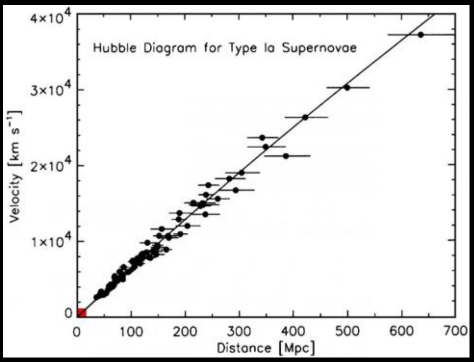
Class is coming down to the end! Some bureaucratic tidbits:

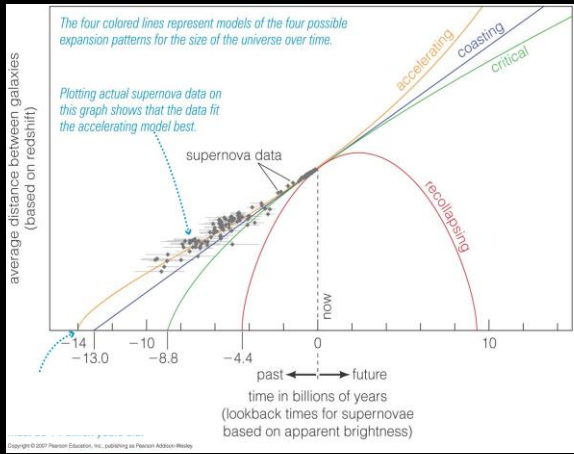
Tuesday, March 10th – The Deep History and Future of the Universe; Quiz 10 emailed, due Friday, March 18th (via email).

Friday, March 13th – Friday, March 20th – Course Evaluations open (online).

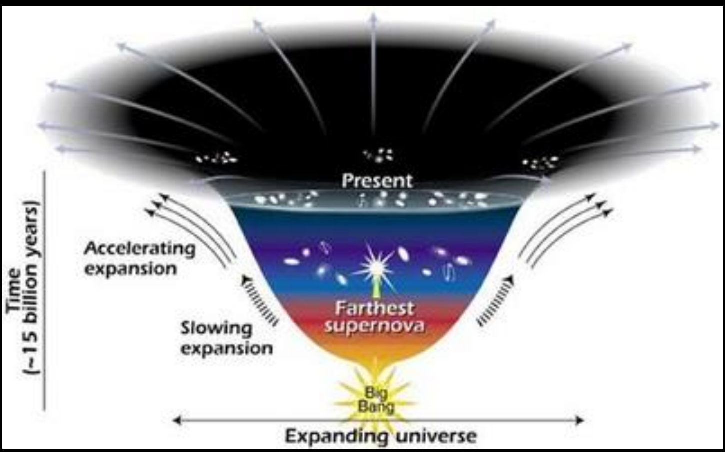


The observed velocity vs. distance relation for galaxies, from Robert Kirshner, PNAS, 101, 1, 8-13 (2004) – key bit of evidence #1!

We turned our attention last time from Hubble's work identifying galaxies to his discovery that these behemoths of stars, gas – and mostly dark matter! – are flying apart from each other as the underlying fabric of space and time continue an expansion that appears to have been going on for over 13 billion years.

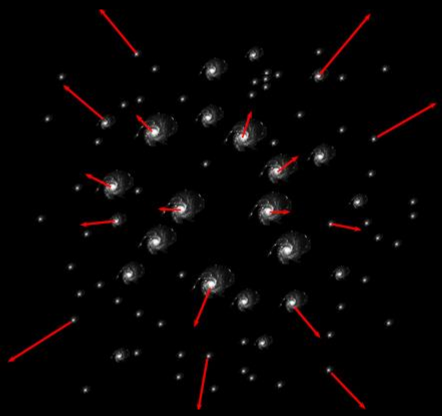


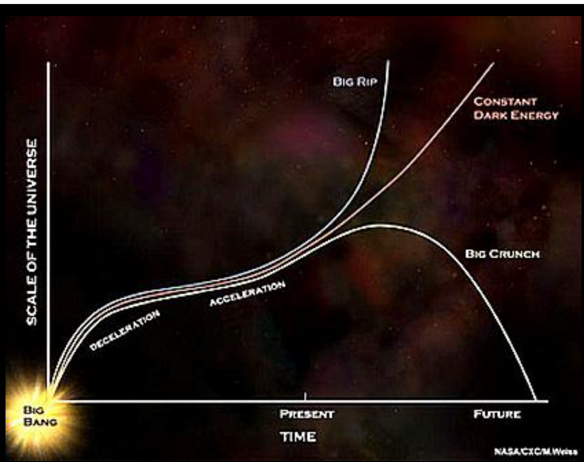
And while we noted that gravity can and does overcome this expansion within clusters and groups of galaxies, we saw clear evidence that there is not enough gravitating matter (of any kind) to eventually halt or reverse this expansion on a universal scale.



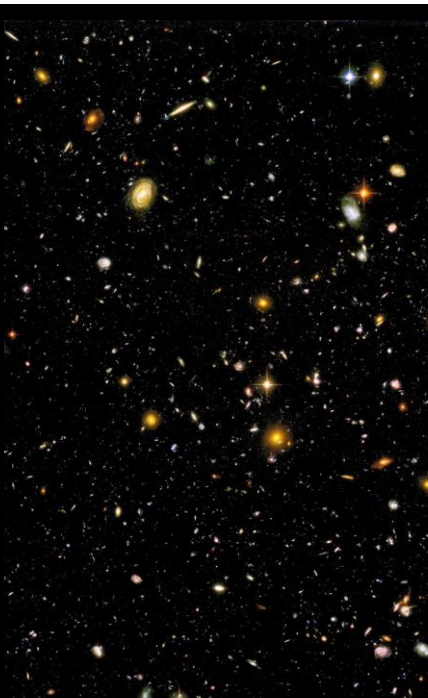
In fact, many independent observations now make it clear that the expansion of our universe has been picking up speed over the last few billion years!

The precise nature of the "dark energy" driving this acceleration is very unclear – if it's some constant 'vacuum energy', our universe will likely expand forever, with galaxies growing ever more distant and isolated as they steadily use up their gas in star formation and grow dark and cold – a second cosmic 'dark age'.



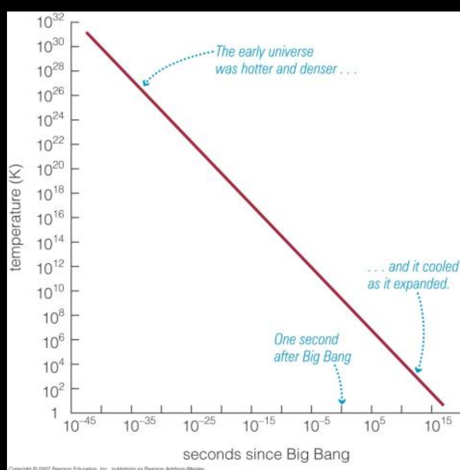


But if dark energy is some entirely new force – as many theories suggest – then it may *not* be constant in time, and could grow stronger, weaker, or even negative in the distant future. At this point, it's very unclear if our ultimate destiny lies in a 'big rip', 'big chill', or 'big crunch'!



Our best clues for resolving these questions lie in the deep past, and that is where we'll turn our attention today. What do we see when we look as far out into space and time as we possibly can? If there was a time before galaxies and stars – as Olber's Paradox demands there was – then what was that time like?

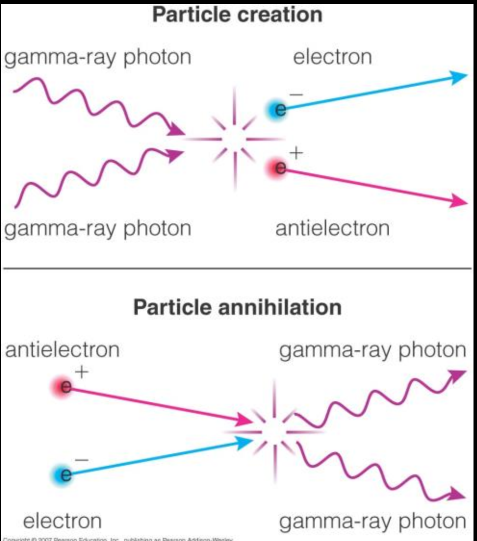
It's clearly the case that the (currently expanding!) universe must have been much smaller in the past – and as early as 1931, Georges Lemaître suggested that the entire universe and all of its contents might once have been in an infinitesimally sized 'region'. If the universe was once this dense, it would have been extremely hot as well!



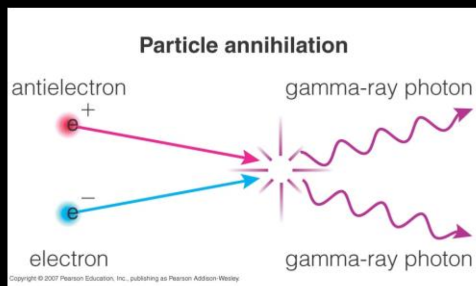
If such a hot, dense era occurred in our universe's youth, we can predict what sort of signals might be left behind to confirm such a thing – signals we could potentially detect from over 13 billion light-years away in space and time.

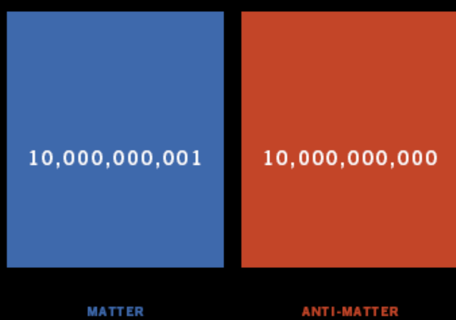
Studies of how matter and energy behave at high temperatures and densities, directly probed in experiments such as those at the LHC (above), constrain those predictions and provide evidence on conditions as early as 10^{-10} sec after the Big Bang!

For example, in such an extremely dense and hot ($T > 10^{12}$ K) universe, matter and photons flow freely between each other, with particles of matter and anti-matter producing radiation, and high-energy photons producing matter and anti-matter. Under these extreme conditions, an equilibrium is reached between the two.



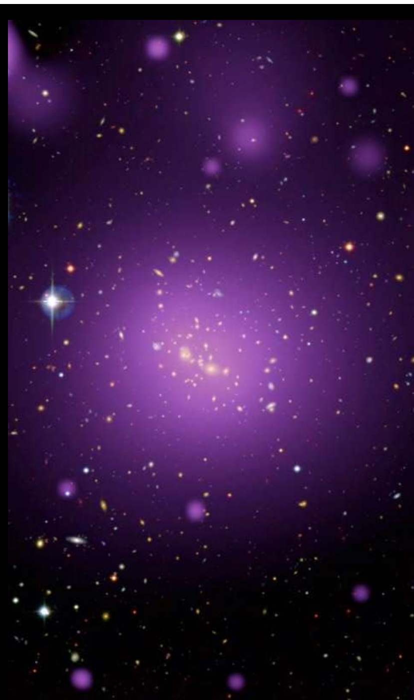
So early on, particles were as numerous as photons – but by the time the universe was 10^{-3} sec old it would have expanded and cooled to below 10^{12} K. At these temperatures there was no longer enough high energy photons available for matter and anti-matter particles to be created in significant amounts.



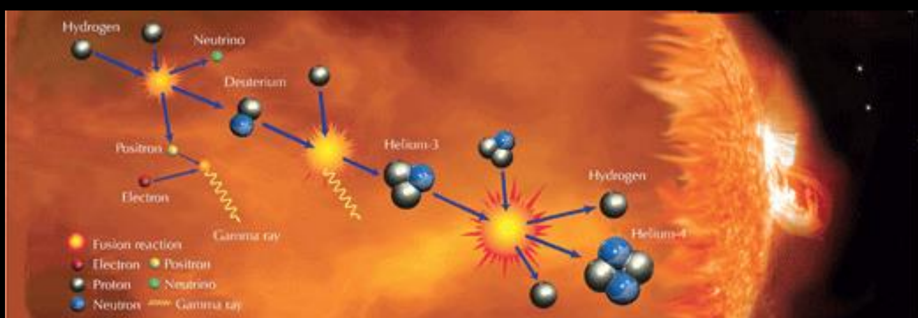


The remaining particles and antiparticles steadily annihilated each other into radiation without being replaced, but a slight imbalance in the number of protons and neutrons compared with their antimatter cousins allowed some very tiny fraction of normal matter to remain behind – and that tiny slice would go on to form all of the stars and galaxies in our universe.

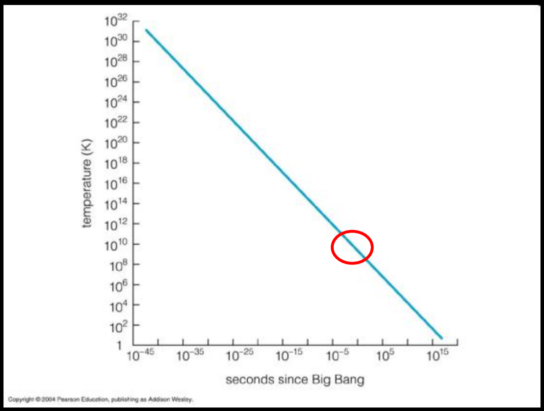
Why this imbalance occurred is not yet fully understood, but the fact that we have no observations of large quantities of antimatter in the universe mean that such an asymmetry in the amount or distribution of matter and antimatter ***must*** have existed.



X-ray emission from galaxy cluster XLSSC006 – lots of hot gas, but no anti-matter stars or galaxies

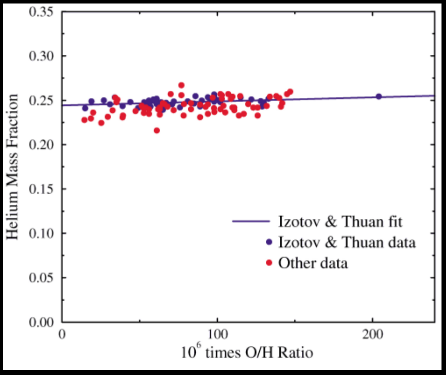


Now for a short time (about 3 minutes) after this, the remaining massive particles would have been packed in densely enough and under temperatures high enough for them to fuse into He – fusion basically the same as that happening in the core of the Sun, except going on throughout the whole Universe at once!

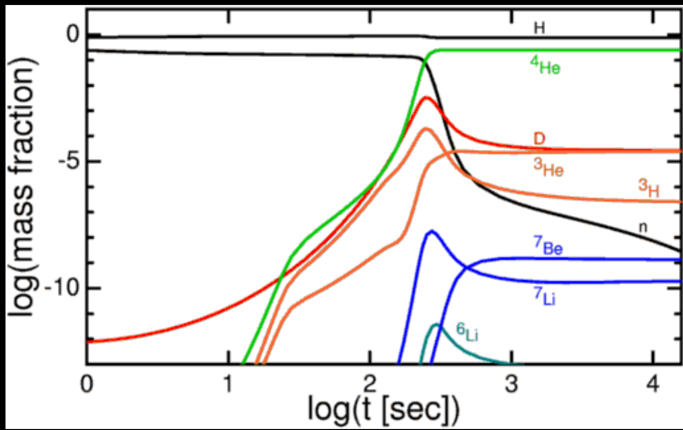


But as the temperature cooled below 10^{10} K, fusion would have stopped because the density of the universe – which was getting smaller – would have finally become too low for fusion. Models of this period predict that for every ^{4}He atom produced by fusion, there should have been 12 H atoms leftover – a 3-1 mass ratio of H to He.

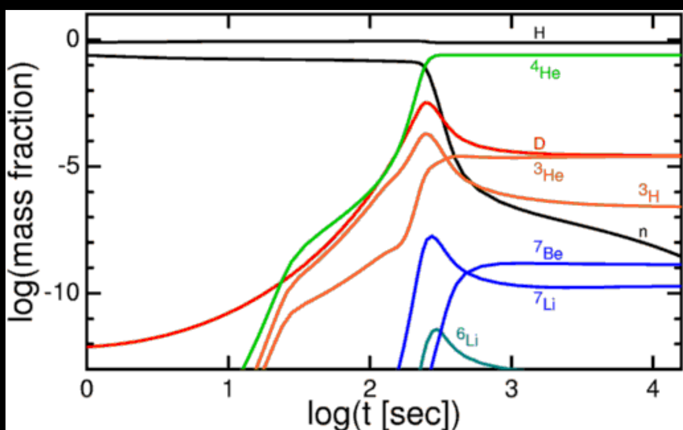
And just like that – without even really trying! – we've explained another great mystery in astronomy: why do ***all*** stars and galaxies, everywhere we look, seem to be made (by mass) of about 75% H and 25% He? It's because that's exactly what this period of early H fusion would have produced, everywhere in the Universe!



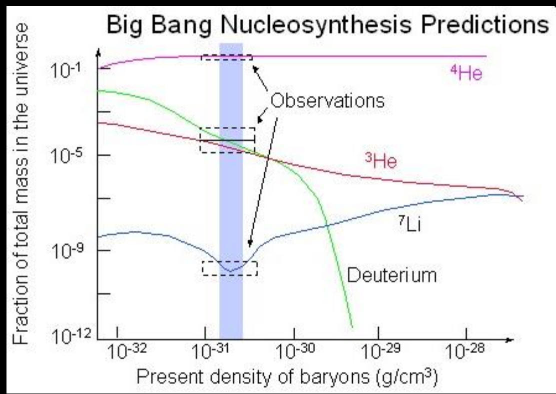
The mass fraction of He in a large sample of galaxies, scaled to enrichment in other heavy elements in order to account for production of He in stars.



And there's more – by the time stable ^{4}He had formed the Universe was too cool and insufficiently dense for He to fuse into C or other heavier nuclei. But under those same conditions ^{4}He *would have* been able to fuse with (rare) ^{3}H and ^{3}He atoms into trace amounts of stable ^{7}Li and ^{7}Be.

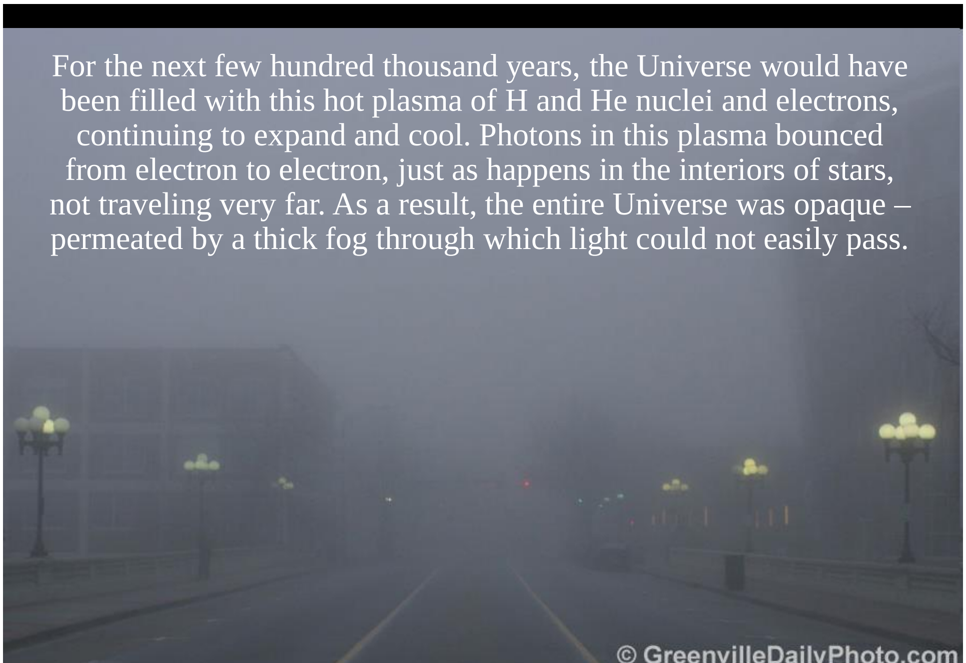


Similarly, the end of He fusion should have left trace amounts of ^{3}He and ^{3}H, as well as Deuterium (^{2}H) – "leftover" isotopes in the fusion processes occurring throughout the universe!

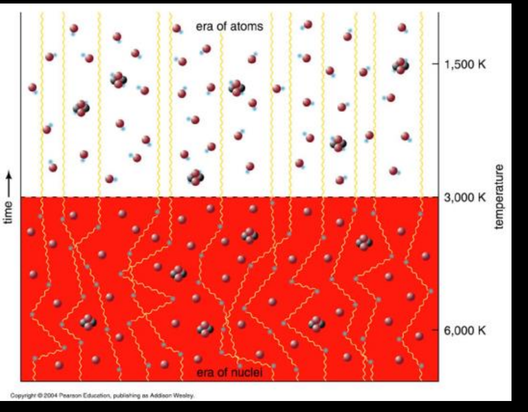


Models of these early few minutes of fusion, based on our understanding of the densities and temperatures at these times, accurately predict the observed amount of leftover ^{2}H, ^{3}He, and ^{7}Li – key evidence that such an ***early dense and hot time of universal fusion really did occur***!

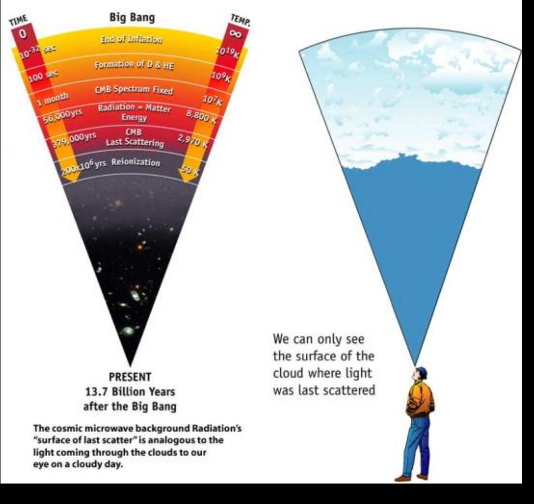
For the next few hundred thousand years, the Universe would have been filled with this hot plasma of H and He nuclei and electrons, continuing to expand and cool. Photons in this plasma bounced from electron to electron, just as happens in the interiors of stars, not traveling very far. As a result, the entire Universe was opaque – permeated by a thick fog through which light could not easily pass.



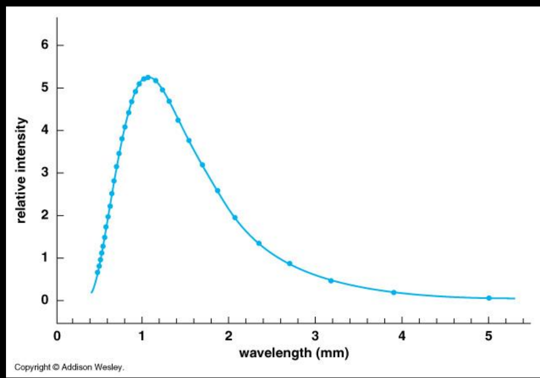
However, about 380,000 years after the Big Bang, the Universe had cooled enough for free electrons to become bound into atoms of H & He. With fewer free electrons to scatter them, photons became able to travel unhindered throughout the universe – making it *transparent* for the first time in its history.



As the first neutral atoms form, photons (yellow squiggles) begin to travel greater distances.



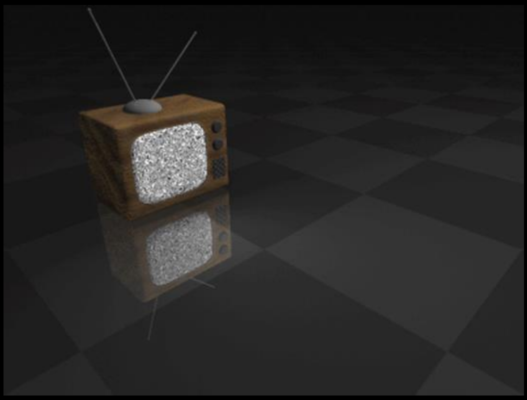
The thermal radiation being produced *everywhere in the universe* was now able to stream freely through space. These free streaming photons – the first of their kind, and the most distant photons we can see – formed a “Cosmic Background Radiation” that continues to permeate the universe today.



The temperature of the universe was 3,000 K at this time, so the spectra it produced was the same as that from a 3,000 K object – like the surface of a red giant, except everywhere in the universe at once! Since then, the universe's size has expanded 1,000 times, and the ***cosmological redshift*** of this expansion has turned that visible and infrared radiation into microwaves.

"Accidental" Nobel Prize winners Penzias and Wilson and their famous microwave receiver.

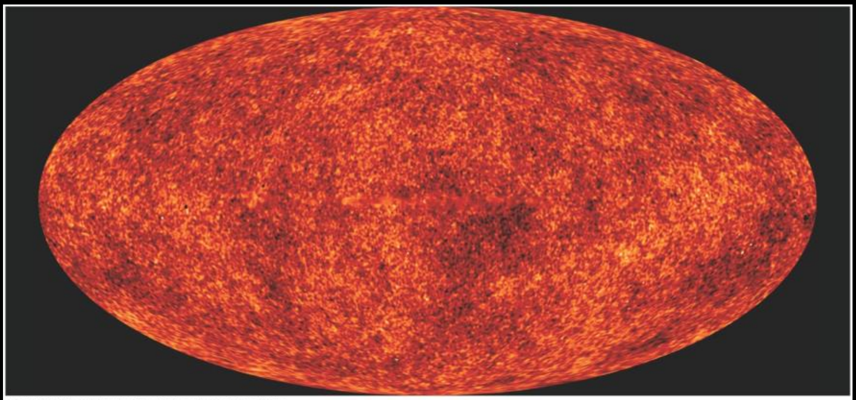
This ***Cosmic Microwave Background***, predicted by theory as early as 1946, was accidentally discovered in 1964 by Arno Penzias & Robert Wilson. They detected a signal that appeared to come from every direction, and which had a perfectly thermal spectrum with a temperature of 2.73 K – *precisely* the temperature one expects from Big Bang predictions.

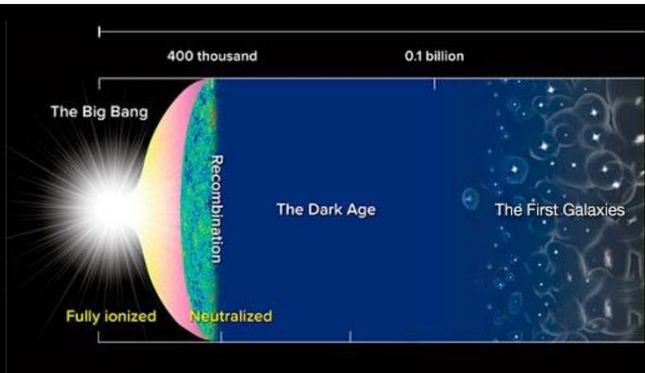


Part of the background noise in old-school broadcast television is actually from the CMB!

This radiation is still present throughout the Universe, and indeed right here on Earth as photons from over 13 billion light years away ***finally*** reach us after having traveled from the very observable edge of existence!

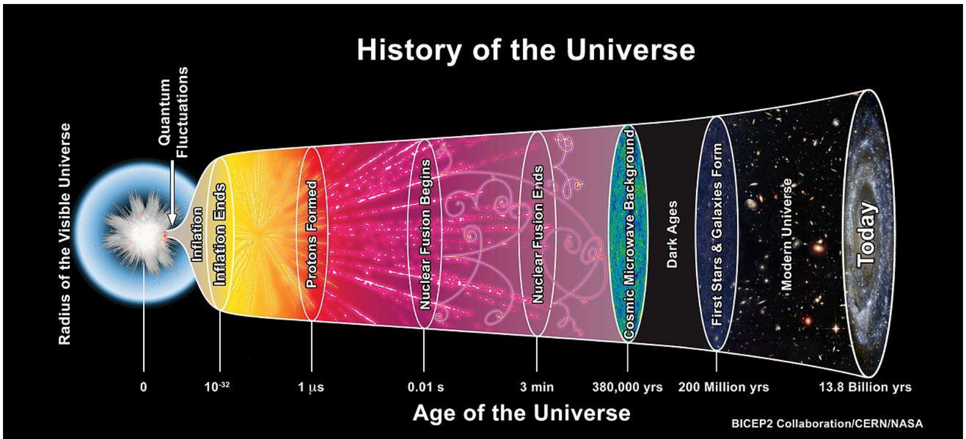
While extremely smooth and uniform across the sky there are slight variations in the CMB on the level of a few parts in 100,000. These temperature variations are clear evidence of fluctuations in the density of matter in the early universe.



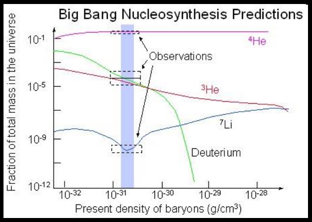


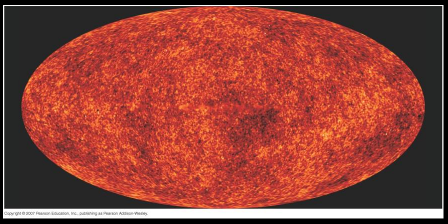
As the early universe continued to expand and cool, the light from the initial heat faded. This time, before the formation of the first stars and galaxies, is sometimes referred to as the ***Cosmic Dark Ages***. But over a timespan of less than a billion years, the gravitational attraction of those density enhancements in the gas and dark matter brought together the first protogalactic clouds – and the first stars and galaxies began lighting up the Universe all over again.

This brings us right up to the work we've discussed so far on the formation of large-scale structure and the birth of those earliest galaxies. Formed in a denser universe than we live in today, collisions of these young galaxies likely powered early AGN and triggered enormous waves of star formation.

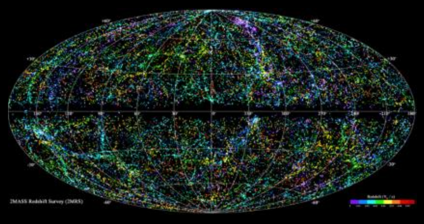


So we have now outlined 4 major events ***predicted*** by the Big Bang Model, and the observational evidence that such events occurred: the formation of light elements, the release of the cosmic microwave background, the dark ages before the formation of the first stars and galaxies, and the recession of distant galaxies as the Universe continues to expand.

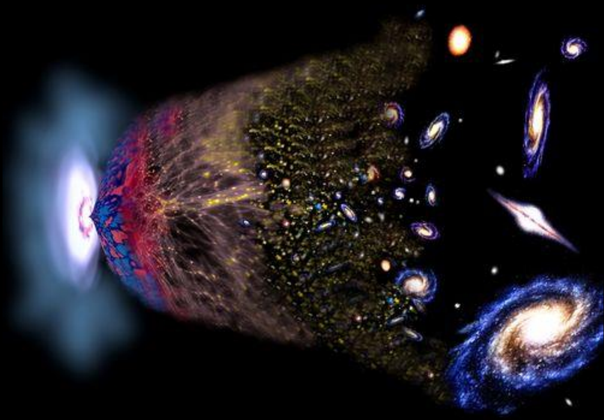




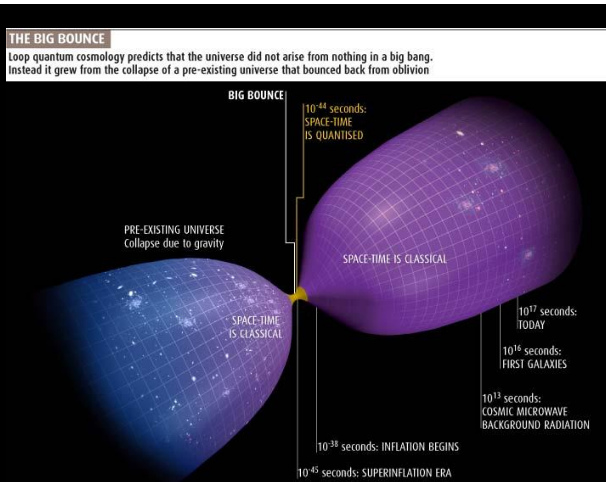
This evidence matches theoretical predictions of the "Big Bang" model to a truly remarkable degree – as odd as it may seem, something like this event definitely seems to have occurred some 14 billion years ago.



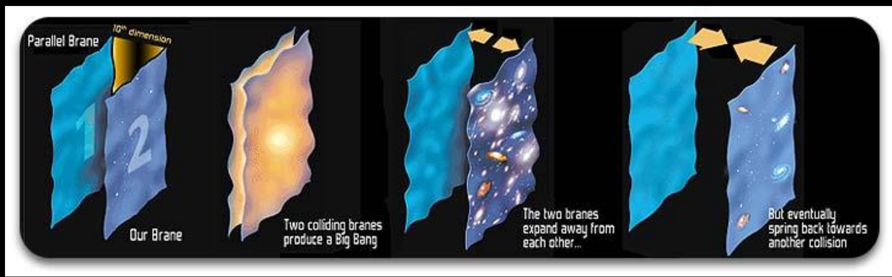
?...



No other cosmological model (and many continue to be proposed!) describes the available evidence ***remotely*** as precisely as the Big Bang model for the universe's early history – but <u>why</u> did it happen? Where did the initial energy input "come from"?



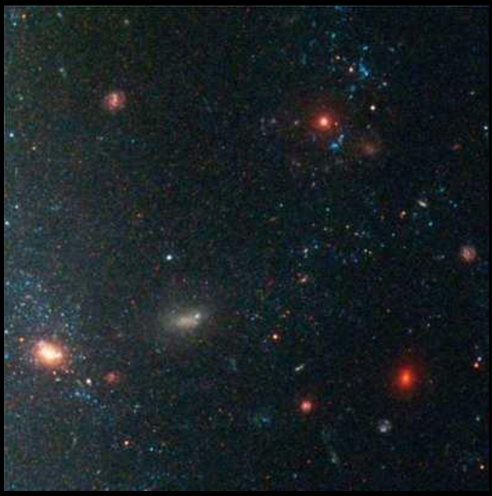
Did our universe form from the collapse of a pre-existing universe that collapsed on itself, as postulated in so-called "big bounce" models? Or perhaps from a spectacular fluctuation in the vacuum energy of a pre-existing universe?



Or is it possible that our universe reached its early hot, dense state through some other means entirely – perhaps by colliding with a completely different universe in some even larger 'multi-verse'?!

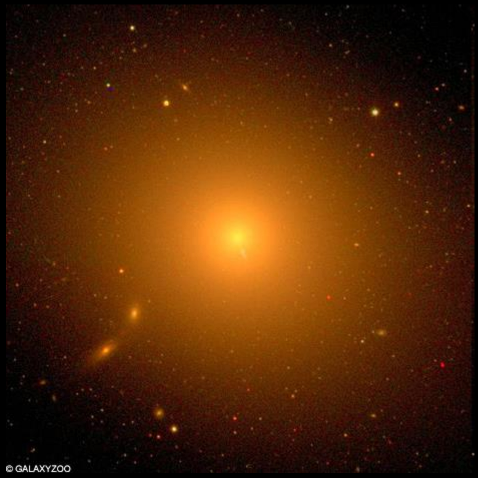
Such questions are ***very*** difficult to answer, as they seem to require evidence from *outside* of our universe, or from "before the beginning of time" – whatever the hell that might mean!

Like many other issues in these last few weeks, we'll have to leave these questions at "stay tuned" for now – or better yet, a charge for YOU to answer in the future!!



Speaking of the future, at the present – and under the simplest of assumptions – it does seem that our universe will continue to expand, and that distant clusters of galaxies will appear to grow redder and dimmer, eventually receding from us so fast that their red-shifted light will no longer be visible at all here on Earth.

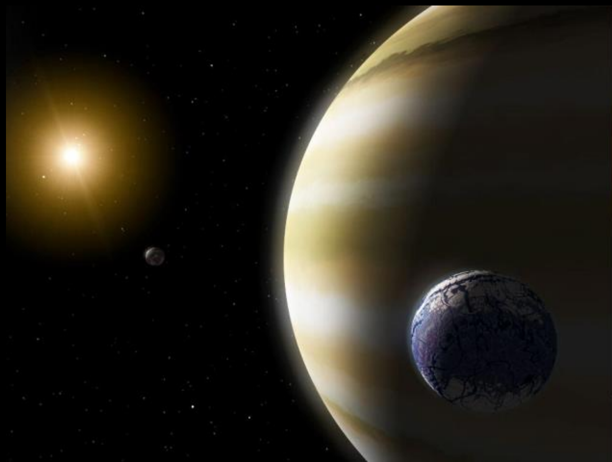
This increasing darkness in our extragalactic view will likely be joined about 100 *trillion* years later by the quiet dimming of our own reddened and elliptical galaxy, as the last remnants of star formation produce the final clusters of stars from the gas of the once bright and blue Milky Way and Andromeda galaxies.



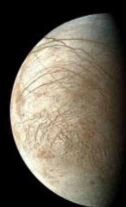
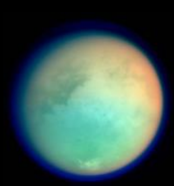
Is that a bit of a downer? Maybe – but we're talking hundreds of trillions of years from now – and we have more pressing issues! Remember, the ever-brightening Sun will evaporate the Earth's oceans in *less than a billion* years, before expanding into a Red Giant in about 4 billion years!

Enjoy the sunshine while it's still enjoyable!

But we've argued in this class that the evolution of our Sun is really a ***motivating*** factor – perhaps the ultimate one – for us to continue our own exploration of the universe, and to find new homes for humans to occupy among the stars.



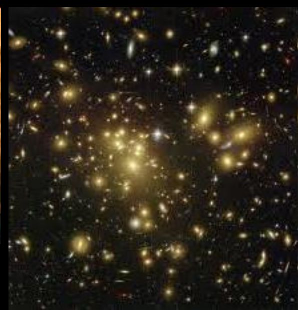
New homes that we are *finding* – as we also learned in this class, well over 2,000 planets have now been discovered around other stars, and thousands more will turn up in the next few decades.

And we’ve seen that missions
to closer worlds such as Mars, Europa,
and Titan, should soon tell us how likely it is that
those more distant planets possess life of their own!
And all of these events will unfold during your lives!

Over the past 10 weeks we have seen how our view of the universe changes as we explore deeper and learn more – it's a trip that's taken us through all of space and time (at 300 miles a second!), from the surface of the Earth, to the planets, stars, galaxies, and to the most distant visible objects in the universe.





And we've seen how remarkable and beautiful the whole place – and our place in it – really is!

So keep doing beautiful things, and living your beautiful lives!

Stay in touch, and stay in touch with astronomy as we continue to explore this ridiculous and amazingly lovely universe together! Thank you for all of your hard work, patience, and dedication!!

The End!

(Almost! Quiz 10 goes out today!)