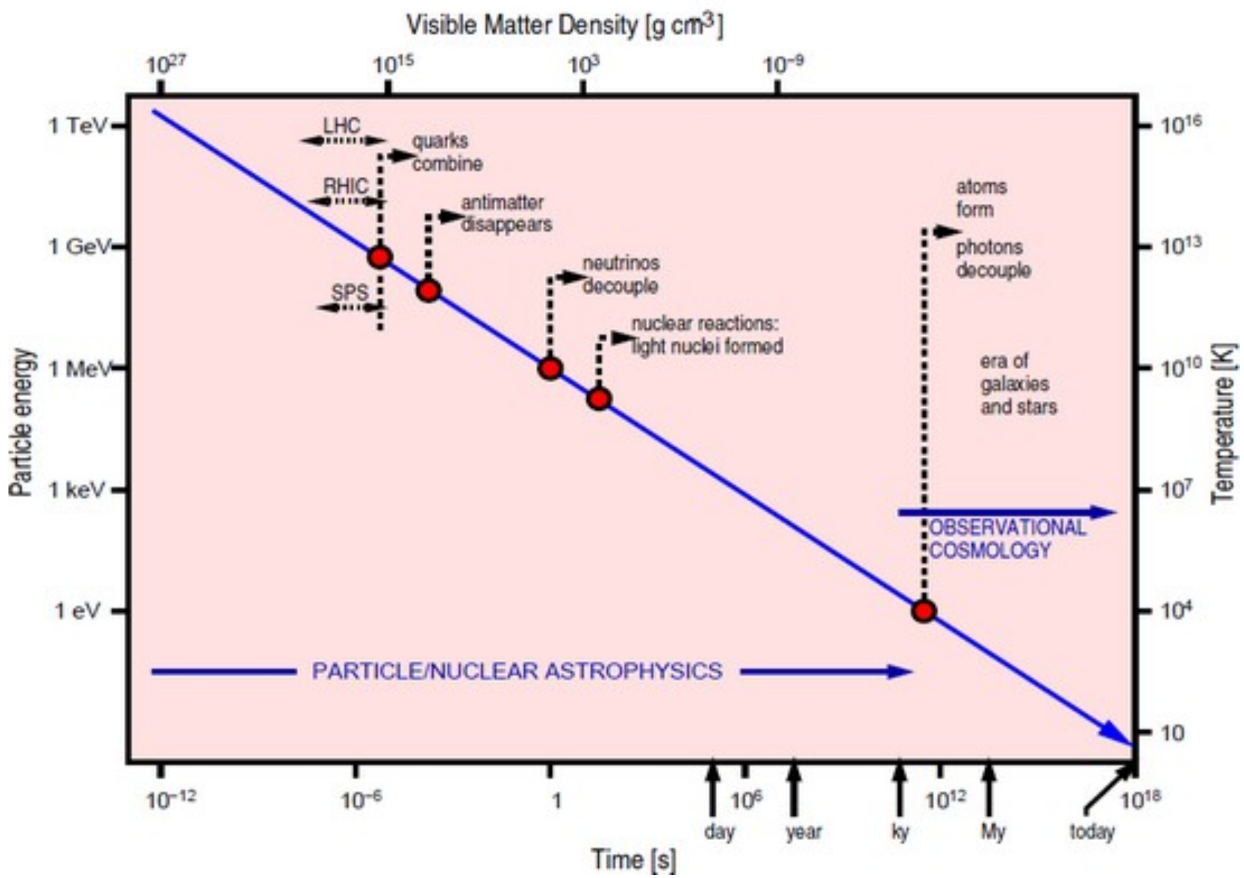
Temperature Falls with Time

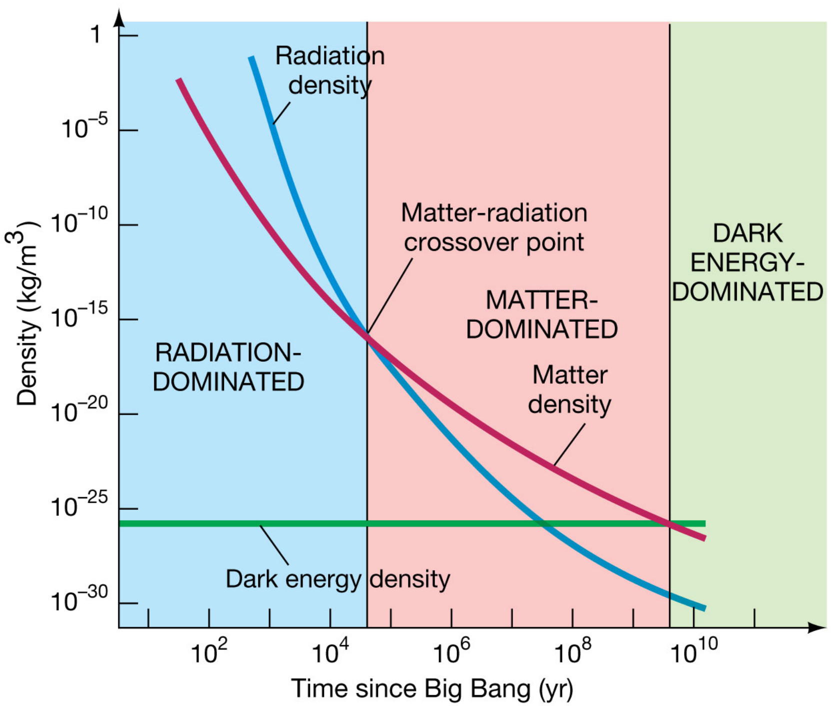
- As Big Bang proceeds the temperature & density decrease
- So as we look back closer to the Big Bang we look at higher and higher temperatures and densities

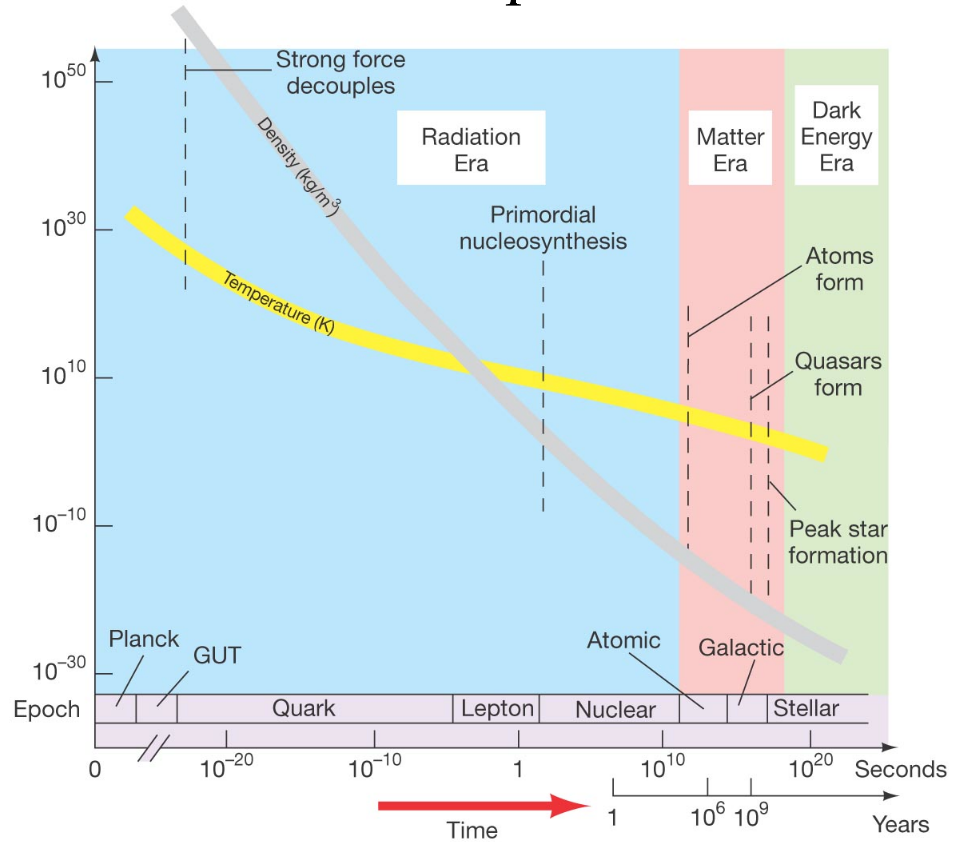
Stages in the evolution of the Universe



Radiation/Matter/Dark Energy Dominated

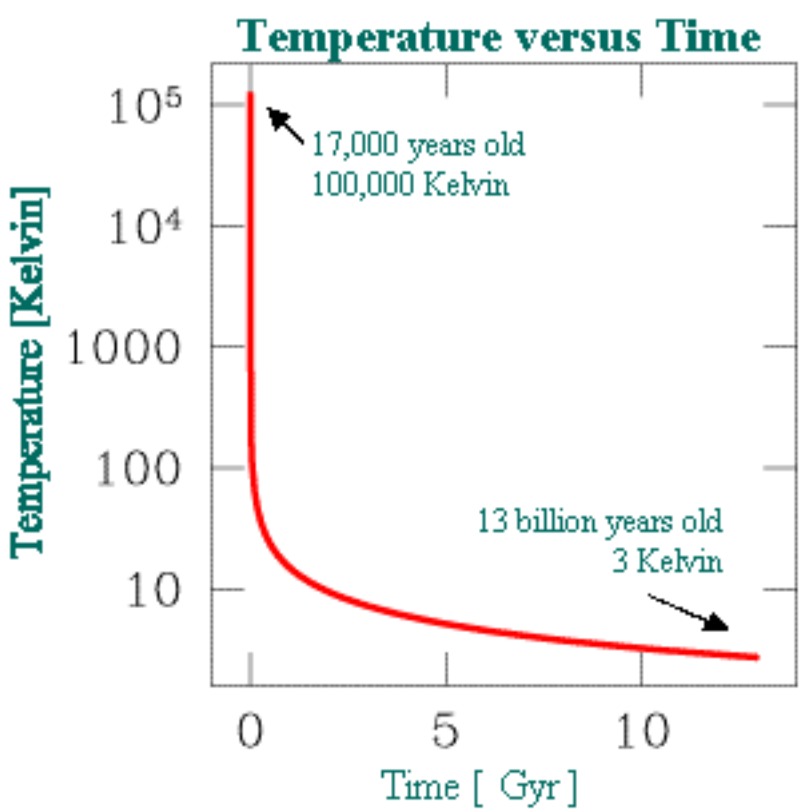
- Energy density of matter became less.
- Energy density of radiation became less faster: it was being redshifted
- Energy density of Dark Energy is constant – constant per cubic meter

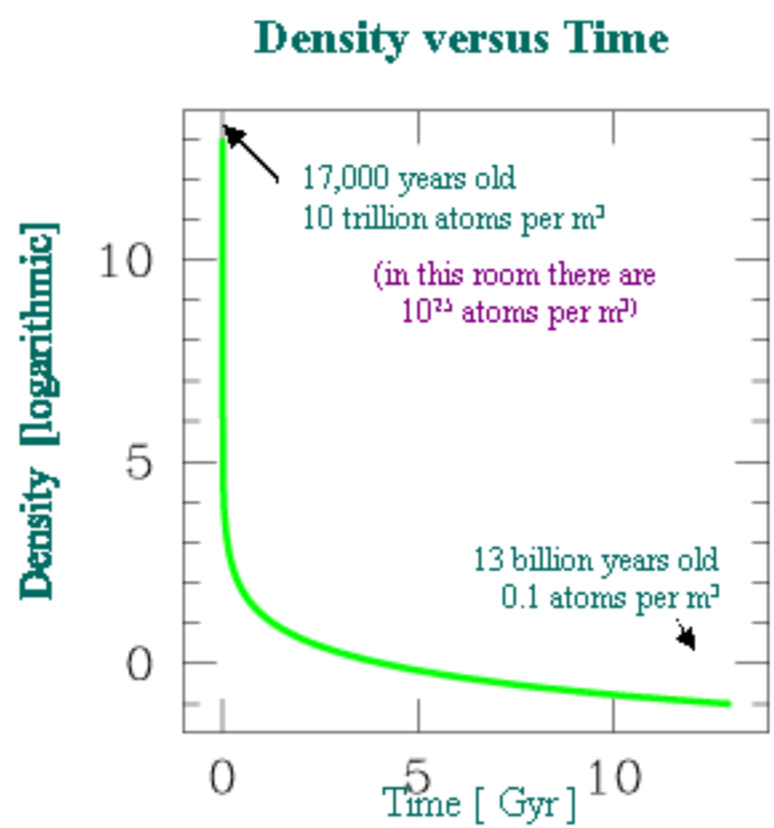




Conditions in Early Universe

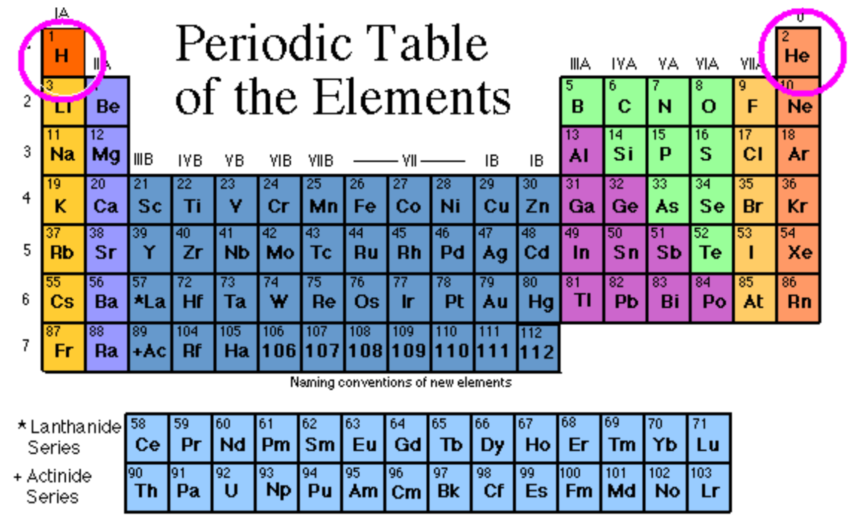
- Expansion and CMB imply Universe was hotter and denser in the past
- At some time when the universe was very young, conditions were similar to those in the centers of stars
- Note: temperature and density decrease with time, different behavior from stars
- There exists some window of opportunity during which conditions are favorable for fusion

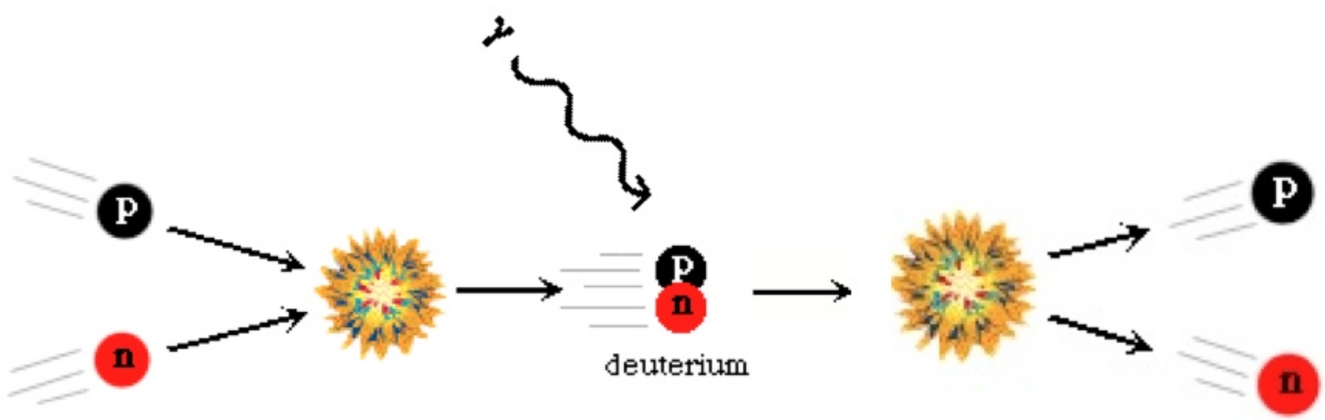




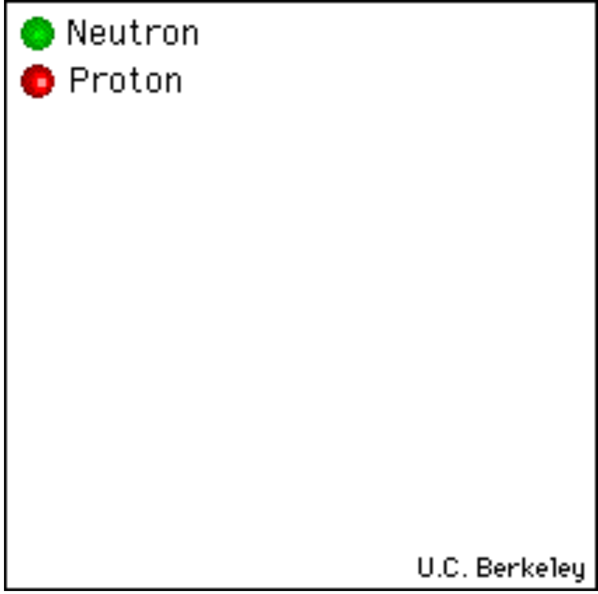
Deuterium Bottleneck

- Early Universe was a hot sea of protons, neutrons & photons
- Free neutrons are unstable thus rapidly disappearing
- Before 1 second photons had enough energy to destroy deuterium (deuterium bottleneck)
- Universe expands and cools
- At 2 minutes Deuterium forms

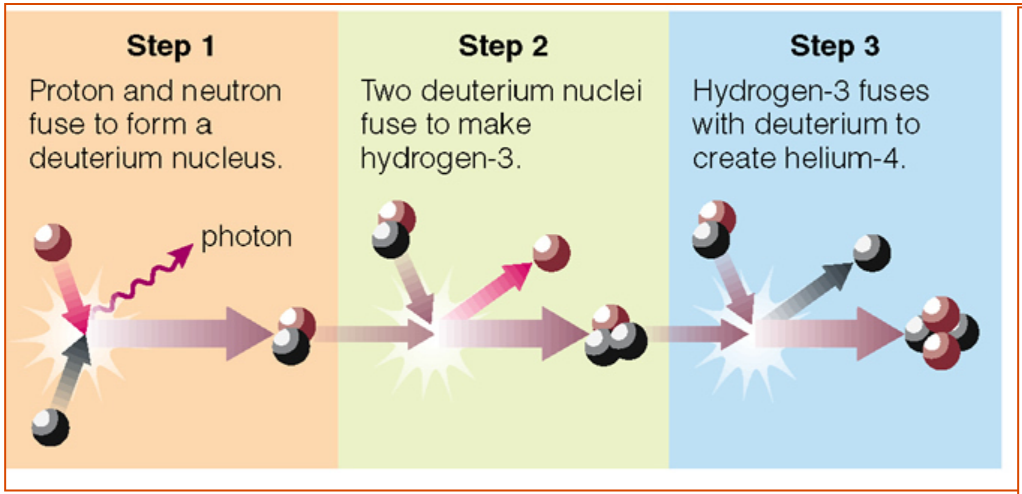


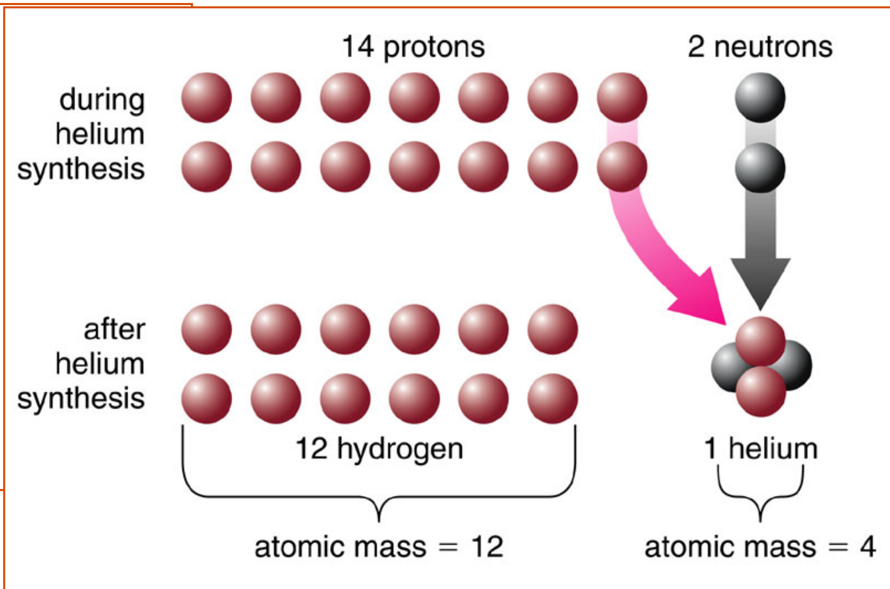


Big Bang / Primordial Nucleosynthesis



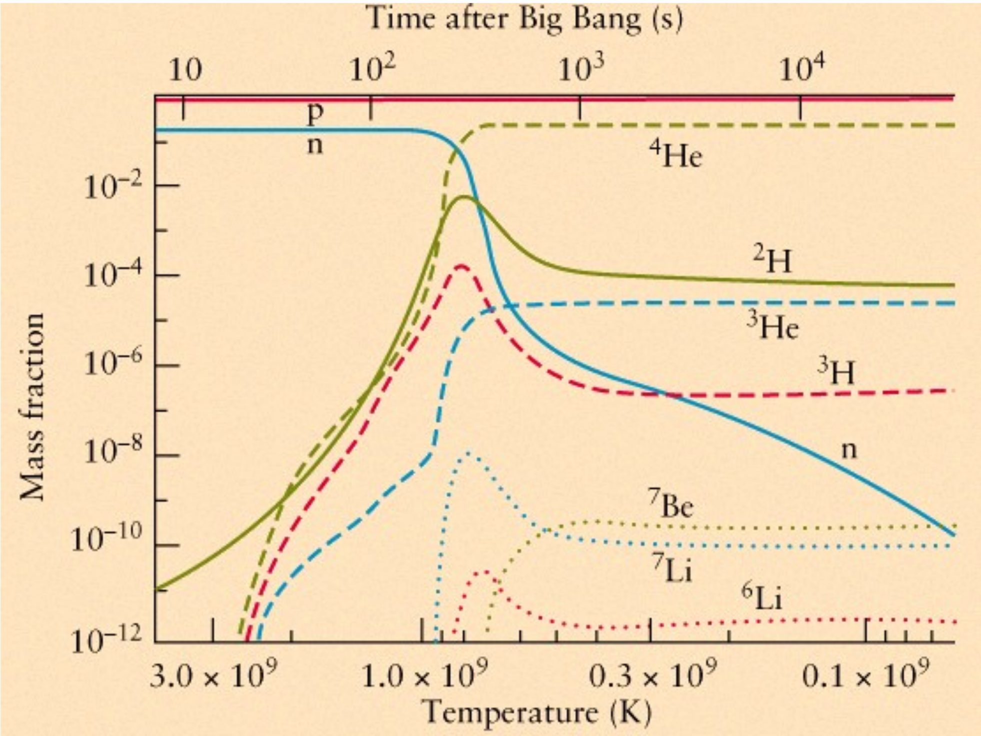
- From Deuterium
- Helium forms at 3-15 minutes
- Only enough neutrons left to make
- 75% hydrogen & 25% Helium by mass

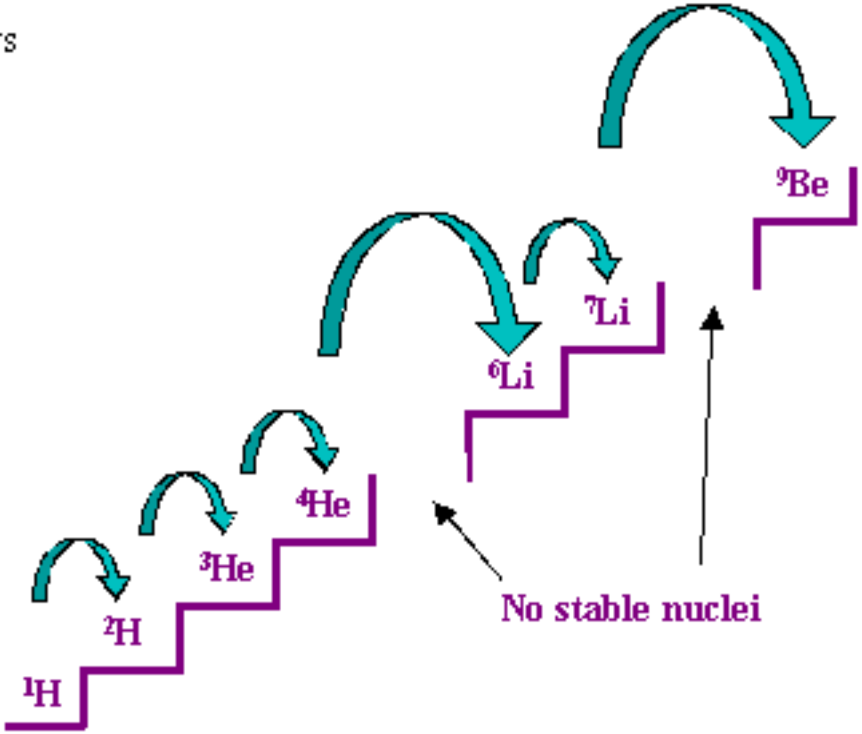




Primodial Nucleosynthesis versus Stellar Nucleosynthesis

- **Timescale**
  - Stellar Nucleosynthesis (SN): billions of years
  - Primordial Nucleosynthesis (PN): minutes
- **Temperature evolution**
  - SN: slow increase over time
  - PN: rapid cooling



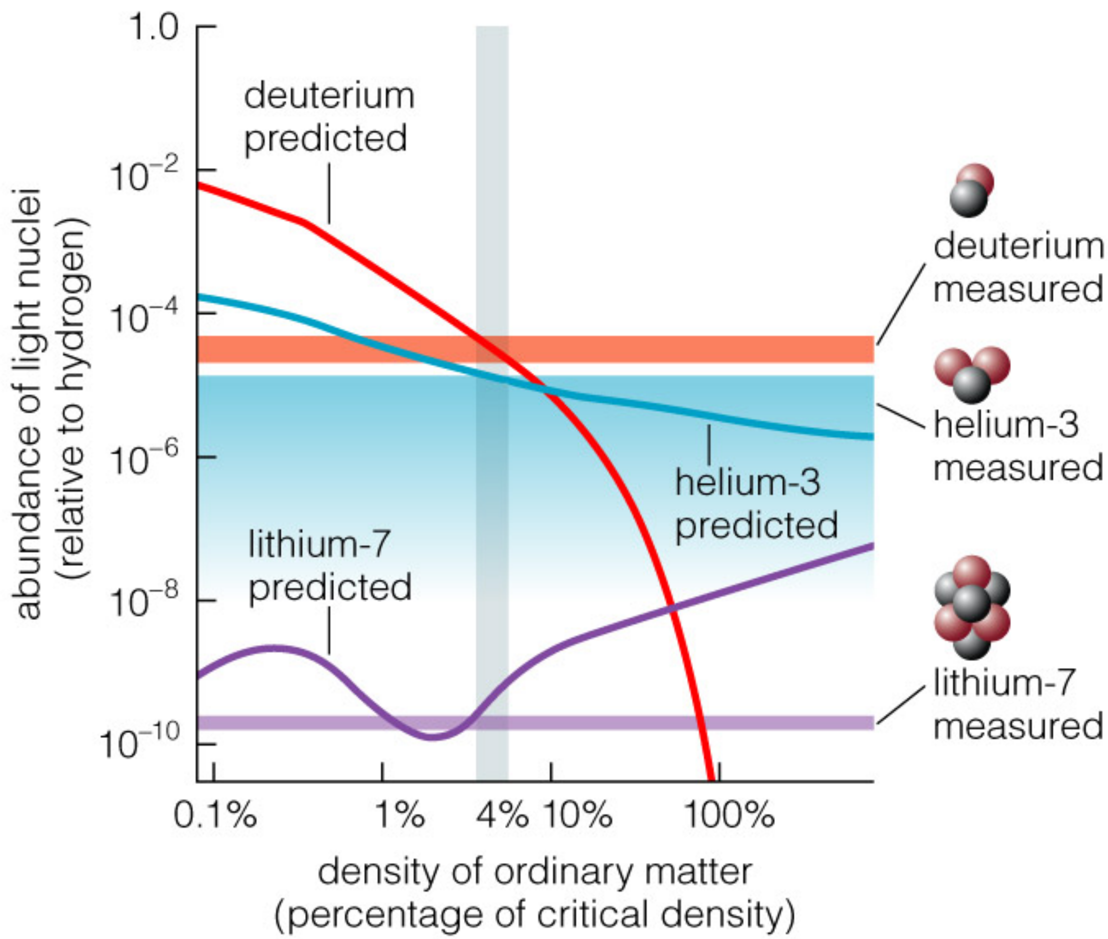


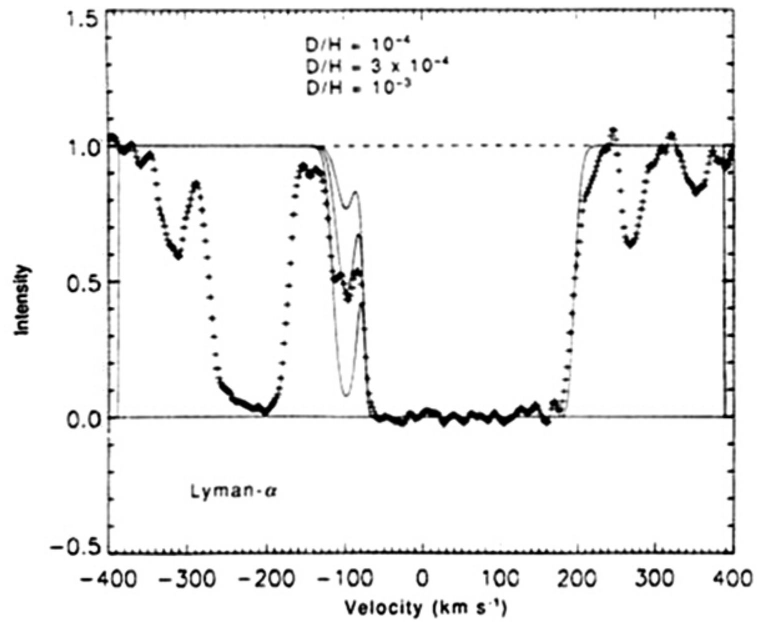
The lack of stable elements with masses 5 and 8 make it more difficult for cosmicnucleosynthesis to progress beyond Lithium and even Helium.

Luckily?

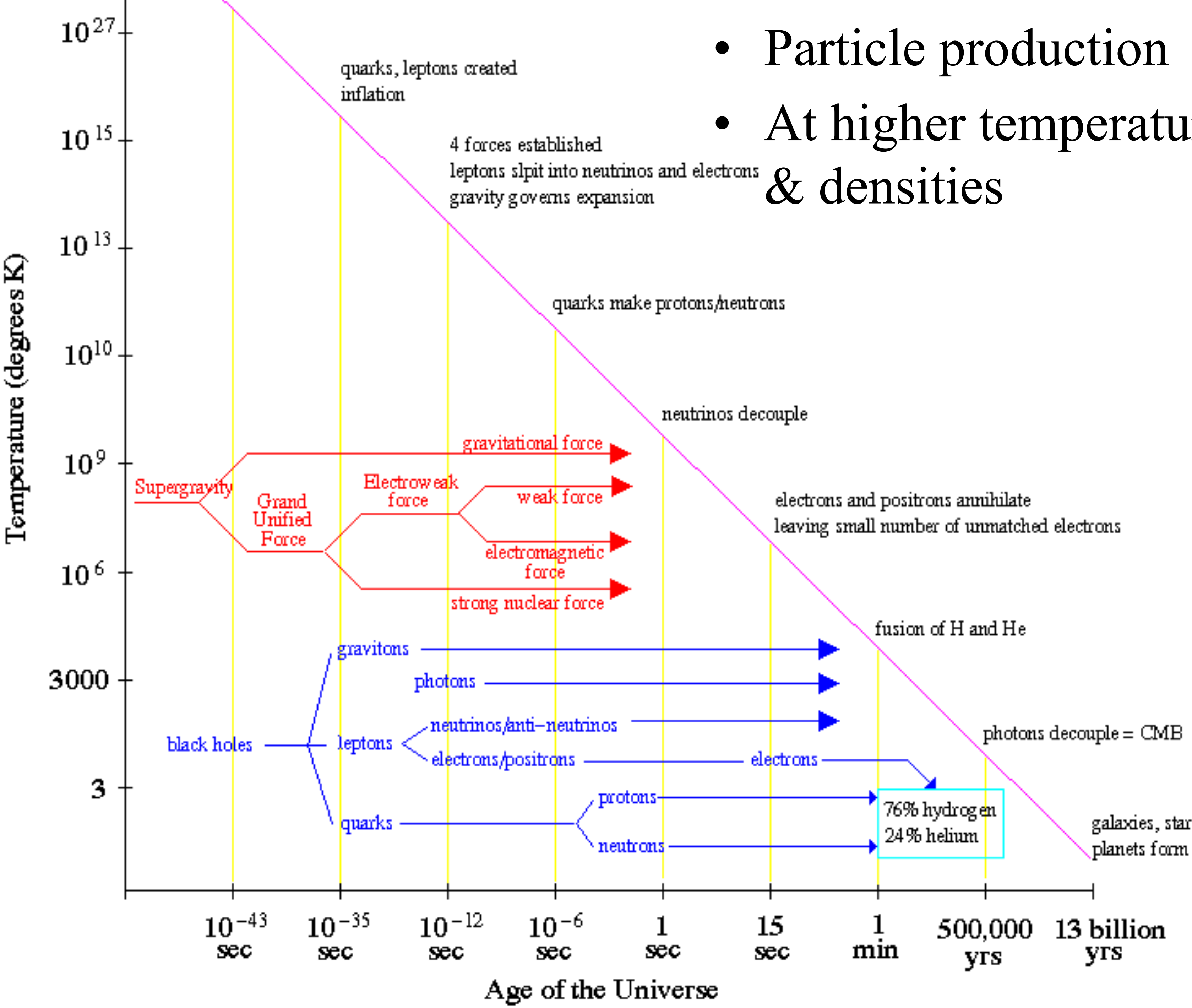
Big Bang/**Primordial Nucleosynthesis**

- Amount of Deuterium left over sensitive to density of ordinary matter
- Measure Deuterium/Hydrogen in gas clouds near quasars
- Ordinary matter is 4.4% of the critical mass of the Universe



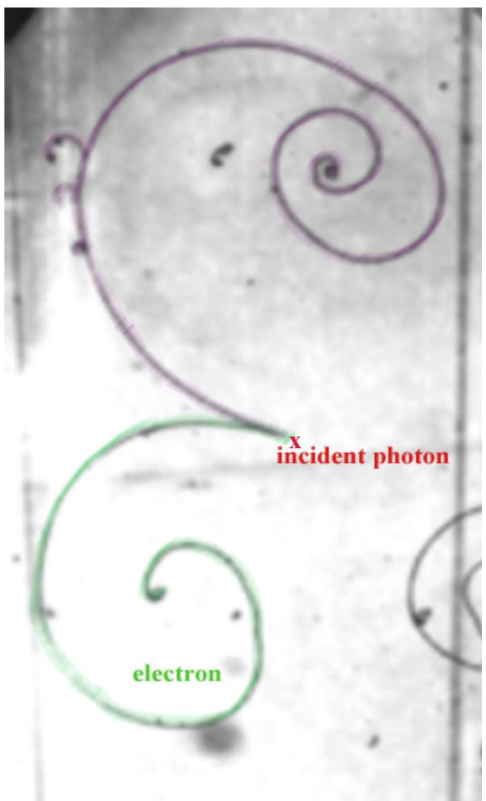


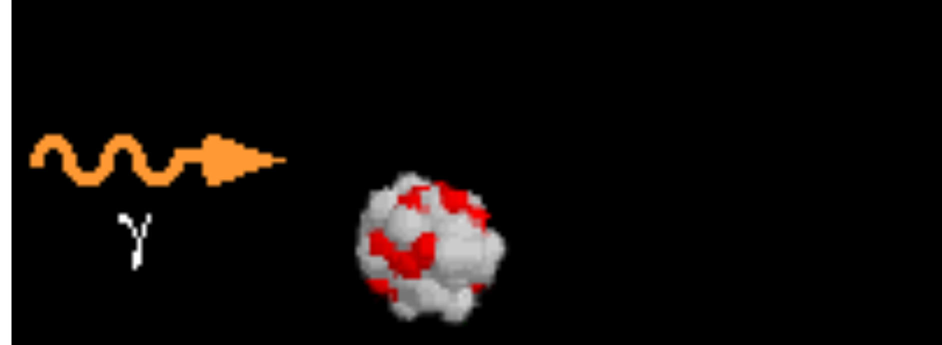
- Particle production
- At higher temperatures & densities

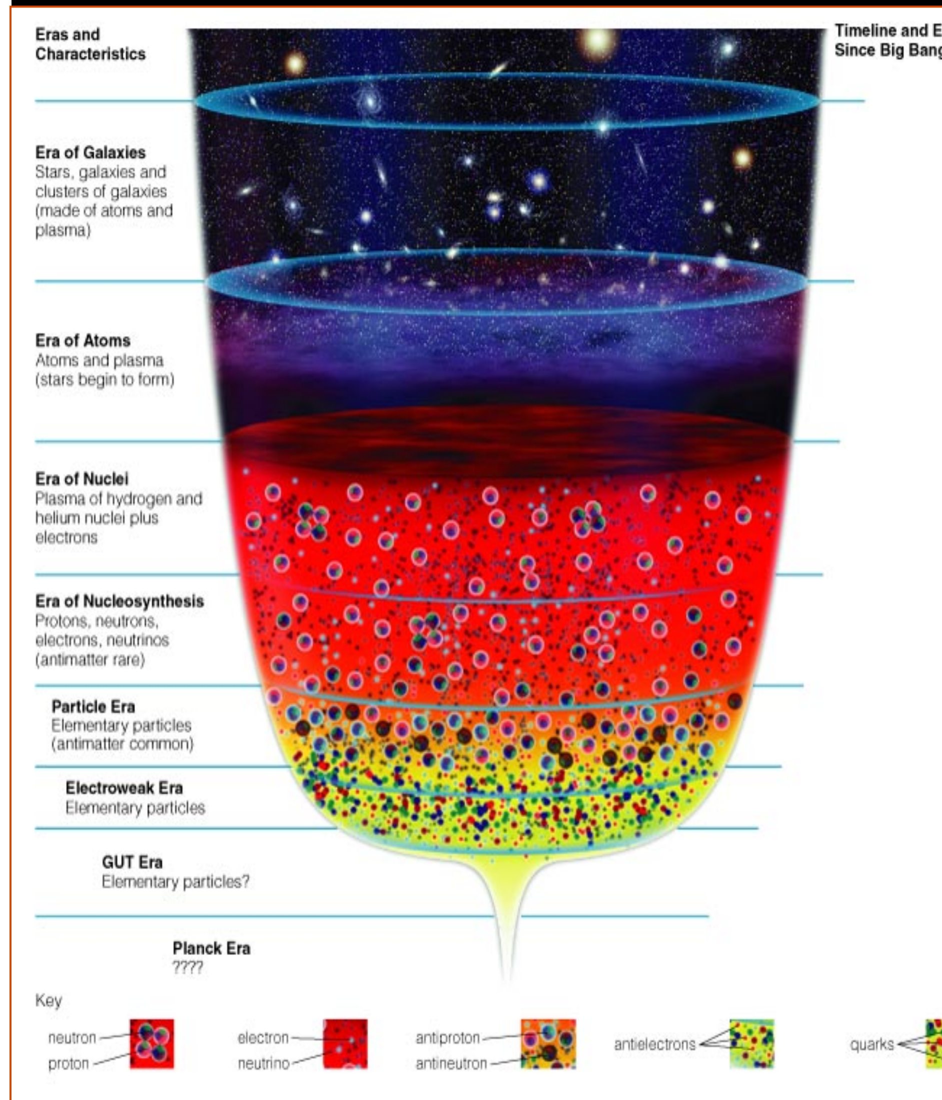


Pair Production

- Photons create a **particle-antiparticle pair**
- Photon(s) have more energy than
- The sum of the masses of the particle and the antiparticle
- $E=Mc^2$



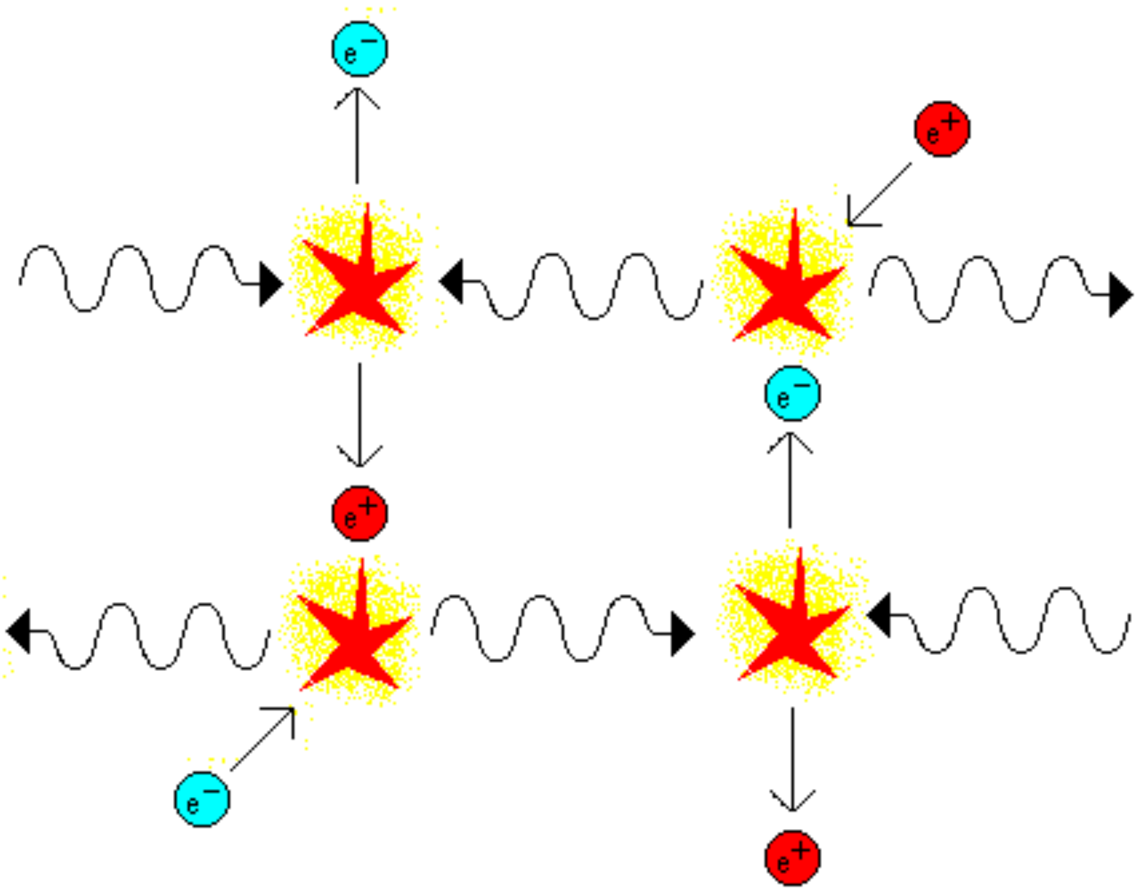




Particle Equilibrum

- Thermal equilibrium

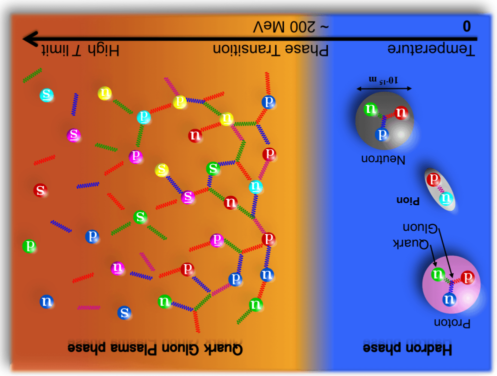
a state of particle equilibrium exists when the number of particle creations exactly matches the number of annihilations. Usually this is because there is no time for matter to decay or combine into new forms before a collision with an anti-particle

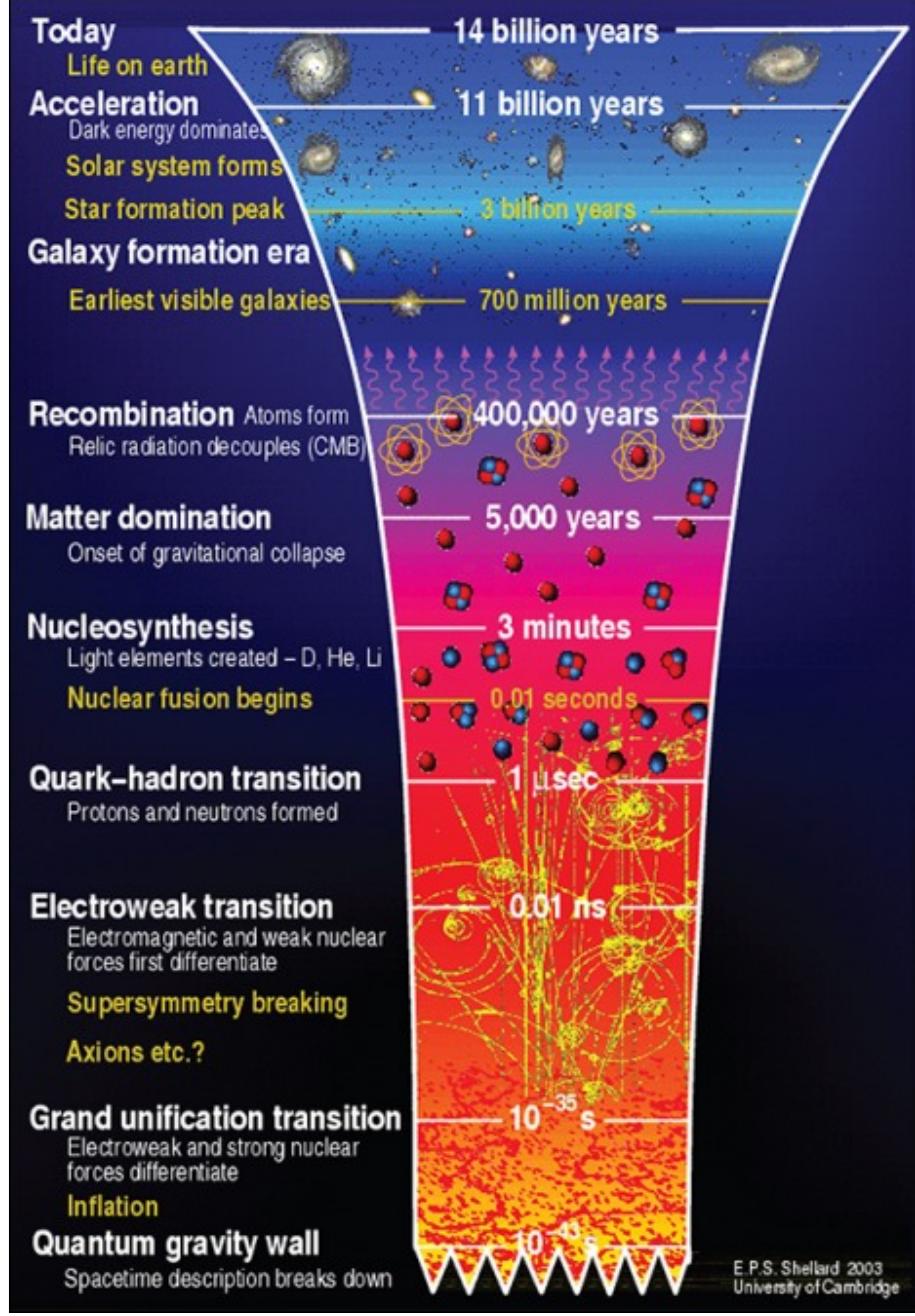


Notice that an equilibrum process keeps the number of matter and anti-matter particles equal.

Freeze Out

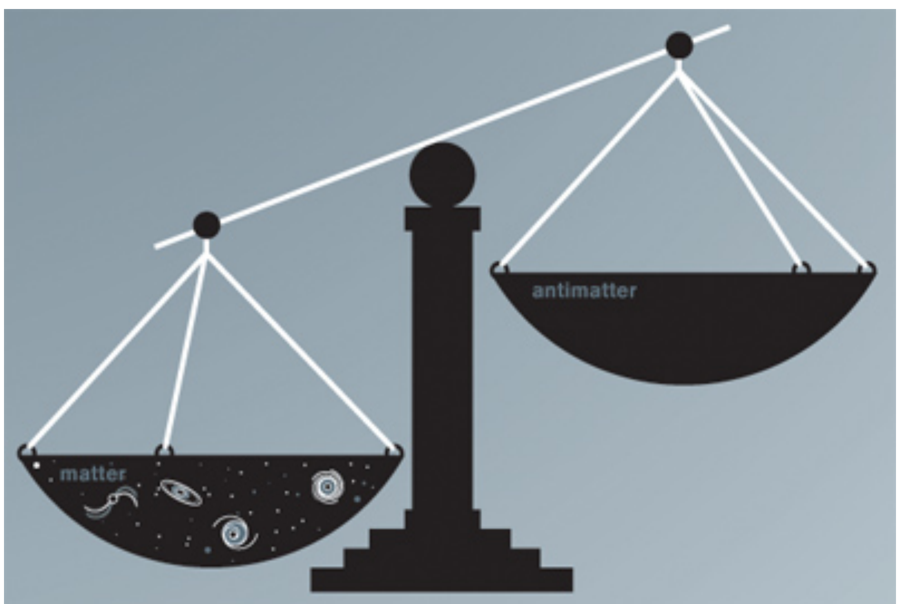
- Universe expanded & cooled – photons did not have enough energy to create massive particles
- Neutrons/antineutrons protons/antiprotons at 0.1 milliseconds= 10^{12}K
- Electrons/positrons at 4 seconds =10^9K
- Quark Soup ➔ Protons





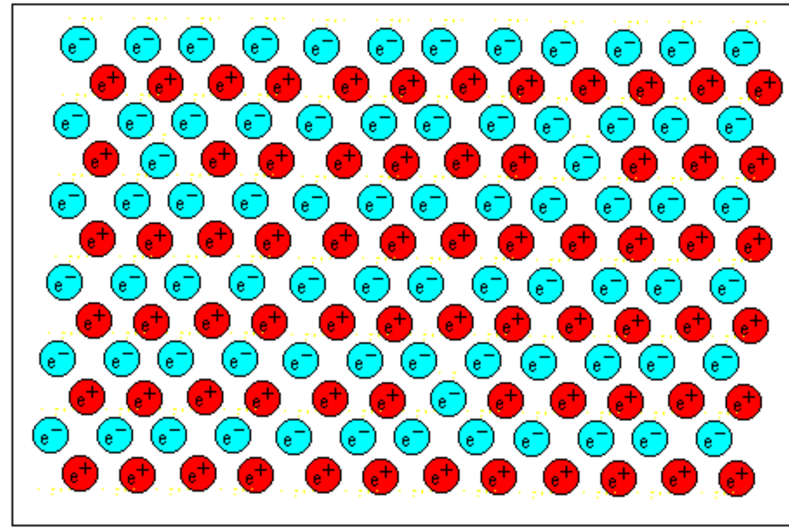
Matter-Antimatter Annihilation

- 10,000,000,001 particles
  -10,000,000,000 antiparticles
  =1particle left
- Lucky for us there was some matter left, same number of protons and electrons and same charge (standard model)

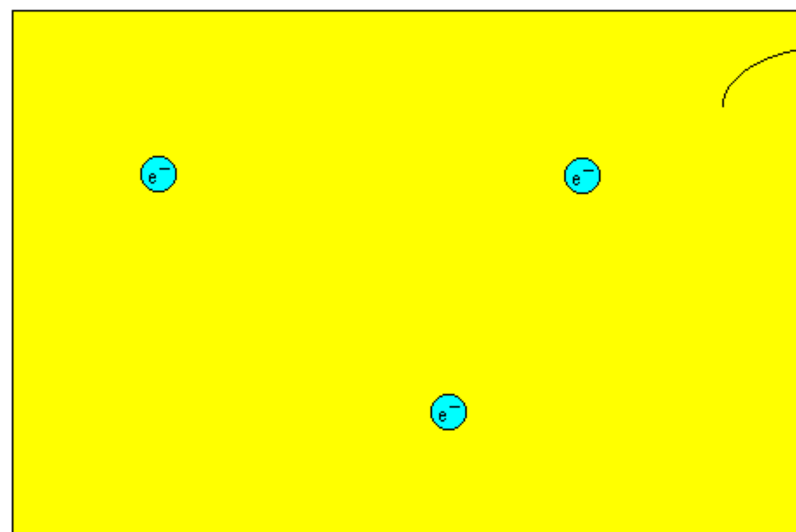


Baryon Number

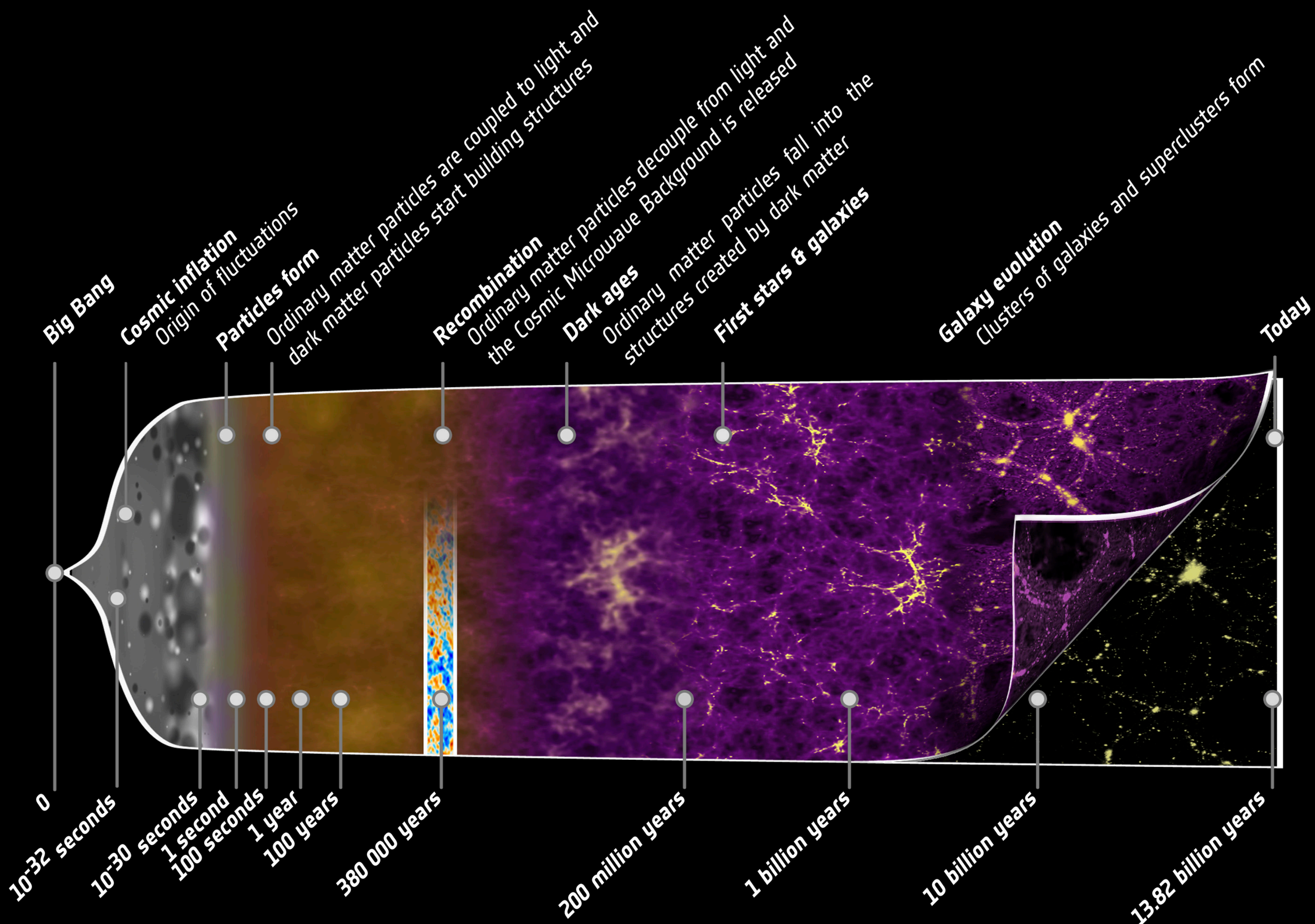
Before

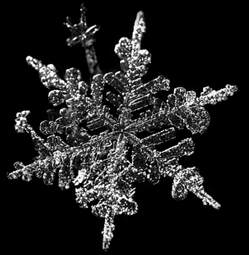


After



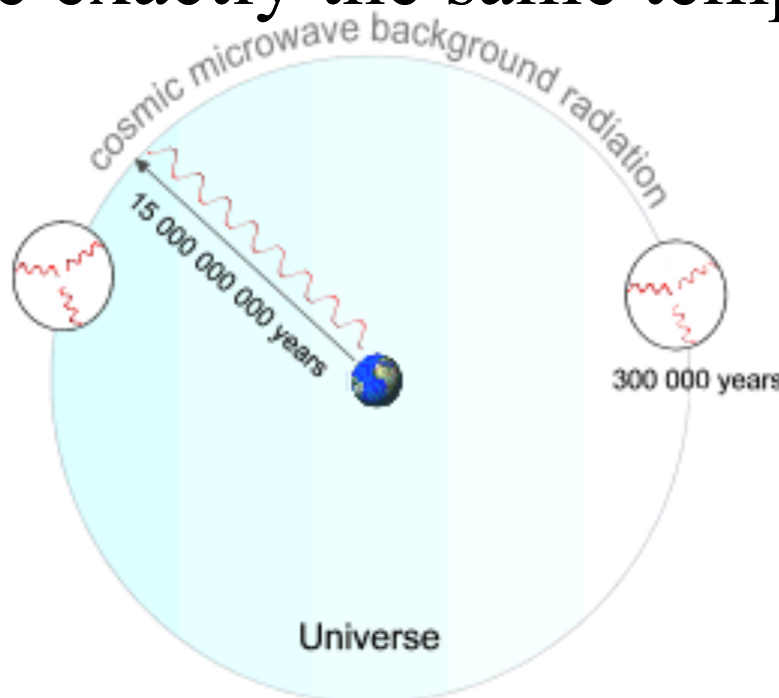
Before Particles Form





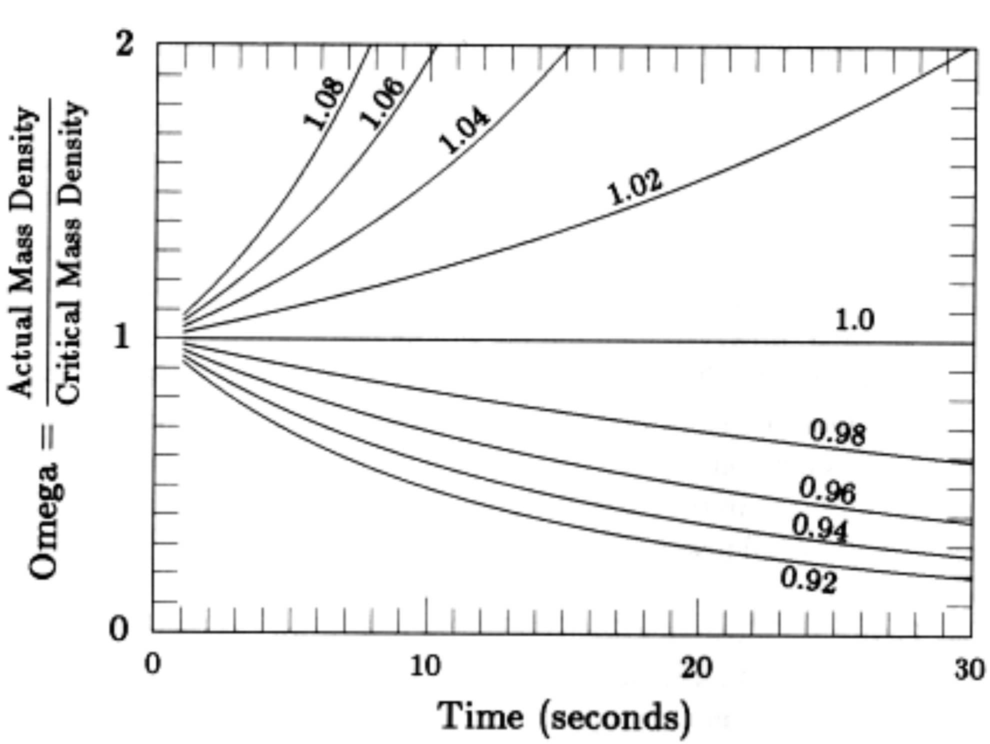
Horizon Problem

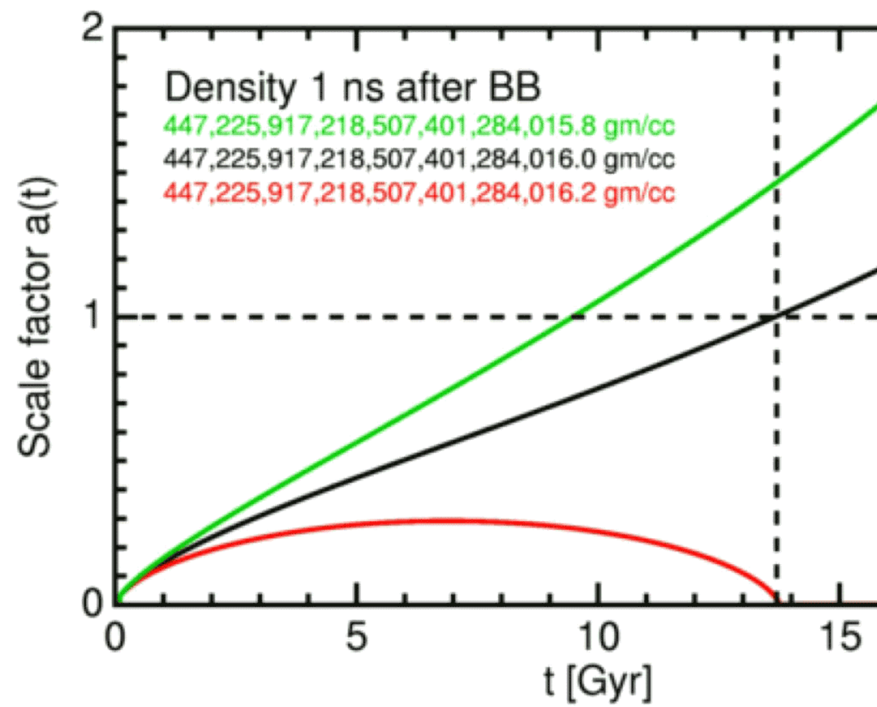
- The two small regions are points on the CMB
- Surrounded by their cosmic horizons
- Since they're beyond each other's horizon they could not communicate/share their temperature/energy
- Yet they are exactly the same temperature???



Flatness Problem

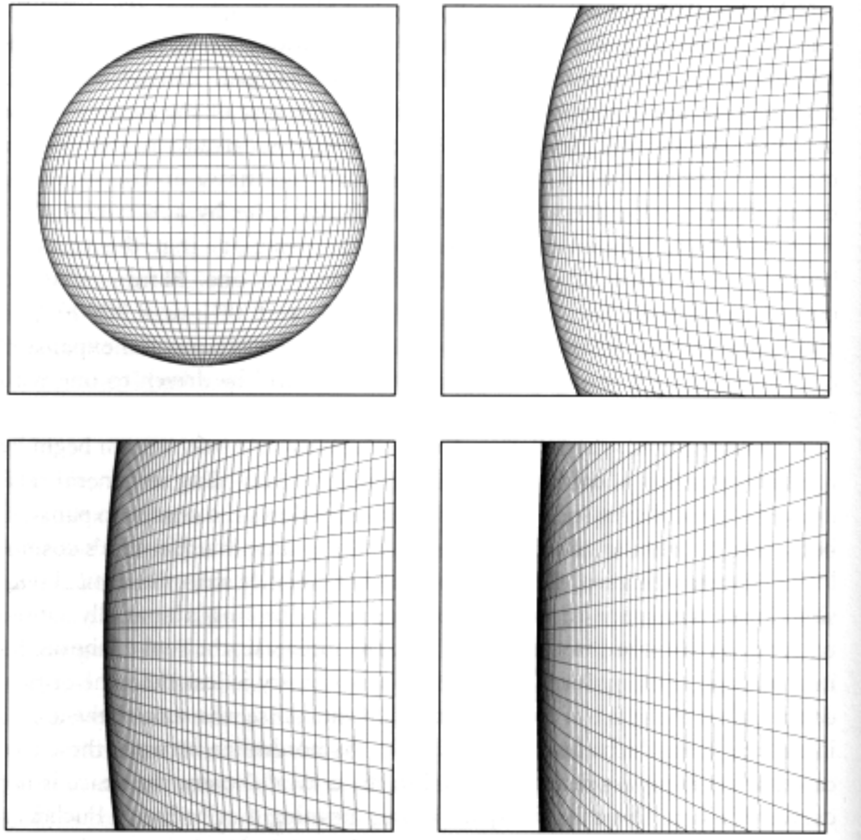
- If Universe has more than critical density, it would not expand as much as flat universe so it would become even more over dense
- For it to seem so flat today it must have been less than 1.000000001critical density (= Flat Universe) at 1second

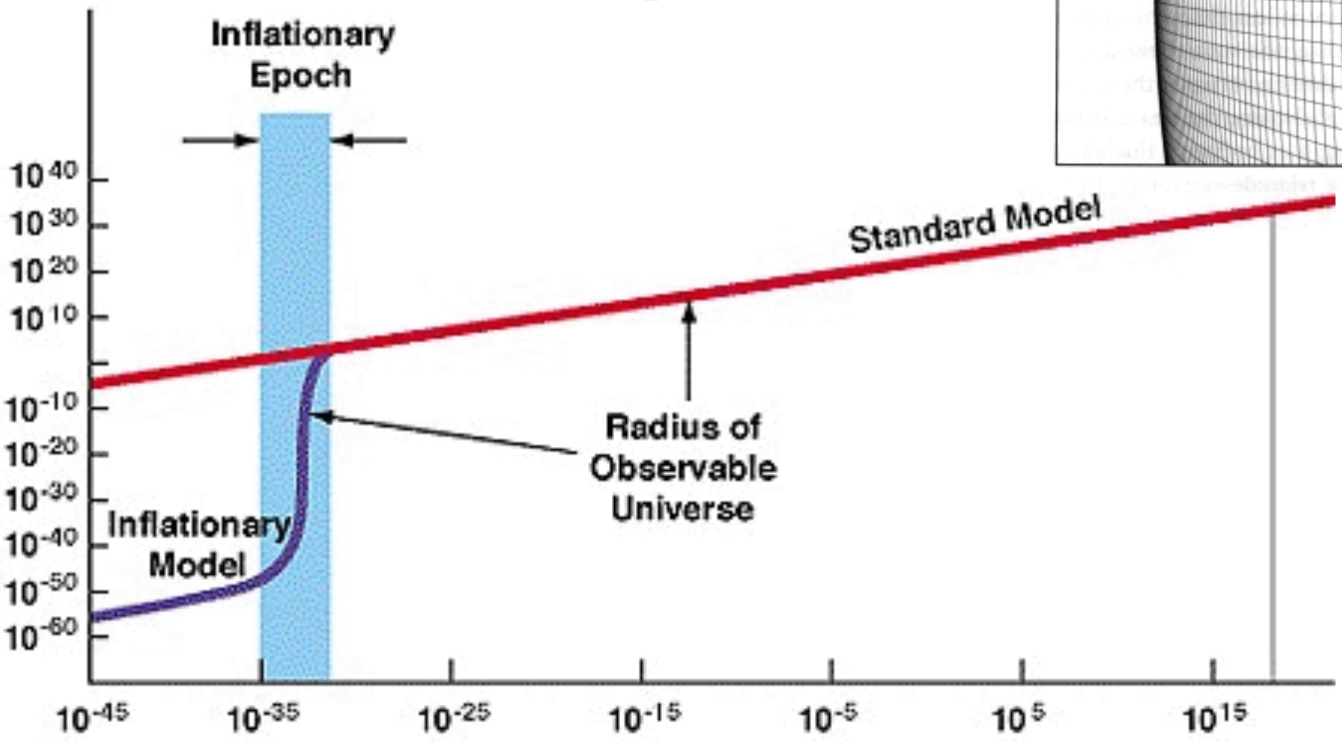




Epoch of Inflation

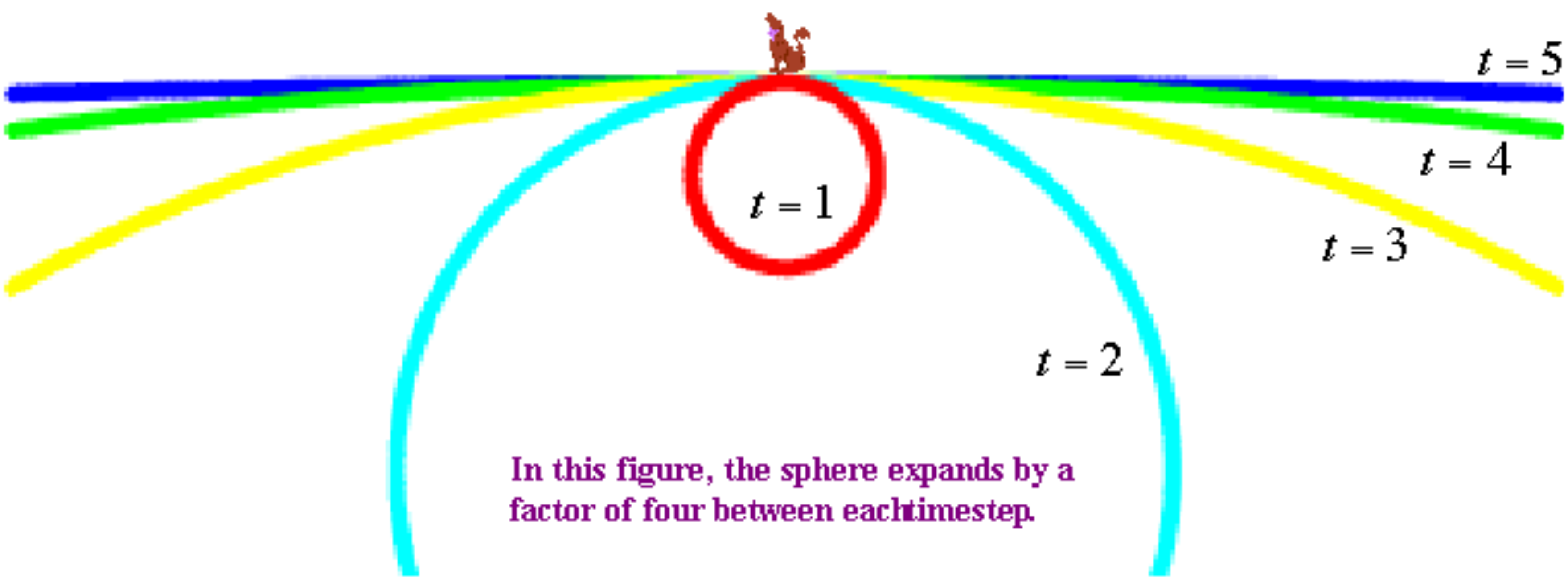
- Occurs at 10^{-35} sec for $\sim 10^{-32}$ sec
- Universe expands by 10^{50} times ~proton to supercluster size
- Not faster than c since it is space expanding not moving thru space
- If golf ball to earth – dimples would be an atom deep x 1300km





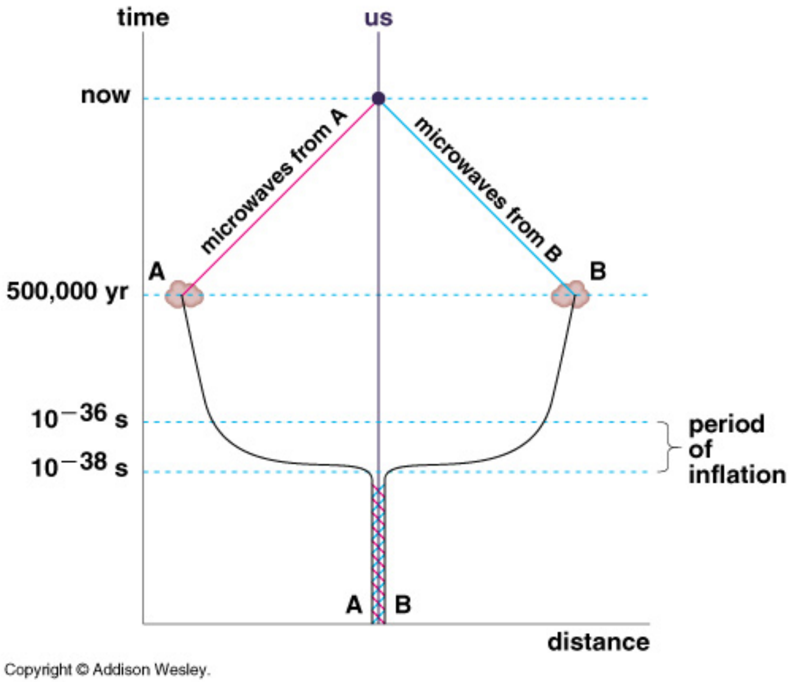
Inflation Also Makes the Universe Flatter

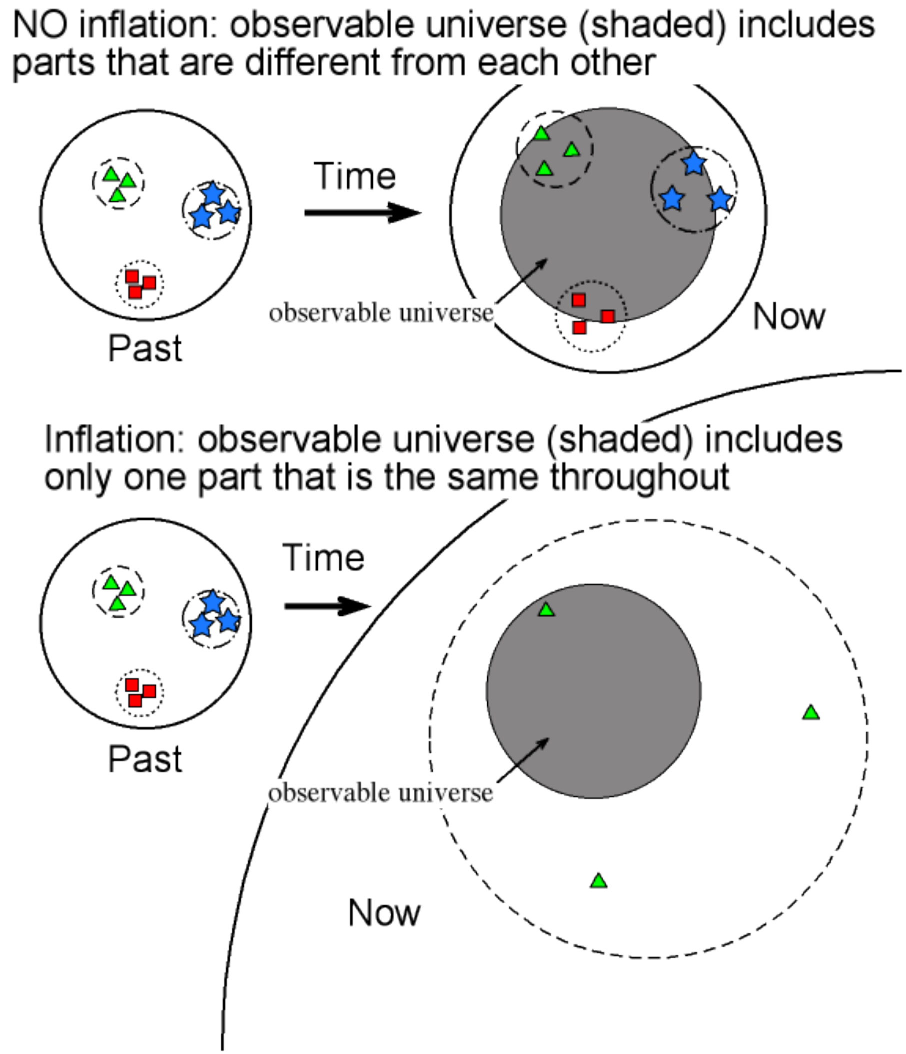
- Imagine you are standing on a large, expanding balloon
  - as the balloon expands, the curvature becomes less apparent
  - what if the balloon were the size of the Earth… would you perceive the curvature of the Earth?
- Inflation drives the Universe towards flatness

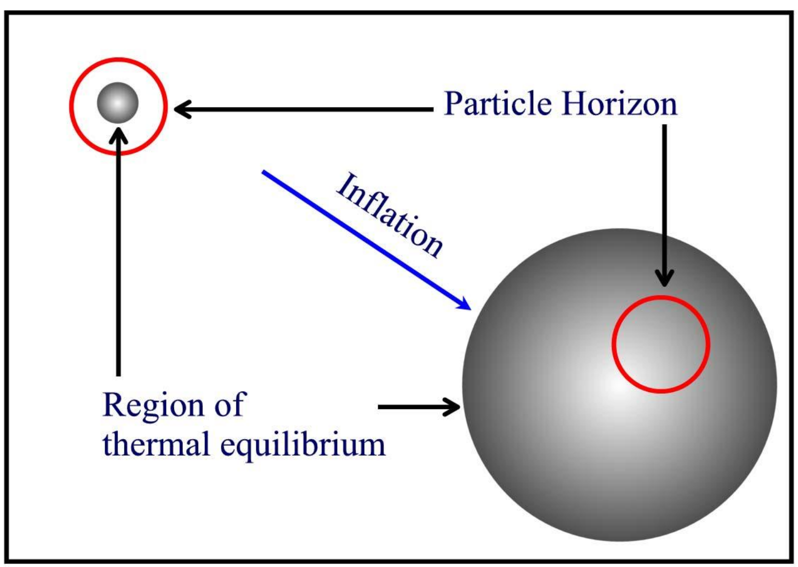


In this figure, the sphere expands by a factor of four between eachtimestep.

Inflation Solves Horizon Problem

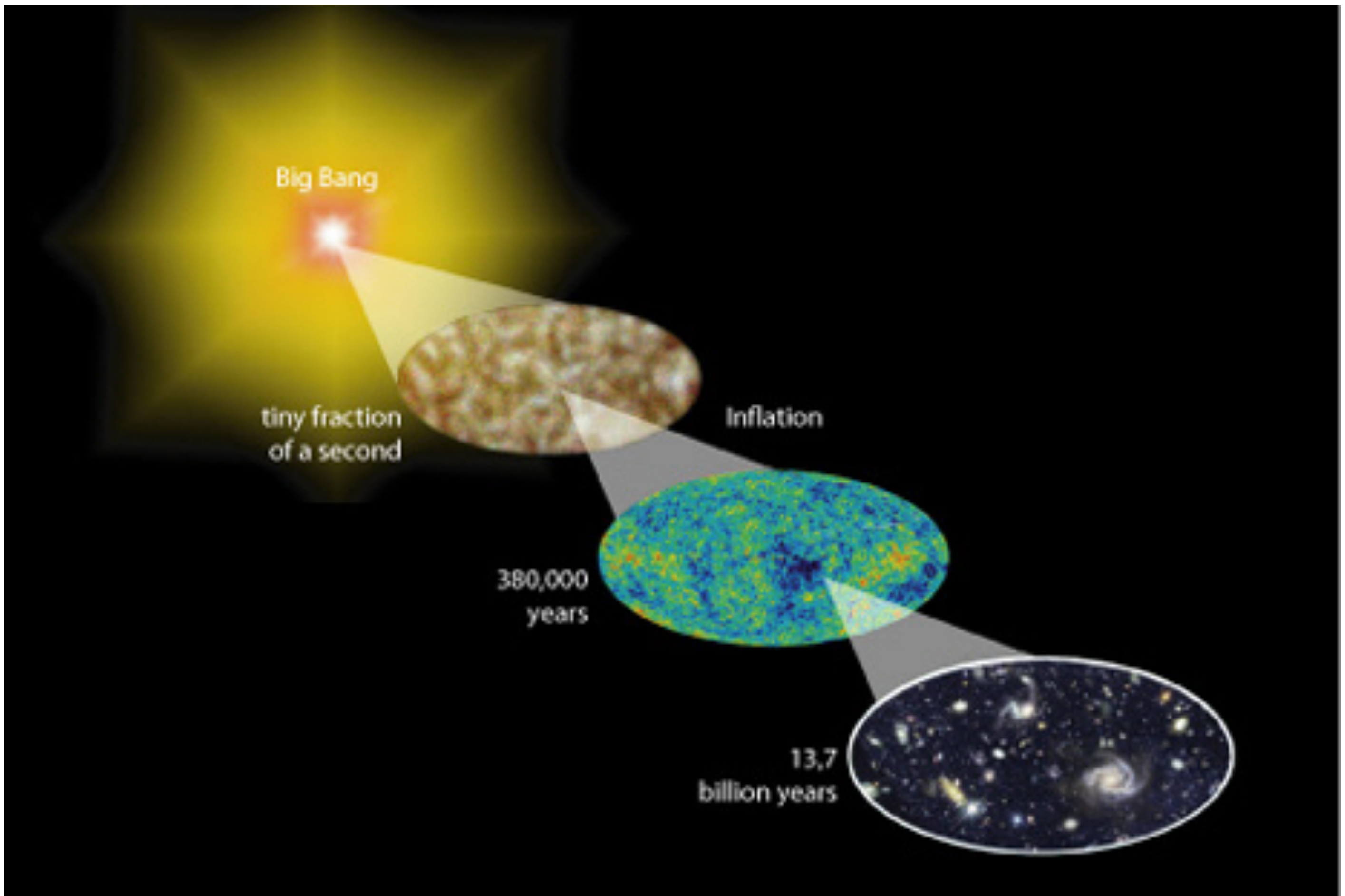






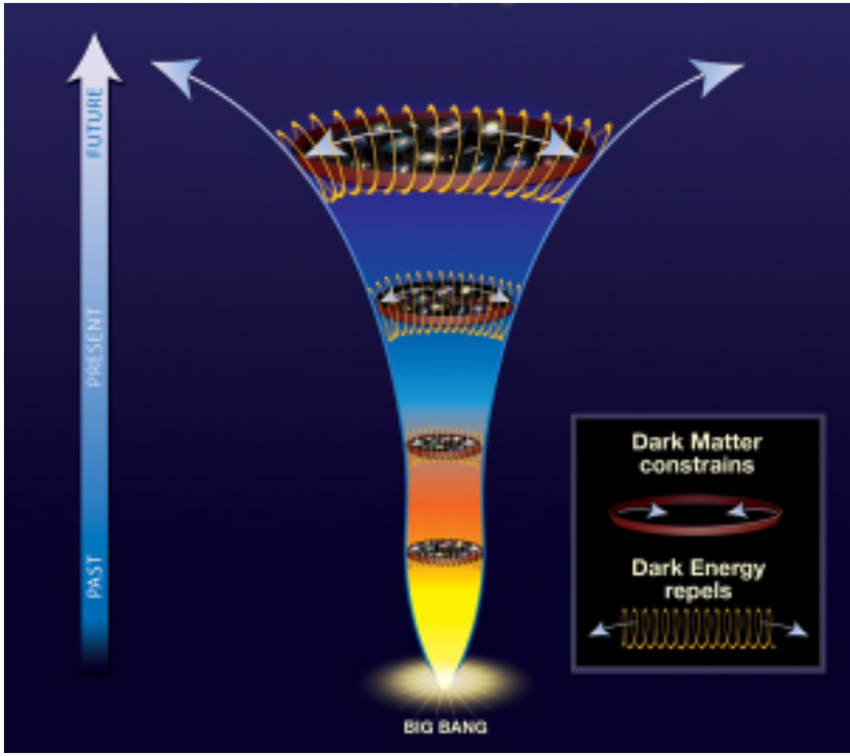
Inflation Sows Seeds of Structure

- Inflation makes quantum fluctuations into the inhomogeneities in the CMB for Galaxy Formation



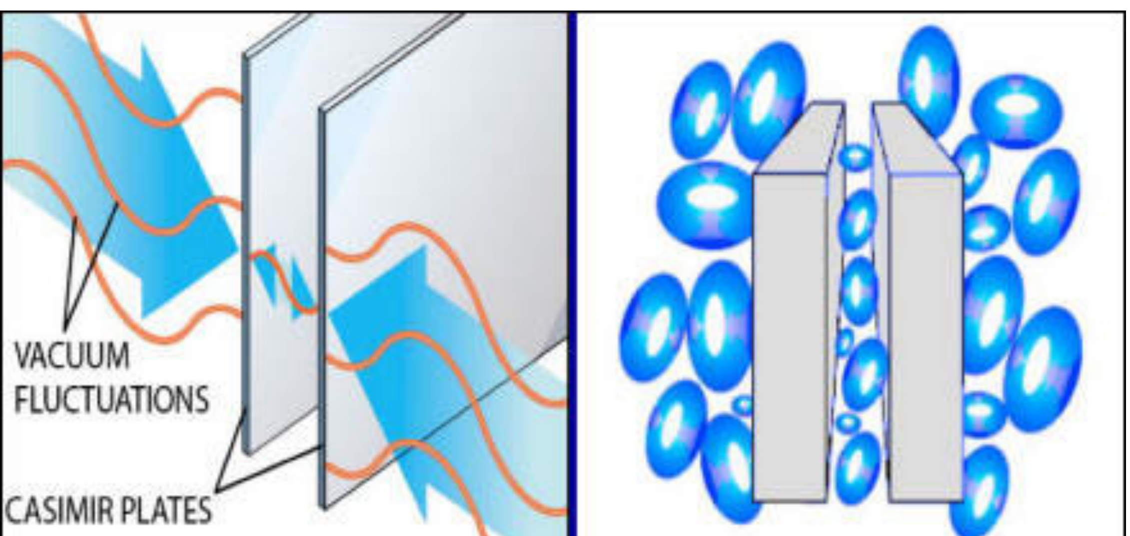
Dark Energy = Cosmological Constant = Vacuum Energy

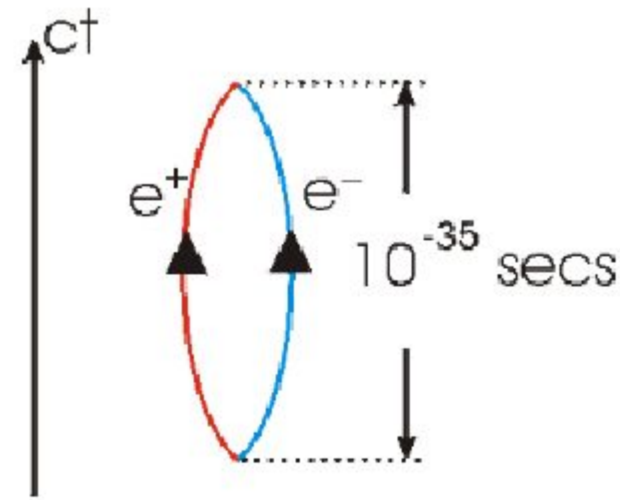
- Invented by Einstein in 1918 to keep universe static
- Einstein's "greatest blunder" when Hubble found expanding universe
- Revived to explain accelerating universe = dark energy
- "Physically equivalent to vacuum energy" density = zero point energy



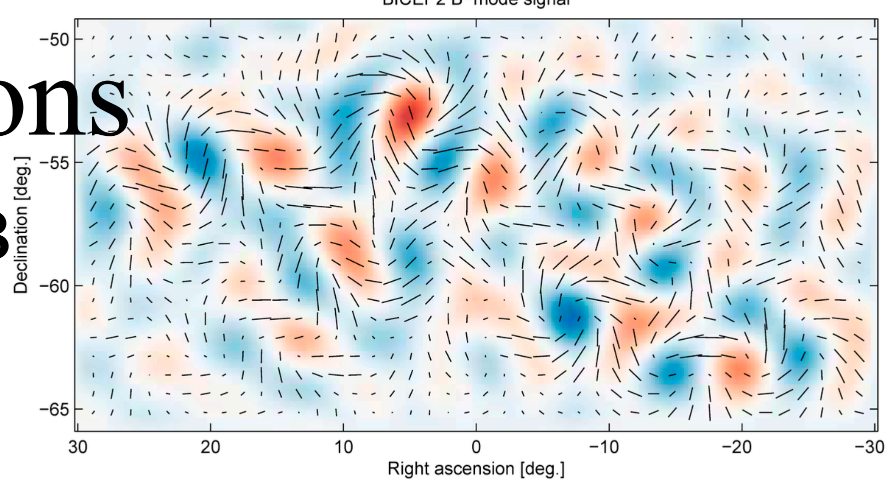
Heisenberg Uncertainty Principle & Virtual Pairs & **Vacuum Energy**

- From Quantum Mechanics: $\Delta E \;\; X \;\; \Delta t < h/2\pi$
- Means particle+antiparticle pairs spontaneously appear even in a vacuum for a very short time
- Even a vacuum has some energy/mass
- From Quantum Mechanics 10^{91}gm/cm^3 but measured to be less than 10^{-29} gm/cm^3 so prediction is wrong by 10^{120} times





Inflation: Observations

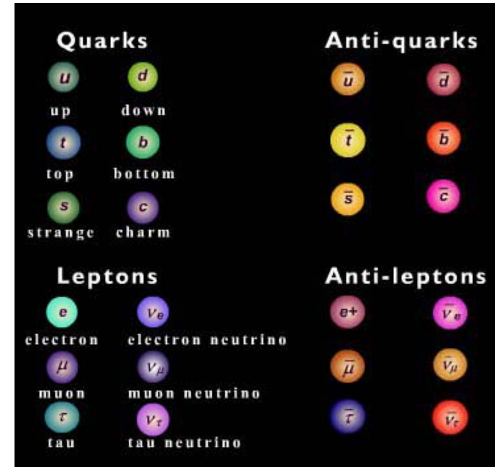


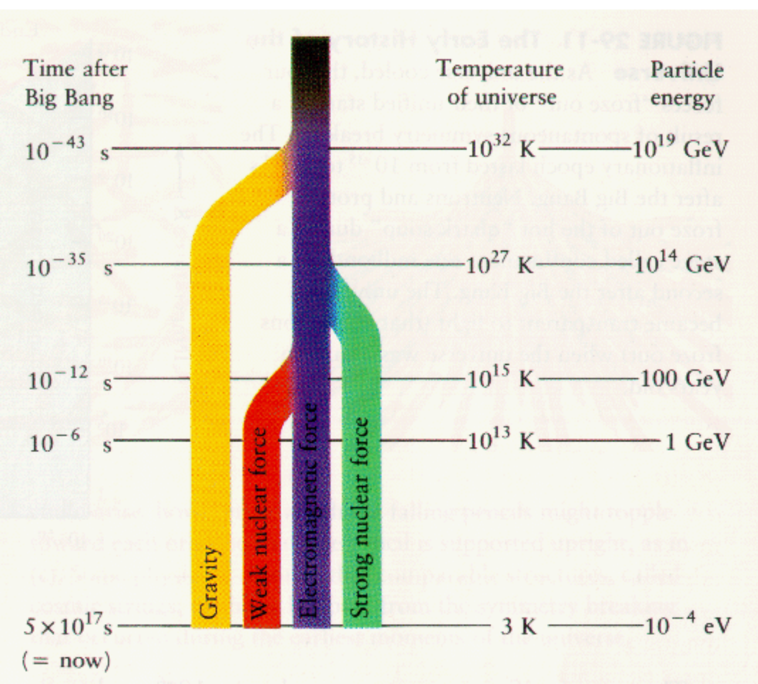
- BICEP2 project measures CMB polarization from south pole
- Inflation did happen
- Gravity waves & gravitons do exist
- Vacuum fluctuations inflated to become seeds of galaxy clusters

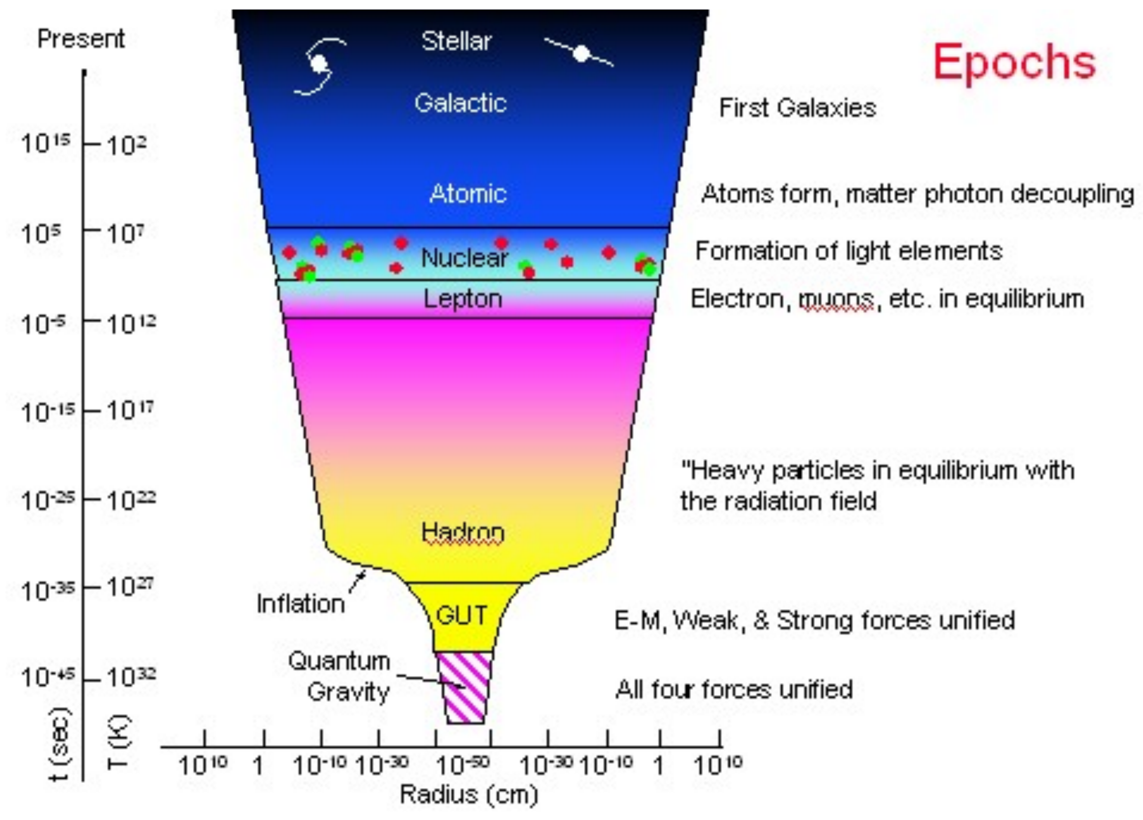
Controversy but Planck will decide October 2014

Grand Unified Theory=GUTs

- Unifies the 3 forces: electromagnetic, weak and strong forces into one theory and views them as low-energy manifestations of a single unified force
- The universe inflated at 10^{-35} sec when electroweak and strong forces differentiated, releasing energy & causing a phase transition
- Formation of quark soup



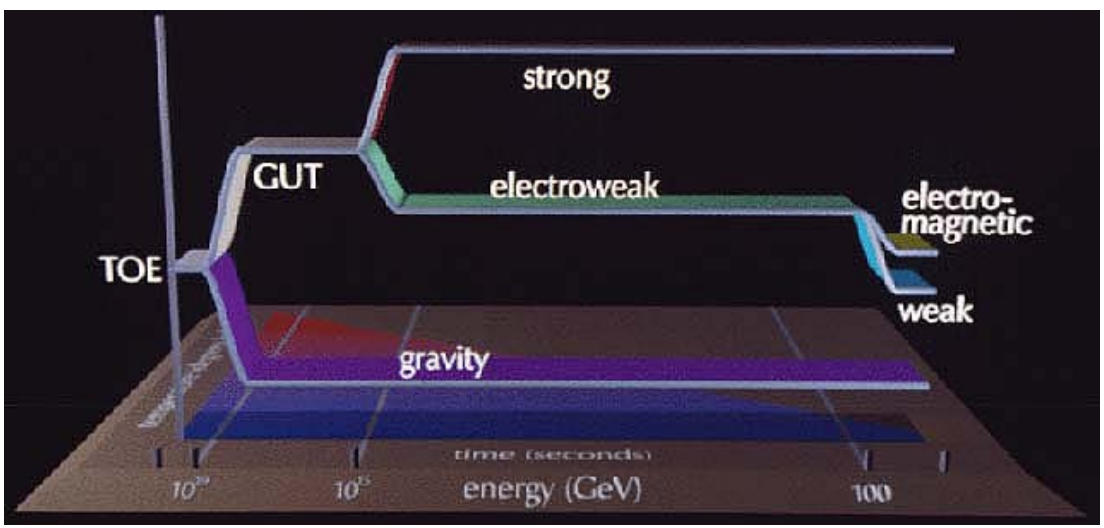


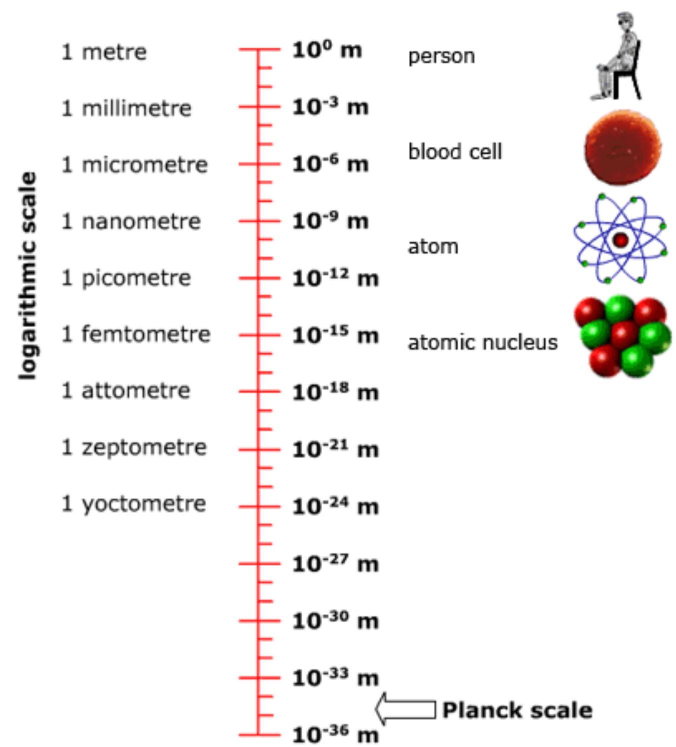


Before Inflation: **Planck Epoch**

Planck Length 10^{-35}m; **Time** 10^{-43} sec

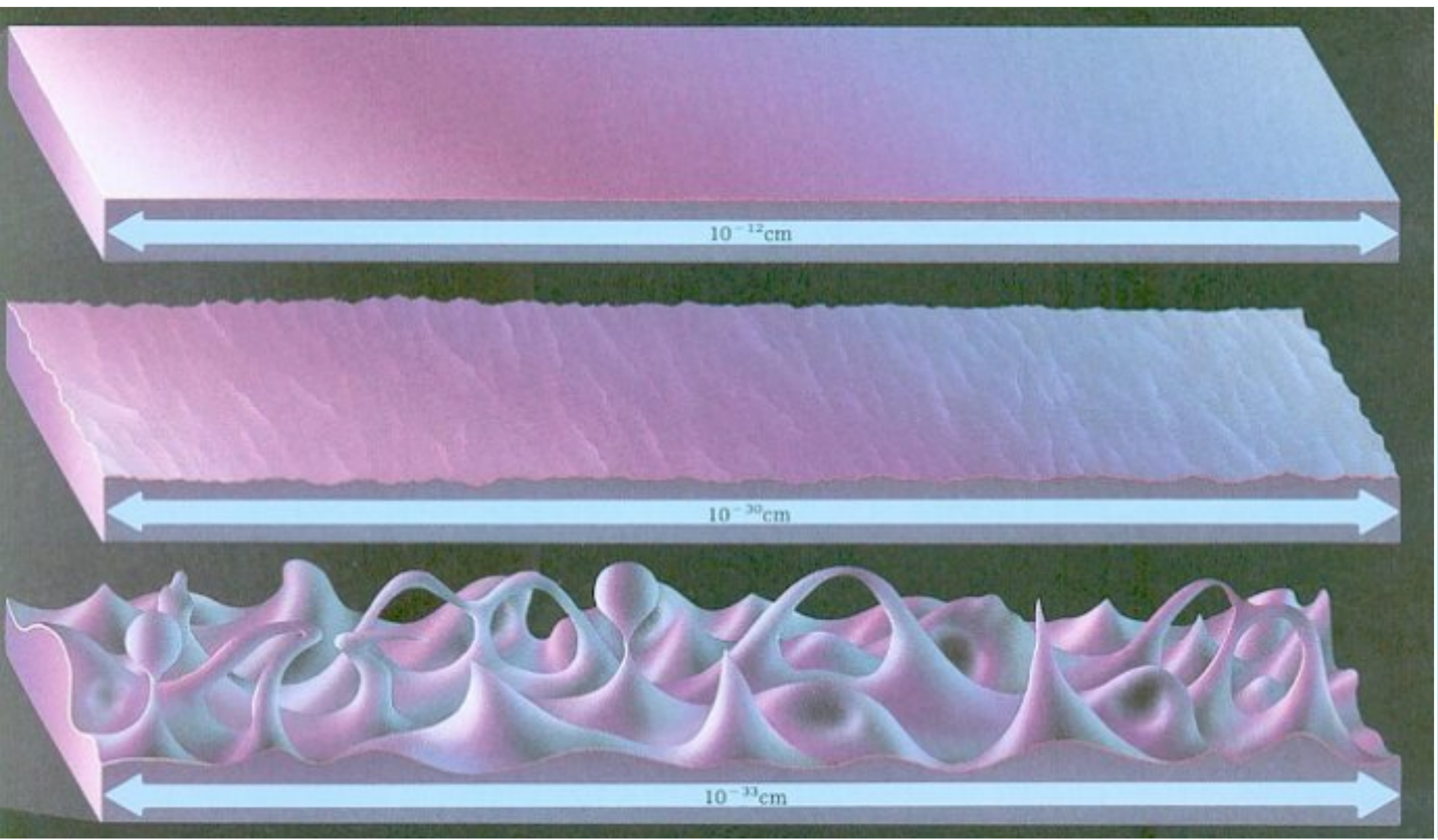
- Particles have a wavelength due to quantum mechanics $E=hc/\lambda=mc^2$
- A very tiny black hole will have an event horizon equal
- To its wavelength at distance of 10^{-35} meters = Planck Length
- At that size singularity would not stay inside event horizon
- Need to have Quantum + General Relativity =
- **Theory of Everything – New Physics**

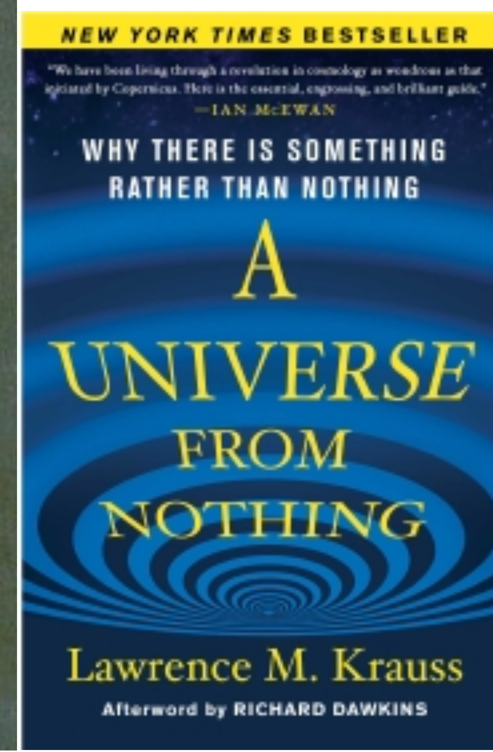




Quantum Fluctuation

- Did one of Heisenberg's vacuum fluctuations inflate to become the Universe?



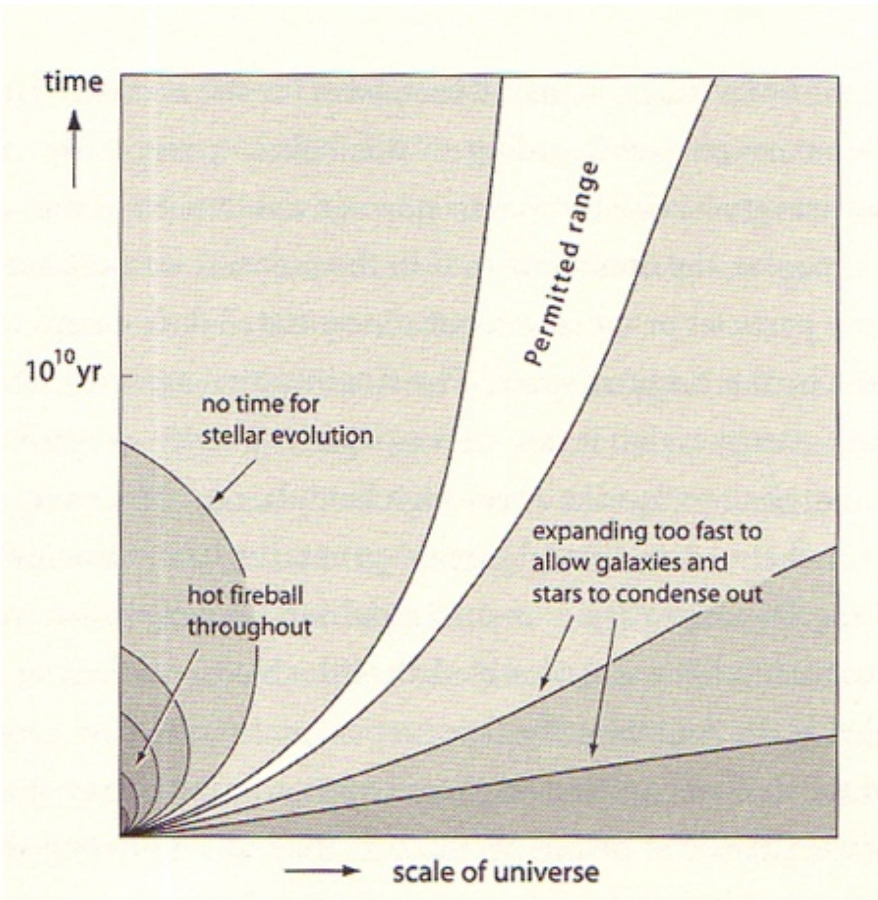


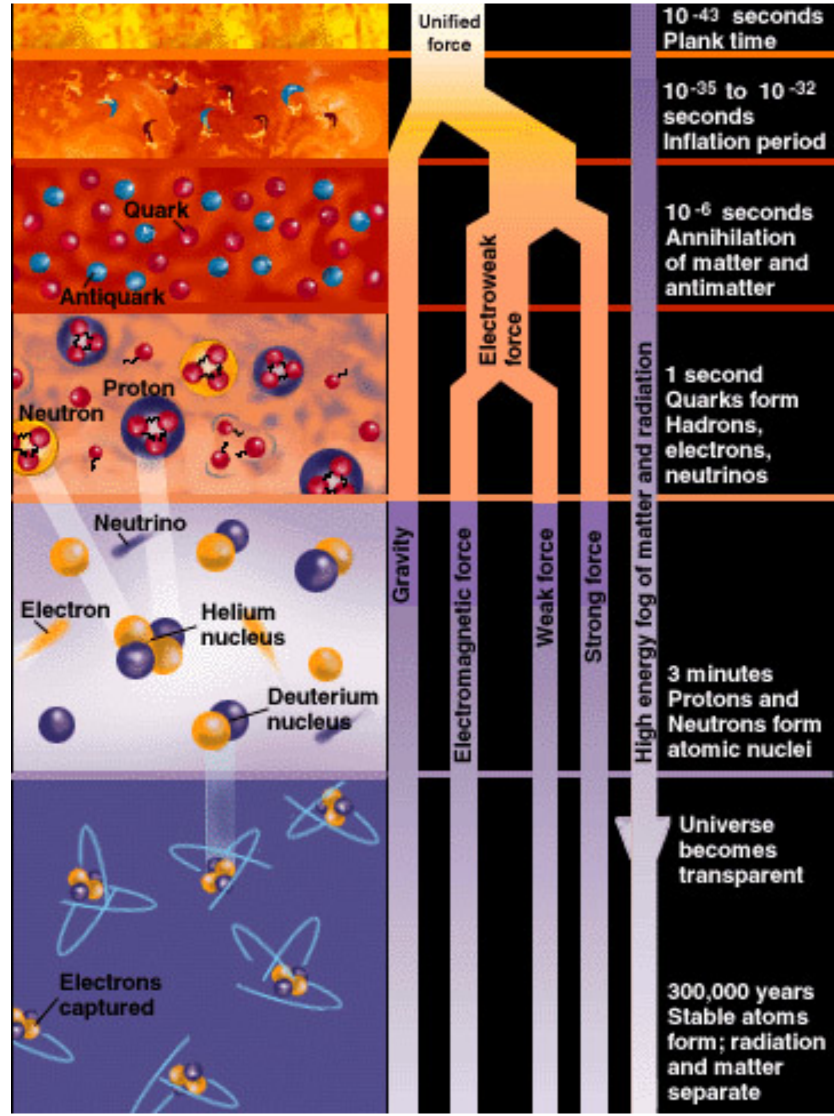
Which of the following statements is NOT correct?

a. Most of the Helium in our universe was formed during the first 3 minutes after the Big Bang
b. Particles and their antiparticles were produced and annihilated continuously in the first part of the first second of the Big Bang
c. Inflation is the 10^{50} expansion of the universe that occurred at 10^{-35} seconds after the Big Bang
d. Inflation made the universe Flat = Critical density
e. All of these are correct

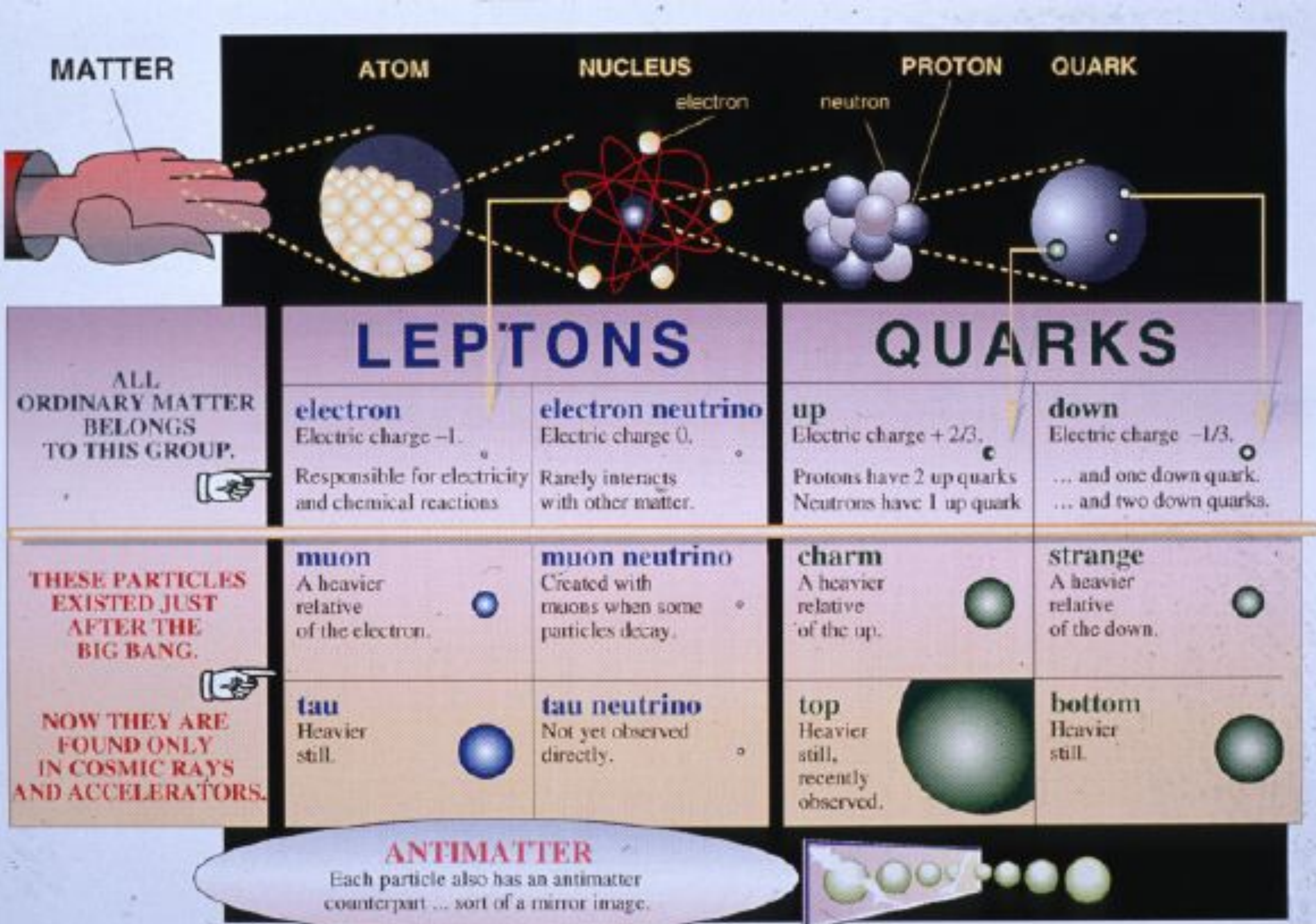
- Primordial Nucleosynthesis formed only helium; no iron?
- Too much or too little matter? or dark energy?

What If ?



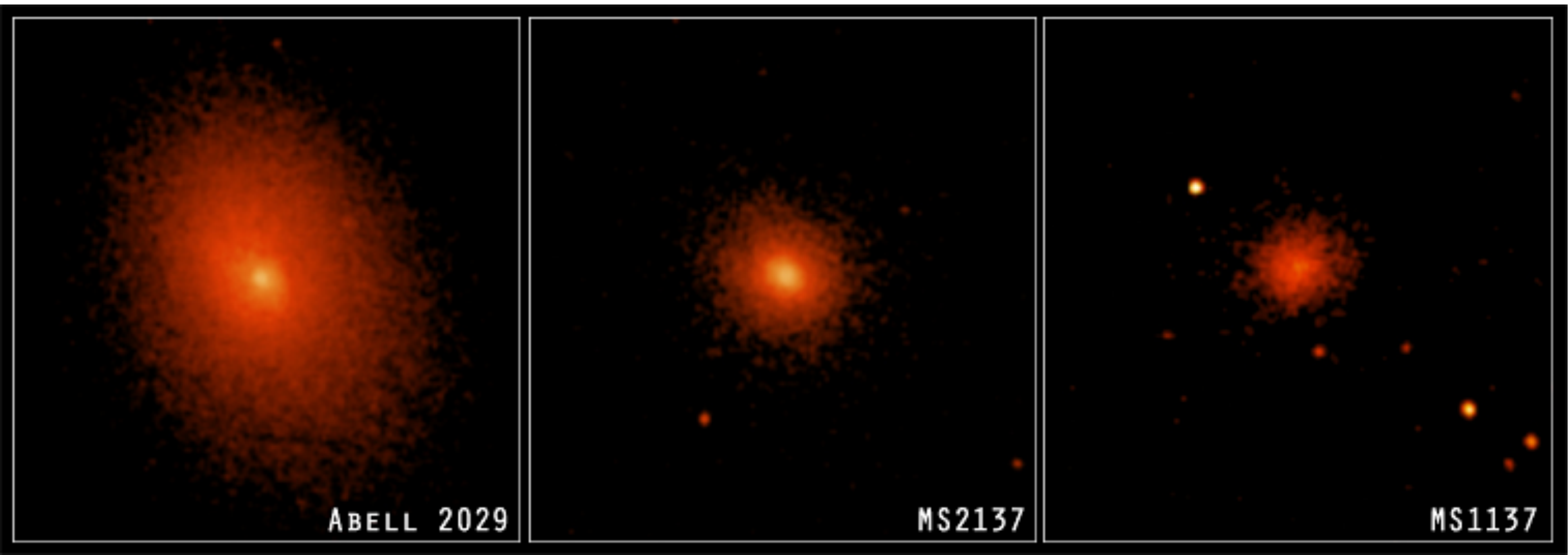


Dark Matter Not Quarks and Leptons



2nd X-Ray Gas → Distance & Velocity

- Ratio of X-ray gas mass to dark matter mass should be constant for homogeneous universe (galaxy cluster sized)
- Gas mass measured by temperature of gas &
- Intrinsic brightness depends on gas mass and temperature
- Plus Apparent brightness gives the distance

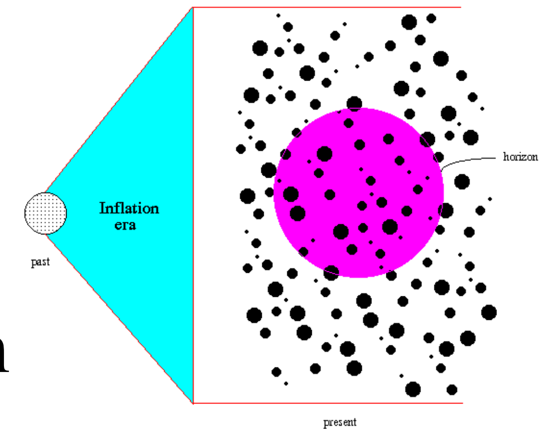


The Horizon Problem

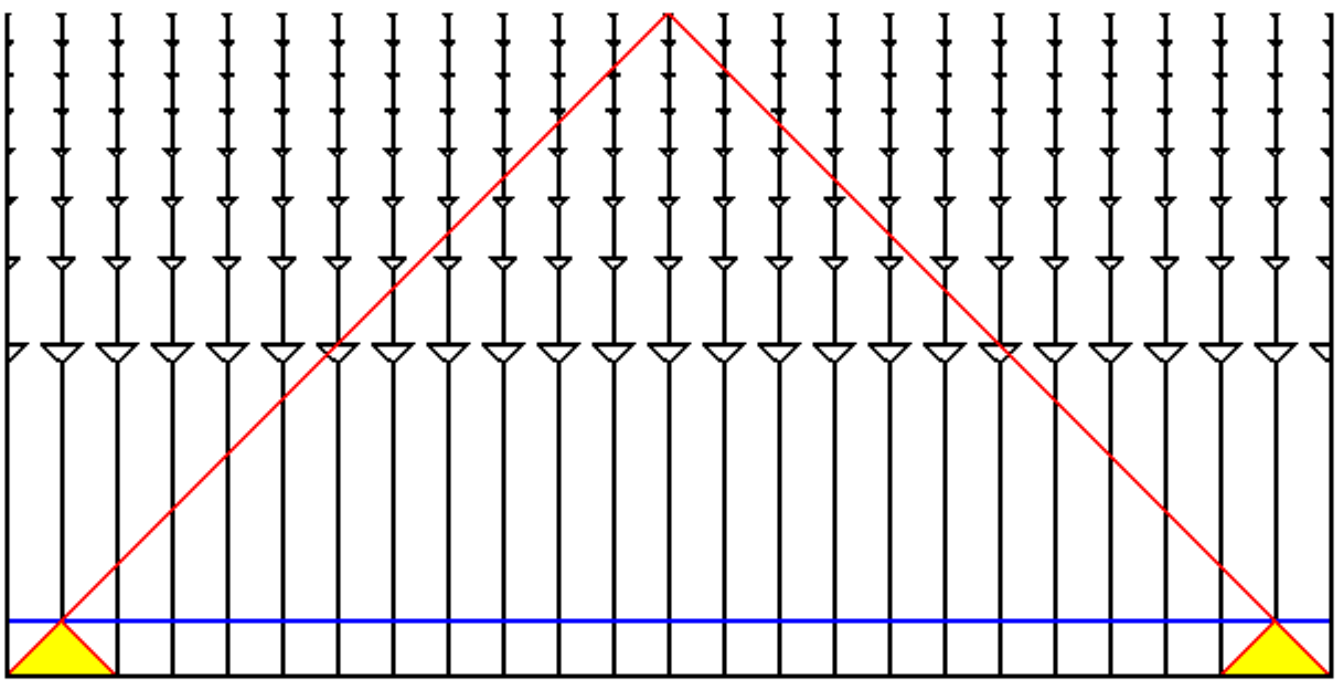
- The red lines delimit our past light cone
- Half way back, half the cone
- The blue line is the "recombination"
- The yellow cones are for two points which
- Are not causally connected and
- Yet they have the same temperature

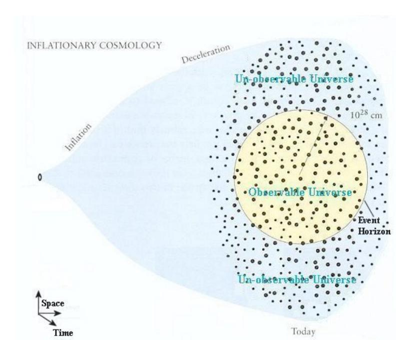
Inflation

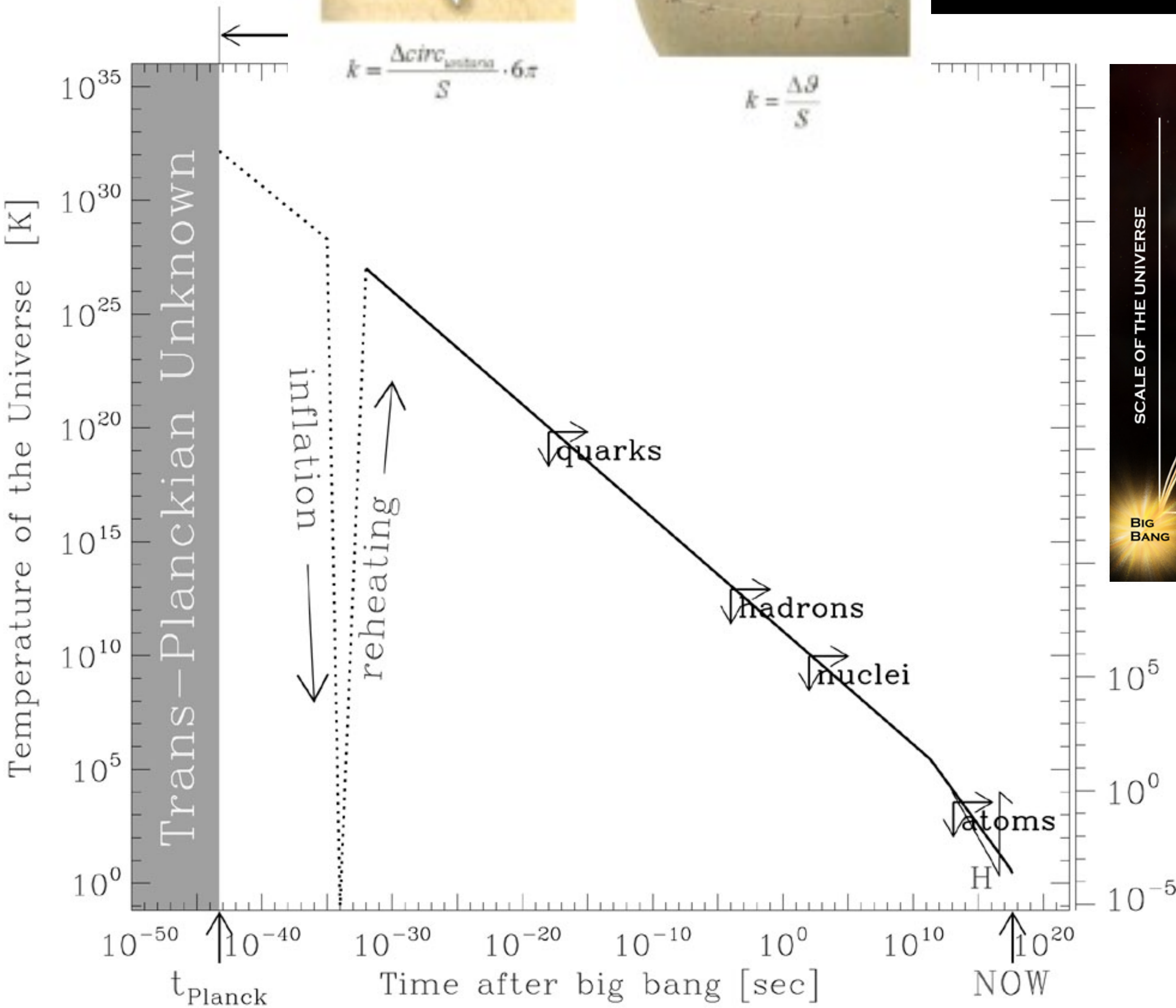
under inflationary cosmology, the Universe underwent a phase change at the GUT era and expanded faster than the speed of light (the spacetime itself expanded, so there is no violation of special relativity)



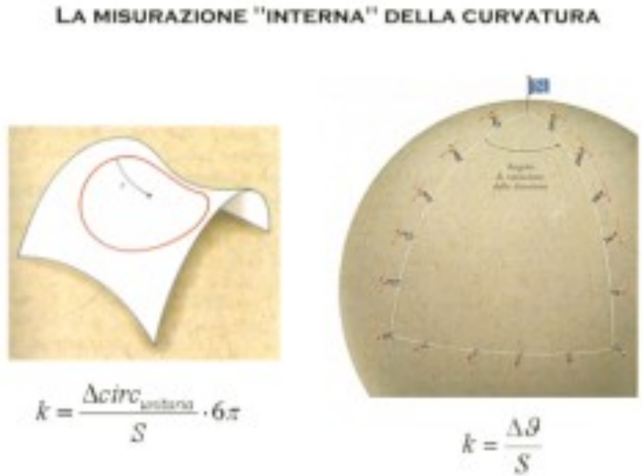
the result is that only a small part of the original Big Bang is within our horizon, what we call our Universe.



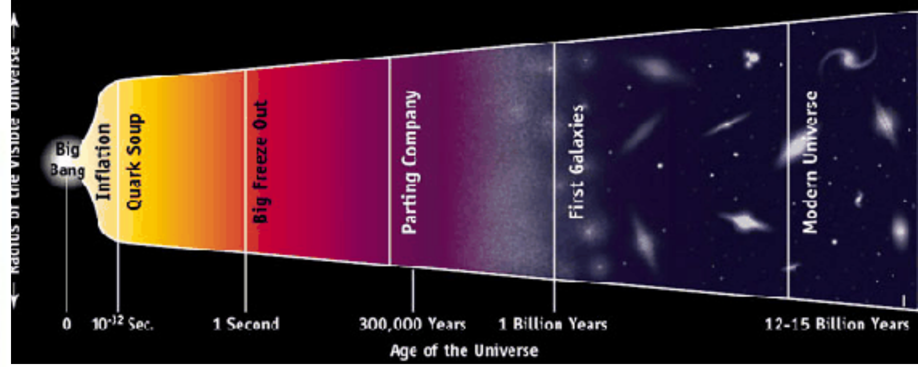




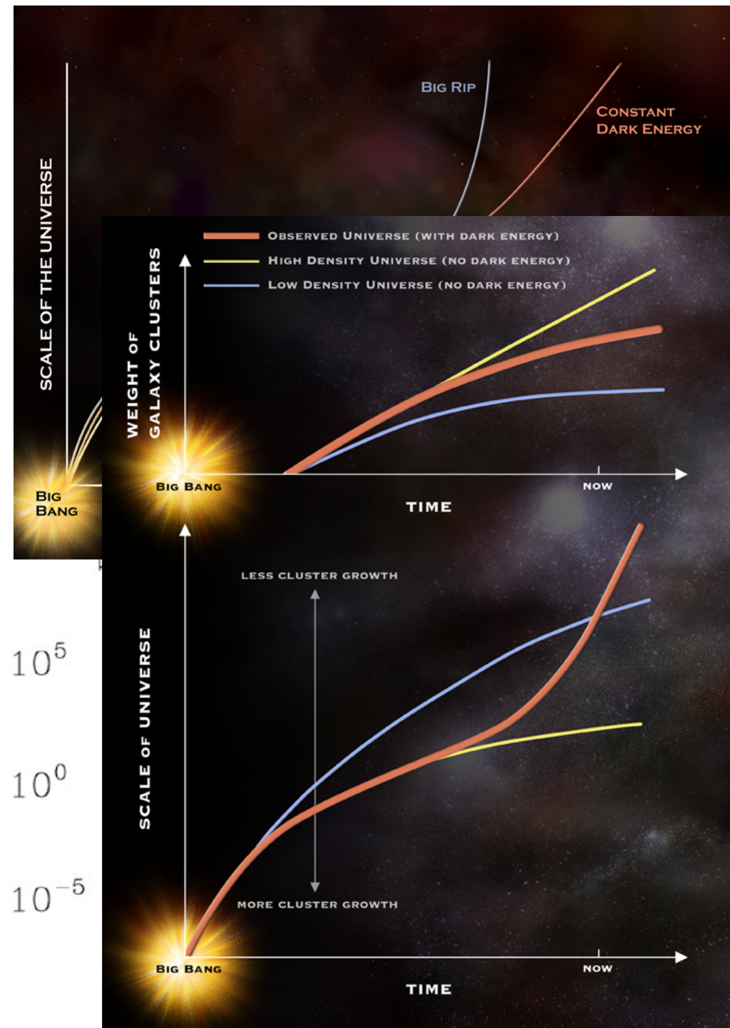
Temperature of the Universe [K]
Trans−Planckian Unknown
inflation
reheating
quarks
hadrons
nuclei
atoms
H
10^{35}
10^{30}
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{0}
10^{5}
10^{0}
10^{-5}
10^{-50}
10^{-40}
10^{-30}
10^{-20}
10^{-10}
10^{0}
10^{10}
10^{20}
t_{Planck}
Time after big bang [sec]
NOW



LA MISURAZIONE "INTERNA" DELLA CURVATURA
$k = \frac{\Delta circ_{unitaria}}{S} \cdot 6\pi$
$k = \frac{\Delta \vartheta}{S}$



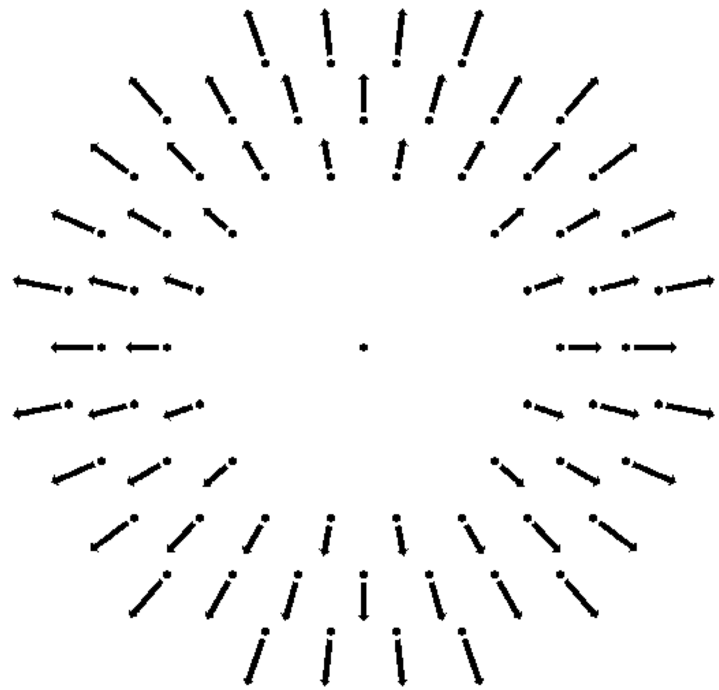
Big Bang
Inflation
Quark Soup
Big Freeze Out
Parting Company
First Galaxies
Modern Universe
0
10^{-12} Sec.
1 Second
300,000 Years
1 Billion Years
12-15 Billion Years
Age of the Universe

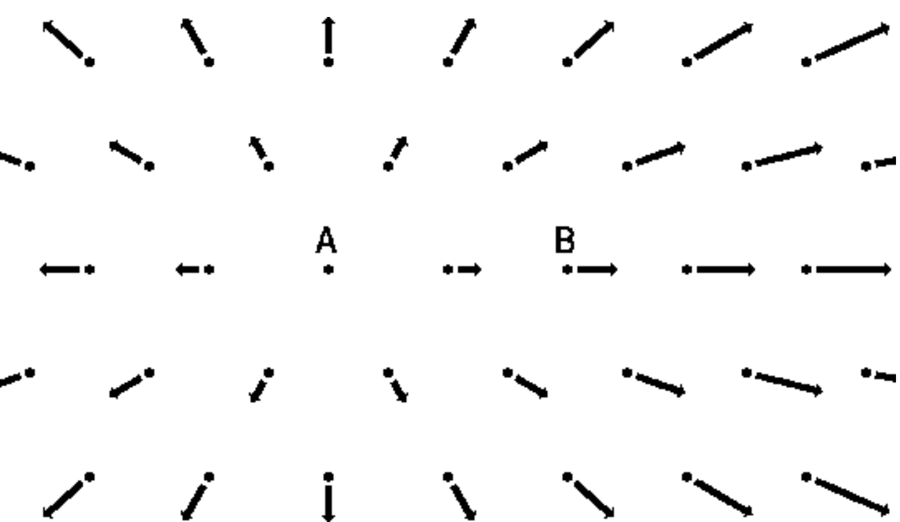


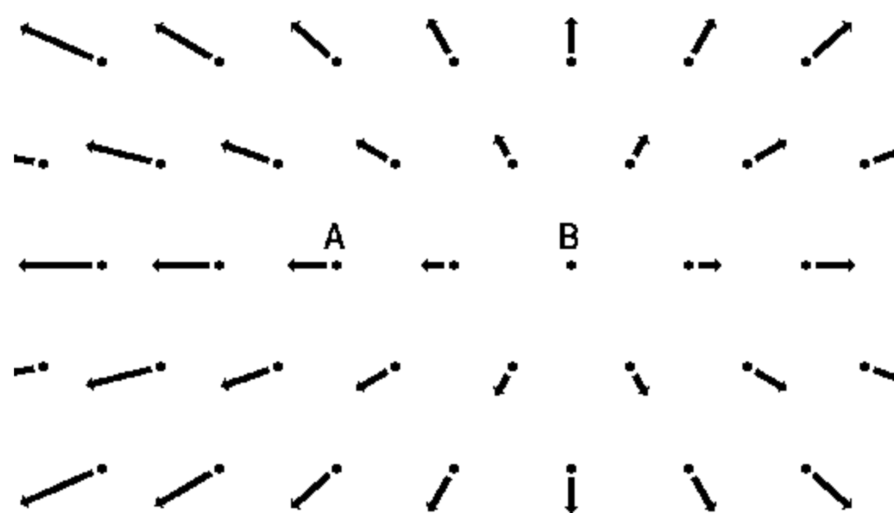
Big Rip
Constant Dark Energy
Scale of the Universe
Big Bang
Observed Universe (with dark energy)
High Density Universe (no dark energy)
Low Density Universe (no dark energy)
Weight of galaxy clusters
Big Bang
Now
Time
Less cluster growth
More cluster growth
Scale of Universe
Big Bang
Now
Time

Homogeneous Expansion

- This top model of the expansion is isotropic but not homogeneous
- From A the expansion is isotropic
- From B the expansion is isotropic too so it is homogeneous as well

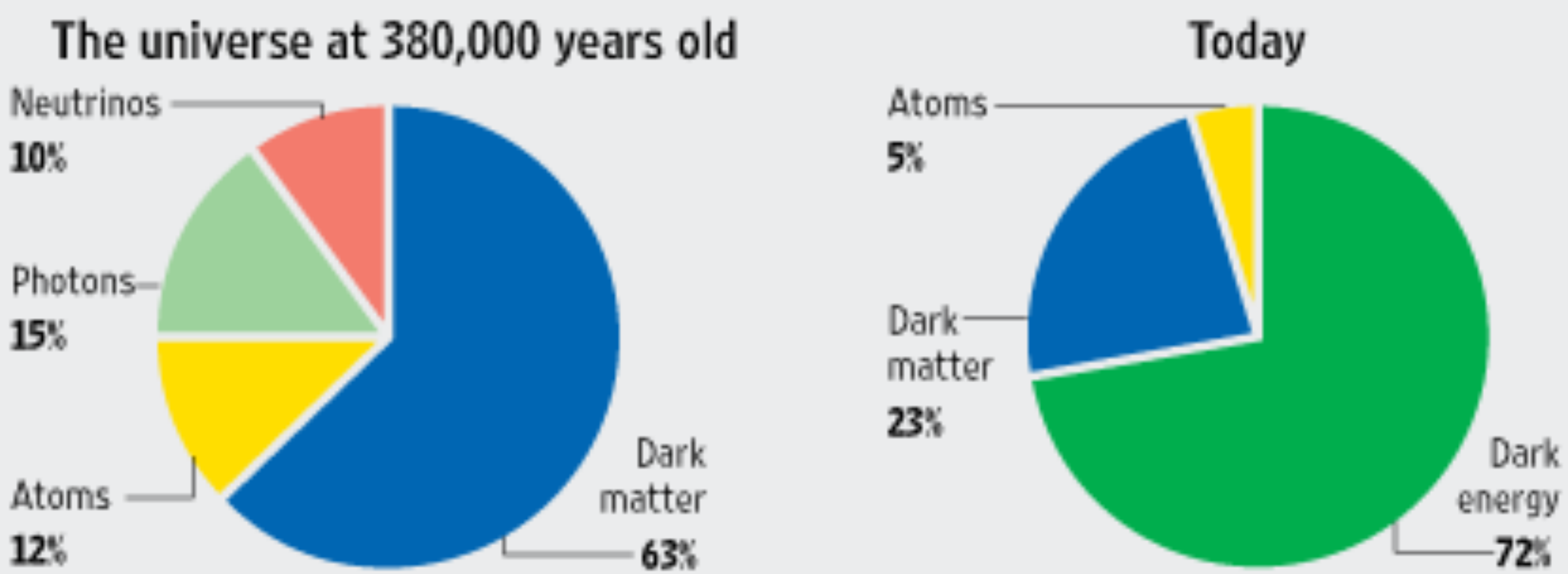




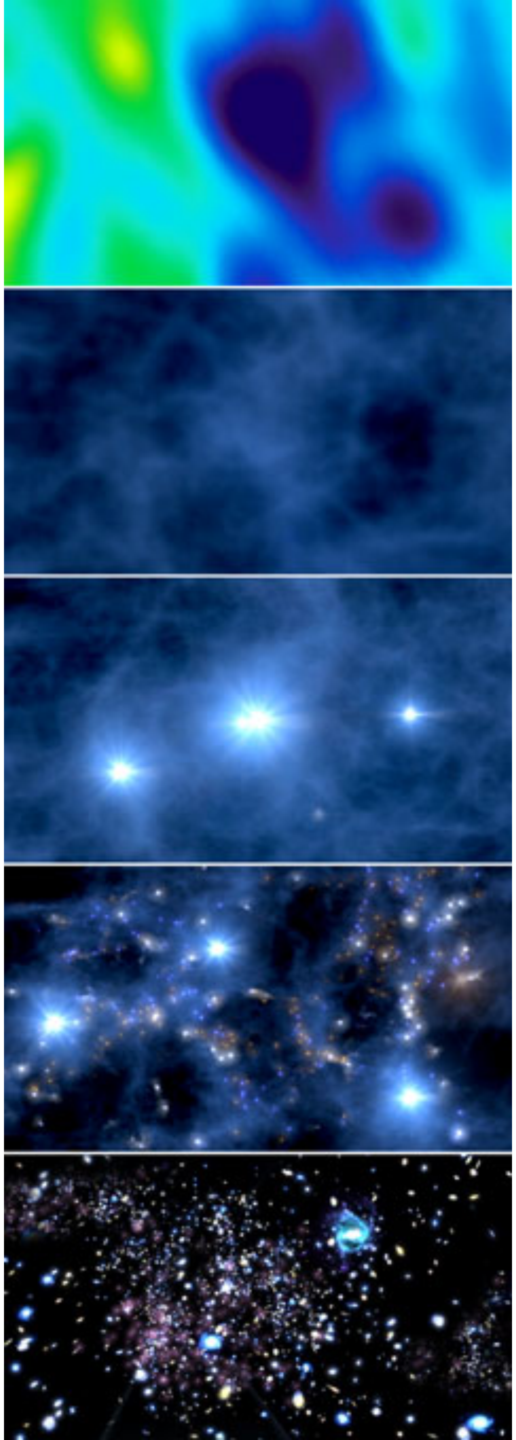


When We Were Young

How the composition of the universe today compares with its origins:

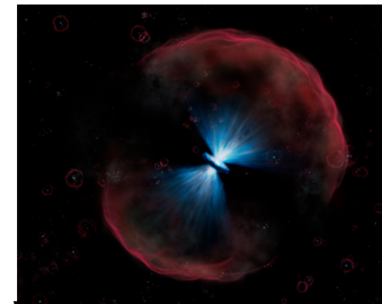


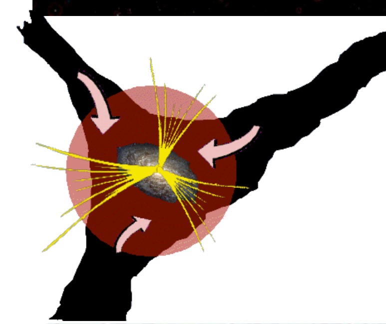
Source: NASA

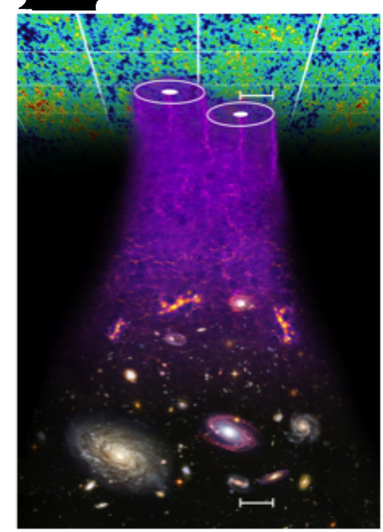


First Star Formation

- Universe started very hot and dense
- During **Dark Age** gravity pulls material from less dense regions
- Dark Age ends when first huge **Population III** stars form at ~200 million years
- **Reionization** = First stars reionize gas between galaxies
- Modern era with billions of galaxies
- Each made of billions of stars







Large Scale Structure

- 250,000 2dF galaxies with spectra out to redshift z=0.2
- Random distribution of galaxies & Actual distribution
- Universe expands
- Gravity pulled galaxies together = merging