The Dark Side of the Universe

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What is the universe made of?

- 5% ordinary atoms
- 30% dark matter
- 65% dark energy

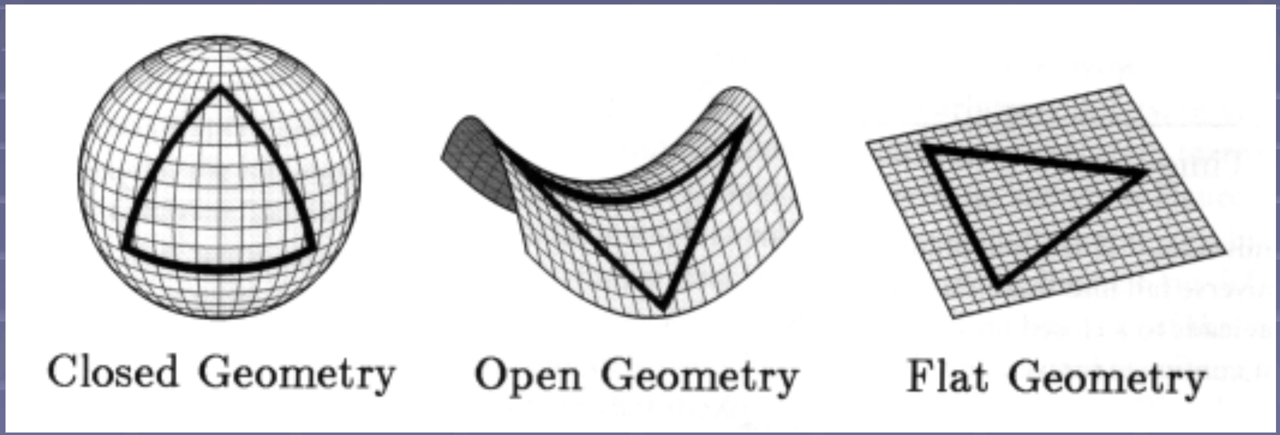
Last week, we discussed dark matter.

This week, the other pieces.

The components of the universe

- How do we know the total mass density and geometry? From measurements of the Cosmic Background Radiation.
- How do we know that ordinary atoms are 4% of the total? Element abundances from nucleosynthesis and the CBR.
- How do we know about the 65% dark energy in the universe? Supernovae.
- What is the dark energy?

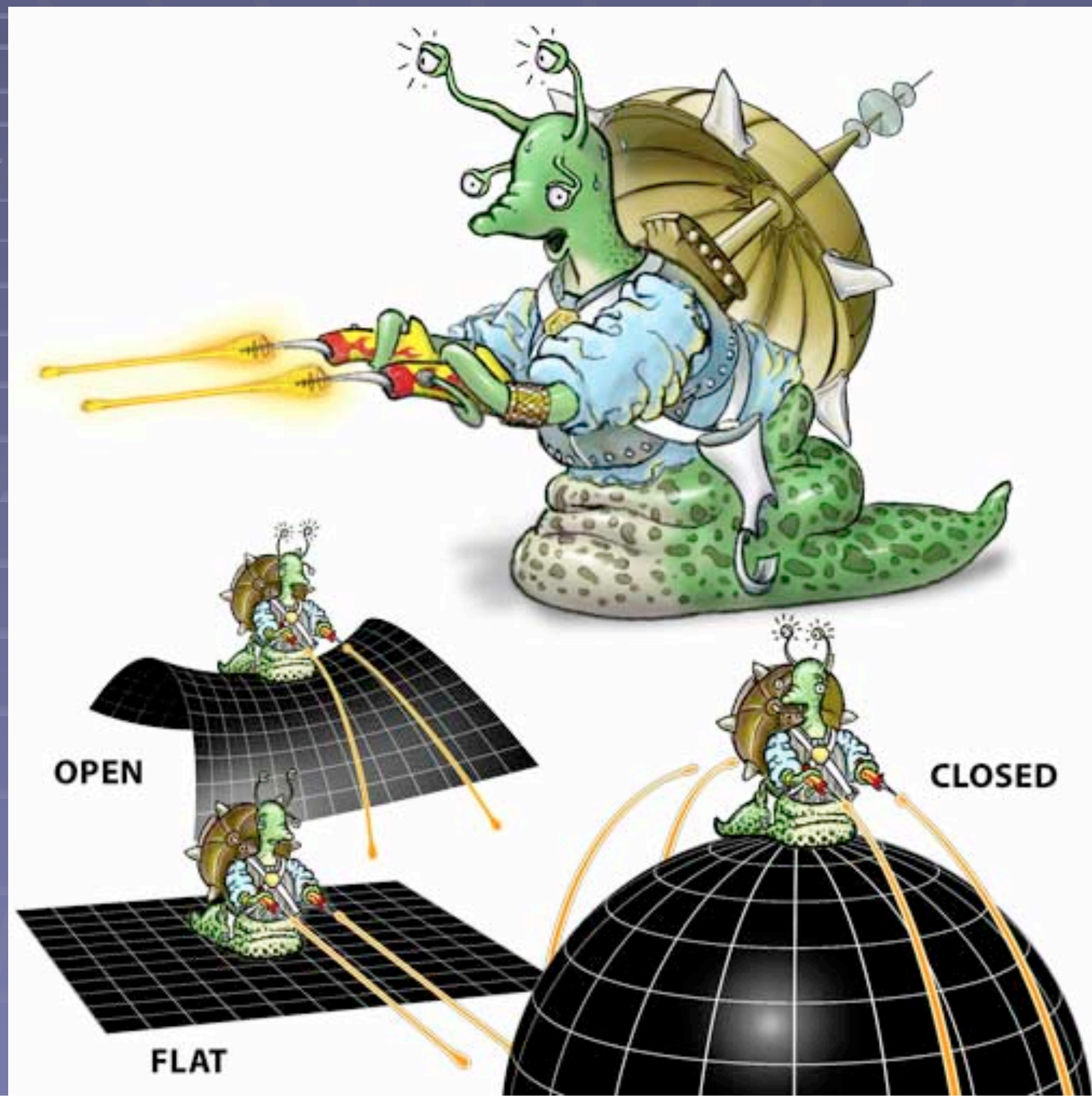
Geometry of the Universe



1930: Three possible geometries for the universe

2000: The geometry of the universe is FLAT!!!!!!

Geometry of the Universe



The amount of mass determines the geometry and the evolution

- The energy density of the universe is

$$\rho = \rho_c = 10^{-29} \text{ gm/cm}^3$$

3

(compare to water, which has 1 gm/cm)

- The geometry is flat.

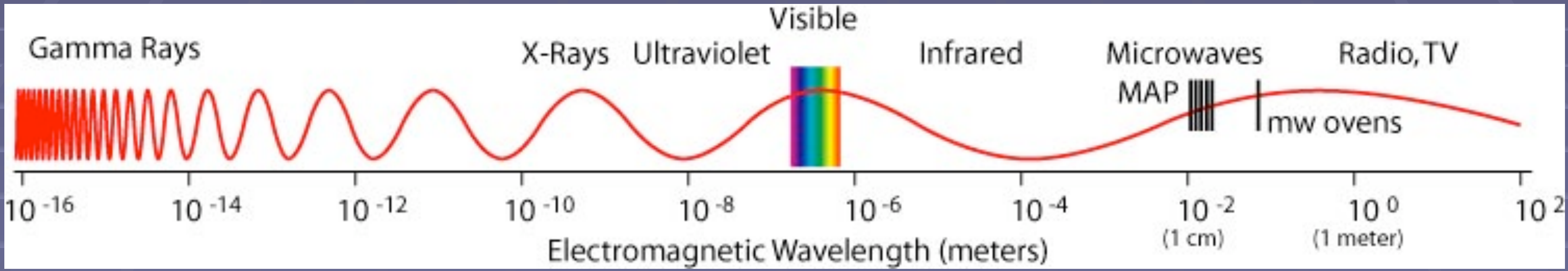
HOW DO WE KNOW THE GEOMETRY AND ENERGY DENSITY? MICROWAVE BACKGROUND EXPERIMENTS.

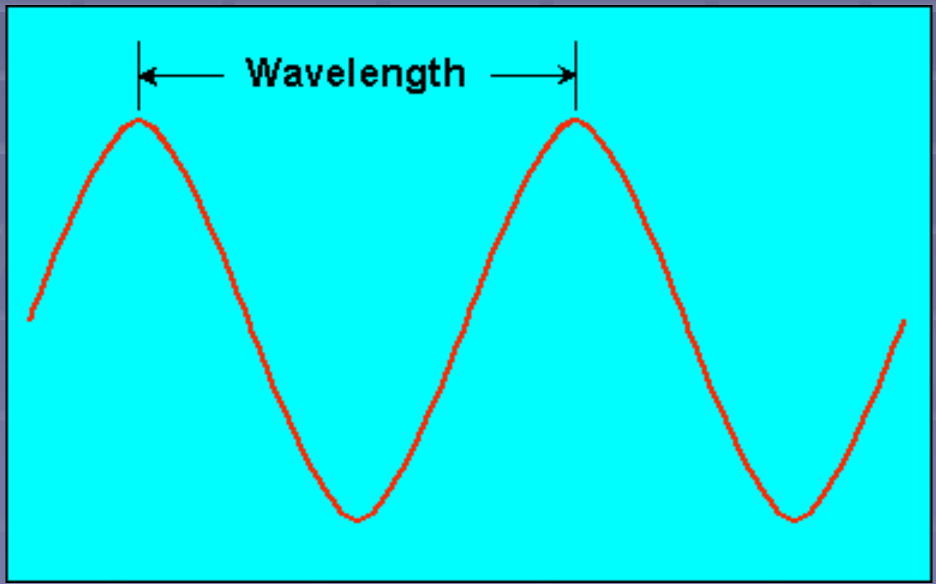
Cosmic Background Radiation

- Today we are still bathed in the faint glow of microwave radiation left over from the hot early phase of the universe.
- This radiation is one of our best probes of cosmology.
- New data was released by the WMAP satellite in February.
- One of the “hottest” areas in cosmology!

The Electromagnetic Spectrum

All electromagnetic radiation is made of photons, or light particles, of different wavelengths.





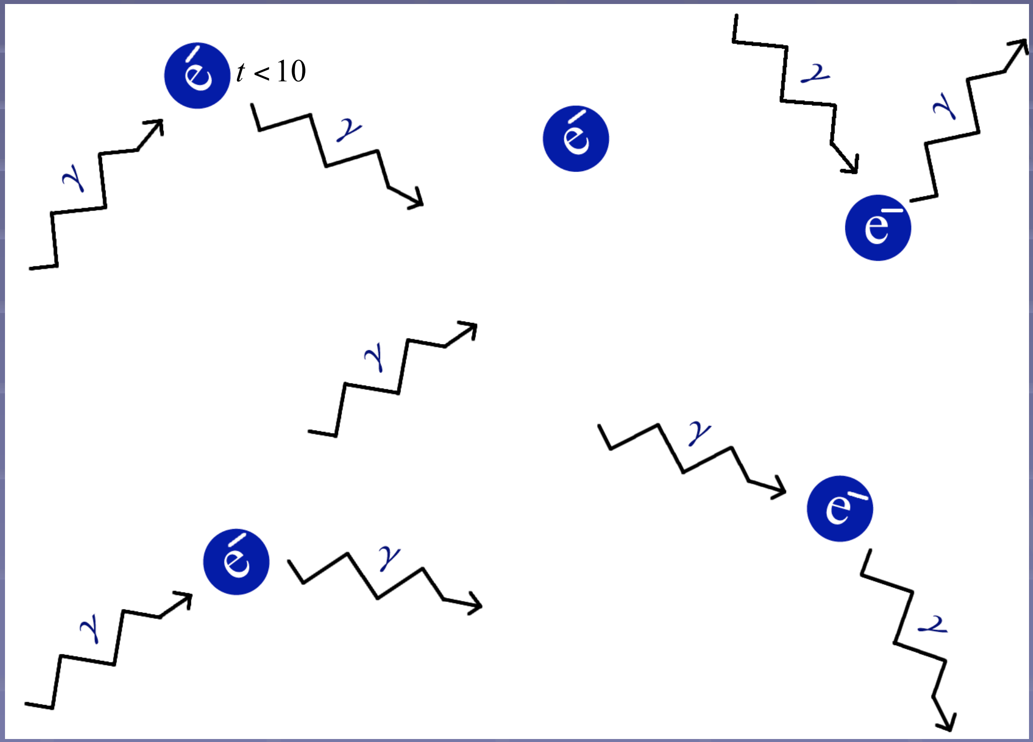
Microwave Background Experiments determined that the universe has a FLAT geometry, and determined the total amount of matter/energy density in the universe.

Cosmic Background Radiation

- Early on, the photons interacted constantly with electrons. Light couldn't travel even a millimeter; the universe was opaque .

Age < million years,
Temperature>3000K

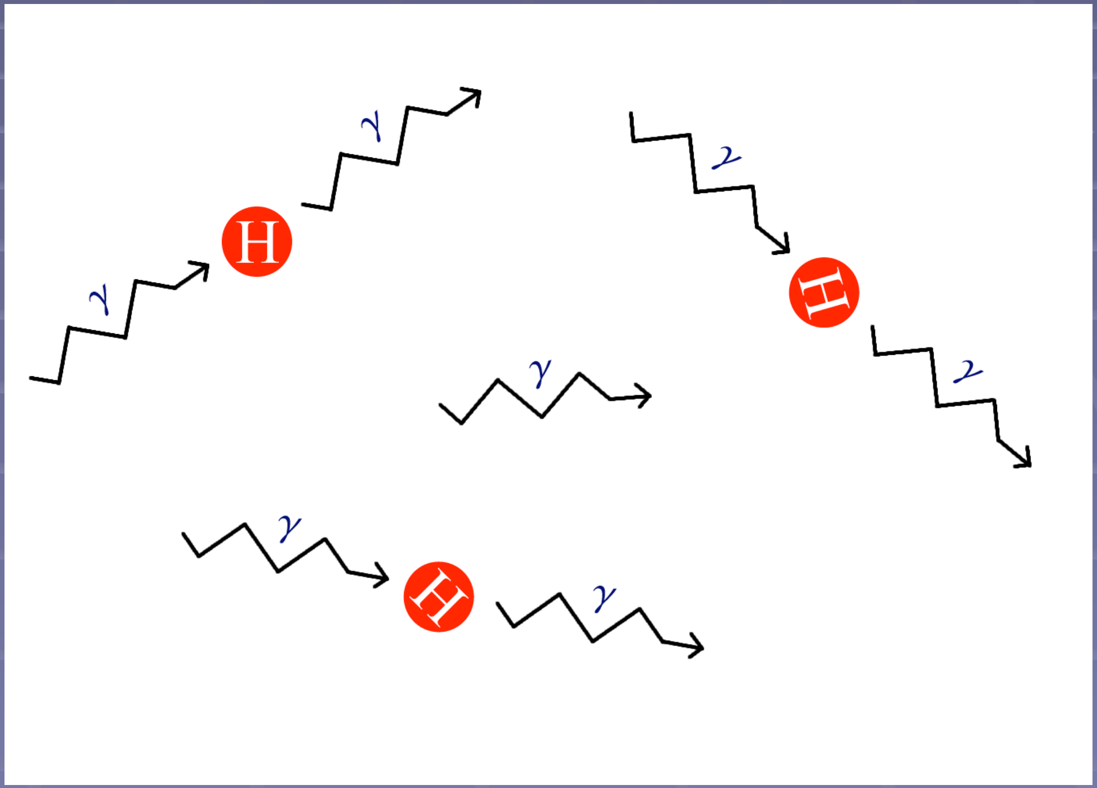
Can't see anything!

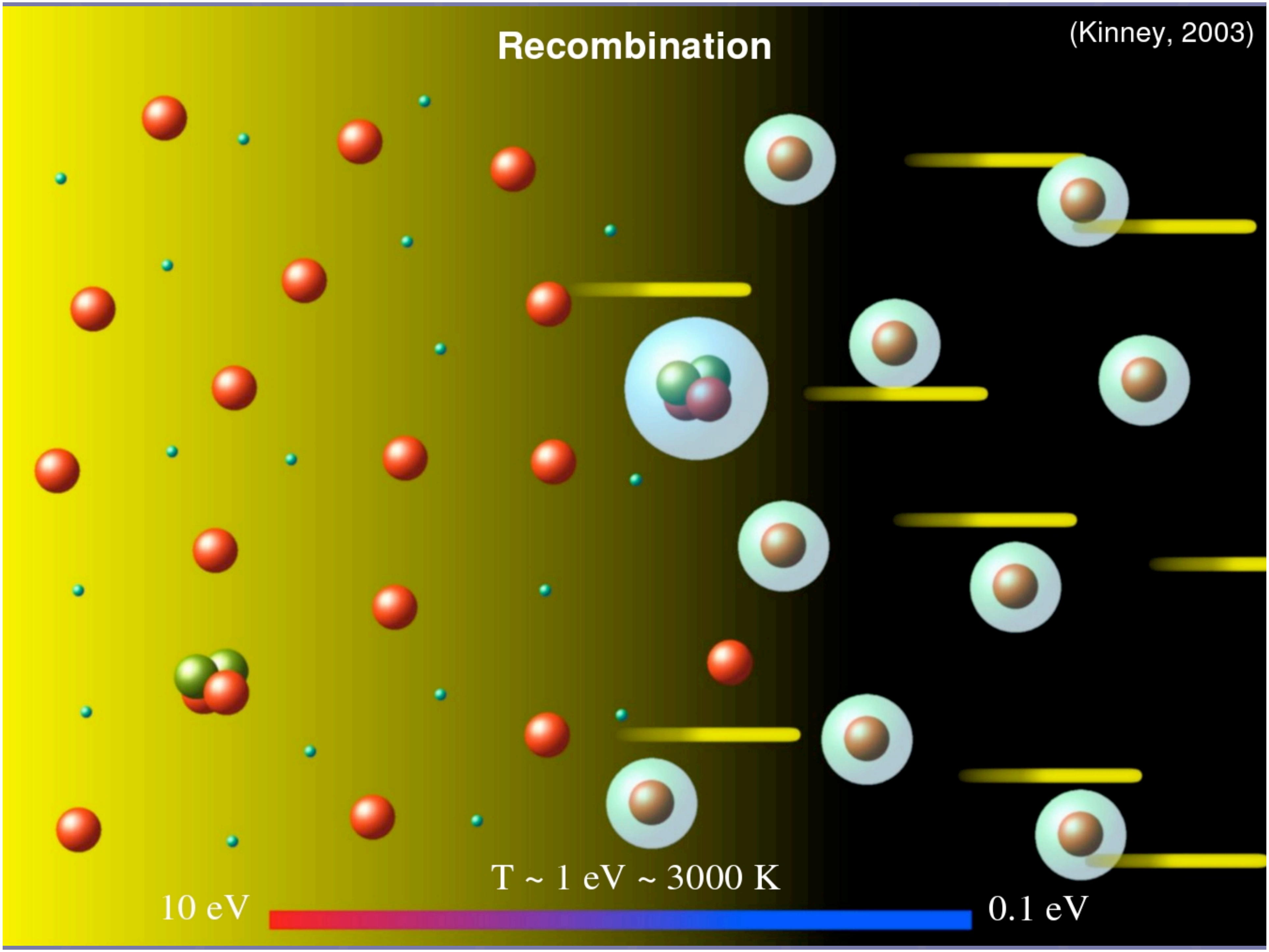


Last Scattering

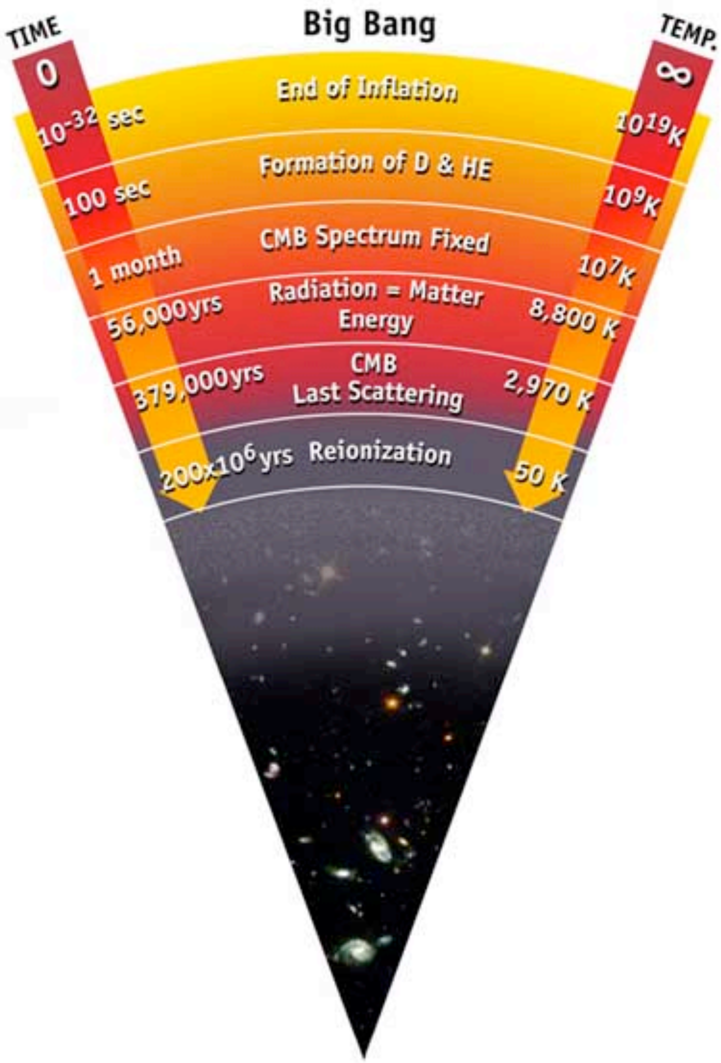
- When the universe is a million years old, at a temperature of 3000K, the photons (light particles) scatter one last time. After that, the electrons are gone (into hydrogen atoms) so that the photons are free to travel all the way to the present universe.

Photons no longer interact.
Universe becomes transparent!





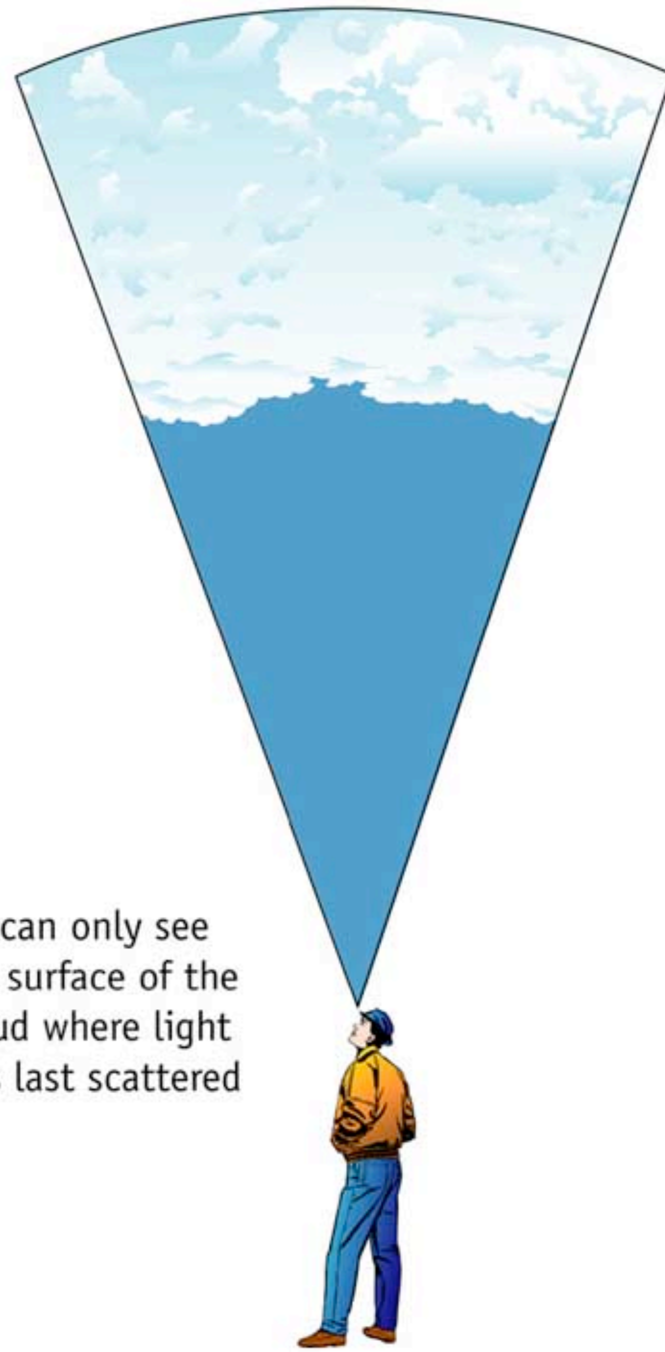
Recombination
(Kinney, 2003)
T ~ 1 eV ~ 3000 K
10 eV
0.1 eV



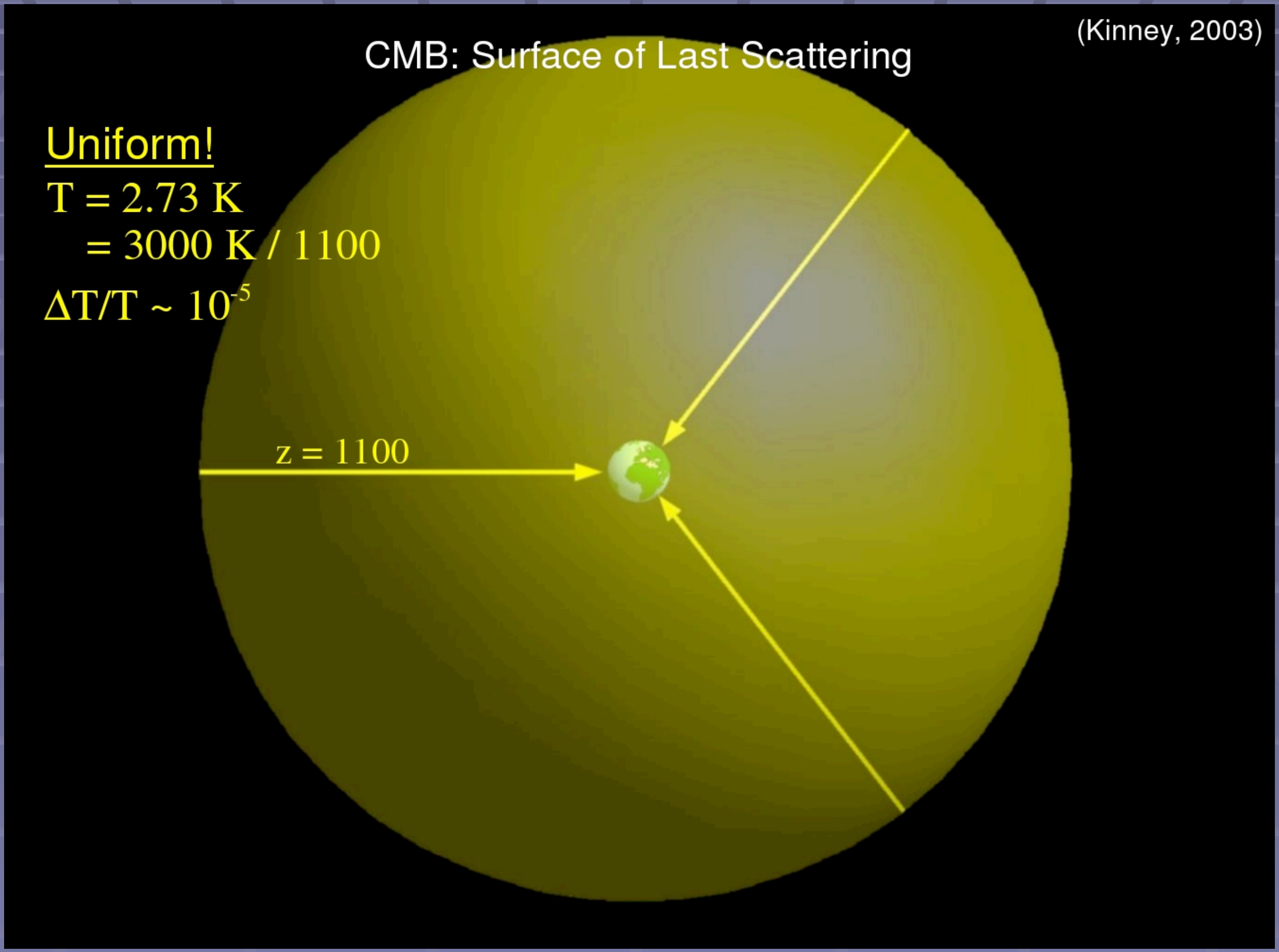
PRESENT
13.7 Billion Years
after the Big Bang

The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

We can only see the surface of the cloud where light was last scattered



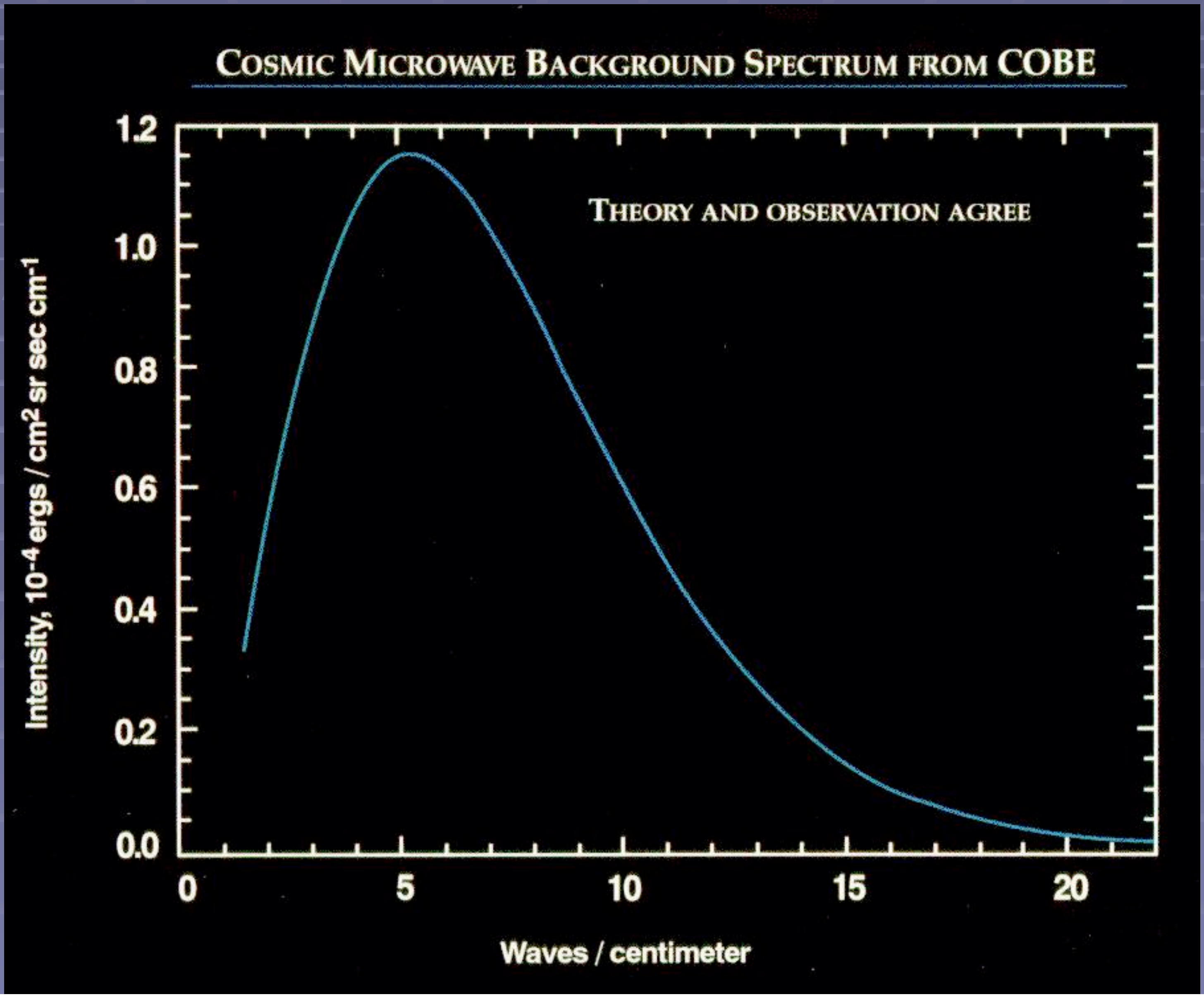
Surface of Last Scattering



Perfect Blackbody Curve

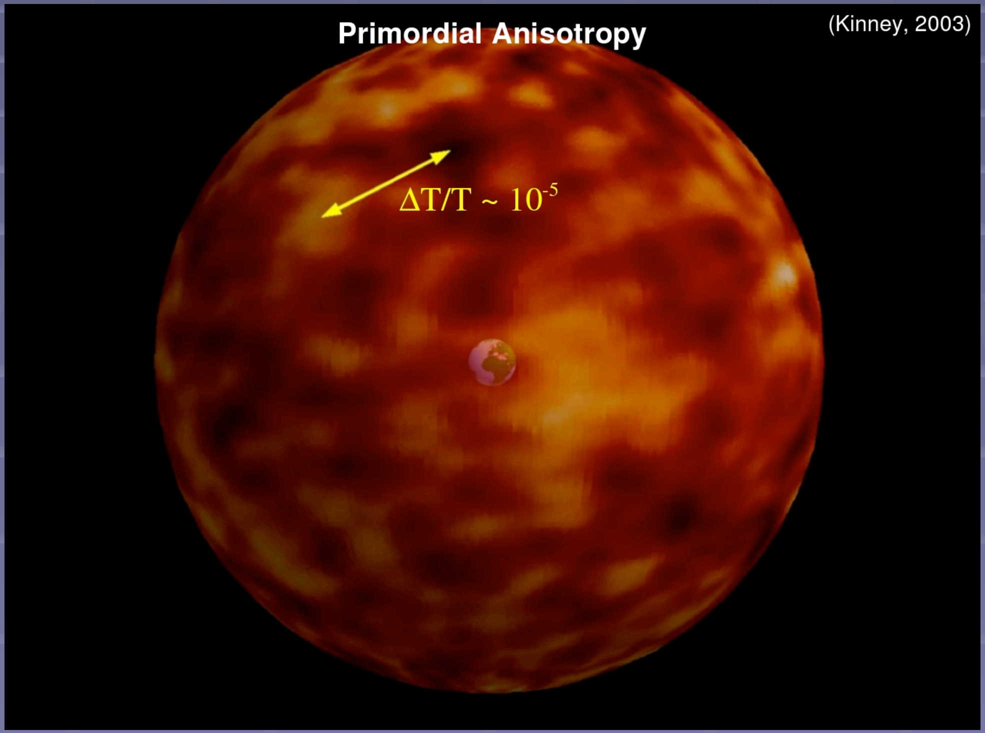
Perfect Blackbody Curve (like hot stovetop): Confirmation of HOT Big Bang.

The peak is at 3 degrees Kelvin, i.e. in the microwave.

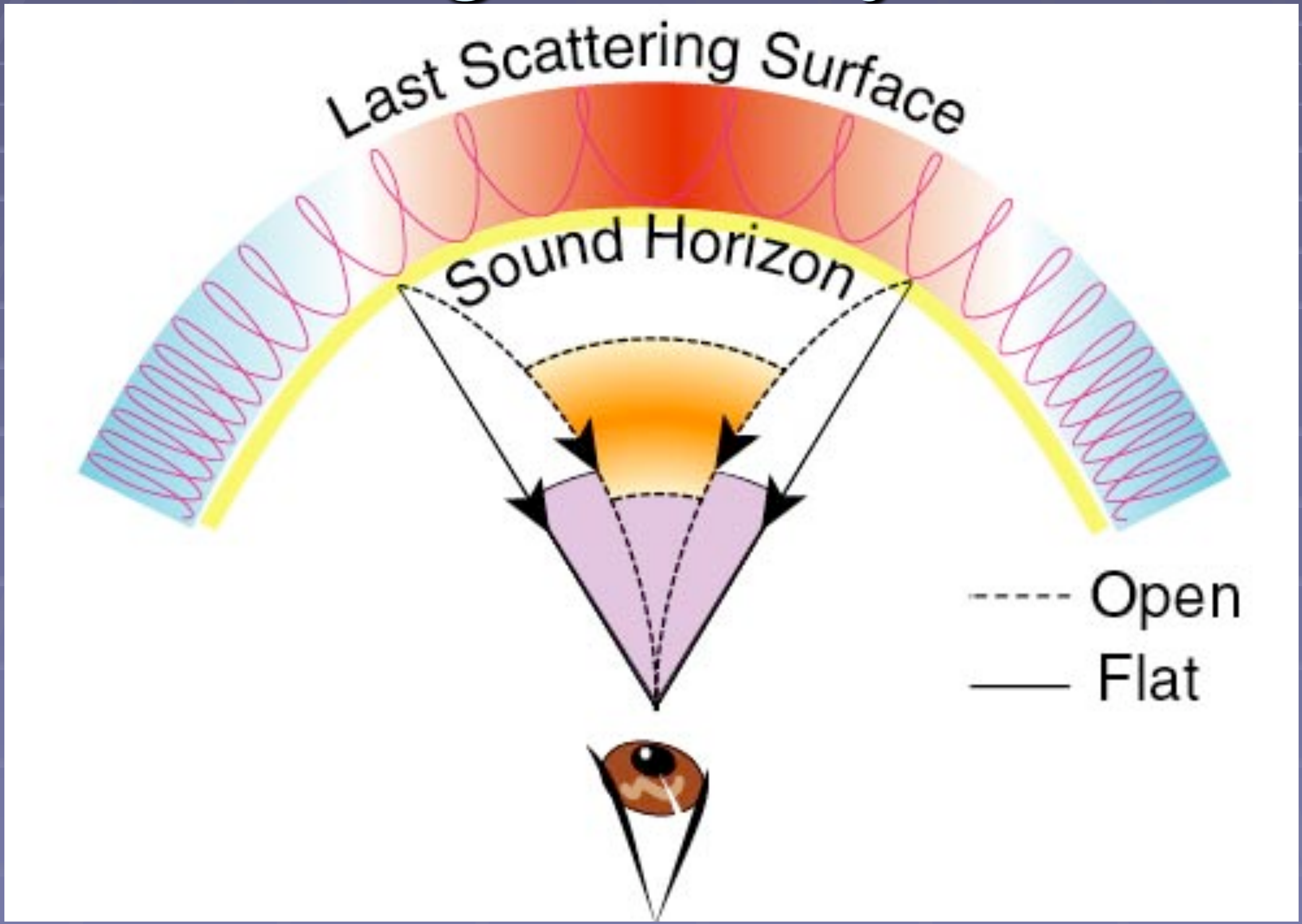


Temperature Anisotropies

- Look at deviations in the microwave background in different directions.



How can Microwave Background tell us about geometry?



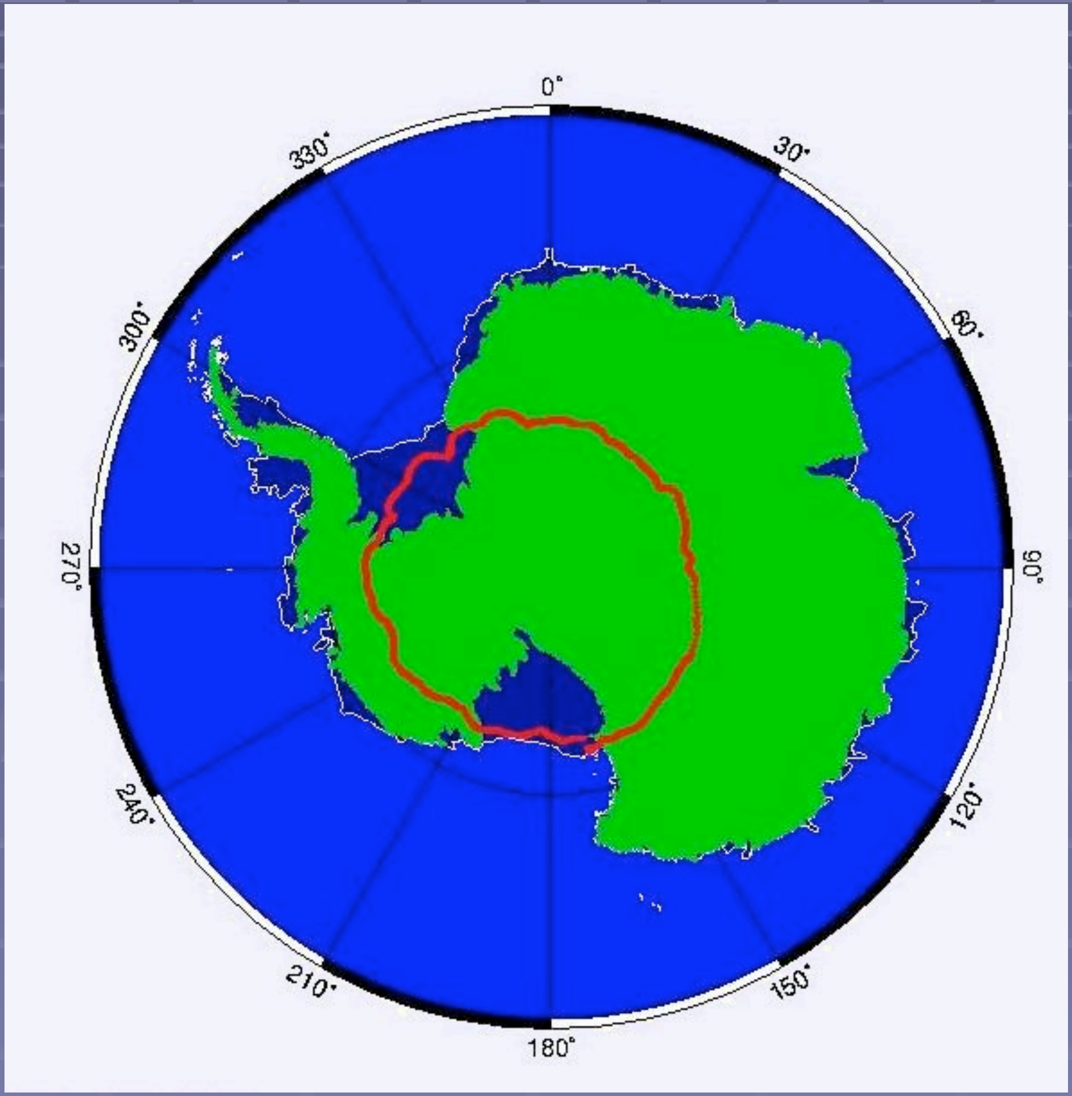
The Doppler Peak

- Acoustic oscillations in the photon/atom fluid are imprinted at last scattering. We expect a peak in the microwave background at the sound horizon (distance sound could travel in the age of the universe).
- If the universe is flat, the peak is at one degree.
- If the universe is a saddle, the peak is at less than one degree.

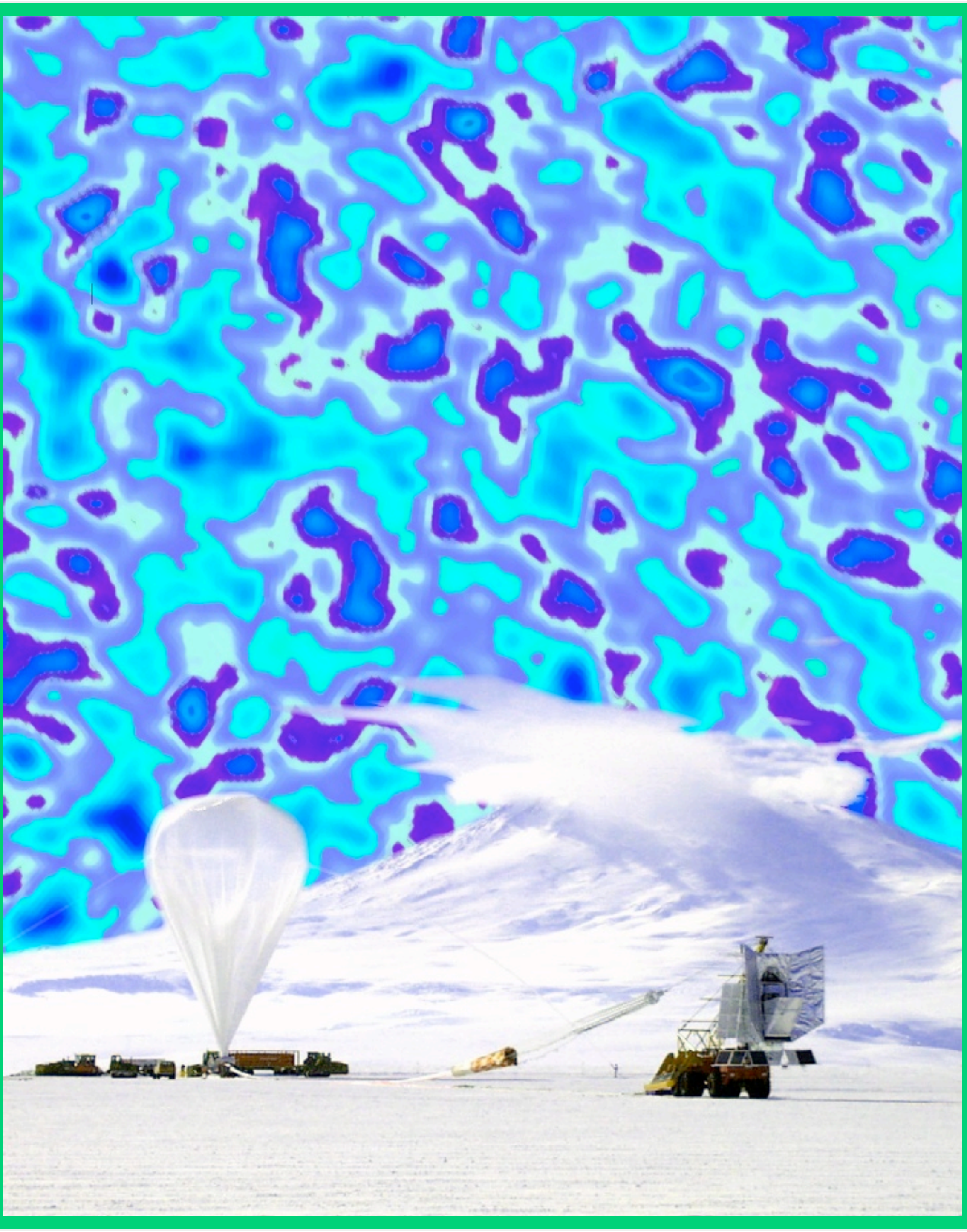
BOOMERANG

- BOOMERANG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics) used a telescope suspended from a balloon that circumnavigated the South Pole for 10.5 days at an altitude of 120,000 feet. Revealed patterns of structure in the microwave background.
- SPACETIME IS FLAT
- ENERGY DENSITY IS DETERMINED

Path of BOOMERANG

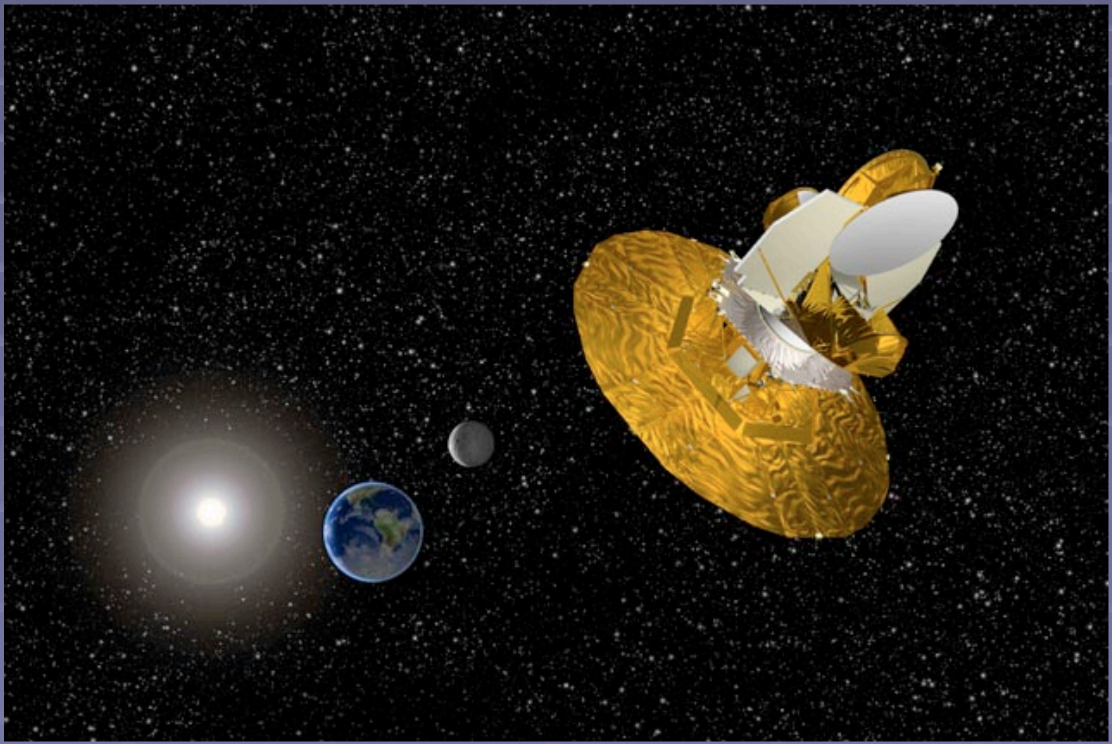


BOOMERANG SKY



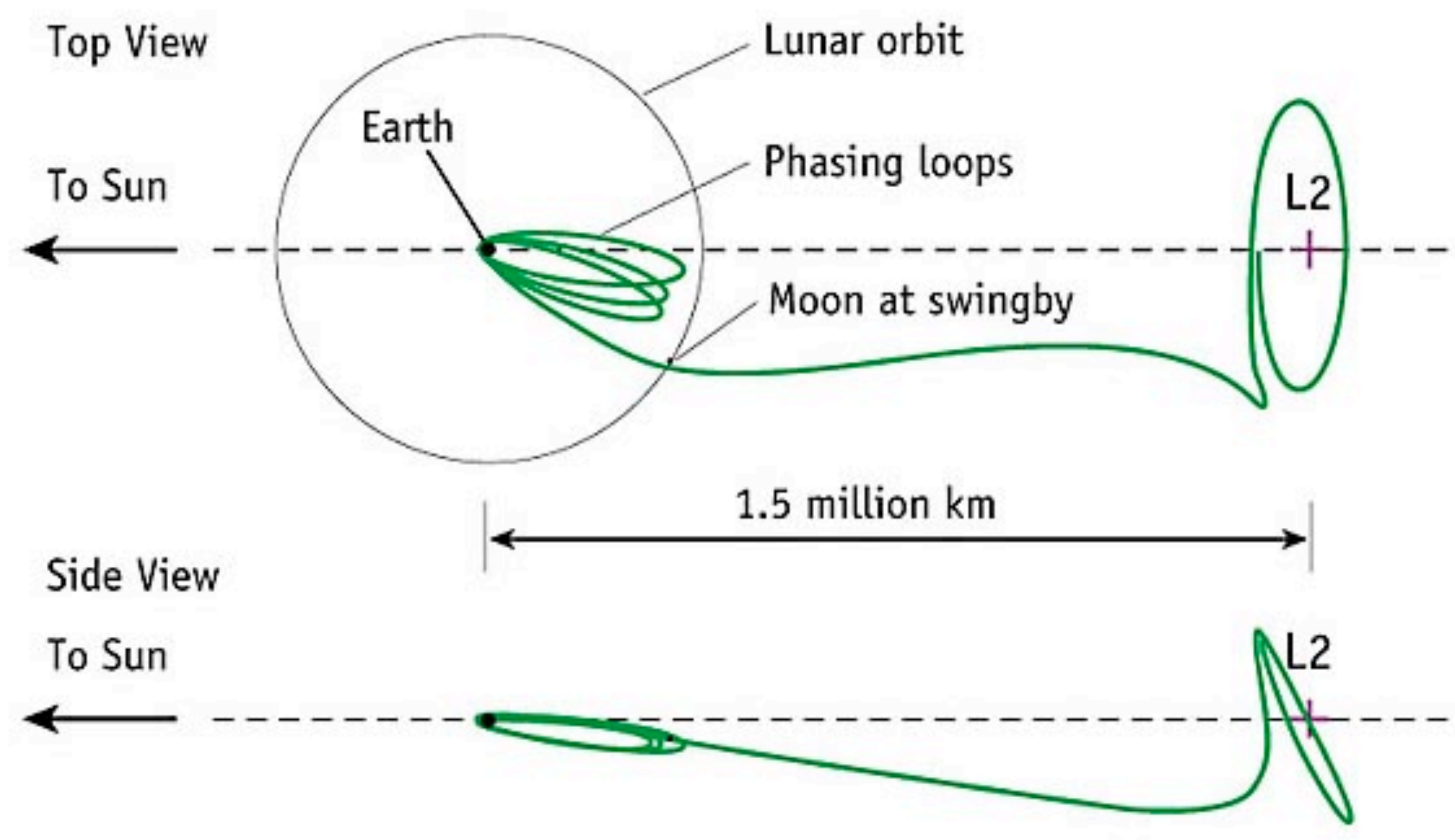
WMAP Satellite

- Launched June 2002
- Data released Feb. 2003

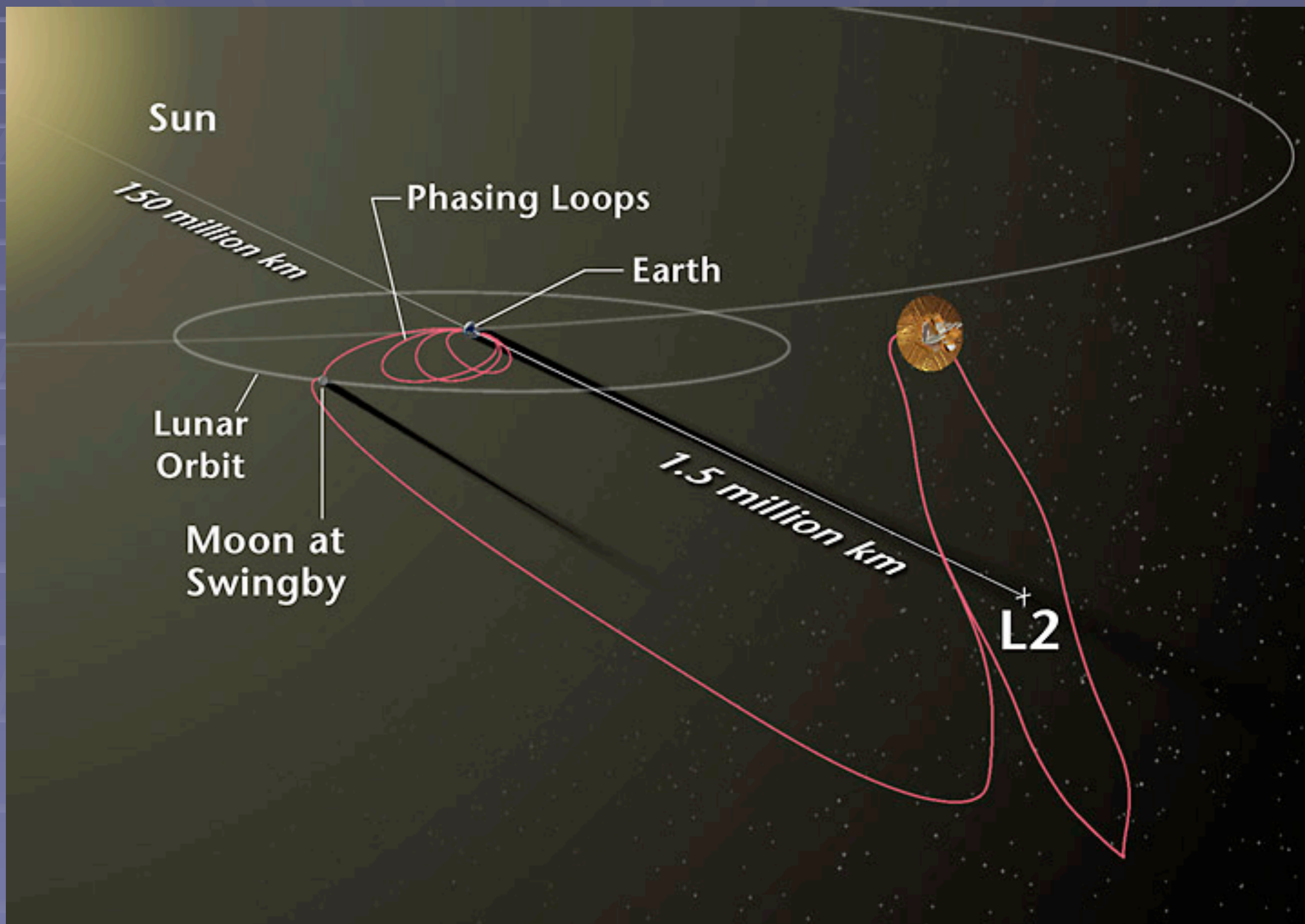


WMAP Launch

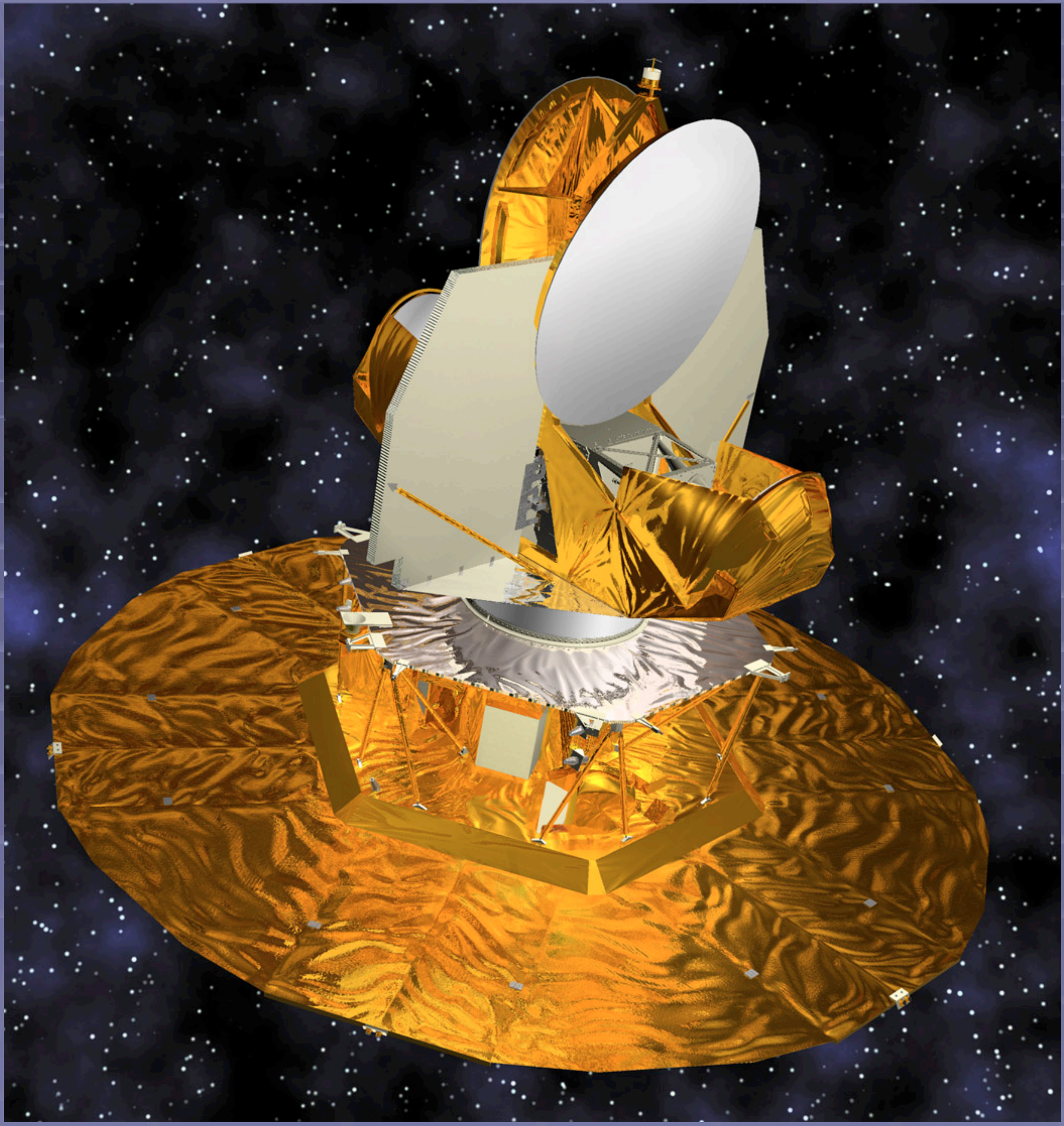
Getting to L2



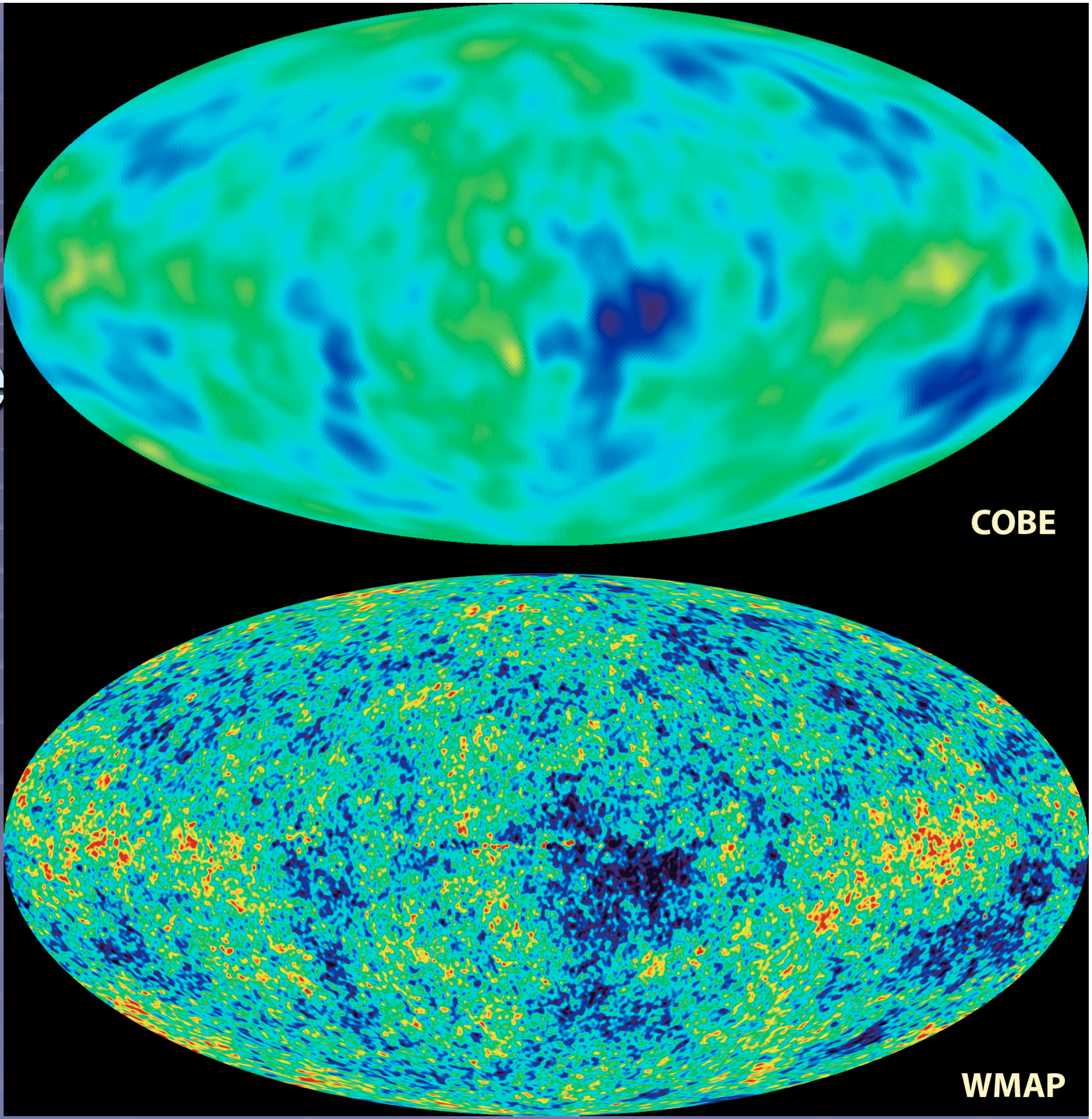
Getting to L2



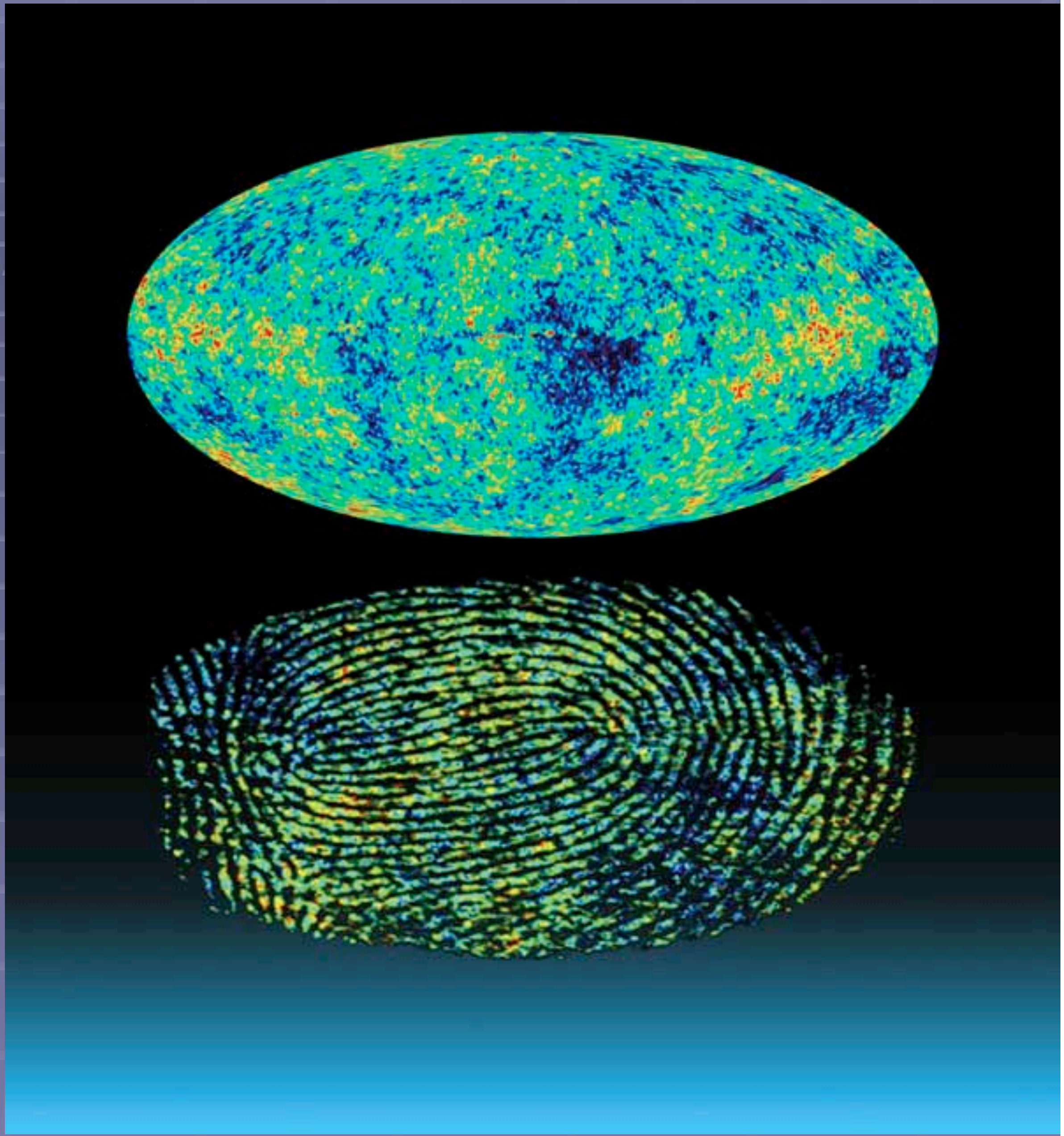
WMAP



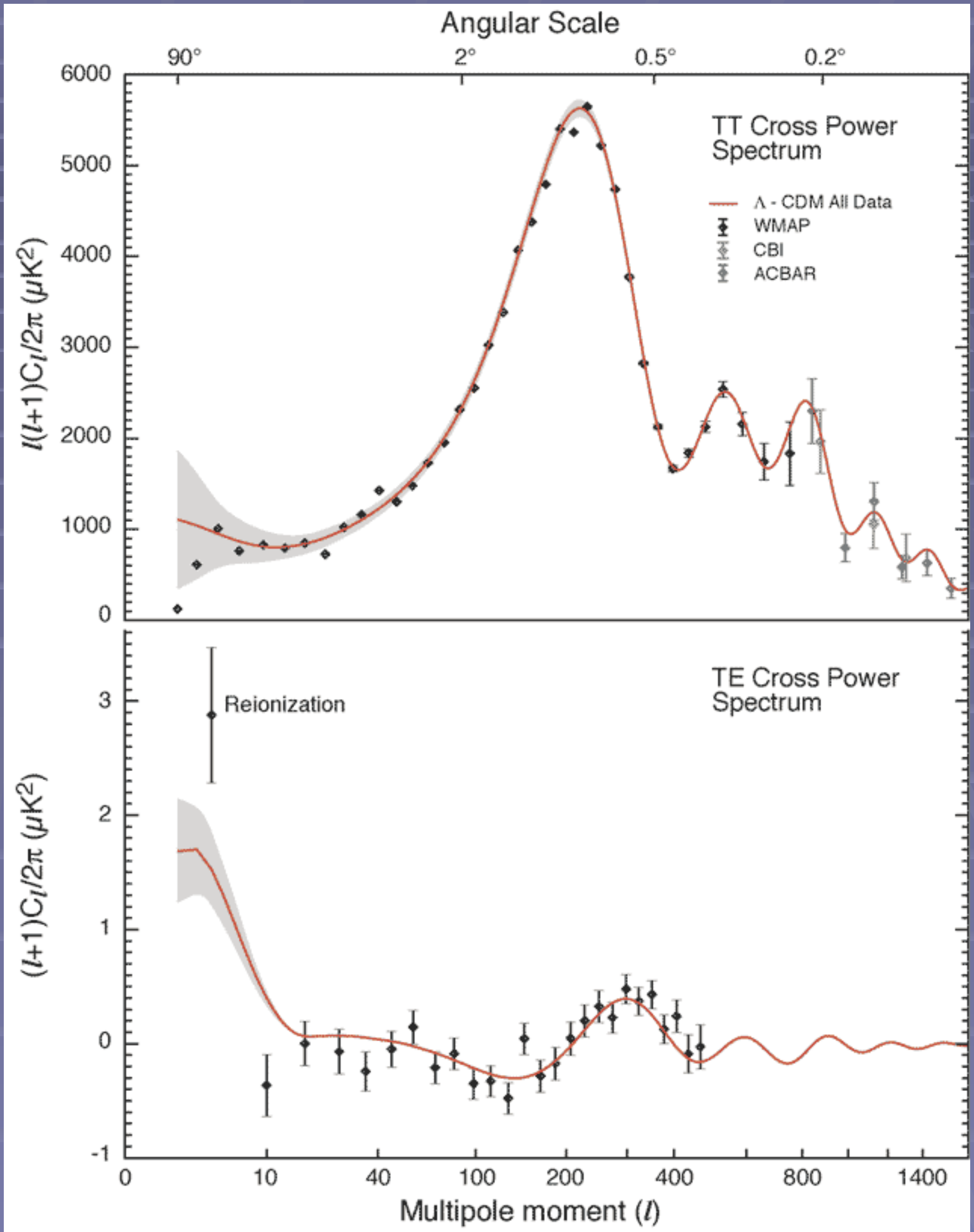
The Microwave Sky



The Microwave Background is like a Fingerprint of the Universe



Doppler Peak at 1 degree



What have we learned from CMB?

- The peak at 1 degree tells us that the geometry of the universe is flat.
- This geometry corresponds to an energy density of $10^{-29}\,\mathrm{gm/cm^3}$
- Height of second peak tells us that 4% of the total is ordinary atoms.
- Matching all the peaks tells us that 23% of the total is dark matter.
- What is the rest?????

Big Bang Nucleosynthesis

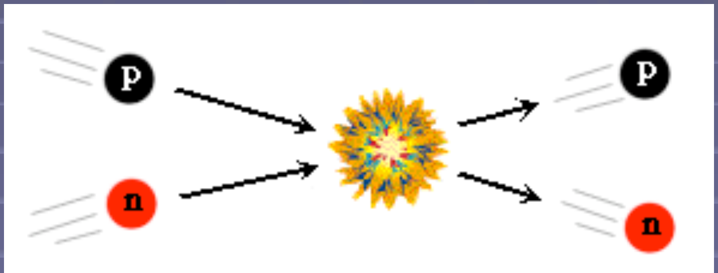
- When the universe is 3 minutes old, at a temperature of ten billion degrees K, Deuterium becomes stable:

$$p + n \rightarrow D + \gamma$$

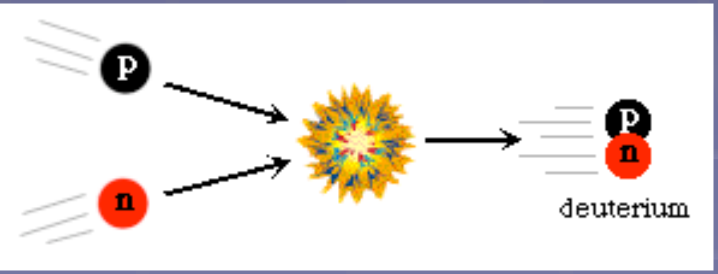
- Make Deuterium, Helium, Lithium
- To make heavier things like C,N,O need high densities in stars (3 He turns into C); this happens much later.

Before and After the first three minutes:

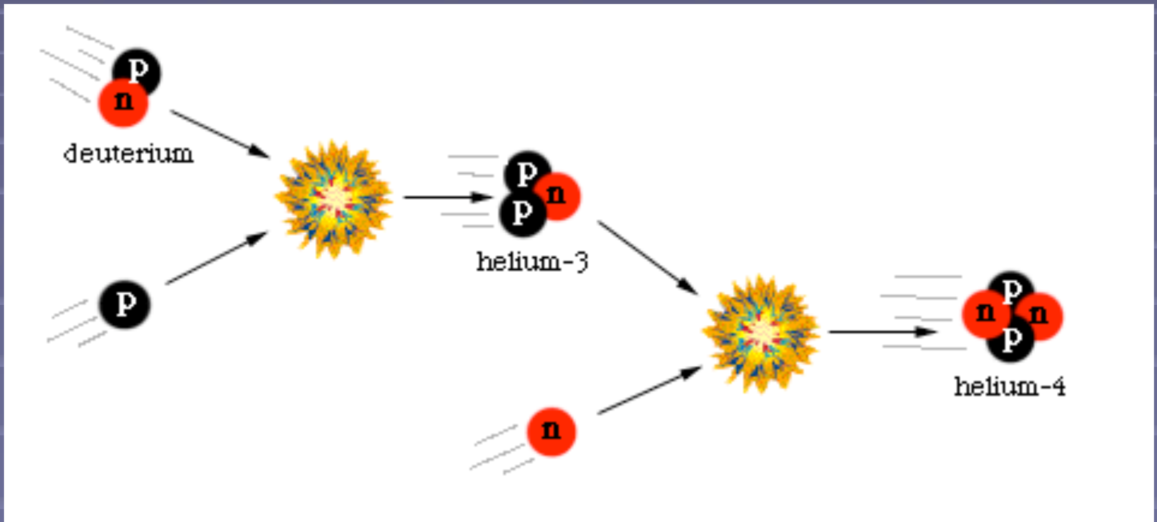
Before the universe is 3 minutes old, Deuterium isn't stable:



After the universe is 3 minutes old, Deuterium is stable:



Helium formation



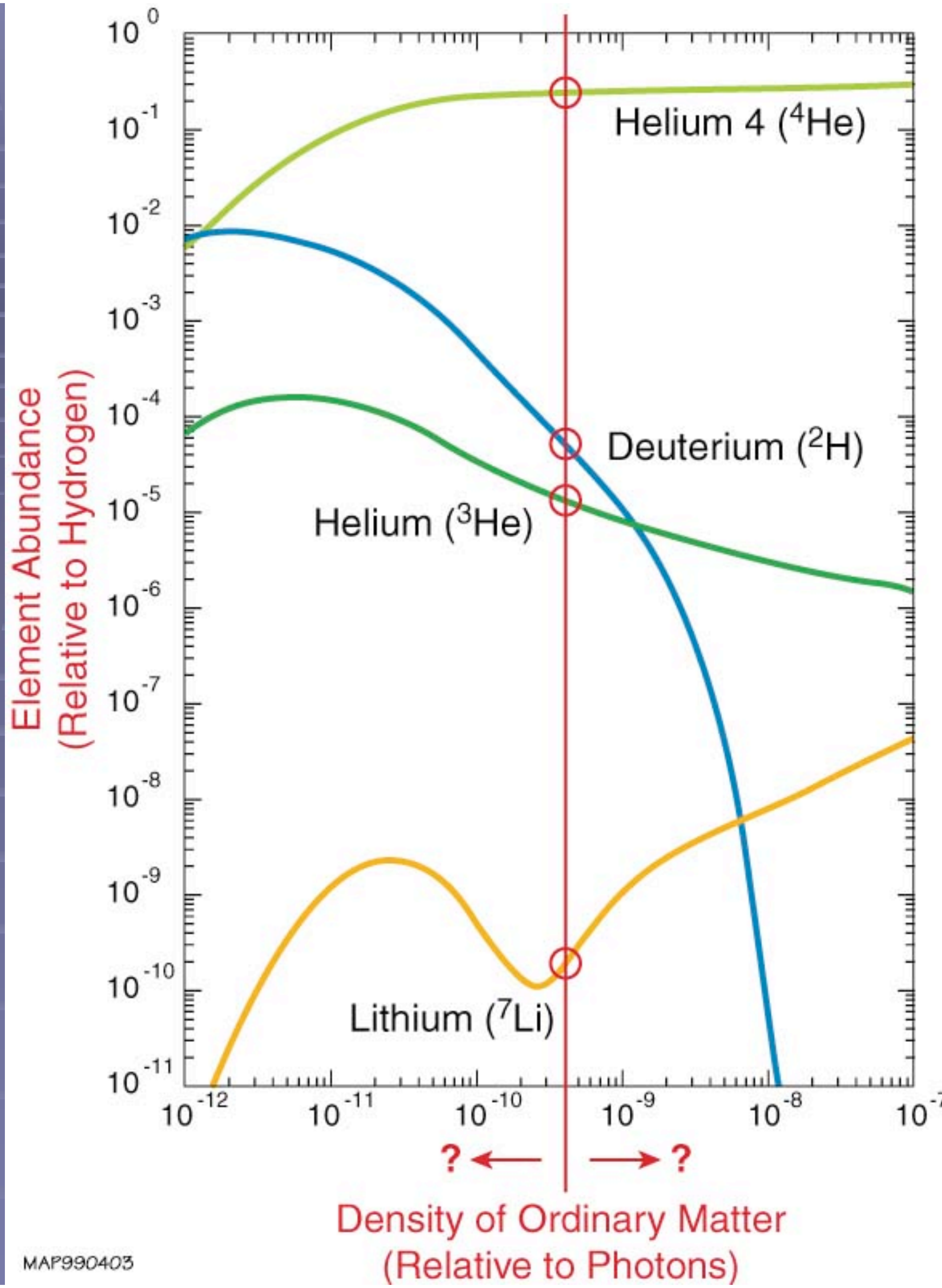
Once Deuterium forms, Helium and Lithium also form

Element Abundances

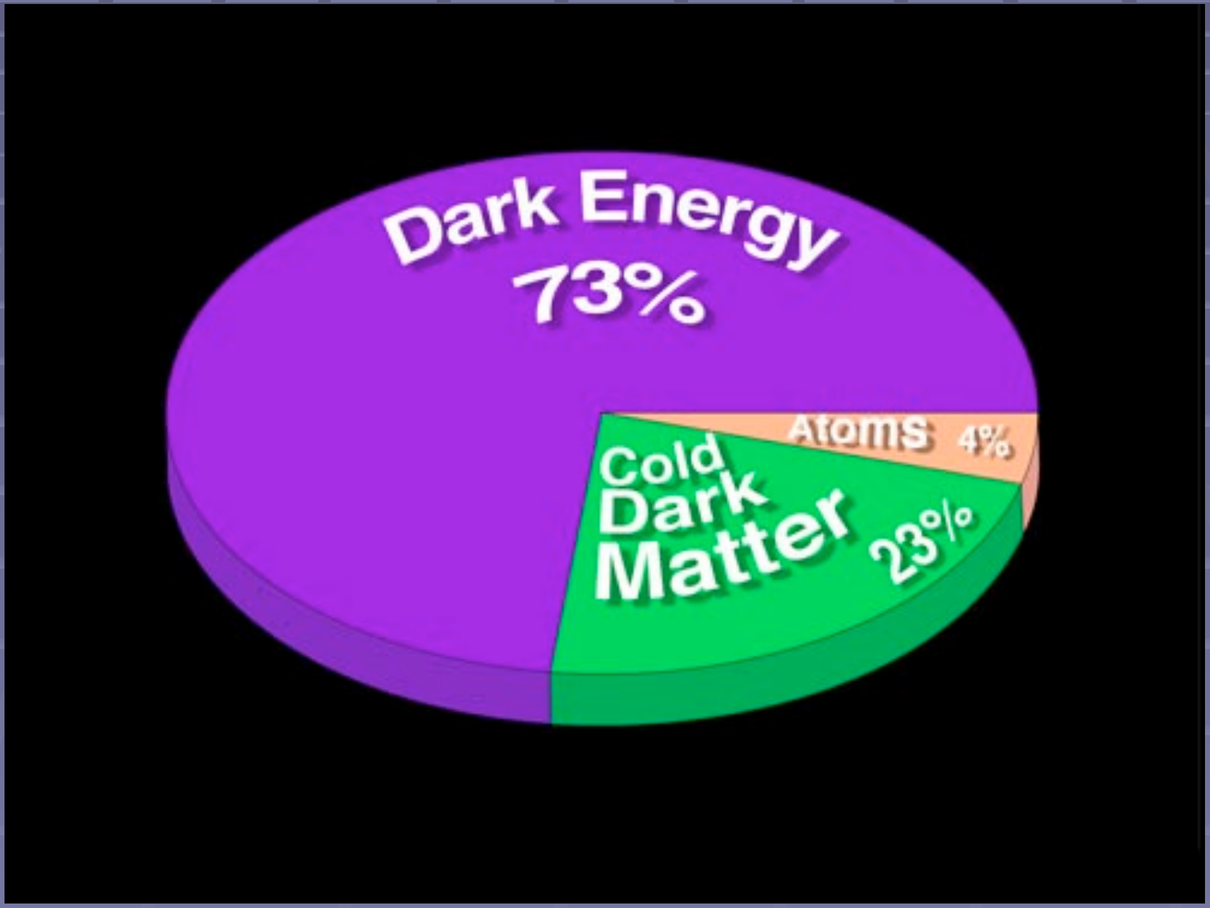
Predictions from Big Bang (e.g. 25% Helium 4) exactly match the data

IF

ATOMS ARE 4% OF THE TOTAL!



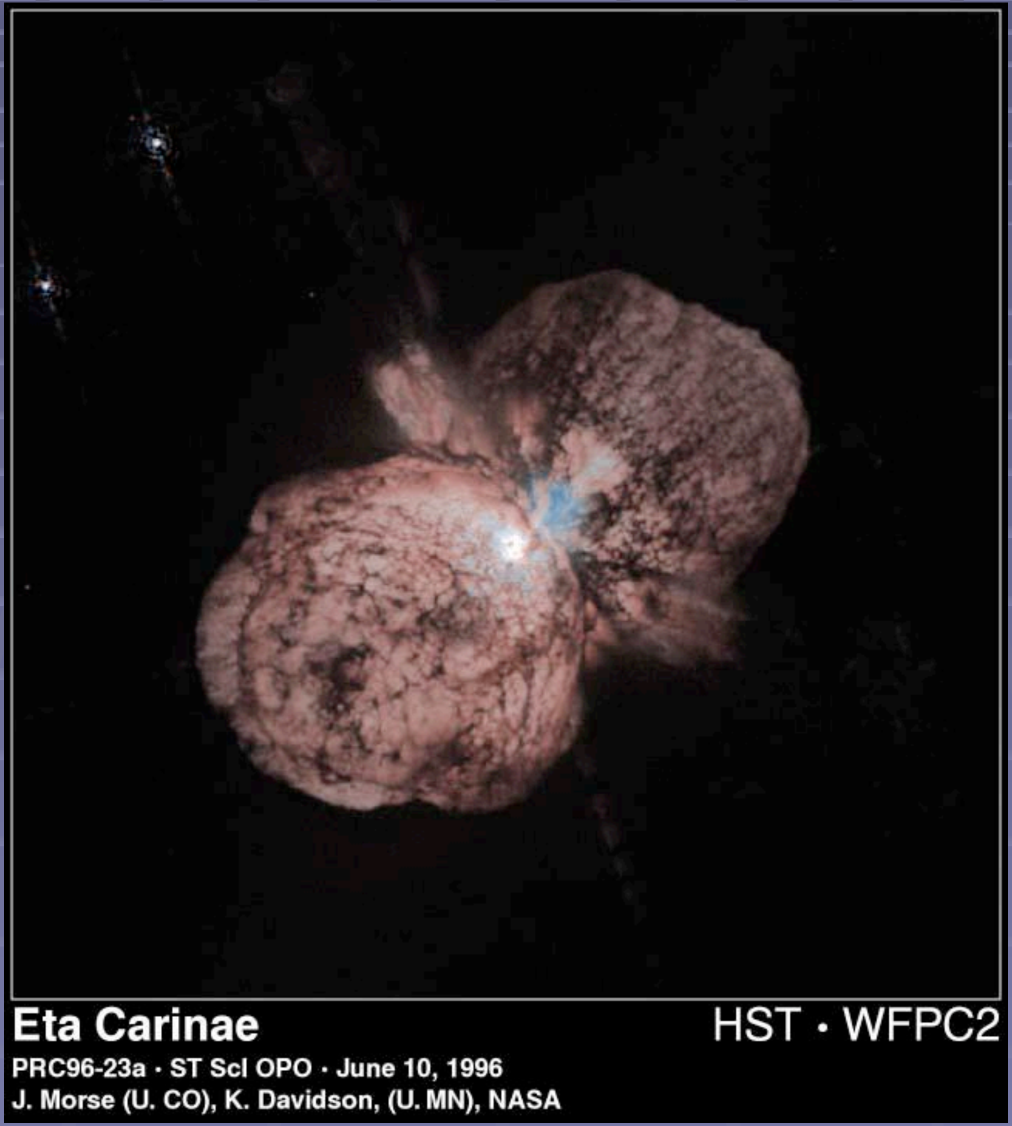
Pie Chart of The Universe



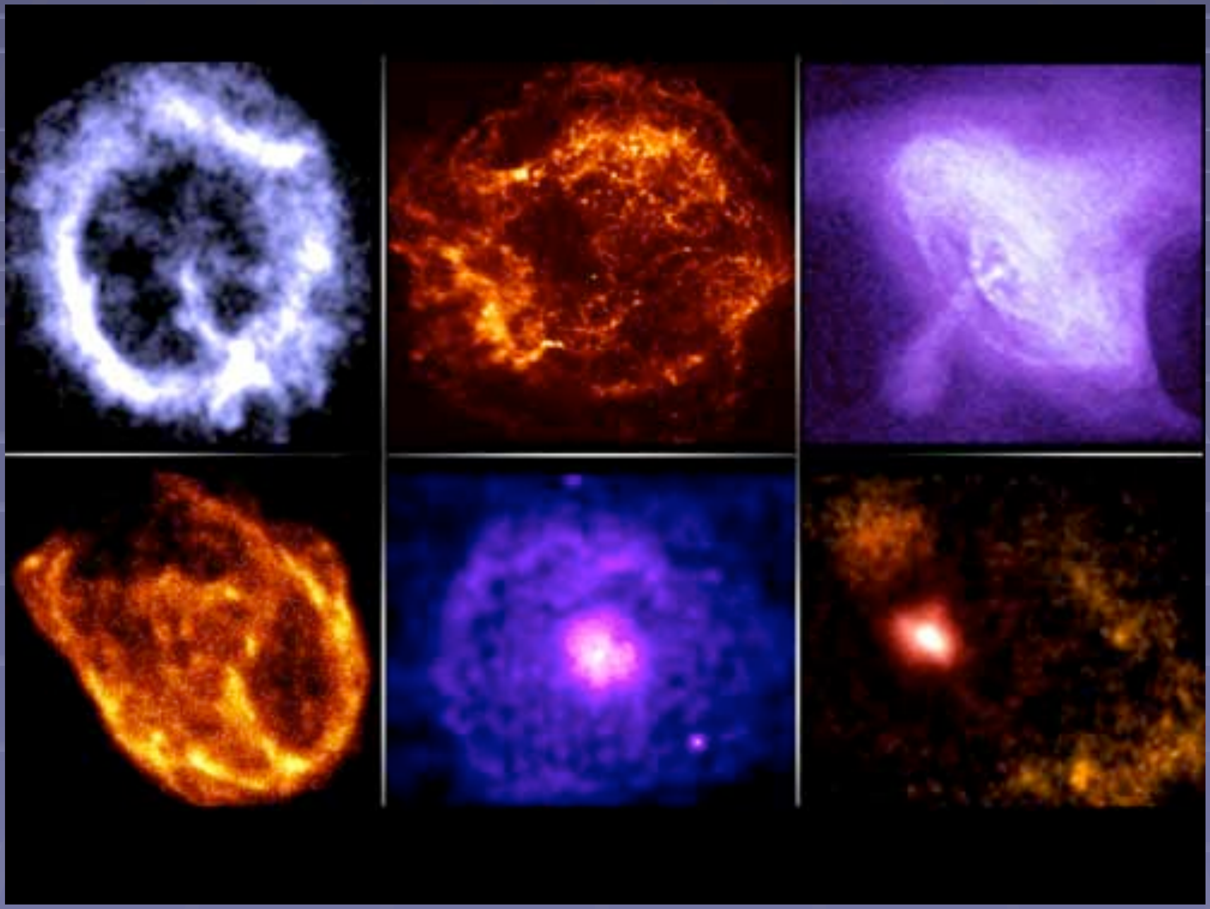
Even more strange:

- All matter, including atoms and dark matter, amount to only roughly a third of the total density of the universe.
- This conjecture arises from studies of SUPERNOVAE, bright explosions of dying stars.

Supernova


Eta Carinae
HST · WFPC2
PRC96-23a · ST ScI OPO · June 10, 1996
J. Morse (U. CO), K. Davidson, (U. MN), NASA

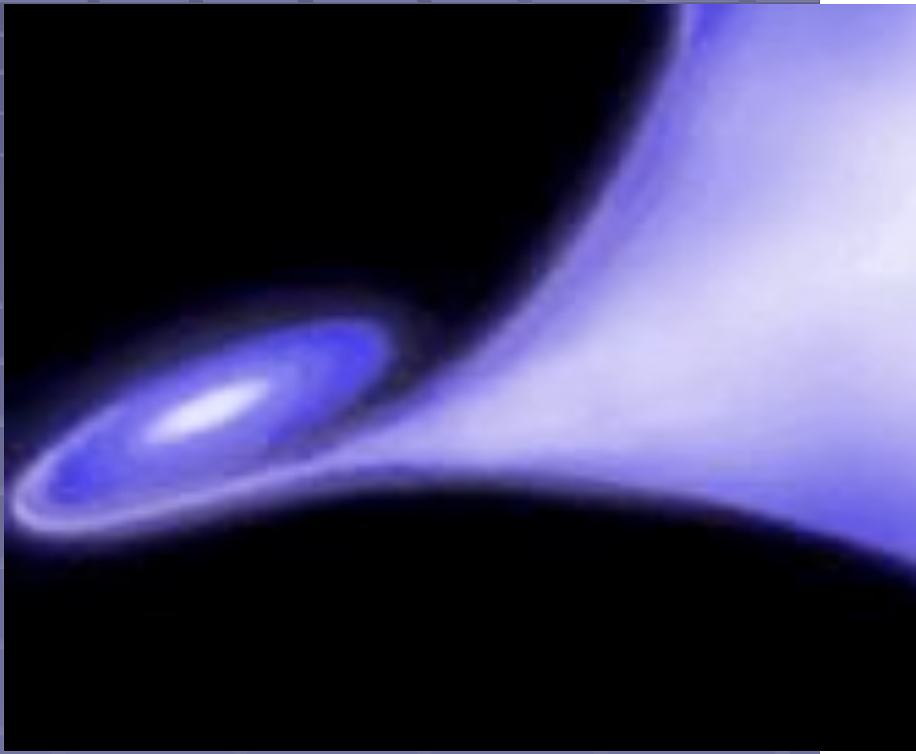
Supernova Portrait Gallery



Type IA Supernovae

- How they form:

  A white dwarf accretes from a companion orbiting around it. When the mass exceeds 1.4 times the mass of the Sun, thermonuclear instability leads to explosion. Always peaks at same brightness.
- These objects are thought to provide a population of standard candles.

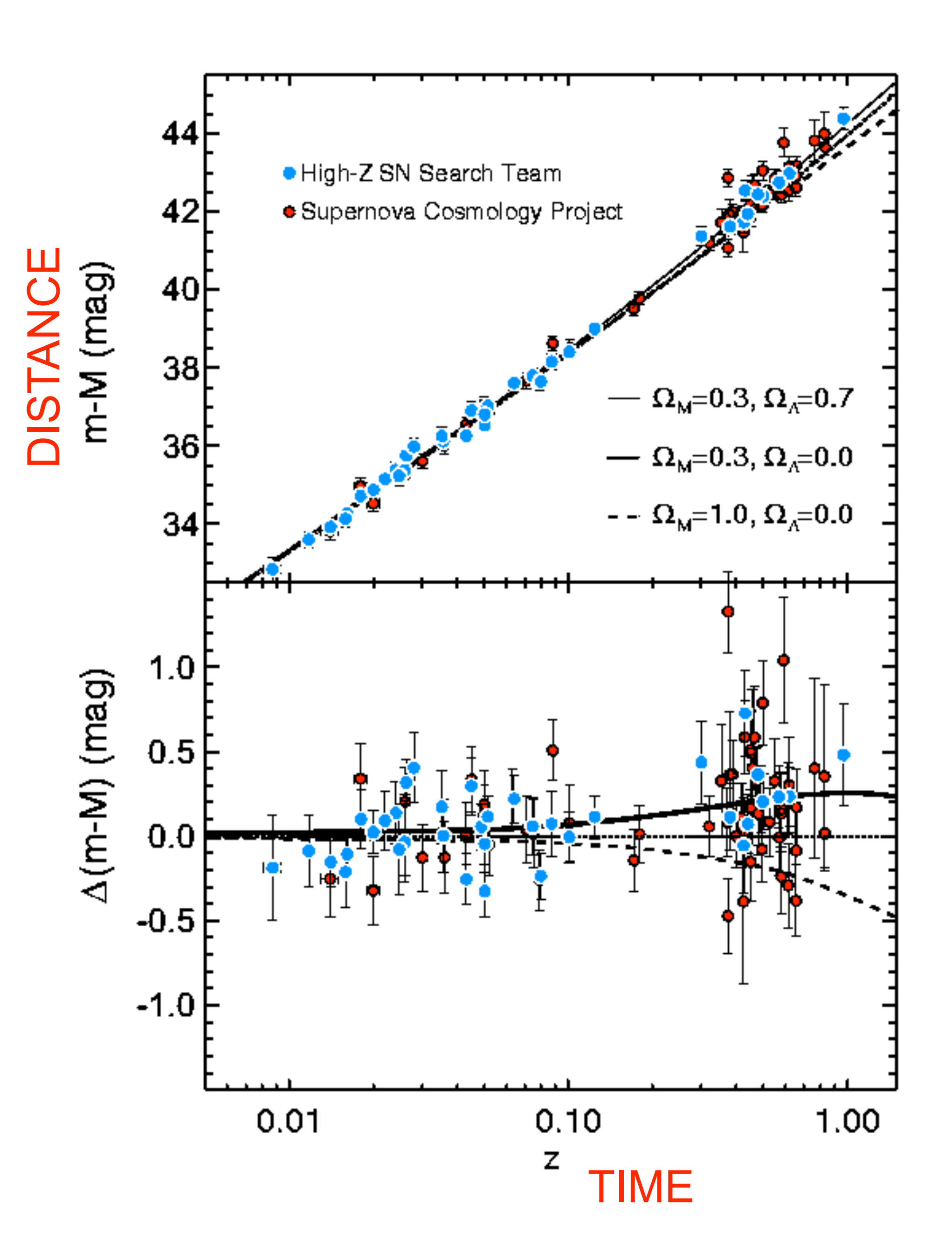


The Light Bulb Model

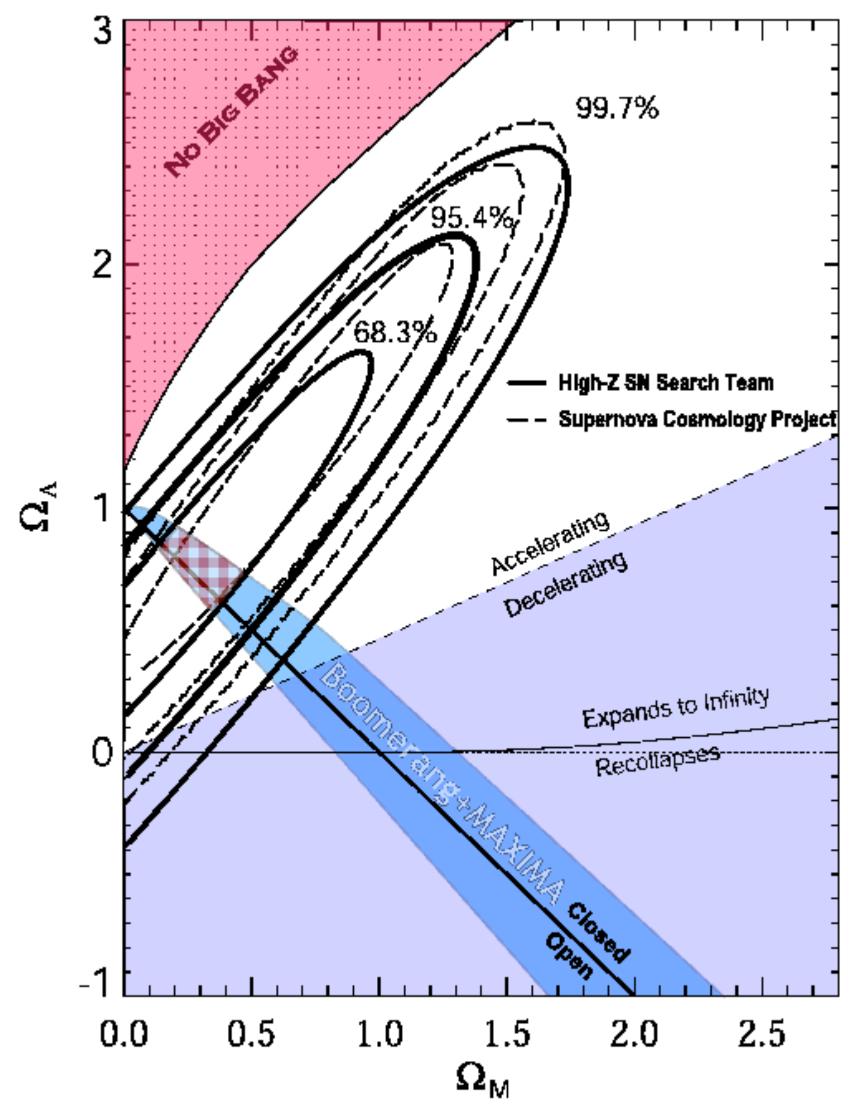
- Supernovae are like light bulbs.
- You know how bright a light bulb really is (it says on the box). Now look at a light bulb some distance from you. From studying how bright the light bulb looks, you can figure out how far away it is.

Accelerating Universe

As we look backwards in time at distant supernovae, they are 20% dimmer than expected! That means they are farther away from us than expected. They are accelerating away from us.



Galaxies are accelerating apart from one another!


No Big Bang
99.7%
95.4%
68.3%
High-Z SN Search Team
Supernova Cosmology Project
Accelerating
Decelerating
Expands to Infinity
Recollapses
Boomerang+MAXIMA
Closed
Open
3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5
Ω_Λ
Ω_M

What causes the acceleration?

- NOT ordinary matter in the standard cosmology. Ordinary matter causes gravitational attraction, not repulsion.
- 73% of the universe must be something new and exotic with a negative pressure:

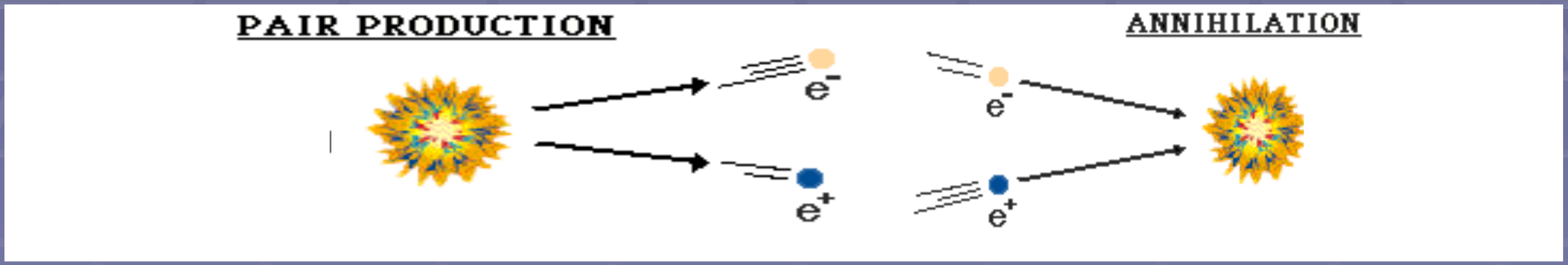
  DARK ENERGY.

What is the DARK ENERGY?

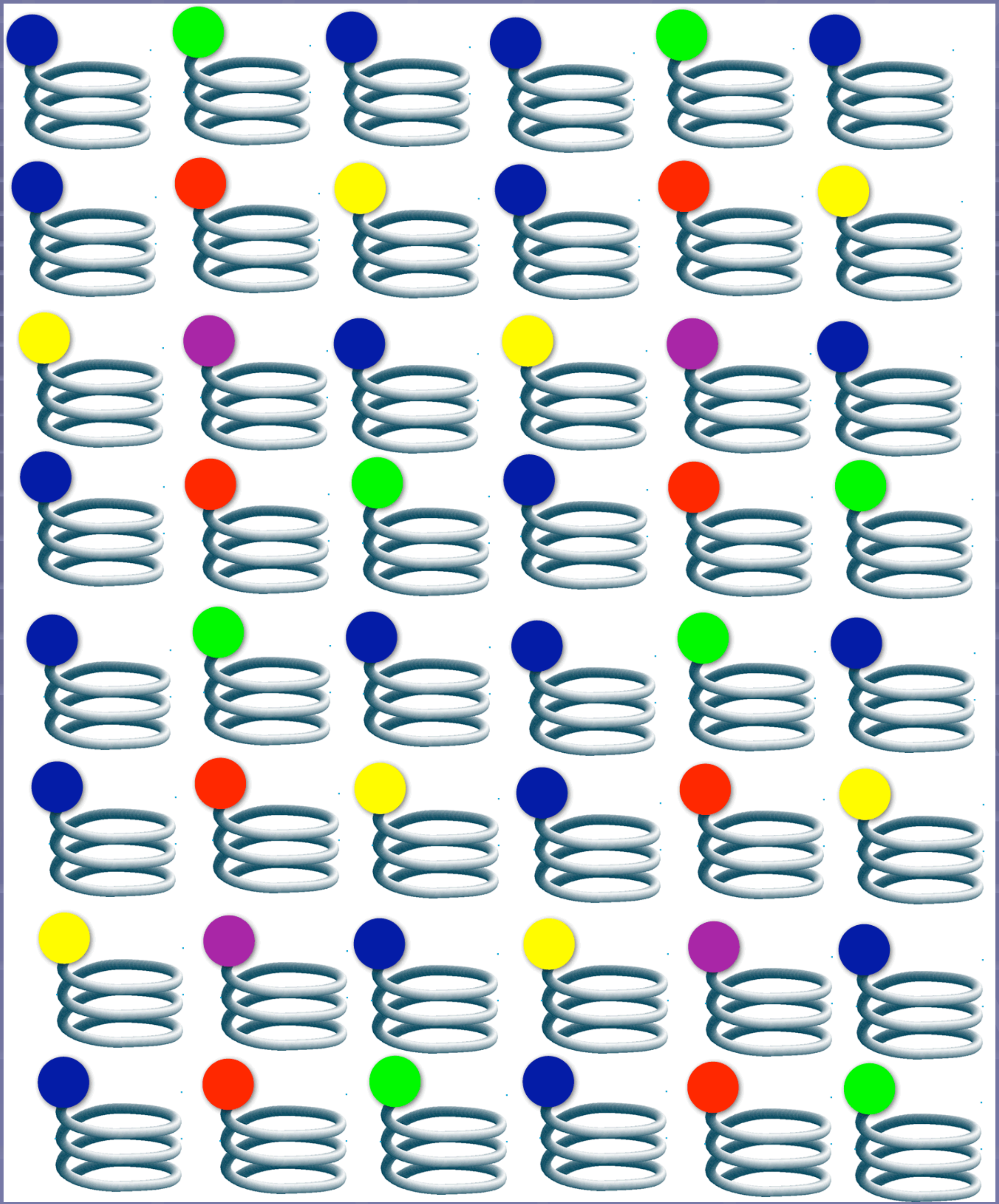
- Possibilities include:
- Vacuum energy:
  - Cosmological Constant?
  - Time-Changing Vacuum?
  - Quintessence?
- Cardassian expansion
  - Exotic fluid
  - Change Einstein's equations

Vacuum Energy

- Virtual particles and antiparticles spring into and out of existence at every point in the universe: they lead to a vacuum energy.



Quantum Field Theory



Different Kinds of Vacuum

- Cosmological Constant: Vacuum is Unchanging in Time or Space.

  First proposed by Einstein to make the universe static; but we know it's expanding! Then Einstein called it his "Biggest Blunder."
- Quintessence: Vacuum is Changing in Time.

Or, Einstein’s equations are wrong!

- Cardassian cosmology: Freese and Lewis 2002
- Motivated by physics of extra dimensions
- The equations may need an extra term that is important in today’s universe (but not before)

Etymology

- Cardassians are an alien race indigenous to the Star Trek universe.
- They appear foreign to us, yet consist entirely of matter.
- They are bent on the accelerated expansion of their empire.


NewScientist

The global science and technology weekly | 3 August 2002

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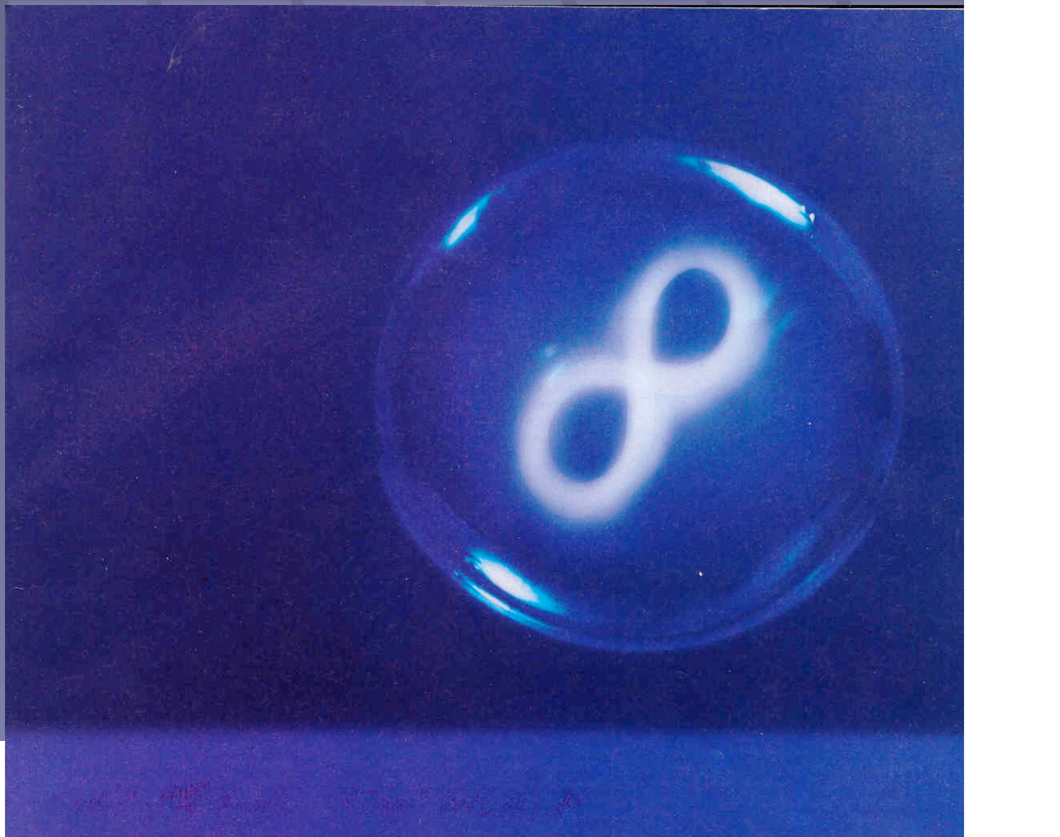
- "Katherine Freese and William Kinney may not look much like superheroes, but they may have just saved the fate of life in the universe"
- (New Scientist)



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