WEBVTT

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00:00:03.389 --> 00:00:13.530
mark convery: Okay, we're very pleased to have Mark Tron from the University of Pennsylvania today to discuss the question. I think it's on everybody's mind, which is what could dark energy to be somewhere, take it away.

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00:00:14.940 --> 00:00:17.609
Mark Trodden: Oh, thanks for having me. It's great to be back.

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00:00:18.119 --> 00:00:23.340
Mark Trodden: I've been I think this may be my fourth or fifth time lecturing at the SSI. So it's always fun.

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00:00:25.530 --> 00:00:26.910
Mark Trodden: Let me, sorry.

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00:00:27.990 --> 00:00:42.630
Mark Trodden: Let me first say that I gave this talk, a version of this talk, three years ago here. And if you were here for that talk, you won't see a lot of difference here, which would give you a clue that I may have a question in the title of it, but I'm not going to answer that question here.

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00:00:44.160 --> 00:00:57.870
Mark Trodden: But nevertheless, I want to give you some ideas I've tried to focus the talk at people who don't spend their time thinking about these things are who are not theorists and I want to go through the sort of logical space of answers to the question of what dark energy could be

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00:00:59.010 --> 00:01:09.330
Mark Trodden: I want to talk about the theoretical issues, particularly that face any approach to explain in dark energy and particular screening mechanisms and the connections to particle physics field theory.

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00:01:09.930 --> 00:01:14.940
Mark Trodden: And then I'll focus in on example which I think sort of encapsulates many of the issues that we face.

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00:01:15.720 --> 00:01:21.720
Mark Trodden: Which will lead me to talk a little bit about massive gravity and Galileo and and then I'll try to sum it all up at the end.

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00:01:22.710 --> 00:01:28.980
Mark Trodden: There's sort of slightly older now. But still, hopefully useful reference. I think for some of the things I'll say, which is this

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00:01:29.460 --> 00:01:40.440
Mark Trodden: Review article I wrote in physics reports with collaborators five or six years ago now. And as I said, you'll find a lot of similarities. If you've heard me speak on this and recent years.

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00:01:41.940 --> 00:01:48.300
Mark Trodden: Okay, so just to get us all on the same page. We all know what doc and you supposed to be, but let's just say it out loud.

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00:01:48.720 --> 00:01:54.450
Mark Trodden: What does data tell us about the expansion rates of the universe. And the answer is that, you know, partly through

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00:01:55.410 --> 00:02:03.450
Mark Trodden: Measurements all of supernovae, in particular, we've been able to push the Hubble Diagram back further into the past, than we ever could before.

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00:02:04.020 --> 00:02:14.760
Mark Trodden: And as a result, we know that the universe is not only expanding scale factor has a positive derivative, but it's accelerating. There's a spinning faster and faster as time goes on.

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00:02:16.170 --> 00:02:25.320
Mark Trodden: And if you trust general relativity. Well, General Relativity is a theory of gravity that tells you how space and time respond in a very specific way.

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00:02:25.650 --> 00:02:36.810
Mark Trodden: To the matter and energy sources that are in the universe. And if you trust general relativity, then there's a very simple equation when applied to cosmology that you need to focus on. And it's the so called acceleration equation.

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00:02:37.290 --> 00:02:44.520
Mark Trodden: And from that you can very quickly infer that the universe must be dominated by some strange stuff with

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00:02:45.120 --> 00:02:54.720
Mark Trodden: A very weird behavior. It's pressure has to be just not just negative. But in fact, less than minus one third of its energy

density. And when people talk about dark energy. That's the thing they mean

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00:02:58.290 --> 00:03:06.390
Mark Trodden: Now it's conventional in this field to explain this in terms of an equation of state. So we write P equals W row.

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00:03:07.080 --> 00:03:17.160
Mark Trodden: And then this accelerating expansion means that the equation of state parameter w of whatever is causing this acceleration is less than minus a third

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00:03:17.880 --> 00:03:25.110
Mark Trodden: And of course, you know, what is the value of that from data. I told you that data is the thing that's telling us this

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00:03:25.500 --> 00:03:35.190
Mark Trodden: And so the volume moves around a little bit as data sets. We get a lot of get a little better. And we combine data sets in better ways which I'll have a little bit more to say about later.

24
00:03:35.640 --> 00:03:40.560
Mark Trodden: But if you look at sort of the latest results from the Dark Energy collaboration chin for

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00:03:41.340 --> 00:03:53.880
Mark Trodden: Ds collaboration. For example, you see the W is hovering around minus one which is I'll explain as a cosmological constant with some reasonable Aero bars around it. But, does everybody have been getting quite a bit tighter in recent years.

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00:03:56.880 --> 00:04:06.390
Mark Trodden: So since w is so close to minus one, there's an obvious first step answer what dark energy could be. And the answer is, it could be a cosmological constant

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00:04:07.140 --> 00:04:12.660
Mark Trodden: We know that quantum field theory tells us that the vacuum is full of virtual particles that carry energy

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00:04:13.110 --> 00:04:23.130
Mark Trodden: And the equivalence principle or if you like lawrenson variance tells us that the energy momentum sense of the average engine momentum center of those fluctuations should behave

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00:04:23.850 --> 00:04:34.020
Mark Trodden: In such a way that it's proportional to the energy to the metric. And that is equivalent to saying that we have a constant vacuum energy in the universe.

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00:04:35.460 --> 00:04:38.940
Mark Trodden: That's very promising that will give us w is exactly minus one.

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00:04:39.960 --> 00:04:43.200
Mark Trodden: But if you quite to do try to do an estimate of how big that should be

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00:04:43.710 --> 00:04:51.360
Mark Trodden: Then, one way to do that is to say, let's suppose the universe only has Standard Model fields that we model as some set of independent harmonic oscillators.

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00:04:51.690 --> 00:04:59.430
Mark Trodden: And then you just some overall the zero point energies up to some cut off and it doesn't really matter where you put the cut off, we know that the

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00:04:59.880 --> 00:05:10.110
Mark Trodden: Quantum field theory of the standard model works up to the electroweak scale, at least, and that's enough already to tell us that the theoretical prediction of how big the cosmological constant should be

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00:05:10.560 --> 00:05:24.810
Mark Trodden: Is about 10 to the minus 120 20 220 times larger than the one we would expect from theory. So somewhere between 10 to 1600 and 20 orders of magnitude rock.

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00:05:26.640 --> 00:05:31.770
Mark Trodden: So this is an enormous problem, as we all know, and it's entirely unsolved. I would say in fundamental physics.

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00:05:32.250 --> 00:05:44.850
Mark Trodden: And we knew about it before we ever discovered the universe was accelerating and if anything the theoretical pressure to solve that problem. One way or another, has been made more by the discovery of cosmic acceleration

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00:05:46.890 --> 00:05:52.230

Mark Trodden: I think it's fair to say, we don't really have any great ideas to solve this problem right now.

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00:05:52.800 --> 00:06:00.660
Mark Trodden: And for the more Weinberg has taught us that there's a quite a strong, no go theorem, which means that most of the sort of simple ideas, you would have

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00:06:01.080 --> 00:06:11.220
Mark Trodden: To explain why the cosmological constant could be tuned to zero or dynamically set to zero run into some sort of problem along the way. So great creativity is needed here.

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00:06:13.830 --> 00:06:22.740
Mark Trodden: Now there is one possibility. That's been suggested, and that is that you don't try to solve this problem in any dynamical sense instead you

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00:06:24.480 --> 00:06:26.760
Mark Trodden: Appeal to the idea of the anthropic principle.

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00:06:28.290 --> 00:06:39.060
Mark Trodden: In particular, in recent years, there's been a resurgence of interest in this, we do the discovery of the string landscape, coupled with the idea of eternal inflation. So the idea here is that

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00:06:40.380 --> 00:06:52.530
Mark Trodden: The universe, maybe is realized, many times over, either in space or in time or in both and as it is realized it falls into one of the very large number of metal stable vacuum.

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00:06:53.370 --> 00:06:58.740
Mark Trodden: Some of which are very large cosmological constant, some of which are very small cosmological constants, but only a slim.

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00:06:59.130 --> 00:07:12.030
Mark Trodden: Region of which allow a universe that looks anything like ours to develop and then the notion would be that we observed the cosmological constant to be what it is because it could not be any other way for us to be here to ask that question.

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00:07:13.440 --> 00:07:29.070
Mark Trodden: So this is a perfectly respectable idea, but there are many important steps and there's no real currently accepted answer on how to

compute the probabilities involved in understanding this problem in the context of string theory and the landscape.

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00:07:30.180 --> 00:07:38.340
Mark Trodden: So the way that I think about this. I say this in all the talks that I give like this as the following. It's a completely logical possibility. People should work on it.

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00:07:38.880 --> 00:07:47.370
Mark Trodden: But in order for it to be successful in the present context, it requires, first of all, string theory to be correct, which may not be the case.

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00:07:48.090 --> 00:07:58.140
Mark Trodden: It requires the string landscape to exist to be robust for there to be stable life method stable string vacuum and that's not completely established either

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00:07:59.100 --> 00:08:07.350
Mark Trodden: It requires eternal inflation to work in that landscape to populate those vacuum and you know there are theoretical issues with eternal inflation.

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00:08:08.160 --> 00:08:18.660
Mark Trodden: And it may be requires a solution have what's called a measure problem. How do you actually sort of divide up probabilities in such a complicated space. And that's also a problem.

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00:08:19.680 --> 00:08:28.050
Mark Trodden: I would say, furthermore, that if a dynamical understanding of the cosmos or constant is found it would be very hard to accept the anthropic principle as an answer.

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00:08:30.330 --> 00:08:37.320
Mark Trodden: So given that, I think it's certainly worth while mapping up the space of alternative ideas, even though, as I said, there are no really compelling models here.

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00:08:39.840 --> 00:08:46.050
Mark Trodden: So the first thing you might think about turning to dynamically ideas now and just putting the cosmological constant aside for the moment.

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00:08:46.560 --> 00:08:55.050

Mark Trodden: Is what you might call dynamical dark energy. And so we imagine that it's some kind of honest to goodness mass energy components of the universe.

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00:08:55.770 --> 00:09:03.450
Mark Trodden: And, you know, nowadays, you can't just write down some fluid. The way that we used to in cosmology and say, oh, it's got a suppression some density and

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00:09:03.810 --> 00:09:08.970
Mark Trodden: We'll just make up the way they are related to each other and see what happens. You need to actually have a theory.

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00:09:09.780 --> 00:09:17.550
Mark Trodden: And our only known way of describing theories right now is through quantum field theory with Lagrangian couples to the metric in some way.

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00:09:18.540 --> 00:09:29.130
Mark Trodden: So you compute engine momentum sensors, plug it into the Einstein equation you figure out how space and time respond to this new mass energy component of the universe.

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00:09:31.260 --> 00:09:40.020
Mark Trodden: So if that's true, then it might you have to buy in a in a notion like this that there's some other principle that sets the background vacuum energy to zero.

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00:09:40.800 --> 00:09:46.680
Mark Trodden: And then dark energy sits just on top of that. And in some sense, it's like inflation at the other end of time.

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00:09:47.310 --> 00:09:59.460
Mark Trodden: Inflation is a notion that the universe undergoes very rapid expansion at early times accelerated expansion at high energies and eventually exits that evolution reads the universe and leads to the Big Bang.

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00:10:00.090 --> 00:10:15.960
Mark Trodden: Here, you would have a similar notion, something is driving universal accelerate, but the scale would be very low. It's happening today, there wouldn't be no need for a minimum, if you like, or reheating and only in front end to this inflation necessarily

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00:10:17.100 --> 00:10:29.100

Mark Trodden: And so, just as you can use scale of fields, for example, to source Einstein's equation and inflation, you can come up with a similar idea often call Quintessence to explain dynamical documented, you get laid times

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00:10:29.700 --> 00:10:40.890
Mark Trodden: And so this is just a schematic potential to draw the eye, you'd have a field that rolls down its potential and as I say there's no minimum in this potential and it's very low scale.

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00:10:41.760 --> 00:10:53.820
Mark Trodden: And then you just use the fact that if you have a potential like this. And there's a small slope than the equation of state associated with the field is dominated by the potential energy term and it can be about as close to minus one is you would like together.

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00:10:57.120 --> 00:11:00.330
Mark Trodden: Now that idea. I think is pretty cut and dried

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00:11:01.440 --> 00:11:08.550
Mark Trodden: It has advantages in the same sense that scale of fields are driving flourish and have advantages and it also has a number of drawbacks.

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00:11:09.330 --> 00:11:17.460
Mark Trodden: I won't focus on it very much here because I really want to talk about that idea encapsulated together with the idea of modifying gravity.

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00:11:18.270 --> 00:11:25.110
Mark Trodden: So to move to that briefly. There's a another possibility here, and that is that, you know, instead of having

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00:11:25.920 --> 00:11:32.610
Mark Trodden: Some new metal components of the universe you instead have a different set of rules that tell you how space and time respond to matter and energy.

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00:11:33.450 --> 00:11:43.200
Mark Trodden: So just the southern guide the AI related tale played out over about a 50 year period over a century ago when people were looking at the way mercury moved around the sun.

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00:11:43.770 --> 00:11:56.490

Mark Trodden: So here's a very exaggerated picture of Mercury's orbit around the sun. And as you know, this is very puzzling to people because instead of going around the ellipses Kepler would have predicted this ellipse processes around the sun.

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00:11:57.510 --> 00:12:08.520
Mark Trodden: And along came a very who had had great success with predicting other planets with this technique and said, what's going on here is obvious. Here's some kind of talk matter or dark energy.

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00:12:09.210 --> 00:12:19.230
Mark Trodden: You said there's another planet. It's on the other side of the sun. We don't see it. It's called Vulcan. And what's happening is it's perturbing the motion of mercury around the sun.

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00:12:19.800 --> 00:12:30.120
Mark Trodden: This would be the analog in some sense of dark energy you postulate a new kind of mass energy in order to explain something odd that's happening that isn't explained by your current theory.

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00:12:31.470 --> 00:12:46.770
Mark Trodden: And we know of course that this is not what happened in that case what happened in that case is the Einstein came along and said, no, this is not what's going on at all. In fact, what's happening is the rules that tell you how matter responds to gravity are different.

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00:12:47.790 --> 00:12:59.760
Mark Trodden: And if you think about that in the context of the accelerating universe, it would lead to the question of could a similar story be unfolding today with cosmic acceleration sort of being the canary in the mine the wonders of the breakdown of gravity.

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00:13:02.250 --> 00:13:10.680
Mark Trodden: So if you want to do that if you want to ask is the universe accelerating because gravity is modified it turns out to be a little bit tricky.

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00:13:11.520 --> 00:13:22.500
Mark Trodden: So if cosmic acceleration is entirely due to some correction to general relativity. The first thing you have to ask is, well, what does it mean to correct general relativity. How hard or easy is that to do

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00:13:23.070 --> 00:13:27.870
Mark Trodden: And the first thing to do there is to understand what are the degrees of freedom to think like a particle physicist.

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00:13:28.350 --> 00:13:32.730
Mark Trodden: Then you need to know what the degrees of freedom are that are explaining gravity.

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00:13:33.690 --> 00:13:39.150
Mark Trodden: So if you take the metric, which is the central objects in general relativity and you ask, what are the degrees of freedom.

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00:13:39.810 --> 00:13:50.940
Mark Trodden: You find if you decompose it as a reducible representation of the park, or a group that it contains a gravity time spent to particle, the thing we're all familiar with from studying gravity.

86
00:13:51.930 --> 00:13:59.280
Mark Trodden: I but it also has a vector field and scale of fields that are hidden in there. And those should be less familiar to you if you just studied general relativity

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00:14:01.200 --> 00:14:12.960
Mark Trodden: And the reason is not because of some intrinsic deep fact necessarily it's because general relativity structure is such that it's equation of motion containing constraints.

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00:14:13.320 --> 00:14:23.040
Mark Trodden: Those constraints pin the vector and scale of fields and make them non dynamical. The only thing that's left over all the two degrees of freedom of the familiar gravity spin to particle

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00:14:25.170 --> 00:14:33.420
Mark Trodden: It turns out that almost anything you do to generativity almost any other action you use almost any attempt, you make to modify generativity

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00:14:34.170 --> 00:14:47.760
Mark Trodden: Does not obey this very constrained form and so almost any other action will free up some of these new degrees of freedom. So for example, the F of all models that we worked on a long time ago now free up the scale of degree of free

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00:14:49.620 --> 00:14:56.490
Mark Trodden: And in fact, there are even more interesting things possible one can get not only new degrees of freedom but massive degrees of freedom. And I'll talk about that later.

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00:14:58.650 --> 00:15:04.710
Mark Trodden: So I talked about a cosmological constant and I talked about the idea of dynamical Dark Energy, new fields in the world.

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00:15:05.340 --> 00:15:12.480
Mark Trodden: I talked about modifying gravity in the end point of talking about modifying gravity was, you can end up freeing up new fields from the metric

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00:15:13.200 --> 00:15:20.490
Mark Trodden: And as a particle physicists one we tend to think that one should discuss those in a common language and that common language is the language of an effective field theory.

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00:15:22.050 --> 00:15:30.900
Mark Trodden: So the way the theorists, think about this is, no matter what is causing the universe to accelerate ultimately around some expanding background, the universe.

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00:15:31.350 --> 00:15:39.480
Mark Trodden: It should just consist of a set of interacting fields in Alexandria and for my purposes here or grungy and contains only three types of terms.

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00:15:40.260 --> 00:15:49.500
Mark Trodden: There are kinetic terms the ad for a scale or vector for me arms spin to particle, etc. Or functions of kinetic terms.

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00:15:50.400 --> 00:16:03.690
Mark Trodden: There are self interactions which you might think of for a scale or as a potential or mass times and then their interactions among fields, for example, between Steelers and firm aeons or vector fields and scholars, etc, etc.

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00:16:05.520 --> 00:16:18.960
Mark Trodden: And depending on the background in the background, you're expanding around the and expanding space time or a black hole or anything really all these terms that appear in Oregon. Jim might have functions in front of them that depend on time or space.

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00:16:21.120 --> 00:16:30.360
Mark Trodden: And many of the concerns that theorists have about theoretical approaches to modifying gravity on dark energy cannot be expressed in terms of this effective field theory language.

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00:16:31.800 --> 00:16:33.060
Mark Trodden: So here's one example.

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00:16:34.080 --> 00:16:47.580
Mark Trodden: When we write down a classical theory described by one of the crunching as well usually implicitly assuming the effects of higher order operate as a small you don't write down every single one of the infinite terms that you could write down in a theory.

103
00:16:48.750 --> 00:16:56.340
Mark Trodden: But if this is going to be consistent. You need to work below, what's called a strong coupling scale of the theory. So the quantum corrections, which you compute and preservation theory of time.

104
00:16:57.180 --> 00:17:02.550
Mark Trodden: Well, the normally means is that the dimension was quantities that determine how higher order operators in the theory.

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00:17:03.270 --> 00:17:11.940
Mark Trodden: Effect low water physics are much less than one. So, for example, in sort of very gross terms, the energy should be less than the cutoff very simple idea that we're all used to

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00:17:13.830 --> 00:17:21.030
Mark Trodden: But this is a very tricky concept in the theories that I'm talking about. Remember that the kinetic terms. The couplings, the potentials can all have

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00:17:21.570 --> 00:17:29.040
Mark Trodden: Functions in front of them of the background. So in cosmology, they might behave one way around the back Hall, they might be a different way.

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00:17:30.000 --> 00:17:40.170
Mark Trodden: And so that means that answering the question of if your theory is under theoretical control something you might have to answer again and again, depending on the different backgrounds, you're interested in

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00:17:40.890 --> 00:17:47.460
Mark Trodden: So that's something that you have to be very wary of when writing down or if you'd like. When asking the question, what can dock energy be

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00:17:49.440 --> 00:17:56.580
Mark Trodden: So to give you an example. If I had two fields in my theory and there was an interaction between one of them chi.

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00:17:57.000 --> 00:18:06.750
Mark Trodden: Say some function JFK tons of kinetic term for the other one, then around some background in which chi is evolving in time, this just becomes a function of time in front of the kinetic term.

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00:18:07.290 --> 00:18:16.500
Mark Trodden: And if the function f, f t goes to zero you automatically or in the strong coupling regime and you cannot trust your theory. And it turns out that this seemingly sort of

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00:18:17.610 --> 00:18:25.470
Mark Trodden: Abstract theoretical notion turns out to be an incredibly severe problem for many ideas that people have written down to explain the accelerated course.

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00:18:27.300 --> 00:18:34.050
Mark Trodden: There's a related issue called technical naturalness. Even if your quantum mechanical corrections. Don't ruin your ability to trust the theory.

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00:18:34.470 --> 00:18:42.390
Mark Trodden: You might need unnaturally small couplings, and the theory to solve your problems. And this is something that happens both in inflation and in dark energy. It turns out

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00:18:43.050 --> 00:18:52.200
Mark Trodden: So suppose, for example, you need a very flat potential are very small mass, the case of dark energy. I've written down just a simple scale of field here with a mask.

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00:18:52.710 --> 00:19:02.040
Mark Trodden: And a fight of the fourth coupling and if you want a chance of this explaining accelerating universe, the mass needs to be no bigger than the inverse Hubble scale.

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00:19:03.630 --> 00:19:11.880
Mark Trodden: It turns out that unless your theory has a special symmetry as you take that master zero quantum corrections to this theory will drive it up to the cut off of your theory.

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00:19:13.230 --> 00:19:28.860

Mark Trodden: And then, unless you have extremely precise fine tunings to keep this potential flat and the mass scale low, the theory will no longer give you the physics you like it'll be entirely trustful you just won't do the thing you wanted to do and this is the challenge of technical naturals

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00:19:31.110 --> 00:19:37.350
Mark Trodden: There are other examples. One particularly severe one that affects many dark energy models is the requirement. That'd be cost free

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00:19:38.550 --> 00:19:40.830
Mark Trodden: If you remember the kinetic terms that I wrote down and

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00:19:42.180 --> 00:19:49.860
Mark Trodden: Then around the given background these terms. Tell us, in a sense, whether the particles associated with the theory carry positive and negative energy

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00:19:50.880 --> 00:20:03.180
Mark Trodden: So again to guide the I imagine that I have one field chi couple to another field Fi in such a way that f of Chi terms of function of the kinetic there should be a fire in there after the first review.

124
00:20:04.290 --> 00:20:17.580
Mark Trodden: Of the connectome have another field fine and then expand that out around some some background and this looks like an effective Lagrangian for the five field that has functions of time, space in front of each term.

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00:20:19.140 --> 00:20:22.440
Mark Trodden: And this term FFT and X sets the sign of the kinetic energy.

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00:20:23.850 --> 00:20:36.870
Mark Trodden: That goes negative than the theory has what I call ghosts and there's enough ghosts in the sense of, you know, for day of pop off ghosts or something that you use to construct the theory and to keep the measure on on on

127
00:20:38.190 --> 00:20:45.480
Mark Trodden: Orbit space. Correct. These are actual honest to goodness particles with negative energies and their catastrophic. If you take them seriously.

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00:20:45.870 --> 00:21:00.720

Mark Trodden: They had have negative energy Audra new particles can decay into heavier particles plus ghosts or the vacuum itself could just cascade and fragment into positive and negative energy particles. And so these are really a death blow to the theory.

129
00:21:03.690 --> 00:21:11.640
Mark Trodden: So I was going to give you an example. But I think I'm going to, well, let's give you a quick. I'm not going to give you an example. I'm going to move on.

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00:21:13.620 --> 00:21:19.890
Mark Trodden: But let me just point out that, for those of you who are used to looking at the engines, all the time. This is an example of

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00:21:20.310 --> 00:21:30.480
Mark Trodden: A single field with higher derivative interactions and I show by introducing an auxiliary field that it's really a theory of two fields and one of those fields has the wrong side kinetic energy.

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00:21:31.200 --> 00:21:37.560
Mark Trodden: And therefore has ghosts. And the reason I wanted to show this is not just to show you that it's, there's a simple example.

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00:21:38.250 --> 00:21:46.800
Mark Trodden: But to point out that you will often see people writing down models of dark energy in which this equation of state parameter w is less than minus one.

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00:21:47.640 --> 00:21:59.100
Mark Trodden: And I'm not going to say that this is true of all of them, but for very, very many of them. The only way they get W less than minus one is by having something with this physics in it. And so, almost by fiat

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00:21:59.970 --> 00:22:05.460
Mark Trodden: They fail as a theorem productions, it's very, very hard theoretically to get W less than minus one.

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00:22:08.820 --> 00:22:19.770
Mark Trodden: There are other things that happen. I really am going to skip simple analogy. And there are many other more theoretical issues and electricity of the matrix, etc. The theorists worry about all the time.

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00:22:20.940 --> 00:22:30.960

Mark Trodden: All of this is really intended, just to say that if you think as a field theorist and you take the behavior of these theories seriously around

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00:22:31.560 --> 00:22:41.100
Mark Trodden: Not just an expanding background of cosmology, or an accelerating background but also about all the other things that exist in the universe black holes neutron stars, etc.

139
00:22:41.490 --> 00:22:48.600
Mark Trodden: There are very large number of constraints on how these theories behave. And when you're asking what could dark energy be

140
00:22:49.830 --> 00:22:56.550
Mark Trodden: It turns out that it's not really the Wild West anymore. You are going to have a lot of trouble constructing consistent theories

141
00:22:57.000 --> 00:23:11.910
Mark Trodden: And this has been a challenge to those of us who take these constraints. Seriously. And I think it's driven us to some very interesting examples, but it's also very much shrunk the space of reasonable theories beyond one, the one that you would think about starting with

142
00:23:14.580 --> 00:23:29.250
Mark Trodden: Now one thing the effective fields every does fear which is incredibly powerful is it tells you a property of dark energy or modified gravity theories that seems to be very common and needed by almost all of them. And that's this thing called screaming

143
00:23:30.780 --> 00:23:38.790
Mark Trodden: So I'm going to go back to an effective field theory and good to write a very simple, effective field theory down. It's a scale of field fi

144
00:23:39.450 --> 00:23:57.090
Mark Trodden: I've written only its kinetic term here with an arbitrary function z Munir in front of that and a potential and a coupling the very lowest order coupling of a scale of field to the rest of the matter in the universe. In this case, couple into the trace of the matter in the universe.

145
00:23:59.100 --> 00:24:08.940
Mark Trodden: And I specialize to a point source for the matter in the universe. So I'm thinking specifically here about I've got some new

field, it might come from modified gravity, it might be a dark energy field.

146
00:24:09.390 --> 00:24:16.800
Mark Trodden: But it's out there in the universe. And I'm asking here how it behaves around a point source. In other words, how does it behave around the sun, for example.

147
00:24:17.700 --> 00:24:33.480
Mark Trodden: Well the point sources appoint mass and expand out the field around this point mass and I find out that the expanded field curly fi a base some wave like equation and I don't expect you to solve this equation, while you're looking at the slides.

148
00:24:35.490 --> 00:24:45.930
Mark Trodden: Excuse me, but I just want to guide the AI to a couple of things in this equation. First of all, as a function of the background outside of the wave equation part

149
00:24:47.010 --> 00:24:59.730
Mark Trodden: Secondly, there's a function describing the mass of the field. And thirdly, there's a function describing it's coupling to matter in the universe. And these things are sort of inevitable for most theories that describe an accelerating background.

150
00:25:01.200 --> 00:25:08.220
Mark Trodden: Now if you imagine that the background value of fields is set by, say, the local density of the local Newtonian potential

151
00:25:08.610 --> 00:25:24.570
Mark Trodden: Then one can write down something quite simple. And that is the potential around this object. And as you might expect, it looks a little bit like it's kind of a one of our piece that looks like a cool on potential and it's got a eucalyptus plus functions of the fields outside of it.

152
00:25:26.760 --> 00:25:29.850
Mark Trodden: This simple equation has very profound consequences.

153
00:25:30.600 --> 00:25:41.970
Mark Trodden: If you know assume that the scale or is light and has parameters of auto one. In other words, it's like, because you wanted to be dark energy of some kind, are coming from a modified gravity theory of some kind.

154

00:25:42.570 --> 00:25:47.160
Mark Trodden: And it has auto one parameters, because it's an effective field theory and you're not going to tune anything

155
00:25:48.030 --> 00:26:04.140
Mark Trodden: Then this new scale of field that you're imagining is accelerating the universe around the sun has gravitational strength long range forces. So it's an order one correction to Newton's laws and that's ruled out by local tests of general relativity by many orders of magnitude.

156
00:26:05.460 --> 00:26:11.940
Mark Trodden: And so this is a rather general issue that's faced by these theories. If you want a workable model of dark energy.

157
00:26:12.570 --> 00:26:27.300
Mark Trodden: That are if you even modify gravity, you're going to need a way to make this force sufficiently week and local environments, while still being the most important thing in the universe on very large scale because it's kind of drive the expansion on the acceleration

158
00:26:30.000 --> 00:26:38.520
Mark Trodden: So if you remember the EFT classification of terms and the Lagrangian. There are three ways you can use those terms to make

159
00:26:39.270 --> 00:26:47.610
Mark Trodden: couplings around a sauce week and these things are called screening mechanisms and there are several versions, depending on which parts of that grungy you use

160
00:26:48.180 --> 00:26:54.540
Mark Trodden: One's called the Einstein mechanism uses the kinetic terms once called a chameleon mechanism uses the coupling to matter.

161
00:26:55.170 --> 00:26:59.220
Mark Trodden: Once called a symmetry mechanism that uses the coupling self coupling of the scale of

162
00:27:00.060 --> 00:27:11.940
Mark Trodden: Each of them has their own advantages and disadvantages and I won't have time here to go through all of these. So what I'll do, rather than doing that is just focus on one here, partly because

163
00:27:12.390 --> 00:27:21.600

Mark Trodden: I think that it's in some sense them the richest example. And one of the things that is attached to one of the more promising theoretical approaches to this problem.

164
00:27:23.970 --> 00:27:29.100
Mark Trodden: So that theoretical approach if I just take a very brief aside here. It's called massive gravity.

165
00:27:30.990 --> 00:27:42.120
Mark Trodden: So, a long time ago now home you know homing in on you know 90 years or so fits in poly showed how to write down a theory of massive gravity at the linear eyes level.

166
00:27:43.740 --> 00:27:48.120
Mark Trodden: This might seem like a jump to you. I was talking about cosmic acceleration non talking about massive craft.

167
00:27:48.630 --> 00:28:07.950
Mark Trodden: The reason I'm interested in this is that forces that are mediated by massive mediators have a finite range. And so if I want gravity, if you like to behave differently on large scales. One way to do that is to introduce a scale dependence and grab a massive gravity is where to do that.

168
00:28:09.150 --> 00:28:20.520
Mark Trodden: If it's a poly showed how to write down linear is version, but their version where they write down a mass term for the gravity on the dizzy clever combination of the trace of the gravity and gravity on squared.

169
00:28:22.410 --> 00:28:36.090
Mark Trodden: It turned out that as a showboat chambray ball were in desert in the 70s any attempt to nonlinear you complete a theory like that into some if you like massive version of general relativity was doomed.

170
00:28:36.720 --> 00:28:49.380
Mark Trodden: Every time you try to complete this linear is theory to our full theory you encounter one of these negative energy ghost fields that I mentioned earlier, and that seemed insurmountable to everyone for a long time.

171
00:28:51.000 --> 00:29:05.130
Mark Trodden: But over the last decade counter example or a class of contract samples to this have been found. And it's a relatively new, I'd

say very near as a decade old now and potentially exciting development and I want to talk a little bit about it.

172
00:29:06.330 --> 00:29:15.360
Mark Trodden: It's all grandjean you see this as a little girl engine for general relativity, but they're really you've got the Einstein Hilbert term. And then you've got a potential for the gravity.

173
00:29:16.590 --> 00:29:28.890
Mark Trodden: You might think that sounds completely obvious. Of course, that's how you write down a massive theory. But it turns out that the only way to do this is a very complicated way and that's why was entirely missed in the ghost in the ghost.

174
00:29:30.600 --> 00:29:33.810
Mark Trodden: In the board as a proof of nonlinear completions

175
00:29:34.530 --> 00:29:42.000
Mark Trodden: Now this theory is complicated and I won't talk about it in great detail here, I just want to say that it's been proven not to have ghosts.

176
00:29:42.300 --> 00:29:51.900
Mark Trodden: And many people have been investigating the cosmology, whether it admits acceleration, whether it solves the cosmological constant problem, etc, etc. For quite some years now.

177
00:29:53.490 --> 00:30:07.920
Mark Trodden: Now it's complicated to explain screaming in this theory, but luckily there's a limit of the theory where the only thing that matters is what's called the Galileo and so I'm going to focus on that as a placeholder for massive gravity to explain to you how screening works.

178
00:30:09.960 --> 00:30:19.680
Mark Trodden: So let's focus on Catalan lands. So there's a limit of massive gravity, where the only thing that remains is a four dimensional effective field theory of a scale of field.

179
00:30:20.490 --> 00:30:26.550
Mark Trodden: And I've been talking about scale of fields, all through this talk. What's so special about this one. Well, first of all, it has an interesting symmetry.

180
00:30:27.330 --> 00:30:35.010

Mark Trodden: It has a shift symmetry. The weeds traditional to call the field Pi, Pi goes to pi plus a constant. And it also has

181
00:30:35.550 --> 00:30:47.460
Mark Trodden: A symmetry in shifts of the derivative, if you took a derivative of that symmetry transformation on the screen, you would see that demystify because the DVD or five plus Vimeo and so

182
00:30:48.450 --> 00:30:54.180
Mark Trodden: What that means is it's got a double shifts in a tree and the any field theory with a cemetery is called the Galileo.

183
00:30:56.070 --> 00:31:03.630
Mark Trodden: It turns out that in four dimensions are there are only a few operates as you can write down that have this property.

184
00:31:04.470 --> 00:31:09.570
Mark Trodden: That's not quite true, as it turns out, there's an infinite number of operators, so I guess it's not true at all really

185
00:31:10.290 --> 00:31:16.440
Mark Trodden: There's an infinite number of operators, of course, any operator, you write down that looks like derivative derivative of pie to some power.

186
00:31:16.770 --> 00:31:24.270
Mark Trodden: Will trivially satisfy the symmetry. That's not the interesting sets of operators there another set of operators, the ones on the screen.

187
00:31:24.930 --> 00:31:37.140
Mark Trodden: All of which obey the symmetry and which are very interesting. So I want to explain this complicated expression LM plus one. So if I said the same four dimensions there are just five search operators and that's it.

188
00:31:38.580 --> 00:31:44.700
Mark Trodden: These theories are fascinating for a number of reasons. One is that there's a separation of scales in the theories

189
00:31:45.030 --> 00:31:55.050
Mark Trodden: That allows for classical field configurations that have auto one nonlinear charities, but their quantum corrects a complete effects are completely under control and I'll mention that again in a moment.

190
00:31:55.680 --> 00:32:12.600
Mark Trodden: But the great advantage of that is that it allows us to use very nonlinear solutions to the field equations that are still classical to try to address cosmological problems such as cosmic acceleration. One of these is the effect of screaming that I mentioned in a minute.

191
00:32:14.490 --> 00:32:19.560
Mark Trodden: So here's screening in this kind of lay on theory. This is a version of what's called the Einstein effect.

192
00:32:20.790 --> 00:32:29.850
Mark Trodden: So I'm good to take a very simple gelei on theory. It has a kinetic term. Don't worry about the normalization. It's just for my convenience. It has a kinetic term.

193
00:32:30.420 --> 00:32:37.890
Mark Trodden: And it has a strange derivative self coupling d pi squared box pie. So that's a higher derivative operator.

194
00:32:38.640 --> 00:32:46.740
Mark Trodden: And then I'm just going to give it the lowest order possible coupling to matter again coupling, just to the trace of the engine momentum of matter.

195
00:32:47.400 --> 00:32:55.740
Mark Trodden: And notice that the coupling constant of the coupling is the plank. So this is a scale of field with a gravitational strength coupling to all the rest of the matter.

196
00:32:56.190 --> 00:33:08.130
Mark Trodden: And a couple of slides back. I tried to convince you that that is usually a disaster for a theory because it leads to order one correction so general relativity in the solar system. And now I'm going to show you that for this theory that doesn't happen.

197
00:33:09.360 --> 00:33:15.540
Mark Trodden: So why is that so let's do what we did before will take spherical solutions around a point mass

198
00:33:16.710 --> 00:33:24.660
Mark Trodden: It turns out that around a point mass. I specialize to engine ransom tensor is that of appointment is the field pi gets a profile.

199
00:33:25.710 --> 00:33:37.800
Mark Trodden: Far away from the point mass in fact part of far away from some additional radius called of Einstein radius, it behaves just like a cool on law, one of our

200
00:33:38.580 --> 00:33:45.240
Mark Trodden: But close by. It doesn't do that close by, it behaves in some other way route r plus a constant.

201
00:33:46.110 --> 00:33:58.740
Mark Trodden: And you can take these two expressions and you can ask the question, what is the force on a test particle compared to gravitational forces at different distances from the source. Think of the sources of the sun, if you like.

202
00:33:59.880 --> 00:34:12.420
Mark Trodden: And here's that expression. And here's the remarkable fact far away. This is an order one correction to general relativity, or in fact to Newton's laws that is what you want from anything that's going to cause the universe to accelerate

203
00:34:14.850 --> 00:34:34.650
Mark Trodden: A close by less than this so called feinstein radius. The forces heavily suppressed by are divided by their Reinstein radius to some power. And so if you're closer than the vine shine radius, you're safe from fifth force tests in this theory. It's a remarkable thing.

204
00:34:36.240 --> 00:34:48.810
Mark Trodden: In fact, you can do better than that. You might wonder, well, maybe I'm safe from fifth false tests. But what about if I start wiggling the source than one tie wiggle the five field and create quantum it and and measure that

205
00:34:49.290 --> 00:34:57.150
Mark Trodden: And the answer again is no I take the equations of motion on a perturb the source which is T MY perturb the field.

206
00:34:57.510 --> 00:35:07.560
Mark Trodden: I get some complicated expression for the perturbations and I won't dwell on the equations here because of the audience. But what I want to say is that this is now your kinetic term.

207
00:35:08.160 --> 00:35:22.050
Mark Trodden: And that goes like our V over R. And so again, around this background. If you look at canonical a normalized perturbations, the

effect of strong coupling scale is high and the coupling to matter becomes very, very small indeed.

208
00:35:23.670 --> 00:35:35.430
Mark Trodden: So this is a long winded a mathematical way of saying the following. If you have these highly nonlinear self interactions have a field of a very special kind. In this case, the gamelan kind

209
00:35:36.600 --> 00:35:47.700
Mark Trodden: It turns out that you can exploit those nonlinear charities to heavily suppress local deviations from general relativity in a regime where the quantum effects can be ignored.

210
00:35:48.930 --> 00:36:00.420
Mark Trodden: Meanwhile, a very large distances. You can again recover an order one change to your original theory. And so as you might imagine when embedded in an actual theory of gravity. This effect.

211
00:36:00.990 --> 00:36:14.730
Mark Trodden: holds out the hope of keeping all the local tests of generativity obeyed, and yet, giving you an opportunity to have very large scale deviations from the predictions of GR. So this is something, for example, the dark energy could be

212
00:36:16.710 --> 00:36:26.460
Mark Trodden: These theories are strange for particle physicists, normally when you have I feel theory or regular field theory, there are sort of two resumes you care about.

213
00:36:27.060 --> 00:36:37.860
Mark Trodden: One is very, very in the far very, very short distance scales. If you like in the far UV your skills are much less than one over the cutoff of the theory.

214
00:36:38.520 --> 00:36:46.650
Mark Trodden: The classical if you like the classical size of classical fluctuations as large and the size of quantum fluctuations as large, you can't trust the theory at all.

215
00:36:48.870 --> 00:36:51.840
Mark Trodden: That's what we usually think of as the quantum regime and the theory.

216
00:36:53.340 --> 00:37:00.270

Mark Trodden: Was usually the far infrared where the classical fluctuations, a small and the quantum fluctuations, a small and you can make pejorative

217
00:37:01.710 --> 00:37:12.930
Mark Trodden: Predictions from the theory. And what this theory has these types of theories with this feinstein screening is a parametric large region in the middle between one of the cutoff and the Weinstein radius.

218
00:37:13.410 --> 00:37:22.380
Mark Trodden: Where you can have classical nonlinear charities that are large and yet the quantum non minorities are entirely under control.

219
00:37:25.710 --> 00:37:30.270
Mark Trodden: The reason this works, partly is due to a very powerful non normalization theorem.

220
00:37:31.170 --> 00:37:39.600
Mark Trodden: This is not something called dwell on but I do want to mention it for the experts. It turns out that terms of this Galilean form. I told you that with the special terms and the Lagrangian

221
00:37:40.140 --> 00:37:52.020
Mark Trodden: Are renowned normalized. Now I see here compared with Susie theories. What I mean there is Susie is another example of a theoretical structure where you have a non real normalization theorem, but here it's for a completely different reasons.

222
00:37:52.620 --> 00:38:01.770
Mark Trodden: As one of the things that makes them useful for particle physics and cosmology for here. I'll just say if you expand the quantum effective action for the classical field around its expectation value.

223
00:38:02.610 --> 00:38:15.900
Mark Trodden: Then once you find is that the endpoint contribution has a particular structure such that all the gun land terms I wrote down before cannot be normalized, you can just do it by hand by computing fireman diagrams and everything vanishes.

224
00:38:16.440 --> 00:38:20.550
Mark Trodden: And this is not quite well understood it was understood originally for the original gavel Leon's

225
00:38:21.450 --> 00:38:35.190

Mark Trodden: We worked on it later for a whole classes of calculations in any number of dimensions and the number of terms and we have a much better understanding of how this works now than we originally did, it's a very powerful feature of these theories

226
00:38:38.760 --> 00:38:52.500
Mark Trodden: So I did tell you that this is an effective technique for keeping things well behaved locally while allowing for example cosmic acceleration of large scales. How effective is it. Well, suppose I fix

227
00:38:53.070 --> 00:39:02.700
Mark Trodden: That the value of parameters in my theory so that I'm getting a modification at this Hubble scale of gravity of auto one cosmic acceleration, for example.

228
00:39:03.420 --> 00:39:13.860
Mark Trodden: And suppose that the object. Take care about is the sun and this line so called via Einstein radius, the distance inside of which things behave. Pretty much exactly like Jr.

229
00:39:14.220 --> 00:39:23.340
Mark Trodden: Is tend to the seven astronomical units absolutely enormous for the galaxy itself, the equivalent distance is 30 galactic radio

230
00:39:23.970 --> 00:39:36.450
Mark Trodden: And even for clusters. It's up to 10 variable radio. So the virus and effect is incredibly effective at suppressing local deviations from GR while allowing you to have long range deviations.

231
00:39:40.140 --> 00:39:48.570
Mark Trodden: So that all sounds quite wonderful. It sounds like theorists have discovered something remarkable that you should be able to use to tackle acceleration head on.

232
00:39:49.020 --> 00:39:56.400
Mark Trodden: It turns out that there are many things to be concerned about in this theory and this class of theories and one is cosmology itself.

233
00:39:57.510 --> 00:40:05.490
Mark Trodden: If you modify gravity in this way with massive gravity. It turns out new constraints arise entirely new constraints.

234
00:40:05.940 --> 00:40:15.570

Mark Trodden: And one of them, which I think was interesting unexpected when people wrote the theory down is that perfect homogeneous is a tropic solutions. The things we think of as

235
00:40:16.020 --> 00:40:28.500
Mark Trodden: Far W solutions. Just don't exist in massive gravity. Now, that shouldn't worry you horribly. You can find slightly in homogeneous versions that work almost test as well. But nevertheless, it's kind of amazing.

236
00:40:29.100 --> 00:40:41.040
Mark Trodden: Okay, so roughly what you're doing is taking the universe to be a bubble and then each bubble the Einstein mechanism works as it did in the solar system so that you can recover GR and approximately fo W solutions.

237
00:40:41.640 --> 00:40:49.170
Mark Trodden: Nevertheless, this is an example of the kind of complexity that any modification of generosity any dark energy theory. If you're like faces.

238
00:40:50.250 --> 00:41:03.930
Mark Trodden: So people have tried to extend massive gravity in a number of ways to get around these kinds of constraints. And I think that's an ongoing project. Some of these deviations might be interesting, but it's not. I would say a settled issue at this point.

239
00:41:06.090 --> 00:41:15.510
Mark Trodden: Is massive gravity up to the job cannot give us what we want. Well, minimal massive gravity has, as I said, fascinating features but faces. Some cosmological challenges.

240
00:41:15.930 --> 00:41:25.410
Mark Trodden: IT solutions are not small modifications of GR in some sense, that's the important point. So people have searched for expansions, they've taken goes free massive gravity, they've

241
00:41:26.340 --> 00:41:32.580
Mark Trodden: Allowed the master very they've introduced new fields into the theory kasi delta massive gravity, they've

242
00:41:32.970 --> 00:41:40.950
Mark Trodden: Extended those models. They've added della lands and on their own, not just as a limit, and they've even worked with theories with multiple metrics.

243
00:41:41.670 --> 00:41:51.150
Mark Trodden: I'm not writing these down as a way to sell you on the idea of tweaking ever tweaking and already very complicated theory. What I want you to understand is

244
00:41:51.630 --> 00:42:03.870
Mark Trodden: There is a theoretical framework here that was sort of unknown before people started thinking in this way. And it might be that as people play with it, something simple and compelling comes out, although that's yet to happen.

245
00:42:04.920 --> 00:42:13.470
Mark Trodden: So far it's a results and mix and there's a nice review article by Kurt enter back or in 2017 that I think really gives a nice summary of the relationships between these ideas.

246
00:42:15.810 --> 00:42:21.300
Mark Trodden: Nevertheless, armed with this general sets of models. You might wonder, how are we ever going to figure out

247
00:42:21.930 --> 00:42:29.520
Mark Trodden: What it is, that's driving cosmic acceleration. What's dark energy and suddenly you've had many other talks and you will have other talks in this

248
00:42:30.330 --> 00:42:40.170
Mark Trodden: SSI about this, but I did want to just say broadly, what the idea is. And then talk about recent developments. So the broad idea is very simple one.

249
00:42:40.860 --> 00:42:54.930
Mark Trodden: Okay, we have many different ways of probing comp gravity behaves week lending CNBC lending SW effect, etc, etc. What that means is that if you look as a function of scale. So here I've plotted the

250
00:42:55.950 --> 00:43:11.190
Mark Trodden: Massive power spectrum, then you get to probe the way in which gravity behaves of many different scales from the microwave background, all the way down to the company of intergalactic hydrogen and Lansing because of that you can exploit the fact that

251
00:43:12.270 --> 00:43:19.890
Mark Trodden: Gravity is not only behind the expansion history of the universe, you've got this complicated theory, the massive gravity Galilean some dark energy theory.

252
00:43:20.280 --> 00:43:30.150
Mark Trodden: It doesn't just cause the universe to accelerate, but it also must affect the way in which thing is clump up and in principle, every time you introduce a new dark energy model.

253
00:43:30.570 --> 00:43:36.150
Mark Trodden: It's a new scale in the theory and therefore, there can be a scale dependent difference in how matter clumps.

254
00:43:36.840 --> 00:43:47.910
Mark Trodden: And so the idea here is to try to distinguish a cosmological constant from dark energy from modified gravity by carefully construct reconstructing how matter clumps at different redshift.

255
00:43:48.330 --> 00:43:54.720
Mark Trodden: And distinguishing the way in which gravity behaves from general relativity at some or many of those wretches

256
00:43:55.770 --> 00:44:03.960
Mark Trodden: There is a massive amount of work to do here, some of it observational you've heard talks about that and much of it theoretical, how do you extract

257
00:44:04.770 --> 00:44:13.650
Mark Trodden: The relevant measurable quantities from these complicated screen theories and screening makes us a very difficult theoretical problem, by the way.

258
00:44:15.030 --> 00:44:16.650
Mark Trodden: Nevertheless, we have lots of tools.

259
00:44:18.150 --> 00:44:28.260
Mark Trodden: This analogy here with particle physics and I couldn't resist putting up in particle physics, you know, we look for new physics by doing two things.

260
00:44:28.650 --> 00:44:34.950
Mark Trodden: We can either increase the energy of collisions that allows us access to new events that just don't appear at lower energies.

261
00:44:35.910 --> 00:44:44.460

Mark Trodden: And then a complementary way to go about looking for new physics is to increase the luminosity of your accelerator. For example, produce more heads and measure decay roads, more accurately,

262
00:44:44.940 --> 00:44:57.420
Mark Trodden: And that can allow you to discover very rare decays all very rare events that at lower luminosity just could not be statistically significant, even though you're perfectly within the energy range in which they appear

263
00:44:58.950 --> 00:45:02.730
Mark Trodden: In survey cosmology, which is what I was really talking about on the last slide.

264
00:45:03.420 --> 00:45:08.760
Mark Trodden: There's a sort of parallel track you can increase the redshift of detection, you can look further away.

265
00:45:09.150 --> 00:45:14.880
Mark Trodden: To see new events new objects that are just absent at lower redshift, you will never have access to the unless you do that.

266
00:45:15.660 --> 00:45:21.510
Mark Trodden: But other way to do is to increase the number of objects detect more objects that allow more precise measurements of in homogeneity is

267
00:45:21.780 --> 00:45:31.050
Mark Trodden: And allow different signatures. For example, in the shape of the spectrum to be discovered at a statistically significant level that you could never have done if you'd only measured a few objects.

268
00:45:31.830 --> 00:45:39.840
Mark Trodden: And so this is a nice analogy, I think. And it allows you access to a lot of new physics and I took this little slide here from

269
00:45:41.190 --> 00:45:49.140
Mark Trodden: The science paper from the cosmic visions dark energy group that I was part of along with Aaron and other people I've listed here.

270
00:45:51.660 --> 00:45:59.340
Mark Trodden: But in recent years, of course, we can do even better or new you know better, but we have a completely complimentary way of thinking about this. We have new tools.

271
00:46:00.270 --> 00:46:19.740
Mark Trodden: Okay, so why go Virgo talking to you, serving and collaboration already bonding, many of the ideas. I told you about in theory spaces. Getting a lot narrower and it's getting a lot a lot narrower very quickly. Okay. So to give you an example of that with a single event in 2017

272
00:46:21.180 --> 00:46:33.990
Mark Trodden: GW 1717 and the associated gamma ray burst a huge region of the modified gravity and related theory space were completely rolled up a solutions for cosmic acceleration by one of that.

273
00:46:35.340 --> 00:46:46.140
Mark Trodden: And as we measure more events. These constraints are going to get tighter and it's possible that we will kill even more theoretical ideas or a spectacular discovery could be just around the corner.

274
00:46:47.190 --> 00:46:57.690
Mark Trodden: I tried to point out in previous slides, how important it is to look at the behavior of whatever you think dark energy could be around every different background.

275
00:46:58.320 --> 00:47:15.240
Mark Trodden: It's fine to get something that gives you cosmic acceleration. But what does that feel though that set of interactions do around a black hole say are on a pair of black holes because it could be that you radiate your new fields and that radiation is already bounded by, like, oh, for example.

276
00:47:16.590 --> 00:47:28.050
Mark Trodden: Give you an example of that this particular event. I'm talking about. There were a bunch of relevant papers. I've picked one here and I probably will regret that when people write to me the landscape for scale of sensor theories

277
00:47:29.100 --> 00:47:34.290
Mark Trodden: Became very different to one or two been prior to October of 2017

278
00:47:35.430 --> 00:47:48.570
Mark Trodden: If you take a theory of scale of sensors and you allow many, many types of different directions, then the landscape becomes summer buys will summarize a book like this fi allow a function of the kinetic term.

279

00:47:49.320 --> 00:47:57.660
Mark Trodden: We had self derivative interactions, like this one, like the gal lamb one and we had coupling. So the ratio scale or you find that terms like this are okay.

280
00:47:58.740 --> 00:48:07.140
Mark Trodden: But as soon as you introduce any other interactions. And again, the equations here just to guide the guide. The point is just this is a rather the first equation here is a rather restrictive one

281
00:48:07.560 --> 00:48:13.200
Mark Trodden: As soon as you go to anything more complex, you hit all kinds of problems due to the gravitational wave constraints.

282
00:48:13.710 --> 00:48:21.510
Mark Trodden: And the only way to resurrect these gravitational theories is if the scale is non cosmological, in which case you're not interested in cosmic acceleration anymore.

283
00:48:22.320 --> 00:48:27.300
Mark Trodden: Maybe there's some sort of tuning between the functions, in which case you have to worry about the theoretical issues I talked about

284
00:48:27.660 --> 00:48:41.400
Mark Trodden: You have a tuning in the initial conditions seems very unnatural or they lie in some very special class of theories which I've called here on desktop class where the tensor speed of sound is equal to the speed of light.

285
00:48:42.240 --> 00:48:48.180
Mark Trodden: So I don't expect you to take away a theoretical conclusion from this slide. What I want to point out is that

286
00:48:48.690 --> 00:49:01.050
Mark Trodden: Not only do we have a very healthy set of cosmological measurements that are allowing us to sort of hone in on the answer if you like, but we're also have new things from astrophysics that are killing theories, day by day.

287
00:49:03.180 --> 00:49:04.500
Mark Trodden: So these theories are difficult

288
00:49:06.060 --> 00:49:12.240

Mark Trodden: What we're doing is laying out criteria that must be satisfied by the theories. If you're asking what doc energy is there's a lot of work to be done.

289
00:49:12.780 --> 00:49:17.820
Mark Trodden: Screening is very powerful. And it turns out it's better than needed to recover local tests of gravity.

290
00:49:18.780 --> 00:49:33.720
Mark Trodden: The behavior around different sources and time dependent ones in particular is complicated and there's a lot of work to do there. The message here is that if we're really going to map out a space of allowed solutions to cosmic exploration of what dark energy could be

291
00:49:34.860 --> 00:49:42.990
Mark Trodden: There's some very hard work that remains to be done, particularly to give the kind of concrete predictions that are experimental and observational colleagues need

292
00:49:44.760 --> 00:49:46.050
Mark Trodden: I mentioned a little bit

293
00:49:47.070 --> 00:49:58.230
Mark Trodden: In passing that these theories have uncertain ultra violent behavior. Some of these theories. When you take them seriously as particle physics theories, you can show do not admit

294
00:49:58.620 --> 00:50:14.460
Mark Trodden: It will Sony on completion UV completion. So it might be that something exotic as needed there, depending on your taste that's either a great worry about the theories or a great challenge opening up a new theoretical Vista and I want way in one way or another here.

295
00:50:15.960 --> 00:50:26.070
Mark Trodden: So to summarize, um, cosmic isolation is obviously one of our deepest problems. But the good news is data just continues to flooded. It's an amazing time to be a cosmologists

296
00:50:27.180 --> 00:50:32.670
Mark Trodden: The theory faces serious questions posed by the data, even if it was a constant as a right answer.

297
00:50:33.120 --> 00:50:43.860
Mark Trodden: And many of us are hard at work on this and it's very clear that if you're going to understand this problem or have a hope of

understanding it, you're going to need insights from cosmology from gravitation and from particle physics.

298
00:50:44.700 --> 00:50:53.790
Mark Trodden: In my personal opinion, we still seem really very far from a solution. But there have been many interesting and challenging new ideas in the recent years and decades.

299
00:50:54.300 --> 00:51:05.730
Mark Trodden: And not only are those ideas still alive and waiting to be explored, but they might actually find uses way beyond this question. So in some sense, theory space has been expanded just by thinking about this problem.

300
00:51:07.740 --> 00:51:17.940
Mark Trodden: But many ideas have been rolled out completely automatically constrained by combined measurements from surveys and completely new types of measurements from Lego. And that's the sign of a healthy field, I think.

301
00:51:19.170 --> 00:51:31.770
Mark Trodden: And the last thing I'd like to say is that serious models only need apply. I spent a lot of time in this talk hammering the issue of theoretical consistency. It's not enough to write down a model that is

302
00:51:33.060 --> 00:51:42.480
Mark Trodden: Abstract and has no connection to fundamental physics but happens to give an accelerating universe we need models in which the right set of questions about theoretical consistency can be asked.

303
00:51:42.930 --> 00:51:52.470
Mark Trodden: And a way to thoroughly investigate the answers or it's not a primetime contender for what dark energy could be. And I think I'll stop there. Thank you.

304
00:51:55.230 --> 00:51:57.780
mark convery: Great, thank you very much, Mark. Very, very compelling talk

305
00:51:59.520 --> 00:52:07.020
mark convery: Yes, you're just almost exactly in time, maybe a minute. A minute early so time for questions. And so I'll pass it over to Saddam expansion. The q&a

306
00:52:09.060 --> 00:52:16.260

dong su: Okay, thanks for the larger. And so let's get on with the questions I think we're on page 11 to make your

307
00:52:17.580 --> 00:52:20.490
dong su: Side 11 511 so um

308
00:52:21.780 --> 00:52:25.710
dong su: So, so what does it mean for a field to be dynamical

309
00:52:28.050 --> 00:52:29.490
Mark Trodden: Ah, sorry I

310
00:52:30.600 --> 00:52:33.720
Mark Trodden: Give me a second here. I'm not making this easy for myself.

311
00:52:34.920 --> 00:52:35.430
Mark Trodden: I'm

312
00:52:38.220 --> 00:52:39.060
Mark Trodden: Sorry, guys.

313
00:52:43.710 --> 00:52:48.840
Mark Trodden: So maybe I'll just say the cosmological constant is very special. Um,

314
00:52:50.370 --> 00:52:52.710
Mark Trodden: You know the name is not an accident.

315
00:52:53.820 --> 00:53:02.580
Mark Trodden: In the cosmos or constant cannot change in space or time. So the you know that that lawrenson various demands that it is completely a constant.

316
00:53:03.150 --> 00:53:18.090
Mark Trodden: And what that means in particular is that all a cosmological constant does is it changes the expansion history of the universe. It can affect the way in which things cluster, because the universe is

317
00:53:20.400 --> 00:53:31.530
Mark Trodden: Expanding in that way, but it does not contribute a new interaction between matter or between the thing between Gravity Forms themselves. There's no new interaction there.

318
00:53:32.070 --> 00:53:48.720
Mark Trodden: It's really, in some sense, just a source term in the equations. So I was trying to distinguish using the word dynamical distinguish it explicitly from dark energy, or what if I gravity, where there is always some new degree of freedom that is evolving in space and time.

319
00:53:52.860 --> 00:53:53.160
dong su: Yeah.

320
00:53:54.240 --> 00:54:00.480
dong su: Okay, so there is a one question. I'm up for a compartment exactly right here is actually on also on page 11

321
00:54:00.600 --> 00:54:11.130
dong su: Okay, it's it's related to the fact you say the, the vector and scale or the pin. And so, so the basic

322
00:54:12.210 --> 00:54:13.260
dong su: Thing. The question say

323
00:54:14.730 --> 00:54:24.210
dong su: What extend the gas. The that is constrained why these components cannot be allow or how how they are constrained and

324
00:54:26.280 --> 00:54:32.700
Mark Trodden: So one of different levels to answer that question. But let me, let me try to be very nuts and bolts about it. Um, general relativity

325
00:54:33.780 --> 00:54:41.130
Mark Trodden: Has a constraint equation you can think of it in some sense as the gases law constraint of general relativity and

326
00:54:42.270 --> 00:54:46.350
Mark Trodden: Within GR that's just a fact. And what that means is that

327
00:54:48.270 --> 00:54:55.920
Mark Trodden: You know, if you decompose the metric in this way you would find that these fields were not dynamical fields at all in the theory.

328
00:54:57.210 --> 00:54:57.810
Mark Trodden: Now,

329
00:54:59.220 --> 00:55:12.330
Mark Trodden: If you, if you modify GR there are, you know, quite benign ways to modify GR in this in a theoretical sense that don't make the theory sick. For example, you can

330
00:55:13.170 --> 00:55:19.980
Mark Trodden: Just make change or in the Einstein Hilbert action to r squared. For example, that's what started been seated.

331
00:55:20.730 --> 00:55:25.650
Mark Trodden: In Stravinsky inflation and what you find is there. That seems like a very simple thing to do.

332
00:55:26.040 --> 00:55:31.560
Mark Trodden: But if you do that and you write down the equations of motion for general relativity, you'll find that the constraint equation of general relativity

333
00:55:31.890 --> 00:55:41.670
Mark Trodden: Now becomes a dynamical equation it describes a propagating degree of freedom and the theory. And as a result, by doing a set of field redefinition you will find that that theory.

334
00:55:42.480 --> 00:55:50.310
Mark Trodden: R squared and Lagrangian is secretly a theory of gravity forms split master spin to Gravity Forms and the scale of field.

335
00:55:51.390 --> 00:55:53.100
Mark Trodden: So I'm not sure if I'm answering the question, but

336
00:55:53.520 --> 00:55:54.390
Mark Trodden: Right, meaning

337
00:55:54.510 --> 00:56:04.440
dong su: That you know maybe also is are some experimental constraints, to what degree there constraint as a sort of from their point of view.

338
00:56:04.500 --> 00:56:11.970
Mark Trodden: Absolutely, absolutely. So it's not a smooth limit right so so once you introduce any change here you have a new scale.

339
00:56:12.360 --> 00:56:24.540

Mark Trodden: And and unless you do something very clever that stay low will now mediate a scale of force that competes with gravity. And so typically within the solar system.

340
00:56:25.440 --> 00:56:40.620
Mark Trodden: Are the simplest things you would do to modify general relativity play around with the Einstein helmet action introduce a new degree of freedom and are immediately ruled out because all the predictions of GR are violated at all to one.

341
00:56:42.030 --> 00:56:54.810
dong su: Yeah, right. Yeah. Okay, so also here. I think you mentioned the later is that there's a question on how live over gumbo. There's, there's one event I already told you the speed

342
00:56:55.380 --> 00:57:04.500
dong su: The speed of the gravitational waves. And it's just like speed of light, how does that actually constrain the modified GR specifically

343
00:57:05.790 --> 00:57:10.380
Mark Trodden: So what I did when I won't never get to that page, unless you need me, sir, but

344
00:57:12.030 --> 00:57:19.230
Mark Trodden: What I focused on there was the following what people have done is they write down the most general

345
00:57:20.100 --> 00:57:34.860
Mark Trodden: theory of gravity couple to scale of fields that has no ghosts that is only second order equations of motion and that most general theory is a very complicated theory and it's called a horn dusky theory as many, many terms.

346
00:57:36.030 --> 00:57:42.900
Mark Trodden: And then within that theory. You can I should say that theory on its own has no guiding symmetry principle or anything, but

347
00:57:43.170 --> 00:57:57.570
Mark Trodden: Contained within that theory are, for example, almost any dark energy model you've ever thought of the gala Leon's so many, many things that people care about a contained in that class of theories and then you know you could wonder, you know, how

348
00:57:58.860 --> 00:58:02.490

Mark Trodden: Which of these terms in this large number of template are allowed.

349
00:58:03.420 --> 00:58:19.620
Mark Trodden: Don't screw up this measurement of the speed of gravity being compared to the speed of light. And the answer is almost all of them actually are a problem. And so if you tune your parameters within the theory to give you cosmic acceleration. It turns out that

350
00:58:21.150 --> 00:58:29.490
Mark Trodden: Many of those terms, you have to set to zero or they will change the speed of gravity enough to come in violation of that single gravitational wave event.

351
00:58:30.360 --> 00:58:41.820
Mark Trodden: So I didn't give you a complete answer for, for example, massive gravity itself I think is unconstrained by that event because the mass of the private time is so low in that model.

352
00:58:42.630 --> 00:58:49.380
Mark Trodden: But many, many other theories are constrained by it. And so that's kind of what I meant about the hope for gravitational wave of astronomy that

353
00:58:49.860 --> 00:59:01.230
Mark Trodden: Not only is it killed a lot of these scale attentive theories with one blow the hope is that as you go on, it will provide constraints on things like massive gravity and other such exotic ideas.

354
00:59:02.370 --> 00:59:07.980
dong su: Okay, thanks. So the next question on page 17

355
00:59:10.950 --> 00:59:18.240
dong su: There's a statement. There's related to the another Tricity of the. So what does that mean

356
00:59:19.080 --> 00:59:23.370
Mark Trodden: Yeah, I looked at slide by critically, didn't I, um, so

357
00:59:25.740 --> 00:59:26.040
Yeah.

358
00:59:28.800 --> 00:59:30.840
Mark Trodden: So when you write down an effective field theory.

359
00:59:32.340 --> 00:59:36.060
Mark Trodden: You know, if you're a particle physicists you're used to the notion that

360
00:59:37.800 --> 00:59:43.620
Mark Trodden: You tell me the cemeteries that I'm interested in, and you tell me the the field you're interested in. And now I write down

361
00:59:44.100 --> 00:59:57.540
Mark Trodden: Every operator that has allowed by that symmetry. And now I have a good effect to feel theory and, you know, if I if, as long as I'm below the cutoff of the theory, I can just truncate that theory and it's fine. It's a perfectly fine effective filtering.

362
00:59:58.920 --> 01:00:08.850
Mark Trodden: And the whole notion of effective theories, really, is that you don't care about the Ultra violence, you have the ultraviolet is you're working in a regime where you don't care about the ultraviolet at all.

363
01:00:09.480 --> 01:00:20.130
Mark Trodden: But it turns out that there are certain things about the low energy theory that are dependent on the ultraviolet theory and one is just to give you an example. The signs.

364
01:00:20.400 --> 01:00:31.290
Mark Trodden: Of certain terms in the Lagrangian. So I'm on slide 17 right now, just to give you an example. You see this equation in the middle where I write down on Lagrangian for a scale of field.

365
01:00:32.580 --> 01:00:38.430
Mark Trodden: And I have this middle term that has one overlander cubed. And let's ignore the final term set that to zero.

366
01:00:39.180 --> 01:00:45.810
Mark Trodden: It turns out that as an effective field theory, you're not allowed to arbitrarily change the sign of that term.

367
01:00:46.350 --> 01:00:58.170
Mark Trodden: And the reason is that there are properties of the whole S matrix of the theory that depend on the sign of some operators in the low energy theory and so

368

01:00:58.860 --> 01:01:13.560
Mark Trodden: What you do is you. What is typically done. And this is a set of techniques that were developed in the 60s. If you look at the sort of complex if I'd asked matrix, you asked how it behaves as an analytic function of them a mentor and you find that

369
01:01:14.760 --> 01:01:28.260
Mark Trodden: The demands of analytic city of the matrix which you can think of as being equivalent to demanding that the theory be unitary ultimately have violated. If you make the wrong choice of certain signs and the low energy theory.

370
01:01:29.460 --> 01:01:31.080
Mark Trodden: I don't know if that's a good explanation or not.

371
01:01:32.640 --> 01:01:39.480
dong su: Okay well take that and so maybe let's move on to the next one. On page plenty of

372
01:01:41.130 --> 01:01:42.360
dong su: What's a nonlinear

373
01:01:42.420 --> 01:01:43.200
Completion.

374
01:01:44.760 --> 01:01:45.600
Mark Trodden: Yeah, so

375
01:01:46.680 --> 01:01:55.050
Mark Trodden: Yeah, very good. So you think about the Einstein Hilbert action for general relativity its root minus t times the richest Keller.

376
01:01:56.220 --> 01:02:08.760
Mark Trodden: And now, if you take the metric G Munir and you do what a good particle physicist should do you say, well, the metric is a background. Think of it as flat space plus a probation each new new

377
01:02:09.120 --> 01:02:20.910
Mark Trodden: New expand out the action, you'll find that there's a kinetic term for the probation and then there are interaction terms which you won't find in general relativity is an interaction term that had looks like a mass

378
01:02:22.230 --> 01:02:34.080

Mark Trodden: Well, feed some poly did is to come at this the other way around. They say take a theory of a spin to particle. So just take the kinetic term if you like from general relativity just

379
01:02:35.160 --> 01:02:36.900
Mark Trodden: That yeah the connector.

380
01:02:37.920 --> 01:02:47.040
Mark Trodden: And add a master, which is this town, and then they say, could I write down a theory which looks like route minus g something

381
01:02:47.580 --> 01:02:52.110
Mark Trodden: That when I specialize to expanding around the background generates a mass term like this.

382
01:02:52.770 --> 01:03:04.890
Mark Trodden: So that would be some very nonlinear theory just in the sense that general relativity is the nonlinear completion of the theory of linear as gravitational waves. This would be a nonlinear version of this massive gravity theory.

383
01:03:07.140 --> 01:03:14.670
Mark Trodden: So it would involve all the curvature and variants that would involve you know an infinite number of terms and principal summed up into some function.

384
01:03:16.110 --> 01:03:27.180
dong su: Right. Okay. So the next question is on Page 29 actually also notice appeared again that later on is what is the RS W effect.

385
01:03:28.890 --> 01:03:31.140
Mark Trodden: Oh, the integrated sex wolf effect.

386
01:03:32.310 --> 01:03:36.090
Mark Trodden: That is the effect of

387
01:03:37.830 --> 01:03:52.470
Mark Trodden: The way in which as photons traverse the universe as they well in this case as photons leave the surface of last scattering, but it also happens at late times as photons traverse the universe. If you imagine you've got some potential well

388
01:03:53.940 --> 01:04:02.400

Mark Trodden: In the universe actually forget the universe. Imagine you have some potential well and I send a photon past it. So I send a photon past the sun, let's say,

389
01:04:03.270 --> 01:04:09.360
Mark Trodden: Then you know what will happen the photon comes along, it sort of falls into the gravitational well of the sun.

390
01:04:09.840 --> 01:04:21.810
Mark Trodden: It gains energy as it falls into the gravitational well and as it comes out of the other side of the gravitational well it gains energy and far away from the sun. It has exactly the same energy as when it came. Does that make sense.

391
01:04:23.700 --> 01:04:29.520
Mark Trodden: So in in cosmology as photons come through the universe or when they leave the surface of a scattering

392
01:04:29.760 --> 01:04:43.620
Mark Trodden: Those potential roles are evolving in time because of the expansion of the universe. And so that can be a net effect on microwave background photons as they traverse changing gravitational potentials in the universe. And that's called the integrated sex wolf effect.

393
01:04:45.690 --> 01:04:50.490
dong su: Okay, thanks. So there's a question on page 15

394
01:04:52.530 --> 01:05:00.840
dong su: Where you have the exclamation mark on has both. So the question is the in what way is the, what's the meaning of the goals and

395
01:05:02.640 --> 01:05:12.030
Mark Trodden: So the ghost for me is at. So it depends on your signature the signatures. I like to use in particle physics much, just like the scale of fields because they're the easiest

396
01:05:12.480 --> 01:05:21.750
Mark Trodden: If I write down what what growth engine for scale field I right to this minus one half defy squared. And if you have a field in your theory that looks like plus one half.

397
01:05:22.410 --> 01:05:33.420
Mark Trodden: Squared that field is a ghost. And that means is that if you were to write down the kinetic energy of particles of quantum that theory, it would be negative. And that would be a ghost.

398
01:05:35.910 --> 01:05:36.570
dong su: Okay.

399
01:05:37.680 --> 01:05:41.160
dong su: Yeah, there's a question. I think I'm more for composter very well here.

400
01:05:42.210 --> 01:05:48.150
dong su: Is related to the massive neutrinos i is how

401
01:05:50.010 --> 01:06:00.360
dong su: What's a consensus on mastering neutrino. That's the part I don't understand what what it meant by the past very up knows in relation to dark energy or in general how the

402
01:06:01.530 --> 01:06:06.900
dong su: The up nomads, and maybe related to the to this question.

403
01:06:08.550 --> 01:06:11.970
Mark Trodden: Well, I'm gonna help you and not the question. Or I guess I

404
01:06:12.360 --> 01:06:19.260
Mark Trodden: I haven't thought about mastering neutrinos in quite a long time. So I'm don't think I can really answer the question as to what people think about them right now but

405
01:06:19.620 --> 01:06:36.000
Mark Trodden: The notes the notion here is that if neutrinos are coupled to some scale of field and cosmology than their masses will vary as the universe evolves and these are these are called mavens on mastering your trainers that people like Nelson and People talk a lot about and

406
01:06:38.700 --> 01:06:55.500
Mark Trodden: I have not thought about. So the reason people were interested, I should say is there is sort of a coincidence of scales between the dark energy scale and the neutrino mass gap scale. So people did try to exploit that by coupling them. I don't know of any

407
01:06:56.550 --> 01:07:02.580
Mark Trodden: You know model that is compelling that people are working on today that does that. But it could just be my ignorance.

408

01:07:05.130 --> 01:07:10.710
dong su: Yeah. OK. So maybe we'll have a one minute I'll maybe throw in a question myself.

409
01:07:11.460 --> 01:07:12.630
dong su: Things actually happen.

410
01:07:13.500 --> 01:07:18.660
dong su: Reason recently there's a paper I think from soccer at all from Oxford on the

411
01:07:20.370 --> 01:07:30.420
dong su: Observation would maybe maybe some hint of non as a property actually from the observational supernovae, which would seem to maybe implying there.

412
01:07:31.740 --> 01:07:47.610
dong su: Were special observer nurse mo whole CMT typo effect which may say that the measurement, we're looking at all. Supernovae is actually bias is not a little more general observation, what, what's your comment on that one.

413
01:07:49.290 --> 01:07:59.160
Mark Trodden: Well, I think I'm going to appeal to theorists modesty there and say you should ask an observation as an observer. And that question i i

414
01:07:59.730 --> 01:08:05.340
Mark Trodden: I know that there has been a lot of controversy over that and I do not see a lot of my

415
01:08:05.850 --> 01:08:18.150
Mark Trodden: Observational colleagues jumping on that result and saying, we agree with it. In fact, I see people saying they disagree, but I'm definitely not qualified to tell you the answer that question. One thing I would say is

416
01:08:19.440 --> 01:08:27.630
Mark Trodden: I didn't get a chance to mention in the talk. But if you really thought that there's a possibility that we occupy a special place in the universe. There are ways to make

417
01:08:28.230 --> 01:08:35.280
Mark Trodden: Some of the effects of acceleration appear from the fact that we live in extremely special place like at the center of avoid

418
01:08:35.850 --> 01:08:47.370
Mark Trodden: But that does require a lot of fine tuning of opposition, indeed, but I suspect that's a different question to the question of the sub bias supernovae question but yeah i i

419
01:08:48.510 --> 01:08:52.110
Mark Trodden: I am way too far away from the data, you should ask Aaron that question or someone else.

420
01:08:54.180 --> 01:08:58.440
dong su: Right. Okay, so maybe by the experimental is have a chance to comment on that one.

421
01:08:58.860 --> 01:09:01.920
Mark Trodden: Yeah, we use into the interrupt Adams talk and ask him that

422
01:09:03.720 --> 01:09:03.930
dong su: Right.

423
01:09:05.190 --> 01:09:17.190
dong su: Okay, I think that's all the all the questions, then we will still hopefully you enter the with a written form. Later on we pass on the Google Doc written on recording

424
01:09:18.210 --> 01:09:19.350
Mark Trodden: Sure. Okay.

425
01:09:19.560 --> 01:09:20.190
dong su: Thanks very much.

426
01:09:20.280 --> 01:09:21.750
Mark Trodden: I think thank you for having me. Bye.

427
01:09:22.320 --> 01:09:23.190
mark convery: Thank you very much, Mark.

428
01:09:24.450 --> 01:09:27.090
mark convery: We will all end the recording here.

429
01:09:27.750 --> 01:09:28.470
Thanks, Mark.

430
01:09:29.550 --> 01:09:29.970
Mark Trodden: Sharp.