WEBVTT

1
00:00:09.719 --> 00:00:11.820
Tim Tait: All right. Can everyone hear me now.

2
00:00:12.540 --> 00:00:15.240
Tim Tait: Yes. And you can see my slide that ticket.

3
00:00:16.260 --> 00:00:16.680
Lisa Kaufman: We can

4
00:00:17.340 --> 00:00:18.210
Tim Tait: Excellent. Okay.

5
00:00:19.140 --> 00:00:30.480
Tim Tait: So here's the outline that we saw yesterday, we got through most of actually what I plan to do for lecture one, and there's a little bit. We're going to catch up with before we move on to talking about specific theories of dark matter.

6
00:00:31.590 --> 00:00:38.010
Tim Tait: So what we saw yesterday is despite the fact that we know very little about its fundamental nature.

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00:00:38.790 --> 00:00:51.570
Tim Tait: What we know about dark matter is still enough that actually constructing a realistic theory, for it is highly constrained. And that's because we needed to be long lived electrically and SU three charge neutral and we have to respect the symmetry of the standard ball.

8
00:00:53.370 --> 00:01:02.070
Tim Tait: Once you have a theory of dark matter, we can ask ourselves how it may have been produced in the early universe, and we saw how to do that using freeze out freeze in which are both thermal processes.

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00:01:02.490 --> 00:01:05.490
Tim Tait: And we very briefly described a non thermal process as well.

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00:01:06.390 --> 00:01:18.210
Tim Tait: For the thermal cases a Boltzmann equation tracks how the number density evolves and can lead to the correct abundance and different regimes both freeze out and freeze and can reproduce the observed abundance in different parts of the parameters space.

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00:01:19.230 --> 00:01:27.150
Tim Tait: So the last thing I wanted to talk about thats related to dark matter production in the early universe is actually talking about some caveats.

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00:01:27.540 --> 00:01:35.490
Tim Tait: There was one very key assumption that we made and all of our discussions yesterday and that assumption was that the universe has a standard history.

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00:01:35.970 --> 00:01:46.260
Tim Tait: So what I've got here is a cartoon of the universe at different temperatures. So the temperature is what's plotted along the axis as we go from earlier times, it was hotter to later times it's colder.

14
00:01:46.770 --> 00:01:54.810
Tim Tait: I put down some of the things that we've actually measured. For example, we have good measurements of the cosmic microwave background which takes place at around EV scale.

15
00:01:55.290 --> 00:02:07.500
Tim Tait: We actually measure the primordial abundances of the light elements which were produced by big bag nuclear synthesis. Those take place at the MTV scale. And you can see that actually as we go backwards in time.

16
00:02:08.370 --> 00:02:18.330
Tim Tait: We started off with the university really described by atomic physics we get into a region where the universe is largely described by nuclear physics. And then above the GV scale or so we get to a universe.

17
00:02:18.720 --> 00:02:28.260
Tim Tait: Which is described by particle physics. So everything actually before Big Bang Nicholas emphasis is somewhat uncertain, because we haven't actually

18
00:02:29.190 --> 00:02:40.860
Tim Tait: Taken any measurements which directly constrain the properties. We know that if we run QC at the high temperatures, it looks like it should be confined and temperature around a GV or so around lambic UCB

19
00:02:41.520 --> 00:02:48.780
Tim Tait: We think the dark matter may have frozen out of course, assuming the present is the way that happens is the dark matter mass is around

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00:02:49.470 --> 00:02:57.300
Tim Tait: 100 GV to a TV that freezes out would happen somewhere around 10 GV to one GB. So somewhere a little bit above the QC confinement scale.

21
00:02:57.900 --> 00:03:01.830
Tim Tait: And it's still earlier times, we think that the electronic symmetry should be restored.

22
00:03:02.220 --> 00:03:08.310
Tim Tait: The WC and all the Permian shouldn't become effectively mass list and that takes place to the temperature of around 100 GB

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00:03:08.730 --> 00:03:19.440
Tim Tait: And somewhere maybe at their or around there. We have to produce any symmetry in the baryons so basically everything going backwards up to BBN

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00:03:19.980 --> 00:03:31.320
Tim Tait: Is someplace where we have data that firmly anchors our understanding. And then as we go past that we really just have what we've measured and discovered in particle physics to give us a guide as to what we expect happened when you run the movie backwards.

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00:03:33.030 --> 00:03:43.110
Tim Tait: So features like inflation dark matter and the existence of the Baron asymmetry are all indications ingredients are missing it earlier times, and that this extrapolation is uncertain.

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00:03:44.100 --> 00:03:53.760
Tim Tait: So let's actually just illustrate where things could be different, by talking about a freeze out relic. So we just discussed the freeze out process in the standard cosmology yesterday.

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00:03:54.420 --> 00:04:00.690
Tim Tait: Let's illustrate how things could be different if in our free calculation. If the universe were to evolve differently.

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00:04:01.140 --> 00:04:06.360
Tim Tait: So of course, as we just said, what we really understand is the universe back to about the time of nuclear synthesis

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00:04:06.570 --> 00:04:12.000

Tim Tait: From the abundance of the primordial abundances of hydrogen, helium and lithium and that's what about the movie scale.

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00:04:12.300 --> 00:04:18.150
Tim Tait: And this is a plot actually from the particle data book that just shows some of those measurements to help us constrain parameters of the universe.

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00:04:18.990 --> 00:04:32.820
Tim Tait: But what does this mean for dark matter that was freezing out so typical Wimp had already frozen out through annihilation at a much earlier time and that means that the physics that was going on at the time of the freeze out is not actually very well constrained by BBN

32
00:04:34.770 --> 00:04:41.340
Tim Tait: But you could imagine that after the freeze out happened. Maybe there was some other particle around which also decayed in the dark matter.

33
00:04:41.700 --> 00:04:52.650
Tim Tait: That would raise the amount of dark matter I end up with at the end of the day, and it would change my calculation, because of the existence of this particle that I'm assuming is there after dark matter has

34
00:04:53.670 --> 00:05:05.430
Tim Tait: Frozen out through annihilation, but that I don't know exists, based on my current understanding. So that would basically change the bridge in a parameter space, I would want to live in to get the right amount of dark matter that I see today.

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00:05:08.280 --> 00:05:15.300
Tim Tait: So you can imagine also that physics could look different from our expectations because of a vacuum expectation value or whatnot.

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00:05:15.660 --> 00:05:20.850
Tim Tait: Right. We already know that the electric symmetry is expected to be restored if we went to temperatures above 100 GB

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00:05:21.210 --> 00:05:26.430
Tim Tait: And so, in fact, we would have to change our present calculation. If we were freezing out of the temperature above 100 GB

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00:05:26.760 --> 00:05:32.490

Tim Tait: Because we would have to take into account the fact that the Higgs doesn't have a vacuum expectation value at those large temperatures

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00:05:32.820 --> 00:05:42.630
Tim Tait: What if there's some other vacuum expectation value that is also changing around the time of freeze out. So maybe, maybe some of the dark matter mass comes from this vacuum expectation value.

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00:05:43.020 --> 00:05:50.820
Tim Tait: Right. Or maybe the fundamental constants of physics are dependent on these vacuum expectation values. Basically, if they change at some point.

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00:05:51.540 --> 00:05:58.500
Tim Tait: Earlier than BBN so we don't mess up any of our measurements, it would change the way the dark matter freezes out by changing the parameters that go into the calculation.

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00:06:00.690 --> 00:06:09.180
Tim Tait: You can also imagine that there's some other particle that decades after the dark matter freezes out, but instead of decaying into the dark matter, it just the haze in the ordinary Standard Model stuff.

43
00:06:09.690 --> 00:06:15.570
Tim Tait: Well, that's still actually dilutes the dark matter. We have by adding more radiation produces entropy basically

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00:06:16.110 --> 00:06:24.510
Tim Tait: So another particle even one that doesn't have anything to do with dark matter, but still the case into the standard model would still actually impact the relevance of the calculation.

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00:06:25.770 --> 00:06:34.920
Tim Tait: And finally, you could imagine that there could be some unexpected early period of matter domination or inflation. Remember our calculations assume that the universe was radiation dominated

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00:06:35.490 --> 00:06:40.710
Tim Tait: If there are these unexpected periods of some other type of evolution of the universe, then we would

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00:06:41.520 --> 00:06:50.280
Tim Tait: Be we would, that would change the effective density of dark matter, we would have today. And so it would actually cause our calculations to get thrown off.

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00:06:50.760 --> 00:07:00.750
Tim Tait: So the point of this actually is that this is a feature we shouldn't think of the freeze out calculation as constraining our theories and telling us where they have to live.

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00:07:01.230 --> 00:07:09.360
Tim Tait: We should actually think about them as showing what a theory predicts for the relic density under the assumption of a given cosmology.

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00:07:09.810 --> 00:07:16.890
Tim Tait: And so with the standard cosmology, we just do the calculation that we had yesterday. If it's non standard in any of the ways of the cartoon here.

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00:07:17.520 --> 00:07:24.570
Tim Tait: Then you would have to change that calculation. So what I would try to say is that once you discover dark matter and start measuring its interactions.

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00:07:24.840 --> 00:07:31.200
Tim Tait: It's not so much that you're going to have constrained the space of those interactions, using the density of dark matter, we see

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00:07:31.620 --> 00:07:37.770
Tim Tait: Instead, what you're going to do is you're going to use the matching between your freeze out calculation.

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00:07:38.520 --> 00:07:44.160
Tim Tait: And the theory to understand whether or not any of the other things that could have happened did happen.

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00:07:44.550 --> 00:07:52.830
Tim Tait: So in other words, the freeze out calculation is not really a probe of the parameters face of a dark matter model. What it is, is it the probe of the cosmological history.

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00:07:53.610 --> 00:07:59.160
Tim Tait: And we often see the state of differently just because we assume a standard history and it may very well be that history is standard

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00:07:59.970 --> 00:08:09.540

Tim Tait: But until we actually use the logic this way and reconstruct it. We're not really sure. So I would like to push that as the way that we should think about this.

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00:08:11.760 --> 00:08:18.210
Tim Tait: So here's how I synthesize that with a cartoon by Calvin and Hobbes, I'll give you a second to read it.

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00:08:20.400 --> 00:08:30.120
Tim Tait: The upshot though is that you should probably call the creation of the universe, the horrendous space completely and I would invite you to use that term and your next paper.

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00:08:34.860 --> 00:08:42.300
Tim Tait: Alright, so now I can finish my full recap for part one, we already went through the first three points that told us about how dark matter is produced.

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00:08:42.720 --> 00:08:50.640
Tim Tait: And then the last to just summarize the discussion we just had, we should really be cautious in terms of how we use the relic abundance to motivate the parameter space of a model.

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00:08:51.270 --> 00:08:57.300
Tim Tait: If our assumptions about the history of the universe or incorrect. It may point us in the wrong direction and a better way would be to look at it.

63
00:08:57.540 --> 00:09:07.200
Tim Tait: A better way to look at it would be the relic two buttons is something that we can combine with a knowledge of the particle nature of dark matter to constrain the properties of early cosmos.

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00:09:09.630 --> 00:09:21.780
Tim Tait: OK, so the bulk of what we're going to talk about today in this lecture are about is about specific theories of dark matter. So these are theories that exists for various reasons. Some of them exist, mostly to explain dark matter.

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00:09:22.350 --> 00:09:31.950
Tim Tait: Most of them explain that exist actually displaying other mysteries of the standard model and we're going to see how they lead to a variety of different visions for what the dark matter can be

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00:09:33.270 --> 00:09:42.990

Tim Tait: So I'm back to my Venn diagram from 2013 again, we're going to talk about some of the theories that we see here in particular will touch a little bit on supersymmetric theories

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00:09:43.560 --> 00:09:49.200
Tim Tait: They're kind of a generic theory of a wimp. And actually, the comments that we make a lot of them will also apply

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00:09:49.620 --> 00:10:03.600
Tim Tait: To theories with universal extra dimensions or theories, with little Higgs and we'll spend a little bit of time also discussing things like sterile neutrinos accion is dark matter and so on.

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00:10:06.300 --> 00:10:18.120
Tim Tait: So in order to talk about these theories, part of what we have to do is discuss the phenomena that we'd expect to see. And this is where this lecture is going to connect very directly with some of the other lectures that you're having this week.

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00:10:19.170 --> 00:10:28.560
Tim Tait: So you've already seen one lecture I guess I'd have to from Tracy slight year and Jonathan thing, who talked about indirect detection and accelerator production.

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00:10:29.010 --> 00:10:32.880
Tim Tait: I'm actually mostly going to be thinking about the high energy end of that or the collider searches.

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00:10:33.330 --> 00:10:39.270
Tim Tait: But you'll see there's a lot of connection between what they were saying. And what I'm going to touch on here and I wanted to remind you of that fact.

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00:10:39.930 --> 00:10:49.440
Tim Tait: And I guess later this week you'll have the first lectures from Professor Jody Cooley, who was talking about direct detection, where the dark matter is scattering with the standard model.

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00:10:50.250 --> 00:10:56.610
Tim Tait: And so the dark matter model has to predict the rate. And all three of these kinds of searches of dark matter for dark matter and it relates them to each other.

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00:10:58.830 --> 00:11:08.160

Tim Tait: So I have a sort of lightning reminder of what each one is you just saw Tracy's first lecture yesterday, so you probably don't really need a an in depth reminder

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00:11:08.430 --> 00:11:15.060
Tim Tait: Right indirect detection is looking for dark matter annihilating and producing high energy standard model particles that we can see on Earth.

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00:11:15.480 --> 00:11:29.820
Tim Tait: And there's a large number of things that we built to look at factors that we built to look for these kinds of events. So for example, the first Fermi Large Area Telescope is something that had a lot of development. It's like National Lab itself looking for gamma rays.

78
00:11:30.840 --> 00:11:39.690
Tim Tait: There is the ice cube detector which is looking for high energy neutrinos. And of course, this is not exhaustive. This is just to give you a couple of examples of this kind of search

79
00:11:41.100 --> 00:11:42.930
Tim Tait: direct detection, what you're going to learn about

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00:11:43.590 --> 00:11:55.230
Tim Tait: Shortly. He's searching for the dark matter scattering with a target. This is typically a heavy nucleus. So now there's a lot of interesting activity going on where you're looking at other targets as well like electrons or even

81
00:11:55.530 --> 00:12:05.670
Tim Tait: Interactions at the molecular or atomic level, but the basic strategy is you look for a low energy recoil of your detector elements when the dark matter comes and brushes against it.

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00:12:06.060 --> 00:12:15.540
Tim Tait: We think there should be dark matter all around us to explain the dynamics of the Milky Way. And so some of that if it interacts appreciably enough should sometimes EXCITED OUR protectors.

83
00:12:16.350 --> 00:12:23.670
Tim Tait: So it's looking directly for the dark matter in our halo a positive signal would be a direct observation. It's a very satisfying way to actually detect dark matter.

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00:12:24.360 --> 00:12:35.940

Tim Tait: These detectors are very sensitive they require heavy shielding and secondary characteristics of the interaction like simulation light or timing to help filter out the backgrounds, you can understand many of them in this way.

85
00:12:36.960 --> 00:12:43.140
Tim Tait: In the non relativistic limit the dark matter nuclear interaction can either be a constant. So a spin independent scattering

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00:12:43.500 --> 00:12:48.510
Tim Tait: Or the dot product of the spin of the dark matter with the spin of the nucleus. And that's called spin dependent scattering

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00:12:48.930 --> 00:12:55.740
Tim Tait: And these experiments typically quote bounds on either one of these two types of interactions. And so that's why I wanted to make sure

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00:12:56.460 --> 00:13:08.940
Tim Tait: I mentioned them here. These images here show some illustrations. One is the supersede EMF detector which is made out of germanium and the second one is xenon based detector LD.

89
00:13:11.550 --> 00:13:17.970
Tim Tait: And then finally we have collider productions, you already heard something from Jonathan yesterday and I saw from his slides that he did talk about this a little bit.

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00:13:18.390 --> 00:13:22.650
Tim Tait: I'm going to be focused just on the highest energy. So, not on the lower energy accelerator production.

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00:13:23.190 --> 00:13:35.490
Tim Tait: But if the dark matter couples to quarks and gluons. We should be able to produce it and high energy colliders the detectors. So here's an illustration of the CMS and the Atlas detectors Atlas is again something that slack works on quite a bit.

92
00:13:36.570 --> 00:13:43.950
Tim Tait: They're not designed to be sensitive to dark matter. The dark matter just interacts to weekly and typically goes right through them doesn't leave any measurable trace

93
00:13:44.190 --> 00:13:49.680
Tim Tait: So what it manifests as it is as an imbalance in the energy momentum of the collision.

94
00:13:50.130 --> 00:14:00.000
Tim Tait: So typically, because we don't know the center of mass energy of the quarks and gluons that are colliding, what we can do, however, is look for momentum balance along the transverse direction to the beam.

95
00:14:00.540 --> 00:14:12.570
Tim Tait: And so usually see this referred to as a missing transverse momentum signal and also you can often call it a missing energy signal, but we're actually measuring the momentum and momentum, the vector. So I don't really like calling it that.

96
00:14:13.740 --> 00:14:27.900
Tim Tait: Sometimes I slip up and say it anyway though. So I guess I'm guilty as well. And this is a lot like the kind of signals that you can produce when you make high energy neutrinos in the standard model and of course the LA. He has too many events of that type already

97
00:14:30.210 --> 00:14:37.080
Tim Tait: So there are sort of two different ways you can imagine dark matter manifesting and a collider. And I think Jonathan focused on the first one at the top.

98
00:14:37.470 --> 00:14:45.210
Tim Tait: This is where you produce some other particles in the dark sector, which then maybe decay into the dark matter and some visible energy in the form of Standard Model particles.

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00:14:45.960 --> 00:14:54.960
Tim Tait: So this is like production of say Wimp or dark matter siblings or maybe mediator particles, which then decay into dark matter and other standard model states.

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00:14:55.890 --> 00:15:05.790
Tim Tait: You can also actually imagine producing the dark matter directly along with some radiation from the initial state and there you can actually directly produced dark matter pairs.

101
00:15:06.240 --> 00:15:13.620
Tim Tait: There may be a mediator inside this process that may or may not be on shell, but this is usually called a Mano jet or a Moto X signal.

102
00:15:14.070 --> 00:15:24.600
Tim Tait: So if this extra radiation is a jet, you would call it moto jet and if it's something else you could call it Moto X or you know Mano de

mano a mano gamma all of those searches actually exist. And they're all interesting

103
00:15:27.060 --> 00:15:37.140
Tim Tait: Alright, so now let's start talking about our first example of a specific theory of dark matter. So that theory is supersymmetry or Susie to it's friends.

104
00:15:37.740 --> 00:15:42.000
Tim Tait: It's the most famous candidate for dark matter is they supersymmetric particle

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00:15:42.900 --> 00:15:48.780
Tim Tait: supersymmetry, of course, very famously doubles the number of fields of the standard models. If I start with the standard model.

106
00:15:49.170 --> 00:16:01.230
Tim Tait: I get a partner for every standard model particle, they're usually indicated by putting a tilda on top of the Standard Model particles name. So for all six of the scores. There are actually

107
00:16:02.280 --> 00:16:06.630
Tim Tait: All six of the quirks of the standard model. Of course, there are actually 12 scores.

108
00:16:07.170 --> 00:16:15.090
Tim Tait: And that's because the Standard Model corks come in both left and right handed varieties. And so there's a score for each one of those the score being a scale or

109
00:16:15.660 --> 00:16:25.230
Tim Tait: Doesn't have a handedness. And so each polarization get sounds killer particle, then the leptons very similarly in a standard model are partnered with slept ons.

110
00:16:25.770 --> 00:16:38.400
Tim Tait: And so these are the scale or partners of the neutrinos or neutrinos. The scale of partners of the charged leptons are which are usually called charged slept ons, or you can also call them select Ron's nuance or spouse.

111
00:16:39.000 --> 00:16:46.590
Tim Tait: I have to say, super symmetries naming convention always strikes me as a little bit silly and then the force carriers are the standard model.

112
00:16:48.150 --> 00:17:02.250
Tim Tait: The photon the glue on the Z and the W get their own super partners. The 14 oh the glue vino vino and the wino and for technical reasons, actually the supersymmetric version of the standard model has to get

113
00:17:03.210 --> 00:17:16.740
Tim Tait: Those arms are two ways Dublin's actually two things doublets really means five Higgs bosons to neutral CP even exists one neutral CP odd Higgs and a pair of charge, take this and this, then turns into two different things. He knows when I supersymmetry.

114
00:17:17.940 --> 00:17:26.490
Tim Tait: So I'm going to focus on how to pick out the features of a supersymmetric theory, such as the minimal super centric standard model that are important to understand how it describes dark matter.

115
00:17:27.360 --> 00:17:39.660
Tim Tait: This image down in the lower left corner. If you haven't seen it before. It's a nice quasi crystal representation of the Standard Model plus supersymmetry of it came out of the particle fever movie of a few years ago.

116
00:17:41.730 --> 00:17:49.920
Tim Tait: So let's talk a little bit about the structure supersymmetry, and what it predicts. We know that we just learned that supersymmetry takes all of the Standard Model particles.

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00:17:50.400 --> 00:17:57.900
Tim Tait: And doubles them by producing superpartner versions of them. And if we break the supersymmetry softly with a technical term that

118
00:17:57.900 --> 00:17:58.590
SLAC IT - Tom Patterson: Just means

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00:17:59.160 --> 00:17:59.880
Tim Tait: We don't actually

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00:17:59.910 --> 00:18:08.730
Tim Tait: Change the interactions of the supersymmetric theory. What we do is we just give masses to the super partners. So that's a soft breaking them supersymmetry.

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00:18:09.270 --> 00:18:14.850
Tim Tait: The masses are different from each other, which explains why we haven't produced super partners, yet at accelerators.

122
00:18:15.660 --> 00:18:21.210
Tim Tait: Or anywhere else that we've seen, but the interactions are still fixed by supersymmetry, and three right for

123
00:18:21.630 --> 00:18:34.290
Tim Tait: For technical reasons you usually want to break supersymmetry softly. If you break it softly. It's just a spontaneously broken symmetry, whereas if you were to break it in a hard way, you would just kind of say there is no actual symmetry here at all.

124
00:18:35.400 --> 00:18:41.220
Tim Tait: So despite having many, many new parameters supersymmetric theories actually inherit a huge structure from the standard model.

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00:18:41.940 --> 00:18:48.780
Tim Tait: This implies that many things can be calculated in a theory that supersymmetric just in terms of the masses of the super partners.

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00:18:49.560 --> 00:19:00.930
Tim Tait: So for example, if I think about the electromagnetic interaction. So starting off with the Standard Model interaction between a photon into electrons. That's the upper fireman diagram. Here are their profile and vertex here.

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00:19:02.430 --> 00:19:10.980
Tim Tait: The supersymmetric versions of that include both a diagram where the superpartner the photon. The fortino interacts with one ordinary electron

128
00:19:11.460 --> 00:19:25.470
Tim Tait: And one supersymmetric electrons are so electron and that has the same coupling strength as the original Standard Model vertex did. They're both controlled by alpha electromagnetic and then

129
00:19:26.610 --> 00:19:38.040
Tim Tait: There are more interactions and blind. There's also an interaction between the photon and to select Ron's so now the photon is the standard model particle. And there are two electrons is the superset particle

130
00:19:38.520 --> 00:19:51.240

Tim Tait: And even interaction between two photons and twos electrons. And these are also governed by the same coupling from you. One electromagnetism alpha electromagnetic as the other vertices are

131
00:19:52.830 --> 00:20:04.110
Tim Tait: There's a very nice review by Steve Martin that's on the archive that has a very nice complete introduction to Susie. I'm really just going to focus on some of the things we need to understand to talk about dark matter and supersymmetric theory.

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00:20:06.060 --> 00:20:15.240
Tim Tait: So if you want to work on a little exercise to see how well you understand that. And here's something you could try to do

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00:20:15.690 --> 00:20:21.540
Tim Tait: So given the interactions of the Higgs boson, and the standard model which you could look up, for example, in the textbook by Michael Peskin

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00:20:21.990 --> 00:20:31.860
Tim Tait: And using the same logic is on the previous slide, try to guess what kinds of vertices exist for the superpartner of the neutral Higgs Boson and the supersymmetric version of the standard model.

135
00:20:32.280 --> 00:20:47.190
Tim Tait: And if you succeed at doing that you can actually check your answer using this archive paper which contains the entire supersymmetric Lagrangian and find minerals. It is a long paper, though. And it's kind of overwhelming. So try not to get lost.

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00:20:49.140 --> 00:20:57.150
Tim Tait: So by itself supersymmetry doesn't say anything about the super particles being stable and therefore it's not clear that we have a stable massive particle

137
00:20:57.660 --> 00:21:06.240
Tim Tait: And it also has another feature which we don't really like it has interactions which would lively violate very on and left on number and you scary things like make proton decay.

138
00:21:06.540 --> 00:21:13.020
Tim Tait: And that's because strictly speaking in the supersymmetric theory, you can write down vertices that contained interactions, like for example.

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00:21:13.440 --> 00:21:28.170
Tim Tait: An anti up an anti down cork interacting with an anti strange superpartner so it's very awkward to call this the strange. So I'm just going to call it this strange score.

140
00:21:29.220 --> 00:21:35.340
Tim Tait: There are also vertices and allow this strange score to interact, for example, with an electron and enough cork.

141
00:21:35.790 --> 00:21:50.850
Tim Tait: And if I put these vertices together in this combination. I can start with a proton, which is made up, up, up to up corks down cork and I can actually use this these vertices to decay it into a positron and apply zero Muslim

142
00:21:51.990 --> 00:21:54.720
Tim Tait: So these vertices would actually allow protons did okay

143
00:21:55.230 --> 00:22:06.210
Tim Tait: And that would be bad because we've looked a lot for proton decay and we have very stringent limits on the lifetime of the proton. That means that if these interactions exist in nature. They have to be really, really weak interactions.

144
00:22:06.750 --> 00:22:14.610
Tim Tait: So the usual thing that one would do is just forbid these interactions from happening at all by adding an extra symmetry to the supersymmetric theory.

145
00:22:15.090 --> 00:22:21.750
Tim Tait: And that symmetry is usually goes by the name of our parody. So our parity is defined in this kind of funny way, it's

146
00:22:22.440 --> 00:22:33.450
Tim Tait: The charge the parody charge of a particle is given by minus one to the power of three times. It's very odd number minus it's slept on number plus two times it's been

147
00:22:34.050 --> 00:22:41.700
Tim Tait: So this is designed in such a way that if I actually evaluated for all the different particles and super particles of the minimal supersymmetric standard model.

148
00:22:42.030 --> 00:22:46.830

Tim Tait: I find that all the Standard Model particles have charged plus one, right, they don't transform

149
00:22:47.400 --> 00:22:57.450
Tim Tait: And all the super partners have charged minus one. So they go into minus themselves. When I act with this summit this parody. And so this is actually an example of the same as the two symmetry that we saw.

150
00:22:58.860 --> 00:23:04.200
Tim Tait: In the previous lecture that would which would force the dark matter particle to be stable.

151
00:23:04.590 --> 00:23:13.740
Tim Tait: It also has the side benefit, which might even be more important from some point of view of making the model be self consistent that it forbids these interactions and allow the proton. Okay.

152
00:23:14.400 --> 00:23:22.680
Tim Tait: So it does two things for us right no proton decay. That's good. And it produces a stable particle that means we've now got a chance to have dark matter and our theory.

153
00:23:24.570 --> 00:23:25.200
Tim Tait: Of course,

154
00:23:26.220 --> 00:23:31.020
Tim Tait: Now, if the dark matter of all the super particles have our charge minus one.

155
00:23:32.340 --> 00:23:45.120
Tim Tait: Then, what that means is that as the heavier ones decay. They'll decay down lightest one the latest one is the lightest particle. That's our parody odd and therefore, we can't get any further. And that means that

156
00:23:45.960 --> 00:23:57.900
Tim Tait: It's the thing that stable. So in order to actually be dark matter, we'd have to make sure that that's light as particle that lights are on particle in the light of supersymmetric particle which is usually abbreviated as MSP

157
00:23:58.560 --> 00:24:06.870
Tim Tait: Is something that is suitable to play the role of dark matter, or in other words, something that has no electric charge or SU three charge and so on.

158
00:24:07.950 --> 00:24:16.020
Tim Tait: So forgiven model of supersymmetry breaking, you can actually calculate what the masses and all the super particles are so calculate the spectrum of the super particles.

159
00:24:16.440 --> 00:24:22.680
Tim Tait: And then determine which one is the lightest and in fact there were some generic trends that come about from the normalization group.

160
00:24:23.160 --> 00:24:28.890
Tim Tait: So remember the normalization group actually lets you evolve the parameters that one of the just scale to another energy scale.

161
00:24:29.460 --> 00:24:39.600
Tim Tait: And the idea is if I know I'm looking at the diagram here. If I look at for some specific theory where Supersymmetry. Is broken at some very high energy scale.

162
00:24:39.960 --> 00:24:45.030
Tim Tait: So like for example 10 to 15 GB or it looks like they chose tend to the 16 GB and the plot.

163
00:24:45.810 --> 00:24:53.100
Tim Tait: What they've done is they have a simple model of supersymmetry breaking that basically says all the scale of particles have one mass parameter

164
00:24:53.610 --> 00:25:01.620
Tim Tait: All of the Fermi on have another mass parameter. And then there's actually a third combination that describes the masses of the Higgs boson, and that theory.

165
00:25:02.940 --> 00:25:11.310
Tim Tait: But we do experiments down at lower energies right at the LA CD energy is TV. So that would be three on this.

166
00:25:14.490 --> 00:25:27.450
Tim Tait: On this particular diagram X axis. So if we look at TV energies, what happens is because of the interactions of these particles their masters, get rid normalized and they take different values that low energies.

167
00:25:27.720 --> 00:25:34.470

Tim Tait: And so you can see that, despite the fact, let's just look at the solid black lines for a second, despite the fact that the glue, we know

168
00:25:34.800 --> 00:25:40.740
Tim Tait: The wino and the Beano right that's the partner of hypercharged direction all had the same mass and high energies.

169
00:25:41.040 --> 00:25:52.170
Tim Tait: Because of the strong interaction. The Guido mask. It's changed by a lot when I evolved down below energies, such that it's much heavier. It's actually, you know, more than a factor of two heavier than it was at

170
00:25:52.650 --> 00:26:01.170
Tim Tait: The high scale where supersymmetry was broken the windows mass has decreased a little bit, but it's still pretty similar to what it was at the high scale.

171
00:26:01.650 --> 00:26:09.930
Tim Tait: And the Dinos decreased a little bit more. So it's a little bit lower. And then looking at the scale or particles, the scaling of particles all actually have

172
00:26:10.410 --> 00:26:19.980
Tim Tait: Interactions with the gauge forces of the standard model. So the particles are SU three charged like the scale or corks

173
00:26:20.430 --> 00:26:31.890
Tim Tait: They all get the same big enhancement, the glue Ino does. And so the colored SU three super partners are all have relatively large masses, whereas the ones that don't experience the

174
00:26:32.370 --> 00:26:43.260
Tim Tait: SU three interaction remain with much smaller masses, and you can see the slept on tier which illustrate that. And then it's pretty natural that will happen is the lightest particle will end up being

175
00:26:43.950 --> 00:26:59.550
Tim Tait: Largely and we'll get into the details of that in a second. The supersymmetric particle of the hypercharged goes on, right, or the Beano and so that is neutral, just like the hypercharged bows on electrically neutral. So I was super particle and so therefore

176
00:27:01.170 --> 00:27:08.130

Tim Tait: It's a good candidate to be dark matter. So even though, in principle, this all depends on a lot of the physics of how supersymmetry is broken.

177
00:27:08.580 --> 00:27:18.240
Tim Tait: In practice these trends would suggest that it's actually pretty likely that you're going to end up with a neutral particle to be dark matter as the lightest one. Anyway, so that's good. Of course.

178
00:27:21.780 --> 00:27:35.490
Tim Tait: So in the middle of supersymmetric standard model, there are four neutrally knows which are marijuana for me ons, which are mixtures of the super particles of the neutral. We know the Beano and the tuna drugs is

179
00:27:36.150 --> 00:27:46.020
Tim Tait: So this extra complication comes about because when the electric symmetry is broken by the Higgs getting a vacuum expectation value just like that mixes the hypercharged goes on.

180
00:27:46.950 --> 00:27:57.270
Tim Tait: And the SU three neutral goes on to form the photon and the Z. It also at the same time mixes. They're super particles and causes them to be some mixture.

181
00:27:57.900 --> 00:28:15.120
Tim Tait: Which, you know, some some hybrid mixture of both of those things and also with the neutral Hayes's so as a result, the interactions are a little bit complicated. If I want to know what the interaction is, it depends on what admixture of each state is present in the lightest neutralino

182
00:28:17.100 --> 00:28:27.210
Tim Tait: Now we just saw that there were normalization group equations typically result in an LS P which is mostly be no with a small amount of heat z. Now, and the neutral, we know

183
00:28:28.740 --> 00:28:39.960
Tim Tait: But of course specific models of supersymmetry breaking could even upset those expectations for example and anomaly needed supersymmetry breaking you pretty famously gather a dark matter, which is mostly the neutral vino

184
00:28:40.620 --> 00:28:57.810
Tim Tait: So the equation up here shows how the lightest neutralino right or the thing that is the candidate to be the dark matter is written as a

linear combination of vino neutral, we know and the two eggs. He knows. So those are called the gauge. I can states because their interactions are simple.

185
00:28:59.340 --> 00:29:06.960
Tim Tait: We interact engage interactions. Anyway, are simple, but then because it's a mixture, the lightest neutralino is actually got four

186
00:29:07.830 --> 00:29:14.880
Tim Tait: Parameters. So, and one, one and one, two and three and then one for the tell me how much of each stage, I can state makes it up.

187
00:29:15.540 --> 00:29:27.180
Tim Tait: And so knowing those parameters, I can then actually take the linear combination of the interactions and find out exactly how the lightest neutralino interacts. So it seems very complicated because of this mixing

188
00:29:27.810 --> 00:29:37.350
Tim Tait: But in practice, if I understand how the underlying engage Ivan states interact. It's not really that complicated. I just have to know how much you need to make sure I have to include

189
00:29:38.100 --> 00:29:43.140
Tim Tait: So let's look at actually what each stage, I can state would look like, since that's the first step to doing that.

190
00:29:45.120 --> 00:29:55.920
Tim Tait: So the Beano has a coupling strength which is given by the hypercharged coupling G one times the hypercharged charge with any standard model for me on and it's super partner.

191
00:29:56.340 --> 00:30:13.140
Tim Tait: Right, so the Beano likes to talk to any standard model for me on and also the standard model for me on Super partner and since all of the standard model for me ons have hypercharged the Beano interacts with all of them will be you know interacts with all of the Standard Model matters.

192
00:30:14.910 --> 00:30:28.050
Tim Tait: The biggest interaction is for the particle that has the largest hypercharged and that's actually the right handed, select Ron Smith on and style. So the Beano particularly likes to interact with the charged slept on

193

00:30:30.390 --> 00:30:33.870
Tim Tait: The neutral. We know couples to buy a

194
00:30:35.070 --> 00:30:40.620
Tim Tait: G to write the week coupling constant times the third component of week I so spin

195
00:30:41.580 --> 00:30:49.230
Tim Tait: So half of the standard model from aeons carry week guys have spin right all of the left handed from aeons couple week ISO spin

196
00:30:49.740 --> 00:31:03.990
Tim Tait: And therefore the the neutral, we know will couple to say left handed electron and left hand, select Run or left handed a cork and a left handed up squirt and so on. It doesn't couple though to any of the right hand of things.

197
00:31:05.040 --> 00:31:13.290
Tim Tait: Now the neutral. We know also inherits the gauge interactions of the W particle. And so, for example, the neutral, we know has an interaction.

198
00:31:13.680 --> 00:31:25.020
Tim Tait: With say w minus and the superpartner they'll be you. Plus, there's also, of course, a conjugated interaction where it interacts with w plus and superpartner W minus

199
00:31:25.380 --> 00:31:33.690
Tim Tait: It doesn't actually interact with the Z bows on and thats related to the fact that the standard model did not have a triple triple the interaction inside

200
00:31:36.030 --> 00:31:45.990
Tim Tait: The Higgs Ino right is the super particle of the Higgs and therefore, it likes to couple of massive particles interactions are large to give the large masses for those particles.

201
00:31:46.680 --> 00:31:51.210
Tim Tait: So the Higgs Ino couples to say a top cork and a top scorer

202
00:31:51.840 --> 00:32:07.110
Tim Tait: A couple. So the other courts to, but because the top is so much heavier. This is the dominant interaction and all the other courts have very small interactions with it. It also couples to the w AMP z. So,

for example, there's a Higgs Ino coupling to another Xena and the Z bows on

203
00:32:08.430 --> 00:32:13.650
Tim Tait: There's also a Higgs, you know, coupling to the w goes on and the charge to Reno as well.

204
00:32:16.080 --> 00:32:21.630
Tim Tait: And there are also interactions with the Higgs boson, and the Higgs boson is interesting. It interacts with

205
00:32:22.980 --> 00:32:32.370
Tim Tait: With a dino or a wino and the Higgs Ino and so that means for this interaction to be turned on. I have to have more than one of these ends.

206
00:32:32.850 --> 00:32:45.750
Tim Tait: That control the mixing of the lightest neutralino to be non zero these interactions actually go like the product of either. No one or and two and then times either and three and one, three, or in one for

207
00:32:49.020 --> 00:32:55.560
Tim Tait: Alright, so now that we have understood something about how the lightest supersymmetric particle is likely to be interacting

208
00:32:56.250 --> 00:33:02.550
Tim Tait: We have everything we need to analyze neutralino annihilation. It's again a complicated process because there's so many different

209
00:33:03.030 --> 00:33:07.590
Tim Tait: Particles and therefore so many different diagrams, but we can understand some generic features.

210
00:33:08.070 --> 00:33:14.490
Tim Tait: So the first and most important thing is the fact that neutrally knows our mirada formula. They are their own antiparticle

211
00:33:15.120 --> 00:33:24.690
Tim Tait: And that means that in the non relativistic limit. They are poly blocked from an initial s equals one state right if the initials net spin of the two neutralino is was one

212
00:33:25.230 --> 00:33:37.560

Tim Tait: That would mean that the two neutrinos would have to have their spins pointing in the same direction. But if they're also non relativistic there's no momentum to distinguish them right if they're not an altruistic. They're basically sitting still, and so

213
00:33:39.240 --> 00:33:45.060
Tim Tait: They have the same momentum and that means we're trying to put two firm aeons which are identical, right. They're both

214
00:33:45.660 --> 00:34:02.490
Tim Tait: The particle antiparticle are the same thing. So to firm aeons are being put in the same spin state and the same momentum state. And of course, Polly direct statistics for business from doing that. So that tells you that reflects itself by saying in the non relativistic limit the interactions.

215
00:34:03.810 --> 00:34:15.690
Tim Tait: Just go to zero, there are still some annihilation, though. And that's because once I go out of the non relativistic limit and other words, once I include the momentum. They can be in different states. And that's allowed

216
00:34:16.170 --> 00:34:19.560
Tim Tait: So the annihilation cross section goes like the velocity that some power.

217
00:34:20.730 --> 00:34:28.830
Tim Tait: And this implies, for example, there's no annihilation through an s channel vector particle, because that would again require me to be in that initial icicles one state.

218
00:34:29.850 --> 00:34:35.610
Tim Tait: I can still exchange scale or firm aeons. So that's the diagram that's written here at the top.

219
00:34:37.560 --> 00:34:42.990
Tim Tait: However, because the scale or for me on has a definite chi reality.

220
00:34:44.640 --> 00:34:54.600
Tim Tait: I need to actually lift the spin of one of my firm aeons in order to get into a net s equals zero final state. And so this annihilation process is suppressed.

221
00:34:55.110 --> 00:35:01.320

Tim Tait: By something like the mass of that for me on. And the final state squared divided by the mass of the neutralino squared.

222
00:35:01.770 --> 00:35:08.340
Tim Tait: So in general, this diagram exists, but it's somewhat smaller than I might expect, especially if the firm aeons or light.

223
00:35:08.880 --> 00:35:16.170
Tim Tait: The dark matters heavy enough to annihilate into a top court when I could put the top nastier and that wouldn't be a very big suppression necessarily

224
00:35:16.830 --> 00:35:29.220
Tim Tait: But let's say it's below the top mass. Then the next heaviest for me on would be the bottom cork and so I would be annihilating into a pair of bottom courts and I would have a suppression that would look like the mass of the bottom squared divided by the massive and web squared.

225
00:35:31.620 --> 00:35:46.800
Tim Tait: If the dark if the lightest supersymmetric particle has a significant Higgs Ino or we know component, then it can annihilate into a pair of gauge Bose ons. Right. We saw that there were interaction say with a W AMP z. So you can imagine.

226
00:35:48.240 --> 00:35:55.110
Tim Tait: Seeing annihilation to gauge bolt ons, but only if it contains a significant things in our we know component

227
00:35:56.040 --> 00:36:05.460
Tim Tait: If it contains both things, you know, and the gauge, you know, component, then it can annihilate into a Higgs boson, which will then go itself into some standard model for me.

228
00:36:06.330 --> 00:36:19.380
Tim Tait: So what we learned is that because they're Marana there. The typical annihilation cross sections for neutrally knows are either suppressed because they go like the mass of the firm eon

229
00:36:19.860 --> 00:36:27.390
Tim Tait: Or their suppressed by the fact that I want my MSP to be both Encino engaged, you know, right. But remember that my mixing parameters.

230
00:36:28.170 --> 00:36:36.720

Tim Tait: If i square them, they have to add up to one. So, therefore, I can't have both of these things be large. At the same time, the best I can do is just make them both kind of medium sized

231
00:36:37.290 --> 00:36:45.270
Tim Tait: which suppresses the cross section or they have to have a large things, you know, are we know component which is actually disfavored for other reasons that we'll see in a minute.

232
00:36:46.380 --> 00:36:55.680
Tim Tait: So the bottom line is, is that the annihilation cross section for supersymmetric particles is typically suppressed and generically. It leads to many dinos

233
00:36:56.250 --> 00:37:04.740
Tim Tait: Right. Remember in the freezer calculation we saw if your cross section for annihilation is low you freeze out early and you produce too much dark matter.

234
00:37:06.810 --> 00:37:17.730
Tim Tait: Now if I want to do this more carefully, even at tree level. It turns out there's a lot of diagrams. I have to talk about. And this is just to show you some of them and that comes from this big physics reports about supersymmetric dark matter.

235
00:37:18.690 --> 00:37:24.360
Tim Tait: This is not even all of them. And of course, modern day calculations often will even include higher order effects.

236
00:37:24.720 --> 00:37:35.280
Tim Tait: Like one loop corrections. So this is not a state of the art calculation is just to convince you that computing around density and super in the middle supersymmetric standard model is actually a pretty involved.

237
00:37:37.620 --> 00:37:50.340
Tim Tait: So let's look at the relative density. I'm going to use this theory, which is not very much favorite today. It's called and Sutra, and as a result, my plots are a little bit old. But they actually illustrate the physics really well. And so I like them for that.

238
00:37:52.140 --> 00:37:57.690
Tim Tait: So what's been done here is this is a model. This is that same model we saw before. In fact, where you set

239

00:37:58.200 --> 00:38:06.840
Tim Tait: All of the spin one half super partners. Right. So the glue. We know that we know the Beano to the same mass. Some high scale and then evolve them down below energy scales.

240
00:38:07.320 --> 00:38:23.130
Tim Tait: You said all the scale or particles. Right. The scorekeeper slept on to some mass scale and then you involve them down below energy scales. As a result, you typically get a LLP which is mostly amino and you remember from

241
00:38:24.930 --> 00:38:29.190
Tim Tait: Our G plot right but typically the Beano is the lightest of the super particles.

242
00:38:31.560 --> 00:38:34.050
Tim Tait: But it has a little bit of we know in his you know in it.

243
00:38:36.090 --> 00:38:40.590
Tim Tait: And so what these authors have done is they plotted the regions where I get

244
00:38:41.850 --> 00:38:50.220
Tim Tait: Too much dark matter. That's the blue region. In fact, actually, the blue region even continues into the white region because they cut this off at omega squared of one

245
00:38:50.640 --> 00:38:57.840
Tim Tait: In principle, you know, you can get a bigger omega squared. It just means there's more dark matter in the universe. And that's what corresponds to this white region here.

246
00:38:58.470 --> 00:39:06.750
Tim Tait: Then the green region is where they get about the right amount of dark matter. And you remember that the measurements right are much more precise than this. And so this is

247
00:39:07.470 --> 00:39:13.680
Tim Tait: A wide range, largely, just so you can see it show up nicely on the plot that clusters around point one or so.

248
00:39:14.160 --> 00:39:27.390
Tim Tait: And then the yellow region is where you get to little dark matter. And that's the these yellow slivers, you see here, then there are some red regions that are not consistent with the theory for other

reasons that don't have to do with dark matter. So let's not worry about them too much.

249
00:39:28.440 --> 00:39:40.470
Tim Tait: And so you can see that the region when you produce the right amount of dark matter here for these parameters. So this is in the plane of that common mask for the gauge. He knows and the common mass for the scale or for me on

250
00:39:41.670 --> 00:39:51.960
Tim Tait: And for a couple choices of the other parameters of the theory, you can see, you get the right relevancy in this green sliver that that starts up here kind of comes down.

251
00:39:52.620 --> 00:39:56.580
Tim Tait: And then there's some other region here also at large values and I'm zero

252
00:39:57.180 --> 00:40:06.780
Tim Tait: And these different regions all work for kind of different physical reasons, the simplest one to understand is right down here. We're all the masses are low, right. So down here where

253
00:40:07.110 --> 00:40:14.700
Tim Tait: I've said one half to about 200 or so and then zero to about 200 and now this is the region that's excluded by the LA see at the moment.

254
00:40:15.180 --> 00:40:29.310
Tim Tait: But in this region, you can understand why the dark matter relic density turned out well because it's all the particles are light, you get a pretty big annihilation for neutralino neutralino goes into to firm aeons and so you can you can get the right relative abundance, they're

255
00:40:31.290 --> 00:40:38.910
Tim Tait: Up here in the sliver that goes up to a larger values of them, one half is actually a co annihilation region and this region.

256
00:40:39.450 --> 00:40:51.960
Tim Tait: The neutralino and the scale or partner of the Tao style are actually very similar in mass. And so there's a lot of extra annihilation of neutrally goes with styles, which are still present present in the

257
00:40:52.290 --> 00:41:03.960

Tim Tait: In the plasma because they're masses are so low, and that gives you a big enough cross section that you can actually still realize the right relative abundance and this goes up into regions at the LLC has not actually been able to probe yet.

258
00:41:05.070 --> 00:41:12.030
Tim Tait: And then finally for large values of zero, you get to a focus point. So this is where the neutralino turns out to have a big

259
00:41:12.600 --> 00:41:24.510
Tim Tait: Both a big Beano and a big casino component and then we saw that you could get annihilation through a Higgs boson. And that works, actually, to explain the relic density up for large values of them zero

260
00:41:27.570 --> 00:41:32.790
Tim Tait: If I look for a different region a parameter space. So this is the same plane. But I just changed the value of tangent beta

261
00:41:33.180 --> 00:41:39.270
Tim Tait: I control something that had that supersymmetric Higgs bosons interact with the firm aeons then I can still see

262
00:41:39.840 --> 00:41:48.180
Tim Tait: Similar regions before the CO annihilation region is still there, the focus point region is still there and the new feature that showed up as an interesting thing.

263
00:41:48.720 --> 00:42:00.240
Tim Tait: We're actually the mass of the extra Higgs Boson gets to be very close to twice the massive neutralino. And so there's a resident enhancement of this diagram in the lower left corner of the screen.

264
00:42:00.750 --> 00:42:09.480
Tim Tait: Because when the neutrinos annihilate they produce a Higgs very close to on shell that gives me a big enhancement from the propagator

265
00:42:09.810 --> 00:42:15.780
Tim Tait: And as a result, I get a bigger cross section and that allows for this green funnel region that you see here.

266
00:42:16.200 --> 00:42:24.720
Tim Tait: It's called a funnel, right, because if I get too close to the Higgs being on shall the cross section gets too big. And I have two little dark matter here in the central yellow region.

267
00:42:25.350 --> 00:42:38.850
Tim Tait: If I'm too far off from being on shell than I have two little dark matter. And that's the blue region and in between though on either side of the resonance right on either side of the Higgs mass. I have a green region where things turn out to be just about right.

268
00:42:41.940 --> 00:42:50.100
Tim Tait: So since we've already learned about how neutrally knows annihilate by studying the relic density. We can also very quickly say something about what this implies

269
00:42:50.490 --> 00:42:58.050
Tim Tait: For indirect searches, like the ones that Tracy is talking about, right, because the same physics controls the search for them annihilating in the halo

270
00:42:58.770 --> 00:43:08.220
Tim Tait: As my erotic particles. They tend to annihilate into heavier firm aeons and or W bows ons, you'll see a lot of times when you see a search for

271
00:43:09.330 --> 00:43:16.230
Tim Tait: for dark matter through indirect detection. They assume the dark matter annihilate into a bottom and an anti bottom of cork.

272
00:43:16.800 --> 00:43:26.850
Tim Tait: And the reason why they make that assumption is precisely for this region read reason they think that if the dark matters Marana it will want to annihilate into a heavier for me on like the work

273
00:43:27.330 --> 00:43:37.020
Tim Tait: Of course, it can also do a W and it could also do next year, but this is very specific to my around a particle and it doesn't have to be true if your dark matter is a direct for me on, or both.

274
00:43:38.460 --> 00:43:39.600
Tim Tait: You can also have

275
00:43:41.040 --> 00:43:49.710
Tim Tait: loops of charged particles, which allowed them to annihilate into two photons or a photon and Z or the dark matter doesn't have true level interactions with the photon.

276
00:43:50.250 --> 00:43:55.590

Tim Tait: But if I imagine the dark matter can form a loop diagram, like the one here, you see.

277
00:43:56.520 --> 00:44:09.300
Tim Tait: Above plot and the loop diagram the dark matter is going through a loop of W's and the charged. We know dark matter to produce two photons. Right. The photon does coupled to the w, both on which has electric charge.

278
00:44:10.050 --> 00:44:23.520
Tim Tait: Of course, there's also tree level annihilation directly into w bows ons to that's just half of that diagram. So what this does. If you look at the spectrum of gamma rays. It produces it produces and the gamma rays are just chosen here as an example.

279
00:44:25.770 --> 00:44:36.900
Tim Tait: You know annihilation into two W's produces a spectrum of gamma rays. So that's the sort of solid curve. You see here that has gamma rays of many different energies represented in it.

280
00:44:37.500 --> 00:44:49.560
Tim Tait: And then if you annihilate directly into two photons, the kinematics tell you that you always get two photons with the same energy, and that energy is the mass of the dark matter. And that's what's responsible for this spike.

281
00:44:51.360 --> 00:44:56.220
Tim Tait: Or line, they call it a line in the gamma ray spectrum that's being produced by annihilation there.

282
00:44:59.490 --> 00:45:07.080
Tim Tait: And actually indirect detection is one of the best constraints that we currently have on Reno's as dark matter.

283
00:45:07.800 --> 00:45:18.990
Tim Tait: This is a plot that was actually made by Tracy and her collaborators. A few years ago, where they looked at gamma ray data from the Hess telescopes has a set of telescopes and Africa.

284
00:45:19.710 --> 00:45:27.990
Tim Tait: They looked actually for that gamma ray line signal. And I think she'll probably tell you a little bit more about this in terms of the Summerfield enhancement today.

285
00:45:28.560 --> 00:45:32.820

Tim Tait: But the prediction for how much annihilation. You should get

286
00:45:33.810 --> 00:45:41.430
Tim Tait: Is their best prediction is given by these red lines and the point of this paper was really to show you, technically, how to do this calculation, which is pretty tricky.

287
00:45:42.150 --> 00:45:50.010
Tim Tait: And that's compared with the limit. And you can see that there are some regions that are still allowed like there's a window where the we know mass is above

288
00:45:51.090 --> 00:46:02.730
Tim Tait: About for TV and below, maybe that 70 TV limits excluded again because of this resonance structure in the cross section and then it becomes allowed again above 10 TV or so.

289
00:46:03.360 --> 00:46:14.610
Tim Tait: And there are projections for my future telescope called CPA, which will rule out even more in the parameter space so indirect detection is a very important limit on the heavy part of we know dark matter.

290
00:46:15.930 --> 00:46:24.720
Tim Tait: And we can also talk about the direct detection of neutrally knows they're the ironic character for them is actually still very important. It has many consequences.

291
00:46:25.200 --> 00:46:32.730
Tim Tait: And that's because they are Mayra particles have no vector currents, so z exchange can only mediate spin dependent interactions.

292
00:46:33.240 --> 00:46:42.690
Tim Tait: And the best constraints around spin independent interactions Higgs exchange. Remember requires both the neutralino to have a genome and his, you know, and it's admixture.

293
00:46:43.080 --> 00:46:47.130
Tim Tait: So the rate is very sensitive to the neutralino mixing angles. It's very model dependent

294
00:46:47.790 --> 00:46:58.740
Tim Tait: And but direct connection is still a very sensitive probe of emphasis on parameter space, it actually rules out a large amount of it

and give them the direct connection experiments that we have. And I'm sure that

295
00:47:00.090 --> 00:47:03.030
Tim Tait: God will be talking about this to some extent in her election.

296
00:47:05.070 --> 00:47:10.140
Tim Tait: And finally, we get the collider signals. I know the Jonathan's got a little bit about this. So maybe I'll go through kind of quickly.

297
00:47:10.740 --> 00:47:21.900
Tim Tait: And hadron collider is like the ELYSEE, the largest signal tends to come from producing the SU three charge super partners. So this diagram for example shows you how to glue ons can produce a pair of glucose.

298
00:47:23.010 --> 00:47:31.680
Tim Tait: Once you produce a color and super practical it then can decay down into the MSP and this may be a complicated process. So, like, for example, I have a cartoon here showing

299
00:47:32.130 --> 00:47:41.550
Tim Tait: A glue. We know that the case into a cork and a superpartner of a cork, then maybe that superpartner the cork itself decays into an antique work.

300
00:47:42.180 --> 00:47:47.970
Tim Tait: And say a charge, you know, right. But one of the charge to gauge bows on Super partners.

301
00:47:48.360 --> 00:47:56.820
Tim Tait: That made the k by spitting out a W goes on and finally getting us down, but the dark matter particle and that w might decay in to say and electronic neutrino.

302
00:47:57.120 --> 00:48:11.640
Tim Tait: So, then each one of the glue. He knows that I'm producing this diagram, if this is the decay chain would actually produce two jet's right, one from each cork a charge left on and then missing momentum because of the neutrino and the dark matter which can't be reconstructed

303
00:48:13.920 --> 00:48:20.700
Tim Tait: So you always have to be very careful to look at the decay chain. Let's assume that, make sure it corresponds to the theory that you're thinking about

304
00:48:21.660 --> 00:48:33.390
Tim Tait: So what I've got here is a plot in the plane of the mass of the glue Ino and the scores and assuming with the mass of the neutralino so the mass of the dark matter. They say it's equal to zero GB

305
00:48:33.840 --> 00:48:37.020
Tim Tait: They couldn't actually be zero GV because then it wouldn't be dark matter.

306
00:48:37.920 --> 00:48:48.270
Tim Tait: It would be relativistic. On the other hand, what they mean is just a very small so you would get the same curve. If you assumed it was point one GED, or one GB or even probably five GB

307
00:48:48.750 --> 00:48:56.100
Tim Tait: And so this is just an interesting limit where the scores and the gloomy now are very much heavier than the than the neutralino is

308
00:48:57.630 --> 00:49:07.590
Tim Tait: So by looking at a simple process where the scores, just the cave very directly into a cork and the dark matter and the glue. He knows decaying. The two courts in the dark matter.

309
00:49:08.430 --> 00:49:15.870
Tim Tait: They combine a bunch of different searches for numbers of different numbers of jets plus missing transverse momentum and they come up with a

310
00:49:16.350 --> 00:49:31.470
Tim Tait: Bound on the parameter space, they're actually using and we're going to talk about the piano sent in just a minute, they're actually using a PM SSM scan to look at all the different nuisance parameters and kind of get rid of them. But you see that they actually put constraints, where

311
00:49:32.910 --> 00:49:43.710
Tim Tait: For they can rule out any guaino who's masses less than about two TV. Right. That's this this limit is the weakest limit, they get on gloomy knows, of course, the limit may be

312
00:49:44.730 --> 00:49:54.750
Tim Tait: Better if they can also specify what the score masses and similarly for squawks, they can rule out any mass, it's less than about two and a half at TV or so.

313
00:49:55.800 --> 00:50:00.600
Tim Tait: It's, it's pretty impressive and it puts very important constraints on supersymmetric theories

314
00:50:02.610 --> 00:50:06.270
Tim Tait: You can also do a similar analysis for things like the standard particle of the top

315
00:50:06.870 --> 00:50:13.020
Tim Tait: I'm not going to say too much about it. This is one particular decay chain that was presented recently at the I check conference.

316
00:50:13.860 --> 00:50:18.030
Tim Tait: even see it reduced produces bottom corks some standard model for me ons.

317
00:50:18.600 --> 00:50:24.090
Tim Tait: Because there are different regions where different particles are on shell. They have different sensitivity and different search strategies.

318
00:50:24.360 --> 00:50:33.720
Tim Tait: Do you have to combine the different strategies together and that's what gives you these very complicated looking contours. So, of course, some of the wiggle is just the back that the statistics that they collect is

319
00:50:34.800 --> 00:50:35.370
Tim Tait: You know, there's

320
00:50:35.400 --> 00:50:36.420
Tim Tait: This is statistical

321
00:50:36.450 --> 00:50:37.230
Tim Tait: Wobble in it.

322
00:50:38.160 --> 00:50:39.090
Lisa Kaufman: But 10

323
00:50:39.270 --> 00:50:40.230
Tim Tait: Us. Yeah.

324
00:50:41.310 --> 00:50:41.730
Lisa Kaufman: Women

325
00:50:42.330 --> 00:50:42.630
Tim Tait: Great.

326
00:50:43.020 --> 00:50:48.930
Tim Tait: That'll be fine. But the most of the structure is actually explained by the different searches that are handing off one to the other.

327
00:50:51.180 --> 00:50:56.070
Tim Tait: Alright, so hopefully we could eventually have many signals to measure the parameter space is very large.

328
00:50:56.460 --> 00:51:04.950
Tim Tait: Even a simplified version of the model has something like 20 parameters and that's what this PMS is n refers to is the version of the supersymmetric scattered bottle.

329
00:51:05.310 --> 00:51:13.590
Tim Tait: With 20 parameters mapping from signal the brand or space is very complicated and it's not generally a one to one problem. It's a complicated inverse problem.

330
00:51:14.070 --> 00:51:18.870
Tim Tait: And to further complicate that the connection to dark matter, specifically is often not very clear.

331
00:51:19.260 --> 00:51:25.770
Tim Tait: And so there are statistical approaches based on simulating many different model points in the parameter space and seeing where they fall

332
00:51:26.100 --> 00:51:38.640
Tim Tait: And this is something that was actually pioneered it slack by professors Tom razon joined us. So here's an example of a scan over PMS, is I'm parameter space and showing us what it actually teaches us about

333
00:51:39.690 --> 00:51:50.460
Tim Tait: The parameter space as it relates to searching for the direct detection of dark matter, the different colors show you which kinds of experiments can actually hope to detect the dark matter.

334
00:51:51.480 --> 00:52:00.000
Tim Tait: The purple points were excluded by the LA FC at the time of this writing I think since then probably the LSC as excluded. Most of the other points as well.

335
00:52:01.140 --> 00:52:09.510
Tim Tait: Then the green and the red or things that could be excluded in the near term future by xenon one time right now online and taking data.

336
00:52:11.100 --> 00:52:17.550
Tim Tait: But and the green versus red just refers to whether it would also be visible at a future gamma ray observatory like CTA

337
00:52:18.630 --> 00:52:23.400
Tim Tait: The blue actually are things where you will see things and CPA, but you're not be able to see them actually

338
00:52:26.460 --> 00:52:38.190
Tim Tait: And you can also see sort of what fraction of models you can cover and how much of it comes from, say, LLC vs CTA so read his village see blue CPA greener places where both of them are kind of working together.

339
00:52:40.380 --> 00:52:46.950
Tim Tait: So the last thing I'll say about supersymmetric models which will probably be the last topic I'll cover before we pause for the day.

340
00:52:47.880 --> 00:52:56.550
Tim Tait: Is that we've already seen the minimal model of supersymmetry is very complicated. It contains a lot of really interesting physics. Nothing tells us nature is chosen something and minimal though.

341
00:52:57.060 --> 00:53:03.000
Tim Tait: You can imagine a simple extension like adding a gauge sink singlet. So say the next the minimal supersymmetric standard model.

342
00:53:03.420 --> 00:53:19.110
Tim Tait: And that can have a big impact on the picture for dark matter by adding more neutral ninos more Higgs Boson more parameters describing couplings and new relationships between parameters and here's a study that looked at the enemy SSM with the Beano MSP and found

343
00:53:20.250 --> 00:53:28.560

Tim Tait: The curves where you have the right relic density for different functions and data and you can see how this moves you around in the plane of the masses of the MSP

344
00:53:29.190 --> 00:53:38.820
Tim Tait: And also the mass of CPR Higgs Boson. And one thing that's interesting is you can get the relevancy correct even for pretty low masses like that around five or 10 years

345
00:53:39.900 --> 00:53:43.770
Tim Tait: So I think what we'll do, actually. Sorry. No, I'll do this one last one, and then we'll stop.

346
00:53:44.520 --> 00:53:51.000
Tim Tait: And even though, so the supersymmetric model also contains a super particle for the gravity. Gravity know

347
00:53:51.540 --> 00:53:59.880
Tim Tait: Even though gravity knows or never an equilibrium, they can still be produced through the reason mechanism. Right. So, so far, we've only been talking about neutrally and I was previously freeze out

348
00:54:00.450 --> 00:54:07.590
Tim Tait: But you can also produce gravity knows a couple say here is a pair of glue on producing a gloomy now and a gravity know at the same time.

349
00:54:08.370 --> 00:54:18.000
Tim Tait: Since they fail to reach equilibrium and their interactions are non were normalized double the quantity that we generate depends very sensitively very sensitively on the reading temperature at the end of inflation.

350
00:54:18.450 --> 00:54:21.420
Tim Tait: In other words, the highest temperature of the universe has that's meaningful.

351
00:54:21.870 --> 00:54:28.080
Tim Tait: And this is actually different from the case, we looked at before, because you remember before we assume the interactions responsible for some reason.

352
00:54:28.500 --> 00:54:35.460

Tim Tait: We're not dependent on the energy or not, depending on the temperature and that makes them insensitive to the initial conditions here because gravity.

353
00:54:35.790 --> 00:54:42.480
Tim Tait: Occasional interactions are not normalized double we end up with a high sensitivity to the initial conditions or to the highest temperatures

354
00:54:43.170 --> 00:54:51.120
Tim Tait: And of course, in general, you may produce too many of them, which leads to a bound know what they're eating temperature would be in the plot here, we have

355
00:54:52.500 --> 00:55:01.440
Tim Tait: As a function of the repeat temperature and four different masses of what the gravity know masses. Those are the different lines. We have a result of

356
00:55:02.130 --> 00:55:14.010
Tim Tait: How much relic density, we expect. And you see that you can actually realize the relevancy for given masses between, say, a GB up to a few hundred GB as long as I choose the reheat temperature appropriately.

357
00:55:15.240 --> 00:55:24.900
Tim Tait: It could be that the gravity know is actually not the MSP but just the NSP, in which case it might actually became a lead times and turn itself back into wimps.

358
00:55:25.200 --> 00:55:37.050
Tim Tait: And I think Jonathan told you about that yesterday, so I'm not going to say too much more about it. So I'm going to pause here and we'll finish talking about specific theories of dark matter and also theories of dark sectors tomorrow. Thanks.

359
00:55:39.750 --> 00:55:47.880
Lisa Kaufman: Thank you, Tim. I wonderful talk our lecture. And I should say. And okay, we'll hand it over them to read. She's going to moderate our Q AMP a

360
00:55:50.520 --> 00:55:55.170
Richard Partridge: Thank you, Tim. For a nice talk. The first question is,

361

00:55:56.490 --> 00:55:59.370
Richard Partridge: If a standard Bart, the SU first to slide 13

362
00:56:01.770 --> 00:56:12.120
Richard Partridge: If a standard model particle, Richard. He came into dark matter particle with that became necessarily be mediated by some dark sector particle

363
00:56:14.310 --> 00:56:22.170
Tim Tait: Right. So the question is, if a standard model Paul particle conduct a into a dark matter particle would that be mediated by a dark sector particle

364
00:56:22.920 --> 00:56:32.040
Tim Tait: It depends. Actually, on the theory. So one thing that we searched for at the LSC is, for example, the idea that maybe the Higgs boson indicate directly into the dark matter.

365
00:56:32.820 --> 00:56:43.140
Tim Tait: And so far. I mean, the fact that we haven't seen that happen means that you can put a limit on how large the interaction between the Higgs and the dark matter should be but

366
00:56:44.520 --> 00:56:52.800
Tim Tait: You know, but as long as you sort of obey that limit. There's nothing to tell us that can't happen directly without having any kind of mediating particle at all.

367
00:56:53.160 --> 00:56:58.200
Tim Tait: So in that case, you don't really need the dark sector, you just need a dark matter that happens to like to interact with the Higgs boson.

368
00:56:58.800 --> 00:57:04.500
Tim Tait: In other cases, though you might imagine that you do need immediate in particle like for example we saw

369
00:57:05.370 --> 00:57:17.340
Tim Tait: Well, for example, you can imagine the top cork like decay into some dark matter particles and there, there would definitely be mediating particles that have to carry SU three color and electromagnetism, that would be part of the dark sector that would be involved.

370
00:57:20.070 --> 00:57:30.930

Richard Partridge: OK, the next question. Is there a lot of theories which could give rise to correct density or summer I guess that's a question there.

371
00:57:31.230 --> 00:57:31.800
Tim Tait: Yes.

372
00:57:32.010 --> 00:57:35.820
Richard Partridge: Very trade between different cosmology and early universe.

373
00:57:36.960 --> 00:57:39.960
Tim Tait: So, that's right. That's why when I frame this

374
00:57:41.010 --> 00:57:48.570
Tim Tait: This message you really have to understand which theory, you're dealing with. If you don't know which theory is the right theory of dark matter.

375
00:57:49.080 --> 00:57:56.130
Tim Tait: Then there's sort of no way to take anything about the abundance of dark matter and map that into some understanding of the early universe.

376
00:57:56.700 --> 00:58:09.840
Tim Tait: If you did, however, have a theory of dark matter that you can firm by by measuring its properties at some other experiments, then you'd be able to actually push back or understanding of the of the universe to early times i think that captures what the questions is

377
00:58:10.650 --> 00:58:12.540
Richard Partridge: Yeah, I think that's a good answer.

378
00:58:14.040 --> 00:58:18.360
Richard Partridge: The next question, given the lack of evidence for Susie and ELYSEE,

379
00:58:19.980 --> 00:58:24.000
Richard Partridge: Why are Susie theories still good candidates for dark matter.

380
00:58:25.200 --> 00:58:36.450
Tim Tait: Right, so it's true that there was no evidence for supersymmetry at the lapd so far. And of course the Le G is going to run

for another more than 10 years, which means that there is still some chance that there will be evidence at some point.

381
00:58:38.880 --> 00:58:49.110
Tim Tait: Basically supersymmetry does two different things for us, it tries to explain why the Higgs mass is low compared to fundamental scales, like the Planck scale or the gut scale.

382
00:58:50.790 --> 00:58:59.040
Tim Tait: And from that point of view, it really would suggest that the partner the masses of the super particles should be around the TV or so.

383
00:58:59.520 --> 00:59:08.400
Tim Tait: So we go to the limits that we saw from the LA FC right what we're talking about is specifically limits like these ones.

384
00:59:08.880 --> 00:59:14.610
Tim Tait: You know, it's getting pretty uncomfortable because the masses of the super particles have to be bigger than about to TV.

385
00:59:15.420 --> 00:59:20.070
Tim Tait: At least these super particles. If I were to look at the masses of the Steeler tops.

386
00:59:20.490 --> 00:59:25.770
Tim Tait: Then, actually it looks like depending on the parameter space, you know, I could live sort of in a little sliver down here.

387
00:59:26.160 --> 00:59:32.460
Tim Tait: Where the Steeler top masses 600 GB and the scale of the neutralino masses say around 500 GB

388
00:59:33.300 --> 00:59:43.560
Tim Tait: That wouldn't be too bad. So I think we tend to put more weight on this statement that the LA. He hasn't seen supersymmetry than it really warrants at this time.

389
00:59:44.070 --> 00:59:46.890
Tim Tait: We could have super particles just around the corner and

390
00:59:47.790 --> 00:59:56.340
Tim Tait: And so really supersymmetry is actually still it's still possible for it to do its, its primary job of the hierarchy problem, right, or in other words, why is the Higgs, so like

391
00:59:57.120 --> 01:00:03.120
Tim Tait: I'm now a separate way of looking at, though, is that the super, super symmetric theory is also a good theory of dark matter.

392
01:00:03.630 --> 01:00:12.210
Tim Tait: And there it turns out it's very easy to have the superpartner masses be you know one TV to TV even 10 TV.

393
01:00:12.660 --> 01:00:24.840
Tim Tait: And at that point, if the perfectly great theory of dark matter. It's just too heavy to be probed that the LH. See, but the ELYSEE limits are not really limiting its ability to be dark matter, what they're doing is they're limiting its ability to solve the hierarchical

394
01:00:27.600 --> 01:00:28.560
Richard Partridge: Thank you can

395
01:00:30.270 --> 01:00:32.550
Richard Partridge: Next question refers to

396
01:00:35.130 --> 01:00:36.240
Richard Partridge: Sorry.

397
01:00:37.590 --> 01:00:39.090
Richard Partridge: To slide 27

398
01:00:41.490 --> 01:00:53.760
Richard Partridge: Could we use our current estimated proton lifetimes to a set instead set a constraint for the rate of relevant Susie interactions, instead of invoking our parents.

399
01:00:54.660 --> 01:01:04.980
Tim Tait: Absolutely, and I mean I think the limits you get are going to be very kind of amazingly small these interactions have to be really, really tiny in order to not

400
01:01:05.460 --> 01:01:19.470
Tim Tait: Be consistent with our limits. But that's actually a perfectly reasonable way to do it. You can say, well, maybe our parodies only approximate symmetry. And so the small couplings, you're just telling me how much I'm allowed to break that symmetry.

401

01:01:27.450 --> 01:01:30.720
Richard Partridge: And this is on slide 32 this next question.

402
01:01:32.100 --> 01:01:41.940
Richard Partridge: Is the problem of neutralino annihilation to too much vino production solvable by tweaking early universe parameter

403
01:01:43.410 --> 01:01:50.610
Tim Tait: Yes, there are actually studies along the lines that have proposed specific ways that you would do that.

404
01:01:51.330 --> 01:02:05.790
Tim Tait: So I wouldn't even call it tweaking, you have to make a relatively big change to the early universe, you know, to the super particles you have available nearly universe, but by playing with the cosmology, you can actually make the problem of too many dinos

405
01:02:06.870 --> 01:02:16.830
Tim Tait: Basically go away. There was some work by gel meanie and gone below if you want to try to look for a reference or you can send me an email and I'll send it. I'll find it specifically for you.

406
01:02:19.650 --> 01:02:27.630
Richard Partridge: OK, the next question is on inside 28 I think I'm going to need to see that slide to

407
01:02:30.510 --> 01:02:30.870
Tim Tait: Hear it is

408
01:02:31.770 --> 01:02:32.370
Um,

409
01:02:34.320 --> 01:02:37.560
Richard Partridge: So the question is why.

410
01:02:38.820 --> 01:02:45.210
Richard Partridge: He or your score you has much stronger Q dependents than 800 square d ID question mark.

411
01:02:46.560 --> 01:02:53.460
Richard Partridge: What's the significance of each. Are you going negative and extended big sector and source of doesn't matter.

412

01:02:54.510 --> 01:02:55.290
Tim Tait: Right, so

413
01:02:57.060 --> 01:02:58.470
Tim Tait: The HQ and HD

414
01:02:58.530 --> 01:03:00.660
Tim Tait: Are the two different Higgs Boson tons of the minimal

415
01:03:00.660 --> 01:03:06.690
Tim Tait: supersymmetric standard model. And I didn't give you all the details, but the technical thing is that in the supersymmetric standard model.

416
01:03:07.140 --> 01:03:23.460
Tim Tait: One of the Higgs doublets couples to the upper works. So that's up to charm top and the other Higgs Boson couples to the downtime corks that's down strange bottom. The reason the HQ is being affected so much then HD is, I think, I think the question extra kind of anticipated this answer.

417
01:03:24.600 --> 01:03:39.210
Tim Tait: Because he couples to the top cork, which has a very big you call interaction with the Higgs HQ gets a big correction from the top interactions HD only couples to the much much lighter bottom court and therefore it doesn't get big interactions.

418
01:03:41.910 --> 01:03:46.620
Tim Tait: So that's what happens. That's why the difference in the size

419
01:03:47.820 --> 01:03:56.910
Tim Tait: The significance of each you going negative is actually what's happening here is both of the exits have positive mask words at high energies, which means that

420
01:03:57.690 --> 01:04:02.970
Tim Tait: Neither one gets a vacuum expectation value. And so in high energies electric century is not broken.

421
01:04:03.540 --> 01:04:14.700
Tim Tait: But when he gets driven to a negative mass squared, it triggers the electric symmetry breaking that we see in our universe right where the W AMP z and permissions have masses. It's actually a great question.

422

01:04:16.830 --> 01:04:17.370
Richard Partridge: Okay.

423
01:04:18.780 --> 01:04:22.530
Richard Partridge: Um, there's a let me

424
01:04:22.590 --> 01:04:23.250
Richard Partridge: Go to

425
01:04:23.550 --> 01:04:24.900
Richard Partridge: This question here.

426
01:04:26.940 --> 01:04:28.500
Richard Partridge: This is on slide 25

427
01:04:30.030 --> 01:04:35.940
Richard Partridge: Are Susie particles described by the same age groups has their standard model, model car.

428
01:04:37.470 --> 01:04:38.430
Tim Tait: Yes, they are.

429
01:04:41.310 --> 01:04:44.610
Richard Partridge: Okay, another question is probably yes. No question.

430
01:04:45.960 --> 01:04:59.100
Richard Partridge: There are lots of parts today label omega each square. This is the same as the strain omega GW each square that the gravitational wave lectures were talking about last week.

431
01:05:00.630 --> 01:05:05.970
Tim Tait: No, this is a different parameter. This refers to the energy density

432
01:05:08.460 --> 01:05:14.070
Tim Tait: In the U verse of a given components relative to the critical energy density

433
01:05:15.030 --> 01:05:23.580
Tim Tait: The universe. So I think that was probably described in the cosmology lectures last week, but it's a different omega squared in this case.

434
01:05:24.210 --> 01:05:36.960
Tim Tait: You can see the mega eight squared about point one, right, that means that the dark matter is about point one on the energy budget of the universe, strictly speaking, it's omega, which is that traction each squared is normalization factor.

435
01:05:42.390 --> 01:05:44.070
Richard Partridge: On slide 11

436
01:05:45.090 --> 01:05:48.930
Richard Partridge: How important our thermal effects for freeze out of calculation.

437
01:05:52.350 --> 01:06:00.420
Tim Tait: So this is something that there has been some effort to work on. But I think there's actually still room for more research in this direction on

438
01:06:01.230 --> 01:06:14.820
Tim Tait: thermal effects can be significant in some cases, but I think if you take a very generic wimp. That is freezing out that typically they're not very important, but you can even come up with theories, where they actually play a huge role.

439
01:06:17.820 --> 01:06:18.480
Richard Partridge: Okay.

440
01:06:20.250 --> 01:06:31.290
Richard Partridge: Next question. I'm flying five. Is there any experimental way to predict what happened before. Big Bang to clear sense of synthesis

441
01:06:32.280 --> 01:06:43.500
Tim Tait: We have very few ways of probing that era of the universe. So the main things we have are things that test inflation. So like, you know, looking at the very

442
01:06:45.060 --> 01:06:53.940
Tim Tait: High K modes of the CM be right so dark matter freeze out would be one way to probate if that's kind of what I've been selling here.

443
01:06:54.450 --> 01:07:03.600

Tim Tait: Maybe something about the universe has a very on a symmetry. And then the other particles, though, that contain information from before, big bag appeal synthesis

444
01:07:04.170 --> 01:07:15.240
Tim Tait: Are neutrinos and gravitational waves. So you could hope to learn something from those articles. If you could detect the relative neutrinos and the relic gravitational waves which no one has done yet.

445
01:07:18.300 --> 01:07:19.620
Richard Partridge: Okay, and

446
01:07:21.090 --> 01:07:31.890
Richard Partridge: I have a couple more questions that are I think just questions that you know people maybe miss something or so.

447
01:07:32.940 --> 01:07:35.370
Richard Partridge: If we've got time. We could go into them.

448
01:07:36.870 --> 01:07:40.050
Richard Partridge: The first is, sorry. What does beta referred to, again,

449
01:07:41.550 --> 01:07:44.100
Tim Tait: Okay, so I think that's probably in the supersymmetric

450
01:07:44.100 --> 01:07:58.950
Tim Tait: Theories and actually I didn't tell you what beta refers to. So that's a good question that I should have actually dealt with tangent beta. So, since there are two Higgs Boson ones. And this theory. They can both have vacuum expectation values and then

451
01:08:00.120 --> 01:08:18.240
Tim Tait: The total v one squared plus b squared, right. The best part of one plus the square to the second one is fixed by the Z, both on mass, but how much it's distributed between the two vacuum expectation values is not fixed and tangent beta is just the ratio of those two expectation values.

452
01:08:20.850 --> 01:08:26.040
Richard Partridge: Okay. And is the Beano the Susie partner of the zeebo

453
01:08:27.690 --> 01:08:33.000

Tim Tait: Not exactly right. The Beano is a Suzy partner of the hypercharged, those are

454
01:08:34.080 --> 01:08:37.770
Tim Tait: The zebras on is a mixture of the hypercharged bows on and

455
01:08:39.030 --> 01:08:49.470
Tim Tait: The, the neutral component of the neutral sq to both on so the Z is a mixture of those two things, and the Beano instead of just the superpartner of one of them.

456
01:08:49.890 --> 01:08:59.310
Tim Tait: Of course, the lightest neutralino as we said is actually also itself a mixture. So the thing is, though, it's usually a different mixture and you have

457
01:08:59.820 --> 01:09:15.090
Tim Tait: So if you had the same mixture for your LM s p of being on we know as you had for the photon and z. And you could call it as, you know, or a week or, you know, or a Filipino. But since, in general, it's a different mixture. We just call it neutralino

458
01:09:17.820 --> 01:09:24.450
Lisa Kaufman: Hey, I think that's all the time we have for questions. Thank you so much. Tim, and we look forward to lecture three tomorrow. Right. OK.

459
01:09:24.480 --> 01:09:25.920
Lisa Kaufman: Now we'll have a

460
01:09:26.640 --> 01:09:27.090
Guess.

461
01:09:28.410 --> 01:09:29.400
Lisa Kaufman: I'll stop the recording.