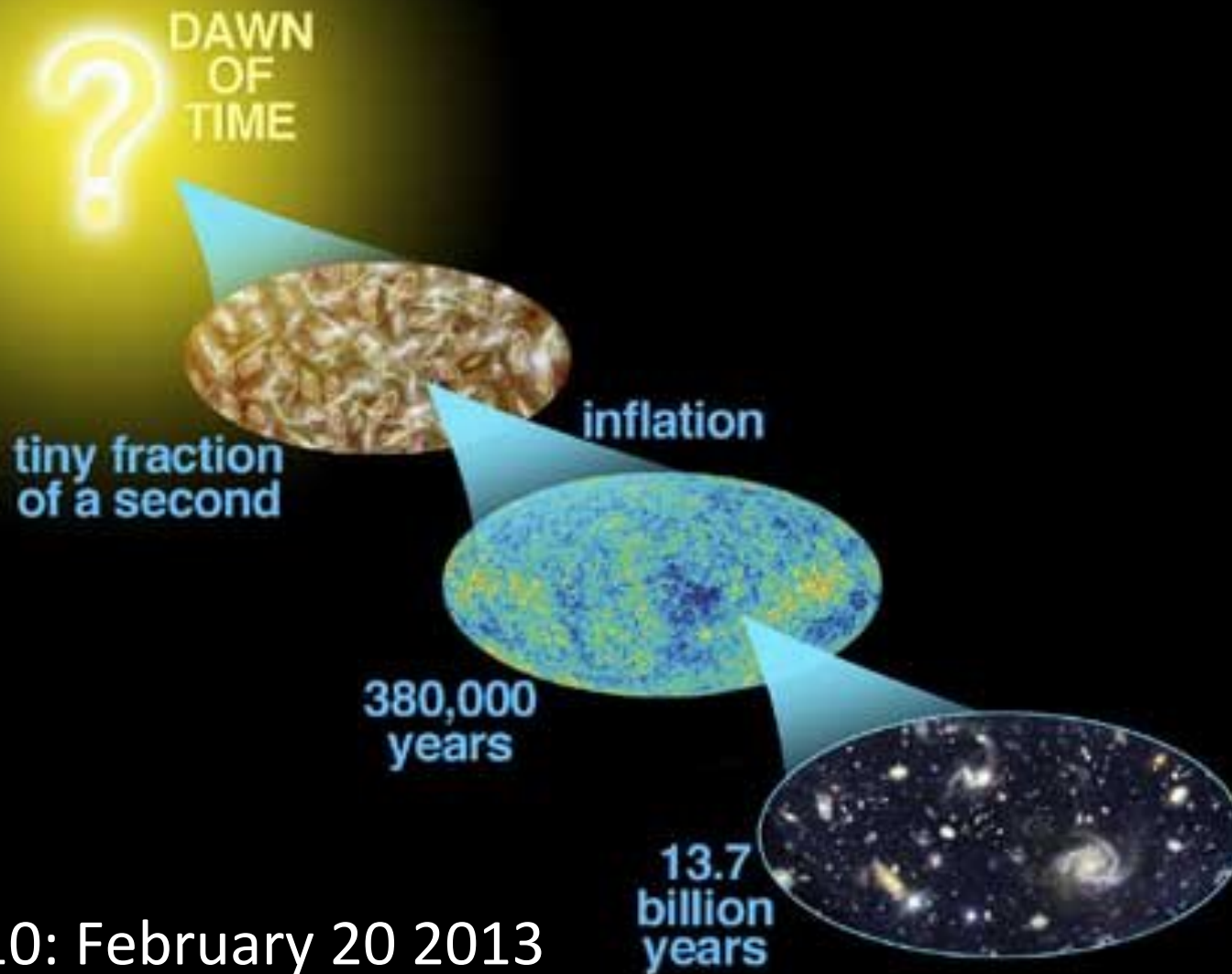


Cosmology W13



Lecture 10: February 20 2013

Presentations

- Teams and schedule

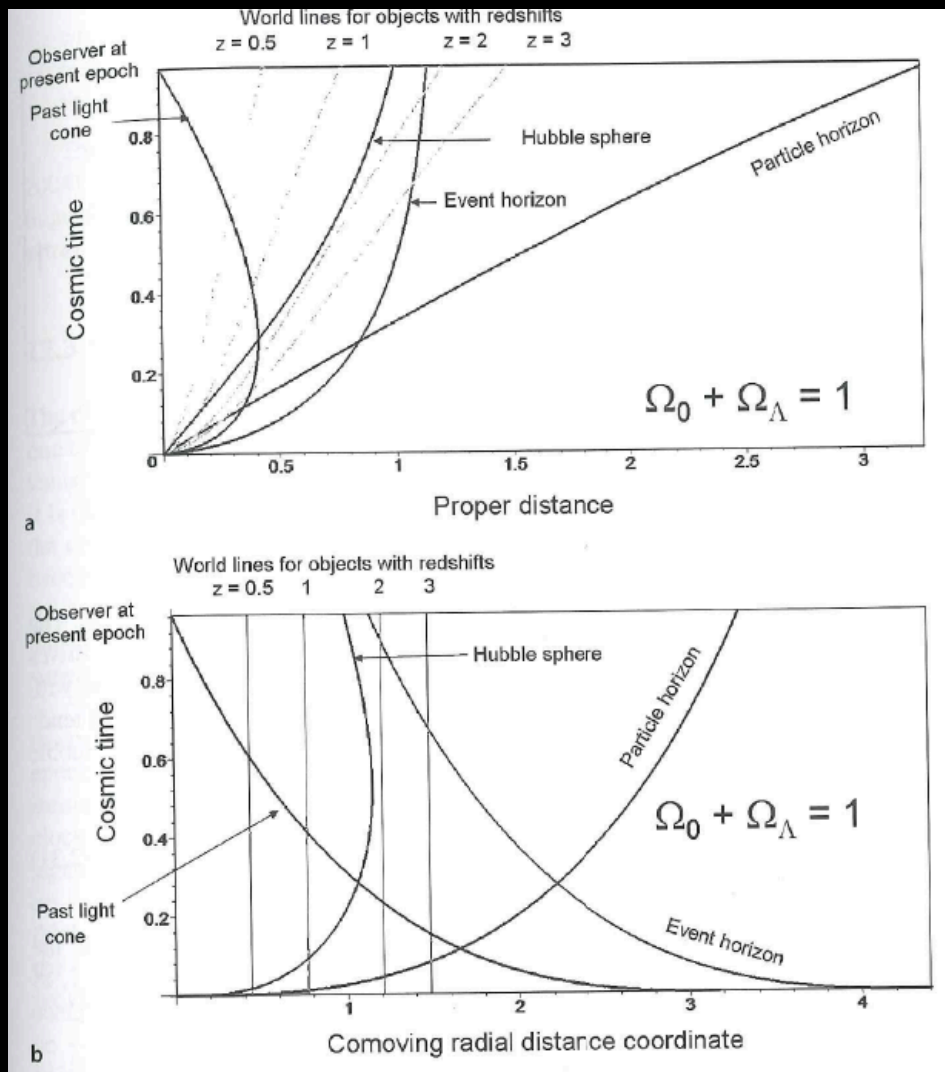
Growth of structure. II

- More on horizons
- Perturbations on superhorizon scale
- Adiabatic fluctuations
- Silk damping
- Isothermal perturbations
- Baryonic cosmology with isothermal perturbations

Key concepts

- Proper radial distance:
 - comoving radial distance projected at time t
- Particle horizon:
 - maximum proper distance for causal contact at time t
- Event horizon:
 - maximum proper distance for an object to ever be in causal contact

Horizons



$$r_H(t) = 3ct \quad \text{matter dominated}$$

$$r_H(t) = 2ct \quad \text{radiation dominated}$$

$$r_H(t) = \frac{c}{\alpha} [e^{\alpha t} - 1]; \alpha = \sqrt{\frac{\Lambda}{3}} \quad \Lambda \text{ dominated}$$

Perturbations and horizons

- The analysis described last week holds for small perturbations below horizon scale
- For superhorizon scales one has to a full GR treatment. In practice (primordial) perturbations on superhorizon scales grow as a^2 (radiation dominated) and then as a (matter dominated)
- Only when they enter the horizon non gravitational physics becomes important, like pressure support etc

Relevant physical scales

- Particle horizon
- Jeans length

$$\lambda_j = c_s \left(\frac{\pi}{G\rho} \right)^{\frac{1}{2}} [non\ rel]; \lambda_j = c_s \left(\frac{3\pi}{8G\rho} \right)^{\frac{1}{2}} [rel]$$

- Diffusion lengths, break down of fluid approximation
 - For Photons (Silk Damping)
 - For collisionless particles (Free streaming; next time)

Baryon-photon fluid

- Adiabatic perturbations:
 - both photons and baryons density – and hence pressure - are perturbed
 - In radiation dominated phase horizon \sim jeans length so any perturbation is stabilized when it enters horizon
 - After recombination jeans length drops
 - Photon diffusion damps perturbation below threshold mass
- Isothermal perturbations:
 - Only baryons are perturbed against constant T background of photons
 - Similar to above, but no photon diffusion

Speed of sound in baryon-photon fluid

- Pre-recombination they are closely coupled and have same T

$$c_s^2 = \frac{(\partial p / \partial T)_S}{(\partial \rho_r / \partial T)_S + (\partial \rho_m / \partial T)_S} = \frac{c^2}{3} \frac{4\rho_r}{4\rho_r + 3\rho_m}$$

- After recombination baryons feel only their own pressure so -> thermal sound speed

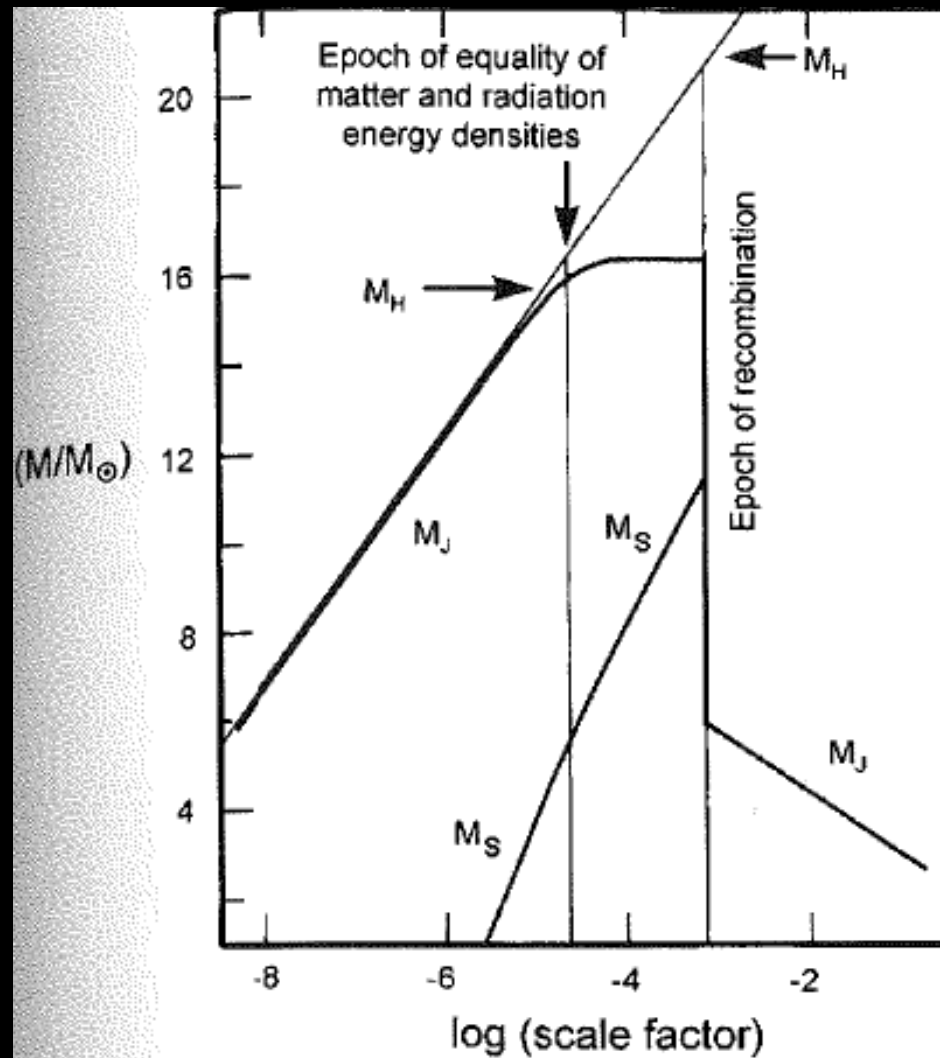
Evolution of Jeans mass

- Radiation dominated era:
 - Photons dominate matter and pressure, so sound speed is almost speed of light
 - Radiation pressure suppresses all fluctuations below horizon scale!

$$r_H = 2ct = c \left(\frac{3\pi}{8G\rho} \right)^{\frac{1}{2}} \sim \lambda_j = c \left(\frac{3\pi}{24G\rho} \right)^{\frac{1}{2}}$$

- Matter dominated era Jeans mass is constant
- After recombination sound speed drops, so does Jeans length and mass!

Evolution of Jeans mass



Silk Damping

- In adiabatic fluctuations photons are perturbed
- However the fluid approximation is only valid for scales much larger than the diffusion length
- Photons diffuse out of overdensities

$$\lambda = (N_e \sigma_T)^{-1} \quad ; \quad r_s \approx \left(\frac{1}{3} \lambda c t \right)^{\frac{1}{2}}$$

- The mass within this length is the “Silk” Mass

$$M_S = \frac{4\pi}{3} r_s^3 \rho_B$$

Silk Damping. Radiation era

$$t = \frac{2.4 \times 10^{19}}{(1+z)^2} \text{ s}$$

$$N_e = \frac{\Omega_B \rho_c (1+z)^3}{m_p} = 11 \Omega_B h^2 (1+z)^3 m^{-3}$$

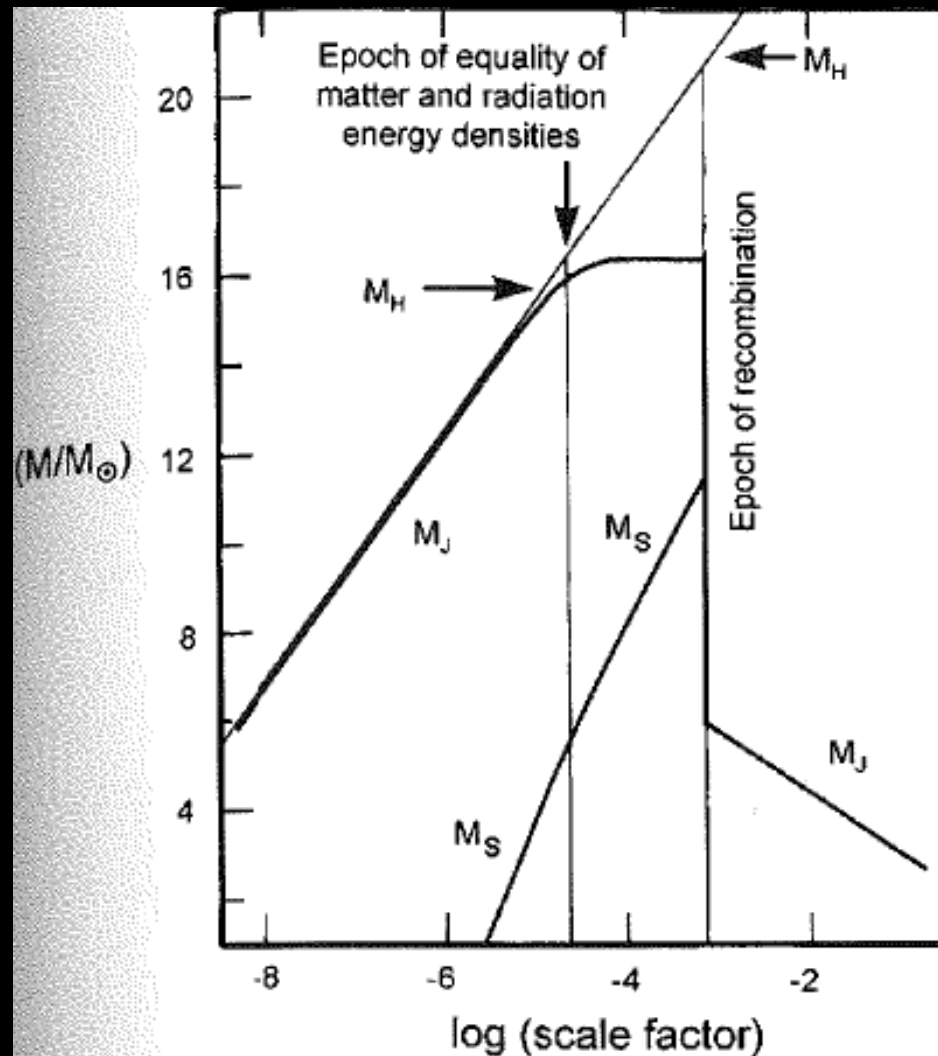
$$M_S = 2.4 \times 10^{26} (\Omega_B h^2)^{-1/2} (1+z)^{-9/2} M_\odot$$

Silk Damping. Up to recombination

$$M_S = 1.3 \times 10^{12} (\Omega_0 h^2)^{-3/2} M_\odot$$

For standard values of Ω_b this is $4e14!!!$

Evolution of instabilities in adiabatic model



Isothermal model is similar but no silk damping, so small scale fluctuations are not wiped out

Baryonic-Adiabatic model

- Primordial perturbation set up early on
- Grow outside horizon as a^2
- At small scales Silk damping wipes them out
- Only large perturbations arrive at recombination and start to grow as a (top down approach)
- These structures are large and flattened and give rise to topologies similar to those that were known at the time (Zeldovich pancakes)

Baryonic-Isothermal model

- Primordial perturbation set up early on
- Grow outside horizon as a^2
- No Silk damping
- All perturbations survive to recombination and suddenly they collapse
- Jeans mass is of order $\sim 10^5$ - 10^6 solar masses, similar to globular clusters
- Structure grows by merging small things (hierarchical clustering)

Some Fundamental Problems of Baryonic Cosmology

- Big Bang nucleosynthesis shows that $\Omega_b \ll 1$
- Cosmic Microwave background fluctuations need to be $\sim 10^{-3}$, as opposed to 10^{-5} as observed; not enough time to grow structure!!
- We know $\Omega_m > \Omega_b$ from many sources
- As we will see CMB also requires two “fluids”

The end