WEBVTT

1
00:00:03.179 --> 00:00:16.049
mark convery: Thank you, Miss zoom and I'm very pleased to introduce Daniel and grew and from slack will be giving us the second in a series of lectures of interaction cosmology. I see sharing his slides. So please go ahead and do

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00:00:17.010 --> 00:00:22.350
Daniel Gruen: Great, thanks so much for the introduction. Mark This is the second lecture on cosmology and I'm

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00:00:22.350 --> 00:00:24.330
Daniel Gruen: Glad to see most of you back this morning.

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00:00:24.630 --> 00:00:32.520
Daniel Gruen: Or this afternoon or evening, wherever you are. To learn more about you know what our universe can tell us about

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00:00:33.000 --> 00:00:39.870
Daniel Gruen: These almost invisibles and today what we're going to talk about is the effect of all the almost invisibles of the universe.

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00:00:40.380 --> 00:00:48.810
Daniel Gruen: On structure. In fact, the universe structure like this cluster of galaxies that you see here in this finger, which, as I already told you yesterday.

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00:00:49.260 --> 00:00:53.970
Daniel Gruen: Is really mostly dark matter, you know, one of the certified almost invisible as if our universe.

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00:00:54.420 --> 00:01:06.300
Daniel Gruen: But also the formation of that cluster of galaxies in our universe is is really influenced very heavily by all the other almost invisible components that we're trying to study. So this is what

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00:01:06.690 --> 00:01:19.740
Daniel Gruen: Today's lecture is going to be very much about. Now you may say with me talking about all the structure in the universe, you know, your What, wait a second. I know my very first slide yesterday.

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00:01:20.160 --> 00:01:27.450

Daniel Gruen: I told you that one of our fundamental principles is that the universe is homogenous and as a tropic it's the same everywhere, no special place.

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00:01:27.960 --> 00:01:36.930
Daniel Gruen: And yet you know we're talking about, you know, the structures, you could take a picture of the sky and you would measure a different temperature, whichever way you look, it would look

12
00:01:37.350 --> 00:01:45.990
Daniel Gruen: Something like this. So I have to qualify my statement there I'll little bit for the purpose of today's lecture. The universe is homogeneous and as a tropic

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00:01:46.440 --> 00:02:00.090
Daniel Gruen: But only on sufficiently large scales. If I you know smoothed out that temperature field in the sky. If I smoothed out the matter density in the universe, you know, overlarge enough scales, then indeed, it would be the same everywhere.

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00:02:00.660 --> 00:02:04.200
Daniel Gruen: But today we're specifically interested in in homogenized

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00:02:04.890 --> 00:02:15.060
Daniel Gruen: And how they evolve over time and what they can teach us about the universe and how they grow into the diverse set of structures that are present in the universe today.

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00:02:15.750 --> 00:02:24.360
Daniel Gruen: So speaking of homogeneity, and in homage and it. I want to find out a little more about your background, actually. Oops, and

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00:02:24.990 --> 00:02:37.350
Daniel Gruen: Let's keep this muted for a second. You can already go now to this URL for half.com slash the guru using your phone or your browser and we're going to use that for interaction, the same way as we did yesterday.

18
00:02:37.950 --> 00:02:45.510
Daniel Gruen: I think I want to find out, you know, on a on a large smoothing scale everybody's a physicist, but the more fine grain structure of this audience.

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00:02:45.810 --> 00:02:53.040

Daniel Gruen: You know, what is your specialty, you can actually cast multiple votes. Do you see yourself more as an experimental or theoretical physicist.

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00:02:53.520 --> 00:03:01.170
Daniel Gruen: Or as a particle physicist or an astrophysicist, or maybe maybe some other speciality that I didn't even that I didn't even think off when I made this poll

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00:03:01.770 --> 00:03:08.820
Daniel Gruen: I'd like to know that I think that would be useful information for all the speakers in the serious, you just just just to see, you know,

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00:03:09.300 --> 00:03:13.530
Daniel Gruen: Who's actually interested in these lectures and what your background.

23
00:03:14.490 --> 00:03:25.200
Daniel Gruen: So I'm seeing more than 200 votes, though. That's great. You're all seem to be finding this webpage and have a look at the responses. Okay. All right. That's, that's quite interesting. So we have a

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00:03:25.710 --> 00:03:39.660
Daniel Gruen: fairly equal share of experimental theoretical physicists, there definitely is a bit of majority of particle physicists compared to astrophysicist, so I'm going to definitely keep my lecture.

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00:03:40.020 --> 00:03:47.400
Daniel Gruen: Accessible even. It's the language of astrophysics isn't what you're usually speaking and then quite a few other people as well with other

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00:03:47.820 --> 00:03:57.720
Daniel Gruen: specializations. So that is very interesting to know. Thanks. Thanks a lot for participating and keep that URL open because we're going to use it for the rest of today's lecture.

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00:03:59.220 --> 00:04:08.490
Daniel Gruen: So the goal of today's lecture is to understand structure than the universe across its whole life, both intuitively, and with a few equations.

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00:04:09.150 --> 00:04:19.710

Daniel Gruen: And we're going to try to understand, particularly the impact of these almost invisible structures how neutrinos hard dark matter or dark energy. How you know even more hypothetical fields.

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00:04:20.190 --> 00:04:29.910
Daniel Gruen: Affect how structure grows in the universe. And we're going to get a very, very light sense of how we can measure structures in the universe. And what that has told us so far.

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00:04:30.780 --> 00:04:37.890
Daniel Gruen: But I'm going to refer to some of the other lectures this week to give you give you more detail on on these measurement aspects as well.

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00:04:38.430 --> 00:04:48.420
Daniel Gruen: So if you compare this to yesterday's goals. Actually, you notice that they're quite parallel now they're basically the same goals, except that I've replaced expansion by structure.

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00:04:49.470 --> 00:04:59.550
Daniel Gruen: That's because the structures really tell the same story just in a characteristically different way that that is the story of the universe as a whole. And so that's what makes them so interesting.

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00:05:00.390 --> 00:05:07.590
Daniel Gruen: We've discussed yesterday, this complete history of the universe as told by expansion. We've looked a lot at this curve.

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00:05:08.010 --> 00:05:16.680
Daniel Gruen: The size of the universe and how it increases over time and the for a pox a rapid exponential inflationary Africa at the beginning.

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00:05:17.520 --> 00:05:30.300
Daniel Gruen: The slowdown of expansion during a radiation and a matter dominated a park, and then the re exploration of expansion at the very late at Parker dark and it starts to dominate the game.

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00:05:30.810 --> 00:05:38.580
Daniel Gruen: All described by this one equation that we derived the freedmen equation that just says what the expansion rate, the slope of that curve.

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00:05:38.850 --> 00:05:47.760

Daniel Gruen: Is going to be as a function of time. If you put all these different components radiation matter curvature and costs and optical constant inside the owners.

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00:05:48.180 --> 00:05:53.490
Daniel Gruen: And so today, we're going to have a look at those same epochs, but we're going to look at structure and we've been a

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00:05:53.790 --> 00:06:05.400
Daniel Gruen: Look at the characteristic ways in which structure is evolving in these for a box of the universe. And what then can tell us about the mostly almost invisibles that govern

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00:06:06.120 --> 00:06:16.800
Daniel Gruen: Government, the university's the box. So I'm going to cut to the chase with a question right and you haven't told me the answer. So this is really just about

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00:06:17.250 --> 00:06:28.200
Daniel Gruen: A gut feeling that you're developing for the universe and what it's doing, which is, you know, what do you think in these for a pox when a structure actually growing the most, which is the best time

42
00:06:28.590 --> 00:06:39.690
Daniel Gruen: For for for massive structure in the universe to form. And so you could take your phone, you could point it at that pole app.com slash the guru URL again.

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00:06:40.290 --> 00:06:46.260
Daniel Gruen: And answer you know just what you're what you're feeling us which arrow of the universe was best for growing

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00:06:46.620 --> 00:06:58.080
Daniel Gruen: The altitude of density fluctuations for growing the amplitude of structure. Was it this early inflation, the radiation era. The era of matter domination. The era of dark entity domination.

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00:06:58.560 --> 00:07:11.730
Daniel Gruen: Or maybe you're not sure yet you need more information to answer that question. But I just want to get your kind of your first feeling for what is happening there. Take a sip of water to give you a few more seconds to respond.

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00:07:16.080 --> 00:07:26.010

Daniel Gruen: And I'm actually really curious what you think. So let's see. Okay, so about half of you think matter dominated era is the heyday of structure formation.

47
00:07:26.640 --> 00:07:35.970
Daniel Gruen: Some of you think inflation is a is a really important era in which structure is growing radiation is a very important area and structure is going or, you know,

48
00:07:36.870 --> 00:07:45.420
Daniel Gruen: I'm a minority, if you think the dark energy dominated area is important. So I'm not going to tell you who's right and you know maybe there's ways in which you could interpret this question.

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00:07:45.810 --> 00:07:54.510
Daniel Gruen: That makes everybody everybody right in some way. So let's rather talk about these arrows, one after another and see what is actually happening.

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00:07:56.040 --> 00:08:08.520
Daniel Gruen: But first, before we do that, we need to find a way of quantifying how much structure there is in the universe. Right, so we can discuss how that how that quantified metric of structure is changing over time.

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00:08:09.180 --> 00:08:19.290
Daniel Gruen: And so what I'm showing you here is a density field. This is the field of dark matter density in a simulation at, you know, at the present time of the universe.

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00:08:20.460 --> 00:08:27.330
Daniel Gruen: But it could be any other density field. And the question is, how do we quantify how much fluctuation, there isn't that

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00:08:28.530 --> 00:08:36.960
Daniel Gruen: So one thing we could write down. It's just the density as a function of position, perhaps as a function of time. What is the density of this field everywhere in space.

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00:08:37.920 --> 00:08:46.230
Daniel Gruen: And a useful way of expressing that is actually this density contrast. So instead of, you know, grams per cubic meter or whatever.

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00:08:46.920 --> 00:08:59.310

Daniel Gruen: We're going to divide out the mean density and subtract one, and this way we're going to get a field that has a mean value of zero. I mean, density contrast zero and that fluctuates

56
00:09:00.030 --> 00:09:07.860
Daniel Gruen: High when there's an over density and low when there's an under density. And in fact, you know, we can express this as a

57
00:09:08.280 --> 00:09:15.600
Daniel Gruen: As a spatial field in three dimensions. We could also express it as the Fourier transform of that spatial field. So instead of

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00:09:16.020 --> 00:09:35.610
Daniel Gruen: The of this delta I could write a little delta k and I could just express all the density fluctuations as a sums of four modes of density fluctuations of a certain wavelength that's determined by this wave vector came here. Okay, so just different ways of expressing this image and

59
00:09:36.630 --> 00:09:37.530
Daniel Gruen: Scale our field.

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00:09:38.940 --> 00:09:46.590
Daniel Gruen: Now there's different ways that we could then see you know how much structure is there one thing we could do with we could count peaks. Right. I could draw

61
00:09:46.920 --> 00:09:56.010
Daniel Gruen: circles around these regions of very high density and I could set some threshold of, you know, how much density, there has to be inside a circle.

62
00:09:56.220 --> 00:10:04.710
Daniel Gruen: And then I could count how many such peaks. I'm finding. So that's one way that people are in fact using to quantify how much structure there is in the universe.

63
00:10:05.790 --> 00:10:15.960
Daniel Gruen: I could look at the full probability distribution function of density or of delta right I could just measure delta in different places in the universe that could make a histogram.

64
00:10:16.530 --> 00:10:29.730
Daniel Gruen: And you know that histogram would describe what structure is I could I could measure say its moments as well. I could measure its

variants and it's Kunis and all that. That would be one way of quantifying how much structure.

65
00:10:31.830 --> 00:10:40.200
Daniel Gruen: And then one other way of quantifying how I structure is is the power spectrum. I could look at the two point correlation of

66
00:10:41.280 --> 00:10:46.530
Daniel Gruen: galaxies are the two point correlation of matter particles in my universe. I could count pairs.

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00:10:46.950 --> 00:10:58.710
Daniel Gruen: For certain separation and I could see whether I find more pairs of that separation than I would expect if all the particles were just randomly distributed. So that's what a two point correlation function is

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00:10:59.220 --> 00:11:10.620
Daniel Gruen: It's for a transform is the power spectrum. And that's what we call P FK here. It's actually equivalent to just taking the the expectation value of delta k squared, you know, if the squared.

69
00:11:10.980 --> 00:11:21.510
Daniel Gruen: Deviation from mean density with a certain scale described by this wave vector k for all way directors that have the same length. Okay, so

70
00:11:21.840 --> 00:11:36.840
Daniel Gruen: That's just another way that I could do it, it's actually, it's equivalent in a way to the variance of matter density so that the width of that PDF when I measure it as a function of scale. The scale being set by k

71
00:11:38.100 --> 00:11:44.550
Daniel Gruen: So this is the this is the most simple quantification of structure. It tells you everything you need to know.

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00:11:44.880 --> 00:11:52.920
Daniel Gruen: If structure is fully defined by a variance of meta density, then this two point correlation is all the information that you need to describe it.

73
00:11:53.310 --> 00:12:00.630

Daniel Gruen: And so that's what we're going to use when we're looking at how structure is evolving in the universe today because it's it's really that simple metric

74
00:12:02.790 --> 00:12:13.980
Daniel Gruen: So let's start out with the seeds of structure in the very early universe, the early universe hosted quantum fluctuations, like any Vacuum. Vacuum was full of little

75
00:12:14.970 --> 00:12:24.750
Daniel Gruen: Virtual particles coming out of nothing but what was different about the earlier this is that these quantum fluctuations were expanded by inflation.

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00:12:25.170 --> 00:12:39.930
Daniel Gruen: Within you know 10 to the minus 30 something seconds to cosmological scales. And so what that did is it it expanded these quantum fluctuations to matter density flux to density fluctuations in the universe.

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00:12:40.440 --> 00:12:51.480
Daniel Gruen: That we see today. Now, what actually happened to these fluctuations depended a little bit on how large they were relative to the size of the horizon. So the size of

78
00:12:51.900 --> 00:13:00.630
Daniel Gruen: Causal contact within that early inflationary universe. While these fluctuations were within the horizon, smaller than the horizon.

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00:13:01.290 --> 00:13:10.110
Daniel Gruen: They would be stretched out by that exponential expansion, so they would decay, whatever their amplitude, was it would decrease over time.

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00:13:11.070 --> 00:13:20.520
Daniel Gruen: But at one point when they passed the size of the horizon after inflation had, you know, stretch them and move things apart with

81
00:13:21.000 --> 00:13:30.690
Daniel Gruen: Velocity exceeding the speed of light. They were preserved from decay and they were they were just frozen in to the fabric of that exponentially expanding space time

82
00:13:31.620 --> 00:13:39.000

Daniel Gruen: So that's a generic thing to happen. And if you continue this process continue making

83
00:13:39.390 --> 00:13:49.920
Daniel Gruen: Little self similar quantum fluctuations you continue to expand and like that and you do this very rapidly, such that they're within the horizon for a very short time.

84
00:13:50.340 --> 00:14:00.720
Daniel Gruen: And there you know outside the horizon for the rest of the history of the universe than what you would produce is a so called scale and variant power spectrum. So that's a power spectrum.

85
00:14:01.200 --> 00:14:13.950
Daniel Gruen: Where this variance as a density fluctuations as a function of scale is proportional to k to the end, the size of a vector to the end with n equals one. Okay, so that's this is what we call

86
00:14:14.460 --> 00:14:19.800
Daniel Gruen: A scale invariant power spectrum. I can plot it like this. You know what you would see is that

87
00:14:20.310 --> 00:14:36.630
Daniel Gruen: There's small fluctuations small p of k's on on on large scales. And then if you go to smaller scale fluctuations. We get larger P of case. So this is the generic prediction of inflation to just keeps on going forever.

88
00:14:38.070 --> 00:14:49.800
Daniel Gruen: Now inflation has to end somehow right we're in. We're currently not in an infinitely exponentially expanding universe just yet. Maybe we will be once dark energy fully takes over.

89
00:14:50.430 --> 00:14:54.060
Daniel Gruen: But there was definitely a time between when inflation wasn't happening.

90
00:14:54.690 --> 00:15:03.750
Daniel Gruen: So this process of stretching out space has to end somehow. And so my question for you. And this is I think one of the most difficult questions for you is

91
00:15:04.110 --> 00:15:13.770

Daniel Gruen: What does that mean for NS right if if you consider the fact that fluctuations decay whether inside the horizon, and then they're frozen in

92
00:15:14.280 --> 00:15:27.210
Daniel Gruen: And now inflation is ending. What does that mean for this scale factor. And again, I'm going to ask you to go to Paul f.de grew Paul f.com slash the crew.

93
00:15:27.780 --> 00:15:40.020
Daniel Gruen: And cast a vote. What you think is happening is this ad is going to be smaller than one. Is it going to be larger than one, is it equal one, or did I not tell you enough yet to to give an answer.

94
00:15:41.550 --> 00:15:51.420
Daniel Gruen: So looking better. The equation, right, if an S is larger than one, then there's going to be larger fluctuations on the smallest scales, which have largest K

95
00:15:51.960 --> 00:16:06.450
Daniel Gruen: Large large and means large fluctuations on small scale and SS smaller than one, then we're going to find slightly smaller fluctuations on the smallest scales than you would expect for an infinite inflation.

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00:16:07.170 --> 00:16:24.150
Daniel Gruen: And effect, you can already tell that if we could measure NS, we would find out something very fundamental about how exactly inflation is ending what that almost invisible field is doing just before it decays and reheat. The universe.

97
00:16:25.080 --> 00:16:32.250
Daniel Gruen: Okay, so let's see what you're thinking. We still have responses coming in. It's great. So let's look at them.

98
00:16:33.000 --> 00:16:40.080
Daniel Gruen: And so about two thirds of you think that NS is one of them. One, and you're exactly right. So what happens here.

99
00:16:40.410 --> 00:16:49.560
Daniel Gruen: Is that these smallest scale fluctuations because inflation was slowing down the spent more time within the horizon. So they had more time.

100
00:16:49.920 --> 00:16:58.920

Daniel Gruen: In which they were decaying. And then, which they were washed out by the by the expansion of that exponentially expanding universe.

101
00:16:59.610 --> 00:17:11.220
Daniel Gruen: And so this is the reason that you would generically always expect NS to be close to one bottle but always a little smaller than one in these theories of inflation that you know come to an end. Some

102
00:17:12.330 --> 00:17:22.290
Daniel Gruen: Great. So this is one way that we could learn it's actually another type of structure. Another type of fluctuations that should be present in the universe, and that's

103
00:17:22.620 --> 00:17:31.470
Daniel Gruen: fluctuations of the gravity field. And so what they do is they introduce so called tensor perturbations to the metric. So you get this

104
00:17:31.890 --> 00:17:40.620
Daniel Gruen: In kosky metric you know really boring space time flat everything as you would draw it on a sheet of paper.

105
00:17:41.070 --> 00:17:48.270
Daniel Gruen: And then you get a perturbation to that metric, H, I, J, okay. Just a little, just a little fluctuation on top of that magic.

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00:17:48.630 --> 00:17:55.920
Daniel Gruen: And so this perturbation here can be interpreted as gravitational waves existing in this early inflationary universe.

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00:17:56.610 --> 00:18:03.540
Daniel Gruen: Now, it's very difficult to observe gravitational waves. It's even more difficult to observe quantum fluctuations.

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00:18:03.900 --> 00:18:10.110
Daniel Gruen: Of the gravity field process completely impossible at the current time but these fluctuations of the gravity field.

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00:18:11.010 --> 00:18:23.010
Daniel Gruen: They could in fact be detectable. We could hope to see them as these polarization patterns in the cosmic microwave background that have a Wiimote so that you know that look like this.

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00:18:23.430 --> 00:18:34.140
Daniel Gruen: This weird spiral like structure. So this is something that current experiments are still looking for and trying to find a top of many other signals that could look like be modes.

111
00:18:34.650 --> 00:18:40.830
Daniel Gruen: But this would be another way that we could find out more about this almost invisible field.

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00:18:41.460 --> 00:18:51.570
Daniel Gruen: inflating the early universe by how much of these be mode polarization patterns. How much of these gravitational wave perturbations. It is producing. Okay.

113
00:18:52.380 --> 00:19:08.850
Daniel Gruen: So we've kind of made our segue here into the second apocryphal universe. The EpiPen which the universe was dominated by radiation. And that's, that's where those remote patterns of photons in the sky would be coming from but there's actually something

114
00:19:09.870 --> 00:19:18.450
Daniel Gruen: Even much simpler to measure and even more fundamentally insightful for Christology over the last couple of decades.

115
00:19:19.170 --> 00:19:24.660
Daniel Gruen: When you emerge. These seas of structure these fluctuations and a hot universe.

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00:19:25.620 --> 00:19:32.280
Daniel Gruen: So there's two things that really happen when you put these fluctuations of density in a hot universe. One thing is

117
00:19:32.700 --> 00:19:40.920
Daniel Gruen: Particles are moving relativistic Lee and so that washes out any density fluctuations on scales that are smaller than the horizon.

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00:19:41.250 --> 00:19:47.820
Daniel Gruen: That's just because particles are moving at the speed of light, so they can travel, you know, any distance within the horizon.

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00:19:48.330 --> 00:19:56.970
Daniel Gruen: And and as long as they're doing that they're going to remove any fluctuations on those skills, but there's a particular scale where

120
00:19:57.720 --> 00:20:10.590
Daniel Gruen: The matter over densities in there to gravitational effect and the pressure of baryons conspire, and I like this sketch here from an article by Wayne who might

121
00:20:11.700 --> 00:20:16.800
Daniel Gruen: Have how how that can create strong peaks in the density of baryons

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00:20:17.610 --> 00:20:27.570
Daniel Gruen: So imagine you start out with some fluctuation of dark matter density cedar by inflation. Okay, you have a slightly higher dark matter concentration here.

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00:20:27.990 --> 00:20:33.270
Daniel Gruen: And you've got your bearing on, you know, doing pressure and speeding around all over the place.

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00:20:34.200 --> 00:20:43.410
Daniel Gruen: This dark matter of concentration is going to attract your baryons through gravity. So they're going to start preferentially, you know, moving towards it and falling into it.

125
00:20:44.100 --> 00:20:54.030
Daniel Gruen: And at some point, they will be maximally concentrated inside these gravitational potential wells seated by fluctuations of the dark matter density

126
00:20:54.510 --> 00:21:01.440
Daniel Gruen: And at that point, actually, what's going to happen is they're going to feel a lot of pressure you know their density is very high. They're going to collide with other barriers, all the time.

127
00:21:01.830 --> 00:21:17.640
Daniel Gruen: And so at that point they're going to start to want to move out again because the pressure is putting them out. So what do you see here is the kind of dynamics that you need for oscillations between the gravitational potential energy and the energy stored in the pressure of those barriers.

128
00:21:18.750 --> 00:21:33.840
Daniel Gruen: But if we're looking at density fluctuations of just the right scale, then by the time the baryons have made it and have fallen into that potential for the first time the universe is going to suddenly become

129
00:21:35.550 --> 00:21:48.540
Daniel Gruen: Empty enough cold enough that those barriers are never going to interact with another Barry on again. Well not maybe not never but they're not going to feel the pressure of all the baritones in their neighborhood quite as much

130
00:21:49.110 --> 00:22:00.090
Daniel Gruen: So that particular scale is going to be a scale in which these fluctuations of baryons are accumulating. And you can even see it in these maps of the cross with markers background.

131
00:22:00.840 --> 00:22:16.590
Daniel Gruen: There's kind of a characteristic anger to scale to these patches of blue and red fluctuations. And it's not because it's a blurry image. It's because that's the scale on which ones are accumulating until they just, you know, freeze out and no longer feel pressure

132
00:22:17.880 --> 00:22:21.510
Daniel Gruen: Now there's actually higher orders to that effect.

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00:22:21.990 --> 00:22:32.310
Daniel Gruen: At half the scale, you're going to go through a full cycle, you're going to go through first or contraction or baryons and then the pressure of those baryons pushing them back out.

134
00:22:32.730 --> 00:22:43.440
Daniel Gruen: And so depending on what order of these fluctuations, you're looking at. So depending on what fraction of the physical size of those fluctuations. You're looking at

135
00:22:44.010 --> 00:22:52.920
Daniel Gruen: Gravity and pressure are going to either interact in a in a constructive way to concentrate the bearing arms like for the first week.

136
00:22:53.310 --> 00:23:03.480
Daniel Gruen: Or they're going to counteract each other as part of that process and gravity is going to pulling them going to be pulling them back while pressure is going to push them out of these gravitational potential

137
00:23:04.560 --> 00:23:21.870
Daniel Gruen: And so the combination of these effects of pressure and gravity is going to act differently on all these overtone modes and what

you're going to see is a characteristic pattern of the temperature fluctuation or bearing on density fluctuation power spectrum.

138
00:23:23.220 --> 00:23:36.780
Daniel Gruen: Call baryonic acoustic oscillation peak. The first peak of this scale and then many additional peaks that we could hope to measure at these smaller scales that are, you know, smaller by a factor of into turnovers.

139
00:23:37.830 --> 00:23:48.600
Daniel Gruen: Now, again, to read this diagram correctly. Remember that this is a large physical scale fluctuations on that scale are tiny. To begin with, from the times of inflation.

140
00:23:49.680 --> 00:23:58.620
Daniel Gruen: There's this first peak scale that corresponds to just the size of patches in this map by one degree in the sky. You see fairly strong fluctuations.

141
00:23:58.950 --> 00:24:04.890
Daniel Gruen: And still just have 10 to the minus five of the main temperature, but you can measure these really well these days.

142
00:24:05.370 --> 00:24:16.020
Daniel Gruen: And then as you go to smaller and smaller scales, while you do see these overtones. They're going to be heavily damned by just the free streaming or relativistic particles washing out these fluctuations.

143
00:24:17.400 --> 00:24:22.950
Daniel Gruen: So with that in mind, you can imagine what has happened to the power spectrum as a fairly complicated

144
00:24:23.610 --> 00:24:30.510
Daniel Gruen: K dependent process, depending on whether you're fluctuation matches those peaks scales of baryons

145
00:24:30.810 --> 00:24:39.840
Daniel Gruen: And depending on how your, your fluctuation clk compares to the scale of the horizon at different times during this hot the universe phase.

146
00:24:40.290 --> 00:24:49.560
Daniel Gruen: You're going to get this function t squared of k, the so called transfer function modulating this initial k to the end power spectrum that comes from inflation.

147
00:24:50.580 --> 00:24:58.020
Daniel Gruen: But overall, one good thing to say about that phase of the universe is that, you know, while that's it's complicated enough to to account for all these things.

148
00:24:58.380 --> 00:25:15.210
Daniel Gruen: It's actually they're totally visible they they're all based on simple physics of gravity and plasma basically that we can calculate extremely accurately and therefore we can make predictions and compare them to measurements of the customer for background, really, really well.

149
00:25:16.680 --> 00:25:29.730
Daniel Gruen: Now, one cool thing, actually, that you can do with this peak scale is it. It's not just present in the crossing my background, but that scale of density fluctuations will remain imprinted

150
00:25:30.150 --> 00:25:39.330
Daniel Gruen: On the density field for the rest of the universe on the scale average galaxies are clustering. The scale of which gases clustering any of that.

151
00:25:39.810 --> 00:25:51.510
Daniel Gruen: Throughout the age of the universe. And so it really gives you this sort of standard ruler, you know its physical size from simple totally visible physics. And you can measure it across time.

152
00:25:52.080 --> 00:26:02.610
Daniel Gruen: And so this is just one way of illustrating I think we looked at yesterday right if we could measure a standard ruler at different redshift. We could measure the distance two different ratchets that way.

153
00:26:03.060 --> 00:26:13.020
Daniel Gruen: Then we could reconstruct the expansion history of the universe, and we could tell what its contents must be to give us that expansion history with the freedmen equation.

154
00:26:13.710 --> 00:26:22.560
Daniel Gruen: And so you can do exactly that. With these Byronic acoustic constellations, you can measure them as the characteristic scale flux resisting the cosmic microwave background.

155
00:26:23.130 --> 00:26:31.800

Daniel Gruen: And then this is a plot from the E boss survey which was released results just two weeks ago where they measure that scale of baryonic acoustical solutions.

156
00:26:32.250 --> 00:26:38.610
Daniel Gruen: With different galaxy samples and they're clustering across you know 12 billion years of cosmic history.

157
00:26:39.150 --> 00:26:49.320
Daniel Gruen: So it is really fantastic because this way you can you can put now six plus one, seven standard rules on this curve and really check you know is you know what that curve.

158
00:26:49.650 --> 00:27:03.000
Daniel Gruen: Is doing, whether it's curving up or down as a function of time. And, and, indeed, a boss the bosses measurements of that standard rule or beautifully match this picture of a universe with a matter of just a 30%

159
00:27:03.720 --> 00:27:08.580
Daniel Gruen: Critical density and dark energy of 70% of critical density at the present time.

160
00:27:10.800 --> 00:27:22.710
Daniel Gruen: Good, so much for the hot universe. Let's move on into the matter dominated regime and we've got to do a little bit of algebra here. But I want to do it with you again.

161
00:27:23.760 --> 00:27:32.580
Daniel Gruen: So the one equation that you still know is this one. That's, again, the only equation that will need a tells us how the expansion rate of a universe.

162
00:27:33.090 --> 00:27:39.360
Daniel Gruen: Will evolve over time as its components thing out. And, you know, for the purpose of this exercise.

163
00:27:39.870 --> 00:27:46.710
Daniel Gruen: Radiation doesn't matter. The universe is old enough that radiation has thinned out, you know, by a to the fourth.

164
00:27:47.640 --> 00:27:54.990
Daniel Gruen: Dark energy doesn't matter that the cosmological concert is small enough that if we go to Russia of, you know, 1234 or five

165
00:27:55.440 --> 00:28:07.710
Daniel Gruen: That this I'll make a lambda is really just a tiny number. So the only thing we have to account for is matter density and perhaps curvature. If our universe wasn't flat. So if the matter density wasn't equal to the critical metrics density

166
00:28:08.640 --> 00:28:21.330
Daniel Gruen: So in this manner dominated universe then consider consider that the universe as a whole has just that critical density, you know, it's just homogeneous and as a topic, and it has the same matter density everywhere.

167
00:28:21.960 --> 00:28:28.470
Daniel Gruen: And then inside that universe. Imagine that there's a little circle patch that's over dense.

168
00:28:29.070 --> 00:28:41.340
Daniel Gruen: You know, the only thing that's different about it is that its density. The little larger than the mean density of the Universe. Other than that, it has the same current expansion rate and it has nothing else going on with it.

169
00:28:42.240 --> 00:28:54.600
Daniel Gruen: And so, again, a question to your gut feeling for this equation for cosmology is what is going to happen to that patch. If we, you know, observe this universe over time.

170
00:28:55.740 --> 00:29:14.460
Daniel Gruen: What will happen to the over dense patch in a matter only universe will it expand more rapidly until it reaches the mean density, the critical density of the Universe will expand more slowly than the rest of the universe, which would increase its density contrast further

171
00:29:16.020 --> 00:29:24.060
Daniel Gruen: Or will it you know it's expanding currently at the same rate as the overall universe will it keep expanding at that same rate as the overall universe.

172
00:29:24.420 --> 00:29:33.780
Daniel Gruen: Or did I did I not give you enough information yet to answer that question. I'll give you a few more seconds to think about it, because this is really this is for the

173
00:29:34.920 --> 00:29:40.350

Daniel Gruen: Or a shortcut way of getting at some really funny equations about the growth of structure.

174
00:29:48.060 --> 00:29:48.480
And

175
00:29:49.530 --> 00:29:51.030
Daniel Gruen: It's great to see that you're all

176
00:29:52.050 --> 00:29:55.350
Daniel Gruen: Still with me and thinking about this and answering this question.

177
00:29:58.350 --> 00:30:00.810
Daniel Gruen: Let's see what most of you.

178
00:30:01.830 --> 00:30:11.070
Daniel Gruen: Thought okay so 70% of you think that that little pocket universe that's over again slowly expand more slowly.

179
00:30:11.460 --> 00:30:18.360
Daniel Gruen: And that will increase its density contrast and that is exactly right. That is exactly what's going to happen. This is how

180
00:30:18.900 --> 00:30:29.790
Daniel Gruen: You know structure in the universe is going to form. Now let's look at just a little bit of algebra, right, I can write the expansion rate of the overall universe like this.

181
00:30:30.300 --> 00:30:39.240
Daniel Gruen: Just, just expressing you know that one equation that you know plugging in the actual matter density here. Okay, so the expansion rate.

182
00:30:39.930 --> 00:30:47.100
Daniel Gruen: Squared will be proportional to the matter density and that will just go down as our universe expands, but that that equation is always going to hold

183
00:30:48.060 --> 00:30:57.600
Daniel Gruen: For the over dense patch. I need to account for a second term and that second term is because the over dense patch actually has a curvature for its density

184
00:30:57.900 --> 00:31:09.900
Daniel Gruen: Is not equal to the critical density. It's all make a matter is not one but maybe 1.1 and so I need an omega curvature to compensate for that going to find that that

185
00:31:10.560 --> 00:31:18.930
Daniel Gruen: The coordinate system of that the lower dense patches in fact curved and what that goes through this equation is just, you know, it's subtract something

186
00:31:19.620 --> 00:31:28.200
Daniel Gruen: H squared, we're going to subtract something that's actually, you know, going to change as a to the minus two.

187
00:31:28.920 --> 00:31:41.550
Daniel Gruen: So my equation for the expansion rate of that little over dense patch. It's going to look the same as for the overall universe except I'm going to have to subtract some constant divided by A squared.

188
00:31:42.450 --> 00:31:48.480
Daniel Gruen: And so now I can put these together, I can just to track these two equations to get an expression for

189
00:31:48.810 --> 00:31:56.850
Daniel Gruen: That difference. The difference of densities between that little patch on the overall universe. It's going to be equal to, it's going to be equal to that.

190
00:31:57.330 --> 00:32:09.450
Daniel Gruen: That key over a squared term here, and then I can use this expression for the difference to write with delta delta. The difference of density is divided by the mean density of the Universe.

191
00:32:09.960 --> 00:32:21.450
Daniel Gruen: The mean density of the Universe is going to go down as you know, one over eight to the third power, the NEO that difference we have derived is going to be proportional to one or a square

192
00:32:21.900 --> 00:32:29.340
Daniel Gruen: So if we put that together we find that delta is over density of the little patch inside our universe.

193
00:32:29.820 --> 00:32:37.410

Daniel Gruen: Is going to be proportional to a the scale of the universe that's expanding over time. Okay, so this is the really cool result.

194
00:32:38.160 --> 00:32:43.140
Daniel Gruen: That we just derive together, the amplitude of small density fluctuations grows

195
00:32:43.620 --> 00:32:51.690
Daniel Gruen: As fast as the scale of the universe. When we're matter dominated. And so this is one example of how you can see whether we look at the universe as a whole.

196
00:32:52.050 --> 00:32:56.760
Daniel Gruen: Or whether we look at a single density fluctuation, the actually tell us the same thing.

197
00:32:57.660 --> 00:33:06.780
Daniel Gruen: Now the attitude or small density fluctuations. We also found here actually grows independently of their scale. It didn't matter at all for our derivation

198
00:33:07.110 --> 00:33:17.430
Daniel Gruen: Whether that was a you know a tiny over dense patch or a huge over dense patch. It's just the same thing is going to happen everywhere all the density fluctuations are going to increase by some factor.

199
00:33:18.840 --> 00:33:30.270
Daniel Gruen: And you know that could lead us to to the following question which which again, I'm going to ask you. So we're so happy without a leg of rock result now. But do these things do these things match up.

200
00:33:30.930 --> 00:33:44.430
Daniel Gruen: Right, so I told you that temperature fluctuations and the cost of marketing background are 10 to the minus five. Okay, that's, that's their delta. And we see them at a record of 1000 so at an A of coin oh one.

201
00:33:46.350 --> 00:33:58.710
Daniel Gruen: By a record of 10 so by a of point one. There are galaxies in the universe. And in order to form a galaxy, you need a delta that's you know that's an order 100 or even even larger.

202
00:33:59.310 --> 00:34:04.230

Daniel Gruen: So, you know, how do you get from 10 to the minus five to 100 that seven orders of magnitude.

203
00:34:04.650 --> 00:34:17.430
Daniel Gruen: When A is just increasing by two orders of magnitude and you know just arrived that delta should be proportional to a like, you know, what did I, what did I miss. And so we're going to, we're going to

204
00:34:18.720 --> 00:34:25.500
Daniel Gruen: Look at that together at the CB had this temperature of just 10 to the minus five. These temperature fluctuations of just tend to the minus five.

205
00:34:26.130 --> 00:34:35.580
Daniel Gruen: We derive the gross during matter domination to be by a factor of 100 right from CNBC to this point where we have galaxies.

206
00:34:35.910 --> 00:34:44.640
Daniel Gruen: But how did we get to mattered entities that are that are of order of 100 that are you know actually missing any orders of magnitude is that five

207
00:34:45.210 --> 00:34:52.860
Daniel Gruen: Or so orders of magnitude and density fluctuations compared to my approximation here so you can actually give multiple answers in this as well.

208
00:34:53.340 --> 00:35:03.750
Daniel Gruen: Was it that we didn't account for a radiation which enhances the growth of density fluctuations. Was it that we did not account for non linear growth of structure, which also enhances growth.

209
00:35:04.680 --> 00:35:09.300
Daniel Gruen: Was it that we did not account for dark energy, which also exonerates growth.

210
00:35:10.110 --> 00:35:21.330
Daniel Gruen: Or was it that we did not account for the fact that dark matter already had larger fluctuations than those baryons know whose temperature we see at the time of the cosmic microwave background.

211
00:35:21.900 --> 00:35:31.380
Daniel Gruen: Or is it may be there may be something else that I invest in that derivation. So really key question kind of probes deeply into your understanding of

212
00:35:32.430 --> 00:35:51.660
Daniel Gruen: What is happening in the almost invisible universe that see what your responses are ok so the top two are actually correct. So the two things we didn't account for was the non linear growth and the second you know most important thing, actually, we didn't account for was that

213
00:35:52.920 --> 00:36:02.100
Daniel Gruen: It wasn't a 10 to the minus five fluctuation of dark matter density dark matter had actually already had time to cluster, while the universe was stolen this radiation dominated face.

214
00:36:02.790 --> 00:36:13.110
Daniel Gruen: And then radiation and dark energy, which some of you thought were important, we can really ignore them here and if anything. What they would do is reduce the growth of structure. So that's

215
00:36:13.710 --> 00:36:23.070
Daniel Gruen: That's what, that's what that story is. Okay, so let's revisit that picture this linear growth of structure here.

216
00:36:23.550 --> 00:36:32.520
Daniel Gruen: It only adds up to producing realized structures like you know any structure that all in the universe. When you account for two things. One,

217
00:36:33.030 --> 00:36:40.290
Daniel Gruen: The fact that there is a lot of pressure loose dark matter that you know doesn't isn't affected nearly as much by these

218
00:36:40.680 --> 00:36:52.140
Daniel Gruen: Pressure forces that drive things Dr. Barry on fluctuations apart and that already gets Coster during the radiation dominated era. So this is one of the key pieces of evidence for dark matter. In fact,

219
00:36:52.710 --> 00:37:03.780
Daniel Gruen: And the second is, once that delta approaches unity. This is actually a runaway process and my little approximation doesn't work anymore. And the simplest way to see that may be that

220
00:37:04.290 --> 00:37:09.930
Daniel Gruen: Delta can never be smaller than minus one, you know all of what I've shown you in that duration of the

221

00:37:10.260 --> 00:37:18.780
Daniel Gruen: Evolution of delta would work for an under dense patch as well. We just have curvature of the opposite sign and it would expand more rapidly and it would get

222
00:37:19.320 --> 00:37:28.740
Daniel Gruen: Empty or empty over time, but you can never be emptier than empty delta can never be smaller than minus one because row can never be smaller than zero.

223
00:37:29.040 --> 00:37:35.520
Daniel Gruen: So obviously the the approximation that are making here is only valid as long as there's a small deviation

224
00:37:36.090 --> 00:37:43.530
Daniel Gruen: Once you get to the regime of order unity deviations from density. This is a runaway process and our universe collapses.

225
00:37:44.220 --> 00:38:03.060
Daniel Gruen: So our final expression then for the power spectrum of meta density fluctuations is these three terms would start off with a primordial power spectrum k to the Ns we modulate that in a scale dependent way during the era of radiation donation with this transfer function.

226
00:38:04.080 --> 00:38:15.030
Daniel Gruen: And then we grow it proportional to a at least while matters dominating. Let's see what happens when matter gives over control to dark energy.

227
00:38:15.630 --> 00:38:21.180
Daniel Gruen: With its growth factor here which we need square because we're looking at the squared density fluctuations.

228
00:38:21.780 --> 00:38:34.110
Daniel Gruen: Plus there's going to be non linear terms important on small scale. So this is going to work on the very large scales, where a density fluctuations remain below order unity throughout the history of the universe.

229
00:38:34.410 --> 00:38:43.320
Daniel Gruen: It's not going to work on the smaller scale for your actually forming individual galaxies or clusters of galaxies here you need you need corrections to that that are quite sizable

230

00:38:45.180 --> 00:38:52.500
Daniel Gruen: Now this is just one more way of illustrating the nonlinear effect what happens here, you know,

231
00:38:53.010 --> 00:39:00.450
Daniel Gruen: An over density acts like a little universe of its own. You could think, and if that over density has a high enough matter density

232
00:39:00.990 --> 00:39:09.690
Daniel Gruen: It can actually collapse upon itself. So if you're starting out here with different you know different first derivative of the expansion rate. That's fine.

233
00:39:09.960 --> 00:39:18.870
Daniel Gruen: But that first derivative is won't, won't describe this yellow curve of the universe that's collapsing upon itself. And this is in fact what is happening all the time. This is what has happened.

234
00:39:19.350 --> 00:39:24.810
Daniel Gruen: To the matter density that eventually form this cluster of galaxies that we're seeing in this picture.

235
00:39:25.740 --> 00:39:33.600
Daniel Gruen: Now this is a couple other things about structure growth that are really, really pointing us to properties of the almost invisible in the universe.

236
00:39:34.320 --> 00:39:40.590
Daniel Gruen: One is they can tell us about dark matter now are now hypothesis and perhaps that's, you know,

237
00:39:40.920 --> 00:39:49.650
Daniel Gruen: That's, that's a good hypothesis, also because it's easy to calculate. Is that dark matter is perfectly cold, so those particles are moving very slowly.

238
00:39:50.220 --> 00:39:59.760
Daniel Gruen: They don't have a lot of thermal motion left from the early universe face and that is perfectly collision less to dark metal particles. They just go through one another.

239
00:40:00.360 --> 00:40:05.310
Daniel Gruen: Without without any interactions and same for matter or other particles.

240
00:40:05.910 --> 00:40:18.870
Daniel Gruen: Now, what if dark matter was worn, what would that change about what structure looks like and one key example is is a neutrino neutrino is a is a hot kind of dark matter right it's weekly interacting

241
00:40:19.290 --> 00:40:30.600
Daniel Gruen: It has a math, but actually it's math is so small that it's you know it's left over energy from the early phase of the universe is still still such that it's moving, you're almost at the speed of light.

242
00:40:31.380 --> 00:40:37.500
Daniel Gruen: So this is just a simulation here that I'm showing you have the same initial conditions, you know, same

243
00:40:38.460 --> 00:40:50.040
Daniel Gruen: Initial density fluctuations one with cold dark matter, forming a galaxy, sort of like our galaxy. This is dark matter Halo have a galaxy. That's sort of like our Milky Way galaxy.

244
00:40:50.490 --> 00:41:00.270
Daniel Gruen: And one with a dark matter that has a temperature that is zipping around according to a finite mass moving with a thermal energy

245
00:41:00.780 --> 00:41:05.640
Daniel Gruen: And what you can see here is that all these very small structures, all these very small

246
00:41:06.000 --> 00:41:13.740
Daniel Gruen: peaks of dark matter are completely washed out in the morning back matter case. And that's evident. They just because document or move out of those density fluctuations.

247
00:41:14.460 --> 00:41:21.480
Daniel Gruen: So if we could observe these small scale fluctuations. The nonlinear very highly nonlinear part certainly

248
00:41:21.870 --> 00:41:35.400
Daniel Gruen: Have the power spectrum, then that would tell us something about you know neutrinos and their mass, which sets at what scale the growth of density fluctuations is suppressed by their free streaming

249
00:41:36.630 --> 00:41:47.490
Daniel Gruen: What if dark matter was self interacting. What if it had some sort of a charge and when one dark matter particle hit another dark

matter particle, you know, they would, they would actually collide in some way.

250
00:41:47.970 --> 00:41:58.020
Daniel Gruen: Well, you know, one way you could look at that is to look whether the dynamics of these structures that are forming shows any signs of self interaction. And this is a picture of a

251
00:41:58.440 --> 00:42:11.010
Daniel Gruen: Famous galaxy cluster. The Bullet Cluster were two clusters of dark matter hit each other and you can see the density of hot gas that was contained in these clusters being

252
00:42:11.460 --> 00:42:24.780
Daniel Gruen: dragged behind because those particles are actually charged particles and they are actually self interacting. You can see that the dark matter concentrations of those clusters. The basic you just pass through one another and so dark matter.

253
00:42:26.130 --> 00:42:43.710
Daniel Gruen: There's a limit to how much self interaction can have from observations like this that shows the, the rate of basically show the cross section of dark matter can be very large, or otherwise it wouldn't be it wouldn't be moving through one another as easily. Okay.

254
00:42:45.000 --> 00:42:48.360
Daniel Gruen: So switching a box for a last time.

255
00:42:49.440 --> 00:42:59.670
Daniel Gruen: Question for you. How does dark energy, which will take over the overall expansion of the universe. Now how does that affect the growth of structure.

256
00:43:00.150 --> 00:43:15.090
Daniel Gruen: Overall, does it speed up the growth early times that it's slow down the growth at early times does it speed up the growth at late times of the universe, or does it slow down the growth of the times of the universe, or does it not affect the cause of structure at all.

257
00:43:16.830 --> 00:43:32.580
Daniel Gruen: In fact structure. I'm going to break the news here is is is going to be a really sensitive pro of when dark energy takes over, because you know I've put in this, this time qualifier into my question because it's really a matter of

258

00:43:33.330 --> 00:43:39.780
Daniel Gruen: Is that a dark matter dominated or a dark energy dominated universe that's going to affect heavily how structures are growing.

259
00:43:40.680 --> 00:43:48.810
Daniel Gruen: And so let's see what most of you thought most of you thought what oh there's kind of a kind of a race here between two options.

260
00:43:49.530 --> 00:43:56.100
Daniel Gruen: Most of you thought that dark energies slows down the growth of structured late times, but quite a few few thought

261
00:43:56.490 --> 00:44:05.460
Daniel Gruen: That dark energy speeds up the growth of structured lifetimes. And so this is this is a weird strange because this is the first time that you know there's this kind of a

262
00:44:05.910 --> 00:44:20.850
Daniel Gruen: An opposite way in which the growth of structure and the expansion of the universe are working. I told you before, and matter domination, the growth of structure is by the same factor as the growth of the scale of the universe dark energy.

263
00:44:21.930 --> 00:44:28.770
Daniel Gruen: accelerates the growth of the scale of the universe, but it actually slows down the growth of structure at times.

264
00:44:29.460 --> 00:44:38.880
Daniel Gruen: It's all that's that's just qualitatively, think a little more about how that happens. Dark Energy. Energy accelerates the expansion of space time

265
00:44:39.630 --> 00:44:53.790
Daniel Gruen: And it does that also to over dense patches even mildly at late times. So what this does, it can delay. It certainly delays, it can't even stop the collapse of these over dense patches into structures.

266
00:44:54.270 --> 00:44:59.610
Daniel Gruen: And so the growth of density fluctuations now becomes less than proportional today.

267
00:45:00.300 --> 00:45:06.480
Daniel Gruen: And effect by measuring this growth as a function of time. If you could measure just how much structure there was at what

268
00:45:07.080 --> 00:45:19.020
Daniel Gruen: Time of the universe. You can constrain the dark energy density to sell when it takes over and you can constrain the dark energy equation of state to tell how it takes over as a function of time.

269
00:45:19.920 --> 00:45:33.840
Daniel Gruen: And so the unexpected presence of clusters at large redshift was actually an early sign. Perhaps the earliest sign for dark energy existing so what people saw is that will those clusters of galaxies in the nearby universe.

270
00:45:34.260 --> 00:45:45.180
Daniel Gruen: But there's also clusters of galaxies at, you know, redshift point five for soul. And so, that's weird because those clusters should have grown a lot since then.

271
00:45:45.630 --> 00:45:53.490
Daniel Gruen: And you know if there were already present it almost the same as as that redshift point five, then, you know, why didn't they grow. Why don't we see even more massive clusters.

272
00:45:53.850 --> 00:45:59.580
Daniel Gruen: Nearby us. And so the reason for that was a dark energy existed, and since wretched point five.

273
00:45:59.970 --> 00:46:13.410
Daniel Gruen: It slow down the growth of these structures considerably. And so this is this is the, you know, has been the answer to multiple puzzles when when it was discovered by by the means of type one, a supernova that we discussed last

274
00:46:14.430 --> 00:46:21.990
Daniel Gruen: Now, actually one said piece of news in that context is that this accelerated expansion of the universe will lead our Local Supercluster

275
00:46:22.470 --> 00:46:31.590
Daniel Gruen: To never actually form. You might have seen this in the media, some time, right, there's this beautiful map that Brent Talia, and others that Hawaii made of all the, you know,

276
00:46:32.250 --> 00:46:39.330
Daniel Gruen: Positions and all the proper motions of local galaxies using infinite amounts of caca observing time

277
00:46:39.750 --> 00:46:50.370
Daniel Gruen: And so this map here shows the trajectories of all these galaxies. We're sitting somewhere here, we should be converging with, you know, 100,000 galaxies into this

278
00:46:51.270 --> 00:46:55.710
Daniel Gruen: supercluster of all the like you know black trajectories called Lanny Acadia.

279
00:46:56.280 --> 00:47:04.710
Daniel Gruen: However, that's never going to happen because the expanded the expanding universe and the acceleration of that expansion is actually going to drive these galaxies.

280
00:47:05.040 --> 00:47:09.450
Daniel Gruen: Apart eventually. So this is where this is where structure grow things

281
00:47:10.320 --> 00:47:20.970
Daniel Gruen: Okay, so how to measure structure, I would ask you to stay tuned on that you're going to hear a whole talk by Aaron Rhuddlan on observing these invisibles

282
00:47:21.360 --> 00:47:30.960
Daniel Gruen: With cosmological measurements basically with telescopes. We can measure the amount of structure using imaging observations and using spectroscopic observations.

283
00:47:31.440 --> 00:47:36.240
Daniel Gruen: And then with millimeter wave and radio telescopes. We can measure the cosmic microwave background.

284
00:47:36.630 --> 00:47:48.870
Daniel Gruen: And so this combination of being able to look at structure at different times is extremely powerful and mapping out its growth and constraining what dark energy and dark matter must be for that growth to happen as it does

285
00:47:50.190 --> 00:48:00.180
Daniel Gruen: So if you want to serve a dark energy then really there's these two effects that you can use. You can use its effect on the overall expansion of the universe, which it is accelerating it lifetimes.

286

00:48:00.660 --> 00:48:06.630
Daniel Gruen: And you can use its effect on the growth of structures which it's slowing down at light times

287
00:48:07.110 --> 00:48:16.020
Daniel Gruen: And so there's these different props. So, which you've heard about in my talk. Already, some of which you're going to hear about in the remainder of this summer school

288
00:48:16.320 --> 00:48:21.300
Daniel Gruen: That are differently sensitive, some of them just to the geometry and the expansion of the universe.

289
00:48:21.630 --> 00:48:34.620
Daniel Gruen: Some of them just are mostly to the growth of structures. And so the the interesting question here is whether all of these measurements really simultaneously agree with the same parameters of our cosmological model.

290
00:48:35.310 --> 00:48:45.540
Daniel Gruen: And I'll, I'll remind you have our current picture based on all these observations of both the growth of structure and the growth of the universe as a whole.

291
00:48:46.170 --> 00:49:05.010
Daniel Gruen: There is a broad agreement that our current universe contains about 70% of this vacuum energy density 25% of dark matter 5% of baryons and that you know time variations of the dark energy equation of cedar certainly allowed but they're consistent with a constant energy density

292
00:49:06.480 --> 00:49:17.250
Daniel Gruen: And the, you know, there's a few tangents. However, that are worth repeating from yesterday's talk that you may, you may understand better now.

293
00:49:18.510 --> 00:49:29.820
Daniel Gruen: I talked a little more about the tension in the local expansion rate. And so the measurement of a local expand and rate just agrees with a parameter that you need to describe the whole expand in history.

294
00:49:30.570 --> 00:49:37.590
Daniel Gruen: Today, you should be able to appreciate more that we make this measurement of the amplitude of late time density fluctuations.

295
00:49:38.070 --> 00:49:42.960
Daniel Gruen: Basically that the power spectrum averaged over scales of eight mega prospects.

296
00:49:43.440 --> 00:49:55.080
Daniel Gruen: And these lifetime density fluctuation attitudes, they tend to disagree with the early time fluctuation amplitude and it's propagation in, you know, through the matter dominated

297
00:49:55.440 --> 00:50:02.880
Daniel Gruen: And dark energy dominated a pop by two to three sigma. We measure a little bit less structure present in the universe today.

298
00:50:03.240 --> 00:50:08.730
Daniel Gruen: Than you would expect, you know, given this whole modeling of density fluctuations across time.

299
00:50:09.300 --> 00:50:14.880
Daniel Gruen: So I'm going to leave it to you to think a little more about you know what that could really mean one of the

300
00:50:15.540 --> 00:50:27.900
Daniel Gruen: Invisible social universe that we've discussed and their impact on structure could potentially be be causing such an effect and could lead us to see less structure in the universe today than we would otherwise expect

301
00:50:28.560 --> 00:50:30.420
mark convery: And we Daniel, you have about five minutes.

302
00:50:30.810 --> 00:50:32.160
Daniel Gruen: That's great. I think I'm

303
00:50:32.850 --> 00:50:33.990
mark convery: Done actually at this point.

304
00:50:34.350 --> 00:50:37.650
Daniel Gruen: So we could just leave that extra five minutes for questions.

305
00:50:38.250 --> 00:50:40.860
mark convery: Excellent. Okay, thank you very much. Daniel for excellent talk.

306
00:50:42.870 --> 00:50:48.270
mark convery: And I will then pass it over to Tom, who is managing that question.

307
00:50:49.410 --> 00:50:58.230
thomas rizzo: Very good. Thanks, Richard, and thanks for that wonderful talk. There's lots of questions. So let's see how many we can get through here.

308
00:51:00.210 --> 00:51:01.020
thomas rizzo: On slide.

309
00:51:02.520 --> 00:51:12.510
thomas rizzo: There's a question about why is the two point correlation function a preferred measure of structure. What makes it better compared to, for example, the endpoint, Carlita.

310
00:51:14.880 --> 00:51:24.630
Daniel Gruen: That's an excellent question. So the, the short answer is nothing makes it better, right, you would you would want to use all the higher orders but

311
00:51:25.350 --> 00:51:38.670
Daniel Gruen: Something doesn't make it worse. Okay, and what doesn't make it worse is that these early density fluctuations were as far as we can tell, at least perfectly Gaussian so

312
00:51:39.000 --> 00:51:44.520
Daniel Gruen: You know, if you measure fluctuations on any scale. Okay, you're going to recover a Gaussian distribution.

313
00:51:45.090 --> 00:51:56.010
Daniel Gruen: Then, what that means is you can describe all the statistics of this early field, which hopefully. Hopefully you can still see my screen. Let me know if that's not the case, you can describe these fluctuations of the early time field.

314
00:51:56.640 --> 00:52:04.830
Daniel Gruen: Purely by its power spectrum, right. So this is where that is coming from. Now, I think it is fair to say, we would like to learn

315
00:52:05.190 --> 00:52:10.530

Daniel Gruen: What you know whether the higher orders of the density field which arguably, this is not a

316
00:52:11.130 --> 00:52:16.830
Daniel Gruen: Gaussian random field the matter density of late times is very young, very highly non Gaussian fluctuations.

317
00:52:17.340 --> 00:52:24.240
Daniel Gruen: We would like to learn. Certainly, whether those non galson features of density fluctuations are are growing as expected.

318
00:52:24.900 --> 00:52:36.480
Daniel Gruen: And you are absolutely right, we wouldn't see that at all. If all we looked at is the power spectrum. And so, you know, we should look at the power spectrum because we can compare it so directly between the CMT and the present.

319
00:52:37.260 --> 00:52:43.950
Daniel Gruen: Present epic, but we should also look at higher order fluctuations of the density of view. And so I've just alluded to.

320
00:52:44.280 --> 00:52:53.220
Daniel Gruen: These two props. Maybe Aaron is going to tell you more about right if you count peaks, the one way of doing that as you count clusters of galaxies, then you're sensitive to

321
00:52:53.790 --> 00:53:02.850
Daniel Gruen: Much higher, you know, much, much more non Gaussian fluctuations, right, because you're looking at these peaks that are of order 200 the density of the mean universe.

322
00:53:03.330 --> 00:53:10.560
Daniel Gruen: If you're looking at that full PDF of density fluctuations. And that's, that's something that I'm working on quite happily these days actually

323
00:53:10.920 --> 00:53:21.270
Daniel Gruen: Then you. You're also able to see not just the variance of density fluctuations, but the skew illness and all the higher order moments of density fluctuations and you can ask all of you know if dark matter.

324
00:53:21.660 --> 00:53:29.490
Daniel Gruen: Is a cold collision as fluid and gravity is working the way that general relativity describes it, you know.

325
00:53:30.330 --> 00:53:41.370
Daniel Gruen: Does, does that match also these higher order fluctuations, or is there for instance a density dependent modification to the laws of gravity that would show up as a higher order.

326
00:53:42.240 --> 00:53:50.580
Daniel Gruen: Moment being off from my prediction. So great question. There's really so much more in structure than just that one number

327
00:53:52.530 --> 00:54:02.550
thomas rizzo: Okay, thanks. So the next question also. On slide 53 I don't understand why fluctuations decay while they're within the horizon and why they don't otherwise.

328
00:54:04.590 --> 00:54:08.550
Daniel Gruen: So yeah, this is a little. This is not overly intuitive.

329
00:54:09.810 --> 00:54:22.830
Daniel Gruen: I'm not sure how to better explain it unless by using a lot of algebra. So what I would, what I would suggest is a book where this is really, really well explained is

330
00:54:23.400 --> 00:54:31.230
Daniel Gruen: The actual stuff McConnell's book on cosmology, I believe you can actually find that online if you just Google, you know, will cut off.

331
00:54:31.710 --> 00:54:42.510
Daniel Gruen: Cosmology so he has a whole chapter devoted to deriving these you know the the evolution of density fluctuations in the inflationary universe.

332
00:54:42.870 --> 00:54:51.240
Daniel Gruen: And it's very instructive to go through that. But I don't think I can really I don't think I can give you a good intuitive image of what is happening there.

333
00:54:52.080 --> 00:54:58.860
thomas rizzo: Daniel, would you say there's a strong link between the this this polarization and the fact that Gravity Forms or spin to

334
00:55:00.240 --> 00:55:14.580

Daniel Gruen: Absolutely, yeah. So, you know, the fact that this is a tensor perturbation kind of a spin to perturbation to something in the universe, and that grabbed hands. I spent two. Yeah, that is that is a one to one mapping. Exactly. Yeah.

335
00:55:16.290 --> 00:55:19.800
thomas rizzo: Okay, so let's see. The next question is

336
00:55:21.810 --> 00:55:23.940
thomas rizzo: So many questions. They are really good ones.

337
00:55:24.240 --> 00:55:24.690
Okay.

338
00:55:25.830 --> 00:55:42.030
thomas rizzo: Why does walk out and slide 62. Why does this explanation of the over dense patches expansion rely on the universe's curvature that is open parentheses. That is you clarify the universe is flat. Why

339
00:55:44.280 --> 00:55:59.700
Daniel Gruen: I'm in one why I mean my calculation is easier if I assume that the universe overall is flat and that's I've pulled that trick. So I get this very simple equation for the expansion rate or the overall universe.

340
00:56:00.750 --> 00:56:12.180
Daniel Gruen: But I wouldn't have had to have done that. Right. So, this you know these equations work as well. If there's if there's a term with a different K, you know, if I if I have the overall universe be not flat.

341
00:56:12.600 --> 00:56:25.020
Daniel Gruen: I'd also get, you know, get a minus k prime over a squared here and I would just get an additional term an additional an additional term were here.

342
00:56:26.370 --> 00:56:35.490
Daniel Gruen: Right, I would get a k minus k prime over a square I would get the same type of behavior, I would get the same behavior of delta being proportional to a

343
00:56:36.300 --> 00:56:46.290
Daniel Gruen: So this is just for simplicity, but what is always going to be true is that the curvature of this over dense patch. If it's expanding at the same rate.

344
00:56:46.590 --> 00:56:52.830
Daniel Gruen: Is going to be different from the curvature of the universe as a whole. So in this case, the universe as a whole was flat.

345
00:56:53.190 --> 00:57:01.950
Daniel Gruen: And over dense patch was curved. But, you know, no matter whether I assume or not that the overall universe just has the right critical density or is in fact curved

346
00:57:02.580 --> 00:57:17.730
Daniel Gruen: I'm going to have a different curvature and that over dense patch and that's what's causing its future trajectory to to be different. And do you know it's it's huge scale to expand more slowly and the over, it's over density to grow.

347
00:57:19.980 --> 00:57:34.230
thomas rizzo: So the next question. Maybe it helps clarify the next question on the slide 64 to 65 says, Why must the over dense patch have the same overall expansion rate has the rest of the universe clearly related to the lesson or

348
00:57:35.040 --> 00:57:46.110
Daniel Gruen: So, so, yeah. Again, that's an assumption that I'm making here. So the assumption, really, is that we're looking at this very early in the process. We're looking at this at a time where the expansion rate still

349
00:57:46.440 --> 00:57:56.760
Daniel Gruen: still hasn't diverged driver, where the universe started out expanding uniformly and this density fluctuation was so small that we're still having the same expansion right so what we're showing is that

350
00:57:57.150 --> 00:58:04.620
Daniel Gruen: That's not going to last the expansion rate of that over dense patch is going to change. And it's going to be, it's going to be smaller over time.

351
00:58:05.100 --> 00:58:13.680
Daniel Gruen: And so, so that's, that's, you know, that's kind of the, the non linearity of the problem that are ignored, is that you know you're not, you're, you're

352
00:58:14.070 --> 00:58:27.510
Daniel Gruen: If you look at this later in the day, then the ordinance petrol struggled with a smaller expansion rate already and you know that

that that growth of its density fluctuation will become faster and this is this is exactly what

353
00:58:28.590 --> 00:58:40.470
Daniel Gruen: What this looks like, right. So if we look at this, at this point in time than the expansion rate of the words pagination zero right it's no longer expanding and what it's going to do is it's going to get a negative and expansion right and collapse.

354
00:58:40.950 --> 00:58:41.160
thomas rizzo: But

355
00:58:41.190 --> 00:58:45.720
Daniel Gruen: We're looking at it at, at, you know, at an early phase of that.

356
00:58:45.810 --> 00:58:47.760
Daniel Gruen: Evolution of density fluctuations.

357
00:58:47.760 --> 00:58:49.860
Daniel Gruen: Where the expansions are still

358
00:58:51.030 --> 00:58:51.810
Daniel Gruen: Aligned

359
00:58:51.840 --> 00:58:53.790
Daniel Gruen: Between the overall universe of that patch.

360
00:59:00.300 --> 00:59:04.740
thomas rizzo: A great the next questions on slide 67

361
00:59:05.970 --> 00:59:07.680
thomas rizzo: It says is this deprivation.

362
00:59:09.150 --> 00:59:14.820
thomas rizzo: Is this derivation of density contrast scaling also balancing the radiation dominated universe, how

363
00:59:15.450 --> 00:59:23.460
Daniel Gruen: So it'll be a little bit different. And you can actually could do it yourself. Right. So on the density dominated universe, there will be a different

364
00:59:24.330 --> 00:59:33.660
Daniel Gruen: You know, a different equation here for the, you know, if you put in the density of radiation. It's not going to go down as one over a to the third power.

365
00:59:34.140 --> 00:59:44.730
Daniel Gruen: But it's going to go down as one over a to the fourth power. And so what you're going to see is, you know, one over eight to the second times age of the fourth, you're going to see an a squared.

366
00:59:45.870 --> 00:59:47.010
Daniel Gruen: A squared term here.

367
00:59:50.910 --> 00:59:55.560
Daniel Gruen: I think that's true, but maybe double check with your textbook of choice.

368
00:59:57.600 --> 01:00:13.050
thomas rizzo: Okay, very good. So then the next question is slide 64. Why does the expansion rate in the over the fence region include the curvature term from the in the freedmen equation. And is this to preserve the value of the Hubble rate.

369
01:00:14.790 --> 01:00:27.960
Daniel Gruen: So let's just look at the freemen equation where we derived it this one. Okay, so this is this convenient form of the freedmen equation where you know all the different

370
01:00:28.620 --> 01:00:36.870
Daniel Gruen: Types of stuff in the universe we express them as fractions of the critical matter density. And so in this universe we only have mattered entity.

371
01:00:37.470 --> 01:00:41.310
Daniel Gruen: And then curvature x like another kind of fluid.

372
01:00:41.730 --> 01:00:52.830
Daniel Gruen: And with a density. That's one minus all these things. So if you have an omega matter that's exactly one, and I'll make a matter that's exactly the critical density and omega curvature will be zero and you don't have to worry about it.

373
01:00:53.400 --> 01:01:05.910

Daniel Gruen: If you have a matter density that's larger than the critical density. So you have an omega matter of maybe 1.01 okay then you would have an omega curvature of minus point on one

374
01:01:06.450 --> 01:01:14.130
Daniel Gruen: So you just you just, you know, you just can't have a deviation from critical density without also having curvature

375
01:01:20.070 --> 01:01:21.840
thomas rizzo: Let's see what's the next one here.

376
01:01:23.790 --> 01:01:24.360
thomas rizzo: On slide.

377
01:01:25.680 --> 01:01:33.180
thomas rizzo: Can you explain the clustering so clustering history of dark matter in a similar way as you did back for baryons on this slide.

378
01:01:34.590 --> 01:01:45.480
Daniel Gruen: So for dark matter, you would be doing the same kind of calculation that we did in in the matter only universe, you will look at a fluctuation and you would see how the expansion rate of that little

379
01:01:45.870 --> 01:01:56.880
Daniel Gruen: Over density patch would change over time. You don't have to account for pressure or relativistic motion. And so you would you would find that delta is is some power law.

380
01:01:57.600 --> 01:02:11.910
Daniel Gruen: Of a and so so dark matter density fluctuations are actually growing quite well in in this radiation dominated universe. It's just the baryons who's pressure and who was zipping around

381
01:02:12.630 --> 01:02:19.350
Daniel Gruen: Is is causing them to do these oscillations and these these washing out of small scale fluctuations.

382
01:02:19.920 --> 01:02:25.800
Daniel Gruen: And now the one thing that's a little more difficult is that of course the dark matter is also pulled around

383
01:02:26.280 --> 01:02:37.170

Daniel Gruen: By the density fluctuation is the baryons right the variants are there only 20% of the matter density, but still they have gravity. So in this scenario where the bargains are all in one place.

384
01:02:37.590 --> 01:02:48.180
Daniel Gruen: They're going to, you know, add to the growth of structure in this scenario where they're all spread out, they're going to do nothing to the growth of structure and in this scenario where they're

385
01:02:48.510 --> 01:02:55.230
Daniel Gruen: You know they're they're where they're where they're currently just out of the density of fluctuation. So where the density of baryons is actually the largest

386
01:02:55.620 --> 01:03:11.220
Daniel Gruen: In the places where the density of dark matter is the smallest. That's where they're going to remove you know amplitude of density fluctuations of the dark matter. So this is the the difficulties is this dragging around of dark matter as the baryons off the light

387
01:03:15.420 --> 01:03:27.510
thomas rizzo: OK, the next question is, on slide 72 it's an experimental question. Yes. How do you, how did they experimentally distinguish between the hot gas where the dark matter is the Bullet Cluster.

388
01:03:27.960 --> 01:03:31.920
Daniel Gruen: Oh, beautiful. I mean, this is for it really gets interesting. I wish I brought my wine glass.

389
01:03:32.400 --> 01:03:40.110
Daniel Gruen: So Aaron will hopefully tell you more about this. But how do you see hot gas, right, one way you see hot gas is you look for

390
01:03:40.470 --> 01:03:47.940
Daniel Gruen: Astrodome x ray radiation. When you know two particles to charged particles in the podcast are kind of colliding and they're sending off.

391
01:03:48.360 --> 01:03:55.230
Daniel Gruen: Photons at for the energies that you for the temperatures that this hot gas has been cluster is you're actually going to get x ray for comes

392
01:03:55.590 --> 01:04:01.530

Daniel Gruen: So you point your x ray telescope there just record where all the x ray photons came from and you get this

393
01:04:01.980 --> 01:04:13.290
Daniel Gruen: Magenta picture here, and there's a lot of stuff going on here like you know shock waves going through that Coster gas and all such complicated baryonic gusto physics.

394
01:04:14.220 --> 01:04:21.960
Daniel Gruen: Now if you want to measure, measure density, then one way that you can do that is gravitational lensing. So if you look at the shape

395
01:04:22.380 --> 01:04:31.590
Daniel Gruen: Of background galaxies in this image. I mean, you can't do it by but you can do it when you get the actual Hubble Space Telescope high resolution image of all those shapes.

396
01:04:32.010 --> 01:04:43.740
Daniel Gruen: What you'll see is that the background galaxies are aligned, kind of like that, you know, along this curve. And actually, you can see one really really highly stretched out image of a background galaxy right here. Okay.

397
01:04:44.220 --> 01:04:48.150
Daniel Gruen: So the background galaxies are going to look like they're tangentially aligned

398
01:04:49.260 --> 01:05:05.070
Daniel Gruen: Around this blue fuzzy blob and that's because the gravitational title field of that matter density is distorting the paths of light rays that have to go past the cluster on the way from a very distant galaxy to us.

399
01:05:05.790 --> 01:05:14.700
Daniel Gruen: And so this effect called gravitational lensing allows you to directly measure the matter distribution, no matter what form it has

400
01:05:15.120 --> 01:05:24.390
Daniel Gruen: Documented it's the same kind of gravitational anything as baryonic matter and these blue contours are any the reconstruction of the matter density

401
01:05:25.290 --> 01:05:36.510

Daniel Gruen: You know, along the line of sight integrated of this cluster based on the distorted shapes of background galaxies and what you see there is there, there are these two peaks.

402
01:05:36.930 --> 01:05:43.680
Daniel Gruen: That actually coincide with the lumps of galaxies of those two clusters that have collided. So this is the central galaxy of one of those clusters.

403
01:05:44.010 --> 01:05:48.630
Daniel Gruen: And then these, you know, these bunch of galaxies. Here there are the galaxies of that other costs that have collided.

404
01:05:49.050 --> 01:05:56.790
Daniel Gruen: So what you see there is that, you know, galaxies. They basically they don't you know they don't have a cross section in that way because

405
01:05:57.210 --> 01:06:05.400
Daniel Gruen: They're so dispersed in space and within the galaxies, stars and gases sodas for so galaxies just they just pass through one another.

406
01:06:05.730 --> 01:06:14.940
Daniel Gruen: And what you see is that the dark matter coincides with the positions of these galaxies that have zero cross section. That means that dark matter of must also have close through the cross section.

407
01:06:17.130 --> 01:06:20.310
mark convery: Um, I guess we should cut it off there since we're a little past time. Yeah.

408
01:06:20.370 --> 01:06:22.950
thomas rizzo: Okay, you're still more you'll get

409
01:06:23.430 --> 01:06:31.470
Daniel Gruen: I'm gonna I'm gonna look at the Google Doc, I didn't do a great job with that yesterday, but I'll have a look. Today I'll respond to your questions. Thank you. Great.

410
01:06:31.740 --> 01:06:31.980
Daniel Gruen: Thanks.

411
01:06:32.040 --> 01:06:33.960

Daniel Gruen: Very much everybody. Yeah.

412
01:06:34.020 --> 01:06:44.520
mark convery: Thank you for the excellent lecture and thanks to the attendees for the good questions and we will resume in about 10 minutes with Andre to be his second lecture on Neutrino theory. So thanks everyone.