PROFESSOR: So I want to begin by reviewing a little bit what I said last time in terms of this overview lecture. And then we'll finish the overview lecture. So summary of last lecture is actually on five slides. It's not all on this one slide. We started by talking about the standard Big Bang, by which I mean the Big Bang without thinking about inflation. And I pointed out that it really describes only the aftermath of a bang. It begins with the description of the universe as a hot, dense soup of particles which more or less uniformly fills the entire available space, and the entire system is already expanding.

Cosmic inflation is a prequel to the conventional Big Bang story. It describes how repulsive gravity, which in the context of general relativity, can happen as a consequence of negative pressure. This repulsive gravity could have driven a tiny patch of the early universe into a gigantic burst of exponential expansion. And our visible universe would then be the aftermath of that event.

As this happened, the total energy of this patch would be very small and could even be identically 0. And the way that's possible is caused by the fact that the gravitational field that fills the space has a negative contribution to the energy. And as far as we can tell in our real universe, there are about equal to each other. They could cancel each other exactly as far as we can tell. So the total energy could in fact be exactly zero, which is what allows one to build a huge universe starting from either nothing or almost nothing.

Inflation. The next item is evidence for inflation. Why do we think there's at least a good chance that our universe underwent inflation? And I pointed out three items. The first was that inflation could explain the large scale uniformity that we observe in the universe and that large scale uniformity is seen most clearly in the cosmic microwave background radiation, which is observed to be uniform to one part in $100,000, that is same intensity all across the sky no matter what direction you look, once you account for the Earth's motion, to an accuracy of one part in 100,000.

Secondly, inflation can explain a rather remarkable fact about this quantity omega, where omega is defined as the actual mass density of the universe rho divided by rho critical, the critical mass density which is the density that would make the universe precisely flat. The statement that that ratio is equal to 1 we know is accurate to about 15 decimal places at one second after the Big Bang. And prior to inflation, we didn't really have any explanation for that at all. But inflation drives omega to one and gives us an explanation for why, therefore, started out so extraordinarily close to 1.

And in fact, it makes a prediction. We'd expect that if inflation is right, omega should still be one today. And we now have measured omega to be 1.0010 plus or minus 0.0065, which I think is fabulous. Finally, inflation gives an explanation for the inhomogeneities that we see in the universe. It explains them as quantum fluctuations which happened during the inflationary process and, most importantly really, as inflation was ending, the quantum fluctuations cause inflation to go on for a little bit longer in some regions than others. And that sets up these inhomogeneities.

Today, we can see these inhomogeneities most accurately. inhomogeneities, of course, are huge at the level of galaxies, so they're obvious. But it's hard to connect them to the early universe. So we can make our most precise comparison between what we observe and theories of the early universe by making careful observations of the cosmic background radiation itself, which has these ripples in the intensity, It is not quite uniform. There really are ripples at the level of one part in 100,000, which can now be observed.

And inflation makes a clear prediction for the spectrum of those ripples, how the intensity should vary with wavelength. And I showed you this graph last time from the Planck satellite. The agreement between the prediction and the theory is really marvelous. So we'll be coming back to that near the end of the course. Finally, in the last lecture, I began to talk about inflation and the possible implications for a multiverse, the idea that our universe might be embedded in a much larger thing consisting of many universes, which we call a multiverse. And the key point is that most inflation models tend to become eternal. And that is once inflation starts, it never stops.

And the reason for that, basically, is that the metastable material, this repulsive gravity material that's causing the inflation, decays, but it also exponentially expands. And for typical models, the exponential expansion completely overpowers the decay. So even though it's an unstable material that decays, the total volume of it actually increases exponentially with time rather than decreases.

Decays happen however, and wherever decay happen, it forms what we call a pocket universe. We would be living in one of those pocket universes. And the number of pocket universes grows exponentially with time as the whole system grows and goes on, as far as we can tell, forever. And that is the picture of the multiverse that inflation tends to lead to.

Finally, this is my last summary slide and then we'll start new material. At the very end of lecture, I talked about a problem, which is very important in our present day thinking about physics and cosmology, and that is the nightmare that this discovery of dark energy leads to. What was discovered at about 1998 is that the expansion of the universe is not slowing down under the influence of gravity as one might expect, but Instead, it's actually accelerating. The universe is expanding faster and faster.

And that indicates that space today is filled with some repulsive gravity material, which we call the dark energy. And the simplest interpretation of the dark energy is that it simply vacuum energy, the energy of empty space. Space does have an energy density that have exactly the properties that we observe, so it seems natural to draw that connection.

Vacuum energy, at first, might seem surprising. If a vacuum's empty, why should it have any mass density? But in a quantum field theory, it's really not surprising because in a quantum field theory, the vacuum is really not empty. In a quantum field theory, there's no such thing as actual emptiness. Instead, in the vacuum, one has constant quantum fluctuations of fields. And in our current theory of particle physics, the standard model of particle physics, there's even one particular field called the Higgs field, which has a non-zero mean value in the vacuum besides fluctuations.

So the vacuum is a very complicated state. What makes it the vacuum is simply that it's alleged to be the state of lowest possible energy density, but that doesn't have to be zero and doesn't even look like there's any reason why it should be zero. So there's no problem buying the fact that maybe the vacuum does have a non-zero energy density. The problem comes about though when we try to understand the magnitude of this vacuum energy. If it was going to have a vacuum energy density, we'd expect it to be vastly larger than what is observed in the form of the expansion acceleration of the universe.

So a typical order of magnitude in the particle physics model for the vacuum energy is, in fact, about a full 120 orders of magnitude larger than the number that's implied by the acceleration of the universe. So that is a big problem. I began to talk about a possible resolution to that problem. It's only a possible resolution. Nobody has really settled on this. But there's a possible resolution which comes out of String theory, and in particular from this idea, which is called the landscape of String theory.

Most String theorists believe that String theory has no unique vacuum, but instead, there's a colossal number, perhaps something like 10 to the 500, different metastable states, which even though they are metastable, are incredibly long-lived, long-lived compared to the age of the universe as we know it. So any one of these 10 to the 500 different states could serve as effectively the vacuum for one of these pocket universes.

And the different pocket universes would presumably fill the whole set of possible vacua in the landscape, giving reality to all these possibilities that come about in String theory. And in particular, each different type of vacuum would have its own vacuum energy density. And because there are both positive and negative contributions-- I think I didn't read that out loud-- but there are both positive and negative contributions that arise in quantum field theories.

So the vacuum energy of a typical state could be either positive or negative. And what we would expect of these 10 to the 500 different vacua is that they would have a range of energy densities that would range from something like minus 10 to the 120 to plus 10 to the 120 times the observed value. So the observed value would be in there, but would be an incredibly small fraction of the universes. Yes?

AUDIENCE: Does this mean that so many pocket universes could be closed and opened as well in terms of their geometry? Or--

PROFESSOR: They're actually predicted to be open due to complications about how they form, which I'm not going to go into. But they should all be open, but very close to flat for the ones that under a lot of inflation. So they'd be indistinguishable from flat, but technically, they'd be open. Yes?

AUDIENCE: Is the minus 10 to the 120 plus 10 to the 120 just chosen because we're off 520 orders of magnitude, or is it predicted somewhere else?

PROFESSOR: Well, when we say we're off by 120 orders of magnitude, the more precise statement is that the estimate of what a typical range of the energy should be is 10 to 120 times the observed value. So this is basically just a restatement of that. And you might wonder why I didn't put 5 times 10 to the 120, but in fact, the 120 itself is only accurate to within a few orders of magnitude, so 5 times that wouldn't have made any difference in the way one actually interprets those numbers. 10 to the 123 is probably slightly more accurate number actually. But this is good enough for our purposes. Yes?

AUDIENCE: Just a general question about inflation properties. We think of attractive gravity as driving the motion of objects through space. So why do we think of repulsive gravity like to drive the expanse of space itself?

PROFESSOR: Well, for one thing, it does actually behave differently. Repulsive gravity, repulsive gravity that appears in general relativity, is not just ordinary gravity with the opposite sign. Ordinary gravity has the property that if I have two objects to attract each other with a force proportional to the masses of those objects. This repulsive gravity is actually an effect caused by the negative pressure in the space between. So if I have two objects, they will start to accelerate apart by the amount that's totally independent of the masses.

This is not really the masses that's causing it. So the whole force was completely different, so we can't really just compare them. In either case, when everything is moving apart, it's really a matter of viewpoint when you think of the whole space as expanding or whether you think of the particles as moving through space. In relativity, there's no way to put a needle on space, put a pen in it and say this is stationary. So we really can't say that the space is moving or not.

In cosmology, we usually find that the simpler picture and the one that we will generally use is that space expands with the matter. It gives a much simpler description of how things behave. Good question. Yes?

AUDIENCE: I have a question going back a few slides.

PROFESSOR: Sure, you want me to go back.

AUDIENCE: How the energy of the early universe seemed to be close to zero. Are there theoretical models that would explain or that would say it should be exactly 0?

PROFESSOR: Yeah, there are. I didn't mention it. But if the universe is closed, which is a possibility. Even if it's very nearly flat, it could still be closed. If it were closed, it would have exactly zero energy. Yes?

AUDIENCE: So the cosmic background, microwave background, picks ups that it's pretty similar in all directions once correct for it. And this leads to the thought that the cosmological principle all over the universe is pretty identical. Is it possible that we are actually located in just a smaller like circular pathway and it may be different than [? allowed. ?] And there's many of these patches, so we-- there's actually like a speckled form.

PROFESSOR: OK. So if you didn't hear the question, I was asked if it's possible that the universe is not really homogeneous on a very large scales, but really speckled, just that speckles are large and our speckle might look very different from other speckles that are far away. And that was the question. And the answer is certainly if the multiverse picture is right. That is exactly the case that's being predicted. These other pocket universes could be viewed as other speckles in your language, and they'd be very different from what we've observed.

So inflation actually changes one's attitude about this particular question. Back in the old days, before inflation, the uniformity of the universe had no explanation, so it became a postulate. And nobody postulates that something is uniform on that scale. If you are going to make a postulate, you just postulate that the universe is uniform. So that was the postulate that was in use.

But now that we think of the homogeneity of the universe as being generated by a dynamical process, inflation, then, it's a natural question to ask, what is the scale of the homogeneity that that generates. And it's certainly a scale that's much larger than what we can observe. So we don't really expect to see inhomogeneity as caused by different pockets of inflation, but the model seems to make it very plausible that is what we would see if we could see far enough. Any other questions while we're on a little break here? Yes?

AUDIENCE: If the universe is expanding, then I think like we are expanding as well, so how can we observe the change from a distance, in particular everything is increasing scale?

PROFESSOR: OK. That's a very good question. The question was if the universe is expanding, then the universe is everything. So everything is expanding. And if everything's expanding, when you compare things with rulers, they have the same length. So how would you even observe that everything was expanding? And the answer to that is that when we say the universe is expanding, we're not really saying that everything is expanding. When we say the universe is expanding, we really are saying that the galaxies are getting further apart from each other, but individual atoms are not getting bigger.

The length of a ruler, determined by the number of atoms and how those atoms move to ground state, does not expand with the universe. So the expansion is now partially driven by the repulsive gravity that exists now, which is causing the universe to accelerate. But most of the expansion is really just a residual velocity from the Big Bang, whatever caused it then. I would assert inflation. And it's just a matter of coasting outward, not being pulled outward, and that coasting outward does not cause atoms to get bigger. Yes?

AUDIENCE: Is the current idea that the expansion, like the acceleration, is indefinite or are we going to reach a stop point?

PROFESSOR: OK. What will be the ultimate future, I'm being asked here. And the answer, as you might guess, is nobody really knows. But in the context of the kind of models I'm talking about, there is a pretty definite answer, which is that our pocket universe-- I'll answer at the level of our pocket universe and I'll answer at the level of the multiverse as a hole. At the level of our pocket universe, our pocket universe will thin out. Life will eventually become impossible because matter density will be too low.

It will probably decay. Our vacuum is probably not absolutely stable. Very few things 2 String theory are, if something like String theory is the right theory. But even though it will be decaying, it will be expanding still faster than it decays. So the decay will cause holes in our universe. It will become like Swiss cheese. But the universe, as a whole, will just go on exponentially expanding, perhaps forever, as far as we can tell, forever.

The multiverse is a more vibrant object. The multiverse, as I always said, would continue to generate new pocket universes forever. So the multiverse would forever be alive even though each pocket universe in the multiverse would form at some time and then ultimately die, die of thinning out into nothingness. Yes?

AUDIENCE: Just to add to that. Do you believe that maybe it's a cyclic process? So it expand and decay and then come back [? yet again ?] and then happen all over again?

PROFESSOR: OK. The question is could it be a cyclic process that expands, reaches maximum, comes back and crunches, and expands again. That is certainly a possibility, and there is some people who take it very seriously. I don't see any evidence for it. And furthermore, there never really was and still really isn't a reasonable theory of the bounce that would have to be a part of that theory. Yeah?

AUDIENCE: But would it be the expansion overtaking the decay in our own vacuum that our universe exists in, our own little pocket vacuums of ultimate decay within our system create more little pocket universes--

[INTERPOSING VOICES]

PROFESSOR: Within. Yes. Yeah, that's correct. They would not be a big fraction of the volume of our universe, but, yes. The pieces in our universe that might decay in the future would produce new pocket universes. Most of them would be very low energy pocket universes that would presumably not create life, but some of them could nonetheless have a high enough energy to create life. So we would expect new, thriving universes to appear out of our own pocket universe as it reaches this expansion death. Yes?

AUDIENCE: What does distinguishes different vacua besides the cosmological constant?

PROFESSOR: The question is what distinguishes the different vacua besides the cosmological constant. And the answer is that they can distinguish in many, many ways. What fundamentally distinguishes them is the rearrangement of the innards within the space, maybe a little bit more precise without trying to get into details which I probably don't understand either. But what's going on is that String theory fundamentally says that space has nine dimensions, not the three that we observe. And the way the nine becomes three is that the extra dimensions get twisted up into tiny little knots, so they occupy too small a length to ever be seen.

But there are many different ways of twisting up those extra dimensions, and that's really what leads to these very large numbers of possible vacua. The extra dimensions are twisted up differently. So that means that as far as the low energy physics in these different vacua-- practically everything could be different, even the dimension of space could be different. You could have different numbers of dimensions compactified.

And the whole particle spectrum would be different because what we view as a particle is really just the fluctuation of vacuum. And if you have a different structure to the vacuum itself, the kinds of particles that exist in it could be totally different. So the physics inside these pocket universe could look tremendously different from what we observe even though that we're predicating the whole description on the idea that, ultimately, it's the same laws of physics that apply everywhere. Other questions? Yes?

AUDIENCE: [INAUDIBLE]?

PROFESSOR: OK. I think you're asking about if we have a small patch, then that goes inflation and the rest doesn't, how does the patch end up dominating because it started out with just a small fraction of the particles. Doesn't it still have the same small fraction of particles? Is that what you're asking?

AUDIENCE: Well, I guess. If you start out with the smooth particles being the excessive matter, and one of the particles behaves and the other two particles [INAUDIBLE] even if it's still just two particles?

PROFESSOR: Right. It isn't the number of particles conserved, basically, as all this happens, is I think what you're asking.

AUDIENCE: Well, even if it eventually [? is called ?] expanded wave because the second part will [INAUDIBLE]

PROFESSOR: Well, let's see. I'm having a little trouble hearing you. But let me make a definite-- let me make a broader statement, and you can tell me if I've answered what you're asking about or not. When one of these patches undergoes the exponential expansion of inflation, the energy is really not very well described as particles at all. It's really described in terms of fields. And fields sometimes behave like particles, but not always. And in this case-- in principle, there's a particle description too, but it's not nearly as obvious as the field description.

So you have energy stored in fields and the region grows. The energy stored in those fields actually increases as the region goes. The energy density remains approximately constant. And that sounds like it would violate the conservation of energy, but we discussed the fact that what saves conservation of energy and allows this to happen in spite of conservation of energy is that as the region expands, it is filled by a gravitational field, which is now occupying a larger and larger volume, and that gravitational field has a negative energy density. So the total energy, which is what has to be conserved, remains very small and perhaps zero, and the region can grow without limit while still having this very small or zero total energy.

Then, eventually it decays and when it decays, it produces new particles, and the colossal number of new particles, and those would be the stuff that we would be made out of. And that number is vastly larger than the number of particles that may have been in this region when the inflation started. Yes?

AUDIENCE: So does the emergence of [INAUDIBLE] just purely a conservation of energy? Like, what do you need to make these [? an organism ?], the negative energy, zero [INAUDIBLE] I guess.

PROFESSOR: Are you saying the conservation of energy maybe controls the whole show, and that this is really the only thing consistent with conservation of energy? I think that's probably an exaggeration because if nothing happened, that would conserve energy too. So I think one needs more than just the conservation of energy to be able to describe how the universe is going to evolve. OK. Let me continue.

Get back to the beginning there, back to the end. OK. So I just finished talking about the landscape of String theory and how it offers all these possible vacua. So in particular, and this is now the new stuff, if there are 10 to the 500 vacua of String theory, for example. We don't really know the number, but something crazy like that. And if only one part in 10 to the 120 of them have this very small energy, thus the energy densities are spread from plus 10 to the 120 times what we observe to minus 10 to the 120 times what we observe.

That would mean that what we observed would be a narrow slice in the middle there occupying about 10 to the minus 120th of the length of that spread. We would then expect-- and all this, of course, is very crude estimates. It's not really the numbers that's important, it's whether or not you believe the ideas. But we'd expect then that about 10 to the minus 120 of the different vacua would have an acceptably low vacuum energy density.

But that's still a colossal number because 10 to the minus 120 times 10 to the 500-- you add the exponents-- is 10 to the 380. So we would still predict that even though they'd be very rare, there might be 10 to the 380 different kinds of vacua, all which would have a vacuum energy density as well as what we observe. So there's no problem finding, in the landscape, vacua whose energy density is as low as what we observe. But then there's the question if they're so incredibly rare, wouldn't it take a miracle for us to be living in one of these incredibly unusual vacua with such an extraordinarily low vacuum energy density.

That then leads to what is sometimes called Anthropic considerations or perhaps a selection effect. And to see how that works and make it sound not as crazy as it might sound otherwise, I want to begin by giving an example where I think one could really say that this effect happens. And that is suppose we just look at our own position in our own visible universe and look at, for example, the mass density.

Where we're actually living is incredibly unusual in many ways, but one of the ways we could talk about, which is just simple and quantitative, is the mass density. The mass density of the things around this room is on the order of one gram per centimeter cubed give or take a factor of 10. The factor of 10 is not very important for I'm talking about here.

The point is that the average mass density of the universe, the visible universe, is about 10 to the minus 30 grams per centimeter cubed. It's really unbelievable how empty the universe is. It's actually a far lower mass density than is possible for us to achieve in laboratories on Earth with the best vacua that we can make in our laboratories.

So where we're living has a mass density of 10 to the 30 times the average of the visible universe. So we're not living in a typical place in our visible universe. We're living in an extraordinarily atypical place within our visible universe. And we can ask how would we explain that. Is it just a matter of chance that we're living in a place that's such a high mass density? Doesn't seem very likely if it's a matter of chance. Is it luck? Is it divine providence, whatever?

I think most of us would admit that it's probably a selection effect. That that's where life happens. Life doesn't happen throughout most of the visible universe, but in these rare places, like the surface of our planet, which is special in more ways than just the mass density, but the mass density alone is enough to make it extraordinarily special. We're off by a factor of 10 to the 30 from the average of our environment.

So if we're willing to explain why we live in such an unusual place within our visible universe and explain that as simply a requirement for life, then it doesn't seem to be such a stretch to maybe imagine-- and it was Steve Weinberg who first emphasized this in 1987. Certainly not the first person to say it, but the first person to say it and have people sometimes believe him.

He pointed out that may be the low energy-- the low vacuum energy density could be explained the same way. If we're not living in a typical place within our visible universe, there's no reason for similar ideas to expect that we should be living in a typical place in the multiverse. Maybe only a small fraction of these different types of pocket universe's can support life. And maybe the only way to have life is to have a very small value for the vacuum energy density.

And there is some physics behind that. Remember this vacuum energy density drives expansion-- acceleration, I should say. So if the vacuum energy density were significantly larger than what we observe, the universe would accelerate incredibly rapidly and would fly apart before there'd be any time for anything interesting to happen like galaxies forming. Weinberg based his arguments here on the assumption that galaxies are a necessity for life. Yes?

AUDIENCE: So that's what I was going to ask. Why do we assume that our universe is the only one that could have like-- why couldn't just all the multi-universes have like--

PROFESSOR: Right. Right. Well, that's OK. That is what I am talking about. I'm trying to answer it. So if the vacuum energy density were significantly larger than what we observe, the universes would fly apart so fast that there could never be galaxies and therefore never planets, none of things that we think of as being associated with life as we know it.

Conversely, if the vacuum energy density were negative, but had a magnitude large compared to what we observed, that would be a large negative acceleration, an implosion. And those universes would just implode, collapse, in an incredibly short amount of time, much too fast for life, of any type that we know of, to form. So there is a physical argument which suggests that life only forms when the vacuum energy density is very low.

And Weinberg and his collaborators-- and this is the same Steve Weinberg who wrote the First Three Minutes that we're reading-- calculated what the requirements would be for galaxy formation. And they decided that, within about a factor of 5 or so, the vacuum energy density would have to be about the same as what we observe or less in order for galaxies to form. So it seems like a possible explanation. It's certainly not a generally accepted explanation. These things are very controversial one.

I guess that's, in fact, what I was going to talk about on my next slide. Some physicists by this selection effect idea. I tend to buy it. But a number of physicists regard it as totally ridiculous, saying you could explain anything if you except arguments like that. And there's some truth to that. You can explain a lot of things if you're willing to just say, well, maybe that's needed for life to happen.

So because of that, I would say that these selection effect arguments or anthropic arguments should always be viewed as the arguments of last resort. That is, unless we actually understand the landscape of String theory, which we do not in detail, and once we actually understand what it takes to create life, we really can't do more than give plausibility arguments to justify these anthropic explanations.

But these anthropic arguments do sound sensible. I think there's nothing illogical about them, and they could very well be the explanations for some things. As I pointed out, I think it is the explanation for why we are living in such an unusual place within our own visible universe. And it means that these selection effect arguments become very attractive when the search for more deterministic explanations have failed. And in the case of trying to explain the very small vacuum energy density, I think other attempts have failed. We don't have any calculational, deterministic understanding for why the vacuum energy should be so small.

So is it time to accept this explanation of last resort that the vacuum energy density is small because it has to be for life to the evolve? Your guess is as good as mine. I don't really know. But I would say that, in the case of the vacuum energy density, people have been trying very, very hard for quite a few years now to try to find a particle physics explanation for why the vacuum energy has to be small, and nobody's really found anything that anybody has found-- that any large number of people have found to be acceptable. So it is certainly a very serious problem. And I think it is time to take seriously the argument of last resort, that maybe it's that way only because in the parts of the multiverse where it's not that way, nobody lives there.

So I would say it's hard to deny, as of now, that the selection effect explanation is the most plausible of any explanation that is known at the present time. To summarize things-- I'm actually done now, but let me just summarize what I said to remind you where we're at. I've argued that the inflationary paradigm is in great shape. It explains the large scale uniformity. It predicts the mass density of the universe to better than about 1% accuracy and explains the ripples that we see in the cosmic background radiation, explaining them as a result of quantum fluctuations that took place in the very early universe.

The picture leads to three ideas that at least point towards the idea of a multiverse. It certainly doesn't prove that we're living in a multiverse. But the three ideas that point in that direction are, first of all, the statement that almost all inflationary models lead to this feature of eternal inflation, that the exponential expansion of the inflating material, generally speaking, out runs the decay of that material so that the volume grows exponentially forever.

Second point is that, in 1998, the astronomers discovered this rather amazing fact that the universe is not slowing down as it expands, but in fact, is accelerating. And that indicates that there has to be some peculiar material in the universe other than what we already knew was here, and that peculiar material is called the dark energy. And we don't have any simple interpretation of what it is, but it seems to most likely be vacuum energy. And if it is, it leads immediately to the important question of can we understand why it has a value that it has. It seems to be much smaller than what we would expect.

And then three, the String theorists give us an interesting way out here. The String theorists tell us that maybe there's not unique vacuum to the laws of physics, but maybe there's a huge number, which seems to be in fact what String theory predicts. And if there is, then of the many different vacua you expect there to be, in fact perhaps even a large number, that would have this very small vacuum energy density, a tiny fraction of the total different vacua, but nonetheless a large number of vacua that would have this property. And then this selection effect idea can provide a possible explanation for why we are living in one of those very unusual vacua which has this incredibly tiny vacuum energy density.

So finally, I'd just like to close with a little sociological discussion here. Do physicists really take this seriously? And I'd like to tell you about a conversation that took place at a conference a few years ago. Starting with Martin Rees, who I don't know if you know the name or not, but he's an Astronomer Royal of Great Britain, former president of Royal Society, former master of Trinity College as well, a very distinguished person, nice guy, too, by the way. And he said that he is sufficiently confident in the multiverse to bet his dog's life on it.

Andrei Linde, from Stanford, a real enthusiastic person about the multiverse, one of the founders of inflation as well, said that he's so confident that he would bet his own life on it. Steve Weinberg was not at this conference, but he wrote an article commenting on this discussion later which became known. And I always considered Steve Weinberg the voice of reason, which is why we're reading the First Three Minutes. And he said that I have just enough confidence in the multiverse to bet-- guess what's coming-- the lives of both Andrei Linde and Martin Rees' dog. That's it for the summary, or the overview. Anymore overview type questions before we get back to the beginning, actual beginning of the class? Yes?

AUDIENCE: You said-- so selection effect argument says that it's because life exists within these certain constraints, omega being one and low energy larger than it generally is allowed, that life could exist in this way. But we're considering carbon-based life. What if there's some other [INAUDIBLE] life forms out there that gives us different energies and radiation and stuff like that?

PROFESSOR: Yeah, what you're pointing toward is certainly a severe weakness of these selection effect arguments, that we really know about carbon-based life, life that's like us, and we can talk about what conditions are needed to make life like us, but maybe there's life that's totally different from us that we don't know anything about that might be able to live under totally different circumstances. That is a real weakness.

However, I would argue-- and this is also controversial. Not everybody would agree with what I'm about to say. But I would argue that if we're willing to explain the unusual features of the piece of the universe that we live in by selection effect arguments-- the fact I used, the example is simply that we're living a place where the mass density is 10 to the 30 times larger than the mean. If we're willing to use the anthropic arguments to explain that, then I think all those same issues arise there also.

If life was really teem-- if the universe was really teeming with a different kind of life that thrived in vacua, then we'd be much more likely to be one of them, extremely unusual creatures living on the surfaces of planets. So I think it's a possible weakness that one has to keep in mind, but I don't think it should stop us from using those arguments completely. But it is certainly a cause for skepticism. Yes?

AUDIENCE: Isn't the point of the selection principle just the fact that exist-- the universe selected for us. Does it matter for the general of just for like carbon-based [? organisms? ?] Is the fact that we exist [INAUDIBLE] that we've been selected for [INAUDIBLE]?

PROFESSOR: You're asking about, I think, how peculiar to carbon-based life should we expect these selection effect arguments to be.

AUDIENCE: Doesn't the selection affect where [INAUDIBLE]?

PROFESSOR: Now that's an important point, and certainly one that's not settled among philosophers, probabilist, physicists, or anybody. What you're asking-- if I'm summarizing it right-- is when we're thinking of the selection effects, should we may be only talk about carbon-based life because, after all, we know that we are carbon-based life. So what does it matter if there's other kinds of life out there? That's one way of looking at it, certainly.

Or, maybe we should think about all kinds of life. That's something else that people say. The problem I would-- I tend to be by the way the kind of person that thinks that all life is relevant, not just carbon-based life. Because we happen to be carbon-based, and we happen to have fingernails that have a certain length, and we happen to have hair that's a certain length or a certain thickness, does that mean we should only think of those things as being relevant when we're thinking about selection effects? And I would say that they're not. If our hair had a different thicknesses, we would still be able to make measurements and so on.

So from my point of view, when one thinks about these issues of selection effects, one should precondition only on the elements that are necessary to ask the question in the first place. And what I would like to think-- and as I point out, this is controversial, not everybody agrees with me-- is that a good theory should be a theory in which you could say that most of the people who ask this particular question will get the answer that we say. If only a tiny fraction of people who ask that question will get that answer, but that same tiny fraction happens to have hair of a certain color and you have hair of that color, to me that's still not an explanation because you don't know why you have hair of that color or why you're living in such an unusual place.

OK that strikes up a lot of conversations. Yes?

AUDIENCE: You mentioned last time that the different pocket universes that comprise the multiverse are disconnected from each other though they start out as patches within the preceding vacua. What starts to disconnect them fundamentally from the vacuum which they formed?

PROFESSOR: The question is what is it that separates these different pocket universe's. If they start out all in the same space, don't they remain all in the same space? And the answer is they do, but the space they started out in was expanding at a very rapid rate. So in most cases, but not all actually, two pocket universes will form far enough apart from each other that they will never touch each other as they grow because the space in between will expand to fast to ever allow them to meet.

However, collisions of pocket universities will occur if two pocket universes form close enough to each other, the expansion of space in between will not be enough to keep them apart, and they will glide. How frequent one should think of that as being is an incredibly tough question to which nobody knows the answer. There are actually-- at least there is at least one astronomical paper in the literature by a group of astronomers who have looked for possible signs of a collision of bubbles in our past. They did not find anything definitive. But it is something to think about, and it's something people are thinking about. There really are quite a few papers about collisions of bubbles in the literature. Yes?

AUDIENCE: How long is long-lived? So if the energy density was too large and too negative would that still be long-lived if it were to collide upon itself?

PROFESSOR: Talking about the lifetime of these universes that I said would collapse very quickly. How quickly do I mean?

AUDIENCE: Like the metastable long-lived.

PROFESSOR: I used the word long-lived at least twice in what I've talked about-- I talked about the long-lived metastable vacua. And there, by long-lived I mean anything that's long compared to the age of our universe since the Big Bang. Long means long compared to 10 to the 10 years in that context.

I also said that if the vacuum energy of a universe were large and negative, it would very rapidly collapse. That could be as fast as 10 to the minus 20 seconds. It could be very fast depending on how large the cosmological constant was. Yes?

AUDIENCE: So I have read that there's an effect such that if you're vacuum can be seen differently by different observers. For example, inertial-- there's something that I read in effect it says that if one inertial observer sees vacuum, another observer that's accelerating with respect to that observer would see like a number of particles [INAUDIBLE] a warm gas. So how much of the effect we observe are due to the fact that perhaps we believe the universe is accelerating, and we're accelerating perhaps with respect to some vacuum and we're just observing that. That's just a fact of our motion not necessarily the--

PROFESSOR: You're touching on something that is in fact very confusing. What is your name?

AUDIENCE: Hani.

PROFESSOR: Hani? What Hani said was that he had heard-- and this is correct-- that if one had simply a region of ordinary vacuum-- and I am now going to talk about special [INAUDIBLE] vacuum. You don't even need relativity. You don't general relativity, you just need this. If you had an accelerating observer moving through that vacuum, the accelerating observer would not see something that looked like vacuum, but rather would see particles that in fact would look like they had a finite temperature which you can calculate, a temperature that's determined by the acceleration.

So the question is, how much of what we see should we think of as really being there and how much might be caused just by our own motion. And there's not a terribly great answer to that question that I know of except that we-- when these questions come up, we tend to just adopt the philosophy that an observer who's freely moving, which really means moving with the gravitational field, a geodesic observer as the word phrase is sometimes used, essentially defines what you might call reality and then if you calculate what accelerating observers might see in terms of that reality.

And we are almost geodesic observers. The Earth is exerting a force on our feet, which violates that a little bit, but by the overall cosmic scale of things where the speed of light is what determines what's significant, we are essentially inertial or geodesic observers. Yes, Aviv? Aviv first and then the one in front.

AUDIENCE: So I'm wondering about the philosophical approach to this discussion and why the very-- by the definition, we can't possibly observe another universe. And so maybe we have a theory that makes a lot of great predictions like inflation. But it may also make predictions about multiverse. We can't possibly empirically determine whether that's true or not, so a nonfalsifiable question. And so I feel like [INAUDIBLE] who [INAUDIBLE] essentially never going to be answered. And if we're going to be strict empiricists, should we not be concerned with this question?

PROFESSOR: The question is if we could never see another pocket universe, is it even a valid question to discuss whether or not they exist, a valid scientific question. That is also a question which is generally debated in the community, and people have taken both sides. There certainly is a point of view, which I think I tend to take, which is that we never really insist that every aspect of our theories can be tested. If you think about any theory, even Newtonian gravity, you can certainly imagine implications of Newtonian gravity that you can calculate that nobody's ever measured.

So I think in practice we tend to accept theories when they have made enough measurements that we've tested so that the theory becomes persuasive. And when that happens, I think we should, at the same time, take seriously whatever those words mean, the implications that the theory has for things that cannot be directly tested.

As far as the other pocket universes, some people think it's important, and maybe I do too, that even though it's highly unlikely, incredibly unlikely, unbelievably unlikely that we'll ever acquire direct observational evidence for another pocket universe, it's not really in principle impossible because of the fact that pocket universes can, in principle, collide. So we could, in principle, describe with evidence that our universe has had contact with another pocket universe in the past. Yes.

AUDIENCE: What determines the stability of a particular vacuum state? Is it simply things with higher vacuum energies are less stable and things with lower vacuum energies are more stable?

PROFESSOR: The question is what determines the stability of the different vacua. Is it simply that higher energy ones are more unstable and lower energy ones are more stable or is it more complicated than that? And the answer, as far as I know, is that there is a trend for higher energy ones to be more unstable and lower energy ones to be more stable. But it's not as simple as that. There are also wide variations that are independent of the energy density.

AUDIENCE: If the one that we're living in is incredibly is really ridiculously close to zero in a city that seems to make it incredibly unlikely that we would pay anything else I soon

PROFESSOR: Right. The question is if our universe has such has such a small energy density relative to the average. Wouldn't that mean that we should also expect to be much more long-lived than average? And the answer is I guess so. But as far as the effect on the Swiss cheese picture that I described for the ultimate future, it doesn't change the words that I used. It just changes how frequent those decays would be. But since the future of this pocket universe, if this picture is right, will be infinite, decays will happen no matter how small the probability is. An infinite number of decays will happen in fact.

OK we should probably go on now even if there are more questions. We have a whole term to discuss things like this. The next thing I want to do is handle some housekeeping details. I'd like to arrange office hours. And the problem sets are due on Friday, so what [? Tsingtao ?] and I thought was that a good time for office hours would be on Wednesdays and Thursdays. One of us on each of those days.

It turns out that I can't really do Thursdays, so one of us on each of those days ends up meaning that I'll probably be having office hours on Wednesdays. This is all provisional depending on how it works with you folks. And [? Tsingtao ?] will probably be having office hours on Thursdays. Generally speaking, if one wants to have an office hour that most people can come to, I think it should be in the late afternoon.

So maybe we'll start by discussing my office hours since it comes before [? Tsingtao's, ?] Wednesday versus Thursday. So on Wednesday, I can do an office hour in the late, normal afternoon, which might mean 4:00 to 5:00 I think after five some people have sports activities and things. We're told to try to avoid those hours. So 4:00 to 5:00 would be a reasonable possibility for my office hour on Wednesday.

If that doesn't work, I could stay and have the office hour in the evening. That's actually what I did two years ago. I had an office hour from 7:30 to 8:30. It was also Wednesdays-- I forget. But it was in the evening, and that's a possibility. So let me ask if I have my office hour from 4:00 to 5:00 on Wednesdays, how many of you who might be interested in coming would not be able to come?

1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12. A significant number, but most of you can come at least. Let me ask the corresponding question for the evening. Suppose I made the office hour from 7:30 to 8:30 in the evening on Wednesdays. In that case, how many of you who might want to come would not be able to come? 1, 2, 3 5, 6, so it's a smaller number, but not vastly smaller.

OK I think I'll do it in the evening for the benefit of the difference between those two groups. And the evening also has the little slight advantage that it can be a little more open-ended if people still have questions after the normal time is over. So I will make my office hour on Wednesday's from 7:30 to 8:30. Is that particular hour as good an hour as any on Wednesday evening. Would people want to move it earlier or later? Any suggestions for moving it earlier or later?

AUDIENCE: I know people have sports til technically at least 7:00, but if it's 6:30 to 7:30 might be a little--

PROFESSOR: 6:30? You'll be starting at 6-- starting at 6:30 versus-- 6:30 to 7:30, starting at 6:30. Well, I'd be happy to do that, but I suspect we might run into problems with people who have sport activities, but let's see. How many of you would be inconvenienced if I started at 6:30 instead of 7:30? 3, 4, 5, 6, a number. So I think we'll honor that and start at 7:30.

I assume 7 is also a bit of a problem for those people. We'll say 7:30.

Now, I have to announce that this week is going to unfortunately have to be an exception because I already have plans for Wednesday night. So for this week, I think the best thing-- the only possible thing, probably the best-- it's almost the only possible thing would be 4:00 to 5:00 on Wednesday. Wednesday's bit tomorrow. I'll send you all an email when I find a room for that. I think I'll probably not have it in my office, but maybe it will be in my office. Comment up there?

AUDIENCE: Oh, I was just going to ask where, but you--

PROFESSOR: Where? OK, I guess then the fourth option's my office. I was hoping to put a sign of my office if we're someplace other than my office. So should put this on the board too. Tomorrow 4:00 to 5:00 PM. So be at my office or I'll send email. Yes?

AUDIENCE: How will we be turning in the Thursday problem set?

PROFESSOR: We're going to talk about that now. For Thursday, for [? Tsingtao, ?] I remember you had some constraints. So what was possible?

TSINGTAO: Yeah. So I usually leave around 7:00 PM, so I have appointment [? meeting ?], and today is probably not very good at 4:00 PM.

PROFESSOR: So 4:00 to 5:00 is a possibility for [? Tsingtao ?] on Thursday, and I guess later than that. But should be over by 5:00-- by 7:00 either or do you want it to be over before then.

TSINGTAO: Oh, 6:00 to 7:002 Oh, 6:00 to 7:002 I guess.

PROFESSOR: 6:00 to 7:00 would be OK?

TSINGTAO: Yeah, that's OK.

PROFESSOR: OK, so let's start with 4:00 to 5:00. If [? Tsingtao ?] was to have an office hour from 4:00 to 5:00 on Thursdays, how many of you think you might want to go would be unable to? Wow, tons! OK, that seems more than half of you I think. So I guess we try to avoid that. This impact's probably an athletic region, but maybe we'll have to do that for lack of an alternative. Suppose it were 5:00 to 6:00. How many of you who would be interesting in coming-- who might be interesting in coming, I should say I guess because it'll vary from week to week-- but how many of you who think you might be interested in coming would not be able to come from 5:00 to 6:00 on Thursdays. OK, a small group. 1, 2, 3, 4, 5, 6, 7. Looks to me like 7.

And let's say, I said 4:00-- That was at 6:00-- that was 5:00 to 6:00. So maybe we should next try 5:30 to 6:30 in smaller increments here. If we're 5:30 to 6:30, how many of you would not be able to come? Looks like pretty much the same people. And if it were 6:00 to 7:00, how many of you would not be able to come? Same people, I think it is literally the same people.

OK. So it looks like 4:00 to 5:00 is very bad. And all other times are about equivalent. So I think if all other times are bad equivalently, we probably might as well make it 5:00 to 6:00. And that way [? Tsingtao ?] can get off to an earliest possible start to wherever he's going at 7:00, and it also means a little more flexibility in the end if there are more questions.

AUDIENCE: Where is that located?

PROFESSOR: That also, I think, will require us to get a room which will be announced. So I will try to arrange rooms tomorrow morning and send it by email, and I guess I'll post it on the website as well. Any other organizational-- and questions limited to organizational questions now? Get back to physics later. Any organizational questions before we start on Doppler shifts? Yes?

AUDIENCE: If I can't make a single office hour, how should I field questions when I have questions?

PROFESSOR: A good question. Yeah, there may be some people, and apparently there is at least one who cannot make either of these times, even though we tried to optimize things. So by all means, don't feel like you don't have a channel for questions. If you have a question, send an email to either me, or [? Tsingtao, ?] or both. And we'll either answer it together with you or answer you by email depending on what the question is and what seems useful. And that goes for everybody.

In that case, if everybody's on board, we will now start the actual material for the term. Well, the overview is an overview of the material for the term, but not at the standard pace and the standard level of detail. So what I want to talk about this week-- and I guess I'll only get to start today and finish on Thursday-- I had planned to tell you everything you need to know for the problem set by today, but that's not going to happen.

So I don't-- if people complain, we could consider postponing the due date of the problem set, so consider that an option. But probably you could do the problem set anyway because it is all described in lecture notes. But if any of you have difficulties meeting that deadline, it will be a somewhat flexible deadline this week because of the fact that I'm not covering the material today as I had planned. And I'll admit that's not necessarily a good thing to do in terms of problem set.

So we're going to begin the course, in principle, by talking about Hubble's law, although Hubble's law will rapidly lead us to the question of the Doppler shift, which is what I'll mainly be talking about for the rest of today and for most of Thursday. Hubble's law itself is a simple equation that v is equal to h r, where v is the recession velocity of any typical galaxy.

Hubble's law is not an exact law, so individual galaxies will deviate from Hubble's law. But in principle, Hubble's law tells you what the recession velocity is of a galaxy, at least to reasonable accuracy. Where h is what is often called Hubble's constant. Sometimes, it is called the Hubble parameter. I like actually-- it's called the Hubble expansion rate.

The problem with calling Hubble's constant is that it's not really a constant over the lifetime of the universe. It's a constant over the lifetime of an astronomer, but not a constant over the lifetime of the universe? And we'll be talking about universes, not astronomers, at least for the most part. And even over history, it's not a constant because the estimate of Hubble's constant has actually changed by a factor of about 10 or so since Hubble's original estimate.

And the r that appears here is the distance to the galaxy. And if you look at the lecture notes from two years ago, they start out by saying that Hubble's law was discovered by Hubble in 1929. When I looked at that first sentence in my notes, and when I started to revise them for this year, I realized that I heard that that statement has become controversial. Almost everything in cosmology is controversial, so even that statement is controversial.

There are claims that Lemaitre really deserves credit for Hubble's law rather than Hubble. And there's some validity to that claim. There's also some [? intrigued ?] that happens, if you want to read about this. It was discovered by several of-- I think amateur historians I think is what they are often referred to in the press-- that we know mainly of Lemaitre's work-- we being the Western speaking, the Western English speaking world-- know mainly of a Lemaitre's work through a 1931 translation in a 1927 paper he wrote about the foundations of cosmology.

And it turned out that several significant seeming paragraphs in the 1927 French article somehow didn't make it to the 1931 English translation, paragraphs about the Hubble constant. And for a while, that seemed like dirty play and there were accusations that Hubble, or friends of Hubble, had suppressed those paragraphs when the article was translated.

The truth finally was discovered a couple years ago by a physicist named Mario

Livio who actually was on the Daily Show a couple nights ago by the way. He has a book out now, not about this, but about other things. But anyway, he discovered by going through the archives of the monthly notices of astronomy, which is where the article was published in English. And turned out it was Lemaitre himself he removed those paragraphs.

The paragraphs basically gave a numerical estimate of the Hubble constant, but by 1931 Hubble's papered already been published, so Lemaitre felt that it was only a less accurate estimate of the same quantity that Hubble had estimated, so he cut it out of his translation. What certainly is true is that Lemaitre knew about Hubble's law on theoretical grounds. Lemaitre was building a model of an expanding universe.

I don't know if he is really the first person to know that an expanding universe model gave rise to a linear relationship between velocity and distance, but he certainly did know about it and understood Hubble's law and give an estimate of it based on data. What he did not do, however, is try to use data to actually show that there was a linear relationship. What Lemaitre did, in those paragraphs that were not translated, was simply to look at a large group of galaxies, figure an average value for v and an average value of r and determine h from dividing those two averages. And he admitted that there was not really good enough data to tell if the relationship is linear or not.

I think it is definitely fair to say that Hubble is the person who deserves credit for arguing first really with a fairly weak argument, but then got stronger over time, that there really is astronomical evidence for this linear relationship between velocity and distance. So probably it will continue to be called Hubble's law. If you look in Wikipedia, it tells you either one is acceptable at the moment, but Wikipedia articles change rapidly, so we'll see what it says next year. It's also mentioned that we should probably root for Lemaitre since Lemaitre, it turns out-- well, he was a Belgian priest, it was often described, but he was also an MIT student, had a Ph.D. for MIT, which he received in 1927.

You can actually read his thesis. When I was writing my [INAUDIBLE] book, I remember going to the MIT archives and actually picking up his thesis and reading it. It's not that well-written actually, but it's interesting. Although he got his Ph.D. from MIT, it also turns out that he did most of his work down Mass Ave at the Harvard College Observatory, but the Harvard College Observatory did not give degrees in those days. It was just an observatory. So he wanted to get a degree, so he signed up at MIT for the Ph.D. Program and wrote a thesis, received a Ph.D.

Onward, what I really want to talk about is, after mentioning Hubble's law-- so Hubble's law as an indication that the universe is expanding. And we'll talk more about the history of all this later, and it actually is very well-described in Steve Weinberg's book. But initially, Einstein proposed a model of the universe that was static, and it was really Hubble who convinced Einstein that observationally the universe does not appear to be static, but does appear instead to obey this expansion law.

So that gave rise to the theory of the expanding universe. But what I want to talk about today is how one measures the v that appears here. There's also a big discussion about how one measures r, the distance. And that is, I think, rather well-done in Steve Weinberg's book, and I'm going to pretty much leave it to your reading of Steve Weinberg's book to learn about how distances to distant galaxies are estimated. Roughly-speaking, I might just say that they are estimated by finding objects in those distant galaxies whose brightnesses you think you know, by one means or another.

And a complicated story is what objects are there in brightnesses we think we know. But once you find an object whose brightness you think you know, those go by the general name of standard candles, a standard candle being an object whose brightness you know, then you can tell how far the object is by how bright it appears. And that becomes a very straightforward way of estimating distances, and that is the only way we really have of estimating distances of distant galaxies. So it's a much longer story than what I just said, and you'll read about it in Weinberg's book.

The velocity is measured by the Doppler shift, and that's what lecture notes one are mainly about, and that's what I'll be talking about for the remaining few minutes of today's class. And what we want to do in the course of this set of lecture notes, this week of class I guess it will be, is understand how to calculate the Doppler shift both non-relativistically and relativistically, and we'll just work out the primary cases of observer stationary source moving, source stationary observer moving, and all in a line, for both the relativistic and non-relativistic cases.

So I think I'll launch into the first calculation, which you might even have time to finish. I'd like to consider a case where the observer is stationary and the source is moving, which is normally how we think of the distant galaxies. We work in our own reference frame, so we're stationary, the galaxy is moving. How do we calculate this redshift I should say at the asset here, however-- I don't know if I said it in the lecture notes-- that the cosmological redshift is actually a little bit different from what we're calculating this week.

This week, we're calculating the special relativity redshift. But cosmology is not controlled by special relativity because special relativity does not describe gravity, and gravity plays a major role in cosmology. So the cosmological redshift, we will talk about a little later in the course, in a more precise way. But for now, we, like Hubble-- Hubble didn't know any better-- are ignoring gravity, which is OK for the nearby stars, and the further away they are, the more important these gravitational influences are, and ignoring gravity one could just use special relativity or even Newtonian kinematics to calculate the relationship between v and the redshift. And that's what we'll be talking about.

So the first problem that we want to talk about-- and I guess I'll just set it up and that's as far as we get-- will be a problem where there's a source of radiation, which is moving to the right in our diagram with a velocity, v, and an observer who is stationary.

Now of course, all these are frame dependent statements, but we're working in a frame where the observer is stationary. And we're also going to assume for the non-relativistic case, that the air-- we'll be talking about sound waves-- but the air is stationary in this frame. So the frame of backboard is not only the frame of the observer, but it's also the frame of the air when we're talking about the non-relativistic sound wave calculation.

So to define our notation, we're going to let u be equal the velocity of the sound wave. And that would normally be measured relative to the air, but the air will be at rest in this picture, so u will be the velocity of the sound wave relative to the diagram. v is the velocity of the source already shown. And we'll be interested in two time periods, delta t sub s where s stands for source, which will be the period of the wave at the source, which is the same as talking about the period of the wave as it would be measured by the source.

And delta t sub O-- that's supposed to be a capital O, not a zero. It is the period of the wave at the observer or as observed. And the important point, which is maybe obvious qualitatively, is that these two times, or time intervals, will not be equal to each other. And the reason, basically, is that because the source is moving-- and I've defined positive v the way astronomers would as moving away from us-- because the source is moving away from us, each successive wave that goes from the source to us has to travel a little bit further.

And that means that each wave crest is slightly delayed from when it would have gotten here if everything were stationary. And if you delay each wave crest, it means the time between crests is larger. And that means that we expect here that delta t sub O will be larger than delta t sub s because of this extra distance that each wave crest has to travel. And what we'll be doing next time-- I think I will just leave the calculations for next time-- is calculating that.

And then doing the same thing for the case where the observers moving and the source is stationary, and then talking a little bit about special relativity, and then repeating both calculations with a special relativity situation where we'll be talking about light rays and velocities that might be comparable to the speed of light. So see you folks on Thursday, but maybe I'll see some of you at my office hour tomorrow. And I will send an email about where exactly that office hour will take place.