Observational cosmology: Large scale structure

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UCL

Large Scale Structure

After these lectures, you should be able to:

- Describe the matter power spectrum
- Explain how and why the peak position depends on Ω_m
- Explain the effect of hot dark matter on the matter power spectrum
- Discuss the issues in relating the galaxy and matter power spectra
- Summarise the latest observations and their constraints on Ω_m and the neutrino content

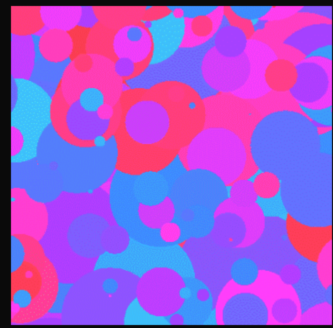
Inhomogeneities in the Universe

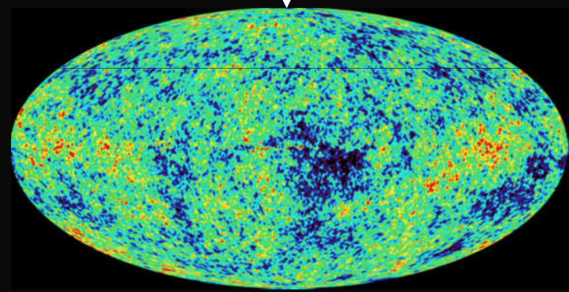
Summary of relevant comments so far:

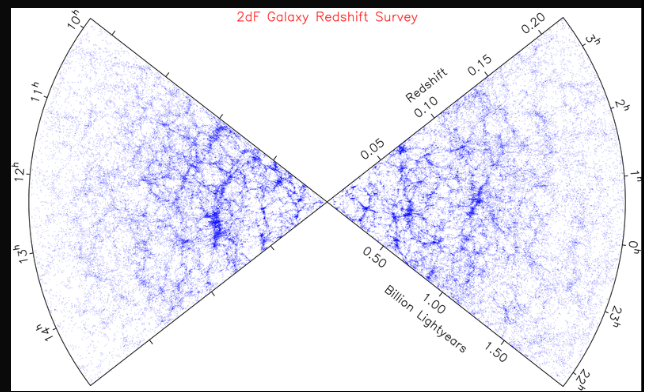
- Quantum fluctuations during inflation produce inhomogeneities
- CMB fluctuations ~ 1 in 100,000
- Galaxies today are clumped

Current thinking:

- Gravity amplifies fluctuations
- Before recombination
  - Competing effects of gravity and pressure
- Laws of physics predict what we see
  - Mainly gravity and electromagnetism



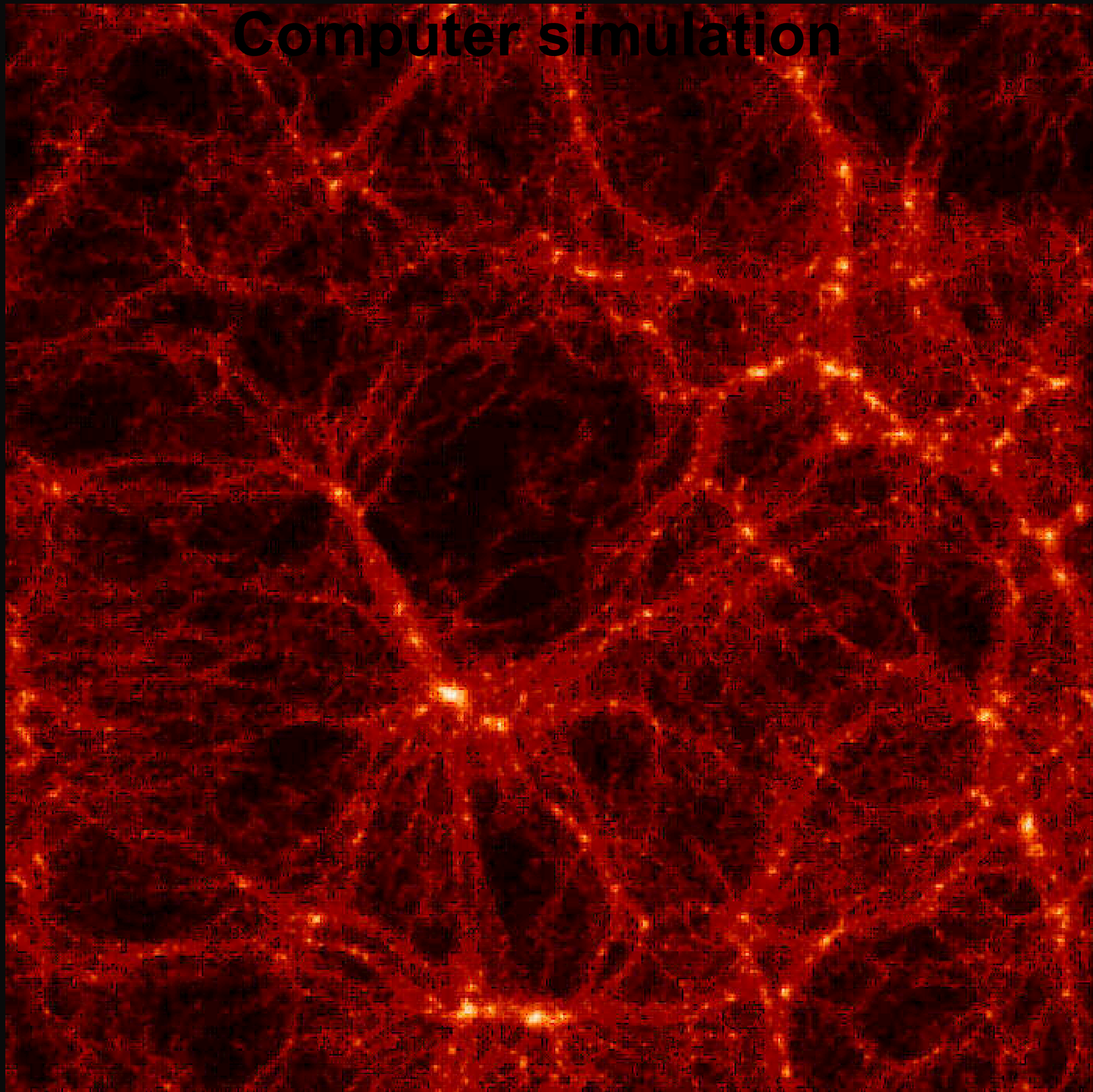




Observations: The 2dF galaxy redshift survey

http://www.roe.ac.uk/~jap/2df/2df_rotslice.mpg

Computer simulation



Power Spectrum of density fluctuations

Field of density fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

Fourier transform

$$\delta(k) = \int d^3x \, e^{-ik\cdot x} \, \delta(x)$$

Power spectrum essentially square of Fourier transform

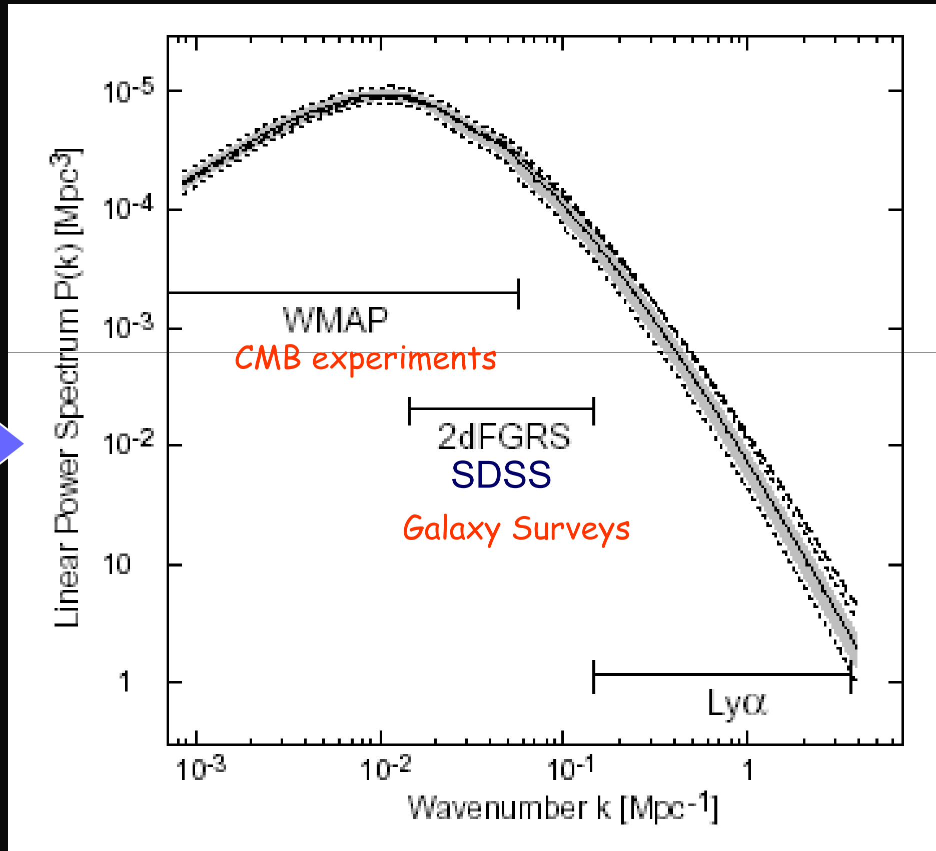
$$\langle \delta(k)\delta(k') \rangle = (2\pi)^3 \hat{\delta}(k-k') P(k)$$

with $\hat{\delta}$ the delta function

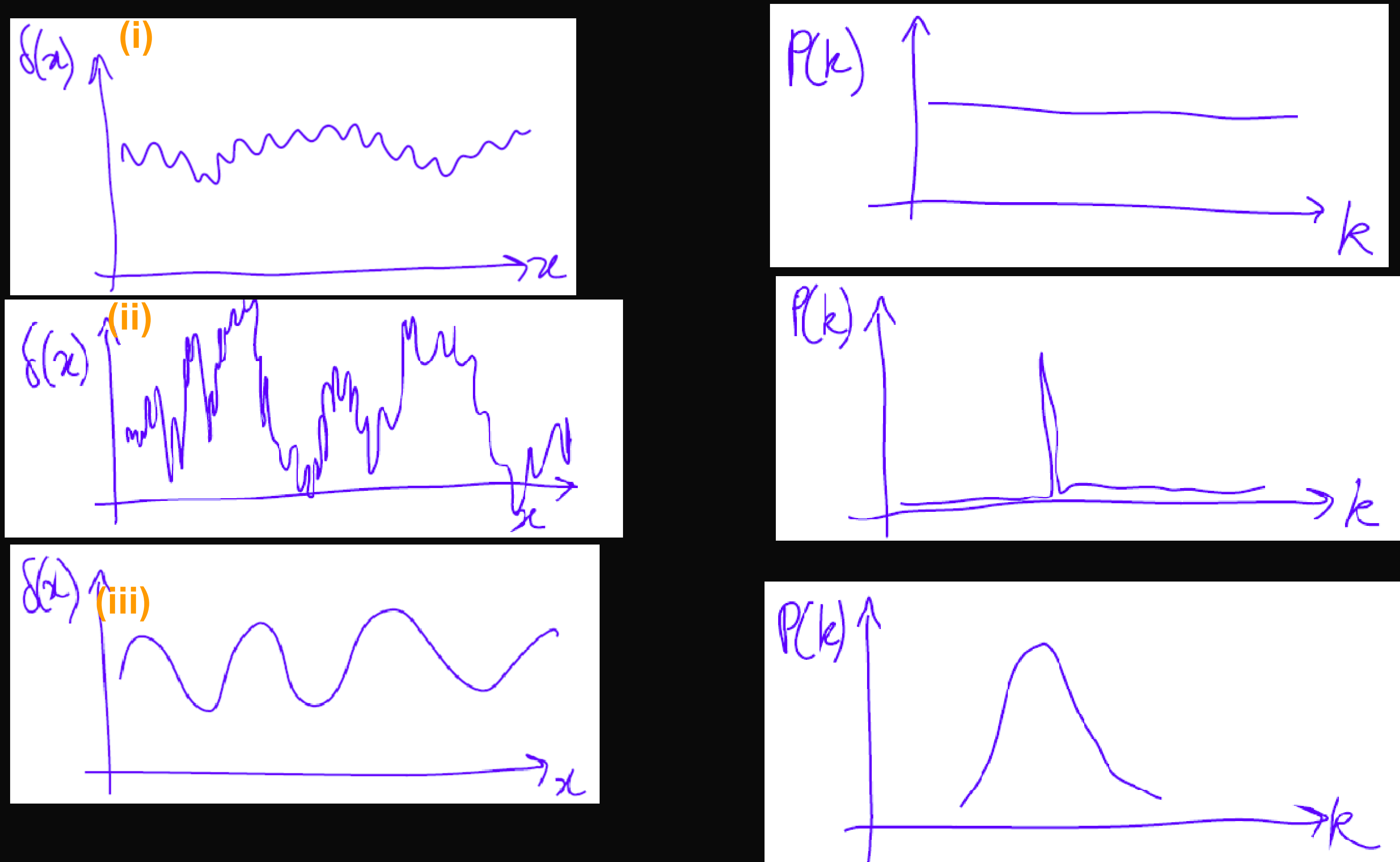
Power spectrum is Fourier transform of two-point correlation function

$$\xi(x) = \langle \delta(x_2)\delta(x_1) \rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik\cdot x} P(k)$$

where $x = x_2 - x_1$



Match up the FT pairs?

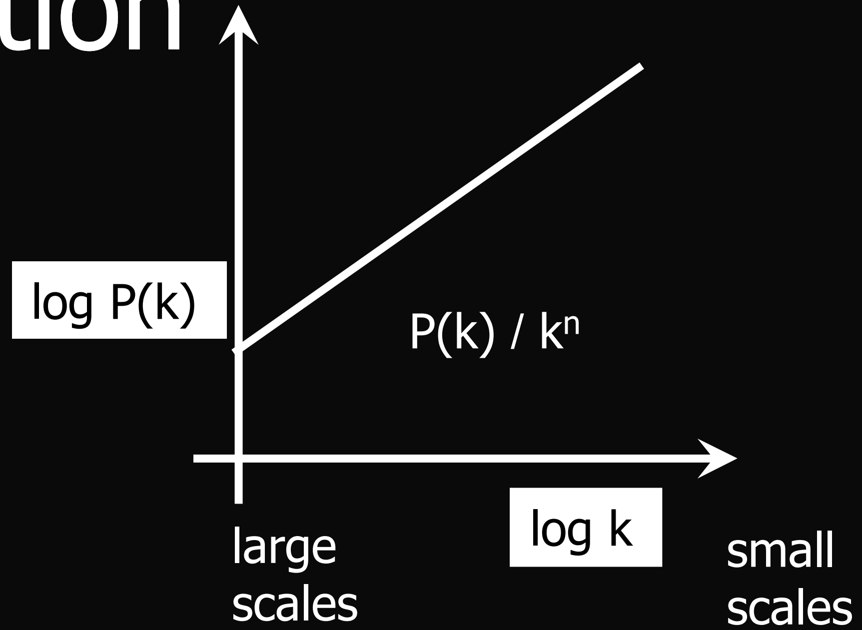


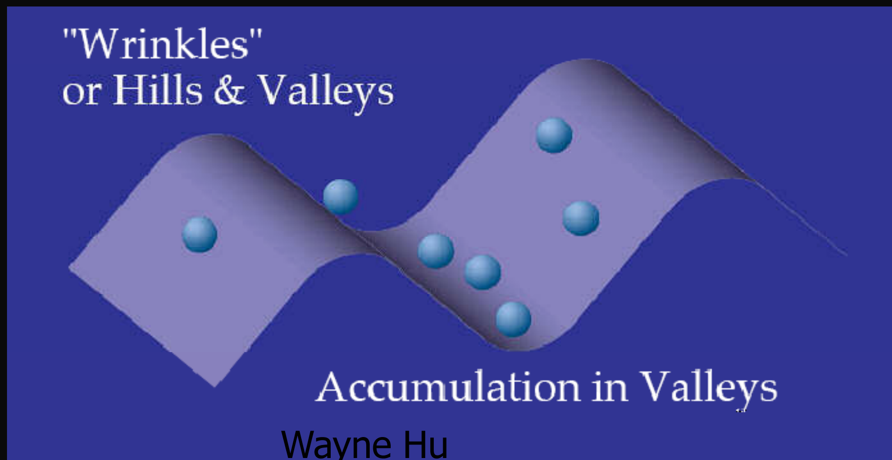
Physical understanding of the theoretical prediction

Ingredients

- Assumption about post-inflation P(k)
- Growth due to gravitational collapse
- Plasma oscillations
- We will see this in the next lectures…

- Inflation predicts $P(k) \propto k^n$
  – where $n \sim 1$
- Gravitational collapse amplifies fluctuations





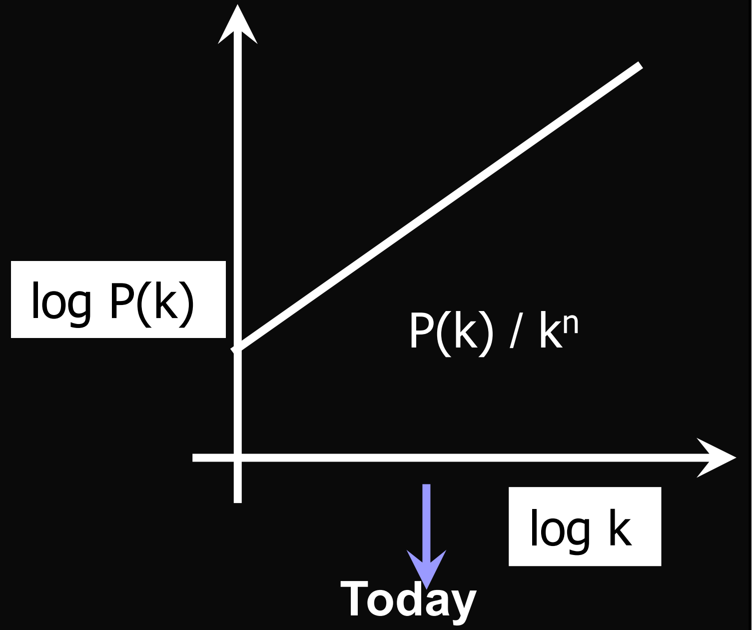
Wayne Hu

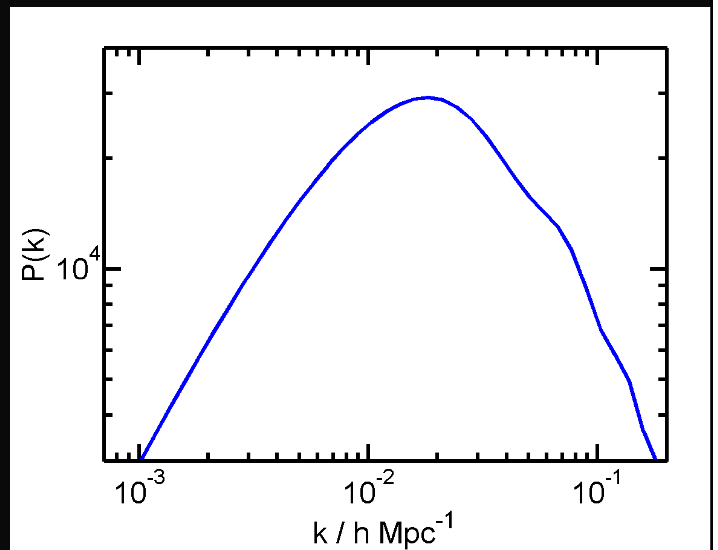
http://background.uchicago.edu/~whu/beginners/introduction.html

Why is there a peak in P(k) ?

Radiation domination

- ~Matter has no gravitational effect
- There is a length called the Jeans length.
- Radiation undergoes acoustic osc.
  - Overdensities on scales greater than the Hubble length
    - don't oscillate they just grow
  - Overdensities on smaller scales:
    - oscillate and so don't grow
  - The Hubble length increases as a function of time





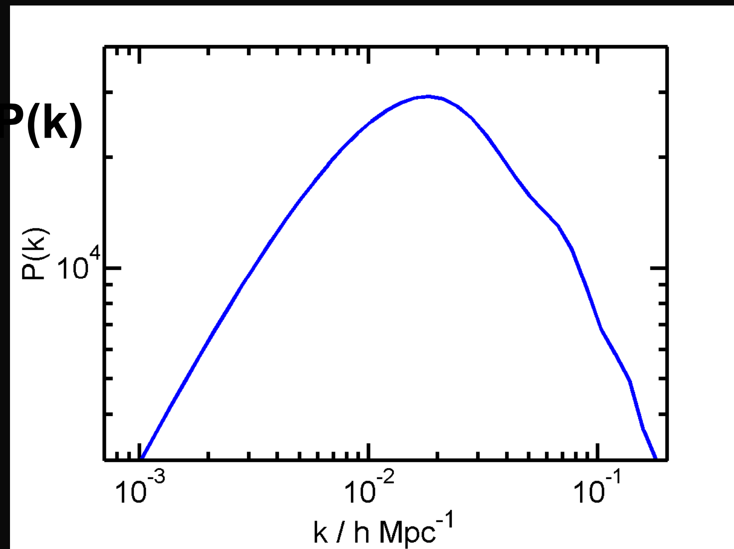
Why is there a peak in P(k) ?

Matter domination

- ~Radiation has no gravitational effect
- Dark matter has no pressure
  - ⇒ There are no oscillations in the DM
  - ⇒ Overdensities on all scales grow

Today

log P(k)



log k

Newtonian perturtabion theory

- On the blackboard!!!

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_0\delta = 0$$

- And the jeans length!

Derive and discuss $a(t)$, $\dot{a}(t)$, $\ddot{a}(t)$ for an Einstein de-Sitter (EdS) Universe

- EdS $\leftrightarrow$ $\Omega_k = 0$, $\Omega_\Lambda = 0$ ($\Omega_r = 0$)
- From $1 = \Omega_m + \Omega_k + \Omega_\Lambda \Rightarrow \Omega_m = 1$
- Friedman eq^n becomes: $\left(\frac{\dot{a}}{a}\right)^2 = H_0^2 a^{-3}$
- Solve the Fr. eqn, to find $a(t)$:

$$\frac{\dot{a}}{a} = H_0 a^{-3/2}$$

Multiply through by $a^{3/2}$, $\dot{a} = \frac{da}{dt}$ $\rightarrow$ $a^{1/2}\, da = H_0\, dt$

$\int$ $\Rightarrow$ $\frac{2}{3} a^{3/2} = H_0 t + \text{const}$

Assume Big Bang, always matter dominated (by def^n of EdS)
$\Rightarrow$ when $t=0$, $a=0$ $\Rightarrow$ const $=0$

Rearrange: $a = \left(\frac{3}{2} H_0 t\right)^{2/3}$ ‖

Differentiate wrt t: $\dot{a} = \left(\frac{3}{2} H_0\right)^{2/3} \frac{2}{3} t^{-1/3}$ ‖

" $\ddot{a} = -\frac{1}{3}\frac{2}{3}\left(\frac{3}{2} H_0\right)^{2/3} t^{-4/3}$ ‖‖

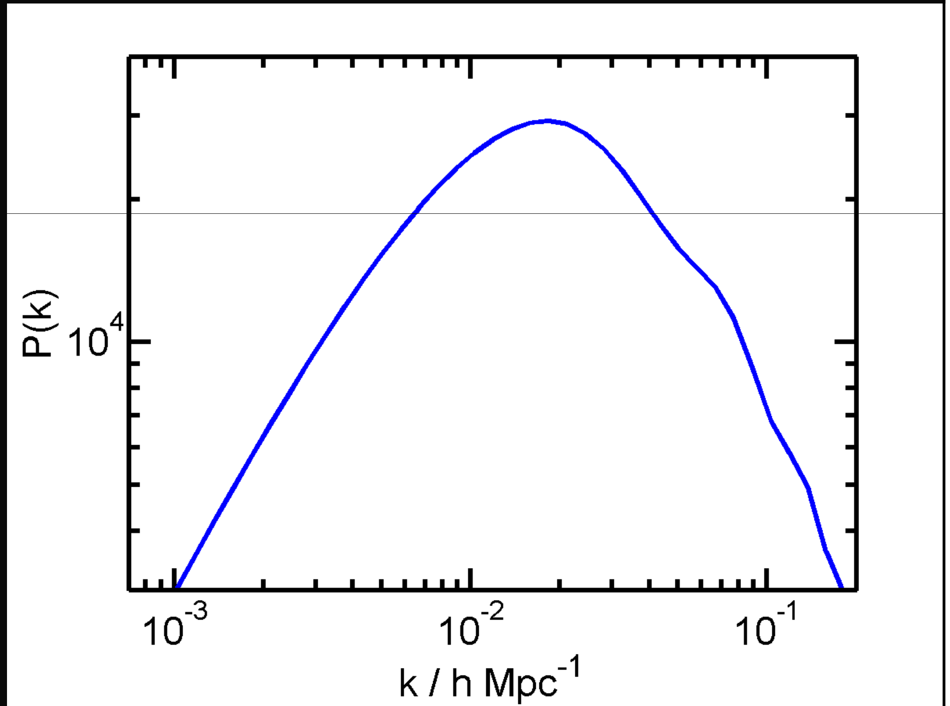
$$4\pi G\rho_m = (3/2)a^{-3}H_0^2 = 2/(3t^2).$$

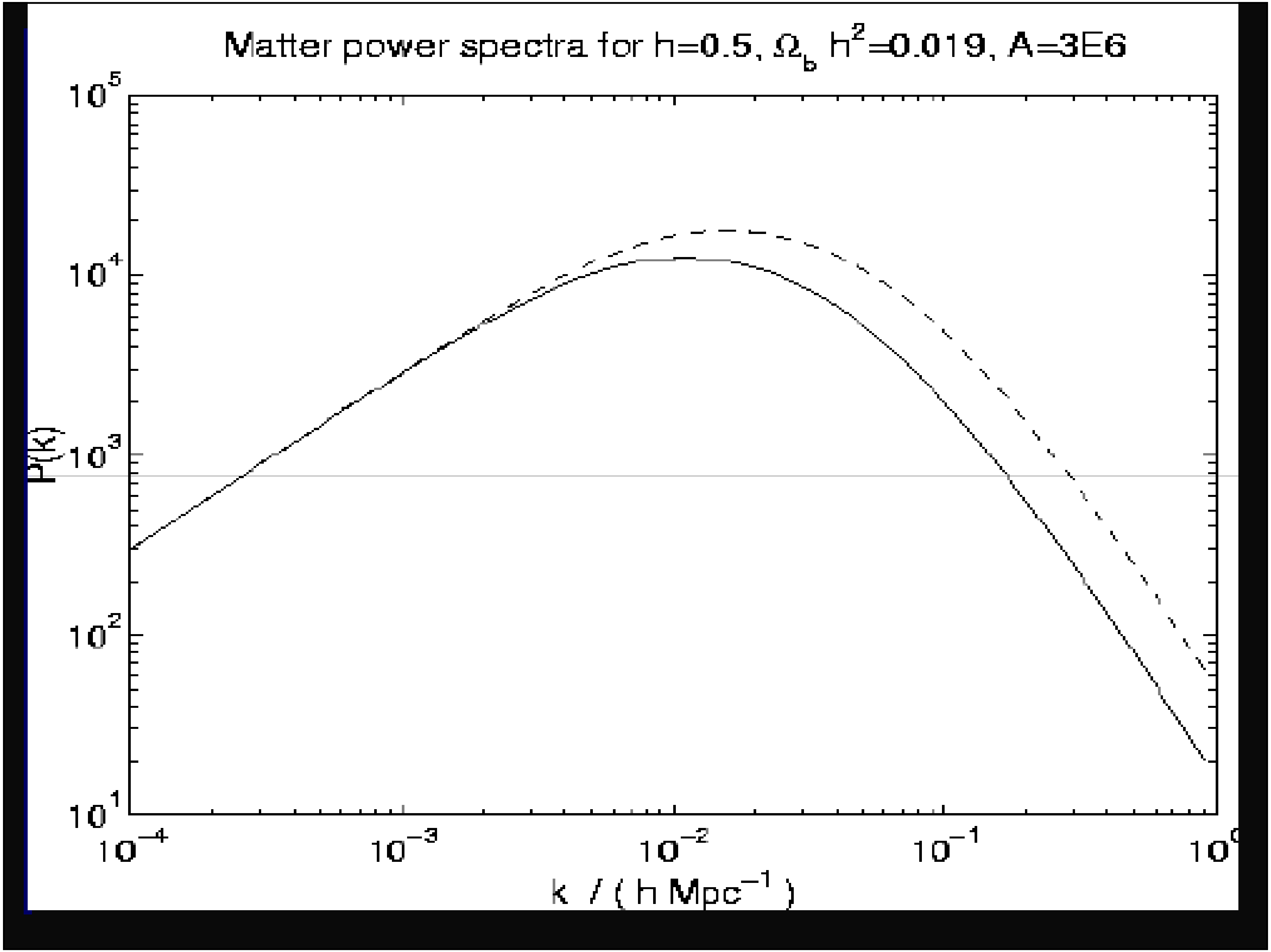
$$\delta \propto t^{2/3} \text{ or } t^{-1}.$$

The power spectrum P(k)

- We predict only statistical properties
  - Quantum fluctuation origin: can't say what happens where exactly
- Use power spectrum P(k)
- Shape depends on
  - Ω_m total matter content
  - H_0, Hubble constant
  - [Ω_b baryon content
  - Ω_{DE} dark energy content]

Theoretical prediction





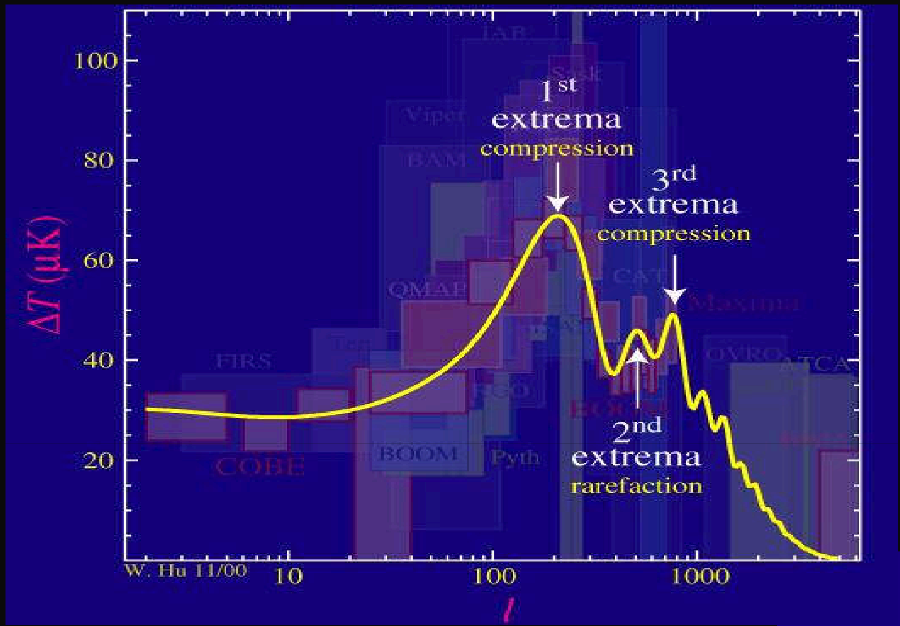
Matter power spectra for h=0.5, Ω_b h^2=0.019, A=3E6
10^5
10^4
10^3
10^2
10^1
P(k)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
k / (h Mpc^{-1})

Acoustic oscillations

- Photon-baryon fluid
  - Gravity pulls together; Pressure pushes apart
- Analogy: mass on spring
  - Gravity pulls spring down; Spring pulls it back up
  - Bounces: Frequency depends on k, m
- Three important components:
  - Photons
  - Dark matter
  - Baryons
    - Interact with photons via EM and gravity
    - Interact with DM via gravity
- Full calculation requires numerical solution

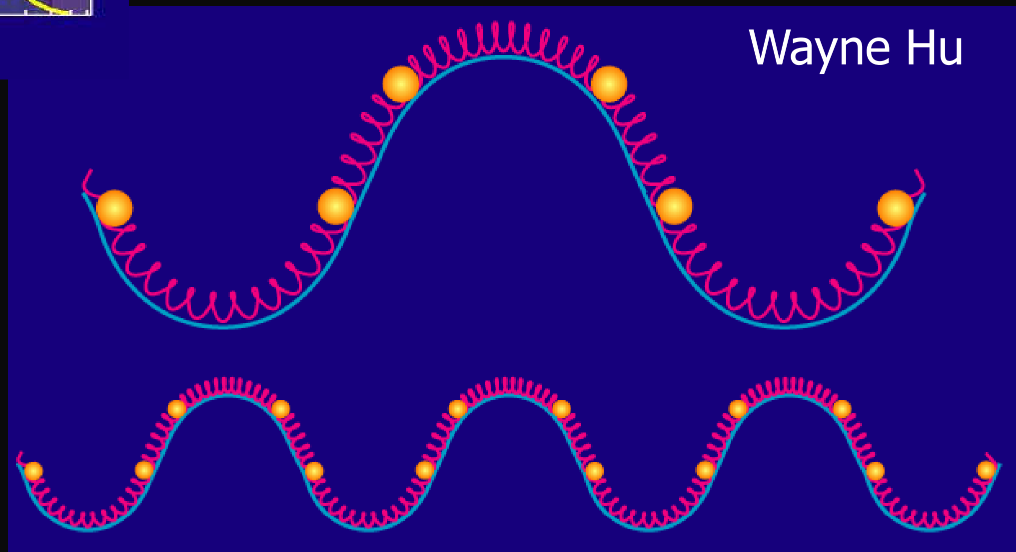
  ~ 1 min of CPU time [See CAMB, CMBFAST, CMBEASY]

Sound waves:



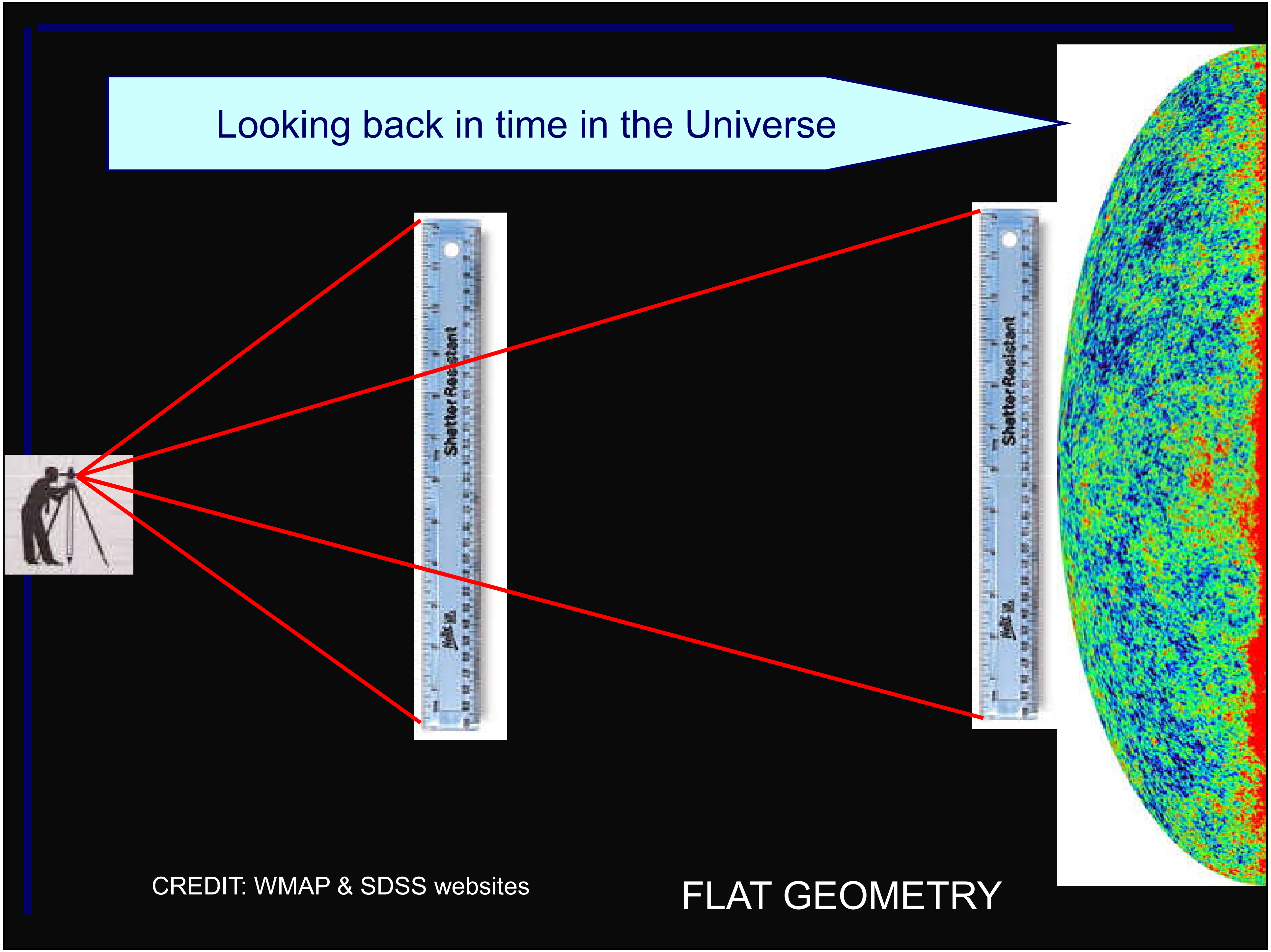
After recombination:

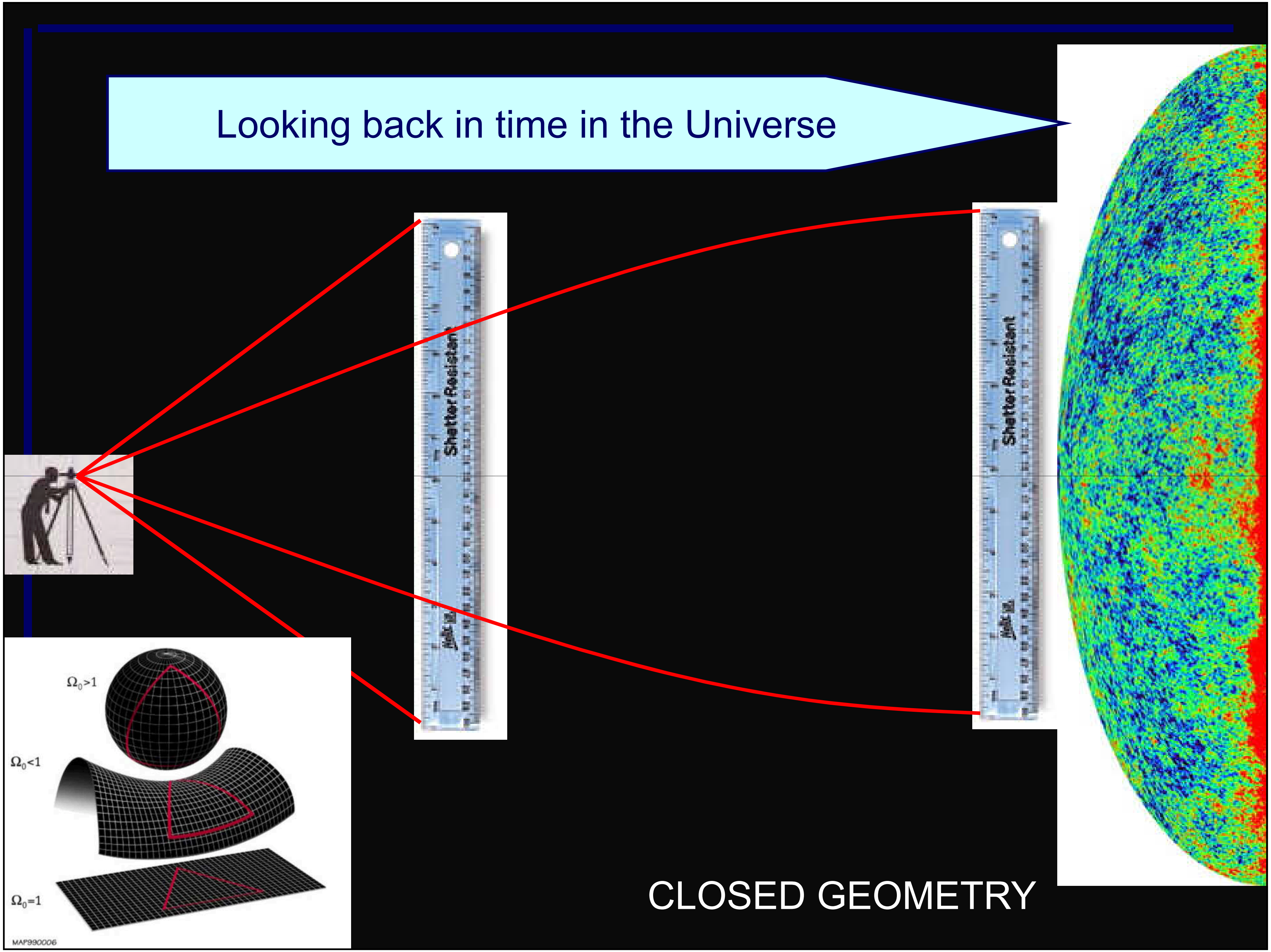
- Universe is neutral.
- Photons can travel freely past the baryons.
- Phase of oscillation at t_{rec} affects late-time amplitude.
- Waves are frozen



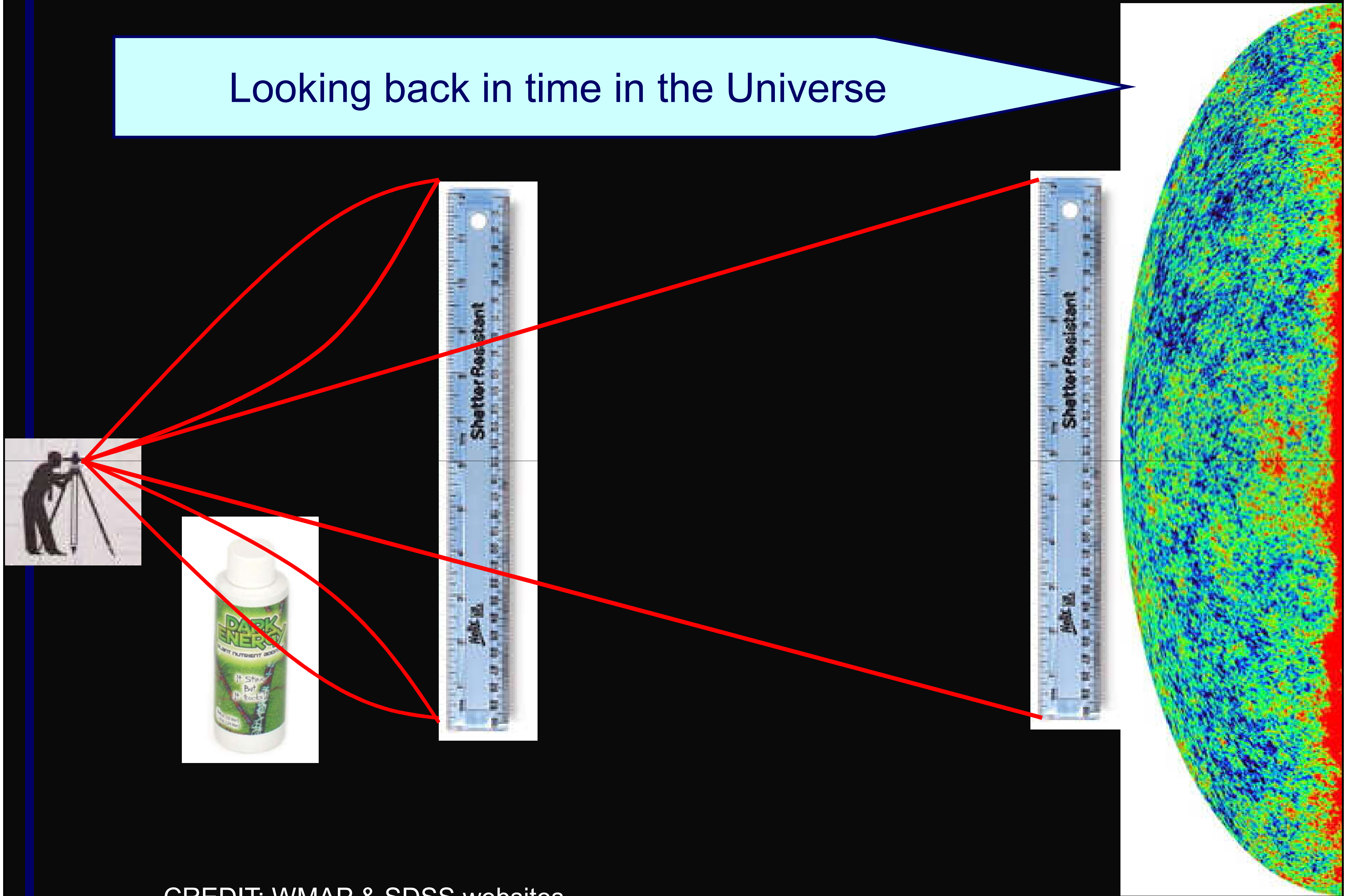
Before recombination:

- Universe is ionized.
- Photons provide enormous pressure and restoring force.
- Perturbations oscillate as acoustic waves.


Looking back in time in the Universe
Shatter Resistant
Shatter Resistant
CREDIT: WMAP & SDSS websites
FLAT GEOMETRY

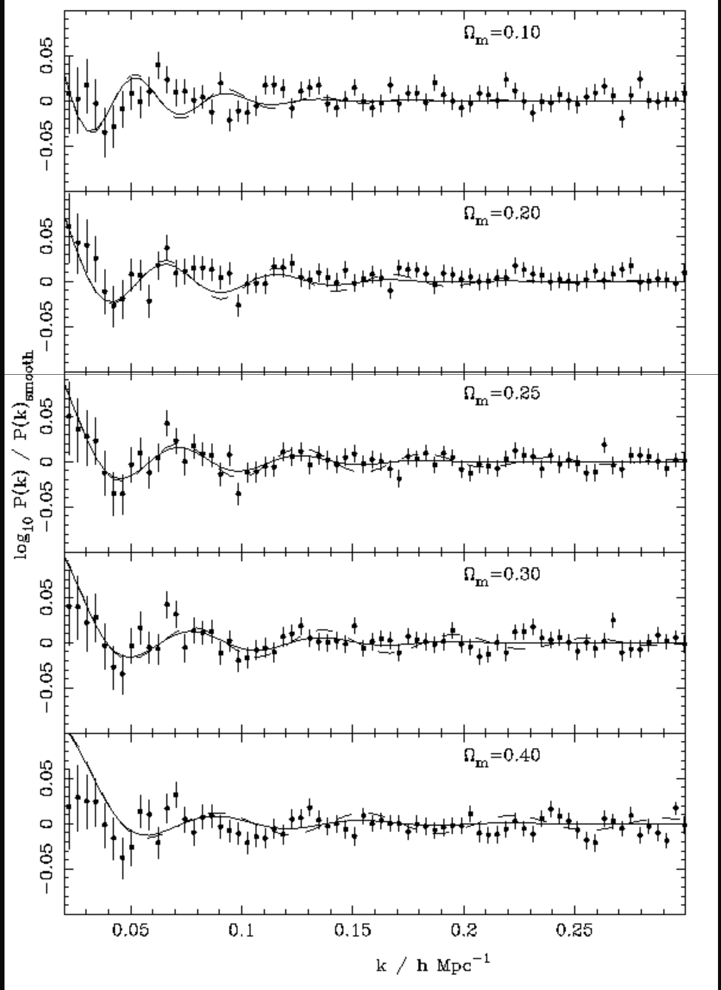

Looking back in time in the Universe
Shatter Resistant
Shatter Resistant
$\Omega_0>1$
$\Omega_0<1$
$\Omega_0=1$
MAP990006
CLOSED GEOMETRY

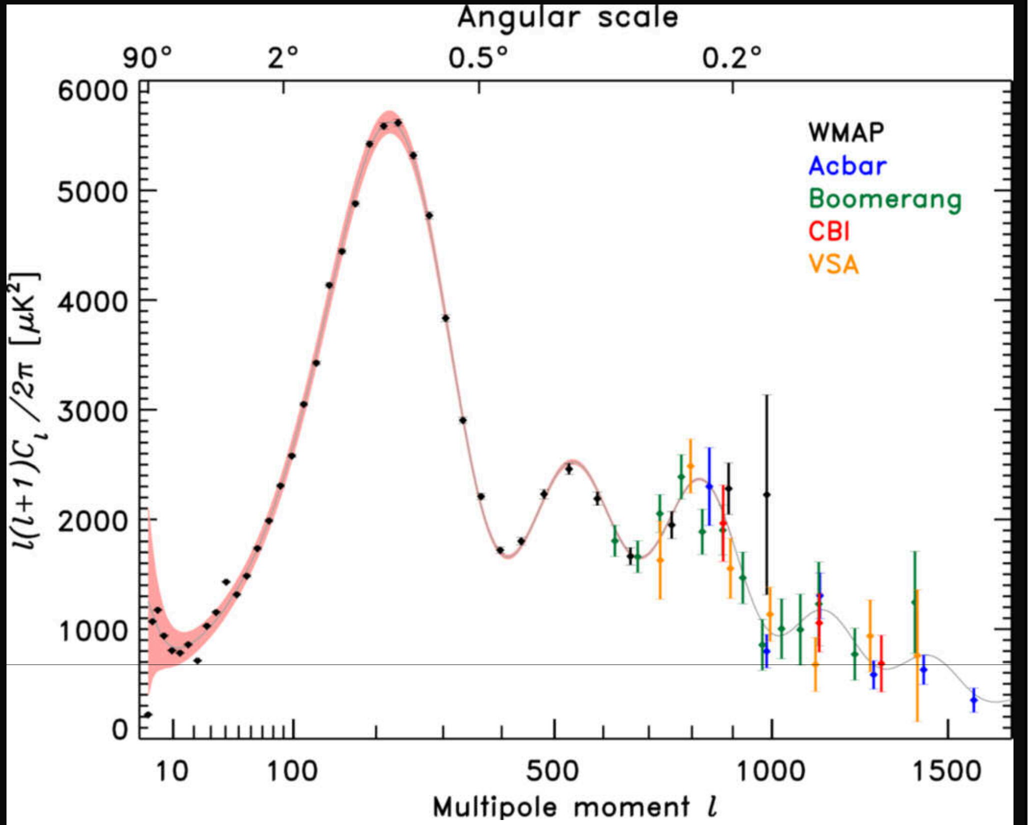
Looking back in time in the Universe

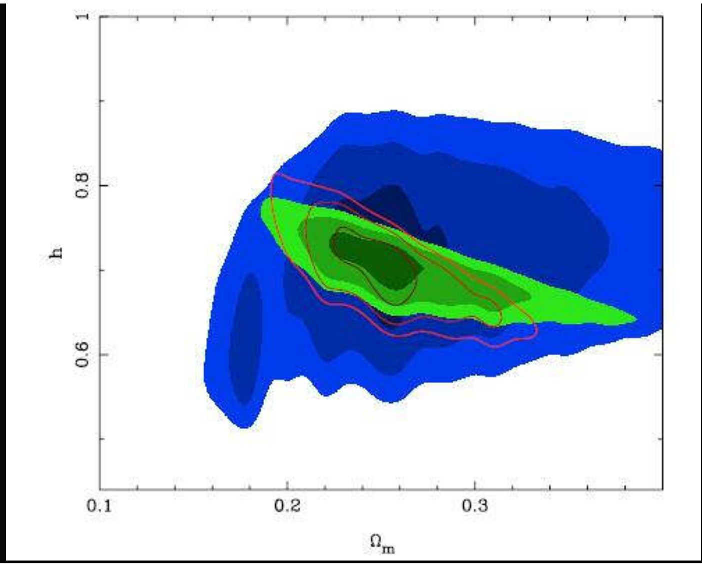


CREDIT: WMAP & SDSS websites

WMAP & SDSS fourrier space







Percival et al. 06

Hot dark matter

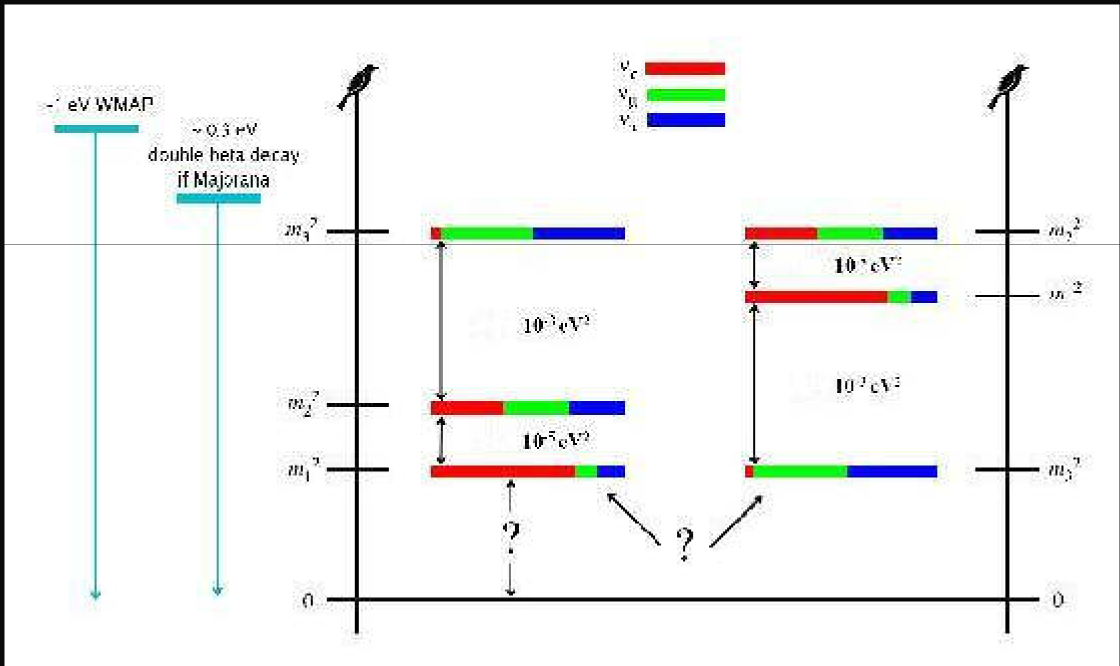
- e.g. neutrinos
- Move quickly

  $\Rightarrow$ can't cluster on small scales

- On largest scales gravity causes collapse
  - too far for neutrinos to travel to wash out the fluctuation

- Effect on the matter power spectrum:

Neutrino Physics – Mass hierarchies



Neutrinos Oscillate

Which means they have mass

2 possible hierarchies given neutrino data: normal and inverted

2 possible scenarios:

Quasi-degenerate or non-degenerate spectrum

parameter	best fit	3σ range
$\Delta m^2_{21}\ [10^{-5} eV]$	8.1	7.2–9.1
$\Delta m^2_{31}\ [10^{-3} eV]$	2.2	1.4–3.3
$\sin^2\theta_{12}$	0.30	0.23–0.38
$\sin^2\theta_{23}$	0.50	0.34–0.68
$\sin^2\theta_{13}$	0.000	≤ 0.047

Neutrinos as Dark Matter

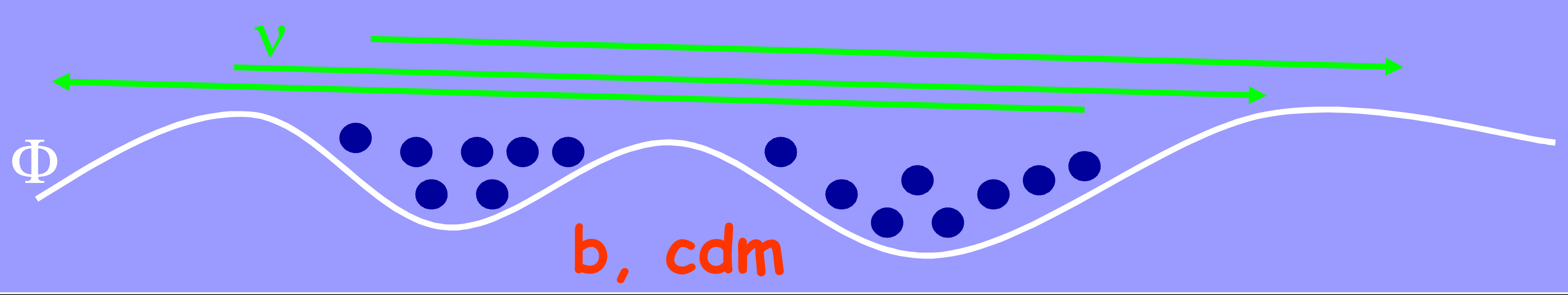
- Neutrinos are natural DM candidates

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\ \text{eV}} \qquad \Omega_\nu < 1 \rightarrow \sum_i m_i < 46\ \text{eV}$$

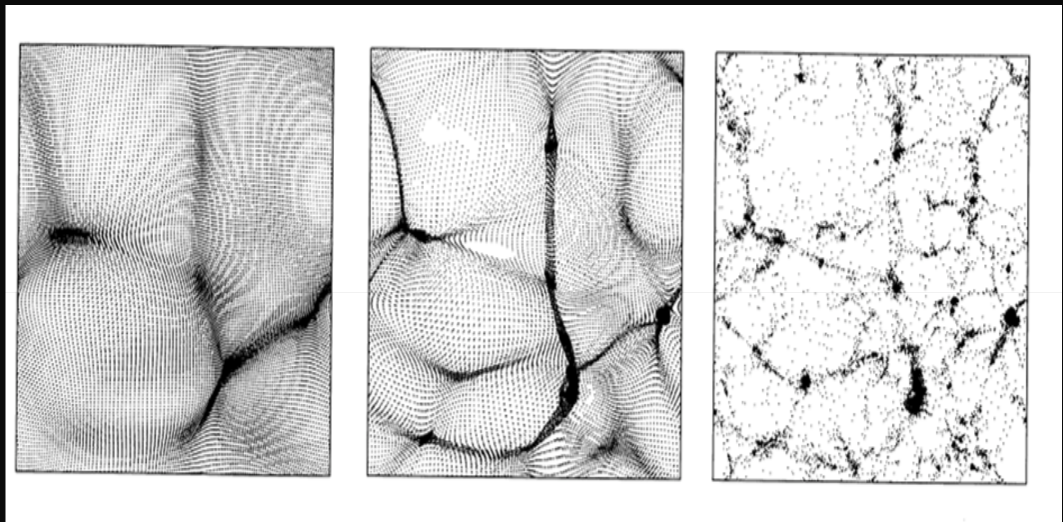
- They stream freely until non-relativistic (collisionless phase mixing) $\Rightarrow$ Neutrinos are HOT Dark Matter

- First structures to be formed when Universe became matter -dominated

Neutrino Free Streaming



Neutrino Physics - LSS



Colombi, Dodelson, & Widrow 1995

$k > k_{nr} = 0.026\ (m_\nu/1\ \mathrm{eV})^{1/2}\ \Omega_m^{1/2}\ h/\mathrm{Mpc}$

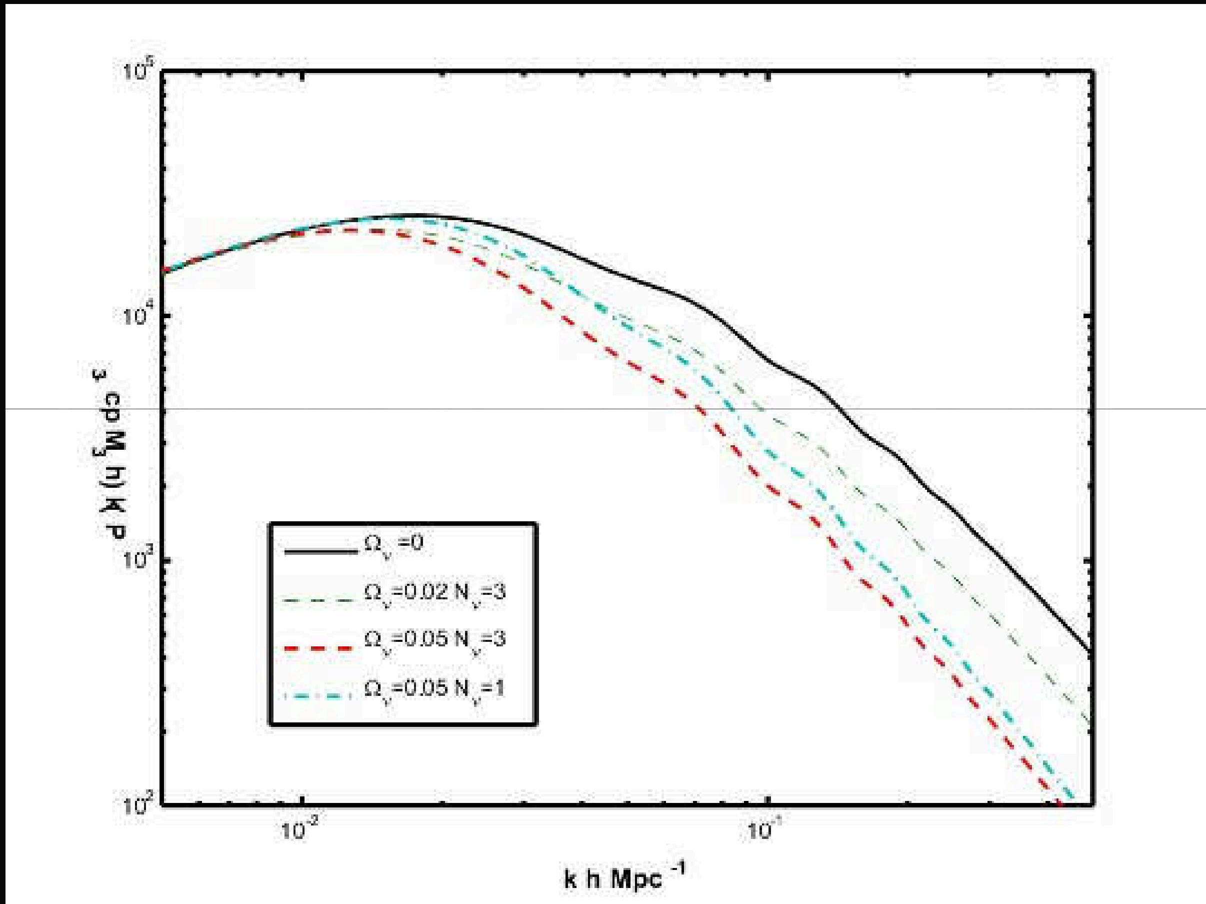
Three observable:

(i) overall damping of the power spectrum at small scales

(ii) Scale where this damping occur

(iii) Growth of structure

Neutrino Physics - LSS



Three observable:

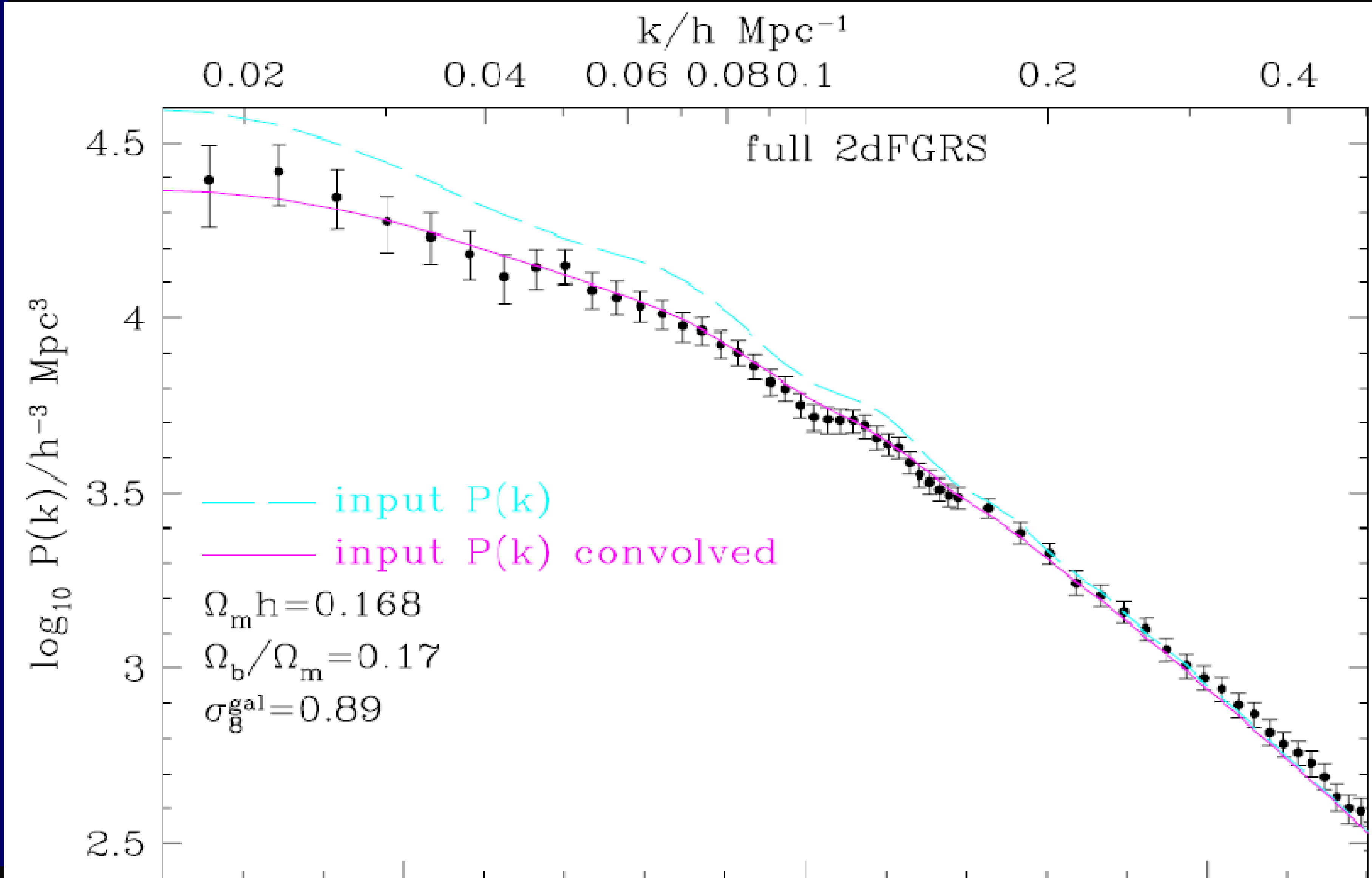
(i) overall damping of the power spectrum at small scales

(ii) Scale where this damping occur

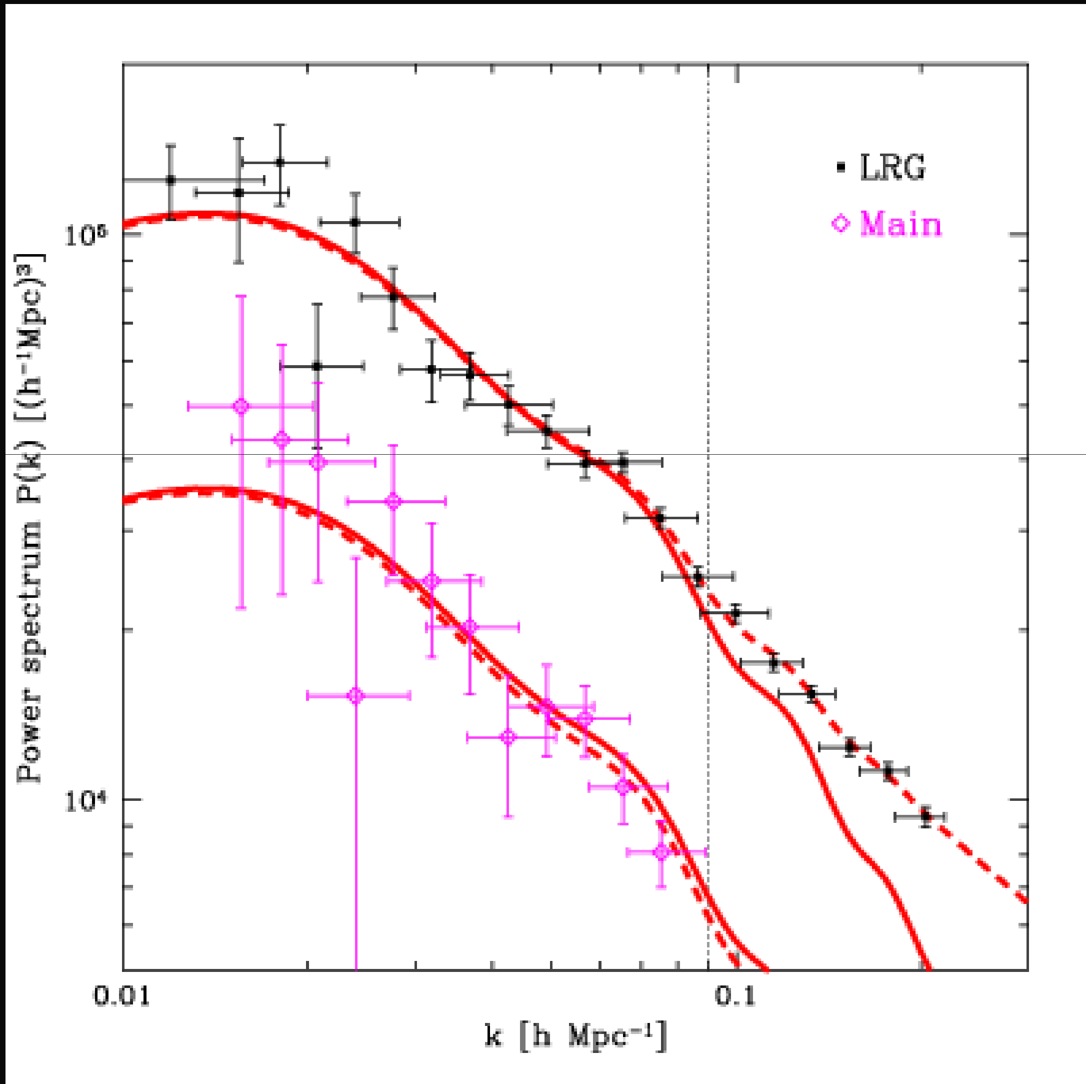
(iii) Growth of structure

In principle we can we distinguish between cases with N neutrinos with mass M and N/2 neutrinos with mass 2M.

Observed galaxy power spectrum (data points)



Observed galaxy power spectrum (data points)



Galaxy formation

- Predicting galaxy distribution is difficult
  - Requires simulating supernovae, AGN
- These problems have not been solved
- The simulations are very simple
  - Contain only dark matter!
- How does the distribution of dark matter relate to the distribution of galaxies?
  - Called "bias"
- Analogy: Does the distribution of light on earth reflect the population density?

- Cosmologists assume $P_g(k) = b(k)^2 P_{DM}(k)$
  - where b ~ constant on large scales

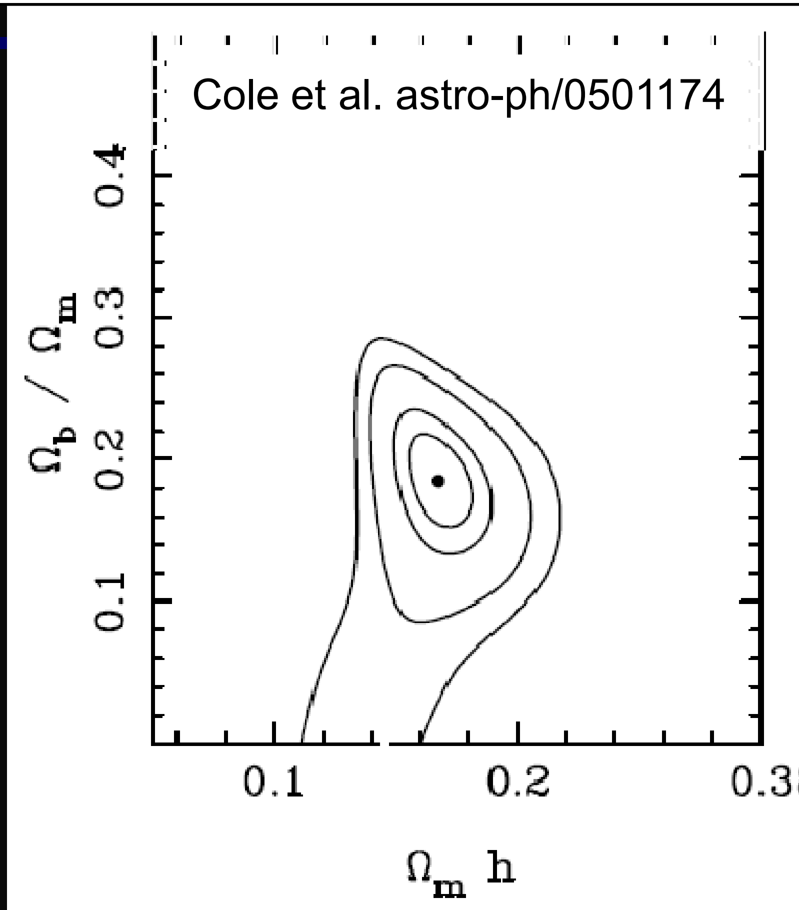
$$\frac{\delta n_g}{n_g} = b\frac{\delta \rho}{\rho}$$

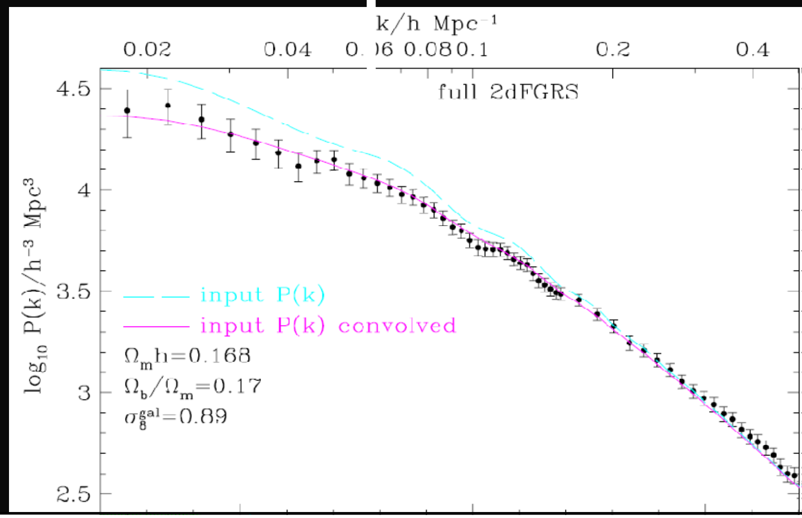
http://antwrp.gsfc.nasa.gov/apod/ap001127.html

Credit: C. Mayhew & R. Simmon (NASA/GSFC), NOAA/ NGDC, DMSP Digital Archive

Results

- What did we learn from the 2dFGRS?
- Ω_m h = 0.17 +/- 0.02 assuming h=0.72
- So Ω_m = 0.24 +/- 0.03
- Neutrinos cannot be the all the dark matter:
  - $\Omega_\nu / \Omega_m < 0.16$
- Similar results from SDSS





END for now!!!