[SQUEAKING]

[RUSTLING]

[CLICKING]

DAVID KAISER: So today, we're going to pick up where we were on the most recent classes. So in the last few class sessions, we were looking at some changes in high energy particle theory with the development of things like quantum chromodynamics and so on and ways to try to make sense of very high energy interactions among elementary particles or at least particles smaller than an atom. And then in our most recent class session, we looked at some of the shifts within the fields of study, including the emergence of this relatively new subfield called particle cosmology, which really came together starting in the mid 1970s partly because of some really exciting new ideas, but also, as we've looked at in some detail, because of some broader institutional even geopolitical shifts in the physics profession that really helped some of these new ideas take hold in a way that they might not have in other times or places.

So today, we're going to focus on a kind of example of that new subfield, a relatively new subfield that's known as inflationary cosmology or simply cosmic inflation. So to make sense of that, we're going to first look at some of the work in cosmology before this merger of fields, before particle cosmology really in into its own. So we'll look at the coalescence of what came to be called the Big Bang model, still enormously successful framework for trying to make sense of very large scale changes in our universe over a long sweep of time.

And then we'll see that already by the 1970s and '80s, there was some curiosities or maybe inconsistencies with that otherwise quite successful model. And so people began thinking about shortcomings of the Big Bang model around the time that this new subfield of particle cosmology began to come together. And then we'll see how cosmic inflation emerged from that particular moment to try to address some of the shortcomings while retaining some of the successes. So it's a framework for trying to understand the evolution of our universe over a huge expanse of time, increasingly using tools at the interface, not just of Einstein's general theory of relativity, but also ideas about particle physics and high energy phenomena.

[BEEP]

So that's we're heading today. And the asterisks are to remind you there's a set of strictly optional lecture notes on the Canvas site which go into a little bit more detail of some of these parts from the lecture. Again, strictly for your own interest as your interest and time allows. But if some of these things go by quickly, there's some more material there. And again, I'd be glad to chat more about this if questions come up beyond that.

OK. So oftentimes, astronomers will describe the most salient features of our universe in terms of what they call large scale structure. It's really quite remarkable. And this [CLEARS THROAT] picture's been emerging really over a century, for 100 years or even more, that when astronomers turn their telescopes to the sky and look at many different length scales, many different characteristic lengths, either very, very, very large length scales-- this is a modern example from the Hubble telescope deep field survey-- where you can look at clusters and even super clusters of galaxies on enormous scales, tens or even thousands of-- let's see. I want to get my units right. Basically billions of light years across. It's a huge scale.

Or we can zoom in to the size of single galaxies like the Andromeda galaxy or our own Milky Way galaxy. Or if we zoom in even closer to home with the solar system or even really in human terms, there are concentrations of enormous matter and energy and activity separated by huge voids. I like to make the joke with my apologies to Tiffany that in the Cambridge example, we have all this stuff happening like by this data center, whereas there's nothing at all happening at Harvard. Is that right, Tiffany? Just a simple nod yes or no. Yeah, OK. Sorry, Tiffany. I'm teasing.

The point is on scales from kilometers out to billions of light years and everything in between, we find this lumpiness, that there's a pattern to it. Matter is not uniformly smushed out in space. Thank goodness, right? There is actually teeming pockets of activity separated by large voids where very little matter or energy is located.

And so one of the questions is, what could account for that structure across these scales from meters or kilometers up to tens of billions of light years? It turns out that ordinary gravity-- even Newtonian gravity, let alone Einstein's fancier version that we looked at in class, general theory of relativity-- that these gravitational frameworks are sufficient to help us make sense of this hierarchy of scales, of structure across large distance scales. [CLEARS THROAT] If we assume, to start, there's some initial, very tiny lumpiness to begin with, if we assume some very tiny inhomogeneity, a little bit of unevenness in the distribution of matter and energy at early times, then gravity will do the rest. Gravity will make those regions that happen to have slightly more matter or energy per unit volume than average-- the gravitational force will then attract more and more matter and energy to those local regions. So it'll become more and more dense, more pockets of activity.

And meanwhile, the areas that happen to start out with slightly less than average matter and energy per volume, slightly under dense regions, will become more and more further evacuated. And so even in much more quantitative precision, much more detail, we can account for this array of structure from human size scales out to the super galactic using really only gravity as long as we start with some initial otherwise unaccounted for lumpiness. A tiny amount of unevenness in the distribution of matter and energy will grow more and more uneven over time.

So a challenge for astronomers for a century or so has been to try to make that account more precise and more quantitative and compare it with more and more kinds of observations. And there have been two main conceptual ingredients, especially as we'll come to in the more recent versions of this in the era of particle cosmology. One of the sets of tools, the conceptual ingredients, not surprisingly, is some theory of gravity. And since [CLEARS THROAT] the early years of the 20th century, as we've seen many times in this class, the framework of choice has been Einstein's general theory of relativity, which, as we've seen, describes the phenomena that we associate with gravitation as really being nothing but geometry, being local deformations, local curvature in this almost physical type fabric of space time in response to the distribution of matter and energy.

And the other main ingredient especially, as I say, refined in recent years with insights from high energy nuclear and particle physics has been some prevailing understanding of matter, especially matter at very high energies and temperatures, matter that consists of things like electrons and photons, matter that nowadays people are pretty well convinced consists of things like quarks and gluons and even some more exotic particles like the Higgs particle that we looked at least briefly in the previous class. So we have these two ingredients of the structure and behavior of space time as governed presumably by Einstein's theory or something perhaps similar to it and then the stuff that's filling that space time, an idea about matter, especially how matter behaves at very high energies and densities.

So with those two ingredients, the goal has been, again, for many decades to account for the observational features of our universe even on very large scales. So as a reminder, the so-called field equations of Einstein's general theory of relativity take this deceptively simple looking form. This side is what he had to learn from his friend Marcel Grossmann. This is the geometry of a warping spacetime, the way to quantify things like gradients, rates of change of space and time. And this tells you where the stuff is. This is the distribution of matter and energy.

Pretty soon after Einstein arrived at this form of his field equations in November of 1915, within a few years, Einstein himself and then soon several other colleagues began applying these equations not only to local phenomena like, say, the warping of space outside the sun. His friend Karl Schwarzschild first found an exact solution for very early in this work not only for local phenomena, but actually for global phenomena. Could one build at least a toy model of an entire universe that might satisfy or might be governed by Einstein's field equations?

And actually some other colleagues were very quick to find that there were some exact solutions even on this global or universal cosmic scale that would satisfy Einstein's equation. They took three particularly simple forms. Depending on the amount of stuff, depending on the distribution of matter and energy, if you assume that the matter and energy was spread out perfectly uniformly as a toy model, a uniform density of stuff per volume, then depending on whether there was more than some critical value, less than some critical value, or exactly equal to some critical value, these Goldilocks situations for the global shape of space in response to how much stuff per volume was filling that toy universe.

If you had more than some critical value, a critical value that came from the equations themselves above that, an overdense region, space itself would warp back onto itself like a closed sphere, the surface of a closed sphere that would be a positively curved geometry globally. If you had less stuff per volume, if the universe were underdense compared to that critical value, then, in fact, the universe would open up away from itself. You'd have a hyperbolic solution or an open geometry with negative curvature. And only if the amount of stuff per volume were exactly equal to that critical value would the sections of space be flat, obey the geometry of ordinary Euclidean geometry.

And so you can have these global features, for example, on a positively curved geometrical surface. Parallel lines, lines that are parallel at the equator like these here, will actually converge at the poles. So lines that are parallel in some part of the space will not remain parallel forever. That breaks the Euclidean assumption, the fifth postulate about parallel lines.

Likewise, on a positively curved surface, you can draw a triangle and add up the sum of the angles contained within that triangle and add up to more than 180 degrees, whereas Euclidean triangles have to have exactly 180 degrees. Likewise for open geometry, parallel lines will actually diverge. They'll get further and further apart from each other over distance instead of remaining parallel. And triangles will sum up to have less than 180 degrees of the internal angle.

So there are these self-consistent, non-Euclidean geometries. And they could apply not only to local physics like the warping of spacetime outside a massive object like the sun, but even to these toy universes, these otherwise very simple models of a universe as a whole.

Well, very soon after that, people-- not Einstein himself. He thought this was horrible. But some of his colleagues who began pursuing these cosmological solutions began to realize that the universe could not only have a shape at a given moment in time. But the shape could change over time, or the size could change over time. You could have expanding or collapsing solutions, also strictly consistent with Einstein's equations.

Einstein thought that was horrible. He had a very strong aesthetic and philosophical preference for a universe that had no beginning that was simply static, that would look the same for any observer at any moment for an infinite expanse of time. But other colleagues showed at least it was consistent with his own equations to have universes that would change over time, that could either expand or contract. That was actually a prediction made by some of these colleagues even before some empirical evidence began to come in starting in the late 1920s with some at the time absolutely enormous telescopes-- now they're pipsqueaks compared to what astronomers have today-- but what was at the time some of the largest telescopes of available on the planet.

Astronomers like Edwin Hubble in Southern California were able to collect information about not just the distribution of distant galaxies, but could also measure how rapidly they were moving with respect to us by measuring a Doppler shift, slight shifts in the spectral lines associated with those galaxies. And Hubble found this remarkable trend that the further away from us a given galaxy was, the faster it tended to be moving away from us further still. So the objects that were relatively close to us were moving away from us at one average speed. Objects that were moving further away from us now were moving even further away from us at a faster speed.

So there's a remarkably close to linear relationship between the object's distance from us today and the rate at which they're moving further away from us that became known as Hubble's law, more recently amended to be the Hubble Lemaitre law because it actually predicted first by a theoretical physicist even before Hubble had found that data. Now we have, of course, as you know, the Hubble Space Telescope named in honor of Edwin Hubble, which has been able to extend this to extraordinarily far distances, not just the ones that Hubble could access with his ground based telescope. And the basic trend holds. There's some interesting deviations. But the idea is nonetheless evidence consistent with our universe expanding, not just having a shape to it, but actually stretching and getting larger over time.

So you can actually then work backwards and say for how long has our observable universe been stretching? When did this stretching or expanding phase begin? You can work it backwards and say given the rate of expansion that can be measured today, whether with Hubble's techniques or now with the more modern ones with space based telescopes, work it back, and it's consistent with the beginning of that expansion being not quite 14 billion years ago, billions of years ago. Our own universe seems to have been stretching and getting larger and larger.

So this gentleman here, whose name I already mentioned briefly, Georges Lemaitre, was really at the forefront of this work, starting in the 1920s and throughout the 1930s. You might notice in this photograph he's wearing a Catholic priest's clerical collar. George Lemaitre is I think a fascinating scholar. He was indeed an ordained Catholic priest.

He was also an MIT trained PhD astrophysicist. And he was originally Belgian. He studied briefly in Cambridge, England with one of the first converge to general relativity, Arthur Eddington. Then he came to MIT to finish his PhD and then was finding many of these solutions to Einstein's field equations even before Einstein did.

And, in fact, Einstein came thinking he must be wrong, and then Lemaitre kept being right. So they became very nice colleagues. But Einstein started off by always being frustrated that Lemaitre found solutions that Einstein found abhorrent or disgusting. [LAUGHS] Yet Lemaitre showed they were at least mathematically self-consistent and gradually became more and more relevant in the light of data like Edwin Hubble's about the expanding universe.

Lemaitre was one of the first to start thinking about playing that filmstrip backwards to say if things are moving further apart from each other on average today, and if the universe in general is expanding today, then was it, in fact, smaller at earlier times? You can imagine playing a filmstrip backwards and watching these galaxies actually approach each other as you look at earlier and earlier times, heading back toward that roughly 14 billion year old starting point.

So it was really Lemaitre who began writing about this both in technical papers and soon in some very charming, more popular books that if the universe is getting bigger today, it must have been smaller in the past. And what if you ride that all the way back? Was there a primeval moment, was there a single moment when all the matter of the universe, at least all the matter that we can see, was actually on top of each other, that the universe should've started in a very, very hot and dense state and been expanding ever since, maybe infinitely dense?

But either way, there was a moment when all the stuff that we see in the sky should've been closer and closer and closer together and been stretching and expanding ever since. So it's Lemaitre who begins thinking about what comes to be known the Big Bang model. He was calling it a primeval atom, that there was this initial fireball from a very, very hot, dense state. And he was very eager to understand the early stages of that expansion.

[CLEARS THROAT] That's where things stood really through the 1930s. As we saw, there were a number of disruptions when much of the world descended into the Second World War. And then soon after the Second World War, new groups began coming back to these somewhat old questions. Some of the newer groups had experience with things like the Manhattan Project and in general were much better versed in things like nuclear physics than had been known even in Lemaitre's day. So the field had expanded, and some of these folks had direct experience from things like the Manhattan Project, one of whom was actually George Gamow.

So one of the most active groups soon after the Second World War was based at the advanced-- excuse me-- the Applied Physics Laboratory. We looked briefly at this when we talked about the Second World War. That was another one of these US based defense laboratories built in a hurry to try to advance a bunch of wartime defense projects. It was much like the MIT Rad Lab. At the Applied Physics Lab, they worked on things like proximity fuses and so on.

Starting very soon after the war, there was some unclassified research going on at that research lab as well. And George Gamow was advising two younger physicists, Robert Herman and Ralph Alpher. Here's a famous composite photograph. They're making a not so subtle gesture to the fact that Gamow was widely rumored at least to enjoy his drink. So his head is emerging from the vapors of Cointreau, of a liqueur.

So this was a trio that began coming back to some of these questions about the very early universe inspired by the writings of Georges Lemaitre but now with a lot more knowledge about high energy interactions among elementary particles as well. And in a series of really quite ahead of its time farsighted work starting in the late 1940s, this trio and a small number of other colleagues around the world began trying to fill in this picture, this primeval fireball picture. And in fact, it soon became known simply as the Big Bang model.

They realized that if the universe was very hot and dense at early times, then the conditions in which these elementary particles would find themselves should be quite different than what we find commonly around ourselves today. In particular, at early times, the ambient energy, the interaction that any random elementary particle would likely carry, should be very, very high. Temperature, after all, is just a measure of kinetic energy of motion.

So you have a very high temperature. That's like saying that the average kinetic energy of each constituent, each elementary particle, was very high. It could've been, for example, higher than the binding energy of stable hydrogen atoms. So if that were the case, then every time some positively charged nuclear particle like even just a single proton would approach or be in proximity to a negatively charged electron, they might begin to form a stable electrically neutral hydrogen atom, which, of course, is just a bound state of one electron and one proton.

But before they could form that single stable atom, some ambient particles from the environment like a single photon would have such high energy, would come and zap them apart because the average energy of everything was higher than that binding energy of the Coulomb attraction of a hydrogen atom. So at early times, you would have an electrically charged plasma, that the universe would not be filled with electrically neutral atoms because they literally couldn't form yet because they were blasted apart every time a single putative atom got close enough to begin to form the average jostling of all this high temperature junk in its environment would blast it apart. So photons then become trapped between charged particles.

They begin to piece all this together. At early times in cosmic history, the universe should've been opaque. You literally wouldn't have been able to see anything because the mean free path of any given photon would be very, very short. The photons would each be trapped, kicked like soccer balls between all these loose electric charges. Light can't propagate in a charged plasma because it's always bouncing between these very nearby free electric charges.

So they could calculate and say when would that effect go away? Well, when the average or ambient temperature fell below the average binding energy of a single hydrogen atom-- and that would happen at a distinct moment in cosmic history. So again, they were trying to flesh out Lemaitre's picture of an evolving universe. It wasn't just hot and dense at one time. But that would mean that certain kinds of interactions among elementary particles would dominate. And then those would change over time.

In particular, as this entire hot ball of gas of charged plasma is expanding, the average temperature should decrease in size, much like the temperature of a gas inside a balloon will fall as the balloon expands. So as the volume of space stretches, as you have an expanding universe as Le Maitre showed what could be possible, the average temperature of all the stuff inside it should fall. It should fall in a quantitatively calculable way, again, using Einstein's equations.

So again, they put numbers to that and say, well, at a particular moment in time, now using the modern values-- they had the right idea that different values for some measurements-- we now calculate at around 380,000 years, after the start of that stretch after that primeval atom begins to expand, the ambient or average temperature of all the junk inside that universe should've fallen below this Coulomb attractive energy for neutral hydrogen. So whereas at earlier times, earlier than 380,000 years, you would have a charged plasma in an opaque universe. At that moment, the average energy per photon or per elementary particle would fall so that you could actually begin to form stable atoms of hydrogen.

So only at that time, a new phase in the universe would begin to unfold. The universe would be filled with neutral atoms of hydrogen. And now you have a mean free path for light that's arbitrarily long. Light can pass through electrically neutral matter. It does so in our own atmosphere, let alone in empty space.

So once you can have stable, electrically neutral atoms like hydrogen atoms at a particular moment in the cooling evolution history of our universe, only then would you have things like photons traveling macroscopic distances. So after that time, when the temperature has fallen below about 10,000 degrees Kelvin, photons are free. And then they can now travel large distances. And their energy continues to redshift. They lose energy as the universe continues to expand.

So the energy of those photons would've started at the equivalent of around 10,000 degrees Kelvin and now today would be much, much, much lower than that because the universe has been expanding and draining that average energy per particle over time [CLEARS THROAT] so that today the universe should be filled with this remnant glow. This is all work that they predict around 1948, '49, '50, Gamov, Herman, and Alpher.

So they argue that today, this bath of remnant radiation from that early hot, dense state should be filling the sky in every direction. It should be more or less even distribution, a uniform glow. But instead of it being a very, very high energy X-ray or gamma ray radiation, it should be redshifted all the way down into the low energy microwave band. So this became known as the cosmic microwave background radiation. And they say this should be filling the sky. It should be everywhere in a uniform pattern.

Here's an aside. I like to think about this. That's very abstract. I think about it as the evolution of a dance party. It turns out I don't attend dance parties very often. This is what the internet tells me they look like. So this, I'm sure, is accurate. If you just Google "dance party" and throw away the bad pictures-- anyway.

So at early times, the DJ's playing some raucous house music, and everyone's just jostling around. The average energy per dancer is very high. So I'm told. That's like the charged particles where the mean free path is effectively zero. No one could cross that dance floor.

And then at a calculable moment, if the DJ knows what she's doing, she'll put on some slow music. And you start having couples form like in Harry Potter at the Yule Ball. Again, that's what I assume school dances are like. I don't know.

So at some later, calculable moment, the average energy in the room begins to fall. The DJ reads the room. And now you start having couples so that you actually could cross the floor because now you have a mean free path to cross the dance floor, unlike that very exciting early universe phase when everything's just a mash or a mush.

This makes perfect sense to me. You can tell me whether it's accurate or not. Anyway, that's the analogy for what Gamov, Alpher, and Herman were putting real numbers to to try to make sense of these different phases of the very early universe. Very high temperature, early dense state should be qualitatively different in its behavior than a later lower energy state.

So they predicted as early as 1948 that there should be this remnant glow from the Big Bang, all those photons that only then at 380,000 years after the Big Bang were able to start streaming freely. And the question was, where is it? Well, almost 20 years later, 15 years later, these two radial physicists working at Bell Labs, Robert Wilson and Arno Penzias, were using a new horn antenna sensitive to radial microwave and radial band frequencies. This was basically left over from the early telecommunications age.

Soon after the launch of *Sputnik,* lots of folks like private companies wanted to get into the satellite communications business. Often it was just bouncing radial waves off of reflectors in the sky in low Earth orbit and then bouncing signal back to Earth. Of course, it became more and more sophisticated than that. And they were actually given time on this telescope not only to fine tune the corporate program for telephonics, but also to conduct actual radial astronomy. They were interested in the evolution of nearby galaxies. They were not doing cosmology. They were interested in radial signatures of astronomically nearby things.

But they found this remnant hum in their electronics. This should've been among the most precise instruments available on the planet for that band of the spectrum. And they couldn't get rid of a residual hum. At one point, they climbed inside that huge horn antenna on their hands and knees to scrub out what they graciously called special dielectric materials from pigeons who had made a nest in there-- that, of course, meant pigeon droppings-- because they figured that might be messing with the electronics of some extra insulating layer. That didn't make any difference.

Finally, they were put in touch with a group at Princeton that was independently rediscovering many of the ideas from George Gamow and his group, actually at the time unaware that Gamow had even done these calculations. And they likewise convinced themselves about this cosmic microwave background remnant radiation. So now the group here, these folks are in Southern Jersey. They were close to Princeton. They all got together.

They said, oh, what you found is actually the remnant glow from the Big Bang. This residual hum in your receiver consistent with an energy of about three degrees above zero, three degrees Kelvin, was really the leftover photons, that remnant hot radiation from the Big Bang that had been streaming freely for the next 14 billion years. And the average energy per photon had fallen steadily since the time when they were first released in that early dance party. They were very soon afterwards awarded the Nobel Prize for actually detecting evidence of the Big Bang.

So let me pause there and ask any questions. Any questions on that stuff so far?

So far so good?

AUDIENCE: This might be a dumb question.

DAVID KAISER: Go for it.

AUDIENCE: But guess I'm just wondering how if you have photons that are like-- I understand that the photons from the CMB, they're from us looking in the past. But I don't understand why they're still there, why they haven't passed this already. I guess are they constantly being emitted? Or why is it still there basically?

DAVID KAISER: Yeah. Thank you. That's actually a really good question. Basically, the idea is that they should've been everywhere at once. So the idea was the whole universe is filled in the early times with very high energy particles that are at early, early times too high energy to form stable, electrically neutral atoms. So you have this huge plasma everywhere, not just in one corner, not just over there in the sky, but everywhere.

And likewise, there are photons everywhere. It was at least the idea of more or less uniformly distributed with no real pattern to it. And so from every part of space, from every single direction in the sky, those photons began to move freely at this single moment in time or a very short lived moment in time. So basically, the universe should've been filled with light, originally a very high energy. And then actually the energy of that light should be falling as the container expands, so as the average energy inside that balloon goes down.

So we're basically just moving through a bath of light. So the photons aren't coming from that direction of sky the way we think of with point-like sources. There's a galaxy there, a quasar, a particular bright star in our neighborhood. The photons were everywhere. And it's like sitting in a bathtub full of these photons. And they're just losing their energy as the overall size of space continues to grow.

So the idea was that there should be-- so it's not just that they should have a particular temperature. They should be everywhere in the sky was the idea, a uniform pattern. So if they could point that radial telescope in any direction, and they should find more or less the same signal, which is indeed what they were finding.

So think about sitting in a bathtub that at first is like boiling hot water. And then you're sitting there while the water continues to cool down, but you're still immersed in that. The photons are coming from every single region of space. And all that's changing is their average temperature per photon is the main idea.

Another way of saying it is it's-- it's hard to get-- [LAUGHS] hard to get one's head around. Believe me. But instead of saying the Big Bang happened over there and things are stretching out from it, the Big Bang happens everywhere. So every part of space that we could see today once had been at the Big Bang, so to speak. The Big Bang happened there. It happened at x equals 0, and x equals 1, equals 2. Any place we could put spatial coordinates to on this model, those all experienced the Big Bang at the same time.

So it wasn't the Bang happened there and stuff was flowing outward from it towards us. Again, think about being inside a balloon or let's say a bathtub. So there should be a uniform set of properties filling that space. And we're just immersed in it trying to measure it as we flow through.

I'd be glad to chat more about that. But I say all that as if that's obvious. It's not obvious. I'd be glad to chat more about it. But that's the kind of reckoning that people like Lemaitre got very comfortable with starting in the '20s and '30s. And it took other people a lot longer to try to get their heads around.

Alex rightly puts in the chat that Edwin Hubble was actually pretty lucky. It's true. There's been a tremendous amount of controversy right to this day or let's just say earnest disagreement over what's called the cosmic distance ladder, which is to say it's actually pretty easy now, relatively easy to measure the speeds with which objects are moving away from us because that has to do with spectroscopy. We can measure these atomic transition lines with great, great accuracy. And so you can just do a Doppler shift to say, oh, I would expect that line to be here. It's over here. And the difference is a direct measure of the relative speed, the recession speed.

What's not so easy is to figure out how far away from us that thing is right now, the actual distance right now. We can get the velocity from these very fancy spectroscopic-- I say we. The people who do it are actually astronomers. They kindly share their information. I don't know how to do it. But one can do it well. Now, whole teams can do it very, very well.

What's hard to do is to calibrate what's called the distance ladder. How far away is that object right now, let alone how quickly is it continuing to move away? And so this was especially off compared to modern day values in Hubble's time. In fact, his value was-- well, let's see. 500 versus 70. So what we now call Hubble's parameter is roughly 70 in appropriate units. And he measured 500. So he measured a much quicker average rate of expansion than what we have mostly settled on today.

But the basic picture was there. The picture was enough to get a small number of people to pay attention to Georges Lemaitre's otherwise quite obscure mathematical solutions. So Lemaitre. There's also a Russian and by then Soviet physicist Aleksandr Friedmann, who was doing very similar work. A few of these mathematical physicists were using Einstein's equations in ways that Einstein thought was awful, as I say. He was not at all a fan of this early on.

But to the few people who paid any attention at all, it looked like just a mathematical curiosity. And it was only when paired with observations most famously from Hubble-- Hubble actually had a number of assistants, and other groups began contributing as well. But it was Hubble's data that got the biggest splash, that made the biggest impact on the community at the time.

And regardless of whether we agree with the number he inferred of the actual rate, it seemed pretty clear to many people at the time that this was consistent with an actual overall expansion, with the change over time. And that made these seemingly pure mathematical solutions like Friedmann's and especially the follow up work by Georges Lemaitre, that made those mathematical solutions look much, much more curious and interesting than they had prior to Hubble's data.

Although, Alex, you're absolutely right. If one took his value literally it looked like the universe would be younger than things inside it. And that's not good, right? So how could the Milky Way galaxy or even the planet Earth be older than the universe in which it resides? So it did lead to these kinds of puzzles. And that was eventually smoothed over or made more consistent by the 1950s. That took a while. It's an excellent point. Any other questions on that? OK.

So this is a, I think, safe to say, remarkably successful set of ideas that eventually becomes called the Big Bang model, going all the way back to really Einstein, but especially people like George Lemaitre, a huge boost to try to give real quantitative teeth to these internal phases or intermediate phases by people like George Gamow and his younger assistants. And it starts to match observations really quite well. And yet we're not done. And people began to get worried about some of these features of the Big Bang model not only to cherish its successes.

So for this next part, it's actually really helpful to adopt convenient coordinates. If we accept the notion that there is a universal stretching of space, then it's actually helpful to adopt coordinates that take that into account. So what astronomers have done really for generations is to adopt what are called comoving coordinates. And then a physical coordinate at any given moment in time would be scaled by this universal stretching, this so-called scale factor.

So Hubble's data was consistent with galaxies sitting still at some fixed comoving location. You could plot down the Andromeda galaxy at r equals 7. And then it's moving away from us because all of space is stretching in between. So you can have galaxies that are more or less sitting still locally but are receding from us just as we are receding from them because the space in between is stretching. And you can accommodate that by inserting this one universal stretching function called the scale factor.

So the distance between, say, the Milky Way and the Andromeda galaxy at any given time, the physical distance really would change. It is getting more distant over time because the space in between is stretching. So if you plot things in terms of what's called comoving distance, you scale out, you take into account that universal scaling, then it would just look like Milky Way at r equals 0, and Andromeda is stuck at r equals 7 in these convenient coordinates.

Then you have to be a little more clever to adopt your clock to make things, again, actually really simple. This is actually called conformal time. That might remind you of our beloved friends, the 19th century Cambridge Wranglers. At least my beloved friends. We looked briefly at the Wrangler stuff at these conformal mappings. We're really doing a Wrangler-ish thing here, very similar idea, to adopt coordinates for the time, for the rate at which we think clocks should tick to be convenient that also takes into account that changing stretching rates over time.

And so what we call conformal time, often labeled by the Greek letter tau, is basically a variable tick rate that is really convenient because then we can start making a dynamical changing spacetime look just like the spacetime of special relativity, look just like a Minkowski diagram. Why do we do all this funny stuff I had to wave my hands around for comoving distance and conformal time? Because when we make spacetime plots where we use comoving distance rather than physical distance for the spatial part and conformal time, this variable clock rate rather than what's called cosmic time or sometimes simply called physical time, then actually we get back to some simple looking arrangements like light rays, once again, travel on 45 degree diagonals.

If we were to try to take into account the changing stretching rate of space, these paths of light rays would become these very complicated, bent, twisted paths. But in these special, very simple fine coordinates, light just travels on 45 degree diagonals. We sit still at a fixed value of comoving location. And then light comes to us at 145 degrees. That sounds very abstract. We do that all the time. This is just an example in space time of a conformal mapping of a sort that we all use every day like a Mercator projection.

So what this does is it inserts certain kinds of location dependent artifacts like Antarctica looks huge on a Mercator projection or Greenland for that matter. The surface area of Antarctica is nowhere near the surface area of Africa even though it looks so much larger. But that's because we've had a stretching. And the amount of stretching increases toward the poles if we do a two dimensional spatial conformal map.

We're doing the same thing here. We're stretching our time coordinate so time gets more and more stretched out towards earlier times. We can take that into account. We know how to use a Mercator projection. And it makes other relationships remarkably easy. Likewise our conformal maps here make the paths of light, for example, very easy to follow.

When people begin using these convenient coordinates, they also go back to some questions about or features of the Big Bang model, and they start having new questions. So we talked briefly last time about Robert Dicke. He was, again, a veteran of some of the wartime projects. He was an expert in microwave electronics, a radar Rad Lab veteran.

And after the war, he went back to Princeton and about 10 years after that became very interested in general relativity and cosmology. And he began retooling his whole research group around questions related to things like the Big Bang. We saw that in 1961, he published this alternate to Einstein's own theory of gravity, the Brans-Dicke theory of gravity, which we looked at last time. It's the same Robert Dicke.

So he introduced this conundrum in 1969, so soon after the discovery of the cosmic microwave background radiation when people began to take the Big Bang model more and more seriously, including Robert Dicke. He goes back to what I mentioned briefly before, that according to Einstein's equations, as clarified by people like Alexander Friedmann and Georges Lemaitre, you can have these very simple geometries. At any given moment in time, the shape of space could either have a positive geometry where it closes back on itself like the surface of a sphere, an open or negatively curved geometry, or a flat geometry. What controls which geometry you have is this ratio of the actual amount of stuff per volume, the actual density of matter and energy per volume, compared to some critical value.

So it became common after Dicke to just introduce the Greek letter capital omega simply to refer to that ratio. What's the ratio of the actual stuff per volume in our universe compared to that critical value? And only for that Goldilocks solution, we have exactly the balanced amount of stuff per volume would you expect to have space obey Euclidean geometry on large scales. If omega is larger than 1, you have more stuff for volume. You have a positive curvature. If omega is smaller than 1, you have less stuff per volume than the critical value. You expect it's open or hyperbolic geometry.

So far so good. Then Dicke plugged this quantity into Einstein's own equations. So this is a time dependent quantity. After all, we're talking about densities. The density should depend on the volume. It's stuff per volume. If you have a universe expanding over time, the volume should be changing over time. So the density should presumably go down. The density should fall.

If you have a fixed amount of stuff in a space time and you stretch that space, the density falls. If you throw four marbles into a bucket, you have a density of four per cubic liter, let's say, a cubic liter bucket. If you double the size of the bucket, then you have still only four marbles, but now a larger volume. The density's gone down.

And so what Dicke demonstrated is that according to Einstein's equations, this solution that looks like the Goldilocks solution, the spatially flat solution where you have just the right amount of stuff per volume, is actually an unstable solution. It's an unstable equilibrium point of Einstein's equations. A universe should generically become more and more different from flat over time.

And if you just plug in the notion that the density is falling 1 over the volume, the volume should go the cube of the spatial dimensions, so go a cubed. So in fact, this part comes just from Einstein's equations, 1 over a squared, a being that scale factor, like the radius at any given moment in time, and rho is the density of stuff per volume. Well, if the rho is going 1 over a cubed, then this whole quantity here should grow with a scale factor.

So the difference from a flat universe, the deviation from spatial flatness Dicke shows, generically should grow over time. If a universe started out being close to but not identically equal to flat at early times, it should look nothing like spatially flat at later times. Depending on the sign, it could either become more and more like a hyperbolic saddle or more and more like a closed sphere. What it should not do is say looking anything like the flat Euclidean solution.

So if you extrapolate this backwards to early times, the time of nucleosynthesis, for example, or even to the times of when the cosmic microwave background radiation was released, you find that you have to fine tune, you have to have some reason why the amount of stuff per volume was not just in the neighborhood of that critical value, but, in fact, was exponentially close to it you. As Dicke points out, you have these exponential fine tunings for the universe to be even remotely close to a spatially flat or Euclidean-like behavior today, which is looking more and more consistent with observations by the '60s and '70s and '80s. Even if it wasn't compellingly equal to flat, this parameter omega was, say, 0.3. It wasn't 10 to the minus 70. It wasn't 5. It was 0.3 or 1.1. It was in the rough vicinity of 1 to the extent that the measurements could converge the observations.

And yet a measurement of anywhere near 1 today suggested that it had to have been exponentially close to 1 at early times. And that seems like this very strange or unexplained fine tuning. If the universe has been stretching for 14 billion years, what set it to be so exponentially arbitrarily close to spatially flat given that is an unstable equilibrium point? That became known as a flatness problem. That was introduced by Bob Dicke in 1969. Dicke actually was really thorough. He was thinking about other things too.

So 10 years later, he introduced the next big real conundrum for the Big Bang model. And this one he did with his younger student, by that point, his collaborator, James Peebles. You might know Peebles' name. He actually just received the Nobel Prize in physics a little over a year ago for much of this work. Peebles had done his PhD with Dicke at Princeton.

So 10 years later, Dicke and Peebles introduced the second big conundrum. And this one's called the horizon problem. So now let's go back to this very convenient, conformal diagram. So I'm going to use the same funny coordinates I mentioned before. I'm mapping the history of the universe using comoving distances. So I've taken into account that universal stretching of space and that variable clock rate, that conformal time.

So now, according to this very lovely picture that people like George Gamow and Ralph Alpher and Robert Herman put together, we should be receiving these microwave photons today from literally every direction in the sky. This goes back to Steven's question. Imagine you have a three dimensional version of this. Everywhere in the sky, you see these photons heading toward us. Some of them are heading away from us. But we're just immersed in the bath.

The ones that we see have been heading on trajectories toward us since they were first released, since that moment 380,000 years after the Big Bang when photons could begin streaming freely, when they could travel macroscopic distances because the universe is filled with electrically neutral matter. There's some moment after which the photons begin traveling large distances. They've been traveling that whole time until some of them enter our antennas and our satellites today.

So remember, in these coordinates, we sit still at some fixed value of comoving location, r equals 7 or whatever you'd like. You can call it r equals 0. And then light travels on these lovely, convenient 45 degree diagonals. So from this corner of the sky, it's like pointing your telescope over there. From this corner of the sky, looking in the opposite direction, we receive this uniform bath of photons that have been traveling towards us this whole time.

Well, here's where Dicke and Peebles start raising some questions. We received this remarkably uniform signal on the sky today from opposite sides-- matter of fact from any direction that we point our radial telescopes both on Earth or now from satellites. There's a comoving distance delta r across which we receive these photons. And they look remarkably uniform.

However, those photons were emitted at a finite age when the universe was only a short portion of its current age. It was only 380,000 years old as opposed to nearly 14 billion years old. Light can only but travel at a fixed speed at least according to Einstein's theory. So if the universe has only been around for so long, then light could only have traveled so far. That's called the horizon distance. What's the furthest possible distance that a light beam could've traveled traveling at that constant speed of light for as long as it was able to?

So even though an actual physical light beam couldn't have traveled because the universe was optically opaque, any information, any physical signal, any force, anything that is limited by Einstein's speed limit should only be able to travel up to and limited by the speed of light. That means there's a furthest distance according to which any information or influence or physical force or anything could've traveled since the Big Bang up to the time when that radiation was first emitted. That's called the horizon distance. And as they show, for any finite age, for any universe that has this beginning a finite time ago, at any moment in time, there's a furthest distance that anything traveling at the speed of light could possibly have gotten to yet. That's called the horizon distance.

So what they show is that at the time that the microwave background photons began their journey when they first began to free stream, the universe was still so young that the furthest possible distance that any causal influence should've been able to travel was a tiny fraction of the distance across which we actually measure remarkably uniform signals on the sky today. So the horizon distance was actually a factor of 100 shorter than the smoothness scale across which we receive remarkably uniform information. How could that be? If this portion of the sky never had a chance to become in any kind of physical equilibrium or even exchange a single tweet, to have absolutely no information of this part of the sky about what the average conditions are in this part of the sky, how could they have become indistinguishable in the signals we receive today? That became known as the horizon problem.

And this was heightened as more and more data came in, more and more careful observations of the microwave background radiation. It became clear that signal really is uniform to one part in 100,000. It's remarkably uniform to a tiny fraction of a percent. It was at 1,000th of 1%. That signal is uniform across every direction we look in the sky today, even though it's coming from all these regions that when that light was emitted couldn't have possibly had any physical interaction with each other or had even a single status update saying, I'm going to release my photons at this temperature. You should do the same. So the time that the light was emitted, the smoothness scale was much, much larger than the causally self-connected scale. That becomes known as the horizon problem.

So why on Earth would the CMB be so uniform today to this exponential accuracy from regions of sky that were never ever in causal contact? Plus, why on Earth do we have this distribution of scales that I started off in the beginning? Where does large scale structure come from? Oh, I'm sorry. I skipped ahead. Sorry. This is my anthropomorphic analogy for why the horizon problem should give you pause.

This usually works better when we're meeting in person in an actual classroom. But imagine we're all sitting in a nice big comfortable room socially distanced. And everyone has come in the room, and I've stolen your cell phones. Sorry. You'll get them back. I've temporarily taken your cell phones and your laptops. I've blindfolded you all and put in earplugs and handed every single one of you a ping pong ball. I won't actually do this, but just imagine.

And then without any prior coordination, I say, please throw your ping pong ball at the same speed at the same time to one part in 10 to the 5 without any chance to coordinate, without anyone saying, ready, set, go or you being able to say to your neighbor, here's my plan. Let's coordinate. That's what it's like to have these causally disjoint regions emitting these photons not just with the same energy, but with the exact same energy released at the exact same time. That's the point of this series of ping pong balls distributed through space.

Now, as I was saying, what about the lumps? This entire Big Bang model has still had to assume by fiat with no real explanation that there was some initial lumpiness, there's some inhomogeneity that over time could then grow to become this cascading hierarchy of scales, which is why we'd have super clusters of galaxies separated by huge voids and all the rest. So the Big Bang model had some amazing successes but some pretty stubborn quandaries as well.

So I'll pause there again and ask the questions about that. Any questions on the shortcomings of the Big Bang as people began articulating them throughout the '60s and '70s? Feel free to jump in or use the chat or either way. And again, there's more on the quantitative details of that in that optional primer you can find on the Canvas site.

So Fisher asks, is it useful to think of the universe as spherical still? Yeah. These pictures get pretty hard. So basically, we can imagine choosing some point of interest and drawing some sphere around it and asking what's happening in that region? Is that region itself will grow over time? And is that region representative of some larger sample from which it's taken? So we can still ask about the behavior of some randomly drawn sphere even if the global shape of space might not be spherical. As you can imagine, filling a perfectly rectilinear Euclidean space with a bunch of representative spheres whose behavior we could study.

Now, it could be that the entire universe has a global shape to it. We could be living in a closed universe where on the largest scales it actually looks like a sphere. But we could, again, do the same trick. We could still ask about locally, let's fill it with some representative shape and ask about the average behavior within that shape. So what we mean by what spherical, we can continue to use spheres usefully even if we live in a flat universe as long as we're careful to distinguish a sample volume versus the global properties. It's a good question.

Alex asks, what about the model problem? Yes, very good. So I left that one out. That was something that exercised Alan Guth in particular because-- maybe that's getting ahead. Maybe I'll talk a bit about that actually in the last part of the class.

That's a good question, Alex. Any other questions about that, about the shortcomings of Big Bang? OK, let me press on because these are actually questions. Alex is already giving us a segue to the next part, which is great. So let's go to that last part for class today.

I love this photograph. This is to me priceless. This is what Alan Guth looked like circa 1980. I think MIT used to have a law that you had to dress so as to match your own blackboard. I think we relaxed that rule. But anyway, he was blending into his surroundings. His room, like the universe, should've been perfectly homogeneous and isotropic.

Anyway, here's a very young smiling Alan approximately 40 years ago. He was wondering about these questions as well as we'll see in a moment. He was, however, coming at this having been trained at MIT in particle theory. He was not trained in relativity or cosmology. He was much more the same generation as Tony Zee, whose work we talked about briefly in the previous lecture.

When Alan was in graduate school, he was studying high energy physics and therefore not gravitational cosmology. He wound up doing a series of postdoctoral studies. He liked Tony Zee, accidentally heard some talks about some of his early work in gravitation. In particular, he heard some lectures by Robert Dicke when Dicke was on the lecture circuit talking about these curiosities or shortcomings of the Big Bang model. And that really stuck in Alan's mind. He was not originally asking questions about the cosmos, but he was haphazardly encountering some of those questions, again, very much like Tony Zee around the same time.

What Alan was interested in was in things like spontaneous symmetry breaking and the Higgs mechanism. That was all the rage for a lot of particle theorists in the early and mid '70s by then. And he was wondering about shapes for the potential energy function of that Higgs field that might have a extra structure. There might be a kind of dimple to that energy function. We could imagine the Higgs field getting temporarily stuck at some metastable state at the origin of its own potential energy function where there's a barrier in any direction, but it's not an infinitely high barrier. So according to quantum theory, that Higgs field should eventually decay to the genuine global state of lowest energy, anywhere along this so-called vacuum circle.

And Alan was realizing upon hearing Bob Dicke's lecture that that could have remarkable cosmological implications. If there were a time, even a short time during which the matter that's filling the universe could be temporarily stuck in a metastable state in which it had some non-zero potential energy, but it couldn't release or relax that energy arbitrarily quickly because it's stuck in this metastable so-called false vacuum, then that could have implications for the global shape of space and not just for the behavior of elementary particles.

I highlight the date. Thank goodness for historians. Alan is unbelievably anal retentive and writes everything down and has pretty neat handwriting. A lot of people who write things down and have egregious handwriting, and there's more people who don't write things down. Alan, although he likes to blend in with his blackboard, writes things down with neat handwriting.

And so I note the date. 41 years ago to the day-- today is December 7-- to the day, he was up very late as is his wont piecing together his ideas about these Higgs like functions with these funny metastable states where the energy density of the universe could get trapped temporarily at some large non-zero value. And he was putting that together in his mind with the lectures he had literally just heard from Robert Dicke not long before. And he calls this a spectacular realization.

So my request number 3 to you scientists is both write things down, use neat handwriting. And when you do something cool, tell us it. Tell us that you're excited and put it in a box because when we're going through your notebooks, honestly, most of it's just garbage. We just don't care. But he actually did us a favor and put it in a box. Pay attention to this. His notebook's actually now on display in the Adler Planetarium in Chicago, literally this page of notes.

He realized that this kind of feature could actually lead to a cosmologically distinct kind of evolution, that if you have a period of time even briefly during which the energy density, the amount of stuff per volume, gets stuck, gets stuck at some non-zero value and can't change quickly, then the energy density could remain constant. If the energy density, the stuff per volume, remains constant, then very counterintuitively, you have a runaway growth in the size of space. That stretch function, the scale factor going back just to Einstein's equations, will grow exponentially quickly, will have a period of accelerated expansion during which the universe won't just get bigger. It'll get bigger faster if you have this counterintuitive even temporary phase during which the stuff per volume stays constant even as the volume grows exponentially. That could happen.

Alan began wondering if you have this weird state of matter that was at least hypothetical and of right interest to particle physicists because they were worried about things like symmetry breaking and the Higgs mechanism, that does not happen with marbles in a bucket. It does not happen with electrons or quarks or protons. It happens for certain kinds of elementary particles, including things like these very simple fields like the Higgs field or Higgs particle, which for other reasons could have some funny shape to their potential energy function.

Alex, I'm going to skip the monopolar problem, but it comes from this discussion as well. And I'd be delighted to chat more about that if you'd like afterwards. But in the interest of time, Alan was worried about some exotic features from these Higgs fields that can get twisted up in some topological shape.

But he was really just wondering what happens if the universe gets stuck even temporarily such that the matter that dominates it, fills it, can't release or relax its potential energy arbitrarily quickly. That's called a metastable state. And if you go back to Einstein's equations exactly in the form that he began learning from Bob Dicke from that series of lectures, then you have these very different solutions for the average size of space. It grows exponentially quickly. And as Alan and others were quick to confirm, this happens very naturally, or at least it's a kind of feature that one stumbles upon readily, if when studying these exotic Higgs-like fields from particle physics. It does not happen with spin one half particles, for example. It does not very easily happen even with photons or gluons or things that happens with these Higgs-like scalar particles most naturally.

Soon after that, actually within a few months, a number of other colleagues, some in the United States, some in what was still then the Soviet Union, were finding similar behaviors and even more generic or simple arrangements. So Paul Steinhardt was working with his then PhD student Andy Albrecht. They were at the time at Penn, University of Pennsylvania. Meanwhile, in Moscow, Alexander Starobinsky and Andrei Linde were working quite independently of Steinhardt and Albrecht.

And then again, realizing that if you study the dynamics, the behavior of these exotic quantum fields like a Higgs field in a stretching space time, if you take that stretching of space seriously, then you don't even need to cook up those exotic Higgs-like potentials that Alan was first thinking about. Quite generically, you'll have a damped oscillator behavior. If you look at the evolution of some field like the Higgs field, its self-consistent change over time, its equation of motion, includes a damping factor like a damped oscillator. This comes from the fact that space itself is stretching. And that alone it turns out is enough to find these self-consistent solutions in which the field moves very slowly.

You can imagine it rolling down this hill, rolling down-- sorry-- rolling down slowly as a function of time because it's like a frictional, overdamped oscillator. Again, there's more of that in the primer if you're curious to see more. Even that not literally fixed behavior-- it's literally changing, just changing slowly enough. That will lead to a slowly enough changing potential energy trapped in that field that you'll still get these nearly exponential-like solutions. So you can have inflation happening even more generically as these folks began to find very soon after Alan even without worrying about a very particular shape for the potential energy function just when you think about these fields like a Higgs-like field in the early universe.

So then you come back to those quandaries that Alan had first heard about from Bob Dicke. And you ask, how would these things look if you now take into account this very early, very brief phase of exponentially fast stretching of space? Go back to the equation that Dicke had first written down for the flatness problem. But now we have a phase during which the scale factor grows exponentially-- e to the something times t, so it grows very fast in time-- while the energy density remains nearly constant. So instead of that falling with volume, it temporarily remains nearly constant.

Now you'd see this expression, the deviation of the universe from spatially flat. That deviation should rapidly fall to 0. The universe today should look indistinguishable from a flat universe because the difference from flatness was driven to 0 dynamically. By having even a very brief phase of exponentially rapid accelerating expansion, you drive the universe towards a flat shape rather than having it flow away from a flat shape. And again, I go through that in more quantitative detail in the primer.

So the latest measurement from the Planck collaboration using a satellite is that this parameter in our actual universe today is 1 to better than a percent level accuracy. Now, let me pause. I know I'm going to run long today, but I just can't help myself.

When I was in graduate school not super long ago-- kind of long ago-- I was friends with a bunch of observational astronomy grad students in the dorm. And they were basically me. They would tease me. Like, you work on inflation, but we know that omega is 0.3. So you're a loser. Why do you waste your time on this? Some were nice, but a lot of them were actually kind of mean.

I was like, oh, no. Go look for more stuff. You're missing two thirds of the stuff out there. Just try again. So maybe I was mean too. But they were meaner. They were more of them.

So when I was in grad school, it looked very much like omega was 0.3. And if you squinted at it, you could maybe make it 0.35. It was not 1 according to the best observations around the world. Today, [LAUGHS] it's 1 to better than a percent level accuracy. And they can just stick it. So I like sending them holiday cards saying, thinking of you. Omega's 1. See you next year. Anyway, this is a remarkable shift even over the course of 20 to 25 years, let alone since the days of Lemaitre and Hubble.

OK. What about the more subtle one that Bob Dicke and James Peebles worked out called the so-called horizon problem? Go back to our funny map, our conformal map. Now, remember, the horizon problem was originally phrased because we thought there was an origin to all of time, this Big Bang surface, at tau equals 0. And if you add up the time between tau equals 0 and when those photons begin to travel freely, there was only a fixed horizon distance. It was much smaller than the smoothness scale that we could measure empirically.

Well, if inflation happened, there should've been a very brief period before what had previously been called the Big Bang. So we're adding more real estate along our time axis. We're unfurling a little bit extra time that hadn't been taken into account in the standard Big Bang model.

So if you allow for more time before what you would call the Big Bang, you can continue tracing those past light cones further and further back and say there should be some time earlier than what we were starting from during which all the past light cones from the entire region we see today would indeed have overlapped. So then it would at least be plausible there's at least now a causally self-consistent mechanism by means of which the universe could have similar conditions everywhere because they actually were causally connected at a time before we had previously taken into account.

So therefore, you could have the horizon distance, the maximum causal distance, becomes actually much larger than the smoothness scale that we measure. So now the horizon distance is larger because there was more time that we hadn't yet taken into account. Any kind of causal influence would've had more time to propagate than we had previously accounted for. So now you get the ratio at least in the right order. You can have a horizon distance that is larger. In fact, it could be much, much larger, exponentially larger than the smoothness scale we observed.

Now, remember, this is a funny coordinate. It takes an unbelievably short amount of physical or cosmic time, the time that we measure on our wristwatches, to accomplish that. In fact, it takes about 10 to the minus 36th of a single second. That's all it takes for this inflation. If the universe expanded exponentially just for that sub, sub, sub blink of an eye, then all of a sudden, the causal structure of the entire observable universe is turned upside down.

You basically erase the horizon problem because there actually was a time when all the stuff we see would've been in causal contact, very comfortably in causal contact. And the universe in that tiny blink, a billion, billion, billion billionth of a second, grew by about 30 orders of magnitude. It didn't keep doing that. It wasn't doing that during the rest of this Big Bang evolution. There's this tiny blip. And taking that into account suddenly rearranges the causal ordering and basically addresses these out of order causal conundra.

So here's a plot in more familiar coordinates, going back now to time measured in seconds and space measured in meters rather than comoving distance and conformal time. You can see that as you trace backwards from today, instead of going back to saying the universe at early times should've been on the order of 1 meter, you say at those early times, the universe was actually exponentially tinier than you had thought. It grew exponentially quickly to map onto where we see today.

And so the universe was so tiny, it could very easily have been in a kind of equilibrium or at least a causally self-connected state. So during this tiny blink of an eye, the universe grew exponentially quickly and then mapped onto the standard Big Bang evolution. And that alone is enough to address the flatness and horizon problems.

It turns out it does more than that as well. This is what gets I think even more exciting and what has occupied much of the community ever since. That Higgs-like field that was driving inflation, that was very slowly evolving in its potential should've been subject to the uncertainty principle just like all matters should be. And this became clear to people about a year or so after Alan and Paul and Andy and all those folks began writing the first papers on inflation.

By 1982, '83, pretty early on, people realized that not only would you have a gross feature of the evolution of those exotic particle physics-like fields. They should also have quantum wiggles because how could they not because they should be subject to the uncertainty principle. These are quantum fields evolving in a dynamical spacetime.

I still can't believe it. But it is the case that you can study the evolution of those quantum fluctuations with a remarkably simple looking oscillator equation. I've hidden all the hard stuff in this term. I made them look easy. But you can actually take into account that frictional damping, the stretching of space, and the reaction of that jittering trampoline back on the evolution of matter.

We can solve these equations to unbelievable accuracy and realize that we should have a prediction today for tiny seeds, tiny unevenness, in a very early distribution of matter and energy because the universe was filled with quantum fields. And as we've seen a number of times now, quantum jitter, the uncertainty principle, means that we can never specify the energy of that field to arbitrary precision at any time. At any given moment, that field would be subject to slight, slight quantum fluctuations in the distribution of energy across space. That starts to yield this tiny little fluctuation in why there's slightly more matter and energy in this region of space than the other one.

So now those very tiny quantum scale fluctuations get stretched as the whole universe stretches. As the scale factor grows exponentially, you have the average length between the distance between crests of those tiny wiggles get stretched to galactic and even super galactic scales all within that blink of an eye. So now you have a reason why there's a primordial inhomogeneity. And you also have a reason why it's on the right length scales. It's going to seed galaxy formation, not mess around with your atoms like a Lamb shift because you have matter in an early quantum state as the universe is stretching exponentially.

So you can go back to now a much more modern picture of a very tiny lumpiness captured in that microwave background radiation. This is from the Planck satellite team. It's exaggerating with false color imaging the slight one part in 100,000 offsets between the regions of sky that are slightly higher energy photons in the CMB and slightly lower energy photons.

And the idea now is that the regions of the sky from which these photons were emitted are telling us about the very, very tiny unevenness in the distribution of matter and energy at the moment those photons were emitted. There's a tiny, tiny little excess gravitational potential. There was a little more stuff per volume at that region. So the photon then had to spend a little more energy climbing out of that gravitational well. We should receive it today as being a little less energy than average, very slightly less.

Meanwhile, other photons would've come from regions that were slightly evacuated, a little less dense than average. So the photons we receive today had to spend less energy gravitationally to overcome that very tiny gravitational potential. They should have slightly more energy on average today than the average. So we can actually map the quantum fluctuations which leave an imprint in this dynamical fabric of space and time that then maps to this distribution of these very tiny unevenness in the CMB.

They have been mapped by three generations of satellites above the ground with increasingly precise ground based measurements as well. And each of these came out 10 years apart with an increase of about a factor of 30 in the angular resolution of the sky. I was a senior in college a long time ago when the first of these released their data in September 1992. I was a senior that year.

And the [INAUDIBLE] team led actually in part by our own Rai Weiss, who later became very famous for his work on gravitational waves-- Rai was one of the science leaders for this early mission, a NASA mission. They were the first ones to measure these tiny, tiny fluctuations on the order of about one part in 100,000 but over huge scales. It was like they had very poor eyeglasses. It was very fuzzy, very poor resolution. Roughly 10 years later, another NASA mission called WMAP was able to increase the resolution by a factor of 30. And they released their data in 2003. Then the European Space Agency collaboration called the Planck satellite released their data 10 years after that starting in 2013 with another factor of 30 in the spatial resolution.

And so we can now make plots like this. The solid green line is the generic prediction from the simplest models of inflation, what's the pattern of bumps and wiggles on the sky you should see today-- it's basically fancy Fourier transform more or less-- what's the power on different angular scales that you should see today. And you can actually measure many, many quantities, many features of that distribution. The red dots are the actual observations from Planck team. And in many cases, the error bars are expanded so we can see them with our naked eye. This is such a precise set of measurements that, in fact, sometimes we have to make the error bars larger.

So now not only do we know do we live in a universe that is indistinguishable from flat as inflation suggests we should, but the actual pattern of those wiggles, the pattern of the very slight early unevenness in the sky matches predictions to, again, better than a percent level accuracy. I find that astonishing.

Let me take a few more minutes. There's one more set of things that were found or I should say that were predicted. So inflation should not only make these early primordial density perturbations where the photons should be slightly more or less energetic depending on the quantum fluctuations of that Higgs-like field. There should be primordial gravitational waves as well.

This is now much like the waves that Rai and his huge team found locally from the collision of, say, black holes. There should be primordial gravitational waves excited by inflation as well. And these are waves that actually stretch and squeeze space in a two dimensional pattern. So these are mathematically more complicated structure. You should have this periodic squeezing, stretching, and then inverted by 90 degrees.

So a version of these were found by the LIGO collaboration and announced early in 2016. These are not primordial. These are from local effects like the collision of black holes in our own galaxy. Inflation says similar kinds of things should've been happening in the earliest moments everywhere in space through this very violent, rapid stretching of space.

So go back to that dance party I was telling you about before. At the moment when the electrically neutral atoms start to form, if there were this sea or bath of gravitational waves, then the high school auditorium-- imagine where this dance is happening-- should've been subjected to this periodic, very particular pattern of squeezing and stretching. So while the atoms are forming, gravity waves would be rippling through them.

That should yield a characteristic twisting or curl pattern of polarization in that cosmic microwave background radiation. Not only should they be slightly hotter and colder spots in the sky. If you zoom in by a factor of another 20, you should actually see a corkscrew pattern, that the hotter and colder regions actually have this twisting pattern, which really is like that container of spacetime being stretched and squeezed as the gravity waves ran through it.

In March of 2014, a team using the BICEP satellite at the South Pole announced they had actually measured exactly that corkscrew pattern. This is from their now famous or infamous paper. We had a celebration here at MIT. This is me [LAUGHS] cheering on Andrei Linde and members of the experimental team. We had a toast with non-alcoholic cider. I want to be clear it was middle of the afternoon. We were getting drunk on the ideas, but not on hard cider.

Unfortunately, pretty soon after that, it turned out the BICEP team had measured data consistent with local noise. Many of my friends on the BICEP team managed to find out the Milky Way galaxy is dusty, which we knew. [LAUGHS] So basically, the signal they had hoped to measure was actually swamped by foregrounds they had not yet been able to control. And this was found by a number of very sophisticated analyzes soon afterwards.

So it remains an open question to this day whether these primordial curling, twisting patterns really can be detected. Maybe there's such small magnitude, it'll evade our detection. We don't know. There are ongoing efforts to this day. BICEP is now souped up, and they have a much more sophisticated series of telescopes. There's another team also at the South Pole, the Planck satellite. There's new efforts being built on the Atacama Desert, very high altitude in Chile. So stay tuned. We'll hopefully learn more about that final prediction from inflation before too long.

Let me wrap up. Cosmic inflation arises from types of matter in interactions that we now know exist that are heart and soul of this particle cosmology community, things like the Higgs boson. And it addresses several of these long standing conundra about the standard Big Bang model and makes specific predictions for what we should see on the sky today, including very minute statistical predictions for things like the cosmic microwave background radiation. And the simplest models fit to unbelievable accuracy despite what my mean dormmates used to say in the mid '90s. Now we have extraordinary agreement with many, many of these predictions, albeit not the final one.

So why is the universe lumpy? Why is this cascade of scales? Because space time is wiggly, and matter is jiggly. Now, there's an alternate hypothesis, my final set of slides. I mentioned this last time. And I just want to make it clear.

I mentioned that Alan Guth been working on this since around 1980, since December 7, 1979, in fact. As you also know, he's won many awards, including the award from *The Boston Globe* for the messiest office in Boston. This was published in *The Globe* at the time that he won first place.

They also published these photographs. These are all shots from his office at the time. I used to have to walk through that just to try to meet with my PhD advisor. It was not OSHA certified. So an alternate hypothesis for why the universe is so messy is actually because Alan's been generating the mess in his own office, and it's expanded to cosmic scales.

So I'm going to close with that. And I'll be glad to stay a bit longer if people have questions. Again, I'm sorry for running late. Feel free to drop off if you need. Any questions on that?

The photos in Alan's office are on Canvas. So if you want to study that part of today's lecture, it's probably the most important lesson, you'll ever take away. You can study those at your leisure as well.