The Simplest Picture of Galaxy Formation and Why It Fails

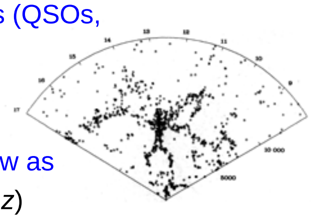
- Cosmic Microwave Background is smooth to a few parts in 10^5

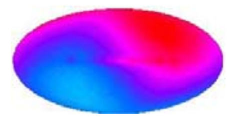
  $\delta\rho/\rho \sim 10^{-4}$

Blue = 0°K
Red = 4°K

- Yet high contrast structures (QSOs, galaxies) by $z \sim 6$.

  $\delta\rho/\rho >> 1$





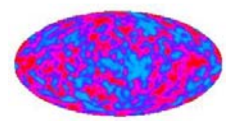
Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy
~ 1 part in 300

- Adiabatic perturbations grow as

  $\delta\rho/\rho \propto t^{2/3} \propto R(t) \propto 1/(1+z)$

- Expect only

$$\left(\frac{\delta\rho}{\rho}\right)_{QSO} = \frac{(1+z)_{CMB}}{(1+z)_{QSO}}\left(\frac{\delta\rho}{\rho}\right)_{CMB} = \frac{1100}{7}\times 10^{-4} = 0.01$$



After removing dipole
Red – blue = 0.0002°K
~ 1 part in 10^5

So where did galaxies and clusters come from?

In an expanding universe, will a cloud collapse?

The Jeans criterion Version 2: $2K < -U$

Pressure support < gravity

Collapse if $2K < -U$

$$2\left(\frac{1}{2}M_T v_s^2\right) < \frac{3}{5}\frac{GM_T^2}{\lambda}$$

v_s = sound speed

$$v_s^2 < \frac{3}{5}\frac{GM_T}{\lambda} = \frac{3G}{5}\frac{(4/3)\pi\lambda^3\rho_T}{\lambda} = \frac{4}{5}\pi G\lambda^2\rho_T$$

$$\left(\frac{3M_b}{4\pi\rho_b}\right)^{2/3} = \lambda^2 > \frac{5v_s^2}{4\pi G\rho_T}$$

$$M_{J,b} > const.\times\frac{\rho_b v_s^3}{\rho_T^{3/2}}$$ = [CO eq. 30.27]

Radiation era

$$v_s = \frac{c}{\sqrt{3}}$$

$\rho_b \propto R(t)^{-3} \propto T^3$

$\rho_T \propto R(t)^{-4} \propto T^4$

$M_{J,b} \propto T^{-3}$

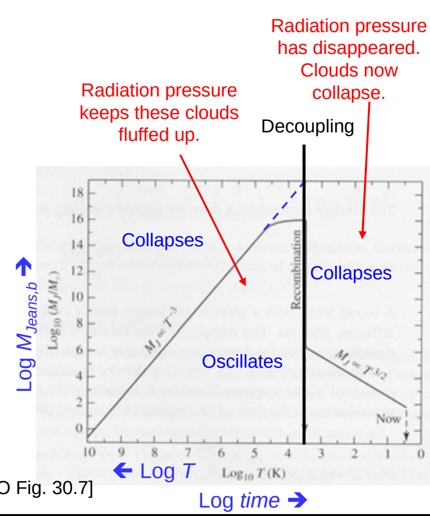
After decoupling

$$v_s = \sqrt{\frac{5kT}{3\mu m_H}}$$

$\rho_b \propto T^0$

$\rho_T \approx \rho_b \propto T^0$

$M_{J,b} \propto T^{3/2}$



[CO Fig. 30.7]

Q.When do the oscillations start?

When

Particle horizon = λ_M

Size scale for mass *M*

$2K < -U$

Pressure support < gravity

Before decoupling:

- Particle Horizon

  $d_h = 2ct \propto R(t)^2 \propto T^{-2}$ (radiation era)

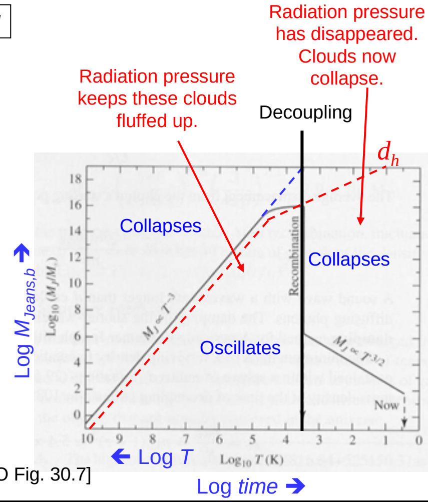
- Proper distance containing mass M

  $\lambda = (M_b/\rho_b)^{1/3} \propto M_b^{1/3} R(t) \propto M_b^{1/3} T^{-1}$

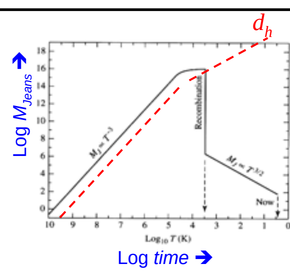
- Mass for which $\lambda = d_h$

  $M_b \propto T^{-3} \propto R^3 \propto t^{3/2}$ (radiation era)

  $M_b \propto T^{-3/2}$ (matter era)



[CO Fig. 30.7]



The Rest of the Story:

- Mass for which $\lambda = d_h$

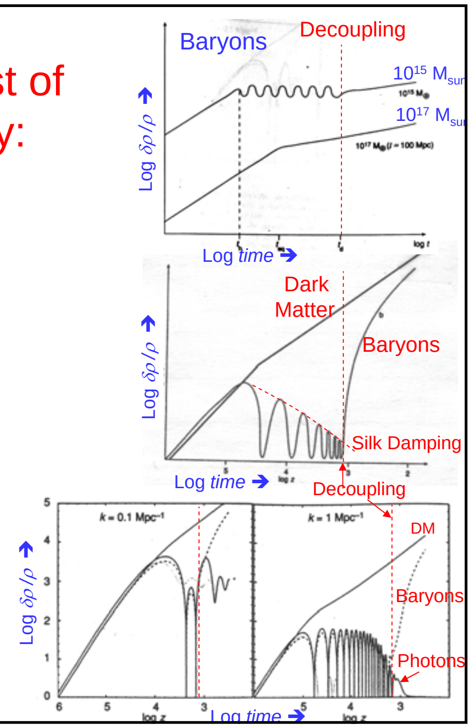
  $M \propto T^{-3}$ (rad. era)

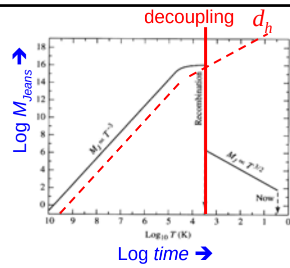
  $M \propto T^{-3/2}$ (matter era)

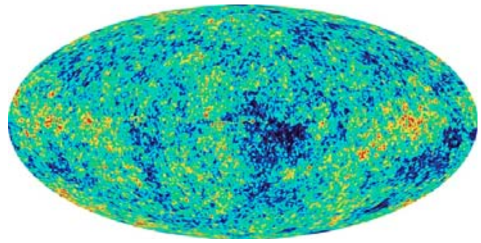
- At $t_{decoupling}$ this mass was ~ 10^{16} $M_\odot$
  - $M > 10^{16}$ $M_\odot$ → continued growth
  - $M < 10^{16}$ $M_\odot$ → oscillations once mass scale comes into particle horizon.

- But Dark Matter not subject to all this.
  - Does not feel radiation pressure.
  - Just collapses away…

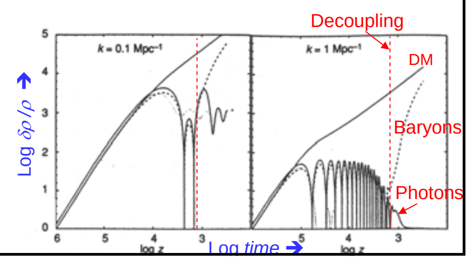
- Baryons fall into Dark Matter potential wells as soon as decoupling removes photon pressure support.

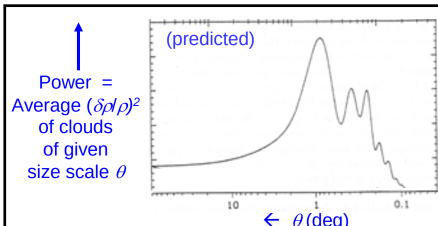


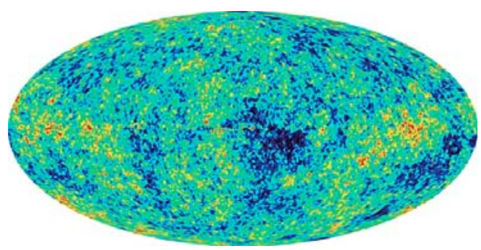




CMB Fluctuations = snapshot of oscillations at $t_{\text{decoupling}}$



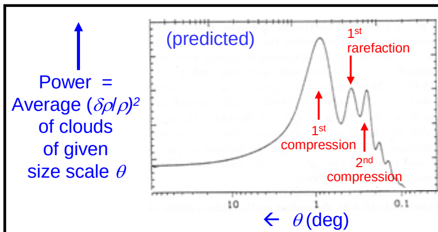


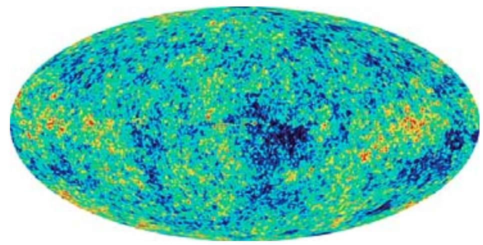


Fourier analyze WMAP image:

- Measures "*Power*" for each size scale θ.
- = *Power* for each mass scale *M.*
- *But why more power for some mass scales than others?*

What is measured?





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- Measures "*Power*" for each size scale θ.
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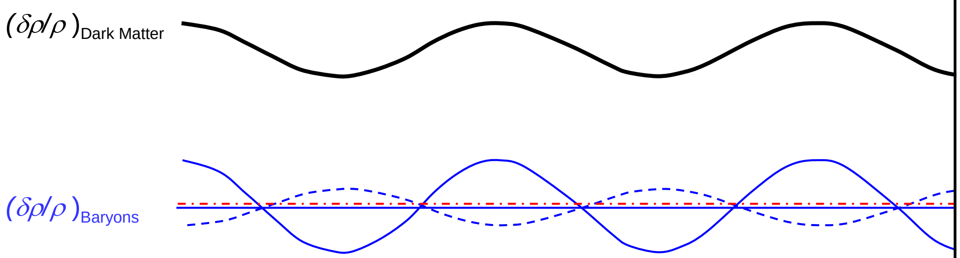
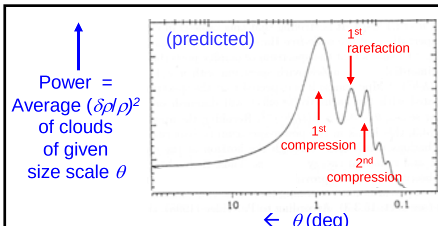
- *But why more power for some mass scales than others?*

- All blobs of same mass *M* oscillate synchronously.
- Peaks are for mass scales that are either fully compressed or fully rarified.



Baryons: Shorter spatial wavelengths oscillate with higher time frequency



First peak:

Size of "acoustic horizon"

$r = v_s\,(t_{\text{Decoupling}} - t_{Horizon}) = c\sqrt{3}\;t$

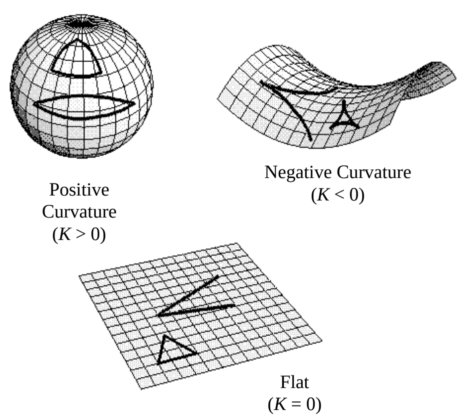
= linear size of perturbation

$\theta = r/\chi(d)$

$\chi = sin(d), d, sinh(d)$

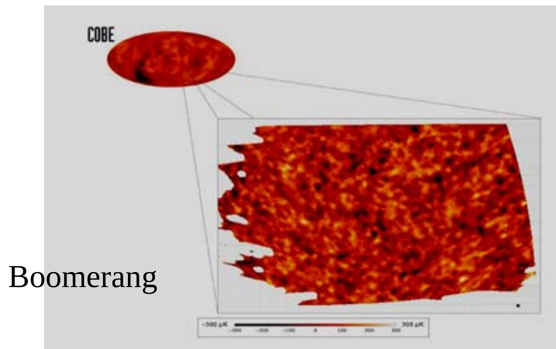
$l_{\text{peak}} = 220/\Omega_{\text{tot}}^{1/2}$ (l = multipole)

Measured l_{peak} ➔ $\Omega_{\text{tot}} = 1.02 \pm .02$



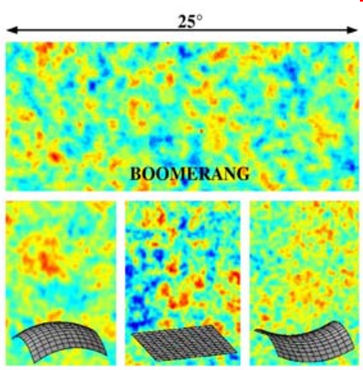
Boomerang balloon flight (1999)

Mapped Cosmic Background Radiation with far higher angular resolution than previously available.



Launch near Mt. Erebus in Antarctica

Position of 1st peak measures curvature



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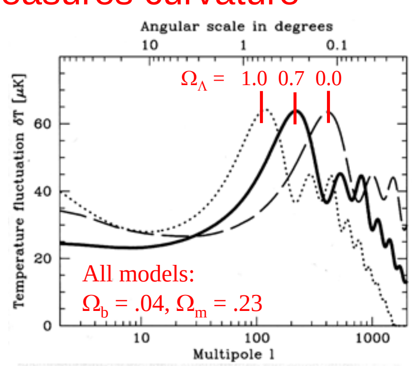
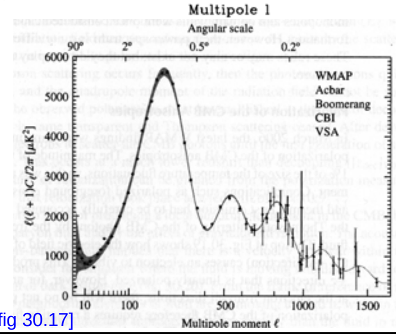
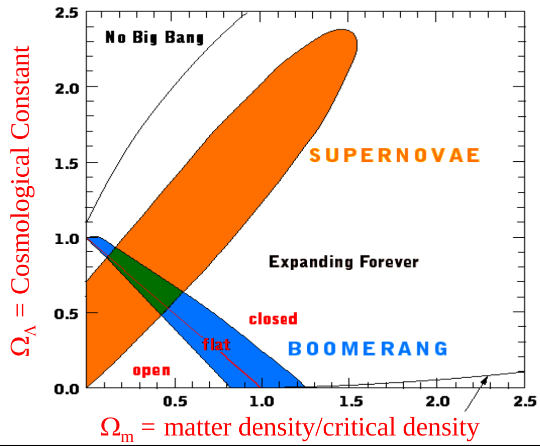




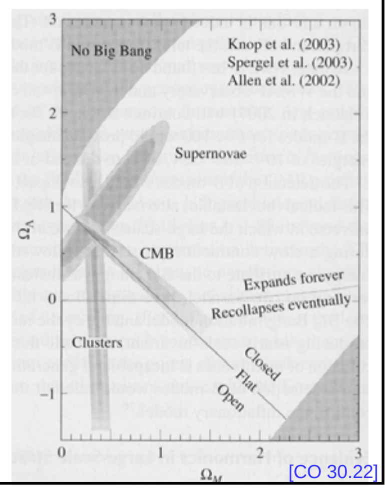
[CO fig 30.17]

The "Concordance" Cosmology (or ΛCDM)

- Type Ia Supernovae as "standard candles"
  - ➔ accelerating expansion
  - ➔ $q_o = \Omega_m/2 - \Omega_\Lambda$
- CMB anisotropy ➔ $\Omega_{total} = \Omega_m + \Omega_\Lambda$
- Can solve for Ω_m , Ω_Λ



Another independent measure:
Rate of galaxy cluster evolution



[CO 30.22]