DJORGOVSKI: But now, let's take a look at how do we measure age of the universe in a way that's different from measuring distance and using the speed of light. And basically, we cannot do this directly. But we can place a lower limit on the age by looking for the oldest things that we can find. And there are 3 of those that have been used.

First, globular clusters themselves, white dwarf stars inside globular clusters, and then heavy elements that decay radioactivity. In principle, if we knew exactly how star formation histories of galaxies change, we can monitor evolution of stellar populations. But they're just too many uncertainties to do this. So globular clusters are the key to this.

Our understanding of stellar structure and evolution is much better than our understanding of distance scale on cosmology. And so you can have these theoretical isochromes that describe positions of where the stars in globular cluster are at any given moment. Now that changes as cluster ages. The stars peel off the main sequence and ascend through red giant branch.

b if you can measure, if you can calibrate the diagram exactly what your point is, you look at your models and find out which model fits your data for what age. And they depend on things like metallicity and so on, but that's the basic idea. And the problem for a long time was, how do you get the absolute calibration of this? And that was all Hipparcos satellite, because they measure parallax's as a whole bunch of population to stars near us.

So I mean, those are the same kind of population to stars as in globular clusters. And that provided the absolute calibration of the HR diagram for globulars and therefore, of their ages. Which worked to be about 12 billion years, give or take a couple. This is actually very good, because now we know from micro background measurements that the universe is about 13.8 billion years old.

And it takes about a billion years or so to make galaxy, and clusters, and there we go. A different approach uses white dwarfs. As you may recall, white dwarfs do not produce energy internally. They just simply cool slowly. They radiate their light and heat. That can be modeled theoretically very well. And so the faintest and the coolest ones are those that have been around the longest, right?

So if you take a picture of global clusters with the Hubble Space Telescope, and look deep enough to see white dwarfs like this, you see that there is an ice cooling sequence, and then cuts off. And that cutoff corresponds to the oldest, coolest, least luminous white dwarfs. You'll read this out from theoretical isochrome, and you've got the age. And that too produced age in a beautiful agreement with measurements from globular clusters.

Which is wonderful, because they're completely different physics is involved here. And finally, you can do radioactive dating of the universe. You're probably familiar with carbon dating on planet earth using carbon-14 as a radioactive isotope in measuring ratio carbon-14 to carbon-12 that can be used to infer the age of a sample you're looking at.

Well, so same thing with universe. These heavy elements are made in supernova explosions, and then they decay. The trick is to find those that have half lifetimes that they're somewhat commensurate with the age of the universe, yet to be able to measure them in the lab, right? It's easy to measure in the lab something that has half lifetimes in days or maybe even years. But decay time of billions of years at a really precise measurement.

Nevertheless, there are some of the elements for which that can be done. And using your radioactive clock for a variety of different isotopes, what was inferred at the age of these oldest elements was about 13.8 billion years, plus or minus 4. Amazingly enough, the age is exactly right, as which we now know for much more precise measurements. But the good thing about this was that it's completely independent yet from previous measurements.

This is very different physics, very different measurements. So the estimates of the age of the universe from these different ways of doing it really well match, and also match measurements that were completely independent.