WEBVTT

1
00:00:00.000 --> 00:00:00.480
charlie young: Everyone

2
00:00:04.290 --> 00:00:05.339
charlie young: Welcome everyone.

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00:00:06.839 --> 00:00:16.800
charlie young: We have the will start today with the third lecture from Tim Tate on dark matter and dark sector theory. So, Tim.

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00:00:18.240 --> 00:00:18.690
Tim Tait: All right.

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00:00:18.779 --> 00:00:20.160
Tim Tait: Thank you very much. It's

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00:00:20.520 --> 00:00:26.100
Tim Tait: Nice to be here again I really wish I was actually seeing you all in person. But this is the era that we live in.

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00:00:27.120 --> 00:00:28.110
Tim Tait: So,

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00:00:30.960 --> 00:00:36.450
Tim Tait: Alright, so this is the third and final lecture about the theory of dark matter and dark sectors.

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00:00:37.050 --> 00:00:45.690
Tim Tait: As a recap of what we've done so far on the first day we talked about some preliminaries and how to build a theory of dark matter that looks like it has a chance of describing dark matter.

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00:00:46.440 --> 00:00:55.470
Tim Tait: We talked about how dark matters produced in the early universe. And then, yesterday we finished up some of those topics and moved on to talk about specific theories of dark matter.

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00:00:56.340 --> 00:01:03.030
Tim Tait: In particularly we spent a lot of time talking about supersymmetry, which is of course the most fleshed out and best understood theory of dark matter that we have

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00:01:03.870 --> 00:01:12.990
Tim Tait: And I think if you were to take a poll. It may still be the most popular though I think other ideas are also very exciting and get a lot of attention as well.

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00:01:13.560 --> 00:01:20.280
Tim Tait: Today we're going to finish up talking about specific theories of dark matter, talk about theories of dark sectors and that'll be the end of these lectures.

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00:01:22.440 --> 00:01:34.650
Tim Tait: So just to recap what we did yesterday. They're actually very many specific detailed models of dark matter. They range from theories designed to solve other mysteries two theories for which dark matter is the principal reason for it to exist.

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00:01:35.160 --> 00:01:40.080
Tim Tait: supersymmetry. Well, often maligned these days. And we even got a question that kind of revealed that yesterday.

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00:01:40.590 --> 00:01:46.140
Tim Tait: Is an interesting theory which easily accommodate a wimp or freeze out relic and other words, which is typically a neutralino

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00:01:46.620 --> 00:01:59.550
Tim Tait: It specific properties are highly dependent on a complicated parameter space and we saw a little bit about how people deal with that issue. And there's a rich program of particle physics experiments that can access a wide swath of supersymmetric parameters space.

18
00:02:01.020 --> 00:02:01.830
Tim Tait: So,

19
00:02:03.450 --> 00:02:05.940
Tim Tait: We're going to talk about a couple other theories and these are not

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00:02:07.290 --> 00:02:11.880
Tim Tait: These are chosen to be a little different than supersymmetry some particular let's start talking about the accion

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00:02:12.480 --> 00:02:19.380

Tim Tait: Now the accion is another particle whose existence was proposed really independently of need for dark matter. In fact, it was posed.

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00:02:20.070 --> 00:02:27.240
Tim Tait: Back before we really understood that we needed a large amount of dark matter in the universe. It's instead motivated by the strong CP problem.

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00:02:27.750 --> 00:02:35.460
Tim Tait: The strong CP problem, which unfortunately don't have time to go through in great detail, but I guess you have lectures with accion, the more specifically that may talk about

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00:02:36.360 --> 00:02:46.650
Tim Tait: This a little bit more is basically the problem that if I write down the QC do a garage in the garage and describes a strong nuclear force there are terms in it which violate

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00:02:47.700 --> 00:02:56.580
Tim Tait: CP charge conjugation and parody and they would predict that the neutron should get an electric dipole moment. So over here, the plot that you see.

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00:02:57.210 --> 00:03:05.940
Tim Tait: shows you a history of measurements of the neutron EDM and also plot. It is the pink band is sort of the range that you'd expect if you just wrote down

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00:03:06.660 --> 00:03:17.310
Tim Tait: Using just dimensional analysis order one parameters and the QC Lagrangian. So you can see that from the very beginning, it was clear that the measurements were far below what they were expected, but even a factor of 1000

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00:03:17.850 --> 00:03:23.130
Tim Tait: And nowadays. These experiments have gotten down to the point where they're like 10 orders of magnitude smaller than they should be.

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00:03:24.540 --> 00:03:34.650
Tim Tait: So the parameter that describes the CP violation in the QC Lagrangian in some normalization should be something like 10 to the minus 10 and that seems like it's too small to be just an accident.

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00:03:35.820 --> 00:03:40.920

Tim Tait: So the accion is introduced as part of the pitch a Quinn mechanism, which was invented there at slack.

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00:03:42.120 --> 00:03:51.480
Tim Tait: To solve the strong CP problem by introducing a new field, which actually compensates for that term in the Lagrangian and makes it effectively zero just through dynamical arguments.

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00:03:52.470 --> 00:04:00.450
Tim Tait: For our purposes. The important thing is that leaves behind the quantum field that's right quantum particles from every quantum field has expectations which are particle

33
00:04:01.080 --> 00:04:13.560
Tim Tait: And that's the particle that we've all the accion its mass and coupling are determined as part of the way that the theory is constructed. It's a pseudo Goldstone, both on if you know what that means. If you don't, it's not really that important for this discussion.

34
00:04:14.940 --> 00:04:19.020
Tim Tait: It just means that it's interactions scale like energy and momentum and

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00:04:19.560 --> 00:04:24.450
Tim Tait: They're all higher dimensional interactions and they're characterized by some energy scale, which is very large.

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00:04:24.840 --> 00:04:32.370
Tim Tait: So the accion decay constant F survey is got to be greater than 10 to the nine GV or I run into problems from astrophysical bounce.

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00:04:32.790 --> 00:04:41.520
Tim Tait: Basically stuff in the universe would lose too much energy by cooling by admitting axioms. The accion mass is predicted by virtue of its connection to Q CD.

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00:04:42.030 --> 00:04:49.200
Tim Tait: It's actually very roughly given by something like the ratio of the pile on decay constant which you might know is something about point one GB

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00:04:49.740 --> 00:04:58.950
Tim Tait: Divided by the accion decay constant, we just mentioned, and then times the pie on mass. So if you put all that together, you get masses that are really, really tiny on the scale of particle physics.

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00:04:59.670 --> 00:05:06.720
Tim Tait: It's unstable. It has an interaction with two photons, but because it has a very tiny mass and because the coupling, which is characterized by FCA

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00:05:07.590 --> 00:05:16.710
Tim Tait: Is so weak basically its lifetime is so long that it lives much, much longer than the age of the universe. So as of now, we should have expected to see no accion sticking

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00:05:18.030 --> 00:05:24.360
Tim Tait: More generally, actually string theories and other beyond the standard model theories often contain accion like particles which are long lived

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00:05:24.810 --> 00:05:33.810
Tim Tait: And could play the role of dark matter, but of course they have less tight correlation between masters and couplings because they're not really introduced to solve a specific problem, like the QC accion is

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00:05:34.530 --> 00:05:41.370
Tim Tait: And some of the original references are listed here on the on the slide. They're actually very well written. Some of them are very good places to work.

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00:05:43.590 --> 00:05:44.280
Tim Tait: So,

46
00:05:45.630 --> 00:05:56.880
Tim Tait: accion has a model dependent coupling to the electromagnetic field. It's a little bit smaller than one over that the scale F's today, but I've written down what what Rajan term here at the top of the slide.

47
00:05:57.360 --> 00:06:01.860
Tim Tait: So I have the coupling constant one over f. And then the accion field multiplied by

48
00:06:02.340 --> 00:06:13.290
Tim Tait: The electromagnetic field strength contracted with it's doable. And if you turn this back into the ordinary language of Jackson e&m you get something that looks like an accion coupling to the electric field and the magnetic field.

49

00:06:14.040 --> 00:06:22.680
Tim Tait: So in order to do things with accion you want to invoke both and electric and magnetic field. The one of them could be the initial state and one of them could be in the final state.

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00:06:23.310 --> 00:06:32.430
Tim Tait: So there's actually a very rich and very program of accion searches based on this coupling. So one particular search looks for the ambient accion that is the axioms that make up the dark matter.

51
00:06:33.030 --> 00:06:40.050
Tim Tait: converting into electromagnetic signals in the presence of a strong background magnetic field, right. So the idea is I use this interaction.

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00:06:40.590 --> 00:06:48.990
Tim Tait: By setting up a strong magnetic field. The accion comes in, it turns it self into an electric field. And then I looked for the effect of the electric field that produced

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00:06:49.830 --> 00:07:00.420
Tim Tait: You can see some of the experiments that have been running plotted here in this plot as a function of the accion mass, which will notice is naturally expressed in micro Ed.

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00:07:01.110 --> 00:07:10.680
Tim Tait: And it's coupling the photons is on the Y axis, you can see that there are bounced from white dwarfs and supernovas that control.

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00:07:11.160 --> 00:07:18.870
Tim Tait: That restrict the parameter space. If the coupling is too large. And then there are experiments like the DMX detector.

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00:07:19.380 --> 00:07:26.250
Tim Tait: Which have got limits where it searches for axons and so far hasn't actually discovered in the axons converting themselves in the magnetic field.

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00:07:26.850 --> 00:07:36.240
Tim Tait: And the range, you expect from a QC accion is shown here as this band in purple lines. And you can see that there are plans to go to even

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00:07:36.960 --> 00:07:44.400

Tim Tait: Cover even more of the parameter space. There's actually a lot of other ideas searching for axioms is a very active area of theoretical research.

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00:07:45.240 --> 00:07:48.780
Tim Tait: I think you're going to have a whole lecture about it. So I'm not going to spend much time about it right now.

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00:07:49.500 --> 00:08:00.120
Tim Tait: But there are very interesting new ideas, looking for, like, things like the time variation of the neutron electric dipole moment or an induced current and an LLC circuit produced by axioms.

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00:08:03.810 --> 00:08:09.270
Tim Tait: Another interesting alternative to dark matter that doesn't look like a wimp would be a sterile neutrino.

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00:08:09.780 --> 00:08:15.150
Tim Tait: So I suspect that this was discussed somewhat in both Andre and Scott's lectures that you've already had.

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00:08:15.780 --> 00:08:24.150
Tim Tait: Dark matter might be connected to the other mystery of the Standard Model neutrino masses, we require physics beyond the standard model to explain neutrino masses.

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00:08:24.720 --> 00:08:31.530
Tim Tait: And I would say the leading theory of how that happens is the seesaw mechanism and you can understand that by looking

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00:08:31.920 --> 00:08:39.060
Tim Tait: At this diagram that I've shown here at the top of the slide where you see two neutrinos to left on double. It's really coming in.

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00:08:39.420 --> 00:08:46.650
Tim Tait: The couple to do Higgs doublets. But there needs to be something that can bridge between the two sides of the diagram, that would be a firm eon

67
00:08:47.340 --> 00:08:55.410
Tim Tait: Right, because it's connecting another for me on and it goes on. It has no standard model charges and so therefore it has the charges or right handed neutrino.

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00:08:56.100 --> 00:09:02.460
Tim Tait: So this particle, you know, of course, there are other ways of realizing the Juno mass. So this is not necessarily the way nature works.

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00:09:03.390 --> 00:09:18.360
Tim Tait: But this is a very attractive way for it to work. And so we would have to add new fields to our theory, the right hand of your Trina fields. It's actually not clear how many of them, you need at least one but very likely there would be more just like there are more neutrinos themselves.

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00:09:20.040 --> 00:09:30.240
Tim Tait: If these additional states are light and not very strongly mixed with active neutrinos. And that's actually a requirement because we have precision data about neutrinos from things like

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00:09:30.780 --> 00:09:39.090
Tim Tait: SLC and left. And they basically tell us that we can't have any light active neutrinos that are strongly. Next, we would have seen them in our experiments.

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00:09:40.080 --> 00:09:46.110
Tim Tait: Then they would be stable on the scale of the age of the universe and other words they will decay, but they want to keep fast enough, just like the accion

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00:09:46.560 --> 00:09:56.970
Tim Tait: And they could play the role of dark matter. So arriving at the right amount of dark matter via neutrino oscillations and the early universe typically requires delicately choosing the massive and mixing angle.

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00:09:57.360 --> 00:10:04.350
Tim Tait: Or invoking some other new physics. And you can see a plot of the parameter space here and I'm not going to go through in great detail. But you see the massive the neutrino.

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00:10:05.220 --> 00:10:13.410
Tim Tait: Is on the x axis looks like it actually got cut off. But what's plotted on the y axis is the mixing angled between the active in the sterile neutrino.

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00:10:14.280 --> 00:10:25.710
Tim Tait: And you can see different predictions for for where you would get the right relic density as these colored lines that make different assumptions about other properties of the universe and also shown our

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00:10:26.790 --> 00:10:33.840
Tim Tait: Constraints that have been flooded here at about one ke VI and below where the neutrinos are to light and they wouldn't form galaxies, the way we expect

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00:10:34.230 --> 00:10:42.870
Tim Tait: There are some constraints, looking from X rays, which I'm going to talk about on the next slide is showing us the red region that's constrained. And so you have to live in this sort of white a sliver

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00:10:44.100 --> 00:10:52.620
Tim Tait: So in other words, masses between about one KGB, and maybe up to a few 10s of kV and mixing angles that are really very tiny somewhere around 10 to the minus 10 or so.

80
00:10:55.890 --> 00:11:06.690
Tim Tait: All right, so still neutrinos actually decay, like I just said. So for example, the five and diagram, you see here on the lower left shows you how you can have a sterile neutrino come in.

81
00:11:07.530 --> 00:11:14.430
Tim Tait: Interact with through a loop of who zones and leptons and end up producing an ordinary active neutrino.

82
00:11:15.210 --> 00:11:30.690
Tim Tait: Right, which would have to be lighter. We know their masters or less than an EV, much less than anybody and a photon. So this decay process will happen, but because it's a loop diagram because it involves week interactions, because the the startling Trina was so light, it probably

83
00:11:31.950 --> 00:11:37.530
Tim Tait: Would be slow enough, at least for the mixing angles. We're talking about that you wouldn't expect it to happen yet.

84
00:11:37.890 --> 00:11:47.430
Tim Tait: However, if it's happening. Slowly, then you'll be able to observe the gamma ray that's being produced, just like the case of the gamma ray lines from women isolation that we saw yesterday.

85
00:11:47.910 --> 00:11:57.210
Tim Tait: This will produce a gamma ray always with the same energy, right, because you have a massive particle arrested case into two particles that are both basically mass less by comparison.

86
00:11:57.690 --> 00:12:11.280
Tim Tait: So each particle will therefore take away half of the energy of the parent and the gamma ray or sorry, the x ray in this case would actually be m sterile divided by two. So here's another plot which isn't the same

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00:12:12.720 --> 00:12:21.630
Tim Tait: parameter space, but with the axes flipped so that mixing angle is plotted on the x axis. The mass is plotted on the y axis, you can see constraints from x ray searches.

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00:12:22.740 --> 00:12:28.470
Tim Tait: You can see some regions that might be favored by theory, trying to explain why pulsars seem to get kicked out of the plane of the galaxy.

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00:12:29.070 --> 00:12:38.400
Tim Tait: And you can also see an interesting little red blob here and this was extracted from a possible x ray signal that was observed in 2014 as processed by

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00:12:39.090 --> 00:12:45.960
Tim Tait: Dissolved in so he's the one who actually provided this content that's pretty exciting. That means that maybe there is actually even a signal of dark matter.

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00:12:46.680 --> 00:12:54.990
Tim Tait: However, of course, this is something that needs to be confirmed and the situation is kind of very confusing at the moment because there have been lots of follow up studies.

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00:12:55.350 --> 00:13:01.290
Tim Tait: Some of them actually see something like this signal, though not none of them and see it as strongly as the original observations did

93
00:13:02.040 --> 00:13:10.110
Tim Tait: But some of them don't see anything at all. And so it's possible that maybe this is just something that's an artifact of the particular place that the original authors were looking

94
00:13:11.340 --> 00:13:19.860
Tim Tait: Or just maybe telling us something more interesting about astrophysics. So this is something that we're going to keep our eye on.

But we can't really declare victory and say that we've seen dark matter. Yes.

95
00:13:23.100 --> 00:13:28.530
Tim Tait: So now moving on. I'm going to go back to something that's a little bit more Wimp like and tell you a little bit about simplified models.

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00:13:28.860 --> 00:13:42.120
Tim Tait: simplified models have emerged as the primary way in which the LSD experiments are communicating the results of their searches for dark matter, and in some cases are being also adopted and some of the plots, you see from

97
00:13:43.170 --> 00:13:50.640
Tim Tait: Searches for dark matter scattering with nuclei or indirect detection searches, too. So let's understand how they work.

98
00:13:51.210 --> 00:14:04.950
Tim Tait: A simplified model is just taking what might be a complete theory, but then cutting it down to just the essential parts that contain the dark matter, as well as the most important particles that mediates interaction with the standard model. So maybe instead of

99
00:14:07.680 --> 00:14:18.570
Tim Tait: Maybe instead of looking at the entire minimal supersymmetric standard model. You might just look at the MSP and then maybe one of the next slightest particles, that's important when you calculate it's cross sections.

100
00:14:19.320 --> 00:14:26.040
Tim Tait: So I'll show you a couple examples of these as the first one. If we're interested in a dark matter.

101
00:14:26.670 --> 00:14:36.690
Tim Tait: Of a theory were dark matters interacting with corks, you could imagine that you include just the dark matter and some SU three charge scale or particle which mediates the interaction.

102
00:14:37.290 --> 00:14:42.570
Tim Tait: So in other words, we have the dark matter. And if I look at the little diagram down at the bottom that's indicated by chi.

103
00:14:42.990 --> 00:14:49.620

Tim Tait: Interacts with the Standard Model cork, but there has to be something else to make this whole vertex gauge invariant. And that thing is.

104
00:14:50.160 --> 00:14:59.430
Tim Tait: A scale are charged and both SU three charged and electrically charged particle. So, this thing would look kind of like a squirt from supersymmetry.

105
00:14:59.850 --> 00:15:09.270
Tim Tait: But supersymmetry would have actually dictated what the structure of this interaction would be, and in this more general simplified model. You're not really constrained to live in the supersymmetric region.

106
00:15:12.060 --> 00:15:19.410
Tim Tait: Trying to conserve flavor in the standard model. In other words, not have this kind of vertex mediates a flavor violation of loop level.

107
00:15:20.280 --> 00:15:27.180
Tim Tait: Usually suggest that we include the mediator particle to also have a flavor index. So in other words, if there are three quirks that can couple to

108
00:15:27.600 --> 00:15:33.750
Tim Tait: You know, let's say the right handed up charm and top cork, then there would be three of the scale or mediators, the

109
00:15:34.350 --> 00:15:38.070
Tim Tait: The partner right of the right handed up the right hand of Charmin the right hand to top

110
00:15:38.760 --> 00:15:47.070
Tim Tait: And that they would all have the same message interactions. And if that's true, we get kind of like a super Jim mechanism which prevents us from getting large flagrant violation.

111
00:15:47.550 --> 00:15:55.590
Tim Tait: So this theory. It looks like a little bit of Susie, but with more freedom in terms of choosing the coupling in mass, etc. And there are only three parameters which makes it much more

112
00:15:56.490 --> 00:16:05.850

Tim Tait: Easy to deal with in the supersymmetric standard model, right. And those are the mass of the dark matter, the mass of the mediator particle. And then the overall coupling strength of each one of the mediators of the quirks.

113
00:16:09.150 --> 00:16:15.060
Tim Tait: Alright, so the ELYSEE experiments have placed very interesting limits on theories like these.

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00:16:15.630 --> 00:16:20.220
Tim Tait: A couple of them are shown here and I even labeled it scores, because that's what I'm translating here.

115
00:16:20.880 --> 00:16:37.140
Tim Tait: Um, so, for example, you could imagine that the la chica Bruce A pair of the scale or particles and then that vertex we saw before would let them decay into a dark matter particle and a jet have had Ron's so this process repair production would produce a net of

116
00:16:38.370 --> 00:16:48.180
Tim Tait: Two jet's have had runs and missing transverse momentum and then plus maybe there could be some also initial state radiation, you have to allow for that it happens very often feel he

117
00:16:49.800 --> 00:16:53.700
Tim Tait: Said, so they devise a series of searches both that list and CMS due

118
00:16:54.750 --> 00:17:06.120
Tim Tait: To the search for for events like those may appear with the background expectations so far all the measurements have been consistent with the background. And so you end up with

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00:17:06.570 --> 00:17:14.760
Tim Tait: Regions a parameter space that you can exclude so in the upper left, you see a plot that's plotted in the plane of the mass of the mediator and the mass of the dark matter.

120
00:17:16.320 --> 00:17:26.130
Tim Tait: So the LLC, for some reason, likes to put the mass of the mediator on the x axis and the mass of the dark matter on the Y axis. That's kind of the opposite of what direct detection experiments. Do I don't know why.

121
00:17:27.270 --> 00:17:44.940

Tim Tait: But it's fine. You just turn your head and you understand what it's telling you. So, and you see that it takes a bite out of the parameter space here for the lower masses of mediator and dark matter, you can sort of robustly exclude dark matter masses up to you know about 400 TV or so.

122
00:17:46.170 --> 00:17:54.210
Tim Tait: And you can you're sensitive to dark matter masses, at the moment, up to about 600 GB or so, whereas for the mediator. You can robustly exclude them.

123
00:17:54.900 --> 00:18:02.280
Tim Tait: Only actually down to about 400 but you can actually, in some cases where the dark matters very light excluded up to one and a half TV.

124
00:18:02.940 --> 00:18:06.570
Tim Tait: Since you're pretty interesting limits that put a pretty tight constraints on the

125
00:18:07.320 --> 00:18:22.230
Tim Tait: On the theory, the blue region is actually just showing you an older result. And so you can see how much progress the hell he made in going from having 3% of our earnings to 36% of words. And of course there's more data already collected and a lot more to come in.

126
00:18:24.840 --> 00:18:29.430
Tim Tait: So you could also imagine looking for a modern jet signature, like the one that we discussed last time.

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00:18:29.820 --> 00:18:37.560
Tim Tait: We're here we have a cork and a glue on which fuses actually into a standard model of cork. But then that splits into the mediator particle and the dark matter.

128
00:18:37.950 --> 00:18:43.170
Tim Tait: So the mediator will decay into a jet have had runs and another dark particle. So, I'll have one hard jet.

129
00:18:43.650 --> 00:18:51.090
Tim Tait: And missing transverse momentum, you know, plus whatever the additional state radiation looks like that has a somewhat different topology and so

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00:18:51.480 --> 00:19:01.680

Tim Tait: There's no dedicated search for this theory that I could easily look at, but there was some work I did with some other authors, where we actually analyze the available searches in the context of the signal.

131
00:19:02.280 --> 00:19:13.680
Tim Tait: And what you can see here is shown in this plot in the lower right part because this process for moto jet actually involves the vertex and involving the cork and the dark matter and the mediator.

132
00:19:14.370 --> 00:19:21.420
Tim Tait: You can actually put a bound in the plane of these masses on the size of that interaction. So, see that's somewhat different than what happens

133
00:19:22.140 --> 00:19:33.000
Tim Tait: When you look at pair production because pair production. The production rate only depends on the QC decoupling, and you can really just actually put a limit on the masses themselves without worrying about the coupling.

134
00:19:33.600 --> 00:19:40.650
Tim Tait: Coupling has to be a big enough for it to decay inside the detector. But that's a very mild constraint that the coupling is bigger than like 10 to the minus 10 or something.

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00:19:41.520 --> 00:19:48.600
Tim Tait: So basically any coupling is ruled out any reasonable coupling is ruled out for masses in this region, whereas for the mono jet signature.

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00:19:49.650 --> 00:19:54.540
Tim Tait: The coupling that you can rule out varies very dramatically as you change the masses of the particles.

137
00:19:57.270 --> 00:20:00.870
Tim Tait: Okay. You can also talk about the direct detection of theories like this.

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00:20:01.800 --> 00:20:10.290
Tim Tait: If the case where it's a micron a particle, it's actually dominated by one loop effects where the dark matter comes in and scatters off of the glue ones that are part of the nuclei.

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00:20:11.040 --> 00:20:21.600

Tim Tait: And you can see some. So there are three local spin dependent interactions, but the loop level spin independent interaction, even though it's one loop is actually a much more constraining

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00:20:22.290 --> 00:20:30.090
Tim Tait: Limit than the tree level is just because of the fact that it's been independent. So you can see the spin dependent is putting bounds on couplings that are, you know, around

141
00:20:30.840 --> 00:20:43.170
Tim Tait: Two or three or four right they're big enough, you start to worry about perturbation theory, whereas the spin independent scattering is putting downs of the coupling that are much less than one and that looks pretty good point of view perturbation theory.

142
00:20:46.740 --> 00:20:51.540
Tim Tait: Okay, another important classes simplified models are models where a vector is exchanged.

143
00:20:52.230 --> 00:21:03.360
Tim Tait: So we could have a corks they're shown here is the blue lines in the diagram. They a couple of some kind of new vector particles and had a dark force carrier. So this could be considered a case of a

144
00:21:05.100 --> 00:21:10.290
Tim Tait: Dark sector theory and then that mediator is the thing that itself couples to the dark matter.

145
00:21:11.340 --> 00:21:18.360
Tim Tait: So there's a lot of parameters and principle that would be needed to describe a theory like this, you need the mass of the dark matter, the mass of the mediator.

146
00:21:18.930 --> 00:21:25.770
Tim Tait: Which I call this the prime here. You need the overall coupling strength of the Z prime and then actually there could be different charges for all of the

147
00:21:26.070 --> 00:21:34.470
Tim Tait: Left handed corks right handed up quirks right handed down corks left handed leptons right hand to charge leptons, etc, etc. Even the Higgs.

148
00:21:35.580 --> 00:21:38.490

Tim Tait: That could also be kinetic mixing what you're going to talk about a little bit later.

149
00:21:39.720 --> 00:21:47.310
Tim Tait: So there are theoretical considerations such as the dark sector more particles to cancel gauge anomalies, etc.

150
00:21:47.790 --> 00:21:51.390
Tim Tait: They are important, but they may not actually matter very much for the LSC searches.

151
00:21:51.750 --> 00:22:01.230
Tim Tait: What's typically done when they present results is they just assume that all the couplings are the same. So all of the Standard Model couplings are the same. And then they treat the dark matter coupling is differently.

152
00:22:01.890 --> 00:22:13.050
Tim Tait: Or maybe they assume that all the court couplings of the same, but there are no couplings. The leptons and then they look at the dark matter of coupling as a separate parameter that gets you down to about three or four parameters and it becomes much more tractable that point.

153
00:22:14.670 --> 00:22:21.840
Tim Tait: And so again, they do similar searches. These are now mostly dominated by the model jet search which is cartoon to get over here where you see corks coming in.

154
00:22:22.290 --> 00:22:31.050
Tim Tait: They emit so it's labeled x here, but the dominant boundaries. You come from the case where x is a jet they produce the mediator particle which then the case in the dark matter.

155
00:22:32.280 --> 00:22:39.390
Tim Tait: And the next slide, we'll see the case where it can dictate even back into the standard model and they place limits on the parameter space that are shown.

156
00:22:39.870 --> 00:22:47.850
Tim Tait: Here on these two images. So you can see again the mass of the mediator, which is labeled as Zb for the Atlas plot and

157
00:22:48.810 --> 00:23:06.510
Tim Tait: M. Ed or for mediator on the CMS blocks are both on the X axis, the mass of the dark matter is plotted on the y axis, the regional

parameter space to gets rolled out is this kind of wedge shaped curve sort of a triangle. You can see that that structure is there for both of the

158
00:23:07.590 --> 00:23:08.550
Tim Tait: Both of the plots.

159
00:23:09.780 --> 00:23:20.610
Tim Tait: They've also plotted regions where the relic density would be expected to work out just to guide your eye. So that's the line that's read here on atlas or blue and CMS.

160
00:23:21.270 --> 00:23:26.370
Tim Tait: And you can understand pretty easily. The structure of the limits. If we think about the sort of kinematic regimes.

161
00:23:27.240 --> 00:23:38.610
Tim Tait: For this process. So first of all, at some point, as I make the mediator. Let's say the dark matter mass is very low. If I make the mediator heavier and heavier at some point the mediator is so heavy. I don't typically have enough energy to produce it.

162
00:23:39.150 --> 00:23:52.020
Tim Tait: The LLC stops producing anything and I get a limit that peters out at about that mass. And you can see that for Atlas. This was about one and a half TV and CMS is very similar. It's like maybe 1.6 or seven or so.

163
00:23:54.030 --> 00:24:03.930
Tim Tait: Now the structure with the dark matter mass is a little bit more complicated. But what's been done here on the Atlas plot to guide your eye is they plotted the line. This is this dotted line here.

164
00:24:04.590 --> 00:24:13.650
Tim Tait: Where the mediator mass is equal to twice the dark matter mass. So this is the line where if I live on this line or below it. The mediator can actually decay into the dark matter directly

165
00:24:14.250 --> 00:24:23.340
Tim Tait: And that gives me a huge enhancement of this process because now I don't have to pay the price of an off shell mediator. I just produced the mediator on shell and then wait for educating the dark matter.

166
00:24:24.300 --> 00:24:34.500

Tim Tait: And so that's why the limits, more or less. Hug this line. And then, of course, eventually they cut off because the mediator just gets too heavy. So that explains why these shapes are sort of these branches.

167
00:24:35.850 --> 00:24:43.200
Tim Tait: Another thing to point out that sort of a hidden assumption. You can see often in these plots is written on the plot, you'll see

168
00:24:43.770 --> 00:24:51.570
Tim Tait: The value of the coupling the quirks and the value of the coupling the dark matter, right, because this process clearly depends on both of those things at least

169
00:24:52.230 --> 00:24:56.370
Tim Tait: It depends on the coupling the quirks in the region where the mediator is on shell.

170
00:24:57.030 --> 00:25:03.810
Tim Tait: And even then, it's still kind of depends on the couple into dark matter because there's a branching ratio for the mediator to go into dark matter versus to go into corks

171
00:25:04.380 --> 00:25:17.940
Tim Tait: That's important. So you have to look at these couplings and make sure that they match the kind of situation that you're thinking about or these plots can actually look very different. So these are important caveats, and you can see that there were slight differences.

172
00:25:19.140 --> 00:25:19.740
Tim Tait: Here.

173
00:25:20.850 --> 00:25:26.970
Tim Tait: In the sense that Atlas decided to do a vector mediator this plot and CMS that an axial vector mediator.

174
00:25:27.660 --> 00:25:37.890
Tim Tait: But they chose the same couplings for the quirks and the dark matter. And that's why the limits you get are very similar. They're not exactly the same nor slight difference between vector an accelerator.

175
00:25:40.710 --> 00:25:47.190
Tim Tait: You can also map these into the plane of direct detection. So this sort of shows you how to compare this type of search

176

00:25:47.670 --> 00:26:00.510
Tim Tait: For this kind of model at a collider versus this kind of search for the same model in the direct detection experiments so translating those wedges gives you a limit that looks like the red line, you see here in the CMS plot.

177
00:26:01.740 --> 00:26:10.740
Tim Tait: This is for a spin independent coupling. So you can see that it takes a bite out of the parameter space that is fairly independent of the mass, up until a mass of

178
00:26:11.310 --> 00:26:16.260
Tim Tait: A few hundred GV and then at some point, it kind of rolls over and closes off.

179
00:26:17.190 --> 00:26:29.730
Tim Tait: The reason for this role over this roll back is actually because you don't really trust your calculations up here because the couplings get too big and your, your simplified model doesn't work. So then for comparison. They've also shown the plots from

180
00:26:31.110 --> 00:26:40.080
Tim Tait: direct detection experiments like Lux xenon and Panda X. These are actually hard to resolve on this particular scale that they're showing, but you can see them all down here.

181
00:26:40.470 --> 00:26:47.160
Tim Tait: As these blue lines. So you can see that direction detection experiments are much more sensitive. If the mass of the dark matter is around

182
00:26:47.580 --> 00:26:57.330
Tim Tait: Say 10 or 100 GB. But actually, much less sensitive down below that. So the, the colliders are really exploring this particular theory very well in this low mass region.

183
00:26:58.230 --> 00:27:09.960
Tim Tait: So for Atlas I've chosen a spin dependent comparison. And so they're actually the spin dependent limits the best ones on on this channel or from Pico

184
00:27:10.500 --> 00:27:22.980
Tim Tait: That they're shown as the magenta line. You can see that the colliders are actually doing better for a wider range of masses. So the colors are really filling an information at low mass and for interactions that produced independent scattering but no spin independent scatter

185
00:27:25.560 --> 00:27:34.260
Tim Tait: And we can also look directly for the mediators. So you can imagine that the corks fuse and to one of the mediators, but then the mediator instead of decaying the dark matter to case back into corks

186
00:27:34.950 --> 00:27:44.100
Tim Tait: There's actually a wide variety of different strategies to search for these particles. You can see the Atlas summary plot kind of has all these different channels put together.

187
00:27:44.700 --> 00:27:55.830
Tim Tait: And you can see that the values of coupling that you're probing are sort of typically around point one or point two, but for specialized searches, they cannot get all the way down to close to point out one or so.

188
00:27:56.550 --> 00:28:06.720
Tim Tait: And it changes a lot with the mass, because the different search strategies require you to trigger on the particles are producing and as you make the mass of immediate or very light. It gets very hard to

189
00:28:07.800 --> 00:28:12.990
Tim Tait: To trigger. So you have to change the way you search and as a result you get a different limit and

190
00:28:13.440 --> 00:28:25.440
Tim Tait: I have to really have to say these limits, especially low masses are extremely creative use of LDC data their limits that I think maybe you would have said they shouldn't be able to get at all. And it's really quite remarkable that they do so well.

191
00:28:26.730 --> 00:28:40.620
Tim Tait: Of course, that high energy is the energy is also the king because it's the only man made source of high energy collisions that we have, but there you'd expect it to be doing well. And so while that's still amazing it maybe took a little bit less effort on the analysis side.

192
00:28:41.670 --> 00:28:49.950
Tim Tait: And over here, there's a CMS plot that shows you a similar way of looking at it in terms of the masses of the mediator in the dark matter and shading the couplings.

193
00:28:51.150 --> 00:28:52.500

Tim Tait: So I'm just gonna leave it at that.

194
00:28:54.630 --> 00:28:55.170
Tim Tait: Okay.

195
00:28:56.400 --> 00:29:06.930
Tim Tait: So I'm going to take a couple minutes and talk about dark matter, a couple of the glue ons. So another possible variation. This is something that I worked on with rotini got ballet and

196
00:29:07.890 --> 00:29:18.270
Tim Tait: Government data is the idea of the dark matter might just interact directly with the glue ons and not really bother with the quirks accepted higher level.

197
00:29:18.780 --> 00:29:24.030
Tim Tait: So for example, you could imagine that there's a dark matter. That's a scam or particle it couples to some kind of

198
00:29:24.420 --> 00:29:37.050
Tim Tait: stealer mediator. So that would be a normalized double interaction that involves to dark matter particles and to color to S3 color and scale or mediator particles, it would look like sort of the left half of the Simon diagram here.

199
00:29:39.030 --> 00:29:44.820
Tim Tait: But this scale or mediator particle doesn't actually have to be stable. It doesn't have to have the two symmetry, it might decay.

200
00:29:45.510 --> 00:29:48.090
Tim Tait: Because it also appears squared and the interaction.

201
00:29:48.690 --> 00:29:55.140
Tim Tait: So then in this case I can actually make a loop of the scale or particles and I can couple the dark matter, primarily the blue ones.

202
00:29:55.380 --> 00:30:01.440
Tim Tait: So of course the dark matter is really coupling primarily to to mediators, but because it's two mediators and not one Mediator.

203
00:30:01.920 --> 00:30:10.080
Tim Tait: The way to get to the standard model and only the standard model is to close the meat eaters into a loop and attach the blue ones. And that's basically what the idea here is

204
00:30:10.950 --> 00:30:20.760
Tim Tait: So actually the color and the flavor representation of the mediator particles are completely free to choose. It's not like the previous case of the skin color mediator.

205
00:30:21.030 --> 00:30:28.230
Tim Tait: Where I had to choose something that would give me a gauge invariant interaction with corks any representation would actually be a gauge and area here.

206
00:30:30.090 --> 00:30:35.130
Tim Tait: So then you can do all of the things that we've looked at so far, you can ask about the relic density

207
00:30:35.940 --> 00:30:42.690
Tim Tait: It turns out that for preservative values of this coupling lambda a thermal relic actually favors the case where the

208
00:30:43.230 --> 00:30:48.120
Tim Tait: Mass of the mediator is less than the mass of the dark matter. So the dark matter can annihilate into the mediator.

209
00:30:48.510 --> 00:30:53.040
Tim Tait: So that was kind of a surprise because normally we would have thought, okay, the scale or should we have yours on the dark matter.

210
00:30:53.460 --> 00:31:04.920
Tim Tait: But again, since it doesn't became to the dark matter. There's really no restriction say that that says that that should be the case. So here it shows in the plot it shows you the value of lambda times

211
00:31:06.180 --> 00:31:11.310
Tim Tait: The square root of the representation of the color scale or

212
00:31:12.420 --> 00:31:15.780
Tim Tait: That just happens to be the thing that scales out of the cross section conveniently

213
00:31:16.830 --> 00:31:27.000
Tim Tait: It shows you how big that would have to be in order to get the right relic density in the plane of the mass of the mediator in the mass of the dark matter. And so you can get small masses.

214
00:31:27.450 --> 00:31:32.910
Tim Tait: And then you require smallish couplings as you go to much larger masses, like a few TV you need larger couplings.

215
00:31:33.300 --> 00:31:43.020
Tim Tait: One thing is that because of the square root of NF times are this is not really a coupling. And so actually you can stay perturb of roughly all the way up to here. If you choose the representation to be large enough

216
00:31:45.900 --> 00:31:56.520
Tim Tait: Then you can search for the mediators of the LSC you can produce them in pairs. Now you can actually just let them to K directly into corks by adding interactions between them. The quirks that depends on what the representation as you choose.

217
00:31:57.360 --> 00:32:09.030
Tim Tait: The bounds are actually relatively weak if they just became the ordinary untangle jets. The bound is just a few hundred GV so that's much less than this, the specialized searches for sports that we saw.

218
00:32:10.890 --> 00:32:18.930
Tim Tait: I we just did a specific example where we considered the mediators to have charged electric charge four thirds and couple to too uptight corks that are right handed.

219
00:32:19.950 --> 00:32:23.520
Tim Tait: There are many different variations, though, that you can play with that assumption.

220
00:32:24.600 --> 00:32:29.520
Tim Tait: In the case where they a couple to the top cork, then you do get some more specialized searches and

221
00:32:30.180 --> 00:32:38.760
Tim Tait: So what's shown in the plot is actually as a function of the coupling of the mediator to the top corks, which is why one and the mass of the mediator.

222
00:32:39.240 --> 00:32:46.050
Tim Tait: There are two different channels, you can use to search for this theory below masses are excluded by looking for two tops plus two jets.

223

00:32:46.470 --> 00:32:57.270
Tim Tait: And then there's this blue region which is excluded by two tops plus one jet all of these constraints are really relatively weak. If you think about it, they're sort of tell you the mass has to be bigger than a few hundred GB at most.

224
00:33:00.360 --> 00:33:11.400
Tim Tait: And then you can also look at the direct searches direct detection generally provides a strong bound unless the dark matter masses, particularly small you can see projections here.

225
00:33:12.450 --> 00:33:13.560
Tim Tait: For the

226
00:33:14.610 --> 00:33:24.270
Tim Tait: Week. Sorry. You can see the Lux experiments results here. That was actually the best experiment at the time that we did this work and you can see that it takes interesting bite out of the parameter space.

227
00:33:26.130 --> 00:33:34.830
Tim Tait: The mono jet signature occurs at one loop we actually did all the one look calculation, because we were curious to see how it would work with all the different momentum dependent for the loop integrals.

228
00:33:35.460 --> 00:33:49.530
Tim Tait: And that was interesting. The results of the ELYSEE, were not particularly helpful though for large enough, our lambda, you can see something with large data set, but something like 100 TV programs aren't on collider would do a lot better if we ever get one of those

229
00:33:52.440 --> 00:34:05.280
Tim Tait: So all of these simplified models are sketches of dark matter not complete theories of dark matter. And the idea is, of course, and if we start to see them, we would put the sketch together and have it come to life. So I believe this is showing us how that would work.

230
00:34:07.470 --> 00:34:13.260
Tim Tait: And so this brings me to the end of the second part of my lectures which

231
00:34:14.520 --> 00:34:19.710
Tim Tait: We've already talked about the first set of conclusions. There are many specific detailed models of dark matter and about Susie

232
00:34:20.460 --> 00:34:29.610

Tim Tait: Now today, this morning, so far we've seen that axons and sterile neutrinos are well motivated extension to the standard model they explained the strong CP problem and neutrino masses.

233
00:34:30.150 --> 00:34:35.790
Tim Tait: And we have more specialized types of searches to find them. But we do have searches. We know how to do and we're looking for them.

234
00:34:36.660 --> 00:34:42.750
Tim Tait: And then we talked a little bit about simplified models that have been adopted as a bridge between searches for dark matter and theoretical constructions.

235
00:34:43.230 --> 00:34:49.590
Tim Tait: They don't contain the full distracting details of a complete theory, but they hopefully summarize the broad impacts of searches on many of them.

236
00:34:51.330 --> 00:34:59.640
Tim Tait: So this brings me to the last section of the lectures which are more like examples of dark sectors and I have a few different examples I've chosen to go through

237
00:35:00.480 --> 00:35:10.740
Tim Tait: I think we should roughly get through all of them, but I may have to speed up a little bit. At one point the person I'm going to talk about is the idea that dark matter could be composite so dark matter could be made out of other things.

238
00:35:12.120 --> 00:35:22.230
Tim Tait: So dark matter, of course, must be weekly interacting with the standard model, but could still be part of a dark strongly interacting system, which plays an important role in terms of what it actually looks like in the galaxy.

239
00:35:23.010 --> 00:35:29.670
Tim Tait: So one example is dark matter could have a light force carrier, leading to it to form dark Adams, or even dark molecules.

240
00:35:30.090 --> 00:35:36.690
Tim Tait: And I've got a reference here to one of the first papers that took this idea seriously, there's actually been a lot of work that's followed up since then.

241
00:35:37.500 --> 00:35:43.680

Tim Tait: The cartoon here, you see that there are too dark matter particles. One has positive dark charge one has negative dark charge

242
00:35:44.070 --> 00:35:54.240
Tim Tait: They exchanged the dark force carriers and they've been bound together to form something like a dark, Adam. In this case, you can imagine more complicated theories. You might even get dark molecules.

243
00:35:55.800 --> 00:36:07.050
Tim Tait: You could have a dark matter which fields are very strong interaction that can find like SU three confines and it could form dark had Ron's. So here I've got a cartoon that shows

244
00:36:07.680 --> 00:36:13.590
Tim Tait: A case where the dark matter is actually just a dark set of gluons now by themselves, they would be mass list.

245
00:36:14.010 --> 00:36:24.570
Tim Tait: But because they're confined to they're stuck together in a little ball of energy. Right. The same way that the proton is much heavier than the quirks of make it up. And so the dark matter could be something like that.

246
00:36:25.650 --> 00:36:31.290
Tim Tait: And of course, if I take this idea a little bit further, there could be a whole range of possible stable states like dark nuclei.

247
00:36:31.710 --> 00:36:41.550
Tim Tait: So if I take something like dark had runs. They may have nuclear interaction, similar to the nuclei that we know about. And they may form actually larger composite objects that are made out of the dark

248
00:36:42.600 --> 00:36:49.320
Tim Tait: The dark nuclei and you can read more about that. There. So these are all actually areas of active research.

249
00:36:49.740 --> 00:36:54.510
Tim Tait: The parameter space is not really entirely mapped out and all the phenomena haven't really been discovered.

250
00:36:54.810 --> 00:37:04.800
Tim Tait: The references, give you a place to start to learn about the ideas, but they're not complete, and I'm sorry, I'd be happy to talk about this offline in more detail and point you to other directions. You can go

251
00:37:06.600 --> 00:37:18.750
Tim Tait: So I'm going to tell you a little bit about a very simple idea. This is something that I worked on a few years ago where actually the theory is just a pure gauge theory, consisting of a hidden sector sqn so basically this is just like you take

252
00:37:20.340 --> 00:37:31.830
Tim Tait: You add a set of dark blue ones of some kind to your theory and nothing else just nothing else at all and maybe even imagine that they don't interact with the Standard Model except through gravity.

253
00:37:33.360 --> 00:37:38.640
Tim Tait: So you can think about this is kind of like a hidden gauge group which just is totally separate from the standard model.

254
00:37:39.480 --> 00:37:45.600
Tim Tait: And of course there are variations, where I would include things like dark quarks, but just to keep things really simple at the beginning. Let's not bother to do that right

255
00:37:46.800 --> 00:37:56.340
Tim Tait: So we know that this theory is defined by the number of dark colors. There are, in other words, what is en su n and the confinement scale, right, which tells me it which energy scale.

256
00:37:56.910 --> 00:38:06.540
Tim Tait: That Dark Age theory confines and you wouldn't be a few just that value what you're really adjusting at high energies is the value of that strong coupling constant

257
00:38:06.930 --> 00:38:13.710
Tim Tait: Because then it's going to run down in a way that you can predict based on and and it will confined at some scale and you could calculate at that point.

258
00:38:14.190 --> 00:38:24.060
Tim Tait: So rather than going through all of that calculation. I'm just going to talk about the confinement scale itself. And I know I can always adjust what the value of that coupling is to get whatever confinement scale.

259
00:38:25.650 --> 00:38:33.060
Tim Tait: So this can find it scale characterizes the masses of the of the dark composite the particles that form.

260
00:38:34.260 --> 00:38:39.990
Tim Tait: Now, since all I have our glow lines. The only had Ron's that exists in this theory are glue balls.

261
00:38:40.500 --> 00:38:46.800
Tim Tait: So the massive the lowest glue ball is, you know, something like two pi times lambda. If you look at lattice calculations.

262
00:38:47.370 --> 00:38:57.930
Tim Tait: And also there are more glue balls. They have all different kinds of spins and parody assignments and they are split by some number that's also similar to lambda, between the two of them.

263
00:38:59.580 --> 00:39:08.250
Tim Tait: So from here on. I'm going to stop saying darker hidden. Most of the time, and I'm just going to say glue and glue ball. But remember, I'm talking about the dark stuff, not, not the ordinary live ones.

264
00:39:10.140 --> 00:39:15.840
Tim Tait: So one interesting feature of this type of theory is the fact that blue balls interact strongly with another with one another.

265
00:39:16.260 --> 00:39:23.670
Tim Tait: Right, and that's obvious because they're made of the strongly interacting glue ons when they get close enough to each other. They actually realize that they like to to interact

266
00:39:24.180 --> 00:39:33.210
Tim Tait: And so if you get to glue balls close to each other. They actually scatter very strongly because of the strong dynamics. You can't really compute this very reliably and perdition theory.

267
00:39:34.080 --> 00:39:39.210
Tim Tait: That you could actually do some calculations on the lattice and they're even have been a few calculations have been done.

268
00:39:39.690 --> 00:39:45.690
Tim Tait: In this case, making the theory. So simple actually makes the calculation. A little easier because pure glue is much easier to deal with.

269
00:39:46.440 --> 00:39:52.020

Tim Tait: So you can cartoon, the self interaction of the glue balls as just like a geometric geometric cross section, you basically just say

270
00:39:52.710 --> 00:40:02.910
Tim Tait: Let's imagine you know that the cross section between these two blue balls that are scattering with each other is equal to the actual area that they see. So that would be, you know, pi r squared.

271
00:40:03.480 --> 00:40:11.970
Tim Tait: Where r is actually set by this confinement scale and then you just ask how likely it is for them to overlap and you get a geometric cross section.

272
00:40:12.690 --> 00:40:20.400
Tim Tait: That cross section obviously struggling interacting. That's where the four five comes from. It goes like one over the confinement scale squared.

273
00:40:22.200 --> 00:40:29.040
Tim Tait: And right and that's, again, just the dimensional analysis of saying that my objects have roughly that size because that's the scale of the interaction that holds them together.

274
00:40:29.550 --> 00:40:43.110
Tim Tait: And then the one over in square. It's a little harder to understand and it basically is something that comes out from large and based on a different kinds of theoretical considerations I can answer questions about that by email, but I'm not going to go into it here.

275
00:40:44.280 --> 00:40:51.390
Tim Tait: But the upshot is really for small in any way a single parameter lambda controls both the mass and the cross section.

276
00:40:52.170 --> 00:41:01.800
Tim Tait: For large and becomes important to and so you can actually just ask yourself, how much would I what lambda. What I need in order to get a cross section that would be observable in terms of

277
00:41:02.310 --> 00:41:08.160
Tim Tait: The dark matter scattering doing something to the galaxies and structure that I observed in the universe.

278
00:41:08.580 --> 00:41:19.710
Tim Tait: And the answer turns out to be around 580 or so, which is pretty amusing when close to the actual value of the strong coupling

constant you know the real glue on have lambda up about two or 300 and maybe

279
00:41:20.880 --> 00:41:24.120
Tim Tait: That's of course a coincidence. But it's, it's an interesting one.

280
00:41:25.350 --> 00:41:31.290
Tim Tait: You can estimate the relevancy of the glue balls by tracking the relevancy of nuance to temperatures where the theory combines

281
00:41:31.650 --> 00:41:40.800
Tim Tait: So that's actually what I've done over here is a quick back of the envelope calculation basically all I do is I just say the blue balls are the blue ones have some temperature

282
00:41:41.700 --> 00:41:46.290
Tim Tait: At any point in the universe that tells me what their energy density is based on the equilibrium density

283
00:41:46.650 --> 00:41:56.730
Tim Tait: Then when I get to the confinement scale a temperature around lambda, the energy of the dark blue ones gets converted into the blue balls. So I just conserve the energy and turn that much glue on into that much blue ball.

284
00:41:58.200 --> 00:42:00.480
Tim Tait: And so then you estimate the relevancy of them that way.

285
00:42:02.370 --> 00:42:11.850
Tim Tait: And this is where it's important that if there are no relevant connectors between the visible the hidden sectors than the temperature in the hidden sector th and the temperature, the visible sector t

286
00:42:12.270 --> 00:42:21.240
Tim Tait: Could actually generically be different from each other and you parameters. This possibility with the ratio of the temperatures, which is fine to be th divided by T.

287
00:42:21.960 --> 00:42:28.860
Tim Tait: So they're interesting corrections and the usual thermal distributions. And that's because your processes were saved three blue balls.

288

00:42:29.580 --> 00:42:36.630
Tim Tait: All annihilate to produce to blue balls. So this is a process that was called cannibalization by the first reference listed here.

289
00:42:36.990 --> 00:42:45.480
Tim Tait: Because what it does is it basically takes the energy of one of the glue balls and the mass energy, one of the blue balls and turns it into kinetic energy of the two that come out.

290
00:42:46.020 --> 00:42:52.680
Tim Tait: Right. Or in other words, it's cannibalization because these three blue balls have gotten together. Two of them have eaten their friend and now they have more energy.

291
00:42:55.110 --> 00:43:06.420
Tim Tait: And so here, if you want to look at this parameter space for blue ball only dark matter I plotted it in the parameter space of this relative size of the temperatures. So let's see parameter on the x axis.

292
00:43:07.530 --> 00:43:19.680
Tim Tait: Right, that's T hidden divided by T standard model and then what the confinement scale is we already calculated that you got interesting self interactions where you might see something funny going on in galaxy formation.

293
00:43:20.370 --> 00:43:25.560
Tim Tait: Is sort of down around a few hundred Nev for the confinement scale.

294
00:43:26.100 --> 00:43:35.430
Tim Tait: And then for different values of the number of colors and you know to is reasonable 10s seems a little larger hundred seems kind of crazy, but just to get an idea how it scales.

295
00:43:36.240 --> 00:43:42.960
Tim Tait: You can see the lines in this parameter space of the relative temperature and lambda, where you get the right relic density

296
00:43:43.500 --> 00:43:48.060
Tim Tait: So, you know, if you live down here, say, on this point, you can have two colors of dark blue ones.

297
00:43:48.630 --> 00:44:00.360
Tim Tait: The relative temperature between the hidden in Standard Model sector would be something like one over 100 and you'd have interesting

cross sections that might lead to observable changes and say small galaxies.

298
00:44:01.980 --> 00:44:13.380
Tim Tait: Okay I think just to make sure I get through some other important things. I'm going to skip the case where I add something like a dark cork. In this case, it was in the joint representation. So it was more like a dark gloomy know

299
00:44:14.400 --> 00:44:18.030
Tim Tait: You can go through those. And you can always send me an email. If you want to talk about them some more.

300
00:44:19.860 --> 00:44:33.240
Tim Tait: But I want to actually finish up by saying something about dark about light, dark force carriers. In other words, cases where the dark force carrier is a light being low mass particle and you'll have to forgive me for indulging in the absurd workplace.

301
00:44:35.430 --> 00:44:41.400
Tim Tait: So recently, there's been a lot of attention given to the parameter space where the mediating particles have low masses that will be couplings.

302
00:44:41.910 --> 00:44:46.680
Tim Tait: This is a natural parameter space that complements high mass searches that colliders

303
00:44:47.670 --> 00:44:56.550
Tim Tait: For Dark Matter of masses below around 10 GB there are strong constraints which favorite cases in which the dark matter annihilate directly into some kind of light, dark mediator.

304
00:44:57.270 --> 00:45:04.860
Tim Tait: So if we would like to realize the abundance of dark matter through the freeze out mechanism we need light mediators for dark matter masses below the GV scale.

305
00:45:05.370 --> 00:45:12.450
Tim Tait: And so here are some plots that were made in the reference. You can see here that came out just this year what they've done is they've looked at

306
00:45:13.530 --> 00:45:26.580

Tim Tait: They were very clever and analyzing the parameters and figuring out which combinations work, which means that they have plots that are really applicable to a lot of parameter space, but it also makes your head hurt a little bit. When you try to analyze it. So,

307
00:45:27.630 --> 00:45:38.070
Tim Tait: Just rest assured that these were a very good choice, but they're just not an easy choice. So what's been done here is the x axis contains the ratio of the mediator mass to the dark matter mass.

308
00:45:38.610 --> 00:45:44.670
Tim Tait: Right, so pick the dark matter mass and the mediator mass is the number on the x axis times that aren't matter mass.

309
00:45:45.420 --> 00:45:55.950
Tim Tait: Then the y axis has got a combination of parameters that includes a kinetic mixing parameter. So in other words, how much this dark mediator mixes with the photon. We're going to see what that means. On the next slide.

310
00:45:56.670 --> 00:46:06.090
Tim Tait: Alpha D is the coupling of that mediator to the dark particle. And then the ratio of the dark matter mass to the mediator mass, right, which is in the opposite.

311
00:46:07.290 --> 00:46:13.050
Tim Tait: Order here to the fourth power. Right. And that's because the annihilation cross section skills like this quantity

312
00:46:13.590 --> 00:46:23.460
Tim Tait: And so you can actually plot what the thermal target is for a freeze out relic here. And so what they've done is they plotted it for a couple different choices of the dark coupling constant

313
00:46:24.090 --> 00:46:27.720
Tim Tait: You can see the thermal target has got this interesting structure.

314
00:46:28.200 --> 00:46:42.870
Tim Tait: It this this dip here right is the same kind of resonant annihilation that we saw could happen for supersymmetric particles. Right. It's what happens basically when r is equal to two and therefore, the, the mediator mass is equal to twice the dark matter.

315
00:46:44.730 --> 00:46:58.800

Tim Tait: So this was a case for something like a dark photon and the upper plot in the lower plot you see a case where you're only a couple of baryons right so you don't couple the leptons that changes the systematics of things a little bit, especially the way that you would search for it.

316
00:47:00.330 --> 00:47:00.750
Tim Tait: Okay.

317
00:47:01.950 --> 00:47:09.750
Tim Tait: So like mediators can also help with some of the puzzling measurements that we wonder might be indications and new physics that we know about.

318
00:47:10.230 --> 00:47:16.230
Tim Tait: The most famous one of these is G minus two of the Milan. So there's a long standing discrepancy between theory and data.

319
00:47:17.070 --> 00:47:27.360
Tim Tait: This plot here shows you the experimental measurements from you, plus minus and their average. You can see they're consistent with each other so doesn't look like a premier plus the vinyl have a different t minus two.

320
00:47:27.990 --> 00:47:30.330
Tim Tait: That's going to do this quantum field theory doesn't really let that happen.

321
00:47:31.830 --> 00:47:38.430
Tim Tait: And the theory theoretical determinations based on some inputs from either a plus or minus data or tower decay data.

322
00:47:38.790 --> 00:47:45.690
Tim Tait: And these are really just trying to actually understand some of the hydraulic contributions to the process because at this point we're sensitive to loop corrections.

323
00:47:46.410 --> 00:47:55.500
Tim Tait: And so there's actually some preference for the plus and minus result, both of them though are pretty discrepant with the experiment by a few sigma

324
00:47:56.130 --> 00:48:08.940
Tim Tait: And so the idea is if you have a light, dark force carrier, like say a dark photon. You could imagine that it also gives you a one

loop contribution to the TG minus two of them you on and it could help fix up this

325
00:48:09.990 --> 00:48:19.320
Tim Tait: This discrepancy so somewhat less established and less. Definitely. Sorry. One last thing of a d minus two of them, the one

326
00:48:19.980 --> 00:48:29.370
Tim Tait: We should actually get updates about measurements of G minus two of them you on now experiment is running a Fermilab and I believe that that should really happen anytime

327
00:48:31.170 --> 00:48:40.080
Tim Tait: So then moving on to a couple other interesting things to keep on your radar. There's a nuclear physics transition which I've got a cartoon here that was made by flip tomato.

328
00:48:40.620 --> 00:48:46.950
Tim Tait: Where an experiment produces and excited state of brilliant. He watches it decay into the ground state plus

329
00:48:47.820 --> 00:48:54.270
Tim Tait: A plus A minus and they see what looks like a resonance structure in the policy minus which might be the sign of a new particle around 17

330
00:48:55.260 --> 00:49:01.770
Tim Tait: So the main thing here with this experiment is that it's really only done by one experimental group and you'd really like to see it reproduced by another one.

331
00:49:02.130 --> 00:49:10.320
Tim Tait: Though they have done more measurements with other nuclei and they seem to see similar effects. So really, though, that just makes me say once again.

332
00:49:11.040 --> 00:49:18.180
Tim Tait: You really would like to see it done by another experimental group because you're really worried a little bit about whether it's something funny about their experiment.

333
00:49:19.350 --> 00:49:26.340
Tim Tait: Though no one has found any problem with that so far. And then the last one is an older measurement of pi zero d plus A minus that was

334
00:49:26.970 --> 00:49:30.480
Tim Tait: Mentioned by Katana it's off by about two and a half sigma or so.

335
00:49:30.870 --> 00:49:40.440
Tim Tait: And it might point to axial couplings to quirks and electrons. So here's a diagram where you have the two quirks and make up the pi zero they fuse into a massive mediator.

336
00:49:40.860 --> 00:49:46.890
Tim Tait: And then that gives you extra he plus a minus in your decay and you need to have axial couplings, at least with the cork side.

337
00:49:51.540 --> 00:50:02.130
Tim Tait: Alright light mediators also open up the possibility to invoke a summer felt like enhancement of the dark matter small dark matter of velocities. So this could enhance annihilation.

338
00:50:03.210 --> 00:50:08.280
Tim Tait: I'm guessing Tracy probably told you a little bit about this yesterday, but unfortunately didn't get a chance to take a look at our lecture.

339
00:50:10.020 --> 00:50:19.200
Tim Tait: Summing up the effect of the mediator on the scattering can lead to a large enhancement compared to the leading order annihilation rate and right the diagram is something like this one here on the lower right side.

340
00:50:19.710 --> 00:50:31.650
Tim Tait: Where you have your dark matter coming in. And the idea is because of the attractive force between the mediator. It's actually more likely to get together and annihilate than it would if there was no such interaction pulling the incoming particles together.

341
00:50:32.040 --> 00:50:34.260
charlie young: Excuse me five minutes.

342
00:50:34.710 --> 00:50:36.000
Tim Tait: Yeah. Absolutely. Great. Thanks.

343
00:50:37.110 --> 00:50:43.320

Tim Tait: The impact is enhanced for small velocities and also for me to your immediate or masses that are much smaller than the mass of the dark matter.

344
00:50:43.650 --> 00:50:48.300
Tim Tait: You can actually see the calculation here, which was done by Tracy and some collaborators, a while ago.

345
00:50:48.960 --> 00:50:54.480
Tim Tait: And this is plotted in the plane of epsilon V, right, which is velocity divided by the coupling alpha

346
00:50:55.170 --> 00:51:03.330
Tim Tait: On the x axis and the y axis is epsilon fi, which is defined to be a mass of the mediator divided by alpha times the mass of the dark matter.

347
00:51:03.960 --> 00:51:15.030
Tim Tait: And you see, you get big enhancements like as big as even factors of 1000 or 10,000 if you go to small values of both of those things. In other words, small velocities and small mediator mass compared to the dark matter less

348
00:51:16.770 --> 00:51:25.380
Tim Tait: So 400 GB dark matter if you want to take advantage of this kind of enhancement. This naturally argues the mediator mash should be down to be somewhere at or below the GPA scale.

349
00:51:27.240 --> 00:51:34.320
Tim Tait: And another interesting thing that gets opened up. If I talk about like mediators is something I alluded to previously when I talked about the relative density.

350
00:51:34.770 --> 00:51:41.010
Tim Tait: You can imagine the dark matter, instead of annihilating in the standard model particles also just annihilate directly into mediators themselves.

351
00:51:41.490 --> 00:51:57.120
Tim Tait: So the rate for this to happen is fixed by the coupling of the dark matter to the mediator and so for example if I have dark matter annihilating into mediators, like in the top diagram that annihilation cross section is going to go like that coupling of mediator to dark matter.

352

00:51:58.860 --> 00:52:07.380
Tim Tait: To the fourth power. So that's what this annihilation cross section go like, and the media, you're going to have much much smaller coupling to the Standard Model particles like called that epsilon

353
00:52:07.770 --> 00:52:12.570
Tim Tait: And that's because you know if I'm worried about seeing the the annihilation products of the dark matter.

354
00:52:13.410 --> 00:52:23.520
Tim Tait: The mediator can travel for killer parsecs before it needs to decay. In other words, this coupling this lifetime could be incredibly long and I would still get the same signal, but I would expect to see in my telescopes.

355
00:52:24.510 --> 00:52:34.320
Tim Tait: So it's a generic way of getting an indirect signal while suppressing direct and collider constraints, because if I look for example at the direct scattering dark matter with a nuclear

356
00:52:36.180 --> 00:52:45.240
Tim Tait: Exchanging a mediator. Right. Well, now I have a vertex of mediator with dark matter. So that's G and the vertex of mediator with sorry Meteor dark matters up here that's G.

357
00:52:45.660 --> 00:52:52.650
Tim Tait: Mediator with the nucleus that's down here is epsilon. Now this cross section goes like epsilon squared d squared. And so

358
00:52:53.490 --> 00:52:58.470
Tim Tait: It's a parametric Lee smaller than the annihilation cross section and obviously

359
00:52:59.130 --> 00:53:05.130
Tim Tait: If I make epsilon small I can have the annihilation. Be very prominent while having the direct section be switched off.

360
00:53:05.700 --> 00:53:14.160
Tim Tait: And we've seen, actually this idea to get some application in terms of the GV access of gamma rays from the direction of the galactic center to construct theories in which

361
00:53:14.700 --> 00:53:23.430

Tim Tait: You get the strong annihilation signal you would need to explain that observation. But while still satisfying the lack of evidence for dark matter scattering with having a clear

362
00:53:25.980 --> 00:53:37.260
Tim Tait: Okay then. Last thing I want to mention or the last topic I want to mention is how you would build a theory of light mediators, they're very important theoretical constraints on theories with light particles.

363
00:53:37.740 --> 00:53:43.050
Tim Tait: So of course, there are the experimental constraints on searches for them or indirect contributions other observable.

364
00:53:43.650 --> 00:53:50.700
Tim Tait: And such constraints are most easily avoided if the mediator carries no standard model charge, but I also have to worry about the Standard Model gauge cemetery.

365
00:53:51.210 --> 00:53:59.970
Tim Tait: The mediator gauge cemetery, if I write down a mediator. That's a vector particle, I need to actually have a gauge symmetry to protect its interactions or generically my theory won't be self consistent

366
00:54:00.720 --> 00:54:07.110
Tim Tait: We need to be able to write down the standard model you call interaction. So when when I introduce new kinds of charge, I run the risk of

367
00:54:07.560 --> 00:54:15.630
Tim Tait: Not being able to write down those interactions and I have to figure out how to engineer them. And of course there could be gauged anomalies, which mean the theory is not self consistent

368
00:54:16.530 --> 00:54:23.490
Tim Tait: All of these summarize actually in this plot here where you see a bunch of different constraints on an axial vector particle

369
00:54:24.600 --> 00:54:29.340
Tim Tait: You see a bunch of constraints experimentally. And then if you

370
00:54:29.790 --> 00:54:37.920
Tim Tait: In particular, if you're looking at what's allowed by g minus two of them Yuan, right. So, g minus to the new on favors a certain range of region region a parameter space.

371
00:54:38.250 --> 00:54:42.210
Tim Tait: It likes this orange band here in terms of the mass. The mediator and coupling.

372
00:54:43.110 --> 00:54:56.190
Tim Tait: To leptons and g minus two of the electron forces you to live in this little tiny sliver that goes like this lightens up a little bit larger masses. So actually, it's very hard to get things to be totally self consistent

373
00:54:59.550 --> 00:55:10.020
Tim Tait: And even if you have canceled. Your anomalies, there are still some contributions that come from processes involving longitudinal modes of your vector particle

374
00:55:11.610 --> 00:55:25.080
Tim Tait: At high energies. So I'm really out of time so I'm actually just going to leave that at that. But these are important constraints that you have to look at that are not obvious because they are really can be thought of at some level was one loop processes, but they're still very important

375
00:55:27.030 --> 00:55:37.050
Tim Tait: So, and then an idea which is a received a lot of attention is the postulate. The new light force carriers, a dark photon and the idea is you add a new vector bows on with a small mass

376
00:55:37.680 --> 00:55:43.080
Tim Tait: And that's probably a whole dark Higgs sector under which the dark matter is charged with the standard model is not

377
00:55:43.530 --> 00:55:50.400
Tim Tait: But then you include this last term in the long run, which is the kinetic mixing term between the dark photon and the hypercharged goes on.

378
00:55:50.790 --> 00:55:56.730
Tim Tait: And then when you die, analyze the kinetic terms, you end up with an effective coupling of g to the dark matter.

379
00:55:57.150 --> 00:56:03.360
Tim Tait: But a coupling to Standard Model particles that looks like the electromagnetic coupling scaled down by the parameter epsilon

380
00:56:04.230 --> 00:56:12.540
Tim Tait: So that's one is small you naturally get small coupling to the standard model. I know. Jonathan things spent some time talking about this case, I'm not going to go through in great detail.

381
00:56:13.830 --> 00:56:20.280
Tim Tait: And of course, he told you all about all the great experimental searches that are currently being plotted to find particles like once

382
00:56:21.450 --> 00:56:27.000
Tim Tait: So to recap, part three, a complex dark sector expands the complexity of the physics of dark matter.

383
00:56:27.570 --> 00:56:33.870
Tim Tait: Given the complexity of that visible sector, it seems natural to imagine that the dark sector could impact could encompass a morally rich physics.

384
00:56:34.290 --> 00:56:41.310
Tim Tait: Dark Matter could be a composite built out of more fundamental ingredients and held together. You either by weak or strong self interactions.

385
00:56:41.910 --> 00:56:47.820
Tim Tait: A light mediator allows for several different phenomena and has become a standard element of the dark matter model, model building toolkit.

386
00:56:48.450 --> 00:56:53.670
Tim Tait: It could make contact with other low energy anomalies that are currently experimentally observed

387
00:56:54.300 --> 00:57:01.530
Tim Tait: They open up new processes for dark matter to participate in, and they can be searched at lower energy but higher luminosity experimental facilities.

388
00:57:02.100 --> 00:57:12.720
Tim Tait: So while we're still exploring the space of possible theories of dark matter. There's a rich experimental program that will explore these interesting regions of parameter space. And of course, there's a lot more to come, both from the theory and from the experiment.

389
00:57:13.650 --> 00:57:17.850

Tim Tait: So I'll leave you with my favorite diagram of dark matter. And thank you very much for listening.

390
00:57:19.500 --> 00:57:32.580
charlie young: Thank you very much. Tim, I really enjoy your series of three lectures on that matter tech sector. Great. So let's go to Q AMP. A now and Greg. Will you take over, please.

391
00:57:33.030 --> 00:57:34.590
grzegorz madejski: Sure. Um, can you hear me.

392
00:57:35.280 --> 00:57:46.770
grzegorz madejski: Yes, yeah. Great. Okay. So let me get cracking on questions, quite a few of them came in, even after your last lecture, we have a grand total of it but 658 for all three like

393
00:57:48.000 --> 00:58:05.010
grzegorz madejski: Yeah, so I certainly will not be able to get through all of them, but let me start with the very first one slide for the question is, is there any special relationship between the accident and the Python. Could you also relate the mass of the axiom to the massive another Meza

394
00:58:06.510 --> 00:58:08.970
Tim Tait: Um, there is actually a special relationship.

395
00:58:10.050 --> 00:58:20.430
Tim Tait: In some sense. I mean, it's not that special. But what happens is the accion mixes have very little bit with all of the pseudo scale or means on right the accion is a pseudo Skyler and because

396
00:58:20.940 --> 00:58:27.030
Tim Tait: By virtue of its existence CP is a good symmetry. So therefore it can only mix with the pseudo scale or maisons

397
00:58:27.540 --> 00:58:37.710
Tim Tait: Now it can mix with all of them. And it doesn't mix with all of them. However, the mixing goes something like the accion mass divided by the pie on, Matt. Sorry, by the mass of the maze on it's mixing with

398
00:58:38.340 --> 00:58:46.470
Tim Tait: And so it mixes the strongest with the lightest pseudo scale or means ons and therefore it mixes most strongly with the pion which is the lightest muscular

399
00:58:48.210 --> 00:58:50.940
Tim Tait: But there's nothing really special about the pie on other than that.

400
00:58:52.410 --> 00:59:04.290
grzegorz madejski: OK, and now the one that has to do with Slide six would the existence of a sterile neutrino in play the existence of a sterile leptons counterpart.

401
00:59:06.360 --> 00:59:15.420
Tim Tait: I mean, in some sense, a sterile neutrino is a sterile leptons. I guess if you're asking. I think probably the question is asking, is there a star. I'll charge left on

402
00:59:16.530 --> 00:59:18.390
Tim Tait: Which doesn't quite make you know

403
00:59:19.530 --> 00:59:26.730
Tim Tait: It doesn't make Samantha semantic sense because if it's sterile. It can't have electric charge. And therefore, it wouldn't look like a charge left on

404
00:59:27.300 --> 00:59:38.940
Tim Tait: But I think, to go back to the real question no. So the standard model left on ones that are left handed coming doublets. And so the neutrino that's left handed comes with an electron that's left handed or some other charge left on

405
00:59:40.380 --> 00:59:46.230
Tim Tait: The sterile neutrino isn't electroweak singlet and so it comes all by itself without the need for anything else.

406
00:59:48.180 --> 00:59:56.580
grzegorz madejski: Okay, the next one has to do Western neutrinos can sterile neutrino dark matter also be produced the ref result.

407
00:59:58.170 --> 01:00:02.400
grzegorz madejski: Can they also be much heavier than the key scale. That's a good question.

408
01:00:03.000 --> 01:00:12.300
Tim Tait: It is a good question. So, in principle, the answer is yes, a sterile neutrino could be produced by freeze out if it had you know sufficiently week interactions.

409
01:00:13.260 --> 01:00:22.650
Tim Tait: The thing is that the sterile neutrino at least the one that's responsible for producing neutrino masses has this decay diagram that I showed here, which means that

410
01:00:23.280 --> 01:00:32.520
Tim Tait: In general, as I make it heavier and the rate of that decay goes up. Right. Remember, because of face space have your particles are more likely to k the lighter particles.

411
01:00:34.200 --> 01:00:41.520
Tim Tait: It becomes more tricky to have the neutrino live long enough to be the dark matter and other words to have a lifetime. That's the board of the age of the universe.

412
01:00:42.270 --> 01:00:52.950
Tim Tait: So I think once you got to the point where you realize this, you'd have to make that mixing angle so tiny that it wouldn't probably be able to explain the neutrino masses that we see.

413
01:00:53.580 --> 01:01:03.150
Tim Tait: So it would still be a sterile neutrino. It could still be dark matter, it could still be producer freeze out but it probably would not be the explanation for why we see the neutrino masses that we do in the standard

414
01:01:05.940 --> 01:01:22.830
grzegorz madejski: Alright, the next one is probably there's sort of two questions that are relevant here that are very similar. Could you speak a little bit more on why the x ray signal is only possible one, I think that they're referring to the three and a half kV line.

415
01:01:24.060 --> 01:01:25.230
grzegorz madejski: The original one at

416
01:01:26.490 --> 01:01:30.450
Tim Tait: Right, so the signal is a three and a half TV.

417
01:01:32.340 --> 01:01:42.780
Tim Tait: It was observed actually by two different groups. So what's been plotted here is the one Bible at all. But there's also another group in Europe, which is seemed very similar results. And actually, in a very similar energy

418
01:01:45.060 --> 01:01:53.670
Tim Tait: The signal is seen by looking at stacks of galaxies. So you take a whole bunch of galaxies and, you know, they all have different they've all got different stuff in them.

419
01:01:55.140 --> 01:01:57.510
Tim Tait: Greg, actually you know a lot about this yourself personally

420
01:01:58.740 --> 01:02:10.260
Tim Tait: I think right that's right. It was the clusters, rather than galaxies, but the dark matter should always occur at the same energy. And so you put them all together all the data together and you hope the dark matter signal when peak true compared to the other stuff.

421
01:02:12.090 --> 01:02:23.520
Tim Tait: And even if you look at certain sets of data, you find a very nice signal. It doesn't seem to be explained by known atomic physics and it seems like it's distinct from the background noise.

422
01:02:24.690 --> 01:02:38.010
Tim Tait: Other groups, however, have looked in other locations. So for example, if you look at the Milky Way, our own galaxy. Right. It's got a lot less dark matter in it, but it's a lot closer to us. So any signal of dark matter, you know, is relatively a lot brighter.

423
01:02:39.150 --> 01:02:43.740
Tim Tait: You see what maybe a hint of a signal, but it's really not very convincing coming from our galaxy.

424
01:02:44.340 --> 01:02:49.650
Tim Tait: If you look at different sets of galaxy clusters, you actually find you don't really see the signal at all.

425
01:02:50.280 --> 01:03:01.920
Tim Tait: So that's the real reason we have sort of two things going on. Experimentally, it doesn't seem like we see the signal absolutely everywhere that we might hope to and so that that cast some doubt as to whether it's really dark matter.

426
01:03:02.550 --> 01:03:10.230
Tim Tait: And from a more theoretical side. There's also been some work that suggests that maybe there are even ordinary Standard Model lines that go to current that energy

427

01:03:10.680 --> 01:03:20.250
Tim Tait: That just you know correspond to kind of exotic atomic physics you know say involving potassium or something that we just don't really have very good measurements of or very good theoretical understanding of

428
01:03:21.480 --> 01:03:34.770
grzegorz madejski: Yeah, I think I can add here that there is a pretty strong evidence that settling does not exist in the observations of the prestigious cluster which we're done with the very high resolution energy resolution instrument on board if he told me before. Anytime you failed.

429
01:03:36.300 --> 01:03:43.380
grzegorz madejski: So hopefully we will have a lot more cluster data and in your future from the Athena and even before that from the prison missions.

430
01:03:45.030 --> 01:04:00.870
grzegorz madejski: Okay, so another question. Where does the Zenon one t experiments axiom hypothesis recently published fit into this plot on slide five, and is it intention with the current astrophysical limits.

431
01:04:02.130 --> 01:04:12.480
Tim Tait: Okay, so it doesn't really fit onto this plot at all the xenon does a report in excess of something scattering with electrons actually

432
01:04:12.930 --> 01:04:22.860
Tim Tait: Relativistic Lee, so something that carries a lot of kinetic energy. And as a result, it doesn't look very much like you'd expect. Dark matter to write dark matter should be non relativistic in order to be part of our Halo.

433
01:04:24.090 --> 01:04:24.840
Tim Tait: So,

434
01:04:27.150 --> 01:04:38.400
Tim Tait: So yeah, it doesn't really fit onto this plot. It is, however, in some tension with astrophysical limits for how astrophysical objects should be cooling. Right. Once you have a light.

435
01:04:38.850 --> 01:04:48.360
Tim Tait: Particle that couples to something say that your, your star is made out of your star can admit those particles and cool down and if it cools down too fast right faster than

436
01:04:48.810 --> 01:04:54.810

Tim Tait: Then is allowed, given the population of those objects you see around you, then you can put a limit on to the existence of that particle

437
01:04:55.770 --> 01:05:11.160
Tim Tait: There has been some discussion that these limits have some fairly large uncertainties that are not really very well quantified and so I think the situation is not totally clear definitely if you do things, you know, very simply, and just make a simple estimate its intention.

438
01:05:12.630 --> 01:05:18.240
Tim Tait: So that would argue, you have to do some work to try to explain your way around that tension by making your theory more complicated.

439
01:05:19.080 --> 01:05:27.000
Tim Tait: However, there is probably enough inherent uncertainty in the estimates that I think there's also a very healthy process going on right now where people are revisiting them and trying to understand

440
01:05:27.600 --> 01:05:40.350
Tim Tait: You know how we can make a bit more informed estimate of the limit, and that also might end up giving a may end up revealing that there's some corner of parameter space that's allowed but you know that hasn't been finished yet.

441
01:05:42.270 --> 01:05:59.820
grzegorz madejski: Okay, there is this actually relevant to another question which you probably answered already in this this last statement on slide 12 the questioner at the person who asked the question says for these plots are the colored areas allowed are prohibited by ATLAS and CMS.

442
01:06:00.840 --> 01:06:14.670
Tim Tait: Yeah, no, that's a good question. The two plots actually use color somewhat differently. So let's start with the Atlas plot basically the Atlas plot is that at 95% competence limit everything enclosed inside this solid black line is excluded.

443
01:06:16.290 --> 01:06:23.640
Tim Tait: And everything outside of it is allowed. Right. So everything that everything, starting with the 00 mass point and you know inside the wedge is excluded.

444
01:06:24.420 --> 01:06:34.080
Tim Tait: The colors here are really just showing what the expected limit was compared to the observed limit. And that's something you always want

to do because you want to make sure that something has not gone wrong with your analysis.

445
01:06:34.560 --> 01:06:46.620
Tim Tait: So, you know, if you get a limit that looks wildly different than one of the one you expected to get, then chances are you forgot to do something or you didn't take some effect into account when you made your estimation and that calls into question kind of the whole thing.

446
01:06:47.820 --> 01:06:54.210
Tim Tait: The CMS actually limit us as something usually uses color in a very different way. So,

447
01:06:55.560 --> 01:07:02.520
Tim Tait: In general what it's doing is it's allowing that the production cross section for this process can be scaled up and down.

448
01:07:04.080 --> 01:07:11.370
Tim Tait: Compared to what you would expect to get for the couplings that they chose so right they chose these couplings to quarks and couplings. The dark matter.

449
01:07:11.820 --> 01:07:18.540
Tim Tait: And if you make that choice, you would be at one on their color scheme. And that's why, if you look at where that color occurs. It's sort of this

450
01:07:19.290 --> 01:07:30.990
Tim Tait: Greenish in between yellow and you know turquoise color. It's the red line and that's their observed 95% confidence limit. So again, what's excluded is inside here. If these couplings are true.

451
01:07:32.130 --> 01:07:42.150
Tim Tait: If you were to scale the couplings down though, you would produce skewer particles and you get a weaker limit. And so then the shading of the colors shows you how to do that. So if you were to

452
01:07:42.660 --> 01:07:56.760
Tim Tait: Scale them down scale, the whole cross section down by a factor of 10 you'd go from this greenish color to this kind of like blue color on the boundary between turquoise and deeper blue and you get a limit that would look I guess something more like

453
01:07:58.200 --> 01:08:00.960
Tim Tait: Like a few hundred GB to maybe a TV.

454
01:08:02.520 --> 01:08:04.290
Tim Tait: I don't know if you can see me trying to

455
01:08:05.910 --> 01:08:07.740
Tim Tait: sketch it with the cursor.

456
01:08:09.060 --> 01:08:20.040
Tim Tait: So yeah, the color on the CMS plot is trying to give you some idea of what would happen if you change your assumptions about the color couplings, the color on the Atlas plot is really just trying to compare what they saw versus what they expected to see.

457
01:08:21.990 --> 01:08:31.170
grzegorz madejski: Okay, now there's a fairly complex question which sort of is listed in two parts. So let me read the first part and then I'll say the second thing I'm not sure.

458
01:08:31.260 --> 01:08:42.300
grzegorz madejski: If I understand completely. Is this quote simplified model basically searching through a more general parameter space of dark matter mass media mass or cap link.

459
01:08:42.930 --> 01:08:52.950
grzegorz madejski: And seeing which overall combinations of values are allowed so far by data or not. Instead of trying to test one particular theory at a time.

460
01:08:53.730 --> 01:09:08.070
grzegorz madejski: And then they elaboration of this is for full models, what is typical range of VR of Z underscore V going to Chi Chi and how do they influence the results.

461
01:09:09.780 --> 01:09:11.610
Tim Tait: So the original

462
01:09:12.660 --> 01:09:13.470
Tim Tait: Question.

463
01:09:16.500 --> 01:09:21.210
Tim Tait: I think the original statement is a fair summary, I would just put the caveat on it that

464

01:09:22.200 --> 01:09:31.110
Tim Tait: You still need to specify the structure of the simplified model. So it's not totally generic in mass, mass and coupling, you have to add the structure, like for example.

465
01:09:31.500 --> 01:09:46.800
Tim Tait: In this case, the dark matter interacts with a vector mediator, which also interacts with corks in the other case, we had a case where the dark matter interacted with a scale or particle that carried us to three color but up to that quibble the statement is correct.

466
01:09:48.930 --> 01:09:51.930
Tim Tait: This question about the branching ratio.

467
01:09:53.280 --> 01:09:55.560
Tim Tait: I'm not sure.

468
01:09:57.960 --> 01:10:08.880
Tim Tait: I mean, it's a model specific question. And so in general a full theory will make a prediction for what that branching ratio is even if a simplified model doesn't. Maybe that's the best way to answer it.

469
01:10:10.770 --> 01:10:27.300
grzegorz madejski: Alright, the next one is in the vector and scale our dark mediator theories are this mediators, then the bulk of what we see as dark matter or are they in addition to the dark matter that makes up 25% of the universe pie.

470
01:10:28.740 --> 01:10:39.570
Tim Tait: Right. So actually, in both of these cases, the mediator particle is not actually the dark matter, it would have dictated into the dark matter by today and so

471
01:10:40.590 --> 01:10:48.960
Tim Tait: It makes up, none of the dark matter and they are some particles that are in addition that are not currently present in the universe. But we're at early times

472
01:10:50.700 --> 01:11:00.450
grzegorz madejski: Okay, I think I'll have time for questions. So we should thank you very much them for great lecture today and series of three excellent lecture so I

473
01:11:01.110 --> 01:11:12.330

grzegorz madejski: Will send you all our questions are in some kind of form for you to put together answers for and then we're going to post them on indigo Charlie, do you have anything else to add before we take a break.

474
01:11:12.870 --> 01:11:20.250
charlie young: No, thank you very much. Tim thank you Greg for doing the Q AMP. A so I think I'll stop the recording now.