QUARK-GLUON PLASMA AND THE EARLY UNIVERSE

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COSMOLOGICAL PRINCIPLE

- Twin assumptions that are foundational to current cosmology
- On large scales (>300 Mpc) the universe is homogeneous
- On large scales the universe is isotropic
- This means the universe has no center

BIG BANG BASICS

- Universe started as “primeval fireball”
  - Enormous heat and density
- Everything in the universe was contained in this primeval fireball
- Universe expanded rapidly causing temperature to fall rapidly
- As temperatures fell, all matter observed today “froze” out

4 PILLARS OF BIG BANG COSMOLOGY

- 1 – Olber's Paradox
- 2 – The Expanding Universe
- 3 – The Helium Abundance
- 4 – Cosmic Microwave Background Radiation

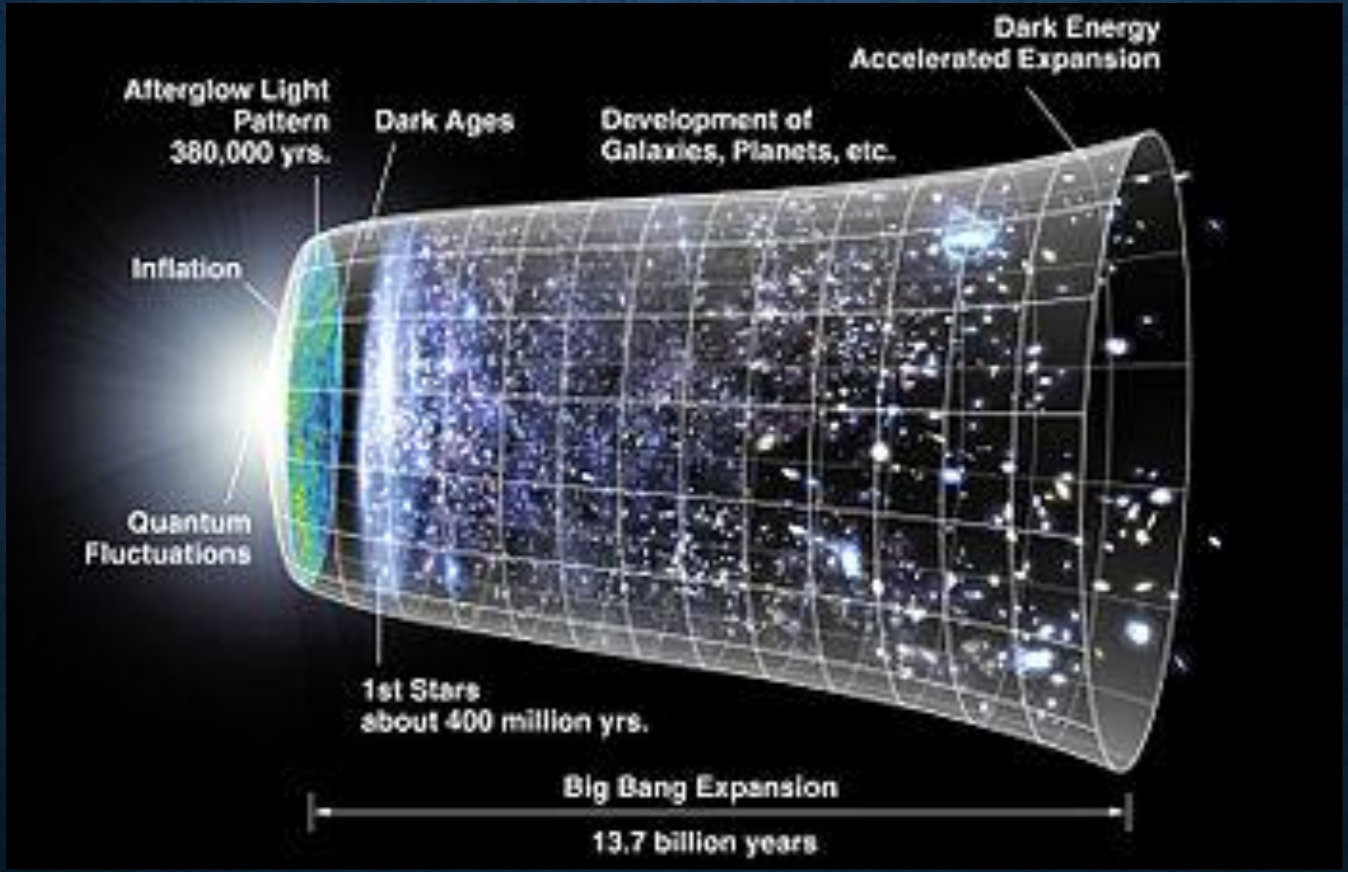
OLBER’S PARADOX

- If universe is infinite and cosmological principle holds, the night sky should be bright
- This is not true, meaning the universe is finite

THE EXPANDING UNIVERSE

- Einstein's theory of general relativity predicted that the universe was expanding, but did not like that prediction so he invented a "fudge factor" to make the universe stable
- Hubble's Law:
    - $v_r = H_0$ x d
        - where H_0 is approx. 70 km/s/Mpc
  - This implies that at some point, all galaxies lay on top of each other
  - Assuming that H_0 has remained constant the time it has taken for each galaxy to move its respective distance away from us is 14 billion years

THE EXPANDING UNIVERSE



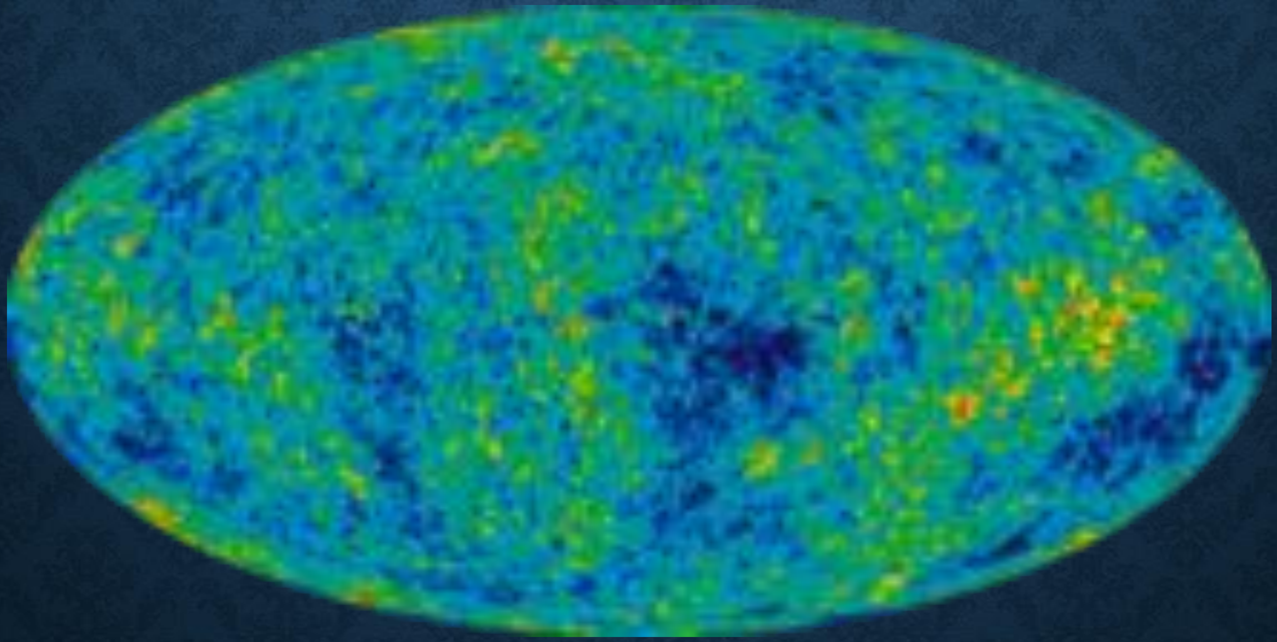
THE HELIUM ABUNDANCE

- The universe cooled so rapidly that 40% of helium in existence today was formed at once
- We should be able to predict the amount of helium in the universe
- The observed results of the fraction of helium in the universe agree with the Big Bang Theory predictions

COSMIC MICROWAVE BACKGROUND RADIATION

- Shortly after the Big Bang, the universe would have been filled with high energy thermal radiation gamma rays
- Researchers at Princeton predicted that this radiation would be redshifted due to the expansion of the universe and would now peak in the microwave range
- This background microwave radiation was discovered in 1964 by accident by scientists at Bell Labs trying to improve the phone system

COSMIC MICROWAVE BACKGROUND RADIATION



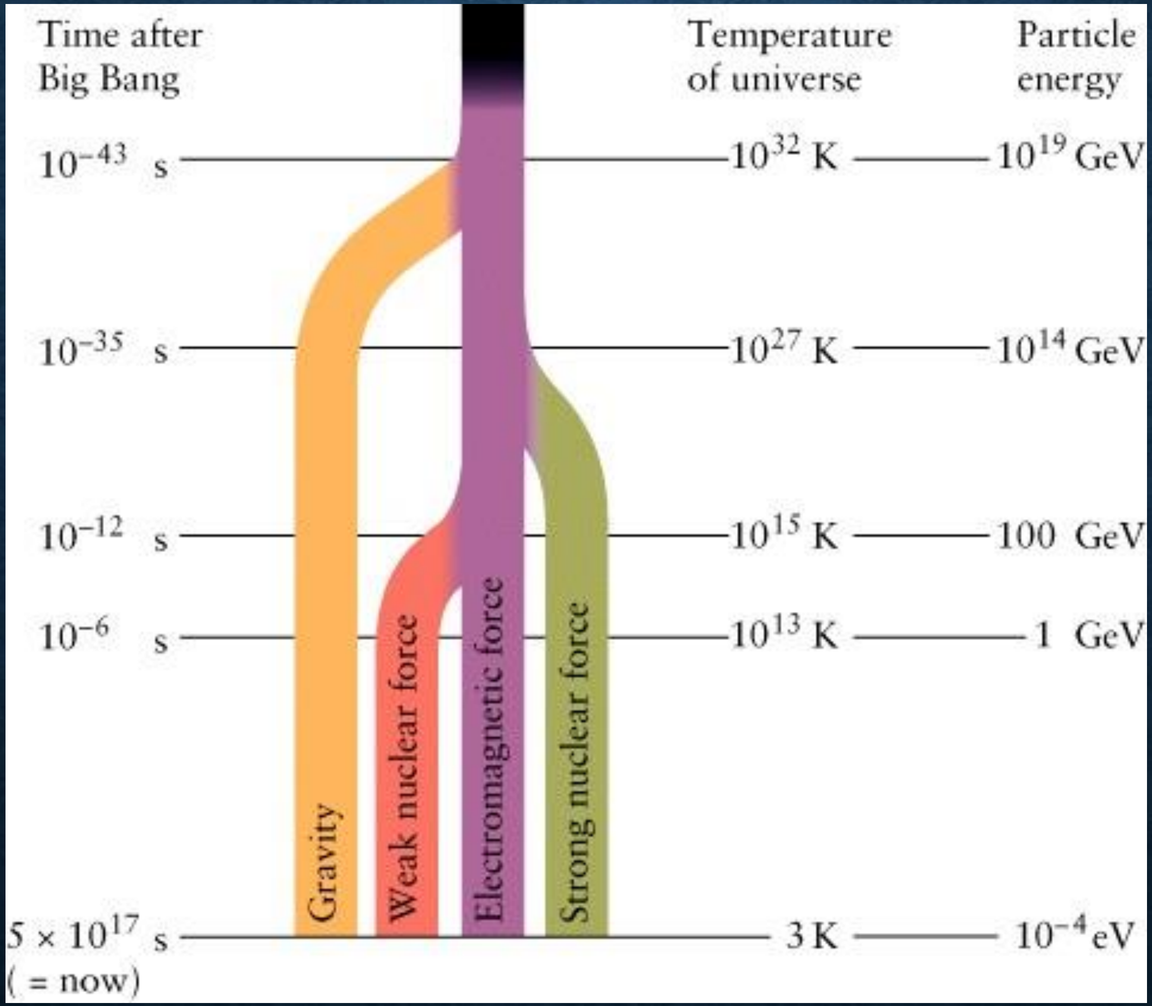
EARLY UNIVERSE WAS RADIATION DOMINATED

- Up until 50,000 years after the big bang, radiation density was greater than matter density and dark energy density
- This is predicted based on the CMBR
- Temperatures were much higher than we experience now
- Pair production occurred at a high frequency during the first few seconds after the big bang

PARTICLE PRODUCTION

- Pair production occurs when high energy electromagnetic energy creates a particle and anti-particle
- These particles can also annihilate each other back into radiation
- The frequency of pair production and size of particles that can be produced are based on the temperature of the environment
- Below a certain "threshold temperature" a given particle can not be produced by pair production

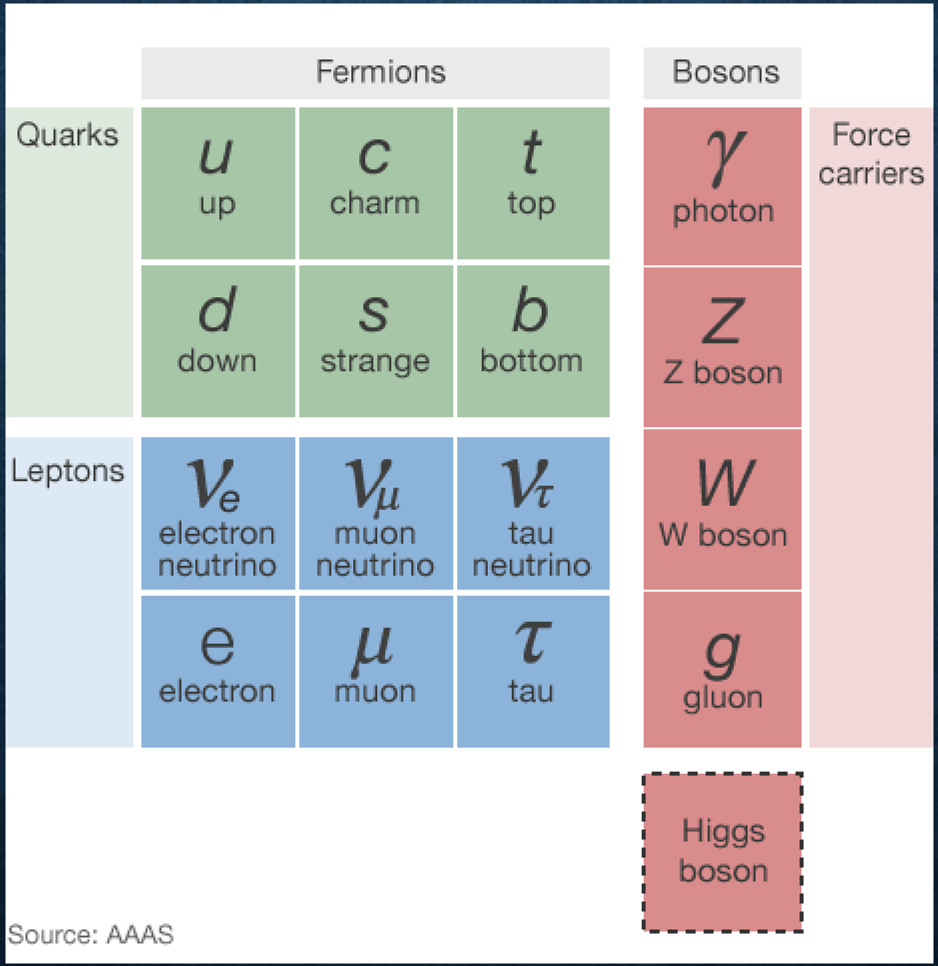
PARTICLE PRODUCTION



STANDARD MODEL

- The universe is made up of 3 kinds of fundamental particles
  - Leptons – Particles not subject to strong force (e.g. electrons)
  - Quarks – 6 “flavors” (up, down, strange, charm, bottom, top)
  - Force-carrying particles – Particles that carry all force interactions between other particles (e.g. photon, gluons)

STANDARD MODEL



Source: AAAS

QUARKS

- Fundamental particles that participate in strong force interactions
- Carry "color" – Analogous to electric charge in QED
- Unlike electric charge which is a scalar charge, color charge is a quantum vector charge
- Never observed in isolation – This is known as confinement
  - Only color-neutral particles appear in nature – Color confinement
- Interact with each other through gluons

GLUONS

- Carrier of the strong force
  - Analogous to photon carrying electromagnetic force
- Unlike photons, there are 8 types of gluons
- Carry color charges

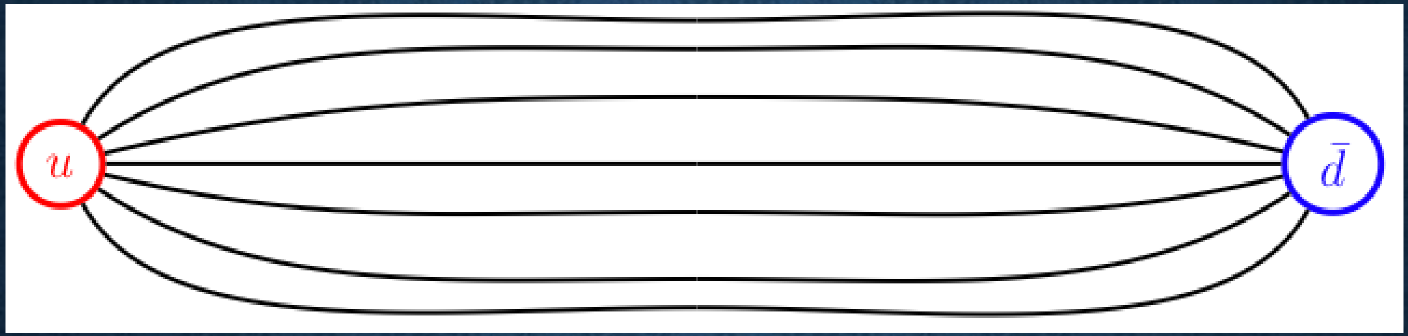
QUANTUM CHROMODYNAMICS

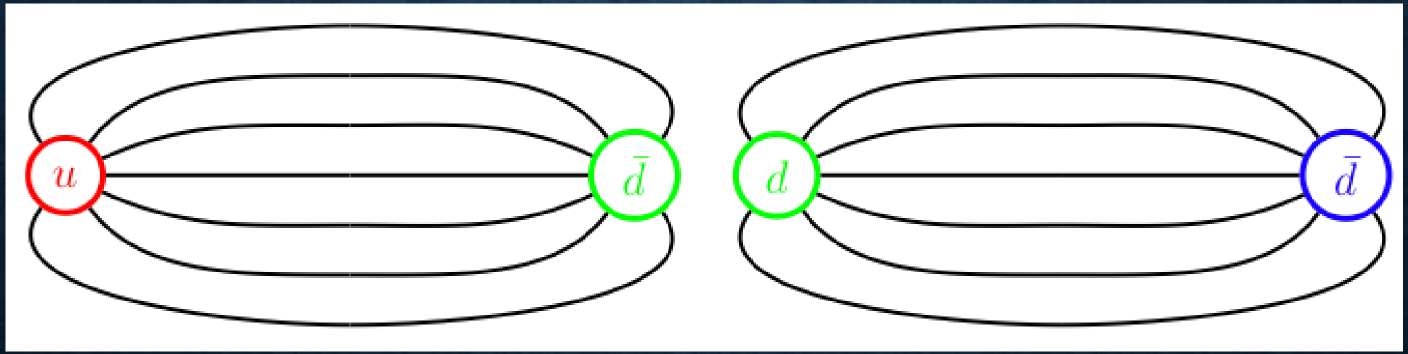
- Study of strong force interactions or the study of quark and gluon interactions
- Two major properties:
  - Confinement
    - No quark can exist alone
  - Asymptotic freedom
    - At high energies, quarks and gluons interact weakly forming a quark-gluon plasma

CONFINEMENT

- As quark-antiquark systems separate, strong gluon interactions continue to affect the two quarks
- The force between two quarks remains constant, but the energy stored in the gluon field between the two quarks increases (V~r)
- This is the different from the potential of gravity and electricity (V~1/r)
- Eventually the energy in the gluon field exceeds the mass energy of a quark-antiquark pair and thus a quark-pair is produced
- As a result, "jets" of hadrons are produced

CONFINEMENT





ASSYMPTOTIC FREEDOM

- Bonds between particles become weaker as energy increases and distance decreases
- Politzer, Gross, and Wilczek won 2004 Nobel Prize in physics for this observation
- Even though the coupling constant between quarks increases with increased distance, the force remains constant

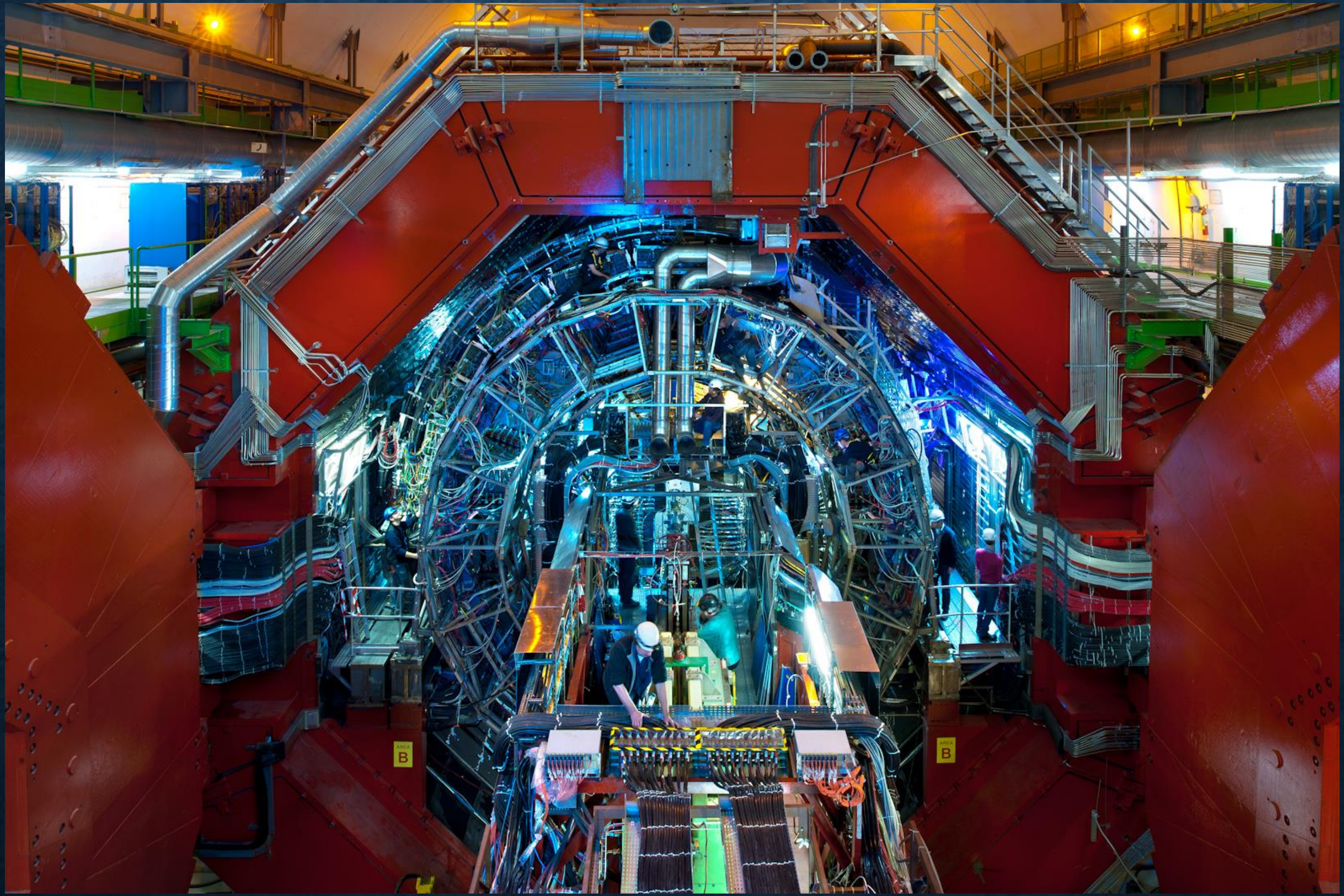
QUARK-GLUON PLASMA

- At very high temperatures (T>100 GeV) all particles were extremely relativistic
- At these temperatures even quarks and gluons interacted weakly due to asymptotic freedom
- At sufficiently high temperatures, quark-gluon plasma can be modeled as a free relativistic parton gas
- As the universe expanded and cooled quarks, antiquarks, and gluons combined to form the matter that we have today

ALICE

- Part of the year, the LHC collides heavy ions such as lead to form small drops of quark gluon plasma
- Temperatures reach over 100,000 times the temperature of the sun
- This creates conditions similar to fractions of a second after the big bang
- Large particle detectors are used to collect data used to study properties of the quark-gluon plasma and its transition to the baryonic phase

ALICE



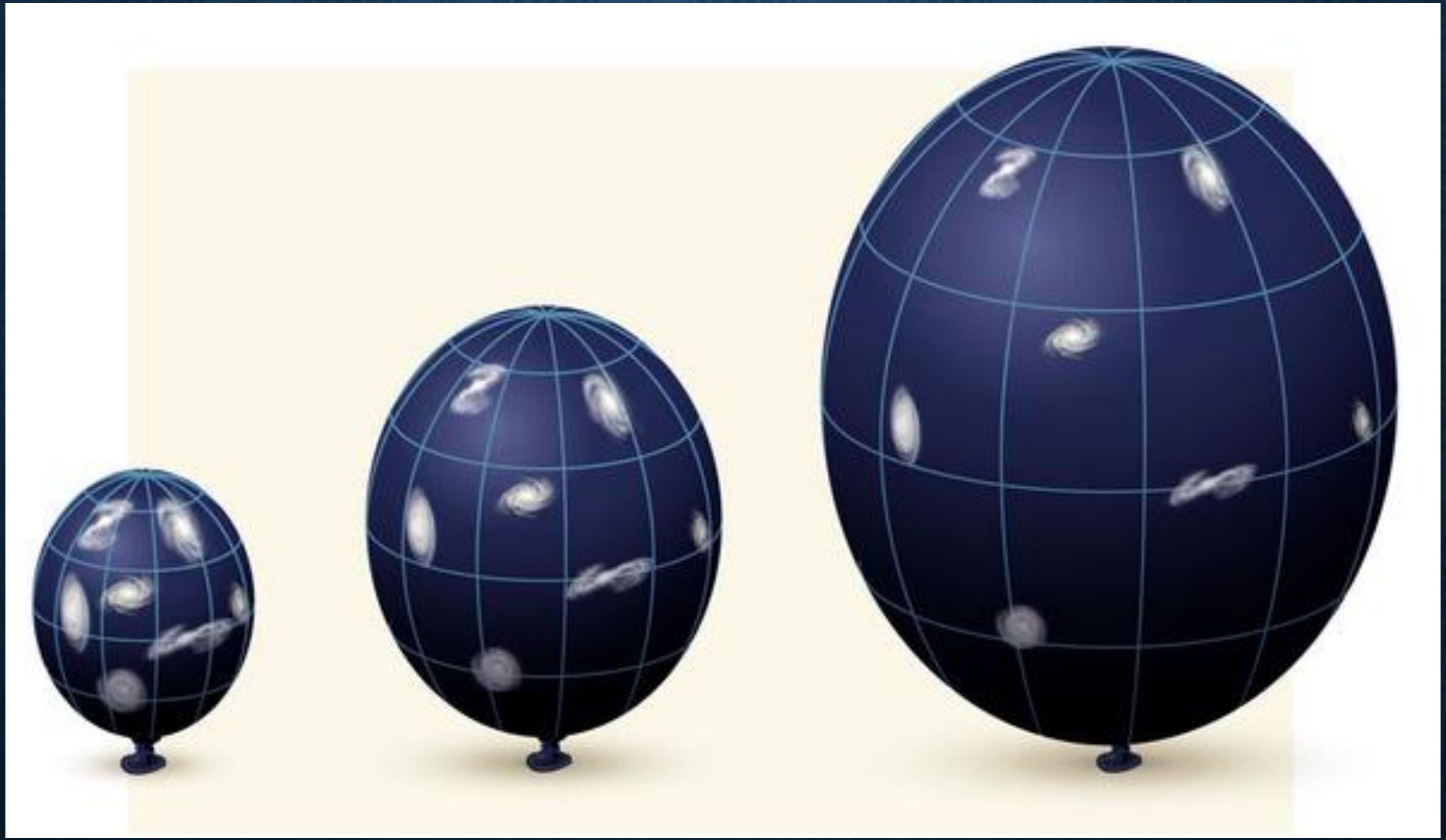
IMPORTANCE OF ALICE

- Provides evidence for quantum chromodynamics
  - Confinement
  - Assymptotic freedom
- Provides evidence for theory of transition from quark-gluon plasma to baryonic state
- Alice has found jets of pions and kaons whose directionality and composition give insight into the properties of the quark-gluon plasma

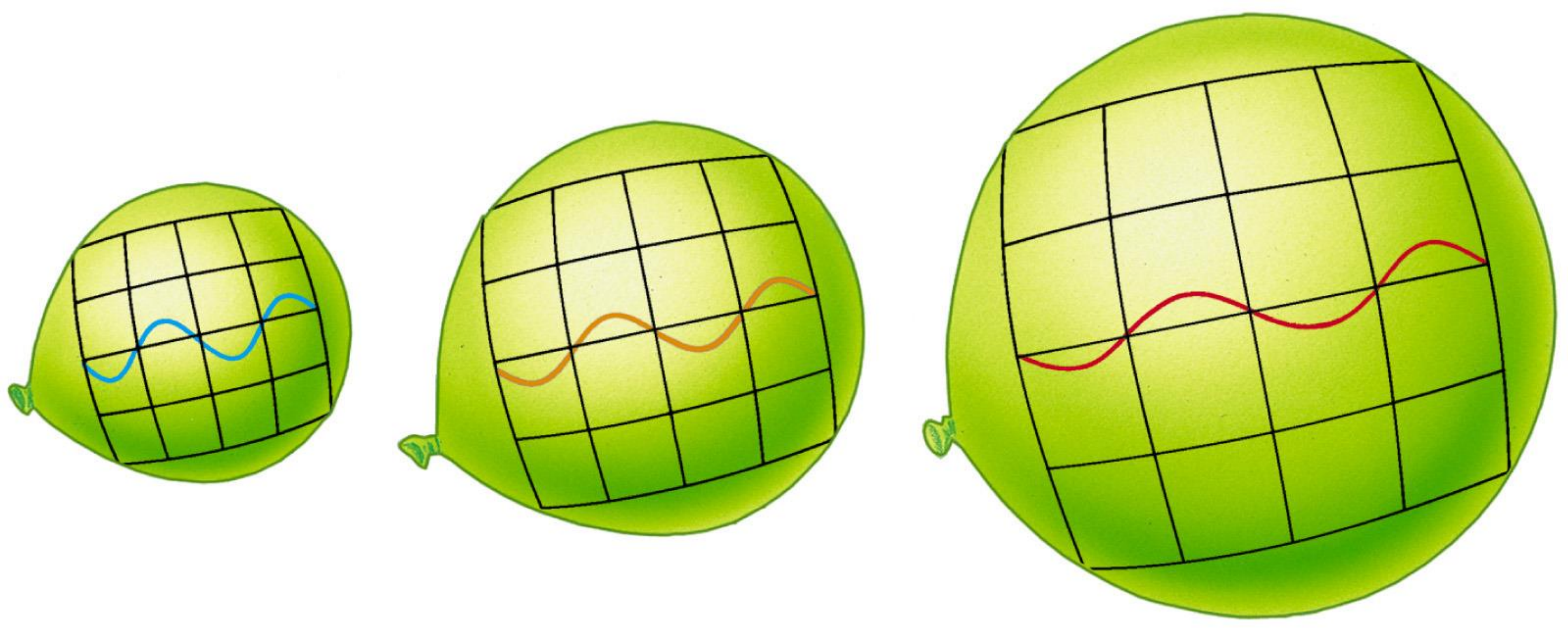
DISCUSSION QUESTIONS

- If only 40% of the Helium in the universe was formed shortly after the Big Bang, what process is hot enough to have formed the other 60%?
- How can a universe that expanded from one point have no center?
- What observations could researchers have used to estimate the peak radiation expected from the CMBR before its discovery?

THE EXPANDING UNIVERSE



CMBR



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