Logistical notes! Lots of 'em

- 4 classes left!
- Homeworks: talk to me if you've fallen behind, please! Only 2 weeks left to catch up.
- Extra credit homework now available: could add up to 10 percentage points to your final grade!
  - It's long. Do in pieces, even partial credit can only help!
  - Covers all chapters
- Homework site will close access to homeworks at
  - 12:00am Thursday, 11/29
    - So, midnight after the last day of classes
  - You will not be able to complete homeworks after this date
  - You should still be able to see them for review purposes

Logistical notes part 2

- Scheduled two more TCO nights for us
  - Tuesday, 11/13
  - Wednesday, 11/14
  - Both nights the forecast looks bad. Argh!

Today in science…

- The arguments over the most accurate/precise measurement of H_0 are ongoing!

First Cosmological Results using Type Ia Supernovae from the Dark Energy Survey: Measurement of the Hubble Constant

E. Macaulay, R. C. Nichol, D. Bacon, D. Brout, T. M. Davis, B. Zhang, B. A. Bassett, D. Scolnic, A. Möller, C. B. D'Andrea, S. R. Hinton, R. Kessler, A. G. Kim, J. Lasker, C. Lidman, M. Sako, M. Smith, M. Sullivan, T. M. C. Abbott, S. Allam, J. Annis, J. Asorey, S. Avila, K. Bechtol, D. Brooks, P. Brown, D. L. Burke, J. Calcino, A. Carnero Rosell, D. Carollo, M. Carrasco Kind, J. Carretero, F. J. Castander, T. Collett, M. Crocce, C. E. Cunha, L. N. da Costa, C. Davis, J. De Vicente, H. T. Diehl, P. Doel, A. Drlica-Wagner, T. F. Eifler, J. Estrada, A. E. Evrard, D. A. Finley, B. Flaugher, R. J. Foley, P. Fosalba, J. Frieman, L. Galbany, J. García-Bellido, E. Gaztanaga, K. Glazebrook, S. González-Gaitán, D. Gruen, R. A. Gruendl, J. Gschwend, G. Gutierrez, W. G. Hartley, D. L. Hollowood, K. Honscheid, J. K. Hoormann, B. Hoyle, D. Huterer, B. Jain, D. J. James, T. Jeltema, E. Kasai, E. Krause, K. Kuehn, N. Kuropatkin, O. Lahav, G. F. Lewis, T. S. Li, M. Lima, H. Lin, M. A. G. Maia, J. L. Marshall, P. Martini, R. Miquel, P. Nugent, A. Palmese, Y.-C. Pan, A. A. Plazas, A. K. Romer, A. Roodman, E. Sanchez, V. Scarpine, R. Schindler, M. Schubnell, S. Serrano, I. Sevilla-Noarbe, R. Sharp, M. Soares-Santos, F. Sobreira, N. E. Sommer, E. Suchyta, E. Swann, M. E. C. Swanson, G. Tarle et al. (7 additional authors not shown)

(Submitted on 6 Nov 2018)

We present an improved measurement of the Hubble Constant (H0) using the 'inverse distance ladder' method, which adds the information from 207 Type Ia supernovae (SNe Ia) from the Dark Energy Survey (DES) at redshift 0.018 < z < 0.85 to existing distance measurements of 122 low redshift (z < 0.07) SNe Ia (Low-z) and measurements of Baryon Acoustic Oscillations (BAOs). Whereas traditional measurements of H0 with SNe Ia use a distance ladder of parallax and Cepheid variable stars, the inverse distance ladder relies on absolute distance measurements from the BAOs to calibrate the intrinsic magnitude of the SNe Ia. We find H0 = 67.77 +/- 1.30 km s-1 Mpc-1 (statistical and systematic uncertainties, 68% confidence). Our measurement makes minimal assumptions about the underlying cosmological model, and our analysis was blinded to reduce confirmation bias. We examine possible systematic uncertainties and all are presently below the statistical uncertainties. Our H0 value is consistent with estimates derived from the Cosmic Microwave Background assuming a LCDM universe (Planck Collaboration et al. 2018).

Comments: 14 pages, 5 figures, submitted to MNRAS
Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO)

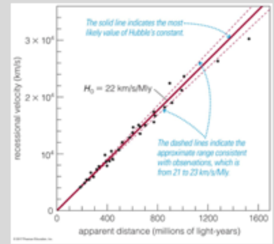
https://arxiv.org/abs/1811.02376

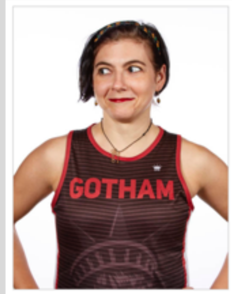
67.77 km/s / Mpc

Or.. 65.69 km/s / Mpc, depending on how they slice their data set.

The age of the universe (for now)

- $H_0 = 67.77\ \frac{km/s}{Mpc} * \left(\frac{1\ Mpc}{10^6 pc}\right) * \left(\frac{1\ pc}{3.26\ ly}\right) * \left(\frac{10^6 ly}{1\ Mly}\right) = 20.79\ \frac{km/s}{Mly}$
- $\frac{1}{H_0} = \frac{10^6 ly}{20.79 km/s}$
- convert ly into km to cancel with denominator…
- $\frac{10^6 ly}{20.79\ km/s} * \frac{9.46\ x\ 10^{12} km}{1\ ly} = \frac{9.46\ x\ 10^{18} km}{20.79\frac{km}{s}} = 4.5\ x\ 10^{17}\ s$
- $4.3\ x\ 10^{17}\ s * \frac{1\ min}{60\ s} * \frac{1\ hr}{60\ min} * \frac{1\ d}{24\ hr} * \frac{1\ yr}{365.25\ d} = 14.4\ x\ 10^9 years$



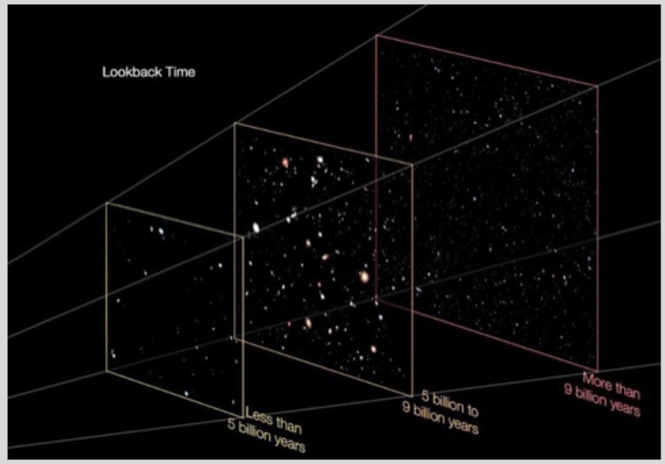


Big Banger #13.7 Gyr

Uh oh. Big banger may have to change her number again..

Also today in science…

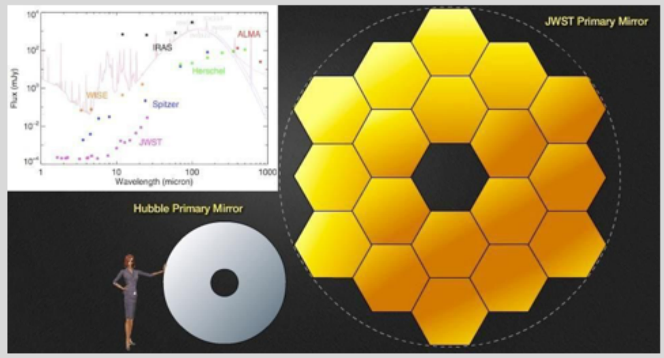
- Things we've learned studying distant galaxies:
  - Smaller and less massive than nearby galaxies; merge and grow over time
  - Bluer and with higher luminosity: formed new stars more frequently at earlier times
  - More spirals and irregulars in early universe, fewer ellipticals: today's galaxies are very evolved
- See fewer galaxies farther back and nearby than intermediate distances
  - Selection effect (faraway ones faint!) and
  - Evolution effect; mergers lower total numbers of galaxies



https://www.forbes.com/sites/startswithabang/2018/11/09/this-is-how-we-will-discover-the-most-distant-galaxy-ever/#547e7eae4d9d

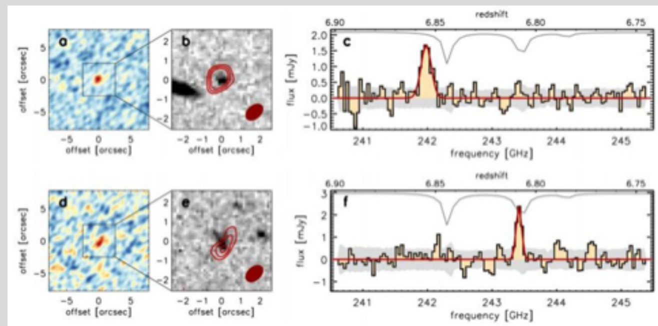
Finding the most distant galaxy ever

- Build huge telescope
  - A mirror 2x as large will collect 2x as much light, observing things 2x fainter



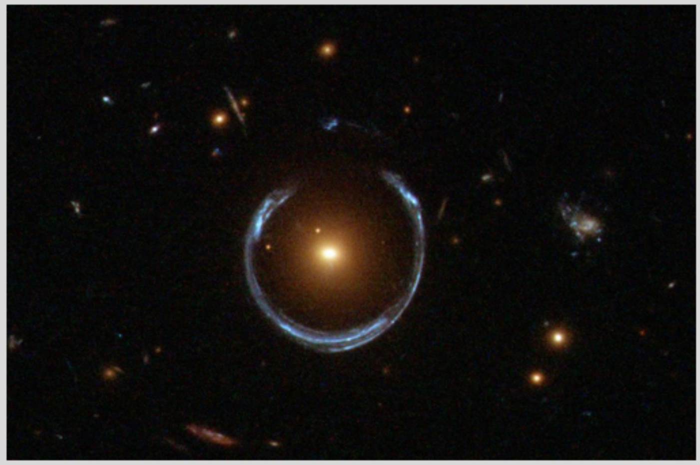
Finding the most distant galaxy ever

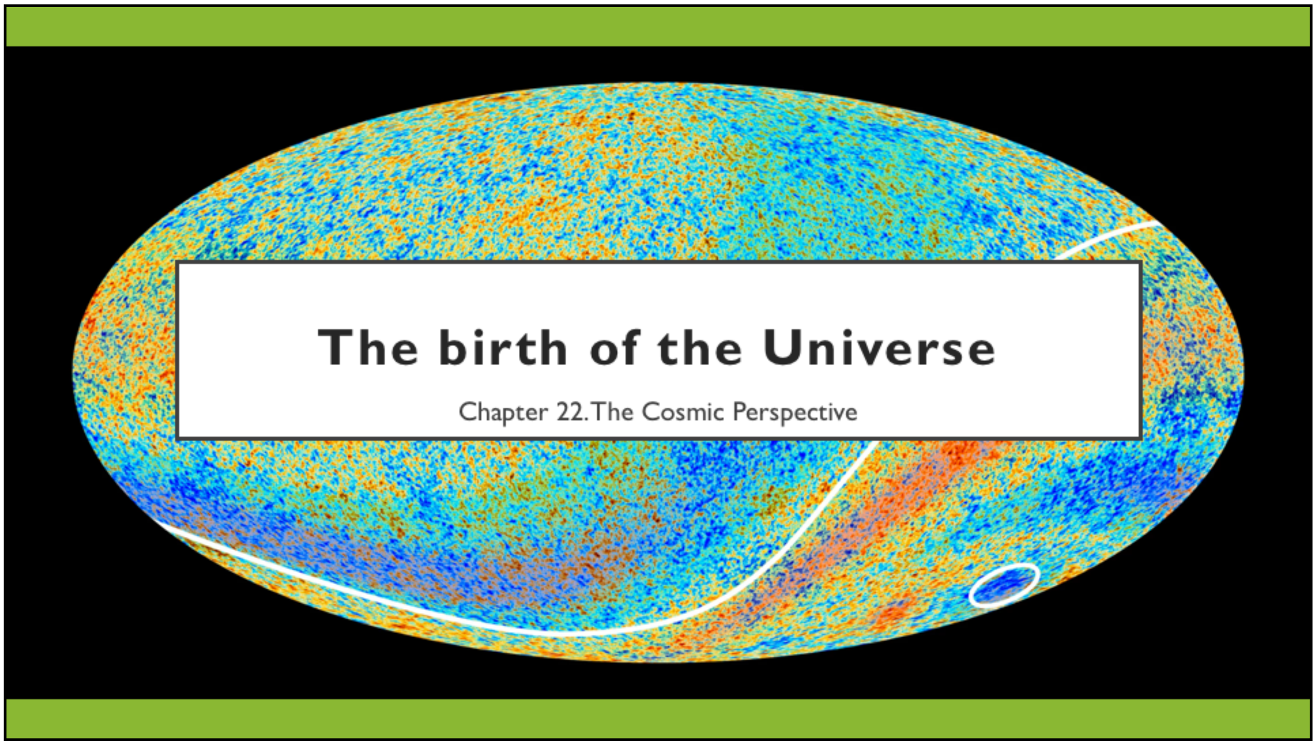
- Build huge telescope
- Look in the right wavelength range (infrared)
  - Can observe very redshifted light
  - Gas in the way largely transparent to infrared light



Finding the most distant galaxy ever

- Build huge telescope
- Look in the right wavelength range (infrared)
- Look in the right places



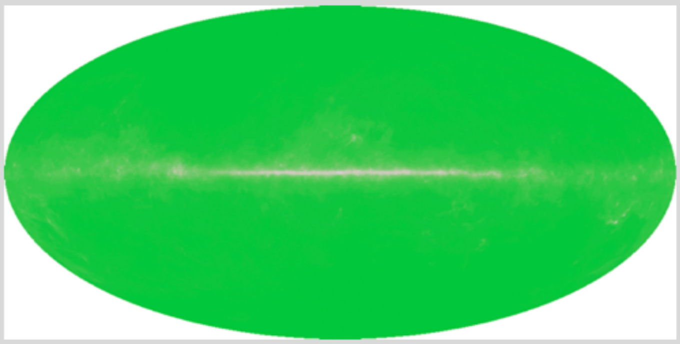

The birth of the Universe
Chapter 22. The Cosmic Perspective

The Big Bang theory

- We've talked about a number of different pieces of evidence that the universe started from a single point, was very hot and dense, and has been expanding ever since.
  - Evidence came first (motions of galaxies, observed metal content in space)
  - Theory began to be developed
  - Predictions of the theory were tested
    - If the early universe was hot and we can look back really far in time, couldn't we see the early universe's thermal emission?
    - *(spoiler: yes, we can!)*

The Cosmic Microwave Background

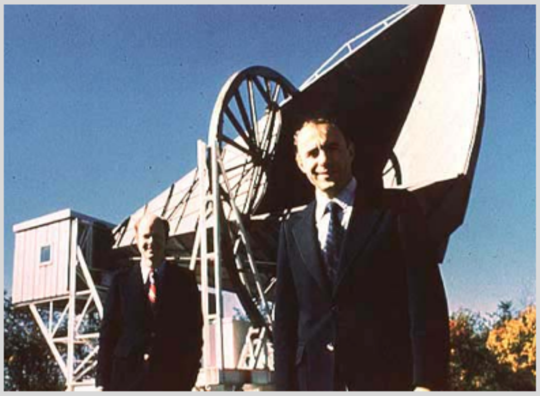
- Existence of CMB was predicted in 1948
- In 1963, Arno Penzias and Robert Wilson were studying microwave emission in the Milky Way
- Discovered a faint signal no matter where they pointed telescope
  - Signal, or noise?



https://www.space.com/25945-cosmic-microwave-background-discovery-50th-anniversary.html

The CMB

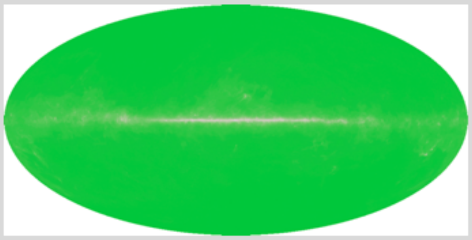
- Penzias & Wilson thought it was noise… specifically, possibly interference from pigeon poop.



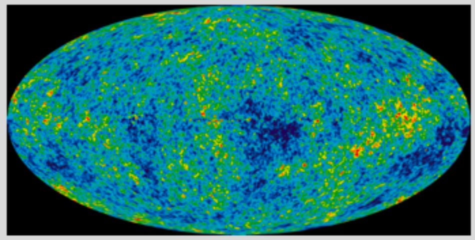
vs.

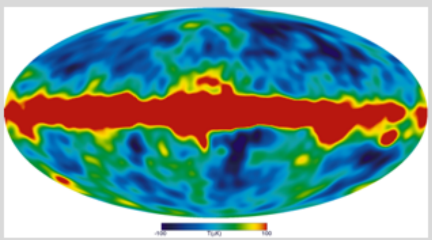
💩

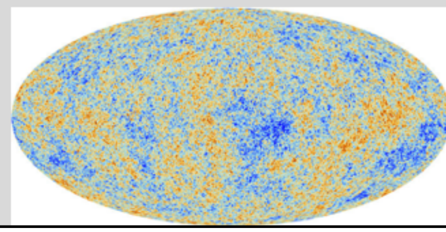
The CMB



- Penzias & Wilson, 1963
- COBE, 1992
- WMAP, 2003
- *Planck*, 2013

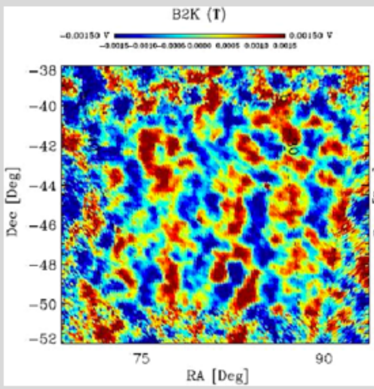


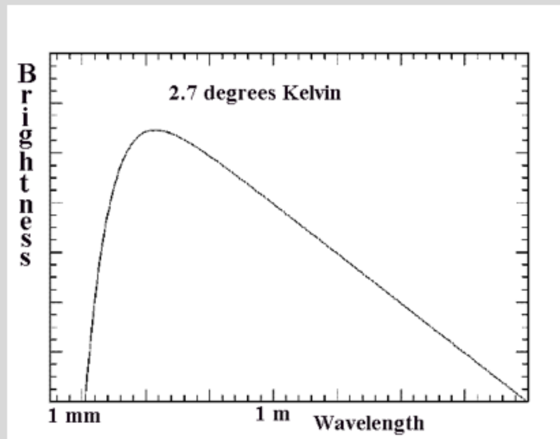




The CMB

- Can be modeled as a thermal black body that is 2.7 K
- Isn't isotropic: degree of anisotropy depends on what you assume the early universe structure was like





The discovery of the CMB is the strongest evidence we have supporting the big bang theory

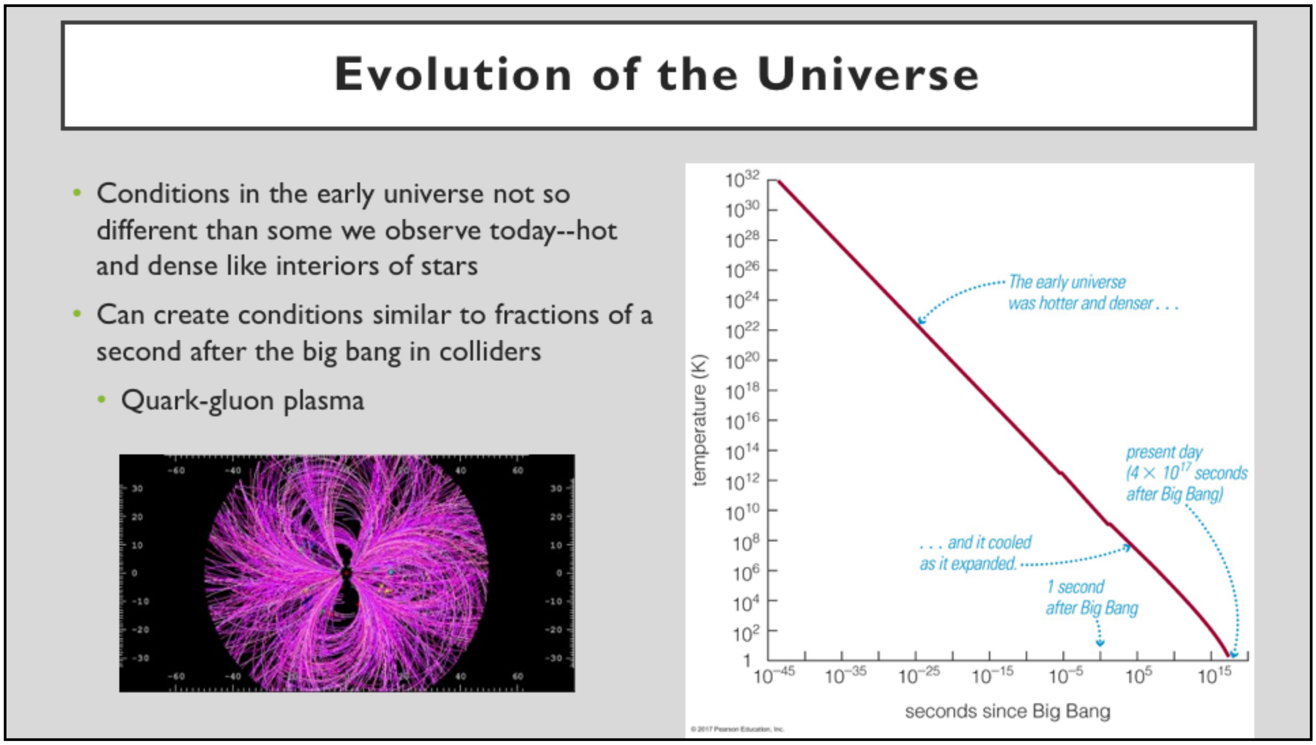
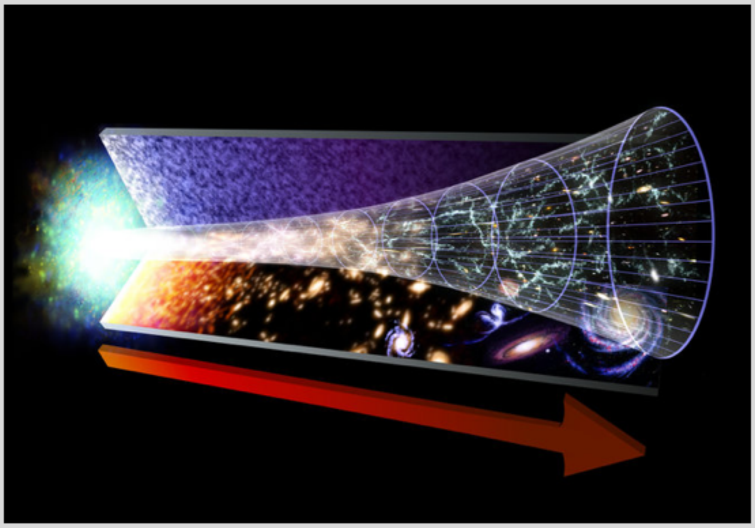
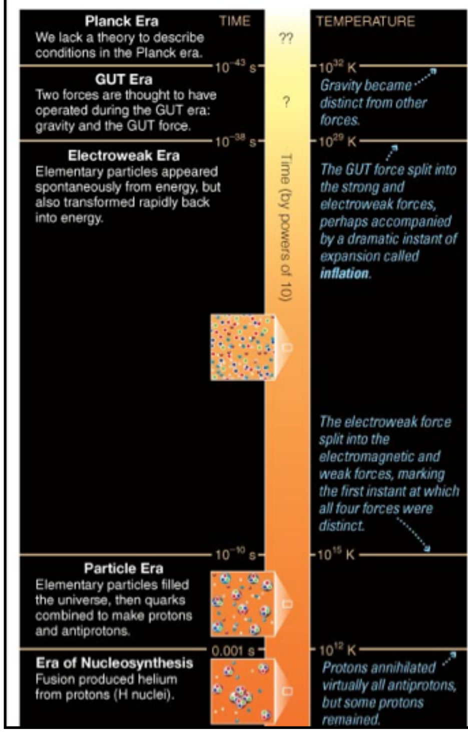


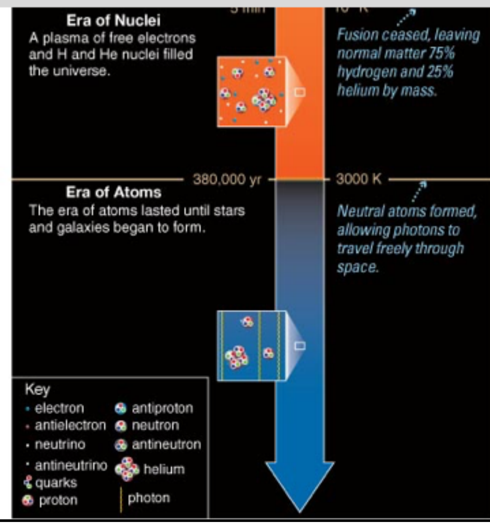
Image is showing tracks of particles after colliding two gold nuclei together. In the <10^-23 seconds after the collision, the conditions are hot and dense enough to create a plasma that resembles what the early universe was like. The early universe was in this state for much longer than what we're creating on earth;

Evolution of the Universe



Evolution of the Universe





Fundamental forces

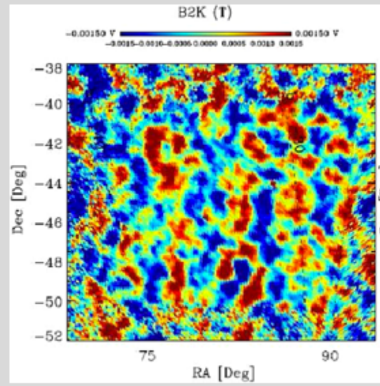
- Strong force – very small length scales (atomic nuclei), binds protons and neutrons together
- Weak force – very small length scales, plays critical role in fission/fusion reactions, only force that interacts with neutrinos
- Electromagnetic force – depends on charges of interacting objects, dominant force in interactions between particles in atoms and in molecules
- Gravity – depends on masses of interacting objects, weakens with distance (1/d2), strengthens with more mass

- Grand unified theory: all of these forces, under the right conditions, are limiting cases of one larger theory.
  - Electroweak force = unifying of electromagnetic and weak forces. At high temperature/energy, you can't tell which force is acting
  - Electroweak force has been proven in lab experiments

Other names for a grand unified theory, or force, are supersymmetry, superstrings, supergravity, or the "theory of everything"

Incredibly brief eras

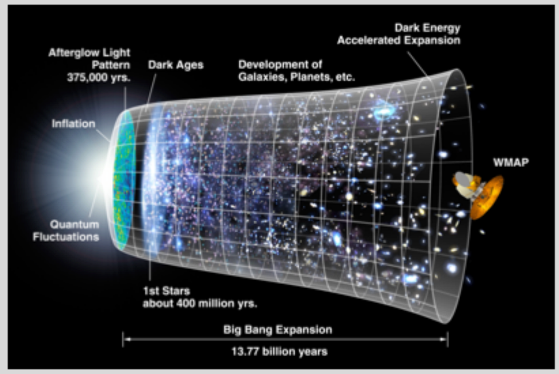
1. **Planck era**: the first 10^{-43}s after the big bang
   - Incredible amounts of energy, rapidly fluctuating
   - Would have created dents and distortions in space-time on small scales that are then stretched out as the universe expands (i.e., CMB anisotropy)



- This is about the best we can figure for this cosmological era, until we know what the grand unification of gravity and quantum mechanics would predict for the system's behavior.

Incredibly brief eras

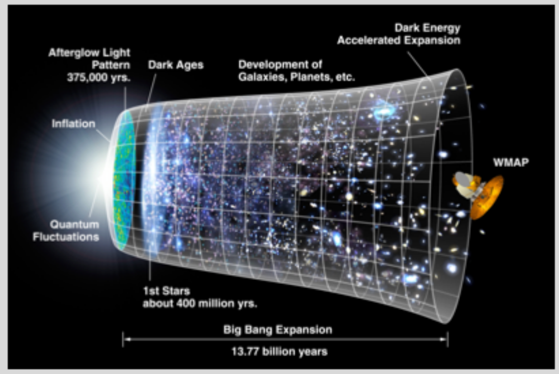
2. **GUT era:** 10^{-43} to 10^{-38}s after the big bang
   - Gravity becomes a distinct force from super- unified force ("freezes out")
3. **Electroweak era:** 10^{-38} to 10^{-10}s after the big bang
   - Energy is changing forms ($E=mc^2$) between photons and elementary particles
   - Gravity, strong force, and electroweak forces all distinguishable
   - Burst of expansion occurs called inflation
4. **Particle era:** 10^{-10} to 10^{-3}s after the big bang
   - Electroweak force splits into electromagnetic and weak forces
   - Temperature is 10^{15}K and cooling
   - Models predict formation of particles and antiparticles (which annihilate if they combine); because there is matter in the universe today, particles must have outnumbered anti- by the end of the particle era

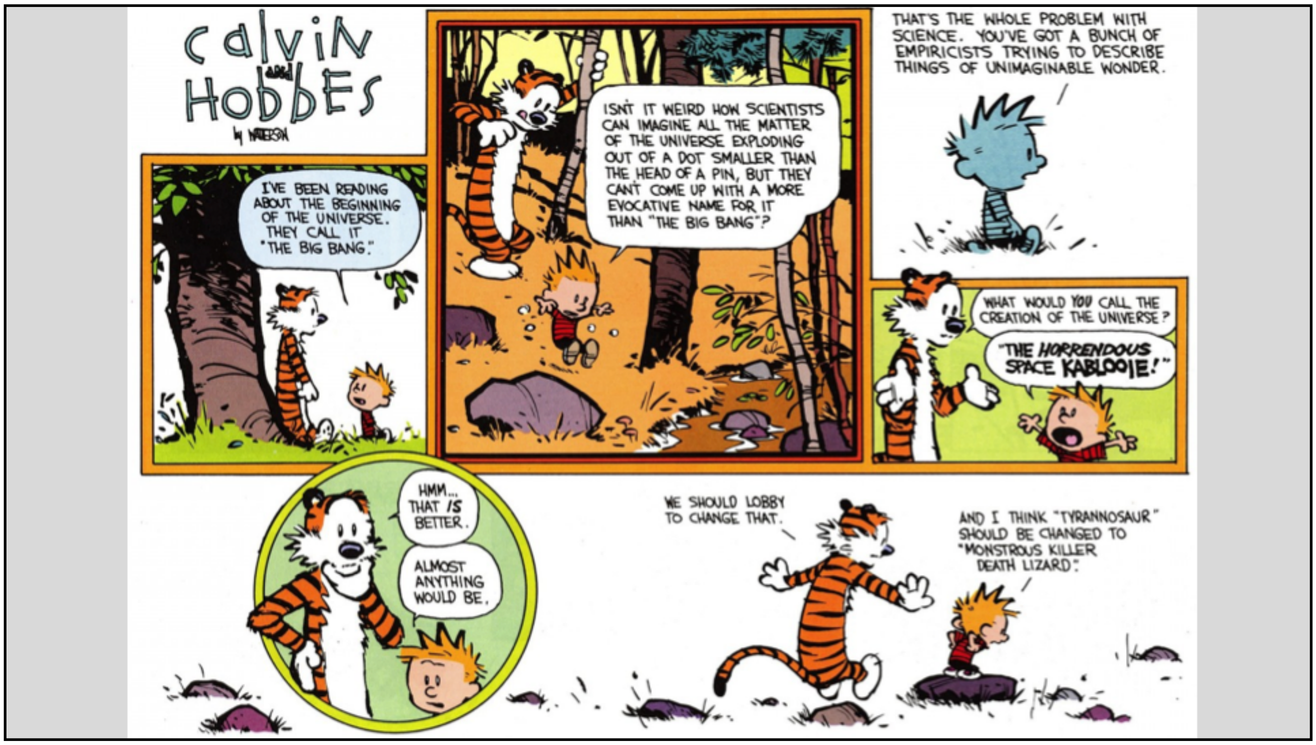


We know about as little about the GUT era as the Planck era. We know more about the electroweak era because we've been able to produce conditions like it in colliders on earth.

Incredibly brief eras

5. **Era of nucleosynthesis:** 10^{-3}s to 5mins after the big bang
   - Temperature is 10^{12} K, particle era produced protons that now fuse into He atoms
6. **Era of nuclei:** 5mins to 380,000 years after the big bang
   - Once temperature drops below 10^9K and expansion has lowered density of universe, fusion stops
   - Nuclei and free electrons fill the universe
   - Universe consists of 75% H and 25% He by mass
7. **Era of atoms:** 380,000 years after the big bang
   - Temperature has cooled to 3,000 K; neutral atoms form
   - Photons can now travel freely through space, density has dropped so they are no longer trapped
     - This is what we're seeing in the CMB
8. **Era of galaxies:** era of atoms ends with formation of stars and galaxies at ~10^8 years after the big bang
   - First galaxies formed ~1 billion years after big bang

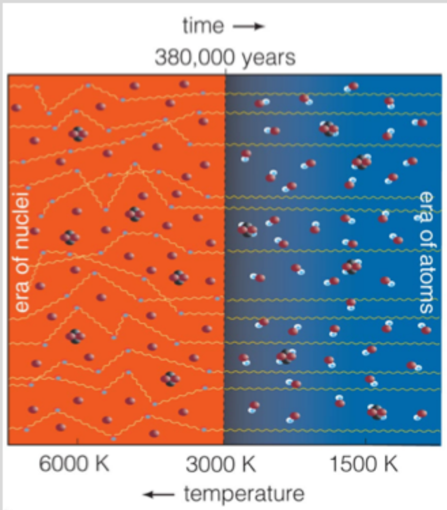



Calvin and Hobbes
by WATTERSON
I'VE BEEN READING ABOUT THE BEGINNING OF THE UNIVERSE. THEY CALL IT "THE BIG BANG."
ISN'T IT WEIRD HOW SCIENTISTS CAN IMAGINE ALL THE MATTER OF THE UNIVERSE EXPLODING OUT OF A DOT SMALLER THAN THE HEAD OF A PIN, BUT THEY CAN'T COME UP WITH A MORE EVOCATIVE NAME FOR IT THAN "THE BIG BANG"?
THAT'S THE WHOLE PROBLEM WITH SCIENCE. YOU'VE GOT A BUNCH OF EMPIRICISTS TRYING TO DESCRIBE THINGS OF UNIMAGINABLE WONDER.
WHAT WOULD YOU CALL THE CREATION OF THE UNIVERSE?
"THE HORRENDOUS SPACE KABLOOIE!"
HMM... THAT IS BETTER.
ALMOST ANYTHING WOULD BE.
WE SHOULD LOBBY TO CHANGE THAT.
AND I THINK "TYRANNOSAUR" SHOULD BE CHANGED TO "MONSTROUS KILLER DEATH LIZARD."

Evidence for the horrendous space kablooie

- Motions of galaxies indicating expansion first got astronomers thinking about origin of the universe
- Cosmology was, at first, considered frivolous and unworthy of study: inconceivable that we might actually be able to rigorously scientifically study the very origin, shape, and future of our universe

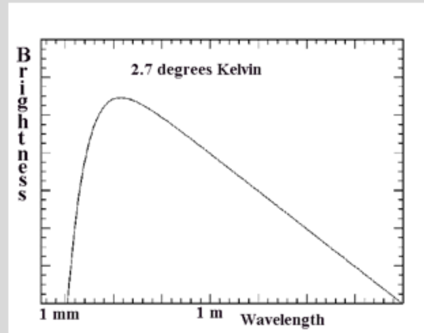
Evidence for the horrendous space kablooie

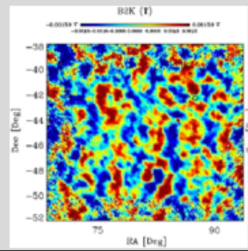


- Let's recap what we think happened in the early universe based on our observations, and the evidence we've gathered to further support it:
- Before visible surface of the early universe:
  - collider experiments show what happens under early-universe-like conditions
  - particle production at high temperatures and densities studied, scientists determine which forces dominate in which physical parameter spaces

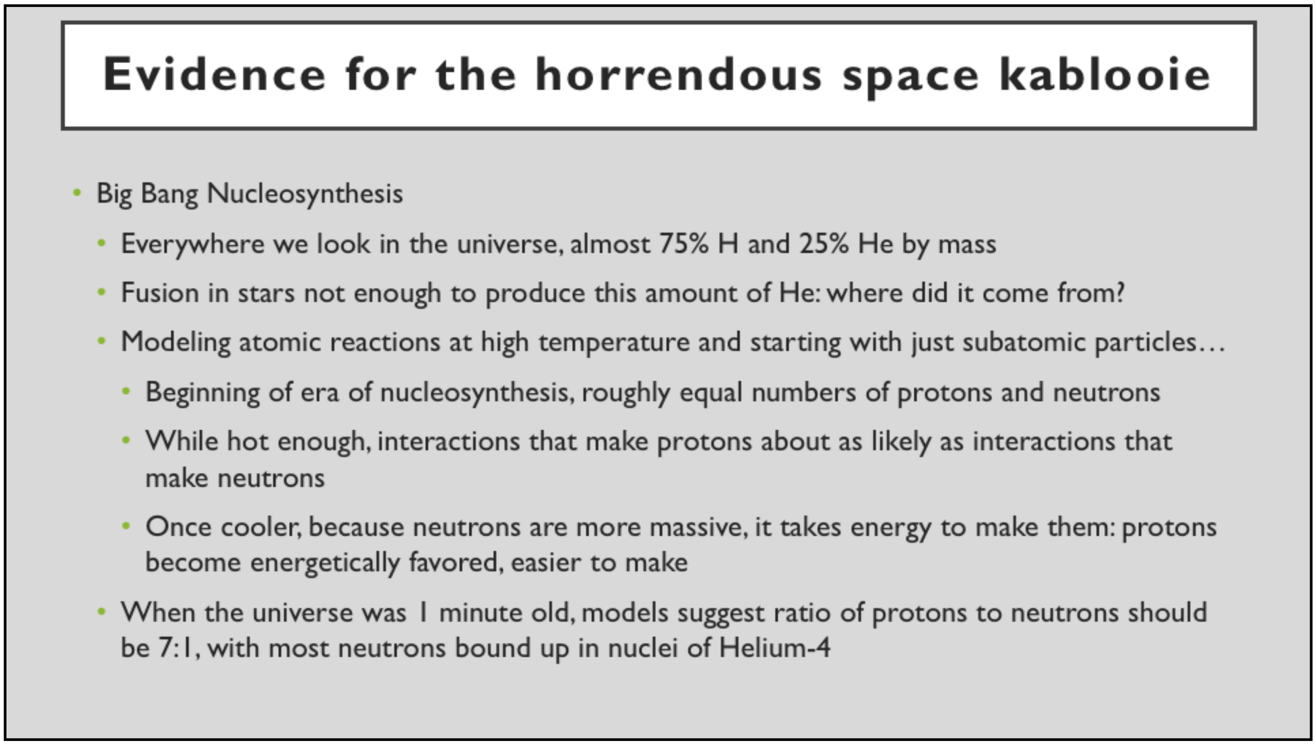
Evidence for the horrendous space kablooie

- Cornerstone 1 for a big bang: the cosmic microwave background
  - Big Bang Theory predicts nearly perfect thermal radiation spectrum, we observe it
    - Some argued scattered starlight– why wouldn't this be a perfect thermal radiation spectrum if it were light scattered from stars in the universe?
  - Peak temperature of thermal radiation spectrum accurately predicted by theory
    - Universe became transparent to photons at temperature of ~3000K, but expansion means those photons are redshifted to ~1mm in wavelength
  - Anisotropy accurately predicted by theory
    - Inconsistency in temperature due to inconsistencies in density: absolutely necessary for galaxies to form!





Doesn't take much difference, either- those scales are showing 1 part in 100,000 variation, very small

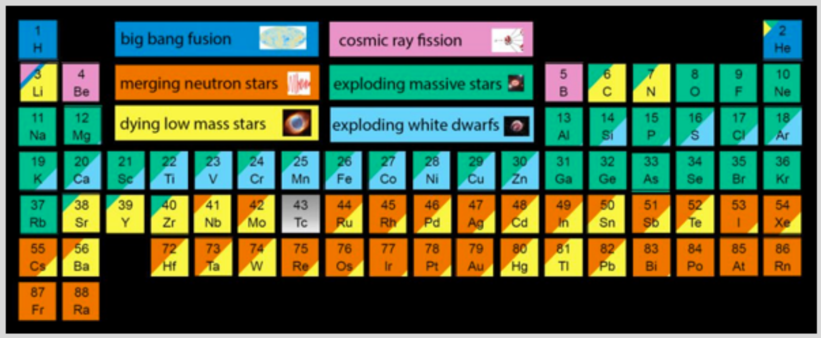


Helium has 2 protons, 2 neutrons, so 14 protons:2 neutrons would be one helium atom for every 12 H atoms.

By mass, H is 1 atomic mass unit, He is 4 atomic mass unit, so by mass, 12 H atoms to 1 He is 75% mass in H, and 25% mass in He.

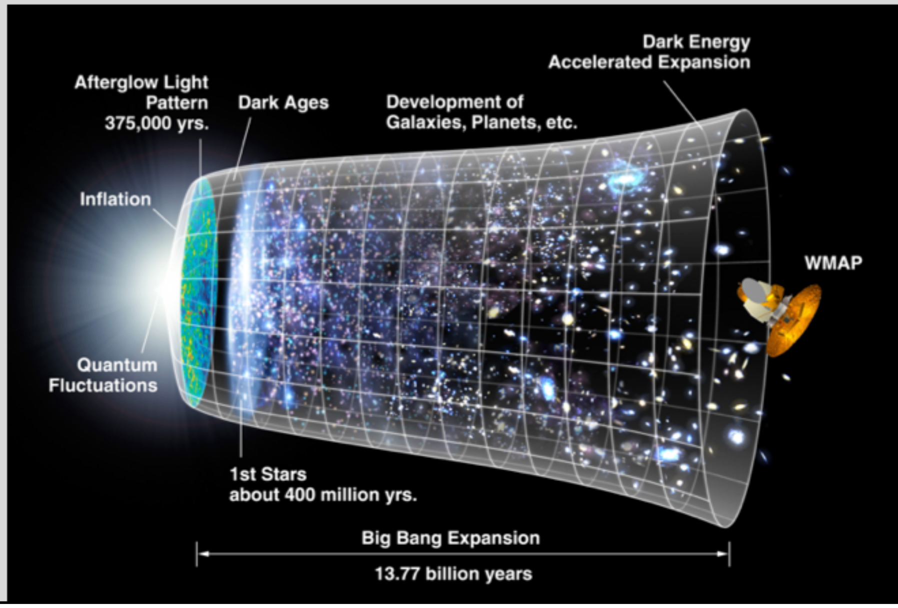
Big Bang Nucleosynthesis and other elements

- Period of high enough temperatures for fusion very, very short
- Not long enough for He to fuse into anything heavier
- Most random fusion isotopes/products unstable, decayed quickly. But…
- Big bang also created some Lithium through fusion of H and He isotopes



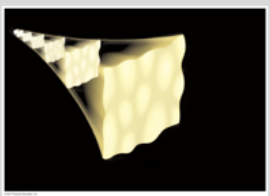
https://www.sciencealert.com/this-awesome-periodic-table-shows-the-origins-of-every-atom-in-your-body

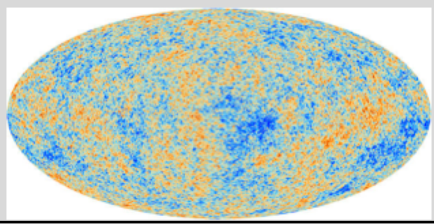
Inflation

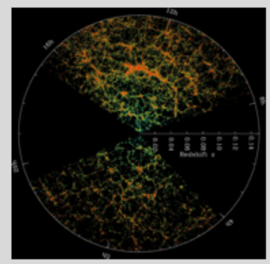

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

Inflation

- Big Bang theory satisfyingly answered some questions, but left a few lingering issues.
  - 1. Where did anisotropy come from?
    - Even in a vacuum, there are fluctuations in energy on short timescales
    - We think these fluctuations, expanded from ~sub-atomic size scales to universe size-scales, are what we're observing in the CMB and in galaxy structure
    - In the earliest times in the universe, remember all physical forces thought to be unified: fluctuations on quantum mechanical scales would leave an imprint on the very fabric of space-time







Probabilistically, any number of states of a system are possible, as long as quantities across the system are conserved. A particle/anti-particle pair could show up out of nowhere and annihilate on short timescales without violating any laws of physics! Dang it, quantum mechanics.. Stop being so weird

Inflation

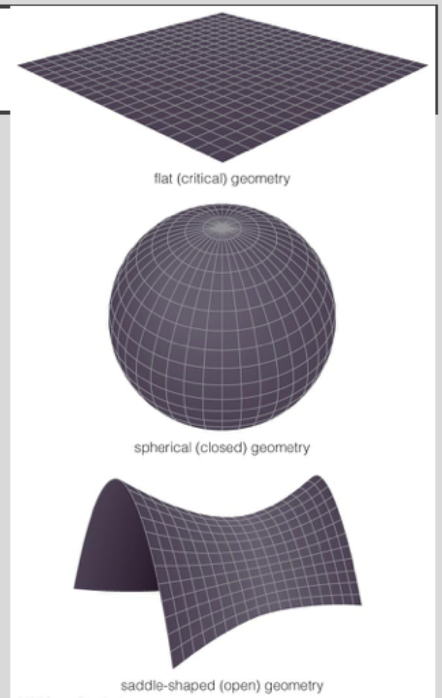
- Big Bang theory satisfyingly answered some questions, but left a few lingering issues.
  - 1. Where did anisotropy come from?
  - 2. Why is large scale universe nearly uniform?
    - The CMB is remarkably uniform no matter where we look around us, be it ~13.8 billion years in one direction or another
    - Things heat up or cool down by emitting or absorbing photons; one side of the universe hasn't had enough time for a photon from one side to travel to the other side
    - Inflation says: CMB not currently in thermal contact on opposite sides, but it once was
      - Material emitting in the CMB was once in contact long enough to equilibrate before being rapidly separated by expansion of space

Inflation

- Big Bang theory satisfyingly answered some questions, but left a few lingering issues.
  - 1. Where did anisotropy come from?
  - 2. Why is large scale universe nearly uniform?
  - 3. Why does the geometry of the universe appear to be flat?

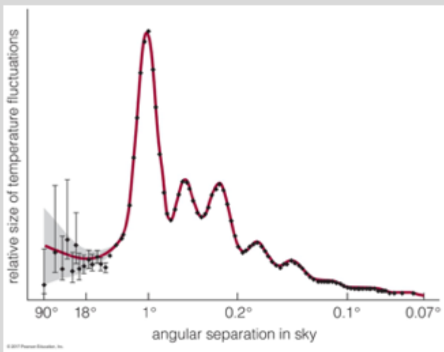
Geometry of the universe

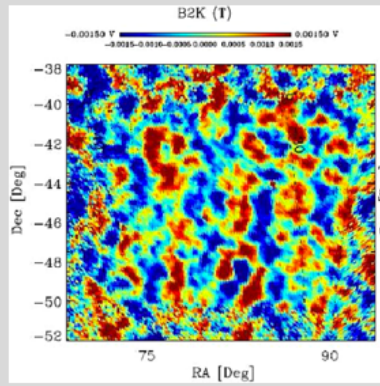
- Einstein's theory of general relativity notes mass distorts space-time
- GR predicts that geometry of universe depends on the distribution of matter and energy in the universe
  - Critical density is defined as where the universe won't continue to expand indefinitely, but won't collapse back onto itself, either
  - Flat
    - Combined density of matter and energy close to a critical value
  - Spherical
    - Average density greater than critical density
  - Saddle-shaped
    - Average density less than critical density



Did inflation happen?

- If we assume quantum mechanical fluctuations are the source of anisotropy in the CMB…
  - Can model what expanded version of small-scale fluctuations would look like
  - Measure distances between features in the CMB





The success of a theory

- The Big Bang Theory is a theory
  - A collection of laws and models that, to-date, gives the best explanation for our observed universe
  - We will never be able to prove it with absolute certainty
  - What kinds of observations would make us seriously reconsider the theory?
    - If we observed a galaxy with much less than the predicted amount of He from big bang nucleosynthesis
    - If we discovered an issue with the treatment of the CMB data that reveal structure varying hugely over the largest scales (this is unlikely)

Olber's paradox

- Why is the night sky dark?
- Many early universe theories assumed the universe is..
  - Infinite
  - Static
  - Uniform
  - And has an infinite number of stars

Olber's paradox

- If this were the case… everywhere we looked, we'd see stars. Stars between stars. Our whole night sky would be lit up like daytime 24/7
- The number of stars would increase with distance as r^2
- Even as the light from the stars drops off with distance as $1/r^2$
  - Sky would be uniformly bright from all the stars
- So, one or more of those assumptions about the universe is wrong

Olber's paradox

- We now realize a lot of things go into making the night sky dark:
  - Finite number of stars
  - Finite number of galaxies
  - Not uniformly distributed
  - Universe is changing with time