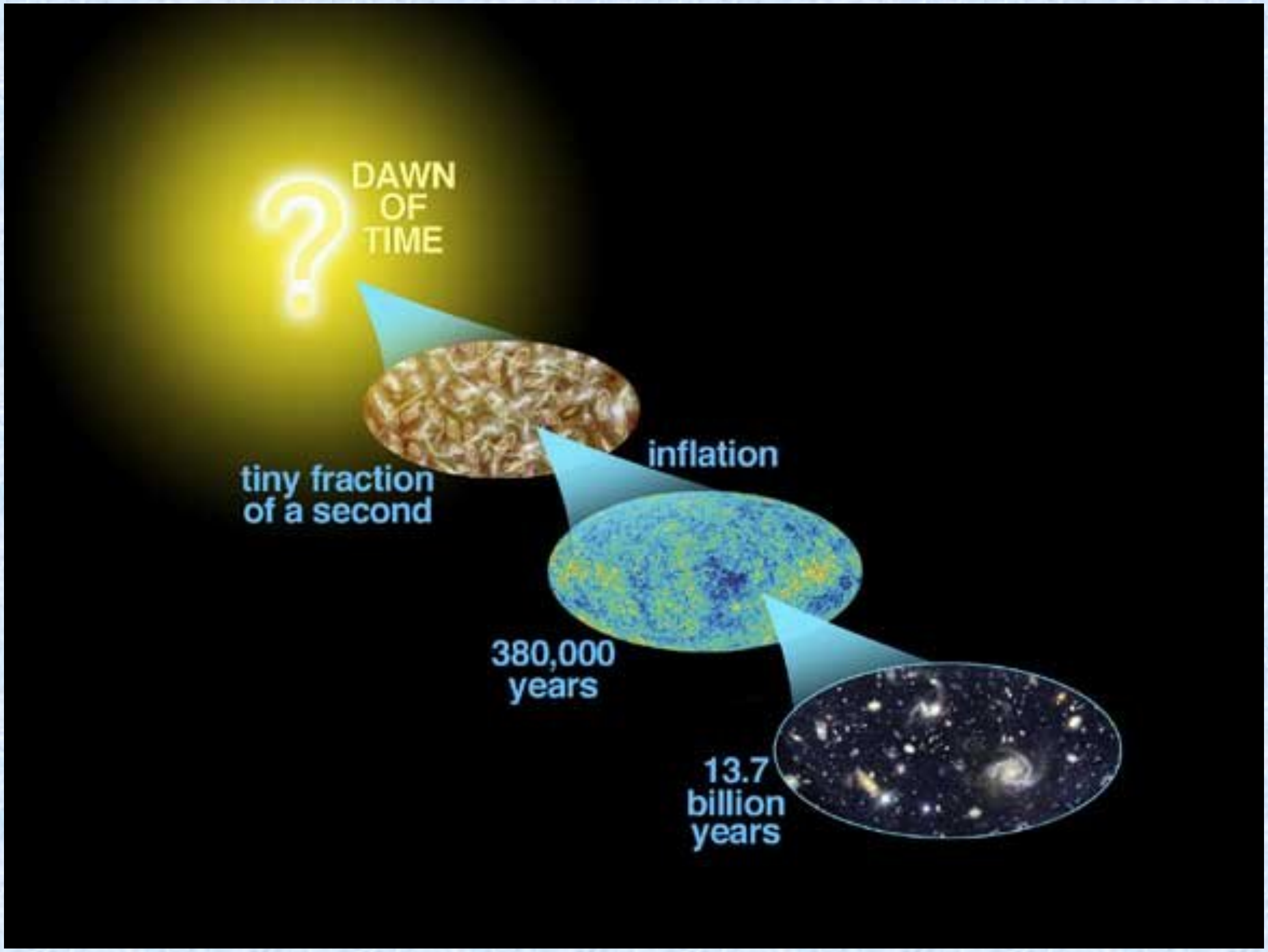
Astro-2: History of the Universe



Lecture 8; May 7 2013

Previously… on astro-2

- Wherever we look in the sky there is a background of microwaves, the CMB.
- The CMB is very close to isotropic better than 0.001%
- The spectrum of the CMB is indistinguishable from a that of Blackbody at 2.725 K.
- In the Big Bang model the CMB is interpreted as the fossil record of an epoch close to the beginning of time, when the Universe was extremely dense and hot and filled with radiation in thermal equilibrium

Previously… on astro-2.

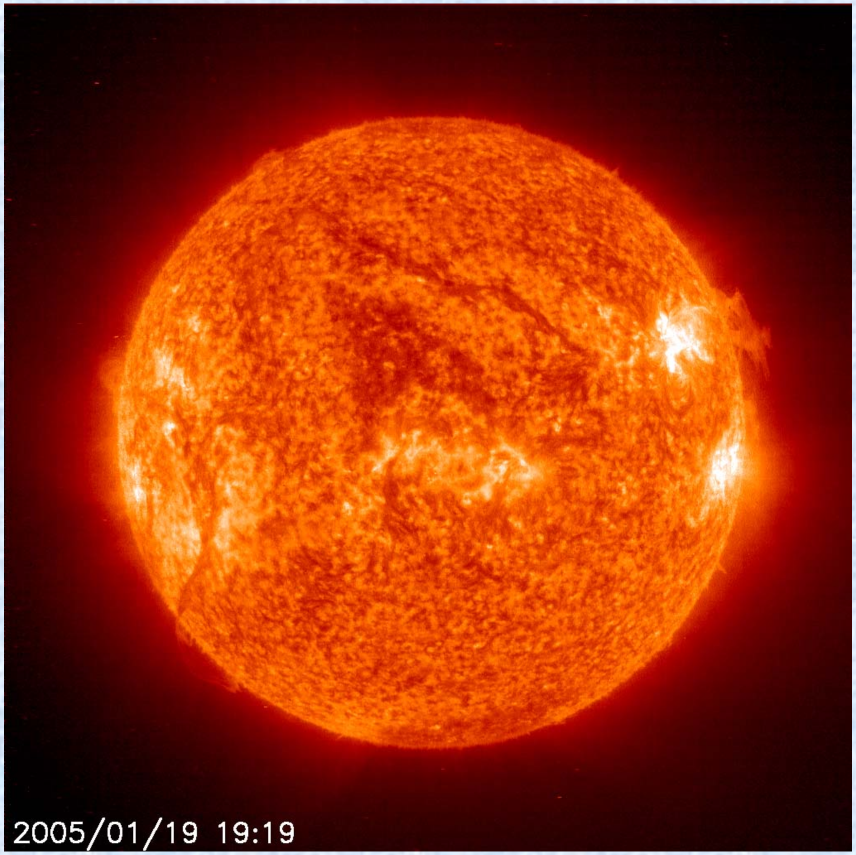
- The region of space that we can see is limited by the finite speed of light
- We can only see as far as light has had time to travel, this is called our “horizon”.
- We can only see inside our horizon, which is finite even if the universe is infinite
- Horizons grow as time goes by.
- Two points can be causally connected only if they are inside each other’s horizons
- How is it possible that the CMB has the same temperature everywhere? This is known as the horizon problem.

Today.. On Astro-2.

1. Chemical composition of stars. Evidence for early fusion (hot big bang).
2. Matter content of the Universe. Definitions and census
3. Brief history of the Universe.

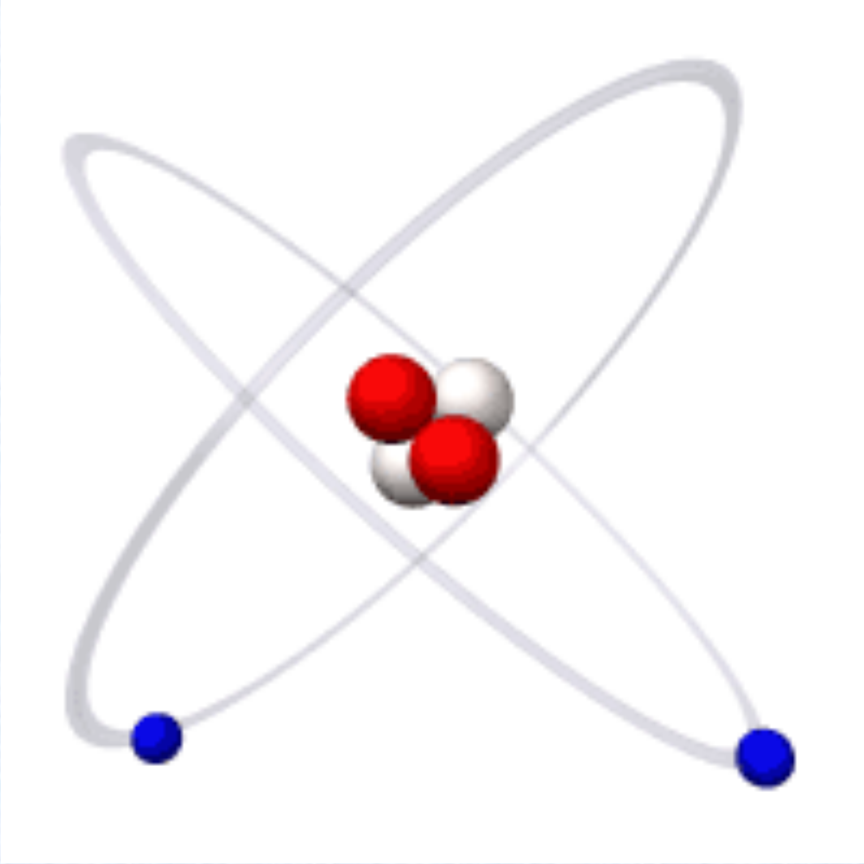
Chemical composition of stars. Sun

- The sun is made of:
- Hydrogen (74% by mass)
- Helium (25%)
- Heavier elements (1%) commonly referred to as "metals" by astrophysicists
- This is way more helium that is expected from a universe initially made of Hydrogen where Helium is produced in stars…
- This is a common problem: Helium abundance is always ~25%



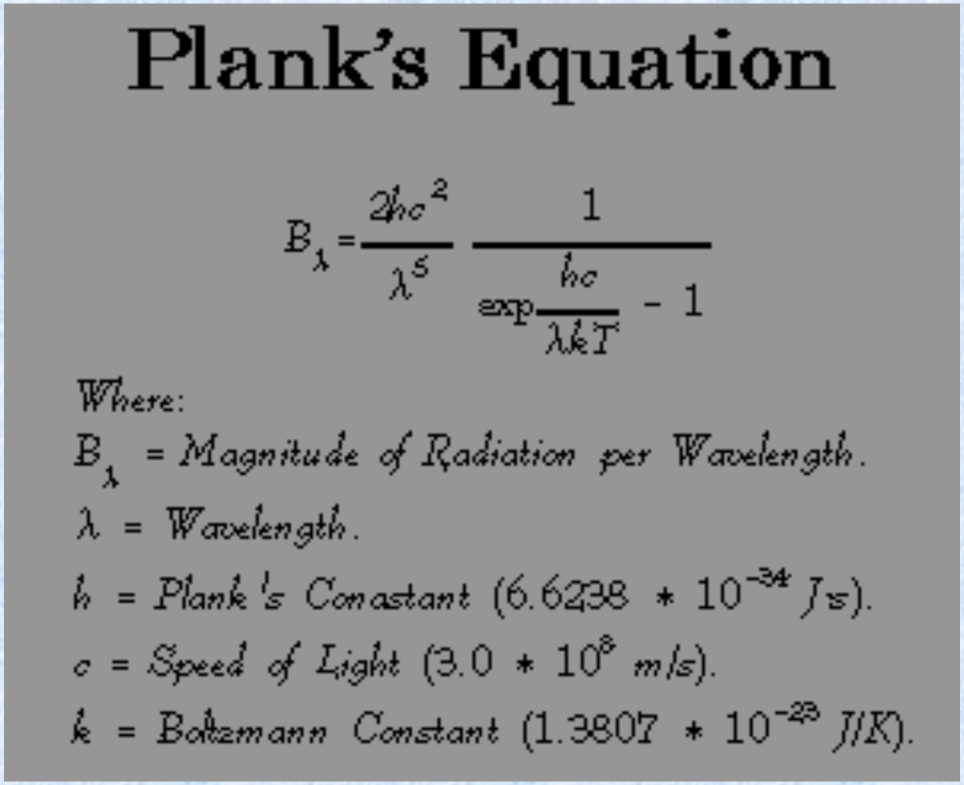
Helium abundance.
The Big Bang solution

- Helium is produced in the early Universe when the average temperature was high enough (above 10^7 10^8 K) to allow for nuclear fusion.
- Why do you need high temperature to do fusion?
- We will see later on that the Big Bang theory predicts exactly the abundance of all heavy elements.



When was the Universe hot enough to form Helium?

- Let's compute this in terms of redshift.
- During expansion, radiation remains a black body, but wavelengths stretch by a factor of (1+z)
- A redshift z a photon of wavelength λ_0 today would have wavelength?
- $\lambda=\lambda_0 / (1+z)$
- So what is the relation between T and T_0?
- $T = T_0 (1+z)$



Plank's Equation

$$B_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\frac{hc}{\lambda kT} - 1}$$

Where:

B_λ = Magnitude of Radiation per Wavelength.

λ = Wavelength.

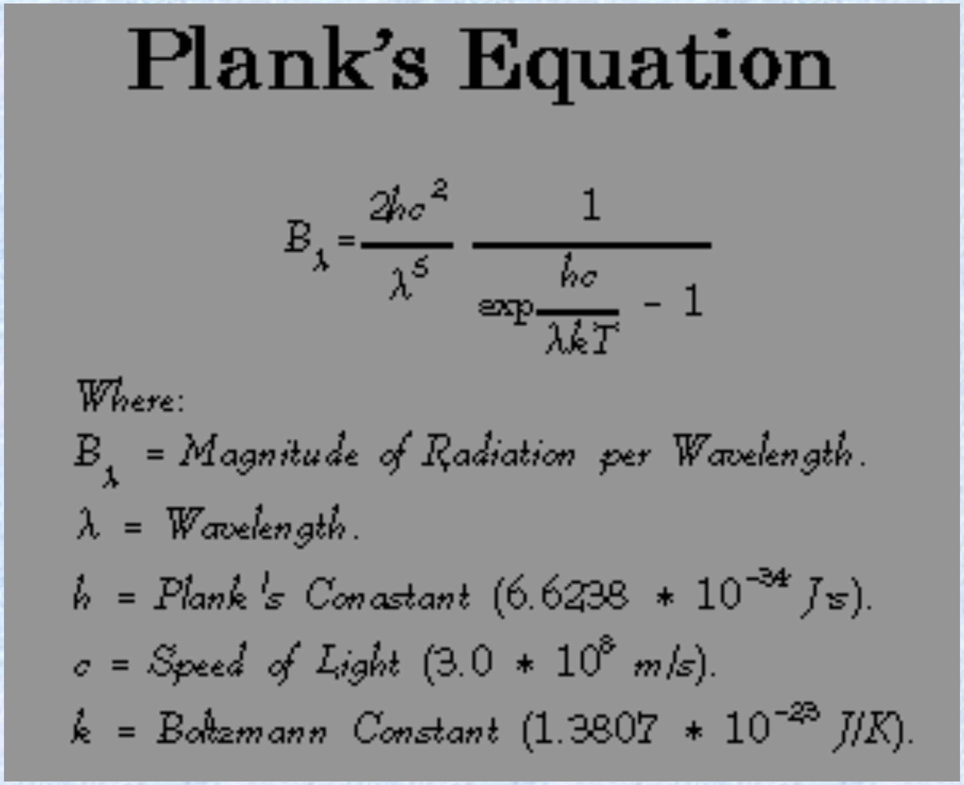
h = Plank's Conastant $(6.6238 * 10^{-34}$ Js).

c = Speed of Light $(3.0 * 10^{8}$ m/s).

k = Boltzmann Constant $(1.3807 * 10^{-23}$ J/K).

When was the Universe hot enough to form Helium?

- $T_{He} = T_0 (1+z_{He})$
- So $(1+z_{He})=T_{He}/T_0$
- $T_0=3K$
- $T_{He} \sim 300,000,000K$
- So $z_{He} \sim 100,000,000$



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Helium abundance. Summary

- Helium is too abundant and too homogeneous to have formed through fusion in stars
- The Big Bang theory explains He abundance with primordial nucleosynthesis when the Universe was hot enough
- T scales as (1+z), so that He was formed up to until z~100,000,000

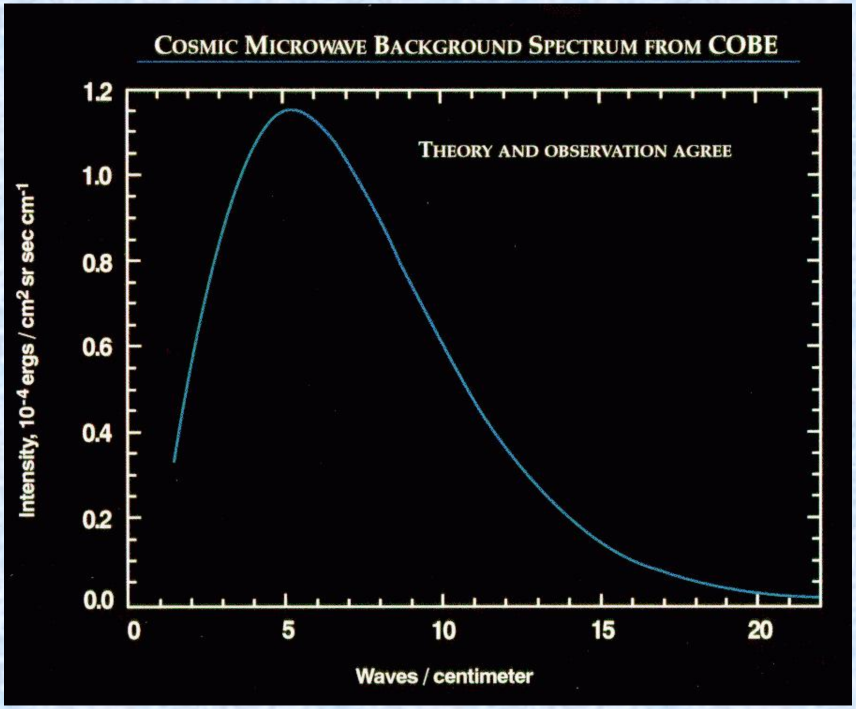
Matter density of the Universe

- Types of matter/energy ($E=mc^2$) that we encountered so far:
  1. Radiation
  2. Neutrinos
  3. Baryons
  4. Dark matter
  5. Dark energy
- How much are they?

Matter density of the Universe.

1: Radiation

- How much light is there in the Universe? The well defined quantity is of course the energy (or matter) density.
- Is it fairly easy to compute the energy density of the CMB because it is a black body
- For a black body the mass density is:
- $\rho_{rad} = 4\,\sigma\,T^4/c^3$



Matter density of the Universe.
1: Radiation

- $\rho_{rad} = 4\ \sigma\ T^4 / c^3$
- Where c is the speed of light (300,000,000 m/s), T is the temperature, σ is constant (the Stefan-Boltzmann constant), 5.67e-8 W m^{-2} K^{-4}
- So $\rho_{rad} = 4.6e\text{-}31\ (T/2.725K)^4\ kg/m^3$
- Where 2.725K is?
- How does this compare to air? [1kg/m^3]

"That wraps it up -- the mass of the universe."

Matter density of the Universe. 1: Radiation in critical units

- It is convenient to write this down in terms of the critical density, the amount of energy/matter needed to “close” the universe
- Defined as:
  - $\rho_{crit} = 3H_0^2/8\pi G$
  - $= 9.5\text{e-}27\ \text{kg/m}^3$
- The density of radiation is 4.8e-5 ρ_{crit}
- This can be written as Ω_{rad} ~5e-5

"That wraps it up -- the mass of the universe."

Matter density of the Universe.
2: Neutrinos

- Limits on neutrino mass density come from:
  - Oscillations (lower limit; superkamiokande)
  - large scale structures (upper limits <0.6eV; Melchiorri et al. 2008; recently Plank claimed a detection, but weak evidence)
- In critical units neutrino mass density is between: $0.0010<\Omega_\nu<0.0025$

"That wraps it up -- the mass of the universe."

Matter density of the Universe.

3: Baryons

- People have counted the amount of mass in visible baryons.
- Baryonic inventory (total=0.045+-0.003 from nucleosynthesis and CMB):
  - Stars Ω_*=0.0024+-0.0007 (more mass in neutrinos than in stars!)
  - Planets $\Omega_{planet}\sim 10^{-6}$
  - Warm intergalactic gas 0.040+-0.003
- Most of baryons are in intergalactic medium, filaments in the cosmic web,

"That wraps it up -- the mass of the universe."

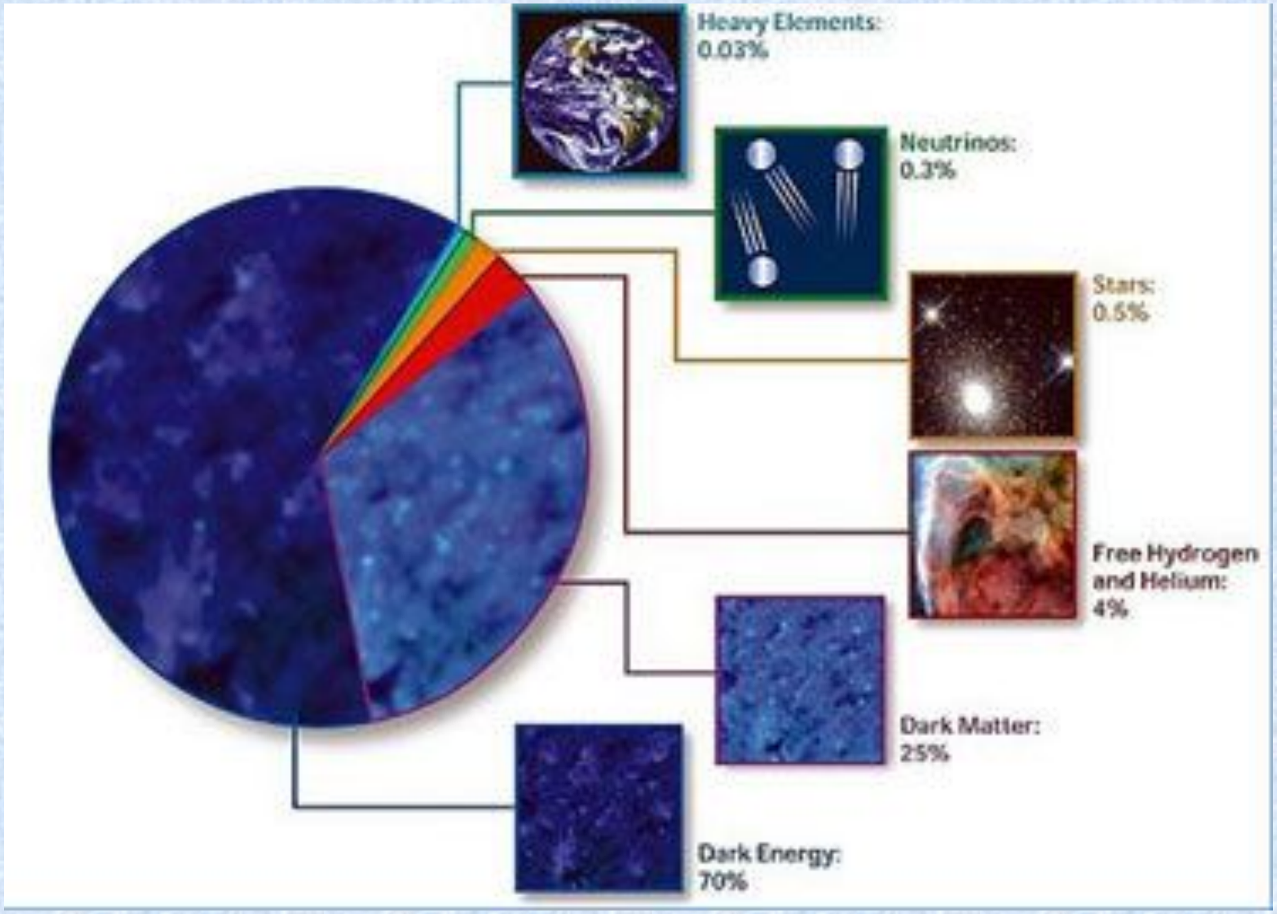
Matter density of the Universe. 4: Dark matter

- Dark matter is much harder to count, because we can only “see” it via its gravitational effects
- One way to count it is for example is to measure the dark matter to baryon ratio in clusters
- Assume that this number is representative of the Universe because the collapsed volume is large
- Take the fraction of baryons (from BBN) and multiply
- This and other methods give $\Omega_{dm}=0.23$
- The total amount of matter is given by: $\Omega_m=\Omega_{dm}+\Omega_b=0.27$

Matter density of the Universe. 5: Dark energy (or Λ)

- Most of the energy in the universe appears to be of a mysterious form called dark energy (because we do not know what it is!)
- Dark energy “repels” instead of attracting, and therefore causes the expansion of the universe to accelerate instead of slowing down
- One form of dark energy is the cosmological constant (Λ), introduced by Einstein a long time ago, and this is a purely geometrical term… [in other words, it needs not be “something” could just be a property of spacetime]
- According to current measurements Ω_{de}~0.72 or Ω_{Λ}~0.72.

Matter density of the Universe. Summary

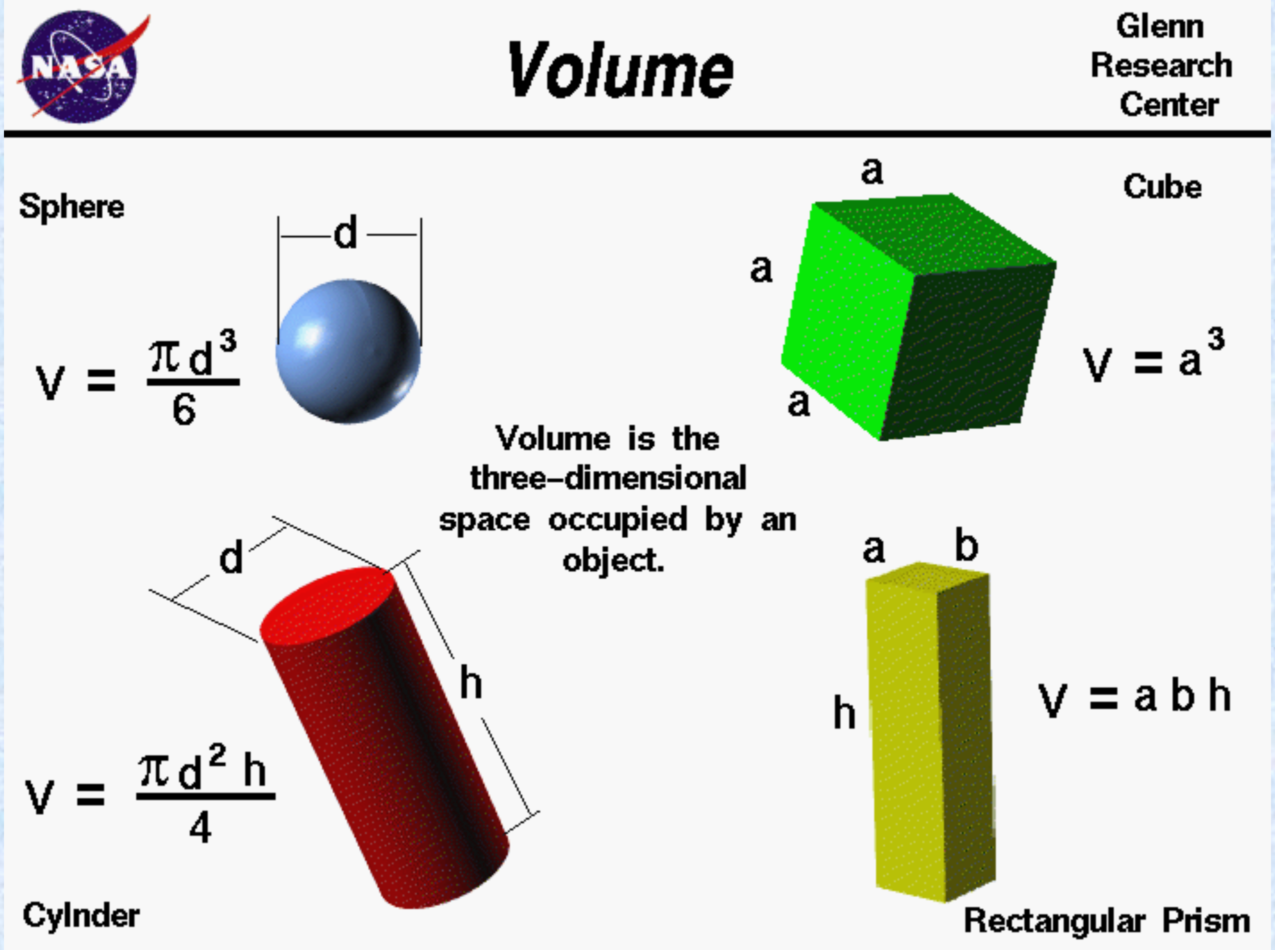


Numbers changed a little bit by Planck

But… was it always like this? A brief history of the universe…

- We know the relative proportion of stuff in the universe nowadays
- How do quantities scale with z?
- What is z, remember?
- Redshift z is connected to the LINEAR stretch factor of the universe $d_0/d=(1+z)$ [subscript 0 means NOW]
- How do volumes change with redshift?
- If I take a box of the universe between some galaxies and measure its volume at different redshifts, what will I find?

But… was it always like this? Volume and redshift



Volumes, by definition, scale as the third power of the linear dimension

But… was it always like this? Evolution of mass density

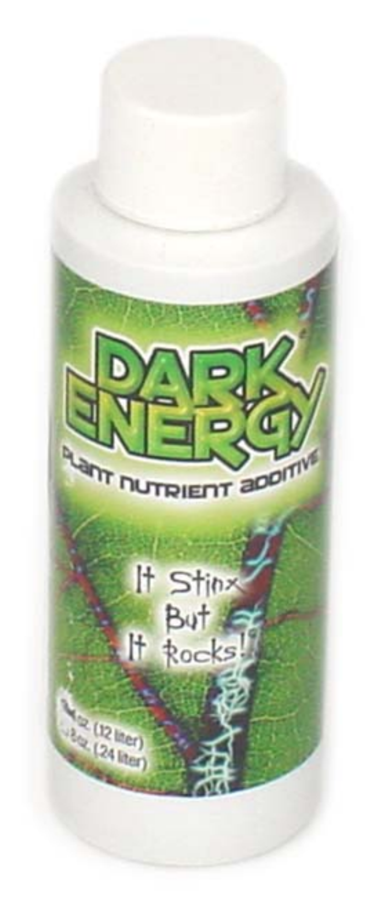
- Volumes scale with redshift as: $V/V_0=(1+z)^{-3}$
- At z=9 my box of the Universe was how many times smaller than now?
- If mass is preserved in a given form, how does density scale with redshift?
- Density is $\rho=M/V$, M is constant, so…
- Density ρ scales as $\rho=\rho_0\ (1+z)^3$
- So mass densities Ω scale as $\Omega=\Omega_0\ (1+z)^3$!

But… was it always like this? Evolution of photon energy density

- With photons there's an extra term.
- As the photons redshift each photon also looses energy (because a photon's energy is proportional to its frequency, Universe Chap 5).
- So for photons (and other massless particles) Density ρ_{rad} scales as $\rho_{rad}=\rho_{rad,0}\,(1+z)^4$
- So photon density scales as $\Omega_{rad}=\Omega_{rad,0}\,(1+z)^4$

But… was it always like this? The cosmological constant

- The cosmological constant is a constant, so it does not scale with redshift.
- So Ω_Λ is a constant

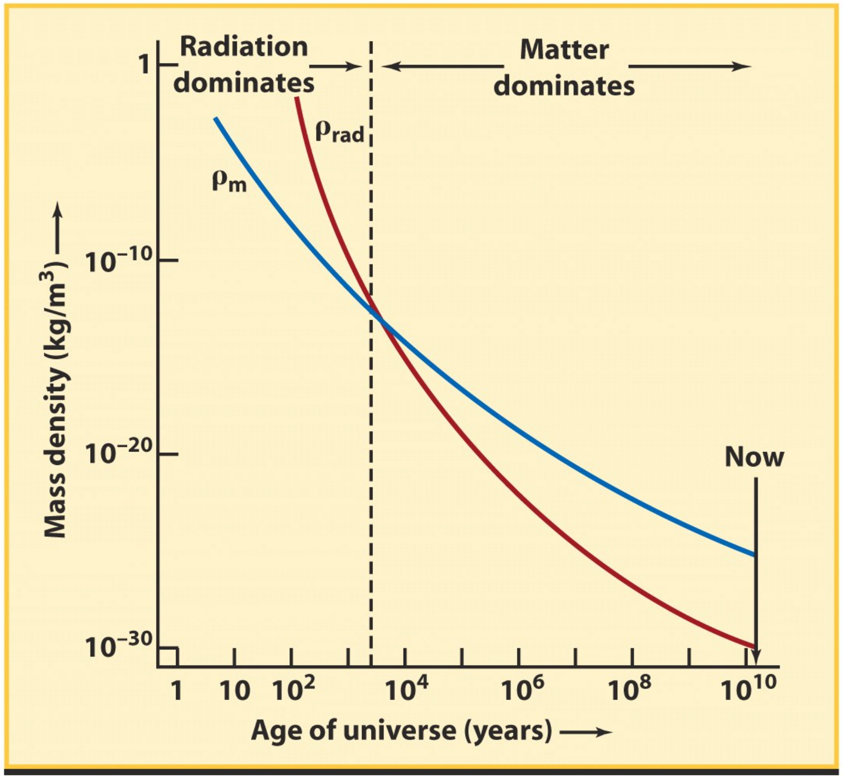


But… was it always like this? A history of the Universe

- Since the scalings are different different objects will dominate a different times.

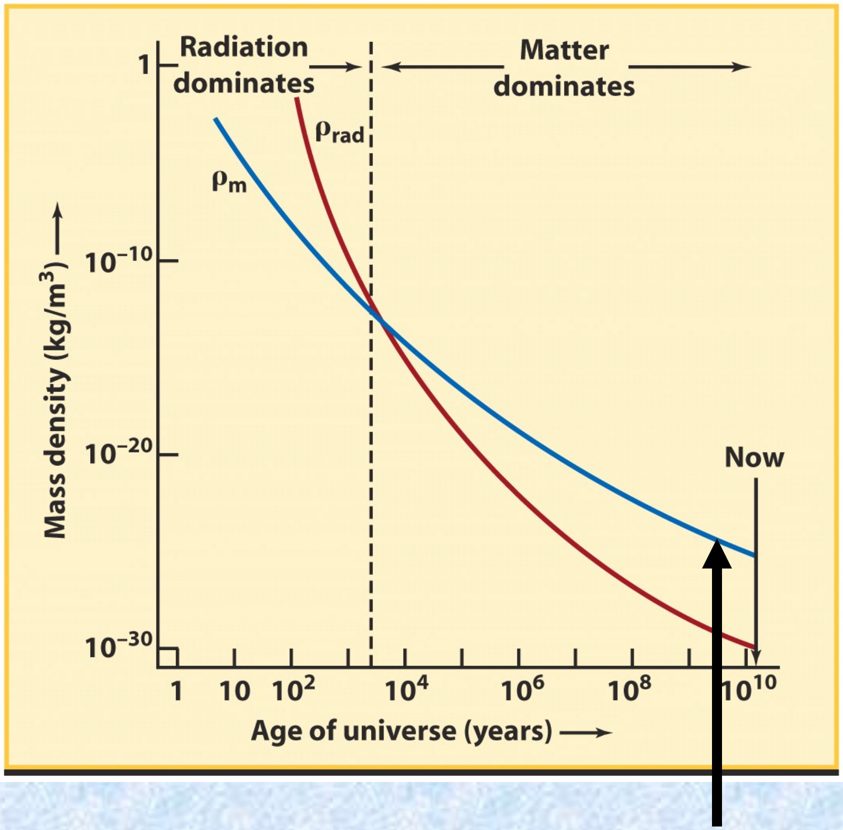
1. $\Omega_{rad}=\Omega_{rad,0}\ (1+z)^4$
2. $\Omega_m=\Omega_{m,0}\ (1+z)^3$

- Dividing the two:
- $\Omega_{rad}/\Omega=1.85e\text{-}4\ (1+z)$
- So at z~5000 the two were approximately equal
- Before that time radiation dominated, after matter dominates



But… was it always like this?
A history of the Universe. 2

- How about the cosmological constant
  1. $\Omega_\Lambda=\Omega_{\Lambda,0}$
  2. $\Omega_m=\Omega_{m,0}\,(1+z)^3$
- Dividing the two:
- $\Omega_m/\Omega_\Lambda=0.375\,(1+z)^3$
- So only very recently (z=0.4; 4 Gyrs ago) the cosmological became important!
- From now on Λ rules!
- Against historical prejudice… (dicke coincidence)



Cosmological constant dominated

Discussion.
Is the big-bang a good theory?

- According to Stephen Hawking: “A theory is a good theory if it satisfies two requirements: It must accurately describe a large class of observations on the basis of a model that contains only a few arbitrary elements, and it must make definite predictions about the results of future observations. Any physical theory is always provisional, in the sense that it is only a hypothesis; you can never prove it. No matter how many times the results of experiments agree with some theory, you can never be sure that the next time the result will not contradict the theory. On the other hand, you can disprove a theory by finding even a single repeatable observation that disagrees with the predictions of the theory."

The End

See you on thursday!