WEBVTT

1
00:00:00.240 --> 00:00:00.659
Daniel Gruen: Great.

2
00:00:02.520 --> 00:00:07.020
Daniel Gruen: Actually, one thing I think I can start my video. The host will have to allow me to do that.

3
00:00:11.519 --> 00:00:12.120
Daniel Gruen: There we go.

4
00:00:12.840 --> 00:00:17.670
Daniel Gruen: Great better. And now I'm sharing my screen again. Can you see that

5
00:00:18.300 --> 00:00:19.020
thomas rizzo: Yes, I do.

6
00:00:19.350 --> 00:00:20.520
Daniel Gruen: Okay, wonderful.

7
00:00:21.540 --> 00:00:36.360
Daniel Gruen: Thanks so much, Tom for the introduction. It's a great pleasure to be opening this year's select Summer Institute with an introduction to cosmology. And so what I'm going to do in the next 15 minutes or so is I'll be talking to you.

8
00:00:36.510 --> 00:00:39.510
Daniel Gruen: About the almost invisibles in the universe.

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00:00:40.740 --> 00:00:50.130
Daniel Gruen: Almost everything in this picture actually is already almost invisible 98 99.8% or so of what is in this picture you can see

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00:00:51.090 --> 00:01:00.540
Daniel Gruen: Most of the baryons in this picture are not in the form of stars in these wonderful galaxies, but they're in the form of gas that you know sometimes can be really hard to detect.

11
00:01:01.170 --> 00:01:12.570

Daniel Gruen: Most of the matter is actually not in the form of baryons at all, but rather in the form of dark matter which, you know, has no directions, besides gravity that we have been able to detect so far.

12
00:01:13.290 --> 00:01:19.560
Daniel Gruen: And then most of the energy content if you did that you made a budget of all there was in terms of energy in this picture.

13
00:01:20.130 --> 00:01:26.400
Daniel Gruen: Is actually not in the form of any kind of matter. It's in the form of something we call dark energy. And so

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00:01:26.910 --> 00:01:38.790
Daniel Gruen: All of these things, you know, while they are almost invisible to us. They are governing how the universe as a whole is evolving with time. And so therefore, by observing the universe, but trying to understand it.

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00:01:39.240 --> 00:01:45.240
Daniel Gruen: We have a gateway to finding out more about them. And that's what we're going to talk about today.

16
00:01:46.170 --> 00:01:58.920
Daniel Gruen: So the goals for my lecture are for us to understand the universe across its complete lifetime both intuitively. And also, as described with equations as physicists that we are

17
00:01:59.700 --> 00:02:11.700
Daniel Gruen: And we're going to look particularly at the impact of these almost invisibles on that system that the universe is neutrinos dark matter, dark energy, even more hypothetical fields that you

18
00:02:12.690 --> 00:02:27.840
Daniel Gruen: Might have to be present, or that you might hypothesize to be present in the universe. And we're also going to get a sense, although only a very rough one of how we can measure the universe. The universe this evolution and what that has told us so far.

19
00:02:29.010 --> 00:02:33.870
Daniel Gruen: So one other thing that my lecture is going to do, and that's why I'm going to try to keep it as accessible as possible.

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00:02:34.320 --> 00:02:40.170
Daniel Gruen: Is it's also setting the foundation for several other lectures that you'll see this week that go into more detail.

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00:02:40.500 --> 00:02:45.000
Daniel Gruen: On each of these topics and I've just listed listed this wonderful lineup here on the side.

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00:02:45.270 --> 00:02:57.060
Daniel Gruen: You can see how you know any of the almost invisible that I'm talking about today, you'll have one or two dedicated lectures that go into great detail on you know what we know about them and what we what we don't know about them.

23
00:02:58.920 --> 00:03:10.620
Daniel Gruen: Now we're going to use two key principles in this lecture that are fundamental to modern physical cosmology. The first principle is that there's no special place in the universe, that the universe.

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00:03:11.370 --> 00:03:18.990
Daniel Gruen: As as a whole is homogeneous and as a topic. And that's, you know, may seem like an obvious starting point.

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00:03:19.470 --> 00:03:28.500
Daniel Gruen: But for the longest history. It really wasn't the starting point of humans, trying to understand their place in nature. Right. It was either our planet or sun.

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00:03:29.040 --> 00:03:36.630
Daniel Gruen: Or our Milky Way that we're at the center of the universe for, you know, the longest history of people thinking about the cosmos.

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00:03:37.320 --> 00:03:45.510
Daniel Gruen: And so using this principle and using the theory of general relativity to describe the dynamics of the universe as a whole.

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00:03:45.870 --> 00:03:54.690
Daniel Gruen: Has really been the the foundation of a, of an age of physical cosmology, where you know what we're talking about. It's not religion. It's not metaphysical

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00:03:55.050 --> 00:04:00.720
Daniel Gruen: But what we're talking about is something that can make predictions about the observable universe that we can test.

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00:04:01.410 --> 00:04:08.700

Daniel Gruen: So these are the two principles that we're going to use. You may notice, you know, in a way, thinking about it, that the universe is very

31
00:04:08.970 --> 00:04:22.080
Daniel Gruen: Egalitarian okay there's no special place in it, and no matter what you do you're going to be covered by a relatively simple set of rules that determine the connection of matter and space time

32
00:04:22.710 --> 00:04:32.760
Daniel Gruen: So the universe is egalitarian. And in some ways, this is also the slack Summer Institute and is brave new world, right, anybody really is welcome to join these lectures.

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00:04:33.360 --> 00:04:42.750
Daniel Gruen: And I'd like to make them a little bit interactive, which is difficult with so many participants. So I'm going to use a tool that that will allow us to communicate a little bit during this lecture.

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00:04:43.260 --> 00:04:53.820
Daniel Gruen: So what I'm asking you to do now is use your phone or use your browser and just type in this short URL here Paul f.com slash D grew

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00:04:54.660 --> 00:04:59.700
Daniel Gruen: And that will lead you to. You don't even have to put your name, you can just say, skip it doesn't, doesn't matter.

36
00:05:00.690 --> 00:05:08.400
Daniel Gruen: So much, but it will then give you this map to click on to indicate where you are joining this lecture from

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00:05:09.000 --> 00:05:15.720
Daniel Gruen: And in part that's, you know, just because we really would like to know, right, it's, it's, we really don't know quite well quite so well.

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00:05:16.170 --> 00:05:23.580
Daniel Gruen: Where you are and you know what you know what you're doing right now and what you're interested in. So this is one way of finding out

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00:05:24.210 --> 00:05:33.720
Daniel Gruen: And I see many of you are already putting down pointers. Okay, so we've got a cluster here in California, that's you know I'm somewhere inside that cluster right now.

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00:05:34.110 --> 00:05:44.160
Daniel Gruen: And across the continental United States plenty of people in Europe as well. This is kind of a time that works from Europe, we have a few people in South America.

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00:05:45.180 --> 00:05:52.230
Daniel Gruen: A couple of really brave people in Asia from the time zone is not so convenient. Thanks, thanks so much for being up at this hour.

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00:05:52.710 --> 00:05:59.070
Daniel Gruen: And then we have a couple people, you know, somewhere in Antarctica or or elsewhere scattered throughout space.

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00:05:59.700 --> 00:06:07.950
Daniel Gruen: Anyway, it's just wonderful to see to see you all from all these different locations on the planet. Join us like summer institute this year. It's wonderful to have you.

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00:06:08.640 --> 00:06:20.040
Daniel Gruen: And it's not actually illustrates another point that we should be aware of in the universe is that, you know, it can be difficult to make a 2D map of space. Hi, this is a way of representing

45
00:06:20.610 --> 00:06:32.160
Daniel Gruen: The planet, which is a spherical coordinate system on its surface. And in a 2D plane. And so let's start by talking a little bit about how we can do that. How would you describe

46
00:06:32.850 --> 00:06:42.690
Daniel Gruen: You know what the surface of a balloon looks like over time. If you're even inflating it. Okay, so I've drawn this cartoon of a balloon here.

47
00:06:43.440 --> 00:07:02.220
Daniel Gruen: It's, you know, it's expanding with time and it so happens that an ant dropped on it on this location of the yellow dot and that while the balloon is being expanded that and has walked to the location of another marking that red dot now.

48
00:07:03.330 --> 00:07:15.600
Daniel Gruen: One way of describing this balloon that is very Einsteinian is you could describe what's happening to that balloon by all the steps that an aunt could possibly take okay so answer or move where the constant and speed.

49
00:07:16.200 --> 00:07:22.020
Daniel Gruen: And if I can tell you the equation that governs all the steps and and could take as a function of time on that balloon.

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00:07:22.440 --> 00:07:29.550
Daniel Gruen: Then that would allow you to map out how that surface of the balloon is changing and expanding over time. And you know what it is like overall

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00:07:30.360 --> 00:07:38.820
Daniel Gruen: So one way that I could do that with equations is I could print the coordinate system X on the balloon okay done that here.

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00:07:39.180 --> 00:07:46.800
Daniel Gruen: I've really only printed one axis which is the x is that the and happens to be moving along. I could I could print it to the court system. No problem.

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00:07:47.460 --> 00:07:55.530
Daniel Gruen: And there's markings on this coordinate system, you know, that's, that's my, that's my you know metric that I haven't printed on the balloon now.

54
00:07:56.760 --> 00:08:06.330
Daniel Gruen: So the steps that and could take right if it's walking for a little time interval dt, with its and speed. The end. Right. That step is

55
00:08:06.960 --> 00:08:23.340
Daniel Gruen: Going to be equal to some amount of dx, that it's moving on this printed coordinate system multiplied by a factor of tea and AMT is just a factor that describes the scale of the universe at the time that the and it's taking that step.

56
00:08:24.480 --> 00:08:29.850
Daniel Gruen: So this is an equation that would describe the metric of the balloon and how it's changing over time.

57
00:08:31.140 --> 00:08:37.560
Daniel Gruen: Now I can do the same thing with the universe. I could imagine printing a coordinate system on the universe and

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00:08:38.040 --> 00:08:44.490

Daniel Gruen: Instead of ants. I could use photons and they have the benefit that they're actually moving with the constant velocity, the speed of light.

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00:08:45.090 --> 00:08:54.180
Daniel Gruen: And so in this cartoon. That's what's being done I there's a there's a 2D universe. It's a surface of this balloon. There's a coordinate system on it that's being inflated.

60
00:08:54.720 --> 00:09:02.160
Daniel Gruen: And you could describe that whole process by the steps that photons take within this little time interval dt.

61
00:09:02.940 --> 00:09:17.940
Daniel Gruen: As being equal to some scale factor of the universe. A times A little dx on the imprinted coordinate system so called co moving coordinate system. So that's the idea of how we could describe reverse

62
00:09:18.780 --> 00:09:27.990
Daniel Gruen: Now, the way that you would do that with a little more algebra is you could define this distance measure the s right.

63
00:09:28.410 --> 00:09:38.190
Daniel Gruen: You could define it as the product of a metric tensor with these, you know, little, little steps along the different coordinates where for the coordinates here we're using both time

64
00:09:38.580 --> 00:09:45.450
Daniel Gruen: And a spatial three dimensional coordinate system and we could say that for light, you know, just, just like for the end

65
00:09:45.780 --> 00:09:57.300
Daniel Gruen: As I showed you, you know that there's there's a combination of these little d x's and DTS, that's zero. And that is how life will always be moving with its constant, constant velocity

66
00:09:58.410 --> 00:10:05.130
Daniel Gruen: Now very quickly after you know these these fundamental thoughts were, were being made by Einstein.

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00:10:05.700 --> 00:10:14.280
Daniel Gruen: For people independently realized that there was this most general form for a metric for for a G tensor.

68

00:10:14.640 --> 00:10:22.380
Daniel Gruen: That could describe a homogeneous and as a topic nurse and that's that might affect that I wouldn't down here so frequent metal robots and Walker figured out that

69
00:10:23.130 --> 00:10:31.080
Daniel Gruen: If you want to describe a homogeneous and as a tropic system with general relativity, this would have to be the form of its metric

70
00:10:32.430 --> 00:10:33.870
Daniel Gruen: So what is part of that metric

71
00:10:35.340 --> 00:10:49.170
Daniel Gruen: There is this thing here, this in the energy records. Okay, that's just a spatial coordinate system and you don't really have much of a choice for your eyes will profit spatial coordinate system.

72
00:10:49.530 --> 00:10:56.700
Daniel Gruen: The only choice you have is that you can make that coordinate system flat and it would just be the Euclidean coordinate system that you know and love.

73
00:10:57.390 --> 00:11:05.340
Daniel Gruen: But you could give it selectively and negative or positive curvature to just a constant curvature for that whole coordinate system.

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00:11:05.970 --> 00:11:19.230
Daniel Gruen: That would make the the some of the angles inside of triangle. Be not equal to one at so that's that's that's one thing that that you could do. And so this is encoded in that little function F to have to K of our here.

75
00:11:20.820 --> 00:11:30.030
Daniel Gruen: And then the second thing that you're allowed to do actually is. You are allowed to scale that coordinate system as a function of time. So I've put a factor A of tea.

76
00:11:30.240 --> 00:11:35.130
Daniel Gruen: In front of that court system. The same way that I did for you know my description of the and for the photon.

77
00:11:35.700 --> 00:11:45.540

Daniel Gruen: And this factor A of tea can do the time dependent expansion of that coordinate system. Okay, so this is all that you can never do. If you assume the universe to be homogeneous and as a topic.

78
00:11:45.840 --> 00:11:53.370
Daniel Gruen: And general relativity. You're not even generativity. This is just the only way that you could describe coordinates in that universe.

79
00:11:55.560 --> 00:12:01.650
Daniel Gruen: So if you take that metric. All right, this is, this is really a G H I J tanzer

80
00:12:02.550 --> 00:12:09.060
Daniel Gruen: And you insert that tensor into Einstein's equations which are breaking down here which on you know their left hand side.

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00:12:09.390 --> 00:12:15.660
Daniel Gruen: They have these combinations of the metric and certain you know expressions and derivatives of it. And on the right hand side.

82
00:12:16.140 --> 00:12:23.280
Daniel Gruen: You will have an expression containing all those stuff all the fluids that fill the universe and, you know, in this case, because the universe is homogeneous.

83
00:12:23.790 --> 00:12:30.480
Daniel Gruen: You're going to have to say, well, this, this, these different fluids. They all have a constant density and pressure throughout the whole universe.

84
00:12:31.200 --> 00:12:48.030
Daniel Gruen: Then you could actually solve this equation. And when you rewrite all the terms you get to something that looks like this. So this is now an equation that expresses the expansion of the universe, the second derivative of the universe's scale.

85
00:12:49.320 --> 00:13:00.780
Daniel Gruen: As a function of the stuff that I put inside the universe. What you see here is the density and the pressure of stuff that I have put inside my universe.

86
00:13:01.500 --> 00:13:11.340

Daniel Gruen: So look at that equation, but because I'm going to ask you a question about it. On the next slide, I'm going to ask you. You know what that universe is possibly going to do

87
00:13:12.810 --> 00:13:20.520
Daniel Gruen: So what is Friedman's universe governed by that equation going to do, go back to Paul f.com slash D grew

88
00:13:21.060 --> 00:13:26.730
Daniel Gruen: And, you know, tell me what you think is that universe going to expand forever. It's going to collapse.

89
00:13:27.270 --> 00:13:36.720
Daniel Gruen: Is its expansion going to slow down over time, or is it going to speed up over time. Or maybe, you know, did I not give you enough information just go back to that equation.

90
00:13:37.380 --> 00:13:49.260
Daniel Gruen: And give you a few seconds to think about it. If you know if I feel that universe with any kind of stuff. What is going to happen to its scale factor, according to this equation that I put on here.

91
00:13:51.090 --> 00:13:57.540
Daniel Gruen: Okay, so I see about 40 of you actually responded give you one more second of

92
00:14:00.690 --> 00:14:01.680
Daniel Gruen: Blind voting.

93
00:14:03.420 --> 00:14:09.840
Daniel Gruen: And then we look at the responses. Okay, so, so, you know, this is democratic physics.

94
00:14:11.580 --> 00:14:16.560
Daniel Gruen: Most of you are actually saying you're not sure that's a great answer, because really I haven't get specified

95
00:14:16.920 --> 00:14:22.890
Daniel Gruen: All the things that I put inside my universe. I've only told you that you know there's row and P I haven't told you what Ron PR

96
00:14:23.700 --> 00:14:30.780
Daniel Gruen: I do sympathize with the 30% of you who say the extension will slow down because if you look at that equation really

97
00:14:31.290 --> 00:14:39.090
Daniel Gruen: You know, for anything that we know from basic physics, the density and the pressure of it can only ever be positive or

98
00:14:39.660 --> 00:14:48.330
Daniel Gruen: Worse zero. So, you know, whatever would happen here we would always get a negative second derivative of the scale factor. So you would think that, you know, the expansion would slow down.

99
00:14:50.010 --> 00:15:04.770
Daniel Gruen: You know, depending what we put it in fact the expansion could speed up the universe could collapse or the universe could expand forever. So, so really a lot of cosmology is going to be about your finding out what is actually happening to that equation.

100
00:15:05.910 --> 00:15:15.810
Daniel Gruen: So let's introduce one concept that that that is going to be important in you know in finding out what happens there. And that's the concept of a cosmological constant

101
00:15:16.560 --> 00:15:24.450
Daniel Gruen: So I've put that additional term into the equation here compared to what you saw two slides ago, I had blanked out

102
00:15:24.930 --> 00:15:35.820
Daniel Gruen: Einstein's term with the you know the cosmological constant in the Einstein equation when you put that back in and you do the same duration, then you end up with another term here.

103
00:15:36.600 --> 00:15:42.930
Daniel Gruen: Positive lambda times a constant term for the acceleration of the scale factor of the universe.

104
00:15:43.650 --> 00:15:49.290
Daniel Gruen: Now you can see that, you know, one, one reason that I didn't really have to put that term in is because

105
00:15:50.010 --> 00:15:56.160
Daniel Gruen: I have a choice here I could instead describe this lambda I could put that on the right hand side.

106
00:15:56.640 --> 00:16:05.040

Daniel Gruen: And I could describe you know whatever the cosmological constant is as a another fluid and other kinds of stuff that I put inside the universe.

107
00:16:05.730 --> 00:16:14.340
Daniel Gruen: It would have to be a kind of stuff that overall produces a negative contribution from the sum of its density and it's it's pressure

108
00:16:15.060 --> 00:16:22.140
Daniel Gruen: So, that is to say, it would need to be a forward with with an equation of state that looks like this, where the pressure

109
00:16:22.500 --> 00:16:29.160
Daniel Gruen: Is a negative constant times its density. So that would have the same effect as me just putting in this lambda. And if the equation.

110
00:16:29.760 --> 00:16:40.200
Daniel Gruen: But what can happen here is that once the density and pressure of all the other components of the universe are small enough, because the universe has expanded in a

111
00:16:40.950 --> 00:16:49.860
Daniel Gruen: Good happen that this positive karma on the, on the right hand side takes over and that overall the right hand side becomes positive and therefore overall

112
00:16:50.250 --> 00:16:59.790
Daniel Gruen: The second derivative of the scale factor becomes positive and the universe begins to accelerate. So this is something you know that that could happen to us so

113
00:17:02.610 --> 00:17:11.190
Daniel Gruen: Let's look in to the description of a universe that has a bunch of stuff that right. We know that there's several things present in our universe.

114
00:17:11.880 --> 00:17:23.490
Daniel Gruen: Most generally you can always describe any kind of homogeneous for it fully by its density and it's equation of state the relation between its density and it's pressure

115
00:17:24.090 --> 00:17:41.730
Daniel Gruen: So there's one free parameter in this equation of state and it's this w this equation of state parameter. So for some fluids that we

do know. Here are their equation of state parameters for quote matter it's pressure is basically zero. So it has a WH zero

116
00:17:42.870 --> 00:17:56.730
Daniel Gruen: For radiation or relativistic matter that it's matter and it's moving so fast, its kinetic energy is is much larger than its rest energy. So it's behaving like RADIATION, IT'S W parameter is one third.

117
00:17:58.020 --> 00:18:05.280
Daniel Gruen: For cosmological construct this thing that I just introduced you could express it as a fluid with an equation of state parameter of minus one.

118
00:18:06.300 --> 00:18:20.610
Daniel Gruen: In fact curvature. You know, if the universe was curved, you could express that as though it was filled with a fluid that had an equation of state parameter of minus one third. That's just going to behave the same way in these equations.

119
00:18:21.630 --> 00:18:23.760
Daniel Gruen: And really, you have freedom to design any kind of flow.

120
00:18:26.700 --> 00:18:28.320
Daniel Gruen: Okay, sounds like we're back on track.

121
00:18:29.580 --> 00:18:43.140
Daniel Gruen: So you could design any fluid that you want that has an equation of state parameter that's, you know, any number and that number can even be depending on time or equivalent. The on the scale of the universe or the density of that stuff for other stuff.

122
00:18:44.340 --> 00:18:48.000
Daniel Gruen: So when you do that, you know, or when you look at any of these fluids.

123
00:18:48.720 --> 00:18:59.190
Daniel Gruen: This equation of a parameter actually determines how the energy density of that fluid is changing as the universe expands according to its a 50. So this is the equation.

124
00:18:59.610 --> 00:19:04.800
Daniel Gruen: That's going to govern that expansion start out with some density row zero at a of one

125

00:19:05.460 --> 00:19:12.780
Daniel Gruen: And then you just like a expand somehow you know your density of whatever stuff that is is going to change with this factor.

126
00:19:13.590 --> 00:19:26.160
Daniel Gruen: And so again, look at that equation, try to make sense of it and then try to answer this question. So again, I'm going to ask you to go to Paul f.com slash G grew

127
00:19:26.730 --> 00:19:30.480
Daniel Gruen: And this time I'm going to ask you to order these components of the universe.

128
00:19:31.200 --> 00:19:40.080
Daniel Gruen: Putting first the one component that dilutes most rapidly. You know, I let the Universe expand the energy density of it goes down the most

129
00:19:41.010 --> 00:19:51.690
Daniel Gruen: To the component that dilutes your lesson lesson lesson. And eventually, not at all. I expand the universe. The density of that you know per unit volume is still going to be the same.

130
00:19:52.320 --> 00:20:00.180
Daniel Gruen: So you can reorder these things and and press Submit going to go back to that equation for you to for you to think about it as, as you do that.

131
00:20:02.700 --> 00:20:15.420
Daniel Gruen: Another born and we're going to give you just a second. Now let's talk about matter density while you do that right so matter density kind of the obvious case that you take a certain amount of mass

132
00:20:15.870 --> 00:20:21.510
Daniel Gruen: If you, if you increase the volume over which you've distributed that mass homogeneous Lee.

133
00:20:22.350 --> 00:20:35.580
Daniel Gruen: Its density is going to be reduced by as just one over the volume. Okay, so this is what happens when I plug in zero here, right, it's going to be an eight to the minus third that's just because the volume increases as a to the third power.

134
00:20:36.720 --> 00:20:45.180

Daniel Gruen: Now let's see where we are. Yeah, we've got plenty of results. Thanks for thanks for coming along with this and

135
00:20:45.810 --> 00:20:51.240
Daniel Gruen: Look at their responses and see what you thought. So many of you thought that, you know, photons are the

136
00:20:51.660 --> 00:21:02.460
Daniel Gruen: Stuff that is diluted the most followed by neutrinos quote matter a cosmological constant and then phantom energy and that's indeed correct. Okay. So looking at these photons.

137
00:21:02.940 --> 00:21:12.810
Daniel Gruen: As the universe expands are going to be diluted as one over a to the fourth. And not only are you going to send out photons as one over x to the third.

138
00:21:13.230 --> 00:21:18.810
Daniel Gruen: But also the energy of each proton is going to be reduced, because it's wavelength get stretched

139
00:21:19.530 --> 00:21:30.240
Daniel Gruen: Neutrinos they start out like photons, but because they have another mass eventually they're going to behave more like matter and matter behaves like one over a to the third, as we just discussed.

140
00:21:31.170 --> 00:21:40.380
Daniel Gruen: Cosmological Constant, you know, is is really a constant density expand the universe, nothing changes. That's what you know. Sounds like a vacuum energy

141
00:21:40.980 --> 00:21:48.930
Daniel Gruen: That's. In fact, one way of explaining it and then you know this phantom energy which you could produce in some theories, maybe

142
00:21:49.230 --> 00:21:59.430
Daniel Gruen: Actually increases in energy density as the universe expands as crazy as that sounds. But, you know, we could still if that's what you want to do, we can put it in the universe. And we can see what happens to it.

143
00:22:00.510 --> 00:22:13.230
Daniel Gruen: Okay, so let's look a little more at the dynamics. Now you know the overall evolution across time of the expansion of the universe. When you put in a bunch of stuff.

144
00:22:13.800 --> 00:22:20.670
Daniel Gruen: And there was one thing I need to introduce here, which is another fundamental parameter in a way the current expansion rate.

145
00:22:21.390 --> 00:22:31.560
Daniel Gruen: We call that ah not. It's the derivative of the scale factor at the present time in relative unit so divided by whatever the scale factor at the present time is

146
00:22:32.220 --> 00:22:44.190
Daniel Gruen: And so the units of h&r is actually inverse time it's you know roughly equal to the inverse of the lifetime of the universe, assuming it you know it was expanding at that rate at all times.

147
00:22:44.790 --> 00:22:59.010
Daniel Gruen: We usually express it as a velocity per distance. So the velocity that everything seems to be receding away from us, you know, per unit distance that it half of us sort of all the gods around us receiving

148
00:23:00.270 --> 00:23:08.790
Daniel Gruen: And so associated with that current expansion rate is actually a specific density. The density be called a critical density and it's given us the equation here.

149
00:23:09.150 --> 00:23:16.170
Daniel Gruen: At a higher their expansion rate, the higher the critical density and, you know, the, the higher the fourth of the

150
00:23:16.500 --> 00:23:28.080
Daniel Gruen: Strength of the force of gravity. The smaller the critical density will have to be the critical density is that density that makes the universe flat. If it's expanding with with this rage, not

151
00:23:28.860 --> 00:23:38.700
Daniel Gruen: Incidentally, you can also think of the critical density as the density that you need for vacuum energy in an otherwise empty Universe.

152
00:23:39.300 --> 00:23:57.570
Daniel Gruen: To expand with the H not right forever. Okay, so there's there's one relation of the universe that that has just critical density, just with our customers and constant. It's going to exponentially expand with this fixed rate of, ah, not according to its density of the vacuum.

153
00:23:59.850 --> 00:24:12.180
Daniel Gruen: No one useful way of rewriting the equation that we looked at earlier, is if you write each component of the errors so matter radiation vacuum energy whatever other component you want

154
00:24:12.720 --> 00:24:20.940
Daniel Gruen: As a fractional density as a fraction of that critical density here and you integrate that equation for a dot dot

155
00:24:22.020 --> 00:24:30.240
Daniel Gruen: That leads you to this useful expression here. Okay, so the point that says is that the expansion rate of the universe at any time.

156
00:24:30.840 --> 00:24:45.390
Daniel Gruen: Is proportional to the expansion rate right now but scaling all its components by their density evolution. So you got all these components that are scaled by a to the, you know, however they dilute over time.

157
00:24:46.800 --> 00:24:53.490
Daniel Gruen: There's actually a curvature term here which I told you is going to act like this, you know, W minus one third type

158
00:24:54.330 --> 00:25:09.240
Daniel Gruen: Fluid that I'll make a k is going to be equal to one minus all the other one is all the other guys. So it's only going to appear if the total density of all stuff is not equal to the critical density of the Universe according to its current expansion rate.

159
00:25:10.470 --> 00:25:17.970
Daniel Gruen: And even more generally, you could just write it like that. Right. It's just going to be the sum over all the components. I have the universal the fluids that I've made up.

160
00:25:19.080 --> 00:25:33.390
Daniel Gruen: Just diluting down according to their equation of state. Okay, so this is going to be describing the expansion of the universe, and it puts us in a place to tell the whole history of the universe in terms of its expansion over time.

161
00:25:34.650 --> 00:25:43.410
Daniel Gruen: So I'm just going to tell you what, what happens here. And then we're going to go through that in the remainder of this lecture. And, you know, understand the different phases better

162
00:25:44.280 --> 00:25:53.610
Daniel Gruen: The universe starts out in this steep exponential expansion face going from microscopic size to a macroscopic size.

163
00:25:54.450 --> 00:26:07.830
Daniel Gruen: And eventually somehow turns around, we're going to talk about how that happens into a phase of hot universe where you know the density of radiation is governing the scale evolution of the universe.

164
00:26:09.030 --> 00:26:19.980
Daniel Gruen: Eventually the universe cools down enough that we get into this phase of decelerated expansion in which gravity is trying to pull everything apart.

165
00:26:21.270 --> 00:26:36.090
Daniel Gruen: And then, strangely enough, a couple billion years ago things turn around again and the size of the universe is expanding at an accelerating rate again. And this is where we are looking back at all that and trying to figure out what is happening.

166
00:26:37.800 --> 00:26:47.640
Daniel Gruen: To give you just a sense of where we are. Here we are 13.8 billion years from this point. Okay. That's how long it took for the universe to get to its present size.

167
00:26:48.450 --> 00:26:56.400
Daniel Gruen: And if you want to imagine the size of the observable universe. I'm just going to offer you a comparison that's helpful for me to just get a gut feeling for it.

168
00:26:57.120 --> 00:27:05.490
Daniel Gruen: That the smallest thing that I kind of can imagine is a grain of dust, because you know I can sometimes see a grain of dust on my glasses and it can be annoying.

169
00:27:07.050 --> 00:27:20.190
Daniel Gruen: So that's the smallest thing I can imagine the largest thing that I can barely imagine is the largest distance human managed object ever traveled. That's the Voyager Pro. Okay. It started before I was born. It's still going.

170
00:27:20.610 --> 00:27:29.100
Daniel Gruen: Kind of as fast as it can, but you know that's that's at least something that, you know, we could imagine as a distance traveling

171
00:27:29.940 --> 00:27:42.150
Daniel Gruen: So the ratio of those the ratio of grain of dust to the scale that the Voyager Pro Plus travel is about the ratio of the size of planet earth which I can still kind of imagine

172
00:27:42.750 --> 00:27:48.360
Daniel Gruen: From back from the time we could still travel from country to country. It's a ratio of the side of the earth.

173
00:27:48.750 --> 00:27:57.330
Daniel Gruen: To about 10% of the currently observable universe. Okay, so it's not, you know, not quite the currently observable universe. But it's at least you know 10% of it.

174
00:27:57.660 --> 00:28:04.710
Daniel Gruen: So, so the universe is is very large, but it's not it's not unimaginably large in that way, it's not it's not in finite

175
00:28:05.580 --> 00:28:15.180
Daniel Gruen: It may be in finite, but the suddenly the observable piece of it is is finite. And that's because the universe has a finite. Ah, there's only so far that light has been able to travel.

176
00:28:16.110 --> 00:28:36.120
Daniel Gruen: Okay, so with that, you know, confusing philosophical remark. Let's go through these steps of the expansion history of the universe, and let's try to understand what is happening here. So in this very first fraction of a second actually sort of a 10 to the minus 32 second

177
00:28:37.560 --> 00:28:50.490
Daniel Gruen: Glimpse of time the universe expanded exponentially increasing its size by a factor of roughly 10 to 30 maybe okay so reminding you of that equation.

178
00:28:51.120 --> 00:29:04.200
Daniel Gruen: This is the second derivative of the scale factor. How can you make that exponential expansion happen. We're going to ask you that question again with a poll after poll. How can you make that exponential expansion happen.

179
00:29:06.240 --> 00:29:17.790
Daniel Gruen: And you can go to the URL. I'm going to give you just a second difference on how can you make the Universe expand exponentially, do you fill it with radiation with a large positive pressure

180
00:29:18.270 --> 00:29:29.490
Daniel Gruen: Juice do just, you know, start completely empty. And that's what the universe is going to do then you fill it with a large cosmological constant or is it something else that you've got to do to the universe to make that happen.

181
00:29:30.600 --> 00:29:33.570
Daniel Gruen: Okay. Give you another second.

182
00:29:35.280 --> 00:29:48.600
Daniel Gruen: This is a really key point. And in fact, the key takeaway right if you're looking for a particle and almost invisible particle to cause inflation. Then when you know what kind of particle does that. What, what kind of properties does it have to have

183
00:29:50.910 --> 00:29:52.710
Daniel Gruen: You on my second take a sip of water.

184
00:29:58.800 --> 00:30:10.110
Daniel Gruen: All right, let's look at the responses. Okay. So kind of a divided response here. Do you want a universe. You know, when radiation that has a large positive pressure

185
00:30:11.040 --> 00:30:22.200
Daniel Gruen: Or do you want a universe that's filled with a cosmological constant. That's, that's, you know, large as well. So let's look at the equation again together, right. So, this equation.

186
00:30:23.070 --> 00:30:33.090
Daniel Gruen: If I put something with a large positive pressure that's actually going to slow down the expansion of the universe. So we know whatever expansion rate I start off with

187
00:30:33.510 --> 00:30:38.580
Daniel Gruen: It's actually going to decrease over time because of this negative pre factor to that term.

188
00:30:39.360 --> 00:30:52.470
Daniel Gruen: So if I, you know, if I put nothing in the universe of the only accept a cosmological constant positive lambda here than what I'm going to get is an equation where a dot.is not proportional to a right and so this is going to lead to an exponential growth.

189

00:30:52.770 --> 00:31:01.620
Daniel Gruen: Of a over time. That's exactly what you need. So you need a large vacuum energy density to make the Universe expand with this exponential

190
00:31:02.010 --> 00:31:11.430
Daniel Gruen: In this exponential behavior at the very early universe. And, you know, we're going to try to find out in some other lectures this week. What could possibly be happening here.

191
00:31:12.360 --> 00:31:22.530
Daniel Gruen: Now one thing that that does. And that's, these are features that make inflation really attractive. Is it completely dilutes all other component of the universe. Right. So, A is increasing by a factor of 10 to the 30

192
00:31:23.040 --> 00:31:31.140
Daniel Gruen: All those other components that go as a to the minus whatever degree to be gone. Okay, so whatever mess you have filled the universe with

193
00:31:31.500 --> 00:31:38.520
Daniel Gruen: At the very, very beginning, you know, whatever. Strange particles whatever magnetic motor poles and crap you put in there.

194
00:31:39.240 --> 00:31:45.900
Daniel Gruen: They're going to be just, you know, they're going to never see each other again, they're going to be so diluted that you know that problem is solved.

195
00:31:46.380 --> 00:31:51.750
Daniel Gruen: You don't. You wouldn't find them in the lap. It also perfectly knows the curvature of the universe. So this is

196
00:31:52.140 --> 00:32:00.690
Daniel Gruen: Going back to this thing, we discussed earlier in this lambda only universe, you're going to get expansion, you're going to get a density a critical

197
00:32:01.020 --> 00:32:06.330
Daniel Gruen: Density of lambda is exactly going to be the critical density of corresponding to the expansion rate that it has. And so

198
00:32:06.900 --> 00:32:15.540

Daniel Gruen: Whatever curvature there was, it's just gonna be completely flattened out and you end up with a flat universe, and it's going to be so flat that it's going to stay flat from that point on.

199
00:32:17.250 --> 00:32:27.090
Daniel Gruen: If I should also causally disconnects different parts of the universe. So parts of the universe that before might have been in, you know, in turn, will contact you, by increasing the

200
00:32:27.990 --> 00:32:37.590
Daniel Gruen: The scale of them so rapidly in moving them apart by more than the speed of light. For the first you know 10 to the minus 32 seconds.

201
00:32:38.040 --> 00:32:57.330
Daniel Gruen: They're going to be outside of cause of contact for a long time. If ever there are not going to exchange radiation or information in other ways, again. Okay, so this is these are great things that inflation. Does that explain some of the features of the universe as we observe it.

202
00:32:59.610 --> 00:33:01.290
Daniel Gruen: And okay so

203
00:33:03.060 --> 00:33:09.030
Daniel Gruen: After this phase right we would end up with a universe that's empty besides this vacuum energy

204
00:33:09.960 --> 00:33:20.970
Daniel Gruen: But somehow, you know, we're not the universe is not empty, right now we're having this conversation. So somehow this this vacuum energy must turn into other forms of energy. And so the first thing that's going to happen is

205
00:33:21.600 --> 00:33:32.760
Daniel Gruen: That that vacuum energy must turn into radiation again by a process that you know we need a mechanism for and that mechanism today is is very hard to see.

206
00:33:33.270 --> 00:33:43.470
Daniel Gruen: We call it reheating and so once you've done that, you're going to see that the term dominating here is going to be this omega are harbor small, the amount of radiation that ends up being in the universe.

207
00:33:43.890 --> 00:33:50.160

Daniel Gruen: Because of that a to the minus forth, you know, when the universe is small that radiation was actually dominating and it's going to

208
00:33:51.030 --> 00:34:00.990
Daniel Gruen: Determine the first couple, you know, the first first amount of for the first amount of time is going to determine how the universe expands so

209
00:34:01.590 --> 00:34:06.900
Daniel Gruen: Lots of really strange things happen in this early universe that you're going to hear more about today, somehow.

210
00:34:07.380 --> 00:34:13.050
Daniel Gruen: In that early universe as particles you know collide on interact and and convert from one form to another.

211
00:34:13.740 --> 00:34:26.070
Daniel Gruen: The abundance of matter exceeds the abundance of antimatter. No, no real reason for that to happen, but it you know that we know off. But, you know, apparently that happened because we're having this conversation and a matter universe.

212
00:34:28.200 --> 00:34:34.650
Daniel Gruen: For the first, second or soul latrines are actually coupled to this plaza, even though there's the weekly interacting

213
00:34:35.370 --> 00:34:43.740
Daniel Gruen: The, the density and you know range of interactions is so high that neutrinos do do thermal lies in this very first second

214
00:34:44.430 --> 00:34:52.050
Daniel Gruen: They actually have a substantial share of the energy density in the early universe as well. So they really matter if you added another neutrino to the mix.

215
00:34:52.350 --> 00:35:01.530
Daniel Gruen: That would really change the energy balance of the processes in this very own universe so you know when you do that, there's, there's a way of making predictions of what's happening.

216
00:35:02.490 --> 00:35:20.160
Daniel Gruen: Eventually the expansion stops all these particles directions, just a, you know, the collisions of particles getting rarer and rarer and one after another. These species of particles freeze out.

So one one really interesting type of freeze out is the freeze out of these light nuclei.

217
00:35:21.780 --> 00:35:36.420
Daniel Gruen: The ratio of these different light nuclei, like you know deuterium Helium, Lithium depends very sensitively on the density of baryons in the early universe and on these these rights that protons and neutrons are colliding with

218
00:35:37.200 --> 00:35:42.630
Daniel Gruen: And so one thing that we see when we measure the density of say lithium and helium and deuterium.

219
00:35:43.200 --> 00:35:51.690
Daniel Gruen: Is that most of the you know the density of variance in the universe must have been really small and you know it doesn't match the density of matter in the universe today.

220
00:35:52.170 --> 00:36:00.840
Daniel Gruen: And so we've got to talk about that you know how to make up for that other almost invisible fraction of the modern entity on the next slide.

221
00:36:01.830 --> 00:36:06.210
Daniel Gruen: But I'll also tell you about, you know, the end of that hot universe phase eventually

222
00:36:06.630 --> 00:36:17.340
Daniel Gruen: The universe becomes cold enough diffuse enough transparent enough that we can still see the the relic photons of this early phase that just haven't scattered since

223
00:36:17.850 --> 00:36:19.980
Daniel Gruen: As what we call the cost of microwave background.

224
00:36:20.760 --> 00:36:26.850
Daniel Gruen: That's about 380,000 years after the Big Bang. And we're going to talk a little more about that tomorrow as well.

225
00:36:27.150 --> 00:36:39.030
Daniel Gruen: Because the cost of mercury background is so crucial in showing us the seeds of in homogenize in the universe. But for today, universe is just homogeneous and this is how the hot soup gets cold.

226

00:36:41.670 --> 00:36:55.560
Daniel Gruen: So let's talk a little bit about dark matter. Oops. This was just Ledger's advancing too fast. There's, there's several different pieces of evidence that really point us to most of the matter being in this this other form.

227
00:36:56.160 --> 00:37:01.650
Daniel Gruen: One is the one I just told you about, there's low abundance of regular matter in in the primordial universe.

228
00:37:02.280 --> 00:37:18.570
Daniel Gruen: Yet there's a presence of massive structures today. And that means that most matter must be non baryonic okay we could equivalent the observed the rotation curves are the motions of galaxies. This is just a rotation velocity of the galaxy as a function of scale from its center.

229
00:37:19.920 --> 00:37:30.510
Daniel Gruen: Most of the gravity must be not due to the visible stars or gas you know if it was just the visible stars or gas and you would expect this rotation curve as a dashed line here.

230
00:37:30.930 --> 00:37:37.140
Daniel Gruen: But you know, it's still there. So there must be a lot of matter that is doing gravity that is no other stars. Don't gas.

231
00:37:38.340 --> 00:37:50.190
Daniel Gruen: Likewise patterns in the cost of microwave background, the expansion of the growth of structure in the universe imply that the total density of matter. Let's be six times the density of burials. Okay, so what do we have here.

232
00:37:50.670 --> 00:38:01.140
Daniel Gruen: As candidates for that. Well, dark matter could be one or possibly more stable massive particles that are that are present in the primordial plasma.

233
00:38:02.100 --> 00:38:14.550
Daniel Gruen: And now non relativistic they must be interacting quite weekly and the primordial plasma so that they don't affect the formation of all the other of all the other you know species that come out.

234
00:38:15.210 --> 00:38:22.170
Daniel Gruen: So in that sense, we're looking for a weekly interacting massive particle. And that's something that for sure you're going to hear more about

235
00:38:23.370 --> 00:38:31.170
Daniel Gruen: Alternatively, it could be one or more stable light particles so particles that are, you know, much much lighter and

236
00:38:31.920 --> 00:38:40.680
Daniel Gruen: But that are present today at non relativistic speeds, somehow, so they couldn't just have decoupled like neutrinos did from that plasma.

237
00:38:41.100 --> 00:38:45.570
Daniel Gruen: They must have some other interactions that makes that make them president of the universe today.

238
00:38:45.960 --> 00:38:53.340
Daniel Gruen: At you know cold temperatures and so accion is another topic that you're going to hear about this week that that is that kind of product.

239
00:38:54.270 --> 00:39:04.530
Daniel Gruen: So with these two conditions here. Standard Model particles that actually ruled out this just nothing in our, in our toolbox that could have these properties.

240
00:39:05.520 --> 00:39:13.290
Daniel Gruen: Another thing that's pretty much rolled out is primordial black holes so you know black holes that were present in the form of baryons at any point in that early plasma.

241
00:39:13.650 --> 00:39:21.870
Daniel Gruen: Can't you know can't be that would destroy all the, all these equilibrium that have led to the densities of species we measure in the universe today.

242
00:39:22.320 --> 00:39:35.640
Daniel Gruen: If just there was black holes produced in inflation in principle that you know that could be, but we also we don't see enough of such black holes floating around in the universe and observational data. So you really have to fine tune

243
00:39:36.090 --> 00:39:40.080
Daniel Gruen: The mass distribution of these primordial blackout black holes to be able to

244

00:39:40.710 --> 00:39:55.260
Daniel Gruen: You know, account for documentary at any relevant density and you know that's it's it's getting increasingly difficult to do that. So promoted by calls probably aren't the answer either. So, you know, big mystery certified almost invisible component of the universe.

245
00:39:56.700 --> 00:39:59.970
Daniel Gruen: So this was the hot universe. We're just going to go to

246
00:40:01.080 --> 00:40:18.090
Daniel Gruen: This next quick exercise for you to do the segway what you know what component of the universe takes over next and tell think this is actually working well. No, it does. Okay, great. So you're just going to go to this poll f.com

247
00:40:20.130 --> 00:40:26.700
Daniel Gruen: And you're just going to click which of these components you think takes over control of the universe. Next.

248
00:40:28.770 --> 00:40:30.600
Daniel Gruen: Okay. Yep. So

249
00:40:31.920 --> 00:40:33.960
Daniel Gruen: Some of you are, you know, our

250
00:41:28.380 --> 00:41:33.780
thomas rizzo: Looks like we lost the speaker maybe Kim. Kim, he can come back. Let's wait a few minutes.

251
00:42:24.810 --> 00:42:25.200
Daniel Gruen: Hey,

252
00:42:27.240 --> 00:42:35.250
Daniel Gruen: My laptop just got kicked out. But I am back now. Sorry for the short break. Hopefully you've used that to get

253
00:42:35.250 --> 00:42:35.670
grzegorz madejski: Some water.

254
00:42:36.420 --> 00:42:37.740
Daniel Gruen: And and

255
00:42:37.830 --> 00:42:38.970

It just

256
00:42:40.830 --> 00:42:43.260
Daniel Gruen: Share screen I can one second.

257
00:42:44.580 --> 00:42:45.690
thomas rizzo: Glad to see you back.

258
00:42:45.900 --> 00:42:47.880
Daniel Gruen: Yeah, this is what happens. Right.

259
00:42:50.160 --> 00:42:54.840
Daniel Gruen: Okay. And it's just it's just takes me a second.

260
00:43:13.620 --> 00:43:19.950
Daniel Gruen: Okay. So that gave you a little more time to answer the poll. Think about it.

261
00:43:21.120 --> 00:43:25.950
Daniel Gruen: We have a few enthusiasts for you. Can you see my screen actually

262
00:43:27.360 --> 00:43:27.780
thomas rizzo: Yes.

263
00:43:28.020 --> 00:43:38.790
Daniel Gruen: Okay, awesome. We have a few enthusiasts for all these other components of the universe, but the majority of you think what comes next is matter domination and you're right that is what is going to happen.

264
00:43:40.740 --> 00:43:43.830
Daniel Gruen: Is really, really slow. So, okay.

265
00:43:46.740 --> 00:43:53.640
Daniel Gruen: Great. So the next phase of the universe matter is dominating the total energy content of the universe.

266
00:43:54.180 --> 00:44:00.540
Daniel Gruen: And what is going to happen is that matter because it's gravitating, you know, with an attractive for is only

267

00:44:00.960 --> 00:44:08.460
Daniel Gruen: Is going to slow down the expansion of the universe. Okay, so basically matter in this equation, it's pressure doesn't matter so

268
00:44:08.790 --> 00:44:16.140
Daniel Gruen: A dot dot over a is just going to be proportional to something negative times the density of matter, which is going to go down as a to the third power.

269
00:44:16.890 --> 00:44:26.340
Daniel Gruen: Now, a lot of things that happen in this matter dominated phase of the universe are totally visible. So they're kind of outside, you know, outside the scope of this lecture.

270
00:44:26.700 --> 00:44:33.270
Daniel Gruen: But what you're going to find is that density fluctuations are going to grow. Gravity is going to be really good at pulling things together.

271
00:44:33.840 --> 00:44:39.960
Daniel Gruen: From you know 10 to the minus five relative fluctuations of density to unity fluctuations of density

272
00:44:40.620 --> 00:44:52.170
Daniel Gruen: We're going to find stars, galaxies galaxy clusters forming all the structures that are present in the universe. Today we're going to find supermassive black hole is growing at the sentence of galaxies.

273
00:44:52.860 --> 00:44:59.490
Daniel Gruen: So all of these things are visible to us when we just record you know record photons from the sky but

274
00:45:00.000 --> 00:45:12.210
Daniel Gruen: You know, mind you, they're all closely related to the clustering of dark matter, none of them would happen. We're not for dark matter being present with. It's very high abundance and so

275
00:45:13.350 --> 00:45:25.020
Daniel Gruen: You know, we're going to talk next time about structure in the universe and what it tells us about these almost invisible. It's going to still be important to understand to understand that if we want to learn about dark matter.

276
00:45:26.070 --> 00:45:27.390
Daniel Gruen: No. Whoops.

277
00:45:28.920 --> 00:45:38.520
Daniel Gruen: As a next step, as some of you already pointed out, it dark energy is going to take over, right. So, in this equation once you've downloaded the density of matter enough

278
00:45:38.970 --> 00:45:50.130
Daniel Gruen: If there's a sufficiently large positive lambda, then the expansion is going to be accelerating. And so this is what happens in that final phase of the universe leading up to today.

279
00:45:50.820 --> 00:46:00.510
Daniel Gruen: For the observations that we're making to match our model we need about 70% of the energy density at the present time to be in this form of vacuum energy density

280
00:46:00.990 --> 00:46:08.220
Daniel Gruen: Now there's a couple things to say about that. One is that strange like close to matter density right it's it's a factor two and a half.

281
00:46:09.000 --> 00:46:18.570
Daniel Gruen: Between them compared to orders of magnitude between matter density and radiation density in the universe today so somewhat suspiciously the vacuum energy

282
00:46:18.570 --> 00:46:20.130
Daniel Gruen: Density and the matter density are quite

283
00:46:20.130 --> 00:46:22.410
Daniel Gruen: Similar one other thing to say is

284
00:46:22.410 --> 00:46:33.570
Daniel Gruen: That this density of vacuum energy is actually very much unexpectedly small if you produce vacuum energy density by, you know, an eighth calculations of

285
00:46:33.960 --> 00:46:41.280
Daniel Gruen: Basically all the types of particles that you have creating an E learning all the time in a vacuum, you would expect a vacuum energy density, that's

286
00:46:41.760 --> 00:46:49.500

Daniel Gruen: You know 100 orders of magnitude higher than what is present in the universe today. So there needs to be a mechanism, if that is really what is happening.

287
00:46:49.860 --> 00:47:00.480
Daniel Gruen: That almost cancels this very finely tuned almost canceled all the vacuum energy up to the point where it gives us this tiny, tiny lambda that's comparable to the matter of necessity.

288
00:47:01.890 --> 00:47:09.420
Daniel Gruen: For to say is that we do not nearly have as many clues to the nature of dark energy, as we have in the case of dark matter.

289
00:47:09.990 --> 00:47:18.750
Daniel Gruen: But we're going to discuss in the next few minutes, you know, one way that we could find out that there is. There's got to be such a thing as dark

290
00:47:19.560 --> 00:47:34.110
Daniel Gruen: And so how do we know that there's dark energy, clearly the the biographies of the universe as I would draw them as curves on this diagram are going to be very different. If we put dark energy into the mix.

291
00:47:34.740 --> 00:47:51.510
Daniel Gruen: So in this matter, only universe in red here. What's happened is the expansion of the universe is slowed down continuously. Okay, so this expansion rate is the slope of that curve and that slope just gets smaller and smaller and smaller over time until it reaches what we have today.

292
00:47:53.040 --> 00:47:55.800
Daniel Gruen: This thinker. If you're violent curve.

293
00:47:57.030 --> 00:48:07.770
Daniel Gruen: For the most part of its history. The same thing is happening because for the most part of its history is actually dominated by, you know, inflation than radiation than matter as well.

294
00:48:08.220 --> 00:48:16.500
Daniel Gruen: But here, there's something happening, it's going to, it's going to accelerate its expansion and the slope of that curve is going to increase again and that you know that tiny change.

295
00:48:16.800 --> 00:48:24.000

Daniel Gruen: Is is, for instance, shifting the time, the age of the universe, a lot that universe must have been a lot older

296
00:48:25.860 --> 00:48:40.740
Daniel Gruen: And because it was expanding more slowly. In the past, before it started accelerating to get to its presence. So the big bang and that follow the universe must have been a lot longer. While ago now.

297
00:48:42.240 --> 00:48:54.570
Daniel Gruen: One thing we could do is measure the redshift of galaxies quite easily. And I've just I've indicated that by inverting the the axes here I've inverted.

298
00:48:54.930 --> 00:49:03.210
Daniel Gruen: The size excess of the universe to now be a redshift access the ratchet of the light received from galaxies at a stage in the universe.

299
00:49:03.660 --> 00:49:09.120
Daniel Gruen: And that redshift. It's just, you know, it's a stretch of the wavelength that determines the redshift of the galaxy.

300
00:49:09.870 --> 00:49:17.490
Daniel Gruen: It's actually that minus one. Sorry, getting the minus one, but it's, it's, you know, it has to do with the side of the universe today.

301
00:49:18.000 --> 00:49:21.450
Daniel Gruen: And the size of the universe at the time the photon was admitted

302
00:49:22.290 --> 00:49:32.850
Daniel Gruen: Also reverted this access to now instead of being, you know, time increasing age of the universe, increasing it's now the distance or the look back time increasing to the left.

303
00:49:33.480 --> 00:49:45.120
Daniel Gruen: And so if we can connect these two, we could connect the redshift of objects to our look out distance to these objects and that would allow us to to map these curves.

304
00:49:45.870 --> 00:49:54.540
Daniel Gruen: Okay, so have a look at this diagram because I'm going to ask you a question about it in the next next slide on Poll Everywhere.

305
00:49:55.620 --> 00:50:07.860
Daniel Gruen: If you know if we observe these galaxies. If we observe the distance to an object at fixed redshift. Is it larger in the universe that has a dark energy. In addition to matter.

306
00:50:08.340 --> 00:50:22.980
Daniel Gruen: Is it's smaller in the universe that has dark energy. In addition to matter or is it the same involve or maybe, maybe. Do you need another piece of information and, you know, we're going to do this live while you respond, how many responses. Do we have

307
00:50:24.540 --> 00:50:38.670
Daniel Gruen: 3535 and growing okay so great. So yeah, a lot of you have have have got this, I've got this understood that it's actually, it's a kind of a tricky. Deep Mind Boggling question type of thing.

308
00:50:39.240 --> 00:50:48.600
Daniel Gruen: But yes, you're right in the universe with dark energy distances to these objects at the fixed redshift will be larger than in the universe made of just matter.

309
00:50:49.110 --> 00:51:03.750
Daniel Gruen: Okay. And so the way that you could understand that is I'm looking at a galaxy at the same redshift. So on that horizontal line. It's going to be at a more distant point in on that violate curve that on that curve of the matter.

310
00:51:05.130 --> 00:51:15.060
Daniel Gruen: So if you can measure relative distances. One way you could do that is with a standard candle. I know objects have known true brightness, you can measure

311
00:51:15.450 --> 00:51:23.580
Daniel Gruen: Their relative apparent brightness, then you can measure the relative distance of such objects in different you know galaxies at different redshift.

312
00:51:24.090 --> 00:51:33.510
Daniel Gruen: This is one way that you could find that, oh yeah, then you know the the the ones that Hi, Richard. They're extra further away than they could possibly be in a universe that's made of dark matter only

313
00:51:34.470 --> 00:51:35.100
Daniel Gruen: Us all

314
00:51:35.250 --> 00:51:37.350
thomas rizzo: You have a little bit less than five minutes. Sorry.

315
00:51:37.650 --> 00:51:39.030
Daniel Gruen: Awesome. Yeah, I think that's going to

316
00:51:39.570 --> 00:51:40.290
Daniel Gruen: Go, it just

317
00:51:40.350 --> 00:51:40.980
Daniel Gruen: Just fine.

318
00:51:42.630 --> 00:51:49.650
Daniel Gruen: Unless you know physically what their true brightness is, you first have to calibrate that if you really wanted to map that whole curve. So

319
00:51:49.860 --> 00:52:06.990
Daniel Gruen: You can easily get a relative distance measure that way if you just know they're all the same brightness. It's much harder to get an absolute distance measure without calibrating the brightness of this nearby standard candle in some other way, knowing its distance in some other way.

320
00:52:09.240 --> 00:52:16.860
Daniel Gruen: You could do the same thing if you had such a thing as a standard ruler, a fixed physical size that you could observe at different shifts

321
00:52:17.640 --> 00:52:26.280
Daniel Gruen: Once it gets a ruler is a scale of the baryonic acoustic isolation peak, which we're going to discuss a little bit tomorrow, you can observe that

322
00:52:26.760 --> 00:52:35.700
Daniel Gruen: That fixed known scale at different distances. Again, the size of the apparent scale that you're observing is going to tell you about the distances.

323
00:52:36.150 --> 00:52:46.680
Daniel Gruen: And the advantage here is if you if you physically know what that scale is as we do in the case of baryonic oscillations based on you know our understanding of plasma basically in

324
00:52:47.970 --> 00:53:02.520
Daniel Gruen: The early universe which, thanks to particle physics we really understand quite well, then this is an absolute measurement of distance now and you can map that whole curve, including measuring what the current expansion rate of the university is

325
00:53:03.840 --> 00:53:12.240
Daniel Gruen: So with these types of measurements. This is what we think the universe looks like today. Based on all observations. There's about 13.8 billion years of history.

326
00:53:12.570 --> 00:53:25.560
Daniel Gruen: And the universe today contains 70% vacuum energy 25% of dark matter and just 5% of baryons that's a flat universities all add up to 100% of the critical matter density

327
00:53:26.790 --> 00:53:33.540
Daniel Gruen: What we, you know, having constrained well at all, is whether dark energy is really a cosmological constant, you know, whether it's

328
00:53:33.870 --> 00:53:47.910
Daniel Gruen: It's equation of state parameter w is fixed in time or whether that equation state parameter maybe time variable. So that's, that's one thing that you have a lot of freedom as a theorists to, you know, come up with well motivated theories and make predictions for

329
00:53:49.530 --> 00:53:58.560
Daniel Gruen: Now while that is the state. Today, the early universe look very different. There was a much larger role for neutrinos and photons and you know any other

330
00:53:59.160 --> 00:54:06.810
Daniel Gruen: Relativistic species that that you could introduce so so we can measure their properties by looking at the early universe.

331
00:54:07.740 --> 00:54:16.410
Daniel Gruen: And I'll just going to mention two tensions that you're probably going to hear about this week, so there's there's really two types of observations that I would say

332
00:54:16.740 --> 00:54:29.490
Daniel Gruen: There's no substantial evidence of a disagreement between different measurements within this model. One is the measurement of the

local expansion rate if you just look at you know the velocity at which galaxies are moving away from us.

333
00:54:30.630 --> 00:54:39.360
Daniel Gruen: Relative to their distance and you compare that to the expansion rate that you need to map out the scale evolution of the universe.

334
00:54:39.660 --> 00:54:52.590
Daniel Gruen: With a standard rulers than those two numbers disagree at roughly four sigma. Now we have local measurements. These are the numbers that you need to explain the whole evolution of the universe started with starting with the cost of microwave background.

335
00:54:53.670 --> 00:54:59.190
Daniel Gruen: They're off before sigma I could point to additional particles or interactions in the early universe.

336
00:54:59.640 --> 00:55:07.230
Daniel Gruen: And you know those to change the size the physical side of the standard ruler that we use to map out that expansion histories. I think that's the

337
00:55:07.710 --> 00:55:17.370
Daniel Gruen: Most interesting candidate, it could point at a very recent additional source of acceleration which is hard to do without you know on

338
00:55:17.790 --> 00:55:27.330
Daniel Gruen: improbable fine tuning or I could point to systematic errors in these measurements either of the early universe or of like universe.

339
00:55:27.990 --> 00:55:34.530
Daniel Gruen: And then the second discrepancy that we're beginning to see is that when you measure density fluctuations in the universe at the present time.

340
00:55:34.890 --> 00:55:44.310
Daniel Gruen: Their attitudes disagree with the athletes to, as you would expect, according to the earlier rules at, you know, two to three sigma, depending which experiments you ask

341
00:55:45.000 --> 00:55:56.220
Daniel Gruen: Again, that could point to a default particles, the right directions. It could point that modifications of gravity or it could, you

know, could just be a statistical fluke still have this point with this relatively modest significance.

342
00:55:56.640 --> 00:56:12.630
Daniel Gruen: Or potentially systematic error, but it's going to be part of what we're going to discuss tomorrow, where we're looking at cosmic structure and what it can tell you about these almost invisibles and I think that brings me to the end of my lecture. Thanks very much.

343
00:56:13.350 --> 00:56:16.830
thomas rizzo: Great, thanks a lot. Thanks. Sorry about the technical thing. I don't know what happened there.

344
00:56:17.220 --> 00:56:19.110
thomas rizzo: But let's turn it over to the Q AMP. A now.

345
00:56:20.280 --> 00:56:23.040
Daniel Gruen: Is there something so I need to open some file or no.

346
00:56:23.070 --> 00:56:24.690
thomas rizzo: No, someone will ask you questions.

347
00:56:24.990 --> 00:56:26.820
Daniel Gruen: Okay, great. I hope

348
00:56:27.810 --> 00:56:30.990
Richard Partridge: All right, Daniel. This is Richard cartridge

349
00:56:32.910 --> 00:56:36.210
Richard Partridge: Looking at the Q AMP a questions we

350
00:56:37.020 --> 00:56:38.100
Richard Partridge: In questions.

351
00:56:39.870 --> 00:56:45.600
Richard Partridge: Listed. And so I think we have 15 minutes every town.

352
00:56:47.940 --> 00:56:49.140
thomas rizzo: Is correct

353
00:56:49.800 --> 00:57:02.040

Richard Partridge: So we probably won't get through all of them online. But let's take a start. The first question for you is, how did you go from the

354
00:57:03.090 --> 00:57:05.220
Richard Partridge: RW metric to the double

355
00:57:06.270 --> 00:57:08.970
Richard Partridge: Over a equation. On slide 13

356
00:57:11.100 --> 00:57:24.240
Daniel Gruen: Okay, if that slide, is that right. Um, so, so this metric here you could express it as one of those GI Joe sensors. Right. It's, it's basically a bunch of entries that connect the

357
00:57:24.630 --> 00:57:36.900
Daniel Gruen: Coordinates and the time you know time element of your, of your metrics into into this DS right using using this equation. That's the definition of your d squared is this metric times

358
00:57:37.410 --> 00:57:50.850
Daniel Gruen: The product of these d coordinate things. Okay, so this whole thing is really just a matrix gi, j and that matrix God appears in this equation derivatives of that matrix.

359
00:57:51.930 --> 00:58:05.550
Daniel Gruen: are combined in certain ways to give you these these know this Richie tensor here and so on the left hand side of that equation you can just plug in that metric. And then the right hand side of the equation. You take a

360
00:58:07.110 --> 00:58:13.020
Daniel Gruen: Tensor describing the pressure and densities of the fluids filling the universe and you just plug that in.

361
00:58:13.620 --> 00:58:22.380
Daniel Gruen: And you know, it's from that point on, it's really just algebra to get to the form of the equation. That's that way. Now that's how you would do it in general relativity

362
00:58:23.130 --> 00:58:31.350
Daniel Gruen: If general relativity is not your strong suit. You could actually do the very same thing with just Newtonian gravity, you could think of a homogeneous.

363
00:58:32.160 --> 00:58:48.210
Daniel Gruen: You know, sparkly symmetric ball of stuff that is acting under its own gravity. And so, you know, a would be the radius of that ball and you know stuff would just be self gravitating and would be collapsing, or the

364
00:58:49.290 --> 00:59:03.930
Daniel Gruen: Size of that all will be decreasing over time. And the second derivative of the size of that ball would be just minus four thirds pie G times roll on the pressure wouldn't really be appearing at that very simple picture that's that's that that comes in.

365
00:59:05.130 --> 00:59:15.270
Daniel Gruen: I would say because of how we describe this Florida in general relativity, but you can get, you know, you can get to something very similar, but just doing Newtonian calculations of a homogeneous ball.

366
00:59:16.440 --> 00:59:24.900
Richard Partridge: Okay, that's great. The second question. I'm going to skip around here a little bit. We get all your questions answered.

367
00:59:25.980 --> 00:59:27.300
Richard Partridge: Offline but

368
00:59:29.520 --> 00:59:40.020
Richard Partridge: On slide 21. The question is, if the universe has a finite edge. Won't it be non homogenous at or near the edge.

369
00:59:41.520 --> 00:59:50.430
Daniel Gruen: So that's a really great question. In a way, right. So the, I think the maybe the interesting scenario isn't isn't even you don't even need an edge right

370
00:59:50.790 --> 01:00:00.480
Daniel Gruen: You could certainly have this vacuum energy in the very early universe. Right. And you're right here, you could have it be taking a different value at different

371
01:00:00.900 --> 01:00:04.500
Daniel Gruen: Places right the lambda wouldn't have to be the same everywhere.

372
01:00:05.100 --> 01:00:13.110

Daniel Gruen: And so you know what you would find them is that some parts of the universe would be expanding more rapidly than others, right, because the lambda

373
01:00:13.500 --> 01:00:20.910
Daniel Gruen: The size of lambda sets the size of the expansion rate of the earlier rows. And so what you would be getting in that

374
01:00:21.300 --> 01:00:32.070
Daniel Gruen: scenario is that, you know, you would basically have these bubbles blowing up within 10 to the minus 32 seconds around places where alumna is particularly large at the beginning.

375
01:00:32.550 --> 01:00:39.660
Daniel Gruen: And they would, you know, they would still form a very a huge you know almost homogeneous almost flat universe.

376
01:00:40.110 --> 01:00:48.540
Daniel Gruen: Out to some edge and and i think you're correct, that there could be there could be spatial variations to lambda that way. They, they would not necessarily be

377
01:00:48.870 --> 01:00:53.730
Daniel Gruen: Observable today because they would still be so small across the size of the

378
01:00:54.210 --> 01:01:00.480
Daniel Gruen: observable universe. Right. So across the size of the observable universe. We might still see that everything is homogeneous.

379
01:01:00.900 --> 01:01:19.620
Daniel Gruen: Even though there could be such variations in the early universe. And again, that's, that's just because this rapid expansion just, you know, removes any any spatial structure any in homogenize it very effectively. But you're blowing up whatever fluctuations over to tech antic scales.

380
01:01:21.990 --> 01:01:26.910
Richard Partridge: Okay, thank you, unsigned 23. We have a couple of questions.

381
01:01:29.010 --> 01:01:37.320
Richard Partridge: Could you explain why a large cosmological constant during inflation dollars the curvature of the universe and also

382
01:01:40.110 --> 01:01:45.210
Richard Partridge: Related inflation would not know the curvature perfectly, but almost perfectly right.

383
01:01:45.660 --> 01:01:46.230
Daniel Gruen: They correct

384
01:01:46.350 --> 01:01:51.750
Richard Partridge: The curvature in principle, start to manifest. So now itself again at some point.

385
01:01:53.190 --> 01:01:58.200
Daniel Gruen: Correct. Let me find the equation that's actually best to this Gus is

386
01:01:59.670 --> 01:02:03.210
Daniel Gruen: This one. Okay, so

387
01:02:05.160 --> 01:02:14.580
Daniel Gruen: If, if I know out all these components. Right. So if I'm, if I'm talking about our universe that only contains Lana. Okay, so I'm gonna

388
01:02:15.780 --> 01:02:26.250
Daniel Gruen: Just going to cross out these components, then each is just a constant, right, this thing is a constant. He is just going to stay the same. So,

389
01:02:27.870 --> 01:02:37.860
Daniel Gruen: The universe expanding exponentially. You know, because it's filled with vacuum energy. It's going to expand with a rate.

390
01:02:38.580 --> 01:02:48.990
Daniel Gruen: That corresponds to the density of vacuum energy such that that universe is flat. This is just the you know if if I'll make a lambda is a little bit smaller than it should be.

391
01:02:49.590 --> 01:02:59.580
Daniel Gruen: Then still over time, you know, the universe is going to not quite exponentially expand, it's going to, it's going to expand a little more slowly at first, and then it's going to hit expansion. Expansion with a

392

01:02:59.910 --> 01:03:08.370
Daniel Gruen: Slightly smaller scale factor and vice versa. Right. So, so you're going to the attractor of that system is exponentially expanding with a rate.

393
01:03:08.790 --> 01:03:15.420
Daniel Gruen: That corresponds to the density of lambda, like that. And so this is what what is happening, you know, whatever value you choose for the

394
01:03:15.780 --> 01:03:21.210
Daniel Gruen: vacuum energy density. Once it takes over the universe is going to go through the expansion rate where it's flat.

395
01:03:22.020 --> 01:03:32.940
Daniel Gruen: Now you're right that you know it's it's never it's never quite going to get there, right. This is an acid topic process this this attraction to that density isn't as toxic process.

396
01:03:33.390 --> 01:03:38.670
Daniel Gruen: And so there's there's going to be room for, you know, a tiny amount of curvature still present

397
01:03:39.390 --> 01:03:47.430
Daniel Gruen: And what's also correct is that whatever departure from flatness is present in the universe at any time. It's going to actually grow.

398
01:03:47.790 --> 01:03:55.470
Daniel Gruen: As long as you know this is not the dominant component as long as the universe is governed by these other components, a deviation from

399
01:03:56.160 --> 01:04:05.040
Daniel Gruen: Flat the deviation from the critical density is actually going to increase. You're going to get an even stronger deviation from critical density, you make your universe, a little bit over dense.

400
01:04:05.670 --> 01:04:14.070
Daniel Gruen: And the universe is governed by matter. The universe is not going to expand as much. And it's going to get more over dense compared to its critical density right so

401
01:04:15.420 --> 01:04:22.710

Daniel Gruen: You're as long as lambda is not the dominant factor, you're going to be pushed away from flat overtime.

402
01:04:23.220 --> 01:04:32.760
Daniel Gruen: But because you know there's a factor of 10 to the 30 expansion at the very beginning, you're really, really close to flat compared to, you know, whatever.

403
01:04:33.300 --> 01:04:49.740
Daniel Gruen: The universe's has been able to do to get away from flatness. In the meantime, so I think the upshot is that we still expect the universe to be very close to flat today, you know, if there was such a thing as inflation acting for just the first very tiny fraction of a second.

404
01:04:52.140 --> 01:05:05.250
Richard Partridge: Okay. Great. The next question I have is what happens to the energy of the photons is they get stretched due to the expansion of the universe. Where does the energy go

405
01:05:05.670 --> 01:05:17.130
Daniel Gruen: Oh, great question. Right. So what do you are finding here is that you know that energy isn't preserved right so so you could say the, the energy of matter is that's the only kind of

406
01:05:18.450 --> 01:05:26.610
Daniel Gruen: Substance whose total energy is conserved total amount of matter is conserved. The total, you know, MC Squared of all the matter is conserved.

407
01:05:27.120 --> 01:05:32.220
Daniel Gruen: So that's great. You know, no matter how I distribute the matter in space. I'm still going to have the same amount of energy.

408
01:05:32.730 --> 01:05:43.770
Daniel Gruen: That's not true for any of the other components. Right. So for for radiation. The energy present in radiation is actually going to decrease over time because the wavelength of each proton get stretched

409
01:05:44.760 --> 01:05:51.120
Daniel Gruen: The reverse happens for London right so you have a certain amount of energy in the vacuum when the universe is a certain size.

410
01:05:51.540 --> 01:06:01.590

Daniel Gruen: Now you increase its size by a factor of two with a constant energy density in a vacuum. You just, you just have twice the energy in the vacuum. It's the ultimate free lunch. I think this is an Ellen Guth quote

411
01:06:02.550 --> 01:06:15.300
Daniel Gruen: To just get energy from from nothing, right, expanding space. So I think the, I think, you know, the question is, do you want to do you want to interpret these changes in energy as

412
01:06:15.810 --> 01:06:23.190
Daniel Gruen: You know energy contained in the geometry of the universe somehow energy content contained in that in that metric somehow

413
01:06:23.940 --> 01:06:33.030
Daniel Gruen: Maybe there's ways that you could do that. But really, you don't have to do that. You could also accept that conservation of energy is only given if

414
01:06:33.540 --> 01:06:43.440
Daniel Gruen: You know, time if all processes are symmetric with respect to time. If you know the physics are the same, regardless of the change to the novel point of the time corner.

415
01:06:44.010 --> 01:06:59.970
Daniel Gruen: And an expanding universe that's actually not the case. The, the geometry of the universe is changing over time. And so it does matter. At what time you start your physical experiment. And so maybe it's okay then or maybe not unexpected if energy is conserved.

416
01:07:01.800 --> 01:07:19.980
Richard Partridge: Thank you. I'm sides 3436. The question is, if the universe was dominated by cosmological constant at the beginning. Do we expect that the universe will again undergo a conversion to a radiation state as well.

417
01:07:21.390 --> 01:07:25.860
Daniel Gruen: Wonderful question. You know, if only we knew right so so it's kind of

418
01:07:26.670 --> 01:07:35.580
Daniel Gruen: It is kind of strange. I agree with you that there are two phases of exponential expansion of the universe as it looks, one at the very beginning.

419

01:07:36.180 --> 01:07:44.460
Daniel Gruen: And then one that you know has started. We're not yet exponentially expanding or there's still matter that is causing a deviation from exponential expansion, but

420
01:07:44.880 --> 01:07:52.740
Daniel Gruen: This goes on for a couple more billion years, then the matter will be diluted and will be mostly a dark energy universe that is actually exponentially expanding

421
01:07:53.940 --> 01:08:01.170
Daniel Gruen: So, you know, are those two processes similar in other ways. Is it just, you know, to

422
01:08:02.190 --> 01:08:10.140
Daniel Gruen: Enter, you know, constant energy density is to vacuum energy densities that are completely separate mechanisms and you know one of them.

423
01:08:10.860 --> 01:08:20.490
Daniel Gruen: Somehow decayed and filter universe with heat. The one is never going to do that. Or it's, you know, what is dark energy going to do in the in the distant future.

424
01:08:20.880 --> 01:08:32.640
Daniel Gruen: I think the answer is we don't know if we knew better, what dark energy was by Francisco making careful observations and comparing them to models, what it is. Maybe we could find out. But, you know,

425
01:08:33.360 --> 01:08:39.390
Daniel Gruen: As far as we can tell right now, dark energy is consistent with a causal knowledge constant without, you know, truly.

426
01:08:39.930 --> 01:08:52.710
Daniel Gruen: Constant vacuum energy density and there's no indication that that would change anytime. And so if it doesn't change any time then low reheating for you, boring cold exponentially. Your turn the expanding universe.

427
01:08:55.230 --> 01:09:03.750
Richard Partridge: Thanks moving back to slide 24 question is what mechanism has been proposed for heating

428
01:09:04.530 --> 01:09:04.920
Oh,

429
01:09:06.450 --> 01:09:18.030
Daniel Gruen: Great question. I you know I i'm really not an expert to talk about the intricate details of that. But the basic idea is that your inflation is caused by a field like

430
01:09:18.750 --> 01:09:26.880
Daniel Gruen: In flat on field or particle and that that particle just has a finite lifetime it decays and, you know,

431
01:09:27.630 --> 01:09:41.400
Daniel Gruen: I think that's that's the basic idea you would have this, you would have this component of the universe that has a constant energy density in a negative pressure you have that component just decay somehow into regular particles. But, but really, you know, we're only

432
01:09:42.810 --> 01:09:46.380
Daniel Gruen: We're only describing it currently very, very much.

433
01:09:47.550 --> 01:09:55.830
Daniel Gruen: Yeah, as a hypothetical field with certain certain properties. It's not like we had a we had a candidate that that would somehow be part of our

434
01:09:56.340 --> 01:10:05.760
Daniel Gruen: Standard Model of particle physics that we could then say, Well, these are the channels by which it decays, but that's that's the kind of. That's the kind of thinking that you need to apply there.

435
01:10:06.900 --> 01:10:07.290
Richard Partridge: Okay.

436
01:10:08.850 --> 01:10:27.330
thomas rizzo: Sorry, I think I have this to call an end of this week. It's not a lot of time available for this, but we're running out. So Daniel. Thanks a lot for for this presentation and much questions will keep coming in online and somebody will be ported to you in some way or other.

437
01:10:28.800 --> 01:10:32.850
thomas rizzo: Your answers and well see you tomorrow. Thanks again.

438
01:10:33.930 --> 01:10:34.290
Daniel Gruen: Thank you.

439
01:10:34.950 --> 01:10:37.110
thomas rizzo: Okay, I'm going to stop the recording now so

440
01:10:37.920 --> 01:10:38.850
We just do that.