WEBVTT

1
00:00:05.190 --> 00:00:24.450
dong su: Okay, so we're starting the second week of the SSI. And if you look at the program. You may have noticed the, the second week, it's a lot of some kind of arc theme. So the various subject related job psycho dark matter and dark energy and so on. So one of the

2
00:00:26.640 --> 00:00:32.460
dong su: One of the person who actually encounter a lot if you go to the doc literature would be can take a

3
00:00:32.580 --> 00:00:33.810
dong su: Lot of things about the

4
00:00:33.810 --> 00:00:36.240
dong su: Various things related copywriter.

5
00:00:37.980 --> 00:00:50.550
dong su: Sector and so on. So, so he's a very good tour guide for us, I guess for starting the series of three lectures on the introduction to the dark matter and not second. Okay. Okay.

6
00:00:51.900 --> 00:01:04.170
Tim Tait: Thank you very much. It's very nice to be here, I think. Unlike most of the lectures for this episode of the SSI. I have actually already lectured remotely to the SSI once before.

7
00:01:05.220 --> 00:01:14.430
Tim Tait: Most of you of course we're not here for that particular lecture, but for those few of you who were I promise that I will do my best not to have any fire alarms go off this time.

8
00:01:16.050 --> 00:01:21.150
Tim Tait: So I was asked to give some lectures about dark matter and dark sectors, but the theoretical aspects of them.

9
00:01:21.870 --> 00:01:31.530
Tim Tait: I'll start off though with the most important thing that you can take away from my presentations, and that is that this animal up here in the corner is an anteater. That's our mascot at UC Irvine.

10
00:01:32.580 --> 00:01:37.620

Tim Tait: We'll see if Jonathan has quite as good a image of one himself to share with his lecture start later today.

11
00:01:39.090 --> 00:01:44.070
Tim Tait: So here's an outline of the lectures. I'm going to start with some preliminaries, these are going to include

12
00:01:44.460 --> 00:01:52.320
Tim Tait: How you can think about building a theory of dark matter what it means to have a theory of dark matter and what it is you would need to specify to define such a theory.

13
00:01:53.010 --> 00:02:00.900
Tim Tait: I'm going to spend a fair amount of time talking about how dark matter could be produced in the early universe. This is a very important way that we used to classify theories of dark matter.

14
00:02:01.380 --> 00:02:05.160
Tim Tait: And it really also informs the way that we think about looking for them.

15
00:02:05.910 --> 00:02:16.080
Tim Tait: So that's going to be what we're going to cover today. In fact, we might not even get all the way through it today. And that's all right i budgeted some time at the end. So we may go a little bit into tomorrow to finish up talking about production.

16
00:02:17.010 --> 00:02:25.260
Tim Tait: Then the next two lectures are about theories specific theories of dark matter itself and then specific theories of dark sectors.

17
00:02:27.450 --> 00:02:37.500
Tim Tait: Alright so preliminaries unfortunately this still needs to be said in this country. And so I leave this slide here just to remind us, but I don't have anything more to contribute about it today, unfortunately.

18
00:02:38.970 --> 00:02:51.180
Tim Tait: So dark matter course, as you've learned I think last week is a non relativistic fluid present in the cosmos, it's necessary to explain its dynamics and evolution. I have two images to very old images as you can see

19
00:02:52.290 --> 00:02:58.020

Tim Tait: One is the rotation curve of the M 31 galaxy that's that's Andromeda. The closest big galaxy to us.

20
00:02:58.710 --> 00:03:08.610
Tim Tait: And next to it. You see the Rubin, who I really like this picture because she has that look that you see on any experimental scientist. When you interrupt them while they're working on their experiment.

21
00:03:09.030 --> 00:03:13.860
Tim Tait: She definitely wants you to just get on with telling her whatever it is you need to let her get back to work.

22
00:03:15.360 --> 00:03:23.280
Tim Tait: So you heard a lot last week about cosmology and why it is we know the dark matter exists. I'm not going to go through that in great detail.

23
00:03:23.880 --> 00:03:35.610
Tim Tait: But just to remind us so we're got everything fresh in our mind for this week, dark matter is something that we is a phenomenon that we can see the evidence of on very many different like skills in the cosmos.

24
00:03:36.180 --> 00:03:48.090
Tim Tait: And it makes up about 20% or so of the energy budget of the universe with the most of the rest being dark energy. This plot that shows you the

25
00:03:49.230 --> 00:03:55.590
Tim Tait: The content in matter in the content and vacuum energy of the universe. It's actually an old plot. It's about 10 years old.

26
00:03:55.950 --> 00:04:09.030
Tim Tait: And the reason is, is that the measurements. Now, or so precise that they're so zoomed in, you kind of lose the majesty and the mystery of the fact that you have three different types of measurements that are all giving you very consistent pictures of how the universe behaves

27
00:04:10.440 --> 00:04:24.690
Tim Tait: And it turns out I learned while preparing these lectures that there's pretty much an ex case CD comic for anything you want to describe in physics. And so here's the first one I found which reminds us that even a bottle of milk is mostly dark energy and dark matter.

28
00:04:26.640 --> 00:04:33.000

Tim Tait: So a dark sector. On the other hand, is a group of related particles, one of which is the dark matter. And so this is schematically indicated

29
00:04:33.450 --> 00:04:40.680
Tim Tait: By this diagram. So over here on the right side we have the standard model, which contains all the ingredients of the standard model that we're used to.

30
00:04:41.100 --> 00:04:49.410
Tim Tait: On the left side we have the dark matter, and it may interact with the standard model by exchanging one or more mediators the mediators are represented by the dashed red line.

31
00:04:50.670 --> 00:04:55.800
Tim Tait: So these mediators are particles that interact, both with dark matter and with the standard model and therefore

32
00:04:56.550 --> 00:05:03.720
Tim Tait: Let two sectors, communicate, we know already that gravity must be a mediator gravity interacts with everything and gravity is in fact

33
00:05:04.620 --> 00:05:08.730
Tim Tait: The mediator that has given us all the evidence for dark matter that we're currently talking about

34
00:05:09.180 --> 00:05:16.170
Tim Tait: Of course, the hope there may be other mediators too and that a big part of understanding what the theory of dark matter is would be discovering them and measuring them.

35
00:05:17.010 --> 00:05:25.110
Tim Tait: But it could be actually that in addition to the dark matter. There are more things over in the dark sector, which may interact with the Standard Model only by these mediators.

36
00:05:25.470 --> 00:05:35.910
Tim Tait: And. These could include things like maybe a dark force carrier some kind of gauge force for the dark matter, kinda like the gauge forces we see for the courts and leptons. The Standard Model.

37
00:05:36.450 --> 00:05:45.180
Tim Tait: Or other kinds of dark, dark particles that are related to the dark matter. We're going to see examples of all of those types of things. When we eventually get there in day three.

38
00:05:45.660 --> 00:05:55.500
Tim Tait: So there's a large number of possibilities for what could be in the dark sector and but the dark sector is basically anytime dark matter comes along with friends that makes things a little more complicated.

39
00:05:57.390 --> 00:06:10.050
Tim Tait: So we need theories to talk about dark matter and dark sectors, I've got here reproduced three plots and I think you're probably going to see at least versions of these plots shown by different people throughout this week.

40
00:06:10.620 --> 00:06:20.820
Tim Tait: They include looking for dark matter annihilating so that's a pure of the blue outline and these are searches that are going to be talked about by Professor Tracy slot here.

41
00:06:21.630 --> 00:06:27.990
Tim Tait: We have dark matter being produced at the LA. See, which I think Professor Jonathan thing and I will also spend some time talking about

42
00:06:28.410 --> 00:06:38.250
Tim Tait: And then down at the bottom in the green we have look searches for dark matter scattering with nuclei, which is going to be the main topic of the lecture by Professor Jody Cooley.

43
00:06:39.000 --> 00:06:46.530
Tim Tait: So all of these measurements are very interesting. They're all all of them. None of them are actually seeing dark matter in any way that is clearly

44
00:06:47.760 --> 00:06:54.060
Tim Tait: Is so well established that we're going to accept it yet. So they're all telling us something about how dark matter interacts with the standard model.

45
00:06:54.360 --> 00:07:03.600
Tim Tait: The point is, is that without a theory, you don't know how to relate them to each other. And so you're not really able to figure out what these things mean at least in reference to each other.

46
00:07:04.380 --> 00:07:07.410
Tim Tait: So we need theory so that we can actually fit the measurements together.

47
00:07:07.770 --> 00:07:19.110
Tim Tait: And then figure out which new ideas are going to be worth testing by giving experiment or in other words which experiments, we should be building in the future and which ones are just going to be retraining ground that we've already covered with some other experiment.

48
00:07:21.150 --> 00:07:34.110
Tim Tait: So there's a lot of activity building theories of dark matter, this is a plot of the number of papers with keywords and a title as a function of year. It's made by Sasha believe it's actually a couple years out of date. But you can see that

49
00:07:35.610 --> 00:07:48.960
Tim Tait: You can see Susie your sort of rising up in the 80s and 90s kind of plateaus maybe going down a little bit at the end. Not that much Higgs, of course, is surging forward and it's getting even higher as the Higgs discovery was taking place.

50
00:07:49.710 --> 00:07:55.020
Tim Tait: Top physics again going pretty strong la she's producing a lot of top works. And so there's a lot of stuff to study.

51
00:07:55.500 --> 00:08:00.870
Tim Tait: Extra dimensions is came on strong and around 2000 but has sort of been diminishing since then.

52
00:08:01.380 --> 00:08:11.220
Tim Tait: And dark matter is really the thing that's actually surging the most. And I think that's because since the discovery of the Higgs dark matter is among the most important questions. It's still remain to cancer.

53
00:08:12.660 --> 00:08:26.760
Tim Tait: There's another X KC D comic here says yes, everybody's already had the idea. Maybe there's no dark matter and gravity just works differently on large scales, it sounds good, but it's very difficult to make it fit the data. It's not actually impossible.

54
00:08:28.800 --> 00:08:38.490
Tim Tait: This is a Venn diagram that I made in the year 2013 which was to try to summarize how different theories of dark matter that existed at the time are related to each other and

55
00:08:39.600 --> 00:08:51.870

Tim Tait: It's nice, in the sense that you can see how different things related. On the other hand, it's very complicated and very weird. And I'm not sure. Really, if the value is largely as abstract art or physics.

56
00:08:53.400 --> 00:08:59.760
Tim Tait: And then finally, you can say I'm a visual person. This is a diagram that appeared in a paper I wrote recently.

57
00:09:00.270 --> 00:09:14.790
Tim Tait: About dark matter and what the different ideas could be. You can see modified gravity is actually one of the ones that still listed there some ideas have actually gotten more traction since 2013 like for example primordial black holes is something that's now discussed quite a bit.

58
00:09:16.800 --> 00:09:18.660
Tim Tait: But I'm not going to say very much about this.

59
00:09:20.550 --> 00:09:31.500
Tim Tait: And of course they lead to a wide ranging set of parameters. So this is a plot that shows you the mass of the dark matter on the x axis and its interaction strength with ordinary matter on the Y axis.

60
00:09:31.920 --> 00:09:45.360
Tim Tait: And you can see different ideas that again existed even in 2007 the basically spanned, you know, on the order of 50 orders of magnitude on both of these directions. So there are many things. Dark matter could be

61
00:09:47.010 --> 00:09:56.730
Tim Tait: So what I'd like to do now is spend a little time talking about the systematics how you build a theory of dark matter. What makes a theory, a good theory of dark matter and

62
00:09:57.420 --> 00:10:06.240
Tim Tait: You know what ingredients are how to understand those ingredients. So again, another comic and all it basically wants you to understand is the dark matter is not squirrels.

63
00:10:08.400 --> 00:10:14.220
Tim Tait: So what is dark matter, if we want to answer all of our questions about how its produced and what it would look like in the detector.

64
00:10:14.520 --> 00:10:21.990

Tim Tait: We needed a description of dark matter of the level of fundamental particles and that means we need to describe it as the login engine density that governs the evolution of quantum fields.

65
00:10:22.590 --> 00:10:27.390
Tim Tait: In other words, you need to add a quantum field to be the dark matter and any other parts of the dark sector that we think are there.

66
00:10:27.720 --> 00:10:31.380
Tim Tait: And then we need to understand how those fields are allowed to interact with the standard model.

67
00:10:32.340 --> 00:10:44.220
Tim Tait: So the theory has to reflect the little the few things that we do know about dark matter. So we know that it's dark. It's right there in the name. And that really means that it's electrically neutral and also neutral under the SU three color interaction.

68
00:10:44.940 --> 00:10:52.410
Tim Tait: Otherwise it would pick up form down states with ordinary corks and it would not actually look electrically neutral at the end of the day.

69
00:10:53.580 --> 00:11:05.310
Tim Tait: It's massive. It has to be able to slow down and build up and form galaxies and it's still around today, which means that it's either exactly stable or it has a lifetime on the order of the age of the universe itself.

70
00:11:05.730 --> 00:11:12.750
Tim Tait: And it turns out the building the theory with these three properties is not totally trivial. It actually restricts quite a bit. The space of possibilities.

71
00:11:13.770 --> 00:11:27.330
Tim Tait: The image you see here is actually a picture of a sculpture. It's called cold dark matter and exploded view it's by an artist named Cornelia Parker. It's actually, at least it was I think it's been taken out since then, but it was in the Tate Modern

72
00:11:28.440 --> 00:11:31.530
Tim Tait: Museum and take was not spelled correctly. So that's a bummer.

73
00:11:32.760 --> 00:11:39.600

Tim Tait: It's a really interesting sculpture. It's three dimensional you can walk around and take a look. I don't really know what it's trying to tell us about the physics of dark matter.

74
00:11:39.990 --> 00:11:51.630
Tim Tait: But the way I parse this is to say that if this is what we can get based on the incomplete view of dark matter we're giving artists right now, just imagine what they'd be able to produce if we could actually tell them what it was.

75
00:11:53.790 --> 00:11:59.340
Tim Tait: So one thing that is for sure is physics beyond the standard model, the standard model of particle physics has no

76
00:11:59.940 --> 00:12:10.320
Tim Tait: Fields in itself that have the right properties to be dark matter, and most of them are just to interactive so photons leptons had runs w goes on they all shine. They're not dark

77
00:12:11.310 --> 00:12:20.190
Tim Tait: Neutrinos are neutral and therefore, there they are dark, but they're too light to actually clump inform galaxies and the kind that we see at least the standard Standard Model neutrinos, or to light.

78
00:12:20.610 --> 00:12:23.760
Tim Tait: There could be other kinds of neutrinos that might be able to play the role of dark matter.

79
00:12:24.600 --> 00:12:37.020
Tim Tait: And then some of the other neutral particles that are heavy in the standard model like Z bows on in the Higgs boson are too short lived so dark matters and manifestation of physics beyond the standard model. And as we saw, there are lots of ideas for what it could be.

80
00:12:38.610 --> 00:12:49.830
Tim Tait: So basically the idea in particle physics is fill out this questionnaire. You want to know all the different properties and dark matter and basically so far all we can really say for sure is that it interacts with gravity. So there's a lot to do.

81
00:12:52.830 --> 00:13:04.860
Tim Tait: So as you start to build a theory of dark matter a theory of dark matter needs to maintain all of the successes of the standard model of particle physics and that means it has to conserve all the right things. It has to be mathematically self consistent

82
00:13:05.550 --> 00:13:13.140
Tim Tait: Etc. So, you know, just very basic things it needs to have one calorie and variance with energy momentum and momentum or conserved.

83
00:13:13.920 --> 00:13:21.720
Tim Tait: You know, that means it needs to be a local quantum field theory adult out of normal fields like scale or fields for me ons and so forth.

84
00:13:22.320 --> 00:13:31.770
Tim Tait: It needs to respect the gauging variants SU three cross su to cross you one of the standard model these mean imply that electric and color charge or conserved.

85
00:13:32.340 --> 00:13:42.210
Tim Tait: It also is necessary for the mathematical consistency of the lecture week interaction, even though it's it's charges not concerned because that interaction spontaneously broken by the Higgs.

86
00:13:43.380 --> 00:13:49.140
Tim Tait: Flavor and CP symmetries are actually violated in the standard model already by the lecture week interactions.

87
00:13:49.620 --> 00:13:58.110
Tim Tait: But we've done a lot of tests of these kinds of violation and so far we've found that the secant matrix for the courts and the

88
00:13:58.590 --> 00:14:03.330
Tim Tait: NS matrix for the neutrinos actually describe all of the violation that we can see.

89
00:14:03.840 --> 00:14:15.570
Tim Tait: So if you're going to violate flavor and CP in some new way when you add dark matter, you're likely to run into strong experimental constraints that come from the fact that we haven't seen any extra breaking of the cemeteries.

90
00:14:16.170 --> 00:14:18.900
Tim Tait: So that's also an important ingredient that you see very much

91
00:14:20.100 --> 00:14:24.600
Tim Tait: It's not often spelled out, but it's very much used in constructing theories of dark matter.

92
00:14:25.710 --> 00:14:41.460
Tim Tait: So basically, dark matter should be described by quantum field corresponding a definite spin uncharged under you want electromagnetism or SU three color. Therefore, there are no tree level interactions with blue ones are photons, there could be loop level interactions, though.

93
00:14:44.370 --> 00:14:53.130
Tim Tait: And one of the mysteries of dark matter is why, despite being massive it is at least to a very good approximation stable as far as we can tell us completely stable.

94
00:14:53.370 --> 00:14:57.330
Tim Tait: Of course, it might be that it will someday decay. And we just haven't waited long enough to see that happen.

95
00:14:58.140 --> 00:15:02.760
Tim Tait: And this is actually telling us something very important about how we can write interactions down the standard model.

96
00:15:03.330 --> 00:15:08.400
Tim Tait: So we need a symmetry or at least an approximate symmetry to prevent the dark matter particles from decaying

97
00:15:08.880 --> 00:15:17.580
Tim Tait: And the simplest example is a new kind of parody or mathematically as the two discrete symmetry, under which the dark matter transforms with the standard model does not

98
00:15:18.060 --> 00:15:26.130
Tim Tait: So under this is the two that I'm imagining the dark matter, which is written here as high goes into minus sky but the Standard Model goes into plus itself.

99
00:15:27.030 --> 00:15:32.940
Tim Tait: So this symmetry would require that any interaction term contain two powers of the dark matter field.

100
00:15:33.450 --> 00:15:40.830
Tim Tait: And then as many powers of the Standard Model field as you would like. And that prevents decay processes from happening. And you can see over here.

101
00:15:41.790 --> 00:15:50.520

Tim Tait: And the diagrams, right, if there's nosy to symmetry, I can just write down and interaction of the dark matter and some amount of Standard Model stuff and this will allow the dark matter to decay.

102
00:15:51.180 --> 00:16:01.980
Tim Tait: Of course, I can still control how fast that happens based on the strength of the interaction, I write down. But once I allow for this coupling the dark matter will eventually became something

103
00:16:03.150 --> 00:16:11.490
Tim Tait: If I have the Z to symmetry, then every interaction has to have to dark matter particles attached to it. And this means that if one comes in at least one has to go out

104
00:16:11.880 --> 00:16:22.770
Tim Tait: And including maybe some standard model things. And so the number of guys would be conserved. And so that's basically how does he to and ensures that something would be approximately sorry exactly stable.

105
00:16:24.210 --> 00:16:31.050
Tim Tait: Now of course you could think about more complicated symmetries. So, for example, is the three symmetry is one in which the dark matter is

106
00:16:31.830 --> 00:16:42.360
Tim Tait: Charged and picks up a phase. And let's say the Standard Model stays the same. So, such a cemetery allows for dark matter number changing processes, but it doesn't allow the dark matter to decay.

107
00:16:43.110 --> 00:16:49.050
Tim Tait: And you can see this actually illustrated over on the right side of the slide.

108
00:16:49.500 --> 00:16:59.790
Tim Tait: You can see that if there's an interaction like high dagger chi, right, which would not transform because high dagger will transform is either the minus the phase and chi is either the plus phase.

109
00:17:00.270 --> 00:17:03.570
Tim Tait: And then time some standard model things that aren't matter can annihilate in this theory.

110
00:17:04.410 --> 00:17:18.360
Tim Tait: You also can have interactions were say to dark matter particles come in and one goes out and that's because dark matter cube is

also very and under the cemetery. And that's because the phase has been chosen. This is what makes it as the three cemetery and such that

111
00:17:19.470 --> 00:17:24.330
Tim Tait: Three phases actually are equivalent to know phase at all in a phase zero

112
00:17:25.980 --> 00:17:33.810
Tim Tait: And of course it's interesting to see that even just thinking about the structure of this theory. Once I asked that the dark matter transformed by picking up a phase.

113
00:17:34.170 --> 00:17:41.940
Tim Tait: It implies that the dark matter has to be a complex field, which wasn't required for the Z to symmetry. So it's already imposing something about what I'm allowed to choose.

114
00:17:42.810 --> 00:17:49.650
Tim Tait: And of course there are different variations of this type I continuous symmetry, such as, for example, a whole you one. In other words, I'm allowed to

115
00:17:50.250 --> 00:17:56.070
Tim Tait: rephrase the dark matter by any Phase I, like, and not just the discrete choice of two pi over three.

116
00:17:56.760 --> 00:18:02.880
Tim Tait: And that would also imply a concert of dark charge. And we've been there would be dark particles and dark antiparticles

117
00:18:03.660 --> 00:18:11.010
Tim Tait: Which would be distinguishable from each other, and it would also imply that the dark matter if it's the lightest such charged object would be stable.

118
00:18:11.880 --> 00:18:21.960
Tim Tait: And of course the dark matter doesn't need to be exactly stable as long as the interactions that lead to the kidneys or weaken off the dark matter could persist as a long live particle which hasn't had time to decay yet.

119
00:18:22.410 --> 00:18:32.460
Tim Tait: And the QC the accion are going to spend a little bit of time talking about tomorrow is an example of something that realizes sufficient lifetime this way.

120
00:18:35.400 --> 00:18:38.130
Tim Tait: So look at that I found another comic

121
00:18:39.240 --> 00:18:52.710
Tim Tait: This one, basically, is something that we should bring up every time somebody wants to talk about something being concerned or not. In this particular case, it's using the illustration of a perpetual motion machine obviously doesn't conserve something

122
00:18:55.020 --> 00:19:03.060
Tim Tait: So I put a couple exercises which you could try your hand at if you are feeling like you'd like to make sure you've understood what's gone on the lecture so far.

123
00:19:03.780 --> 00:19:14.340
Tim Tait: In this first one I asked you to write down the theory in which the dark matter is a real spins euro field that is a triplet of su to week and has hypercharged zero

124
00:19:14.970 --> 00:19:20.520
Tim Tait: So that already tells you how to write down its cage interactions. Because you know how it transforms under the Standard Model gauge cemeteries.

125
00:19:20.970 --> 00:19:25.260
Tim Tait: It's odd under is the two symmetry. So dark matter goes into minus itself under the z two.

126
00:19:25.920 --> 00:19:31.860
Tim Tait: And then I asked you to include all of the normalized interaction terms that it could have both with itself, and with the standard model.

127
00:19:32.340 --> 00:19:45.660
Tim Tait: And right because this dark matters a triplet of su to it's really a complex of three fields, including one electrically positively charged on a neutral one, which is the one that would actually be the dark matter, in this case, and then a negative one.

128
00:19:47.310 --> 00:19:47.820
Tim Tait: So,

129
00:19:48.840 --> 00:19:49.320

Tim Tait: If you

130
00:19:50.490 --> 00:19:56.310
Tim Tait: If you want to take a stab at this. I'd be happy. Actually, if you sent me an email to give you some advice about how you did on it.

131
00:19:57.360 --> 00:20:01.890
Tim Tait: And for bonus points. You can confidently refer to your dark matter particle as the square Lena

132
00:20:05.130 --> 00:20:18.810
Tim Tait: So now I'm going to spend the rest of the lecture today talking about how dark matter could be produced in the early universe. This is very interesting. It's very tied down to the way you would write down the theory of dark matter. And I think there's a lot we can learn from it.

133
00:20:20.250 --> 00:20:28.560
Tim Tait: So when we talk about the dark matter production in the early universe, what we're really trying to match on to is the relic abundance or how much dark matter, there is today.

134
00:20:29.160 --> 00:20:38.610
Tim Tait: And we often actually classify theories of dark matter just based on how we realize the relative abundance and therefore match on with the observations that cosmology is telling us about

135
00:20:39.690 --> 00:20:45.600
Tim Tait: So there's something fundamental about thinking about dark matter theories. This way you could sort them differently if you wanted to.

136
00:20:46.320 --> 00:20:55.020
Tim Tait: But having a picture for how the population that we observed came about as part of having an appealing explanation of why this is a good candidate of dark matter we're talking about

137
00:20:55.440 --> 00:21:03.840
Tim Tait: And also, it does necessarily require that we talked about how the dark matter interacts with the theory of fundamental particles. So,

138
00:21:05.340 --> 00:21:10.800
Tim Tait: It is actually a very useful way to classify dark matter theories and I think that's why a lot of times it's done.

139

00:21:11.670 --> 00:21:21.120
Tim Tait: If we make assumptions about the history of the universe, and I'll come back and actually revisit this at the end of this discussion, the quantity of dark matter can very often be predicted

140
00:21:22.230 --> 00:21:32.760
Tim Tait: That means that actually by looking at how the dark matter is expected to be produced in the early universe we can identify regions of parameter space of a given theory that are particularly interesting

141
00:21:33.120 --> 00:21:40.320
Tim Tait: Because they nicely aligned with the measurements of the dark matter abundance. So we can find the regions of the theory that are more likely to be true.

142
00:21:42.690 --> 00:21:49.710
Tim Tait: So a lot of this discussion focuses on thinking about the content of different particles in the early universe.

143
00:21:50.100 --> 00:21:56.790
Tim Tait: And in particular by thinking about the equilibrium distributions just understanding the equilibrium distributions can actually be very helpful.

144
00:21:57.300 --> 00:22:02.430
Tim Tait: So we're going to actually talk about equilibrium for all different sorts of particles.

145
00:22:03.420 --> 00:22:13.350
Tim Tait: But the basic point is if the particles have rapid interactions which exchange energy between them when they're described by a common temperature T. And so if they do have these rapid interactions.

146
00:22:14.100 --> 00:22:22.680
Tim Tait: You can talk at least about their kinetic energies by just saying, what is the temperature of the universe at this point and that saves a lot of bookkeeping. You know, you don't want to keep track of.

147
00:22:23.250 --> 00:22:35.130
Tim Tait: What's the kinetic energy and the photons compared to the kinetic energy and the neutrinos, or the electrons. It turns out at early times they're all described by the same temperature and then lead times actually they diverge when they stop interacting officially each other.

148
00:22:37.110 --> 00:22:44.970

Tim Tait: If there are rapid reactions that change the numbers of particles. Right. So the first thing was to say if we exchange energy, then we have a common temperature

149
00:22:46.140 --> 00:22:51.510
Tim Tait: If we can change the number of the particles, the number density will approach the Maxwell Boltzmann distribution.

150
00:22:53.100 --> 00:22:58.800
Tim Tait: And this distribution looks very different depending on how the temperature compares with the mass of the particle.

151
00:22:59.340 --> 00:23:05.370
Tim Tait: At very high temperatures. The mass is negligible and the equilibrium number density goes like the temperature tube.

152
00:23:05.910 --> 00:23:13.140
Tim Tait: So it's basically just a power of the temperature. Right. The universe is expanding and cooling. And so, therefore, that would tell us something about

153
00:23:13.950 --> 00:23:21.030
Tim Tait: How the number densities of the particles are changing, but for temperatures below the mass equilibrium number density drops exponentially.

154
00:23:21.750 --> 00:23:26.640
Tim Tait: Right, it's given by the famous Maxwell Boltzmann distribution which is reproduce down here at the bottom.

155
00:23:27.120 --> 00:23:34.500
Tim Tait: So he does have some power loss sensitivity of the temperature, but once I actually and that's what governs at that sort of temperatures around the mass

156
00:23:34.830 --> 00:23:42.630
Tim Tait: But as I go to temperatures far below the mass, the exponential takes off and the number of density really just goes down very fast. So

157
00:23:43.770 --> 00:23:52.440
Tim Tait: This is shown in this plot, which is photocopied actually from the early universe textbook. What it shows on the Y axis is the number density of

158

00:23:52.980 --> 00:24:04.020
Tim Tait: Some particle with which has some mass and then the x axis is parameter is by quantity that they called x x is defined to be the mass divided by the temperature

159
00:24:04.560 --> 00:24:14.130
Tim Tait: So if you think about it, if the masses fixed, then as x increases. That means that T is decreasing. And that's the same thing that corresponds with time increasing

160
00:24:14.850 --> 00:24:23.400
Tim Tait: For the periods of the universe that we're interested in. So the solid line here shows the equilibrium density, it just set to one at some early time

161
00:24:23.880 --> 00:24:33.210
Tim Tait: As a normalization. And then you see following Maxwell Boltzmann we get this solid curve which is dropping. Very, very fast. As the temperature is going down.

162
00:24:36.840 --> 00:24:49.680
Tim Tait: So the evolution of the dark matter number density is controlled by a Boltzmann equation which tracks the effect of the expansion of the universe, and also the creation and destruction of the dark matter. So there's a differential equation here.

163
00:24:51.090 --> 00:25:00.030
Tim Tait: Which has the the time derivative of the number density of dark matter. And then it has some terms related to the Hubble expansion of the universe. So that's the plus three. Hmm.

164
00:25:00.690 --> 00:25:08.670
Tim Tait: And then on the other side, we have the collision terms which could either correspond to dark matter decaying right or being produced by two particles using into it.

165
00:25:09.120 --> 00:25:18.240
Tim Tait: Or annihilating and of course I could add more terms, if I wanted to have more complicated processes. These are just some illustrate illustrative ones that show us what's going on so

166
00:25:19.380 --> 00:25:33.360
Tim Tait: In terms of analyzing the Hubble term which is usually called the Hubble friction term because if you think about this as a dynamical equation. This equation. So if you want to make them the analog with Newton's laws think that end is kind of like the velocity

167
00:25:34.440 --> 00:25:41.280
Tim Tait: Right, so therefore the Hubble term looks like a fictional term because so DVD t. Right, just like the acceleration and then

168
00:25:42.870 --> 00:25:43.290
Tim Tait: The

169
00:25:44.340 --> 00:25:50.550
Tim Tait: The second term, the three ah n term goes like n, right, which is like velocity. I said, so that's like a friction term.

170
00:25:50.850 --> 00:25:56.460
Tim Tait: And then the other terms can be thought of is that the dynamics, the actual potential terms that are causing the forces act.

171
00:25:57.270 --> 00:26:02.790
Tim Tait: So the Hubble fictional term is easier to analyze. If we remember that the Hubble and during radiation domination.

172
00:26:03.210 --> 00:26:15.030
Tim Tait: The Hubble constant is given by g star, which tells us basically how many light things there are in the universe that time or how much stuff is like compared to the temperature at that time and then times the temperature squared over the Planck scale.

173
00:26:16.410 --> 00:26:20.250
Tim Tait: Then the collision terms include a decay term and annihilation term.

174
00:26:20.580 --> 00:26:28.560
Tim Tait: I've used the usual trick of rewriting these in terms of equilibrium density. So there were some assumptions made they're actually that the stuff that I'm either decaying or annihilating into

175
00:26:28.980 --> 00:26:33.960
Tim Tait: Is in thermal equilibrium. Now usually these are standard model particles. And so that is actually true.

176
00:26:34.500 --> 00:26:52.470
Tim Tait: And you can see the decay term goes like number density minus equilibrium density and the violation term goes like minus the cross section averaged with the velocity times n squared minus and equilibrium squared. So both of these terms actually look like.

177
00:26:53.610 --> 00:27:04.050
Tim Tait: Negative feedback terms, if, if I can ignore the Hubble friction term than both of these terms, but the decay and annihilation term would just like the dark matter to have its equilibrium density

178
00:27:04.440 --> 00:27:12.810
Tim Tait: And that's, again, not shocking, right. We know that in the limit where we have fast processes that change the number of particles, the number of particles should approach equilibrium

179
00:27:13.470 --> 00:27:19.770
Tim Tait: If the system is characterized by single temperature. So it's pretty easy to analyze what happens in sort of extreme limits.

180
00:27:20.310 --> 00:27:32.220
Tim Tait: If gamma or sigma v times N equilibrium or large compared to h i can neglect the friction term and I'm basically just going to say I'm going to get something like the equilibrium number density

181
00:27:33.900 --> 00:27:44.670
Tim Tait: However, if he has large, then these interactions are not large enough to maintain equilibrium and actually gets frozen and just scales with the expansion of the universe. So it's constant for Co moving volume.

182
00:27:46.560 --> 00:27:52.350
Tim Tait: a universe where the dark matter stayed in equilibrium, or in other words the universe where I could ignore the Hubble friction at all times.

183
00:27:52.590 --> 00:28:02.730
Tim Tait: Would actually be pretty boring, from the point of view of dark matter because as the temperature falls below the mass, the number density of the dark matter particles would actually themselves fall exponentially.

184
00:28:05.970 --> 00:28:14.040
Tim Tait: So we can get more sophisticated in our analysis of this equation. We're going to try to develop a little bit of intuition. But basically,

185
00:28:14.610 --> 00:28:21.090

Tim Tait: And I'm going to go back one slide per second, it's always good. All of our intuitive understanding is going to come about from either

186
00:28:21.690 --> 00:28:30.300
Tim Tait: Either comparing the decay rates to the Hubble constant or the annihilation cross section, times one power of the equilibrium density

187
00:28:30.720 --> 00:28:44.340
Tim Tait: To the Hubble constant, right. And the reason for that is if you think about it, there's one power event here. There's one power event here. There's actually two powers event here. So that's the fair thing to compare with would be h gamma and sigma v times in

188
00:28:47.580 --> 00:28:56.520
Tim Tait: OK, so the fact actually that the number changing interaction through when the number changing interactions are an equilibrium we get driven to the equilibrium density is a nice thing.

189
00:28:57.630 --> 00:29:09.600
Tim Tait: These equilibrium arguments actually make us insensitive to the initial conditions of the universe. It doesn't really matter what density. You start out with if you reach equilibrium because you know you're just going to end up with equilibrium density

190
00:29:10.170 --> 00:29:20.280
Tim Tait: And that'll happen pretty quickly. If these interactions are in our inner equilibrium. So now as I said on the previous slide because of the expansion.

191
00:29:20.880 --> 00:29:31.380
Tim Tait: The Hubble Constant goes like t squared. And therefore, it falls with time, at least in the radiation dominated era. So in these plots. I've got here, which we're going to look at

192
00:29:32.250 --> 00:29:41.460
Tim Tait: In a few different contexts. What I've plotted is temperature decreasing. So you can think of. It's more like time is increasing as I move along the access and the universe is expanding and cooling

193
00:29:41.970 --> 00:29:51.360
Tim Tait: So that's why the line for the Hubble constant, right, which goes like P squared actually has a slope of tea to the minus two. In this

194
00:29:52.470 --> 00:29:53.640

Tim Tait: log plot, I should say.

195
00:29:55.110 --> 00:30:05.970
Tim Tait: So then I've imagined different values for what gamma or sigma v times the equilibrium could be. And those are shown by the red line and the blue line as well.

196
00:30:06.930 --> 00:30:16.830
Tim Tait: One thing to keep in mind though is that the density and equilibrium falls exponentially. Once the temperature gets below the mass. So once I hit this line that I've indicated for the mass of the particle.

197
00:30:18.450 --> 00:30:24.990
Tim Tait: An equilibrium is going to go to zero. And anything that involves an equilibrium is going to fall out of equilibrium at that point.

198
00:30:26.250 --> 00:30:33.990
Tim Tait: So if I look at the case for a temperature independent decay right gamma is just a constant in this plot.

199
00:30:34.440 --> 00:30:40.710
Tim Tait: That means that it's very likely that very early times the Hubble rate is going to be larger. So I'm going to be frozen.

200
00:30:41.520 --> 00:30:49.500
Tim Tait: Right gamma is just not important enough. But then as the Hubble constant falls, because the universe is cooling eventually it's going to cross gamma

201
00:30:49.890 --> 00:31:02.910
Tim Tait: And these interactions are going to come into equilibrium. So decays, you know, are very are typically out of equilibrium and early times because novel constant would be big, but come into equilibrium at late times

202
00:31:04.350 --> 00:31:08.790
Tim Tait: Annihilation works differently if sigma v is

203
00:31:10.020 --> 00:31:16.410
Tim Tait: Independent of temperature than sigma v times an equilibrium either scales like three powers of temperature.

204

00:31:17.760 --> 00:31:25.350
Tim Tait: at early times right when the temperature is higher than the mass or exponentially falls at Lake times when I crossed the mass

205
00:31:25.650 --> 00:31:38.190
Tim Tait: So the equilibrium density actually would sort of come down as a power law that is steeper than the Hubble one and then when it gets to the mass, it'll actually just crash and go to zero very quickly because of the exponential dependence.

206
00:31:39.930 --> 00:31:57.750
Tim Tait: So this suggests two different ways to think about dark matter being produced thats related to the equilibrium density. The first one is called freeze out. And the way it works is as follows. So I've set the mouse in some value on the diagram you can see that the Hubble

207
00:31:59.250 --> 00:32:03.390
Tim Tait: Hubble constant is following with time following with temperature.

208
00:32:04.800 --> 00:32:12.360
Tim Tait: As expected, then as I mentioned earlier, if, let's say I have a particle which is primarily decaying. It starts out

209
00:32:13.410 --> 00:32:18.540
Tim Tait: Out of equilibrium because the Hubble rate is big. Eventually, it comes into equilibrium

210
00:32:20.340 --> 00:32:27.390
Tim Tait: Until of course I get to the mass. And then at that point it's likely to fall out of equilibrium because again.

211
00:32:28.320 --> 00:32:38.040
Tim Tait: The density is just falling too fast. So this is a freeze out process where I come into equilibrium. And then I leave it and where I leave it, it's going to sort of depend is going to determine

212
00:32:38.700 --> 00:32:40.380
Tim Tait: How many particles. I have leftover

213
00:32:40.860 --> 00:32:52.320
Tim Tait: Now for annihilation. This works a little bit differently because annihilation is probably in equilibrium at all times. In the early universe you imagine extrapolating this blue line back to early times it's never below the Hubble stale.

214
00:32:52.890 --> 00:32:58.200
Tim Tait: In fact, I mean if there was nothing going on if there was no mass for the particle, it would always be about scale.

215
00:32:58.920 --> 00:33:03.090
Tim Tait: But what happens though is that I follow the blue line, but then when I get to the mass line.

216
00:33:03.630 --> 00:33:15.630
Tim Tait: The equilibrium density goes to zero. And so this line basically falls down to zero and at that point I do cross the Hubble scale and freeze out. So both of these actually are able to describe freeze out of a particle

217
00:33:17.010 --> 00:33:24.180
Tim Tait: Now freezing in some ways is the opposite limit freezing is the case where the Hubble scale is always larger

218
00:33:24.750 --> 00:33:34.530
Tim Tait: Than the rates for either decay or an annihilation. And you can actually do freezing with either one of these things, just like you can do freeze out with either one. So,

219
00:33:35.460 --> 00:33:44.940
Tim Tait: For example, if I'm talking about a decay. You can imagine that the decay is is again, independent of temperature. So it's a straight line in this plot.

220
00:33:45.510 --> 00:33:55.740
Tim Tait: It's below the Hubble scale as it's some it's not an equilibrium. So let's say I start off with a negligible amounts of particles.

221
00:33:56.670 --> 00:34:03.360
Tim Tait: In the early universe. I'll be generating them with time, but they don't reach an equilibrium value and then I get to the mass and the whole thing shuts off.

222
00:34:03.930 --> 00:34:08.790
Tim Tait: And the same thing is true for annihilation. Let's say that the annihilation is weak enough

223
00:34:09.120 --> 00:34:15.270

Tim Tait: That it's always below the Hubble scale, though. Again, if you imagine extrapolating at some point it's always going to be above the Hubble scale.

224
00:34:15.630 --> 00:34:24.630
Tim Tait: The difference here though for the freezing case that I've drawn is that if I extrapolate back they cross well before the mass. And so they cross when the particle is still relativistic

225
00:34:25.530 --> 00:34:33.210
Tim Tait: But OK, so we depart from the equilibrium density. And then when we get to the mouse. We're actually stuck with the amount of dark matter there.

226
00:34:35.370 --> 00:34:38.160
Tim Tait: So let's talk a little bit about freeze out in more detail.

227
00:34:39.780 --> 00:34:47.580
Tim Tait: Freeze out is naturally associated with a dark matter candidate in the broad class that's called a wimp or weekly interacting massive particle

228
00:34:48.270 --> 00:34:57.450
Tim Tait: And I think the most attractive thing about WIMPs is really the fact that freeze out can naturally explain the amount of dark matter we observe in the universe.

229
00:34:57.870 --> 00:35:13.170
Tim Tait: With very little sensitivity to initial conditions, of course, it's also very significant that WIMPs occur automatically and many models of physics beyond the standard model such as, for example, supersymmetric extensions and so I mean Windstar very popular also for that reason.

230
00:35:14.310 --> 00:35:22.680
Tim Tait: And Webster revision of dark matter of which we can use particle physics experimental techniques to search very effectively. Right. Which also means that particle physicists have a lot to tell us about them.

231
00:35:23.760 --> 00:35:30.480
Tim Tait: We have to be a little bit careful with the precise definition of the term wimp. Some people take the week.

232
00:35:31.170 --> 00:35:40.320

Tim Tait: In Wimp very seriously the W and they think that they use it to refer to particles, which literally have an electroweak interaction.

233
00:35:40.800 --> 00:35:44.190
Tim Tait: So these literally talk to the W and Z of the scattered model.

234
00:35:44.850 --> 00:35:54.300
Tim Tait: However, I would say probably a few more people use the term bit more generically. They use it to refer to particles of interactions and masses that are around the electric sized

235
00:35:54.690 --> 00:36:06.270
Tim Tait: But they're not really connected to the Standard Model week interactions directly. And so one thing when you are talking to someone about wimps. You have to figure out which type of which definition, they're using to actually specify what they mean.

236
00:36:08.700 --> 00:36:18.360
Tim Tait: The image you see here is a bottle of dark matter which it turns out you can buy online on the internet for about $60 you get about 20 servings.

237
00:36:19.110 --> 00:36:29.190
Tim Tait: It's available in three flavors blue raspberry fruit punch and grape. I think that if we do discover that dark matter has three flavors just like the types of corks and

238
00:36:29.700 --> 00:36:37.170
Tim Tait: leptons, what we know about have three flavors. We all have to agree that these clearly are the flavors that we have to label, they have to call them this

239
00:36:38.700 --> 00:36:47.280
Tim Tait: The bottle is actually pretty big. It's a big bottle. You probably can't see because I'm very small window on your screen right now but

240
00:36:49.200 --> 00:36:56.400
Tim Tait: It apparently builds muscle mass. So I guess it's good for wimps. And the other thing I can tell you is that I have a friend in Korea, who actually bought

241
00:36:56.820 --> 00:37:01.620
Tim Tait: A bottle of this stuff because he wanted to use it as a prop and talks and take it out and show it to people.

242
00:37:02.430 --> 00:37:08.010
Tim Tait: His kids started eating it, and they liked it but he said it tasted absolutely disgusting.

243
00:37:08.640 --> 00:37:22.470
Tim Tait: Which I think we probably could have guessed based on the fact that the flavors are blue raspberry fruit punch and great but maybe that just reveals more about me than about the actual flavors. Alright, so let's learn a little bit more about freedom.

244
00:37:23.880 --> 00:37:26.790
Tim Tait: And freeze out is often referred to as the miracle.

245
00:37:28.620 --> 00:37:33.360
Tim Tait: So the miracle and we go through it again. We already sort of went through it very quickly.

246
00:37:34.290 --> 00:37:44.670
Tim Tait: So the Wimp miracle. Remember assumes that we start off with particles that are annihilating fast enough that they're in equilibrium with the standard model. So if you imagine thinking about a little bit

247
00:37:45.270 --> 00:37:55.200
Tim Tait: A little region of the universe, a little box here like my dashboard here. It's got dark matter and standard model and the RELATIVE quantities of each one is set by the equilibrium densities.

248
00:37:56.040 --> 00:38:00.840
Tim Tait: I'm going to assume the dark matter has an exact Z to symmetry. So it can annihilate and not decay.

249
00:38:01.650 --> 00:38:06.180
Tim Tait: That's the standard assumption, but it's not a necessary one, you can actually modify that a little bit.

250
00:38:07.140 --> 00:38:13.920
Tim Tait: So, and of course we don't know a freeze out is really the right picture to talk about how dark matters produced, but it's it's a very nicely.

251
00:38:14.550 --> 00:38:18.120
Tim Tait: So we started off in chemical equilibrium, like we just said with the standard model.

252
00:38:18.540 --> 00:38:26.220
Tim Tait: Plasma and the dark matter particles and its equilibrium is maintained by scattering of the dark matter particles are two women come in and some standard model goes out.

253
00:38:26.550 --> 00:38:32.820
Tim Tait: And of course, because we're an equilibrium, the same reactions going at the same rate. So also Standard Model particles have enough energy to

254
00:38:34.290 --> 00:38:34.680
Tim Tait: To

255
00:38:36.150 --> 00:38:40.830
Tim Tait: To collide and give me to dark matter particles. And that's, that's how equilibrium gets maintain

256
00:38:41.730 --> 00:38:55.440
Tim Tait: And then we know how to write down a Boltzmann equation, which describes the situation we've got it here at the top of the screen. And so we can see the Hubble fictional term we've got the annihilation cross section which is trying to set us to the equilibrium density

257
00:38:56.880 --> 00:38:57.720
Tim Tait: So,

258
00:38:58.770 --> 00:39:05.970
Tim Tait: And so here I've actually reproduce on my plots for before you can see the Hubble scaling. So it's falling as temperatures decreasing

259
00:39:06.690 --> 00:39:17.670
Tim Tait: You can see sigma v times equilibrium density, right, which starts off as a power law, but when it gets to the mass. So this time, instead of making you do it mentally yourself. I'm actually cut it off at the mass. And you can see it go to zero.

260
00:39:18.030 --> 00:39:30.510
Tim Tait: So where exactly this happens is where these interactions, go out of equilibrium. And from that point on, we have a fixed number of dark matter particles for coal moving volume. So after that freeze out

261
00:39:31.710 --> 00:39:34.620

Tim Tait: We're just stuck with whatever dark matter was there at that time.

262
00:39:37.050 --> 00:39:42.030
Tim Tait: And of course, thats related to the fact that the universe is expanding its the expansion of the universe, which causes

263
00:39:42.360 --> 00:39:50.940
Tim Tait: The, the temperature to fall below the mass of the particle. And therefore, for us to fall out of equilibrium. So this is just cartoon over here on the right.

264
00:39:51.450 --> 00:39:58.170
Tim Tait: You can see the universe expanding eventually I get to a point where the dark matter is so diffuse because of the university's expansion.

265
00:39:58.530 --> 00:40:13.170
Tim Tait: Right. And the fact that I'm going below temperatures below the mass of the particles expands, but eventually the dark matter particles can't find each other anymore. And that's a touristic way to understand why it is the sigma v times an equilibrium is small compared to the Hubble rate.

266
00:40:15.360 --> 00:40:19.920
Tim Tait: So the basic picture is you start off with the dark matter and equilibrium with the Standard Model plasma.

267
00:40:20.820 --> 00:40:30.630
Tim Tait: Is actually a plot that Jonathan thank made who you're going to hear from later on today. So we start off here in equilibrium. So we're tracking this equilibrium curve that we saw before.

268
00:40:31.830 --> 00:40:38.730
Tim Tait: Of course, is the temperature falls now because we're at temperatures below the mass of the particle. The number of WIMPs falls to exponentially.

269
00:40:39.840 --> 00:40:44.670
Tim Tait: We track that equilibrium density until we get to the point of freeze out. So the point where we really

270
00:40:45.090 --> 00:40:53.100

Tim Tait: Don't have enough interactions to maintain equilibrium and you can estimate where that's going to be, I mean I'm sort of given you all the pieces. Now I'm just putting them together here.

271
00:40:53.790 --> 00:41:04.710
Tim Tait: To do it for you. So the equilibrium density, we know is the Boltzmann distribution sigma times V while there's some coupling strength and maybe the mass of the particle to give it the right dimensions.

272
00:41:05.160 --> 00:41:11.580
Tim Tait: And when these two multiplied together are similar to the Hubble scale, right, which is the temperature squared divided by the Planck scale.

273
00:41:12.630 --> 00:41:14.640
Tim Tait: That tells us where we get to this magic point

274
00:41:16.230 --> 00:41:20.640
Tim Tait: And at that point, things rapidly get stuck and that's just how much dark matter, we get

275
00:41:21.690 --> 00:41:30.270
Tim Tait: So there are a few more estimates for what em over key when you expect to get if the mass is sort of around 100 god like you'd expect from it.

276
00:41:33.420 --> 00:41:41.100
Tim Tait: So for when the whole point is, once we know its mass and cross section of the Standard Model particles, you can predict its relative density. So if you

277
00:41:41.580 --> 00:41:47.760
Tim Tait: For example, were to take the measurement of the amount of dark matter in the universe, like the ones that you heard about last week.

278
00:41:48.120 --> 00:41:53.490
Tim Tait: You can imagine that it provides you some bands for what the cross section bands for how much dark matter. There should be

279
00:41:53.790 --> 00:42:00.840
Tim Tait: So I put that on my plot here, or rather, Jonathan, put it on his blog here as these contour bands and yellow, green, and blue.

280
00:42:01.500 --> 00:42:13.800

Tim Tait: You can think about them as maybe like one sigma sigma and three sigma on the amount of dark matter as we increase the annihilation cross section we stand equilibrium longer. And so the place you would freeze out becomes

281
00:42:15.090 --> 00:42:20.610
Tim Tait: Is later on. Right. So you would go further down the curve and freeze out at a later time we'd end up with less dark matter.

282
00:42:21.090 --> 00:42:30.600
Tim Tait: And how low, we can make this cross section is really determined by say these measurements for how much dark matter, there is we don't want to make it too low, so that it would be inconsistent with the measurements.

283
00:42:31.170 --> 00:42:38.790
Tim Tait: And again, something will come back to eventually is that this does make an assumption that the universe is expansion has been standard

284
00:42:39.120 --> 00:42:49.680
Tim Tait: In other words, we have to know that we can describe the universe back at the temperature is where this process was happening accurately and if we don't get that physics, right, then we're going to throw off our calculations.

285
00:42:52.050 --> 00:42:58.770
Tim Tait: So ideally the program with WIMPs is that we'd like to measure the women interactions with the standard model. This would let you compute

286
00:42:59.340 --> 00:43:05.040
Tim Tait: The dark matter annihilation and the Standard Model particles and then you would check the relevance and you can see if you've got the right amount

287
00:43:05.550 --> 00:43:13.350
Tim Tait: And if the predictions, check out, then what we've learned is that the particle we've discovered, you know, looks like it can easily explain all the dark matter, we see

288
00:43:13.710 --> 00:43:19.260
Tim Tait: And that would be indirect evidence that we understand cosmology at the temperatures were freeze out happens

289
00:43:19.560 --> 00:43:28.230

Tim Tait: Usually for wimps these temperatures are pretty high. And so there are temperatures. We don't really have other observational probes, this would actually tell us a lot about what's going on in the universe at that time.

290
00:43:29.220 --> 00:43:35.070
Tim Tait: Will be pretty exciting. So there's actually a big payoff. If we can understand how dark matter interacts with the standard model.

291
00:43:36.060 --> 00:43:39.090
Tim Tait: Of course, it may be that the calculations are not going to check out

292
00:43:39.540 --> 00:43:45.690
Tim Tait: And then we're going to have to do something to either make up the difference. So it might be the dark matter has yet more interactions that we haven't discovered yet.

293
00:43:46.470 --> 00:43:53.730
Tim Tait: Or it could be that the cosmology of the universe was different. Those early times and we had assumed. And both of those could actually help us make up the difference.

294
00:43:54.330 --> 00:44:02.880
Tim Tait: But the first step is to I said rediscover dark matter here by seeing it interact through some forces other than gravitational and that also would tell us a lot about how to

295
00:44:03.390 --> 00:44:09.510
Tim Tait: Place it in the context of how it interacts with standard model particles and in some cases that would even tell you about the Spin Master

296
00:44:12.030 --> 00:44:14.730
Tim Tait: Alright, so here's another exercise that I came up with.

297
00:44:16.140 --> 00:44:26.010
Tim Tait: If you are good with either Mathematica, or Python, you can actually program that differential equation, the Boltzmann equation for a particle that annihilate so that was the same case, we were looking at

298
00:44:26.550 --> 00:44:36.030
Tim Tait: And just on the Standard Model particles and you can find it convenient to use the variable x that we saw before, where x is the mass divided by the temperature

299
00:44:36.330 --> 00:44:45.300
Tim Tait: And you can use that to replace the temperature and the expressions and also for radiated radiation dominated universe, you can actually relate the time

300
00:44:45.840 --> 00:44:51.960
Tim Tait: To the Hubble scale. And since the Hubble scales related the temperature. That means you can also relate the time to temperature

301
00:44:52.440 --> 00:44:59.520
Tim Tait: So my advice would be is turn time and the temperature turn temperature in the x, and then you have a differential equation and will be using it from problem solving.

302
00:45:01.290 --> 00:45:16.470
Tim Tait: And another hint, actually, is that they're using all these facts that I've listed in the middle, you can actually compute the derivative, the TT is just the Hubble scale times x itself. That would save you some steps in terms of driving all those things.

303
00:45:17.520 --> 00:45:23.400
Tim Tait: So if you choose some arbitrary initial value for the number of density and treat the cross section of some constant parameter

304
00:45:23.640 --> 00:45:31.230
Tim Tait: You could then evaluate the long term number density for different cross sections and plot it as a function of x, right, which is the same as time or temperature

305
00:45:31.740 --> 00:45:37.080
Tim Tait: And that would basically give you some numerical understanding for the arguments that I just went through it. You can see it for yourself.

306
00:45:38.190 --> 00:45:43.080
Tim Tait: I gave a paper down here at the bottom where you might actually want to take a look. If you're interested in this.

307
00:45:43.800 --> 00:45:52.770
Tim Tait: To see how it works. It just goes through the calculation. It does analytically, though, so it actually does even more than I'm asked me to do. I'm saying you can just do that numerically and that would be good enough.

308
00:45:55.200 --> 00:46:04.560
Tim Tait: Okay, so the next type of dark matter production of I want to tell you about is called freezing. It's another very interesting possibility.

309
00:46:05.820 --> 00:46:19.950
Tim Tait: And so freezing assumes that there's an initially some negligible number density. So there's no dark matter in the universe. To begin with, or at least a very tiny amount and it requires small couplings of the particle doesn't actually reach its equilibrium number density

310
00:46:21.120 --> 00:46:25.590
Tim Tait: And so again, this was cartoon up here in the upper part of the right hand side of the slide.

311
00:46:26.790 --> 00:46:34.080
Tim Tait: Where we have either annihilation or decay that is below equilibrium when we cross the mass and then

312
00:46:35.190 --> 00:46:41.550
Tim Tait: That's going to determine how much dark matter reproduce. So, oops, if a couple things are small enough

313
00:46:42.120 --> 00:46:51.840
Tim Tait: Then the relic particles lifetime could be large enough for it to be dark matter even if it does decay. So in some sense, freezing is actually a natural way to talk about particles that can decay.

314
00:46:52.650 --> 00:47:03.240
Tim Tait: Because the couplings are so small, but it often doesn't matter anyway. Of course, there may be some region where the couplings or are too big to be dark matter and it all would have decayed away, we wouldn't have form galaxies that would be dead.

315
00:47:04.470 --> 00:47:07.440
Tim Tait: So you do have to live with very small couplings.

316
00:47:08.490 --> 00:47:22.110
Tim Tait: This is very different from the case of freeze out where the relevant interactions, need to be large enough to maintain equilibrium at early times. And so basically something that freezes out just can't. Okay, it's just not gonna, you're not going to be able to make it consistent

317
00:47:23.430 --> 00:47:27.810
Tim Tait: And there are many different scenarios, corresponding to different interaction types with the standard model.

318
00:47:28.530 --> 00:47:33.900
Tim Tait: There's actually a very nice paper that summarize the number of them, it's here at the bottom from oh nine.

319
00:47:34.770 --> 00:47:47.760
Tim Tait: So one example that they look at is a quarter interaction of the form dark matter squared. So imagine the dark matter is a Steeler particle, you have dark matter scaled times to Standard Model particles which may be or Higgs bosons.

320
00:47:49.080 --> 00:47:56.160
Tim Tait: So this allows for dark matter particle chi. That's exactly stable, right. This is the two symmetry because pi squared. The inner

321
00:47:56.730 --> 00:48:01.530
Tim Tait: Appears in the interaction vertex and interacts with to Standard Model particles and the thermal bound

322
00:48:02.310 --> 00:48:11.940
Tim Tait: And so they analyze these theories in terms of the strength of this interaction which they just sort of generically called a little lambda that's here on the y axis and their fees diagram plot.

323
00:48:13.080 --> 00:48:16.800
Tim Tait: And then the mass of the dark matter particle is on the x axis.

324
00:48:17.670 --> 00:48:23.610
Tim Tait: And what's interesting is that as I move around in the parameter space. I can actually realize both freeze out and freeze in

325
00:48:24.000 --> 00:48:34.830
Tim Tait: So if the coupling is big. I go to an equilibrium density I follow the freeze out calculation that we saw before. And in this region, which they called region one

326
00:48:35.790 --> 00:48:44.100
Tim Tait: Then of course there's a specific relationship between the mass and the coupling that would give you the right relevancy so that's shown as a cartoon by the dash line.

327
00:48:44.700 --> 00:48:57.210
Tim Tait: And you can see that, of course, it applies to couple things that are order one. If the mass of the particles around the TV scale, but I can move them down together and if I move them down together in the right way.

328
00:48:58.470 --> 00:49:02.220
Tim Tait: This is actually something else that Professor thing wrote a nice paper about early on.

329
00:49:02.610 --> 00:49:17.730
Tim Tait: If I move them together in the right way. I can continue to freeze out. It's still get the right relative density. Even if the mass of the particle is quite a bit lower than TV as long as the coupling is also commensurately lower to now freezing is in what they called region three

330
00:49:20.310 --> 00:49:38.880
Tim Tait: And so it's what takes place when the coupling is too small to reach equilibrium. And there you can see that the amount of dark matter I produce is actually roughly independent them the mass. And so I just have to choose the right coupling that would give me the right relic density

331
00:49:40.320 --> 00:49:47.760
Tim Tait: And that coupling turns out to be about 10 to the minus 12 or so for the simple quarter interaction. So if I made the coupling, a little bit bigger.

332
00:49:48.900 --> 00:49:52.200
Tim Tait: And the mat, but kept the mastic are such that I stay out of equilibrium

333
00:49:53.520 --> 00:50:00.900
Tim Tait: I can get too much dark matter, and I made the coupling smaller and kept the mass fix and get to little dark matter, but there's a sweet spot right there.

334
00:50:03.600 --> 00:50:11.160
Tim Tait: And of course, different kinds of interactions have different systematics leading a different phase diagrams for dark matter production.

335
00:50:11.850 --> 00:50:21.900

Tim Tait: So another example that they showed chose a you Kala interaction of the forum chi side one side too. So chi is the dark matter particle

336
00:50:22.320 --> 00:50:29.460
Tim Tait: Size. One is a heavier dark particles. This is actually a dark sector theory already and then side to is the standard model particle

337
00:50:30.270 --> 00:50:38.070
Tim Tait: So the idea is that I have sigh one right which is some heavy dark particle which can decay into the dark matter itself which is chi.

338
00:50:38.430 --> 00:50:54.210
Tim Tait: Plus the standard model. So this is more like a decay scenario, though. It's actually one that still has a Z to symmetry, because both chi inside one are odd under the Z to. So then, then they assume that they the mass of sight to is

339
00:50:55.950 --> 00:51:01.950
Tim Tait: Larger than chi. So eventually, any leftover side two particles. Actually, I'm sorry.

340
00:51:03.390 --> 00:51:11.040
Tim Tait: The assume that the mass and one is larger than em Chi and eventually any leftover side one particles with the came to the dark matter. Okay.

341
00:51:12.270 --> 00:51:13.980
Tim Tait: So they get a presentation very

342
00:51:13.980 --> 00:51:16.290
Tim Tait: rich and interesting things.

343
00:51:17.910 --> 00:51:30.390
Tim Tait: And different values with the coupling correspond to either freeze out of Chi. So we saw that before, right, this is what this looks like up here, it cuts off though earlier because I have another massive particle that's engaged and my friends that process.

344
00:51:32.220 --> 00:51:47.940
Tim Tait: So that's up here for very large companies for smaller couplings. I can get into a situation where the dark matter still freezes out but it freezes out when it's relativistic and there it actually has his relic density, which is fairly independent of the coupling.

345
00:51:48.960 --> 00:51:56.670
Tim Tait: And then as I go to smaller couplings and larger masses, I get into the region three this is freezing. Again, this works exactly the way we saw before.

346
00:51:58.080 --> 00:52:02.190
Tim Tait: Where it's roughly independent of the mass but depends strongly on the coupling.

347
00:52:02.700 --> 00:52:08.640
Tim Tait: And then finally, actually, I can even get into a situation where the interaction is so small. The mass is so big.

348
00:52:09.000 --> 00:52:18.000
Tim Tait: But it's actually the side one particle that freezes in but then it became the kind of giving you the dark matter. And so then actually things become more insensitive to the complaint again.

349
00:52:20.610 --> 00:52:22.500
Tim Tait: Okay, and

350
00:52:23.970 --> 00:52:38.400
Tim Tait: The last type of production. I want to briefly talk about is non thermal production. If my dark matter is the boat Sonic field, it could actually just pre produced as an initial condition of the universe to, for example, at the end of inflation particles can be produced gravitational

351
00:52:39.870 --> 00:52:46.500
Tim Tait: If the masses and interactions are small enough and the field can persist as an expectation value of the field is until late times

352
00:52:46.860 --> 00:52:54.930
Tim Tait: Until eventually the mass actually is comparable to the Hubble scale at which point the field starts oscillating and it starts behaving like a collection of particles.

353
00:52:55.980 --> 00:53:03.720
Tim Tait: This type of production is famous and the discussion of Axion dark matter in the particular case where the cache Quinn symmetry is broken before inflation.

354
00:53:04.380 --> 00:53:14.220

Tim Tait: But it also applies to other lights Taylor and vector particles as well. And so the cartoon here shows you a plot that was taken from a nice review of axioms.

355
00:53:15.390 --> 00:53:22.500
Tim Tait: Where you see that the accion field which is written as beta a starts off at some initial value. So that's the green line.

356
00:53:23.520 --> 00:53:25.770
Tim Tait: And nearly universe.

357
00:53:27.420 --> 00:53:40.500
Tim Tait: When the mass is very small compared to the Hubble scale basically the Hubble Christian is so great that even the masses are relevant and the field just stays constant then eventually, when I cross the mass

358
00:53:42.150 --> 00:53:45.270
Tim Tait: When the mass becomes important, I should say, then the

359
00:53:46.530 --> 00:53:57.930
Tim Tait: The mass takes over and the field starts oscillating right because a pre field looks like a harmonic oscillator. And so I end up turning into some amount of accion particles that I've converted from my initial accion field.

360
00:54:00.570 --> 00:54:12.450
Tim Tait: Okay, so I think probably since I'm out of time. I'm going to pause here and we'll finish up our discussion of dark matter production next time.

361
00:54:15.060 --> 00:54:24.870
dong su: Okay, thank you very much for the nice introductory tour. And so now I'm going to turn over to a compliment charity. The Q AMP. A 15 minute

362
00:54:26.970 --> 00:54:34.950
thomas rizzo: Thanks a lot to him. That was really good. There are a lot of questions. So we're not going to get through all of them, but so let's try here. So, you know, far we go

363
00:54:36.090 --> 00:54:43.740
thomas rizzo: First question is on slide a team. How do we know the dark matter is uncharged under SU three color.

364
00:54:46.410 --> 00:54:52.080
Tim Tait: Great. So that's actually an excellent question. And the answer is, at some level, we don't, for sure.

365
00:54:53.070 --> 00:54:59.160
Tim Tait: But if you imagine most scenarios where the dark matter has SU three charge right so i mean what happens with the dark matter is SU three charge

366
00:54:59.490 --> 00:55:13.500
Tim Tait: Like everything else like quarks and gluons that I see three charge. Once the universe is cool down to the scale where the strong interactions confine then the dark matter particles are going to get confined into had runs so

367
00:55:15.390 --> 00:55:21.780
Tim Tait: Because you know there are like up courts and down courts which have different electric charges you would guess that

368
00:55:22.170 --> 00:55:29.700
Tim Tait: No matter what the charge of the dark matter itself was originally some of those hydrogens. They may actually be neutral and then in that case, they probably could be dark matter.

369
00:55:30.300 --> 00:55:36.330
Tim Tait: And they're still be some things to worry about. You don't probably have to. So they get pretty heavy to escape from some bounds, but

370
00:55:37.140 --> 00:55:41.250
Tim Tait: But certainly some of the nearby ones would be electrically charged and they wouldn't look light.

371
00:55:41.970 --> 00:55:48.420
Tim Tait: So the real problem with SU three is not not that S3 is a problem, per se. It's just that we have light.

372
00:55:49.020 --> 00:56:01.110
Tim Tait: Fields in the standard model, the light corks with your charge interest you three and they have different electric charges the up and down works on different electric charges. So, therefore, you end up with dark matter particles and have different electric charges to

373
00:56:03.540 --> 00:56:12.300

thomas rizzo: Consume a general question. Is there any classical approach for describing dark matter and not using quantum field theory.

374
00:56:14.070 --> 00:56:28.290
Tim Tait: I mean, if you talk to astronomers very often. That's exactly what they're doing, because you know they're measuring macroscopic things. And so the micro physics of the dark matter, doesn't really matter. And of course, at some point we have to connect the dark matter to the standard model.

375
00:56:29.310 --> 00:56:36.900
Tim Tait: You know, in some sense, if you say the dark matter interacts with ordinary matter then well ordinary matter is made out of quantum fields and so

376
00:56:37.380 --> 00:56:46.230
Tim Tait: It depends on the question you want to ask, but for many questions we want to ask them, particularly if you want to talk about dark matter being produced right from the earlier in the universe is very hot.

377
00:56:47.010 --> 00:56:57.930
Tim Tait: You really can't get away from quantum field theory. So I guess I would say there's sort of two ways of looking at that question. The first thing is dark matter has to be part of the quantum field theory because everything we know is part of a quantum field theory.

378
00:57:00.420 --> 00:57:05.700
Tim Tait: But the second one is, it depends on the question you're asking. And certainly you could go into the realm into the

379
00:57:06.720 --> 00:57:14.580
Tim Tait: You know, into a regime where the dark matter does behave. Classically, but you would not be able to talk about things like its interaction with ordinary matter.

380
00:57:15.930 --> 00:57:17.700
Tim Tait: Or production very easily that way.

381
00:57:20.580 --> 00:57:36.990
thomas rizzo: Okay great, thanks. Um, let's say, on slide 20 who use the symmetry to stabilize the the dark matter into the theories tend to favor the dark matter conservation using either a discrete or a global symmetry.

382

00:57:38.520 --> 00:57:47.010
Tim Tait: That's a great question. So right now, all we know is that the dark matter is still there in the universe as. And so anything that

383
00:57:47.400 --> 00:57:52.860
Tim Tait: Anything that accomplishes that goal is perfectly fair game. And there's really nothing that favors one over the other.

384
00:57:53.280 --> 00:58:06.720
Tim Tait: So, you know, you could have the example that I invoked of the QC accion where there's actually no symmetry at all. It just the case really really slowly because it's really light and the interactions are really weak and you know that's a perfectly great fit to the dark matter, we see

385
00:58:07.830 --> 00:58:18.810
Tim Tait: Or you could invoke a discrete cemetery, like the Z two, or the three, then the dark matter would probably be exactly stable and that would also be a perfectly good fit. Everything we see

386
00:58:20.160 --> 00:58:32.160
Tim Tait: And then the last thing I talked about was the continuous symmetry, where there would be say dark particles and antiparticles. And again, there's really nothing that can actually distinguish those observations only so far from the other cases.

387
00:58:34.140 --> 00:58:39.390
thomas rizzo: Okay great, thanks. Um, let's see. I'm on slide 28

388
00:58:41.340 --> 00:59:01.440
thomas rizzo: It says, sometimes the freeze out condition is simply stated as gamma equals age and sometimes it is stated is gamma equals x F times age where x A bath is the freeze out temperature scale to the mass, can you please tell us which are these relations is quote better. Unquote. Sure.

389
00:59:03.870 --> 00:59:11.940
Tim Tait: Both of them are not quite right, is the answer. And really what one wants to do is go back and solve this differential equation.

390
00:59:13.410 --> 00:59:22.290
Tim Tait: At which point, one can see exactly what the evolution is doing that said I simplified things in my discussion by just comparing H with gamma

391

00:59:22.740 --> 00:59:35.160
Tim Tait: But because of this fact that the dark matter will fall out of equilibrium when we cross the mass that's where that each times X condition comes from. And I would say each times x is a little bit more accurate. It's still not very good.

392
00:59:35.580 --> 00:59:38.100
Tim Tait: I would really just think about the differential equation directly

393
00:59:39.510 --> 00:59:46.080
thomas rizzo: Yeah, I'd agree with that too. Um, let's see. On slide 37

394
00:59:48.660 --> 01:00:02.820
thomas rizzo: Because the assumption that dark matter is an equilibrium with standard model particles at early times if it's enough information to predict the interaction strengths between the between the standard model and the dark matter particles.

395
01:00:04.500 --> 01:00:11.880
Tim Tait: At some level, yes. So if I have a given theory of dark matter at hand. Then, absolutely. It does.

396
01:00:13.140 --> 01:00:18.480
Tim Tait: Right, I can just ask, under what conditions that theory has the rights has the right interactions.

397
01:00:19.110 --> 01:00:28.740
Tim Tait: But if I'm very agnostic about how the dark matters interacting with a standard model, meaning if I'm allowed to write down all different kinds of interactions, maybe with different mediators, then

398
01:00:30.240 --> 01:00:40.920
Tim Tait: It still in principle tells us something, but it is such a wide theoretical space of theories that I'm not sure how you would summarize it in any useful way.

399
01:00:42.030 --> 01:00:43.980
Tim Tait: So, yes, but I'm not sure it's always useful.

400
01:00:48.000 --> 01:00:50.220
thomas rizzo: Okay. On slide 30

401
01:00:51.930 --> 01:01:00.990

thomas rizzo: What happens when dark matter has a different temperature than the standard model bath. Is there a simple simple way still to proceed with this calculation under those conditions.

402
01:01:01.590 --> 01:01:07.530
Tim Tait: There is. And in fact, actually a lecture three. I'm going to go through an example of something like that.

403
01:01:08.880 --> 01:01:14.400
Tim Tait: However, it's more complicated because now you have to keep track of both of the temperatures separately.

404
01:01:15.090 --> 01:01:24.060
Tim Tait: And so you have to know something about the two different you know sets of particles. Right. So there's a the standard model with one temperature. And then there's the dark matter.

405
01:01:24.480 --> 01:01:33.990
Tim Tait: Maybe with other particles or maybe not, which has a separate temperature, but you can actually understand these calculations that way you have to correct for the different temperature by keeping track of it.

406
01:01:37.680 --> 01:01:38.220
thomas rizzo: Very good.

407
01:01:41.070 --> 01:01:55.620
thomas rizzo: On either slide 28 or 40 I guess both are involved here in the freezing scenario is the assumption of negligible initial in justifiable if the annihilation rate is higher than eight at large t

408
01:01:56.580 --> 01:02:02.070
Tim Tait: Know, so basically you would have to assume that inflation ended and gave you a temperature, such that

409
01:02:02.700 --> 01:02:18.660
Tim Tait: sigma v times and is less than age right as long as your initial condition is such that that's true. The diagram shows that it'll stay true, but if you if you imagine that that the universe was hot at early times then you would be an equilibrium

410
01:02:24.480 --> 01:02:27.270
thomas rizzo: Um, let's see. On slide 41

411
01:02:30.270 --> 01:02:45.690

thomas rizzo: Is there a possibility that dark matter can still freeze out while being relativistic and still be fine with structure formation. For example, a fairly heavy dark matter particle whose masses much greater than the ke VI scale.

412
01:02:46.620 --> 01:02:53.670
thomas rizzo: If true, then why most. Why then are most models. Consider freeze out and not a non relativistic phase.

413
01:02:55.950 --> 01:03:05.850
Tim Tait: That's right. So that's anticipating a very important point, which is that if the dark matter freezes out when it's relativistic it's going to have a non zero velocity, it's going to happen.

414
01:03:06.450 --> 01:03:22.140
Tim Tait: Its energy will be comfortable to its mass. And as a result, when you try to form structure. It's not going to form the same way, because as the particles are streaming away from each other. They can escape from the gravitational potentials and you'll end up instead of forming

415
01:03:23.160 --> 01:03:29.640
Tim Tait: You know, very nice concentrated dense galaxies, you'll end up with sort of more puffy and wispy galaxies, because things were

416
01:03:30.660 --> 01:03:37.770
Tim Tait: The things collapse later on. But it's sort of a detailed question of the parameter space, whether or not it can be fine.

417
01:03:38.130 --> 01:03:50.760
Tim Tait: But you can make a scenario like the one that was described work. However, it's not going to work for just any choice of mass and you are going to have to make sure that the dark matter is not moving is not too energetic at the time of free zone.

418
01:03:54.600 --> 01:03:56.580
thomas rizzo: Okay. On slide 42

419
01:03:57.720 --> 01:04:02.910
thomas rizzo: What does it mean for a field that be produced as an initial condition of the universe.

420
01:04:04.470 --> 01:04:06.720
Tim Tait: Yeah, I mean, so that's a there.

421
01:04:06.750 --> 01:04:18.450
Tim Tait: There are different things you can talk about. But one very simple one is when you study inflation right inflation is a period where the the universe, the size of the universe expands exponentially.

422
01:04:18.990 --> 01:04:27.870
Tim Tait: Or a more colloquial way of saying that right is inflation kind of solves all the initial conditions problems with the universe by just picking one point of the universe.

423
01:04:28.230 --> 01:04:37.620
Tim Tait: And then making that point so big that the entire Hubble volume is inside that point. So there's no variation, right, because one point has now become the entire universe.

424
01:04:38.160 --> 01:04:46.290
Tim Tait: So if you have a very light field, who's dynamics doesn't require that it's field value equal to zero, then when you pick a random point and

425
01:04:46.410 --> 01:04:54.480
Tim Tait: Of the universe and inflate it into into everything that we see, it's good that field is going to take some value and you know that value cannot be predicted

426
01:04:55.950 --> 01:05:08.310
Tim Tait: Because, you know, it depends on things that happened before inflation so you know that point it's really just an initial condition. It's just where you happen to be when you inflated.

427
01:05:09.810 --> 01:05:17.340
Tim Tait: And if you have chosen a different point in the field would presumably have taken a different value and you would have ended up with a different in this case amount of dark matter.

428
01:05:21.240 --> 01:05:39.090
thomas rizzo: On the same slide in non thermal reduction would we see imprints of these oscillations on things like the C NB with like with light particles like this. Do we go looking for the frequency of oscillations in detection or individual particle interactions themselves.

429
01:05:41.340 --> 01:05:46.410
Tim Tait: So there were sort of two questions there. And I'm not sure I fully understood the second one and

430
01:05:48.150 --> 01:05:53.610
Tim Tait: In principle I guess you could look for some imprint on this end, but in practice for

431
01:05:55.680 --> 01:06:07.800
Tim Tait: Your practice for theories like the accion that effect wouldn't be something that would be observable. But if you were to tune the theory, a bit you could maybe get into a resume or you could see something that would be visible on the CMT

432
01:06:09.780 --> 01:06:12.330
Tim Tait: And sorry, can you repeat the second half of the questions on

433
01:06:19.200 --> 01:06:19.380
thomas rizzo: Right.

434
01:06:20.760 --> 01:06:29.400
thomas rizzo: We light particles like this. Do we go looking for the free agency of oscillation in detection or for the individual particle interactions themselves.

435
01:06:31.590 --> 01:06:35.580
Tim Tait: And that also sort of depends. But when the particles are light enough

436
01:06:36.120 --> 01:06:49.050
Tim Tait: Typically the number density sort of per unit volume is so large that you would be more interested in their collective effect. So you'd be looking actually at the frequency of oscillation and less looking at the individual quanta that make up the field.

437
01:06:53.670 --> 01:06:54.870
thomas rizzo: And slide 28

438
01:06:59.730 --> 01:07:13.950
thomas rizzo: Under the freeze in context, one could extend the annihilation line backwards to intersect the Hubble expansion line is this intersection possible in real scenarios before the temperature drops below the mass

439
01:07:15.570 --> 01:07:17.550
Tim Tait: So it is possible

440

01:07:18.600 --> 01:07:27.180
Tim Tait: Well, okay. So let me give a little bit of more context. Let's imagine that the place where the x axis begins right so in other words the

441
01:07:27.930 --> 01:07:35.130
Tim Tait: The line that's described by the y axis itself. Let's imagine that that's where deflation ends. So that's the initial point of the universe.

442
01:07:35.520 --> 01:07:43.770
Tim Tait: So at that point, if I make that assumption that I can't really extend anything backwards because you know the universe was going through a very different phase.

443
01:07:44.130 --> 01:07:53.670
Tim Tait: It wasn't radiation dominated. He was not scaling like t squared at that point. So if I make that assumption, right, then you can have three isn't in the way that I described it.

444
01:07:54.570 --> 01:08:05.880
Tim Tait: If I were to now assume that inflation ended up with a earlier ended up with a larger temperature as the initial condition, then, of course, I should extend these lines, all the way back to wherever inflation started

445
01:08:06.870 --> 01:08:13.080
Tim Tait: At that point, though, it's going to look more like the plot that's on the top. It's going to be freeze out because what will happen is

446
01:08:14.880 --> 01:08:18.150
Tim Tait: The cross section times equilibrium density will be larger than Hubble

447
01:08:18.180 --> 01:08:19.410
Tim Tait: It'll be an equilibrium

448
01:08:19.800 --> 01:08:34.380
Tim Tait: Now, if the mass is like in the bottom diagram right so let's imagine that the blue line is extended back and so is the Hubble scale, then the freeze out will still happen when the dark matter is relativistic right and I'll have to worry about structure formation and that kind of thing.

449

01:08:35.640 --> 01:08:51.150
Tim Tait: But that would still be a viable freeze out process. It wouldn't be freezing though for freezing to take place. I really need to assume that the initial conditions from inflation are such that sigma v times and equilibrium is less than the Hubble constant from the very beginning.

450
01:08:54.540 --> 01:08:58.830
dong su: Um, and Tim. Maybe we can go for one last question. Sure.

451
01:08:59.280 --> 01:09:03.240
thomas rizzo: Okay, um, let's go back to the beginning. It's Slide eight

452
01:09:05.250 --> 01:09:18.690
thomas rizzo: Where you had the Standard Model separated from the dark sector, etc. And you talked about the possibility of evil dark bozos dark photons, etc. If they were dark bows on will be also called that dark matter to

453
01:09:21.120 --> 01:09:28.650
Tim Tait: Probably not. I mean, kind of depends on what the properties of that dark posts on are. So if you imagine, let's say there's some dark force carrier

454
01:09:29.310 --> 01:09:32.580
Tim Tait: And let's say it's even heavy enough that it would decay in the dark matter.

455
01:09:33.270 --> 01:09:39.270
Tim Tait: If it's not present in the universe today and it's not actually what's making up the galaxies we see, we would not call it dark matter.

456
01:09:39.930 --> 01:09:48.030
Tim Tait: On the other hand, you can also imagine a dark goes on, which still interact with dark matter. But let's say it's mass is very small, such that it can't became the dark matter.

457
01:09:49.080 --> 01:09:54.660
Tim Tait: Or anything else. So it's still around still part of the universe, then you would call that actually part of

458
01:09:55.200 --> 01:10:04.620
Tim Tait: The dark matter part of the dark sector and because it made up galaxies. So it really depends what I would say is the way to distinguish say what's part of the dark matter and not is

459
01:10:05.040 --> 01:10:17.550
Tim Tait: If it's here right now making up galaxies explaining the observations we make when we look at the motions of stars and so forth. It's dark matter if it is a decade. It's not dark matter anymore. Maybe it wasn't the past

460
01:10:21.840 --> 01:10:22.830
thomas rizzo: Okay. Thanks, Tim.

461
01:10:25.200 --> 01:10:25.860
Great questions.

462
01:10:27.540 --> 01:10:28.410
dong su: Thank you.

463
01:10:29.760 --> 01:10:37.320
dong su: Tom, so we're going to end the recording now and go for a 10 minute break and come back at 1020. Okay, thank you.