WEBVTT

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00:00:05.670 --> 00:00:24.480
dong su: Okay, let's get going with our third letter of today and our speaker and to be honest and phone from UC Irvine as well. And he is an expert on the interplay between accelerator and astrophysics in terms of doc for the dark matter.

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00:00:27.120 --> 00:00:38.280
dong su: related topics and also have been very nice work on the complementarity between the different approaches of searching dark matter and how we how they relate and confidence to each other.

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00:00:38.670 --> 00:00:51.030
dong su: And of course of. Besides, it also you endeavors will talk about on the dock sector today. So he's to lecture starting today going to be on accelerator searches of a doctor.

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00:00:54.780 --> 00:00:58.920
Jonathan Feng: Okay, well thanks and thanks to the organizers for the cancer talk here again.

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00:01:00.540 --> 00:01:02.580
Jonathan Feng: Like salmon city it's our is one of my favorite

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00:01:03.690 --> 00:01:04.920
Jonathan Feng: Activities programs.

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00:01:06.720 --> 00:01:09.660
Jonathan Feng: So I'm talking about the accelerator searches for the dark sector.

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00:01:11.520 --> 00:01:12.750
Jonathan Feng: So let me get started.

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00:01:14.640 --> 00:01:22.620
Jonathan Feng: So before we really begin properly. I think we should acknowledge the temerity of the title of these two lectures accelerator searches for the dark sector.

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00:01:23.580 --> 00:01:31.590
Jonathan Feng: That is why I said these completely human made experiments on her have any hope of telling us about what the universe looks like say a giga parts that go away.

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00:01:32.910 --> 00:01:36.660
Jonathan Feng: This is truly amazing thing. If you think about it, step back a little bit.

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00:01:38.940 --> 00:01:46.230
Jonathan Feng: There's a number of ways to think it's amazing. First, you know, this is not what accelerators were made to do right accelerators are part of

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00:01:46.950 --> 00:01:58.380
Jonathan Feng: Nuclear Physics particle physics and they were made to investigate small and scales to probe into the atom into the nuclei. Now I learned scales of 10 to the minus 18 meters.

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00:01:59.280 --> 00:02:17.190
Jonathan Feng: And what we're saying here is that they may actually tell us about the dark sector, which is really in the European astrophysics and cosmology, then scales up say 10 to the 25 years. So it's just kind of an incredible task to think that one could use accelerators to Provo probe the universe.

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00:02:18.240 --> 00:02:25.410
Jonathan Feng: Especially accelerators, because now these are completely healed and made experiments. There's at the beginning, no input from the universe.

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00:02:25.920 --> 00:02:42.060
Jonathan Feng: direct detection of work better indirect effect on dark matter, at least you have the dark matter playing a role at the beginning right scattering annihilating here we're just starting off with protons, electrons positrons, and so how could this then tell us about the drug sector.

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00:02:43.440 --> 00:02:48.570
Jonathan Feng: So I'm going to see in these lectures. In fact, it is that one of the great wonders, there were a field, I would say.

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00:02:49.050 --> 00:02:58.830
Jonathan Feng: That there are actually reasons for optimism and for some people, I would say they would think it's strong reasons for optimism that accelerators really could tell us about the dark universe.

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00:03:00.420 --> 00:03:13.950

Jonathan Feng: Existence of the dark sectors. Now one of the strongest reasons to expect. Not only that need particles exists, that's obviously true, but also that these new particles will actually appear at the particle experiment. So we are now building

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00:03:15.300 --> 00:03:16.350
Jonathan Feng: And second,

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00:03:17.790 --> 00:03:30.630
Jonathan Feng: Gen arguments that have been developed very much in the last few years have motivated, a huge number of new ideas for experiments accelerators and colliders which could actually be built.

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00:03:31.350 --> 00:03:36.660
Jonathan Feng: And so this is an extremely exciting time and it's my my task to try to

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00:03:37.410 --> 00:03:49.260
Jonathan Feng: summarize some of these developments, but also I tell you where you know there are things that are just not known yet. And I'm sure there's many new ideas that are very good that are yet to explore and hopefully some of you can do that.

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00:03:51.630 --> 00:03:55.500
Jonathan Feng: So the outline of these lectures is here. It's going to be increased parts.

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00:03:56.850 --> 00:04:08.940
Jonathan Feng: First, let me just step back and talk about particle physics kind of the state of the field and then connected to the relativity of dark matter, and we're going to see that that relevancy is where a lot of these very interesting connections come

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00:04:11.130 --> 00:04:19.890
Jonathan Feng: After that we're going to see that sort of the cases for a star executive theories break roughly into two categories, you know, sort of heavy dark sectors.

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00:04:21.450 --> 00:04:37.410
Jonathan Feng: Which means, like, whoops, for the week scale dark sectors dark matter. So we'll talk about that first. And that actually overlaps quite a bit with Tim Tate's lectures. So he and I, you know, we have no excuse for not collaborating or

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00:04:38.730 --> 00:04:53.310

Jonathan Feng: Working out these two lectures, we talked about this, and he will do this in some detail. He's the world's expert at this, but I will also sort of get the ball rolling and talk about some some general features about Windsor colliders and accelerators.

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00:04:55.290 --> 00:05:05.670
Jonathan Feng: Those will be probably fairly roughly fairly brief sections. And then the third section is really where we get into the meat of this talk about light, dark sectors.

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00:05:06.150 --> 00:05:13.650
Jonathan Feng: And these are developments are happening really in the last few years, and there's a lot of excitement to talk about their hand, trying to get into that.

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00:05:16.830 --> 00:05:17.730
Jonathan Feng: Alright, so

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00:05:19.740 --> 00:05:22.290
Jonathan Feng: First part particle physics in Iraq, then sit back matter.

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00:05:24.660 --> 00:05:30.540
Jonathan Feng: So let me, as I said, step back and talk to, just a brief history of the field particle physics.

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00:05:31.950 --> 00:05:37.710
Jonathan Feng: So if we want to look for new particles. Now we're not even talking about commodity cages any new particles.

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00:05:38.880 --> 00:05:45.930
Jonathan Feng: How could we do it well we could try to figure their properties in this plane where there's the mass of the particle or the interaction aspect of the particle.

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00:05:47.550 --> 00:05:54.270
Jonathan Feng: And if we're talking about accelerators and clockers they basically shine a light on this plane from the upper left hand corner.

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00:05:55.590 --> 00:06:12.120
Jonathan Feng: And so they're very good at putting things up in that corner but not in the other corner so up here are already discovered particles. So, starting with the electron hundred 25 years ago and then moving on to quarks. And then, you know, hey, we get quirks and wmc bows on the Higgs boson.

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00:06:13.650 --> 00:06:21.120
Jonathan Feng: Down here are things that are impossible to discover with a collider. It just never ever going to get too heavy weekly interacting particles.

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00:06:22.470 --> 00:06:30.660
Jonathan Feng: So then all the interesting stuff occurs on this line in the middle. And up here. Good classify these sort of particles of strongly interacting heavy particles.

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00:06:31.170 --> 00:06:37.080
Jonathan Feng: By strongly interacting. I don't mean SU three strong interactions. I just mean that they have couplings are sort of order one. Okay.

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00:06:38.250 --> 00:06:39.810
Jonathan Feng: And. They're heavy, they're like TV.

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00:06:41.010 --> 00:06:52.650
Jonathan Feng: And then down here on the others corner weekly interacting light particles. So, these inside of me VC DB range, and I would actually strengthen our say sort of Millie or micro charged

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00:06:54.060 --> 00:07:03.450
Jonathan Feng: And so all the action in collider physics is basically taking place right now on that sort of grey diagonal line which is one of the state of the art is

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00:07:05.700 --> 00:07:21.870
Jonathan Feng: You look in the past, you could kind of call this first is X axis, the Lawrence axis because he started with accelerators building bigger and bigger ones culminating now on the LSC so he's trying to basically say, let's move along that direction to find the particles.

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00:07:24.030 --> 00:07:41.370
Jonathan Feng: And that's been extremely successful. But there's also the other axis which is the y axis which is maybe most famously exemplified by Fred rinus who discovered the new trainer, which is down in that area very light protocol, but very weakly interacting so hard to find.

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00:07:42.600 --> 00:07:48.780
Jonathan Feng: And so what we're going to find is that these two great traditions are kind of the position that we can talk about right now.

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00:07:49.290 --> 00:08:03.270
Jonathan Feng: Up in this town when I'd be happy particle sector, there are heavy dark sectors that heavy dark matter sort of TV back matter, and we'll talk about that. And then down here are like dark sectors and maybe this is maybe the most

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00:08:04.500 --> 00:08:13.590
Jonathan Feng: Sort of write down the main line of this this program in that these are the things that are almost invisible right very weakly interacting. How do you find that

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00:08:14.700 --> 00:08:17.160
Jonathan Feng: We can sort of break this plane into two parts.

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00:08:20.190 --> 00:08:26.550
Jonathan Feng: So let's talk about then because module. So that was basically our particle physics. So now let's talk about cosmology.

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00:08:27.540 --> 00:08:30.960
Jonathan Feng: What do we know about dark matter on the first thing, of course, we know very little.

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00:08:31.890 --> 00:08:47.340
Jonathan Feng: And we know very little about the dark matter and very little about the dark sector, and we just know that they didn't this to talk stock sector means dark matter and related sort of particles. So, I'm not talking about dark energy all know that sometimes I'm lumped in it's dark sector.

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00:08:49.620 --> 00:08:59.400
Jonathan Feng: There is, however, one thing we do know precisely and that is the documentary rock density. So here are some plots from recent thank collaboration fits

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00:09:00.540 --> 00:09:13.680
Jonathan Feng: This is an extraordinary thing. We know that dark matter relic density is 0.100 plus or minus 0.0012. Okay, so this is a 1% determination of how much dark matter. There is

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00:09:15.060 --> 00:09:20.640
Jonathan Feng: Now you might think, well, I don't know how much there is doesn't tell you very much about what it is, but

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00:09:21.600 --> 00:09:31.800

Jonathan Feng: We can actually learn a fair amount from this genetically, it's true. We can't learn anything is, you know, the total for the macroscopic amount of documentary doesn't tell you anything but the microscopic

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00:09:32.820 --> 00:09:39.270
Jonathan Feng: But turns out that if we assume that matters produced through thermal freeze out actually. We can learn a lot about that matter.

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00:09:41.640 --> 00:09:45.690
Jonathan Feng: So thermal fees that was actually covered in Tim Tate's lectures earlier this morning.

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00:09:46.890 --> 00:10:04.260
Jonathan Feng: So I want to do it in the detail. He did. Let me just remind you of the sort of broad features I read because it's a really beautiful thing. The idea is that in the early universe. We had a dense hot universe and Batman, we had this big thermal soup basically every particle

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00:10:05.580 --> 00:10:17.670
Jonathan Feng: Lighter than the temperature was in thermal equilibrium. And of course, if you go back far enough get high enough then pretty much all particles were lighter than the temperature. And so you have this soup of particles.

61
00:10:18.870 --> 00:10:20.460
Jonathan Feng: For a democratically represented

62
00:10:21.690 --> 00:10:29.580
Jonathan Feng: And they can annihilate each other this x is going to stand for documented on these lectures and XX and going to kick you bar and people see my name is so whatever

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00:10:30.960 --> 00:10:39.900
Jonathan Feng: So then that is in the early universe. And so this figure here is as a function of temperature going down and temperature which is going forward in time. Okay, so we start up here.

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00:10:40.410 --> 00:10:49.560
Jonathan Feng: At high temperature and eventually the universe pools. Now when it cools you continue to have x x particles annihilate the light corks

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00:10:50.100 --> 00:10:57.930
Jonathan Feng: But if the x is heavy enough that you don't go the other way. So corks don't go back and make heavy particles, because they just simply don't have the kinetic energy to do that.

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00:10:58.740 --> 00:11:07.470
Jonathan Feng: So you start losing the amount of X particles and you would just lose all of them and have nothing left. Except for the fact that not only is the universe cooling. It's also expanding

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00:11:08.130 --> 00:11:14.610
Jonathan Feng: As it expands. Eventually these x particles are the kind of magically they're perfectly able to annihilate the QQ bar.

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00:11:15.420 --> 00:11:25.620
Jonathan Feng: They just can't find each other. And so these x's wander around the universe by themselves very lonely and sad and they freeze out until you have basically

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00:11:26.190 --> 00:11:34.170
Jonathan Feng: And you get off this exponentially falling curve and you have just some amount of data that's left over, and continues on to the present day.

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00:11:35.730 --> 00:11:44.760
Jonathan Feng: And so as I said temptation explain this beautifully. So I won't go into the details, but bottom line though is that if you have increasing annihilation strength.

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00:11:45.420 --> 00:11:55.350
Jonathan Feng: Then you stay on this curve longer and you give off later and you have less stuff, but just kind of makes sense, meaning the more you annihilate the less you have leftover now.

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00:11:58.440 --> 00:12:11.100
Jonathan Feng: So it turns out that this relationship between the amount of leftover and annihilation strength is wonderfully simple for a huge range of parameters. Basically, the amount of dogma leftovers one over the annihilation cross section.

73
00:12:12.120 --> 00:12:16.830
Jonathan Feng: Okay, so you doubled in at least in cross section you get half as much stuff left over.

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00:12:18.210 --> 00:12:25.950

Jonathan Feng: And an interesting fact you know the mass, for example, drops out, it doesn't matter really what the masses and matters, really what the cross section is

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00:12:27.450 --> 00:12:37.650
Jonathan Feng: However, if you were just to estimate what this cross section should be based on dimensional grounds, you know, it has units of area. So it has to one over mass squared.

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00:12:38.370 --> 00:12:46.290
Jonathan Feng: And so if you think that it's doing something like this annihilating through this sort of a diagram here, then you should have five dimensions.

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00:12:47.400 --> 00:12:56.550
Jonathan Feng: Sigma goes as one over x squared. So that means one over sigma causes n squared, and then there's some couplings here. And so they're going to be done in the denominator. Okay.

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00:12:57.630 --> 00:13:08.850
Jonathan Feng: And so assuming that this process can be characterized by a single mass scale, you know that the x and whatever's in this T channel thing about the same mass, then this is a pretty good estimate

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00:13:09.540 --> 00:13:15.690
Jonathan Feng: So be a really bad estimate if you know excellent neutrinos and this word like that who was on or something. But we're not thinking of that right now.

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00:13:18.150 --> 00:13:34.680
Jonathan Feng: Okay, so you have this relationship. Now there's a there's a proportionality here if you keep track of the concepts of proportionality, you find that if you stick in 100 GB here and the week G point six year and outcomes. Omega point one, which is exactly what you want.

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00:13:35.700 --> 00:13:52.260
Jonathan Feng: And so this is a remarkable effect. That's the fact that the particles of the right relic thermal density. I now at our Energy Frontier, they weren't at our Energy Frontier 30 years ago and presumably they won't be at our energy front here 50 years from now.

82
00:13:53.430 --> 00:13:59.640
Jonathan Feng: But they are right now. And so that's a very interesting coincidence that we are now probing the energies that are

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00:14:00.750 --> 00:14:04.200
Jonathan Feng: The right energies to make particles that had the right relic density

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00:14:05.850 --> 00:14:14.520
Jonathan Feng: In other words, the hell he is a big back my research experiment, even though the people who propose it and the 1980s, right. Very few of them thought of it that way.

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00:14:17.520 --> 00:14:26.700
Jonathan Feng: Now, one thing I'd like to just mention is that this will update to this thing that I just mentioned, is called the miracle. It motivates these weekly interacting massive particles. The links.

86
00:14:27.810 --> 00:14:40.380
Jonathan Feng: One feature that isn't often discussed, but it's actually an important one is to note that this is not all you need to make a good case that you can make dark matter colliders

87
00:14:41.490 --> 00:14:43.740
Jonathan Feng: Because dark matter also has to be stable.

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00:14:44.790 --> 00:14:46.590
Jonathan Feng: And so it's a natural question.

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00:14:48.900 --> 00:14:52.890
Jonathan Feng: How likely is it that some of these hundred GB particles are stable.

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00:14:53.850 --> 00:15:01.740
Jonathan Feng: And you might think, at our priority. It's not very likely at all because you know all stable particles are like electrons and protons and your trainers are very light.

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00:15:02.130 --> 00:15:11.430
Jonathan Feng: What's the chance that 100 GB particle is going to be stable. Now, otherwise we make a bunch of particles they stopped, but the lowest latest one, and that go farther down

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00:15:13.020 --> 00:15:19.530
Jonathan Feng: And there's an argument had a frontier, which is, I think, quite a bit of argument, which is that the gate hierarchy problem.

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00:15:20.580 --> 00:15:29.520
Jonathan Feng: acquires that we have some new particles in a loop contributing to the Higgs mass stabilizing quadratic registers and things

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00:15:31.590 --> 00:15:35.910
Jonathan Feng: So, you know, these new particles, ideally, do this.

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00:15:37.050 --> 00:15:51.930
Jonathan Feng: But we also know that they don't do this in their lower. They don't mediate for point Standard Model particle interactions. And this is because they're extremely tight bounds on that kind of a particle from lap and other decision measurements.

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00:15:54.030 --> 00:16:01.890
Jonathan Feng: So the simplest solution is if you want to keep this kind of diagram and get rid of this one incident pose a discrete parody.

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00:16:02.760 --> 00:16:13.920
Jonathan Feng: So that you only have interactions that have pairs of new particles in pairs, a red lines coming to the vertex that will of course keep these diagrams and get rid of these diagrams.

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00:16:15.540 --> 00:16:23.220
Jonathan Feng: But in doing that. It also means that you can't the k, the latest new particle, because that would violate this discrete Perry.

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00:16:24.540 --> 00:16:34.170
Jonathan Feng: So basically, what I'm saying is here that just from particle physics measurements alone, knowing that there's a gauge happy prom and precision measurements.

100
00:16:34.830 --> 00:16:48.990
Jonathan Feng: You have a very strong reason to consider models that do have some discrete parody that keeps the latest new particle stable. And so this is of course realized in a bunch of different ways. Heart Perry and supersymmetry KK parody.

101
00:16:51.090 --> 00:17:02.280
Jonathan Feng: Explanation operator cetera but basically it gives you an understanding of why this became such a sort of favorite framework for so many years because the particle physics.

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00:17:03.300 --> 00:17:07.980
Jonathan Feng: Is sort of automatically telling you that you have the right properties.

103
00:17:12.660 --> 00:17:18.330
Jonathan Feng: Okay, so that was dark matter. But let's talk now about something a little bit more general direct sectors.

104
00:17:19.590 --> 00:17:28.680
Jonathan Feng: Miracle relies on the choice of gauge coupling being about what I stick in a point six before but you know the level of these estimates point 1.6 and one or the same

105
00:17:30.420 --> 00:17:42.030
Jonathan Feng: Why do we do that. Well, that's a reasonable choice, since it is true for all the known gauge horses right you know electromagnetism has a gauge coupling of point three. So, you know, everything's about order one.

106
00:17:43.710 --> 00:17:48.930
Jonathan Feng: But this means because electromagnetic and strong and reactions for that fight or large excluded.

107
00:17:51.210 --> 00:17:58.890
Jonathan Feng: This means that the last choice of the dark matter has week. Yes. You too, and our actions and this leads them to this huge

108
00:17:59.910 --> 00:18:05.640
Jonathan Feng: Industry and thinking about weekly interacting NASA particles when weekly interacting and I mean as you to interacting

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00:18:09.270 --> 00:18:18.660
Jonathan Feng: But I'll evidence for God matters actually gravitational so you know there's no reason for it to have couplings with order when interactions.

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00:18:19.260 --> 00:18:34.350
Jonathan Feng: They may therefore have only gravitational interactions with Santa ma particles. And that's always an open possibility, at least so far. And that is actually incredibly depressing because that means that all these particle experiments will see nothing.

111
00:18:36.270 --> 00:18:40.050
Jonathan Feng: However, now that we bracketed the sort of nightmare and the good scenario.

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00:18:41.010 --> 00:18:48.240

Jonathan Feng: We can also realize that there's a continuum. There's also the possibility that it might have highly suppressed but non negligible interactions.

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00:18:48.660 --> 00:18:57.000
Jonathan Feng: With Standard Model particles that is with Park couplings that are sort of not gravitational not super tiny. But, you know, much less than this one that we use up there.

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00:18:58.080 --> 00:19:02.460
Jonathan Feng: And what we're going to see is that in fact we are just very naturally and models with Doc sectors.

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00:19:03.090 --> 00:19:11.850
Jonathan Feng: That sector, being a sort of group of particles which contain, not just at dark matter particle, but also possibly additional matter and forces.

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00:19:12.330 --> 00:19:21.270
Jonathan Feng: And so the picture we have is then there's the visible sector, the standard model. And then there's the stock sector which, so enough has the documentary hit it, but it also under the things in it.

117
00:19:21.810 --> 00:19:26.370
Jonathan Feng: Maybe their own its own forces and other matter particles are sort of related to different manner.

118
00:19:27.240 --> 00:19:42.810
Jonathan Feng: And we're going to see is in this sort of scenario, then it's quite natural that there is a little bit of talking between these two, but definitely not at full strength, not a couple things of order one and made have young couplings 10 to the minus three x minus six of them like this.

119
00:19:44.910 --> 00:19:49.290
Jonathan Feng: So what does that do realizing that that's a problem. Certainly we can revisit this one article

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00:19:50.610 --> 00:19:58.470
Jonathan Feng: So the went miracle, remember, is this fact that this drug. And he had this sort of form came out here and it's wonderful coincidence that

121
00:19:59.430 --> 00:20:15.060

Jonathan Feng: These masters and couplings give you the right rock country or the dark sector, what we realize is, we don't really need to have that coupling the order one. It could be something much less. So here is a plot where we have the document and mass. And here's the document and coupling concept.

122
00:20:16.350 --> 00:20:31.080
Jonathan Feng: And you realize that if all you have constraining is the relevancy that's really all you know that this is about point one. Obviously there's a line of solutions in this parameter space where can max and TX have different values and they lie on this diagonal

123
00:20:32.520 --> 00:20:40.560
Jonathan Feng: And so the point is that up here, sure enough, there are wimps. They lie on this line because they give you the way miracle.

124
00:20:41.100 --> 00:20:58.890
Jonathan Feng: But there's a whole continuum of other possibilities which also be the right relic density through this beautiful mechanism freaks out but don't have WIMPs in them in the sense that they don't have week interaction particles with masses of hundred GV

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00:21:01.410 --> 00:21:10.260
Jonathan Feng: So this is something that Jason Kumar and I called the simplest miracle that had been also discussed earlier via slee environment PFA

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00:21:12.240 --> 00:21:20.580
Jonathan Feng: Basically, the point is that if all you know as a rock density, there's a lot of opportunities to satisfy that hop dancing with them or freeze out

127
00:21:21.660 --> 00:21:31.920
Jonathan Feng: That don't require wins. And so in other words you can have much say lighter particles citizen GB. Right. So here we're talking my GV any we

128
00:21:33.510 --> 00:21:38.580
Jonathan Feng: Allege vessel strongly couple that is sort of can be almost invisible category.

129
00:21:39.330 --> 00:21:51.120
Jonathan Feng: And these all give you the right redundancy, all within the standard cosmology. You don't have to stand on your head. And these strange things to cosmology, just simple normal cosmology, but these particles present whether a rock and

130
00:21:54.870 --> 00:22:06.570
Jonathan Feng: So then let's revisit this claim that we had. Okay, so this plane as I told you was basically a particle physics plane simply asked her, where can we find the particles and answer was along this diagonal

131
00:22:07.500 --> 00:22:11.880
Jonathan Feng: But what happens now that we think about the cosmology of this plane. So what's the remote relic landscape.

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00:22:13.770 --> 00:22:22.320
Jonathan Feng: So up here in this upper corner we want to discover these particles, but they give you too little too dark matter they annihilate too fast.

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00:22:23.340 --> 00:22:27.510
Jonathan Feng: Then there's not enough for them left over to be dark matter. So they're not documented case anyway.

134
00:22:29.040 --> 00:22:39.870
Jonathan Feng: Down hands other corner. These days, and Eileen very, very poorly and so they'd be too much. We got they went over. Close the universe. And so they aren't so good for you, cosmological either

135
00:22:41.100 --> 00:22:50.370
Jonathan Feng: Place where they are good for you is on this diagonal, which is right here. And this is sort of the Goldilocks region where you have just the right amount to be got better.

136
00:22:51.660 --> 00:23:04.110
Jonathan Feng: And the point here is that this green line here also overlaps the Legion where we're sort of at different fear trainer liquid particles.

137
00:23:05.040 --> 00:23:11.670
Jonathan Feng: So, this is this amazing fact that, you know, for example up here in this corner, there's the wimps.

138
00:23:12.270 --> 00:23:17.850
Jonathan Feng: And you know that we're kind of looking forward to their life see right now and you also know that they have the right like density

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00:23:18.420 --> 00:23:28.830
Jonathan Feng: But that's just a plate on this plane. There's a whole line and sort of the region where we can look for stuff in the region where we have the right real density sort of line up on top of each other and coincide.

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00:23:29.490 --> 00:23:39.900
Jonathan Feng: That's this beautiful connection that gives us some reason for optimism that these experiments are thinking about building might actually see something with relevance for the dark universe.

141
00:23:43.170 --> 00:23:45.300
Jonathan Feng: Okay, so here's the summary of part one.

142
00:23:46.500 --> 00:23:53.070
Jonathan Feng: We know little about dark matter. But what we do know very precisely Israelite density. So we want to suck as much information as we can.

143
00:23:54.210 --> 00:24:09.600
Jonathan Feng: If black mass produced the term or freeze out this reluctance. He actually tells us about the microscopic particles properties and remarkably flavors particles that masses and couplings that are not yet excluded, but are within reach of current in the future experiments.

144
00:24:11.250 --> 00:24:22.560
Jonathan Feng: As the continuum, as you saw from that plane but roughly, we can break these sort of target areas into two classes. So there's sort of heavy particles and light particles.

145
00:24:23.580 --> 00:24:32.400
Jonathan Feng: The heavy ones are typically referred to as went dark matter, and I'll discuss them. Next, the light winds will talk about a little bit later in part three of these lectures.

146
00:24:33.960 --> 00:24:43.830
Jonathan Feng: Here in the heavy typical couplings order one kind of like, you know, Santa Monica planes here you have much smaller complaints in the most almost invisible category.

147
00:24:44.400 --> 00:24:51.750
Jonathan Feng: Here you have mastered that that week scale and the light side you have things that are much lighter say between the electron, proton mass

148
00:24:52.680 --> 00:24:59.850
Jonathan Feng: Here you're talking about probing TV particles. So, you know, you're only side at that in particle physics is that the Energy Frontier

149
00:25:00.630 --> 00:25:17.280
Jonathan Feng: Here you're talking about things that are much lighter and so the Energy Frontier is possible but also sort of things you might call intensity frontier and also able to prove this. And so this is led to a whole new sort of feel the intense and high energy sort of the probes.

150
00:25:19.890 --> 00:25:24.840
Jonathan Feng: Now I should know before I go on. So, as I say, we're going to talk about heavy first and then we're going to talk about light.

151
00:25:26.910 --> 00:25:31.860
Jonathan Feng: But before I go on and let me just know that there are many, many caveats that everything I've said here, right, so I'm

152
00:25:32.640 --> 00:25:39.240
Jonathan Feng: simplifying things. Hopefully pedagogically. That's a good idea, but also just to get them within two hour long lectures.

153
00:25:40.110 --> 00:25:44.820
Jonathan Feng: But there are many caveats, and exceptions extensions to what I've been presenting above. Okay.

154
00:25:45.720 --> 00:25:56.970
Jonathan Feng: Obviously, for example, that you don't need thermal freeze out there are other ways to make dark matter. So freeze in as Tim talked about has another one. And that's a whole different category of models.

155
00:25:58.200 --> 00:26:05.280
Jonathan Feng: But anyway, I just want to make you aware of that, but also aware that, you know, if you find exceptions. If you find loopholes.

156
00:26:06.990 --> 00:26:18.810
Jonathan Feng: You know that might actually be a paper right that might actually be new. And so some of these things are I'm ignoring you just for brevity sake, some of these things are just not really well explored and

157
00:26:19.470 --> 00:26:23.820

Jonathan Feng: You know, you could do well to think about them a little bit more and see if they might Pete somewhere.

158
00:26:27.180 --> 00:26:32.820
Jonathan Feng: Okay, so now we're on to part two of three in the lectures and I'm talking about heavy dark sided sectors.

159
00:26:37.170 --> 00:26:44.640
Jonathan Feng: So dark matter particles are in this heavy range, which is the hundred g to TV range. They are not going to be easy to make.

160
00:26:45.570 --> 00:27:05.490
Jonathan Feng: You basically have two options. First you use nature Tameka okay mater is an amazing place. And if you're clever, you can explain it. So for example, in the Big Bang, because we had enormous high energies and possibly the dark matter just live safely through that we have

161
00:27:07.020 --> 00:27:18.360
Jonathan Feng: A dark matter source that just hanging all around us and we can use indirect detection and direct detection to try to use that document of sorts of hundred GV TV particles.

162
00:27:19.410 --> 00:27:26.250
Jonathan Feng: And so this is a diagram I made a long time ago. In fact, I think I might have made it for a slack Summer Institute.

163
00:27:27.990 --> 00:27:38.070
Jonathan Feng: But it illustrates the sort of ways to look for when stack matter you have dark matter, dark matter cork this for planner action.

164
00:27:38.460 --> 00:27:58.110
Jonathan Feng: And depending on which way you read the diagram, you can have indirect detection as Tracy talked about where the document annihilating gives a bar scattering or Chi got better to scatter off each other and lead to recoils which God Cooley will talk about in a couple days.

165
00:27:59.370 --> 00:28:11.400
Jonathan Feng: Or you can go the other way and have started off with quirks and make that matter. And so this is particle colliders. So this is what we're going to talk about here, but also Tim table talk about it a lot more in his lectures.

166
00:28:12.870 --> 00:28:21.030

Jonathan Feng: I know one other way that you can explain nature is that you can look for ultra high energy cosmic rays. And this is actually an interesting

167
00:28:22.260 --> 00:28:39.060
Jonathan Feng: Area, you know that there are cosmic rays, which are colliding with protons in the atmosphere CENTER MASS energies way above the LSC so if you're clever. You can maybe use that to look for dark matter as well. But that's represented in the lectures at the school.

168
00:28:40.650 --> 00:28:43.770
Jonathan Feng: Anyway, those are the ways to use certain natural sources of dark matter.

169
00:28:44.850 --> 00:28:53.310
Jonathan Feng: Failing that, you're only other choices to use Particle colliders by colliders Harriman colliding beings not just accelerators not target experiments.

170
00:28:53.850 --> 00:29:01.950
Jonathan Feng: Because you got to get the highest possible CENTER MASS energies. And the only way to do that is with colliding beams. So that's what we're focused on here.

171
00:29:04.920 --> 00:29:11.940
Jonathan Feng: So as I said to him, take we'll talk about this in much more detail and but we've arranged that I will sort of just mentioned a few things here.

172
00:29:13.890 --> 00:29:32.790
Jonathan Feng: So very broadly. There are a couple very well known ways to look for dark matter at colliders firstly is to consider some full models like supersymmetry or maybe simplified models where you just picking out a few states in in this

173
00:29:33.960 --> 00:29:45.840
Jonathan Feng: You know, in this model. And what you do is you produce other markets but particles indicated that matter. And then you look for missing etc nutters because the dark matter escapes without being detected

174
00:29:47.220 --> 00:29:57.360
Jonathan Feng: Here's a classic example protons come in, in this case, they make a score can glue Ino and then those things. The key down and eventually you get to this.

175
00:29:57.900 --> 00:30:12.540
Jonathan Feng: neutralino which is the dark matter when on this side and one on this side and these two things and escape, and that's where you get them missing at. And so that's this very classic missing at signature of lateral colliders

176
00:30:17.040 --> 00:30:34.440
Jonathan Feng: Another pretty classic way to look for that matter colliders is called, we call it Moto X. So this way you say okay, let's not talk about producing much heavier states and then having them decay that back, man. And let's just get straight to the point to produce a dark matter directly

177
00:30:36.240 --> 00:30:41.190
Jonathan Feng: So, you know, you have like QQ bar comes in and makes dark matter, dark matter.

178
00:30:42.930 --> 00:30:48.600
Jonathan Feng: Of course, if that's all that happens, then you don't have anything to say because you just need something and it visible to see it.

179
00:30:49.230 --> 00:31:04.050
Jonathan Feng: But if you radiate off something like in this case the Jet Blue one, then you can actually say, you might have used it to tag this thing and you have them can have some evidence of having made dark matter and looking in this case management signals.

180
00:31:07.530 --> 00:31:14.730
Jonathan Feng: And then, you know, the question always will be. Then, or what's in this blob here. This is for planar action of dark matter and quirks.

181
00:31:15.360 --> 00:31:26.220
Jonathan Feng: And the answer is, well, you can sort of go through systematically and for various kinds of dark matter characterize that blob as an effective operator and try to put downs on it.

182
00:31:27.540 --> 00:31:44.610
Jonathan Feng: So here's a table from the early papers in this direction. I think this is from 10 page paper with good minute call and, you know, they go through all these different operators which parameter is this blob and then you look to put bounds on these operators.

183
00:31:45.990 --> 00:31:53.580

Jonathan Feng: Look, and you set off of here. Well, the first things people thought about where photons actually in this Bergdahl paper. It was a photon mana photon.

184
00:31:54.210 --> 00:32:10.920
Jonathan Feng: But then quickly Mano jets and then this has become a minor industry or you can set up a w or z. Now even Higgs Boson and popcorn basically anything. And it's this Mano X industry or exes any of these particles. And so that's another very

185
00:32:12.030 --> 00:32:13.440
Jonathan Feng: Interesting direction to go.

186
00:32:16.080 --> 00:32:31.470
Jonathan Feng: So Tim will talk more about that. But let me just move on. Can say that I'll miss Paula missing energy and Moto X are by far the most study signatures of black matter. There are actually many, many others. And so just to give a flavor of these

187
00:32:32.700 --> 00:32:36.630
Jonathan Feng: You know, we're talking about dark sector probes and accelerators.

188
00:32:37.860 --> 00:32:43.020
Jonathan Feng: Let me just mention a few of these other very different kinds of signatures want going to have

189
00:32:43.620 --> 00:32:48.660
Jonathan Feng: And and part of doing this because I want to, you know, complement the standard stuff that Tim, what about

190
00:32:48.990 --> 00:33:04.470
Jonathan Feng: But, in part, I also want to do this because it will affect introducing us to this really interesting zoo of interesting signatures that will be discussed next for like vectors. They're not just for like vectors, even for heavy executors we see these. If we look hard enough.

191
00:33:06.300 --> 00:33:14.790
Jonathan Feng: So let me give an example. So the first one is that staying even within the framework of supersymmetry, you know, there are other candidates besides

192
00:33:15.750 --> 00:33:28.500

Jonathan Feng: Me know there's also the documentary might be the neutral window. So this is a Suzy partner, the SEC to gauge designs. So there's the W AMP Z gauge bows on that Susie partners or Windows vino

193
00:33:29.760 --> 00:33:38.340
Jonathan Feng: The really interesting thing about this is that the neutral, we know as part of an se two triplet. So actually, one of three states in this triplet.

194
00:33:39.540 --> 00:33:50.160
Jonathan Feng: And when st symmetry is perfect not broken by the Higgs. These are completely be generate these three particles are exactly the same mass.

195
00:33:52.020 --> 00:33:59.040
Jonathan Feng: Now of course we know that st to doesn't last forever. It is broken. And so these will then be

196
00:34:00.630 --> 00:34:16.530
Jonathan Feng: Have some mass splitting, but it's a remarkable fact that one can calculate the mass splitting, and it's tiny. So even if these are say multi TV to TV and mass. The mass splitting of them is like 160 MTV three orders of magnitude down

197
00:34:18.390 --> 00:34:28.020
Jonathan Feng: And so what this means is that in a very generic Susie dark matter theory. What you do is you can make charged winos like this.

198
00:34:28.740 --> 00:34:42.990
Jonathan Feng: And today will decay to the lightest supersymmetric particle which is the neutral, we know which is the dark matter, but they have so little energy that the only open mode is to pions how except the dominant open mode.

199
00:34:44.040 --> 00:34:58.440
Jonathan Feng: And they have a very long. The Kayla. So here's a plane where the contours that are labeled by their splitting and mass splitting and also by their see town that the Caleb.

200
00:34:59.490 --> 00:35:06.210
Jonathan Feng: And you see that you have here, you know, like a TV particle that actually travels several centimeters before it decades.

201
00:35:07.530 --> 00:35:15.060

Jonathan Feng: And wanted to K is. What do you see, well, basically, you see nothing because this charge product called the case to an invisible particle

202
00:35:15.720 --> 00:35:26.490
Jonathan Feng: And then a Python the Python has an energy you know hundred 60 MTV. And so basically, you know, extremely high. And we're never going to see 100 MTV pine.

203
00:35:27.000 --> 00:35:41.970
Jonathan Feng: And barely see. And so all you see is disappearing track you have this nice charge track that came out and was seeing it in silicon tracker and then all sudden poof, it's gone after going through a couple years.

204
00:35:43.980 --> 00:35:48.090
Jonathan Feng: So that's a very different kind of signature than the previous ones I guess just

205
00:35:50.430 --> 00:35:56.820
Jonathan Feng: Another one which is maybe even more generic is to think about gravity know dark matter.

206
00:35:58.410 --> 00:36:11.340
Jonathan Feng: And this leads to genetically along with particles. So in also perspective models you know that because there's a grammar town in the real world to prospective buyer calls have to have a super partner that I worked on the gravity.

207
00:36:12.570 --> 00:36:28.050
Jonathan Feng: And its mass as incredibly interesting theory can be anything from TV to pee pee, but typically it's things are extremely weak as you might expect, because it's kind of inheriting down from the gravity is only gravitational interactions.

208
00:36:29.940 --> 00:36:37.110
Jonathan Feng: So, so what. Okay, so we have this particle, the gravity. Oh, well that's not the lightest supersymmetric particle

209
00:36:37.680 --> 00:36:44.130
Jonathan Feng: Then what happens at a collider is you make a bunch of slept dancers quirks and stuff and they decay down into your doctor.

210
00:36:44.970 --> 00:36:52.320

Jonathan Feng: And the gravity. You know, it's just this innocent bystanders sits over here and doesn't get involved in this at all because it's so weak.

211
00:36:52.740 --> 00:37:05.100
Jonathan Feng: That no one's going to decay to him and he's not going to be produced. So basically his existence. Here is just totally irrelevant to colliders and this is the assumption of most of the literature usually kind of an unspoken assumption.

212
00:37:06.660 --> 00:37:15.450
Jonathan Feng: But in the other half of the parameters space where the gravity knows actually lighter than any of the slept on sparks and beans and things

213
00:37:16.200 --> 00:37:24.090
Jonathan Feng: You have this case, what happens is you make storks and growing as a staff and they decay down to what's the next delighted to prospective particle

214
00:37:24.810 --> 00:37:31.080
Jonathan Feng: But then, this one has no trees, and eventually realizes it has to dedicate to gravity. You know, and I'll do that.

215
00:37:32.070 --> 00:37:44.550
Jonathan Feng: And so in this case the gravity know is not an innocent bystander that actually takes part in every single supersymmetric event if you wait long enough for this to happen, you get a completely different cosmology and different particle physics.

216
00:37:45.990 --> 00:38:00.930
Jonathan Feng: And this came to the for the heyday of gays community supersymmetry breaking were dying at all and others started thinking about this, but it leads to some really interesting different kind of opportunities that colliders

217
00:38:03.420 --> 00:38:13.410
Jonathan Feng: Let me give you one of these in the so called super limp Brock matters now yeah if you have for example, gravity mediated Susie, which is a standard Susie

218
00:38:14.460 --> 00:38:16.890
Jonathan Feng: Gravity know can have a massive 100 GB

219
00:38:18.150 --> 00:38:27.900

Jonathan Feng: But it has extremely we couplings suppressed by the Planck scale. So you then can I am week over implant, which is a number of doors 10 minus 16

220
00:38:29.040 --> 00:38:36.450
Jonathan Feng: So basically this practical interacts gravitationally with the rest of the particles, that's the

221
00:38:37.560 --> 00:38:43.050
Jonathan Feng: Source of this and plank and pink squared is union. And so this is

222
00:38:44.580 --> 00:38:47.640
Jonathan Feng: manifesting itself in the fact that has extremely we come

223
00:38:49.470 --> 00:38:57.540
Jonathan Feng: On this case the gravity know is the ISP WIMPs freeze out as usual. But then after they go along. So here's the Wimp freeze out like this.

224
00:38:58.080 --> 00:39:10.590
Jonathan Feng: But then after a long time, but we don't realize is that it has to decay and advocates and it's gone and the cases super Ramses gravity nose and makes a gravity in a population which is actually surviving through the day. And it's the back matter.

225
00:39:11.640 --> 00:39:18.660
Jonathan Feng: And this can take actually seconds, two months for this last decade to happen here. So it can be very late.

226
00:39:20.430 --> 00:39:31.080
Jonathan Feng: But what it means is that the end of the day, you have a gravity, the population that has just as much right to have the right formula that's a sign of thermo relic. But it has the right relevant to me.

227
00:39:31.560 --> 00:39:41.340
Jonathan Feng: Because it's getting it from like a 200 G Wimp that the case 200 GB clever Tino but now what you have at the end is an extremely, extremely

228
00:39:43.650 --> 00:39:45.960
Jonathan Feng: non interacting particle is gravity now.

229

00:39:47.910 --> 00:39:55.740
Jonathan Feng: But the interesting thing here is that when this is the gravity know then this thing, this Wimp doesn't have to be a good back when a candidate.

230
00:39:56.130 --> 00:40:09.630
Jonathan Feng: In particular, it could be charged so it could actually be a slap down say because it's not actually going to be the dark matter. And so now you can have this particle which is charged, which has a lifetime of, say, two weeks.

231
00:40:11.010 --> 00:40:13.260
Jonathan Feng: And it's perfectly valid for your cosmology.

232
00:40:14.310 --> 00:40:17.130
Jonathan Feng: And gives you the right sort of dark matter scenario.

233
00:40:20.010 --> 00:40:33.240
Jonathan Feng: So this leads then to meta stable charged particles. So, you know, the possibility is that we could actually have slept Dan's charged particles coming out of the LLC.

234
00:40:33.990 --> 00:40:47.850
Jonathan Feng: Which are completely stable as far as the LLC is concerned. So they just stream out of here this enormous looks like a heavy anyone missed comes barreling out of this collider and doesn't interact with any of the component. I mean, doesn't

235
00:40:49.170 --> 00:40:50.460
Jonathan Feng: Stop in any of the components.

236
00:40:52.470 --> 00:40:59.850
Jonathan Feng: So we can collect these particles and stay there, the case. Okay, so you had like 100 GB new one coming out of here.

237
00:41:00.930 --> 00:41:04.410
Jonathan Feng: And several ideas had been proposed. So you could actually

238
00:41:05.850 --> 00:41:17.010
Jonathan Feng: Track the trap the slept Dunn's in a water tank. So there's a proposal, I was involved with you put a one meter thick tank of water under say Atlas.

239
00:41:17.880 --> 00:41:31.080

Jonathan Feng: And some of these slept eyes will then just stop and get stuck in our water and then you can then drain it off to a reservoir and, you know, drive it in a bus down to Grand SAS or something and watch it decay.

240
00:41:33.840 --> 00:41:39.210
Jonathan Feng: That is, you know, kind of a crazy idea, but it's something that comes out of this dark matter scenario very natural.

241
00:41:41.310 --> 00:41:45.120
Jonathan Feng: When we publish this he thought it was crazy. But then it got even crazier.

242
00:41:47.190 --> 00:41:58.920
Jonathan Feng: Jerry at all, said, well, you can actually catch the slap dance in the LSE detector. Some of them were stopping here and then you just turn the lights off and you wait for this.

243
00:41:59.730 --> 00:42:10.230
Jonathan Feng: Detector to just start spewing out charge tracks, you know, a month later or something like that. And then maybe the most ambitious idea as from

244
00:42:11.970 --> 00:42:17.220
Jonathan Feng: A Baroque john Ellis fabulous jannati long before she was director general

245
00:42:18.450 --> 00:42:19.740
Jonathan Feng: Market, you know, and

246
00:42:20.760 --> 00:42:27.930
Jonathan Feng: And basically they said, Well, another way to do it is the slap Diane's can come out and then go large themselves and the detector wall.

247
00:42:28.470 --> 00:42:43.020
Jonathan Feng: And then what you should do is go to the detector wall you know which direction they went, you know how energetic was you know how far away into the wall and got large and basically just dig out the wall get dig out the rock and find that slept die.

248
00:42:44.880 --> 00:42:57.690
Jonathan Feng: So basically what I'm saying here is that there are huge number of interesting signals that come out of very generic dark matter scenarios, even at the highest energy at high energy colliders

249
00:42:59.430 --> 00:43:11.460
Jonathan Feng: So to summarize this part here. We backed by at least two interesting signals colliders there's these classic signatures missing up and Moto X, but there's also exotic signatures that are also motivating I talked about a couple of them.

250
00:43:12.960 --> 00:43:21.480
Jonathan Feng: So documented is not simply motivate missing ETFs the signatures that colliders has sort of what everyone says, but it's not true. There's a lot of

251
00:43:22.200 --> 00:43:31.890
Jonathan Feng: depth and richness to this and we should be on the lookout for qualitatively new signatures and opportunities accelerators and colliders that are motivated by dark matter scenarios.

252
00:43:34.890 --> 00:43:37.080
Jonathan Feng: Okay, let's see how much time to have

253
00:43:41.820 --> 00:43:49.440
Jonathan Feng: 10 more minutes, I think. So let me go on to the last the longest section. Okay, so now I'm going to talk about like dark sectors and accelerators.

254
00:43:53.130 --> 00:44:02.130
Jonathan Feng: Okay, so this is really the meat of these lectures, I think this is probably the topic that the organizers have most in mind to make sure we're represented in this program.

255
00:44:03.660 --> 00:44:12.000
Jonathan Feng: So this is how we traditionally think about dark matter we are the standard model which is in full glory has all sorts of interesting parts.

256
00:44:13.680 --> 00:44:31.740
Jonathan Feng: All these different particles and a whole bunch of them. We can contribute to the current universe protons, electrons neutrinos. Then we have back matter, which is this monolithic featureless black thing that's out there and we need to go find it.

257
00:44:34.380 --> 00:44:41.700
Jonathan Feng: But in recent years, it's been realized why I think is realized, years ago, but it's been so I've taken seriously.

258
00:44:42.390 --> 00:44:52.080
Jonathan Feng: That this picture is probably a lot closer. That true that the visible sector is full of all sorts, testing things, but the dark sector probably is also

259
00:44:52.920 --> 00:45:03.240
Jonathan Feng: After all, the dark sector is six times more prevalent in terms of mass density, then the visible sector. So there's a lot of room to play, and why should it just be say all one particle

260
00:45:04.590 --> 00:45:16.710
Jonathan Feng: So then we're concerned with this idea that the dark matter is not just this one particle out there, but actually part of a much more rich dark sector.

261
00:45:17.670 --> 00:45:35.730
Jonathan Feng: Which certainly does contain the dark matter, but it also contains other stuff other matter particles that might or might not be closely related to the dark matter, and then also Dark Forces gauge bosons other kinds of things that are sort of, you know, very prevalent in our sector.

262
00:45:37.170 --> 00:45:42.870
Jonathan Feng: So the question is, what consequences and this generalizing chromatic that sectors, how

263
00:45:46.290 --> 00:45:46.710
Jonathan Feng: So,

264
00:45:48.150 --> 00:45:53.460
Jonathan Feng: First thing to say is that if you have a dog sector, it doesn't have to interact with us, except through gravity.

265
00:45:55.020 --> 00:46:01.470
Jonathan Feng: And if it doesn't, that's as I mentioned before, the nightmare scenario. And that's too bad. And all these particle physics discussions are a waste of time.

266
00:46:03.060 --> 00:46:14.100
Jonathan Feng: But if it does interact with us. Certainly we would want to go find it. And so the question is then, what are the most likely non gravitational interactions. This stuff might have with us.

267
00:46:16.080 --> 00:46:23.550

Jonathan Feng: So we'll get to the general sort of complete answer to this question in a bit. But let me start out by just proposing something

268
00:46:24.480 --> 00:46:40.230
Jonathan Feng: So suppose the dark sector has its own electromagnetism. Okay. It has a UN gauge for us in the dark sector and particles in the tech sector scattering off each other you know Rutherford scattering the stuff with this dark, dark he when he goes on.

269
00:46:42.210 --> 00:46:55.590
Jonathan Feng: Now there are infinitely many ways to write down back matter standing all interactions, given the particle content of the dark matter or the tech sector mainly the dark matter and this sort of dark photon thing.

270
00:46:56.190 --> 00:47:16.980
Jonathan Feng: And that's okay. You can write many, many interaction turns down. But there's one that's very special which is this one that I written here, which is a coupling the field strength cancer are photon are engaged bows on the new with the dark you engage those on a Dark Moon.

271
00:47:19.350 --> 00:47:29.190
Jonathan Feng: Why is it so special. Well, first of all, it's allowed by all the cemeteries right he wants to keep you engaged in variants intact and this term respects that

272
00:47:31.500 --> 00:47:53.100
Jonathan Feng: It's also induced by mediators in a loop. So if you have any particle say some friend me on that has charged under the usual photon and also charged under the one dark photon, then a loop like this will geeks this coupling between the answers.

273
00:47:54.780 --> 00:47:55.560
Jonathan Feng: But it's more than that.

274
00:47:56.760 --> 00:48:00.150
Jonathan Feng: It also has dimension for mass dimension for

275
00:48:01.170 --> 00:48:02.250
Jonathan Feng: Any of us for

276
00:48:04.020 --> 00:48:16.650

Jonathan Feng: Which means that there's no mass of the mediator in this operator. So this mediator particle has some mass em, but it doesn't show up in here has a power.

277
00:48:18.210 --> 00:48:35.850
Jonathan Feng: Which means that even if the M is very heavy. This operator still just sits there and is not smaller, it's not suppressed. In other words, this is a non decoupling effect. This thing is induced by a mediator, irrespective of how heavy that neediness

278
00:48:37.140 --> 00:48:46.740
Jonathan Feng: And that's very special. For example, if you look at this diagram. This operator, which is just some other F, which is f cubed over and m squared. Well, obviously.

279
00:48:47.550 --> 00:48:59.250
Jonathan Feng: If m goes to some big number, then this operator is going to be couple. This is going to go to zero and so that effect probably come smaller and smaller, you need a break. Like mediator can make this not negligible.

280
00:49:00.720 --> 00:49:11.070
Jonathan Feng: But this one is not that way. Okay, so, said in another way. This is in some sense the most likely way that the visible sector is going to talk to the tech sector.

281
00:49:11.670 --> 00:49:22.380
Jonathan Feng: Because all you need is a particle which couples the two and it doesn't have to be light even heavy media's will make an operator like this.

282
00:49:24.930 --> 00:49:28.620
Jonathan Feng: So that's what's so special about this is dimension for it. So we normalize largely there.

283
00:49:29.790 --> 00:49:31.230
Jonathan Feng: A census loop induced

284
00:49:32.310 --> 00:49:47.580
Jonathan Feng: We do expect it to be a little smaller than one right and so I put a little epsilon out here in the front. And, you know, just using the standard ways of estimating things. This is a loop and these thing. And so this epsilon probably is tend to ministry are smaller.

285
00:49:48.600 --> 00:49:48.990

Jonathan Feng: But

286
00:49:50.070 --> 00:49:55.170
Jonathan Feng: It's not like suppressed by, you know, some giant mass. Okay, but it is

287
00:49:56.610 --> 00:49:57.750
Jonathan Feng: Not Porter one either.

288
00:50:01.380 --> 00:50:02.640
Jonathan Feng: Now we can do this in

289
00:50:02.910 --> 00:50:03.630
Jonathan Feng: More detail.

290
00:50:04.620 --> 00:50:05.580
dong su: But five minutes left.

291
00:50:06.210 --> 00:50:06.930
Jonathan Feng: Okay, thanks.

292
00:50:08.250 --> 00:50:08.580
Jonathan Feng: Perfect.

293
00:50:08.610 --> 00:50:12.360
Jonathan Feng: So we can do this in a bit more detail. And so that's what I've sort of

294
00:50:13.320 --> 00:50:22.050
Jonathan Feng: outlined here. Okay. And there was actually homework on this slide. I've only got one homework problem. And this entire lecture. But if you want to sort of see if

295
00:50:22.590 --> 00:50:35.160
Jonathan Feng: You get what's going on here. I strongly suggest you do this little exercise. So what is the exercise. So what we'll do is investigate what is this dark sector with the dark you want in it before you

296
00:50:36.780 --> 00:50:40.800
Jonathan Feng: Okay, so we're going to do this again now with some equate to a little bit more carefully.

297
00:50:42.960 --> 00:50:51.360
Jonathan Feng: So we have again the same setup. I'm gonna visible sector with the photon a dark sector with another photon to you and controls on

298
00:50:53.520 --> 00:51:05.250
Jonathan Feng: Which has a mass case. I didn't tell you about that, but it has a mass. So it's broken to see when is broken out of it. And so these are the terms on engine. So here is the kinetic energy of our standard photon.

299
00:51:06.600 --> 00:51:09.840
Jonathan Feng: Here is the kinetic energy of the dark photon thing.

300
00:51:10.920 --> 00:51:13.380
Jonathan Feng: And then it has a mass. OK.

301
00:51:14.790 --> 00:51:25.110
Jonathan Feng: And then we're going to envision that there is something that mediates a connection between these two. This operator afternoon from the visible side times f mean you from the dark side.

302
00:51:27.300 --> 00:51:27.990
Jonathan Feng: Now,

303
00:51:29.910 --> 00:51:30.630
Jonathan Feng: This

304
00:51:31.860 --> 00:51:37.080
Jonathan Feng: You know, you kind of know what this is going to do you have a visible sector or the photon that propagates

305
00:51:37.590 --> 00:51:44.010
Jonathan Feng: You have a duck sector with photonic profits and then these next which kind of means that the photon could turn into a dark for tennis moving along.

306
00:51:44.670 --> 00:51:51.390
Jonathan Feng: Well, that's not really the right way to look at it, right, the right way to look at it is to read and analyze this thing eliminate this mixing term.

307
00:51:51.870 --> 00:52:01.800

Jonathan Feng: by redefining fields so that you end up with canonical kinetic parents with just one particles FF here another particles FF here and know mixing

308
00:52:02.940 --> 00:52:05.940
Jonathan Feng: And so I'd encourage you to try this. And this is really

309
00:52:06.990 --> 00:52:13.080
Jonathan Feng: The work of Bob hold them in 1986 so you can look at the classic proton paper if you're not aware of it.

310
00:52:14.310 --> 00:52:26.610
Jonathan Feng: For help in reading redefining these fields to read agonizes and you can also go to the appendix of this paper where it's done in gory detail. Definitely not the first time, but it's kind of a nice

311
00:52:27.750 --> 00:52:30.480
Jonathan Feng: Has all the notes, you'll ever need. If you want to see how to do this.

312
00:52:32.640 --> 00:52:46.140
Jonathan Feng: This will be very instructive. Because what you'll find that is the end the end the physical states are a mass plus Standard Model Alpha Gamma and a massive quote dark photon which is typically a prime

313
00:52:47.460 --> 00:53:05.010
Jonathan Feng: And you might not think that's amazing. But it kind of is. I mean, here we have a mass of the time you're now going to mix this dark you one will be standard mile you one. And you might think that this mass will now get spread over both particles. And so instead of

314
00:53:06.030 --> 00:53:19.290
Jonathan Feng: Having mixing and only one massive particle, you're going to have no mixing, but now to massive particles. And the fact is that no it's not true, you end up with still one masters photon which is a darn good thing, because of course our photon is mass was

315
00:53:21.150 --> 00:53:31.620
Jonathan Feng: The other thing you're going to find is this very interesting fact that when you get this in the physical basis the photon this gamma does not couple the Star Trek sector particles.

316
00:53:32.520 --> 00:53:37.800

Jonathan Feng: So, you know, this dark matter might be sort of like a dark electron over here which couple. So this whole time.

317
00:53:38.610 --> 00:53:48.540
Jonathan Feng: Then when you mix this up. We do some sort of, you know, an orthogonal transformation. You might think that all of a sudden, then this photon here is now going to talk to

318
00:53:49.050 --> 00:53:57.900
Jonathan Feng: This dark electron. And what you'll find is that that's not actually true. The photon our standard photon. Not only does it remain mass list.

319
00:53:58.410 --> 00:54:10.770
Jonathan Feng: But it doesn't talk to all the dark sector matter, which is also a good thing because that would lead to extremely tight bounds. If there was sort of photons propagating along and banging into dark stuff. So, you know,

320
00:54:12.600 --> 00:54:21.450
Jonathan Feng: The other hand, there is this new partner called the dark photon. A prime and this that brought on a prime does talk to our standard particles.

321
00:54:22.500 --> 00:54:33.690
Jonathan Feng: And it talks to it with a coupling, which is given here, where he QF is just the standard model charge of this F for me on so forth. Electron it's minus one.

322
00:54:35.100 --> 00:54:51.780
Jonathan Feng: But multiplied by this epsilon or this epsilon is very similar to not identical to but very similar to this epsilon. Basically, there's a little bit of mixing between these two sectors that manifests itself in the dark photon having a little coupling to electrons and clocks in our world.

323
00:54:54.030 --> 00:54:58.080
Jonathan Feng: And this is a good thing, because then, this is how we can actually detect this thing and remember

324
00:54:58.620 --> 00:55:12.630
Jonathan Feng: This epsilon is typically lead generated. So 10 to the minus three maybe to loop temporary Academy six. So this is a small coupling, but it's not you know negligible. It's like a million tires for a company and it happens is some hope we can find this thing.

325
00:55:15.810 --> 00:55:26.910
Jonathan Feng: Okay, so that was the dark photon which is sort of the poster child of the sort of dark sector theories. The dark photon is called the portal particle

326
00:55:27.480 --> 00:55:40.020
Jonathan Feng: Because it's connecting the standard model and the dark sector, right. So, you know, talks to us over here, but it also of course talks to the dark electrons on this side. So it kind of immediate

327
00:55:41.670 --> 00:55:43.170
Jonathan Feng: Reactions between these two.

328
00:55:44.640 --> 00:55:58.890
Jonathan Feng: So that's the name portal particle. And now that we've had some success with that we can look for other portal particles mainly other dimension for interactions that are sort of be the most likely are the leading interactions between this data model and the dark side.

329
00:56:00.150 --> 00:56:06.270
Jonathan Feng: And so this is a little exercise. You can also do you go to the standard model and find

330
00:56:06.720 --> 00:56:15.720
Jonathan Feng: What sort of ways can I hook up the Standard Model interaction but just gauging grain satisfies all the necessary conditions to a dark

331
00:56:16.530 --> 00:56:22.800
Jonathan Feng: You know, operator, such that I keep Matthew mentioned four or less, but for

332
00:56:23.790 --> 00:56:30.450
Jonathan Feng: And so you'll find that if you are going to put in the spin one particle into here. There's only one way to do it. That's the dark photon which we did

333
00:56:31.440 --> 00:56:39.000
Jonathan Feng: And that couples standard model for Amiens would suppress couplings to the dark photon with this charge I talked about just in the last slides.

334
00:56:40.710 --> 00:56:49.020

Jonathan Feng: There's two other common ways to do it. If you're going to consider spin zero stay in a mile articles or spend zero dark particle

335
00:56:49.680 --> 00:56:59.550
Jonathan Feng: There's this for scale or operator or this is the standard model hates. And so you can have a staggered Higgs and then five dagger five or five is a duck sailor.

336
00:57:00.330 --> 00:57:06.600
Jonathan Feng: And this thing that will emerge is a dark takes balls on a couple of sustainable model for me and

337
00:57:06.990 --> 00:57:13.230
Jonathan Feng: But with this interesting you call a coupling because it's inherited from the fact that it's getting to that stage, Mr Hicks coupling.

338
00:57:14.160 --> 00:57:27.360
Jonathan Feng: And then you can say, well, what if I put a premium on in the tech sector. Can I do it. And there's one other way to do it and that is this Higgs Santa Monica left hand double and then the dark from you.

339
00:57:28.380 --> 00:57:39.990
Jonathan Feng: And this is emerging in this very sort of dark secret shut away, but he look at this, you guys go I knew all about this all along. This is the stair on your trainer.

340
00:57:40.590 --> 00:57:47.670
Jonathan Feng: This is typically, you know, h i n, l, m, right. This is the gate total gauge singlet and, you know,

341
00:57:48.240 --> 00:57:59.910
Jonathan Feng: And this is the only trainer here. We call it for me. And it's awesome literature, called the heavy neutral laptop, but basically this thing. Then mix of the standard money pre nose and also have some suppress mixing

342
00:58:01.770 --> 00:58:13.710
Jonathan Feng: Bottom line is, though, that then they're sort of free portal particles that emerge from this sort of analysis that quote on tracks Higgs Boson stay on the trainers and we can now go and trying to figure out what they do.

343
00:58:15.210 --> 00:58:26.730

Jonathan Feng: So I think I'm bad at a time. So let me just say the following. What we're going to do next is we have it will take me out of time, so

344
00:58:30.420 --> 00:58:32.850
dong su: Yes, I think you're out of time, so maybe

345
00:58:32.880 --> 00:58:33.120
Okay.

346
00:58:35.460 --> 00:58:46.050
Jonathan Feng: Good. So let me just say, sort of a preview what we're going to do next, we have now these portal particles and what we can do is try to figure out what kind of parameters.

347
00:58:47.310 --> 00:58:47.820
Jonathan Feng: Are

348
00:58:48.870 --> 00:59:01.830
Jonathan Feng: You know, once we should probably and it turns out that there's a kind of a favorite region and parameter space where the mass of these protocols and maybe the GV and the coupling is my cord, Emily.

349
00:59:02.880 --> 00:59:06.510
Jonathan Feng: And what I will do then is sort of go through

350
00:59:07.680 --> 00:59:18.540
Jonathan Feng: Some of the reasons this is a particularly interesting part of the parameter space and then discuss the zoo of possible ways to probe them in the next lecture this sort of whet your appetite.

351
00:59:20.130 --> 00:59:22.980
Jonathan Feng: You know, you see plots like this.

352
00:59:24.810 --> 00:59:30.480
Jonathan Feng: Talking about how to probe dark photon parameter space where every one of these is any experiment proposal.

353
00:59:31.170 --> 00:59:47.220
Jonathan Feng: And I'm certainly not going to go through each one of these in detail. But what I've tried to do is give you kind of a broad brush understanding of the general shapes of these contours and the general requirements of experiments to to say something interesting about these tech sectors.

354
00:59:48.390 --> 00:59:49.740
Jonathan Feng: But that's next time. So I stopped playing

355
00:59:52.020 --> 00:59:56.490
dong su: Defense very much Jonathan so very nice collector. So turn over to Tom

356
00:59:58.530 --> 01:00:00.030
thomas rizzo: Thanks a lot. JOHN AND THAT WAS GREAT.

357
01:00:01.260 --> 01:00:06.390
thomas rizzo: Okay, here's a few questions. Let's start on slide 12

358
01:00:10.680 --> 01:00:20.370
thomas rizzo: While you're getting there for the windless miracle. Do we need some amount of fine tuning in the dark sector. If you want to get the relic density. Right.

359
01:00:22.740 --> 01:00:44.370
Jonathan Feng: So, you know, in some sense, you always need some fine tuning, right, because if you're just out in mass coupling parameter space, you could be anywhere in this plane and and what's the chance that you just happened to get on that line within the experimental bounds with her, you know, 1%

360
01:00:45.390 --> 01:00:49.590
Jonathan Feng: So in that sense, yeah. You need some time to but

361
01:00:51.150 --> 01:01:08.370
Jonathan Feng: In some sense, there's no greater fine tuning. Well, I mean wings. I'll send you the fine tuning tip right so everything I've talked about here is sort of order of magnitude dimensional estimates, you actually want to get exactly right. And again, given that the blood density is known 2%

362
01:01:09.510 --> 01:01:15.360
Jonathan Feng: You have to always find something. And so it's going back kind of that kind of

363
01:01:16.410 --> 01:01:17.580
Jonathan Feng: fine tuning. Yeah.

364

01:01:19.200 --> 01:01:21.600
Jonathan Feng: I should say there are some theories were

365
01:01:22.620 --> 01:01:32.640
Jonathan Feng: Actually this behavior. The fact that g is related to em in this particular way comes out of the theory. So in particular,

366
01:01:33.600 --> 01:01:42.930
Jonathan Feng: Gave me scenarios anomaly media supersymmetry scenarios. They actually the mass of these new particles is actually generated by gauging our actions.

367
01:01:43.380 --> 01:01:56.520
Jonathan Feng: And so it actually comes up that was proportional to d squared. And so you follow this line, some time, naturally, but barring, something like that, some structure like that. Yeah, you need a little thing to do, but nothing more than you'd need for when salsa.

368
01:01:58.800 --> 01:01:59.910
thomas rizzo: Okay, great things.

369
01:02:01.020 --> 01:02:02.340
thomas rizzo: And slide 16

370
01:02:03.480 --> 01:02:10.350
thomas rizzo: Can you describe a little more how the ultra high energy cosmic rays could be used for the protection

371
01:02:12.030 --> 01:02:19.020
Jonathan Feng: Yeah, so this is a fascinating area, which probably could see, you know, hasn't been fully plumb yet.

372
01:02:20.160 --> 01:02:20.730
Jonathan Feng: So,

373
01:02:22.200 --> 01:02:38.640
Jonathan Feng: Okay, the basic fact is that, you know, we have TP collisions going on in our upper atmosphere better at center mass energies, not just energy center mass energies way above the LLC. So as you might know these are trying to the cosmic rays.

374
01:02:39.870 --> 01:02:50.370

Jonathan Feng: Some of them have energies of tend to the team tentative 20 EV, and so the center mass energies are sort of like in the P or hundred TV region.

375
01:02:51.840 --> 01:02:58.710
Jonathan Feng: So you have the energy and the question then is, what do you do with it. And you could say, for example, you could

376
01:03:00.180 --> 01:03:00.600
Jonathan Feng: Have

377
01:03:02.820 --> 01:03:08.190
Jonathan Feng: Was just give an example you have ultra high energy neutrinos to so you could have a neutrino.

378
01:03:08.790 --> 01:03:20.820
Jonathan Feng: Come in and just making up stuff here. But you could have a neutrino come in and hit a proton and the atmosphere so new Q cork goes to say slept on score.

379
01:03:21.600 --> 01:03:36.510
Jonathan Feng: Okay, you could make supersymmetric interaction, like that. And then that slept on eventually what the k to the dark matter, but it might take a while. As I mentioned, and the slack time then could just streamed through, you know, Ice Cube, or something like that.

380
01:03:38.070 --> 01:03:57.390
Jonathan Feng: So that's what I'm talking about. You can basically use paltry handy cosmic rays to be your particle collider. And then you just need to figure out some distinctive signature of them that you know that you could actually see had a cosmic ray detector. So ice cube or PR OJ.

381
01:03:59.070 --> 01:04:01.530
Jonathan Feng: You know park or something like that.

382
01:04:02.790 --> 01:04:09.930
Jonathan Feng: That's a possible way to sort of look for dark matter production or at least start executive production in not 100% increase

383
01:04:15.420 --> 01:04:19.290
thomas rizzo: Okay, thanks. I'm on slide 19

384
01:04:20.670 --> 01:04:22.380
thomas rizzo: You said that there is a

385
01:04:23.550 --> 01:04:25.470
thomas rizzo: There's a su to symmetry.

386
01:04:26.550 --> 01:04:37.980
thomas rizzo: relating them them making the masses of these the wino all it's all the same. And then eventually it's broken, what what motivate motivate the value of 160 MTV.

387
01:04:39.180 --> 01:04:42.540
Jonathan Feng: Okay, yeah. So this is a fascinating story.

388
01:04:44.100 --> 01:04:50.790
Jonathan Feng: So those are you familiar with supersymmetry. Now there's track Gino and neutralino mass matrix.

389
01:04:51.750 --> 01:04:59.970
Jonathan Feng: And this has some parameters in it. Actually, they're giving here. Well this one's for him to that we, you know, mass. And down here. There's a view which is the Higgs, you know, mass

390
01:05:00.690 --> 01:05:08.730
Jonathan Feng: And so there's this you know mass matrix, he died he buys it you can find the masses of these two guys and you can take the difference and you find the mass difference

391
01:05:09.990 --> 01:05:17.460
Jonathan Feng: It turns out that the tree level mass difference is extremely small. It's like, you know, one and maybe or something.

392
01:05:18.660 --> 01:05:29.700
Jonathan Feng: And that depends where you are in this parameter space so that you know you wouldn't get a solid value for that. But the dominant piece is actually a loop level of contribution, basically.

393
01:05:30.690 --> 01:05:39.660
Jonathan Feng: Kind of the fact that the charge Gino has charged and so couples two photons is a little full time diagram for the star Gina that's missing for the neutral, we know

394
01:05:40.530 --> 01:05:54.270
Jonathan Feng: And it turns out that that loop level splitting is what dominate and that's turns out to be no is 160 MTV. And so that's why throughout this plane. This number is pretty constant

395
01:05:55.290 --> 01:06:06.840
Jonathan Feng: More than you might think. Because the tree, level one was very is a lot is sub dominant and the loop level 160 and maybe it's just big enough for you to barely making a travel plan.

396
01:06:11.280 --> 01:06:11.610
thomas rizzo: Great.

397
01:06:12.660 --> 01:06:13.890
thomas rizzo: On slide 26

398
01:06:15.750 --> 01:06:19.740
thomas rizzo: Is FB new the electromagnetic tensor for the dark photon.

399
01:06:20.640 --> 01:06:24.900
thomas rizzo: I assume. Yeah, I mean, I assume. Amen. Definitely with the label. I don't know.

400
01:06:25.260 --> 01:06:26.040
Jonathan Feng: Yeah, that's right.

401
01:06:26.370 --> 01:06:35.340
thomas rizzo: Yeah. Could you please explain how this interaction turn, leads to the fireman diagram of the one coupling of the Standard Model photon that the dark one.

402
01:06:38.430 --> 01:06:39.450
Jonathan Feng: Okay, so

403
01:06:40.680 --> 01:06:46.350
Jonathan Feng: So the answer is yes. So this afternoon. You is just the field strength tend to have the standard

404
01:06:47.670 --> 01:06:53.190
Jonathan Feng: Standard Model photon are full time. Okay. And then there's FDA new do is

405
01:06:54.510 --> 01:07:07.890
Jonathan Feng: The same thing for the UN dark quote unquote photo right. The one bows and the director. And so, you know, just the usual del mew a new or a new is the dark

406
01:07:09.630 --> 01:07:09.840
Jonathan Feng: Side.

407
01:07:11.100 --> 01:07:16.140
Jonathan Feng: And so what you do is then you simply can write down this

408
01:07:17.910 --> 01:07:18.900
Jonathan Feng: This loop diagram.

409
01:07:19.980 --> 01:07:26.340
Jonathan Feng: And sometimes integrate out the same in this case and maybe the Furman that's in the center of this loop.

410
01:07:27.450 --> 01:07:43.830
Jonathan Feng: And what that will do is that will generate for you this afternoon. You know where that have, you know, both we have speed of being on this visible side on the dark side because you have a photon coming and decide in a dark photon coming in this side he generated this cross trim.

411
01:07:45.420 --> 01:07:46.140
Jonathan Feng: And so

412
01:07:47.370 --> 01:07:57.570
Jonathan Feng: Yeah, I guess maybe I can refer you to some of the original papers particular Bob Holden's classic paper which made this a lot. You can take a look there and you can even find

413
01:07:59.280 --> 01:08:05.220
Jonathan Feng: How this parameter here is a function of the various massive that might go into this diagram.

414
01:08:09.720 --> 01:08:12.090
thomas rizzo: Okay, great. Um, the next slide.

415
01:08:13.680 --> 01:08:21.750
thomas rizzo: Why is it a good guess that the dark sector has its own you one symmetry is you one favorite over other gauge groups for some reason.

416
01:08:22.680 --> 01:08:24.270
Jonathan Feng: Okay, that's a good question. So

417

01:08:26.250 --> 01:08:37.350
Jonathan Feng: This is just an assumption. Okay, so we just assume this has a UN in it and see what happens. And we see this can be generated. It's very special. That is true. Because if you had

418
01:08:38.370 --> 01:08:53.040
Jonathan Feng: You know, su to instead. Then you know that the usual way to write this F F term is there's an FPS to a FEMA or a or a summer's over, you know, one, two, and three. Right.

419
01:08:53.640 --> 01:09:06.870
Jonathan Feng: Because that's all you need for the SEC to gauge. And so basically, then in that case you can't write down this coupling for su to for you and is very special in that you can have something that's

420
01:09:08.100 --> 01:09:11.970
Jonathan Feng: Cage and gray on one side, engage the great the other side and

421
01:09:13.620 --> 01:09:15.330
Jonathan Feng: combine them together and get this thing.

422
01:09:16.650 --> 01:09:17.610
Jonathan Feng: So that's why

423
01:09:18.900 --> 01:09:20.190
Jonathan Feng: We do it.

424
01:09:21.630 --> 01:09:26.430
Jonathan Feng: Is there any reason to think that the dark sector has a UN in it and not anything else.

425
01:09:27.990 --> 01:09:39.180
Jonathan Feng: Not particularly. Other than the fact that, you know, it's possible. And also, I should say that, you know, if the director had a you know when su 500 or something.

426
01:09:39.600 --> 01:09:51.540
Jonathan Feng: But eventually, it broke down to a UN just like in our case it could have been that way that you and will suffice. Also, right. So it's not like it has to have only you and all the way up to high energies.

427
01:09:52.950 --> 01:09:59.430

Jonathan Feng: If it's got a guide or something, but eventually it breaks and there's a human factor, then that you when can be used here. Okay.

428
01:10:00.570 --> 01:10:10.110
Jonathan Feng: So, so it's not you know definitely there, but it's not to specialty there that the ultimate answer though, really, is that, in some sense, I've done this thing.

429
01:10:10.110 --> 01:10:12.480
Jonathan Feng: Backwards. Right. What I wanted to do.

430
01:10:12.540 --> 01:10:13.410
Jonathan Feng: Is give you

431
01:10:13.590 --> 01:10:21.240
Jonathan Feng: An example worked out where you could really see how this works. But once you see it, this is really the logic is really the logic is

432
01:10:21.720 --> 01:10:22.710
Jonathan Feng: That we find that

433
01:10:23.070 --> 01:10:28.260
Jonathan Feng: Sort of. We want to figure out what are the dominant ways that the Standard Model contract with the tech sector.

434
01:10:28.920 --> 01:10:37.050
Jonathan Feng: And in most ways when we write down an operator, it will be suppressed by some giant mass presumably giant mass

435
01:10:37.500 --> 01:10:42.360
Jonathan Feng: And we'll have to assume that that mass is not too big so that we can you know see this connection.

436
01:10:42.690 --> 01:10:48.750
Jonathan Feng: And of course the mass, not too big. Well, then I might have been excluded by existing limits and so then we run into all sorts of trouble.

437
01:10:49.410 --> 01:10:56.610
Jonathan Feng: Then the thing here is that we can be led by this organizing principle. We're going to look for be normalized but cufflinks.

438
01:10:57.060 --> 01:11:06.150
Jonathan Feng: Because probably. Those are the dominant ones in any way. It's nice to sort of pair our possibilities down, we can't look for an infinite number of different interactions.

439
01:11:06.480 --> 01:11:17.250
Jonathan Feng: So let's think what just one of the favorite ones and this we normalize ability gives us a sort of a logic rationale for simplifying our life and we lead them to the sort of three.

440
01:11:18.660 --> 01:11:28.800
Jonathan Feng: Three possibilities. And in that case, it turns out that this one only works if this is a UN spin one gauge cosine. So that's really the rationale

441
01:11:30.300 --> 01:11:39.660
Jonathan Feng: But, you know, in some ways, what I want to do is provide a guide to the literature and what you'll find is that when people evaluate accelerator probes of sectors.

442
01:11:40.770 --> 01:11:43.440
Jonathan Feng: Basically this is universally the case that

443
01:11:44.790 --> 01:11:45.690
Jonathan Feng: What we do is

444
01:11:46.290 --> 01:11:50.070
Jonathan Feng: We analyzed the experiments ability to probe these three

445
01:11:50.070 --> 01:11:50.670
dong su: Scenarios.

446
01:11:51.090 --> 01:11:52.200
Jonathan Feng: And so this is why

447
01:11:57.840 --> 01:11:59.280
dong su: I think we're out of time now.

448
01:12:03.780 --> 01:12:04.890
thomas rizzo: Thanks a lot, Jonathan.

449
01:12:05.520 --> 01:12:08.670

Jonathan Feng: Okay, thank you. See you tomorrow.

450
01:12:10.110 --> 01:12:18.270
dong su: Thanks a lot. Thanks. Jonathan and all the lectures for today. And so we're gonna stop recording and today's session and see everyone small