Physics 133: Extragalactic Astronomy and Cosmology

Week 7

Week 7 Outline

The Early Universe, Long Before Stars & Galaxies Formed

- Cosmic microwave background
  - Recombination of electrons and protons
  - Photon Decoupling
  - Last Scattering Surface (optical depth)

- The Primordial Helium Abundance & Cosmic Nucleosynthesis
  - What can be predicted and measured?
  - Introduction to nucleosynthesis
    - Neutron decay
    - Deuterium and helium production
    - Baryon – antibaryon asymmetry

Quiz 12

How many photons are there in the universe for every baryon?

Calculate the number density of baryons of today.

Use $\Omega_{b,0} = 0.048$ and $\rho_{crit,0} = 1.28e11\ M_{sun}/Mpc^3$ of baryons.

$n_{b,0} = 0.048\ (8.67e\text{-}30\ g/cm3)\ /\ 1.67e\text{-}24\ g/amu$

$= 2.5e\text{-}7\ cm\text{-}3$

Calculate the number density of CMB photons today.

Use energy density and mean photon energy (2.7 kT).

Or use [2.32] for blackbody radiation,

$n_\gamma = 20.29\ cm^{-3}\ K^{-3}\ T^3$

$= 410\ cm^{-3}$

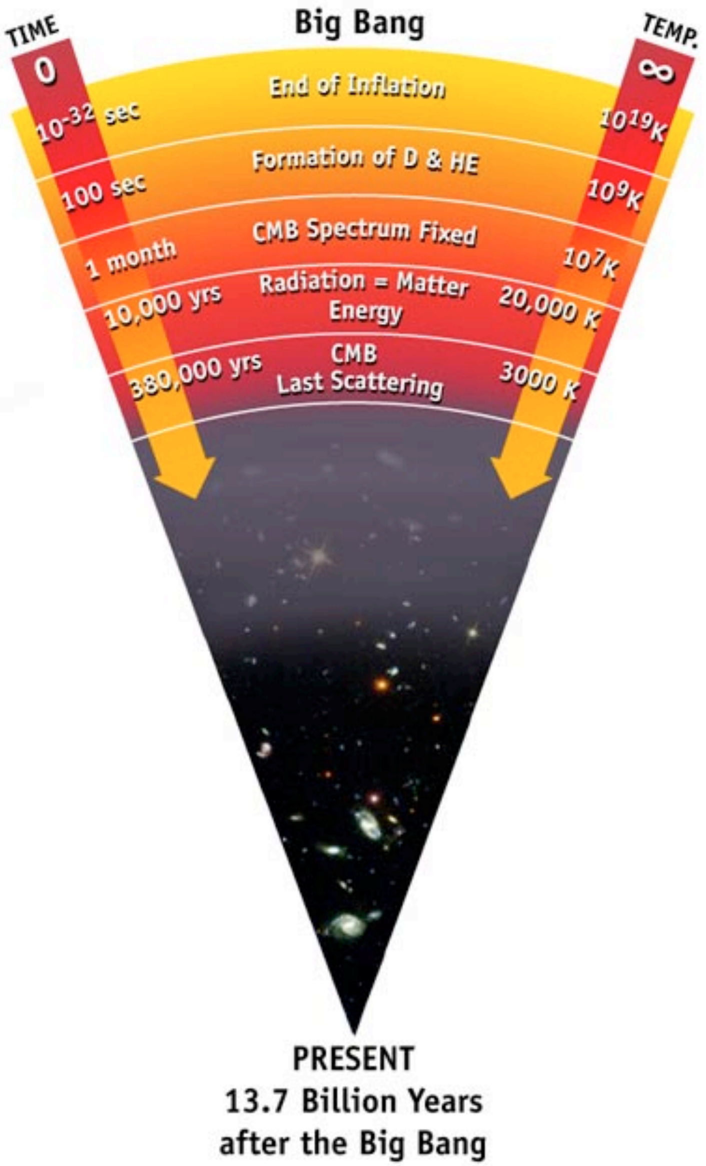
So 1.6 billion photons per baryon!!

Photons vs. Baryons

- CMB photons:
  - Energy density: 0.261 MeV/m^3
  - Number density: 4e8/m^3 = 400 /cm^3
- Baryons:
  - Energy density 210 MeV/m^3
  - Number density: 0.22/m^3 = 2.2e-7
- Ratio:
  - ε(baryons) ~ 800 ε(photons)
  - η = n(baryons)/n(CMB)=5e-10
- **Photons greatly outnumber baryons in the universe.**
  - When? At all times!
  - **So there really are a billion photons available per H atom, and we only need one of them to have hν > 13.6 eV to ionize H.**

Physics of the CMB. Three key epochs

- Recombination
  - z~1370
- Decoupling
  - z~1090
- Last scattering surface
  - z~1090 (1000 – 1200)



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.

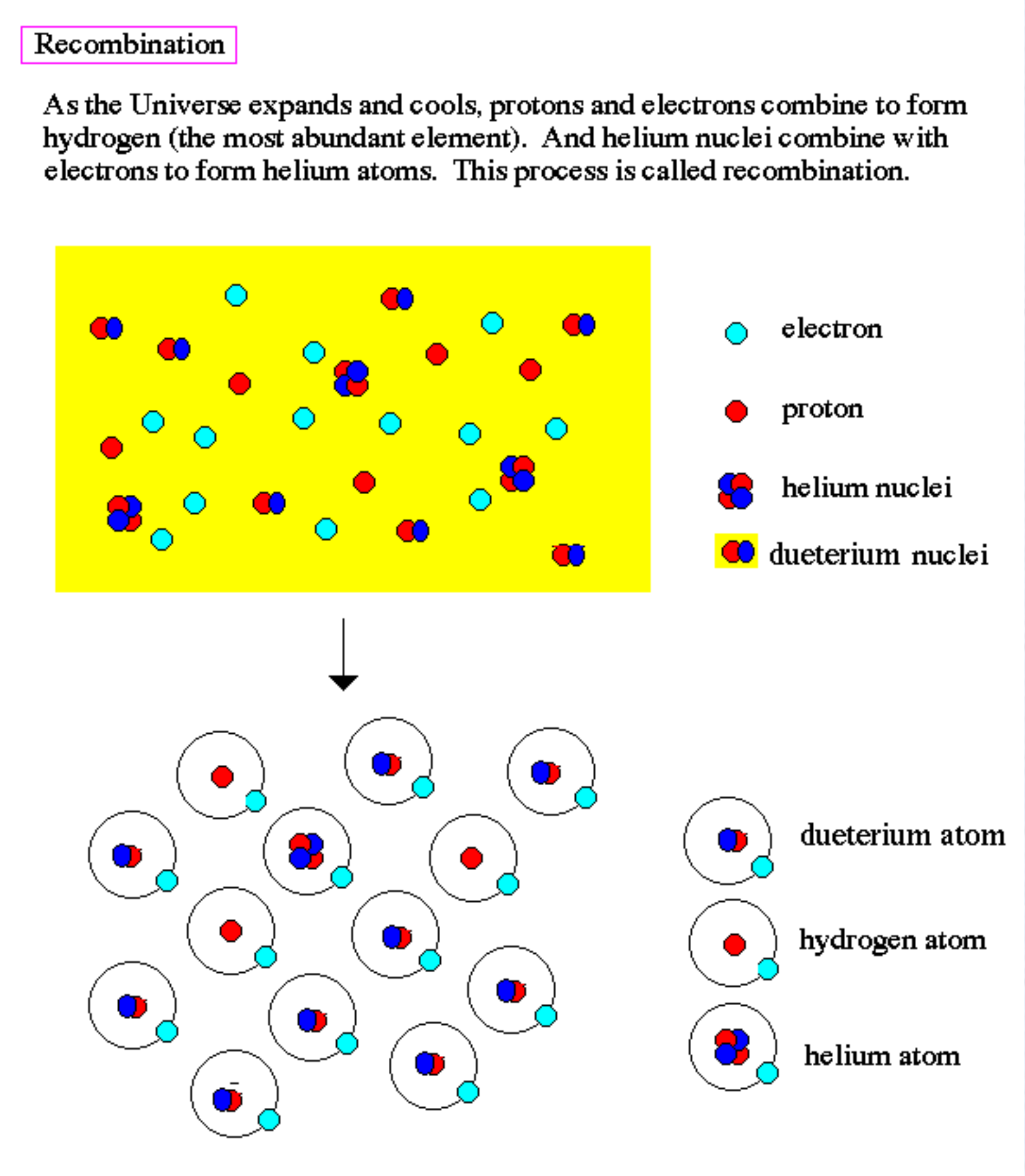
Hydrogen Recombination

Protons combine with electrons to form H atoms.

To understand when and how this transition, we will review the concepts of …

1. Thermal Equilibrium
2. Kinetic Equilibrium
3. **Chemical Equilibrium.**

Thermal Equilibrium means that different types of particles have the same temperature.



Recombination

As the Universe expands and cools, protons and electrons combine to form hydrogen (the most abundant element). And helium nuclei combine with electrons to form helium atoms. This process is called recombination.

Incorrect ‘back of the envelope’ Estimate

- Protons combine with electrons to form H atoms.

$p + e^- \rightarrow H + \gamma$

- Mean energy per photon (2.7 kT) falls below 13.6 eV when T drops below 60,000 K.
- Might expect recombination at T = 2.7 K (1+z), where T = 60,000 K, or z ~ 22,000
- But hydrogen recombination actually happens at significantly lower T ~ 3700 K.
- Why?

Kinetic Equilibrium

Kinetic equilibrium means we the know the distribution function of particle momenta or energies. Let's review.

$$n_x(p)dp = g_x \frac{4\pi}{h^3} \frac{p^2 dp}{exp([E-\mu]/kT) \boxed{\pm 1}}$$

Fermions vs. Bosons

$$n_\gamma(\nu)d\nu = \frac{8\pi}{c^3} \frac{\nu^2 d\nu}{\exp(h\nu/kT) - 1}$$

Example: Photons are bosons with 2 different spin states.

$$n_\gamma = \frac{2.4041}{\pi^2} \left(\frac{kT}{\hbar c}\right)^3$$

Integrate over frequency to get number density of photons.

$$n_x(p)dp = g_x \frac{4\pi}{h^3 c^3} \exp\left(\frac{-m_x c^2 + \mu_x}{kT}\right) \exp\left(-\frac{p^2}{2m_x kT}\right) p^2 dp$$

$$\boxed{n_x = g_x \left(\frac{m_x kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{-m_x c^2 + \mu_x}{kT}\right)}$$

Maxwell-Boltzmann distribution describes non-relativistic p, e-, and H. Integrate to get density.

Hydrogen Recombination

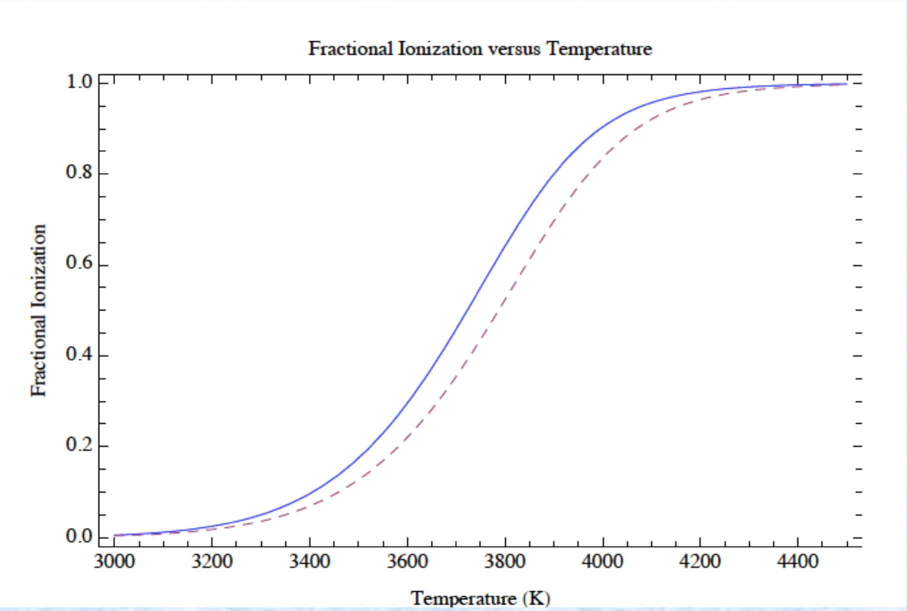
- In chemical equilibrium the sum of the chemical potentials on the two sides of an equation are equal.

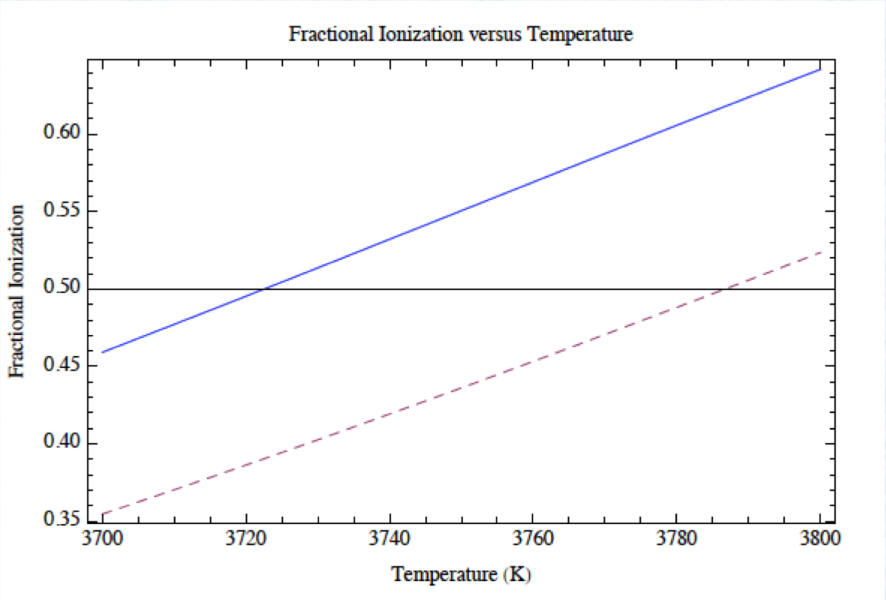
[blackboard]

- Saha Equation explain T ~ 3700 temperture for hydrogen recombination.
- T(z) = 2.7 K (1+z) = 3700 at z=1370.
- What is the age of the Benchmark model at z = 1370?
- What is ionization potential of Helium? **When does Helium recombine relative to Hydrogen?**

Redshift of Recombination

- Define hydrogen recombination where $X = n_p/(n_p+n_H) = 0.5$.
- Find $T_{rec} \sim 3740$ K, which is much lower than $3kT = 13.6$ eV.
  - Why does this happen? [See next slide]
  - **HW #6 includes Ryden 8.1**, where you explore how T_{rec} changes if the relative number density of baryons and photons, $\eta = n_p/n_\gamma$, increases by a factor of two.



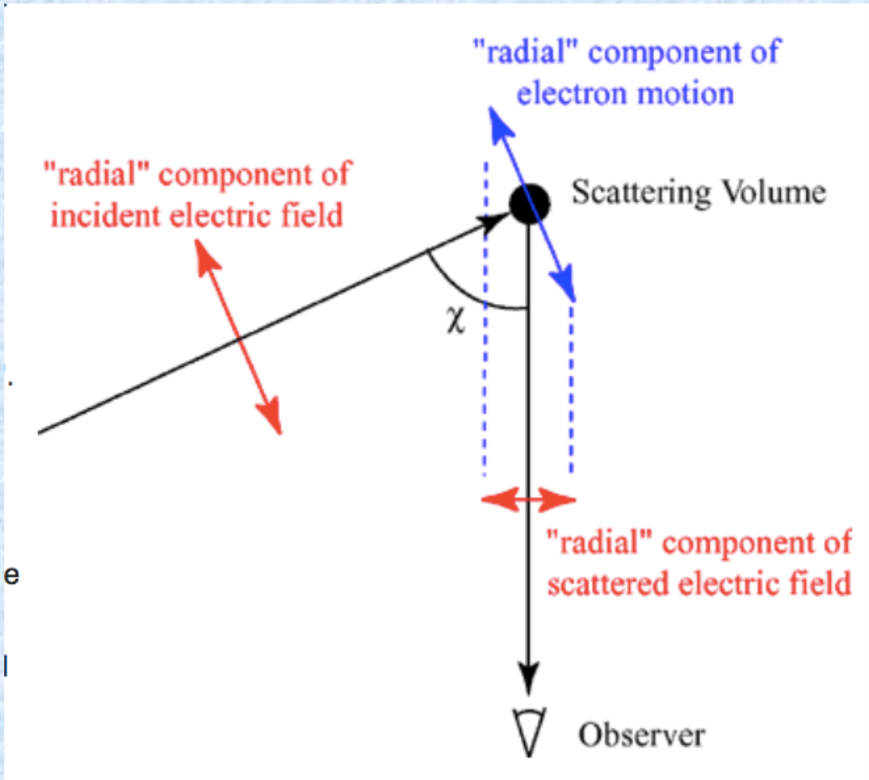


Thompson Scattering

- Photons scatter off free electrons.

- Large cross section for interaction, 6.65e-25 cm^2.

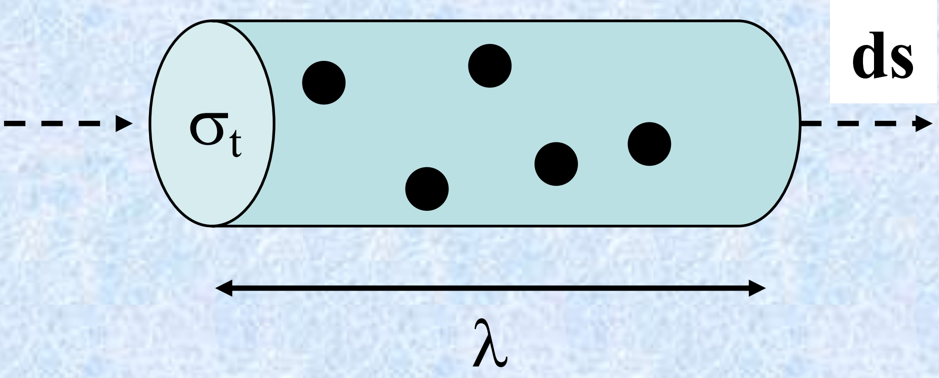
$$\sigma_t = \frac{8\pi}{3}\left(\frac{\alpha\hbar c}{mc^2}\right)^2$$



- Mean free path, $\lambda = 1 / (n_e \sigma_t)$

- Optical depth

$$\tau = \int_0^l \sigma n(z)\, \mathbf{ds}$$



Photon Decoupling

- Photons scatter off free electrons as long as their interaction rate is fast compared to H(t)

- Universe becomes transparent when photons cease to interact with electrons. That happens when their interaction rate is slow compared to the expansion rate.

- The photons decouple soon after recombination because the electron density is dropping rapidly.

[blackboard]

$z \sim 1120$ and $T \sim 3060$ K

- When H(a) >> scattering rate, the gas is more ionized than the Saha equation predicts. The correction gives

$z \sim 1090$ and $T \sim 2970$ K.

Last Scattering Surface

- Probability of scattering in some time interval is

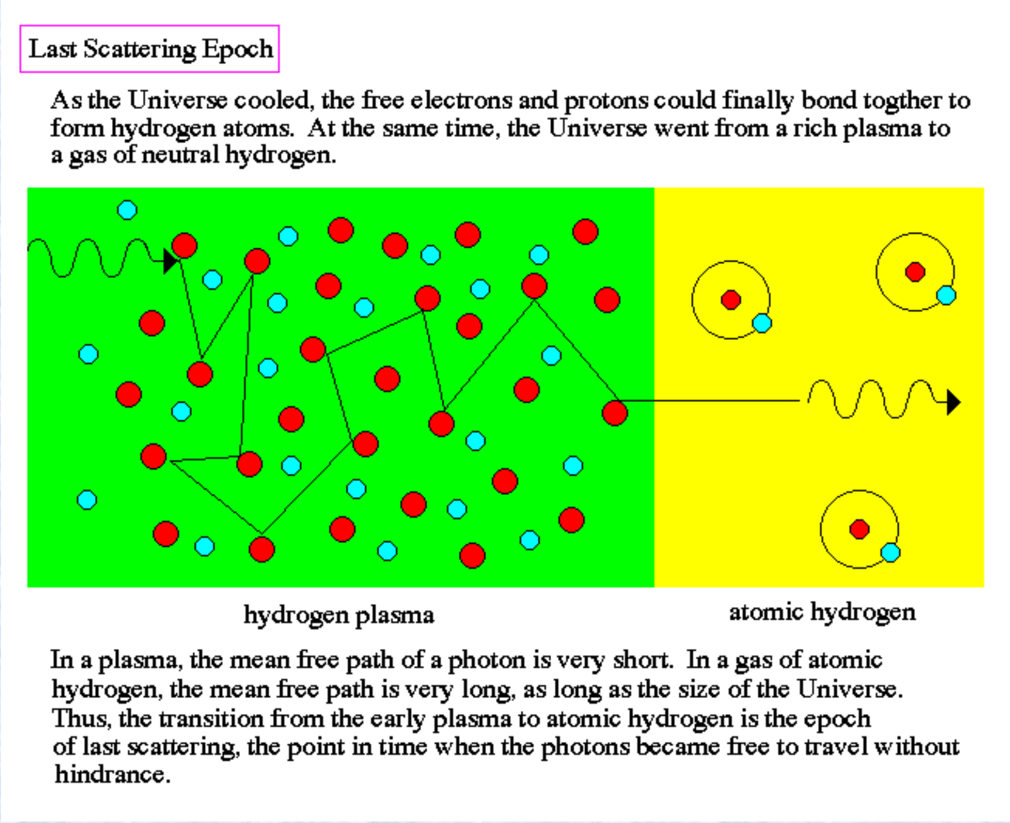
  $$dP = \Gamma \, dt$$

- The optical depth is the total number of scatterings between the time of emission and observation.

- A photon emitted at the time that corresponds to one scattering defines the surface of last scattering.

  [Blackboard]

  $z_{LSS} \sim$ **1000-1200**



Last Scattering Epoch

As the Universe cooled, the free electrons and protons could finally bond togther to form hydrogen atoms. At the same time, the Universe went from a rich plasma to a gas of neutral hydrogen.

In a plasma, the mean free path of a photon is very short. In a gas of atomic hydrogen, the mean free path is very long, as long as the size of the Universe. Thus, the transition from the early plasma to atomic hydrogen is the epoch of last scattering, the point in time when the photons became free to travel without hindrance.

Summary:
Origin of the Microwave Background

- The CMB gives us a view of the universe at z~1100 (last scattering surface)
- This is very close to the epoch of recombination, when nuclei captured electrons to form atoms z~1300
- After photon decoupling, the baryons were no longer kicked around by the photons and they began to collapse under their self-gravity.

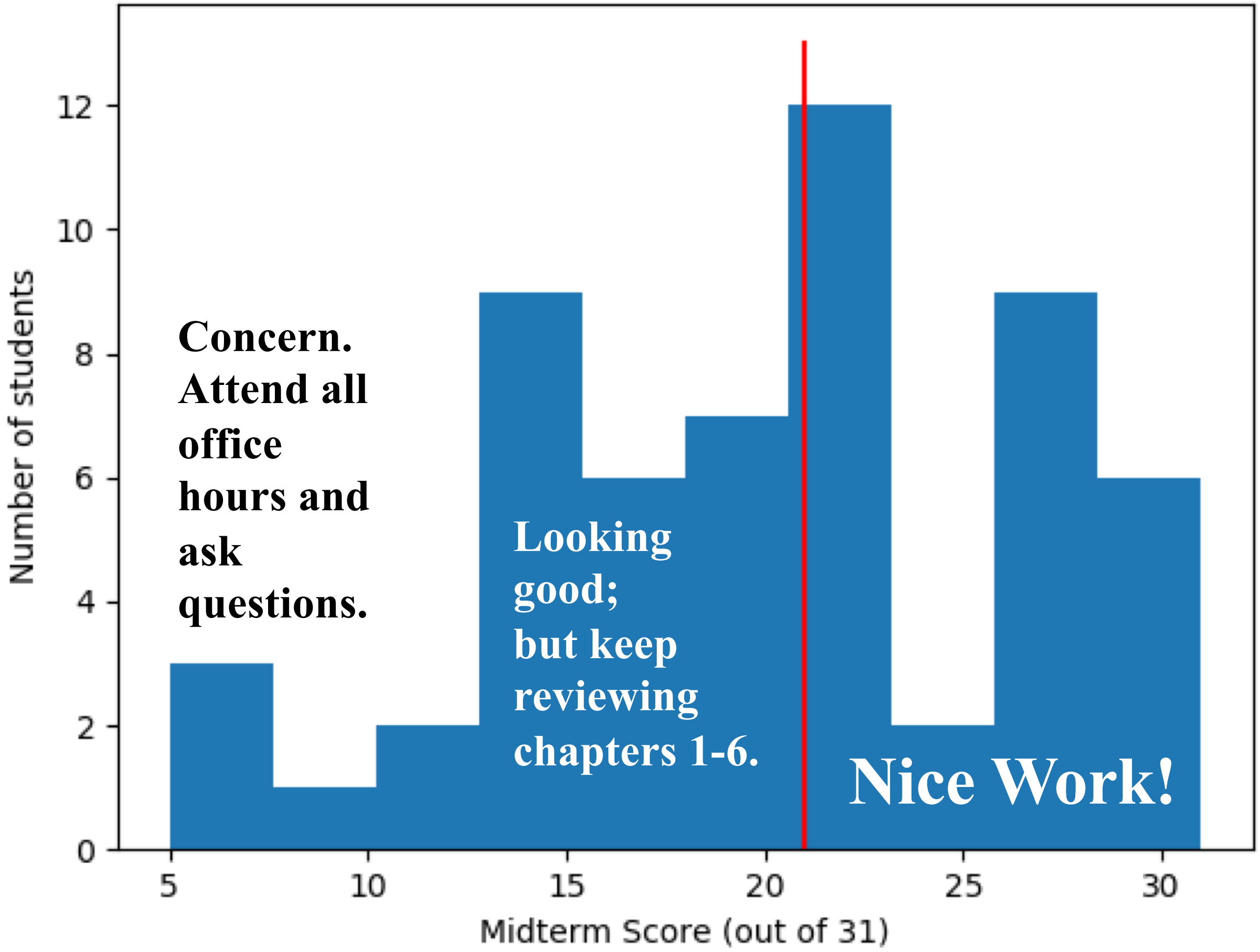
Now let's apply the concepts of thermal, kinetic, and chemical equilibrium can be applied to nuclear fusion reactions at even earlier epoch, the first few minutes. See [R] ch. 9.

Special Office Hours to Review Exam:

Wednesday May 12 (11-1)

Thursday May 13 (11-1, after HW question are answered)

No, we will not post solution keys to exams.



Concern. Attend all office hours and ask questions.

Looking good; but keep reviewing chapters 1-6.

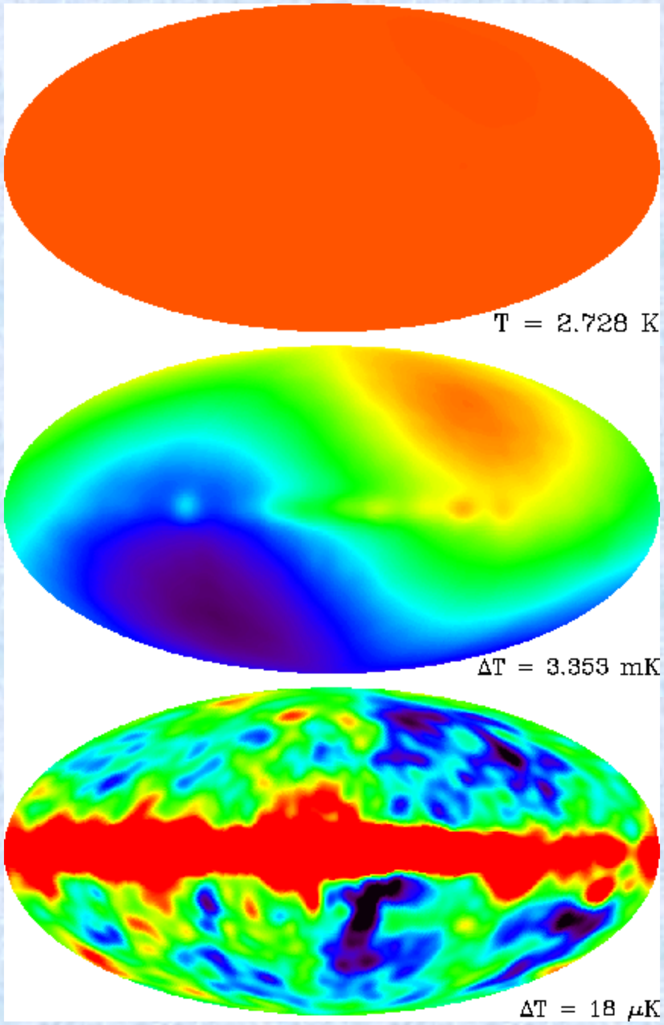
Nice Work!

Review: Observed Properties of Cosmic Microwave Background

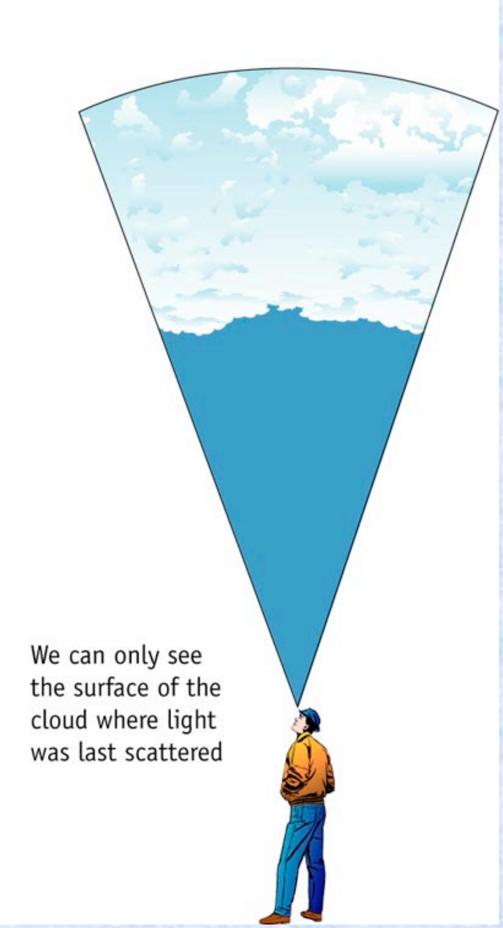
1. Each patch of sky is a blackbody within 1 part in 10,000
2. There is a dipole distortion in the BB temperature corresponding to the motion of the Earth with respect to the CMB
3. There are temperature fluctuations:

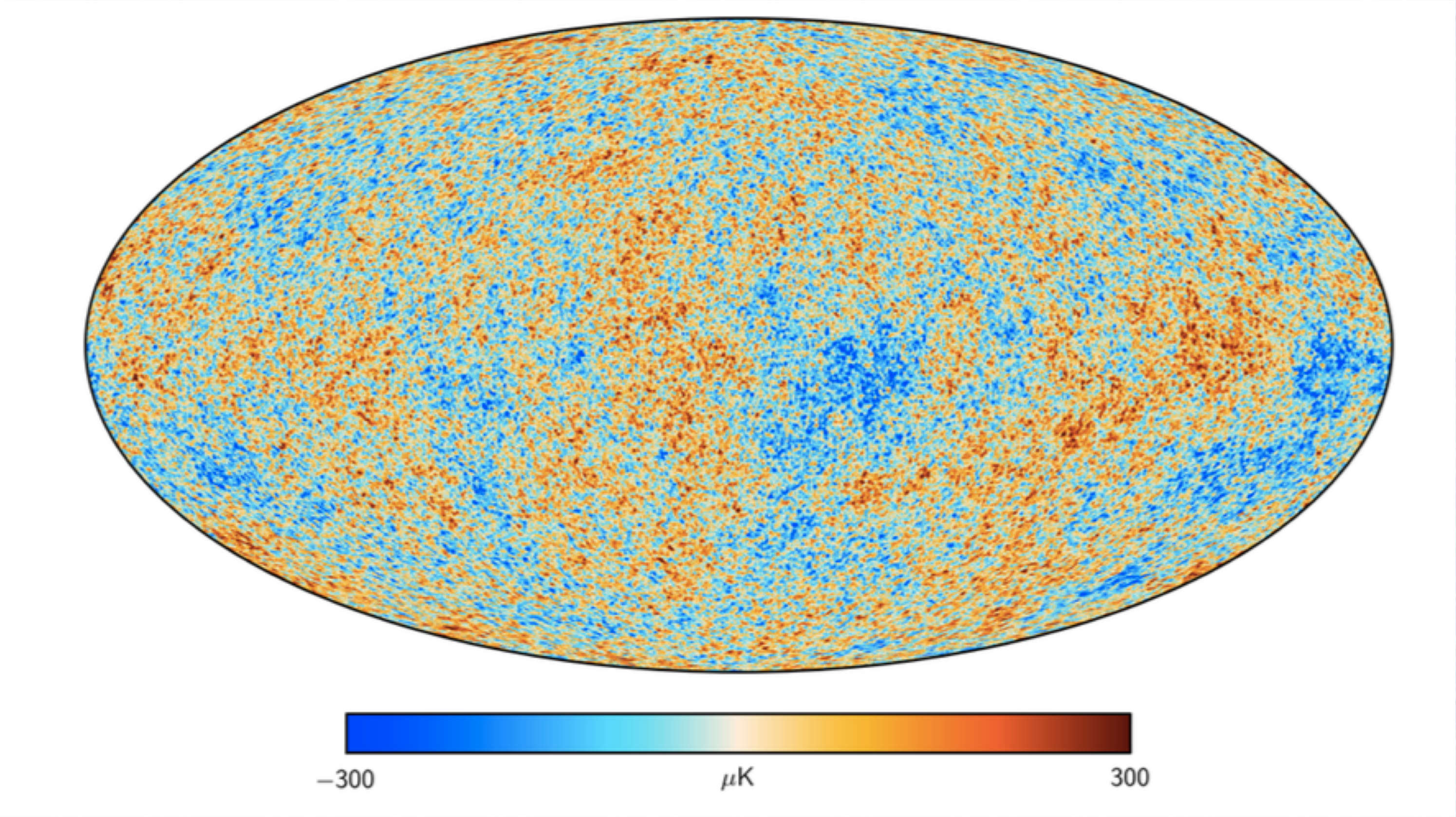
   $<(\delta T/T)^2>^{1/2} = 1.1\text{e-}5$

   - Dust and gas in our Galaxy imprint foregrounds.
   - The interaction of the CMB photons with matter between the surface of last scattering and us causes additional fluctuations (SZ effect, polarization, etc).
   - **We will only discuss the primary fluctuations.**



The Surface of Last Scattering

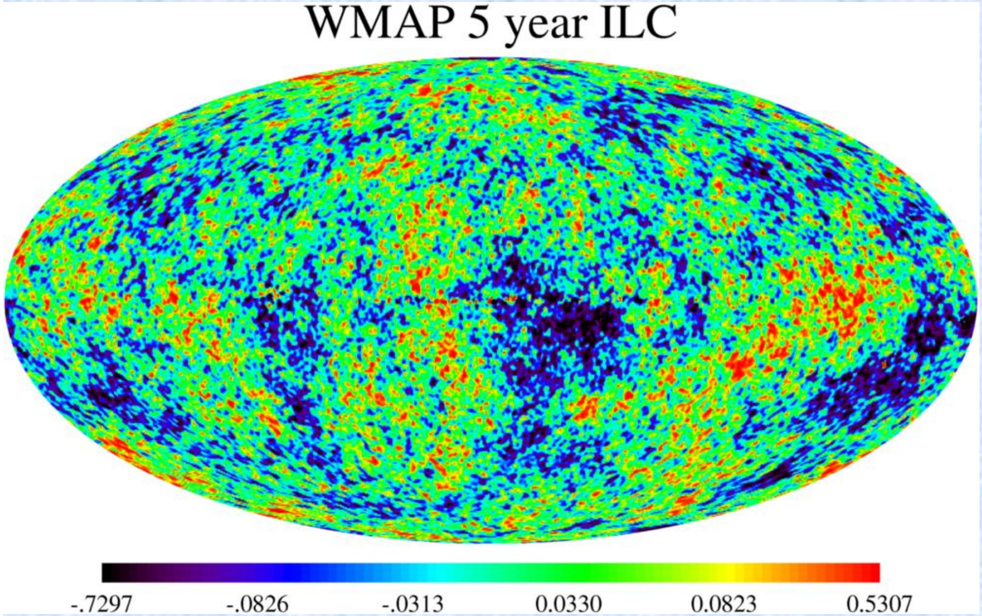


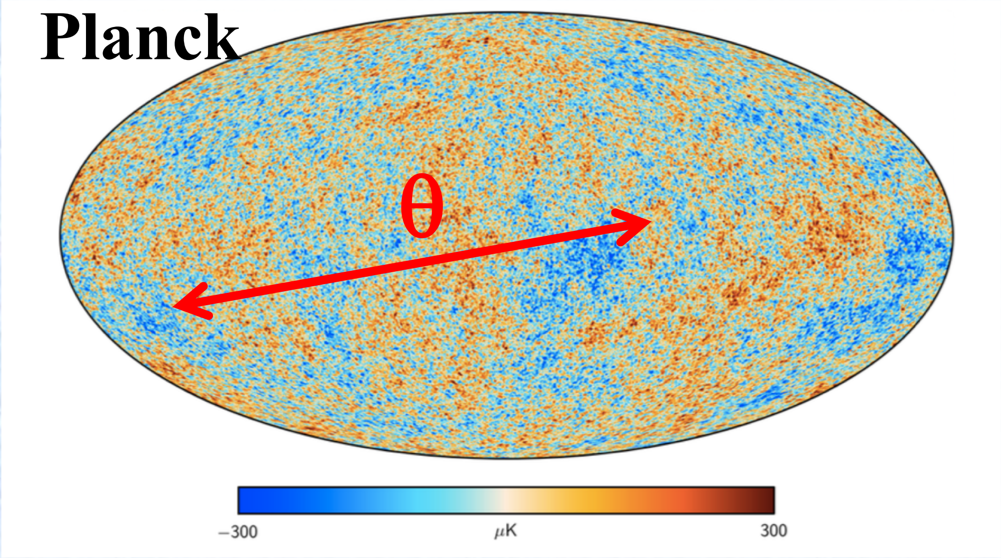


z ~ 1090

t ~ 370,000 years

CMB Temperature Fluctuations





- **Define the temperature fluctuation at each point on the sky:**
- $\delta T(\theta,\phi) / \langle T \rangle = [T(\theta,\phi) - \langle T \rangle] / \langle T \rangle$.

- **Describe the fluctuations with spherical harmonics:**
  $\delta T(\theta,\phi) / \langle T \rangle = \Sigma_l \Sigma_m a_{lm} Y_{lm}(\theta,\phi)$, **where l = [0,inf] and m = [-*l*,*l*]**

- **Average over all pairs of points:**
  $c(\theta) = \langle \delta T(n)/T \; \delta T(n')/T \rangle$

Temperature Fluctuations. Statistical Description

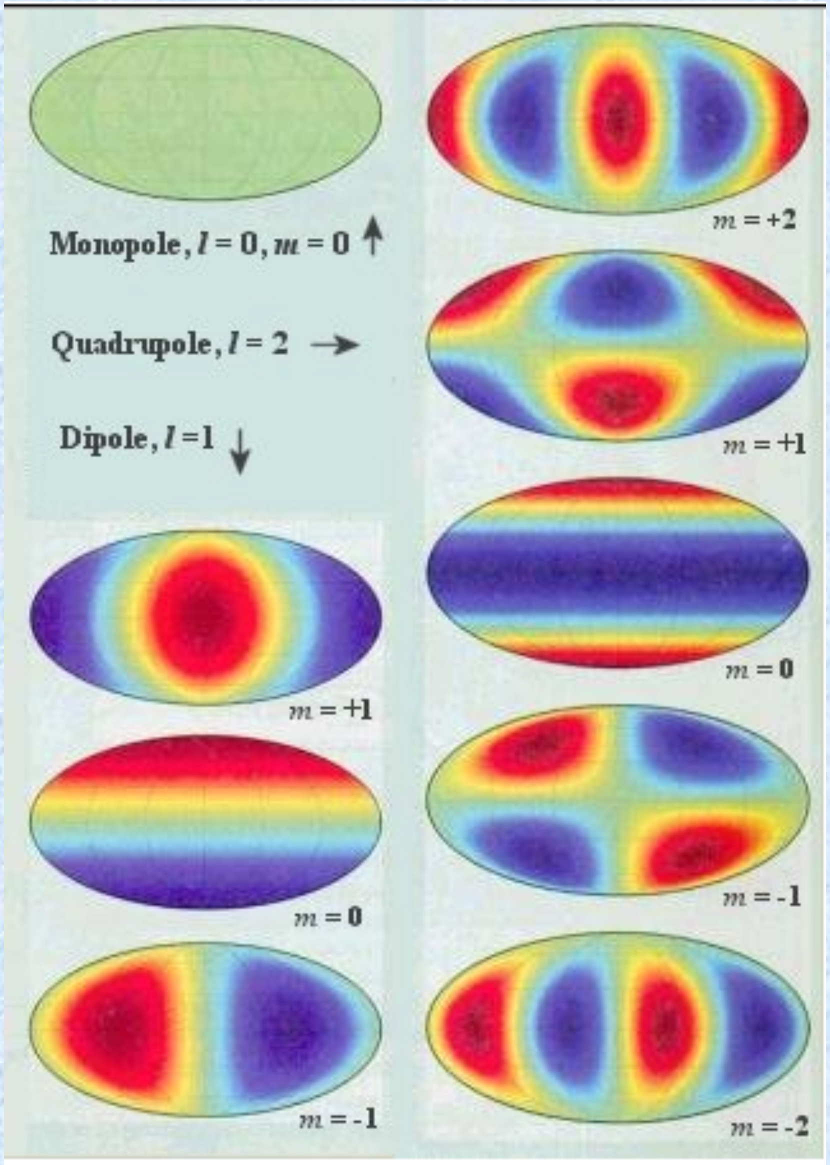
- Correlation function describes pattern statistically on all angular scales:

$$c(\theta) = 1/4\pi\, \Sigma_l\, (2l + 1)\, c_l\, P_l(\cos\theta)$$

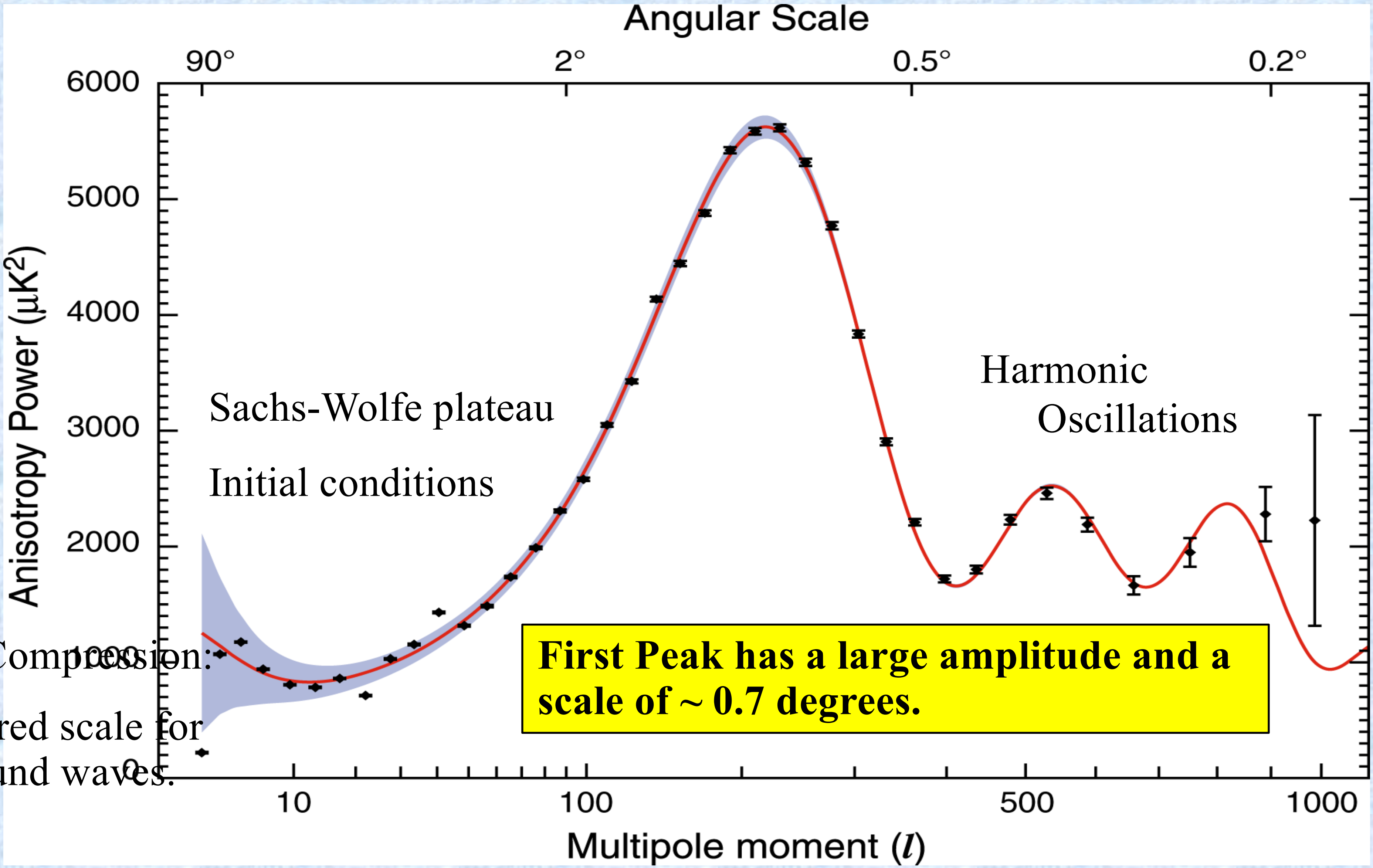
- Plot the contribution to the total temperature fluctuation from each logarithmic interval in *l*.

$$\Delta_T = [l\,(l + 1)\, c_l\, /\, 2\pi]^{1/2} <T>$$

- Angular spectrum of the CMB temperature fluctuations encodes a great deal of information about the universe



Guide to CMB Angular Spectrum



Sachs-Wolfe plateau

Initial conditions

Harmonic
Oscillations

rst Compression:

eferred scale for
sound waves.

First Peak has a large amplitude and a scale of ~ 0.7 degrees.

Origin of CMB Temperature Fluctuations.

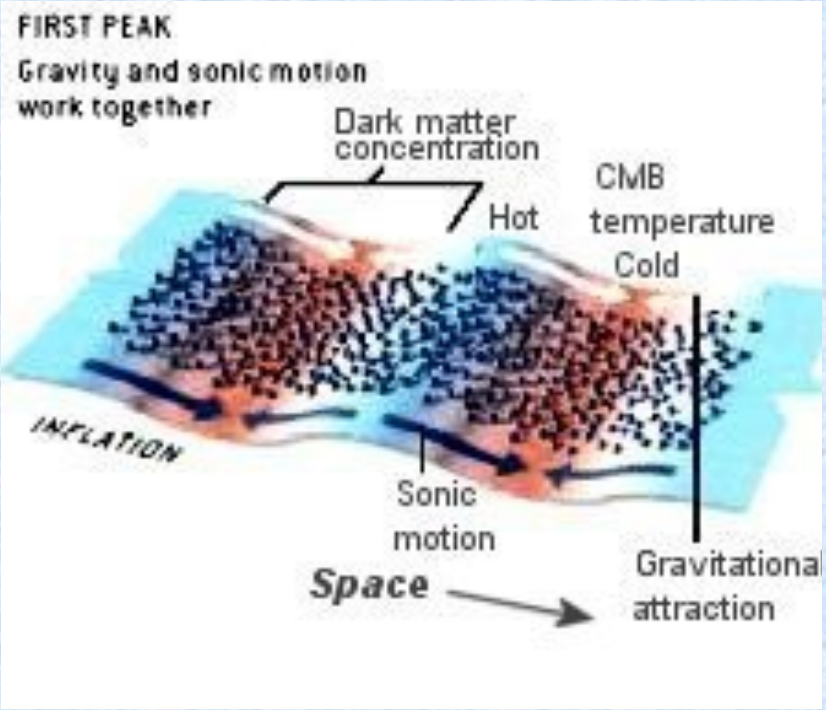
- What is the horizon scale at last scattering?
  - We calculated the Hubble distance $cH^{-1}(t_{LS}) = 0.215$ Mpc.
  - The horizon distance is $2.24\ c\ t_{LS} = 0.251$ Mpc [blackboard].
    - Corresponding to an angular scale **$\theta_H = 1.1^o$ (or $l = 160$).**
  - HW8 (Next Week): Find the *sound* horizon at last scattering.
    - It is only a bit smaller than the horizon because the baryons are pulled around by the photons prior to baryon-photon decoupling.

- **Large Scales $\theta > \theta_H \sim 1^o$**
  - These disturbances are not in causal contact.
  - Gravity rules.

- **Small Scales $\theta < \theta_H \sim 1^o$**
  - The baryons resist compression.
  - Generates sound waves.
  - We call these standing waves *acoustic oscillations*.

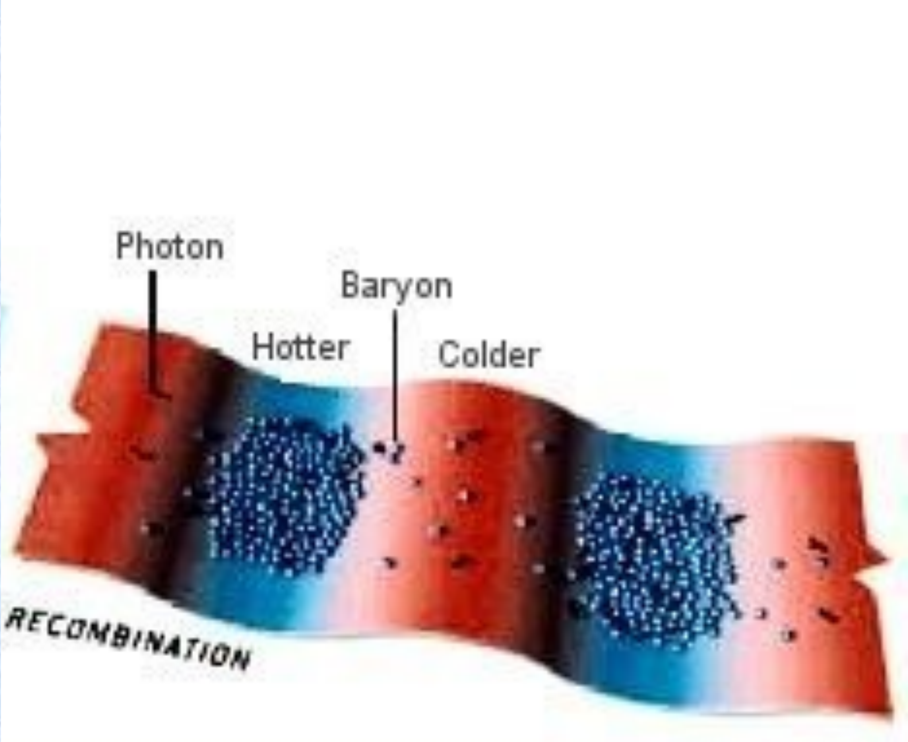
Origin of Temperature Fluctuations.
Large Scales $\theta > \theta_H \sim 1^o$

- Nonbaryonic dark matter dominates the gravitational potential at Last Scattering
- On large scales the photon-baryon fluid is falling into these potential wells for the first time
- The gravitational redshift ocurring on the surface of last scattering makes hot and cold spots.



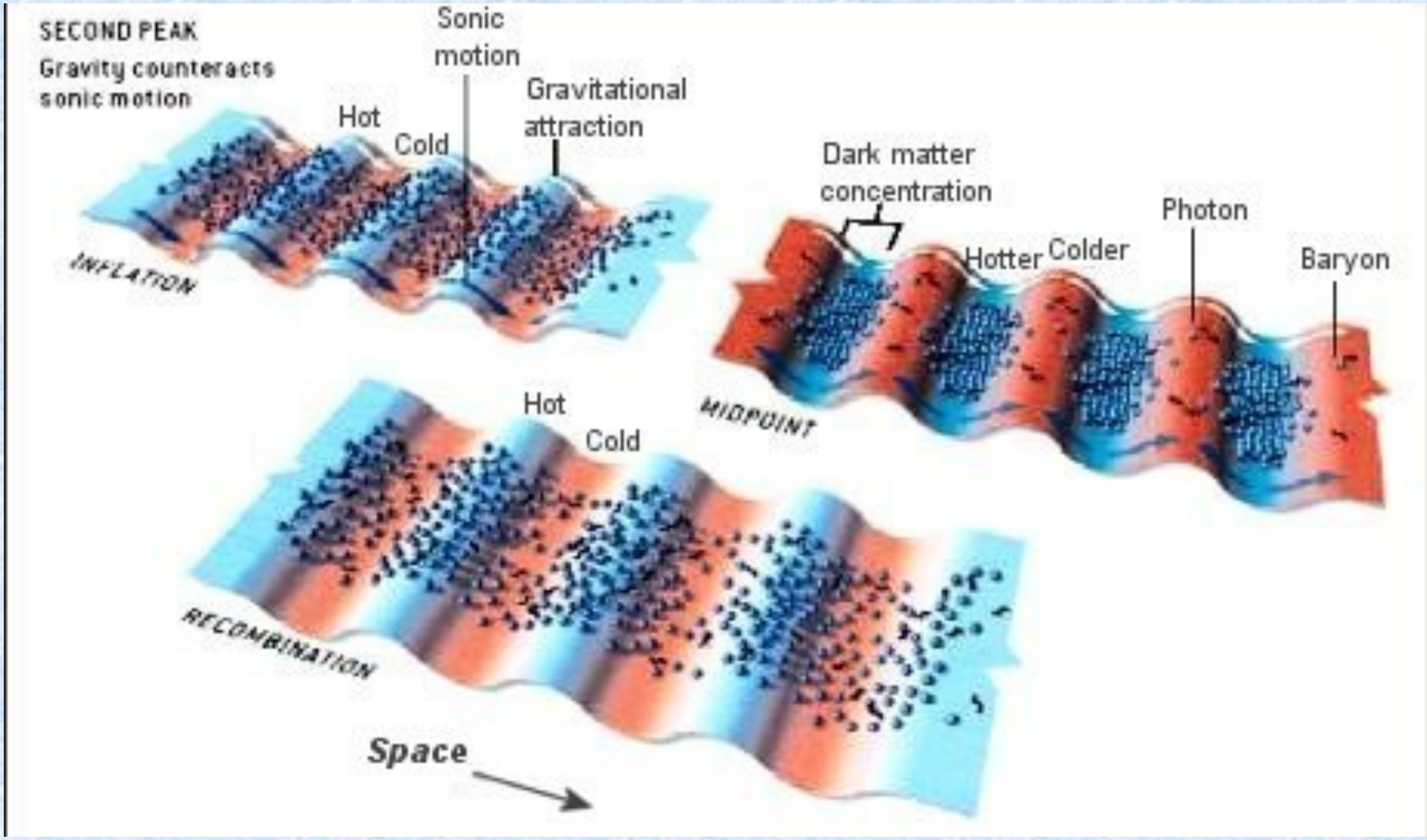
Origin of Temperature Fluctuations. Small Scales $\theta < \theta_H \sim 1^o$

- **Compression of the photon-baryon fluid in a potential minimum heats the fluid.**
- **The increase in pressure eventually reverses the direction of the flow. Expansion cools the fluid down.**
- **These standing sound waves are called acoustic oscillations**
- **The main peak is the mode that had gone through exactly 1/4th of an oscillation at the time of last scattering**



Even Smaller Scales

- When gravity and sonic motion oppose each other a smaller 2nd peak is created.
- Temperature fluctuations are damped on scales smaller than the thickness of the last scattering surface



Sensitivity of Acoustic Peaks to Cosmological Parameters

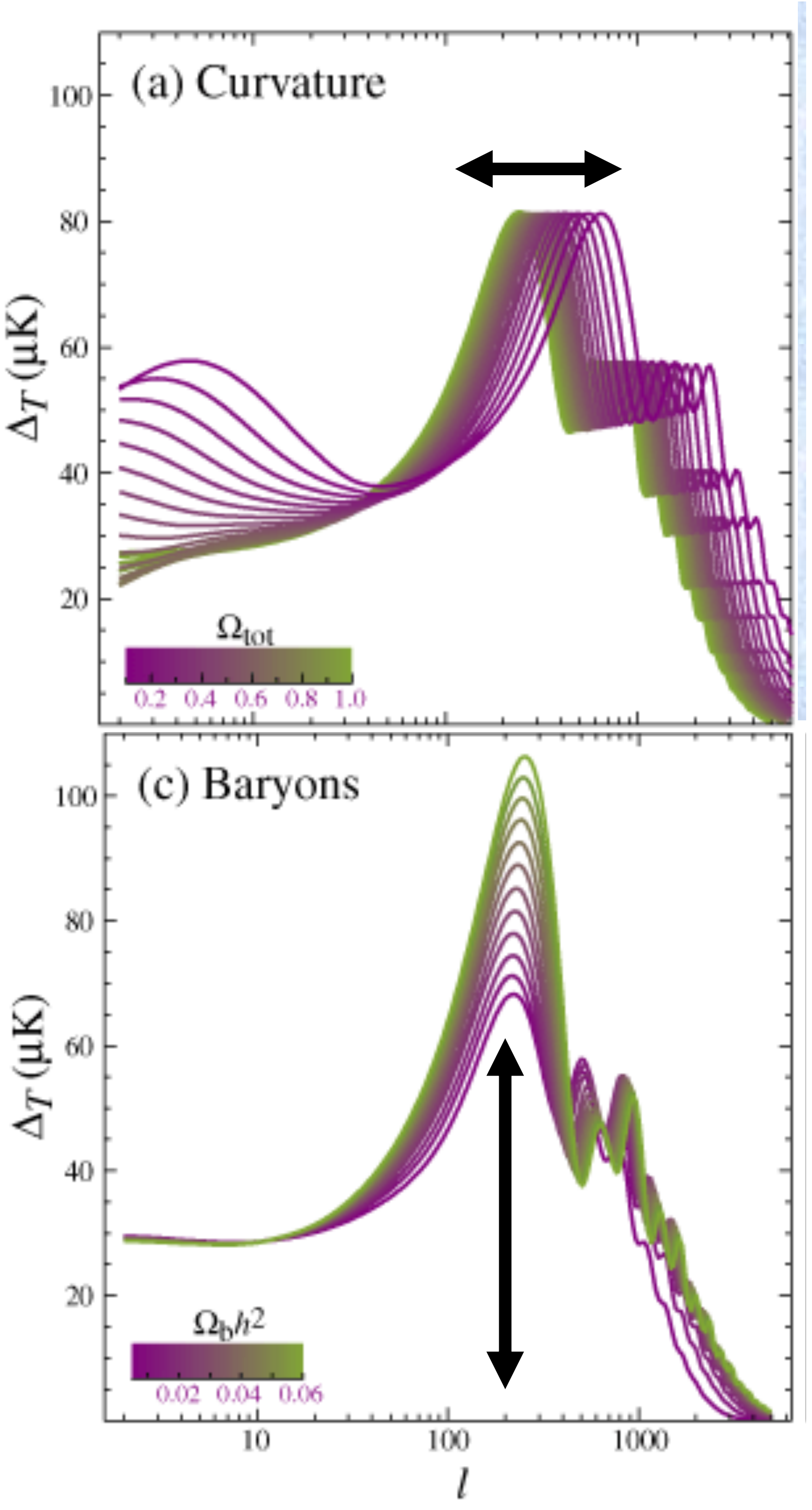
- The angular size of the first peak is sensitive to Ω_{tot}.

- This angular scale measures curvature of the universe.

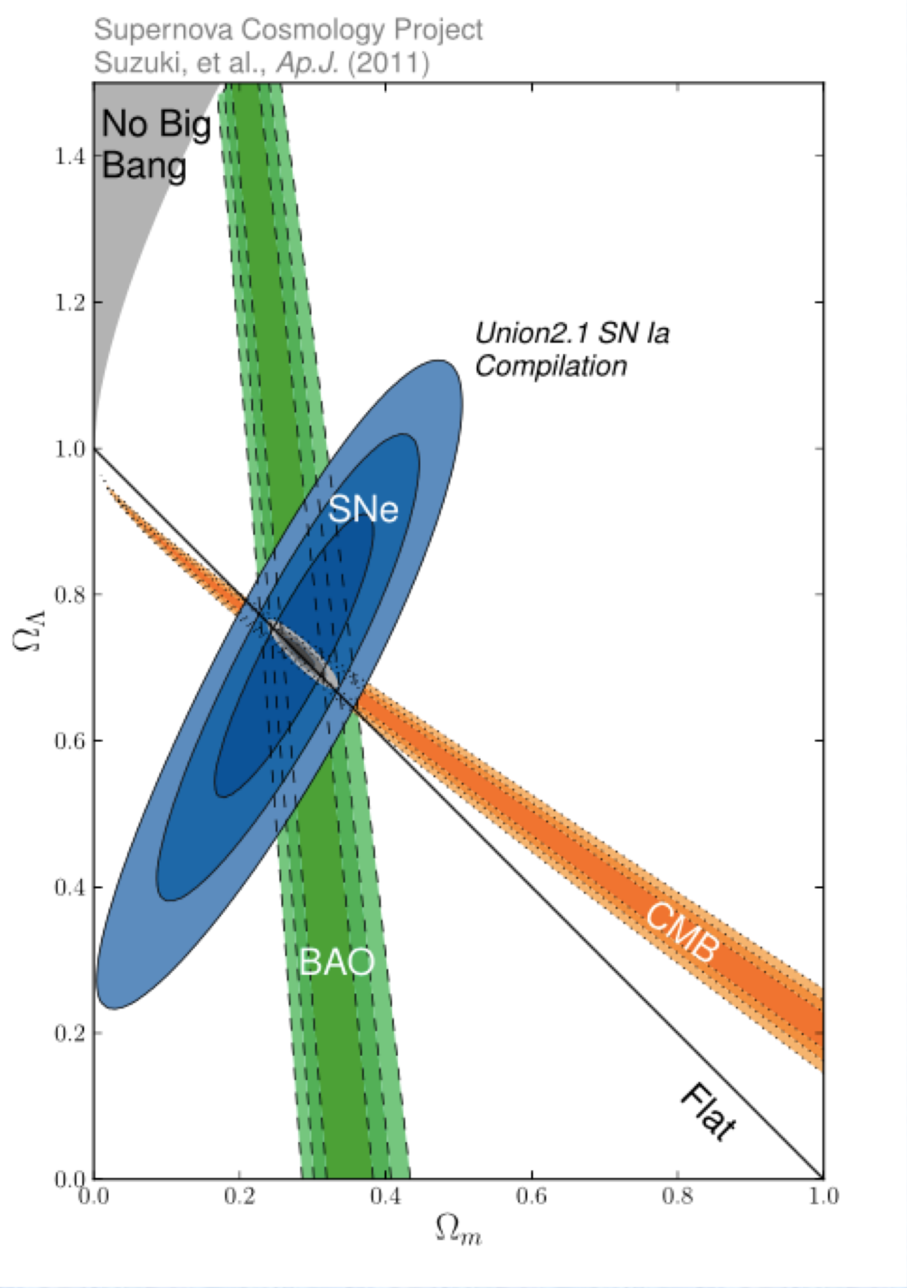
- The result is that $|1 - \Omega_{tot,0}| < 0.2$.

- The amplitude of the first peak is sensitive to the baryon density.

- The result is that $\Omega_b = 0.04$ (0.02) for $H_0 = 70$ km/s/Mpc.



Summary of Cosmological Parameters



Cosmic (or Big Bang) Nucleosynthesis

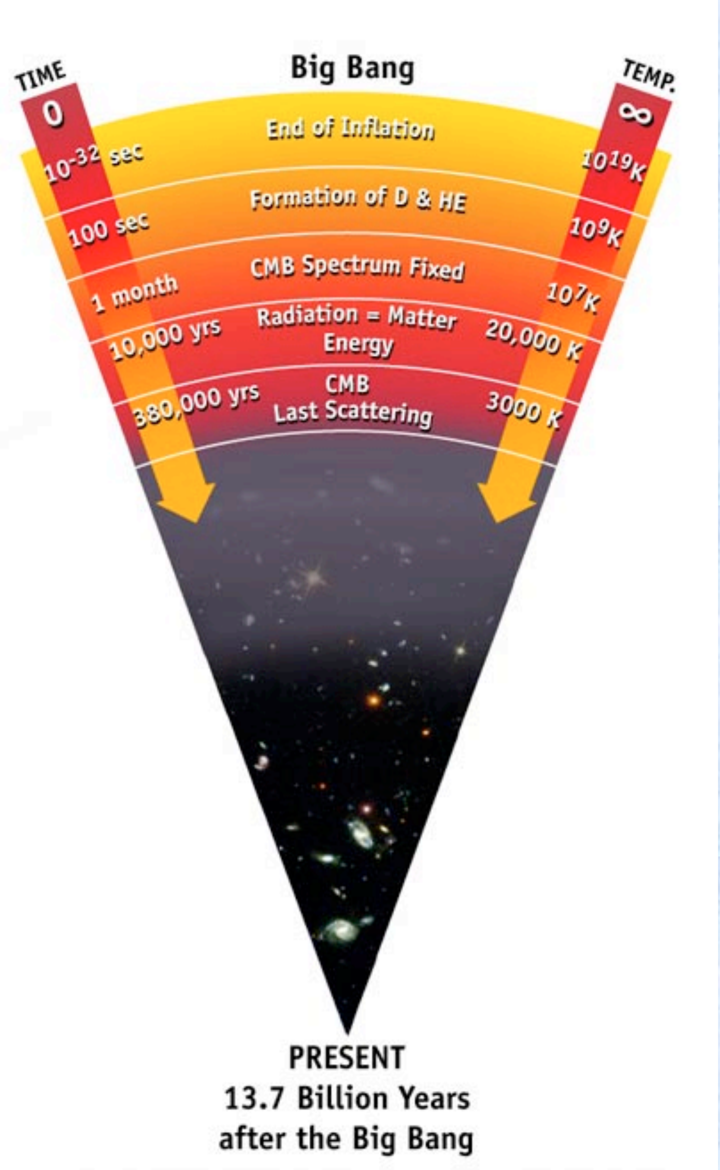
An independent measurement of Ω_b

The First Few Minutes

- Nuclear binding energies are on the scale of MeV. Was the universe ever this hot?
  - Well 3 kT ≈ 1 MeV when T ≈ few X 10^9 K.
  - Remember T = 3 K (1 + z)?
  - So z (nuclear Rx) ≈ 10^9!
  - How old was the universe then?

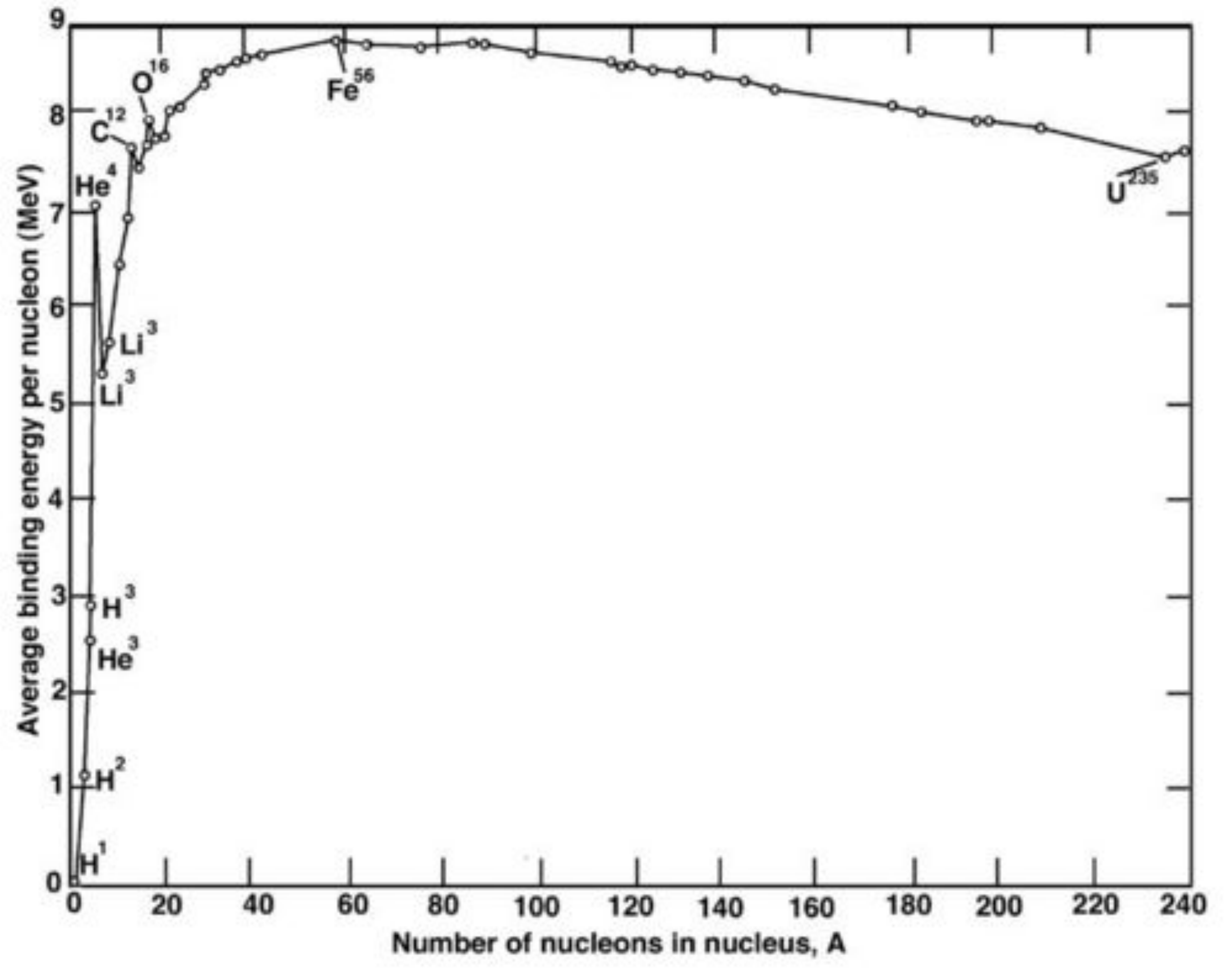
- What component dominated the dynamics?
  - At t << 47,000 yr, scale factor $a \propto t^{1/2}$
  - $T(t) \sim 10^{10}$ K $(t/1\ s)^{-1/2}$
  - Hot enough for nuclear reactions at an age of a few seconds.
  - *Let's discuss what nuclei formed.*

- Note: At t~1ps, TeV scales (LHC)!



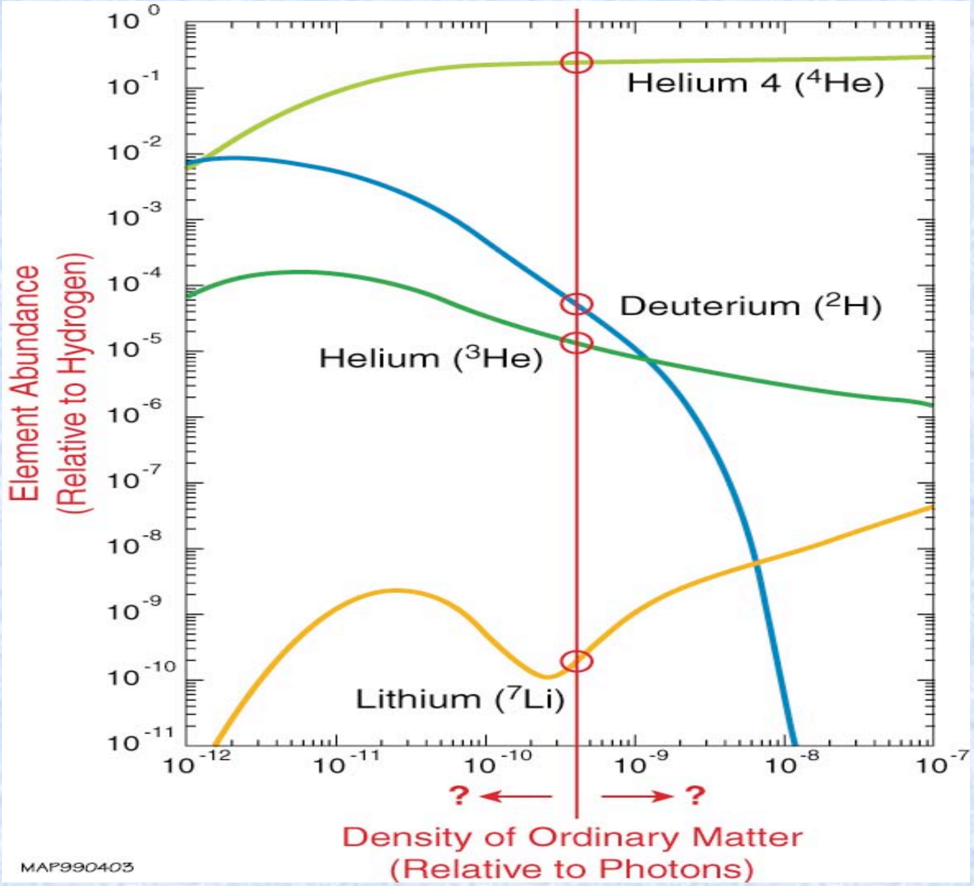
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.

Basics of Nuclear fusion/fission



Baryon-to-photon ratio, η, is the critical parameter

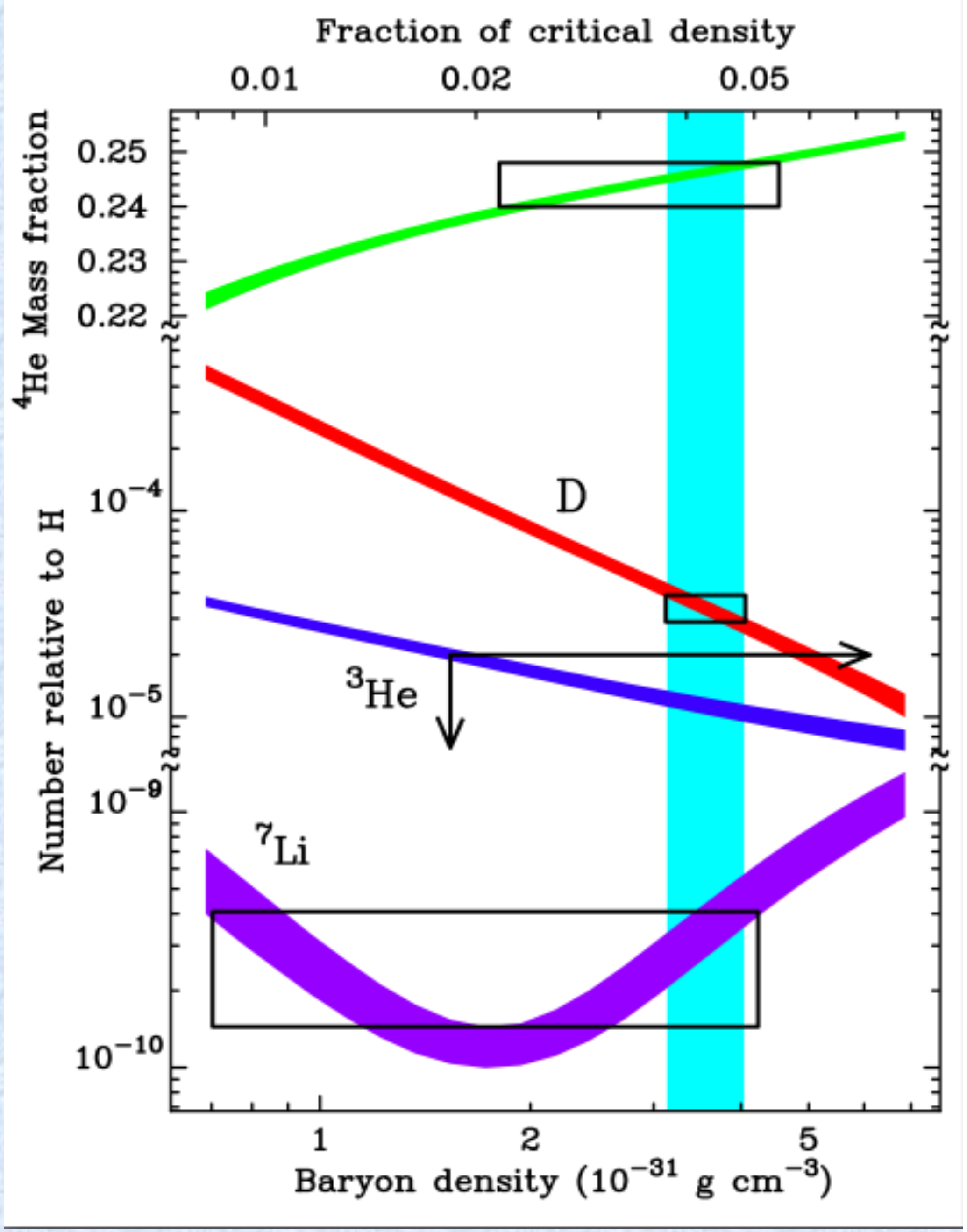
- The yield is dominated by η (remember recombination?)
- High η starts BBN early and is more efficient at producing He
- So there are fewer leftovers..
- Li is more complicated since there are competing channels



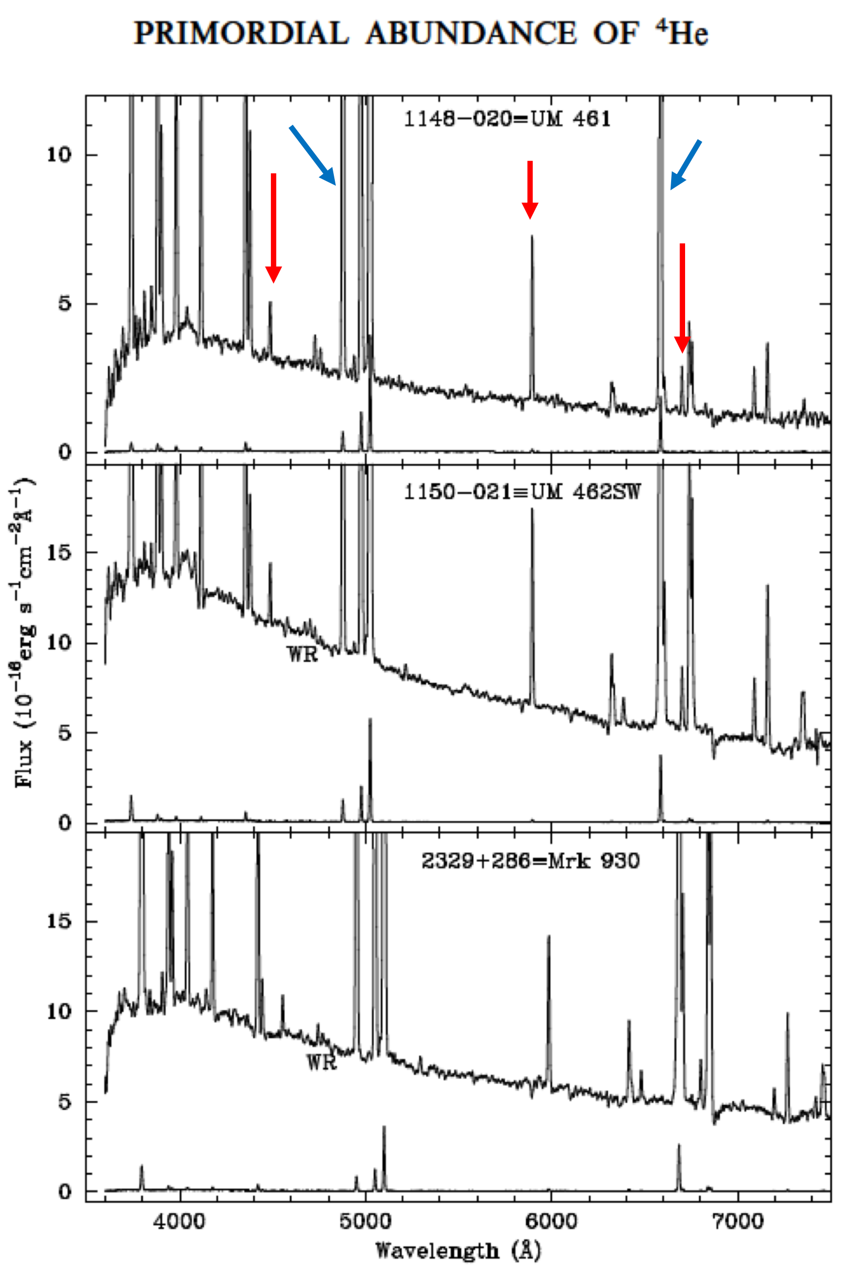
Composition of the Universe

- If we measure the abundance of light elements, we infer η.
- We measure D/H for example and obtain

  η = 5.5±0.5e-10
- We know T(CMB), so we obtain n(baryons)!

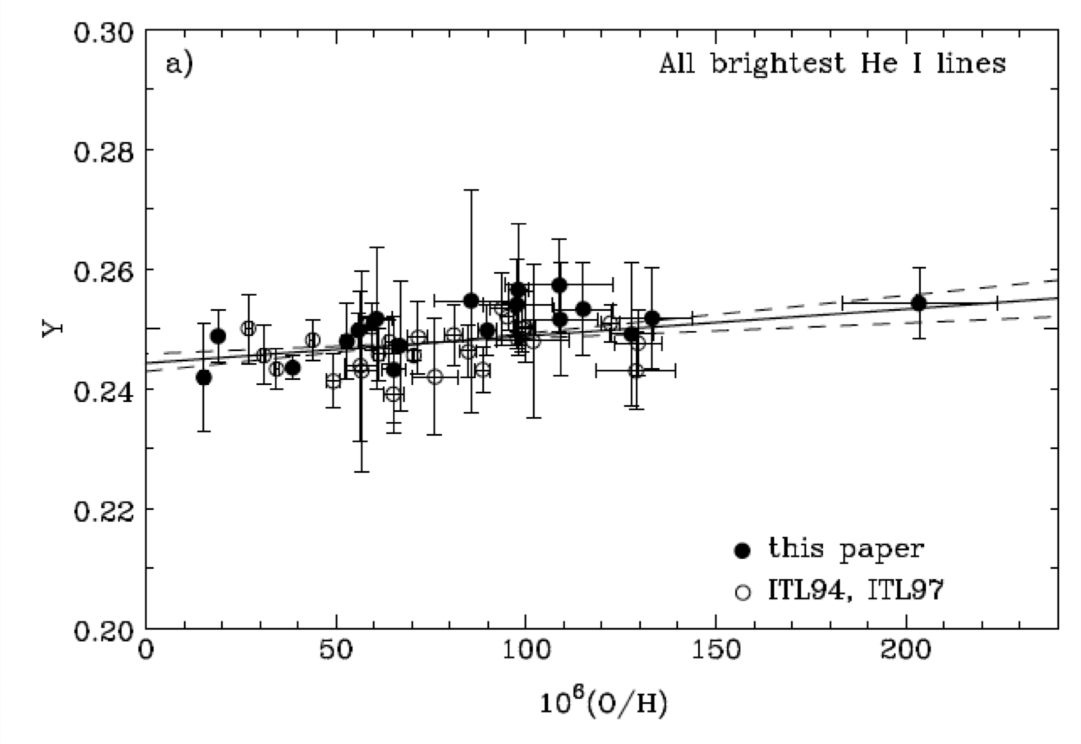


How Is the He Abundance Measured?


PRIMORDIAL ABUNDANCE OF ^{4}He

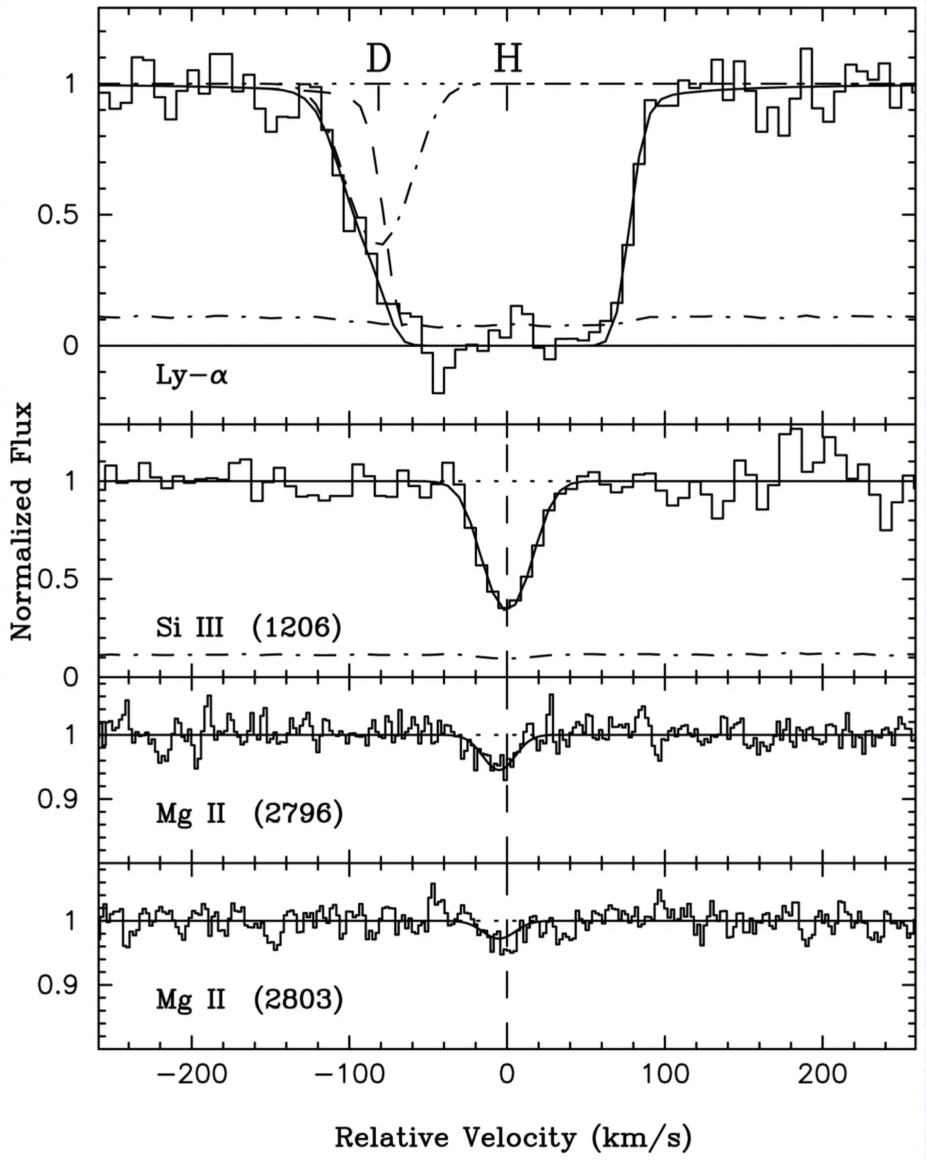
- Measure He mass fraction from **He** and **H** emission lines in spectra of young galaxies.
- Wait! But don't the stars in these galaxies produce the He we see?
  - ➢ Production of He in stars increases Y with time; estimate in **HW 7** [9.3].

He mass fraction



How do we measure D/H?

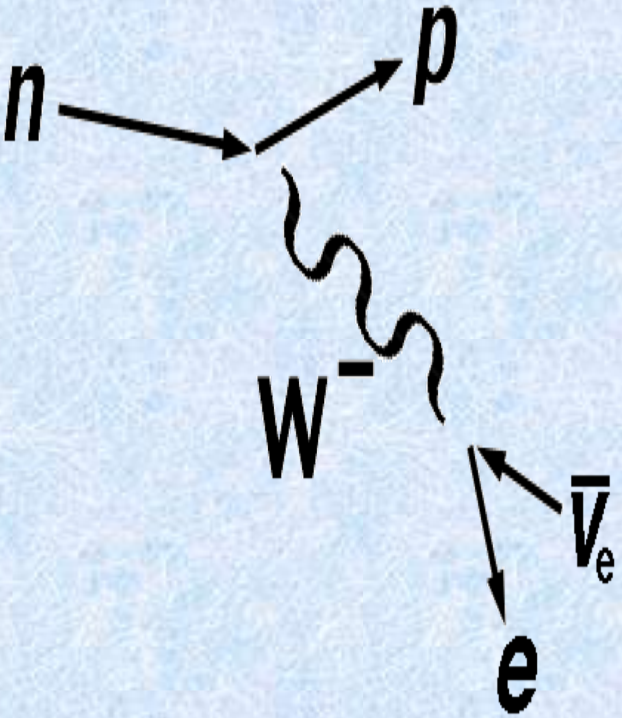
- Stars burn D.
- The gas in the interstellar medium has been cycled through stars.
- Where can we find nearly primordial gas?
- Intergalactic Space



Quasar Spectrum showing intervening absorption (Tytler 2001)

Statistical Equilibrium

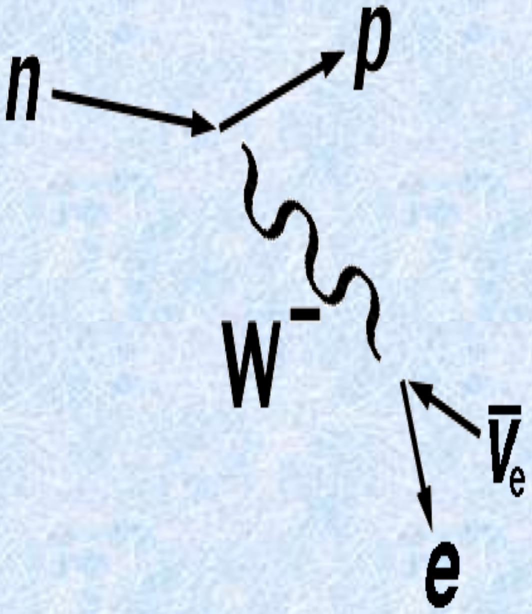
- Neutrons decay on a timescale of **890 s**.
- At very early times reaction is in equilibrium (<<1s) [enough e- e+]
- Relative abundances given by kinetic equilibrium:
  - **$N(n)/N(p)=(m_n/m_p)^{3/2} g_n/g_p \exp(-Q/kT)$**
  - High T favors neutrons
  - Expansion/Cooling removes the neutrons
- Mass difference ➔ Q = 1.29 MeV
  - What temperature is this?



…but then

- Cross section for weak interactions decays very rapidly with temperature
- Eventually interaction rate drops below expansion rate:
  - FREEZE OUT!
- Freeze at t=1 sec when T=9e9 K and n/p ~ 2/10
- **What's the maximum He mass fraction possible?**

  [blackboard]

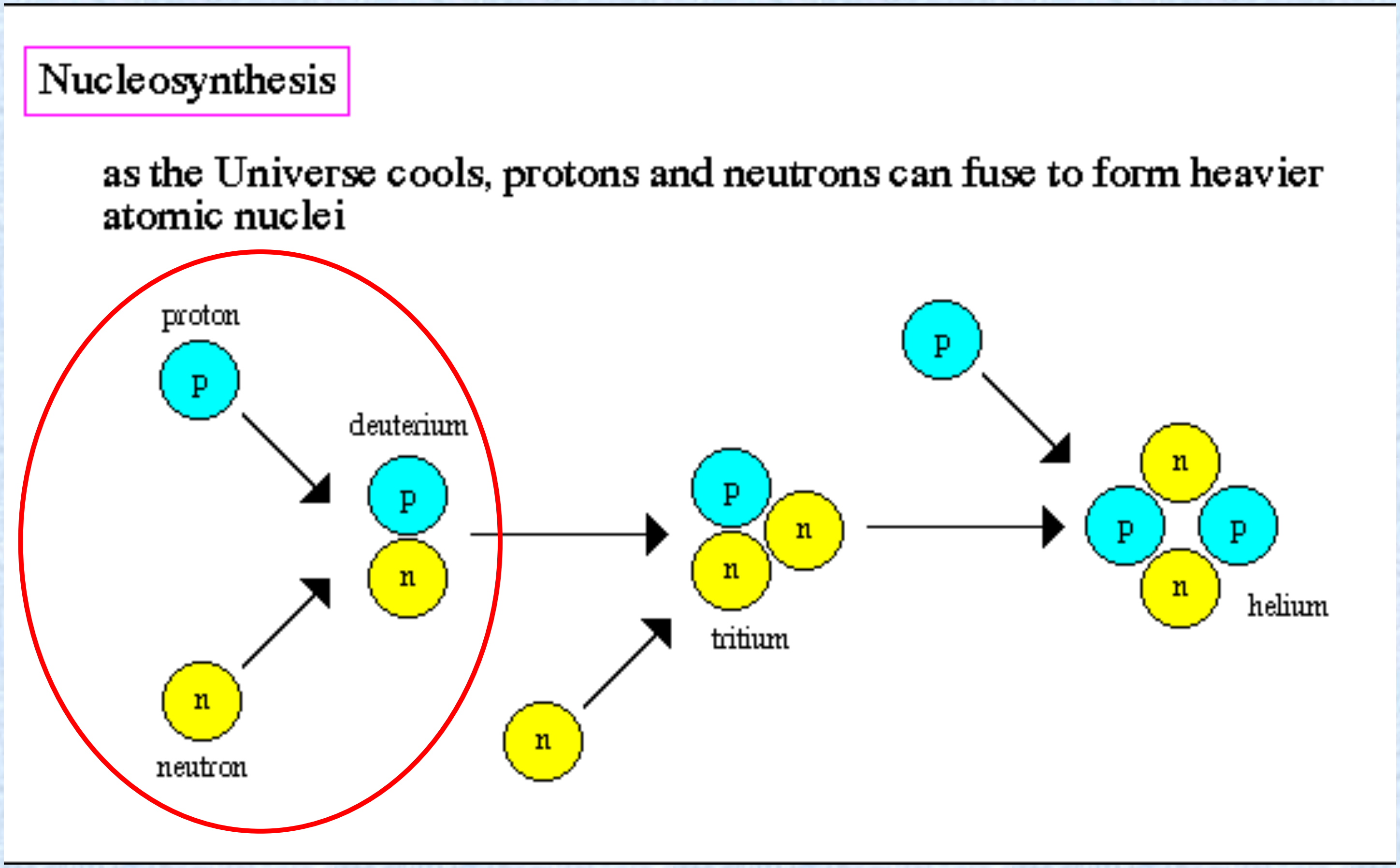


- Why is this a maximum?
  - Free neutrons are not stable.

HW 7 [R 9.1] – what happens to Y if the decay time is shorter?

After neutron freeze out

- Why don’t protons fuse with protons directly?
- Most remaining neutrons get captured by p forming deuterium.
    - Note similarity to photoionization; get analog to Saha equation. [Blackboard]

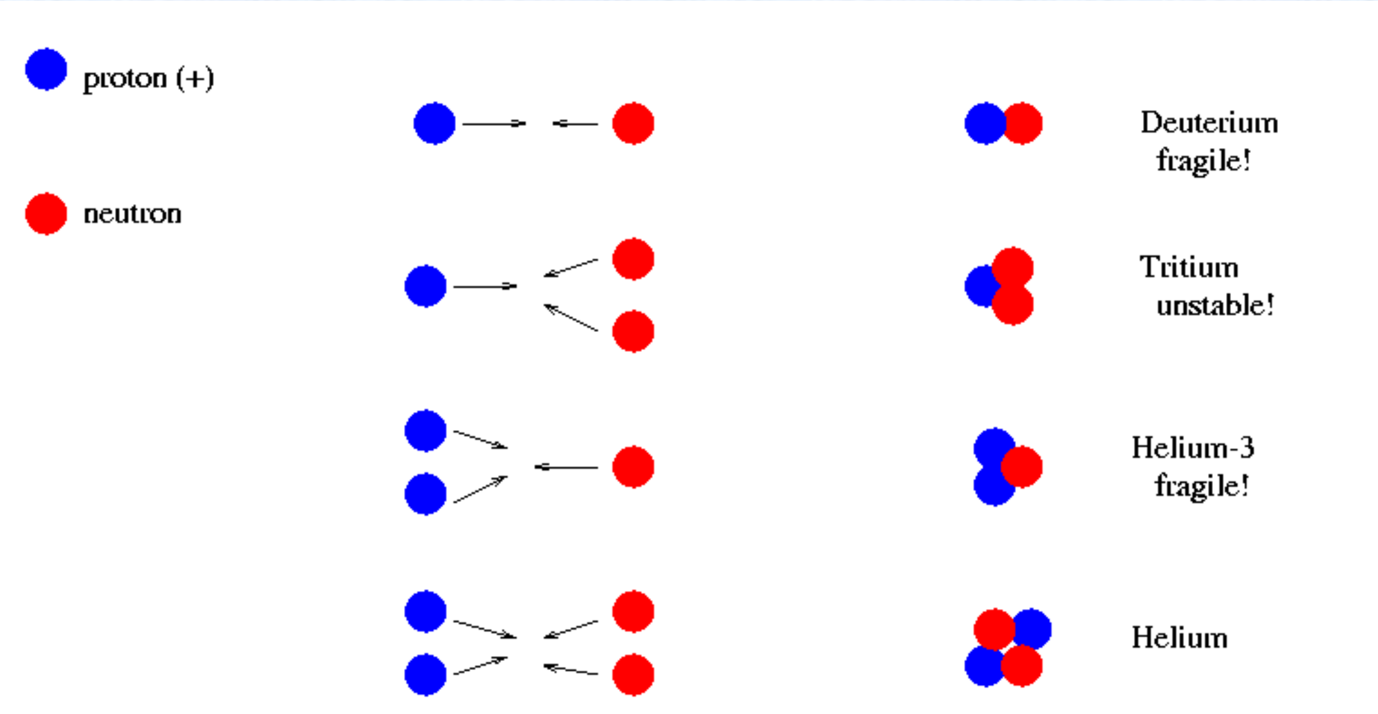


Nucleosynthesis

as the Universe cools, protons and neutrons can fuse to form heavier atomic nuclei

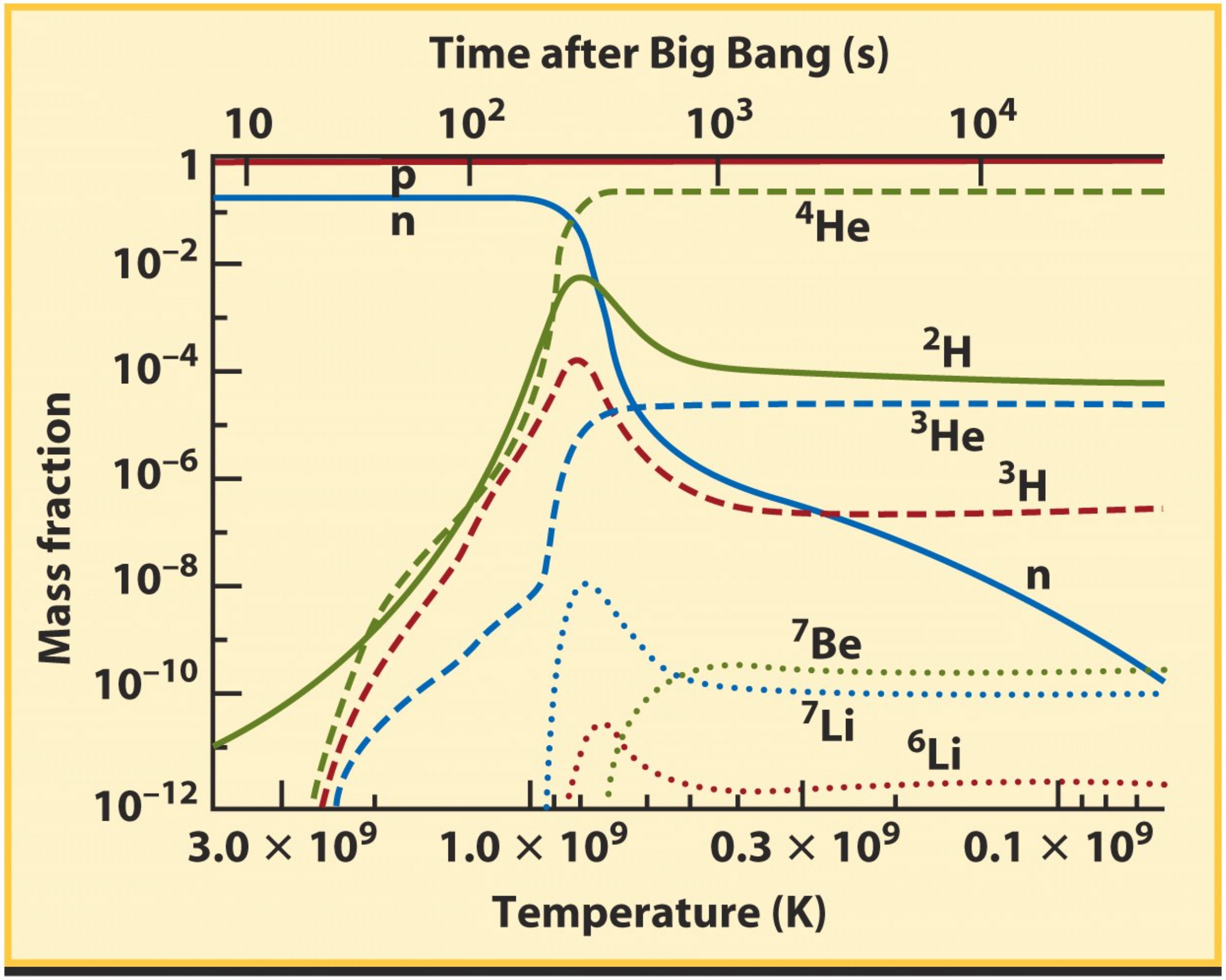
Primordial Nucleosynthesis

- Maximum number of non-H nuclei is set by abundance of n at freeze-out and their decay.
  - Time delay until start of nucleosynthesis when T=8e8K and $n_D=n_n$.
  - Additional neutron decays reduce n/p ratio from 0.2 to 0.15.
- Most of the non-H nuclei end up as He because it's the most stable nucleus



Final outcome

- Nuclear reactions last as long as the expanding universe supports them (rate > expansion rate)
- By ~5min everything is over!



Summary: Nucleosynthesis

- Theory of big bang nucleosynthesis predicts the abundance ratios of light elements remarkably well.
- So well that it can be used to measure baryon abundance.
  - By the way: this is another piece of evidence for non-baryonic dark matter
- The dominance of matter over antimatter is explained in the standard model by a tiny violation of symmetry
  - The expansion of the universe takes the system out of thermodynamic equilibrium, and that likely breaks the symmetry.