it

212
00:34:00.180 --> 00:34:06.570
Kent Irwin: And if you do simple at that rates. You can reconstruct it without any loss of information. So that's one important thing

213
00:34:07.020 --> 00:34:20.010
Kent Irwin: The second theorem is the Shannon Hartley theorem and that basically is saying, how many bits per second of data is in a signal. If you were to reduce it to just a logical bits. So to be able to answer that.

214
00:34:21.750 --> 00:34:33.330
Kent Irwin: It's not enough to know the Nyquil sampling rate because micro sampling rate is not just a bit rate because in any different period of time, a signal can have many different voltage levels, not just two.

215
00:34:33.840 --> 00:34:41.820
Kent Irwin: And you can consider that sort of like an alphabet each individual sample, you know, if it's digital can only have two values. But if its analog can have many, many, many

216
00:34:42.480 --> 00:34:48.540
Kent Irwin: So what you need to do is be able to have a signal to noise ratio as well as a band with the sampling rate.

217
00:34:48.930 --> 00:34:54.450
Kent Irwin: And when you know the signal noise ratio, then you can combine these things to get the total bits per second of information in a signal.

218
00:34:54.810 --> 00:35:04.530
Kent Irwin: This is the Shannon Hartley theorem is that the channel communication capacity is equal to the bandwidth terms of the log base to have one plus the signal noise square

219
00:35:05.670 --> 00:35:07.650
Kent Irwin: Where the signal noise in this case is amplitude

220
00:35:08.970 --> 00:35:17.100
Kent Irwin: Okay, so what is the information content of a typical signal that a particle physicists will care about, let's consider the CB

221
00:35:17.430 --> 00:35:24.420
Kent Irwin: I'll put in some kind of normal sorts of numbers. If you have one pixel and a big camera, looking at the cosmic microwave background.

222
00:35:25.110 --> 00:35:33.090

Kent Irwin: You might be getting say with a ground based system like 150 gigahertz color emitter, you might be receiving about five people watts of peak.

223
00:35:33.690 --> 00:35:43.860
Kent Irwin: Power from the sky and your noise. You also have a noise that's fundamentally coming from the sky, which is that the power is coming in this in the form of photons and then some shots.

224
00:35:44.220 --> 00:35:51.960
Kent Irwin: And that shot noise, you can calculate coming from the sky so its intrinsic you cannot do better than that. It's about four times 10 to the minus 75 watts per hurts.

225
00:35:52.710 --> 00:36:00.120
Kent Irwin: Now what sort of bandwidth you care about with the CBS very small because you can stare at a patch to the sky. You should be able to average down

226
00:36:00.570 --> 00:36:09.480
Kent Irwin: But you don't quite stare. In fact, you scan back and forth across the sky. So if you look at a typical, average, you know, kind of normal sort of scan strategy.

227
00:36:09.750 --> 00:36:13.950
Kent Irwin: You typically want your detectors to be able to have like maybe 100 Hertz of bandwidth

228
00:36:14.550 --> 00:36:22.620
Kent Irwin: So you put this all together with the Shannon Hartley theorem is, first of all, you get a signal to noise ratio from the ratio of the power and the noise equivalent power.

229
00:36:22.950 --> 00:36:32.610
Kent Irwin: And then you have a bandwidth plug that into the Shannon Hartley Thurman. There you go. The average pixel and the CMT camera has about three kilo hertz bit rates in terms of data.

230
00:36:33.690 --> 00:36:38.520
Kent Irwin: So what does this tell you about how many you can mix will consider a squid. In the first case.

231
00:36:39.060 --> 00:36:47.670

Kent Irwin: Now, if we're not thinking about really complex feedback schemes, but just, hey, a squid is this periodic amplifier, then it's it'll have some dynamic range.

232
00:36:48.180 --> 00:36:59.160
Kent Irwin: It'll have some noise associated with magnetic flux that you're putting into it and it'll also have some magnetic maximum magnetic flux. Throw it is period that actually the periodicity of a squid.

233
00:36:59.550 --> 00:37:05.370
Kent Irwin: In terms of the magnetic flux in it is the flux quantum into quantum mechanical thing and it turns out this quits.

234
00:37:05.910 --> 00:37:17.040
Kent Irwin: On average, pretty naturally will have about a micro flux quantum pervert hurts of noise. So you put this together. A typical squid can have about a mega to bed with the DC squid.

235
00:37:17.550 --> 00:37:27.060
Kent Irwin: And you so you basically have a signal to noise ratio, the squid can carry, which is the flux over one microphone upper it hurts a bandwidth, you put that in the shin and Hartley theorem.

236
00:37:27.300 --> 00:37:31.980
Kent Irwin: And you get a channel information capacity of about 20 megahertz in the squid.

237
00:37:32.670 --> 00:37:44.490
Kent Irwin: Ah, this is great news. If a CFP pixel has about three kilohertz of information, but a squid as 20 megahertz using one squared per pixel is terribly wasteful.

238
00:37:44.880 --> 00:37:51.030
Kent Irwin: You really want to have one squid reading out many, many pixels. So that's great and

239
00:37:51.750 --> 00:37:59.220
Kent Irwin: There's actually other amplifiers will mention that with the other types of ways to do frequency division, a high electric mobility transistor that are even bigger.

240
00:37:59.700 --> 00:38:06.180
Kent Irwin: If you take a hemp transistor which a gigahertz transistor to read out an initial first stage junctions.

241
00:38:06.570 --> 00:38:23.790
Kent Irwin: Then you can get channel information capacities of hundreds of gigahertz. So what this means is you can mix all you want. All you can figure out practically how to do. And there's really no fundamental barrier to making a raise of millions of TS pixels for particle physics applications.

242
00:38:24.840 --> 00:38:29.280
Kent Irwin: So what do you need to do that. Well, we know from the necklace theorem.

243
00:38:29.850 --> 00:38:38.460
Kent Irwin: That you can only reconstruct a signal perfectly if you sample it up, you know, to twice per period if the highest frequency

244
00:38:38.850 --> 00:38:44.550
Kent Irwin: So one thing you definitely want to make sure if you want to limit the band with the detector. So, there weren't these spurious higher frequencies.

245
00:38:44.790 --> 00:38:49.860
Kent Irwin: That won't be properly reconstructed because if they aren't Mr constructed a process called aliasing occurs.

246
00:38:50.100 --> 00:38:56.850
Kent Irwin: Where you make errors on D multiplex thing and you put signal at high power frequencies down to low frequencies, you get messed up.

247
00:38:57.210 --> 00:39:04.050
Kent Irwin: And you get cross talk and aliasing noise and all sorts of terrible things. So you need to be able to have a low pass filter.

248
00:39:04.470 --> 00:39:12.000
Kent Irwin: And in time division multiplexes you'll see that's typically an elevator. Our RC just resistor capacitor low pass filter.

249
00:39:12.300 --> 00:39:19.290
Kent Irwin: For frequency thing you need a tuned resonance that has some resonant frequency like an LLC and that will get rid of all the out of band stuff.

250
00:39:20.100 --> 00:39:25.320
Kent Irwin: So you need to have a single channel ization technique that means also that you need to be able to modulate your signal.

251
00:39:25.890 --> 00:39:41.640
Kent Irwin: For time division. You can do that by turning squids on and off for frequency division. You can do that by Ac modulating a detector, for instance, then you need to be able to combine the signals and then have fancy electronics to take the signal apart to D multiplex again.

252
00:39:42.720 --> 00:39:53.400
Kent Irwin: Okay, so it's easy to understand how this work conceptually with time. I already showed you this essentially you've got orthogonal function. If you have four pixels black, red, green and blue.

253
00:39:54.600 --> 00:40:07.740
Kent Irwin: One of them will be on in the first period that the one the second, the next. The third, the next the fourth. This is sort of like a matrix, an identity matrix with ones on the diagonal and zeros everywhere else. So it's an orthogonal basis set

254
00:40:09.090 --> 00:40:18.900
Kent Irwin: So you can define a time bound by turning school john one at a time and then from our math with the Shannon Hartley through them, you should be able to put tons and tons of pixels into one into one output.

255
00:40:20.580 --> 00:40:30.150
Kent Irwin: But that's not the only orthogonal basis set. The only way you can switch. Another one is frequency division and another one that I probably not going to take the time to describe his code division.

256
00:40:30.510 --> 00:40:40.980
Kent Irwin: Or you actually turn them on, but instead of being you know you switch, switch, switch on in different patterns but you have them all on at different times. But you switch the polarity.

257
00:40:41.280 --> 00:40:45.990
Kent Irwin: And that's practical we've made that work with squids as well, but we probably won't get into it to it too much today.

258
00:40:47.490 --> 00:40:53.460
Kent Irwin: Okay, so let's talk about a bit about the history and then see where it's gone. See what the state of the art is on multiplex thing.

259
00:40:53.700 --> 00:41:02.280
Kent Irwin: And then that will put us in a position to launch into talks about, you know, millimeter wave detection and for looking for week interactions and also dark matter.

260
00:41:02.880 --> 00:41:09.330
Kent Irwin: So the first time division multiplication. The first multiplication was done at least when I was there as a postdoc

261
00:41:09.630 --> 00:41:18.270
Kent Irwin: And the paper that I'm referring referencing, they're actually I was, I was actually a step by that was by children. I got off driven actors now actually at NASA Goddard.

262
00:41:18.630 --> 00:41:26.400
Kent Irwin: And that demonstrated time division multiplexes squids will get a little more into depth at this because this is actually the most mature technology.

263
00:41:26.640 --> 00:41:35.370
Kent Irwin: It's now the baseline for CNBC H4 it's what's being used in the Athena cetera satellite it's ready to go with very large series of pixels.

264
00:41:35.730 --> 00:41:41.250
Kent Irwin: Another exciting way to go is frequency division, where you actually multiply x two yeses by

265
00:41:41.640 --> 00:41:50.430
Kent Irwin: Actually biasing them at AC signals and then putting them through resident filters and adding them together and this is developed initially at Berkeley.

266
00:41:50.760 --> 00:42:01.620
Kent Irwin: By unit all in a release group and also by some very nice demonstrations by the Dutch and the fins be cookie Veronica here is from Finland and as well as the Japan.

267
00:42:02.160 --> 00:42:13.440
Kent Irwin: Group in Japan did this technique called cabbage. Then finally I mentioned a different type of frequency division multiplication, which is terribly exciting for very, very high marks marks levels in the future.

268
00:42:13.950 --> 00:42:23.640
Kent Irwin: It still is being developed to see if it could come in for CB Stage four, and that is frequency division, but instead of oscillating TS biases like megahertz.

269
00:42:23.880 --> 00:42:33.390
Kent Irwin: It's actually using microwave technology to actually use these gigahertz amplifiers that have extraordinary dynamic range and I'll show you a bit how that works. Before I end

270
00:42:34.620 --> 00:42:44.880
Kent Irwin: Okay, so let's talk. Just to give you a flavor of the complexity, but also this is complexity that actually works robustly reproducible and many instruments that are on the sky today.

271
00:42:45.330 --> 00:42:56.340
Kent Irwin: Let's look at the actual circuit for a time division multiplexes and I'll give you a guide to talk about basic ideas of functionality. You don't have to understand the current flow through every part of the circuit.

272
00:42:57.180 --> 00:43:12.720
Kent Irwin: But let me actually give you a guide as I build the circuit up from one pixel to Mini. Okay, so first of all, we have a tea. Yes, which I've drawn as a variable resistor heater and that tea. Yes. Could be anything. It could be looking at a CFP pixel at the sky.

273
00:43:13.830 --> 00:43:26.640
Kent Irwin: Or it could be looking for dark matter in a CMS experiment or it could be looking for x ray pulses and measuring their energy and doing spectroscopy in the Athena x ray satellite

274
00:43:27.120 --> 00:43:37.710
Kent Irwin: This basic diagram still works for all of these, and this device is voltage biased. In this case, the way we voltage bias is we put a constant current down a wire.

275
00:43:38.040 --> 00:43:46.140
Kent Irwin: Down to a superconducting SHIP WHICH IS DOWN AT THE BASE TEMPERATURE like 100 million Kelvin. And what we do is we put a very, very low resistance shut

276
00:43:46.500 --> 00:43:55.260
Kent Irwin: So we put a resistor in parallel with the tea. Yes. If the TSA and own we make the shot resistor like 10 million homes or something like that.

277
00:43:55.590 --> 00:44:05.550

Kent Irwin: And then the vast majority of the current flows to the shop resistor which means that the TASC is like a hard voltage bias, as long as the th resistance is large compared to our shunt

278
00:44:05.910 --> 00:44:09.990
Kent Irwin: That's a hard voltage bias, like what we talked about that gives you stable operation.

279
00:44:10.830 --> 00:44:19.290
Kent Irwin: Then the current that flows through the TS flows through an inductor and just converted, you know, as it current goes around inductor, it's converted to a magnetic field.

280
00:44:19.770 --> 00:44:28.560
Kent Irwin: That flows into one of these superconducting interferometer is intended by forward in the 60s, which is basically two different justice injunctions in the superconducting loop.

281
00:44:29.040 --> 00:44:36.960
Kent Irwin: And then modulates feature constructive and destructive interference. Here's one pixel and then it turns out we actually take the output of that squid.

282
00:44:37.260 --> 00:44:44.880
Kent Irwin: And put it through a second stage of squids, where we put it through the we put its output to the input coil have a whole bunch of squids in series.

283
00:44:45.120 --> 00:44:51.630
Kent Irwin: That just so we can get it up to a voltage swing or you could take it up to room temperature and read it with a semiconductor amplifier.

284
00:44:51.960 --> 00:45:03.810
Kent Irwin: That's the basic idea, then you can do you can do a PCI loop you can do apply feedback signal from temperature some more complexity. We don't have to go into. But here's the idea of one pixel in a more complicated diagram.

285
00:45:05.100 --> 00:45:11.730
Kent Irwin: Now we do something we add a switch and it turns out you can make switches out of just as injunctions as well.

286
00:45:12.090 --> 00:45:24.120

Kent Irwin: And the device. These devices you something that's called a Zappa interferometer it's something like a squid itself. It's a device that you modulate the critical corruptive by a quantum interference. Only in this case.

287
00:45:24.480 --> 00:45:33.480
Kent Irwin: You apply a signal to either go from zero critical current to high critical current. So it just looks like a switch. It's either on or off. So I just draw as a switch here.

288
00:45:35.130 --> 00:45:52.170
Kent Irwin: And now that we've got a switch. We can add a second squid and a second T. Yes. The second squared is no in series with the first squid and it has a switch. But now we can see if we have one switch open and one switch closed only one us, which is on

289
00:45:53.190 --> 00:45:57.990
Kent Irwin: Because we actually have a bias current to turn on the squid that comes through temperature

290
00:45:58.470 --> 00:46:06.690
Kent Irwin: And as you see the switches open in that first squid on top. So all the current flows to this squid, squid gets turned on and you have an amplifier.

291
00:46:07.260 --> 00:46:14.460
Kent Irwin: But if you have the switch closed in the second switch all the current flow is shunted away and the second squid turns off.

292
00:46:14.820 --> 00:46:23.160
Kent Irwin: And now, by changing the state of the switches. You can look first at TS one at the top. Then it TS to and back and forth and back and forth.

293
00:46:23.490 --> 00:46:30.960
Kent Irwin: And this is the circuit that's actually being used as the baseline for seeing cosmic Gregory backgrounds teach for the day we project.

294
00:46:31.350 --> 00:46:40.020
Kent Irwin: It is the technology that's been deployed in the Athena x ray satellites. It is the technology has deployed at the Stanford temperature and Radiation Laboratory here at slack.

295
00:46:41.070 --> 00:46:51.270

Kent Irwin: In two different beam lines. It's been displayed broadly. It's in the the bicep three C and B experiment that's at the South Pole right now that was put there by

296
00:46:51.780 --> 00:47:03.630
Kent Irwin: By collaboration of slack and Harvard and a few and Caltech and a few other groups. It's very mature, it works. And you can fabricate this all on one ship as a superconducting integrated circuit.

297
00:47:04.320 --> 00:47:10.800
Kent Irwin: Okay, then what you do is I just drove this row signal is this is the turn signal that turns that switch on or off.

298
00:47:11.370 --> 00:47:16.230
Kent Irwin: Okay, then what you can do is you can make a two dimensional array that seem too simple.

299
00:47:16.860 --> 00:47:24.780
Kent Irwin: But the idea is now if you actually have a chip that's like square, you can have many, many columns and then you, you have a turn signal.

300
00:47:25.170 --> 00:47:33.360
Kent Irwin: Actually the switches as rose and you can make a two dimensional array with like 32 channels 32 rows. A total of 1000 pixels.

301
00:47:33.960 --> 00:47:43.560
Kent Irwin: Okay, so you put this all together, then I can have cartoons about show how you interleaved the pixels. But let's actually skip that for right now. This is an example I mentioned device or three experiments.

302
00:47:43.920 --> 00:47:53.670
Kent Irwin: This is a picture I I picked off because one thing is it has a very young zetia Ahmed, who will be giving the talk talk later in this in this talk. He doesn't look that young anymore.

303
00:47:54.360 --> 00:48:05.040
Kent Irwin: But there are, as you see, you see each of these little squares. Each of these little squares is a silicon chip that has more than 1000 superconducting tradition and sensors on

304
00:48:05.430 --> 00:48:06.930
Kent Irwin: There's a whole bunch of them tiles.

305
00:48:07.320 --> 00:48:17.070
Kent Irwin: And each one of the superconducting transit, it's just, it's just goes to one of these integrated circuits with with many different squids that you turn on one at a time.

306
00:48:17.280 --> 00:48:26.220
Kent Irwin: So this entire array of thousands and thousands of thousands of Ts is can be read out with a much smaller number of output channels to room temperature.

307
00:48:26.550 --> 00:48:33.540
Kent Irwin: And this experience was deployed is taking multiple seasons of great data at the South Pole studying the cosmic microwave background.

308
00:48:33.990 --> 00:48:43.770
Kent Irwin: And is this sort of experiment which is why it is technology so mature that it's been chosen as the baseline for this big ultimate 500,000 pixels CNBC H4 experiment.

309
00:48:44.700 --> 00:48:49.500
Kent Irwin: Okay. Last thing I want to do, because I'm not going to get into all that quantum stuff, which is what I expected.

310
00:48:49.770 --> 00:49:03.330
Kent Irwin: Would be to say what's exciting going for in terms of TS arrays going to even bigger race. We'd like to be able to eventually be putting millions of pixels on one check for x ray applications, but also for submillimeter

311
00:49:05.520 --> 00:49:07.260
Kent Irwin: So time divisional detection is great.

312
00:49:08.460 --> 00:49:16.470
Kent Irwin: It's mature, we can make many thousands of pixels. We can even make 500,000 pixels for seeing the stage for if there are lots of different flavors.

313
00:49:17.580 --> 00:49:27.330
Kent Irwin: Putting a million pixels on the one way for there's going to be too many wires. Still, you're not putting many thousands of Time Division Multiple pixels under one wire.

314
00:49:27.630 --> 00:49:33.480

Kent Irwin: You need put many, many thousands under one wire if you want to have millions on one chip.

315
00:49:33.930 --> 00:49:46.800
Kent Irwin: And so an exciting way to do that is with a different type of frequency division multiplexes called a microwave squid multiplexes. This is something that I developed when I was at NIST in the early 2000s, or the mid 2000s.

316
00:49:48.120 --> 00:49:57.810
Kent Irwin: And it's the same basic idea where you have an AC modulation only now you're not modulating the tea is in this case the tea. Yes. Is this variable resistor. You see here

317
00:49:58.110 --> 00:50:03.180
Kent Irwin: It's got a voltage bias which in this case I've drawn as a battery in reality it's a little shut resistor.

318
00:50:03.690 --> 00:50:12.000
Kent Irwin: And that voltage bias means that there's a current that flows again through a coil and that coil couples into a different type of squid.

319
00:50:12.420 --> 00:50:20.310
Kent Irwin: I talked about the the to silicon interferometer the DC squid and vetted by Ford. In this case, this is just a one junction

320
00:50:21.240 --> 00:50:33.630
Kent Irwin: Justice injunction any superconducting loop and obviously the critical current of that superconducting loop isn't actually being modulated, in a sense, because all the current can just flow in the right hand side is what you'd imagine

321
00:50:34.230 --> 00:50:40.980
Kent Irwin: So this device is actually not an on and off current sort of thing with this. Is it a reactive element.

322
00:50:41.430 --> 00:50:44.580
grzegorz madejski: That we should try to be finishing 757 minutes

323
00:50:44.910 --> 00:50:47.490
Kent Irwin: Yeah, yeah, I'll be done. I'm perfectly on track for that.

324
00:50:49.440 --> 00:50:53.310

Kent Irwin: So, and what happens in this device is that

325
00:50:54.000 --> 00:51:03.180
Kent Irwin: If you solve the justice and relations, going back to brain justice again of the current being seniors totally dependent on the fluff on the phase and the phase.

326
00:51:03.420 --> 00:51:13.290
Kent Irwin: Being a temperature dependence of the voltage applied across where you get as an inductor. It's basically a red inductive elements, whose value is changing, depending on how much flux, you put in

327
00:51:13.740 --> 00:51:24.810
Kent Irwin: So now if you make a microwave resonator, imagine you have a quarter wave resonator. So this is some frequency where you'll get a standing wave in this written this in this microwave circuit very standard thing.

328
00:51:25.560 --> 00:51:33.210
Kent Irwin: And you have many different ways of these resonators at different frequencies. You can modulate each frequencies. This device. And this is the last circuit. I'm showing

329
00:51:34.890 --> 00:51:43.110
Kent Irwin: And this is actually a slide that I stole from a dish so you'll be you'll probably talking about this, but you just talk and he talks about looking for a week interactions here.

330
00:51:43.350 --> 00:51:53.730
Kent Irwin: This is actually a photograph of a microwave squid multiplex are also fabricated in this in this folder. And what you see here is on this this chip which is about the size of a cent.

331
00:51:54.360 --> 00:52:02.910
Kent Irwin: You have many different quarter wave resonators each of these little white lines you see is one of these, which you can imagine this red and green and blue thing.

332
00:52:03.420 --> 00:52:12.150
Kent Irwin: And what you do is you put in a signal somewhere between five and six gigahertz, and all these resonators have a resonant frequency between five and six gigahertz.

333
00:52:12.390 --> 00:52:19.110

Kent Irwin: And depending on what signal you frequency you put in, if it's not at the frequency in any of these resonators, it passes straight through.

334
00:52:19.620 --> 00:52:23.430
Kent Irwin: But if it hits that resonant frequency. It'll reflect it'll bring it up and reflect off.

335
00:52:23.970 --> 00:52:36.450
Kent Irwin: And this plot up here on the right is a plot of all the residences data on that actual check. So if the x axis we have the frequency and gigahertz from 5.5 to 5.65. So these are like cell phone frequencies now.

336
00:52:37.110 --> 00:52:43.890
Kent Irwin: Then if you put in a signal at all crossing at these different frequencies these dips. You see, each one of these depths

337
00:52:44.250 --> 00:52:54.480
Kent Irwin: Is one of these resonators couple, three doses injunction to a tee. Yes. And now what happens is you can look at all those resonators at the same time, all the time.

338
00:52:54.900 --> 00:53:02.100
Kent Irwin: And each one of these resonators will wiggle back and forth like you see on the bottom right, depending on how much current is flowing from the tea. Yes.

339
00:53:02.520 --> 00:53:07.050
Kent Irwin: So now if you put down a coma frequencies to tickle all those resonators

340
00:53:07.440 --> 00:53:25.710
Kent Irwin: And you look at how much the resonant frequency changes you can reconstruct to the signal from the Ts. And now one wire can carry many, many thousands of T SS each of them just a five gigahertz cell phone frequency wiggling around depending on what's going on in the tea. Yes.

341
00:53:26.970 --> 00:53:36.990
Kent Irwin: Okay, and then this is basically a couple slides just want to show that this is also a mature mature in the system that's been chosen to be deployed at the Simon's Observatory at the sea at the

342
00:53:38.310 --> 00:53:48.540

Kent Irwin: The also at the Atacama and that's a Princeton and you pen and Berkeley experiment and some of their institutions. And here's some infrastructure.

343
00:53:49.080 --> 00:53:57.090
Kent Irwin: For the actual kind of detector array itself and zooming in here is actually an array with many, many different microwave squid chips.

344
00:53:57.660 --> 00:54:03.390
Kent Irwin: That are all being read out again on one different coaxial cable. So anyway, that the the

345
00:54:03.870 --> 00:54:12.330
Kent Irwin: Technology has matured technology has matured to the point where it's widely deployed, but also it's nowhere near the end.

346
00:54:12.900 --> 00:54:19.380
Kent Irwin: There are these technologies like microwave squids that are that are pushing us further into the future so that eventually

347
00:54:19.680 --> 00:54:27.720
Kent Irwin: At least for applications where you can be very, very small pixels, we should be able to put millions of pixels on a chip. So let me skip over all the quantum stuff and just go to that end.

348
00:54:28.350 --> 00:54:35.310
Kent Irwin: Summary right on time so superconducting centers have mature. They have brought applications across science.

349
00:54:35.670 --> 00:54:43.380
Kent Irwin: And they're having real impact now on particle physics and on exploring the weekly couple universe as you'll hear more about as we go.

350
00:54:44.310 --> 00:54:49.800
Kent Irwin: Into to example talks to the US to. Yes. Is there. We'll talk about that as the show. Matt and Jody Cooley.

351
00:54:50.160 --> 00:55:02.970
Kent Irwin: And also they're they're related technologies involved in quantum manipulation, which are really exciting going forward for accion searches and Jihad. Follow me indeed discuss that as well, even though, as I expected. I did not have time to get to it.

352

00:55:03.240 --> 00:55:06.360
Kent Irwin: So I will leave it right there. Back to you, Greg.

353
00:55:07.860 --> 00:55:11.910
grzegorz madejski: Okay, thank you very much. I can for very clear and very interesting talk.

354
00:55:12.810 --> 00:55:28.470
grzegorz madejski: And obviously, there is a follow up that presentations, they will be coming gap over next while those on your slides at this point let me turn over to sue Donk who is handling the questions that came on the via our indigo site. So, so don't go ahead, take it on.

355
00:55:29.580 --> 00:55:46.710
dong su: And thanks kind of the lecture and we don't have so many questions. And actually, maybe we can start with some like any simple ones to start with. There's a question on what what is the sharp, sharp noise on page 19. What is a sharp noise and how does determined

356
00:55:50.400 --> 00:55:59.520
Kent Irwin: There's two. There's a simple answer. And there's a really complex answers. What I would say so. The simple answer is a very classical answer.

357
00:56:00.090 --> 00:56:08.100
Kent Irwin: Which isn't quite right, but it'll give you the basic idea. So Einstein basically proposed based on clocks work.

358
00:56:08.430 --> 00:56:14.460
Kent Irwin: That actually light comes in chunks. The light doesn't isn't basically just a simple wave

359
00:56:14.730 --> 00:56:25.380
Kent Irwin: That the wave comes in individual chunks of energy delivered with your photons. And I think we're all familiar with that and of course that was demonstrated with the photoelectric effect what he predicted that

360
00:56:25.710 --> 00:56:40.590
Kent Irwin: If you shine a light on a piece of material where it takes a certain amount of energy to liberate and electron that the frequency of the light is what determines whether the electron comes out, because the energy of each chunk of light goes as punk content at times f

361

00:56:41.040 --> 00:56:49.980
Kent Irwin: And so what photon truck noise in a simple over simplified classical sense is just if light comes in chunks, then even if you're getting

362
00:56:51.150 --> 00:57:00.750
Kent Irwin: Constant power flow. If you look close enough. You should see it arriving in little like raindrops and that should that's what's called photon shot. Nice.

363
00:57:01.050 --> 00:57:12.720
Kent Irwin: That actually if in one period of time you get say and photons during the next you might get n plus 100 photons and depending on the frequency

364
00:57:12.870 --> 00:57:14.970
Kent Irwin: If you're up in the really classical regime.

365
00:57:15.150 --> 00:57:25.950
Kent Irwin: Then it will have sort of cross on statistics or if you you where you get sort of squirter of in variations, where if you got 100 photons and one time period you might get 90 or 110 in the next

366
00:57:26.340 --> 00:57:33.360
Kent Irwin: So that's still a classical sort of idea, but that's the idea of shot noise that if you're actually looking at light from the sky, you

367
00:57:33.390 --> 00:57:37.050
Kent Irwin: can only make your sensors so accurate before you start being limited by

368
00:57:37.170 --> 00:57:55.950
Kent Irwin: The chunkiness of the light that coming to you now. That's actually massive over simplification, as we know from dealing with really quantum information type applications that it's not actually just the generic act of measuring light that makes it

369
00:57:56.190 --> 00:57:56.850
Kent Irwin: Break into

370
00:57:57.240 --> 00:57:57.720
dong su: Light isn't

371
00:57:58.260 --> 00:58:00.450

Kent Irwin: Light isn't always in chunks, let's say,

372
00:58:01.530 --> 00:58:10.980
Kent Irwin: That actually depending whether it's in a chunk depends on what you look at what you measure. It's one of these strange things about quantum mechanics.

373
00:58:11.340 --> 00:58:21.300
Kent Irwin: That the actual act of measuring determines what the measured object is. And it turns out that you can have a

374
00:58:21.900 --> 00:58:31.110
Kent Irwin: Photon signal in an icon. I can see the photon number if you actually measure the number of photons, then it will be in chunks and it will be an integral number

375
00:58:31.560 --> 00:58:42.870
Kent Irwin: But if you don't measure the number of photons. If you just measure the phase or the amplitude, you don't necessarily have to

376
00:58:43.320 --> 00:58:49.830
Kent Irwin: Have it collapsed into one particular I can say the photon number, but I'll say it's a little bit more nuanced thing is that anytime

377
00:58:50.130 --> 00:59:00.870
Kent Irwin: You take like say coherence signal like a laser which is coming out as a sine wave. And then you collapse it onto an I can say the photon number by measuring the

378
00:59:01.710 --> 00:59:09.300
Kent Irwin: Number of photons, then you'll get shot noise and then you can evade that in a lot of different ways, especially if you can control the source.

379
00:59:09.540 --> 00:59:18.900
Kent Irwin: And can do lots of tricks like squeezing and things like that. So that's a simple answer in a more complicated answer but shot noise does limit astronomy and it's a fundamental

380
00:59:19.560 --> 00:59:28.830
Kent Irwin: And that's why we're seeing be I would say one of the thing is we're seeing these big C and B experiments for a long time. They weren't big CB experiments for multiple decades.

381

00:59:29.340 --> 00:59:38.070
Kent Irwin: You did see him be with one pixel or like a few pixels and and and you made big events is by making that pixel more and more sensitive

382
00:59:38.910 --> 00:59:47.520
Kent Irwin: But sometime around the you reached a point where the pixels were so sensitive that you started being limited by the photon noise from the sky.

383
00:59:47.820 --> 00:59:53.370
Kent Irwin: Then you had to start going to erase the pixels and these arrays were hundreds in the 1990s.

384
00:59:53.790 --> 01:00:05.160
Kent Irwin: And thousands in the early 2000s and then 10s of thousands. Now, and CNBC for the only way to get enough statistics to really constrained cosmology and fundamental physics now.

385
01:00:05.370 --> 01:00:12.330
Kent Irwin: Is to have these giant arrays with a million pixels, looking at large portion to the sky, because one pixel is as good

386
01:00:12.480 --> 01:00:13.530
Kent Irwin: As it ever will be.

387
01:00:13.560 --> 01:00:14.580
dong su: Because of shot. Nice.

388
01:00:16.080 --> 01:00:16.740
dong su: Okay, thanks.

389
01:00:17.040 --> 01:00:19.170
dong su: Actually, there is a two parts to that other

390
01:00:19.410 --> 01:00:26.730
dong su: Mentioned the how you specifically determine the noise in distinction other type of noise matter.

391
01:00:27.420 --> 01:00:29.340
Kent Irwin: Practically speaking, that's a very good question.

392
01:00:30.840 --> 01:00:33.750

Kent Irwin: And really, you just like, like in every case.

393
01:00:33.780 --> 01:00:37.110
Kent Irwin: You have to build models and you have to do careful calibration.

394
01:00:38.190 --> 01:00:39.900
Kent Irwin: You have to actually have a good model of your

395
01:00:39.900 --> 01:00:48.120
Kent Irwin: Detector and know all the different sources of noise, including the pathological ones, but you're always going to have some thermal fluctuation noise in the detector.

396
01:00:48.690 --> 01:00:54.300
Kent Irwin: You may have some added on amplifier noise. Then you have the shot and ways of the intrinsic signal that's coming in.

397
01:00:54.660 --> 01:01:08.580
Kent Irwin: But what you can do is you can start by a signal that you understand very well like often these devices are calibrated, not by looking up at the sky, but by actually making you source inside your Christ next to the TV. Yes.

398
01:01:08.970 --> 01:01:20.520
Kent Irwin: And then what if that source is the black body, it's basically just a some black material at a temperature that you fixed, then you know exactly the spectrum of light that's coming up.

399
01:01:21.030 --> 01:01:27.810
Kent Irwin: And if you then put in a filter against a blackberry spectrum event for the filters you you've chosen the executive been with guests detector.

400
01:01:28.200 --> 01:01:42.990
Kent Irwin: Then, you know, very, very accurately what the signal is coming in and what it shot noises and by changing the temperature, you can change it in controlled ways. And you can use that to validate your model of the detector and putting all of the efficiencies.

401
01:01:43.050 --> 01:01:47.790
Kent Irwin: All of the other noise sources and once that all works. And you've got it very well calibrated

402

01:01:48.060 --> 01:01:52.440
Kent Irwin: Then you have confidence that when you put it on the sky, you're going to be able to

403
01:01:52.620 --> 01:01:55.830
Kent Irwin: Resolve the sharp noise at the accuracy. You want to resolve.

404
01:01:56.070 --> 01:02:06.810
Kent Irwin: But actually it's a very complex process and a lot of the effort in programs like CNBC Stage four is spent on building apparatus to do calibrations and measurement to do precisely that.

405
01:02:08.340 --> 01:02:17.010
dong su: Okay, thanks. So then actually well on this page you have Ltd on the title little some people complain to never defined that

406
01:02:17.130 --> 01:02:26.790
Kent Irwin: Oh, I'm sorry. Yes, leftover because actually I still a few of these like they just did for low temperature detector a generic phrase that includes traditional sensors.

407
01:02:27.390 --> 01:02:36.930
Kent Irwin: And that's hardwired enough that I that I didn't spell that anyway information content because this was this slide was developed to be a little bit more broad than just transition and sensors.

408
01:02:37.230 --> 01:02:53.040
Kent Irwin: Because there are multiple different types of low temperature detectors, including him kids and nano wires and tunnel junctions and things like that. So, but a TS traditional center is one type of Ltd low temperature detector.

409
01:02:54.840 --> 01:03:09.270
dong su: Okay. So actually, the next one is actually very interesting to three people ask the same thing. So it must be important question. So, so you mentioned the, the two technical time division versus frequency division.

410
01:03:09.540 --> 01:03:18.840
dong su: So what's the disadvantage, an app. And the advantage of each and the what circumstances. What conditions you prefer the one versus the yellow

411
01:03:19.380 --> 01:03:28.560

Kent Irwin: Very good question. And there's a very the answer. The there's a fundamental answer and there is a practical answer.

412
01:03:29.700 --> 01:03:33.390
Kent Irwin: And what I would say is that they're actually

413
01:03:34.410 --> 01:03:35.850
Kent Irwin: And they're actually pretty nuanced.

414
01:03:36.330 --> 01:03:37.980
Kent Irwin: First of all, let me tell you.

415
01:03:37.980 --> 01:03:52.950
Kent Irwin: Fly right now. Time Division multiplication is the baseline technology for both Cosmic Microwave Background. Stage four, and for the unit x ray satellite and it really comes down to just one word, which is maturity.

416
01:03:53.370 --> 01:04:00.750
Kent Irwin: large projects are extraordinarily risk averse. This is not a fundamental statement is not a statement, the time division is better than the other things.

417
01:04:01.260 --> 01:04:08.310
Kent Irwin: But, but I mentioned the history. Time Division multiplication was the first technique that was developed, it's been deployed in more instruments it has more Scott

418
01:04:08.640 --> 01:04:18.570
Kent Irwin: Time more pixels have been fabricated. It's very well understood. And even though in some ways it's inferior to some of the other techniques.

419
01:04:18.930 --> 01:04:27.210
Kent Irwin: You can actually calculate what the risks are going to be and what it's going to cost and make a judgment about whether you're going to be able to make it and be successful.

420
01:04:27.450 --> 01:04:40.110
Kent Irwin: And often agencies funding a big experiment are going to be willing to pay more and work harder for something with lower risk. So in a mature experiment at this particular snapshot in time.

421
01:04:40.590 --> 01:04:47.700

Kent Irwin: Time Division waves for big mature experiments where agencies have extremely low risk tolerance.

422
01:04:48.150 --> 01:05:02.550
Kent Irwin: But time division, I do not believe is the wave of the future for anything like building megapixel race. So right now, all the time division multiplication techniques really can only multiplex like you know

423
01:05:03.120 --> 01:05:10.380
Kent Irwin: Maybe up to 100 pixels on each wire and you can do a million pixels with 100 pixel multiple flexing.

424
01:05:10.740 --> 01:05:19.320
Kent Irwin: That means you got 10,000 wires coming out as long as they're in multiple different experiments, you know, at different locations and different races that are widely separated

425
01:05:19.620 --> 01:05:30.420
Kent Irwin: You can sort of do it by brute force. But if you're ever going to be making like a mega pixel away. So one way for unless you develop a different kind of time division, where you can get a very high multiplication factor.

426
01:05:31.110 --> 01:05:39.270
Kent Irwin: Time Division is not going to be the choice and there is a fundamental trade off. And that is can really be summarized by the fact that in time division.

427
01:05:39.660 --> 01:05:49.320
Kent Irwin: You're not looking at every pixel all the time. And if you've got a max factor of n and like 100 then each pixel, you're only working at one 100th of the time.

428
01:05:49.890 --> 01:06:01.920
Kent Irwin: Now, that's fine. In terms of not losing any information about the pixel up to a point, because the necklace theorem tells you, as long as you sample fast enough, you can still without error reproduce it

429
01:06:02.520 --> 01:06:11.640
Kent Irwin: But if you got one amplifier on that chain that amplifier is going to have a much higher bandwidth, then each of the individual pixels. It turns out that that means

430
01:06:11.940 --> 01:06:20.400

Kent Irwin: That you're going to be degrading the effective noise of the amplifier. So you're not going to be able to do hundreds of thousands of pixels, like on one wire with time.

431
01:06:20.760 --> 01:06:26.520
Kent Irwin: So time is in this golden era, at the moment, I believe that for most applications, it will eventually be superseded

432
01:06:27.330 --> 01:06:31.500
Kent Irwin: So frequency division. There's two different types to two different implementations are common.

433
01:06:32.160 --> 01:06:39.150
Kent Irwin: One is a low frequency. Frequency Division, which was done first to very nice technique where you AC bias. Each of the two yeses.

434
01:06:39.360 --> 01:06:54.780
Kent Irwin: And that works and it works well. It's been deployed in a number of experiments and the other one is where you do sort of cell phone technology where you actually have these diggers microwave resonators that recharge individual pixel. So I believe that long term.

435
01:06:55.800 --> 01:07:03.480
Kent Irwin: Something using microwave technology is going to be in the multiplexes technique that is used, at least in very large arrays.

436
01:07:03.750 --> 01:07:15.540
Kent Irwin: And that's simply because of the Shannon Hartley theorem stuff that I talked about, which is right here that the gigahertz amplifiers. The microwave amplifier cell phone style amplifiers us

437
01:07:15.750 --> 01:07:21.990
Kent Irwin: To read out the individual pixels are like this high electric mobility transistor. They have gigahertz of bandwidth

438
01:07:22.230 --> 01:07:33.270
Kent Irwin: Instead of megahertz band was like individual squids and so they have enormous channel capacities. So I think it's going to be some sort of microwave technology, probably a frequency

439
01:07:34.170 --> 01:07:43.980
Kent Irwin: Division technology like in cell phones that eventually is used in these big race code division is also very interesting and there's hybrid things which are exciting as well.

440
01:07:43.980 --> 01:07:45.180
Kent Irwin: But I think that's way beyond

441
01:07:45.390 --> 01:07:47.790
Kent Irwin: The scope of what I can do in this q&a

442
01:07:50.250 --> 01:07:58.650
dong su: Okay, thanks. So you may be human. On the right page. And last question is how badly will cell phone signal interfere with the micro of mock signal.

443
01:07:59.610 --> 01:08:06.840
Kent Irwin: Yes, that's very, very good question. Are you really, I would say that there is there's good news and there's bad news.

444
01:08:08.940 --> 01:08:17.160
Kent Irwin: The bad news. The bad news first. Yes, this is this is it a point where if you have a cell phone signal that's in your band. It's can certainly interfere

445
01:08:17.910 --> 01:08:23.130
Kent Irwin: And you really have to do your engineering to prevent that effect. I mean, say it's good news and bad news or

446
01:08:23.760 --> 01:08:28.680
Kent Irwin: Bad news. Good news, bad news. Let's get the bad news. First, the good news is a couple different things.

447
01:08:29.490 --> 01:08:35.520
Kent Irwin: One thing is is you have some degree of flexibility. These can be very narrow band singles very high IQ resonators

448
01:08:35.820 --> 01:08:46.620
Kent Irwin: And so the chance of actually be hitting a cell phone interference line is not that great in we have superconductors. We're cold, so we can make these these electromagnetic

449
01:08:47.370 --> 01:09:02.190
Kent Irwin: Shielding that's very good at keeping out the the electromagnetic signal. And now let me get to the real bad news, which is if you're talking about T SS here's just my observation from many decades of working on this technology.

450

01:09:02.820 --> 01:09:13.200
Kent Irwin: Doing the microwave readout technology, you have to work to make sure that things like cell phones don't mess you up, but it's not nearly as hard as you have to work for TSS

451
01:09:13.950 --> 01:09:23.970
Kent Irwin: Because T yeses. Are these thermal detectors. They'll detect anything and practically, what you see is if you're in the lab and you have a crass debt that's not perfectly shielded

452
01:09:24.360 --> 01:09:31.470
Kent Irwin: And you and you get a call on your cell phone if you haven't done things right, all those two yeses are going to go normal

453
01:09:31.890 --> 01:09:47.130
Kent Irwin: That basically they measure. It's the actual kilometers that measure the cell phone signal practically long before the microwave technology does. So you have to do a really good job in shielding your receiver elements.

454
01:09:47.160 --> 01:09:48.270
Kent Irwin: Your T yeses.

455
01:09:48.570 --> 01:10:03.450
Kent Irwin: And you can do an excellent job of shielding your microwave script readout technology. In some cases, you have to work really hard to shield your Ts and that's because your TSH, you're not just putting them in a superconducting can and shielding it from everything

456
01:10:03.720 --> 01:10:04.800
Kent Irwin: If you're doing like a CB

457
01:10:04.800 --> 01:10:20.730
Kent Irwin: Experiment. You have to be receiving signals from the sky microwave signals from the sky. And so working to make sure that if you're opening up your pixel of the sky and you don't receive cell phone information is really, really hard, but that's true really for any sort of see and

458
01:10:20.730 --> 01:10:21.540
Kent Irwin: Be technology.

459
01:10:21.780 --> 01:10:25.860
Kent Irwin: And that practically is much harder than the retail chain, in my experience,

460
01:10:27.330 --> 01:10:30.150
dong su: I kind of think there's a similar thing with us with

461
01:10:30.180 --> 01:10:30.720
dong su: The average

462
01:10:31.050 --> 01:10:36.660
dong su: People curious how badly, the cell phone can interfere. It basically what happens when you after you

463
01:10:37.110 --> 01:10:37.980
Kent Irwin: Okay, so

464
01:10:39.450 --> 01:10:55.500
Kent Irwin: So so so first of all, it's pretty easy to shield the microscopes, you actually don't get much interference. Like I said, but if you do, what happens is you basically just lose track. So what I haven't talked about is is is how the room temperature.

465
01:10:55.530 --> 01:11:04.380
Kent Irwin: Electronics that's reading out these microwave signals operates. It's actually quite complex. I mentioned about how you can have one wire that has like 1000

466
01:11:04.920 --> 01:11:16.560
Kent Irwin: Pixels each on a resonator to slightly different frequency. And then you've got a room temperature circuit that is actually putting down a coma frequencies one, sine wave tunes each one of these resonators

467
01:11:17.070 --> 01:11:26.550
Kent Irwin: And then it takes that coma frequencies goes down and some of the power reflects back so that goes forward its phases changed.

468
01:11:26.850 --> 01:11:36.090
Kent Irwin: This signal then comes out and your router electronics test to kind of cross correlate the signal and put down the signal that came out, sometimes you do some feedback processes in that

469
01:11:36.480 --> 01:11:48.570
Kent Irwin: And what happens is that basically you just lose track if you've got a really bad pickup. Then you just lose track of which resonances, which you and you just don't get anything until you until you fix your shielding.

470
01:11:51.210 --> 01:11:51.720
dong su: Okay, thank

471
01:11:53.010 --> 01:11:53.220
dong su: You

472
01:11:53.250 --> 01:11:54.960
Kent Irwin: Yes, he has a bigger problem. Yeah.

473
01:11:56.430 --> 01:12:00.450
dong su: Okay, thanks. Can I think that's all the questions we have. So Greg, you can take it.

474
01:12:01.530 --> 01:12:12.180
grzegorz madejski: Okay, thank you very much. Can't this was really excellent and I particular enjoy the chapter position of time division versus fixes in division. And I think this was the clearest explanation. I've seen. So thanks again.

475
01:12:12.900 --> 01:12:14.910
grzegorz madejski: All right, I'm gonna stop recording now and

476
01:12:15.180 --> 01:12:17.370
grzegorz madejski: Again, looking forward to us you back in the lab.