S. GEORGE DJORGOVSKI: First let's look at some of the basic notions, both theoretical and observational, to set the stage for what cosmology really does. And the inflating balloon analogy is commonly used describe expansion of the universe. It all really began with the general theory of relativity. That you can say would be the start of modern cosmology.

Which Einstein published in 1915. This is the actual paper that was in Annalen de Physik. And as I already probably mentioned, the important things about relativity, aside from being a fundamentally different way of looking at space and time and matter energy, is that they've connected geometry of space with presence of matter or energy in it. And the box here is two line summary of what general relativity is all about.

So there has to be a consistent behavior. If space does something, it expands or contracts, then it has to follow whatever Einstein's laws of gravity say. Now from the cosmology viewpoint, the important part is that this is the theory of gravity. Nothing else. That's for general relativities.

And since gravity's the only interaction that's important at large scales-- subatomic ones are limited to subatomic particles, electromagnetism usually doesn't matter very much because charges will be mixed. So if you want to have a theory of universes at all and dynamical behavior, you need theory of gravity. So this was it.

Now observationally in the early part of 20th century astronomers started measuring velocities of galaxies. This is even before they knew that galaxy were galaxies. They were just nebulae. But thanks to Hubble's discovery of variable stars in Andromeda, in the 1920's it became clear that indeed galaxies are other island universes. And so the study of extra-galactic world began in earnest.

And in particular, one neglected pioneer is astronomer called Vesto Mevin Slipher, who worked at Lowell observatory. And he got a lot of first velocities of galaxies. Hubble used his data in his famous paper, without necessarily giving him much credit. So Hubble plotted estimated distances to galaxies, which he judged based on their brightness I think, versus their velocities. and saw that there is a linear trend.

And this is now known as Hubble's law, that the velocity of a galaxy receding from us is directly proportional to the distance to it. And the constant of proportionality is called Hubble constant. And the plot's called a Hubble diagram. Turns out that this still plays a very major role in modern cosmology, it began this way.

So you will instantly recognize that this really corresponds to the uniform expansion of space. And since there was already some notion about it from general relativity, this was accepted right from the get go. Now where does the Hubble Law come from?

So imagine space filled with galaxies, and the volumes stretch uniformly. So this is multiplicative change. Every volume gets multiplied by some factor of one point whatever over a period of time. So that means that the increment over any given time interval is going to be also proportional to the length that you're looking at.

So the incremental distance is proportional to the distance itself. And since it's the same delta t for all the galaxies you look at, then velocities will be also proportional to the distance. And this is what Hubble's Law says. In fact it's equivalent to the statement that if the space is uniform, homogeneous, isotropic, if you see this effect that means the space expands and vice versa.

Now there was another piece of, well assumption that one had to make, and that is what we call The Cosmological Principle. It's related to The Copernican Principle, which stated that earth is not in the privileged place in the universe. And this says that the galaxy itself is not in a privileged space in the universe. And that at any given time things are pretty much the same in all locations in all directions.

And this is what makes cosmology possible. This may not be the case in principle, but it just happens to be correct. And so that simplifies this problem enormously, as I'll show you a moment. Now that can be generalized further to the so-called Perfect Cosmological Principle, which says that it also should be same at all times. But how can you have that if the space is expanding?

Well you can have it if you keep creating matter, so that it fills up whatever's left. The new space stays the same density. And that was the principle behind so-called steady state cosmology. The universe expands, but new matter appears out of nowhere. And so it's always the same. And this was a serious contender for cosmological model, until it was dis-proven largely by the cosmic microwave background, but also other things, like counts of radio sources.

So just to clarify what these symmetry assumptions mean, here are the three cases. The first one there is a preferred direction. So it's the same everywhere, so homogeneous, but there is preferred direction. So not all directions are equal. So it's homogeneous but not isotropic.

The other one, in the middle, all directions are equal. But that's a privileged place. And so it's isotropic from that point, but it's not homogeneous. And finally, if you just have random blobs going on forever, that's homogeneous and isotropic, except around the blobs themselves. Where they define local direction. And so the question is, how true is this?

Well it's actually pretty good. And so if you look at scales larger than about 100 Mpc, that's really cosmological scales, which is what matters here. We find out that yeah, the universe seems to be pretty much homogeneous, isotropic. The map on the upper right is distribution on the sky of radio sources from particular survey. The missing pieces are parts where a telescope could not observe. And it's pretty uniform, so it seems the universe at large scales really is homogeneous.

The ellipse on the lower left is symbolic representation, a picture of what cosmic microwave background would look like. Now you've seen those garish blue green yellow pictures of cosmic macro background filtrations. That's with the contrast turned up by a factor of a million. If you just look at any lesser contrast it's pretty damn uniform. It's equal in all directions to a few parts in a million.

Well that's a very large scale. Now as we studied large scale structure, we know that this is not true at scales of about 100 Mpc or less. There are all these blobs and filaments and clusters and voids and so on. And certainly their preferred directions, wherever local acceleration pulls you, there is more matter in some places than others. But if you average this over hundreds of Mpc, it's pretty good. And so on a global scale this doesn't really matter very much.

So homogeneity and isotropy are good. We'll use them in a moment. But what about the expansion of the space? This is something that people tend to get a little confused about.

And the essential point is that there are actually two kinds of coordinates in general relativity. There are coordinates that expand with the expanding space, or contract. And there are those the really stay constant. Otherwise how could you tell if everything was expanding at the same rate? You just couldn't tell, so there has to be comparison.

So it turns out that things that are not gravitationally bound, the galaxies far apart, or mass-less quanta or any relativistic particles actually, stretch with the expanding space. Or move along with the expanding space. But physical systems that are bound by any forces, gravitational, electrostatic, and so on, do not participate in that expansion.

So sizes of atoms, or planets, or solar system or even galaxy, doesn't change. The space kind of expands underneath. And so as long as the system is bound, it stays the same physical proper size. So this is how we can tell.

We can ask well why not the other way around? Why aren't proper coordinates shrinking and space is staying constant? Well at some mathematical level it's equivalent, but on the other hand it will require inventing a whole new physics completely. And there is really no reason to do it.

So the first question said OK, space is expanding, but into what? And the best thing that we can offer is two-dimensional analogy embedded in three-dimensional space. So we can have surface of a sphere, which is finite, and the sphere can grow or shrink in time in the third dimension. So what's the equivalent of that in four-dimensional space-time?

Well you can think of time perhaps as the radius, is if you will. And the three-dimensional universe expands. Or take just coordinated grid, infinite coordinated grid, squares all the way to infinity. You could start expanding it, and there is knowledge that it just expands to infinity. But it expands nevertheless.

So there are two possibilities. Either the universe is of a finite volume, so-called closed models. Or infinite volume, an open model, or some clever combination of the two. Which comes with multiverses and so on. But it expands into itself, if you will. And so there are no edges ever, and there is no center. All places are equally good. That's homogenetic isotropy.

So what we call Cosmological Red Shift is stretching of the photons due to the expansion of the space. And again, if you take inflating balloon and glue little galaxy spots on it, like coins or something, the balloon will inflate but they'll stay the same size. But if you draw wiggly lines on the balloon that correspond say to photons, they will stretch as the balloon stretches.

And since longer wavelengths correspond to redder shift, that's called a red shift. And this is related to the Doppler shift that you're familiar with. This is formula for the special relativistic version of the Doppler effect. The red shift is ratio velocity to the speed of light, and that corresponds to relative change in wavelength or frequency, for that matter.

So that's the familiar formula. Now it turns out that's actually completely equivalent to thinking that for some reason, whatever reason, galaxies is moving away from us. And so they have to have Doppler shift due to that motion that's caused by the expansion of the universe. And that turns out to be exactly the same factor as if you just consider expansion of the space.

So if you take any two points apart, they're not bound, and just let go, and then universe will kind of, space will carry them apart. And we can choose any two in comoving coordinates and call it R as a function of time. And so the wavelengths or photons will behave in exactly the same way. And so the stretch factor of the universe is one plus red shift.

So if we measure red shift of one for some distant galaxy, that means that universe is exactly 1/2 the present size at that time. Or rather, things were closer by a factor of two. And the two are completely equivalent. So the important concept here is that the space itself expands and carries galaxies and other stuff with it. And then there are two different kinds of coordinates, those that do expand and those that do not expand.

And thanks to the expansion, we see light coming from further away, meaning faster away from us, stretched more. And that's what we call the red shift. So you can use, you can substitute, measurements of red shift which are relatively straightforward by taking spectra for measurements of how much universe has inflated since then.

And now here is the important part. I'm going to now tell you that the holy cow of physics that you've been told is absolutely true, that energy is conserved, is actually not true. Energy is not conserved in an expanding or contracting space. Locally expansion is completely negligible, this is why locally you would see that energy is conserved just fine.

But those photons that are getting stretched? That means that their energies are getting lower. Sort where does that energy go? It doesn't go anywhere. It's just not conserved, it's not exchanged with energy, looking kinetic to potential or whatever.

Likewise take two galaxies, there's some distance apart, there's some binding edge in between them, even if they're not completely bound. But they're still potential energy. Space carries them apart, that potential energy will change. Again there is no conversion between kinetic, potential, or whatnot. Energy is just not conserved in an expanding space.

There's a deeper reason for this, and it has to do with symmetries of nature. There is a so-called anti-matter theorem. And that relates conservation of quantities, like energy, momentum, angular momentum, to symmetries in space and time.

And so for example, conservation of momentum is related to homogeneity of space. And conservation of angular momentum is connected to isotropy of space. And conservation of energy is related to homogeneity of time. But if the universe just keeps expanding, then not all times are equal, things are changing because that energy is not conserved.