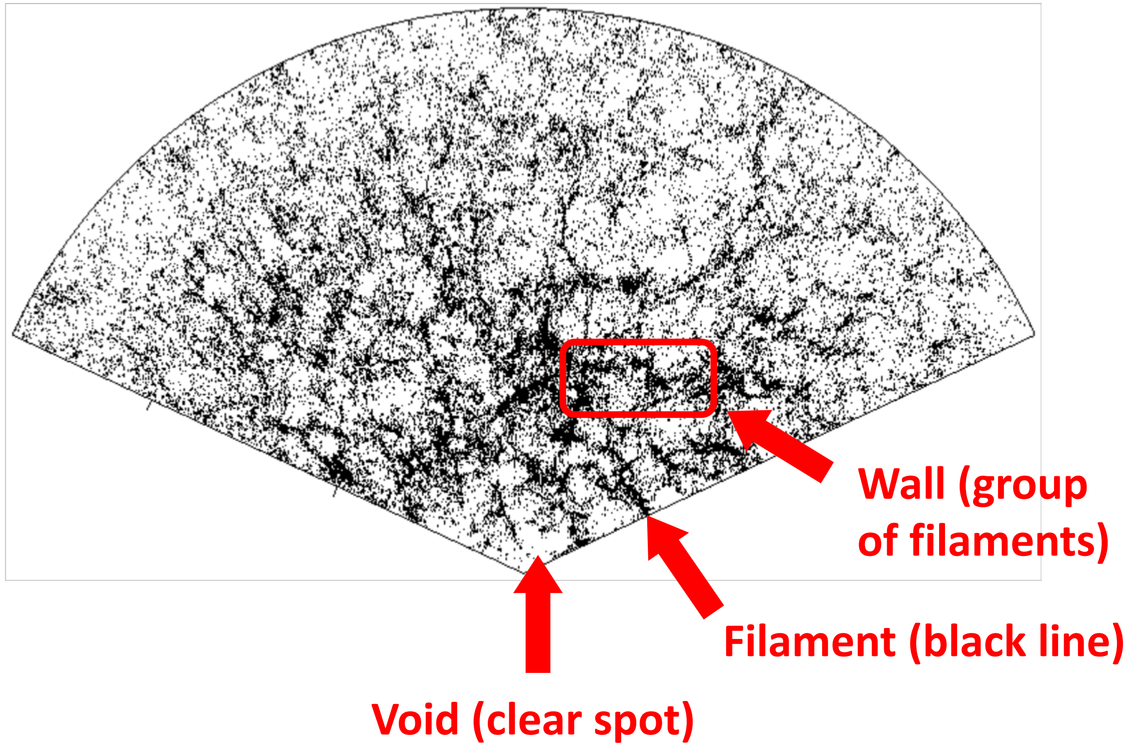
Chapter 15:
Cosmology and the Universe

Prof. Douglas Laurence

AST 1002

Universe at Large Scales

- Particles → Atoms → Stars → Star clusters → Galaxies → Local Groups → Galaxy clusters → Superclusters → Voids, filaments, walls
- The last bit of structure – voids, filaments, and walls – is thought to be the largest structure in the universe.
  - Voids, filaments, and walls exist at distances of ~100 Mpc; you have to look extremely far out to see them.

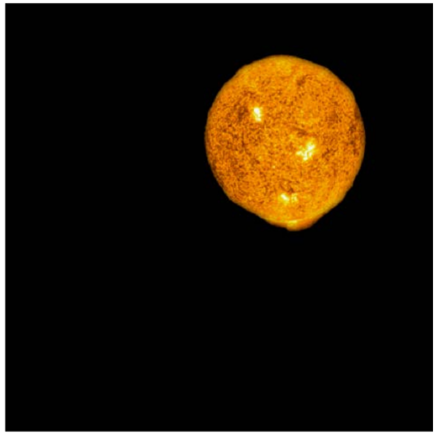


Cosmological Principle

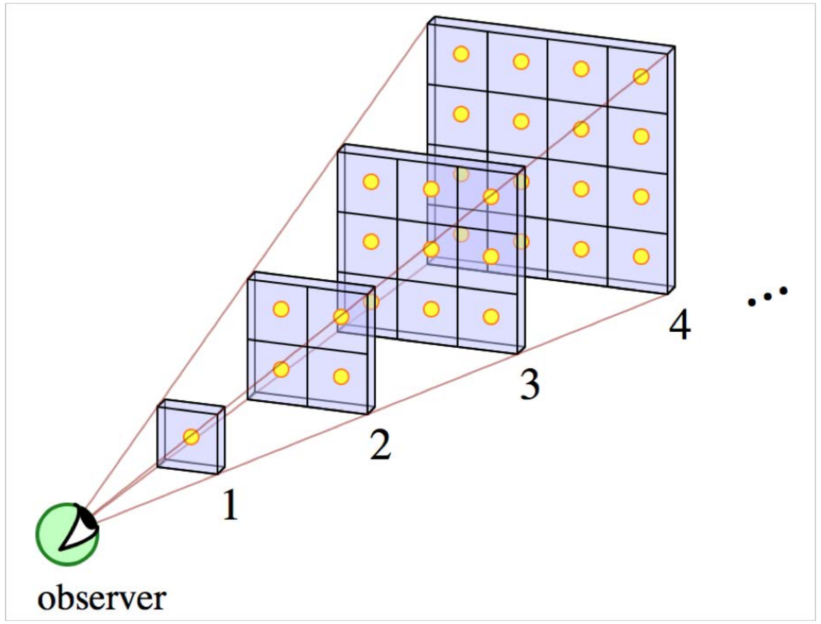
- At distances larger than for voids, filaments, and walls (~300 Mpc or 1 Bly), the universe looks very different: it loses all sense of structure.
- The **cosmological principle** is the idea upon which all of modern cosmology is based. It states that at large, **cosmological distances** (~300 Mpc or 1 Bly), the universe appears to be:
  - **Homogeneous**: no points in space have more mass than any other points in space, and so there is no ”preferred” location in the universe.
  - **Isotropic**: appearing the same in all directions, so that there is no “preferred” direction in the universe.
- Based on the **Copernican principle**, which basically states that we (humans) aren’t special.

https://upload.wikimedia.org/wikipedia/commons/d/d2/Olber%27s_Paradox_-_All_Points.gif

Olbers' Paradox



- Credited to Heinrich Olbers in 1823, though many others had proposed it (Kepler in 1610, Halley c. 18th century, etc.)
- Imagine a homogeneous/isotropic universe filled with stars, all of the same luminosity. We imagine space to be infinitely large and **static** (not changing with time).
- This will lead us to the conclusion that the night's sky should be as bright as the day's!



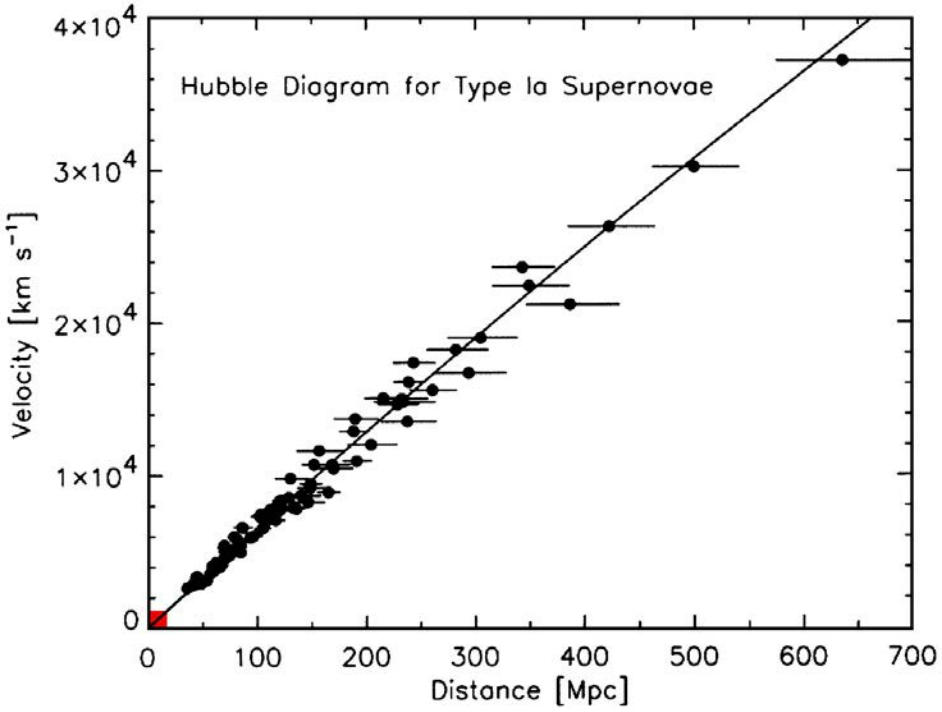
Flux decreases like $1/r^2$ but number of stars increases like r^2 so total flux (number * flux) doesn't change with distance!

Solution to Olbers' Paradox

- Physicists did not want to abandon the cosmological principle (thankfully), so they assumed that the universe was truly homogeneous and isotropic.
- This means that something must be wrong with the other two assumptions of Olbers' paradox: that the universe is infinitely large and static.
- It turns out that both of these assumptions end up being wrong! The universe is not infinitely large, but has a finite size, and the universe is not static, but is expanding in size. More on this later.

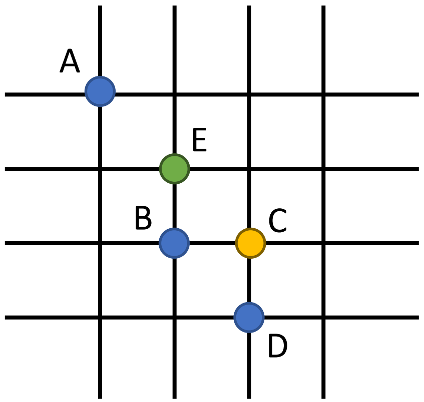
Hubble's Law

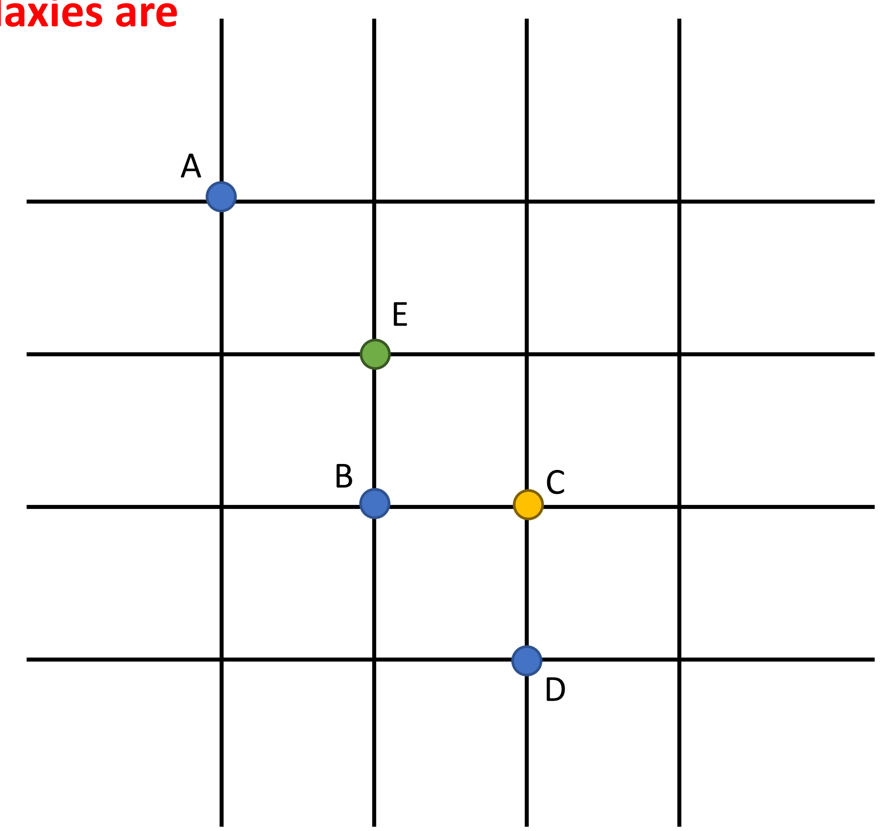
- Hubble's law tells us that the all galaxies are moving away from us, and that all galaxies are moving faster the further away from us they are.
- This seems to imply that we're at the center of the universe, doesn't it?
  - *Hint: not if we think about it cleverly!*
- Remember the Copernican principle: we are not special, and the center of the universe is a very special place.



Expansion of the Universe

Distances between the Earth and all distant galaxies increased, therefore all distant galaxies are moving away from us





But distances between C and all distant galaxies *also* increased, and therefore all distant galaxies are *also* moving away from C! We are not at the center of the universe!

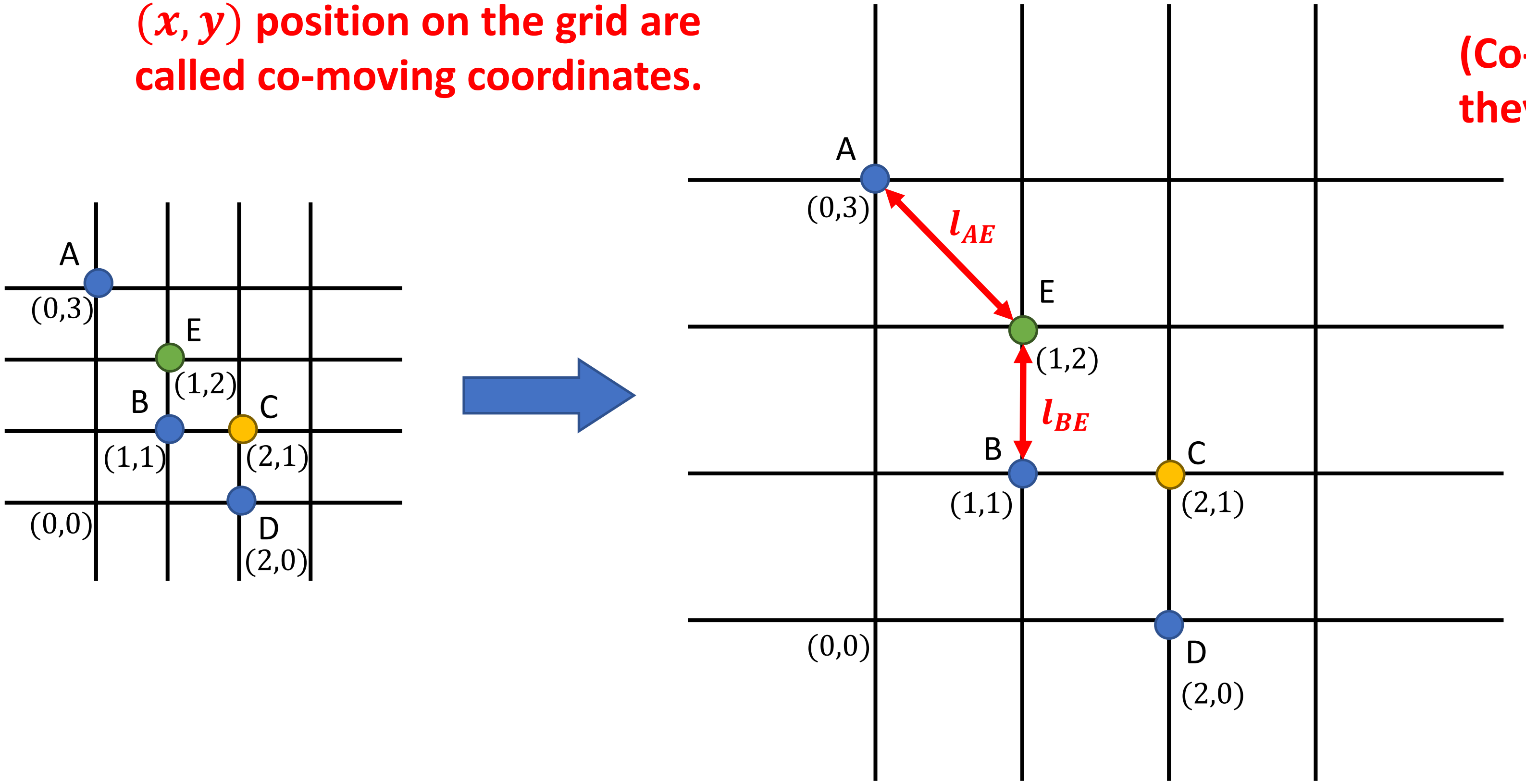
Co-moving coordinates

$$l_{AE} = \sqrt{(0-1)^2 + (3-2)^2} = 1.4$$

$$l_{BE} = 1$$

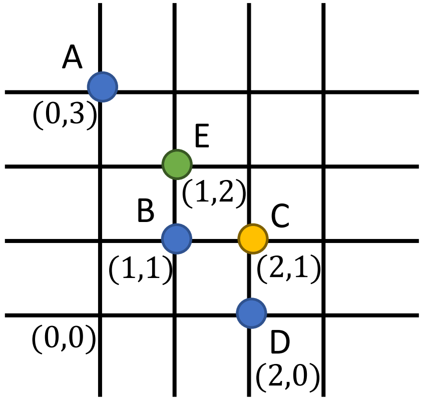
(x, y) **position on the grid are called co-moving coordinates.**

(Co-moving distances are unitless and they do not change with expansion!)

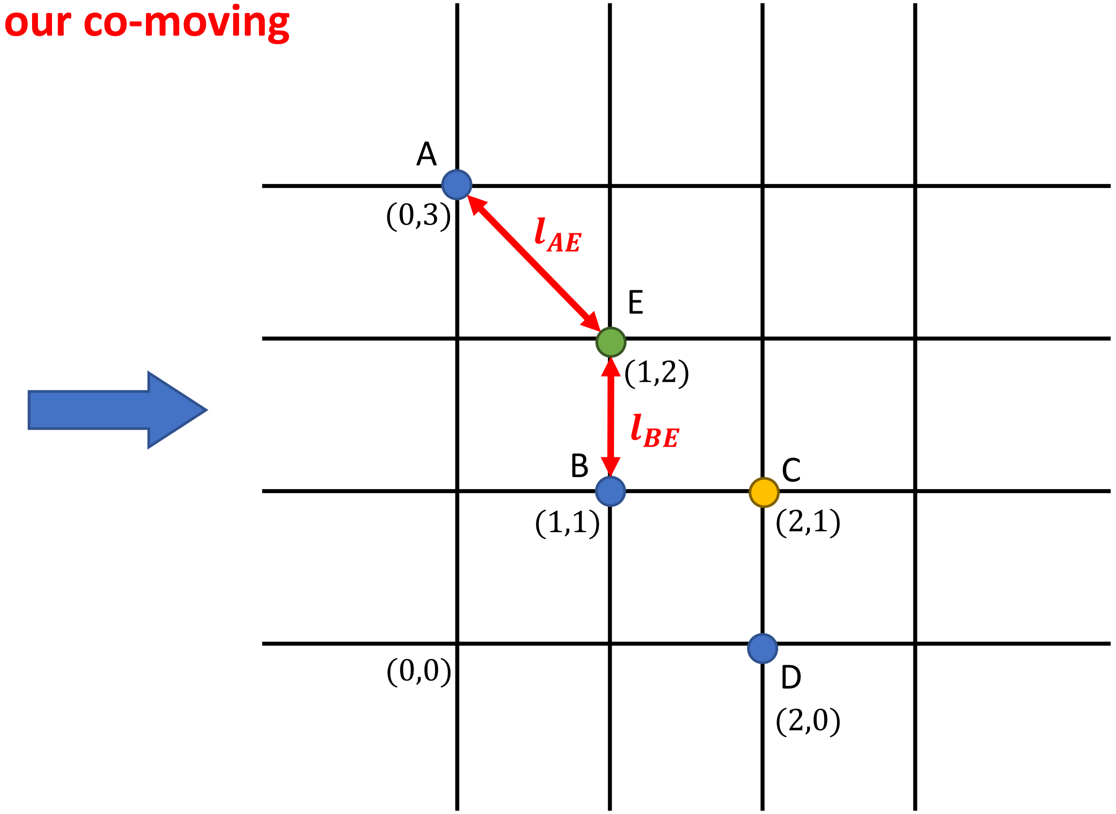


Scale Factor

If we consider a scale factor $a(t)$ to be the size of a ruler at any time t, then the scale factor gives our co-moving distances units!



$a(t)$



$a(t')$

$l_{AE} = 1.4$

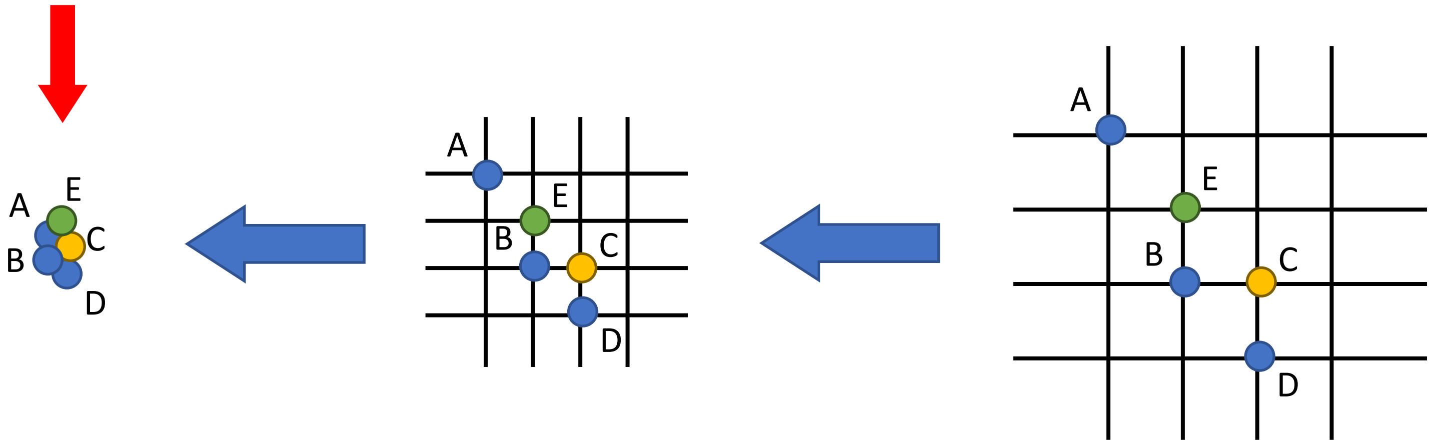
$l_{BE} = 1$

$d_{AE} = 1.4a(t')$

$d_{BE} = a(t')$

Going Backwards in Time

If we go back far enough into the past, Hubble's law implies that everything started out at rest with $\boldsymbol{d = 0}$

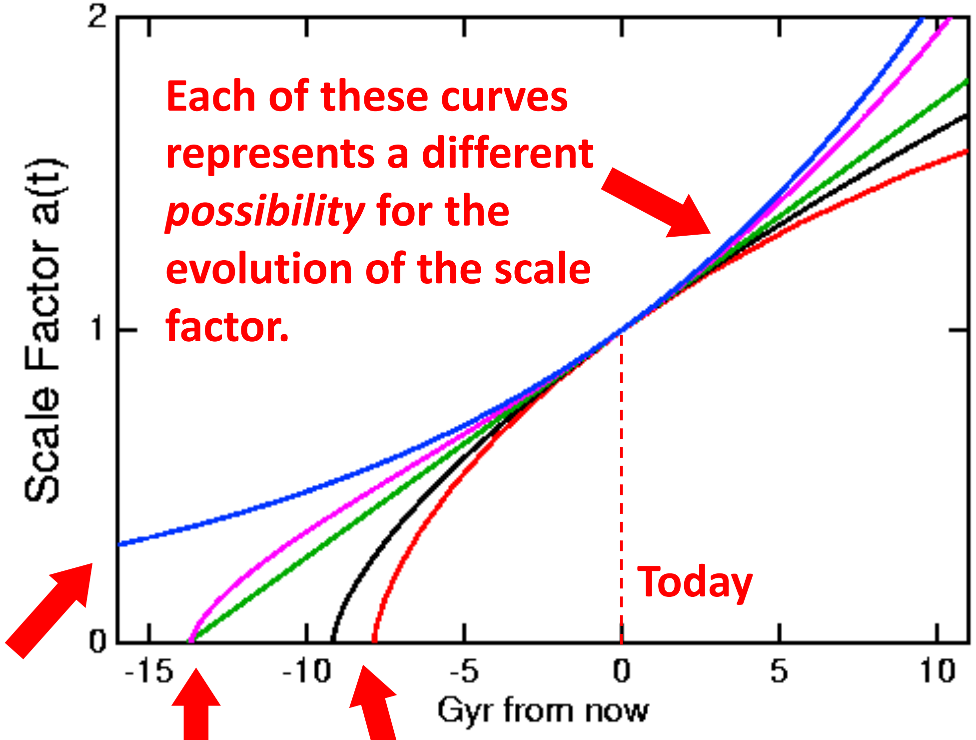


$\boldsymbol{a(t) = 0}$

This is the basis for the Big Bang theory – the idea that, far enough back in time, the universe started out extremely small with all matter in the universe extremely close. (It's more complicated than this, but this is a good place to start.)

Evolution of the Scale Factor

- Since the universe is expanding, at progressively greater times, $a(t)$ should get progressively larger.
- Since the expansion of the universe *is* what we're interested in, if we know how $a(t)$ changes with time, we know everything about the expansion of the universe!



Too old

The universe is about 14 By old, so either of these would work.

Both are too young for our universe

Age of the Universe

- We can find the (approximate) age of the universe from Hubble's constant (this is known as the **Hubble time**):

$$t_H = \frac{1}{H_0}$$

- For instance, if we take $H_0 = 70$ km/s/Mpc, which is equal to 2.27×10^{-18} 1/s, the age of the universe is approximately:

$$t_H = 4.41 \times 10^{17}\,\mathrm{s} = 13.98\ \mathrm{By}$$

- So the universe is approximately 14 billion years old.
    - It's actually younger than this estimate, about 13.6 By for $H_0 = 70$ km/s/Mpc.

➡ http://www.astro.ucla.edu/~wright/CosmoCalc.html (**Cosmological Calculator**)

Hubble Distance

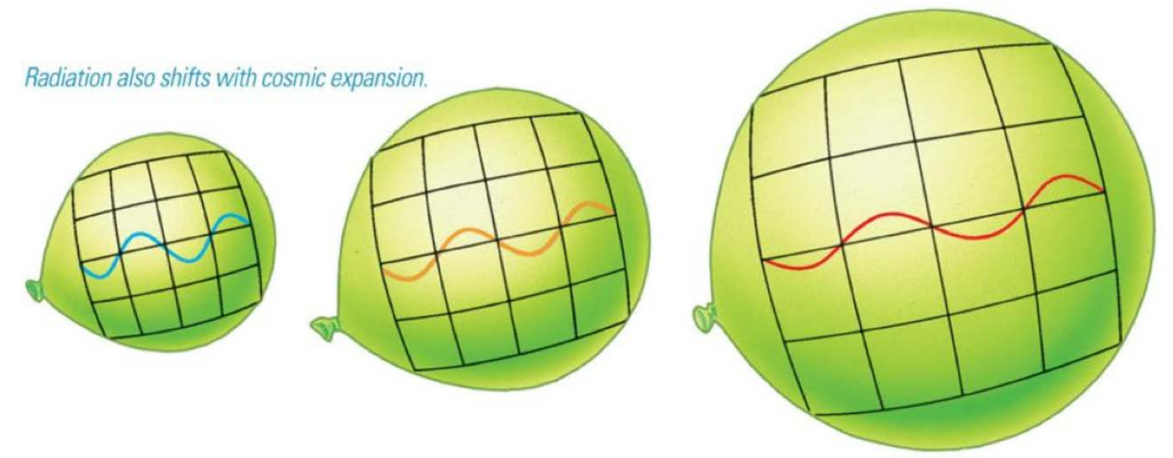
- Since the age of the universe is roughly the Hubble time, $t_0 \sim t_H$, then the furthest object we could see in the universe is roughly a **Hubble distance** away:

$$d_H = ct_H \sim 14 \text{ Bly}$$

- With this, we have shown the two assumptions of Olbers' paradox, that we wanted to get rid of, to be incorrect:
  - A static universe: Hubble's law proves that the universe is expanding
  - An infinite universe: the furthest objects that we can see are roughly a Hubble distance away, not an infinite distance.

Cosmological Redshift

- There turns out to be a cosmological Doppler effect, which acts to produce a **cosmological redshift** for all distant galaxies which are moving away from us.
  - This isn't quite the same as the redshift we saw before; that redshift was based on the idea that the galaxies were *actually* move away from us, but galaxies only *appear* to move relative to us due to the universe's expansion.



Cosmological Redshift (cont'd)

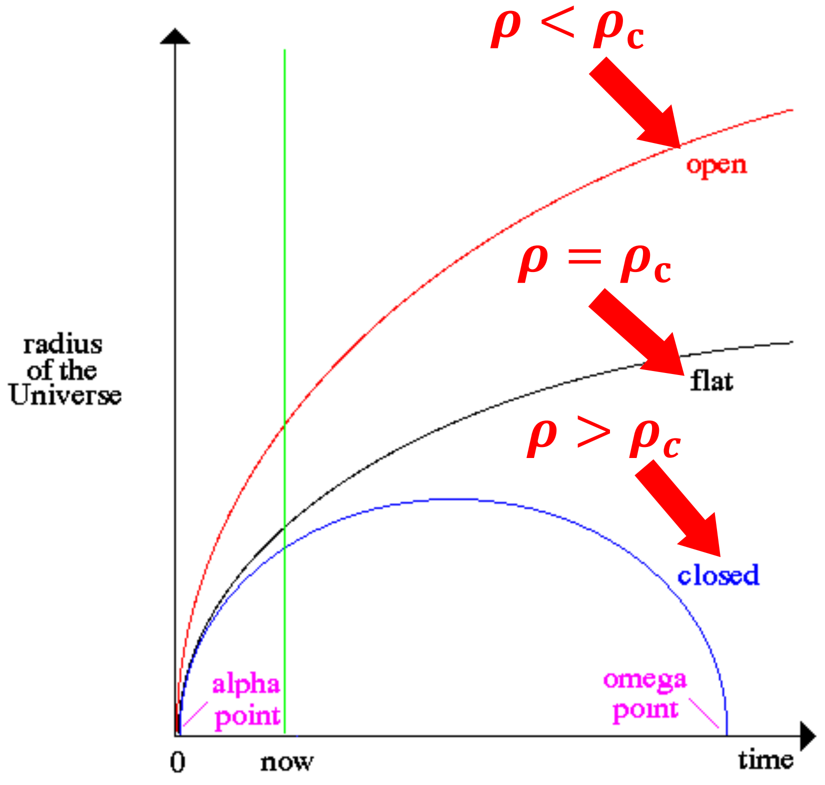
- Cosmological redshift measures the expansion of space that a photon has to travel through to reach us from a distant galaxy.
- If you observed a distant galaxy to have a redshift of $z = 4$, then the universe would be $1 + z = 5$ times bigger now than it was when the photon was emitted.
  - The wavelength increases with $1 + z$, so the wavelength is 5 times larger when we observe than it was when it was emitted by the distant galaxy.
  - Since z is a measure of the expansion of space, and the expansion of space changes with time, we'll use z interchangeably with time. In essence, as you look away from Earth across cosmological distances, you're looking backwards in time; the farther away something is, the older it is.

Density and Scale Factor Evolution

- Gravity is a universally attractive force – it will always act to pull things together. However, gravity gets **weaker** as distances increase.
- If space is initially expanding with a large enough speed, it will continue expanding forever because gravity will become too weak too quickly for space to be pulled back inward.
  - This is the same idea as **escape velocity**, which was the minimum speed needed to escape an object’s gravitational pull.
- If you increase the density of matter in the universe for the same initial speed, gravity has an inherently stronger pull since there’s more mass, and maybe now the initial speed isn’t large enough.

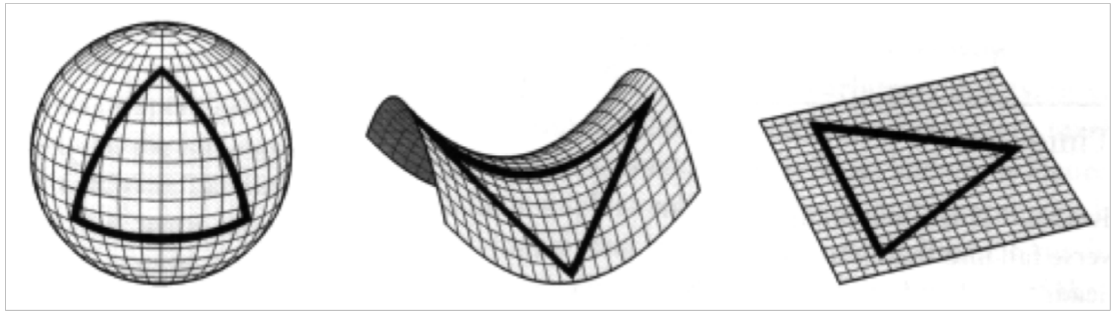
Critical Density ρ_c

- There are three possible evolutions of $a(t)$ based on the density of the universe ρ
  1. The density is too low, $\rho < \rho_c$, and the universe expands forever. This is called an an **open** universe, and it will grow to $a(t) = \infty$
  2. The density is too high, $\rho > \rho_c$, and the universe collapses on itself. This is called a **closed** universe, and it goes back to $a(t) = 0$
  3. The density is exactly equal to a **critical density**, $\rho = \rho_c$, and the universe *just* barely escapes gravity and expands forever. This is called a **flat** universe, and it expands to some non-infinite, maximum size a_{max}



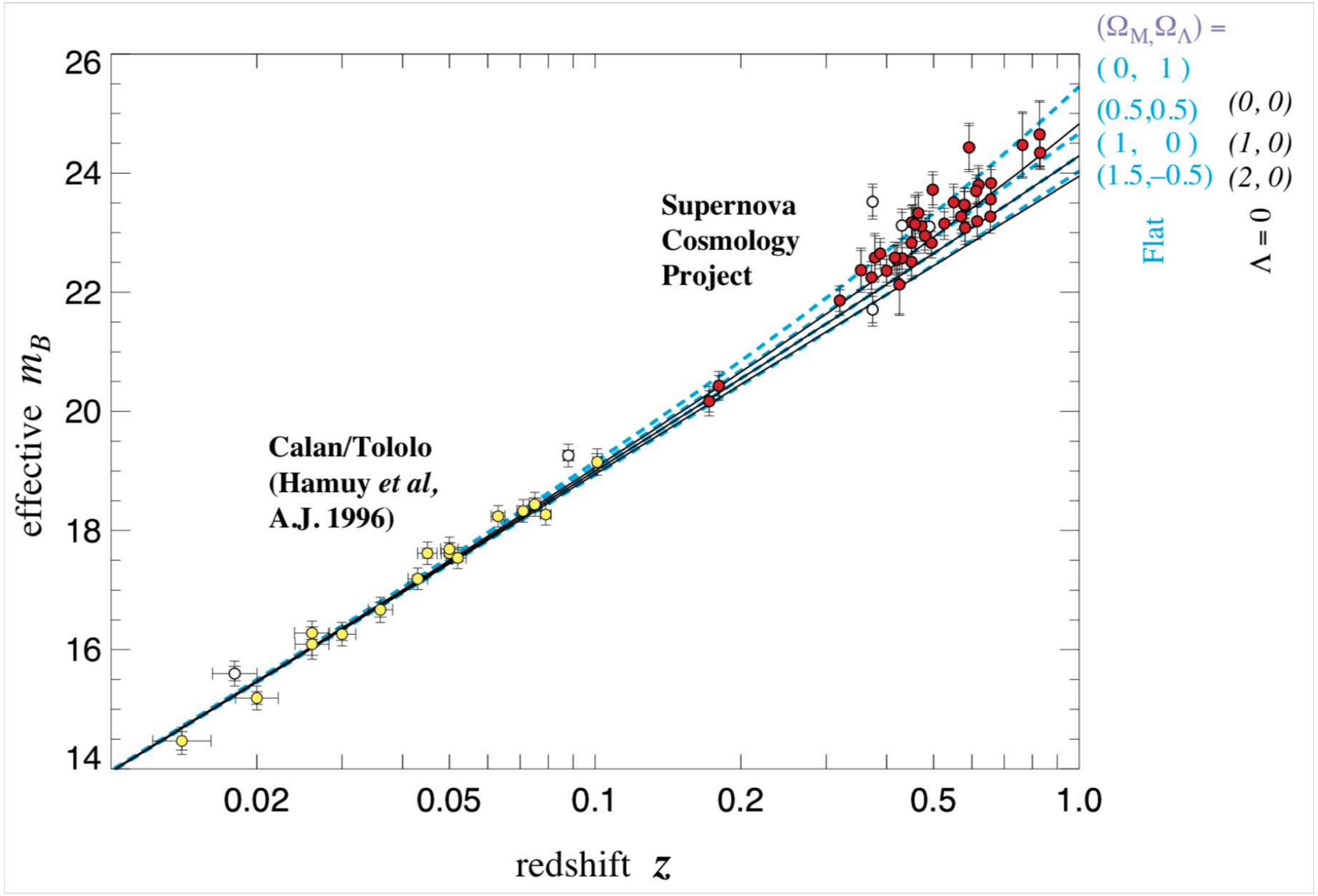
Geometry of the Universe

- As we know, relativity models gravity as the curvature of space.
- Each type of universe (open, closed, flat) will have a unique geometry.
  - An **open** universe has the geometry of a hyperboloid (a saddle).
  - A **closed** universe has the geometry of a sphere.
  - A **flat** universe is, as the name implies, flat.



Closed $\boldsymbol{\rho > \rho_c}$ **Open** $\boldsymbol{\rho < \rho_c}$ **Flat** $\boldsymbol{\rho = \rho_c}$

Evidence of Accelerated Expansion



What Gives?

- When introducing the three types of universes, I only mentioned gravity as a long-range force.
- What, then, explains the acceleration of the universe? We need to introduce a *second* long-range force, one that causes the universe to accelerate in its expansion. We say this is due to **dark energy**.

(Note that dark energy and dark matter have nothing to do with one another.)

What is Dark Energy?

- This question is one of the most important (if not *the* most important) open questions in cosmology.
- We don’t know what dark energy is, but we know its properties:
  - It must produce a repulsive force; that is, drive the expansion to accelerate.
  - It’s density **remains constant** as the universe expands. This means that the force gets stronger as the universe expands, while gravity gets weaker.
- There are currently two theoretical explanations for dark energy:
  - **The Cosmological Constant**: also called vacuum energy; it describes an inherent energy of space-time which is repulsive.
  - **Quintessence**: a type of quantum particle (a quantum field) that, under certain conditions, has the same properties as dark energy.

What is Dark Energy? (cont'd)

- The vacuum energy Λ – the repulsive energy woven into the fabric of space-time – is the leading candidate for dark energy.
- However, there's a problem with it: vacuum energy is a quantity that should be calculable in quantum mechanics, and given the correctness of QM, we expect to accurately predict Λ.
- Detailed calculations in quantum mechanics (which are almost always correct!) predict a value for the vacuum energy that is at least 10^{110} times too big! For some reason, we cannot explain vacuum energy using quantum mechanics, which is very troubling (trust me).

(The number of particles in the observable universe is 10^{90}, and the number of seconds the universe is old is 10^{17}. If we could produce the entire amount of particles in the universe every *second*, we would end up with 10^{107} particles, which is still 1000 times smaller than 10^{110}.)

Vacuum Energy in Quantum Mechanics

This estimate of the vacuum energy density has been termed

> *The most spectacular failure in all of theoretical physics.*

It is not yet clear

1. whether this means that vacuum fluctuations are not responsible for the acceleration of the Universe, or
2. whether it means that we have a (monumental) lack of understanding of how to properly calculate the vacuum energy density.

(I don't know if I'd go that far.)

(Meaning inflation is incorrect.)

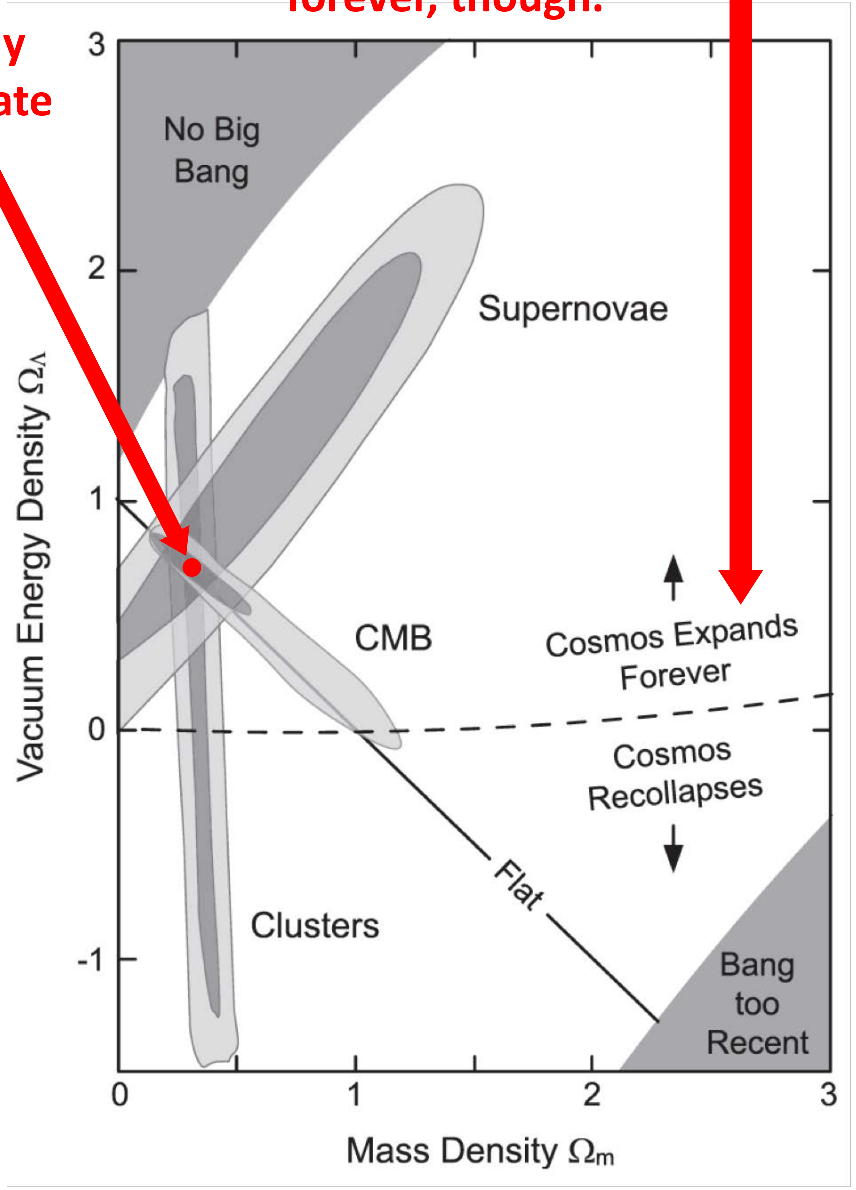
(Meaning quantum mechanics is incorrect; even worse!)

Our Universe

We are somewhere here in the overlap, but we don't know exactly where, so we don't have an accurate measure of our geometry.

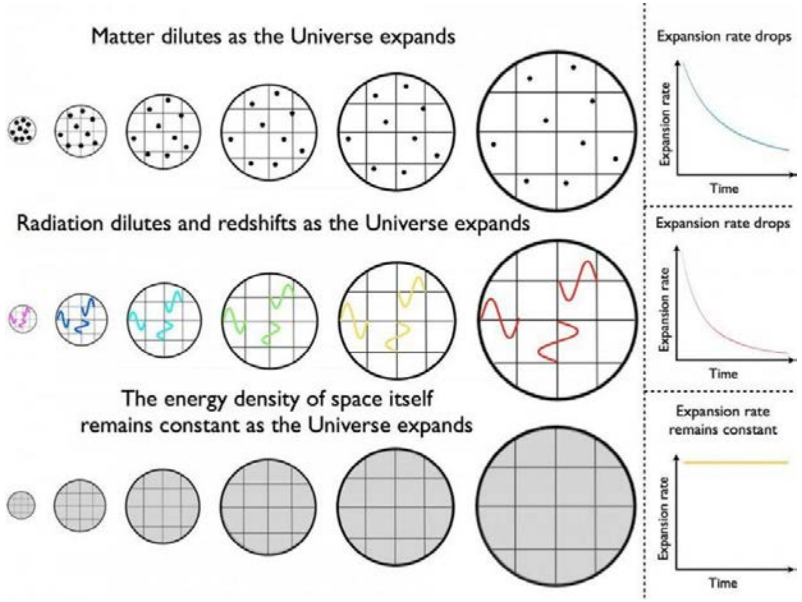
We're definitely expanding forever, though.

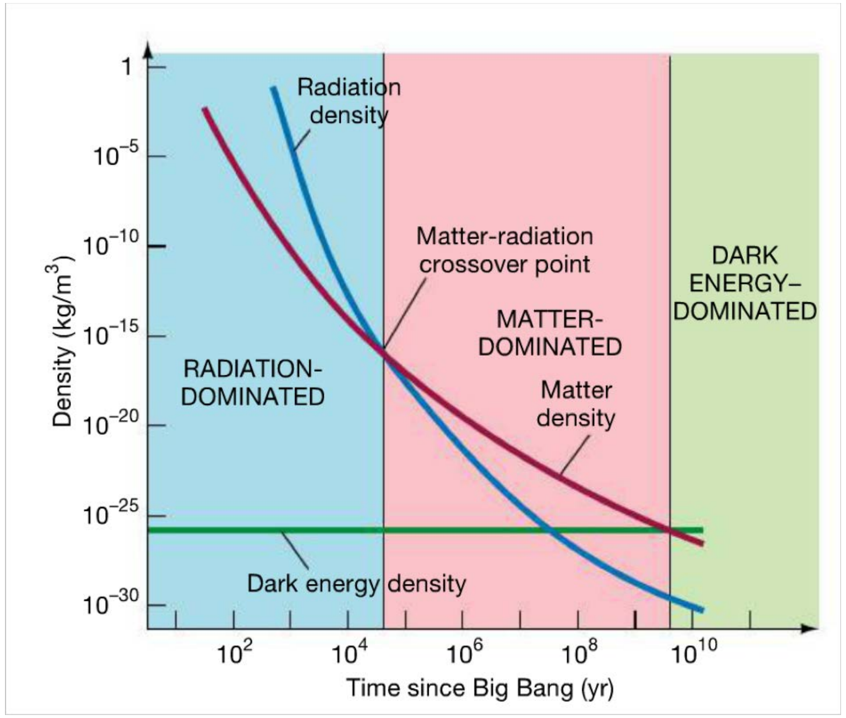
- Our universe will expand forever. As space expands more and more, dark energy gets stronger while gravity gets weaker, so nothing can stop the universe from expanding forever.
- Despite this, as far as we can tell from observations, the universe is **still flat**; rather, the universe is so close to being flat that we can't tell for certain that it isn't flat.
- This is another open question in cosmology: what is the *exact* geometry of the universe?



Composition of Our Universe

- There are three (accepted) types of energy densities in the universe:
  - **Radiation density ρ_r**: this is the energy density of all radiation in the universe. Radiation density decreases the **fastest**, like $1/a^4$.
  - **Matter density ρ_m**: this is the energy density due to all forms of matter in the universe, both dark and baryonic. Matter density decreases **more slowly than radiation**, like $1/a^3$.
  - **Dark energy density ρ_Λ**: the density of dark energy, as the name implies. Dark energy density **doesn't change**.





Density Parameters

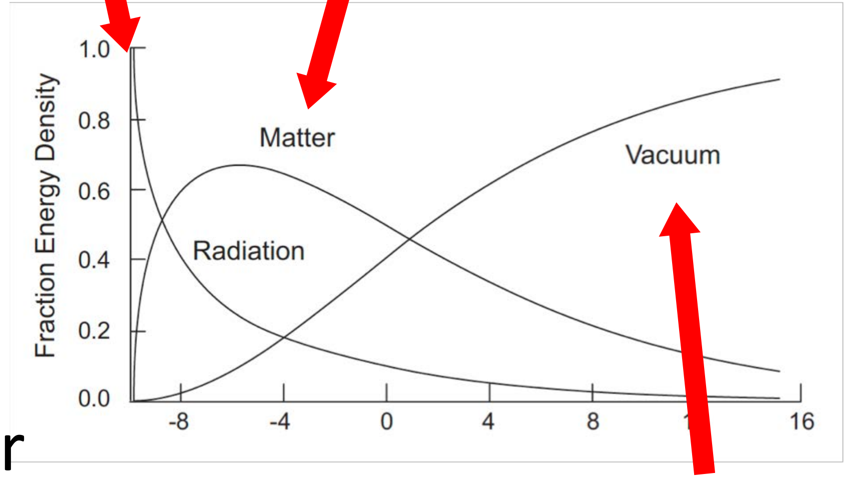
- We define the **density parameter** as being the ratio of the universe's total density to the critical density:

$$\Omega = \frac{\rho}{\rho_c} = \frac{\rho_r + \rho_m + \rho_\Lambda}{\rho_c} = \Omega_r + \Omega_m + \Omega_\Lambda$$

- The density parameter of the universe is (roughly) constant, so if the density parameter of one (say radiation) drops, the other two (matter and dark energy) must increase.
- **Currently**, $\Omega_r = 0, \Omega_m = 0.32, \Omega_\Lambda = 0.68$

Initially, radiation density parameter starts out the largest, but quickly falls.

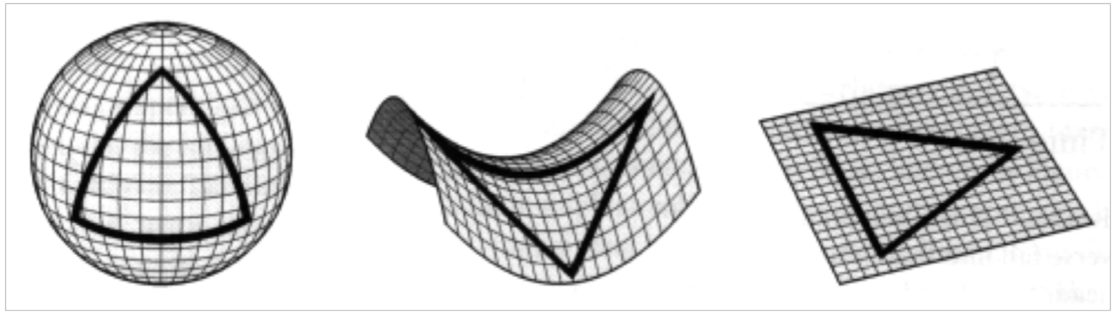
Matter density parameter must rise to compensate for the drop in radiation, but it eventually drops too low, and then dark energy dominates.



Dark energy (vacuum) density doesn't change, but the density parameter must increase as the radiation and matter density parameters drop.

Geometry in Terms of Density Parameters

- The geometry of the universe is set by how the universal density compares to the critical density: if $\rho > \rho_c$, then the universe is closed; if $\rho < \rho_c$, then the universe is open; and if $\rho = \rho_c$, then the universe is flat.
- We can re-write the above conditions in terms of the density parameter: if $\Omega > 1$, the universe is closed; if $\Omega < 1$, the universe is open; and if $\Omega = 1$, the universe is flat.



Closed $\boldsymbol{\Omega > 1}$ **Open** $\boldsymbol{\Omega < 1}$ **Flat** $\boldsymbol{\Omega = 1}$

Cosmic Microwave Background (CMB)

- One of the core predictions of the Big Bang theory is the existence of the **cosmic microwave background (CMB)**, which is radiation (microwaves) leftover from the Big Bang that permeate the universe.
- Early in the Big Bang, the universe was very, very compressed, and so it was extremely hot. The thermal energy was too high to allow any atoms to exist, so the universe existed as an ionized gas (a plasma).
- Light can't move through plasma, so light was trapped.
- When the universe cooled to 3000 K, the nuclei and electrons in the plasma suddenly combined to form a neutral atomic gas, and suddenly light was free. This light is the cosmic microwave background, and was produced ~400,000 yr after the Big Bang.

Properties of the CMB

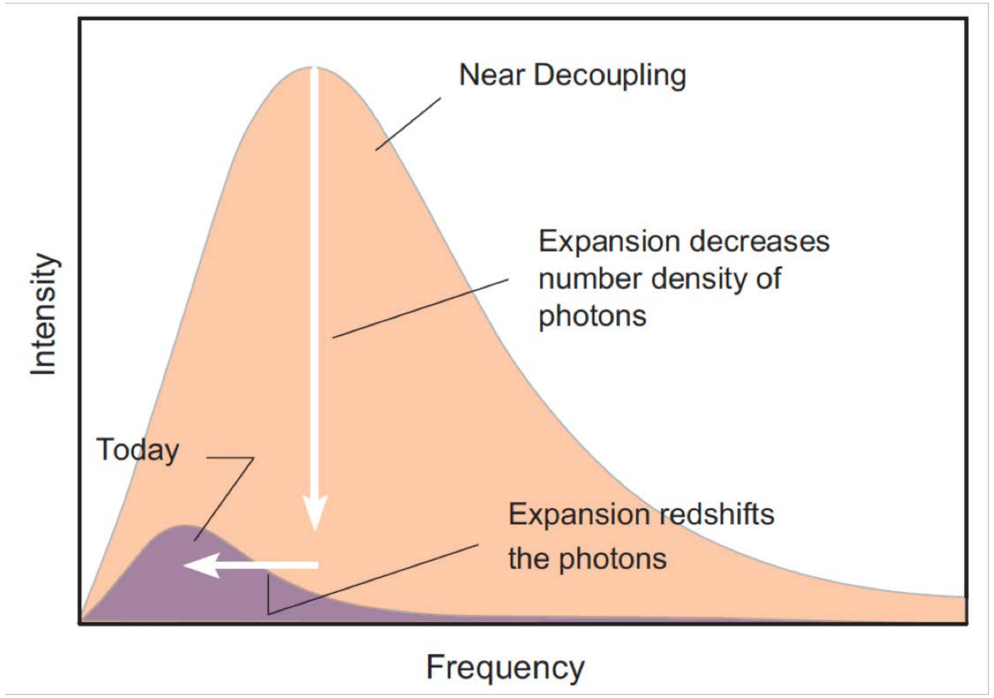
- The CMB is a type of **blackbody radiation**. This was proven around 1993 by the COBE satellite group. The CMB was first detected by Arno Penzias and Robert Wilson, of Bell Labs, by accident in 1964.
- We've estimated that the CMB is produced at a redshift of 1100 (recall that large redshifts occur at long ago times) at 3000 K (the temperature at which the plasma becomes a gas). The temperature of a blackbody spectrum has the following relationship:

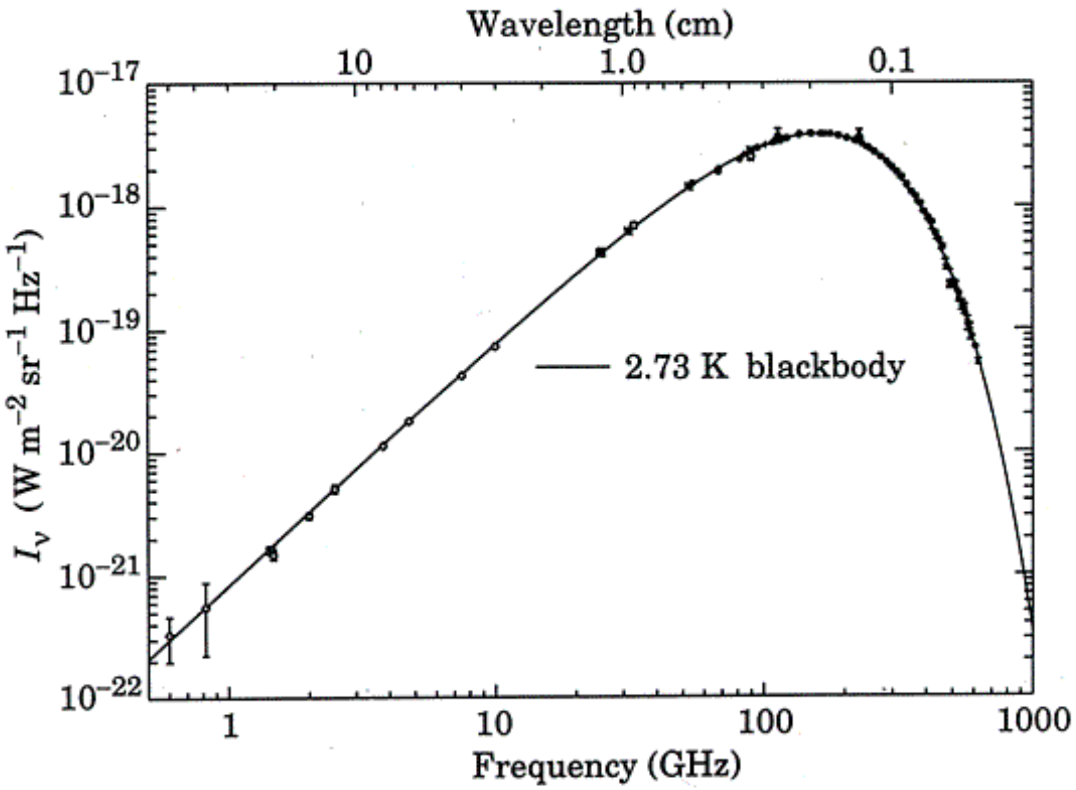
The subscript 0 refers to a current value.

$$T_0 = \frac{T}{1+z}$$

- This corresponds to a current temperature of $T_0 \approx 2.7$ K.

Properties of the CMB (cont'd)





Theoretical blackbody spectrum at 2.73 K plotted against COBE data.

Chapter 27:
The Early Universe

Prof. Douglas Laurence

AST 1004

Summer 2018

Informal Description of the Big Bang

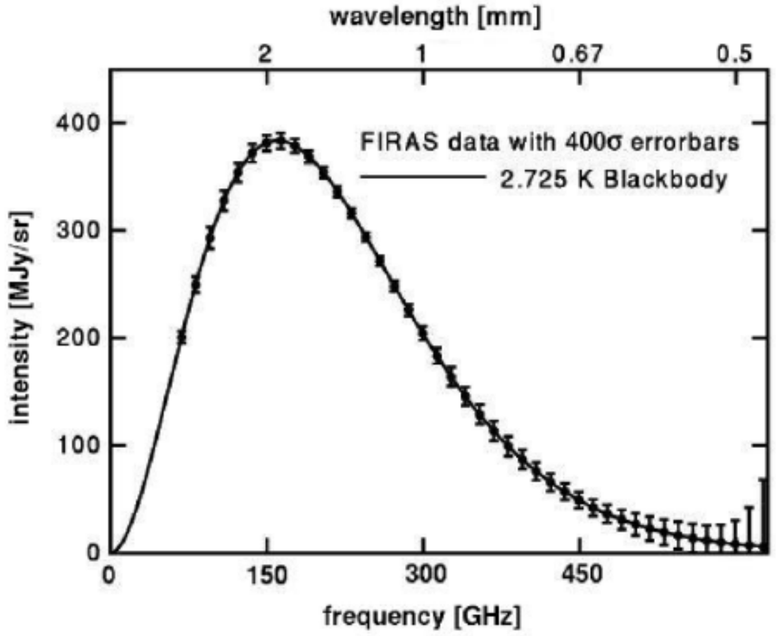
- Stephen Hawking and Roger Penrose formalized much of our current notions on the Big Bang from the 1970's to the 1990's.
- Initially, the universe began as a small plasma.
- The plasma in the early universe **did not** occupy a small volume in space; rather, space **itself** was significantly smaller.
- Somehow, energy in the form of radiation, matter, and dark energy was introduced into the universe, which caused this plasma to become extremely hot and dense, causing expansion.
- As the universe expanded, the temperature cooled, allowing for physics to become "less extreme" (i.e. more like physics today).

Some History of the Big Bang

- Hubble's original estimate of H_0 gave a Hubble time of ~2 Byr.
  - The Earth was well known, even in the 1930s, to be around 5 Byr old!
- Our discussion of cosmology so far has been a discussion of a type known as **Friedmann cosmologies**, but there are many others.
  - de Sitter cosmologies, steady state cosmologies, etc.
- There was no theoretical way to choose which cosmology was correct, a fact that disturbed Einstein more than anyone.
- A lack of theoretical and observational success of cosmology meant that interest in the physics community was dwindling by the 1960's.

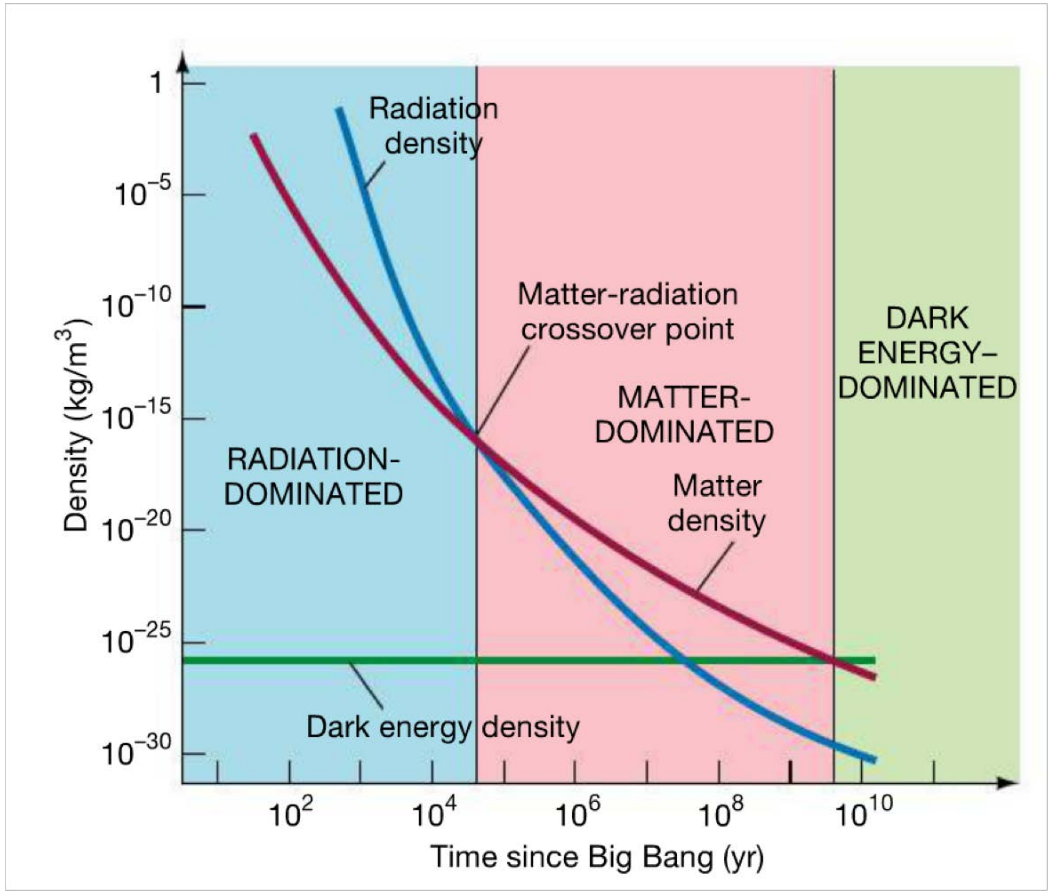
Breakthrough: Discovery of the CMB

- In 1964, Arno Penzias and Robert Wilson made the first (recognized) detection of the CMB (Nobel Prize, 1978).
- Confirmation that this was, in fact, a blackbody spectrum took a while. In 1990, John C. Mather and George F. Smoot definitively showed that this signal was a blackbody spectrum, using the COBE satellite (Nobel Prize, 2006).
- After the discovery of the CMB in the '60s, cosmology (and the big bang) became widely accepted scientific theories.



Densities During the Big Bang

- Initially, the universe was **radiation dominated**, meaning that ρ_r was the largest density, and thus the evolution of the universe was determined by it.
- After about 50,000 yr, the universe became **matter dominated** when ρ_m grew larger than ρ_r.
- About 4 By ago, the universe became **dark energy dominated**. Now the universe has no choice but to expand forever.



Timeline of the Big Bang

No theory of quantum gravity currently exists, hence the question marks.

“Planck” anything (Planck time, Planck distance, Planck mass, etc.) represents the quantity at which quantum gravity becomes important.

The point at which GUTs no longer apply.

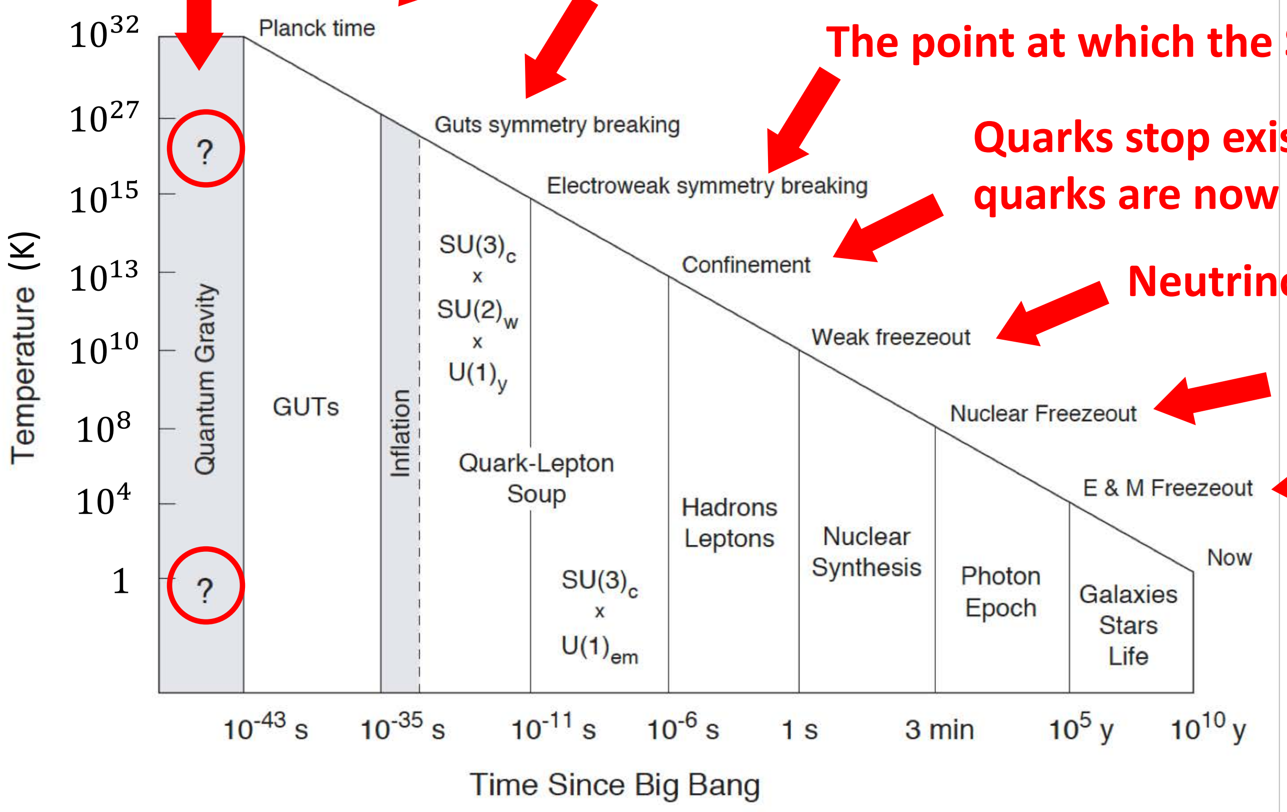
The point at which the Standard Model no longer applies.

Quarks stop existing on their own (free quarks); quarks are now confined to hadrons.

Neutrinos are freed

Nuclear fusion begins

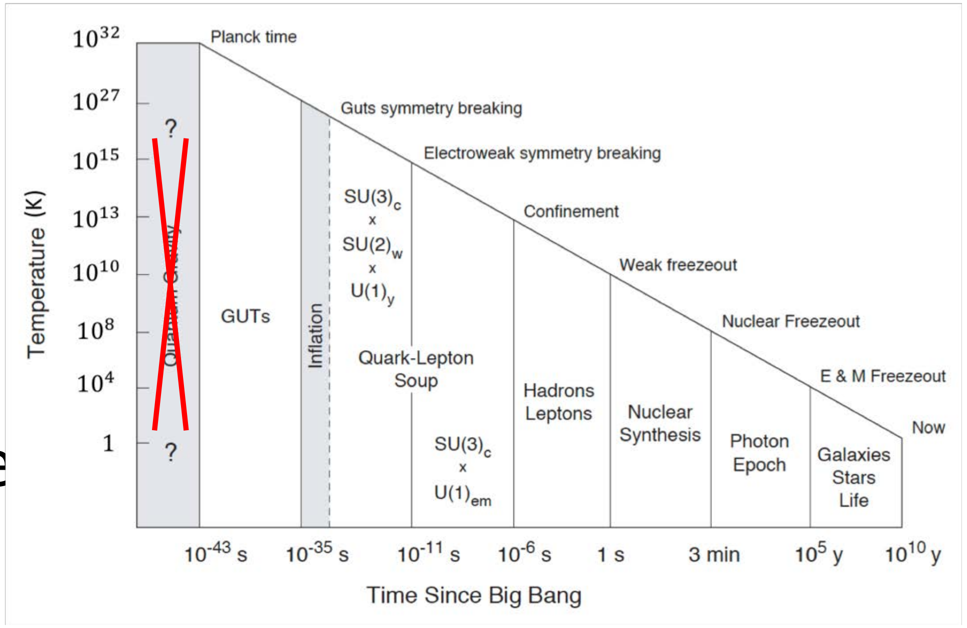
CMB is produced



(GUT = Grand Unified Theory, which combines the 3 quantum forces, and not gravity. Quantum Gravity = a complete theory of the 4 fundamental forces.)

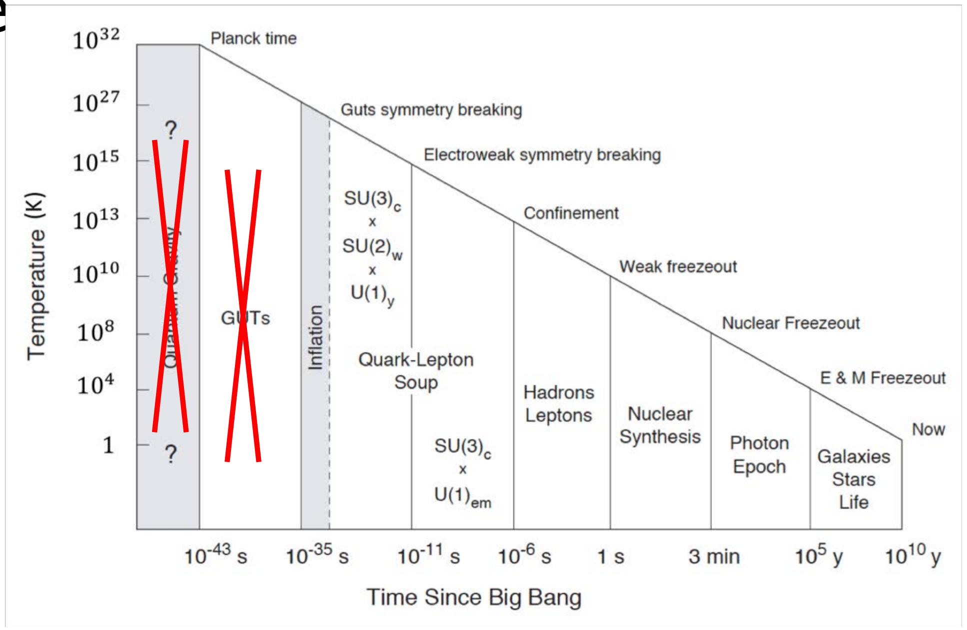
The Planck Epoch

- For the first 10^{-43} s of the Big Bang, we don’t know **anything**.
- Do not assume that the universe started with $a(t) = 0$ (the singularity) – we don’t know what the universe looked like!
- Theories of quantum gravity, such as string theory and loop quantum gravity (LQG), are in development to try and investigate this period of the Big Bang.



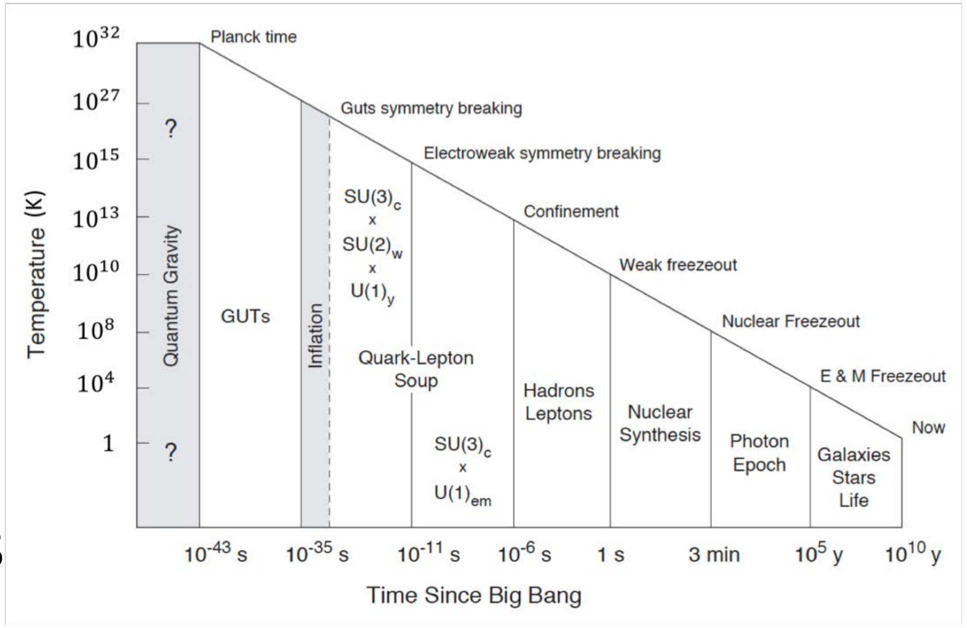
The GUT Epoch

- Between 10^{-43} s and 10^{-35} s, we **still** don't really know what's going on. We don't have a complete GUT either!
- String theory and LQG are both GUTs and theories of quantum gravity.
- To correct issues with the Big Bang, the theory of **cosmic inflation** was introduced in the 1990's. We estimate that inflation occurred at the end of the GUT epoch.



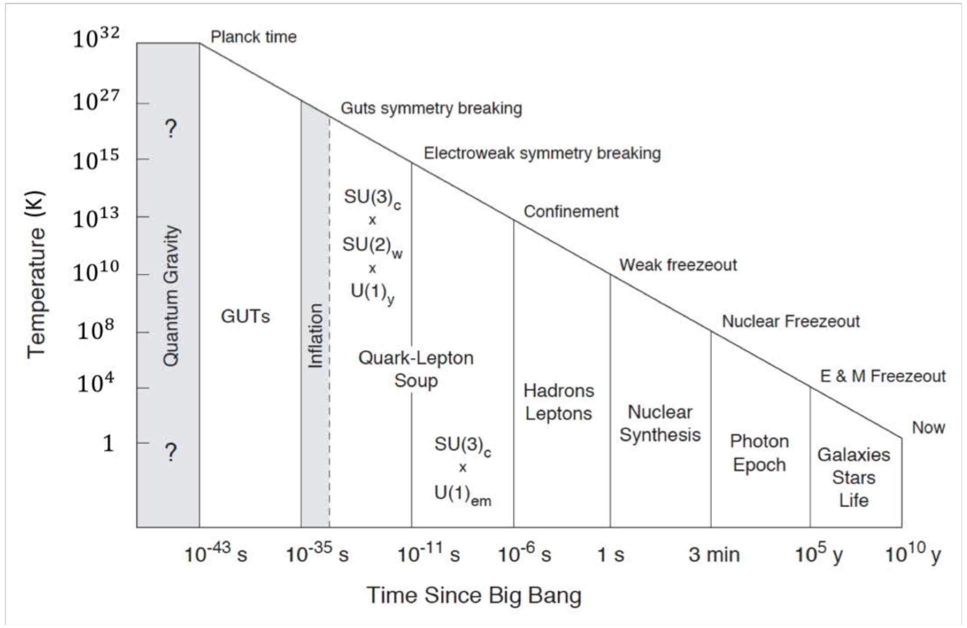
The Electroweak Epoch

- Sometimes this epoch is wedged in between the GUT epoch and the quark epoch (occurring after this epoch).
- Between 10^{-35} s and 10^{-11} s, the electromagnetic and weak interactions were actually the same interaction.
- This is the time period when the Higgs boson gave elementary particles their mass (technically during electroweak symmetry breaking, at the end).



The Quark Epoch

- Sometimes this epoch includes the previous electroweak epoch.
- Between 10^{-11} s and 10^{-6} s, the quark epoch is defined by free quarks.
- At the end of the quark epoch, during **confinement**, all quarks are forced into hadrons (multiple quark combinations).

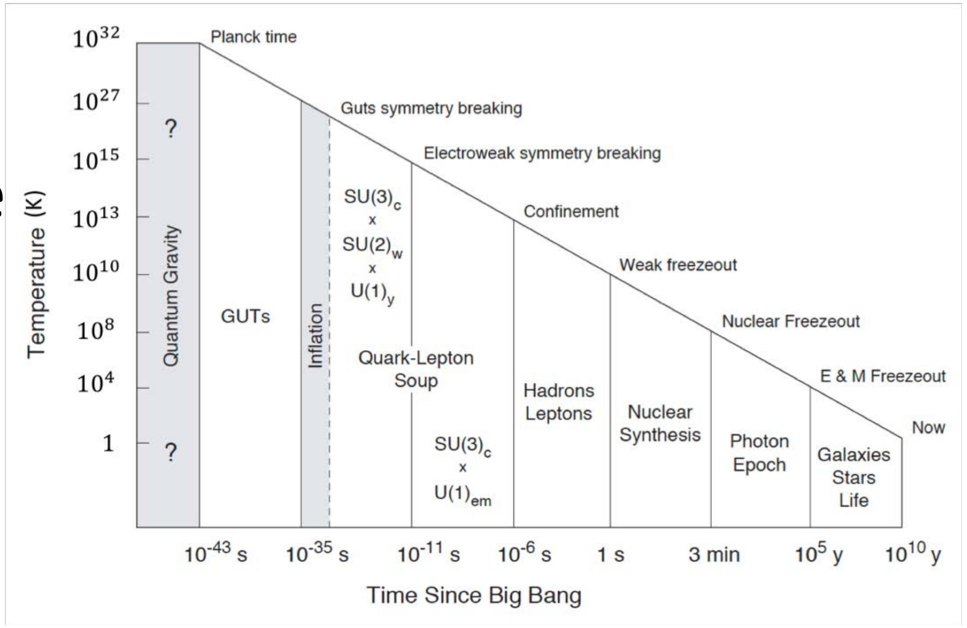


The Hadron Epoch

- Between 10^{-6} s and 1 s, the hadron epoch is (ironically) defined by what leptons are doing, not quarks.
- The temperature is still high enough for the following **thermal equilibria**:

$$e^+ + e^- \leftrightarrow \text{photons} \quad \nu + \bar{\nu} \leftrightarrow \text{photons}$$
$$\bar{\nu} + p^+ \leftrightarrow e^- + n \quad \nu + n \leftrightarrow e^- + p^+$$

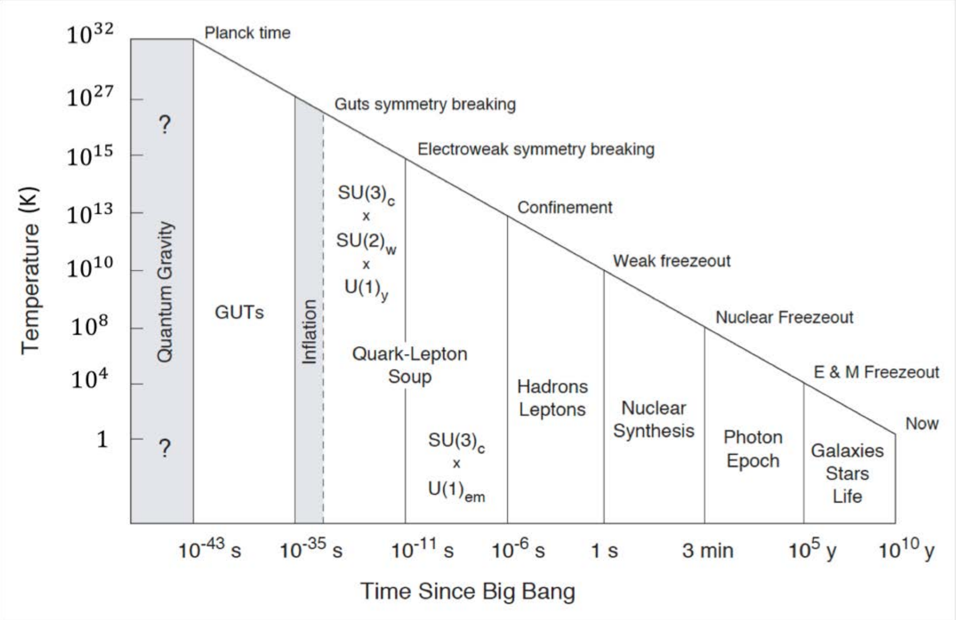
- The number of protons and neutrons are equal at **the start** of this epoch.



(Thermal equilibrium = when the temperature is high enough that reactions go each way equally.)

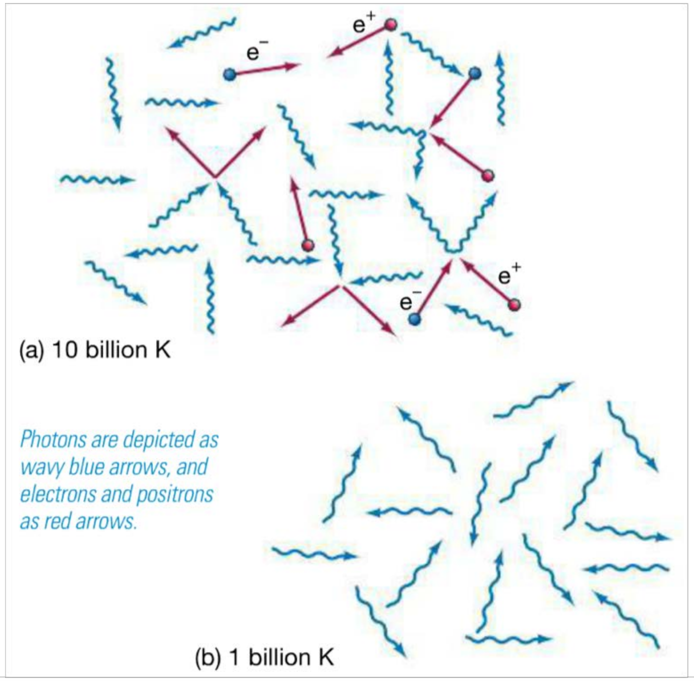
The Hadron Epoch (cont'd)

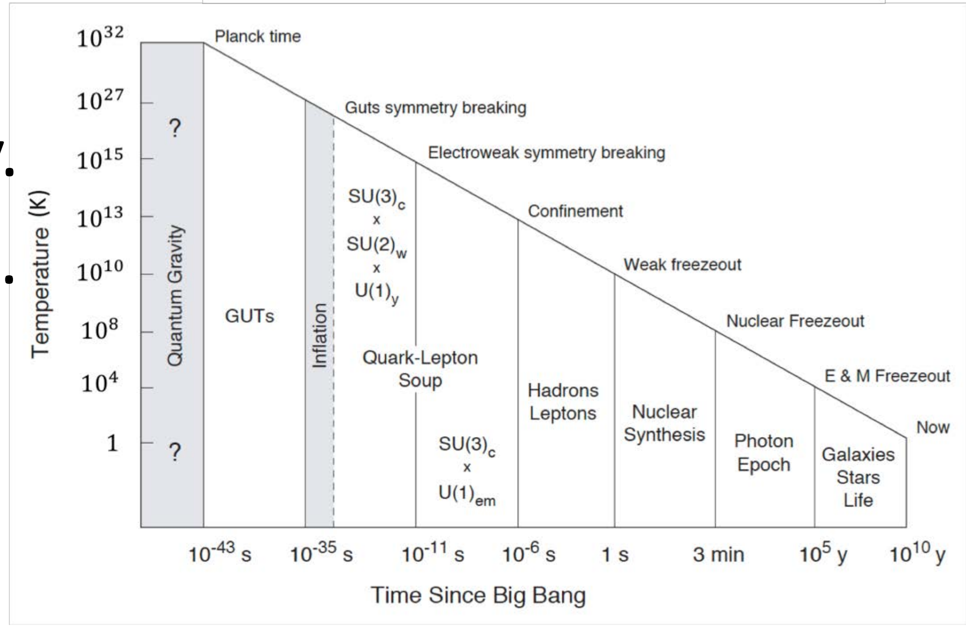
- Once the temperature drops to ~10^{10} K, the neutron/proton equilibrium dies off.
- By ~0.1s after the Big Bang, many neutrons have decayed into protons.
- Neutrons are heavier than protons, so they are unstable and decay into protons until the temperature is low enough (10^9 K) for nuclei to form (the **deuterium bottleneck**).
- Currently, the universe is 62% protons and 38% neutrons.



The Lepton Epoch

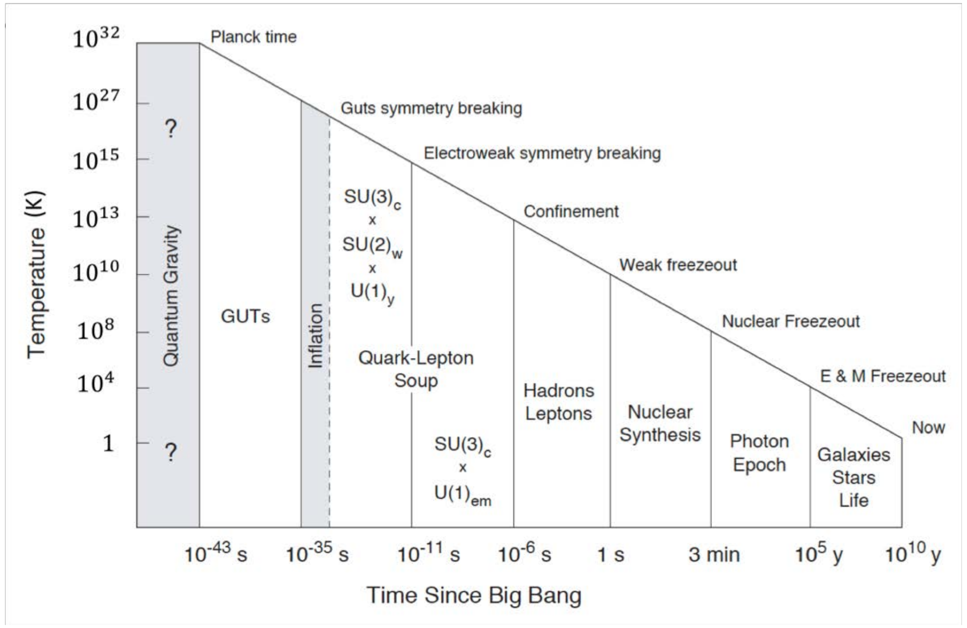
- Between 1s and 10s after the Big Bang.
- The energy is now lower than twice the mass of an electron ($T \approx 10^9$ K), so the electron-positron equilibrium dies off.
- Very rapidly, $e^- + e^+ \rightarrow \text{photons}$, causing an energy release and T to increase slightly.
- Universe is ***87% protons*** and ***13% neutrons***.
- ***Deuterium bottleneck still in effect.***





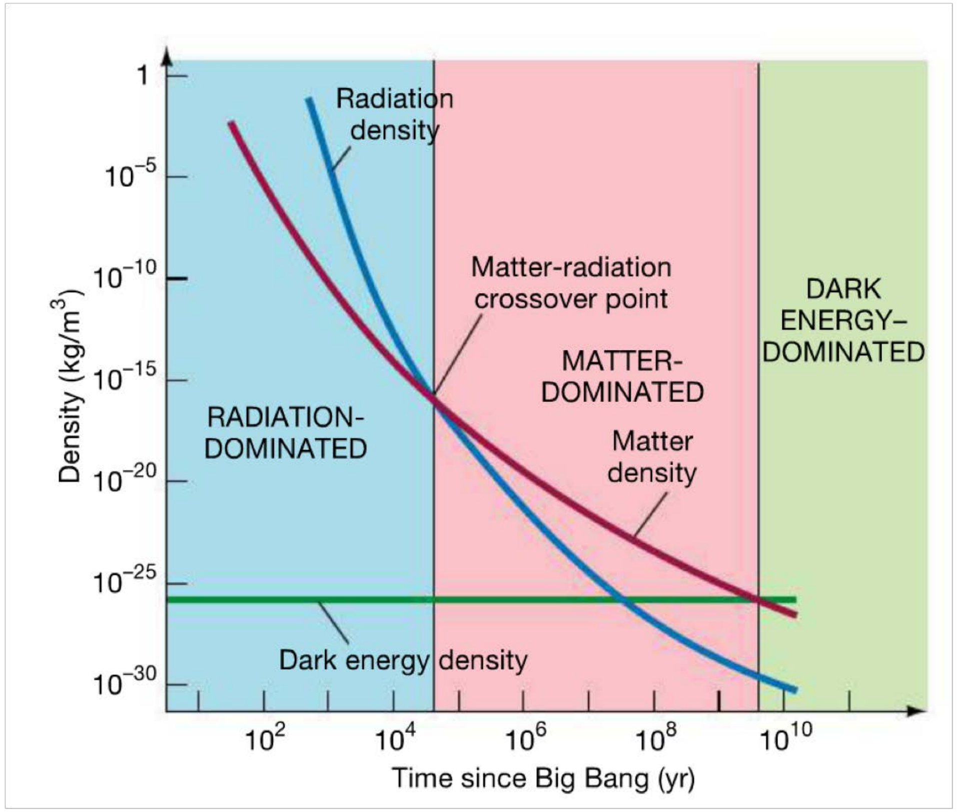
The Photon Epoch

- Between 10s and ~400,000 yr after the Big Bang. The end is marked by release of CMB
- Around 4min after the Big Bang, the temperature finally drops below the deuterium bottleneck.
- Very rapidly, all remaining neutrons are cooked into helium-4, fixing the percentages of neutrons and protons.
- The universe is 74% protons and 26% neutrons **by mass**, not abundance.



The Photon Epoch (cont'd)

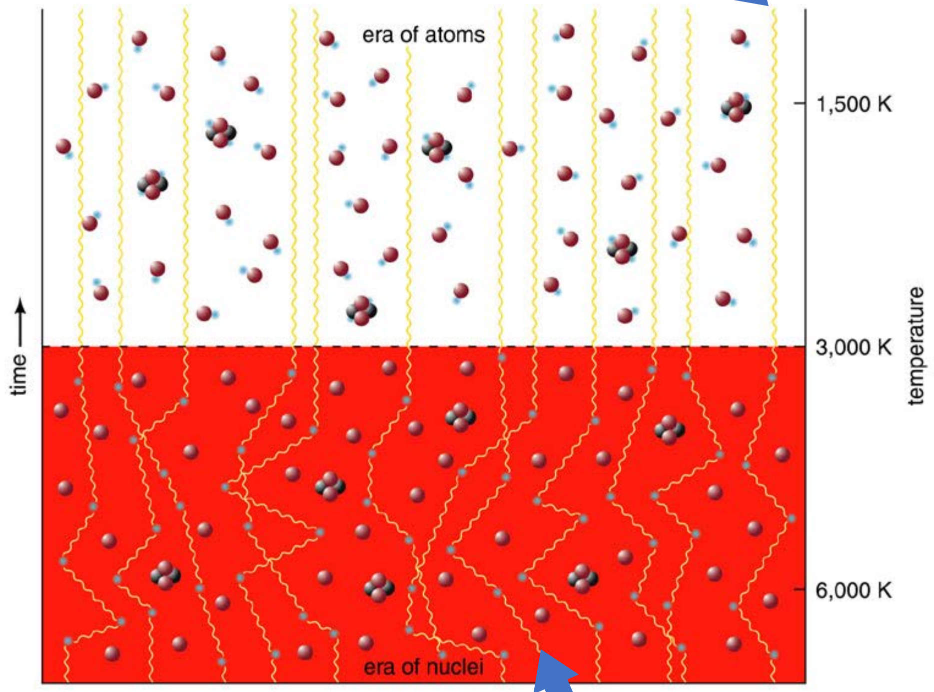
- The **matter-radiation crossover point** occurred ~50,000 yr after the Big Bang.
- This is the time at which the universe transitioned from being radiation dominated to being matter dominated.
- Matter domination occurred until ~4 By ago, when dark energy took over.
- The universe was ~16,000 K at this point, with CMB that peaked in UV.



The Photon Epoch (cont'd)

- ~400,000 yr after the Big Bang, the temperature has dropped (~3000 K) enough for atoms to form.
- This is known as **photon decoupling** (decoupling for short) or **EM freeze-out**.
- Electrons bind with nuclei to form neutral atoms (hydrogen and helium). This is known as **recombination**.
- Photons are now free to move through the gas, releasing the CMB.

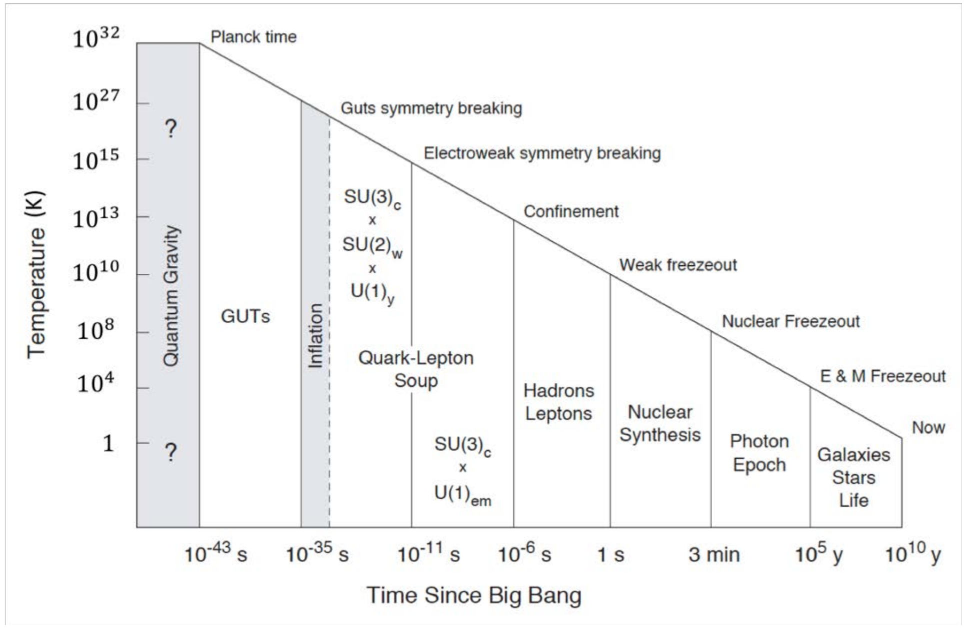
Once atoms form, and the gas becomes neutral, there are no more charged particles to get in the way of light.



Light is constantly bouncing off the charged particles, and has trouble going anywhere.

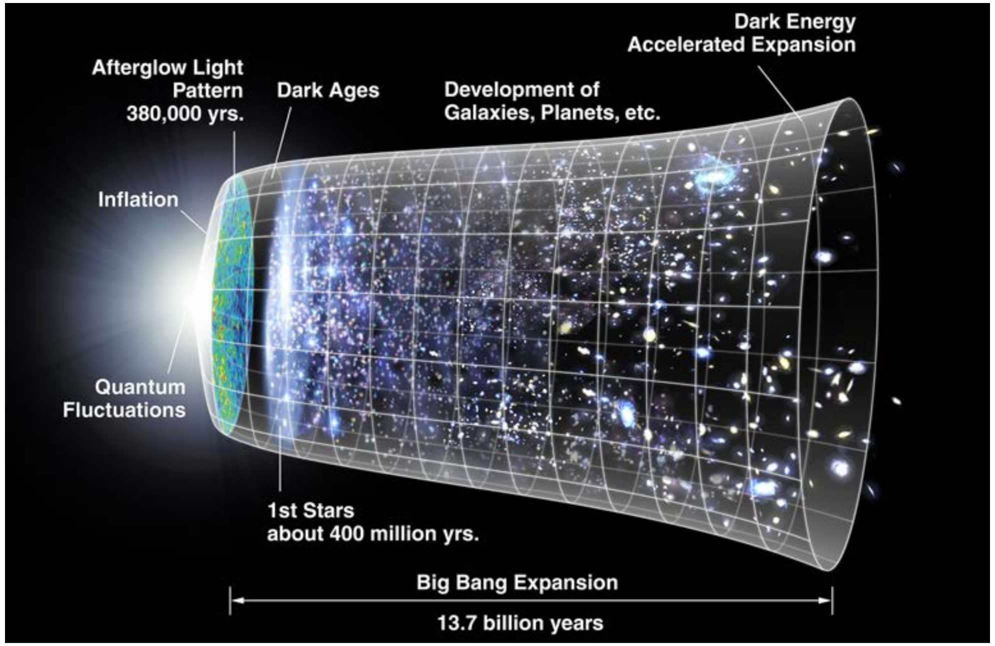
The Structure Formation Epoch

- Since ~400,000 yr after the Big Bang, we've been in the structure formation epoch.
- As the name implies, this is when the temperature had cooled enough for structure (stars, galaxies, etc.) to begin forming.
- Gas needs to fragment for structure to form, which means some gas needs to be denser than nearby gas.

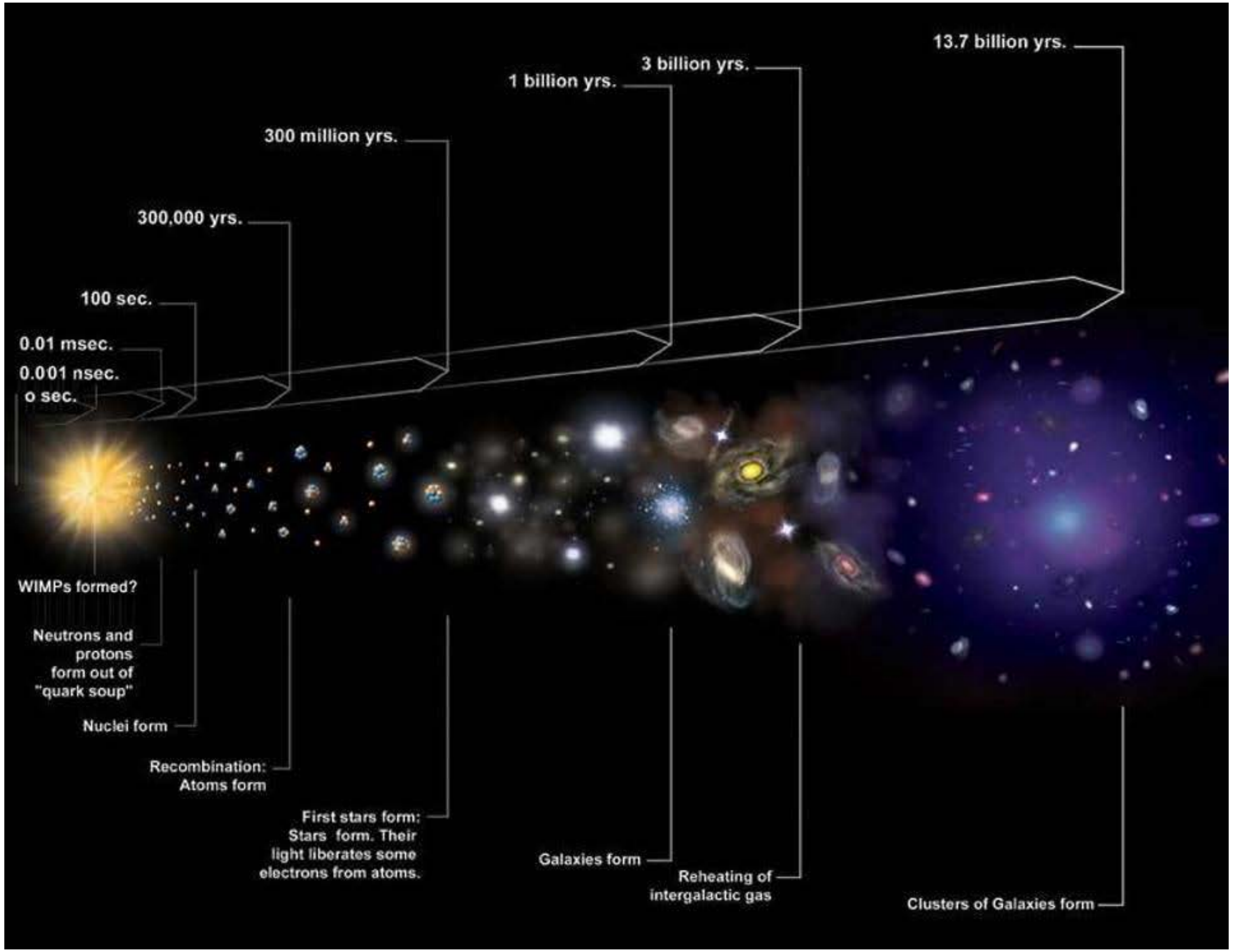


The Structure Formation Epoch (cont’d)

- For ~400 My after the Big Bang, we were in the **cosmological dark ages**. No light-emitting structures had formed yet.
- From ~400My until ~1 By after the Big Bang, there was a transition from the dark ages to **large-scale structure formation**. Most galaxies in the universe were formed during this time.
- Large-scale structure formation will occur until ~100 By after the Big Bang.



Evolution of the Universe



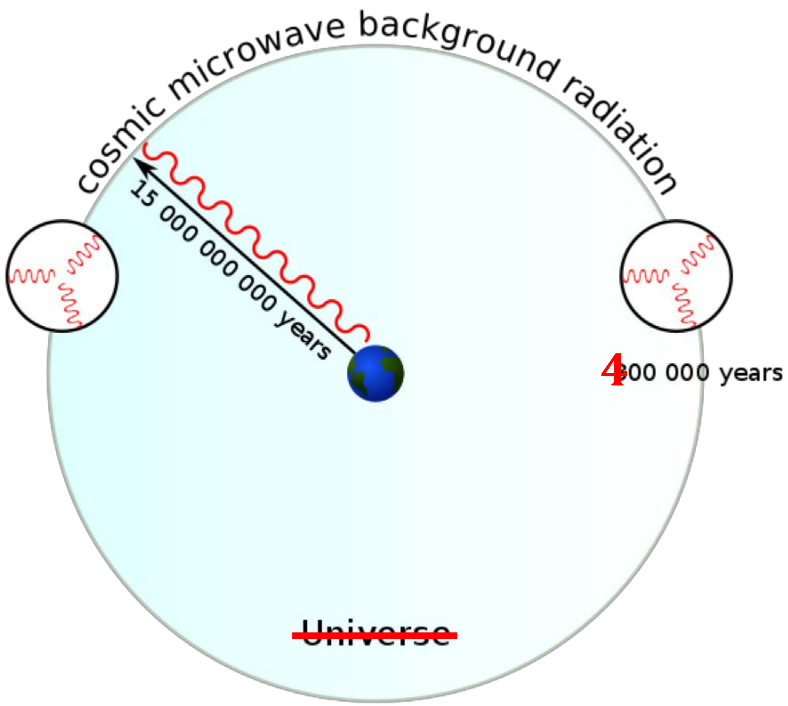
Problems with the (Classic) Big Bang

- We call the uncorrected (with inflation) theory the “Classic” Big Bang.
- The Classic Big Bang has many issues with it, but the 3 worst are:
  1. **The Horizon Problem**: Ironically, despite the cosmological principle, it turns out that the CMB is *too* perfect. The universe can’t actually be this perfect.
  2. **The Flatness Problem**: We measure $\Omega = 1.0002 \pm 0.0026$, so the universe is within 0.1% of being perfectly flat. It turns out that a flat universe isn’t stable, and the universe has been expanding for 10^{10} yr. The fact that it’s **so** flat is a problem; we should expect it to deviate significantly from $\Omega = 1$.
  3. **The Magnetic Monopole Problem**: GUTs predict exotic particles, most notably the magnetic monopole. These have **never** been observed. Why aren’t they around? They should be. GUTs need them to be.

(With enough time, particle horizons will become ∞, but for event horizons, it depends on expansion. If expansion is accelerating, then you'll be limited in how far out you can look: once expansion is faster than c, you will not be able to see any farther.)

The Horizon Problem

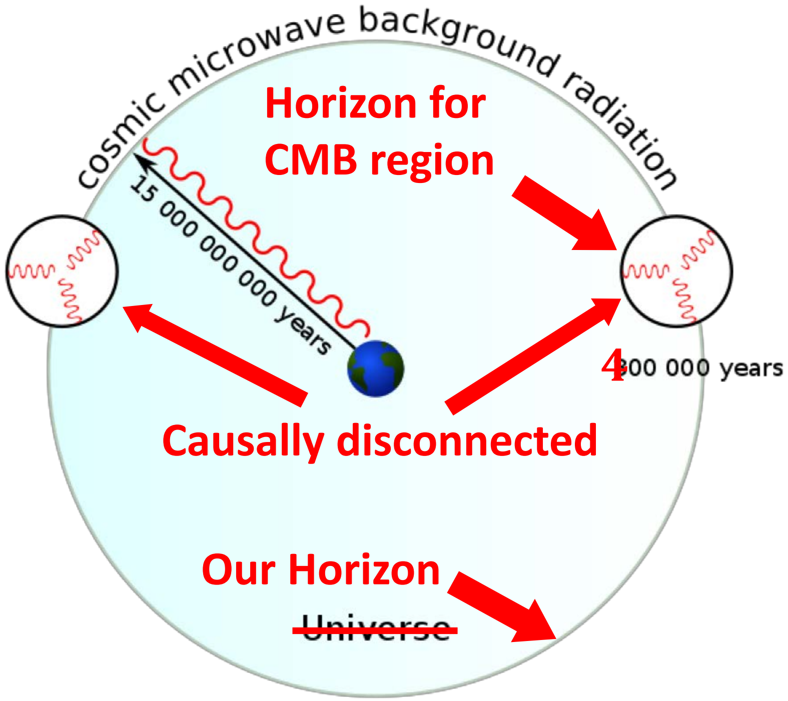
- A **horizon** is the furthest point of influence.
- Two horizons: **particle horizons**, which represent the farthest back you can look, and **event horizons**, which represent the farthest forward.
- When the CMB was released ~400,000 yr after the Big Bang, the horizons of each region it came from was very small (~400,000ly).
- This means that two opposite regions in the sky, which are separated by 15 Bly, **did not** have enough time for their horizons to overlap before releasing the CMB.



The Horizon Problem (con't)

(You can distinguish horizons by causal influence. A particle horizon defines the farthest galaxy that can influence you, while an event horizon defines the farthest galaxy that you can influence, given an infinite amount of time.)

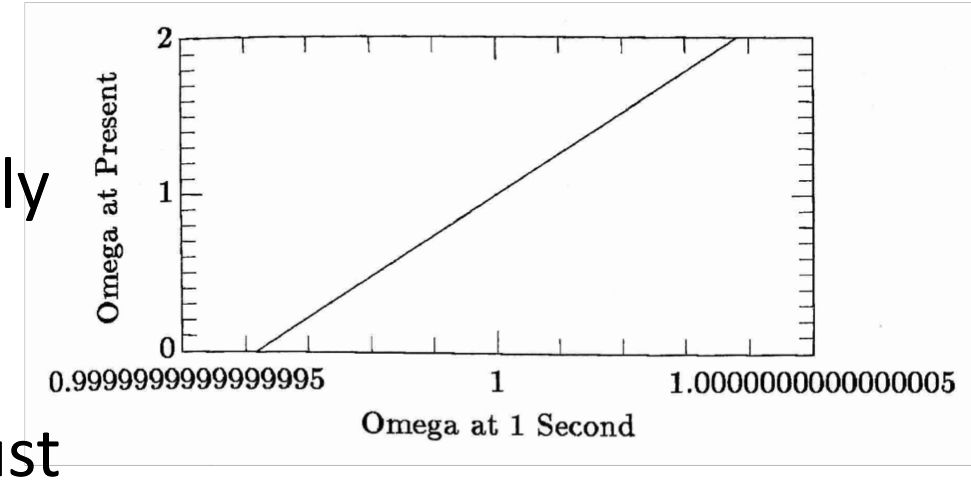
- Since their horizons never overlapped, they never had **causal influence** over one another; nothing that happened in one region had any effect over anything in the other.
- Yet, when we observe the CMB, the temperature is almost **perfectly** the same (to within 0.001%). Everywhere.
- If these regions had no causal influence over one another…how did they know how to align their temperatures so precisely?

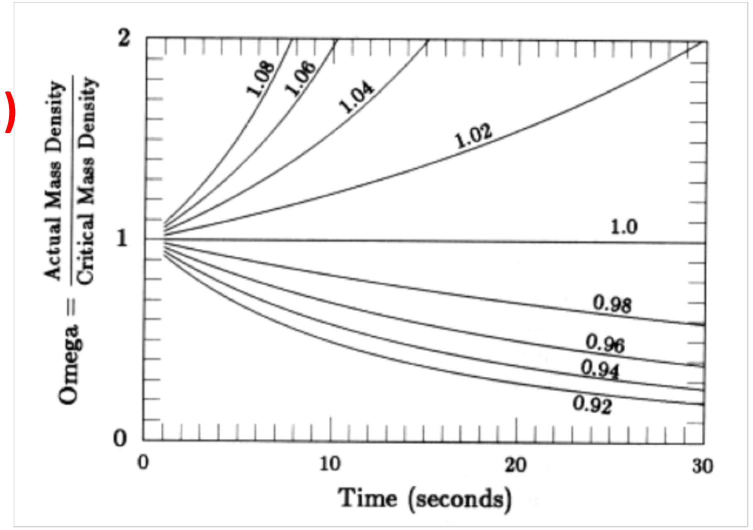


The sky is made up of ~10,000 causally disconnected CMB regions. No two causally linked regions can be more than 1^o apart.

The Flatness Problem

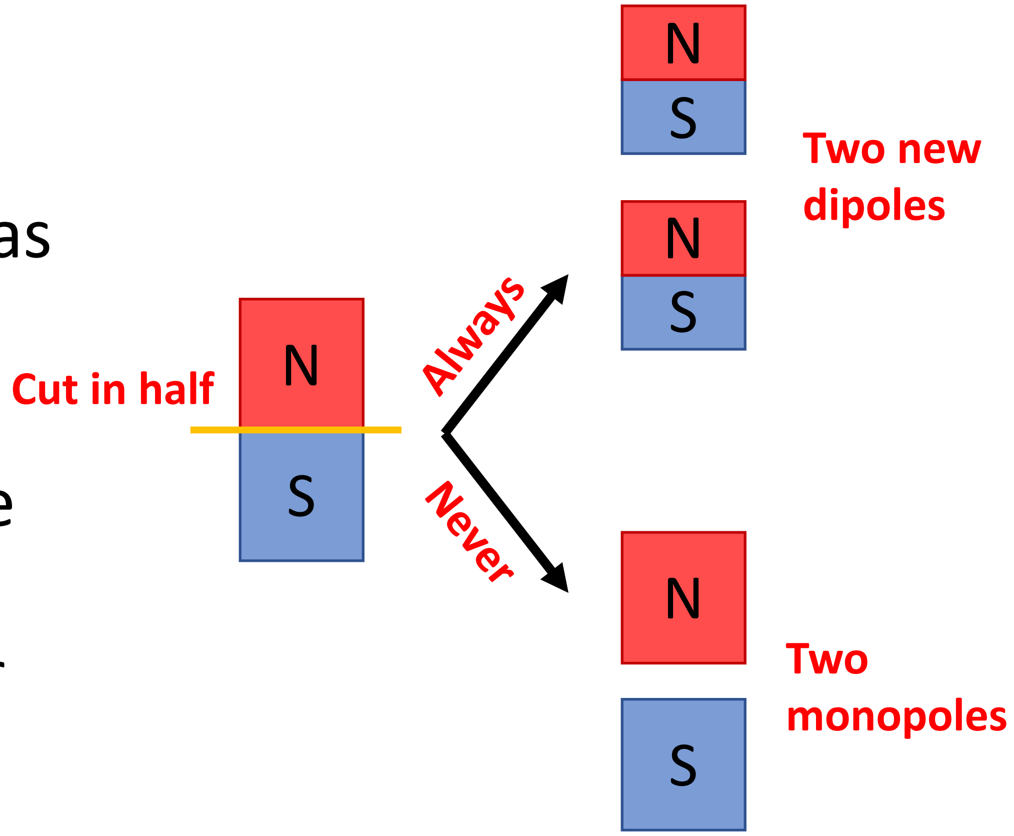
- The three types of universe all start out nearly the same. But after time, they diverge.
- If we are **so close** to a flat universe (critical density) today, to within 0.1%, how close must we have been to a flat universe at the beginning? Very, very close. **(Flatness typically called a fine tuning problem.)**
- At 1s, $\Omega \approx 1$ tuned to 1 part in 10^{15}.
- At the Planck time, $\Omega \approx 1$ tuned to 1 in 10^{45}.
- Why should the initial state of the universe be **so** finely tuned. The universe would be completely different if it weren't. Are we just lucky?





The Magnetic Monopole Problem

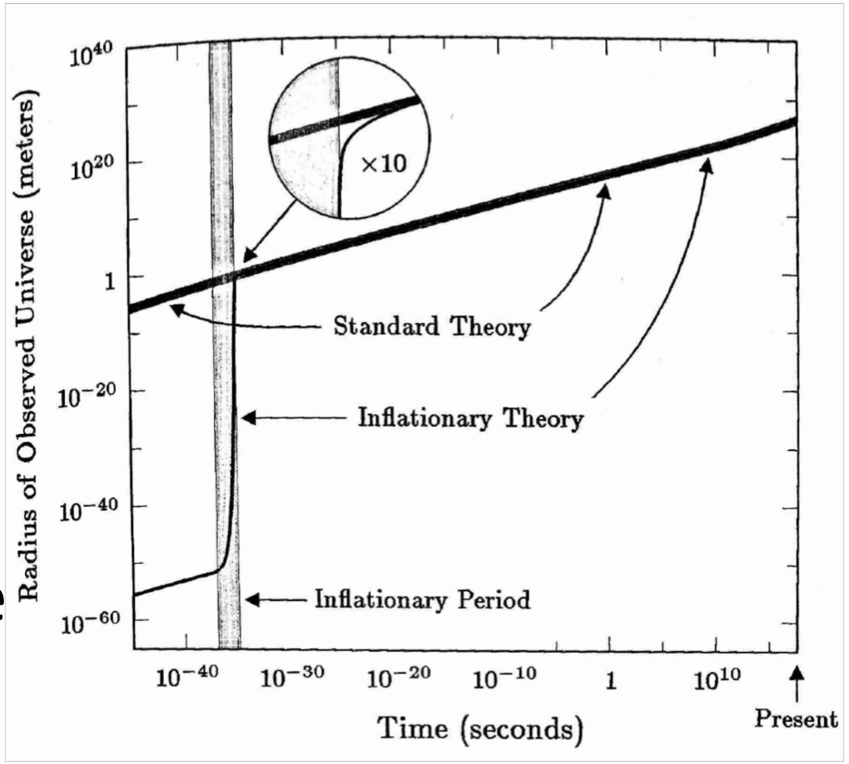
- Normal magnets are **dipoles**
- A **monopole** is a unique particle, which has only a north or south pole.
- *All* GUTs predict the existence of these at extremely high temperatures, and like the CMB, we should see some today.
  - A "Cosmic Monopole Background" has never been observed!
- Also, monopoles have are so heavy, they would have caused a big crunch long ago.



The Solution: Cosmic Inflation

(Inflation can be estimated by "e-folding." If inflation stops at 10^{-36} s and lasts 10^{-37} s, then it "occurs" 10 times, and $e^{10} \approx 22,000$, so space grew 22,000 times larger. If inflation occurs until 10^{-35} s, then it "occurs" 100 times, and $e^{100} \approx 10^{43}$. So, if inflation "occurs" 115 times, then $e^{115} \approx 10^{50}$.)

- Inflation was developed by Alan Guth in 1979.
- Inflation isn't the same as expansion; it's an **extremely rapid** expansion.
- The CMB was released at $z \approx 1100$. The universe expands as $1 + z$, so the universe today is ~1100 times larger than it was at CMB release.
- On the other hand cosmic inflation causes the universe to increase by $\sim 10^{50}$ near the end of the GUT epoch (taking ~10^{-37} s per step).

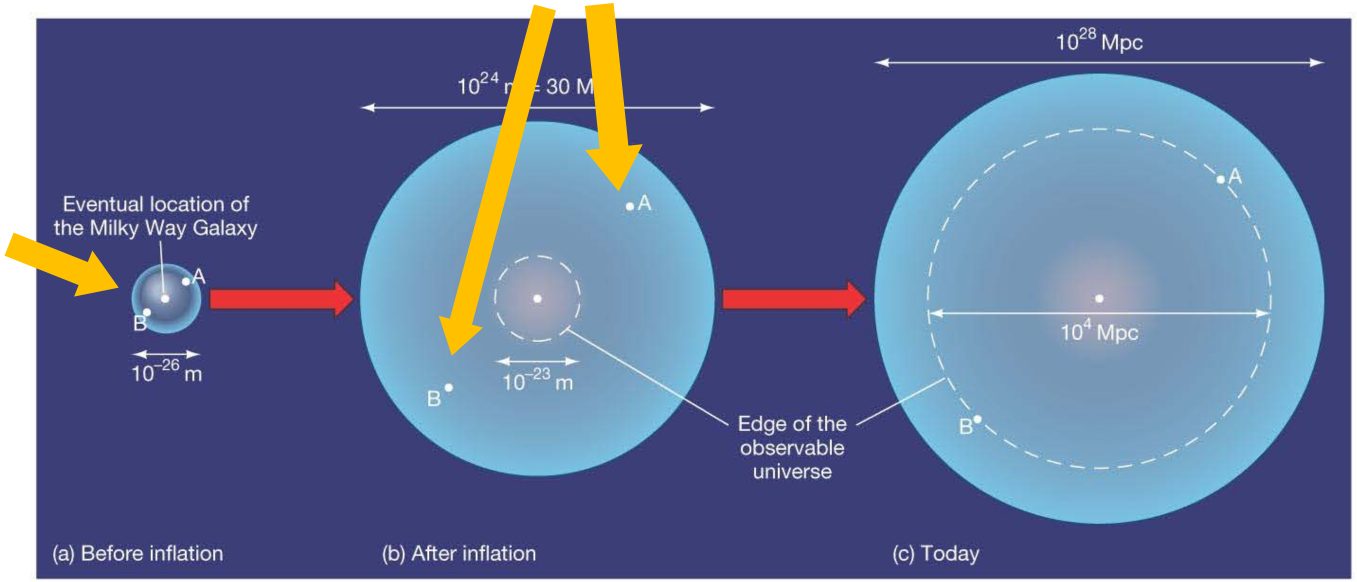


Inflation and the Horizon Problem

- Prior to inflation, the opposite sides of the sky were in causal contact.
- Inflation caused the universe to expand **much** faster than horizons.
- It took until today for our horizon to reach these sides of the sky, so it doesn't *seem* like they were every in causal contact. But they were.

A & B out of causal contact.

A & B in causal contact

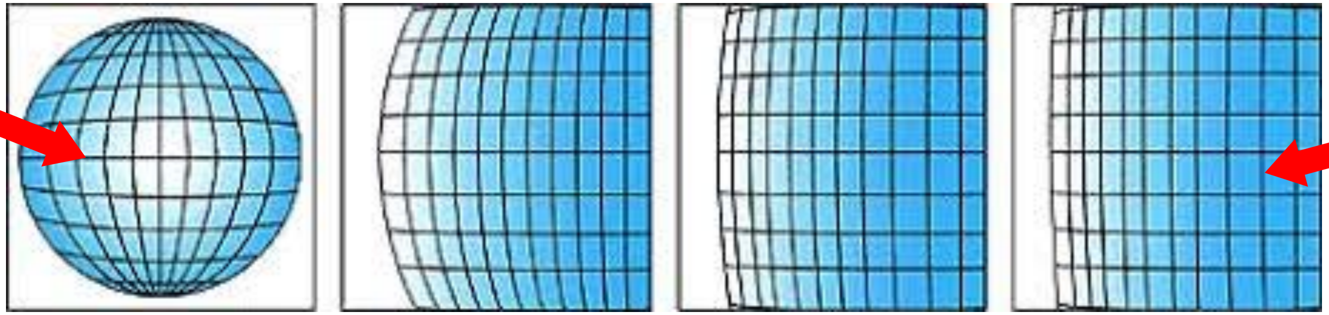


A & B align their temperatures before inflation, while in causal contact. That's why their temperatures are *nearly* identical today.

Inflation and the Flatness Problem

- Inflation naturally drives the observable universe towards flatness.
- Flatness is no longer an "unstable" point (one that is naturally driven away from), but is the natural end product of inflation.
- Note that, due to inflation, the universe is much, much larger than we can observe. Inflation says that the **observable universe** will *seem* flat, not that the entire universe is *actually* flat.

Geometry is actually spherical (closed)



After expansion, the observable universe *seems* flat, though this universe is actually spherical (closed).

(The box represents the observable universe.)

Inflation and the Magnetic Monopole Problem

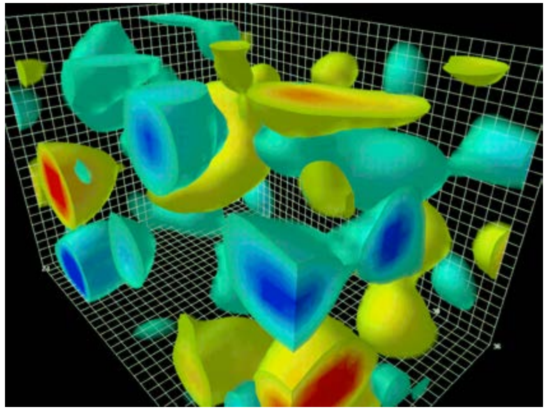
- This is the easiest issue to resolve.
- Inflation occurs at the *end* of the GUT epoch, when magnetic monopoles are theorized to be produced.
- Inflation, however, causes the universe to expand so rapidly that the density of magnetic monopoles dropped to essentially zero. (If the universe's radius increases by 10^{50}, then the magnetic monopole density decreases by $1/10^{150}$.)
- Since the GUT epoch is over after inflation, no new magnetic monopoles can be created, and the density of magnetic monopoles in the universe is basically zero. That's why they've never been seen.

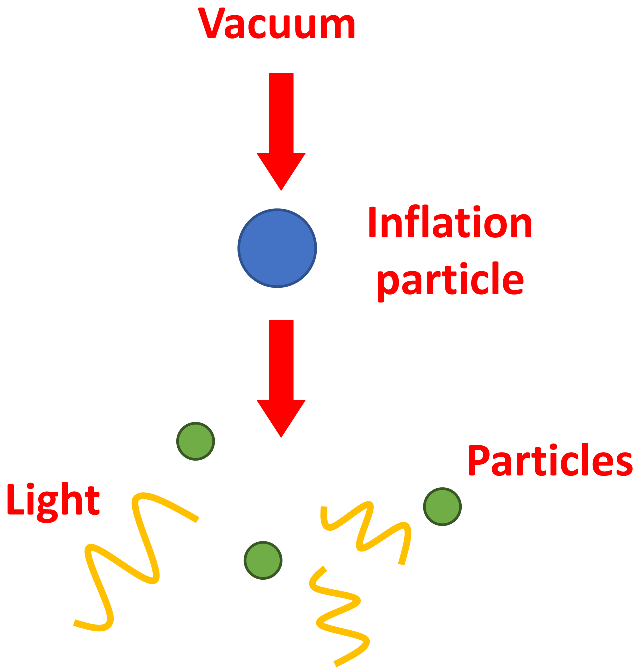
https://thumbor.forbes.com/thumbor/960x0/smart/https%3A%2F%2Fblogs-images.forbes.com%2Fstartswithabang%2Ffiles%2F2018%2F03%2Fleinie.gif%3F

Pros of Cosmic Inflation

- Obviously the resolution of the 3 major problems with the Big Bang.
- In addition, cosmic inflation might provide the answer to *why* the Big Bang occurs at all:
  - Inflation is thought to occur as a result of a quantum mechanical process known as a “fluctuation.”
  - In quantum mechanics, energy can seemingly be brought into the universe for no reason. This energy can power inflation and then be converted into radiation, mass, and heat when inflation ends, powering the Big Bang.

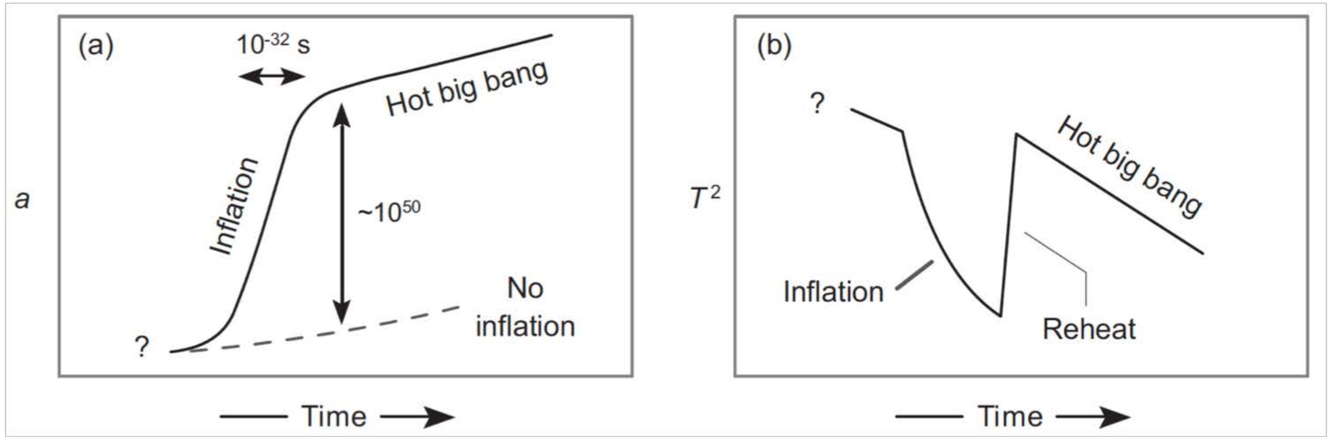
(Quantum fluctuations)





Pros of Cosmic Inflation (cont'd)

- There now need to be two time periods of accelerated expansion: the initial inflation and the vacuum dominated universe at the end.
- Cosmic inflation explains **both** inflation and vacuum energy! More properly, vacuum energy and inflation are powered by the same source.
  (Recall that a big issue with vacuum energy was the inability to explain it quantum mechanically. Inflation also solves that problem.)
- **Reheating**: during inflation, the universe dramatically cools; it'll have to reheat after this. At the end of inflation, the inflation particle decays and releases a ton of energy into the universe, which heats it.



(This also explains why the universe was initially mass & radiation dominated, not dark energy dominated!)

Cons of Cosmic Inflation

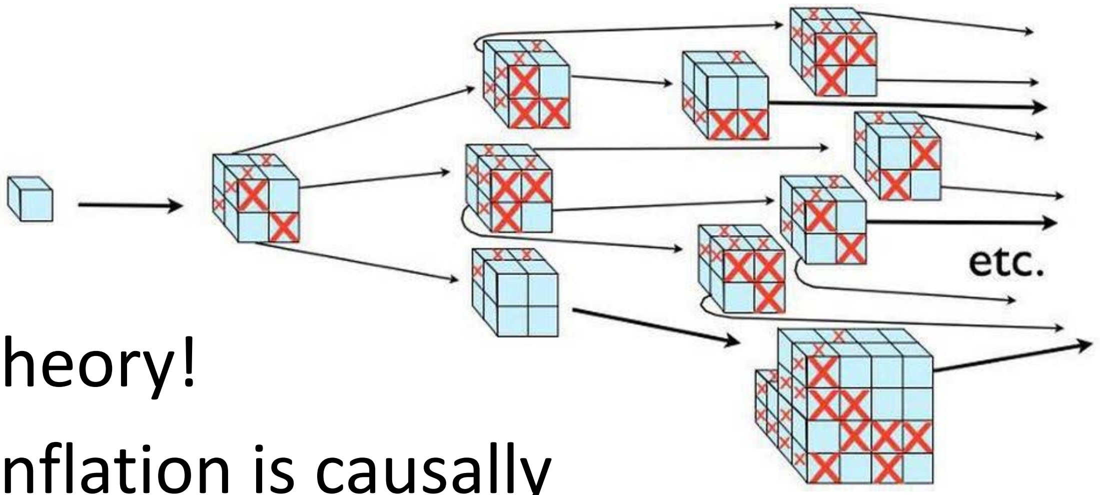
- **Fine tuning**: the flatness of the universe requires fine tuning; the initial value of Ω had to be so close to 1 it seemed impossible. Cosmic inflation, unfortunately, has a very similar fine tuning problem.
- **Quantum mechanics**: the quantum mechanics required by the theory is, let's say, "unconvincing." There needs to be a very precisely chosen quantum mechanical system to produce inflation without any justification for the choosing of that system.
- **Eternal**: inflation doesn't seem to have any natural end to it in **any** theory of inflation.

Eternal Inflation

- Eternal inflation was a modification to inflation proposed by Paul Steinhardt in 1983 to correct the initial theory proposed by Guth.
- Eternal inflation seems to work pretty well in explaining away the issues of inflation, but ironically Steinhardt is the main opponent to his own theory; he's convinced it isn't correct.
- Eternal inflation, essentially, explains inflation as a process that is everlasting for the universe as a whole. Smaller regions called "bubbles" in the universe can expand for a small amount of time due to inflation and then stop. Each region of the universe is going to have a unique set of physical laws and will be causally disconnected.

(This claim really only makes sense in the context of string theory, and for some reason everyone insists on trusting string theory.)

Multiverse Theory



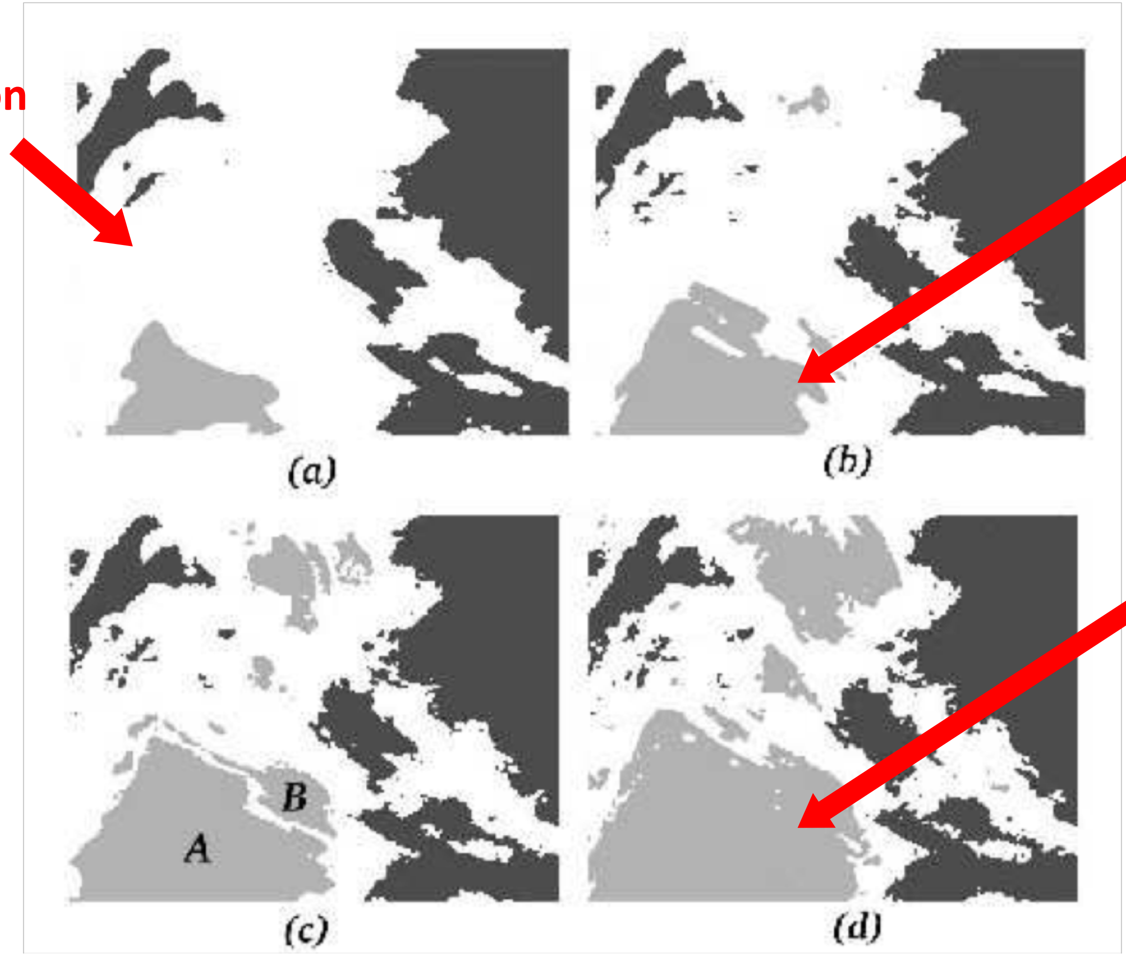
- Incorporate eternal inflation into the theory!
- Because each “bubble” of temporary inflation is causally disconnected, and has its own laws of physics, we call each bubble a unique universe and the entire universe a **multiverse**.

(Once again, string theory really gives context to the multiverse theory.)

- It turns out that each universe costs zero energy to create, so it also costs zero energy to create an infinite number of universes (i.e. an infinite multiverse).
- Eternal inflation and the multiverse theory seem to be the only consistent theory of cosmic inflation, so despite any hesitance one might have about the theory, it’s the only game in town.

Multiverse Simulations

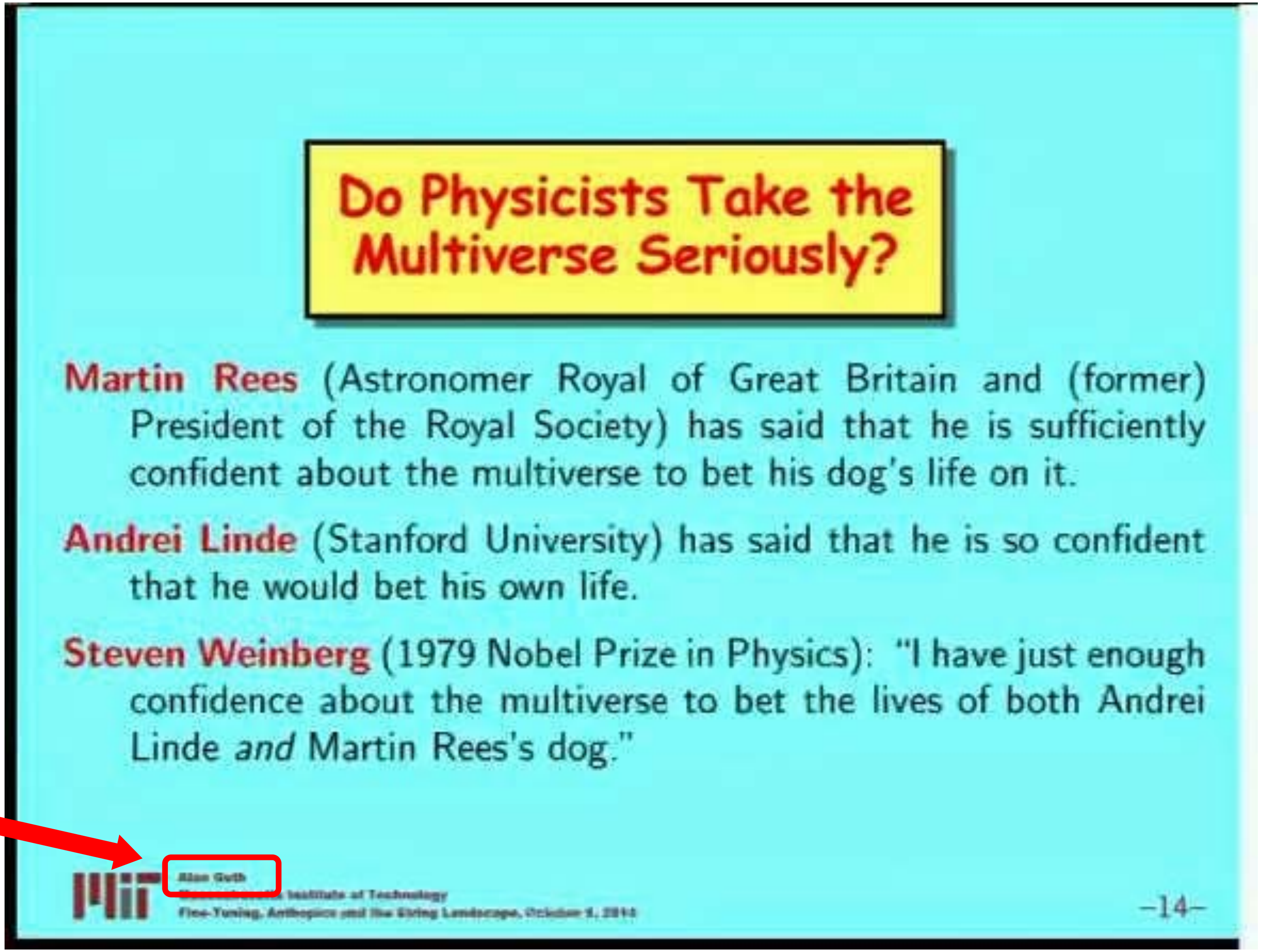
White = region of eternal inflation



Grey = newly forming bubble universe

Universes A and B from the previous picture merged into one universe.

V. Vanchurin et al., “Predictability crisis in inflationary cosmology and its resolution,” *Phys. Rev. D* 61, 083507 (200). [arXiv:gr-qc/9905097]

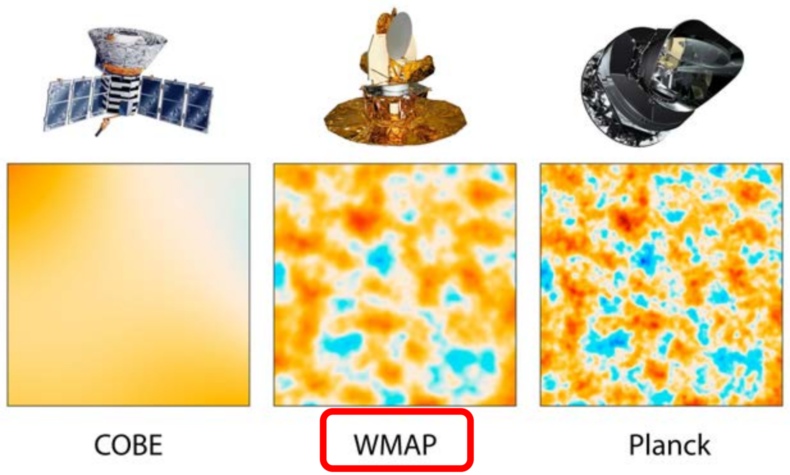


"Alan Guth," the inventor of inflation theory.

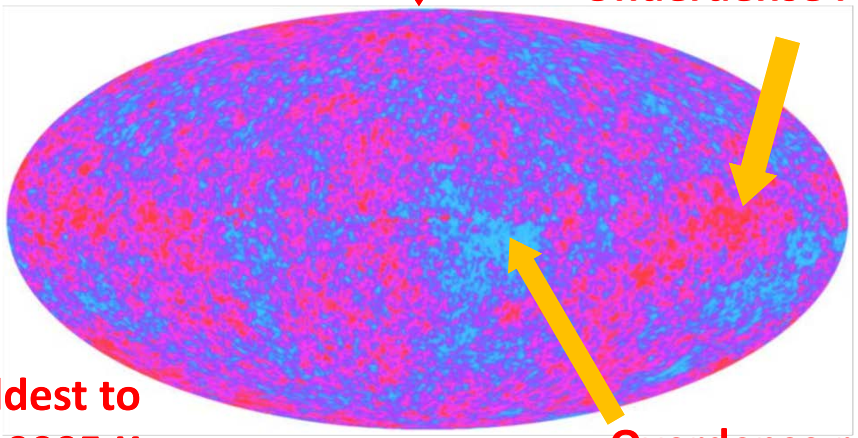
Structure Formation and the CMB

- The CMB looks **very** homogeneous and isotropic upon first inspection.
- Only when you look really close, down to 1 part per 10^5, do you see the irregularities (called **anisotropies**).
- These are regions of lower T and higher T, so they are regions of higher density (overdense) and lower density (underdense), respectively.
- Structure forms in the anisotropies.

(Better satellites = better data.)



Underdense region



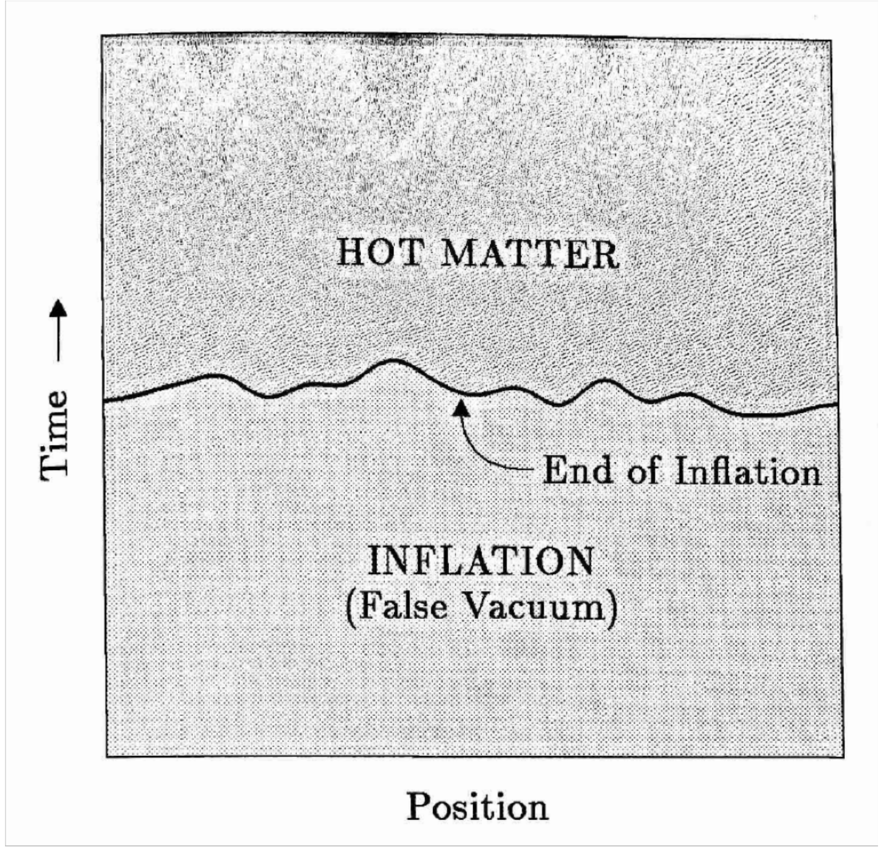
Overdense region

T change from coldest to hottest regions: 0.0005 K.

http://www.astro.ucla.edu/~wright/NASA-PR-LA_Times_lede_05Sep03.jpg

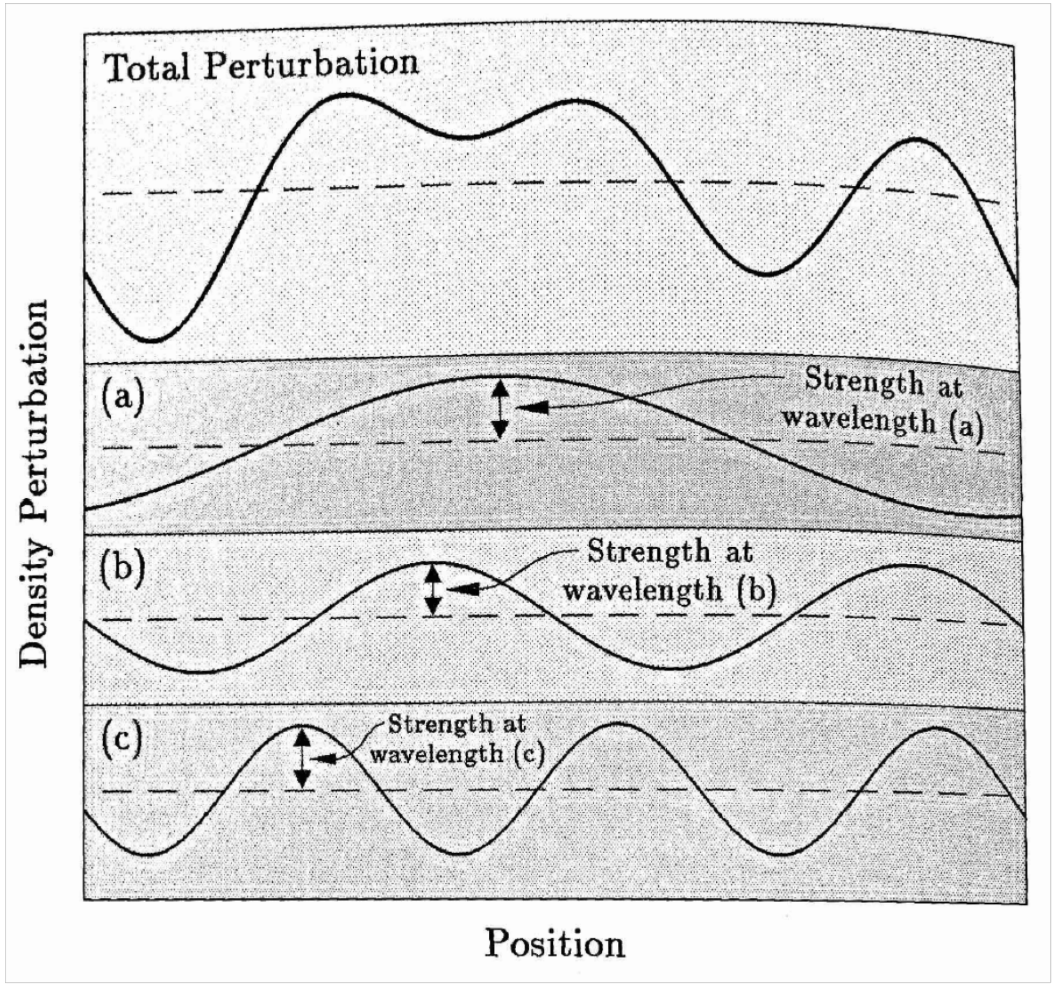
Inflation and Structure Formation

- Inflation provides an excellent model to explain structure formation (i.e. to explain anisotropies in the CMB which lead to structure formation).
- Originally proposed by Hawking c. 1982, he imagined quantum fluctuations caused changes to when inflation ends, causing a wave-like structure to form along various positions.
    - Longer inflation, higher density → anisotropy



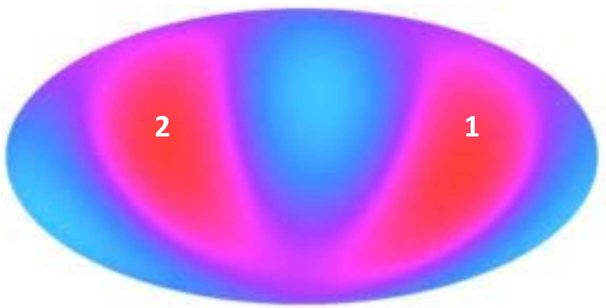
Inflation and Structure Formation (cont'd)

- Any wave can be broken up into "clean waves," defined by a single wavelength.
  - This are typically called **modes**; each wavelength defines a different mode.
- The total wave (which seems completely random) is composed of a **spectrum** of different wave modes.
  - The various amplitudes of each mode is a signature of the spectrum.

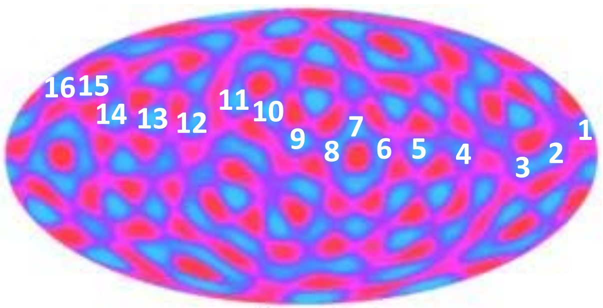


PhET: Fourier (Wave Game)
https://phet.colorado.edu/en/simulation/fourier

Observational Evidence for Inflation

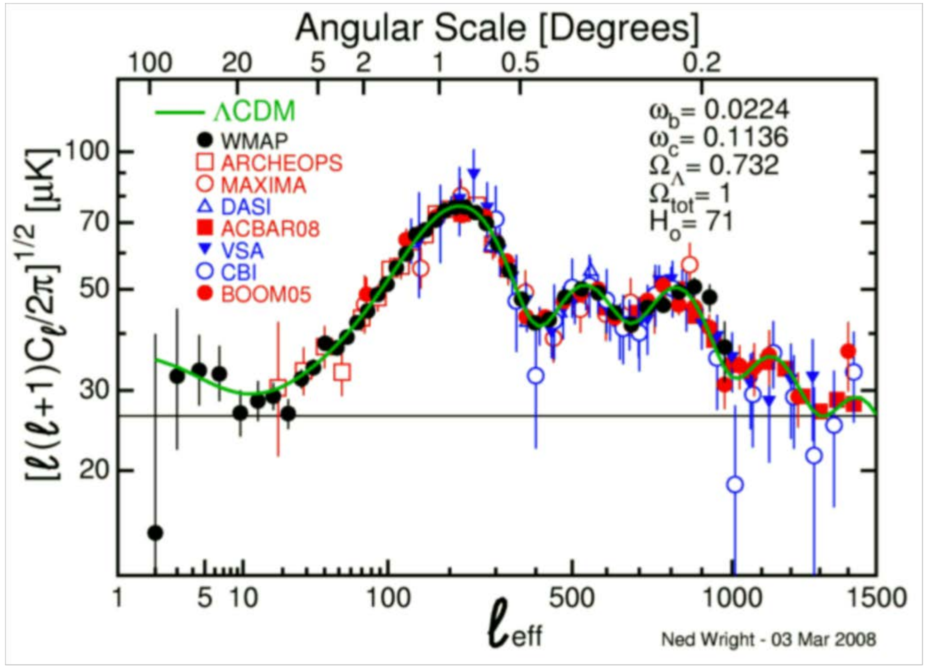


$\ell = 2$

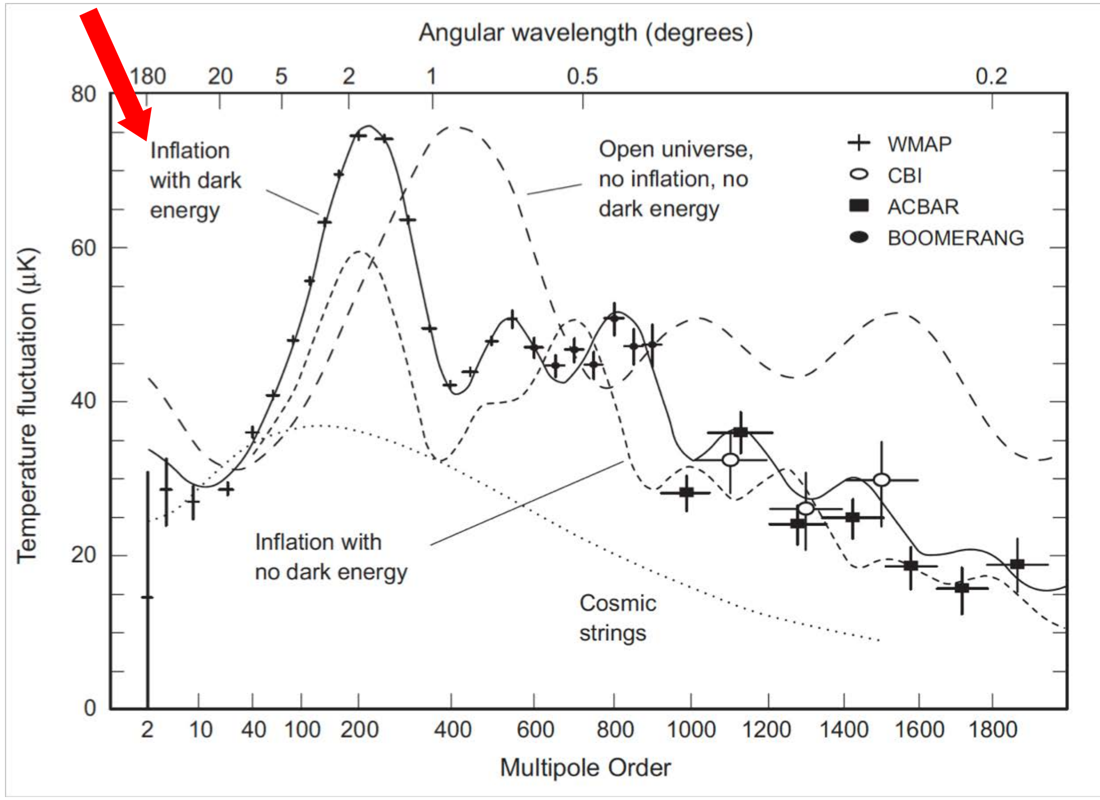


$\ell = 16$

l = number of times fluctuations repeat themselves.



Inflation with vacuum energy is the only cosmological theory that agrees with observations!

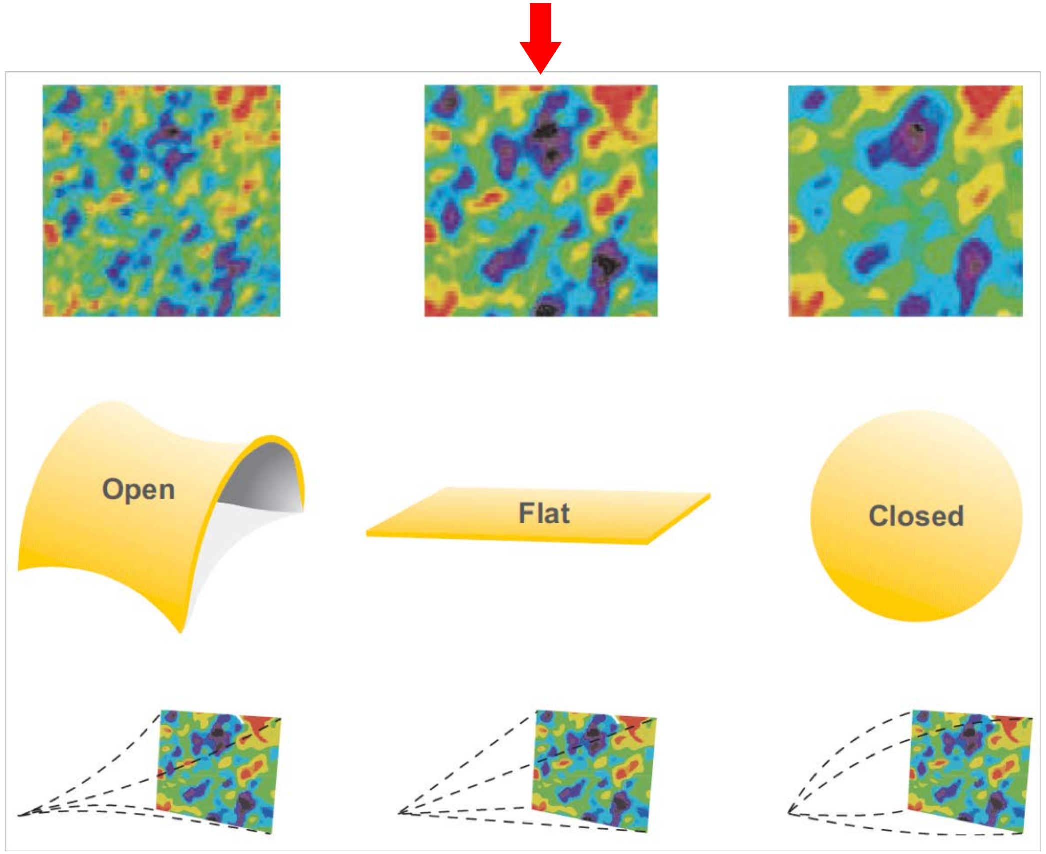


All current theories, other than inflation with vacuum energy, are ruled out! (Other theories are still possible, but not these.)

CMB Anisotropies and Geometry

- The size of the anisotropies would be warped by the geometry of the universe: open universes would shrink the anisotropies, closed universes would expand them, while flat maintained the correct size.
- Baryonic acoustic oscillations (BAOs) allows us to estimate the size of the anisotropies. They are estimated to be ~150 Mpc in today's universe.

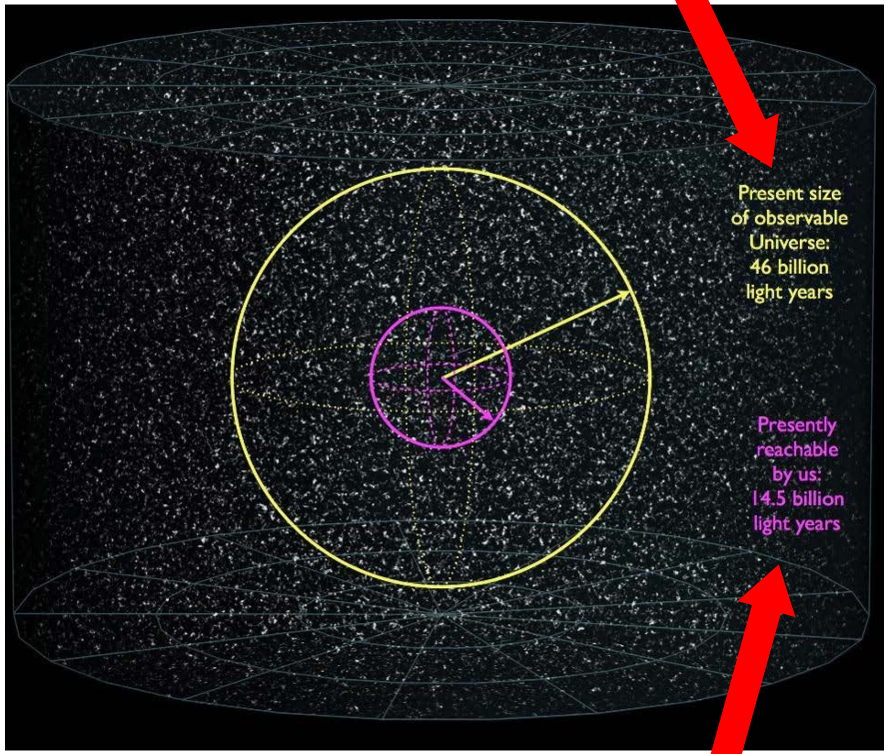
BAOs allow us to independently estimate the size of the anisotropies. It turns out a flat geometry matches.



End-Stage Evolution of the Universe

- What will our universe be like at the the end of it's evolution?
- At the current rate of expansion, we estimate that the farthest point of influence (the event horizon) that we will ever reach is about 16 Bly. After that, the universe will be expanding faster than the speed of light, and we will never be able to influence anything farther.

(Current particle horizon is 46 Bly.)



(Event horizon is 16 Bly.)

Heat Death of the Universe

- The currently-accepted fate of the universe is the so-called **heat death of the universe**.
- Eventually, the expansion of the universe is going to rip anything apart that isn't held by gravity. We know that the event horizon is 16 Bly, so nothing beyond that can be gravitationally bound.
- What will be left is, essentially, clusters of galaxies. In each galaxy, the stars will take many billions, if not trillions, of years to finally die. After that, the supermassive black holes must evaporate ($\sim 10^{100}$ yr). After the last supermassive BH evaporate, there will be nothing left with structure in the universe -- we will have reached its heat death.

(There *might* be the possibility of a new Big Bang occurring spontaneously in our universe within 10^{5600} yr, but most physicists think this idea is probably BS.)