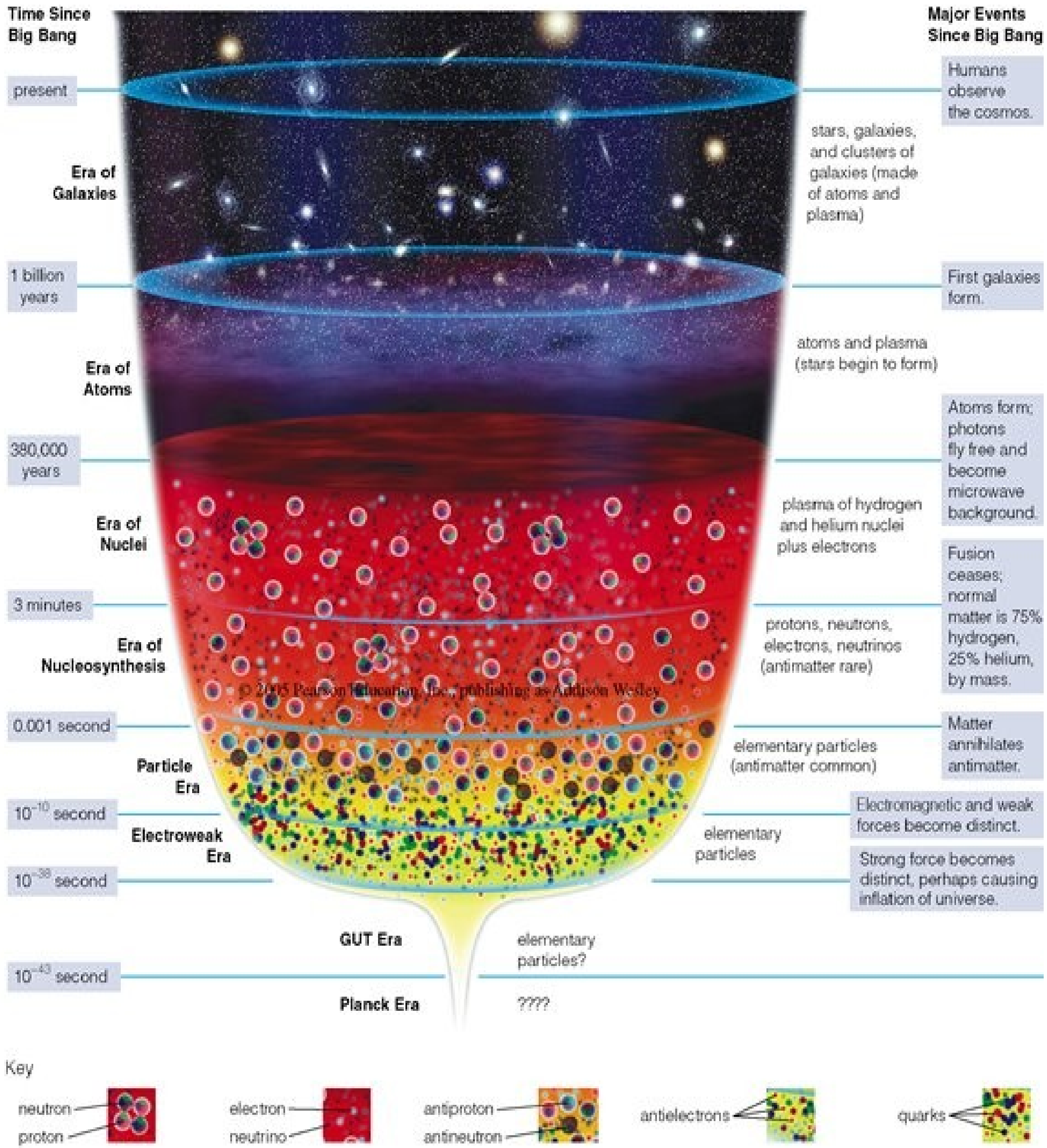
The Big Bang

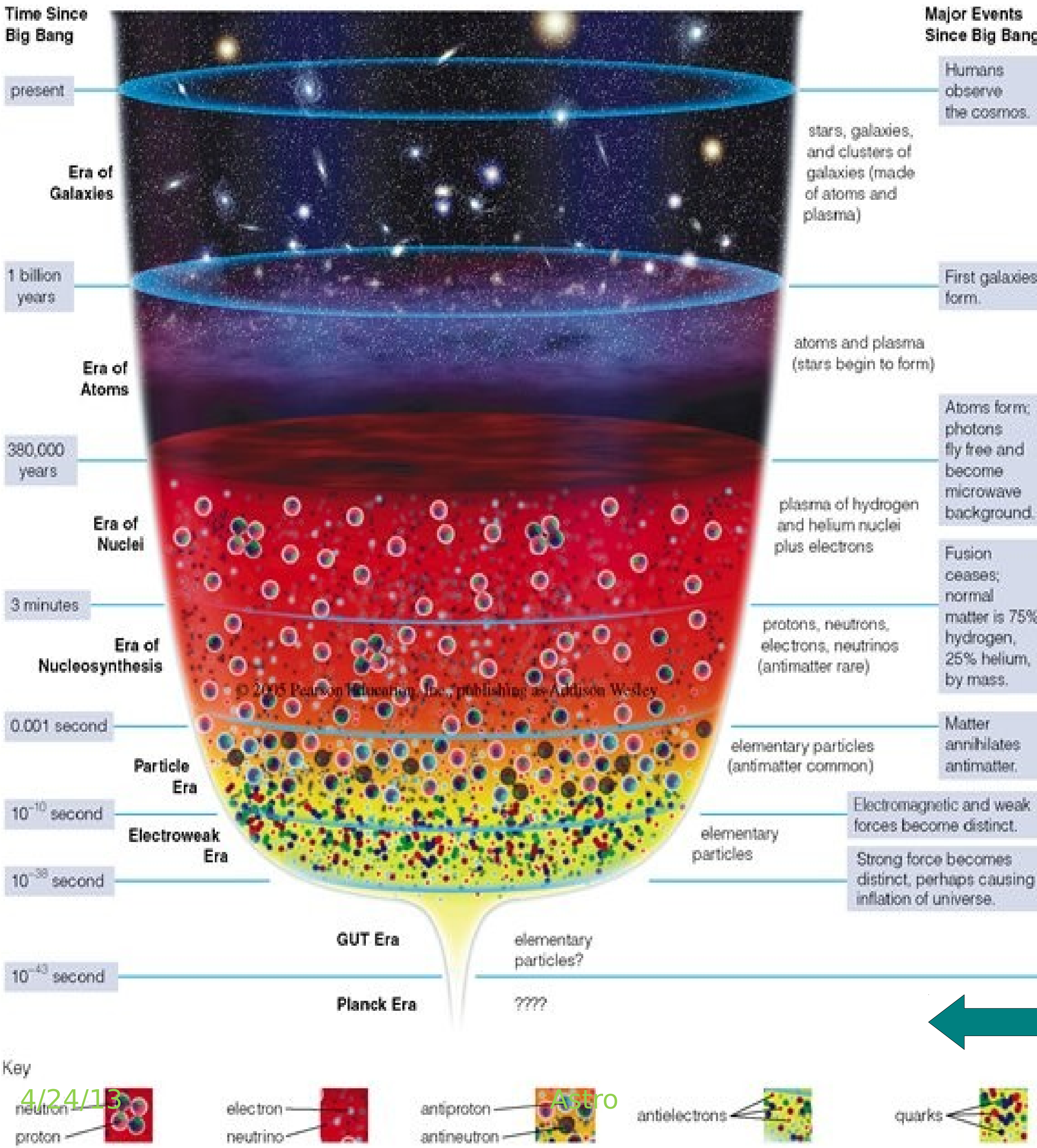
"In the beginning the Universe was created.
This has made a lot of people very angry and has been widely regarded as a bad move."
- Hitchhiker's guide to the galaxy

The Big Bang

working our way forward to Now



Eras since the Big Bang



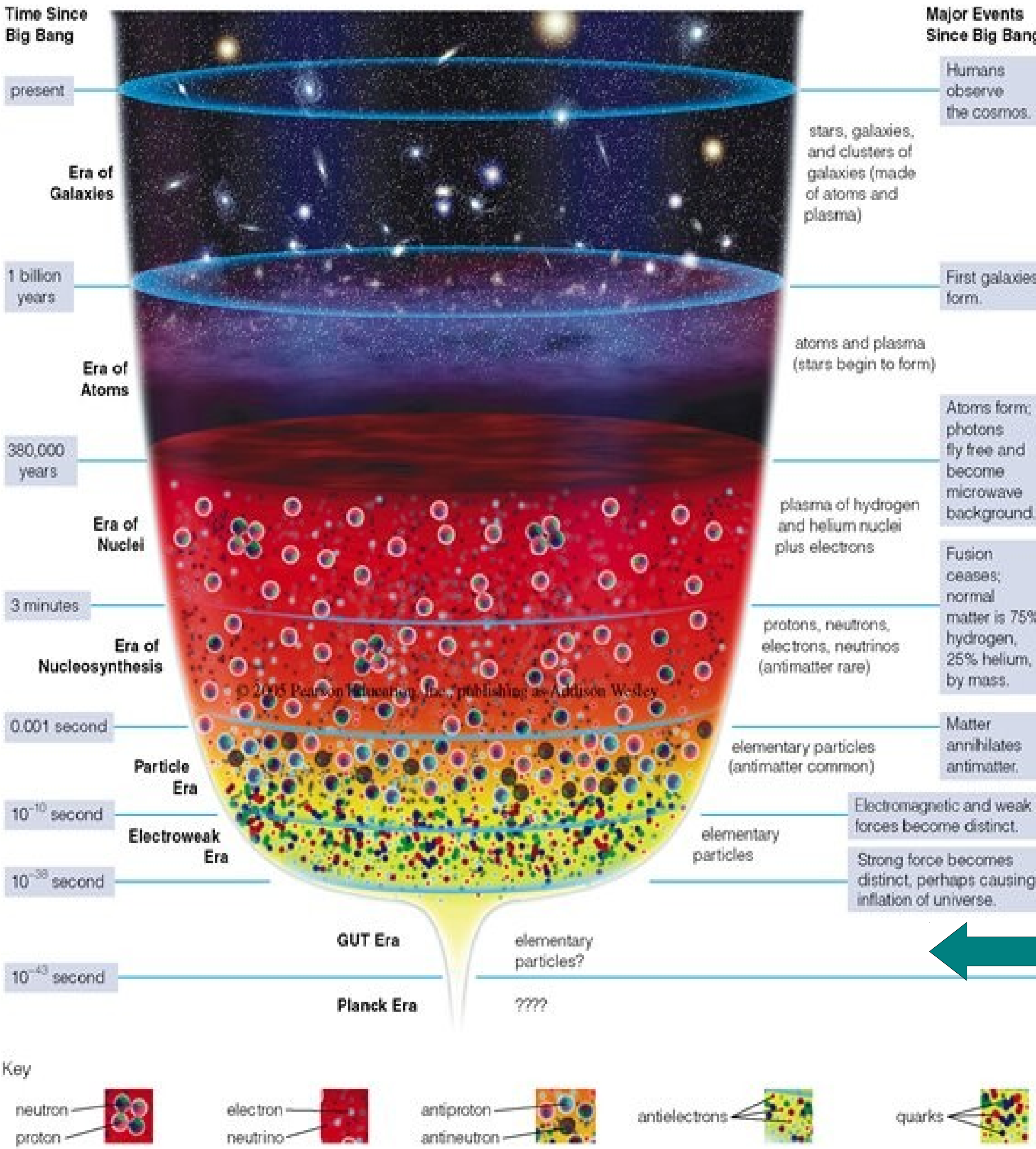
The first instant: Planck time

10^{-43} seconds

Quantum energy fluctuations imply “large” gravitational fluctuations

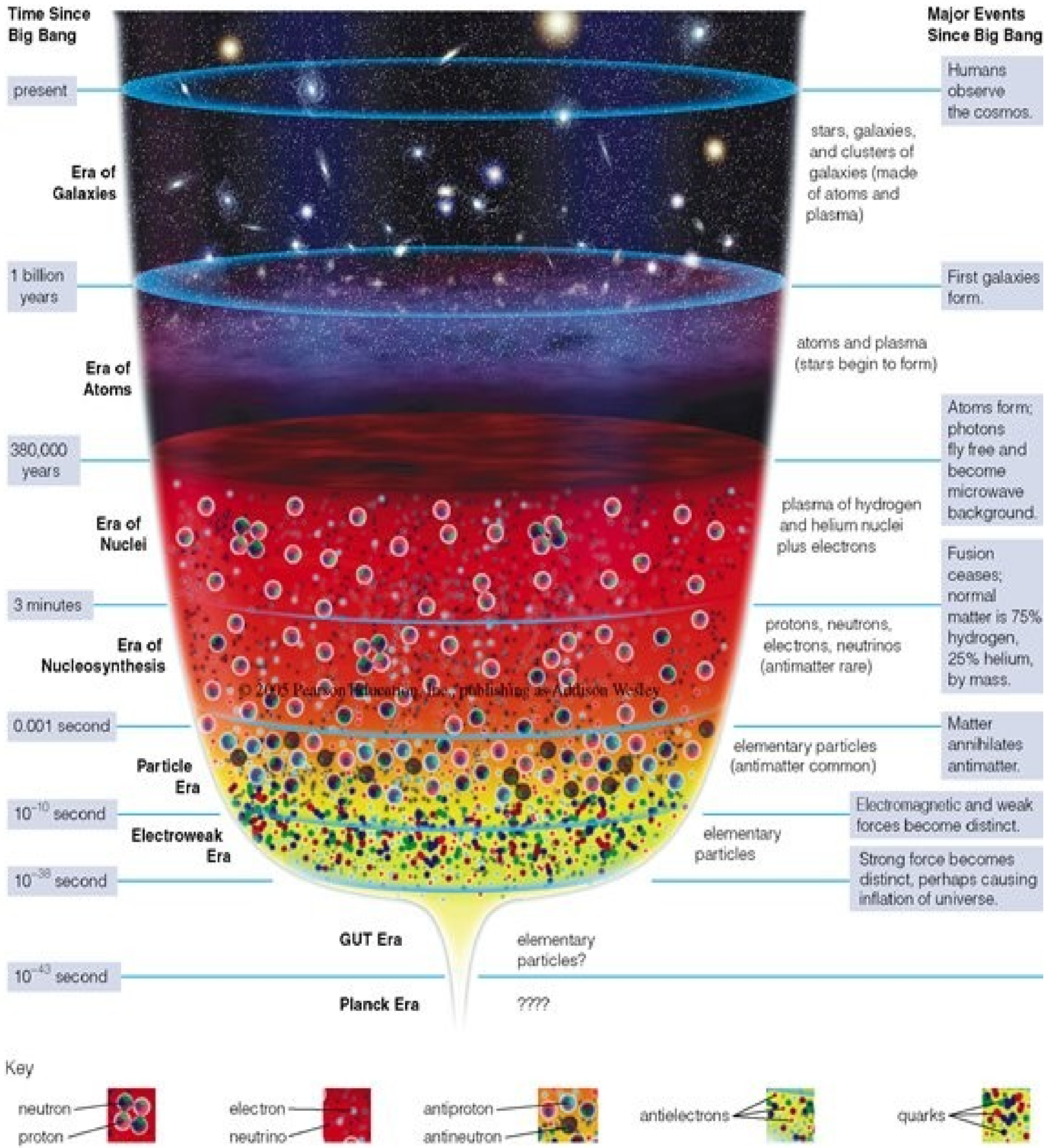
But we don't yet have good ideas about this era, and before it

(we have no good Theory of the Connection between Quantum physics and gravity)



The grand unified (GUT) era ended at 10^{-38} seconds

At the end of this era was a period of rapid expansion called inflation (more on that later)



Next came the electroweak era..

Electroweak and strong forces exist separately

We have learned about the physics prevailing in this era in the laboratory

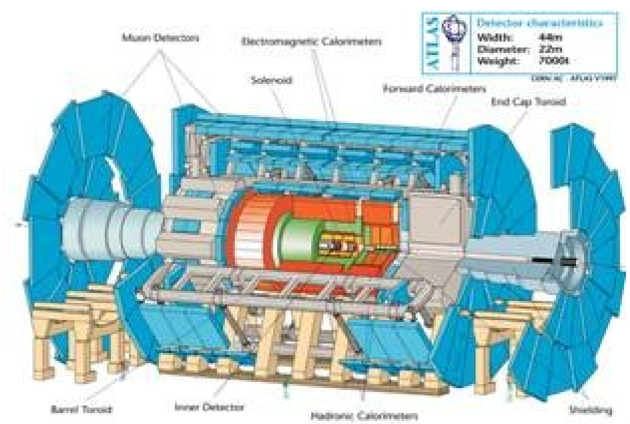
CERN,
a European accelerator laboratory

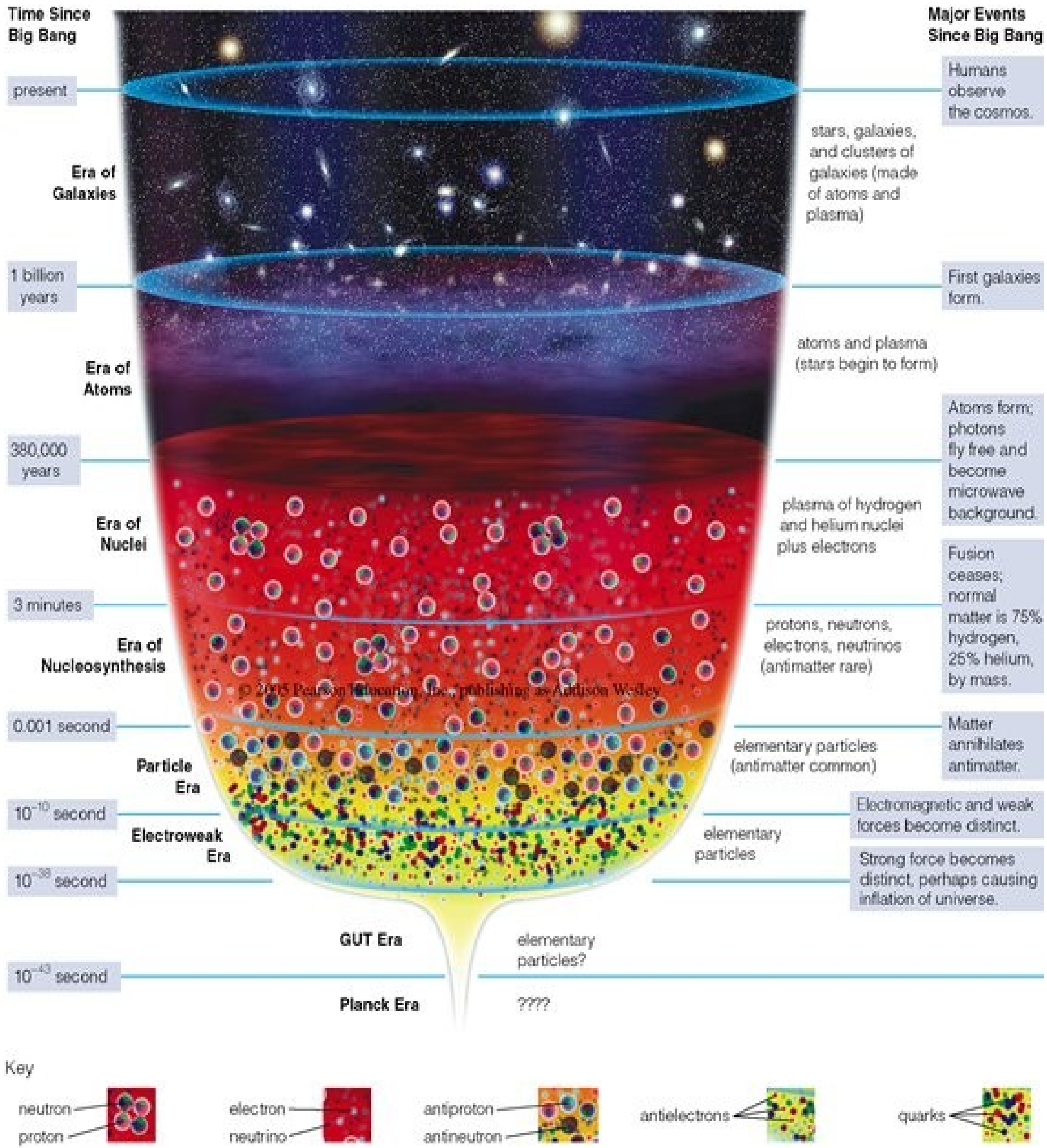
Fermilab,
near Chicago

Protons hitting antiprotons

Atlas and CMS experiments underway to understand the details of electroweak physics!

LHC at CERN





Next, the particle era..

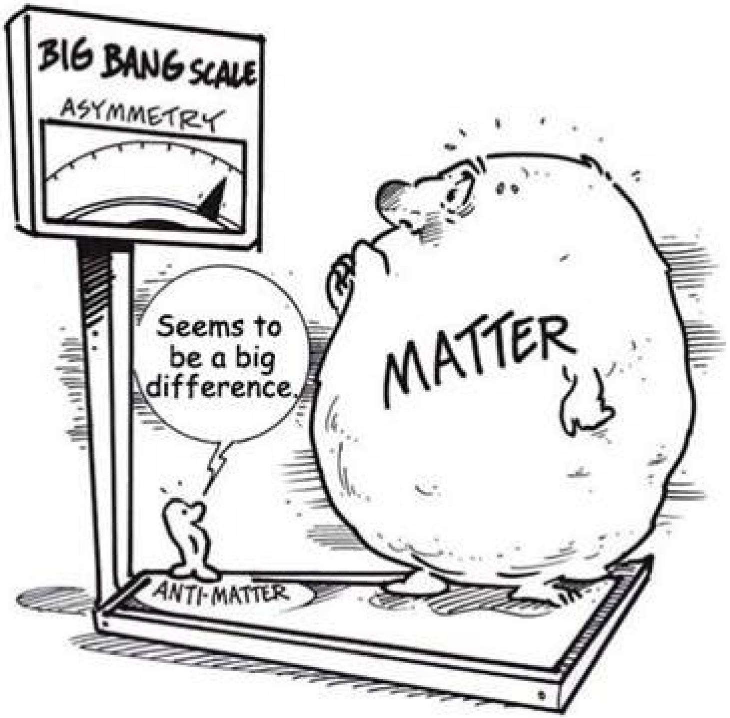
A soup of radiation and particles being created and annihilated *(quark-gluon plasma)* eventually quarks combine into protons and neutrons as the Universe cools

At the end of the particle era, the universe had cooled so much that the average energy was too low for nucleons and antinucleons to be spontaneously created out of energy...

Matter and antimatter then annihilated creating photons

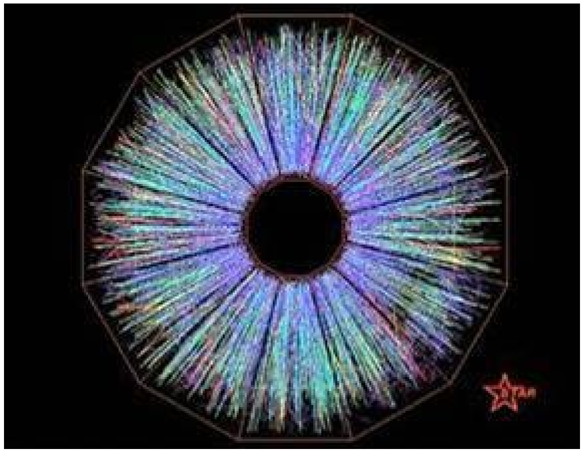
For some unknown reason, we ended up with slightly more matter than antimatter... we are left with a universe *made almost entirely of matter and almost no anti-matter*

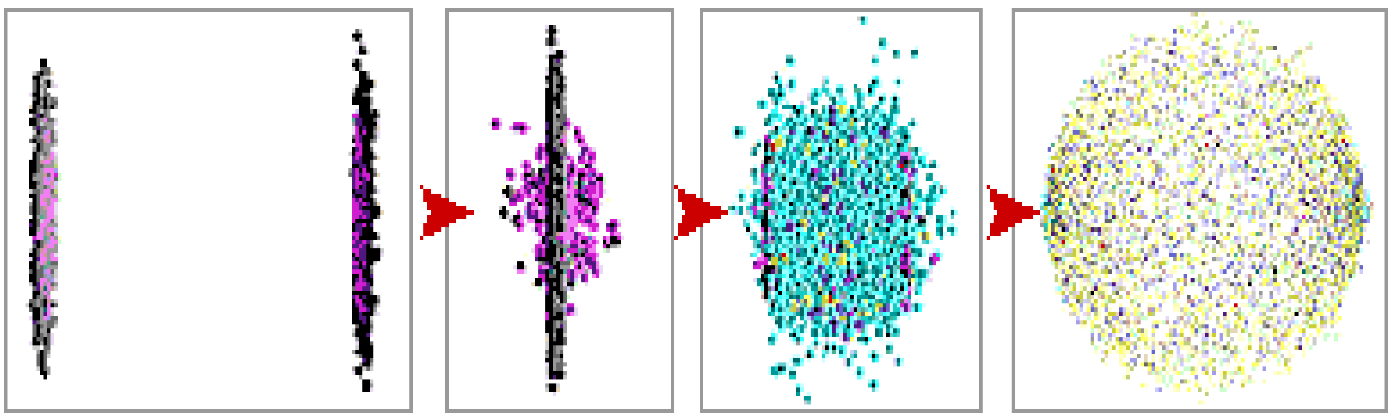
This is another of the gigantic questions remaining to us: *what is the origin of the matter-antimatter asymmetry?* (baryogenesis)



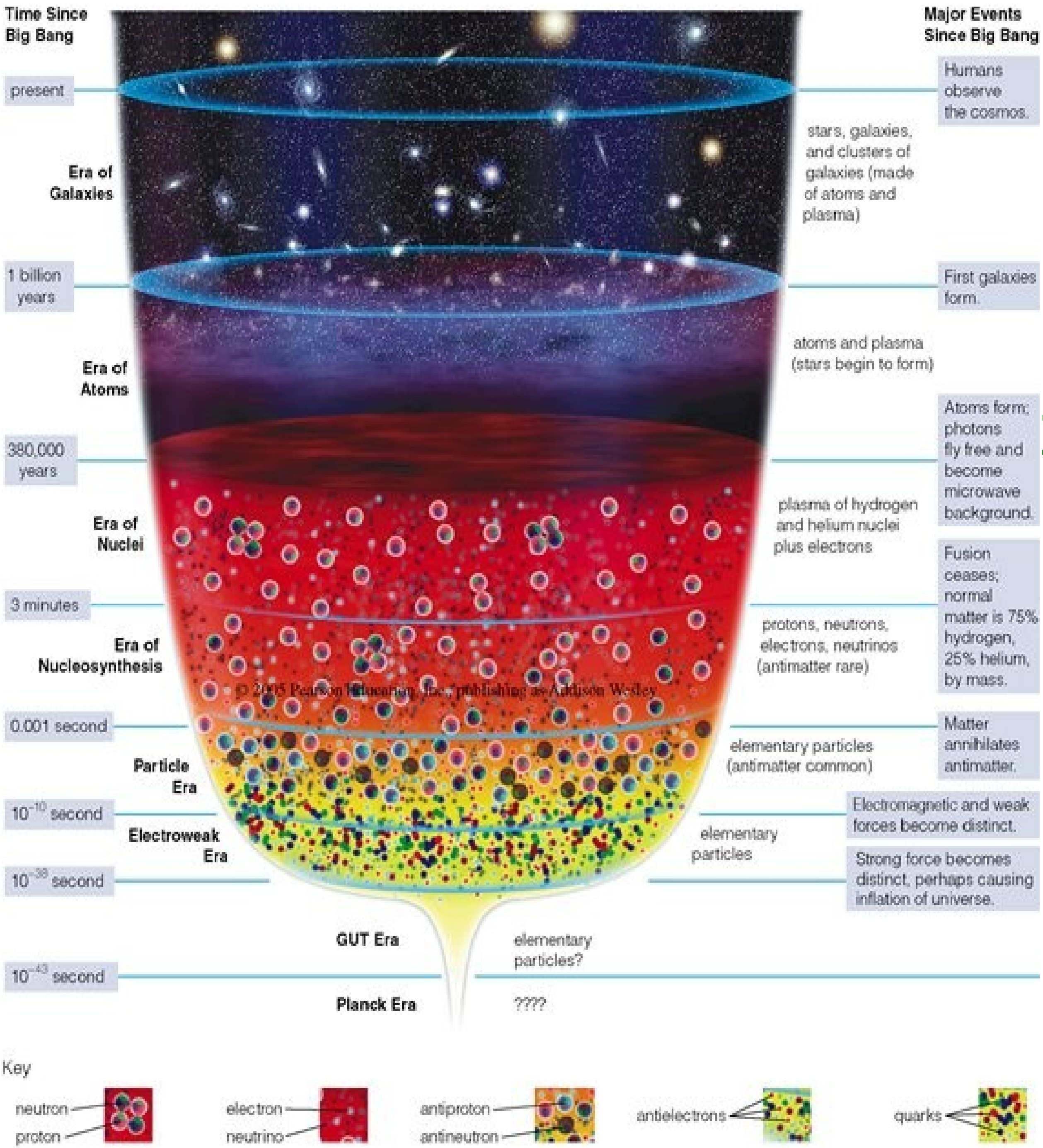
Many particle experiments are trying to determine the fundamental differences between matter and antimatter, to shed light on this question

RHIC: Relativistic Heavy Ion Collider at Brookhaven National Laboratory (+LHC)





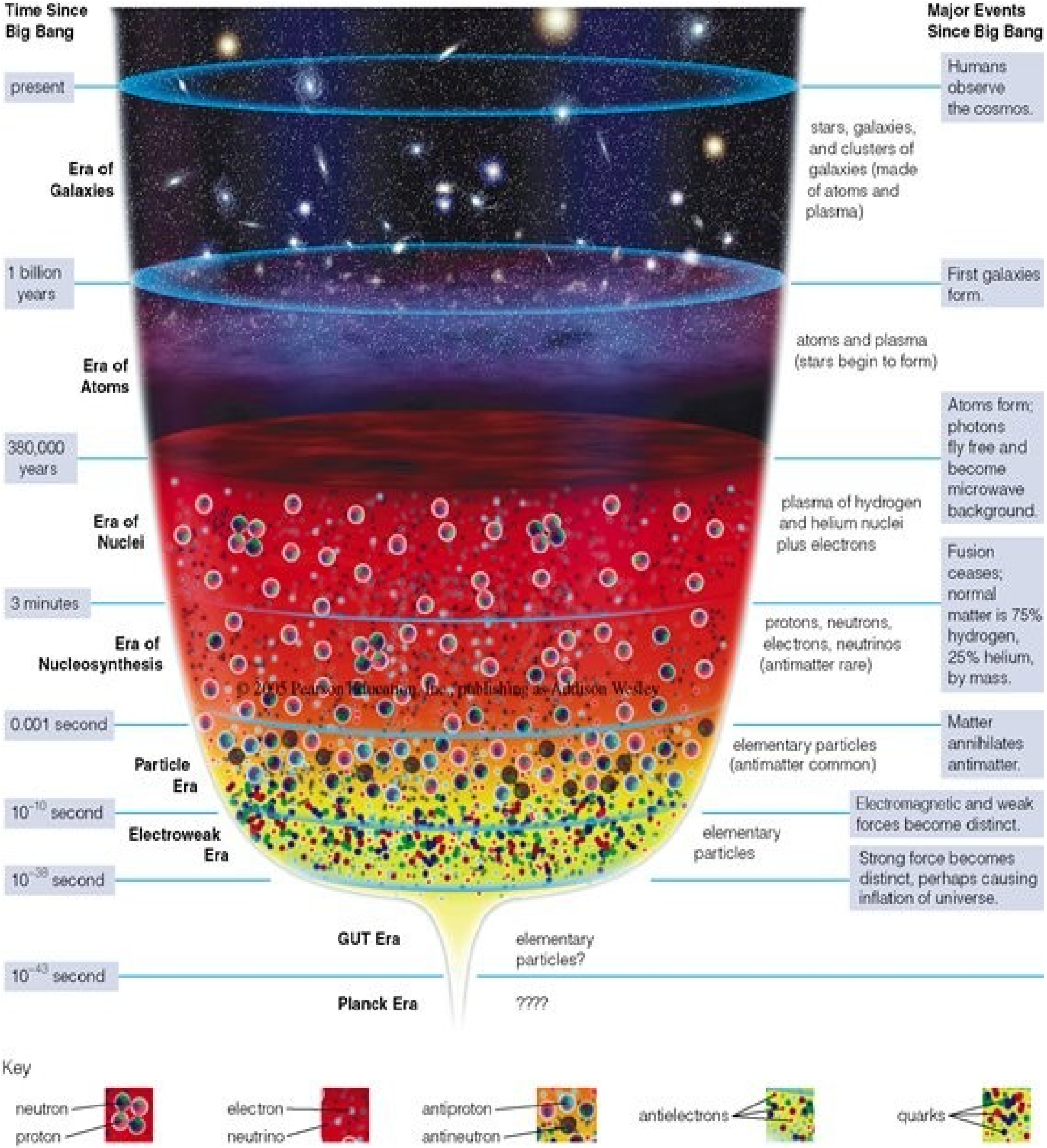
Collide heavy nuclei to recreate the conditions of the particle era of the Big Bang



Big Bang Nucleosynthesis: Protons and Neutrons fuse into Nuclei (75% H and 25% He)

Universe as hot as the Sun's core

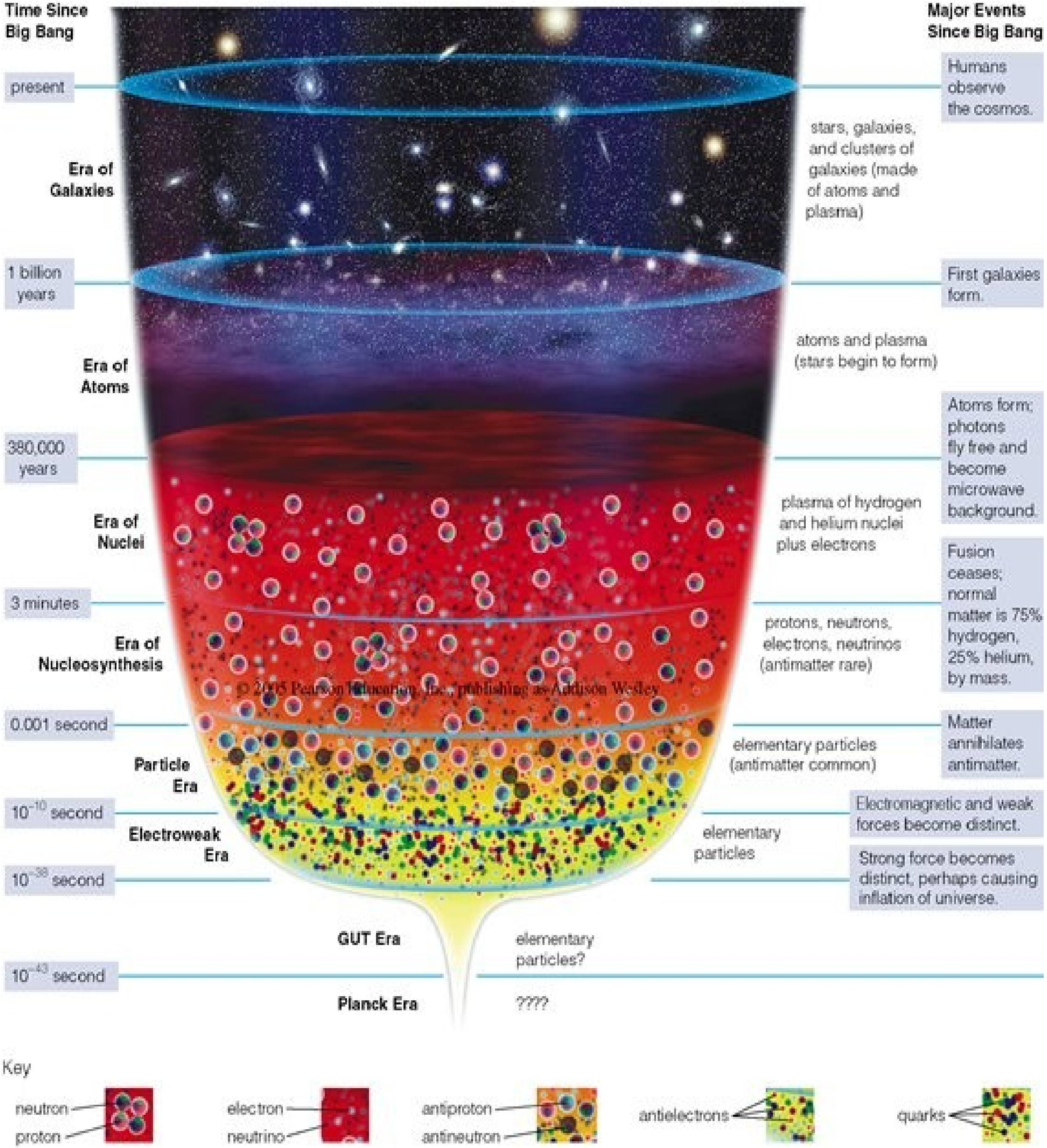
Ends about 3 minutes after the Big Bang



Era of nuclei:
lasts 380,000 yr

Universe consists of plasma (fully ionized nuclei) and radiation; universe continues to expand and cool

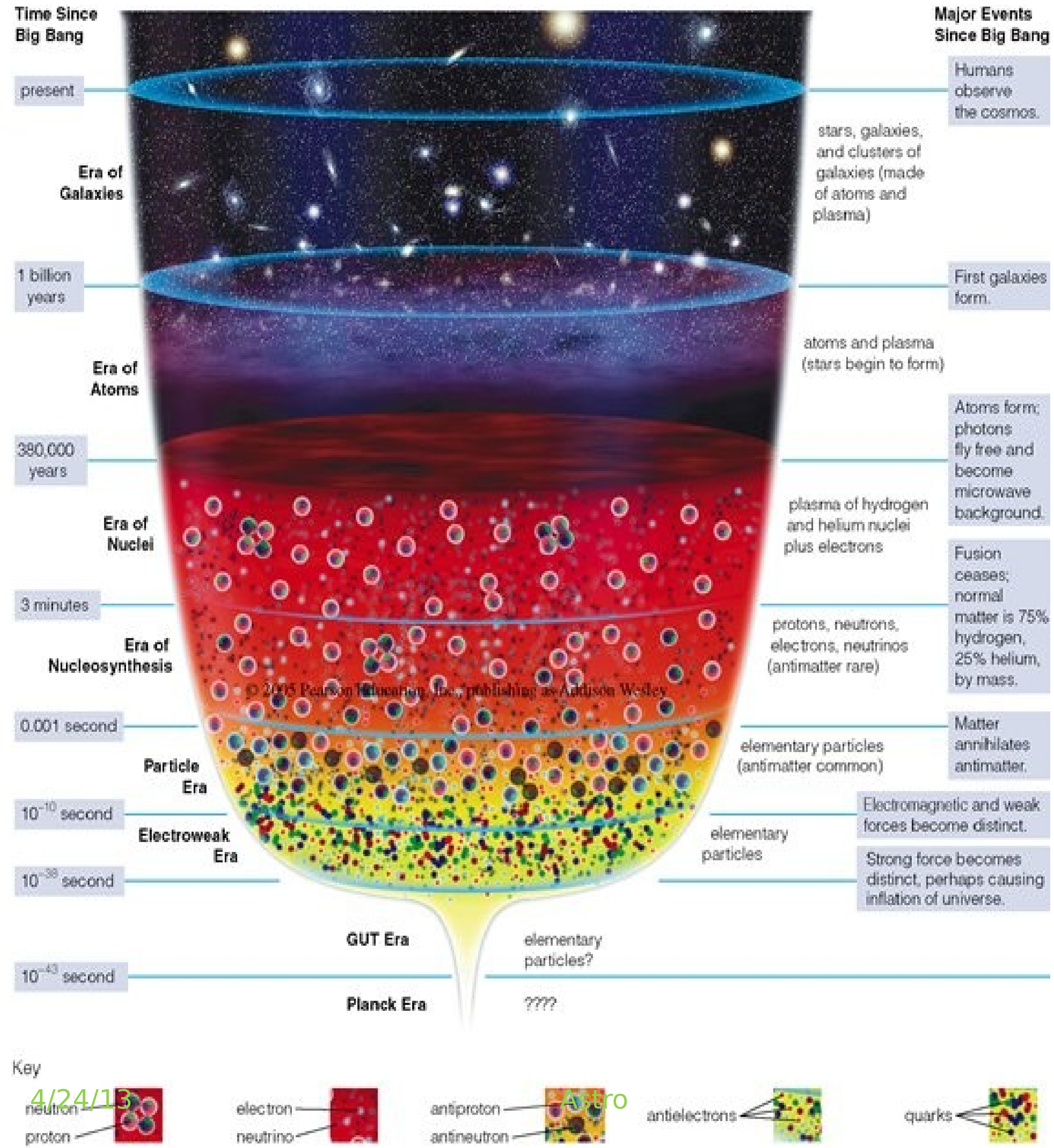
Photons interact with free electrons



Finally, when the temperature cools to ~3000 K, at 380,000 yr, electrons and nuclei can combine into atoms *(recombination)*

Photons, unimpeded by free electrons, begin to stream freely

The Universe becomes Transparent

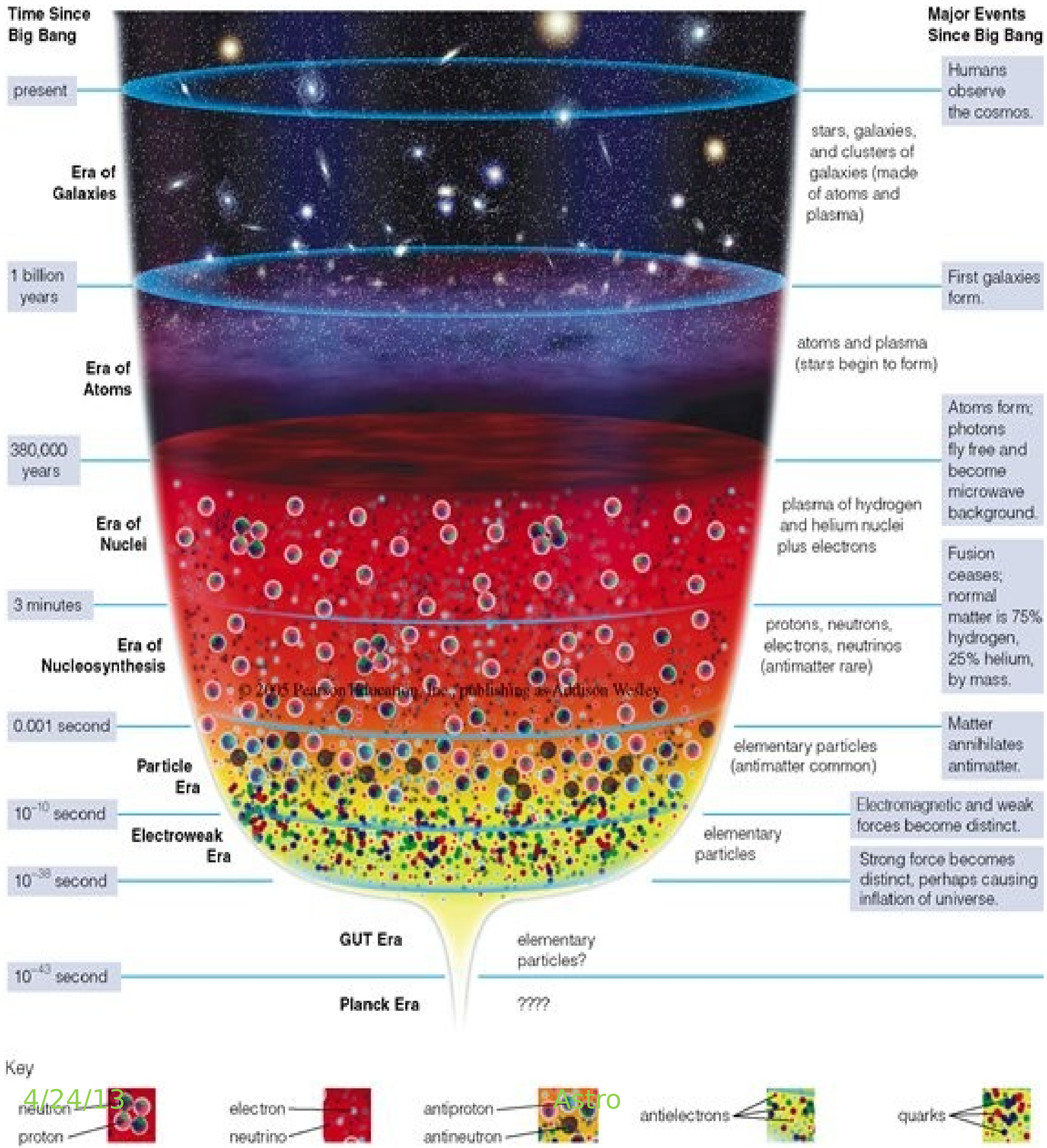


Era of atoms:

Lasts for about
1 billion years

The first 400 millions years there are no stars – gas is too hot, moving too fast

Called the “dark ages”



Era of Galaxies (Current era)

Finally, at a bit less than 500 million years, Galaxies start to form

By 1 billion years they are the dominant feature in the Universe

This basic “Big Bang” picture has been widely accepted since the 1970s

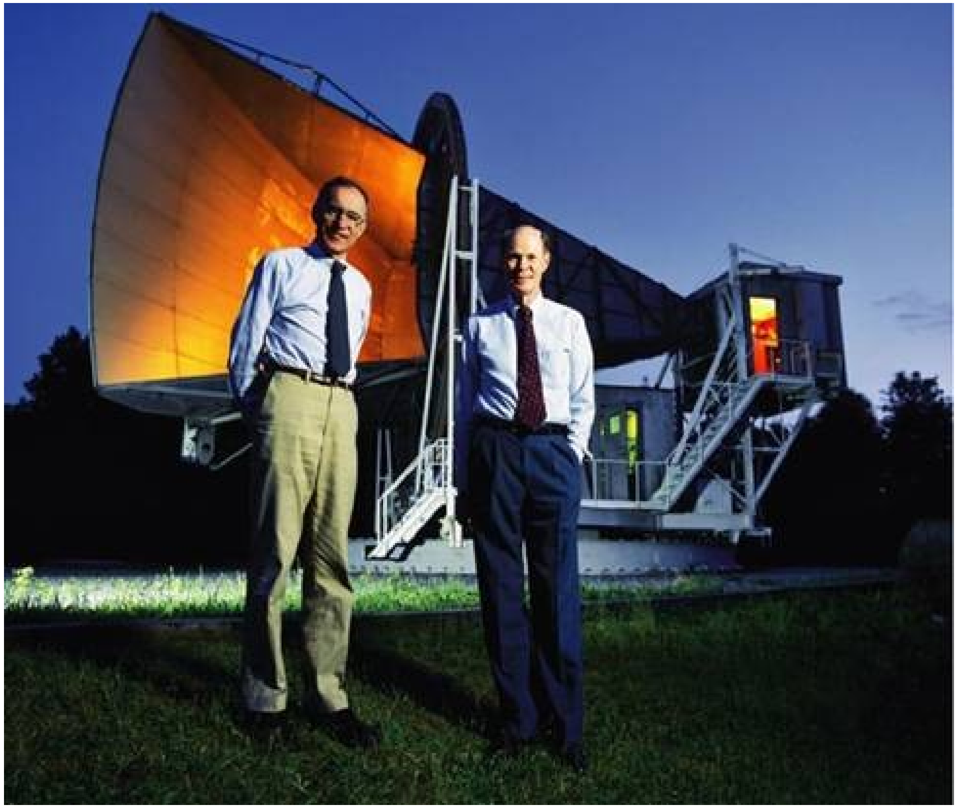
It made clear predictions that were verified

1. Helium content of the universe is that predicted from Big Bang nucleosynthesis
2. The photon radiation that was emitted when the universe became transparent should still be present today; will have been cosmologically red shifted to microwave frequencies COSMIC MICROWAVE BACKGROUND (CMB)

COSMIC MICROWAVE BACKGROUND

Discovered by Penzias and Wilson, 1965

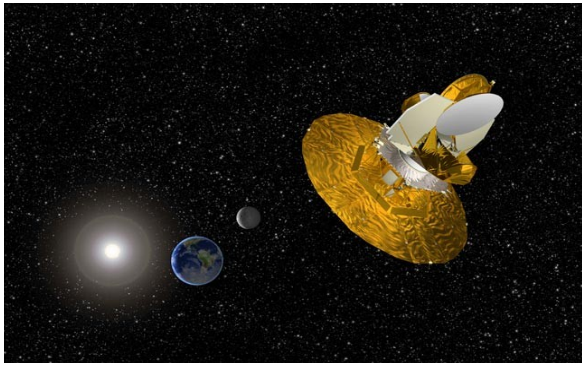
Bell Labs (microwave antenna for satellites)

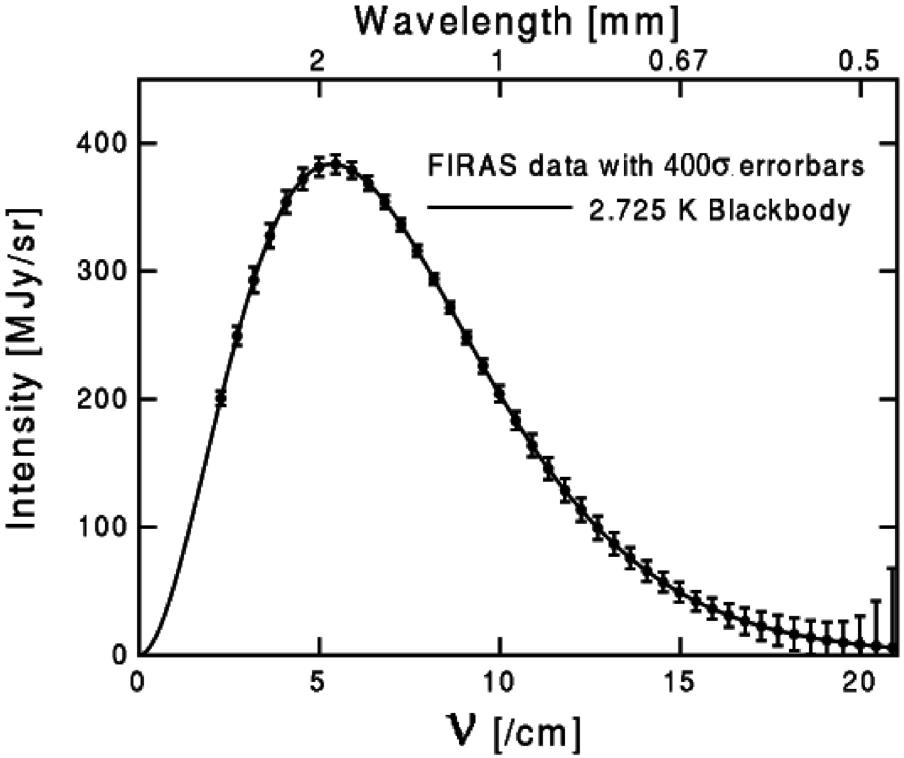


Found strange 'noise' with their microwave antenna, which turned out to be CMB radiation

Nobel prize, 1978

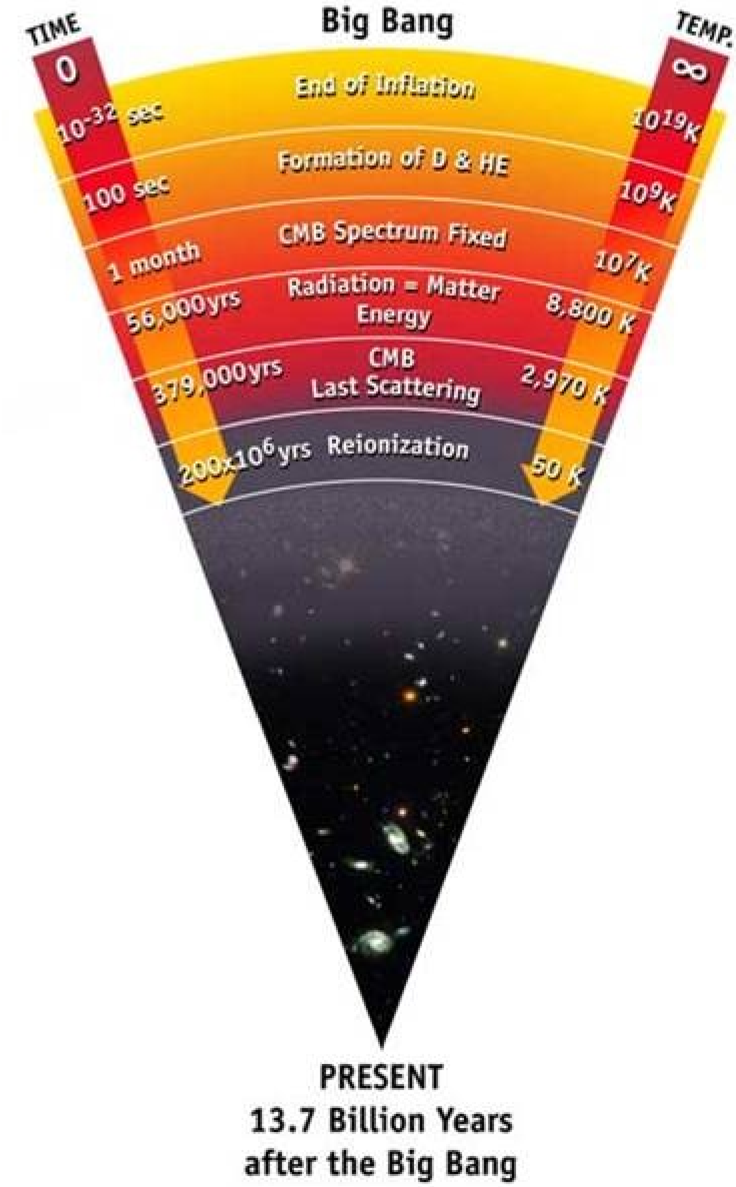
Evidence for the Big Bang from COSMIC MICROWAVE BACKGROUND RADIATION, from era of recombination when the universe went transparent



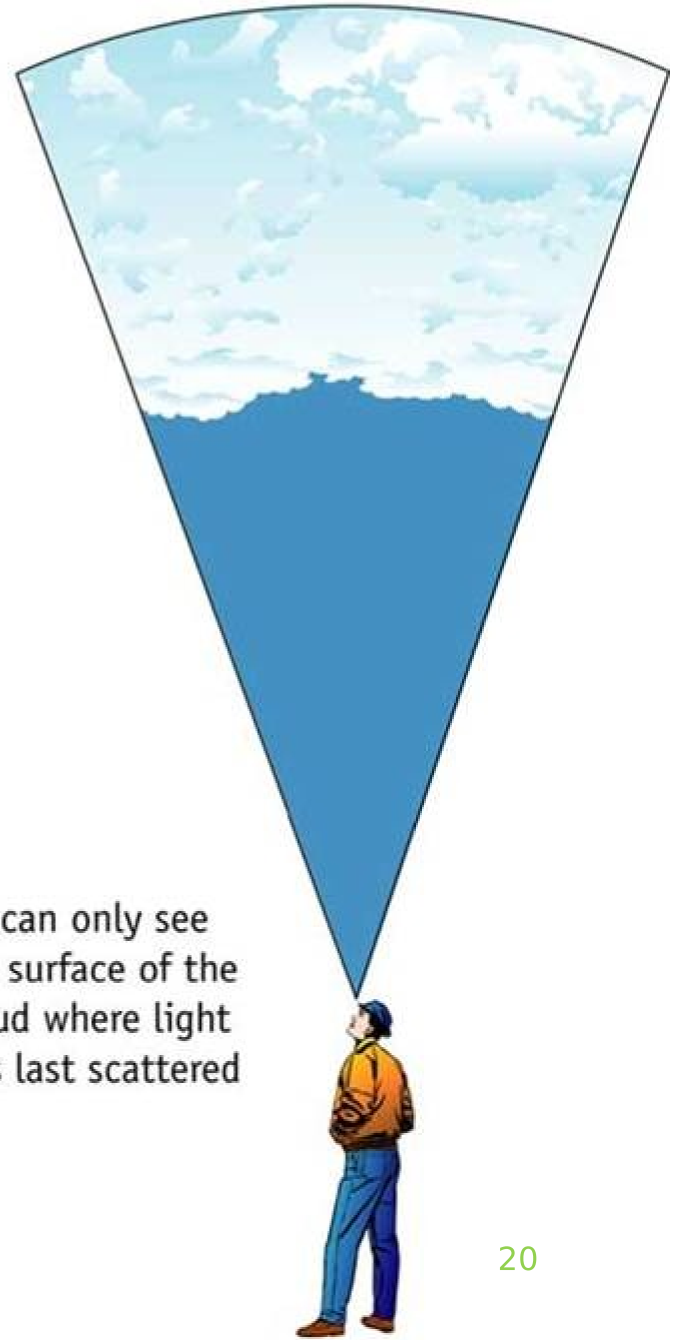


Cosmic Background Explorer (COBE) (NASA 1992, 2006 Nobel Prize)

- Thermal, T=2.7K
- Small temperature variations map density fluctuations after recombination 0.00001 level

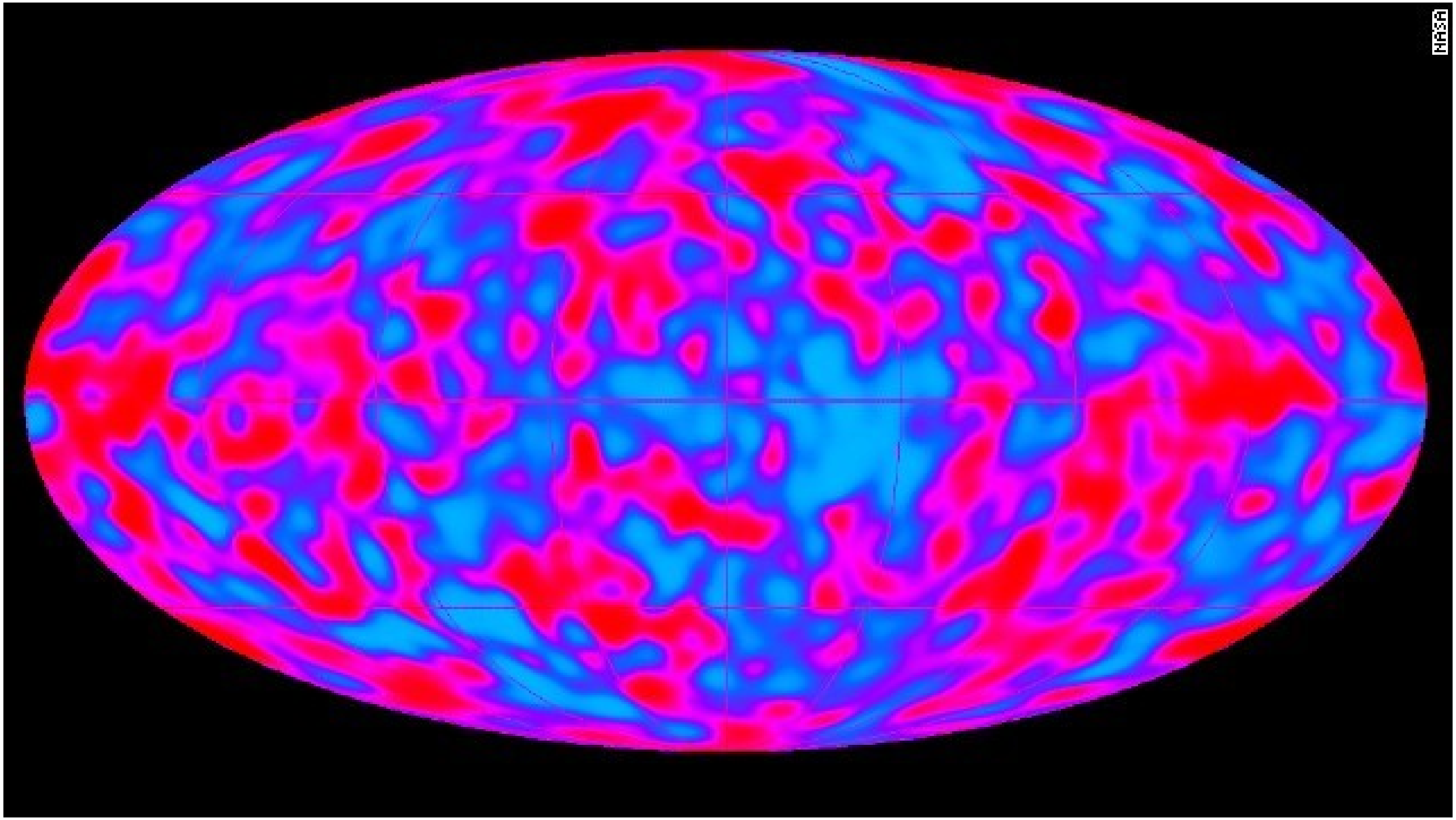


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

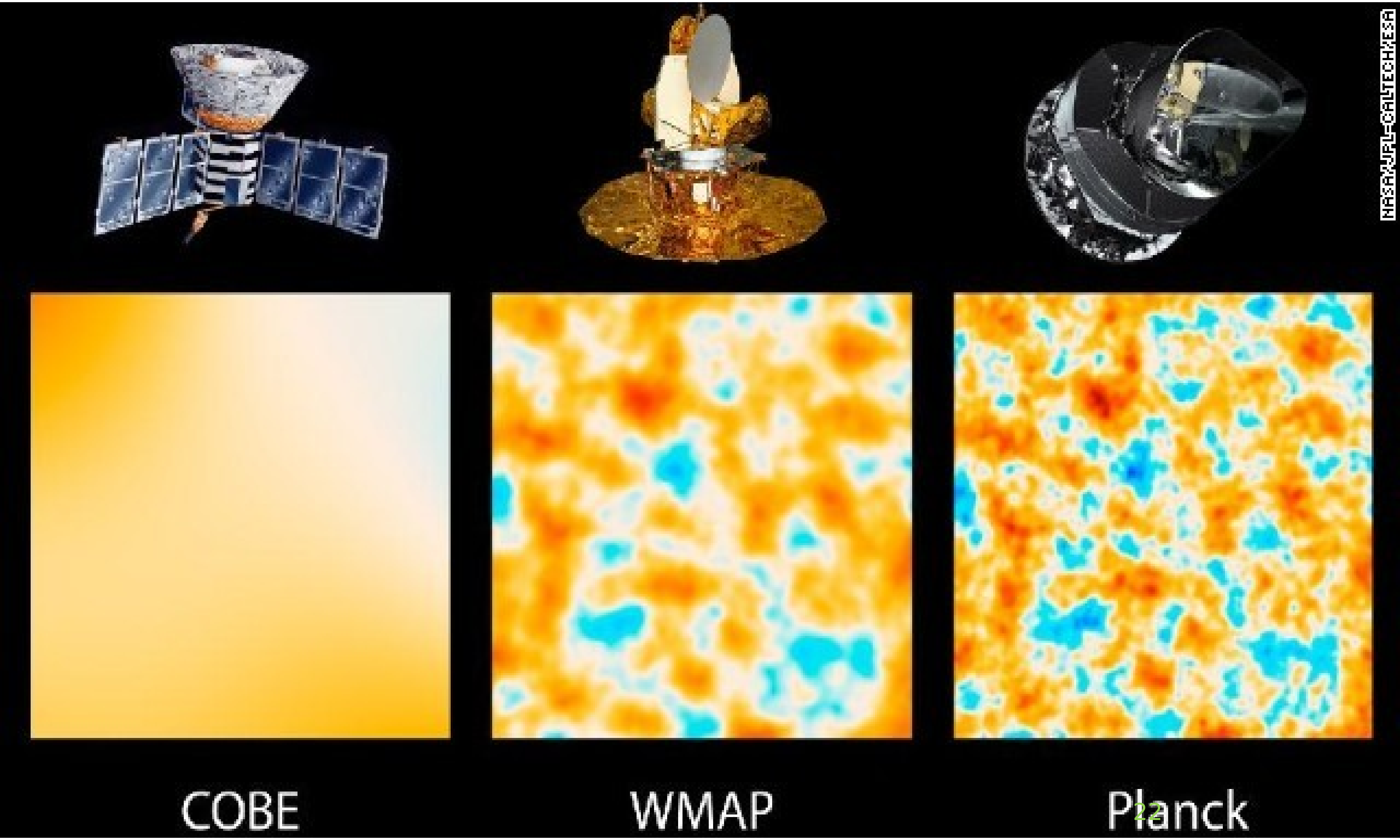


We can only see the surface of the cloud where light was last scattered

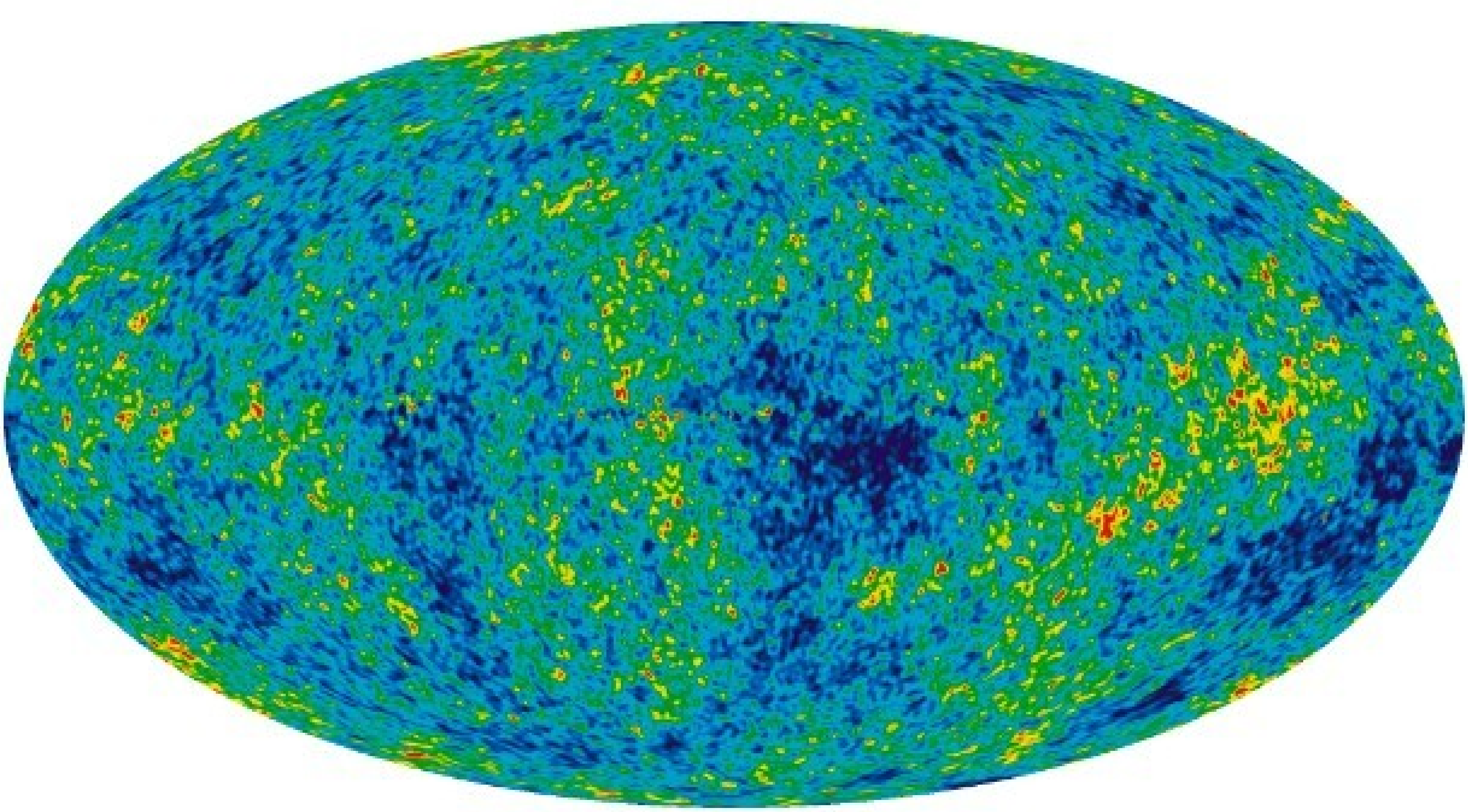
COBE (NASA 1992)



Results from different generation experiments



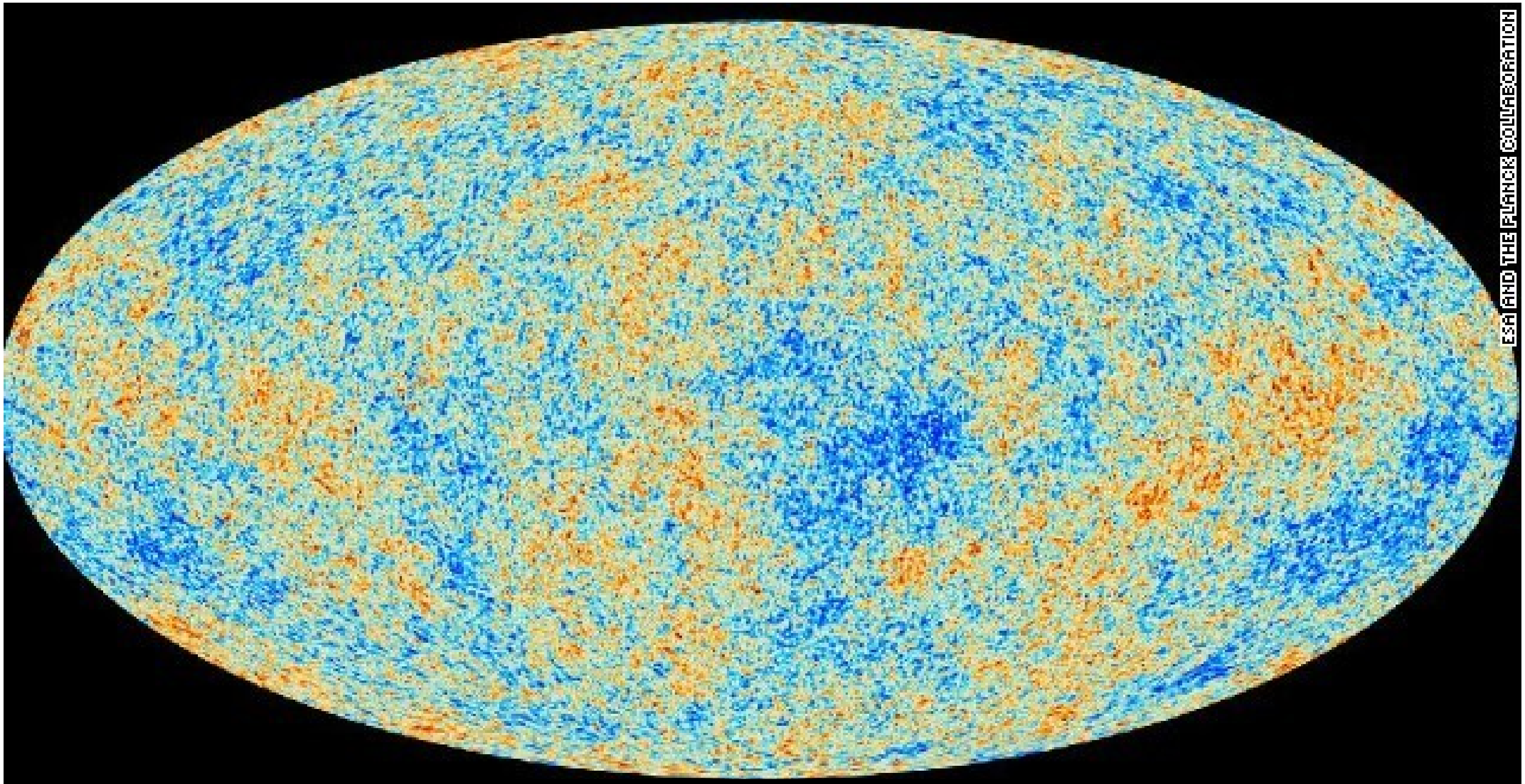
WMAP (NASA, 2005)



NASA / WMAP SCIENCE TEAM

PLANCK (ESA, March, 2013)

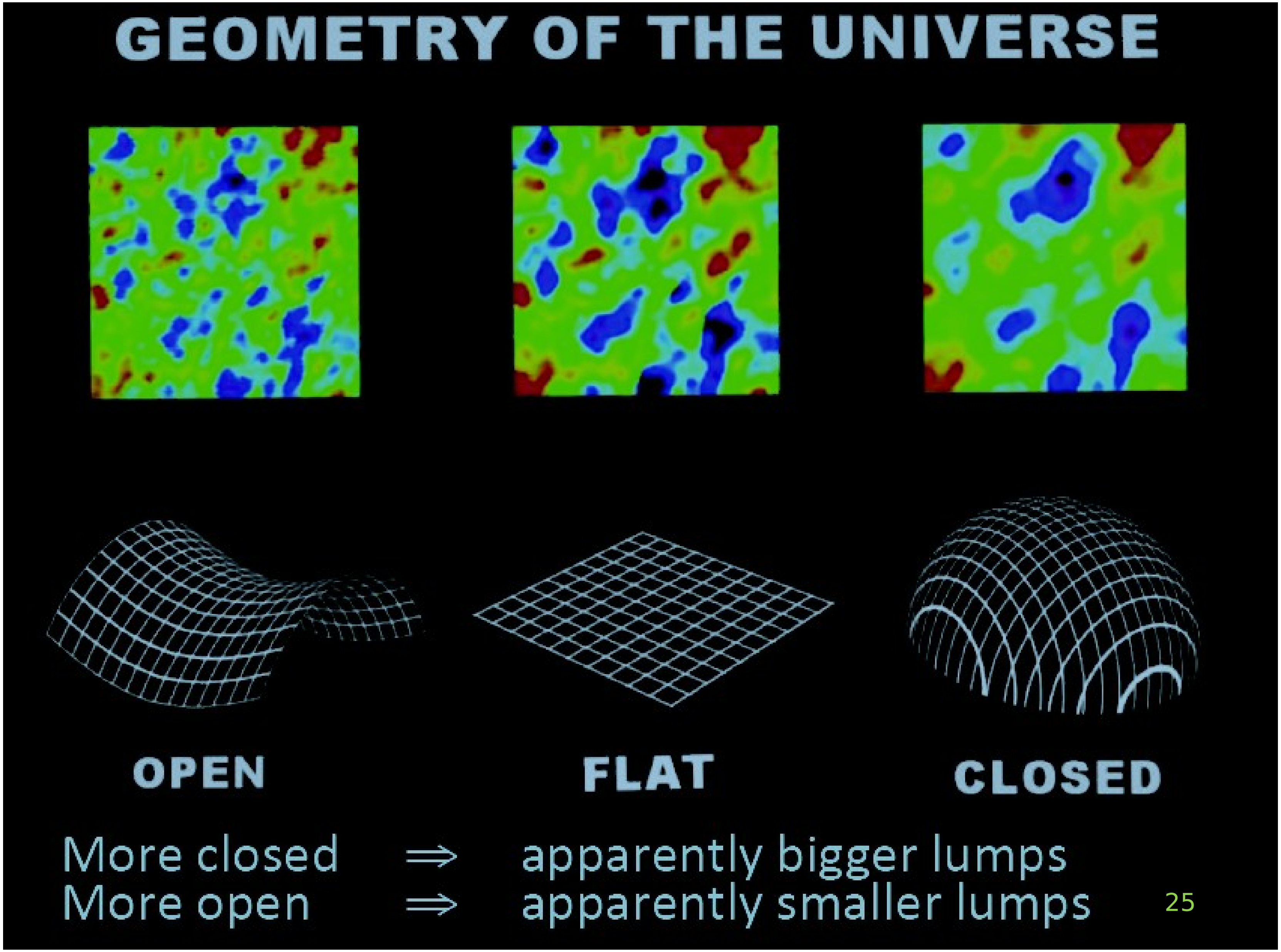
Much more precise… we learn a huge amount

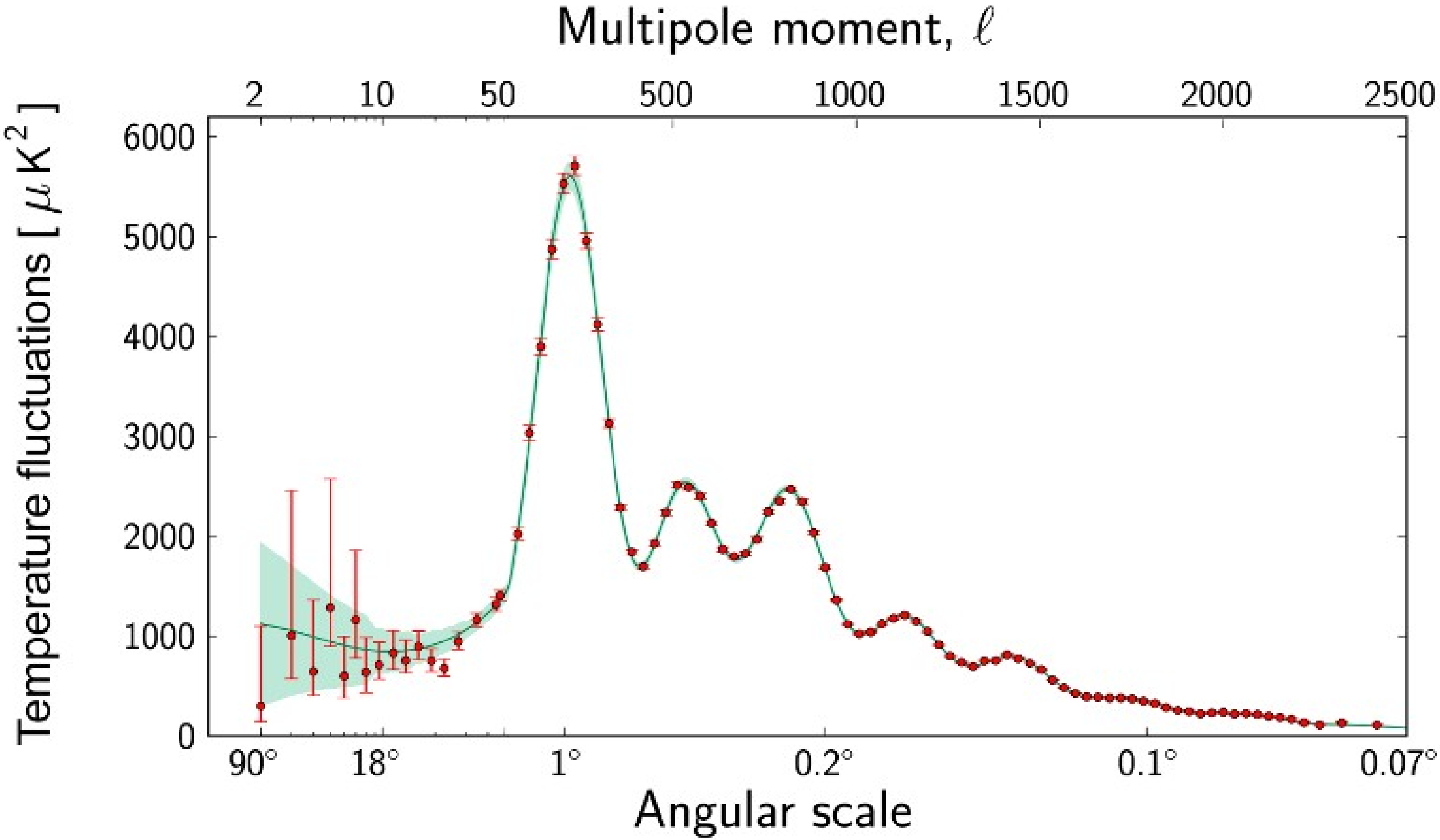


The precise shape and structure of the fluctuations depend on

- The amount of dark matter
- The amount of dark energy
- Total geometry of the universe (overall density of the Universe)

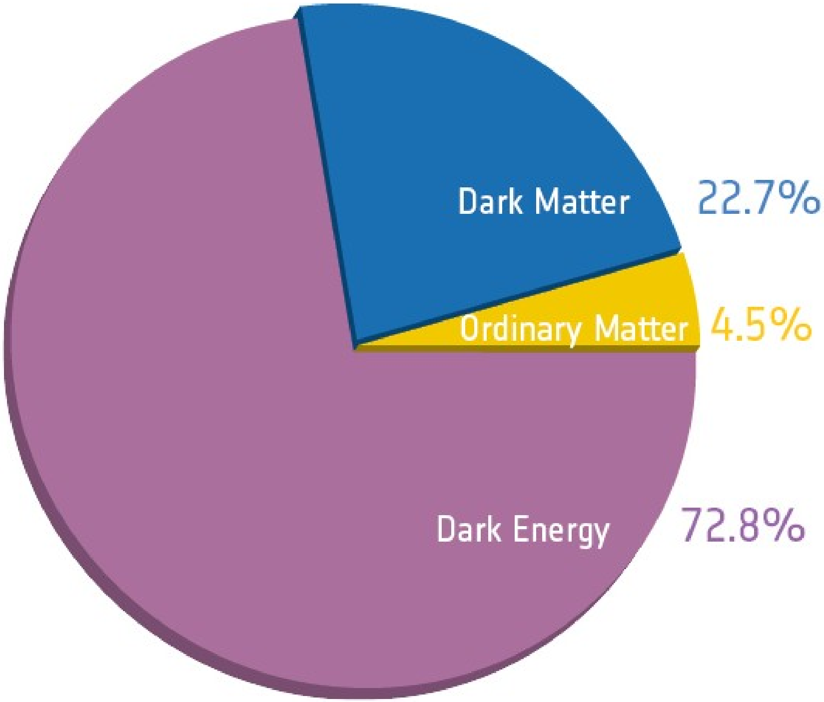
The sizes and separations of the hot/cold spots depend on the curvature of space



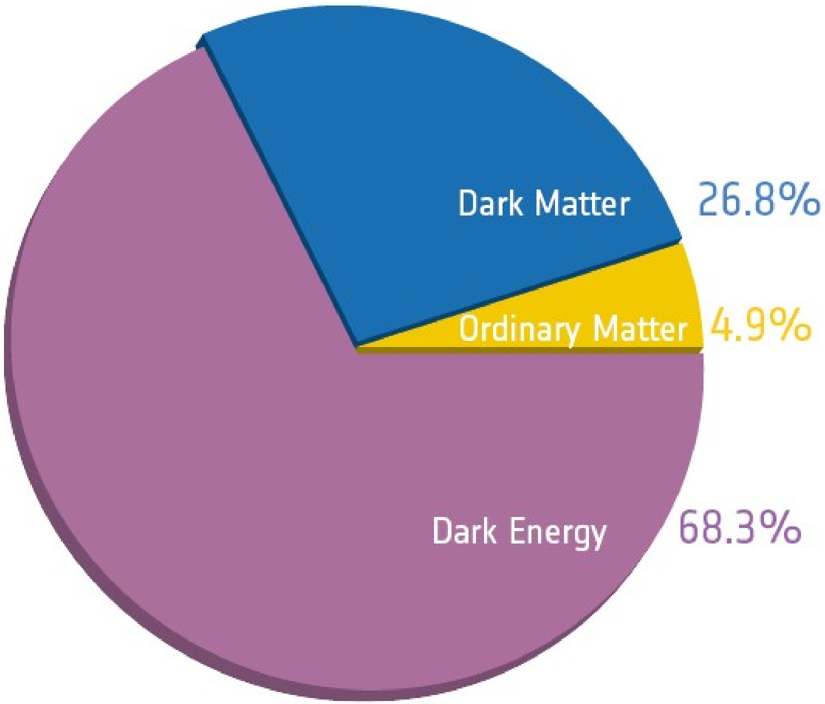


Multipole moment, ℓ
2
10
50
500
1000
1500
2000
2500
Temperature fluctuations [μK²]
6000
5000
4000
3000
2000
1000
0
90°
18°
1°
0.2°
0.1°
0.07°
Angular scale

Composition of the Universe



Before Planck



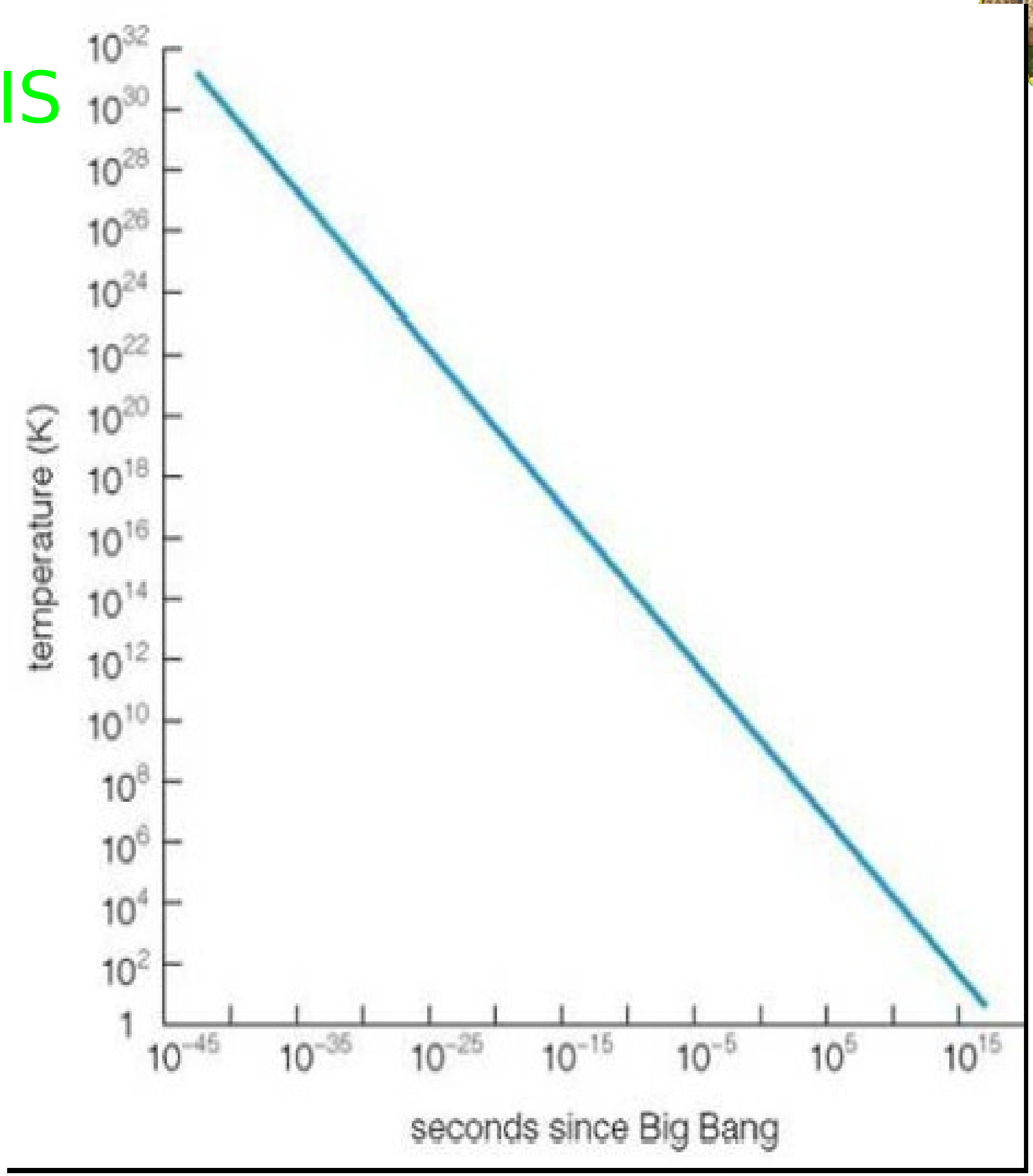
After Planck

Other “anisotropies”

- Galaxy cluster distributions and CMB fluctuations
  - Both the results of primordial density fluctuations
  - Each of the denser spots should lead to galaxy clusters a billion years later
  - We can also look at the anisotropies in the galaxy cluster data to look for the same patterns
- Galaxies and CMB are consistent !

Big Bang NUCLEOSYNTHESIS

- Above a few billion degrees, nuclei can't exist
- This corresponds to 1 second after the Big Bang
- At this time, there were protons, neutrons, electrons, photons, neutrinos.



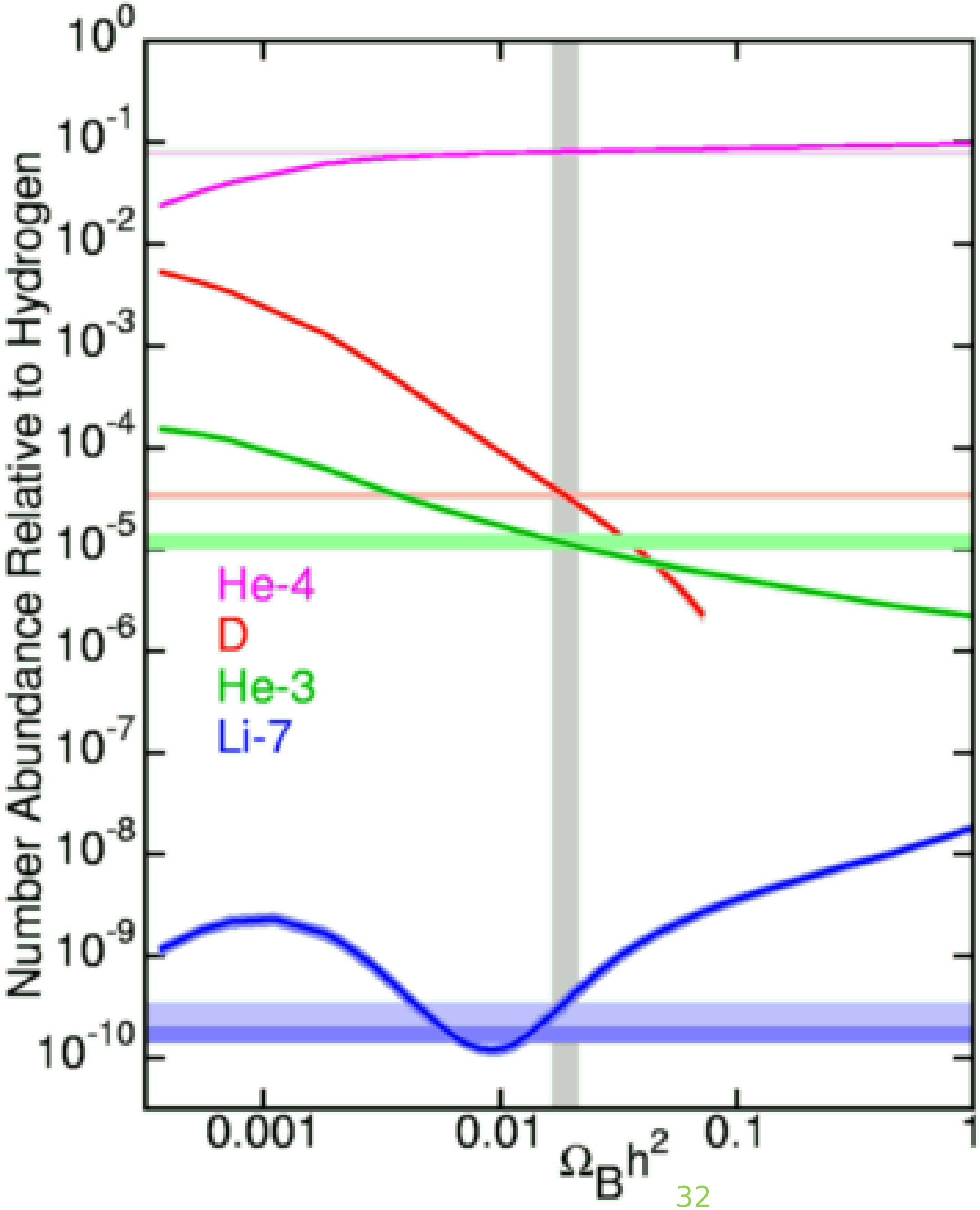
At t = 1 second

- The ratios of protons, neutrons, electrons and neutrinos were all completely fixed by the temperature and their masses
- As the universe cooled, nuclei could form
- 2 important factors:
  - Initially p + n --> D (or 2H)
  - D interact with p to make 3He & eventually 4He
- 2 reasons it ends (other than getting cooler)
  - But D is very weakly bound, so if it forms it gets destroyed quickly
  - Also, the neutron lifetime is 15 minutes.

New measurement of ancient gases (Nov. 2012)

- http://physicsworld.com/cws/article/news/2012/dec/05/ancient-gas-sheds-light-on-universes-first-billion-years
- To analyze the ancient gas, they examined absorption lines in the spectrum of the farthest known quasar
  - Its light travels 12.9 Gly before reaching Earth
  - We see the quasar as it was 770 Myr after the Big Bang
- The gas itself is much too faint to see
  - They searched for wavelengths at which intervening gas absorbed the quasar's light
  - The gas is probably a few million light years from the quasar and so has no connection to the galaxy containing the quasar
- It is hydrogen & helium with traces of lithium
  - The lack of detectable metals indicates the gas has no more than 1/1000 the metal-to-hydrogen ratio of the Sun

- The amount of each element can be determined by theory
  - The number of protons and neutrons left after matter-antimatter annihilation
  - Matter density (Ω_B)
  - How fast the Universe expanded
  - Hubble's constant (H)
- Plot shows good excellent agreement between data & predictions
  - Data are the bands
  - Theory are the curves

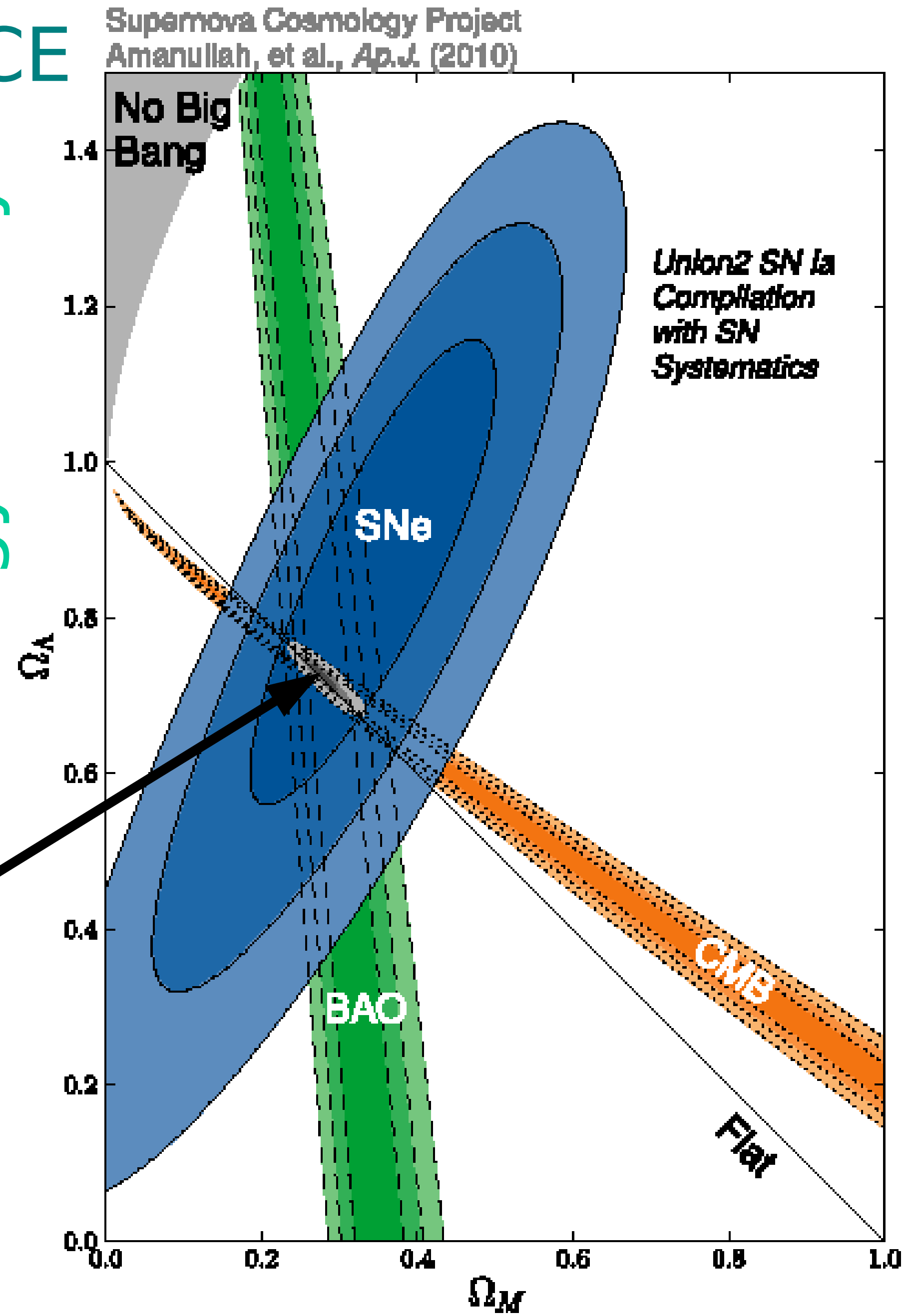


The current CONCORDANCE MODEL of cosmology

Different data:
- WD supernovae
- CMB
- BAO
- Quasar absorption lines
- Galaxy clustering
- Big Bang nucleosynthesis

all agree at one point where the Universe is at the Critical Density

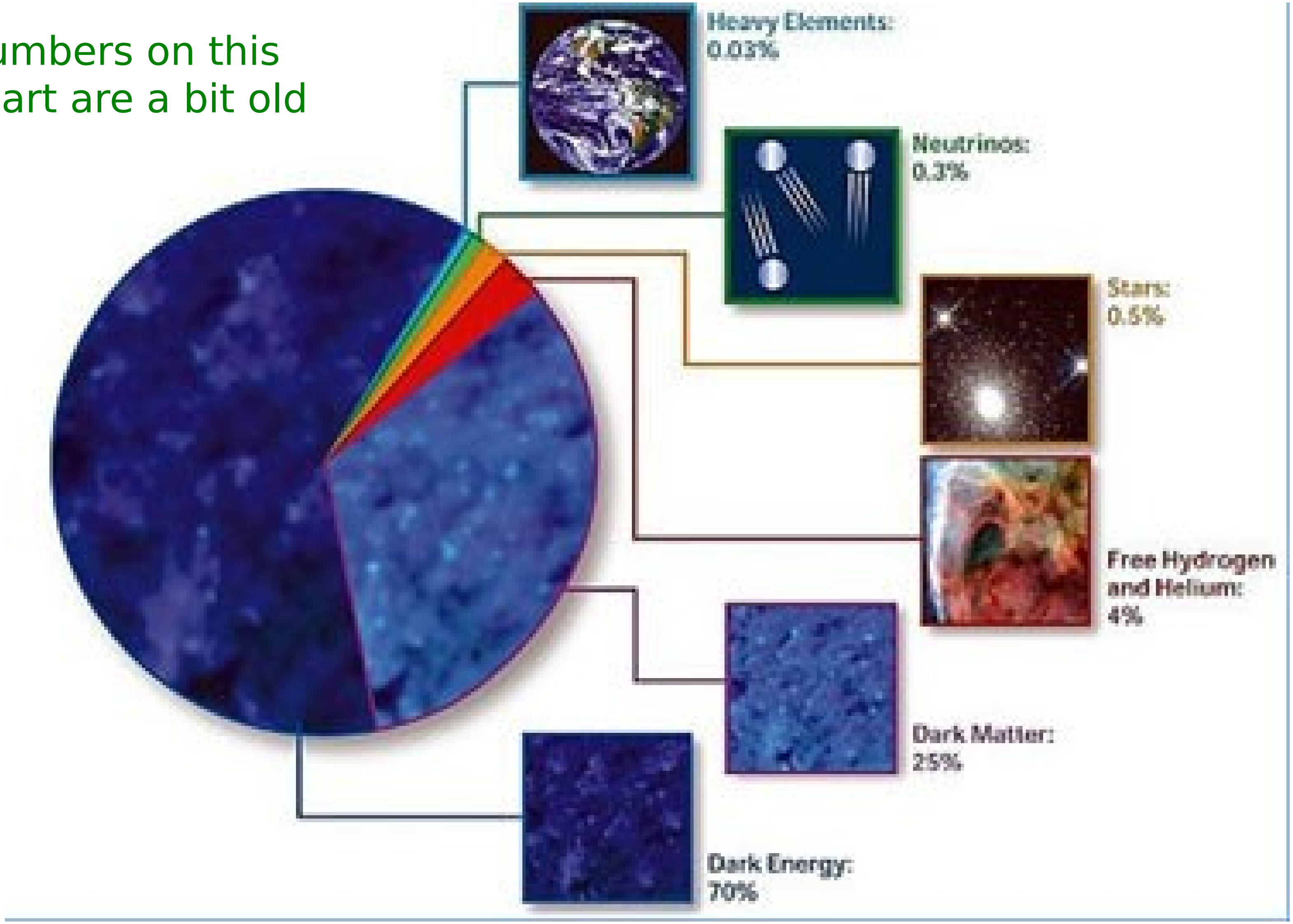
Dark energy density



Matter density

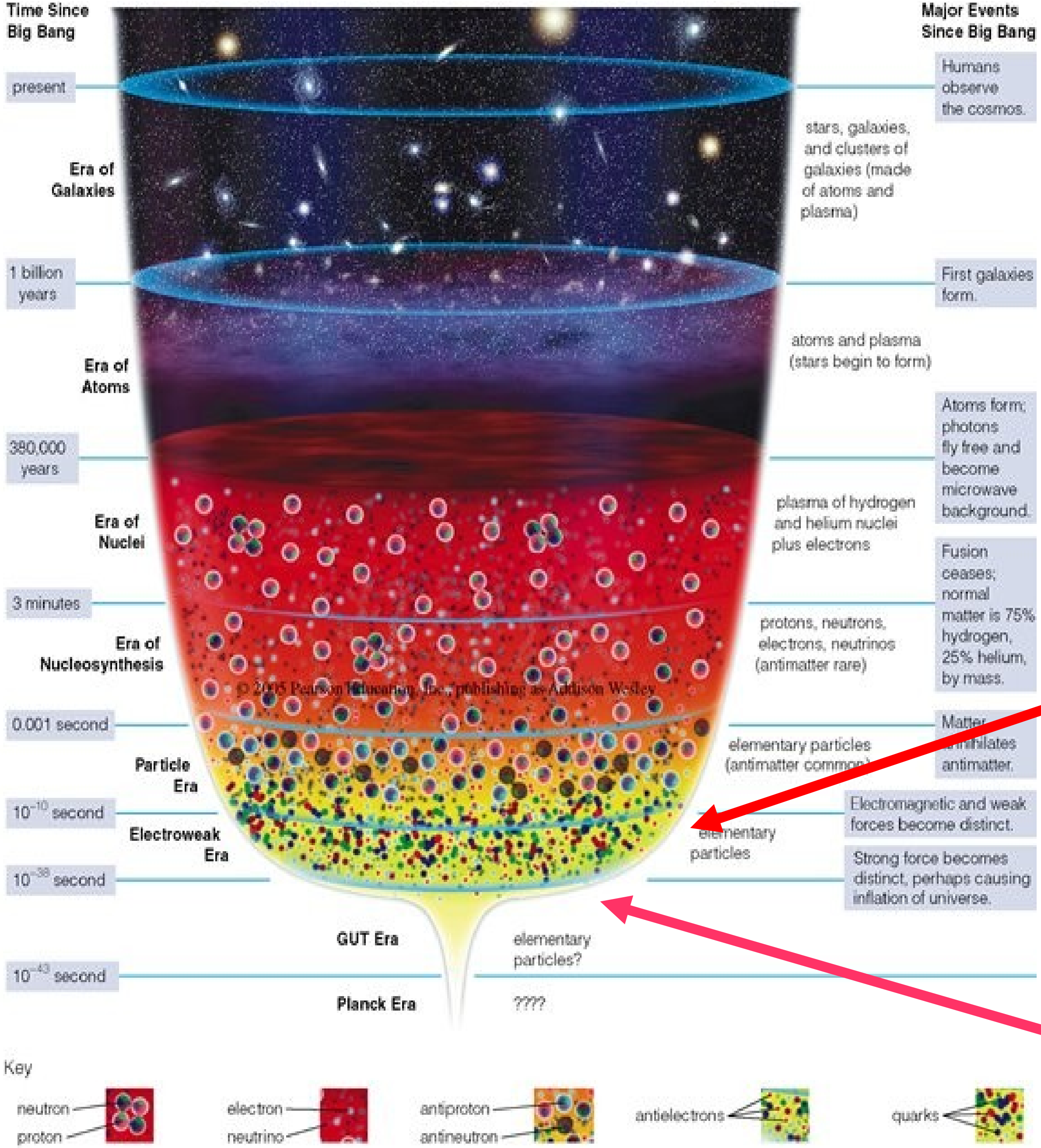
All normal and dark matter: 31.7% of critical

Numbers on this chart are a bit old



The contribution of DARK ENERGY: 68.3%

Inflation



Particle physics is reasonably well understood back to here

Let’s zoom in here

Before 1980 ... questions with no good answers

Where does the universe's structure (galaxies, clusters, large-scale structure) come from?
(structure formation problem)

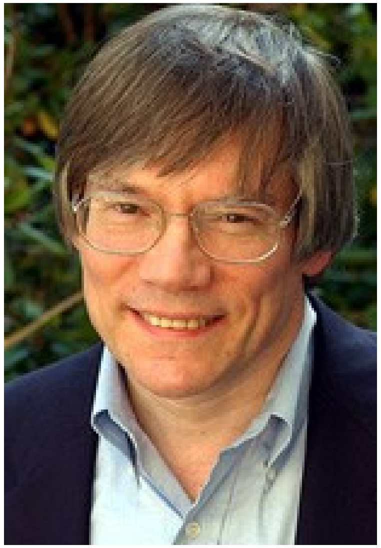
Why is the large scale universe so smooth?
(isotropy or horizon problem)

Why is the density so close to critical?
(flatness problem)

The flatness problem

- Today, $0.98 < \Omega < 1.02$
  - But $\Omega = \rho/\rho_c$, and the numerator and denominator change differently with time, so Ω changes with time
  - At t = 1 sec., $0.999999999 < \Omega < 1.00000000001$
- Of course, it could be EXACTLY 1.0 (flat geometry), but why?
  - If it isn't exactly 1.0, it must be tuned to be very, very close to 1.0 at early times.
- Problem: Why is the universe so close to flat?

A theory which explains all of these problems: INFLATION



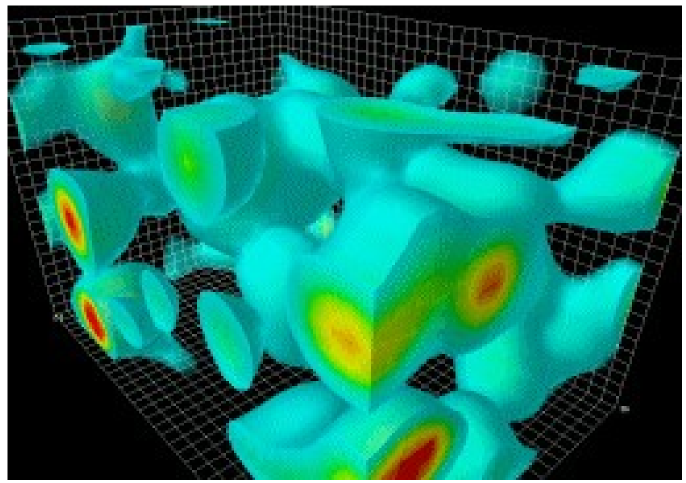
Alan Guth, MIT

Expansion by a factor of $\sim 10^{50}$ in $\sim 10^{-32}$ seconds

What this means for the early universe:

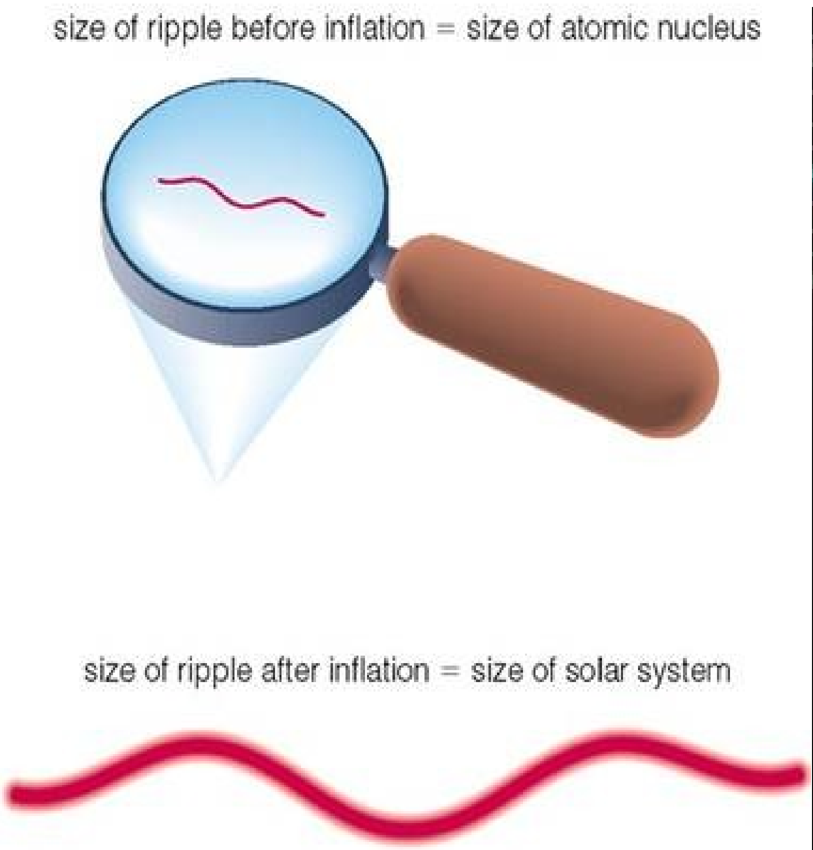
For tiny sizes in the early universe, there are relatively large fluctuations in energy:

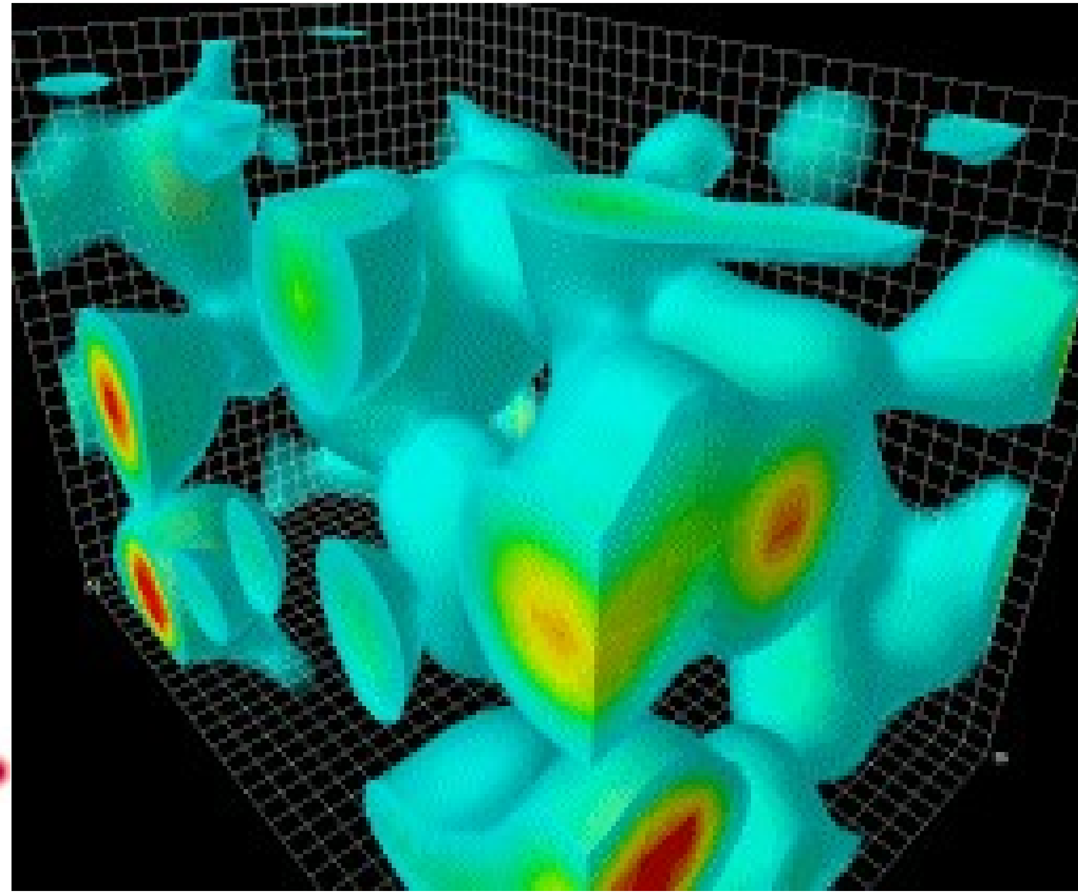
'quantum fluctuations' or 'ripples'

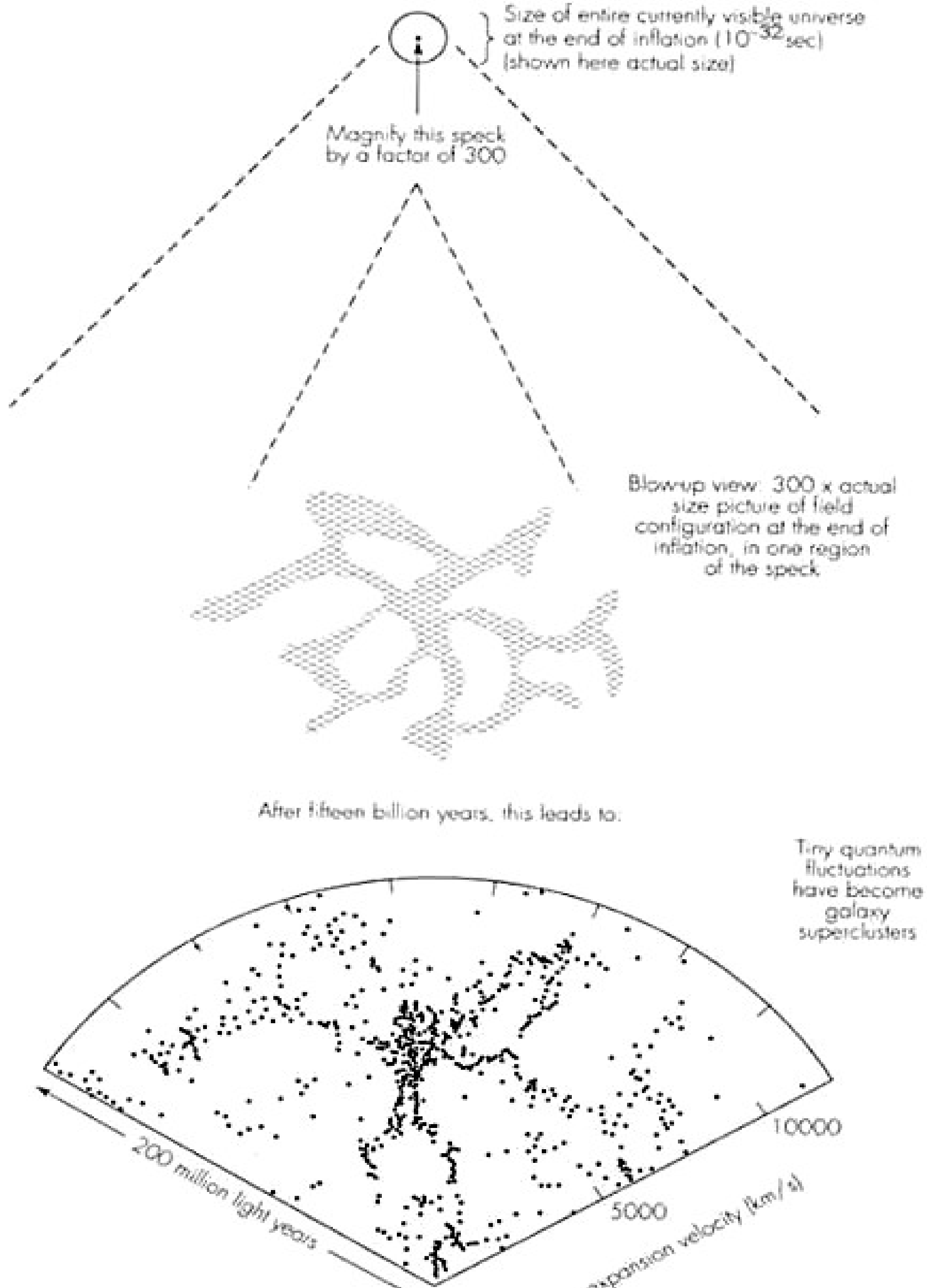


But these mass-energy density fluctuations are *not* big enough to 'seed' structure formation...
so how did the galaxies & clusters form?

Inflation helps to fix this problem by *magnifying* the density fluctuations



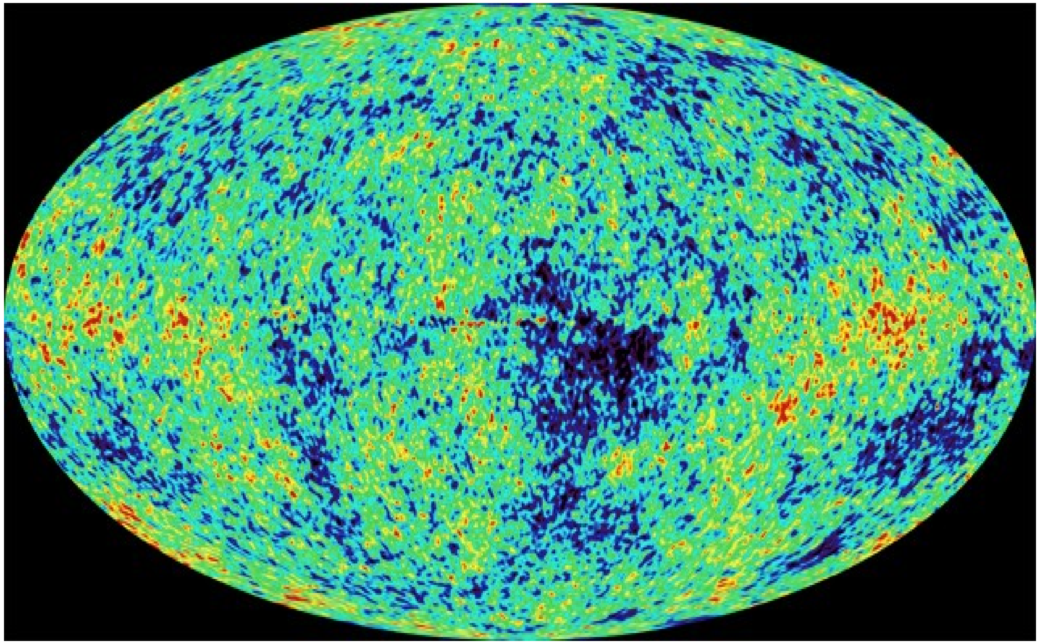




Size of entire currently visible universe at the end of inflation (10^{-32} sec) (shown here actual size)
Magnify this speck by a factor of 300
Blow-up view: 300 x actual size picture of field configuration at the end of inflation, in one region of the speck
After fifteen billion years, this leads to:
Tiny quantum fluctuations have become galaxy superclusters
200 million light years
10000
5000
expansion velocity (km/s)

Next problem: smoothness of the universe (the ISOTROPY or HORIZON problem)

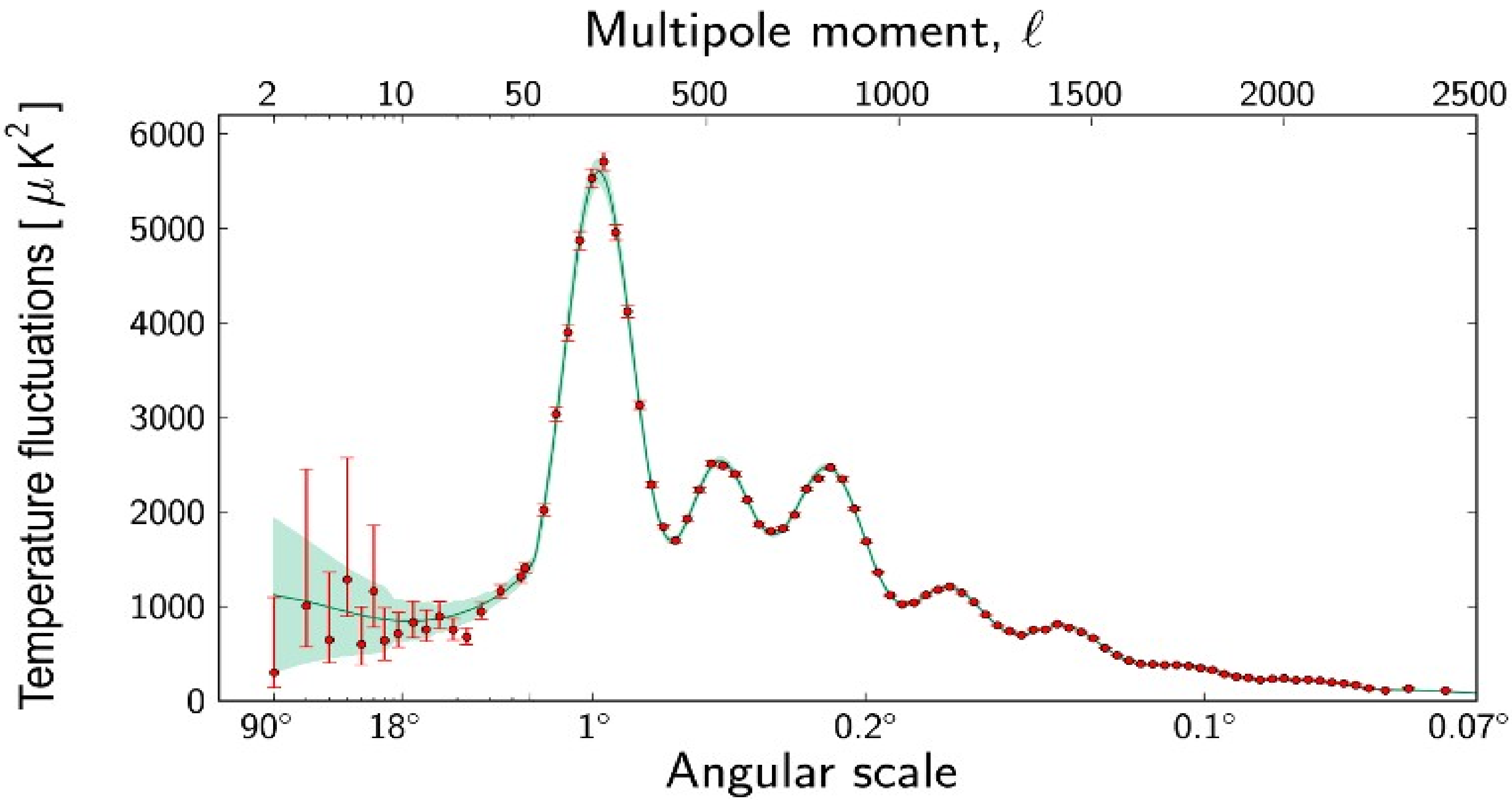
CMB is *very* uniform



The temperature differences represented by this plot are only a few parts in 100,000

Two spots on the sky in opposite directions have almost exactly the same temperature

(on average, the sky looks uniform on very large scales)



For a flat universe, expect biggest temperature differences at about 1 deg: this implies we are exactly at the critical density !

This is confirmation of inflation!

Problems solved by inflation

- The Horizon problem
  - Everything is the same temperature if they are too far apart to have communicated
  - Everything was much closer together before inflation
- The Flatness problem
  - Blow up a balloon by a factor of 10^{50} and it will look VERY flat if you are on the surface
  - Prediction: $\Omega = 1$ to very, very high accuracy
- Structure & isotropy problem
  - Just after inflation, we can compute how large “quantum fluctuations” became
  - Typically 10-20 ppm with precisely the shape and distribution observed by WMAP
  - These become the seeds for galaxy and cluster formation
- So inflation explains the remaining mysteries but adds new questions
  - But why is there a huge “vacuum” energy density?
  - Think about water, ice, steam… it was a phase change but we don’t know what kind
  - We need better data with the next generation of physics and astrophysics facilities

What’s still in question?

- What caused inflation?
- What is dark matter?
- What is dark energy?
- What caused the matter-antimatter asymmetry?
- Why is the Universe so compatible with life on Earth?