Principles of Astrophysics and Cosmology

Welcome Back to PHYS 3368

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June 24, 1915 - August 20, 2001

Announcements

- Reading Assignments: Chapter 9.
- Problem Set 12 is due by 4 pm on Tuesday, May 5th. You may turn your problem set into Lacey Porter in the main office during regular business hours. She will provide you a copy of the solutions.
- The final exam in this course will be on Wednesday, May 6th from 6:30 - 8:00 pm. It will cover the second half of the course. Open book, open note — NO LAPTOPS, NO PHONES, NO INTERNET ENABLE-ABLE DEVICES!!!

Today's Lecture

- How and why is the CMB so isotropic?
- How were elements formed?
- What other probes of cosmology exist?

Last Time: Acoustic Oscillations in the early Universe

- Inhomogeneities in the nearly uniform cosmic mass distribution exist at the end of the inflationary era.
- The mass density is mostly dark matter, mixed with a relativistic baryon gas and matter.
- Attraction via gravity and repulsion via gas pressure result in a compression and expansion of sound waves.
- These oscillations are in phase when the Universe emerges from the inflationary period.
- At the time of recombination, baryons and photons decouple.
- The impressions of cool (rarified) and hot (compressed) regions are left imprinted on the sky.

Recall the relation between wavelength, frequency and period.

$$\lambda = c_s \nu = \frac{c_s}{\tau}$$

c_s ← speed of sound

τ ← period of the mode

The equation of state for early universe (rad. dominated)

$$P = \frac{1}{3}\rho c^2$$

The speed of sound is then just

$$c_s = \sqrt{\frac{dP}{d\rho}} = \frac{c}{\sqrt{3}}$$

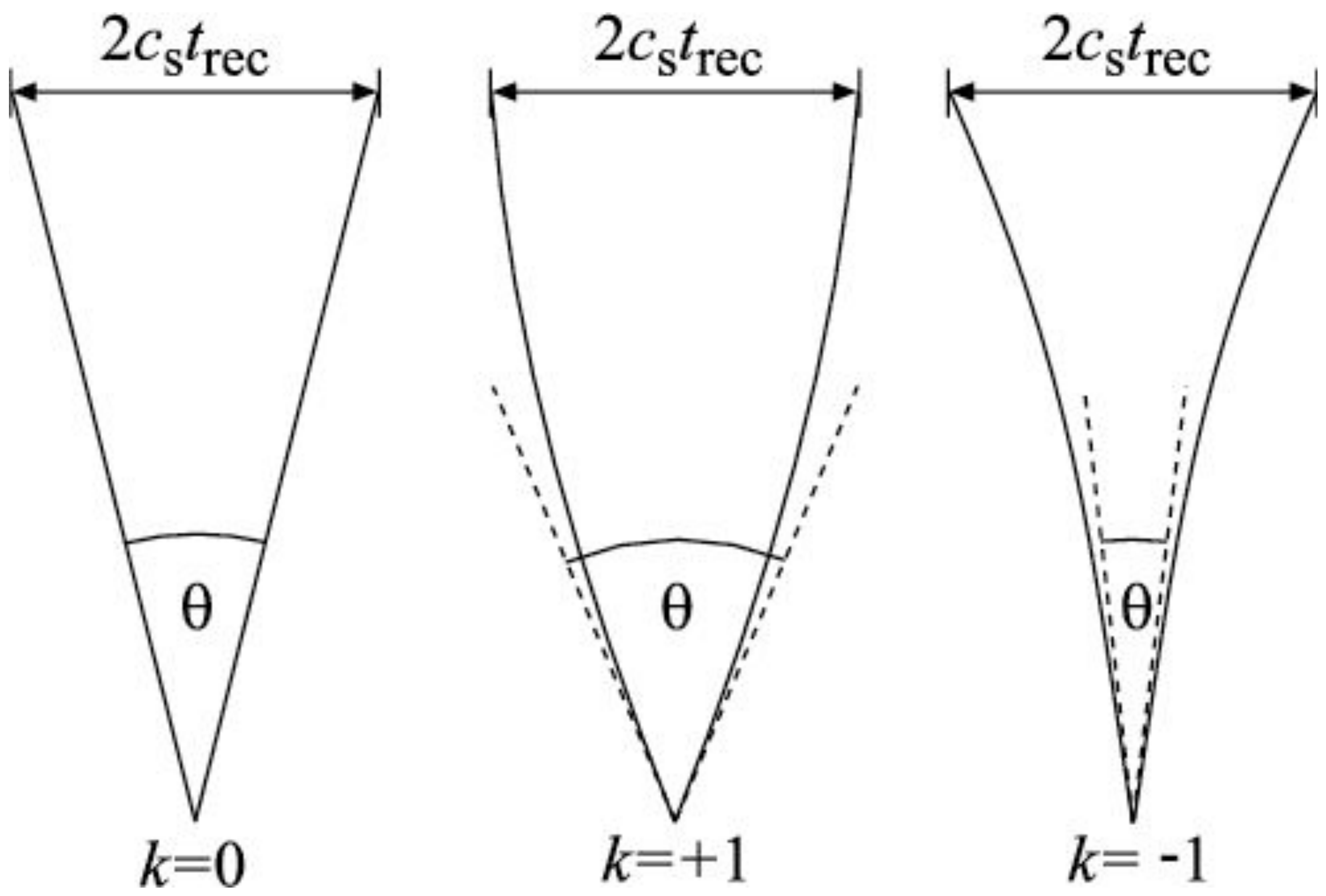
At recombination, the fluctuations will be largest. So, $\tau = t_{rec}/2$.

$$\lambda = \frac{c_s}{\tau} = 2 c_s t_{rec} = \frac{2 c t_{rec}}{\sqrt{3}}$$

← "ruler" size of fluctuations in CMB at known distance (distance when age of universe = $t_{rec}/2$)

Angular Scale of First Acoustic Peak

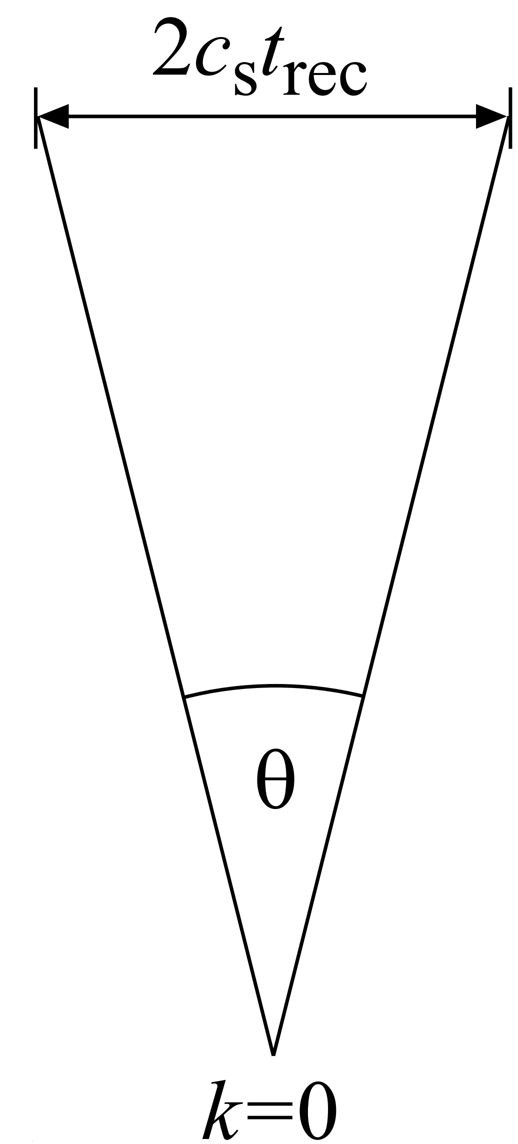
We can use this to measure the geometry of the Universe!



Compare measured angular size of fluctuations to the calculated size.

$$\lambda = \frac{c_s}{\tau} = \frac{2ct_{rec}}{\sqrt{3}}$$

Calculate the angular size of the first peak.



Flat space: k=0

The angular size as it appears on the sky today is

$$D_s = \frac{2ct_{\rm rec}}{\sqrt{3}} = \frac{2 \times 400,000 \text{ l.y.}}{\sqrt{3}} = 140 \text{ kpc}$$

Before recombination, the Universe expansion was matter dominated. So,

$$\frac{R}{R_0} = \left(\frac{t}{t_0}\right)^{2/3} = \frac{1}{1+z}$$

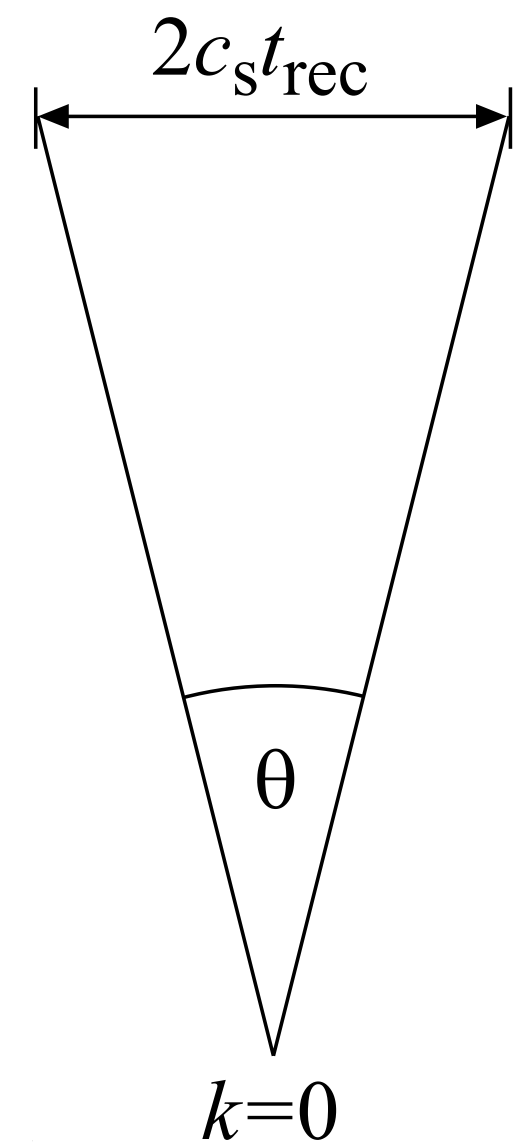
Thus, we can write

$$D_s = \frac{2ct_0}{\sqrt{3}}(1+z_{\rm rec})^{-3/2}$$

- The angle subtended = size / distance at time of emission.

- The distance we are interested in is the **proper motion distance** = r x R_0 (currently).

- The proper motion distance is found by solving the null geodesic in the FRW metric.



$$0 = c^2dt^2 - R(t)^2\frac{dr^2}{1-kr^2}$$

$$\int_{t_{\rm rec}}^{t_0}\frac{cdt}{R(t)} = \int_0^r \frac{dr}{\sqrt{1-kr^2}}$$

Substitute:

$$c\int_{t_{rec}}^{t_0}\frac{dt}{R_0}\left(\frac{t}{t_0}\right)^{3/2} = \int_0^r dr$$

$$c\int_{t_{rec}}^{t_0}\frac{dt}{R_0}\left(\frac{t}{t_0}\right)^{3/2}=\int_0^r dr$$

$$D_s=\frac{2ct_0}{\sqrt{3}}(1+z_{\rm rec})^{-3/2}$$

Solving yields:

$$rR_0=3ct_0[1-(t_{\rm rec}/t_0)^{1/3}]\;=3ct_0[1-(1+z_{\rm rec})^{-1/2}]$$

We also need to account for the fact that at the time of emission, the scale factor was 1+z times smaller. The **angular diameter distance** to the last scattering surface is thus

$$D_A=\frac{rR_0}{1+z}\;=3ct_0[(1+z_{\rm rec})^{-1}-(1+z_{\rm rec})^{-3/2}]$$

The angular size at the recombination era is then

$$\theta=\frac{D_s}{D_A}=\frac{2ct_0(1+z_{\rm rec})^{-3/2}}{3\sqrt{3}ct_0[(1+z_{\rm rec})^{-1}-(1+z_{\rm rec})^{-3/2}]}\;=\frac{2}{3\sqrt{3}[(1+z_{\rm rec})^{1/2}-1]}$$

Substituting known quantities: $T_{rec}\sim$ 3000 K, $T_0 = 2.7$ K and zero ~ 1100.

$$\theta\approx 0.012\text{ radian}=0.7^\circ$$

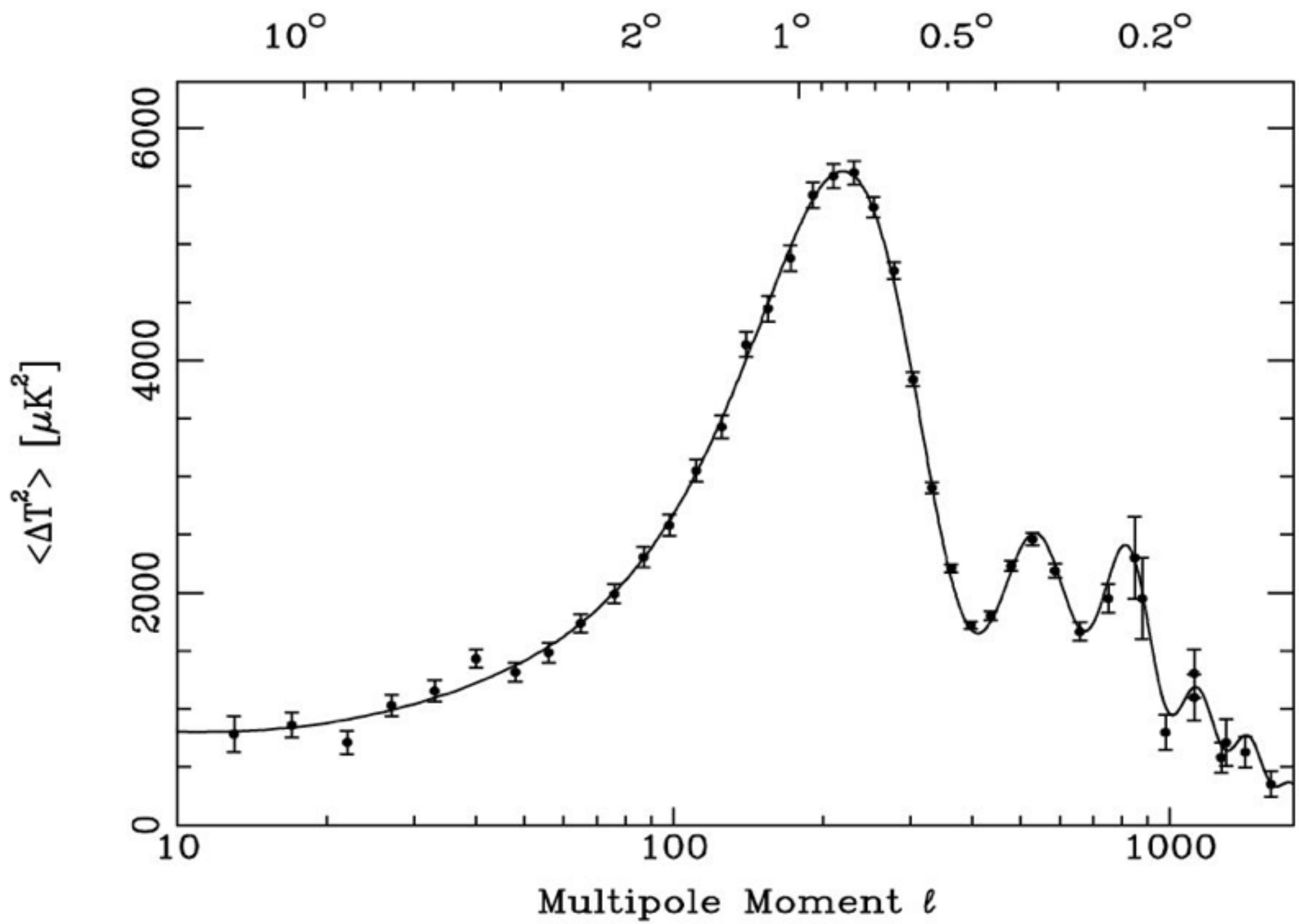
angular scale of first peak for k = 0 and $\Omega_\Lambda = 0$

Angular scale of first peak in the Fourier spectrum of CMB fluctuations:

$$\theta \approx 0.012 \text{ radian} = 0.7^\circ$$ for k = 0 and $\Omega_\Lambda = 0$

For negative curvature (k = -1), angles add up to < 180° and angle subtended < $2c_s t$.

For positive curvature (k = +1), angles add up to > 180° and angle subtended > $2c_s t$.



The first peak is at 0.8°, consistent with a flat geometry.

$$\Omega_m + \Omega_\Lambda = 1.02 \pm 0.02$$

A number of cosmological parameters are determined by the analysis of the CMB.

$$\Omega_m \approx 0.3$$

when combined with SN-1a data

$$\Omega_\Lambda \approx 0.7$$

if the Universe is exactly flat

$$t_0 = 13.7 \pm 0.2 \text{ Gyr}$$

$$\Omega_\text{B} = 0.044 \pm 0.004$$

Implications:

- The existence of the acoustic peaks in the power spectrum means that density perturbations existed long before the time of recombination "primordial". Inflation predicts these perturbations.

- The structure we see today formed from the growth of the initial small fluctuations.

- Once the first massive stars formed, they reionized most of the gas in the Universe. (150 - 750 Myr)

Nucleosynthesis

During the earliest times in the Universe, the temperatures were high enough that electrons, protons, positrons and neutrons were in thermo equilibrium.

Question: What is the difference in the rest mass of the proton and neutron?

$$(m_n - m_p)c^2 = 1.3 \text{ MeV}$$

At t << 1 s, the temperature was T >> 1 MeV, thus

$$e^- + p + 0.8 \text{ MeV} \rightleftharpoons \nu_e + n$$

$$\bar{\nu}_e + p + 1.8 \text{ MeV} \rightleftharpoons e^+ + n$$

The ratio of neutrons and protons can be obtain from statistical mechanics and described by the **Saha Equation**.

$$\frac{N_n}{N_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left[-\frac{(m_n - m_p)c^2}{kT}\right]$$

$$\frac{N_n}{N_p} = \left(\frac{m_n}{m_p}\right)^{3/2} \exp\left[-\frac{(m_n - m_p)c^2}{kT}\right]$$

- What happens when T >> 1 MeV?

The ratio is very close to 1.

- What happens as the temperature decreases?

The ratio also decreases. Protons outnumber neutrons.

- Does this trend continue forever?

No, when T < 0.8 MeV, the mean reaction time becomes longer than the age of the Universe at that epoch (t = 2 s).

This time is called **neutron freeze-out** since neutrons can no longer be created.

For a few minutes after neutrons freeze-out, most of the neutrons become incorporated into helium nuclei

$$n + p \rightarrow \mathrm{d} + \gamma$$

$$p + \mathrm{d} \rightarrow {}^3\mathrm{He} + \gamma$$

$$d + d \rightarrow {}^3\mathrm{He} + n$$

$$n + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + \gamma$$

$$d + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + p$$

- Numerical computation show that the ratio of neutrons inside ^{4}He to protons is 1/7.

- Each ^{4}He nucleus has 2 protons, 2 neutrons and there are 12 free protons for each ^{4}He nucleus.

- Thus, the ratio of helium to hydrogen atoms is 1/12.

The mass fraction of ^{4}He is then

$$Y_4 = \frac{4N(^4\mathrm{He})}{N(\mathrm{H}) + 4N(^4\mathrm{He})} = \frac{4\frac{1}{12}}{1+4\frac{1}{12}} = \frac{1}{4}$$

Measurements of He abundance in astronomical settings (stars, H II regions, planetary nebulae) indicate the mass abundance is consistant with this number.

Where other elements also produced in the first few minutes?

deuterium (10^{-5})
^{3}He (10^{-5})
^{7}Li (10^{-9})
^{7}Be (10^{-9})

As the Universe expands, the baryon-to-photon ratio does not change.

$$\eta \approx 5 \times 10^{-10}$$

Why?

- ☑ We know the radiation density declines as R^{-4}.
- ☑ The Planck spectrum also declines as T α 1/R, before and after recombination.
- ☑ The energy of photons scales with kT. Thus, the photon number density declines as R^{-3}.
- ☑ Baryons are conserved, so their density also declines as R^{-3}.

Thus, we can write the baryon-to-photon ratio (in terms of critical closer density) as

$$\Omega_B = \frac{n_B m_p}{\rho_c} = \frac{\eta\, n_\gamma m_p}{\rho_c}$$

CMB photon density today

$$0.01 < \Omega_B < 0.05$$

An analysis of the CMB power spectrum (based on relative amplitudes of the acoustic peaks) yields

$$\Omega_B = 0.044 \pm 0.004$$

Both the elemental abundance and CMB analysis tells us that baryons make up only a small fraction of the mass in the universe.

$$\Omega_m \approx 0.3$$

The remaining dark matter component is unknown to nature.

In addition, less than 1/10 of the baryons are in the form of stars. The majority is in the form of hot, dense intergalactic gas.

Table 1: History and Parameters of the Universe

Curvature: $\Omega_m + \Omega_\Lambda = 1.02 \pm 0.02$.
Mass density: $\Omega_{m,0} \approx 0.3$, consisting of
$\Omega_{B,0} = 0.044 \pm 0.004$ in baryons, and
$\Omega_{\rm DM,0} \approx 0.25$ in dark matter.
Dark energy: $\Omega_\Lambda \approx 0.7$.

time	redshift z	temperature T(K)	event
$\sim 10^{-34}$ s	$\sim 10^{27}$	$\sim 10^{27}$	Inflation ends, $\Omega_m + \Omega_\Lambda \rightarrow 1$, causally connected regions have expanded exponentially, initial fluctuation spectrum determined.
2 s	4×10^9	10^{10}	Neutron freezeout, no more neutrons formed.
3 min	4×10^8	10^9	Primordial nucleosynthesis over – light element abundances set.
65,000 yr	3500	10^4	Radiation domination $\rightarrow$ mass domination, $R \sim t^{1/2} \rightarrow R \sim t^{2/3}$, dark-matter structures start growing at a significant rate.
400,000 yr	1100	3000	Hydrogen atoms recombine, matter and radiation decouple, Universe becomes transparent to radiation of wavelengths longer than Lyα, CMB fluctuation pattern frozen in space, baryon perturbations start growing.
$\sim 10^8 - 10^9$ yr	$\sim 6 - 20$	$\sim 20 - 60$	First stars form and reionize the Universe, ending the "Dark Ages". The Universe becomes transparent also to radiation with wavelengths shorter than Lyα.
$\sim$6 Gyr	~ 1	~ 5	Transition from deceleration to acceleration under the influence of dark energy.
14 Gyr	0	2.725 ± 0.002	Today.

Quasars as Cosmological Probes

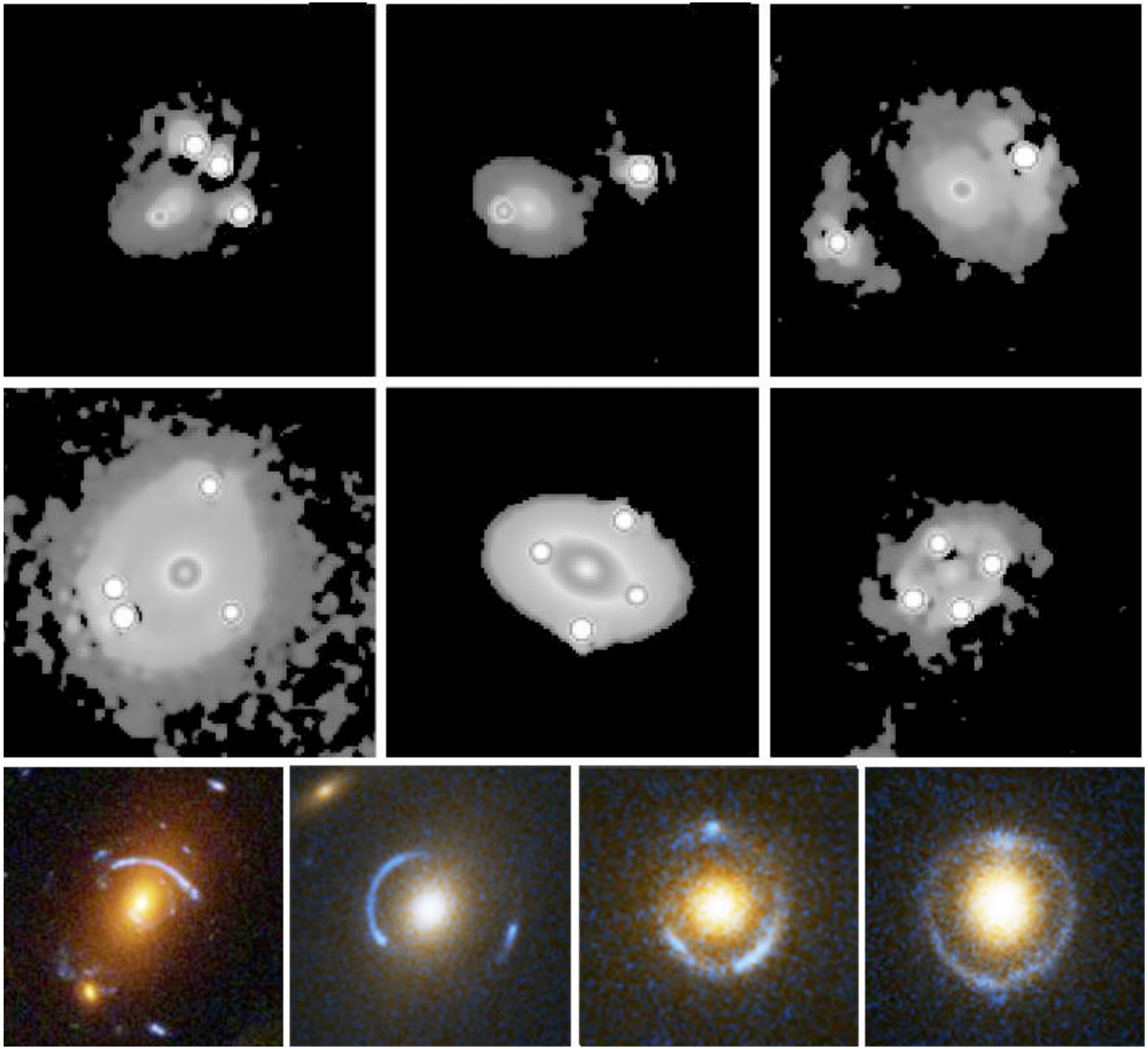
- Quasars are supermassive black holes accreting at rates that produce luminosities near the Eddington limit (10^1 - $10^4 L_{sun}$).

- Recall, the Eddington limit is the maximum luminosity possible in a system powered by accretion (chapter 4).

- Quasars are easily visible to large cosmological distances. Allows us to probe the assembly and accretion history of the central black holes in galaxies.

- Very luminous quasars are now rare. Most galaxies are now accreting at low or moderate rates. Most dense at z ~2 (10 Gyr).

- The most distant quasars are at z ~ 6 (1 Gyr) — also time of galaxy formation.

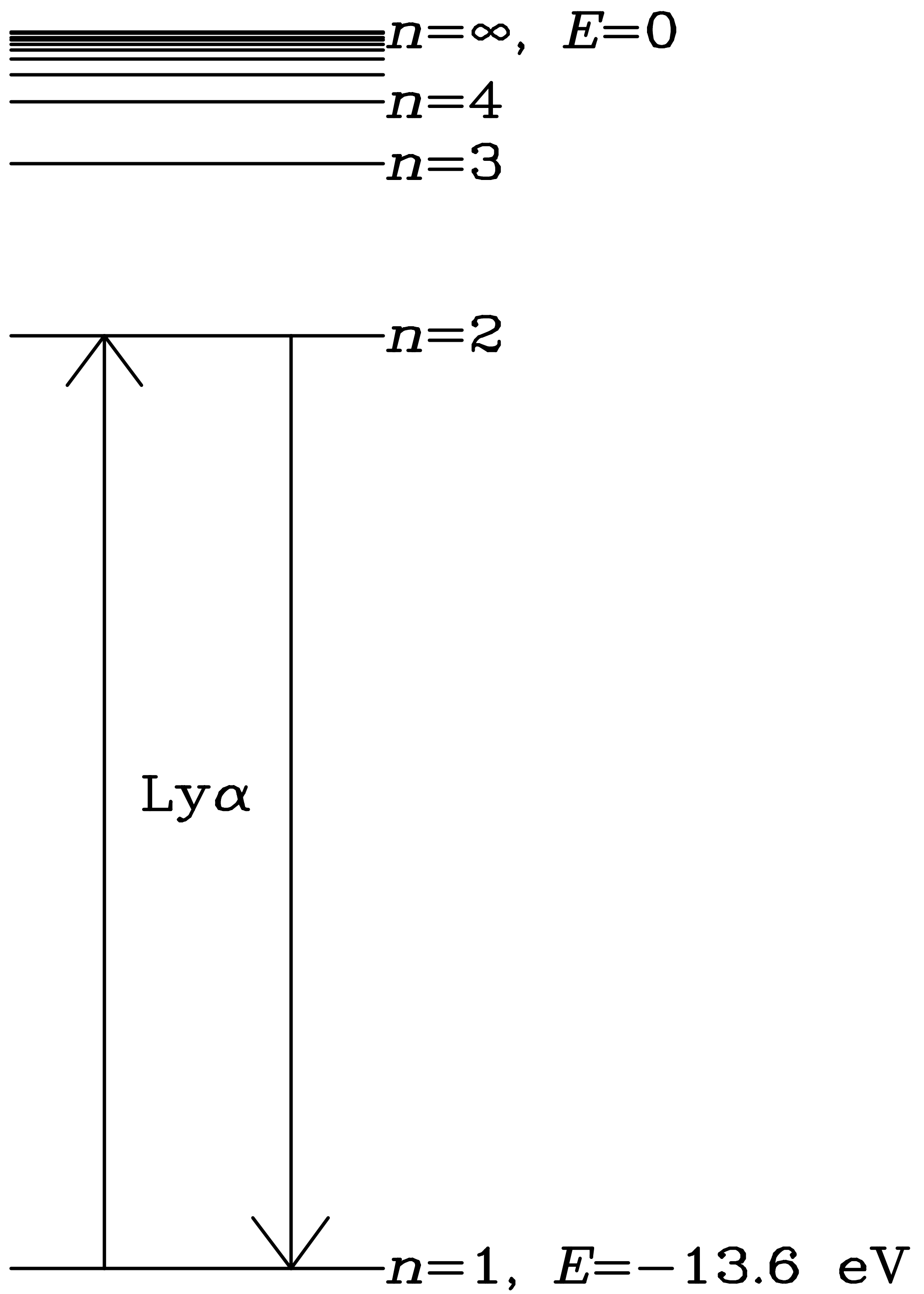


Review: Lyman Series:

All transitions of atomic hydrogen to the n = 1 ground state.

$\mathrm{Ly}\alpha$: $2 \leftrightarrow 1, 1216$ Å;
$\mathrm{Ly}\beta$: $3 \leftrightarrow 1, 1025$ Å;
$\mathrm{Ly}\gamma$: $4 \leftrightarrow 1, 972$ Å;

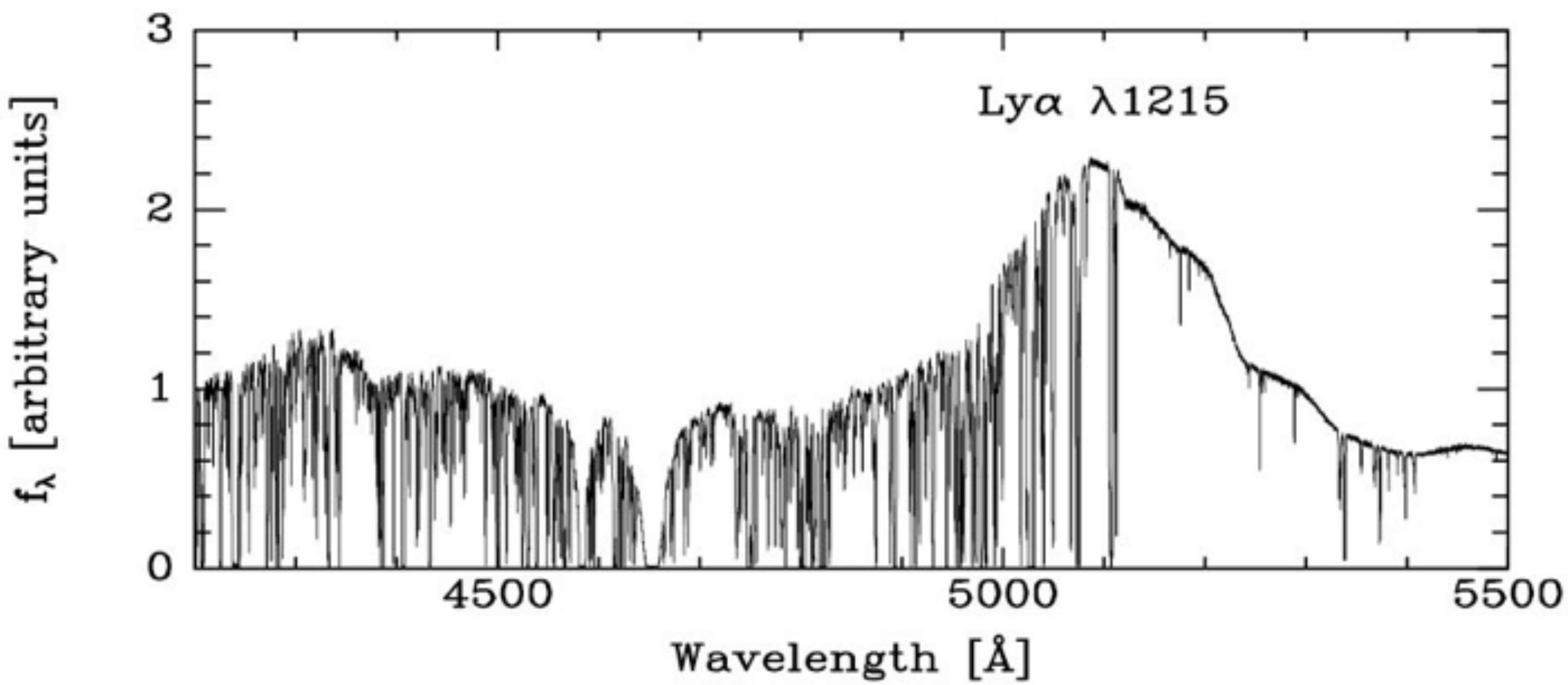
$\mathrm{Ly}_{\mathrm{con}}$: $\infty \leftrightarrow 1, < 911.5$ Å



Lyman-α Forest

- Studying the absorption lines from distant quasars gives us information about the clouds of gas along the line of site between us and the quasar.

- Each Lyα line is redshifted according to the distance between us and the particular absorbing cloud (neutral hydrogen).



Uses of the Lyα Forests:

Neutral Hydrogen: Since we see light at all, we can limit the amount of neutral hydrogen between us and the quasar and learn about its distribution.

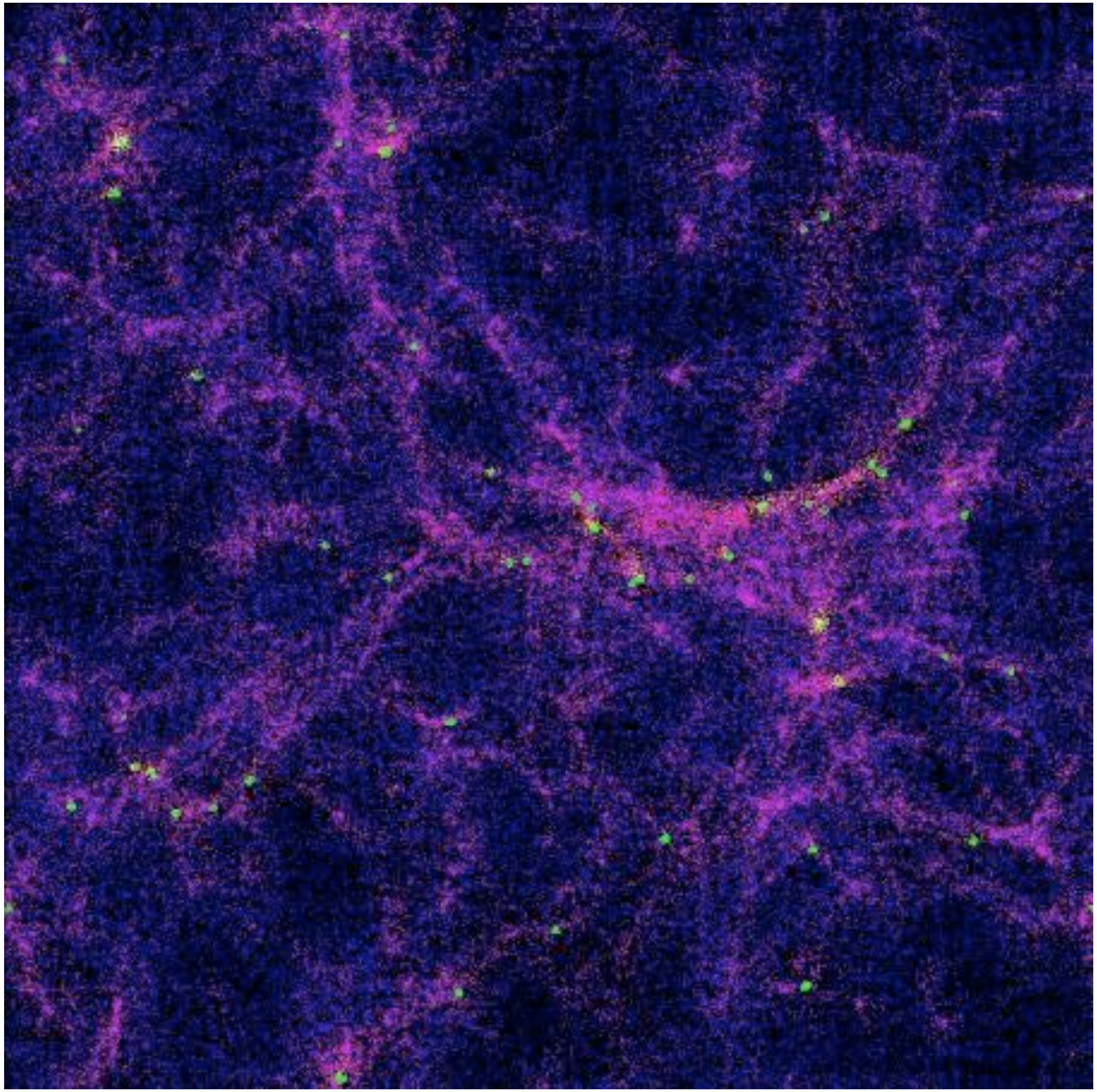
Structure Formation: Lyα simulations produce structure (filaments and voids) by starting with small fluctuations in the matter density and letting gravity and other know forces act.

Hot Dark Matter: Numerical simulations also show that one can not have too much hot dark matter in order to get agreement with observations. Too much hot dark matter erases structure on small scales.

Dark Matter Tracers: Lyα regions are formed by gas falling into gravitational wells of matter (luminous and dark).

Nucleosynthesis: Deuterium is produced in the first 3 minutes and afterwards is thought to be destroyed. Lyα systems have deuterium in them. Provides constraints on primordial deuterium.

Cosmological Constant: By comparing the redshift due to expansion of the universe to the angular extent of an object one can constrain the expansion history of the universe.



Simulation of Lyman alpha forest clouds at z=5.

We have explored a variety of techniques for studying the universe. Scientist hope that by using these techniques along with others, we will be able to construct a consistent picture of the cosmic history.

Questions still exist:

1. What is the origin of cosmic rays?
2. What is the dark matter?
3. What can compact objects teach us?
4. How were galaxies formed and how do they evolve?
5. How do we deal with the complexity of big data?
6. What is dark energy?
7. How will we ever understand inflation?

https://www6.slac.stanford.edu/news/2013-11-27-kipac-seven-mysteries.aspx

The End! And Thank you!