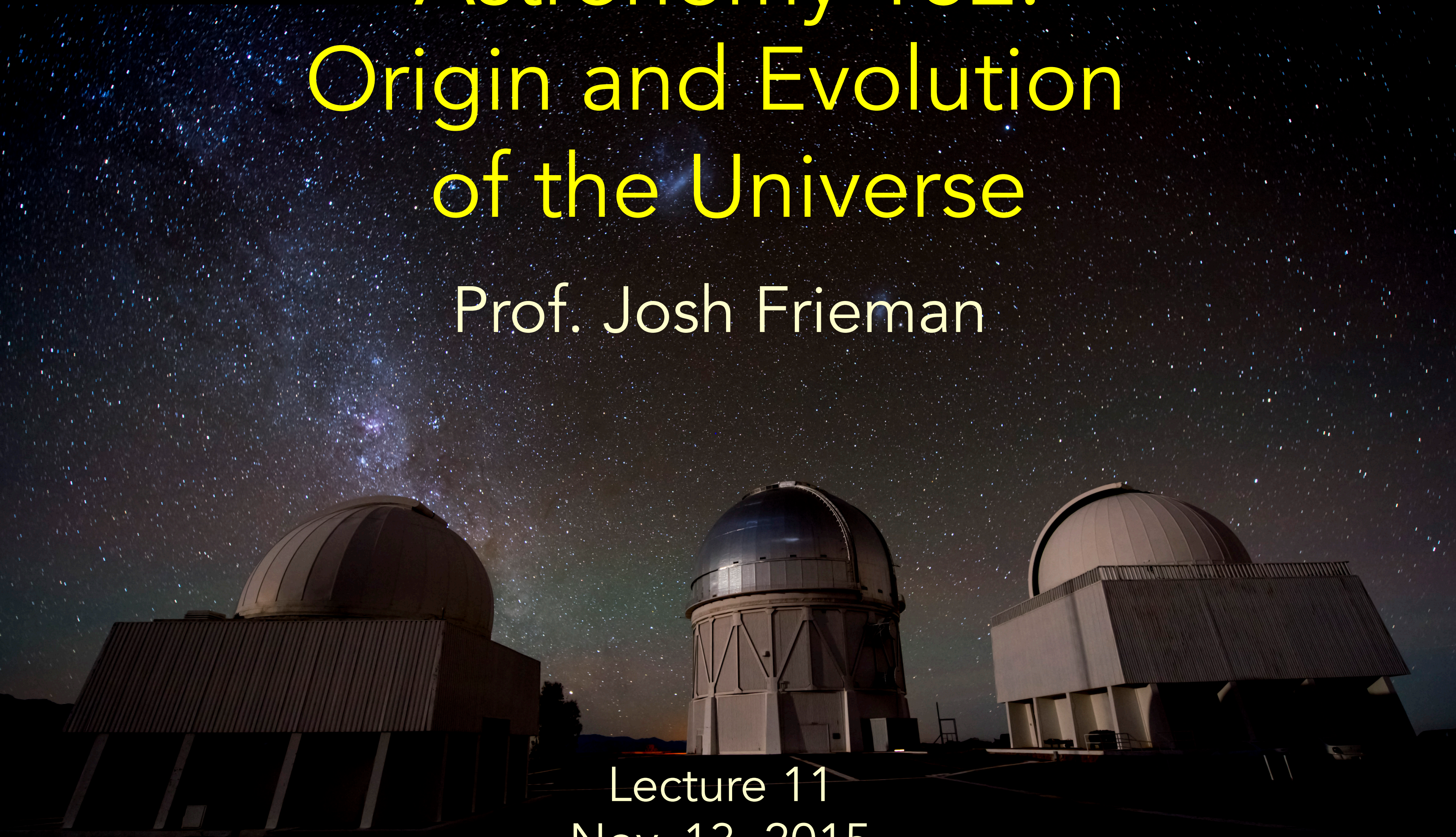


Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman

Lecture 11
Nov. 13, 2015

Today

- Cosmic Microwave Background
- Big Bang Nucleosynthesis

Assignments

- This week: read Hawley and Holcomb, Chapter 12 .
- Today: Essay 3 due on HH, Chapter 13. Optional re-write of Essay 1 on Chap. 10 due.
- Next Friday: Essay 4 due on HH, Chapter 12.

The Big Bang Theory

- The Universe has been expanding from a hot, dense beginning 13.7 billion years ago.
- This paradigm provides a successful framework for interpreting all cosmological observations to date.
- Three Classical Observational Pillars of the Big Bang:
  - Hubble's law of expansion
  - Cosmic Microwave Background
  - Big Bang Nucleosynthesis

Atomic Recombination

- At temperatures above T~3000 deg, ordinary matter consisted of nuclei and electrons: ionized plasma. Photons scatter frequently with charged particles, establishing thermal equilibrium: Planck Blackbody spectrum.
- When the expanding plasma cooled to T~3000 deg (when the Universe was 380,000 years old, and about 1/1000th its present size), CMB photons were no longer energetic enough to knock electrons out of H atoms.
- Electrons and protons "recombined" into neutral Hydrogen atoms at that time.

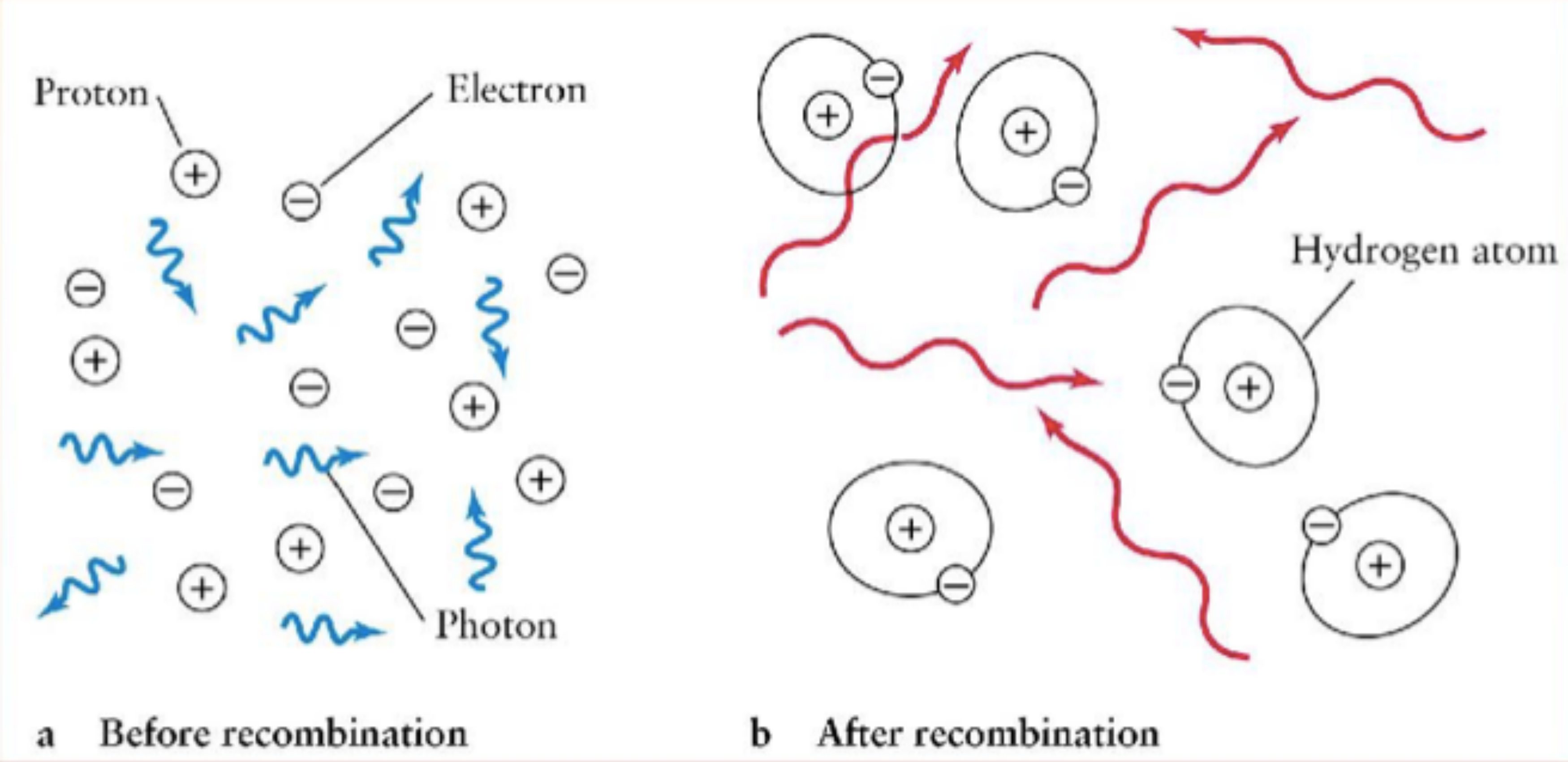
Recombination and Decoupling

- Prior to H recombination, CMB photons interacted rapidly with charged electrons in the plasma.
- Once recombination occurred, the scattering rate of photons dropped precipitously:

Photon Decoupling (Last Scattering)

- CMB photons have travelled freely since then. Maps of the CMB temperature provide a snapshot of the Universe when it was 380,000 years old.
- Cosmic Weather report: Universe was ‘foggy’ before decoupling, clear since then.

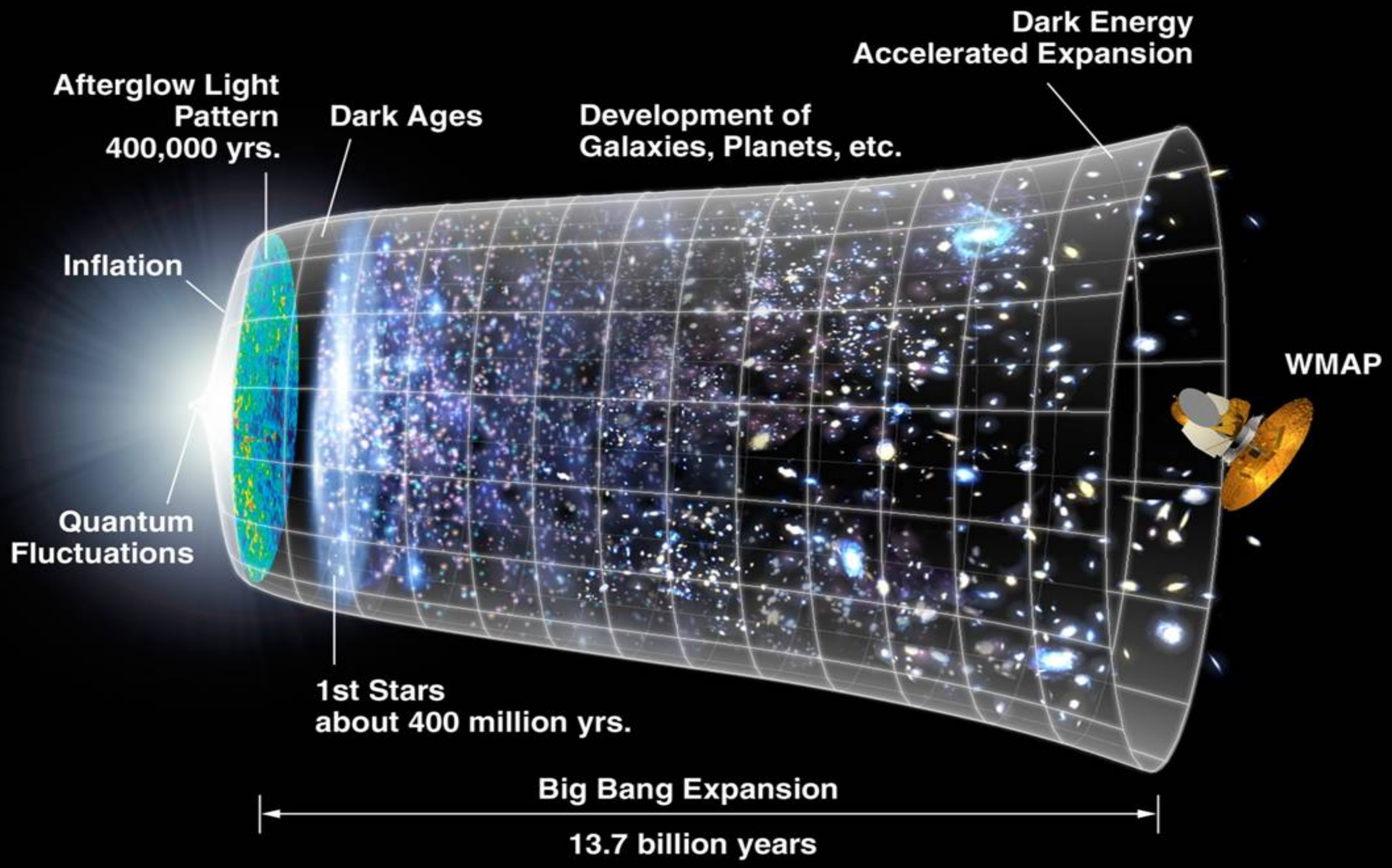
Before and After Recombination



a Before recombination

b After recombination

Brief History of the Universe

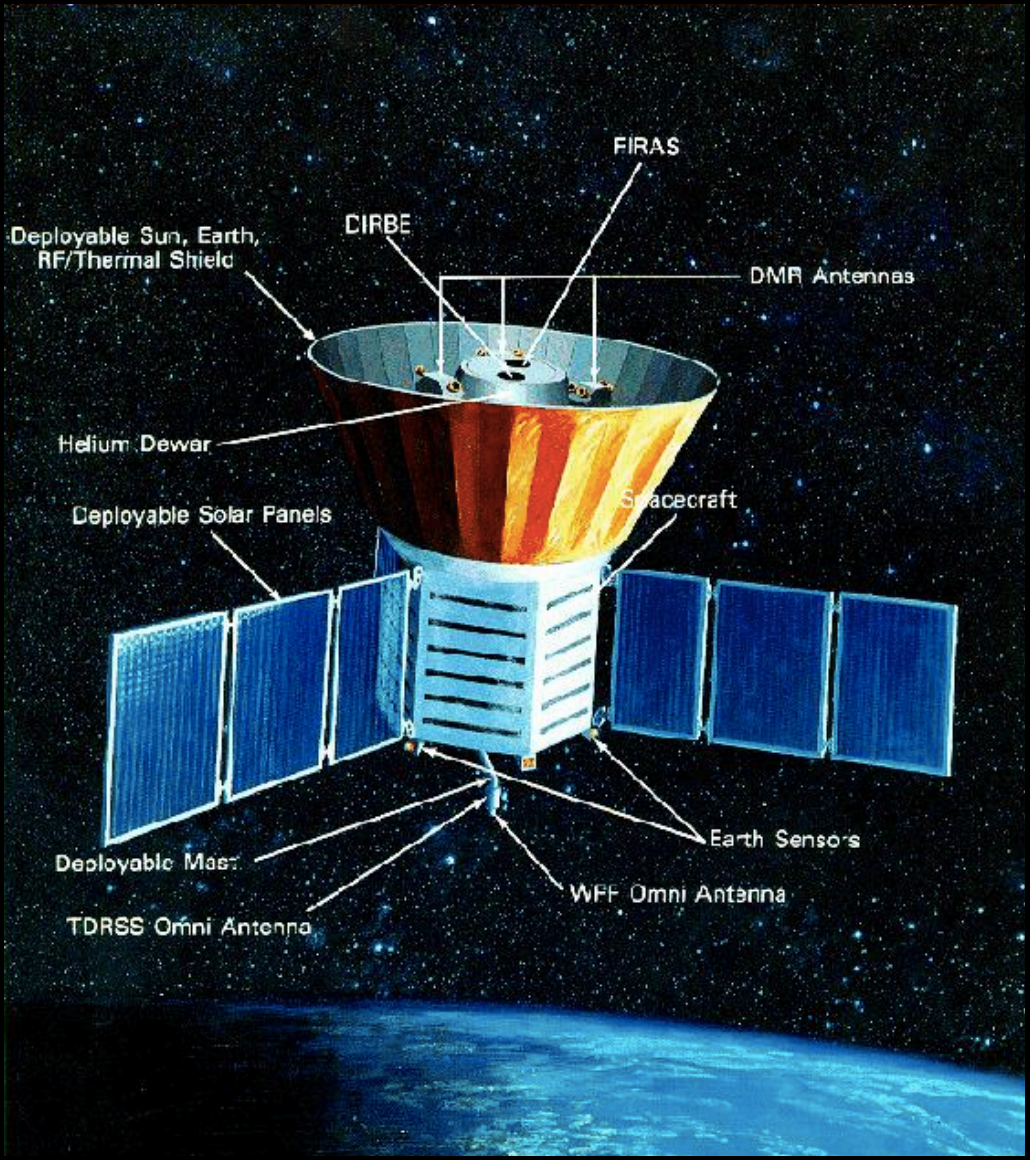


COBE Satellite (Cosmic Background Explorer)

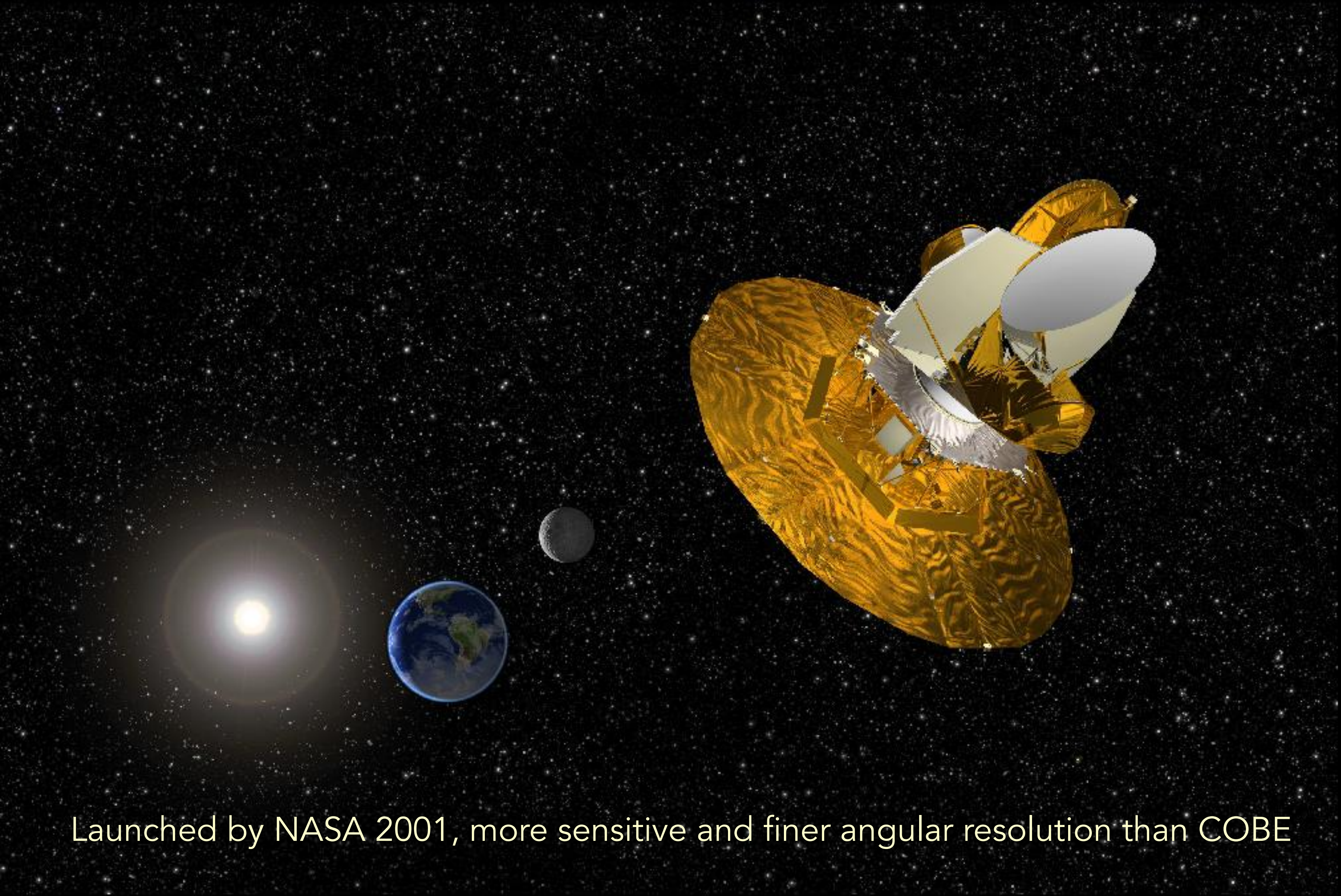
Launched by
NASA 1990

Precision measurement of CMB Blackbody spectrum

First clear detection of CMB anisotropies (Temperature differences across the sky)

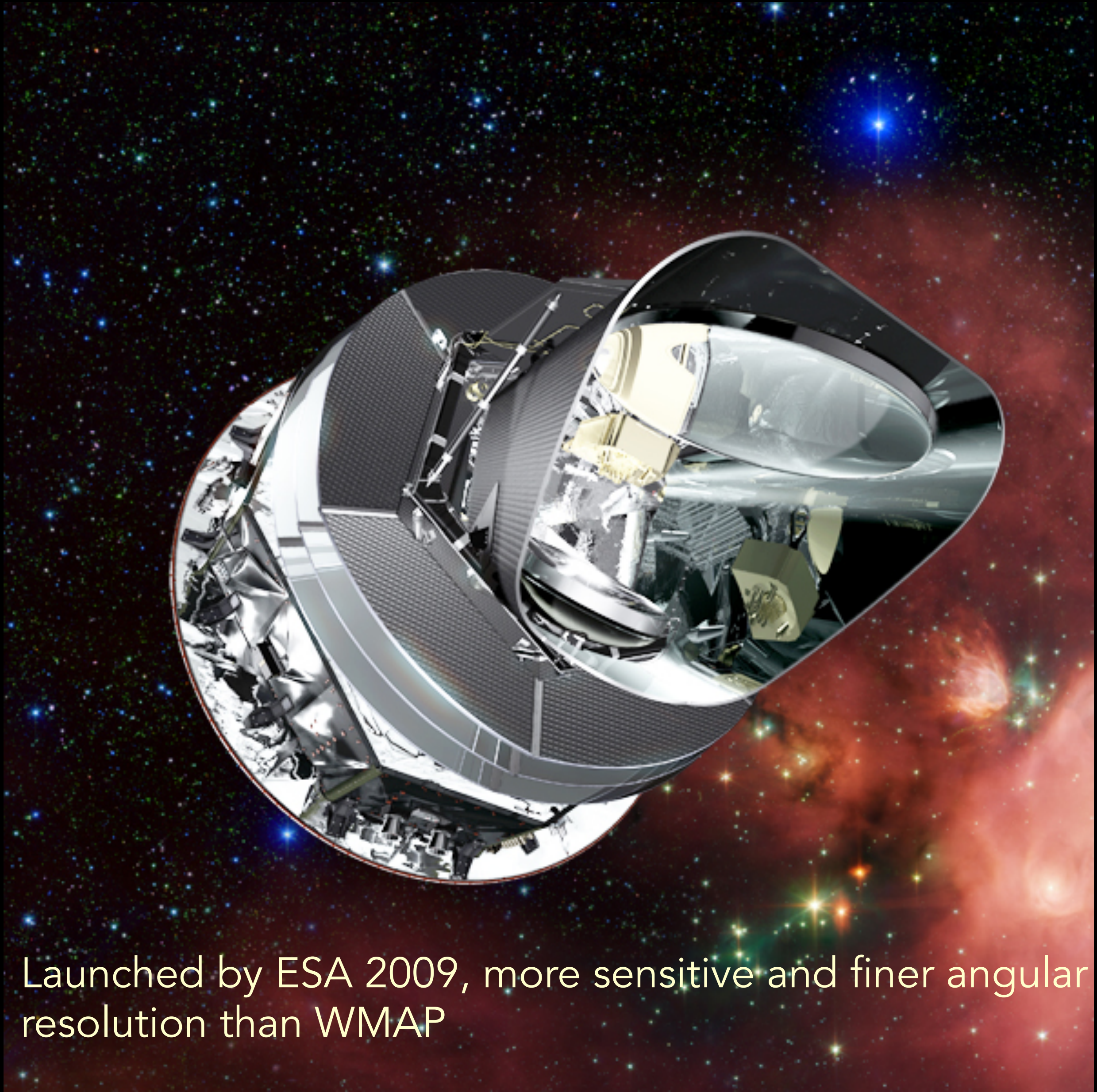


Wilkinson Microwave Anisotropy Probe (WMAP)



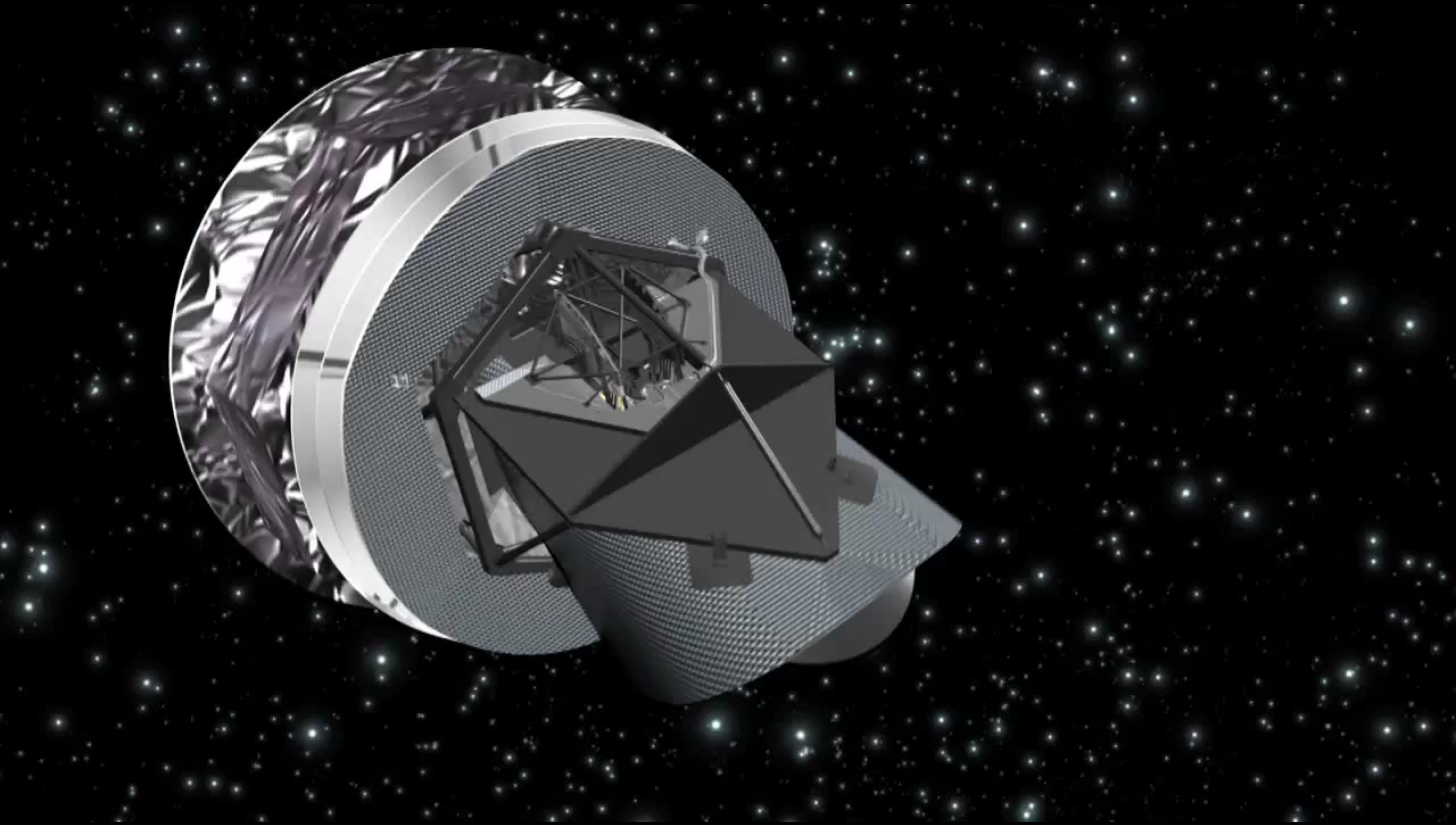
Launched by NASA 2001, more sensitive and finer angular resolution than COBE

Planck Satellite

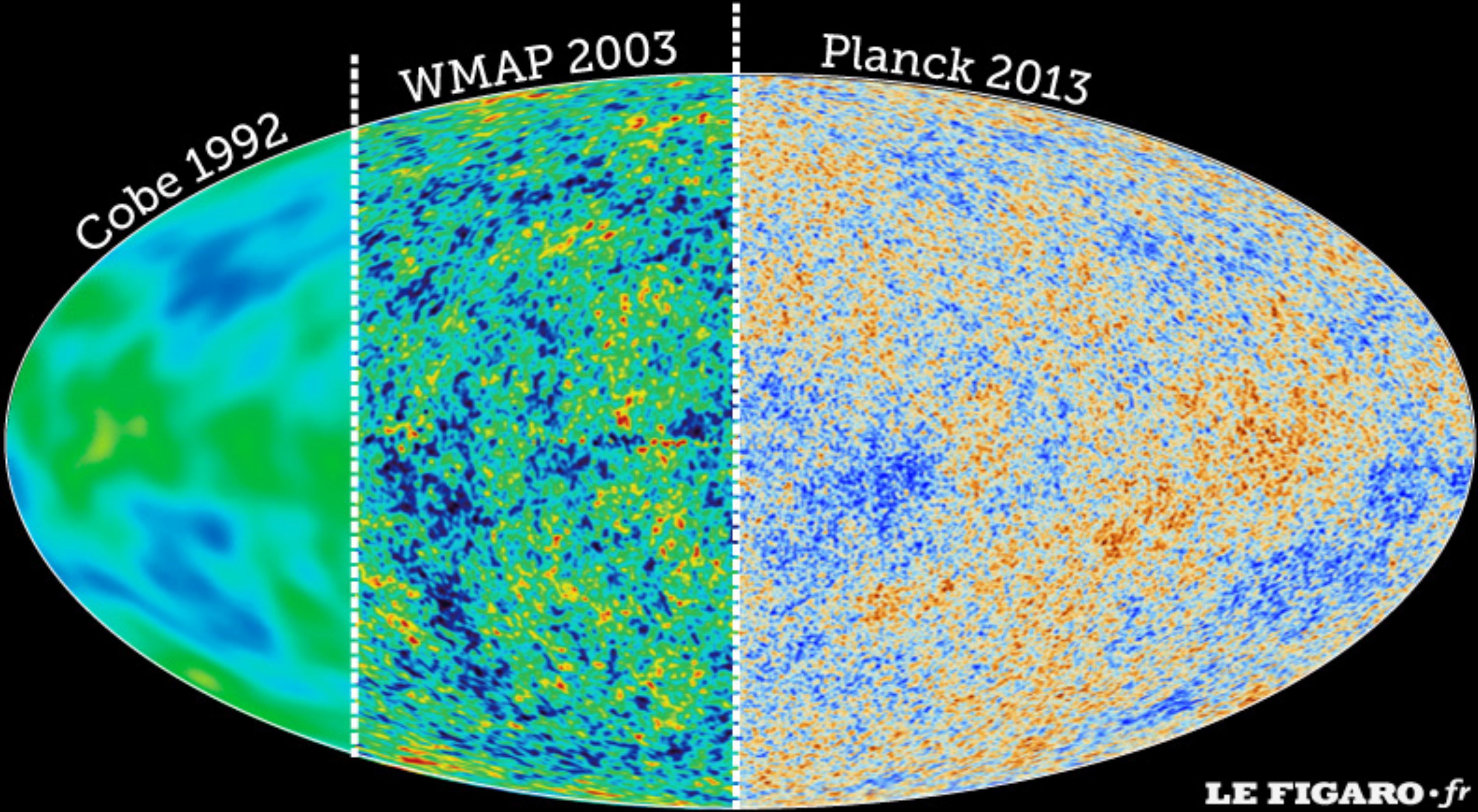


Launched by ESA 2009, more sensitive and finer angular resolution than WMAP

Planck Satellite

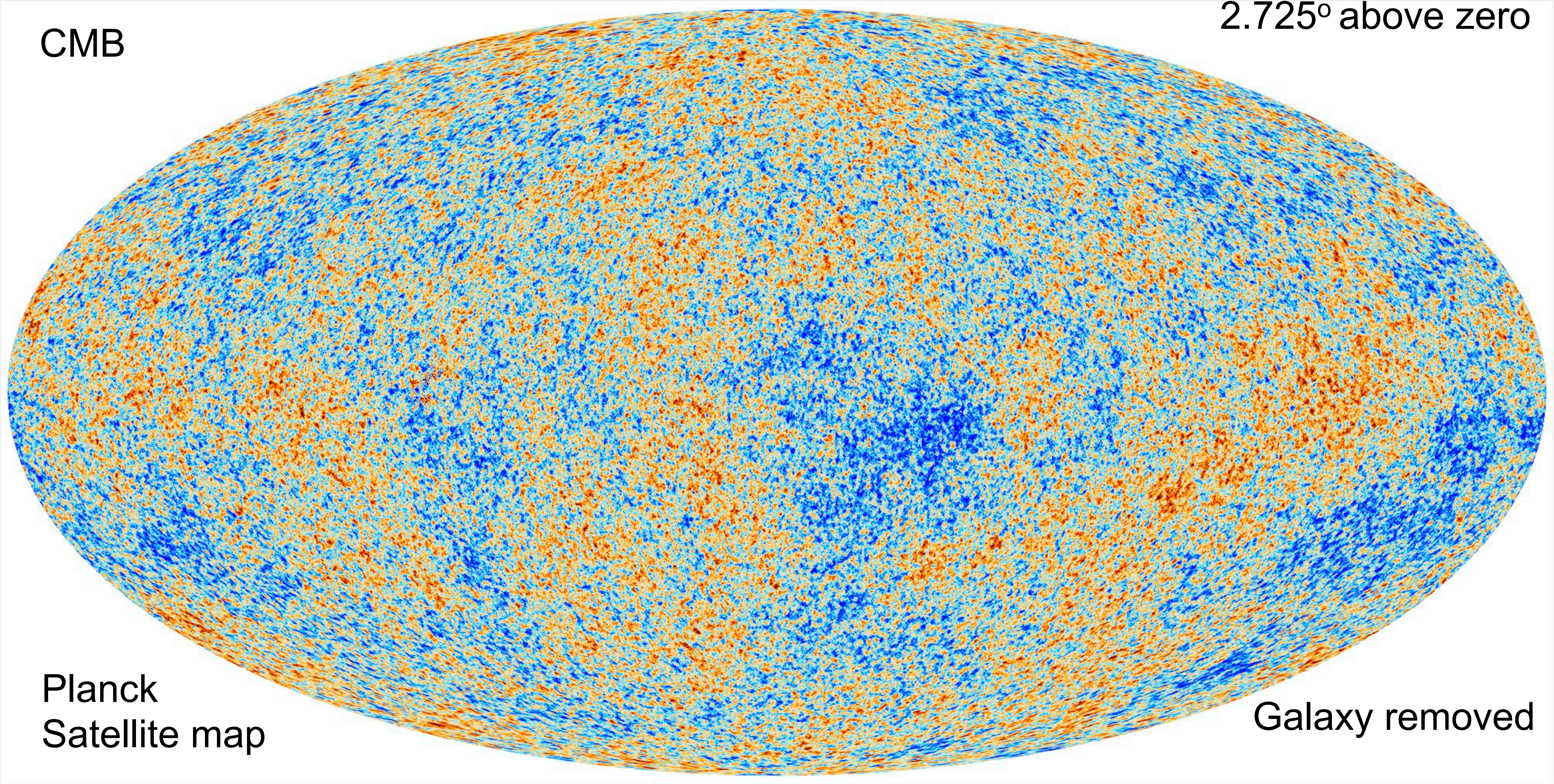


CMB Temperature Maps



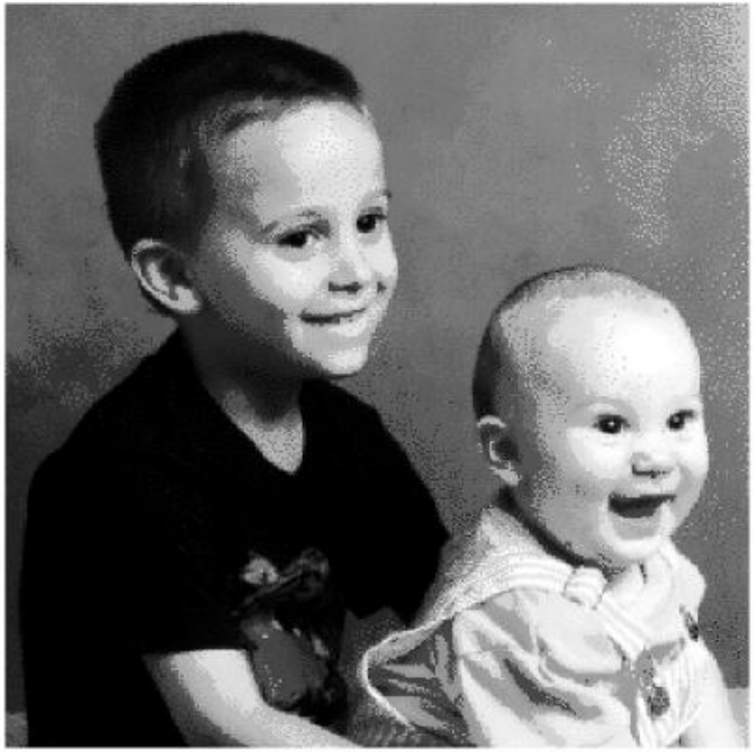
Snapshot of the Universe when it was 380,000 years old.
Temperature varies by only 0.00001 deg across the sky.

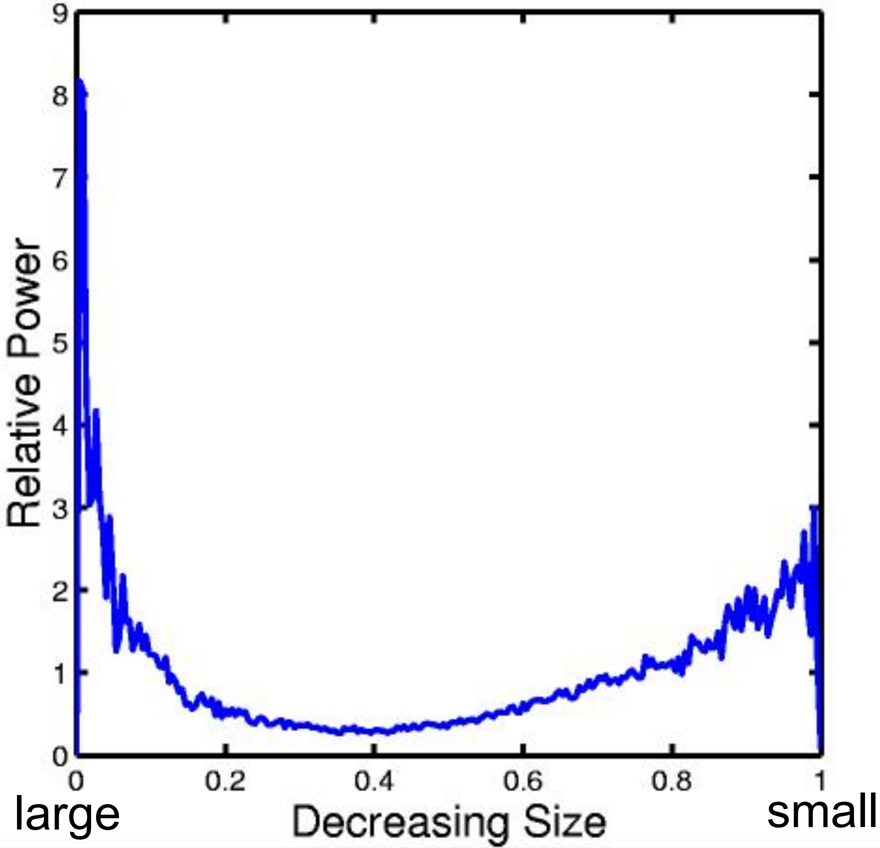
Planck CMB Temperature Map



This map encodes information about cosmological parameters (density of baryons and matter, curvature of space, etc). How do we extract that information?

Image and Its Power Spectrum I

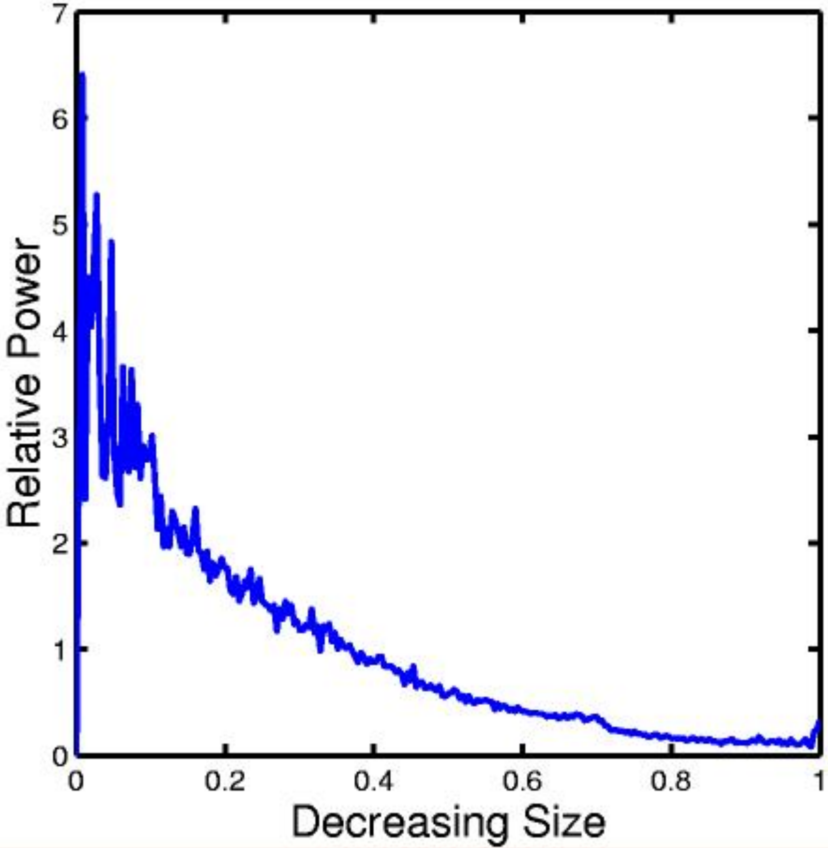




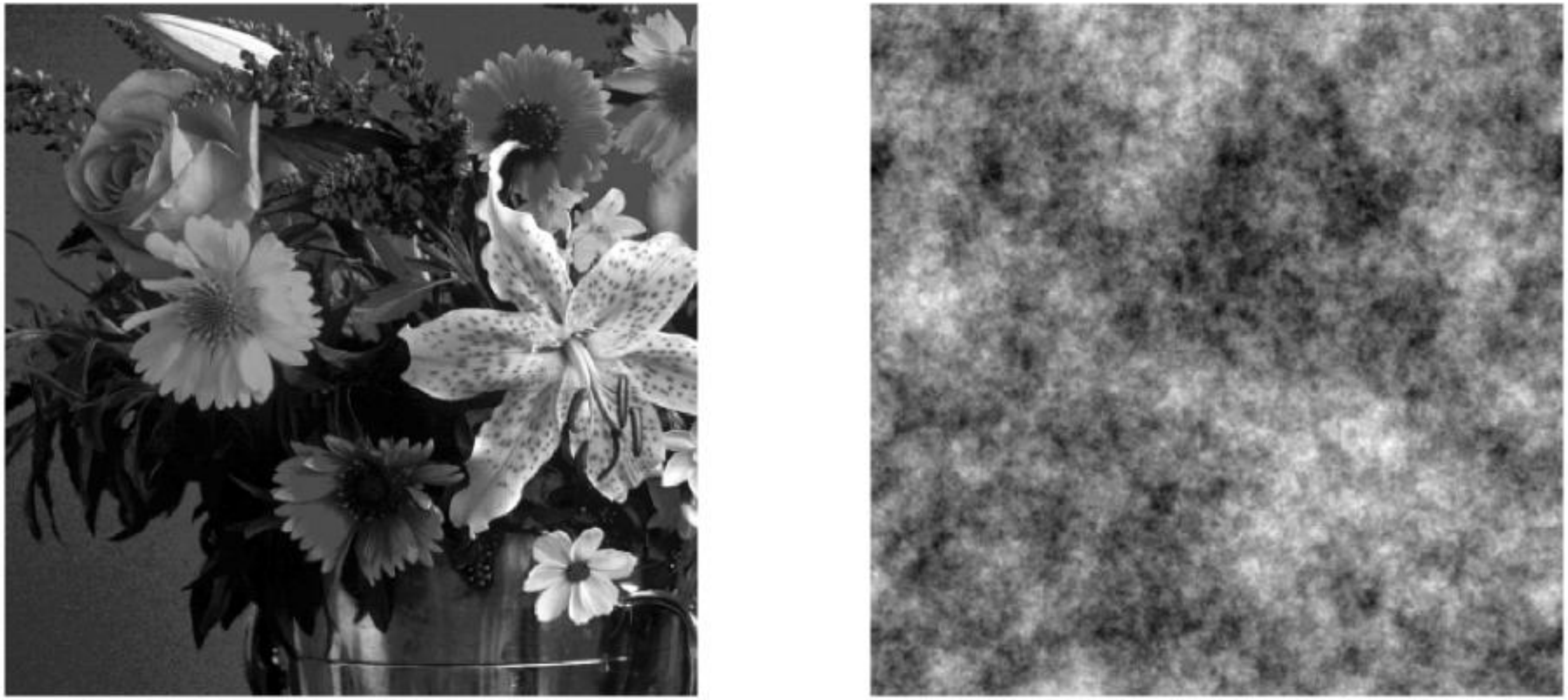
Angular power spectrum quantifies how much structure there is in an image on different spatial scales.

Pryke

Image and Its Power Spectrum II

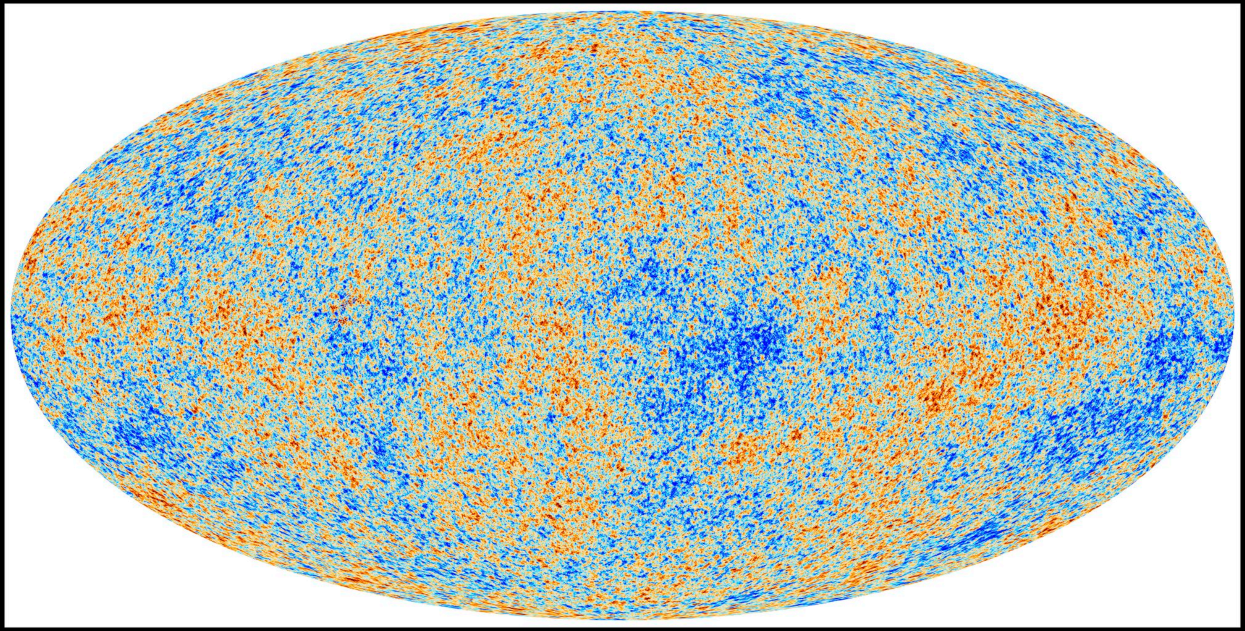


Two Images with Same Power Spectrum



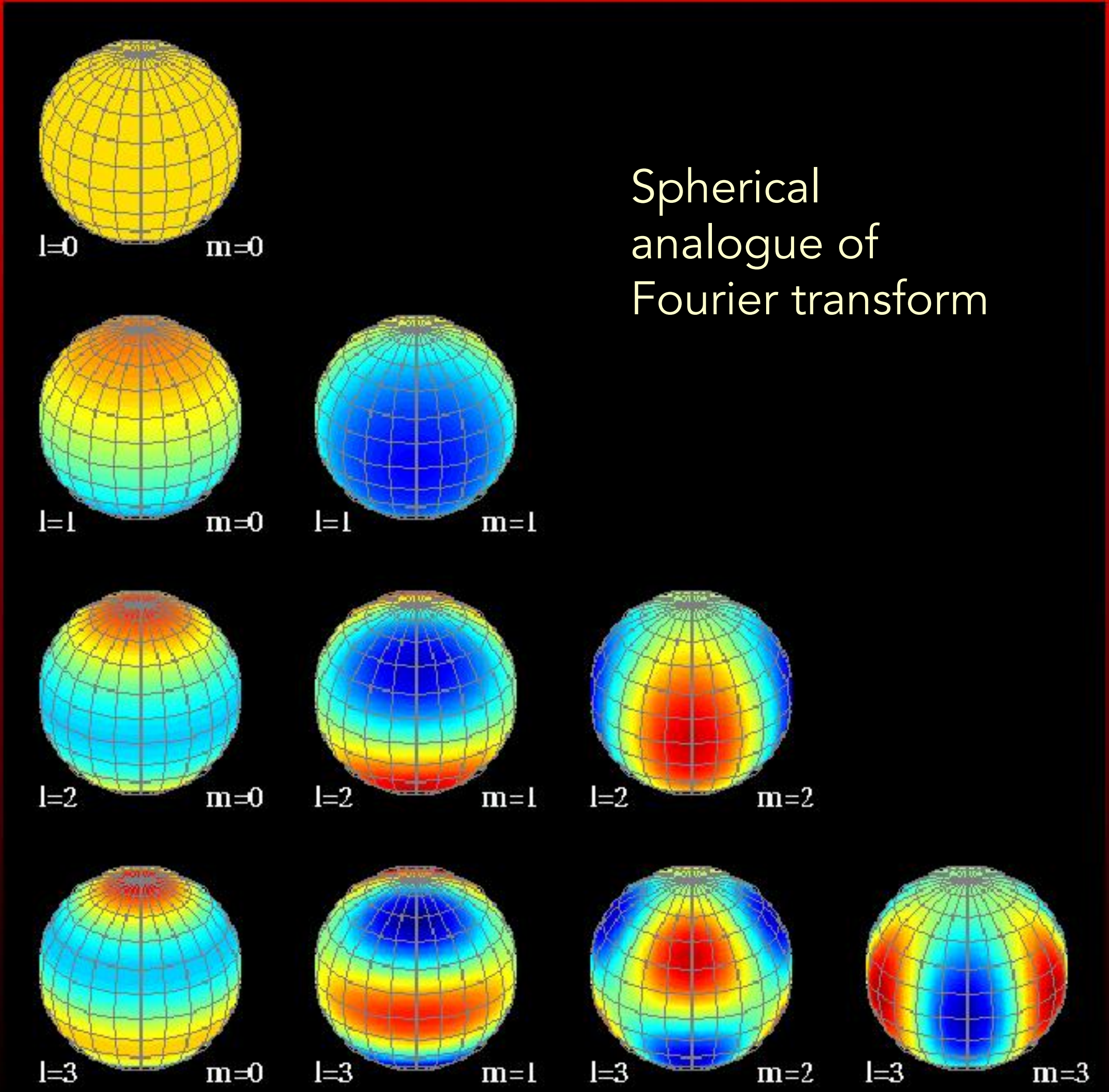
Left image contains much more information than is encoded in its power spectrum. For the right image, the power spectrum contains all the information.

Angular Power Spectrum of the CMB



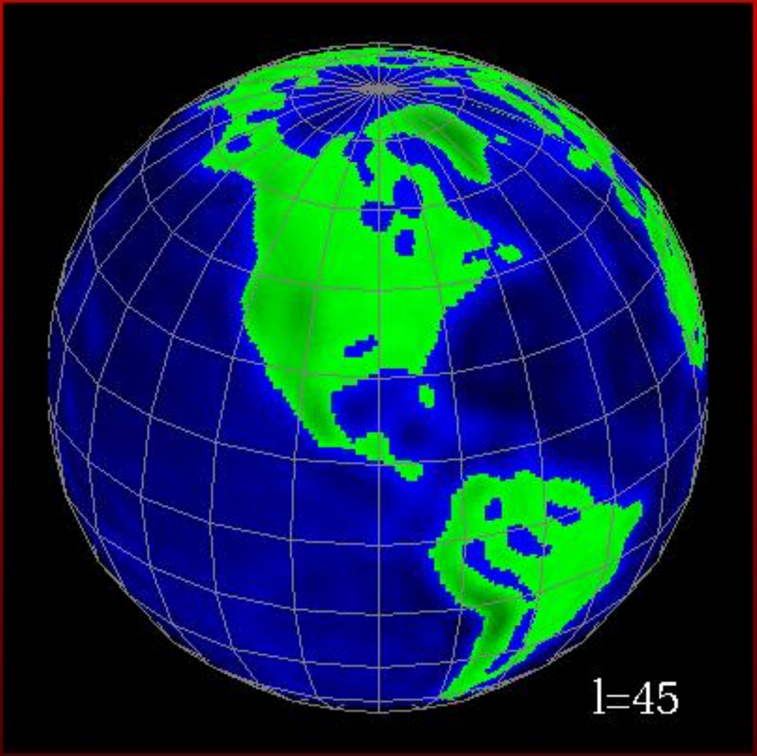
- Theory of the origin of these temperature fluctuations (which we'll discuss later) predicts that all the information in the temperature map is contained in the power spectrum.

Spherical Multipoles

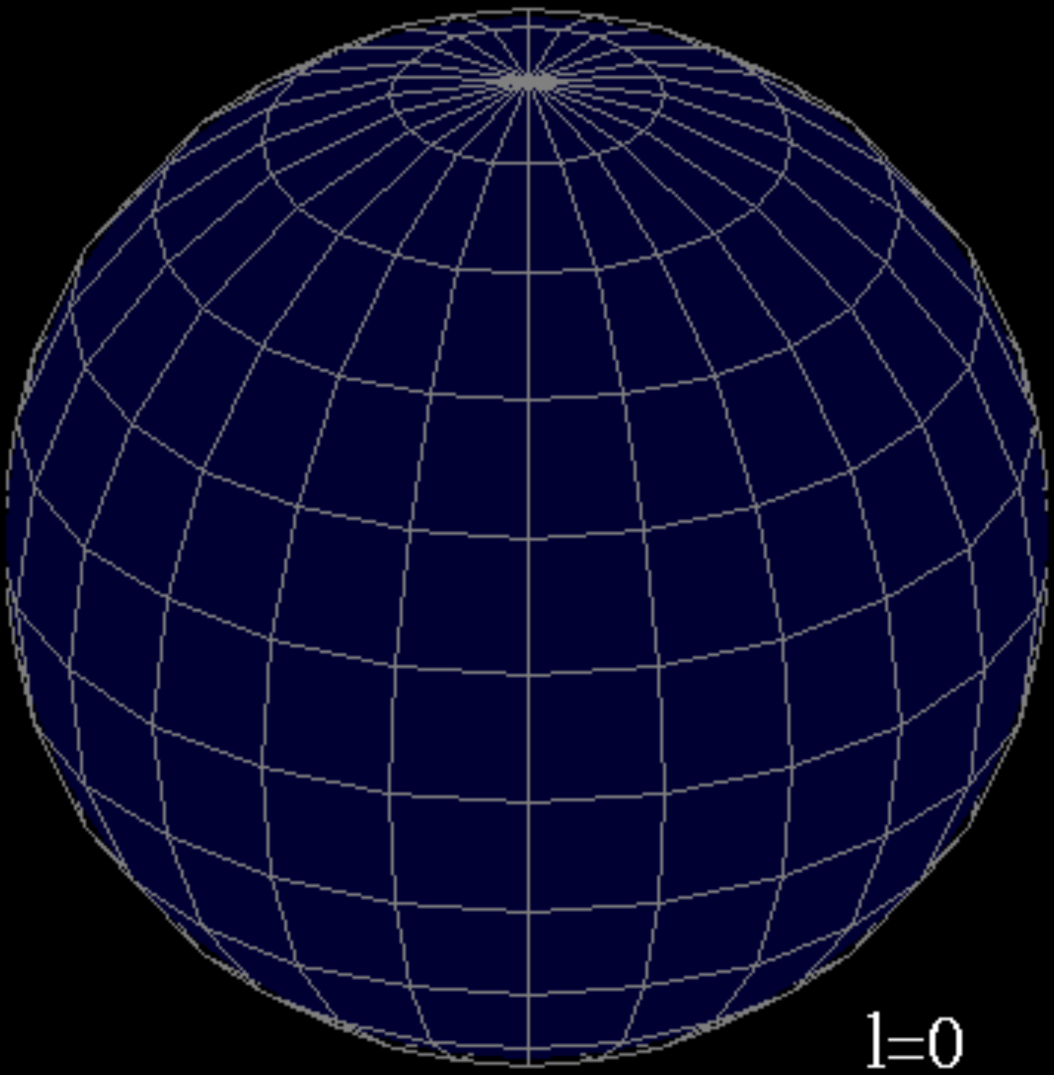


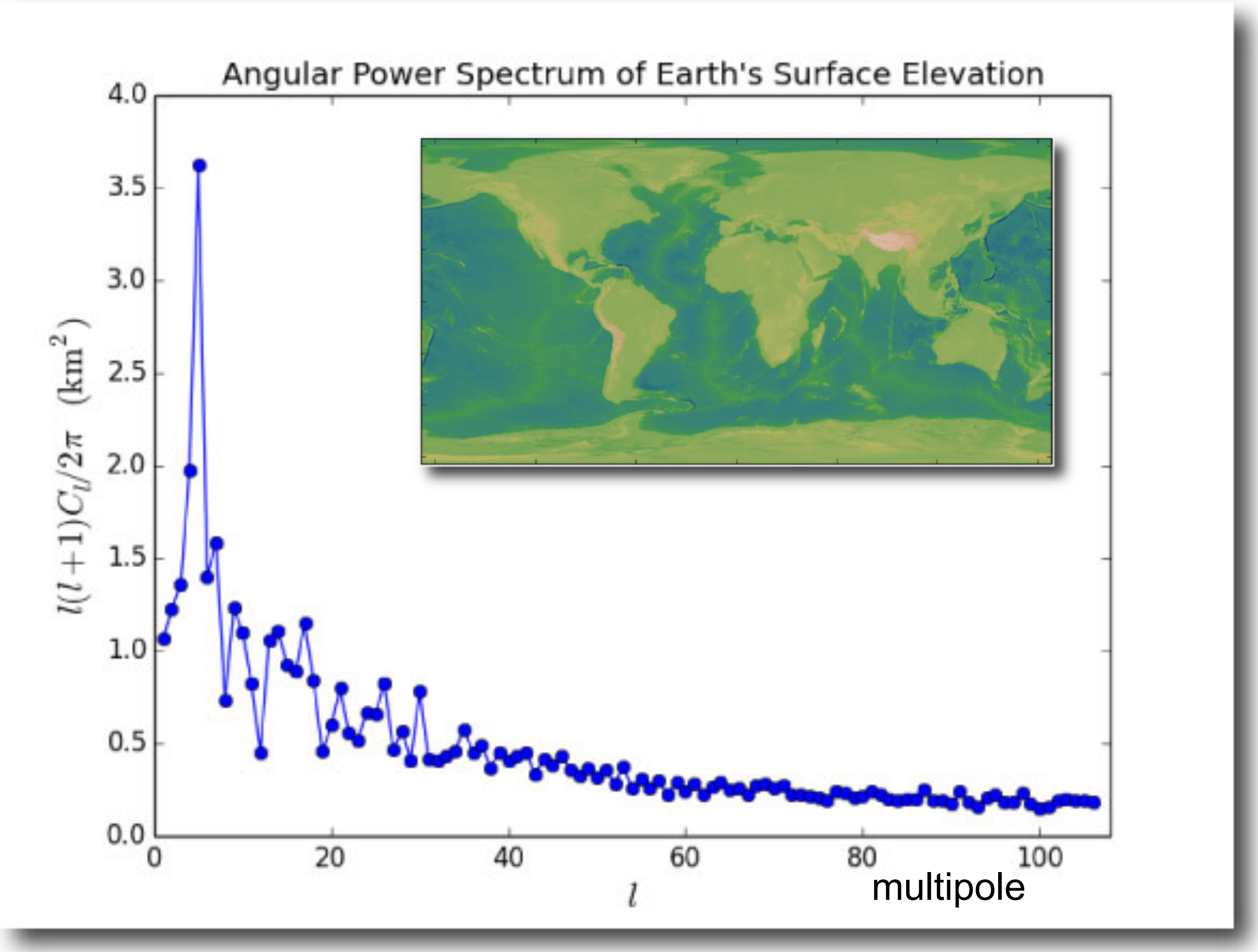
Spherical analogue of Fourier transform

Topographic Map of the Earth

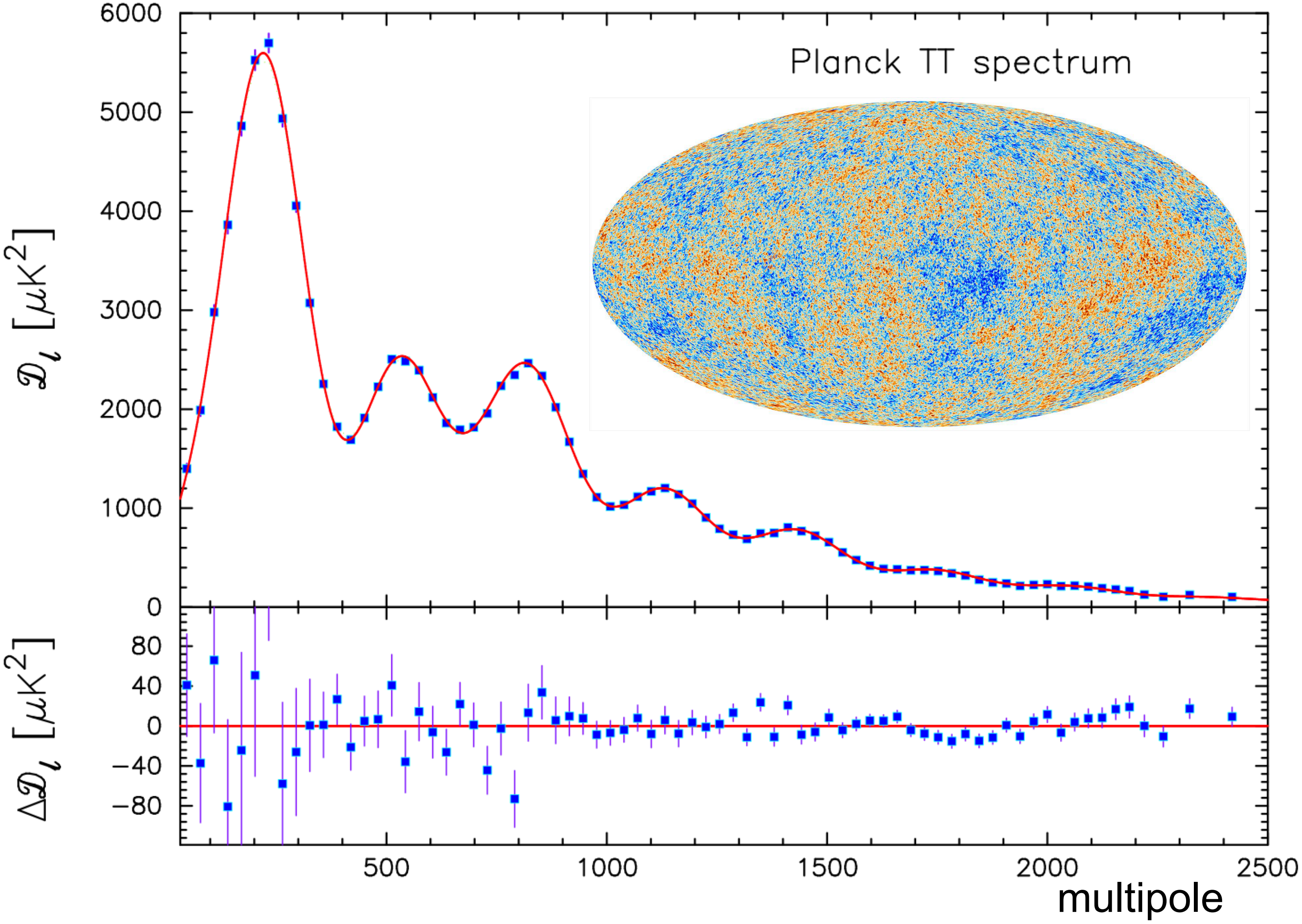


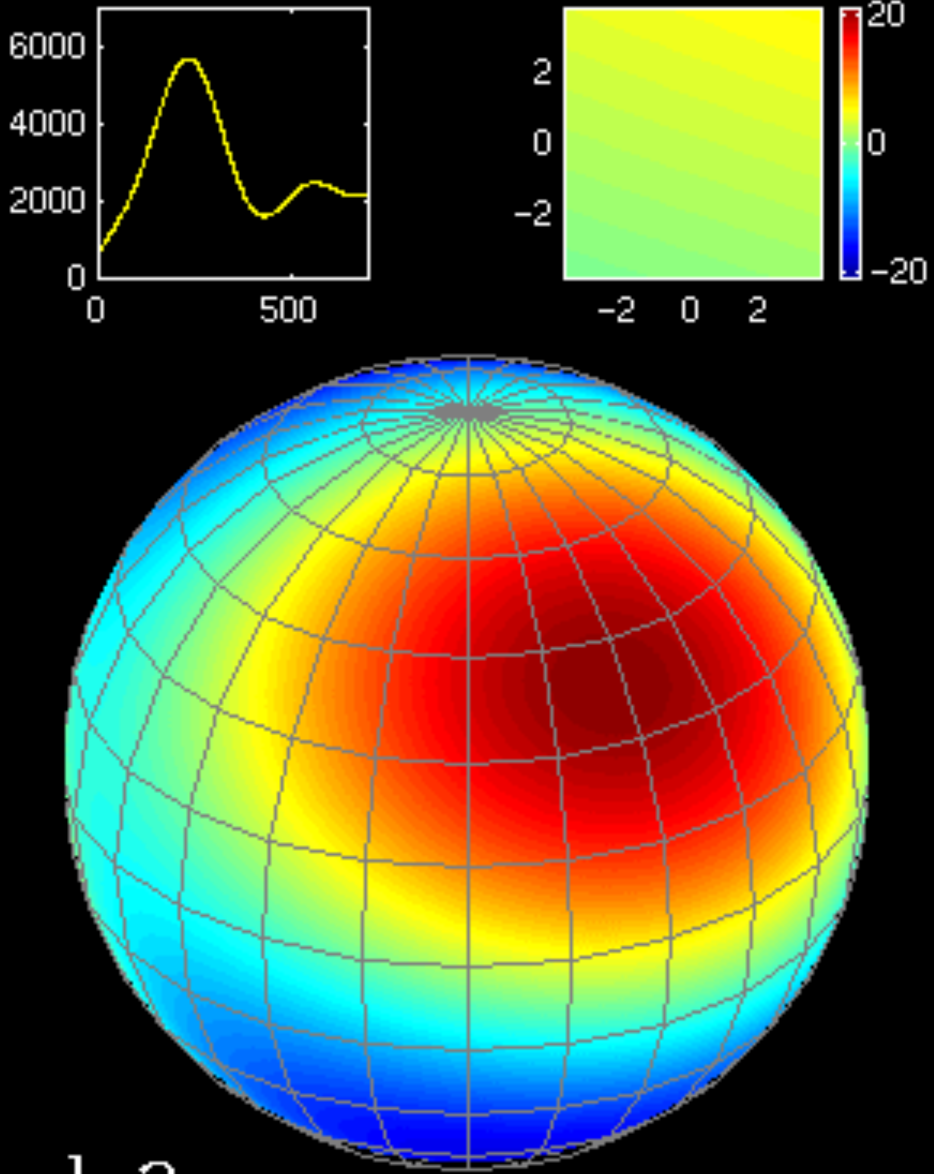
By adding up multipole patterns we can make any map


l=0


Angular Power Spectrum of Earth's Surface Elevation
$l(l+1)C_l/2\pi$ (km^2)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
20
40
60
80
100
l

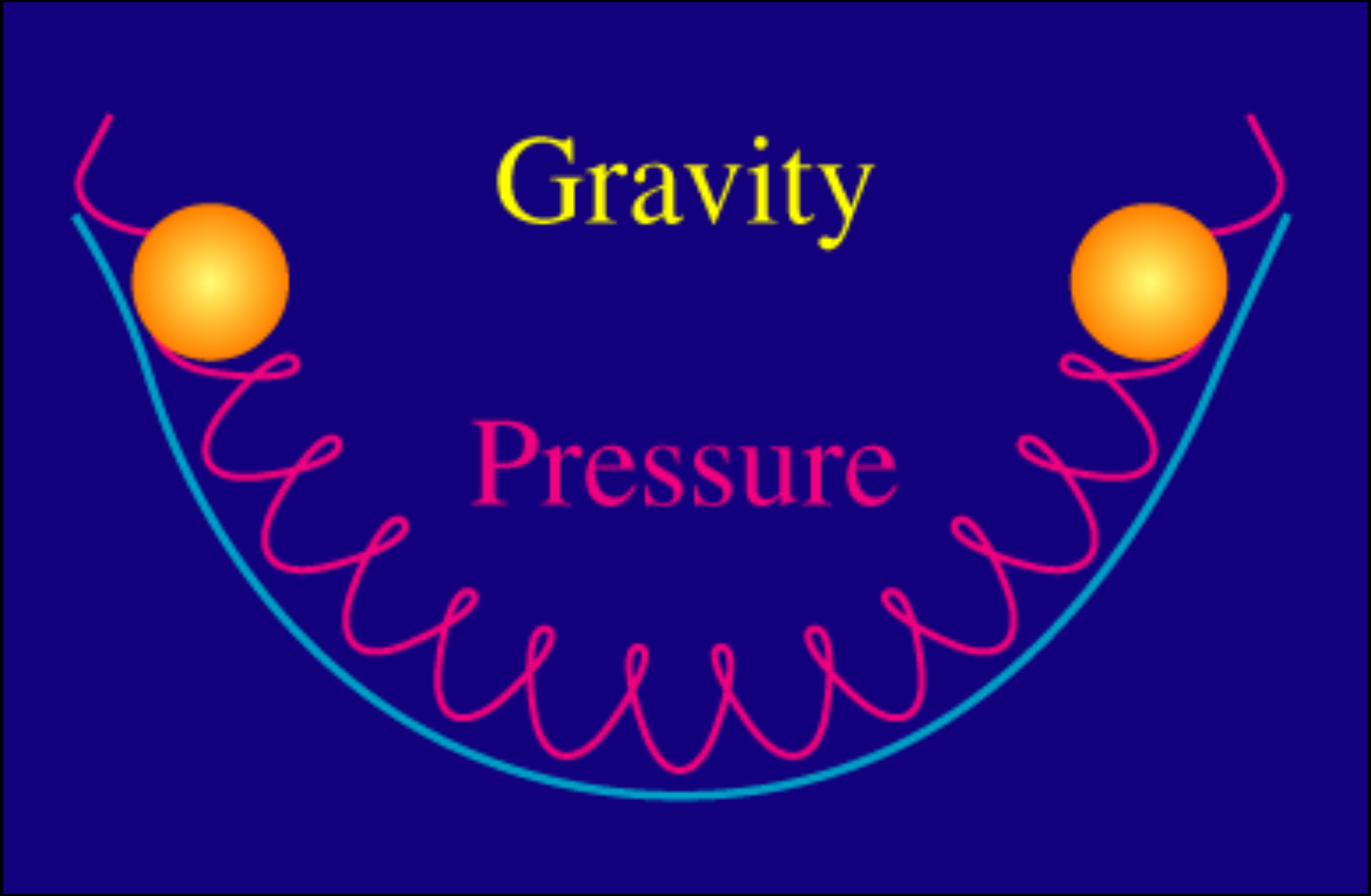
multipole


Planck TT spectrum
$\mathcal{D}_\ell\ [\mu K^2]$
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
80
40
0
−40
−80
500
1000
1500
2000
2500
multipole



l=2

Where does this Harmonic Structure Come From?



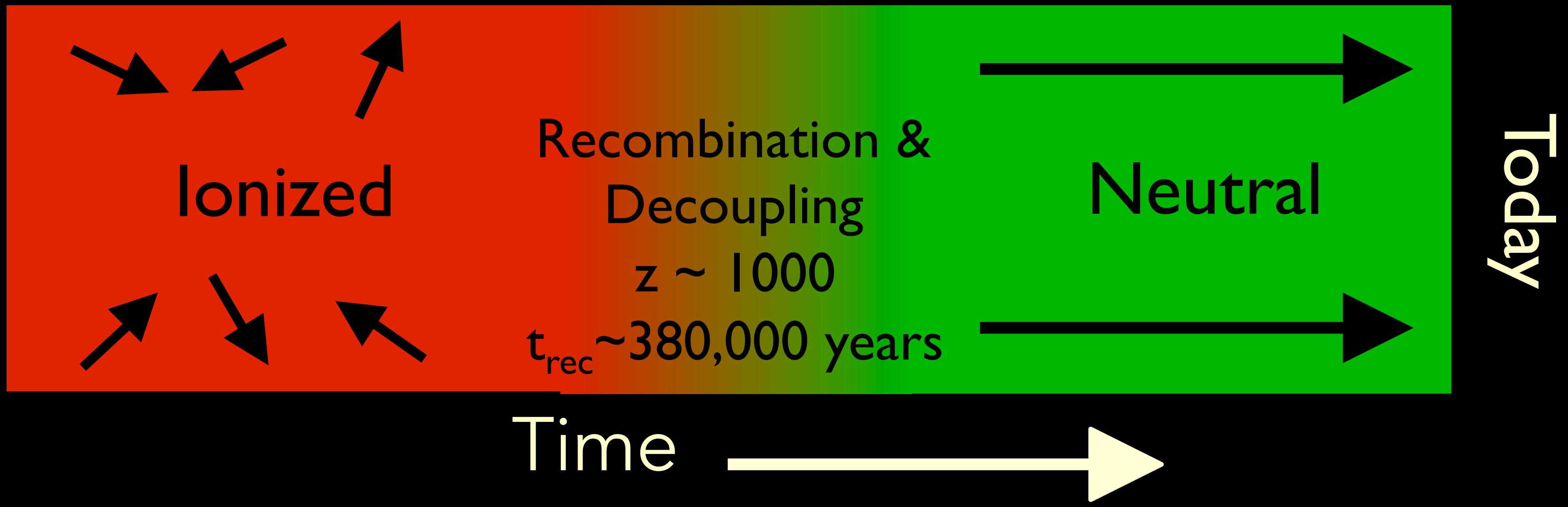
Sound Waves in the Early Universe

Before H recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Photon-baryon perturbations oscillate as sound waves.

After H recombination:

- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at recombination affects late-time amplitude.



Ionized

Recombination &
Decoupling
z ~ 1000
t_{rec}~380,000 years

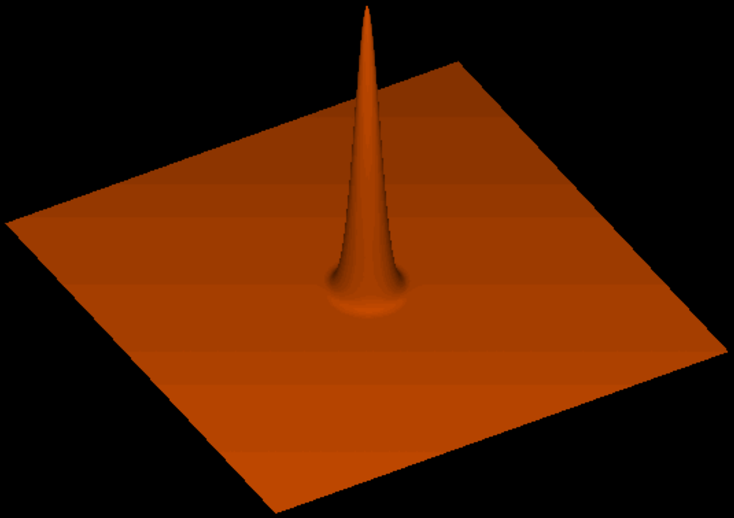
Neutral

Today

Time

Sound Waves

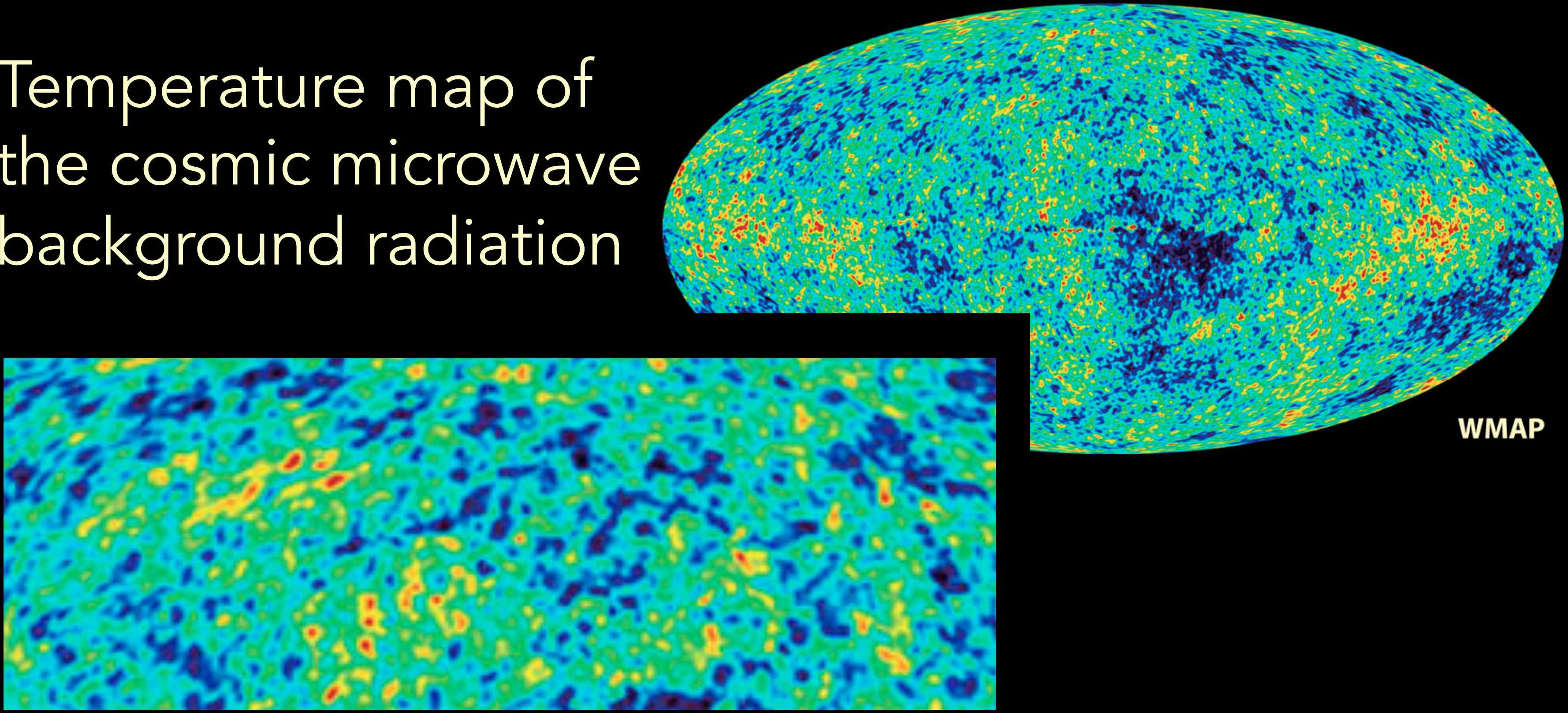
- Each initial overdensity (in dark matter & baryons) is an overpressure that launches a spherical sound wave.
- This wave travels outward at the speed of sound c_s in the photon-baryon fluid, which is 57% of the speed of light.
- Pressure-providing photons decouple at recombination, and wave stalls. Photons travel to us from these spheres.



Eisenstein

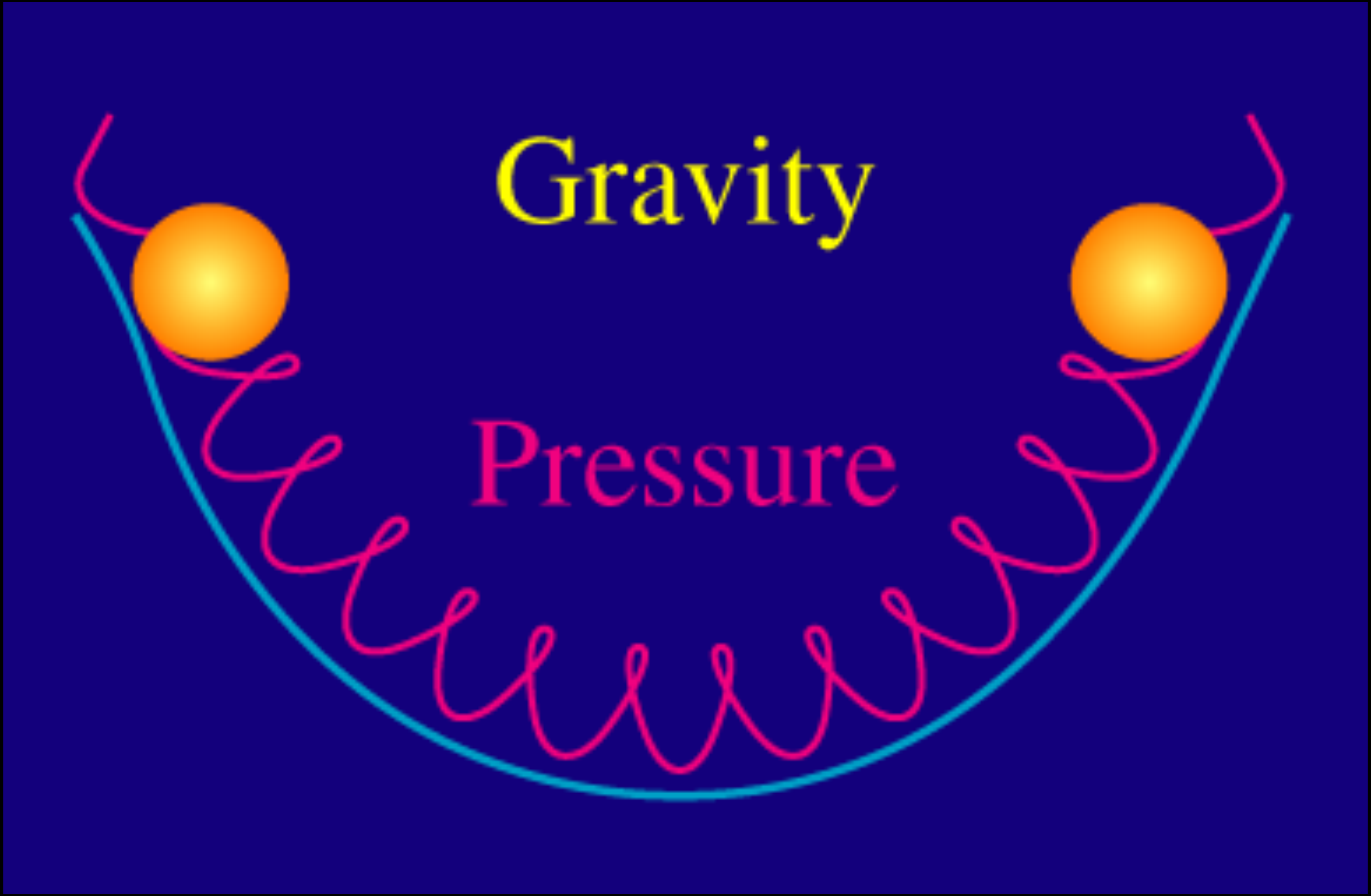
Anisotropies in the CMB

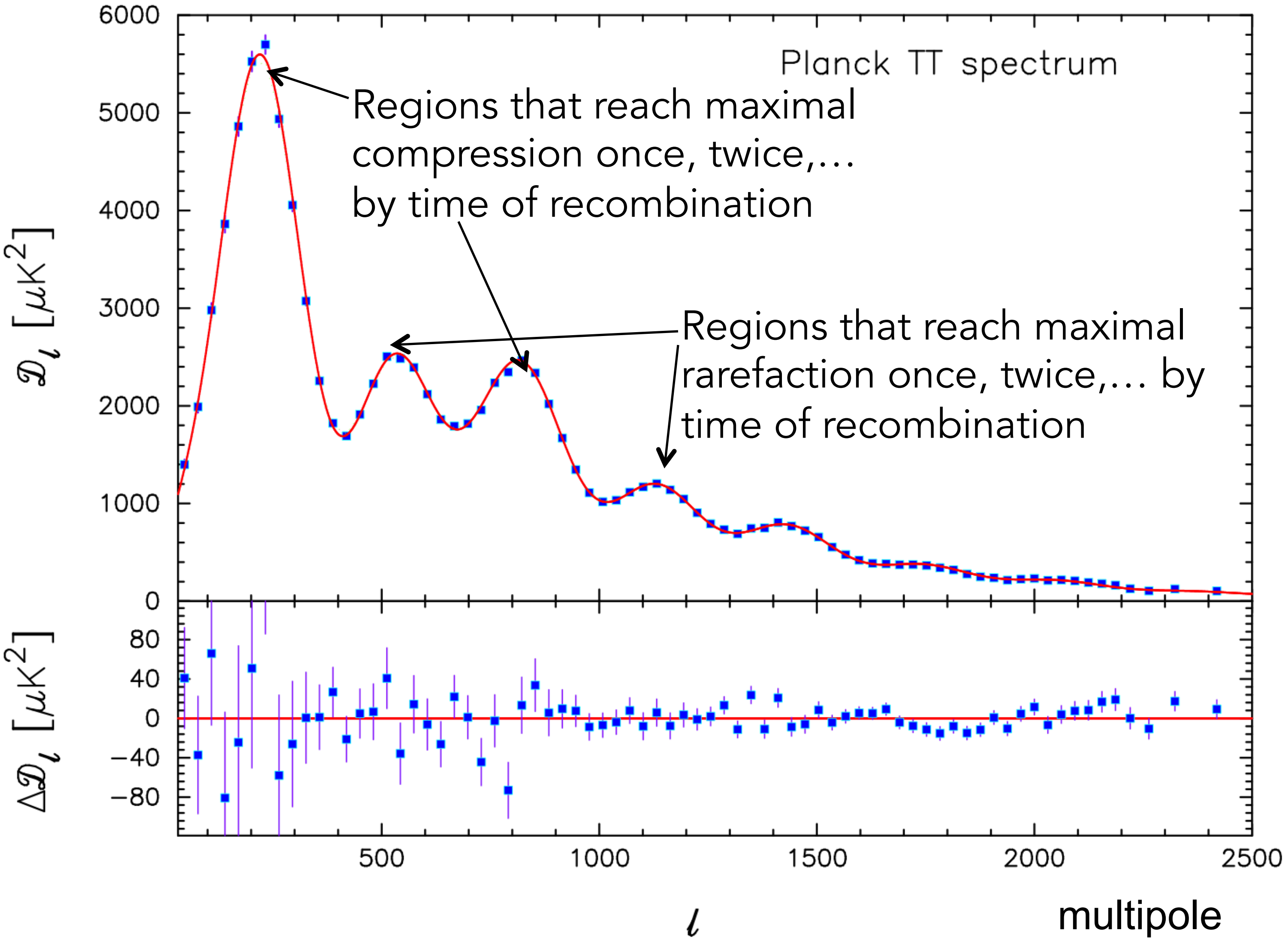
Temperature map of the cosmic microwave background radiation



- There is a characteristic angular scale, ~1 degree on the sky, set by the distance sound waves can travel just before neutral atoms form: sound horizon distance $s=c_s t_{rec}$

Where does this Harmonic Structure Come From?

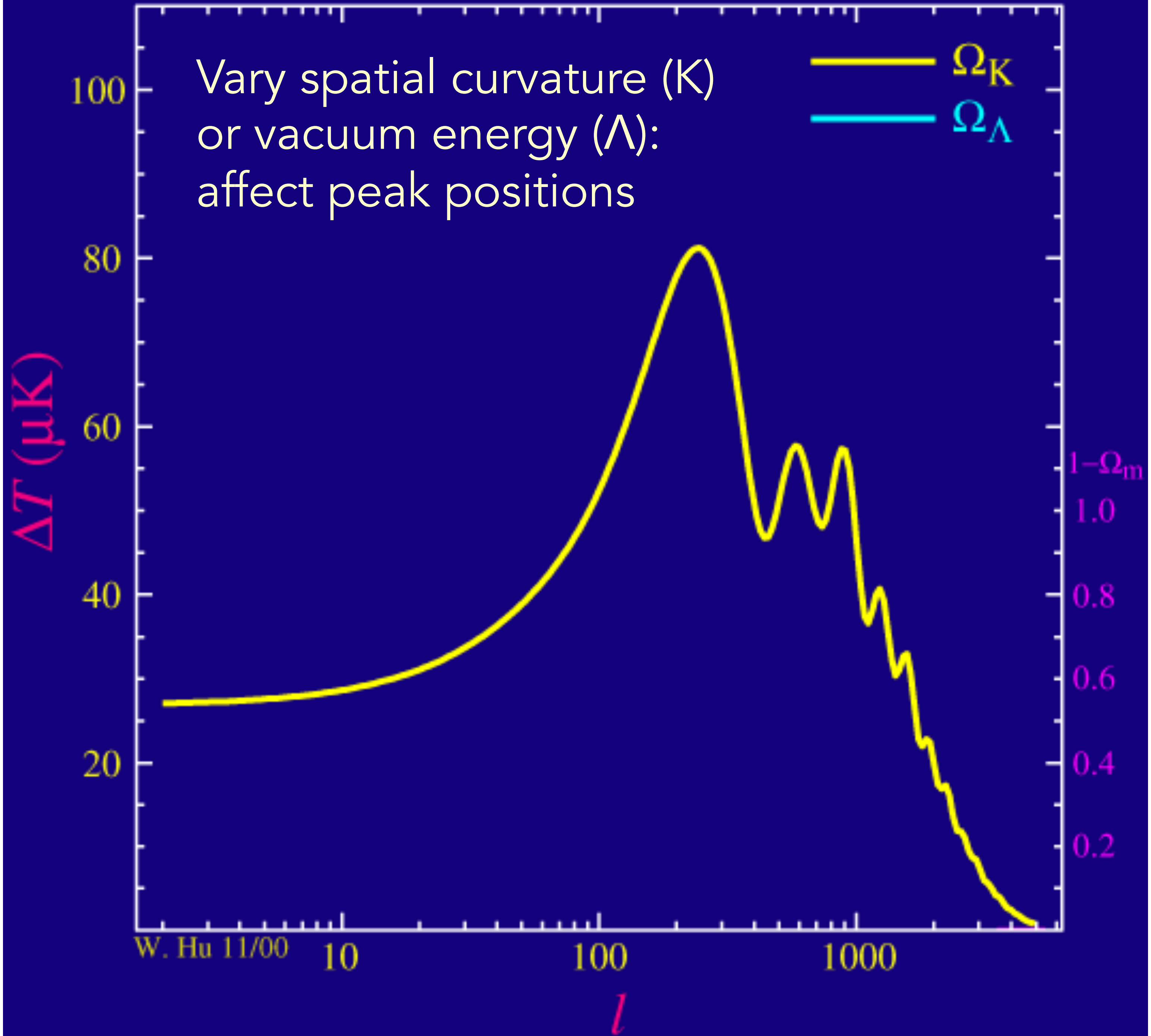




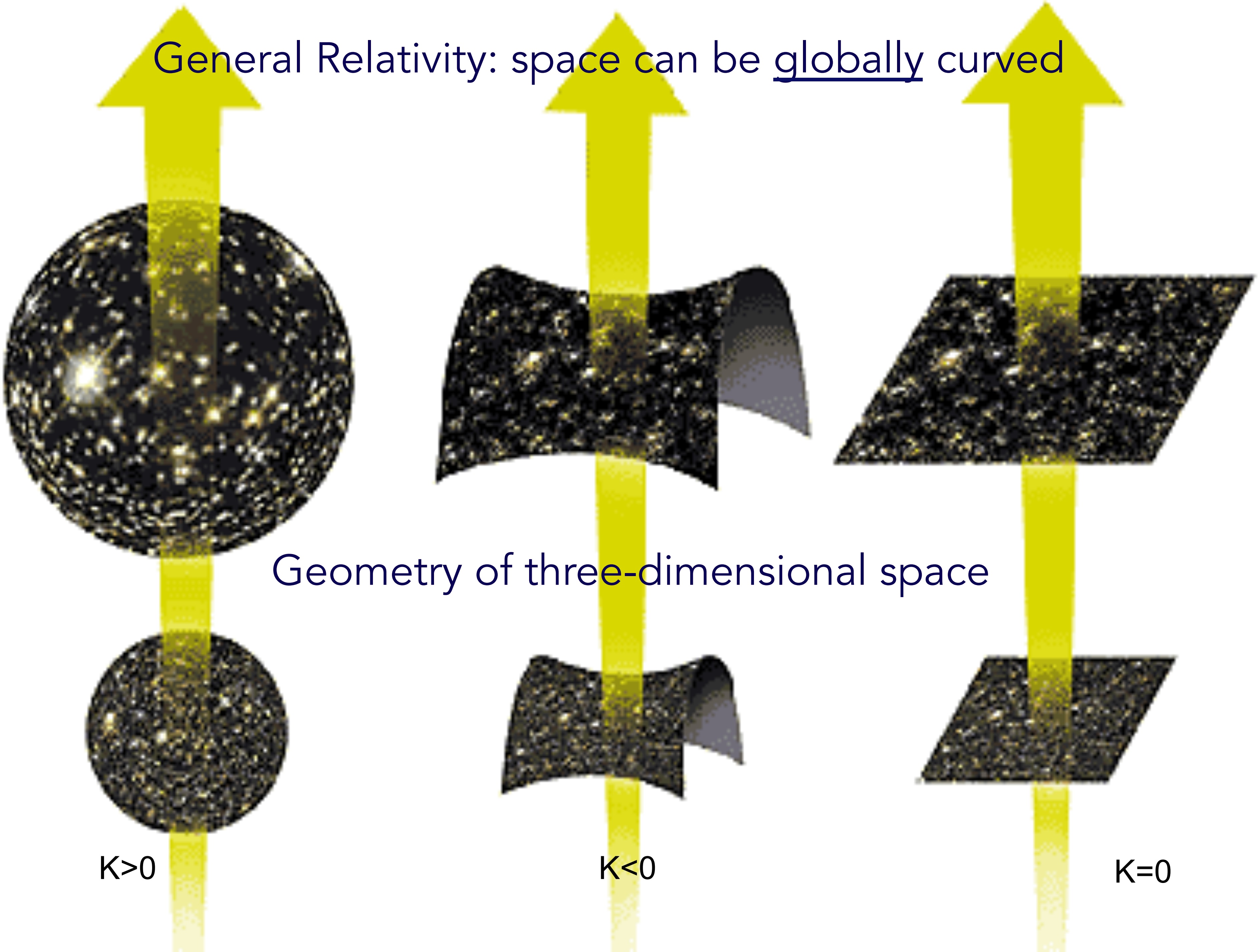
Regions that reach maximal compression once, twice,… by time of recombination

Regions that reach maximal rarefaction once, twice,… by time of recombination

Vary spatial curvature (K)
or vacuum energy (Λ):
affect peak positions

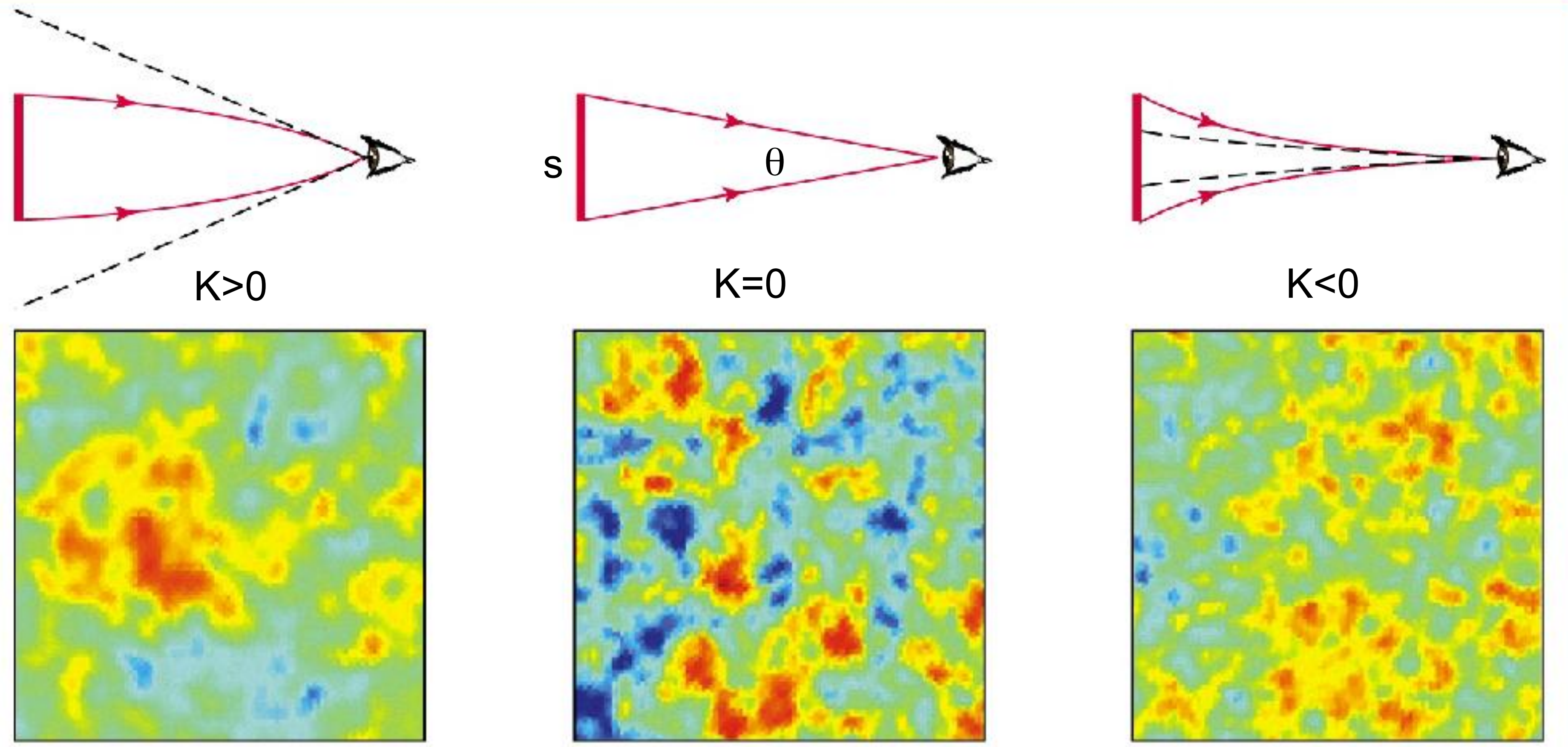


General Relativity: space can be globally curved



Geometry of three-dimensional space

Seeing the Sound Horizon

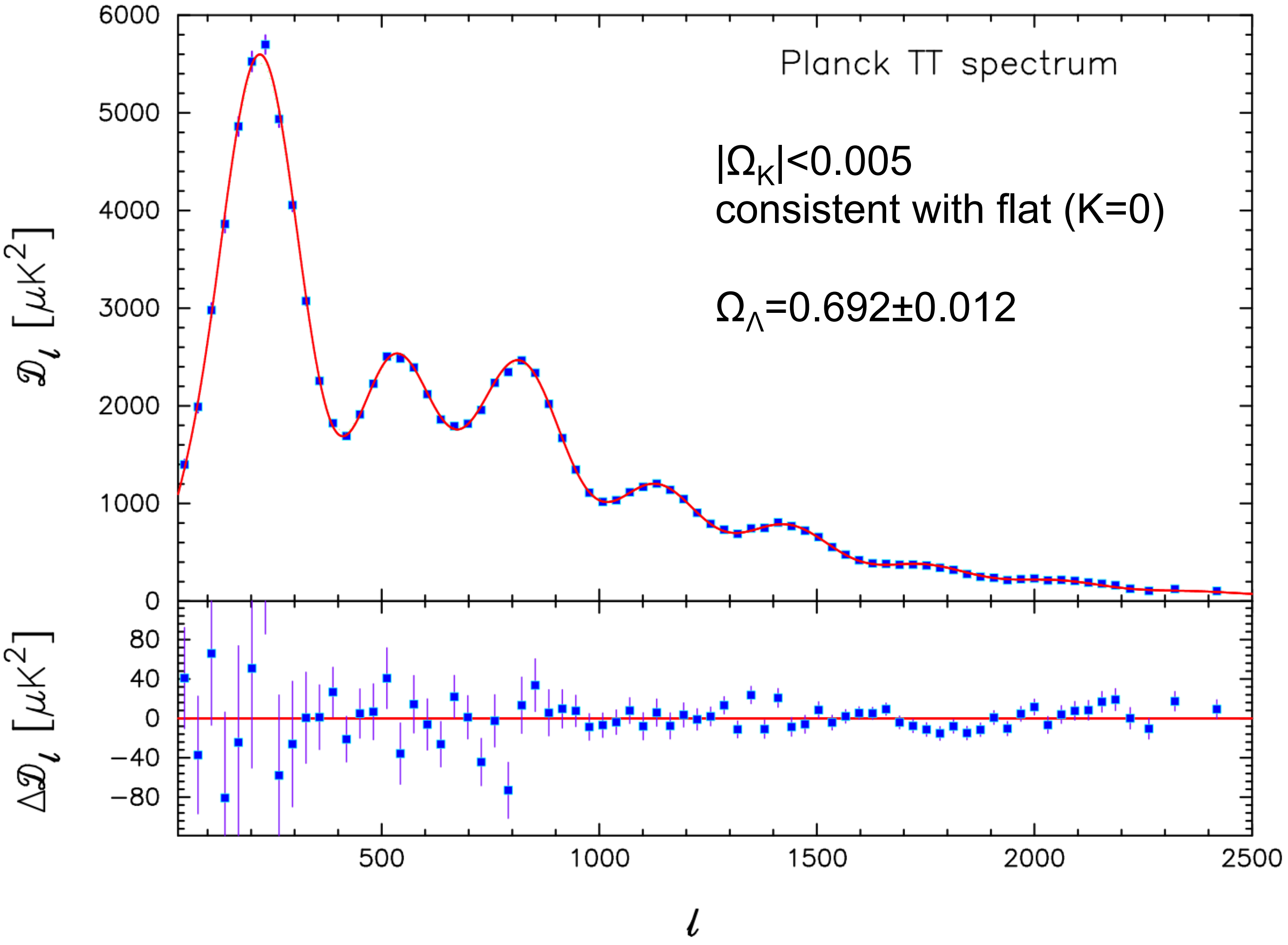


a If universe is closed, "hot spots" appear larger than actual size

b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

CMB Maps tell us space is nearly flat



$|\Omega_K|<0.005$

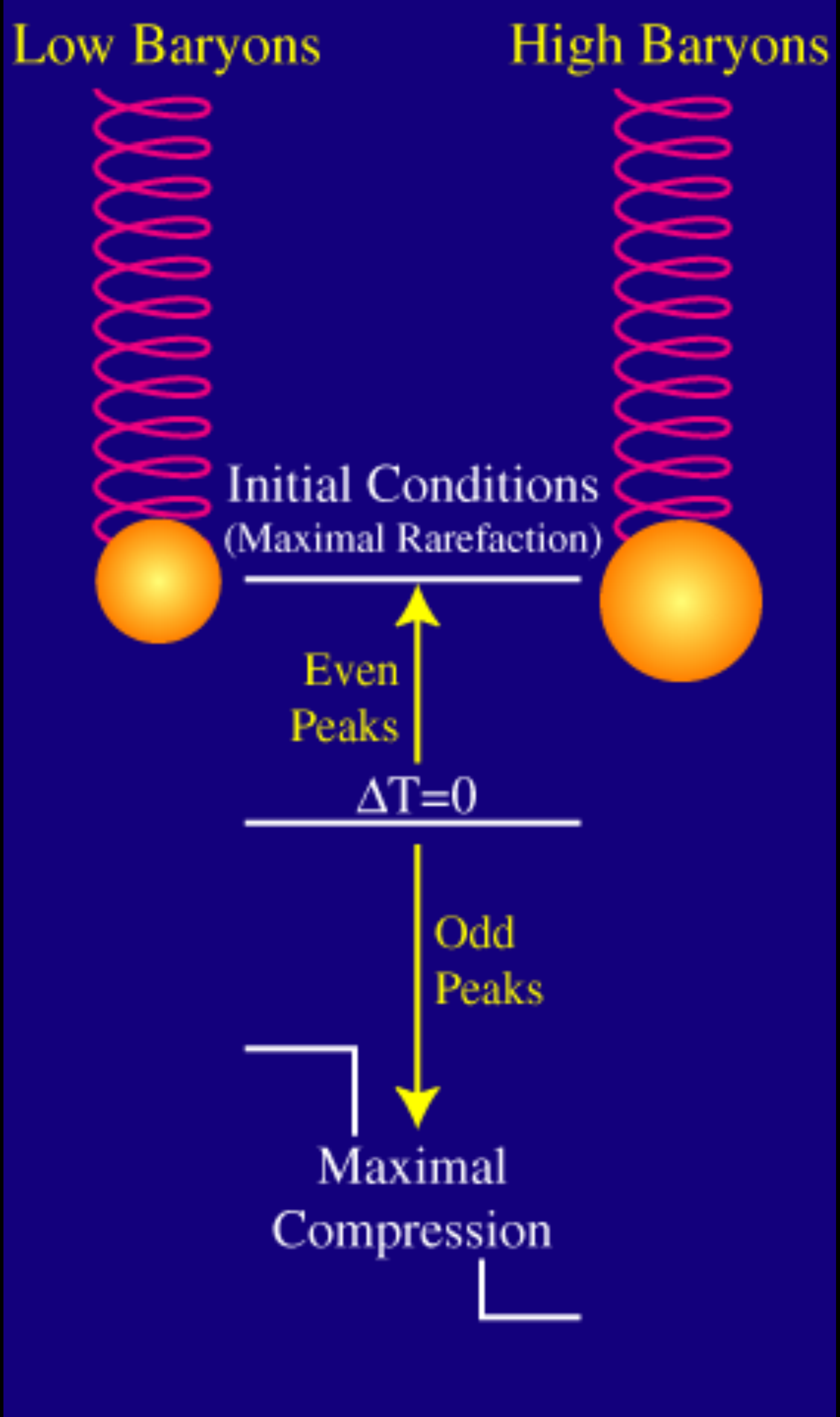
consistent with flat (K=0)

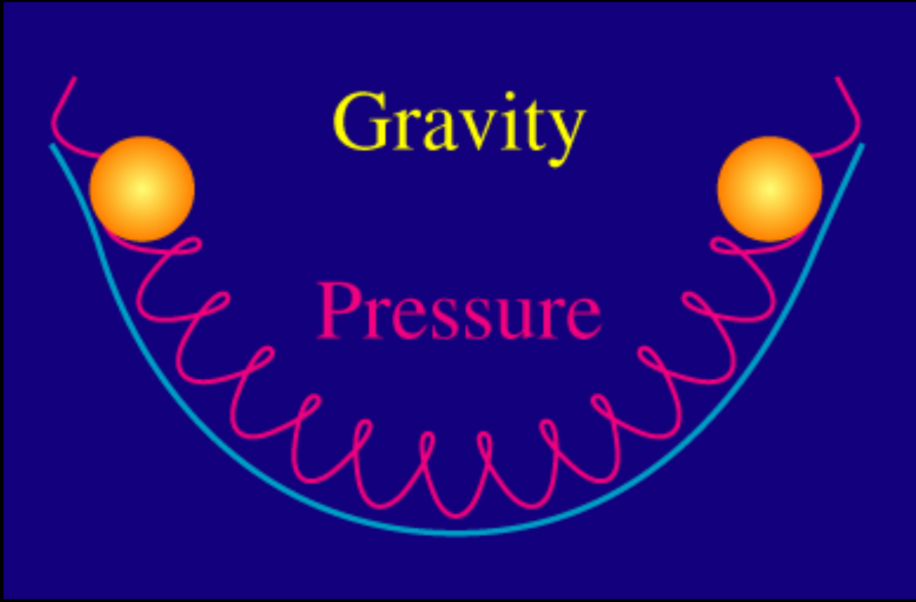
$\Omega_\Lambda=0.692\pm0.012$

CMB & The Baryon Density

Around the time of photon decoupling (recombination of atomic H), the `outward’ pressure of the photons pushing against the `inward’ compression of the gravity of the baryons leads to a set of coherent oscillations (like an oscillating guitar string) in the density and pressure: these are sound waves (aka acoustic waves), with a characteristic fundamental frequency of oscillation, plus higher harmonics (overtones).

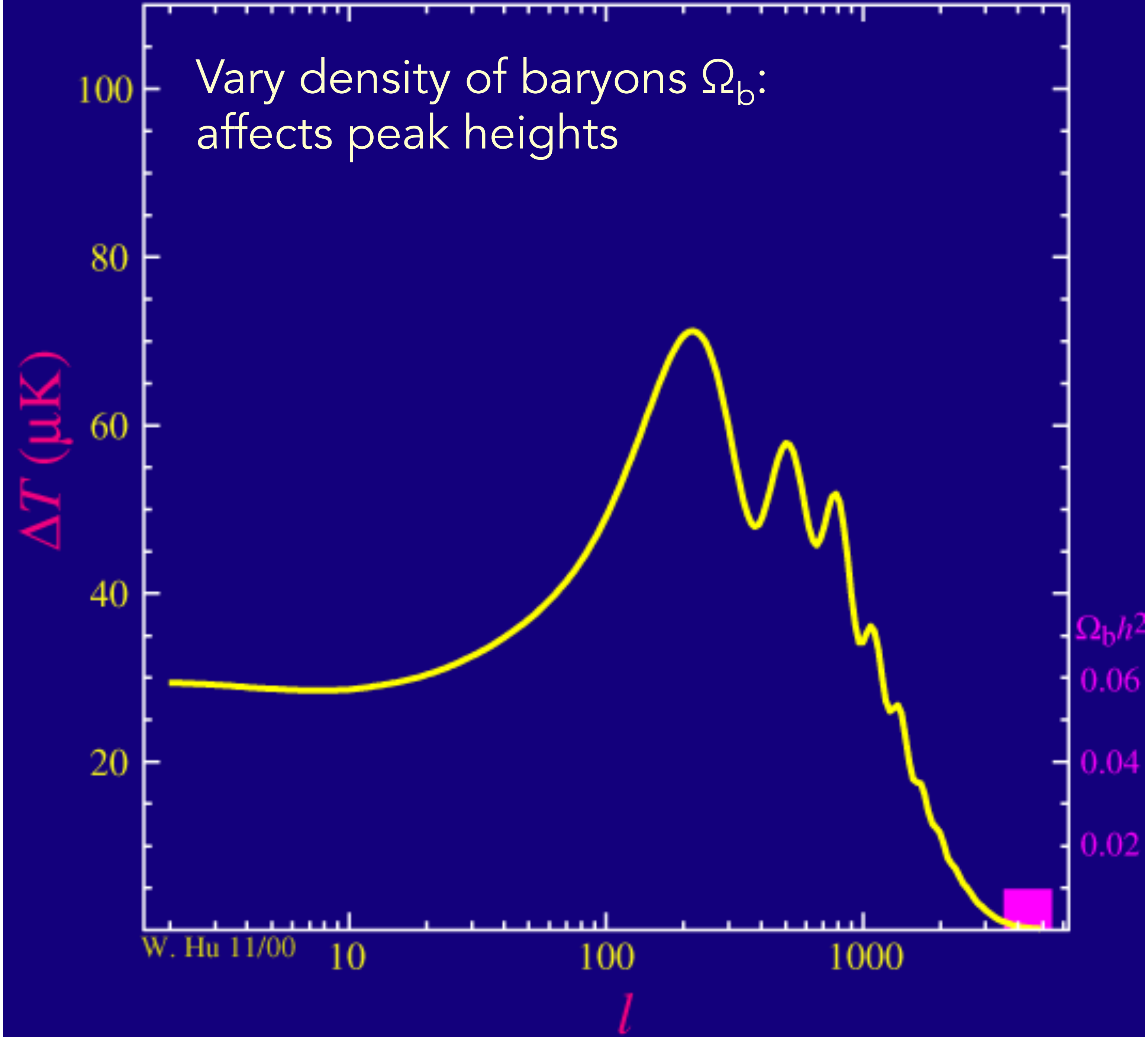
Compression → Heat the gas → Hot spot on the sky
Rarefaction → Cool the gas → Cold spot on the sky



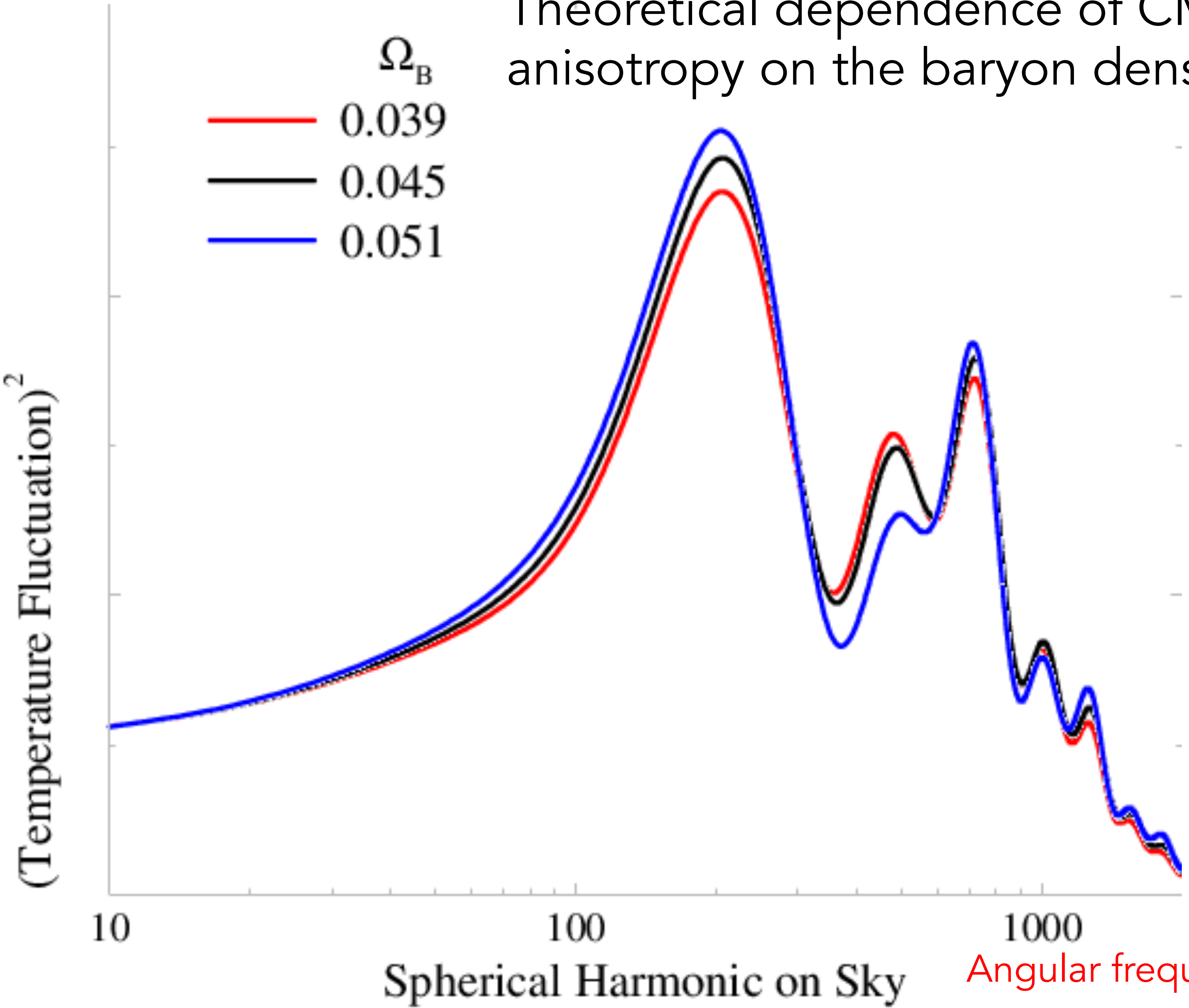


Higher baryon density → larger amplitude of the \`compressional' modes, smaller amplitude of the \`rarefaction' modes.

Vary density of baryons Ω_b: affects peak heights

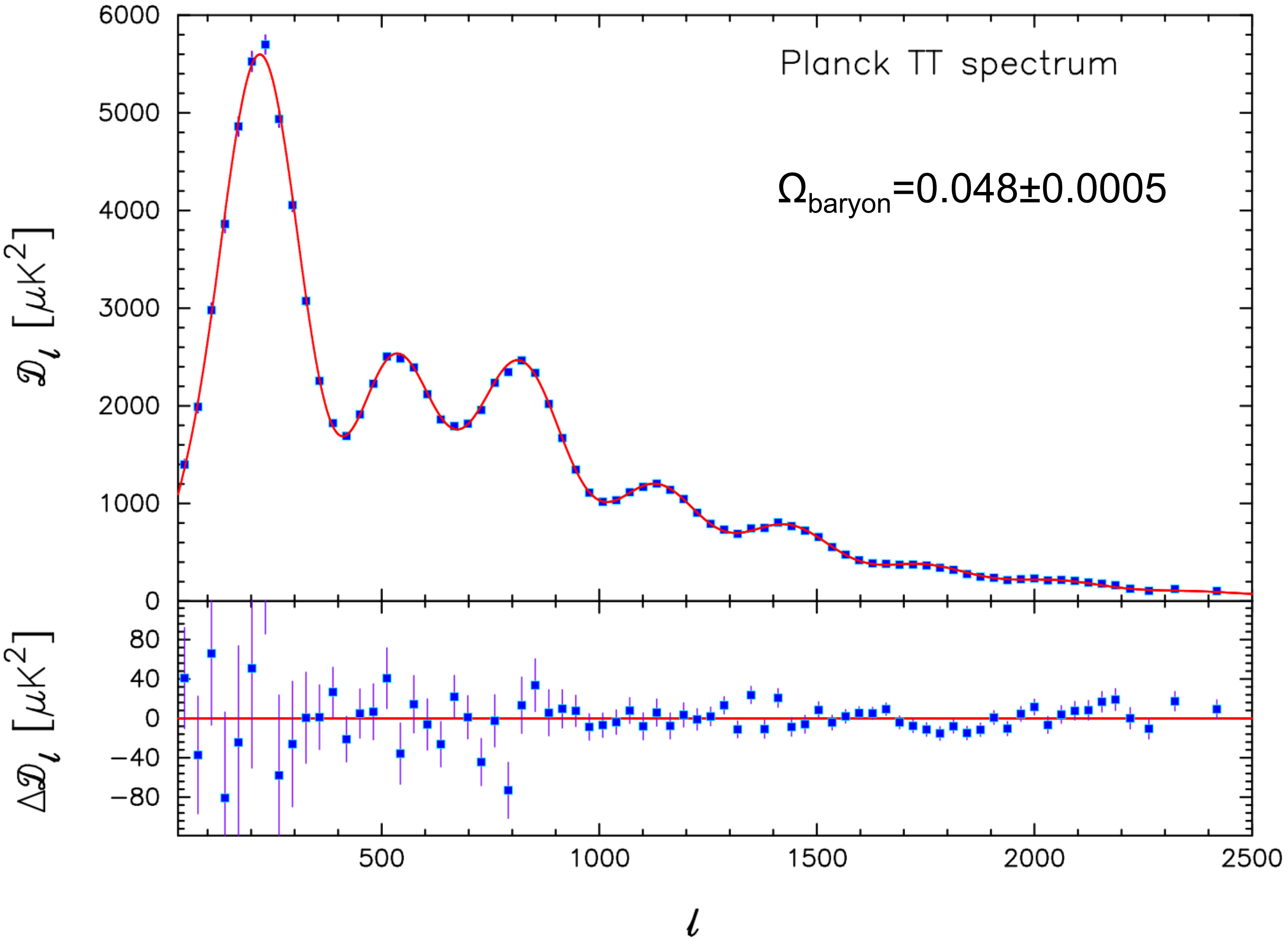


Theoretical dependence of CMB anisotropy on the baryon density



Angular frequency

← Angular separation on the sky



Ω_{baryon}=0.048±0.0005

Logarithmic view of Cosmic History

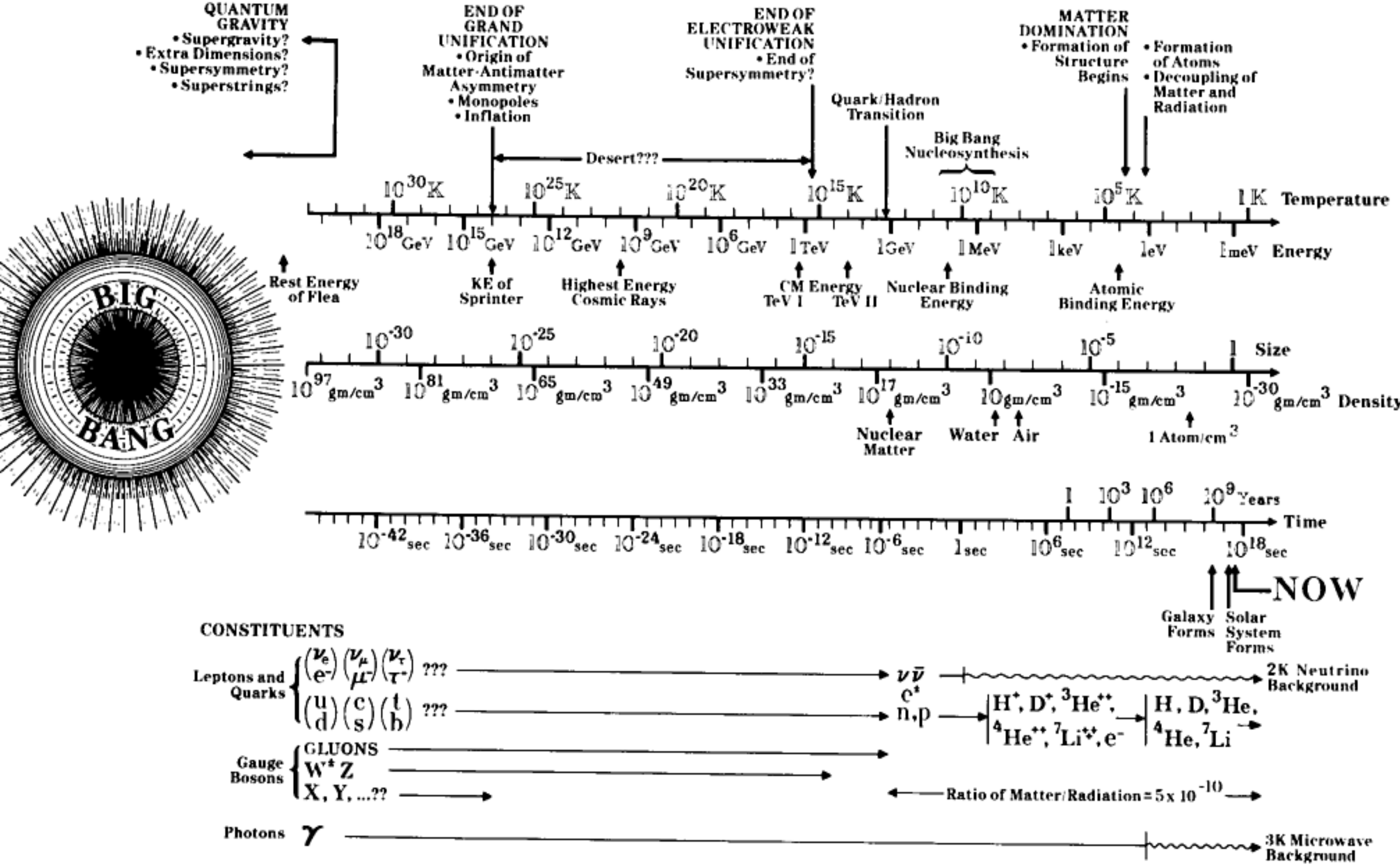


Fig. 1.5.

Cosmic History

- Going back in time from the present toward the Big Bang, first significant epoch we reached was Hydrogen recombination/ photon decoupling at t ~ 380,000 years (T ~ 3000 deg).

- Continuing back, the next major epoch is that of Big Bang Nucleosynthesis, at t ~ 3 minutes (T ~ 10^9 deg).

Big Bang Nucleosynthesis

- Origin of the Light Elements: Helium, Deuterium, Lithium,…

- When the Universe was younger than about 1 minute old, with a Temperature above ~ 1 billion degrees, atomic nuclei (e.g., He^4 nucleus = 2 neutrons + 2 protons bound together) could not survive: instead the baryons formed a soup of protons & neutrons.

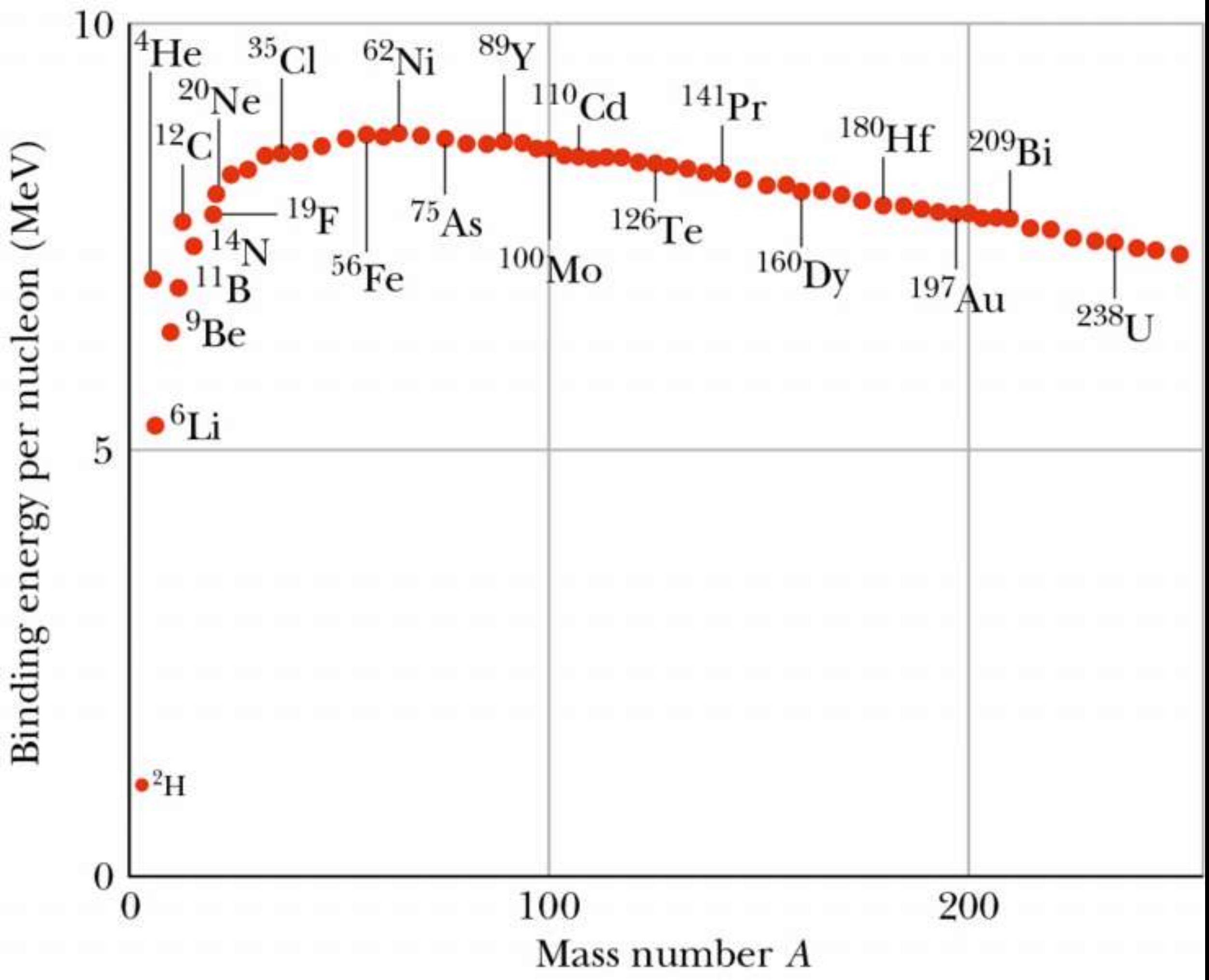
- As the Temperature dropped below this value (set by the binding energy of light nuclei), protons and neutrons began to fuse together to form bound nuclei: the light elements were synthesized as the Universe expanded and cooled.

Nucleosynthesis reactions

- Sequence of nuclear fusion reactions, starting with neutrons and protons, produces light elements in different amounts.

- Fusion reactions release energy (in form of photons & neutrinos) and thereby provide the energy that makes stars shine and Hydrogen bombs explode. (Controlled fusion may be an effectively limitless source of energy in the future: use seawater.) In fusion reactions, lighter nuclei combine to form heavier (generally more stable) nuclei.
- In fission reactions (which power nuclear plants and atomic bombs), very heavy nuclei (e.g., Uranium) are split apart into lighter (more stable) nuclei, again releasing energy. The most stable nucleus is Iron.

Nuclear Binding Energy



Light Element Abundances: Predictions

Stage 1: t < 1 sec, kT > 1 MeV (T > 10^{10} deg)

Universe at this stage consists of protons (p) (Hydrogen nuclei), neutrons (n), electrons, neutrinos, thermal background radiation (photons). Nuclei destroyed by radiation.

Weak and electromagnetic interactions keep all these particles in thermal equilibrium.

Neutrons are slightly heavier than protons:

$$\Delta \equiv m_n c^2 - m_p c^2 = 1.3 \text{ MeV}$$

Since weak interactions interconvert n and p, as the Universe cools there will be fewer neutrons than protons

$$n/p \equiv n_n/n_p = \exp(-\Delta/kT)$$

Light Element Abundances: Predictions

Stage 2: t ~ 1 sec, kT ~ 0.75 MeV

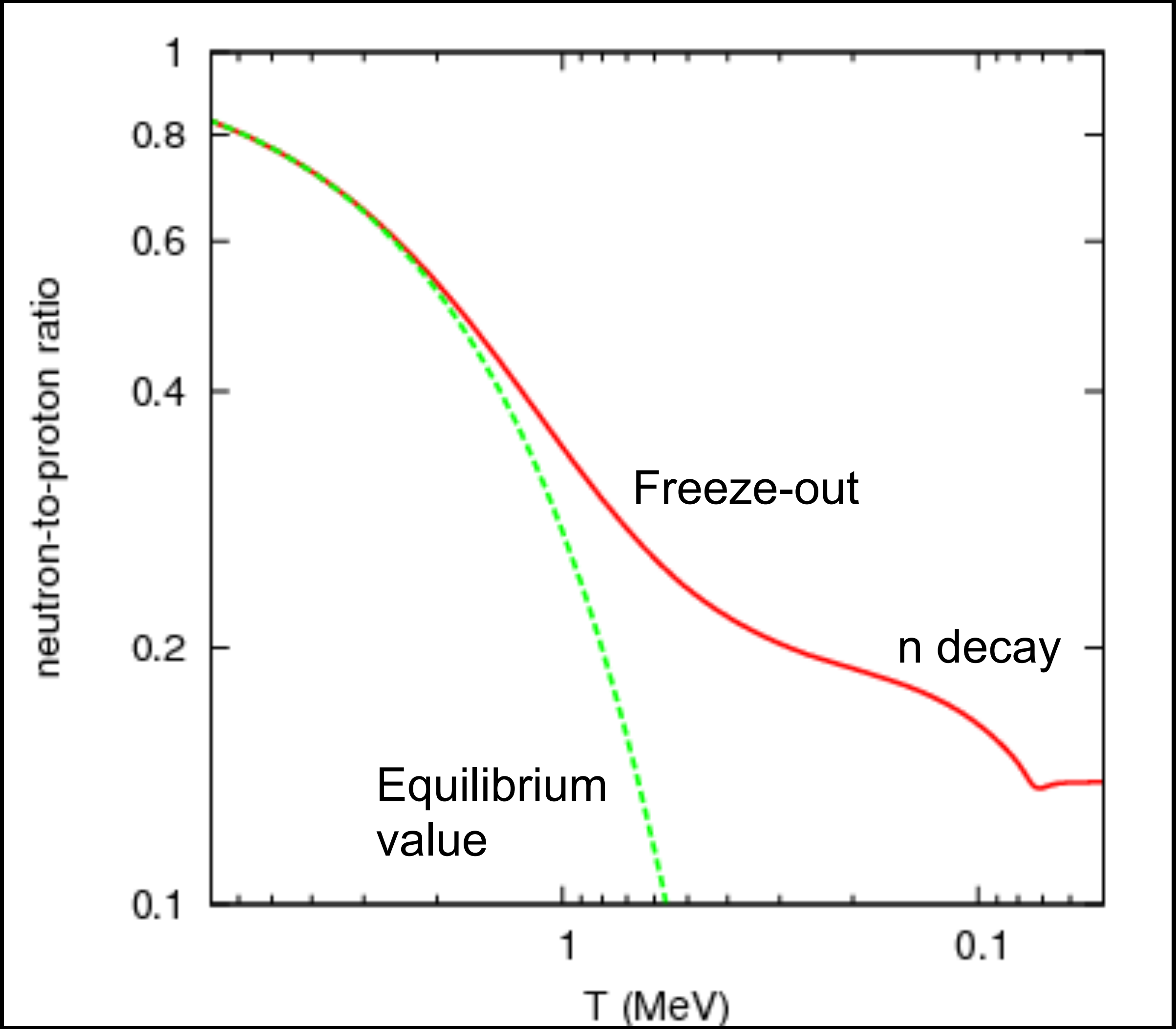
At this stage, the rate of weak interactions n ←→ p drops below the expansion rate of the Universe: neutrons & protons stop converting into each other. These interactions `freeze out'.

When this happens, there are about 6 protons for every neutron:

$$n/p = 1/6$$

and this ratio stops decreasing (except for an occasional neutron decay).

Neutron to Proton Ratio



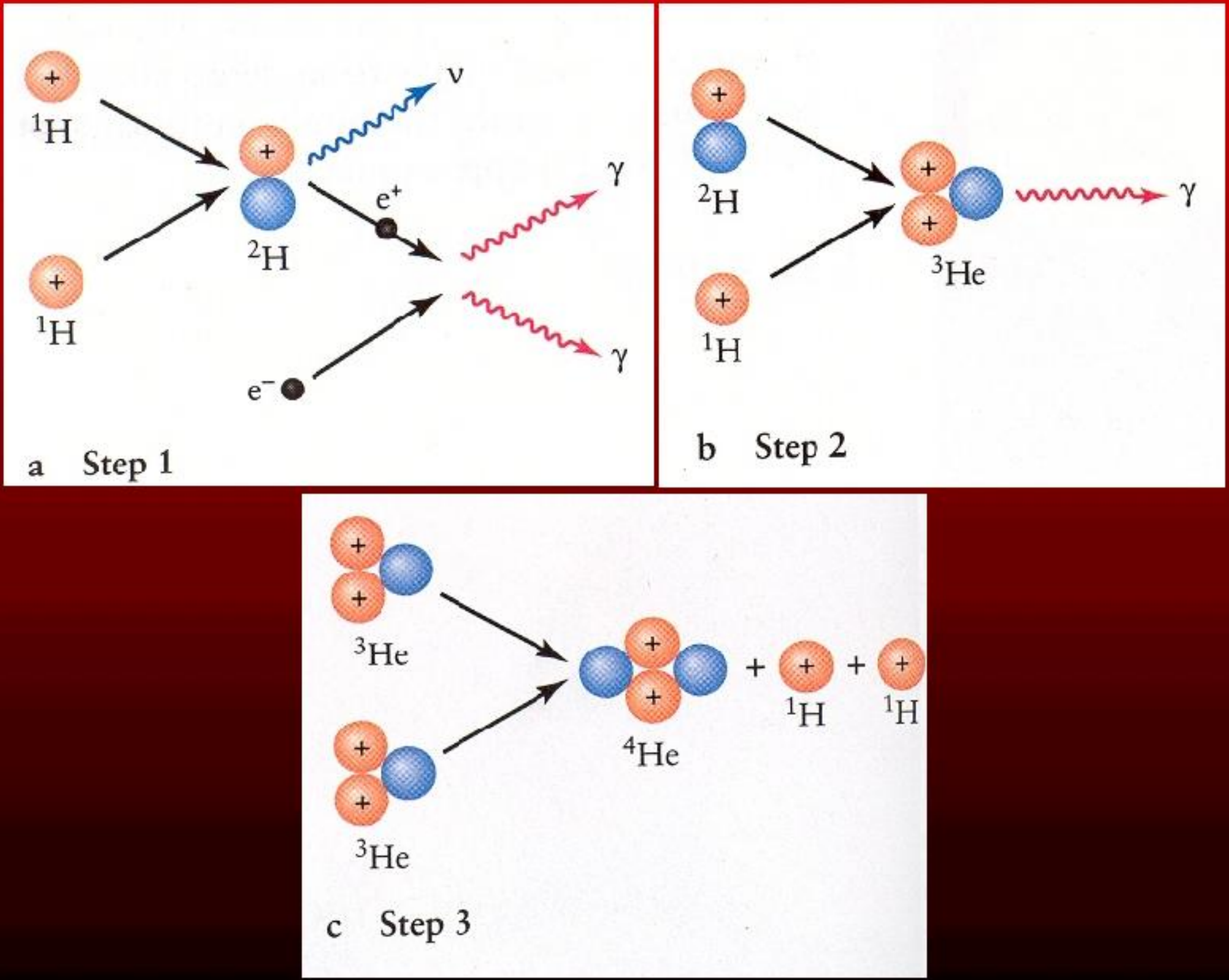
Light Element Abundances: Predictions

Stage 3: t ~ 2.5 minutes, kT ~ 0.08 MeV (T ~ 10^9 deg)

At this stage, the energy of the ambient radiation (photons) is low enough for neutrons and protons to fuse into nuclei of Deuterium (D = H^2=1 neutron+1 proton). Before this time, the weakly bound D is destroyed.

Subsequent reactions produce Tritium (T=H^3=1 proton+2 neutrons), He^3, $Helium^4$ (2 neutrons + 2 protons), and $Lithium^7$ (3 protons, 4 neutrons). Heavier nuclei are not produced (they are produced much later in massive stars). By this time, due to neutron decay, n/p ~ 1/7.

Fusion of Hydrogen to Helium



Primary source of energy in a star like our sun.

Light Element Abundances: Predictions

Stage 3: t ~ 2.5 minutes, kT ~ 0.08 MeV (T ~ 10^9 deg)

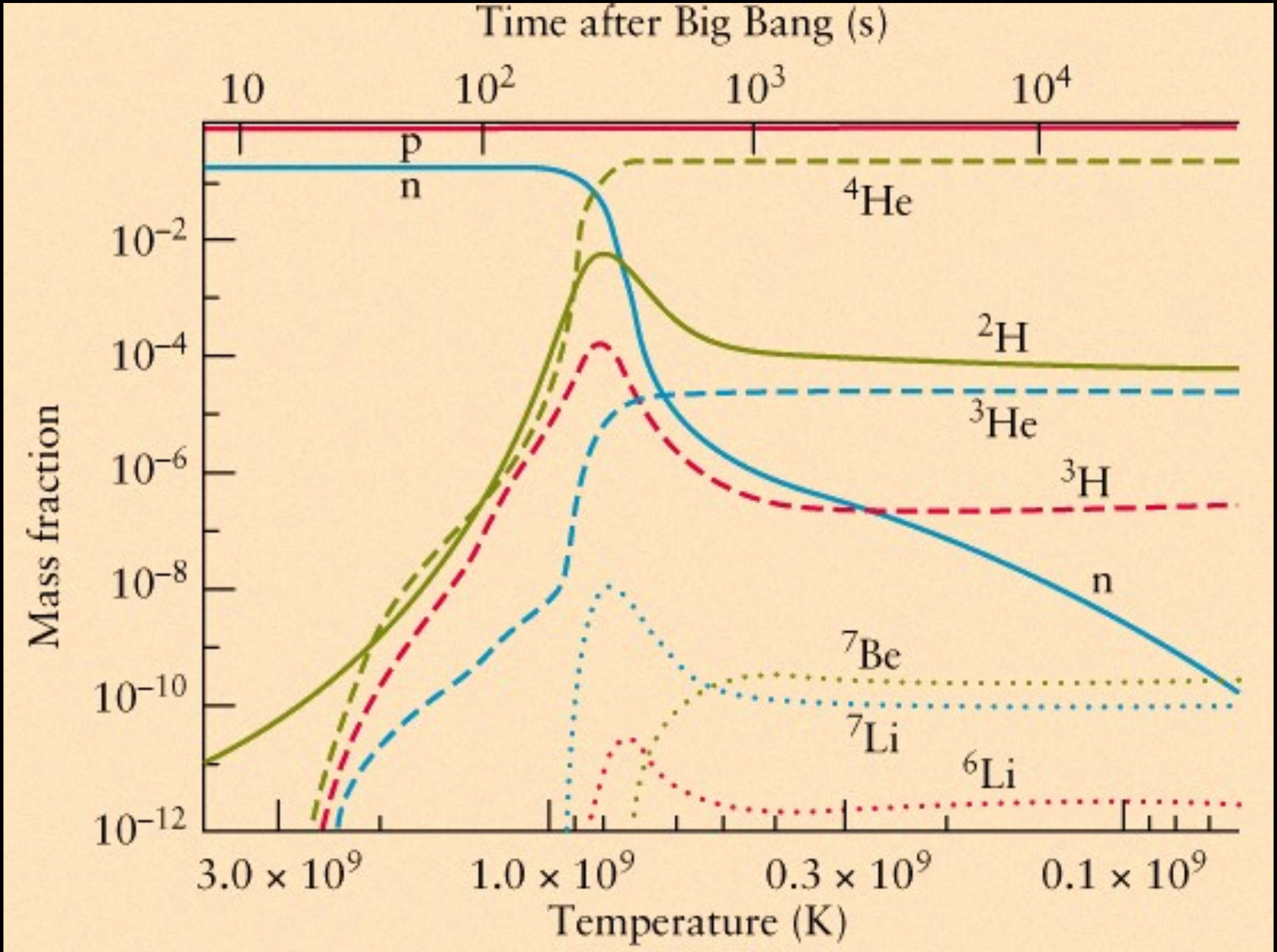
By this time, due to neutron decay, n/p ~ 1/7.
He^4 is the most stable (most strongly bound) *light* nucleus, so essentially all the available neutrons end up in He^4.

Since each He^4 nucleus contains 2 neutrons+2 protons, for every He^4 nucleus there are 12 remaining protons = H nuclei. He^4 mass fraction is therefore (since $m_{He} = 4m_H$)

$$Y = m_{He}/(m_{He}+m_H)=4/(4+12) = ¼$$

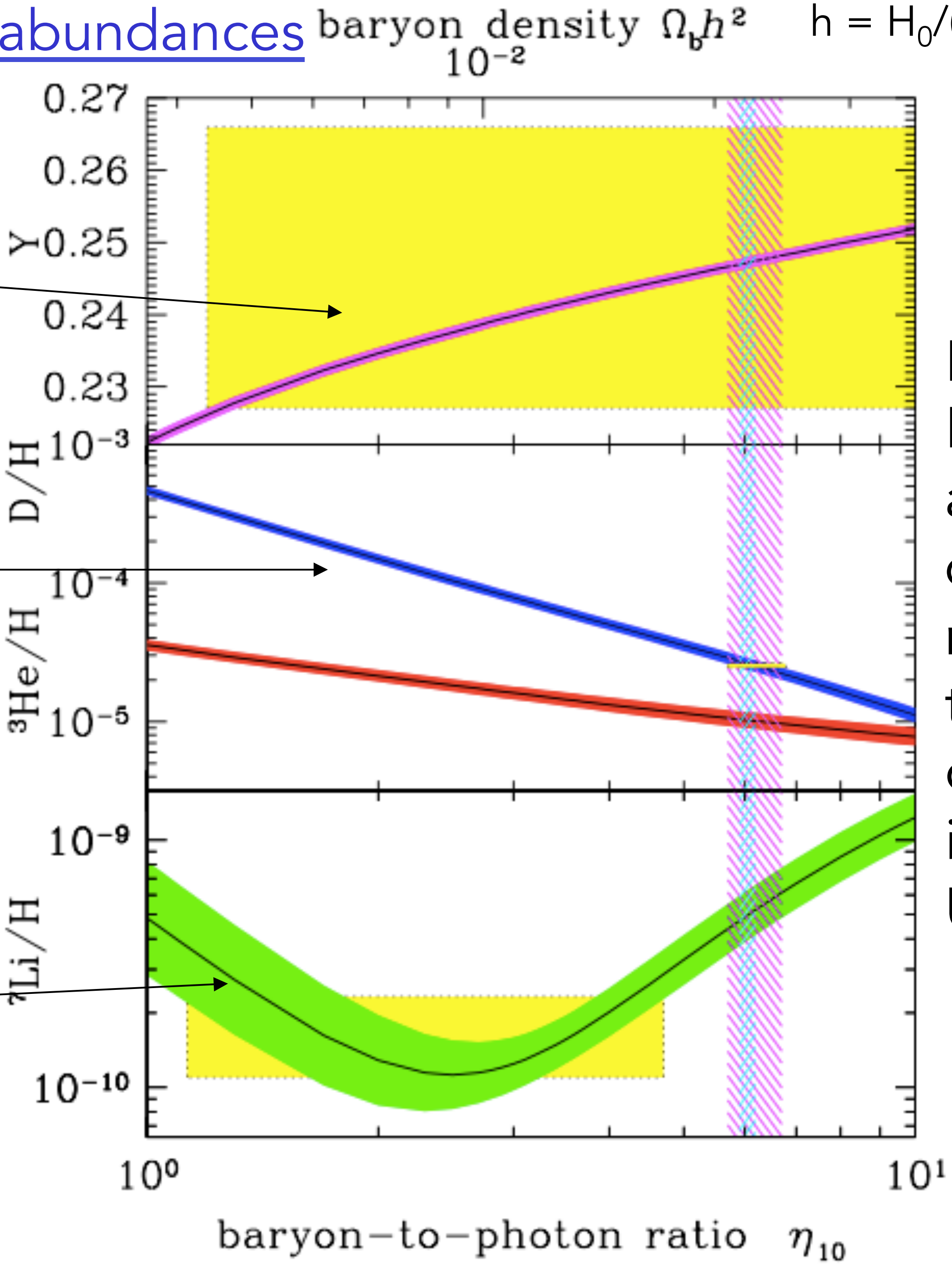
25% of the baryonic mass ends up in Helium, essentially all the rest in Hydrogen, plus trace amounts of Deuterium and Lithium.

Light Element Abundances: Evolution



BBN predicted abundances

h = H_0/(100 km/sec/Mpc)



Fraction of baryonic mass in He^4

Deuterium to Hydrogen ratio

Lithium to Hydrogen ratio

Light Element abundances depend mainly on the density of baryons in the Universe

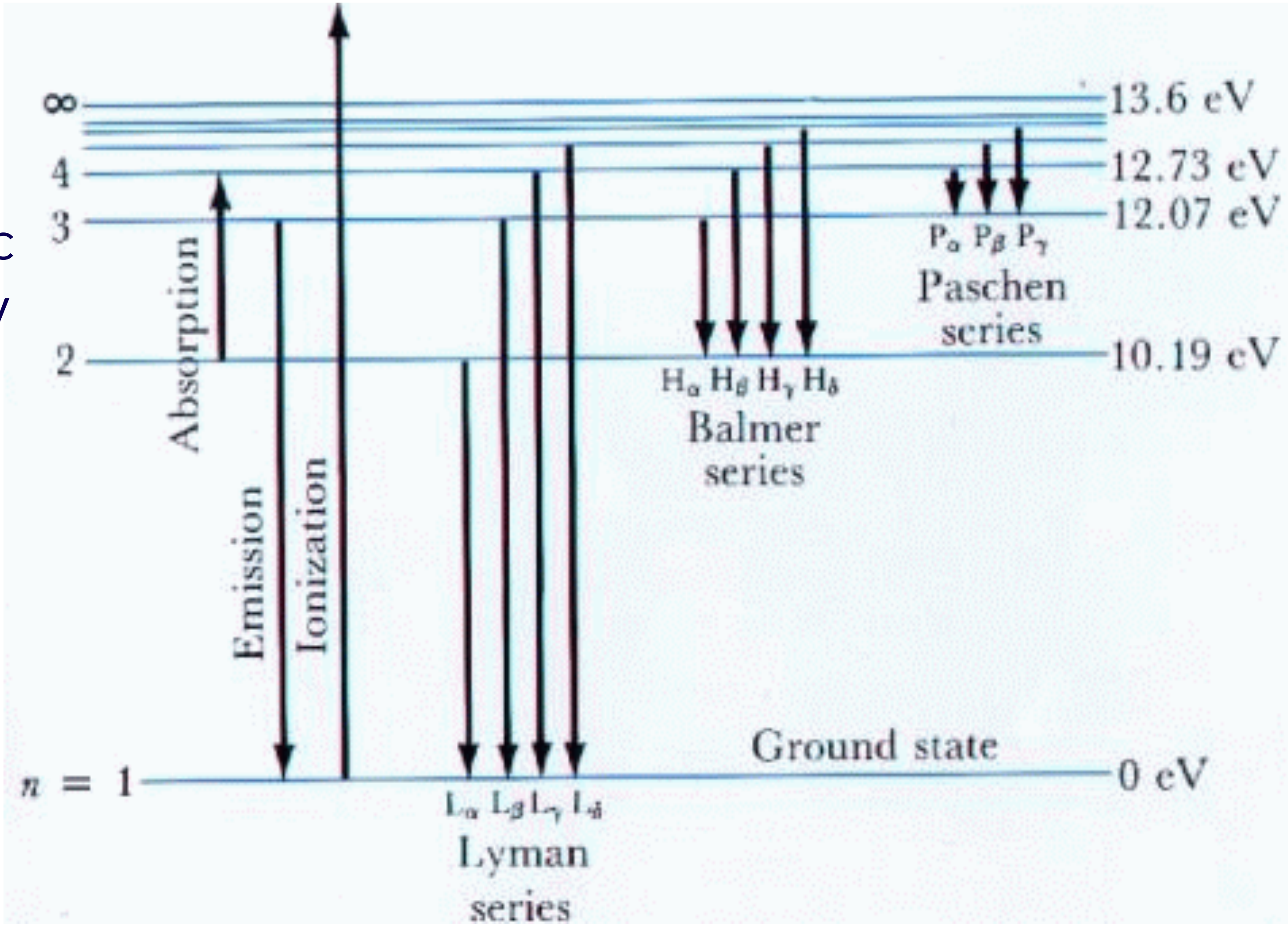
Element Abundances: observations

Measure light element abundances in very old stars (Li), in the interstellar medium, in ionized gas clouds in other galaxies (He), and in Quasar absorption lines (D).

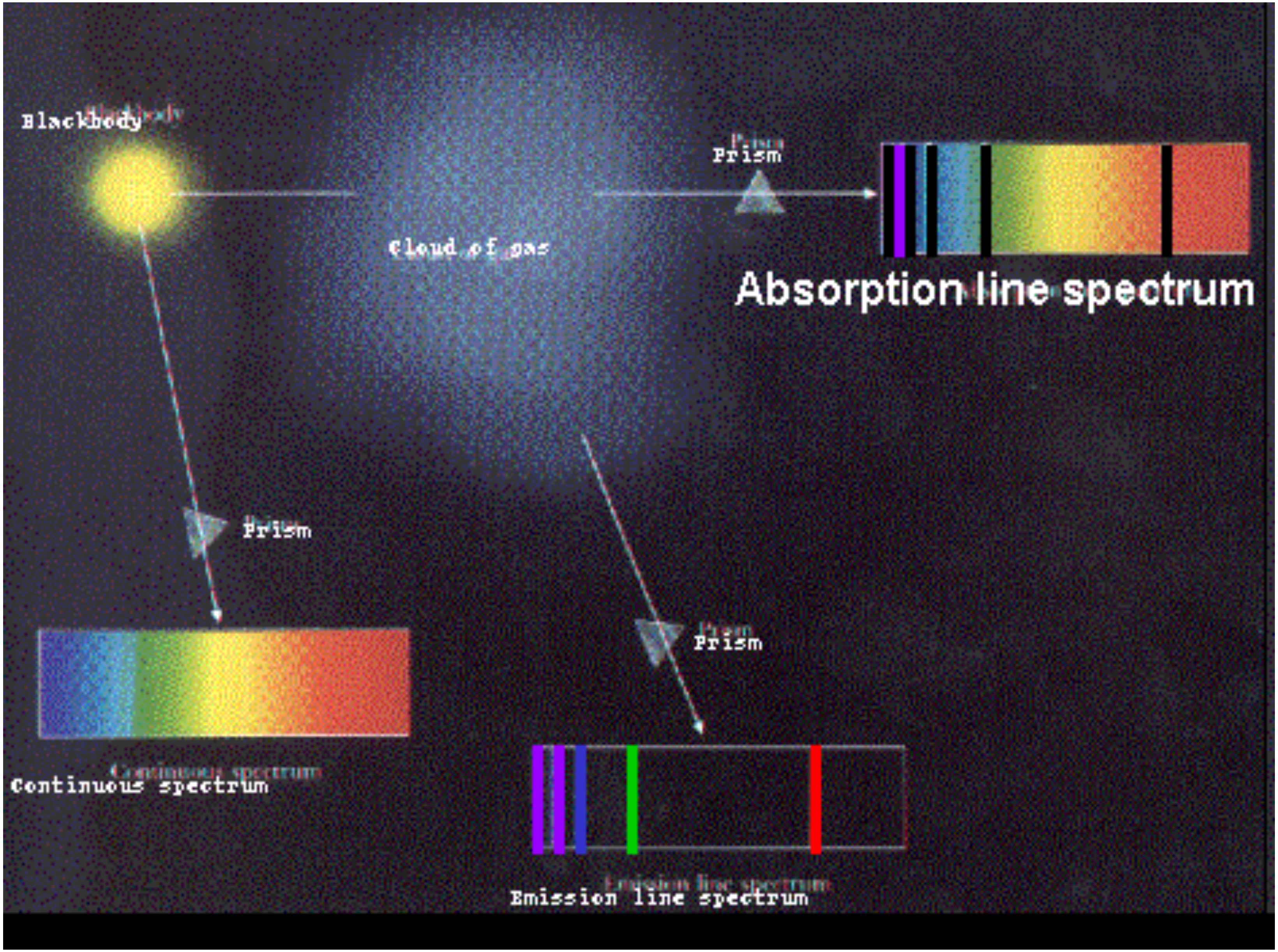
Challenge: find primordial material that has not been processed through stars, which burn lighter into heavier elements through fusion reactions, changing their relative abundances.

Hydrogen emission and absorption lines

Atomic
Energy
Levels



Downward (upward) transition between two energy levels of an atom accompanied by emission (absorption) of light: ΔE = energy difference between the levels; it determines wavelength of emitted or absorbed light



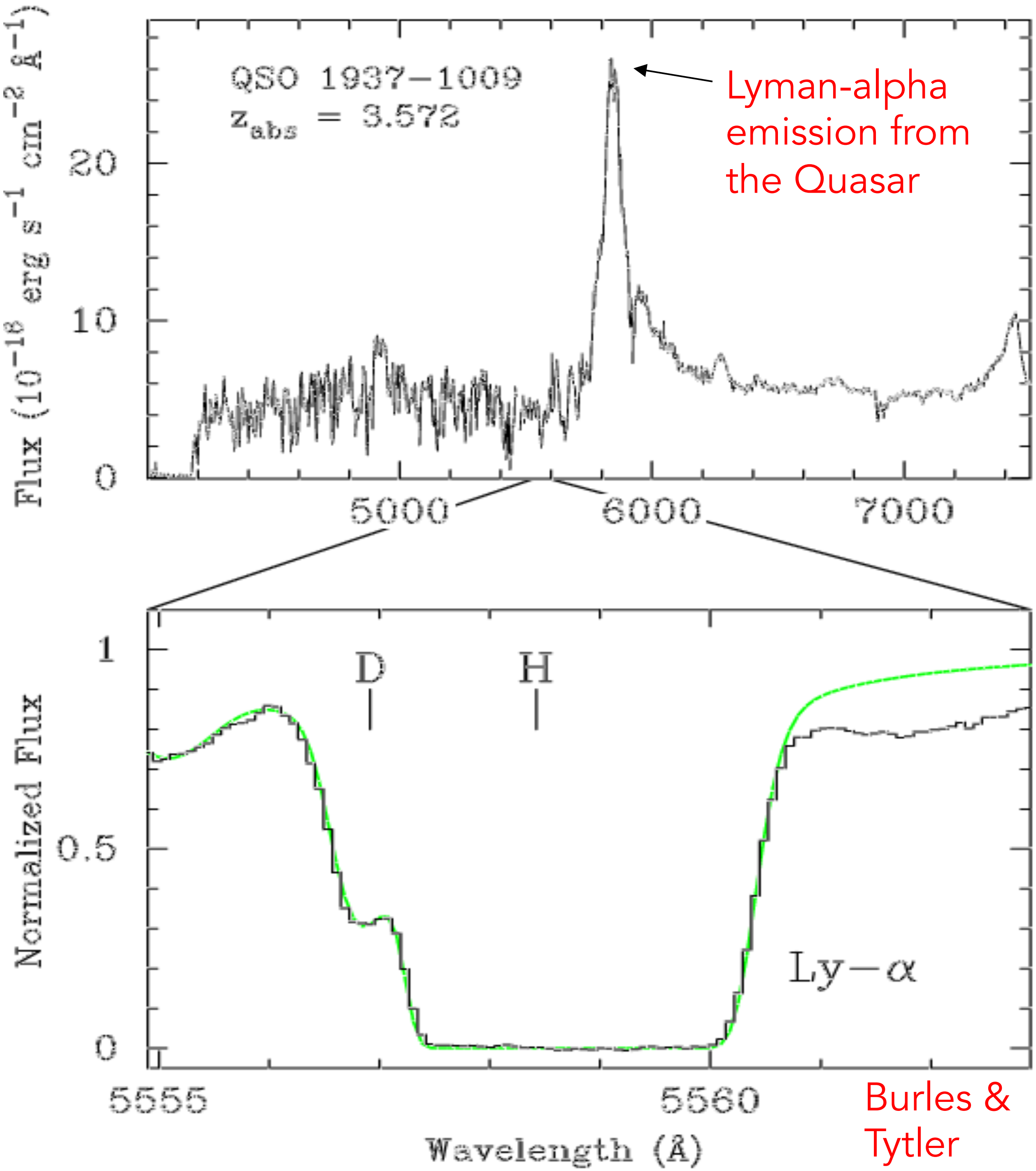
Emission and absorption lines in Spectra

Absorption of Quasar Light by Hydrogen and Deuterium in a gas cloud along the line of sight

Best fit curve to the data:

D/H = 2.5×10^{-5}

Deuterium isn't produced in stars, only destroyed by them: lower limit

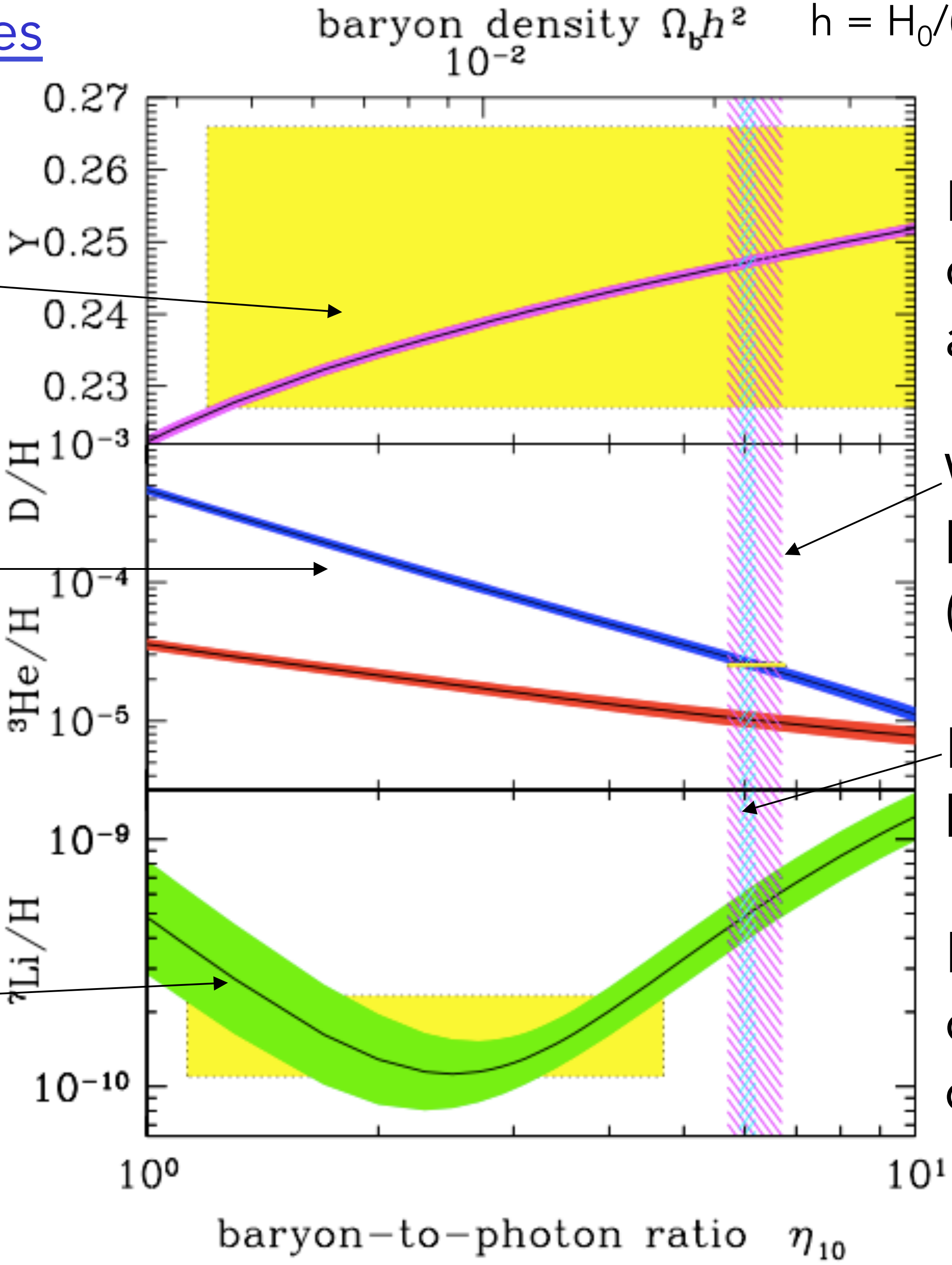


Lyman-alpha emission from the Quasar

Burles & Tytler

BBN abundances

h = H_0/(100 km/sec/Mpc)



Fraction of baryonic mass in He^4

Deuterium to Hydrogen ratio

Lithium to Hydrogen ratio

Boxes: observed abundances

Wide vertical band: BBN (mainly D)

Narrow band: CMB

Lithium in old stars is discordant

BBN & the Baryon Density

Light element abundances are concordant (except for Lithium) if the baryon density of the Universe is in the range

$$0.021 < \Omega_b h^2 < 0.025$$

Since the Hubble parameter $h = H_0/100$ km/sec/Mpc=0.7, this yields

$$0.043 < \Omega_b < 0.051$$

This determination is in excellent agreement with the amplitude of the `acoustic peaks' in the CMB temperature anisotropy from the Planck satellite, establishing validity of the Big Bang model back to ~1 second after the birth of the Universe. Next week we will discuss pushing even further back in time, to a tiny fraction of a second.