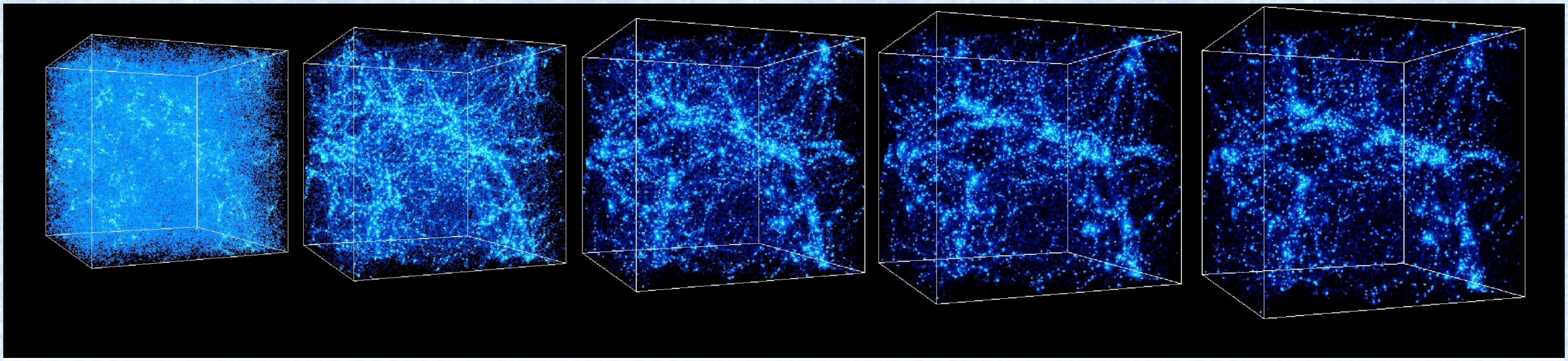
Physics 133: Extragalactic Astronomy and Cosmology



We will learn that the formation epoch of galaxies requires dark matter and that the galaxy distribution us something about the composition of dark matter.

Week 9

Outline for Week 9

- Gravitational instability determines how structure grows.
  - HW9 [11.4] (Reviews dynamical timescale)
  - Evolution of the Jeans Mass
  - Growth of density fluctuations in the linear regime
- The initial power spectrum of mass fluctuations
  - Inflation predicts the initial power spectrum at t_f.
    - Understand why a power law index n~1 is special.
  - P(k) evolves between t_f and t_{mr}.
    - Understand impact of the horizon
    - Why CDM predicts bottom up structure formation
- Insight from the distribution of galaxies
  - Why CDM is favored over HDM
  - The signature of baryon acoustic oscillations

Jeans Length. II. Temporal Evolution

- How large was the Jeans mass when baryonic structures began to form (i.e., at decoupling)?

$$\lambda_J = 2\pi c_s t_{dyn}$$

$$t_{dyn} = \left(\frac{1}{4\pi G\rho}\right)^{1/2}$$

$$M_J = \frac{4\pi}{3}\rho_b \lambda_J^3$$

- The Jeans length depends on the equation of state, which changes at decoupling.
- A relativistic gas has a fast sound speed and a large Jeans length.

Review: Sound Speed in Photon-Baryon Fluid

- Photon gas determines how the baryons move up until decoupling because $\varepsilon_m > \varepsilon_\gamma > \varepsilon_b$.
- We can find the sound speed in the photon-baryon fluid.

$$\epsilon = \epsilon_\gamma + \epsilon_b \text{ and } P = \frac{1}{3}\epsilon_\gamma$$

[Blackboard]

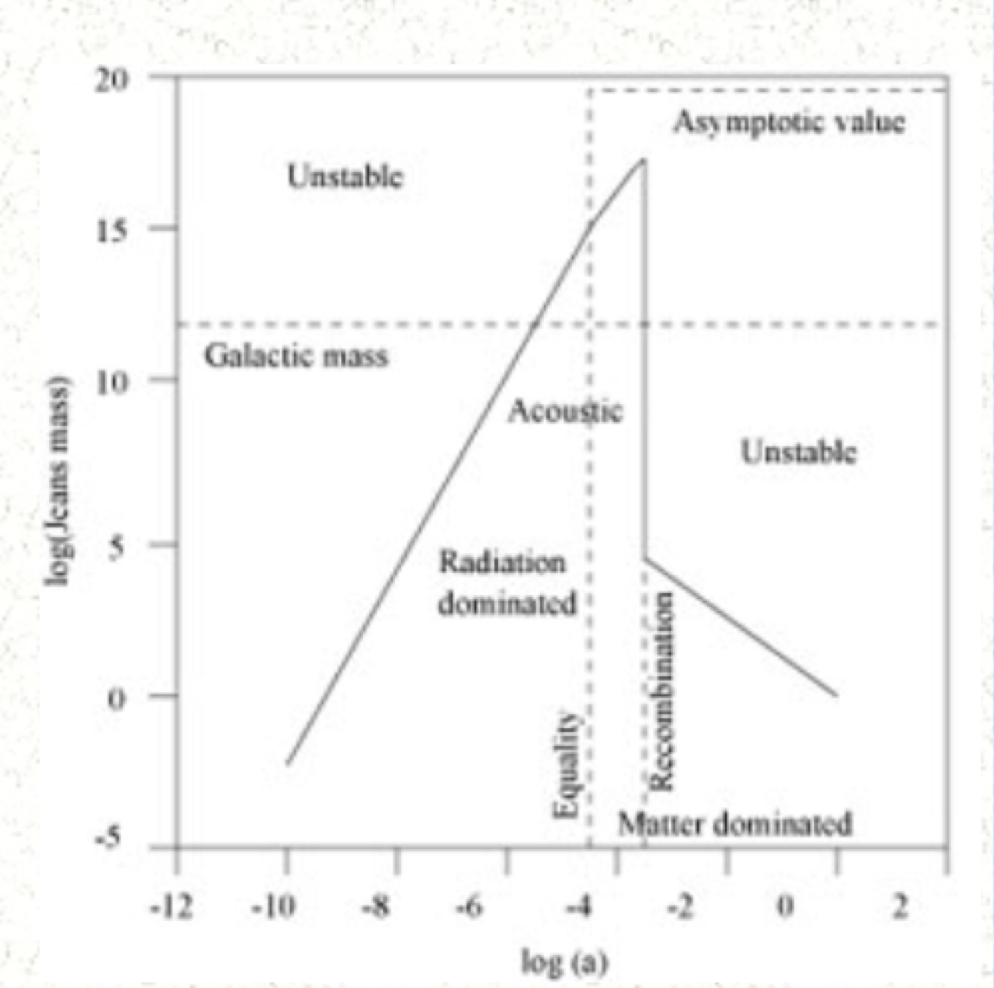
$$c_s^2 = \frac{dP}{d\rho} = \frac{dP}{d\epsilon}c^2$$

$$c_s^2 = \frac{4}{3}\frac{\Omega_{\gamma,0}}{4\Omega_{\gamma,0} + 3a\Omega_{b,0}}c^2$$

(HW8 [R] 11.3)

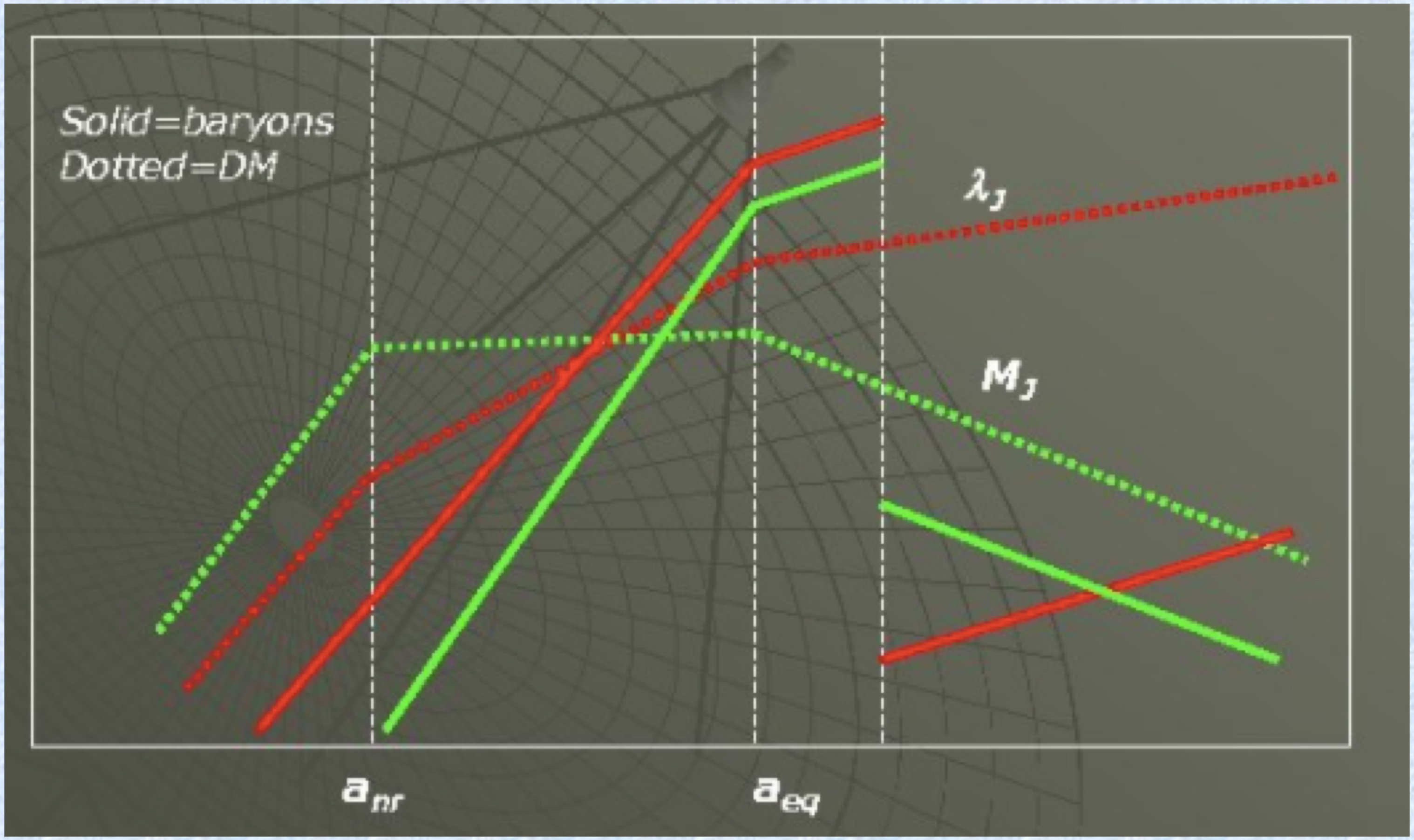
Jeans Length. II. Temporal Evolution (cont'd)

- Prior to photon-baryon decoupling density fluctuations simply create sound waves (on sub horizon scales)
- **After decoupling the Jeans length drops by a factor ~10^5.**
- And the minimum mass scale of an unstable region drops to that of large star clusters or small galaxies



Baryonic vs. DM
Jeans Mass (and Length)

The dark matter gets a head start on the baryons!



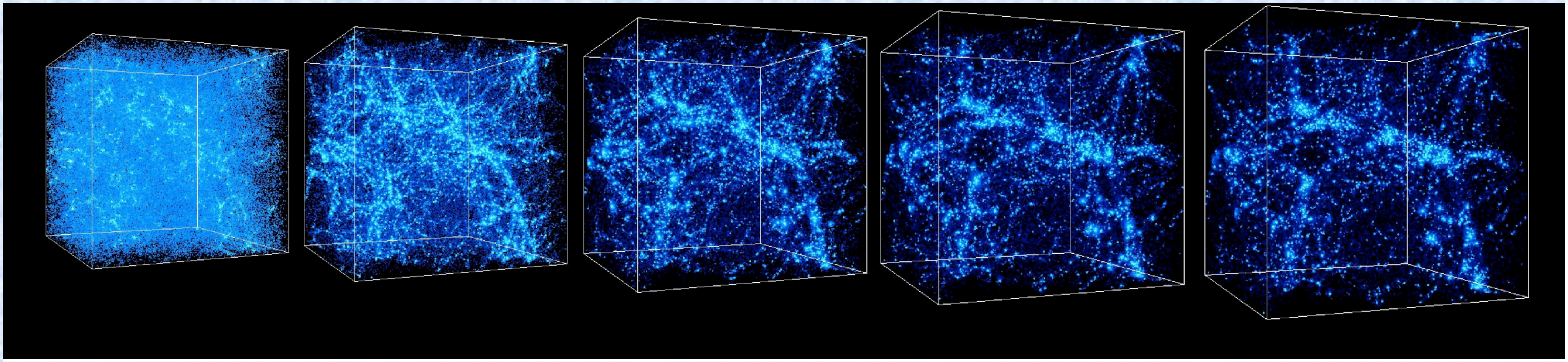
$\mathbf{t_d}$ $\mathbf{t_{mr}}$ $\mathbf{t_{decoupling,\ baryons}}$

Quiz 15

How large is the baryonic Jeans mass right after decoupling?

[Enter your mass in units of solar masses. An order of magnitude approximation is sufficient.

Gravitational Instability



- Density fluctuations are measured relative to the mean density over a large volume.
  - The fluctuation at a location $\delta(\mathbf{r},t)$ has contributions from many scales, which can describe via a Fourier transform.
- Gravity makes the amplitude of density fluctuations grow.
- We gain insight by considering simpler, idealized problems.
  - For example, a density fluctuations in a static medium grows exponentially in time.

Growth of Perturbations (Linear Regime)

- Recall – growth of density perturbation in a static medium:

For $\delta(t) << 1$

$$\ddot{\delta} \approx 4\pi G\bar{\rho}\delta(t)$$

$$\delta(t) = \frac{1}{2}\delta(0)e^{t/t_{dyn}} + \frac{1}{2}\delta(0)e^{-t/t_{dyn}}$$

$$t_{dyn} = (4\pi G\bar{\rho})^{-1/2}$$

$$t_{dyn} = 1100 \text{ s } (1 \text{ g cm}^{-3}/\bar{\rho})^{1/2}$$

- How does the expansion of the universe change the growth?

[Blackboard - Derivation]

For $\delta(t) << 1$

$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G(\bar{\epsilon}_m/c^2)\delta(t)$$

  - Can be applied to a universe that contains multiple components, but $\delta(t)$ represents the matter (dark and baryonic) density alone.

Solution Depends on a(t) and hence the Dominant Component $\varepsilon_w(a)$

For $\delta(t) << 1$

$$\ddot{\delta} + \underbrace{2H\dot{\delta}} = 4\pi G(\bar{\epsilon}_m/c^2)\delta(t)$$

- Expansion of the universe works against gravity.
- **Hubble friction** slows down the collapse.
- Looks like the static medium when H=0.

$$\ddot{\delta}(t)+2H(t)\dot{\delta}(t)-\frac{3}{2}H(t)^2\Omega_m(t)\delta(t) = 0$$

- Flat, radiation-dominated universe:

$$\Omega_m << 1 \text{ and } t = \frac{1}{2}H^{-1}$$

$$\delta(t) \approx A_1 + A_2\ln(t)$$

Perturbations grow VERY SLOWLY in the radiation dominated era.

How Does the Growth Change with Time?

$$\ddot{\delta}(t)+2H(t)\dot{\delta}(t)-\frac{3}{2}H(t)^2\Omega_m(t)\delta(t)=0$$

- Matter dominated era

$$\Omega_m = 1 \text{ and } t = \frac{2}{3}H^{-1}$$

$$\delta(t) \approx A_1 t^{2/3} + A_2 t^{-1}$$

Structures grow faster than in radiation dominated era but slow compared to static medium.

- Era dominated by a cosmological constant

$$\Omega_m << 1 \text{ and } H(t) = H_\Lambda = \frac{8\pi G\epsilon_\Lambda}{3c^2}$$

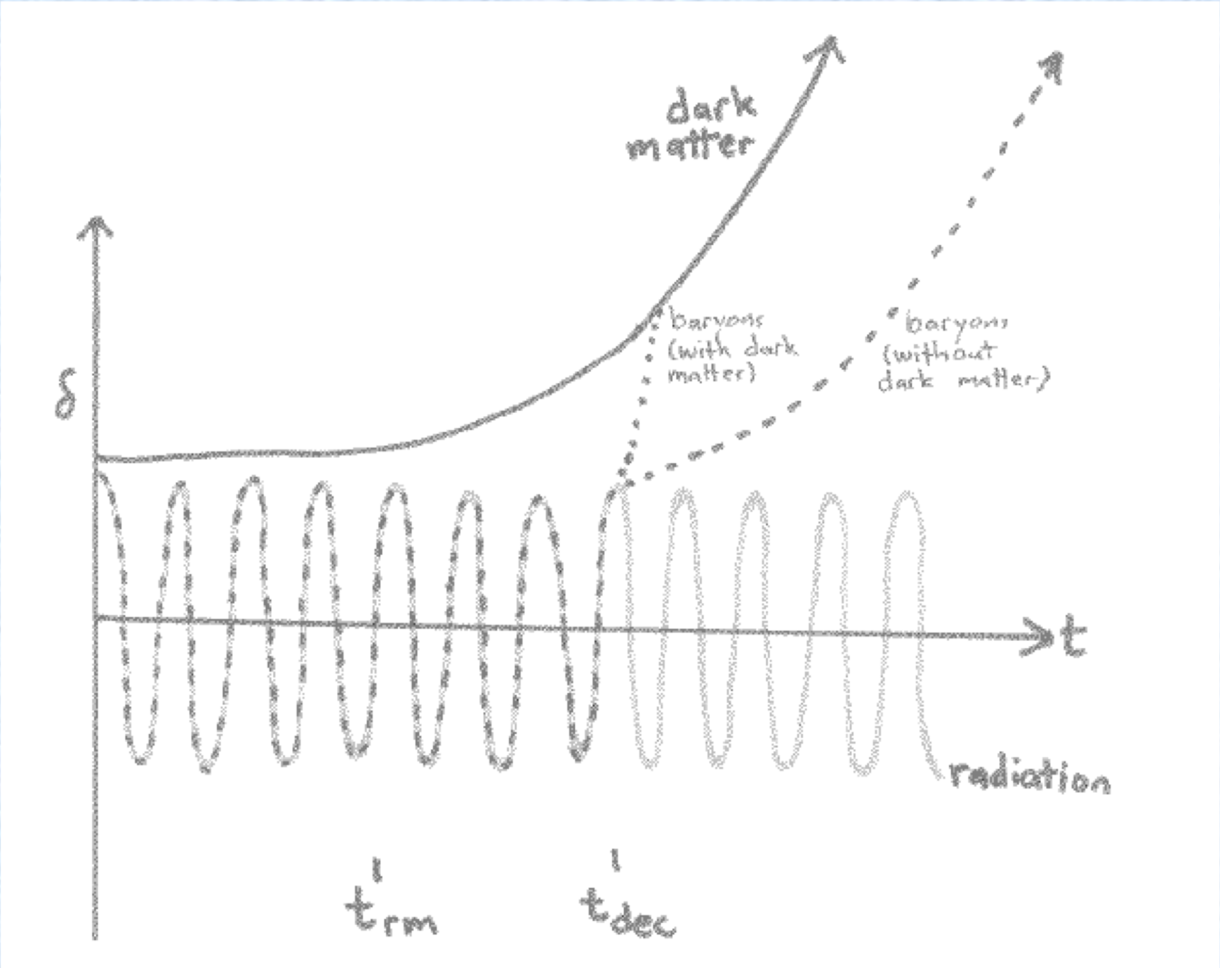
$$\delta(t) \approx A_1 + A_2 e^{-2H_\Lambda t}$$

Structures will eventually stop growing when a cosmological constant dominates.

Growth of Density Fluctuations

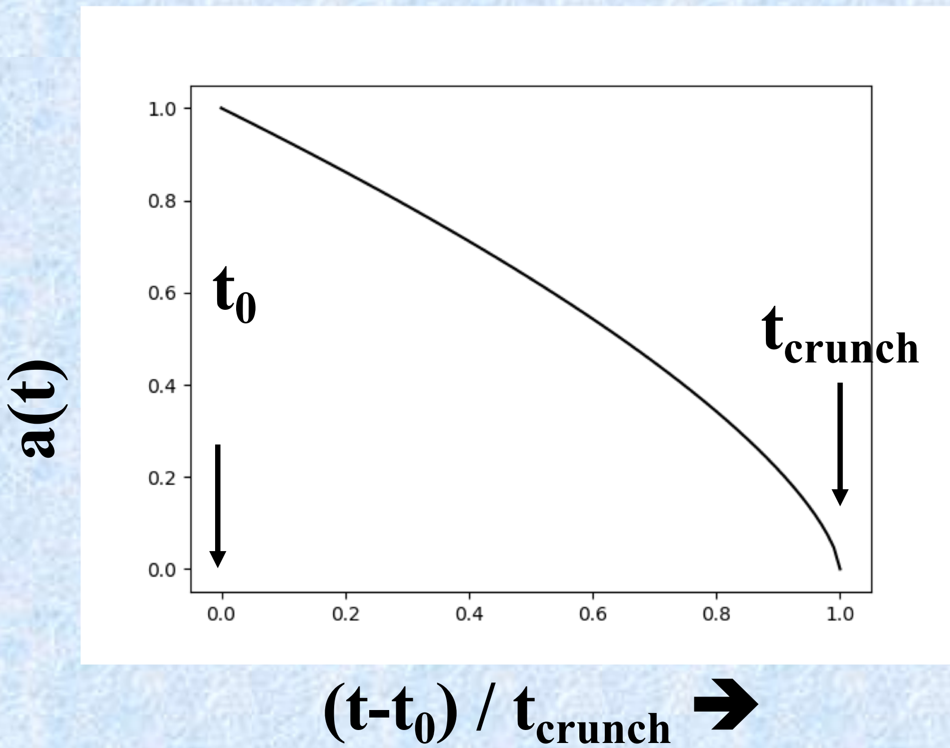
Now let's put these results into context, taking into account how the dominant component (in terms of energy density) evolves.

- Why is there little growth before t_{rm}?
- Baryonic perturbations do not grow before $t=t_{dec}$. Why?
- Baryons 'fall' into the gravitational potentials already formed by the dark matter.



Homework: Structure Formation in a Collapsing Universe

- HW8: Ryden 11.1. Expectation?
- We still have a matter dominated universe, so $a(t) \sim t^{2/3}$.
  - Since time runs forward not backwards, we want to write this as



Homework: Structure Formation in a Collapsing Universe

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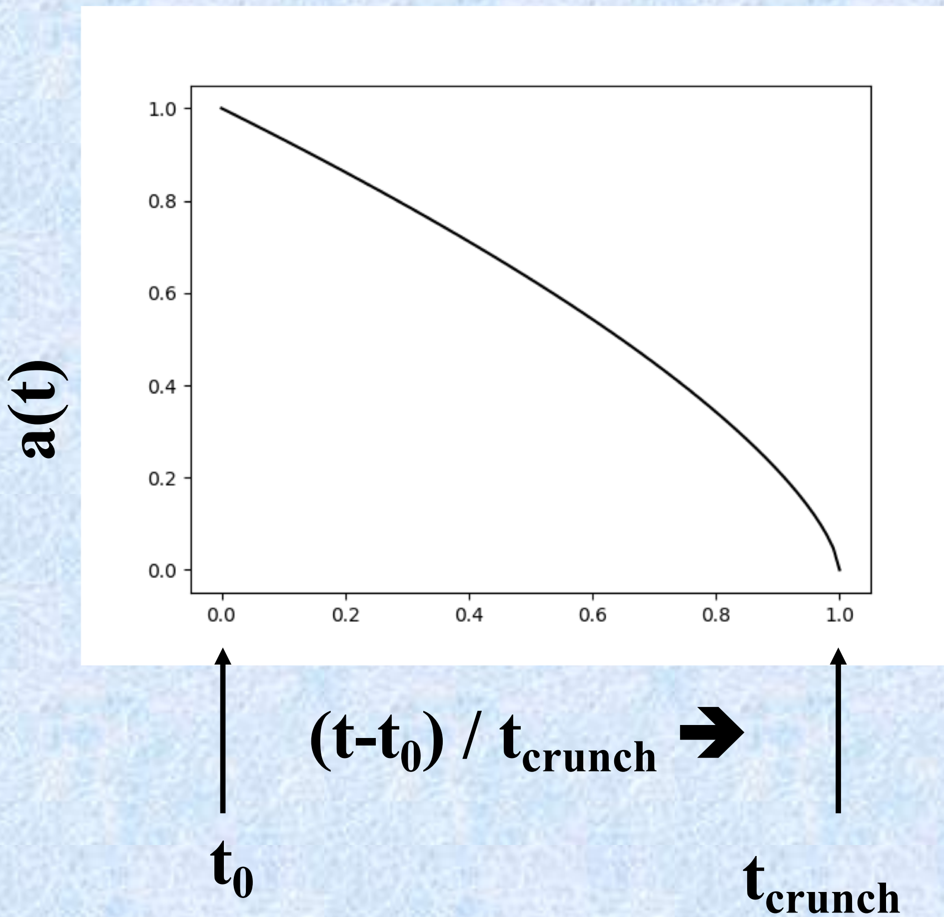
Additional Hint:

$$a(t) = \left(\frac{t - t_{crunch}}{t_0 - t_{crunch}}\right)^{\frac{2}{3}}$$

$$\Longrightarrow H = \frac{\dot{a}}{a} = \frac{2}{3}\left(\frac{1}{t - t_{crunch}}\right)$$



Quiz 16

We showed that an overdensity δ grows as $\delta \sim t^{2/3} \sim a$ in the matter-dominated era.

Prior to matter-radiation equality, how do density fluctuations in the dark matter grow with time?

[Assume the perturbation is unstable, i.e. on a length scale λ such that $\lambda_J < \lambda < c/H$.]

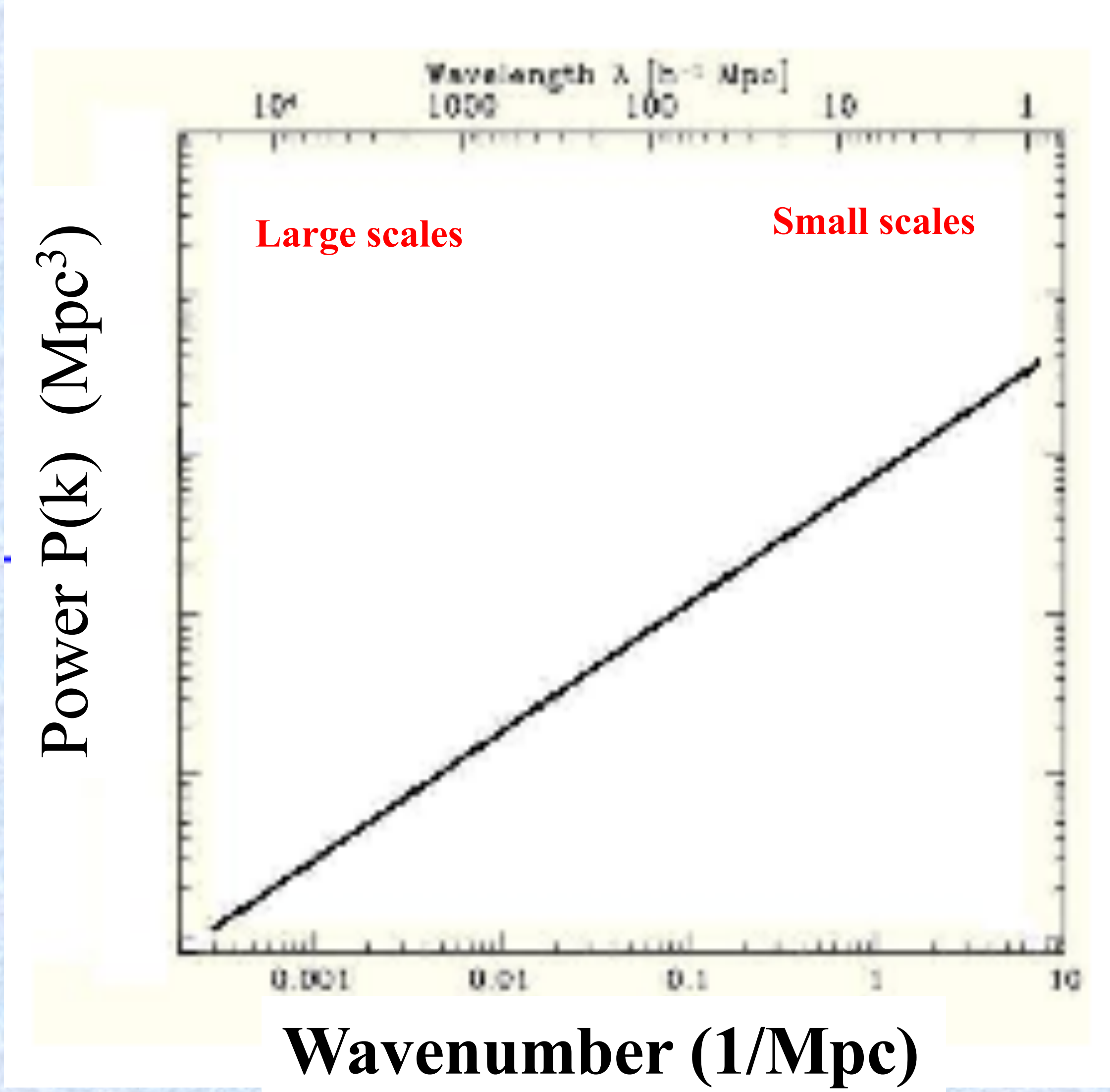
Note: **You need to be able to substitute H(t) for any single-component model into 11.49 and solve for $\delta(t)$.**

Structure Formation

- Density fluctuations are created during inflation.
- Gravity amplifies them.
  - Super horizon scales can grow.
  - Sub-horizon scales that are larger the Jeans length are also unstable.
  - *We showed how the dynamics of the universe affects the growth rate.*
- What does inflation predict the universe looks like?
- The properties of dark matter change the power spectrum between t_f and t_{mr}.
  - The observed distribution of galaxies tells us that structure grows bottom up instead of top down.
- Structure formation in baryons is different.
  - Delayed until photon-baryon decoupling (z~1000)
  - Just as the photons at last scattering left their mark on the CMB, the baryon fluctuations leave a mark on the galaxy distribution.
  - Cooling allows much higher densities to be reached.

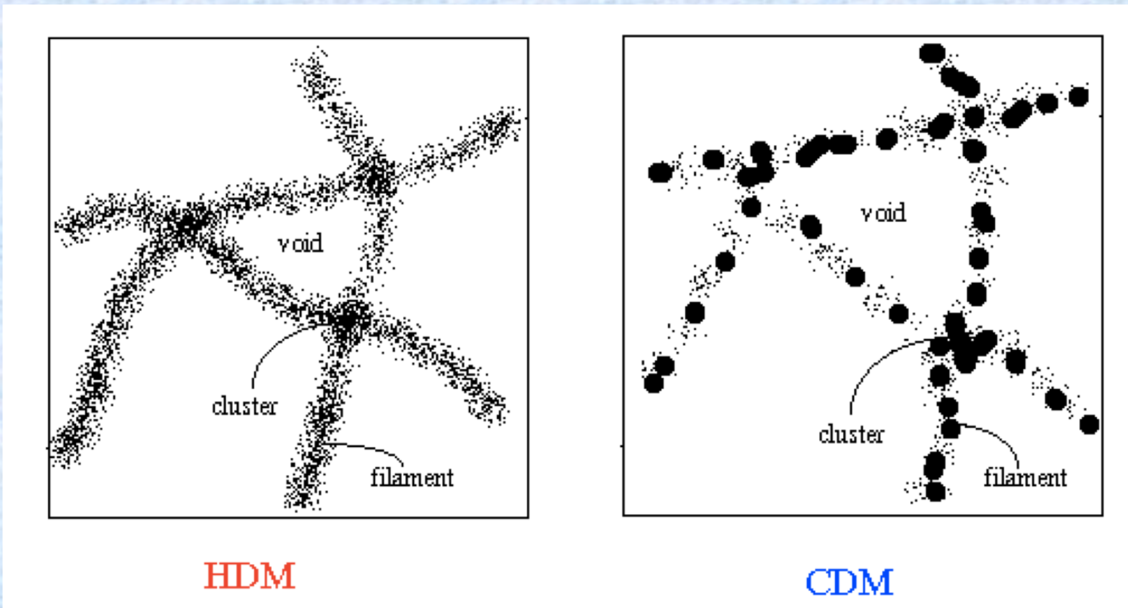
Initial Power Spectrum Predicted by Inflation

- The index "n" in the power spectrum P(k) ~ k^n has a value very close to n = 1.
- Since there is less power on large spatial scales, the universe becomes nearly homogeneous on large scales.
- n=1 is special because it is the only power law that prevents the divergence of the potential on both large and small scales.



The Horizon Grew to Include Mass Scales Comparable to the Milky Way

- The n=1 spectrum in place at the end of inflation can be modified depending on the properties of the dark matter.
- The modification depends on the thermal properties of the particles as a specific time. Find $t_{h.}$
- Free streaming of HDM particles wipes out density fluctuations with wavelengths smaller than ct_h.

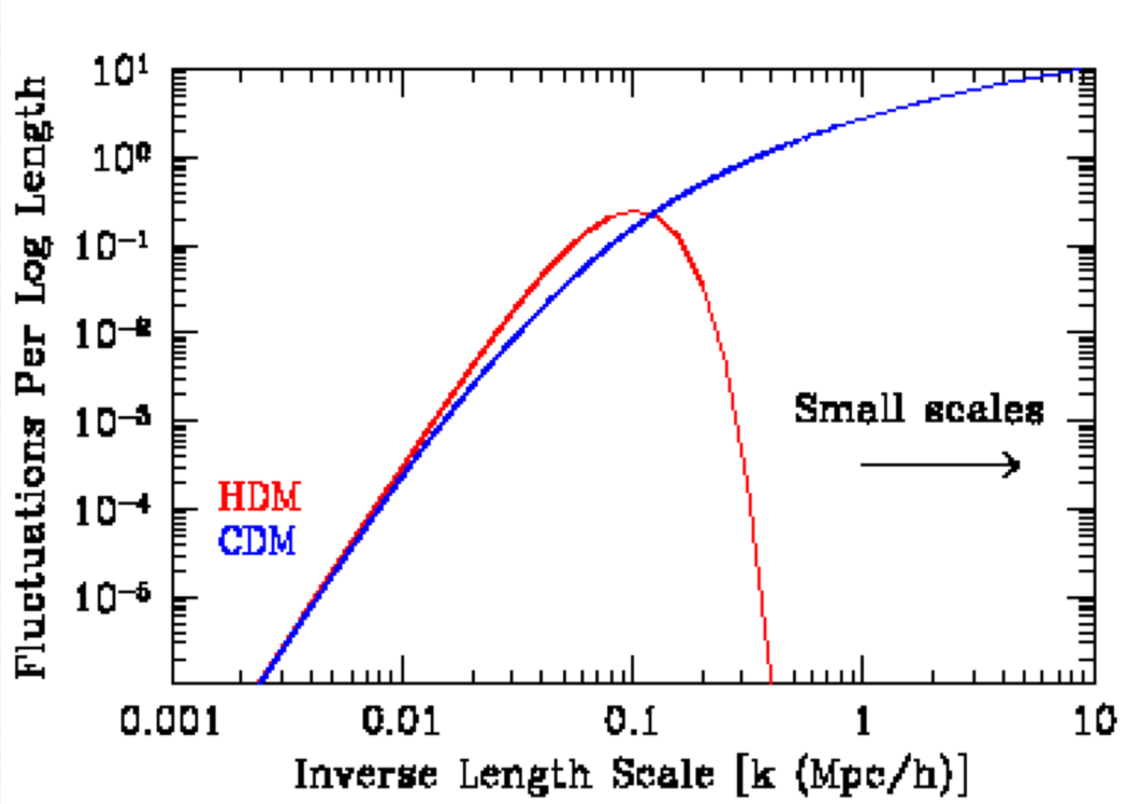


Dark Matter Particles Decoupled Earlier

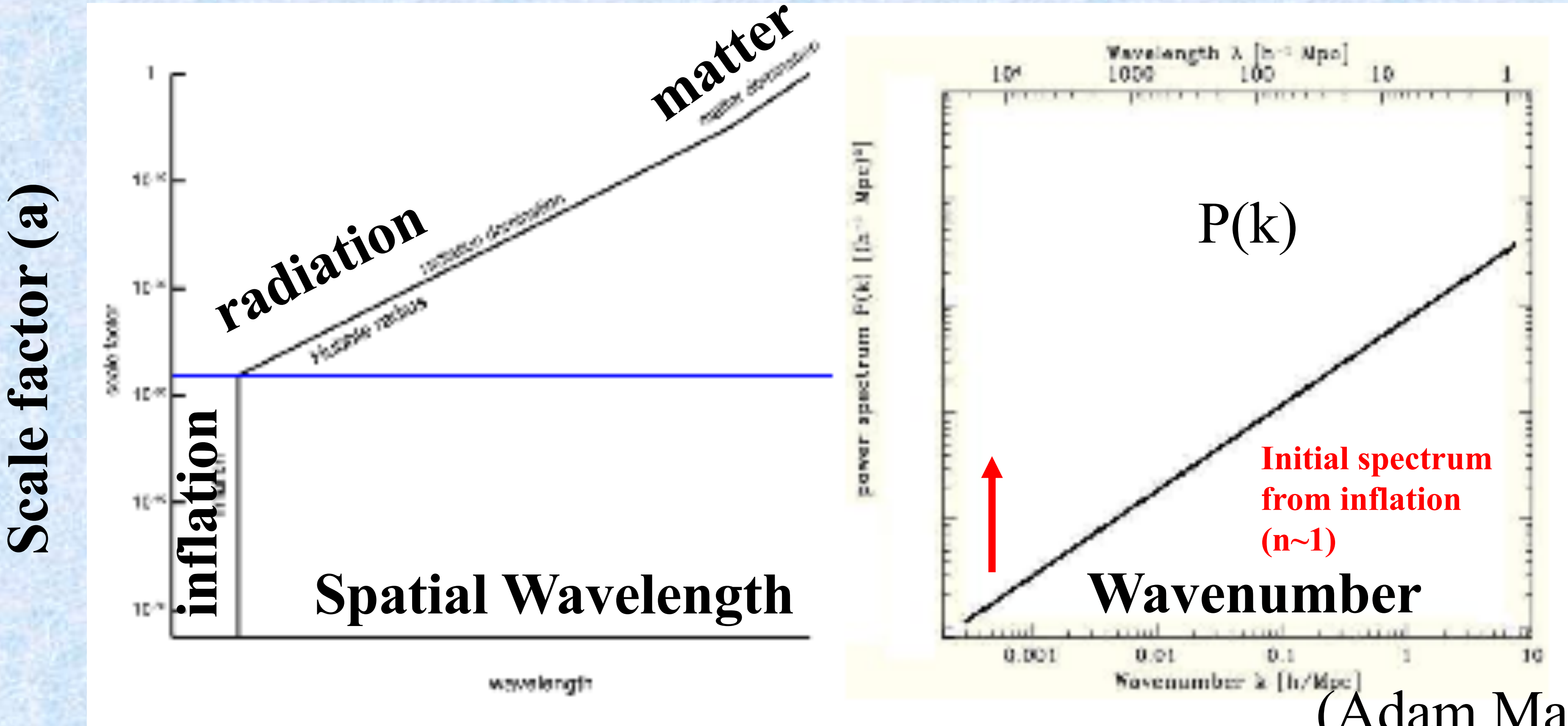
- Compare WIMPs and neutrinos
  - CDM consists of particles that were nonrelativistic at the time they decoupled. Example: WIMPs (mass ~ **100 GeV/c^2**) decoupled at t ~ 1s when the universe had a mean particle kinetic energy of 3 kT = 3 MeV. They were not relativistic: $mc^2 >> (pc)^2$.
  - HDM consists of other weakly interacting particles that remain relativistic into the period when the universe becomes matter dominated. Example: Neutrinos also decoupled around an age of 1 s. If they have masses << 3 MeV/c^2, then they were highly relativistic.

Power Spectrum. Hot vs. Cold DM

- Free streaming of HDM particles wipes out density fluctuations with wavelengths smaller than ct_h.
- Prior to matter-radiation equality, growth is slowed (nearly stopped) on small scales as those scales enter the horizon.
- This bends the power spectrum.



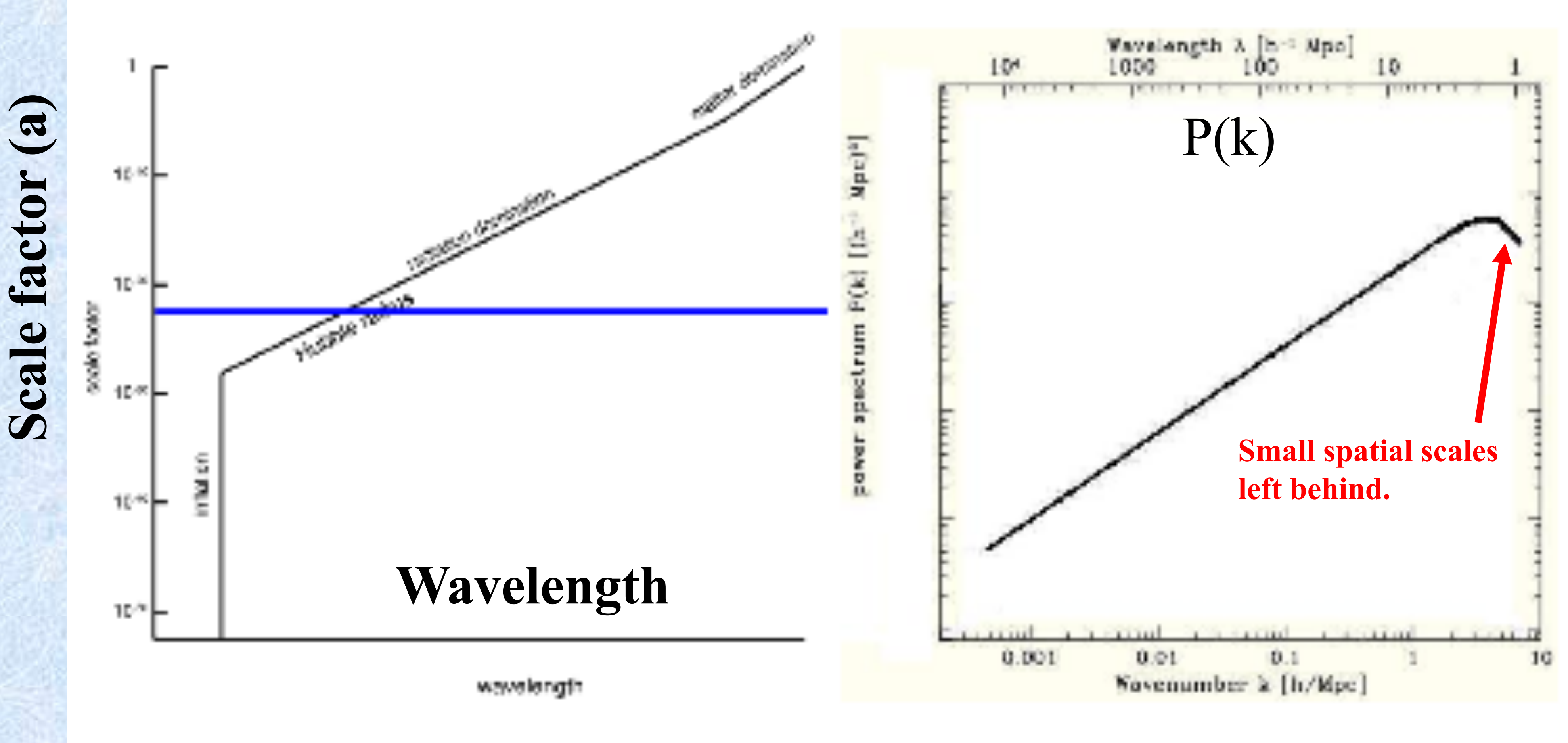
Evolution of the Power Spectrum



(Adam Mantz)

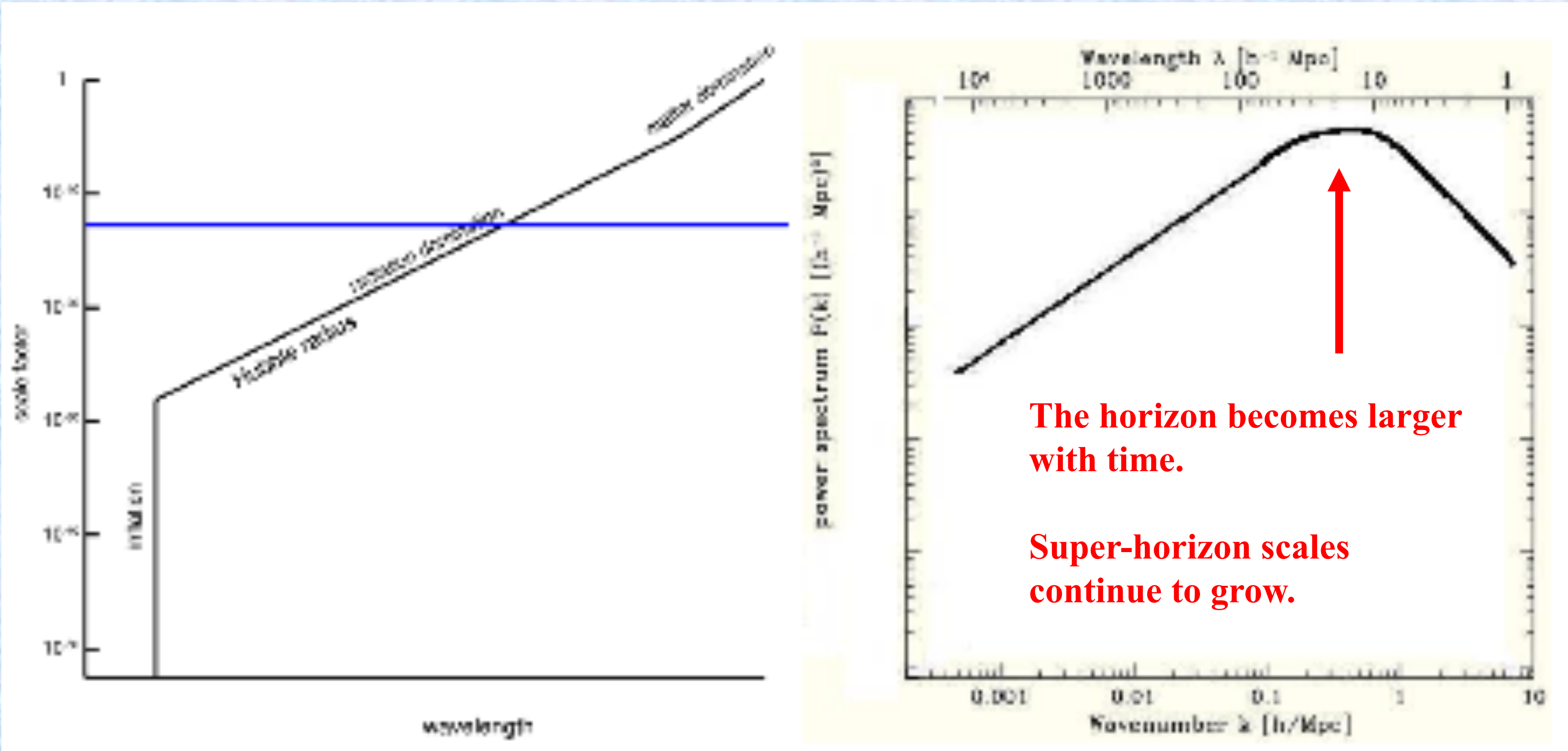
- Radiation dominated era -- wavelengths smaller than the horizon grow extremely slowly because pressure of the photon gas opposes gravitational collapse.
- The super-horizon scales grow faster.
- ➔ Power on large scales increases continuously

Evolution of the Power Spectrum



- Radiation-dominated era

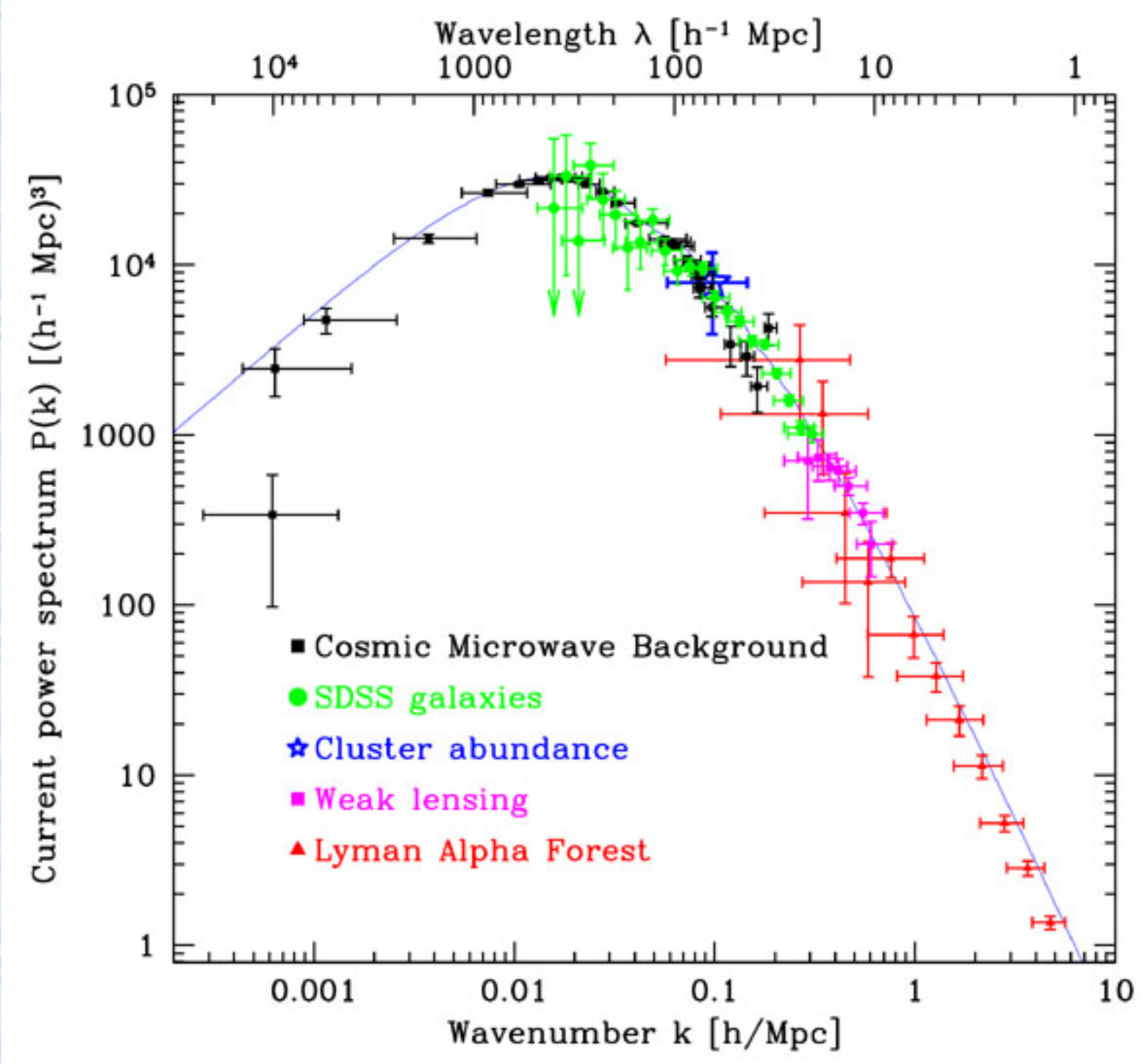
Evolution of the Power Spectrum



- Once matter begins to dominate all modes can grow
- The shape of P(k) is fixed from that point on

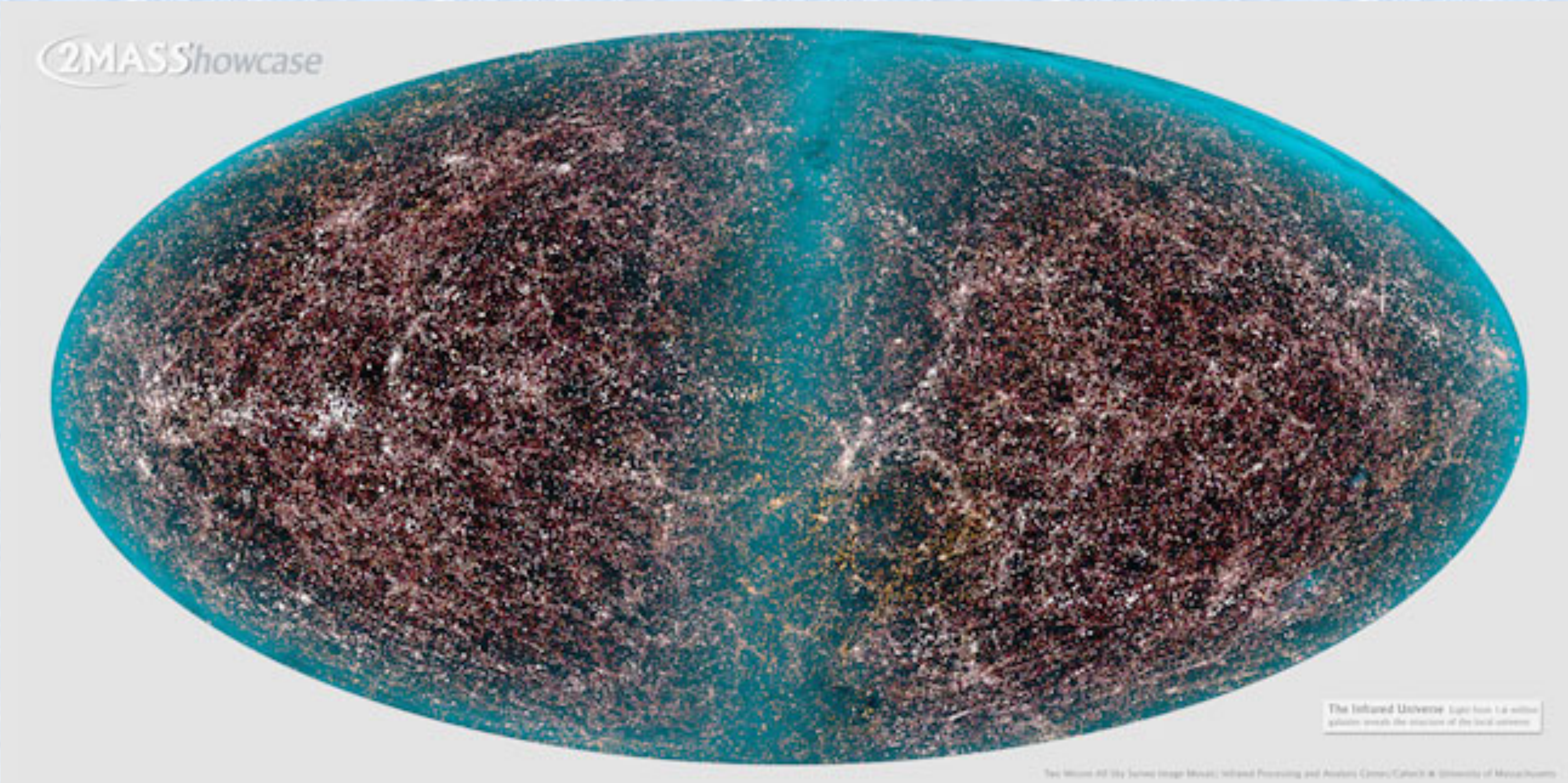
The Measured Power Spectrum.

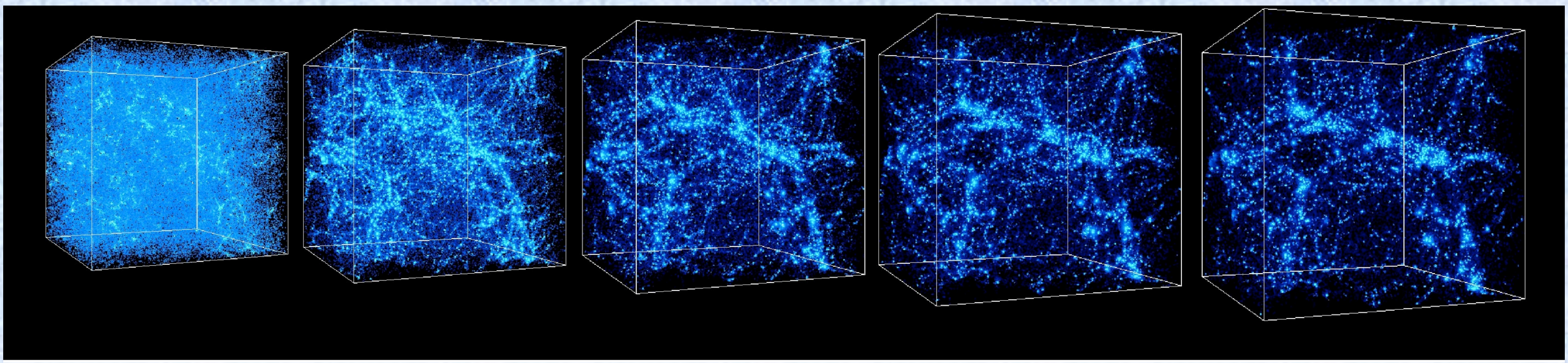
- Deviation from a straight line confirms that the dynamics of the universe have changed with time.
- Exact scale of this deviation provides a measure of the total density of the universe.
- Fluctuations become weak at large scales, i.e. the galaxy distribution is nearly homogeneous



(Tegmark + 2002)

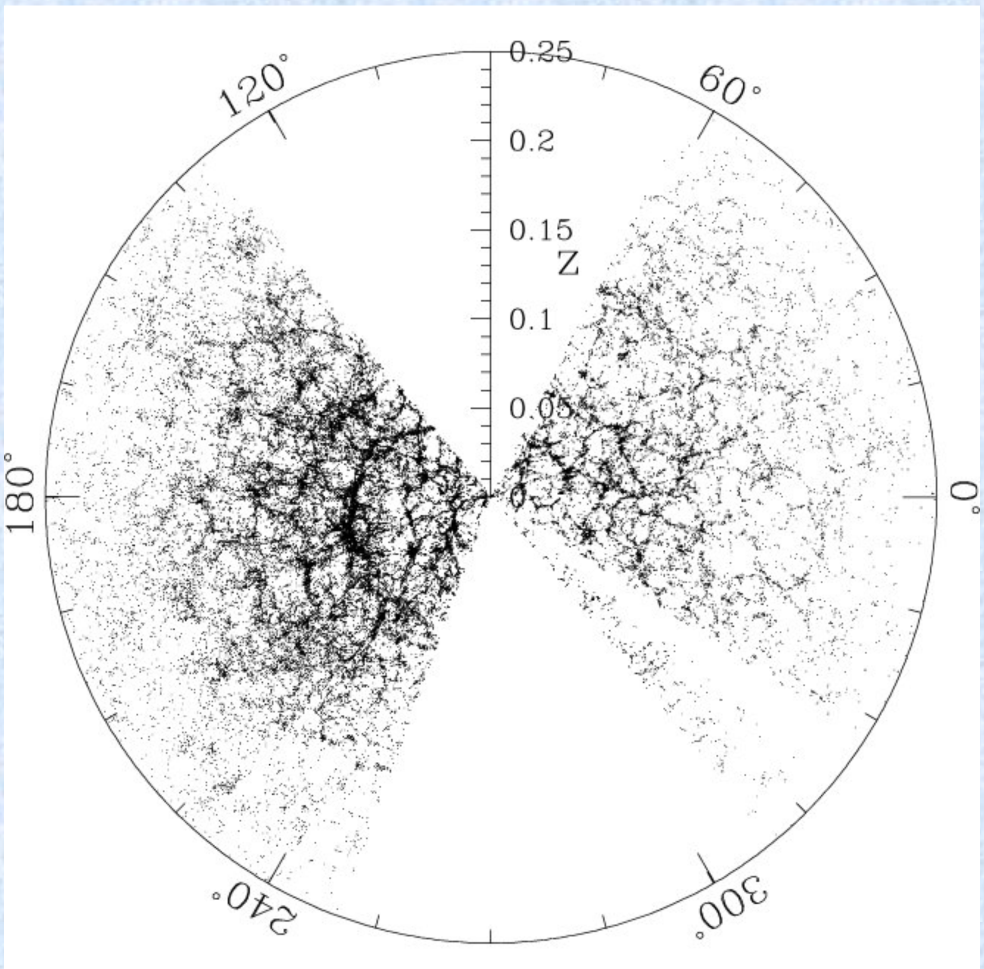
Galaxy Surveys vs. Simulations

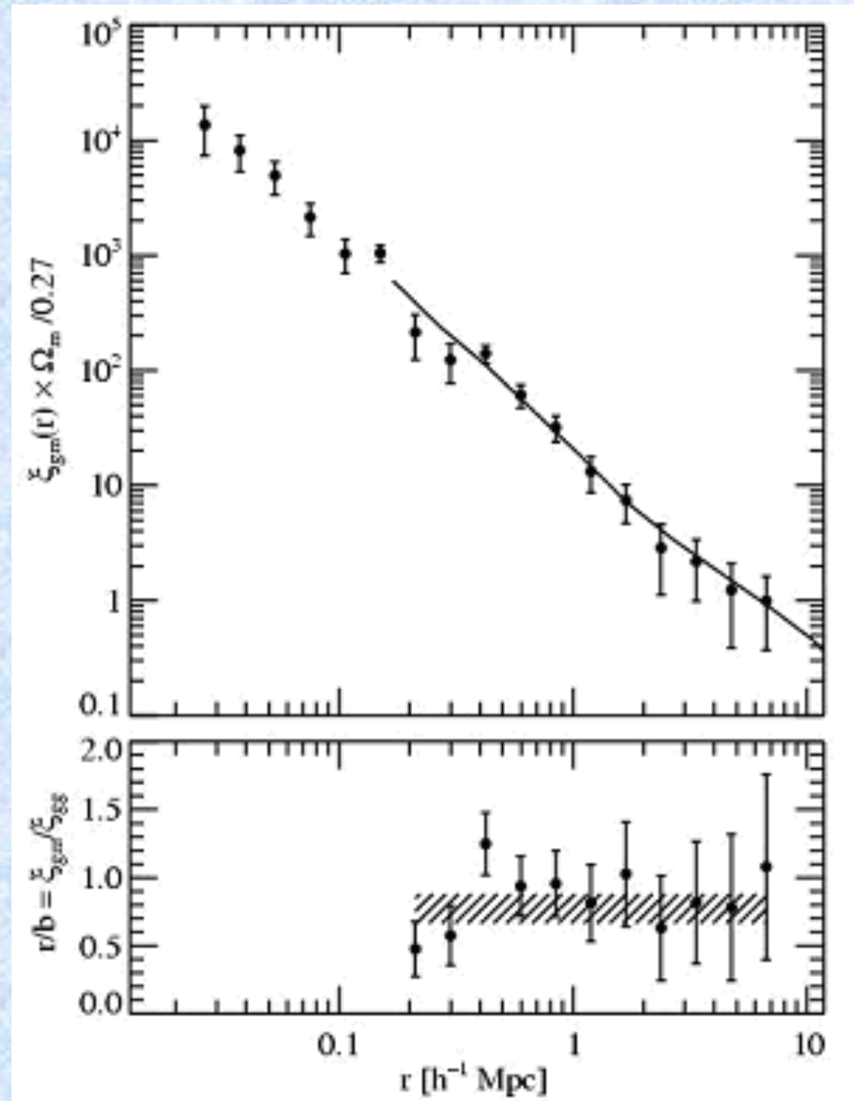




Galaxy Surveys

- Density fluctuations are measured from galaxy surveys.
- Decompose density fluctuations into Fourier components.



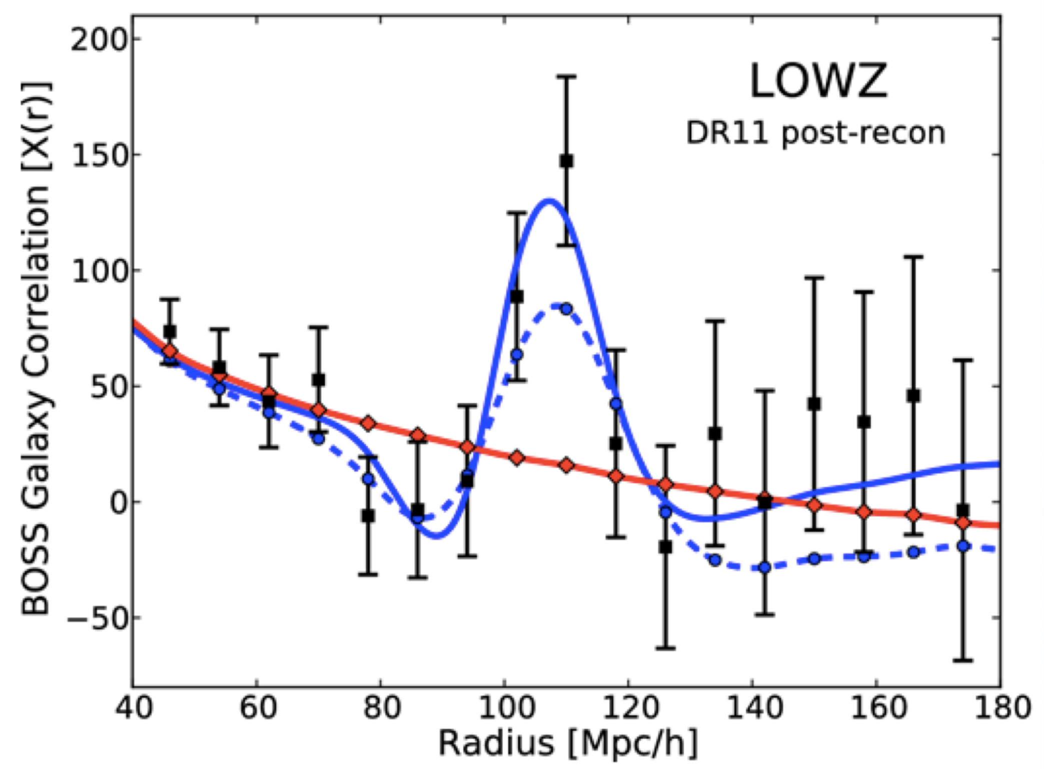


Baryon Acoustic Oscillations (HW 8 #4)

- The horizon at last scattering is smaller than the light horizon.
- The sound horizon leaves its mark on the baryons.
  - We can't observe the baryons directly at z = 1090.
  - The mass scale (7e17 Msun) is too large to have collapsed yet.
  - The corresponding comoving scale is $r_{BAO} = d(t_{LS})\,(1 + z_{LS}) \sim$ 160 Mpc.

Observations detect the relic signature of baryon acoustic oscillations.

$h = H_0 / 100$ *km/s/Mpc*



Summary for Week 9

- Gravitational instability determines how structure grows.
  - HW9 [11.4] (Reviews dynamical timescale)
  - Evolution of the Jeans Mass
  - Growth of density fluctuations in the linear regime
- *The initial power spectrum of mass fluctuations*
  - *Inflation predicts the initial power spectrum at* t_f*.*
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