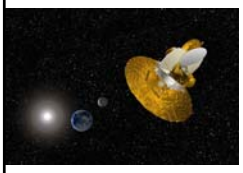
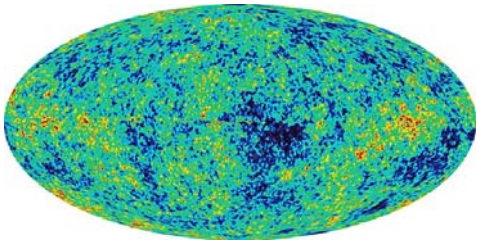
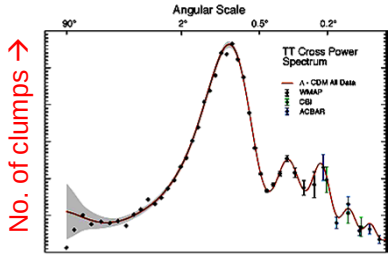
Measuring the Shape of the Universe



WMAP
Wilkinson
Microwave
Anisotropy Probe
Launched 2001

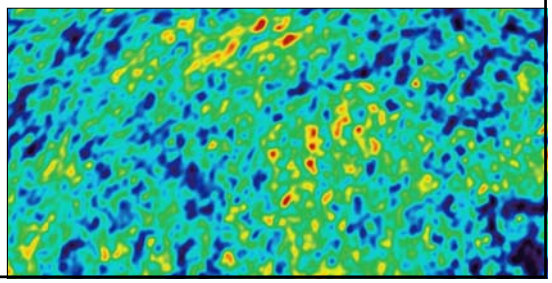


Cosmic Microwave Background map



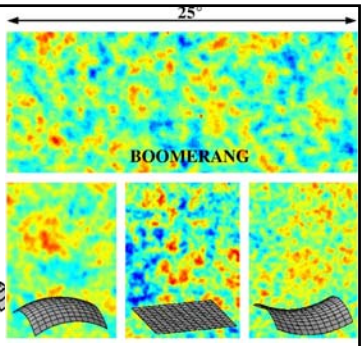
← Larger angular size

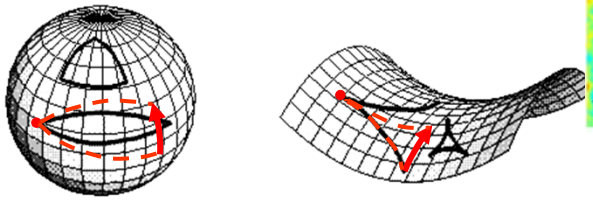
Measure amount of structure on different angular scales.



Measuring the Shape of the Universe

Average size in LY of density fluctuations is known

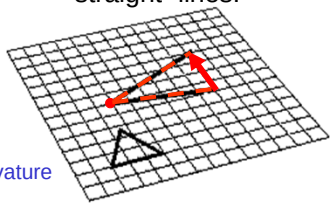




Positive Curvature

Negative Curvature

Light follows "straight" lines:

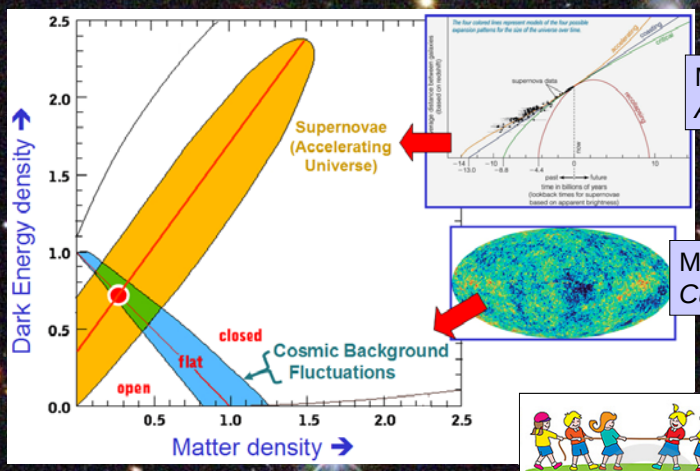


Flat Curvature

Different curvatures
➔ different lensing effects
➔ different angular size on sky

The Answer:
The Universe is FLAT

What is the Universe Made Of ?



Measures *Acceleration*

Measures *Curvature*

Acceleration = (Dark Energy) – (Matter)
Curvature = (Dark Energy) + (Matter)

What is the Universe Made Of ?

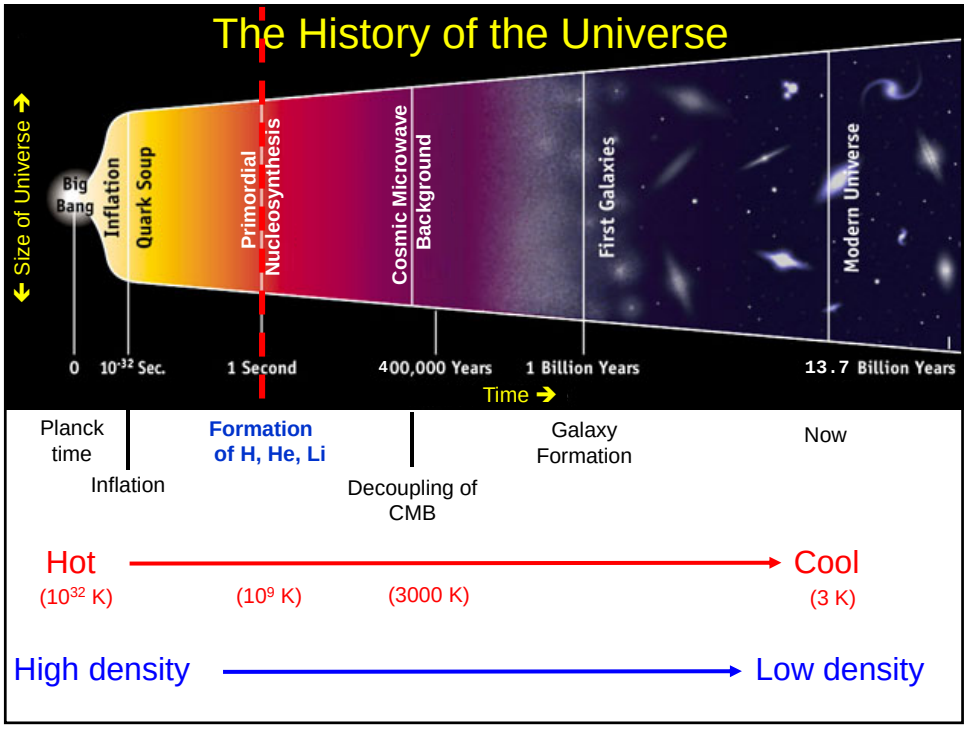
This is the only part we see.

4% ~~15%~~ Normal Matter
- protons, neutrons, electrons.
- arranged into *atoms*

23% ~~85%~~ Dark Matter

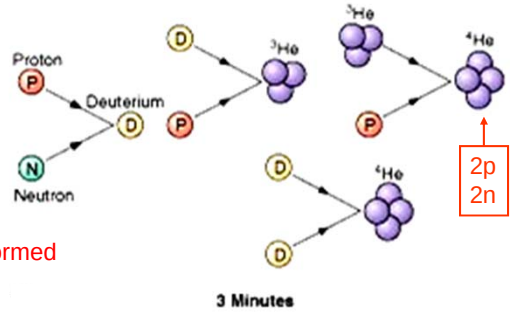
We infer it is there, but we don't know what it is.

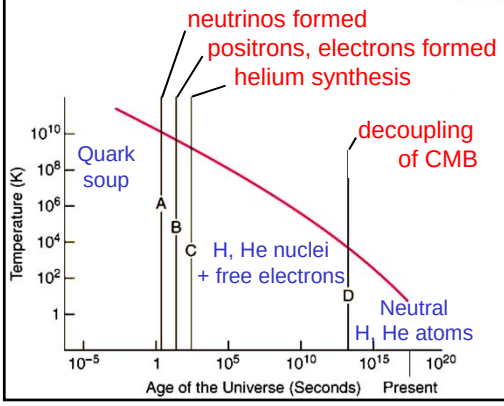
73% Dark Energy
(using $E = mc^2$)



Where did Hydrogen and Helium come from?

- Nucleosynthesis in the Big Bang.
- First 3 minutes.

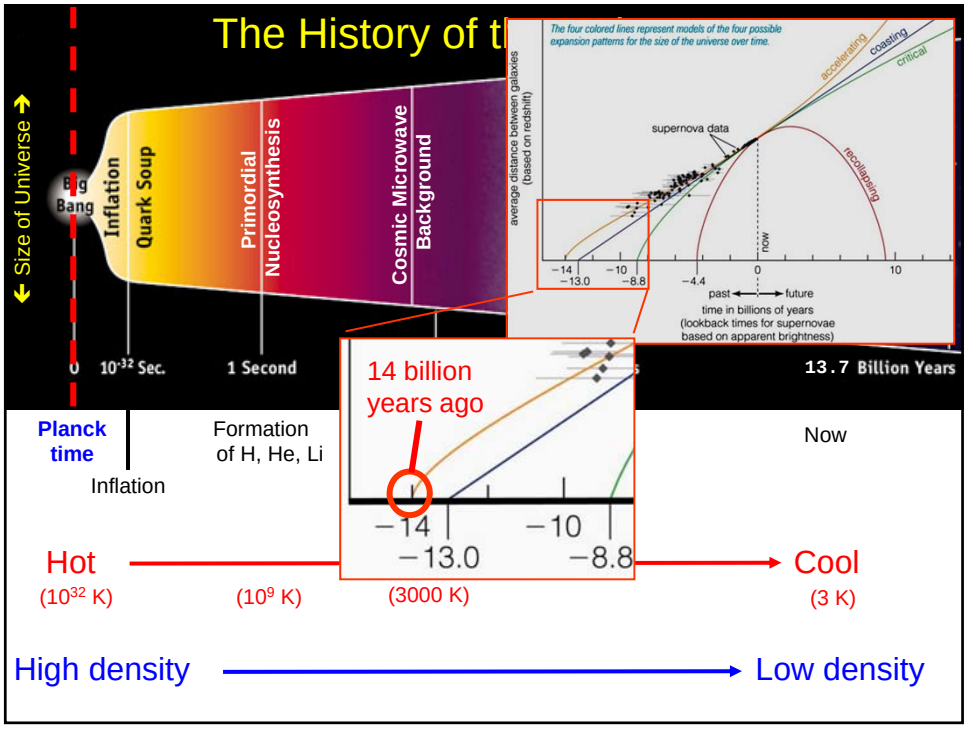


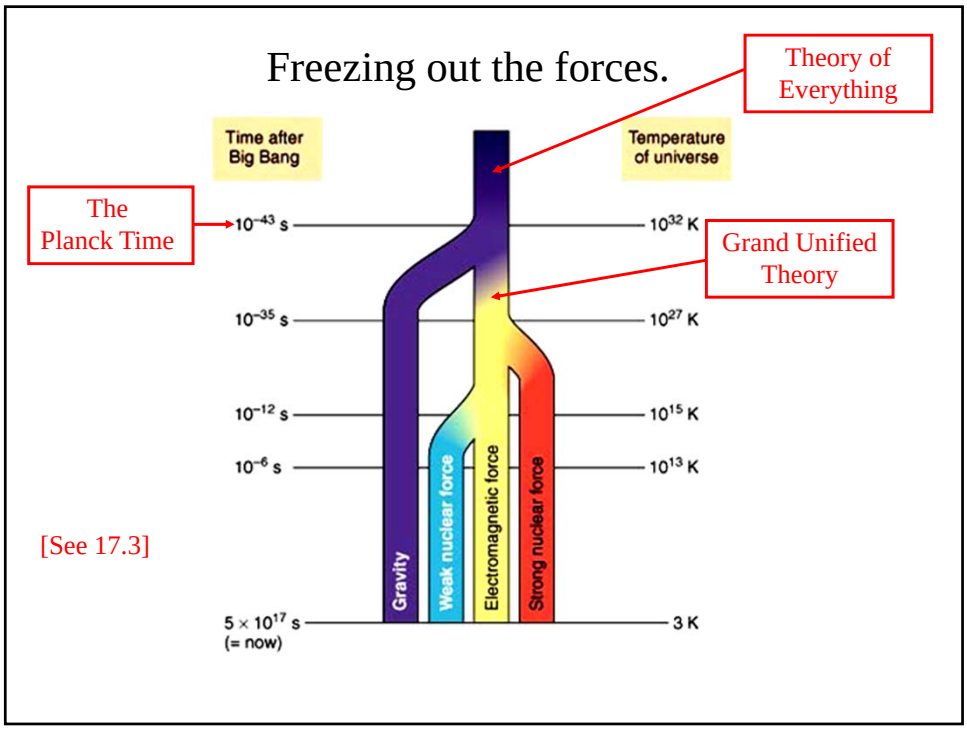


Produced 75% H
25% He

Some Lithium also formed

Then all heavier elements formed by *stars*.


The History of t
Size of Universe
Big Bang
Inflation
Quark Soup
Primordial Nucleosynthesis
Cosmic Microwave Background
0
10⁻³² Sec.
1 Second
13.7 Billion Years
The four colored lines represent models of the four possible expansion patterns for the size of the universe over time.
average distance between galaxies (based on redshift)
accelerating
coasting
critical
supernova data
recollapsing
now
past
future
time in billions of years (lookback times for supernovae based on apparent brightness)
14 billion years ago
Planck time
Inflation
Formation of H, He, Li
Now
Hot
(10³² K)
(10⁹ K)
(3000 K)
Cool
(3 K)
High density
Low density


Freezing out the forces.
Theory of Everything
Time after Big Bang
Temperature of universe
The Planck Time
Grand Unified Theory
10⁻⁴³ s
10³² K
10⁻³⁵ s
10²⁷ K
10⁻¹² s
10¹⁵ K
10⁻⁶ s
10¹³ K
5 × 10¹⁷ s (= now)
3 K
Gravity
Weak nuclear force
Electromagnetic force
Strong nuclear force
[See 17.3]