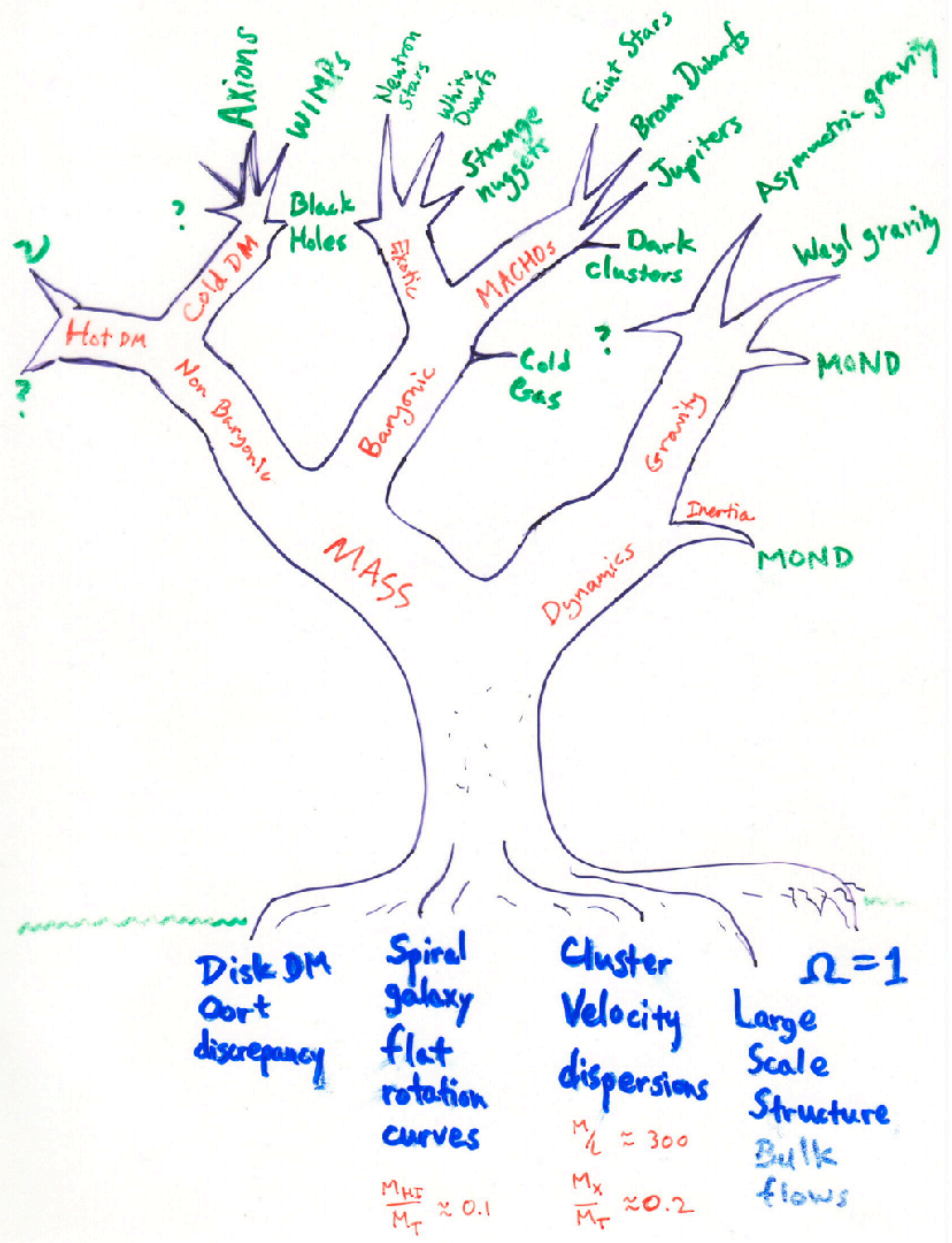
Dark Matter

ASTR 333/433
Spring 2024
TR 11:30am–12:45pm
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

Prof. Stacy McGaugh
Sears 558
368-1808
stacy.mcgaugh@case.edu

Case Western Reserve University EST. 1826



Measurements of the gravitating mass density

- Cluster M/L
  - measure M/L of a cluster, combine with measured luminosity density of universe.
- Weak lensing
  - measure shear over large scales
- Peculiar Velocity Field
  - measure deviations from Hubble flow
- Power spectrum of galaxies
- CMB fits

Measurements of the gravitating mass density

- Weak lensing
  - measure shear over large scales

Dark Energy Survey
arxiv:2002.11124

$$\Omega_m \approx 0.18 \pm 0.04$$

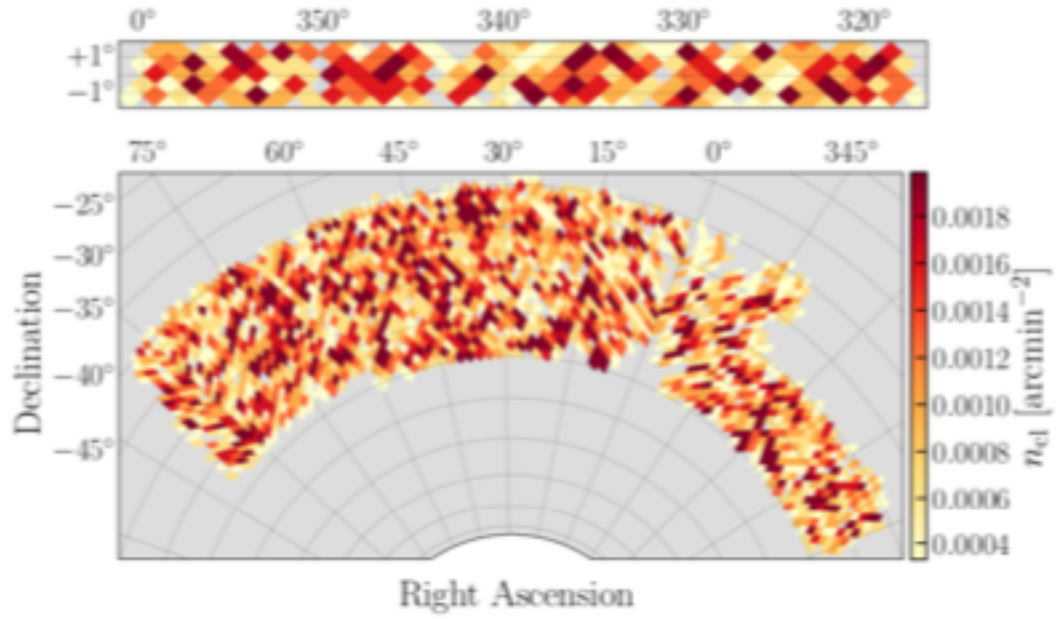


FIG. 1. The DES Y1 redMaPPer cluster density over the two non-contiguous regions of the Y1 footprint: the Stripe 82 region (116 deg^2; *upper* panel) and the SPT region (1321 deg^2; *lower* panel).

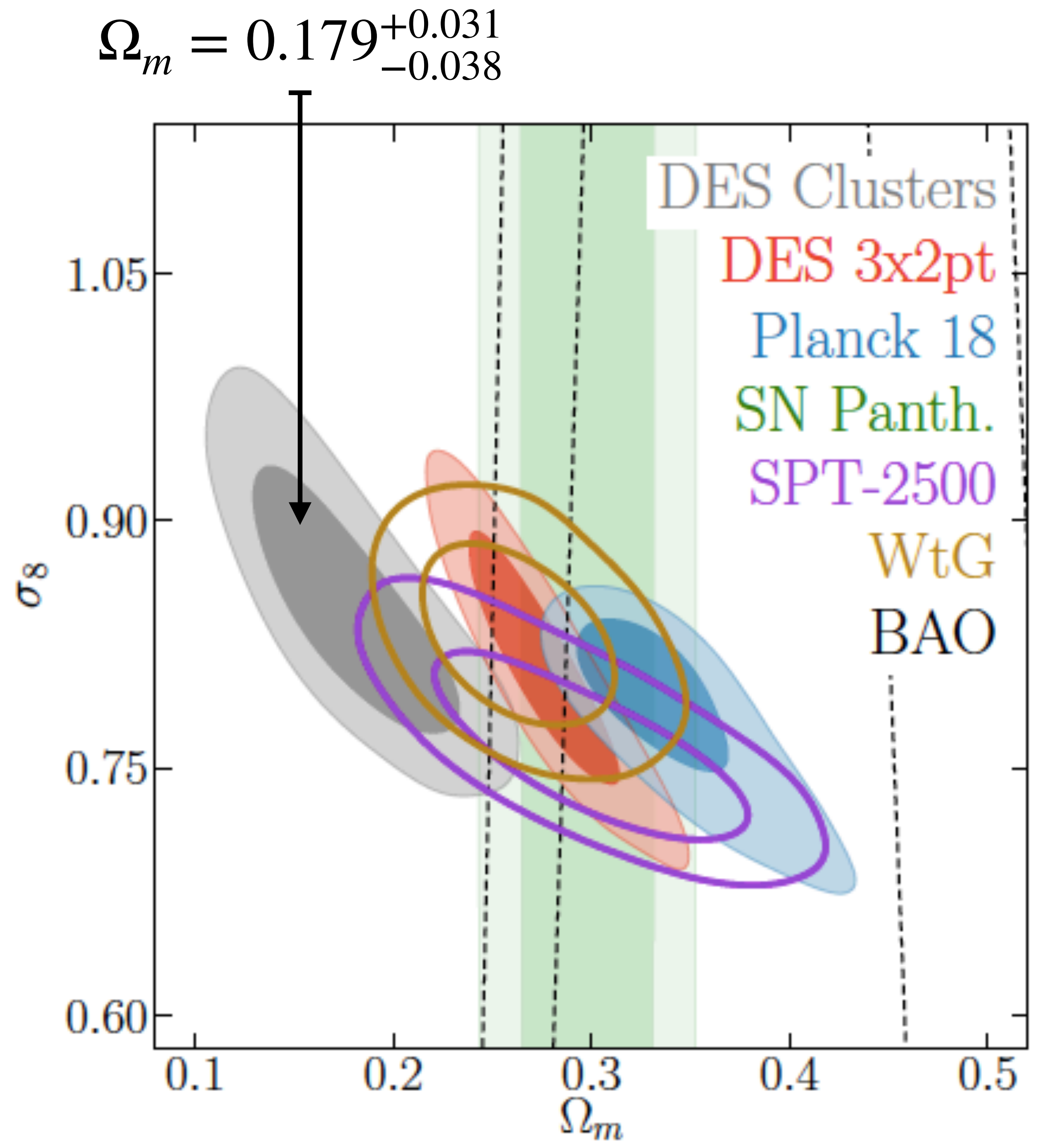


FIG. 6. Comparison of the 68% and 95% confidence contours in the σ_8-Ω_m plane derived from DES Y1 cluster counts and weak-lensing mass calibration (*gray* contours) with other constraints from the literature: BAO from the combination of data from Six Degree Field Galaxy Survey [6dF [62]], the SDSS DR 7 Main galaxy sample [63], and the Baryon Oscillation Spectroscopic Survey [BOSS [64]] (*black dashed* lines); Supernovae Pantheon [65] (*green* contours); DES-Y1 3x2 from [20] (*red* contours); *Planck* CMB from [2] (*blue* contours); SPT-2500 from [9] (*violet* contours); WtG from [7] (*gold* contours).

cf. review by

Mandelbaum 2018 ARA&A, 56, 393

Measurements of the gravitating mass density

- Peculiar Velocity Field
  - measure deviations from Hubble flow

The Virgo cluster is the largest nearby over-density.
Its gravity distorts the Hubble flow.
We fall towards it so it appears to recede less than it should by an amount that depends on its mass

in linear regime $\frac{\delta\rho}{\rho} \ll 1$

$$\frac{\delta v}{v} \approx \frac{d\ln H}{d\ln\rho}\frac{\delta\rho}{\rho} \approx -\frac{1}{3}\frac{\Omega_m^{0.6}}{b}\frac{\delta\rho_g}{\rho_g}$$

peculiar velocity

distortion in Hubble flow induced by

mass over-density

bias

BIAS ***b***
relates
galaxy over-densities
to mass over-densities

$$\Omega_m = 0.25 \pm 0.05$$

Tonry & Davis (1981) ApJ, 246, 666

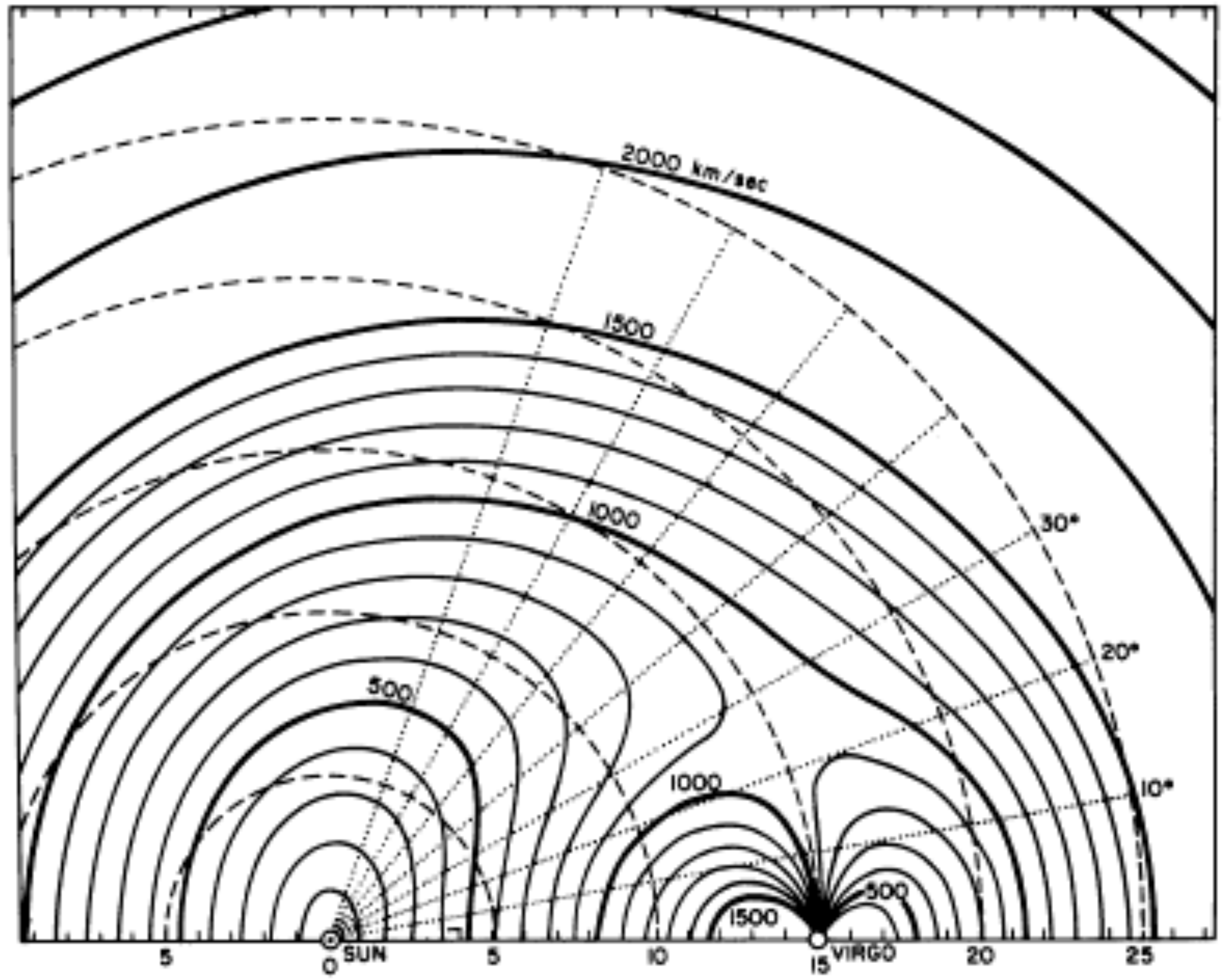
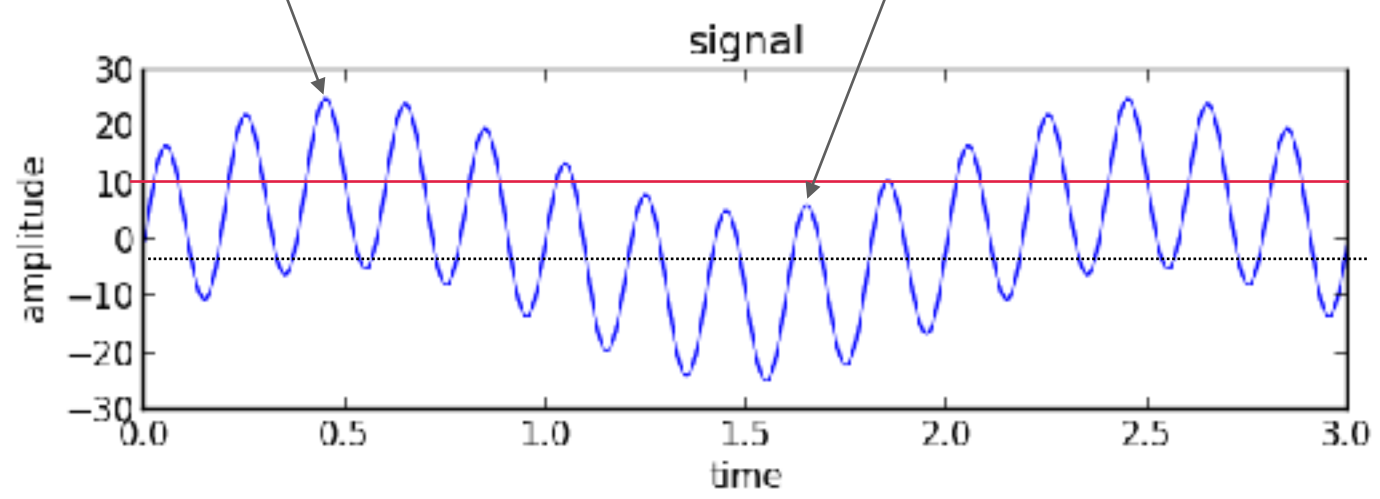


FIG. 1.—On a two-dimensional grid with the Earth and the Virgo cluster on the x axis, redshift contours are plotted for a Hubble flow perturbed by a Virgocentric flow. An infall velocity of 400 km s^{-1} at our position is assumed. A pure Hubble flow would be concentric circles.

BIAS ***b***
relates
galaxy over-densities
to mass over-densities

Peaks above line make a galaxy

Peaks below line do not



bias

$$\frac{\delta\rho_g}{\rho_g} = b\frac{\delta\rho_m}{\rho_m}$$

$$\sigma_8 = \frac{1}{b}$$ in a sphere of radius 8 Mpc

Davis et al. (1980) found

$$\Omega_m = 0.4 \pm 0.1$$

with modern distances this becomes

$$\Omega_m = 0.25 \pm 0.05$$

basically unchanged for nearly 40 years

Lines are lines of constant

TABLE 1

ESTIMATES OF v_p

Velocity	Source
380 ± 75	Smoot and Lubin 1979
480 ± 75	Aaronson *et al*. 1980
350 ± 50	de Vaucouleurs and Bollinger 1979
290 ± 30[a]	Yahil 1980
190 ± 130	Schechter 1968

[a] Calculated with respect to the centroid at the local group as defined by Yahil *et al*. 1977.

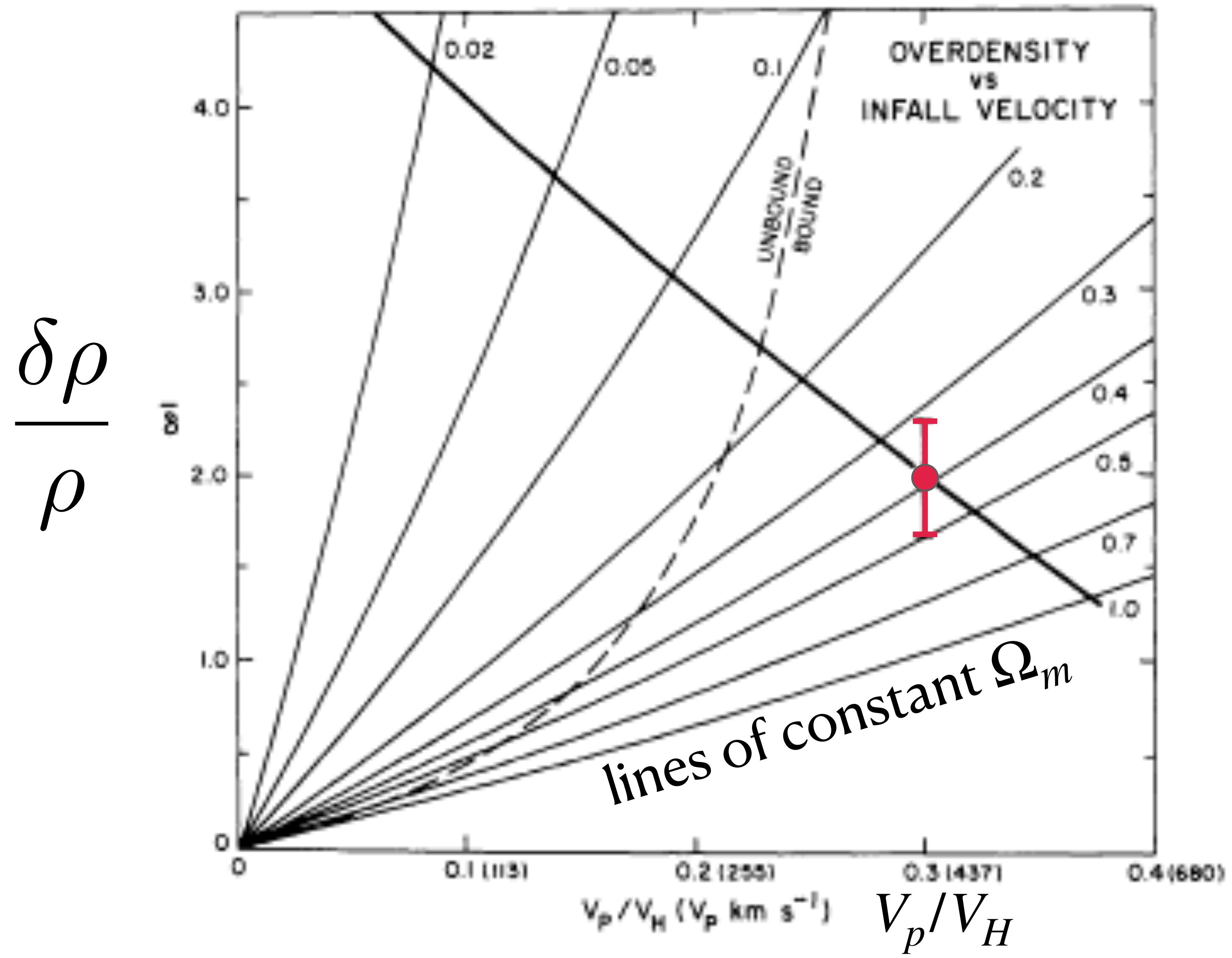
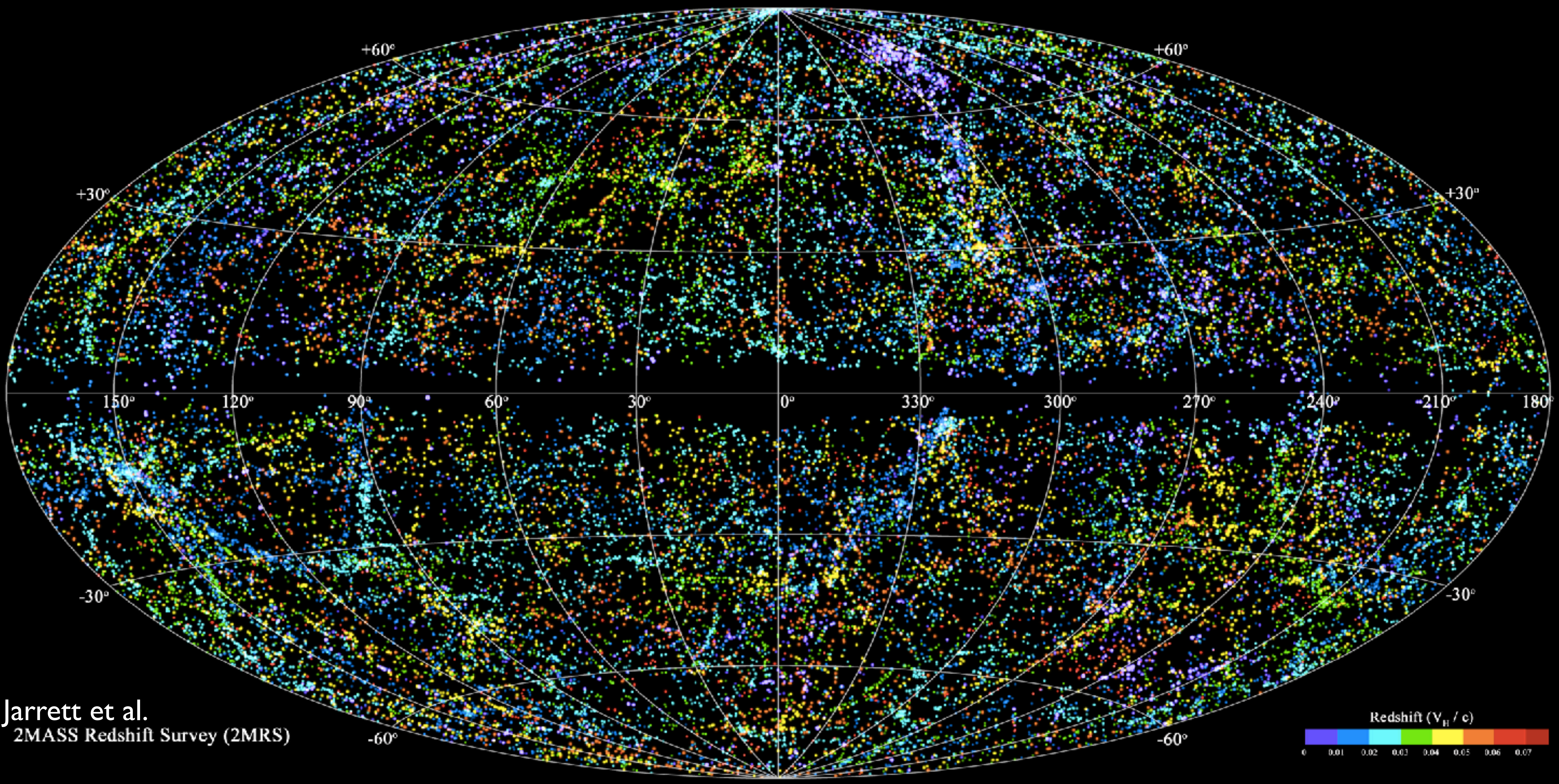


FIG. 1.—The mean overdensity of Virgo vs. v_p/v_H for various values of Ω. The x-axis is also labeled with v_p, using a recessional velocity to Virgo of 1020 km s^{-1}. The measured overdensity is prescribed by the heavy line, and is marked at the favored position as given by the anisotropy of the Hubble flow and microwave background radiation. The error bar is an estimate of the 90% confidence limit of our determination of $\bar{\delta}$. Models to the right of the dotted line are bound to Virgo.

Measurements of the gravitating mass density

- The power spectrum provides a statistical description of the clustering of galaxies, which are not randomly distributed in space



Jarrett et al.

- # Power spectrum of galaxies

$$\delta \equiv \frac{\delta\rho}{\rho}$$

The power spectrum is commonly used to quantify large scale structure.
It is the related to the 2 point correlation function via Fourier transform.

2 point correlation function: $\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$

The 2 point correlation function is the probability of finding one galaxy near another in excess over a random distribution.

Power spectrum: $P(k) = \langle |\delta_k|^2 \rangle$ where $k = \dfrac{2\pi}{\lambda}$

where k is the wavenumber corresponding to the scale λ

Fourier transform:

$$\xi(\vec{r}) = \frac{V}{(2\pi)^3} \int \underbrace{|\delta_k|^2}_{P(k)} e^{-i\vec{k}\cdot\vec{r}} d^3k$$

averaged over volume V

Large Scale Structure

Quantified with the **correlation function** $\xi(r)$ which is the Fourier transform of the **power spectrum** $P(k)$.

The correlation function is the excess probability of finding a galaxy near another galaxy over that in a random distribution.

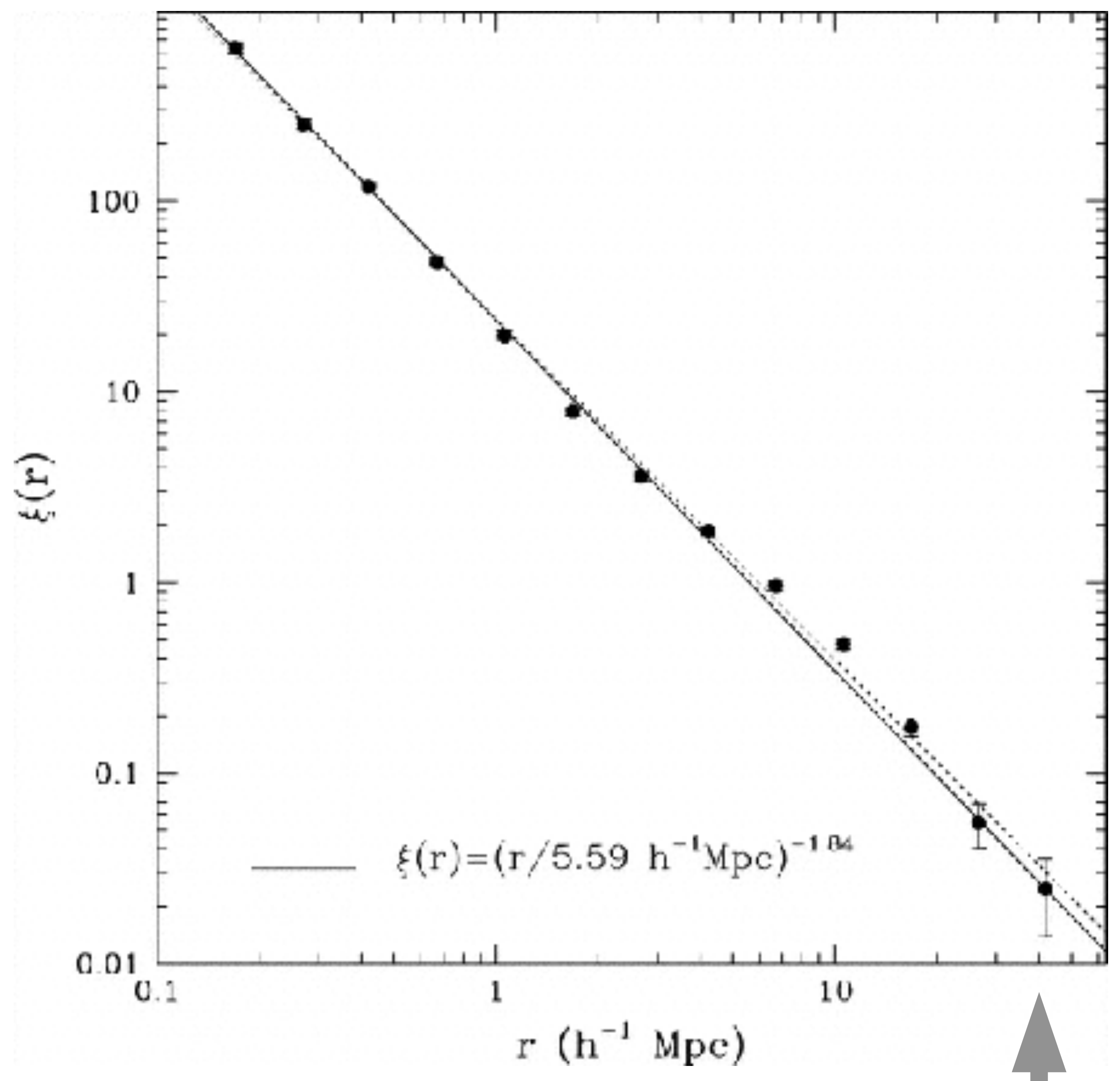
$$\frac{dN}{N} = [1 + \xi(r)]dV \qquad \xi(r) = \frac{V}{(2\pi)^3}\int P(k)e^{-\vec{k}\cdot\vec{r}}\, d^3k$$

$$P(k) \propto |\delta(k)|^2 \propto k^n \qquad \xi(r) \propto r^{-(n+3)} \qquad \delta \equiv \frac{\delta\rho}{\rho}$$

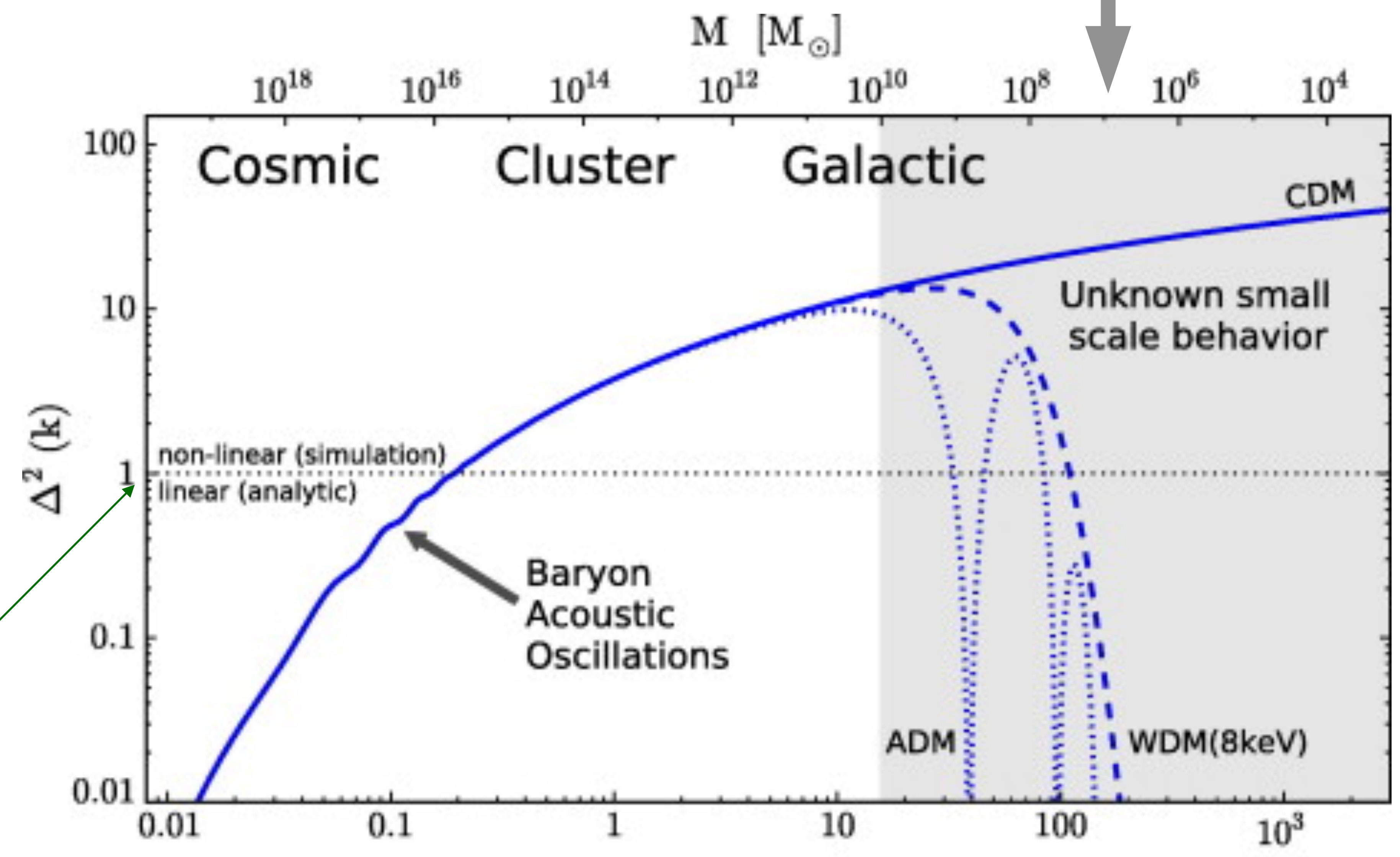
Harrison-Zeldovich spectrum has $n = 1$, which is a Gaussian random field. Inflation predicts $n \approx 1$, but different flavors of Inflationary theory predict slightly different values depending on the shape of the Inflationary potential (the Inflaton). Planck measures $n = 0.965 \pm 0.004$

$\delta > 1$ marks the transition to the non-linear regime where perturbation theory no longer applies.

SDSS correlation function (Zehavi et al 2005)



Power Spectrum



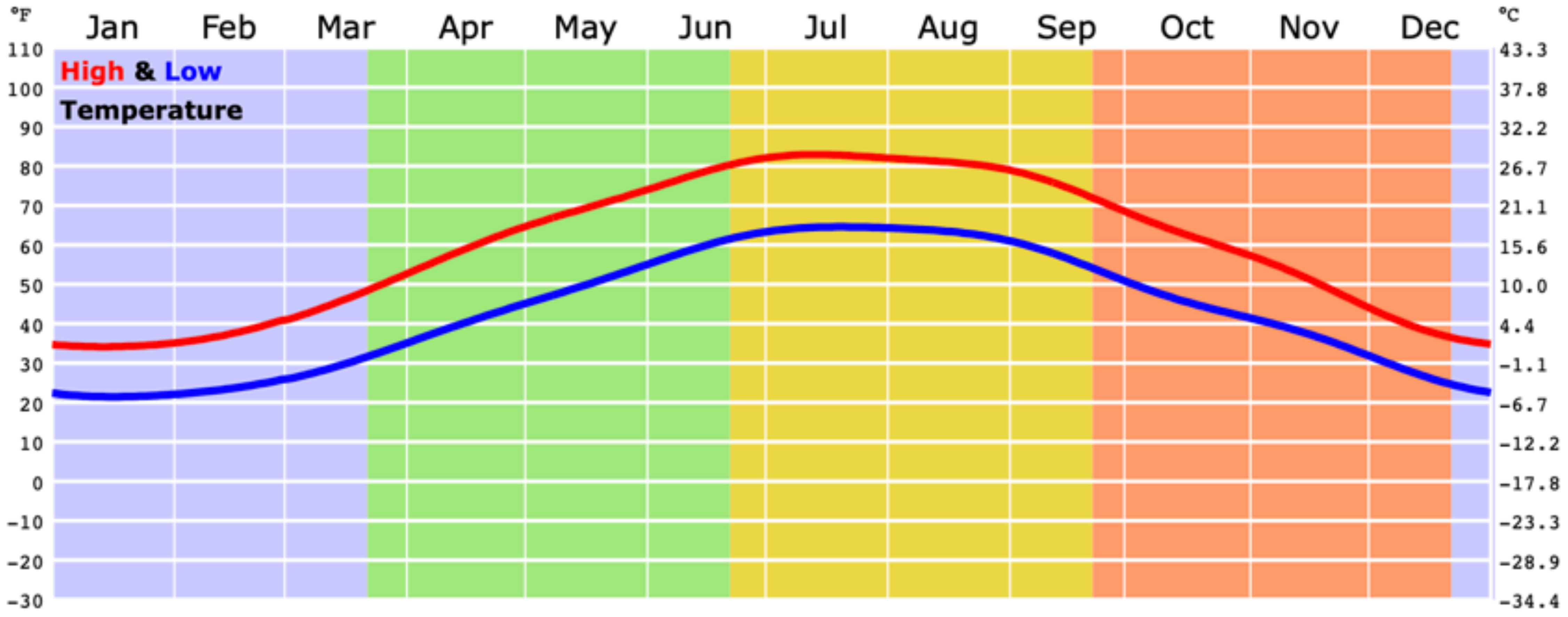
Power Spectrum

Example: weather in Cleveland and Santa Barbara
More power on long time scales in Cleveland (seasonal variation)

Cleveland, Ohio

Latitude: 41.4131 Longitude: -81.8600

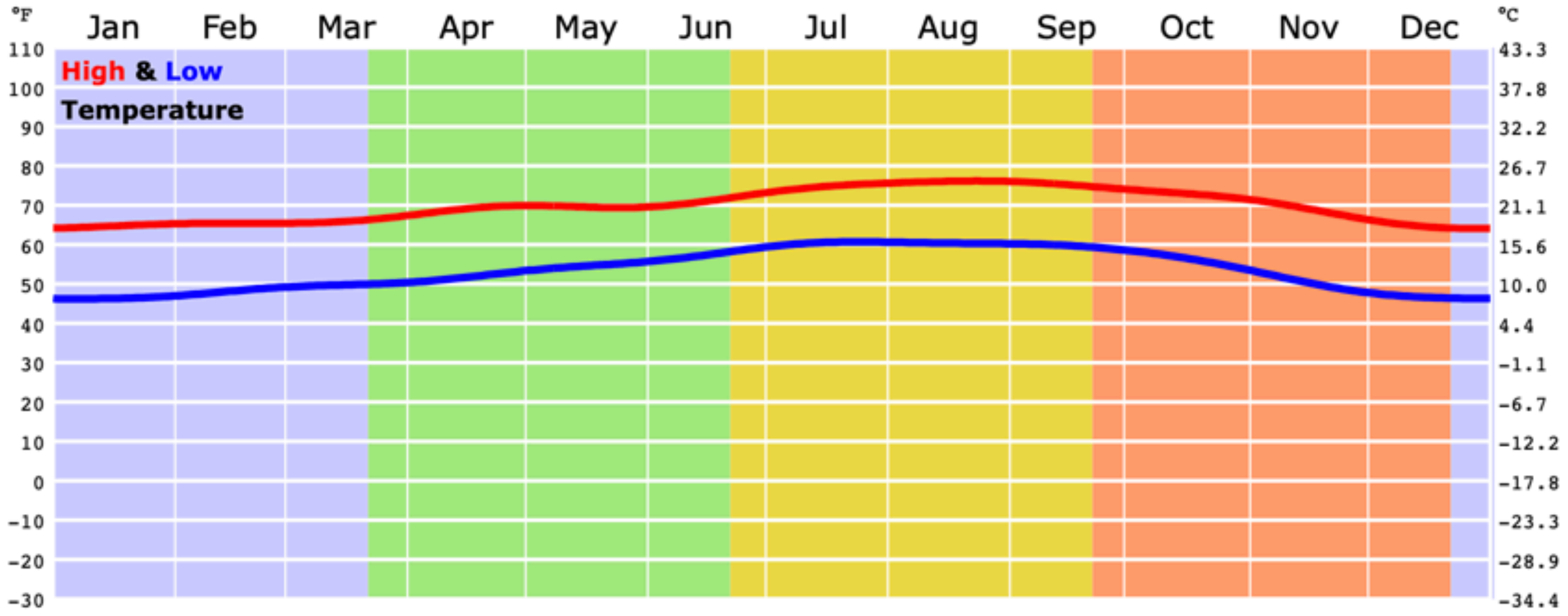
Elevation: 763.1 feet (232.6 meters)



Santa Barbara, California

Latitude: 34.4167 Longitude: -119.6844

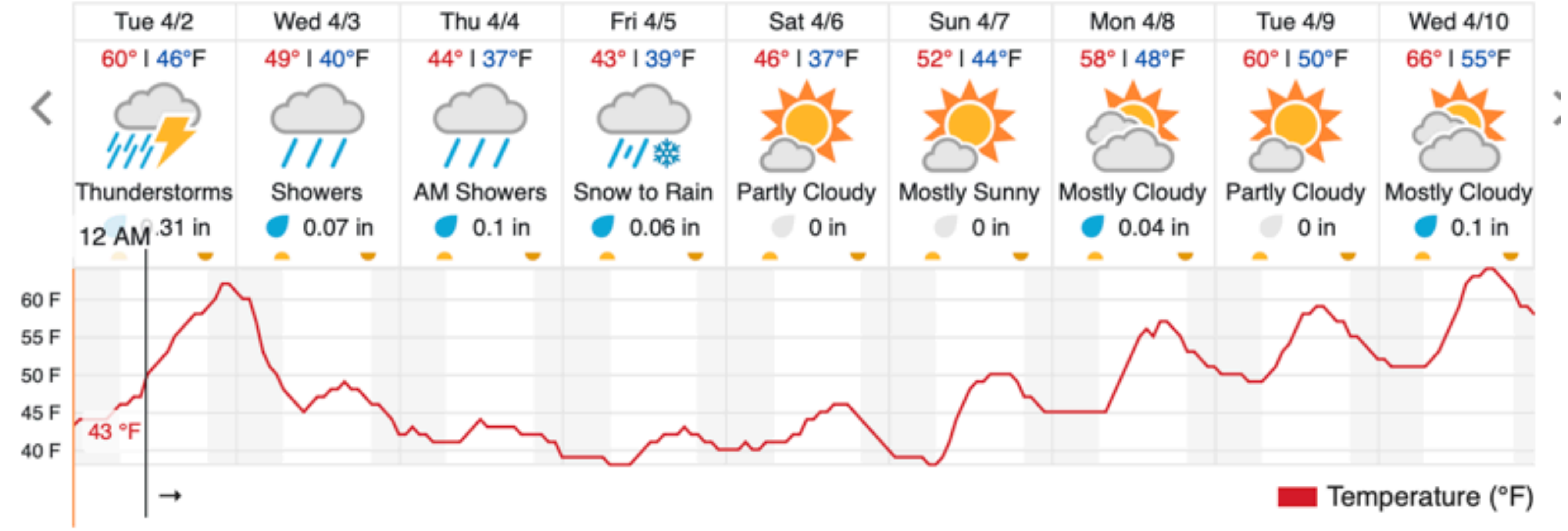
Elevation: 4.9 feet (1.5 meters)



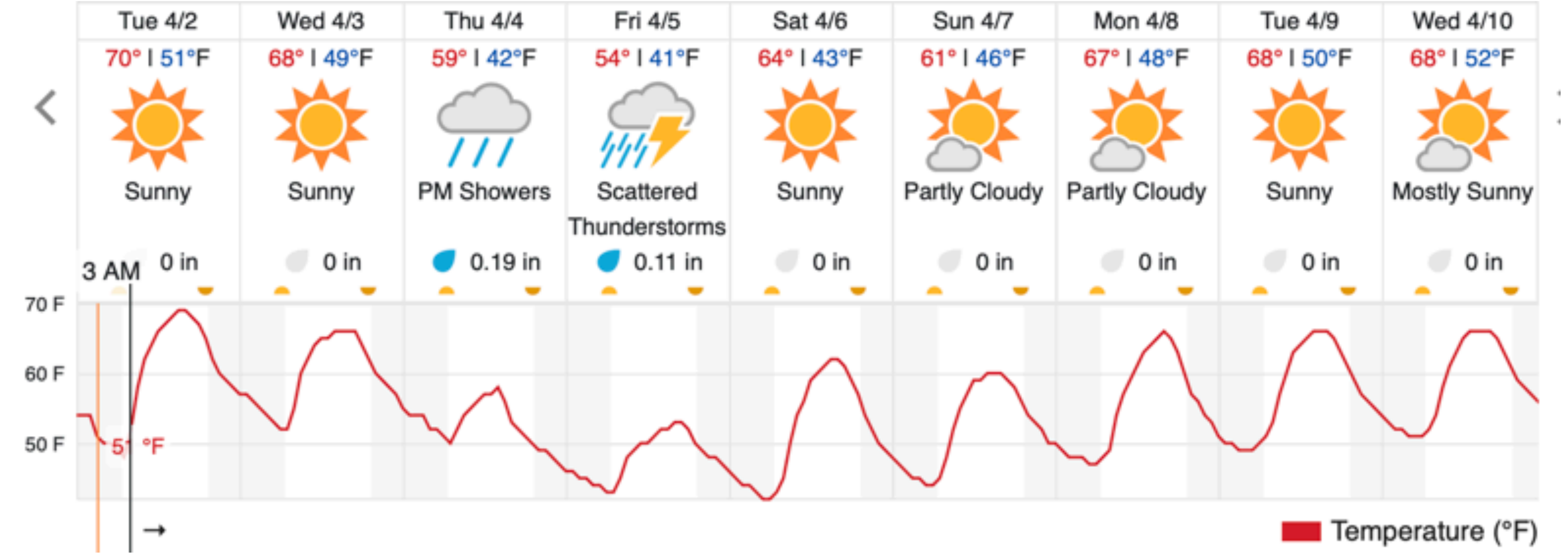
Power Spectrum

Example: weather in Cleveland and Santa Barbara
Similar power on short time scales in Santa Barbara (diurnal variation)

Cleveland forecast



Santa Barbara forecast



A power spectrum is a Fourier transform that quantifies
the relative variability on different scales

- Power spectrum of galaxies $\quad \delta \equiv \frac{\delta\rho}{\rho} \quad k = \frac{2\pi}{\lambda}$

Power law power spectrum: $\quad P(k) = \langle |\delta_k|^2 \rangle \propto k^n$

where n = 1 is scale free, with the same power on all scales.
This is observed to be nearly the case on large scales that have not yet collapsed. It is modulated on small scales by structure formation.

One way to think of it is the rms variation at each scale $\quad \lambda$

$$M \sim \lambda^3 \qquad \delta_{\mathrm{rms}} \propto M^{-(n+3)/6}$$

There is more rms variance on small scales, so more power there.
[On very large scales, the universe is homogeneous, so no variance.]

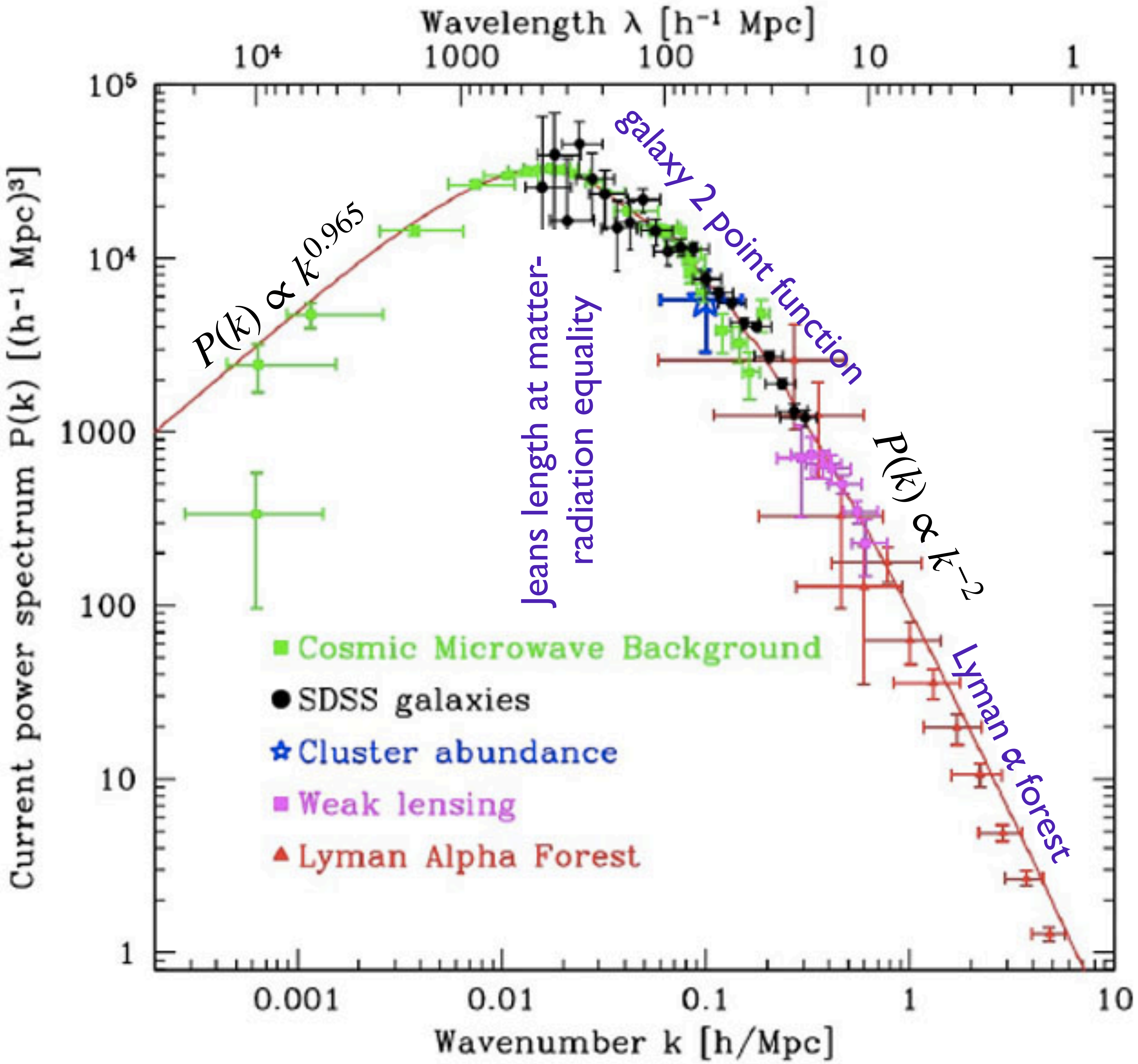
By convention, the normalization is set on a scale of 8 Mpc, where

$\frac{\delta N_{gal}}{N_{gal}} = 1$ with corresponding mass variance $\quad \sigma_8$

Planck estimates: $n = 0.965 \pm 0.004$

$$\sigma_8 = 0.811 \pm 0.006$$

$P(k)$ at $z = 0$



Jeans length at matter-radiation equality

$$\lambda_J = c_s \sqrt{\frac{\pi}{G\rho}}$$

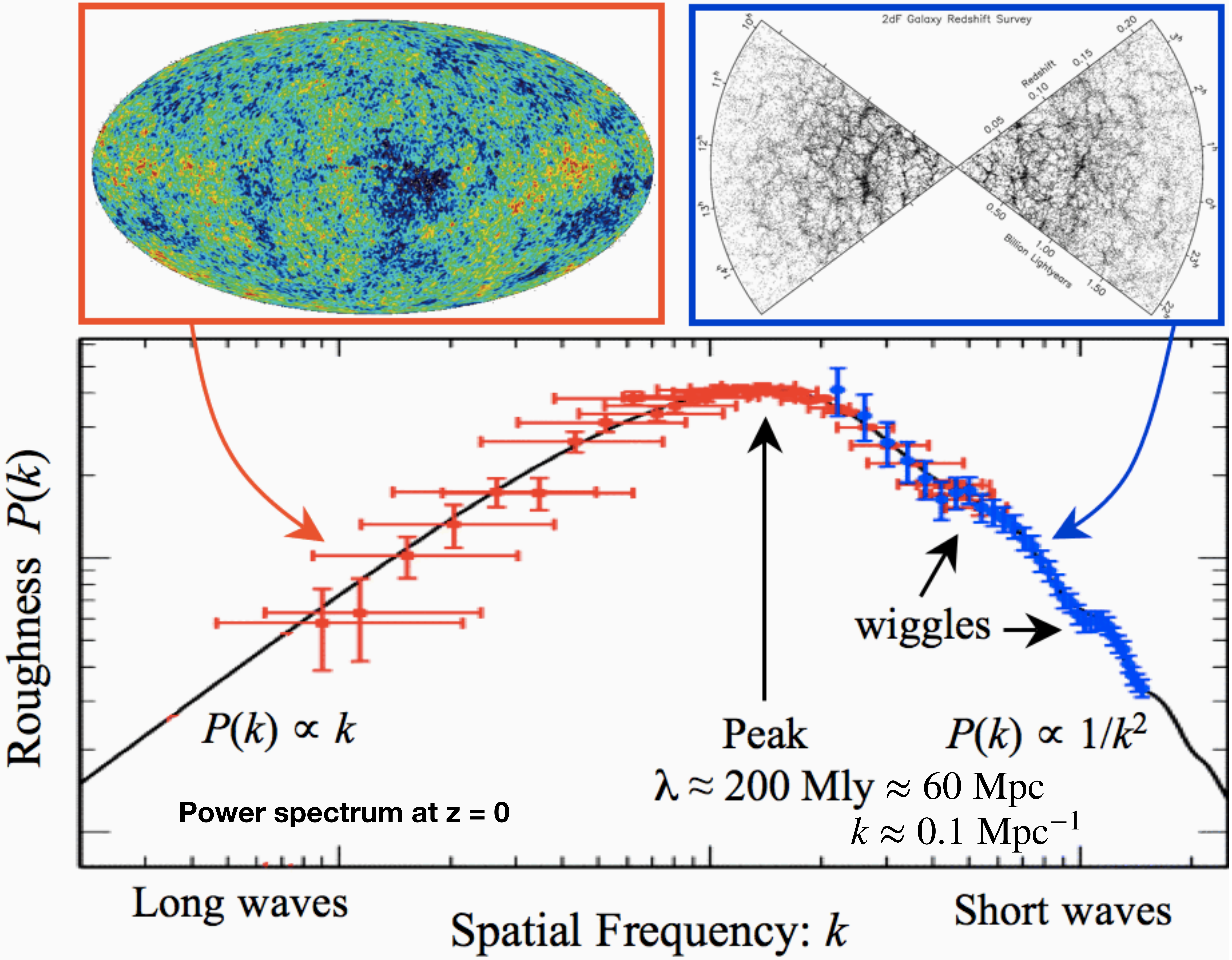
sound speed

$$c_s^2 = \frac{\partial P}{\partial \rho} = \frac{1}{3} c^2$$

at smaller scales, things go non-linear from gravitational collapse, pressure, dissipation, feedback, etc. Described by a Transfer function

$$T(k) \equiv \frac{\delta_k(z=0)}{D(z)\delta_k(z)}$$

where D(z) is the linear growth factor - what it would have been without all these nasty non-linear effects.



2dF Galaxy Redshift Survey
Redshift
Billion Lightyears
Roughness $P(k)$
$P(k) \propto k$
Peak
$\lambda \approx 200$ Mly ≈ 60 Mpc
$k \approx 0.1\ \mathrm{Mpc}^{-1}$
wiggles
$P(k) \propto 1/k^2$
Power spectrum at z = 0
Long waves
Spatial Frequency: k
Short waves

From an accident report in the *Boston Driver's Handbook*:
"The guy was all over the road. I had to swerve several times before I hit him."

The power spectrum of SCDM missed badly:
too much power on small scales;
too little power on large scales.

<u>SCDM</u> ("Standard" CDM)

$$\Omega_m = 1$$
$$H_0 = 50$$

$\Omega_m h = 0.5$ expected

$\Omega_m h \approx 0.2$ observed

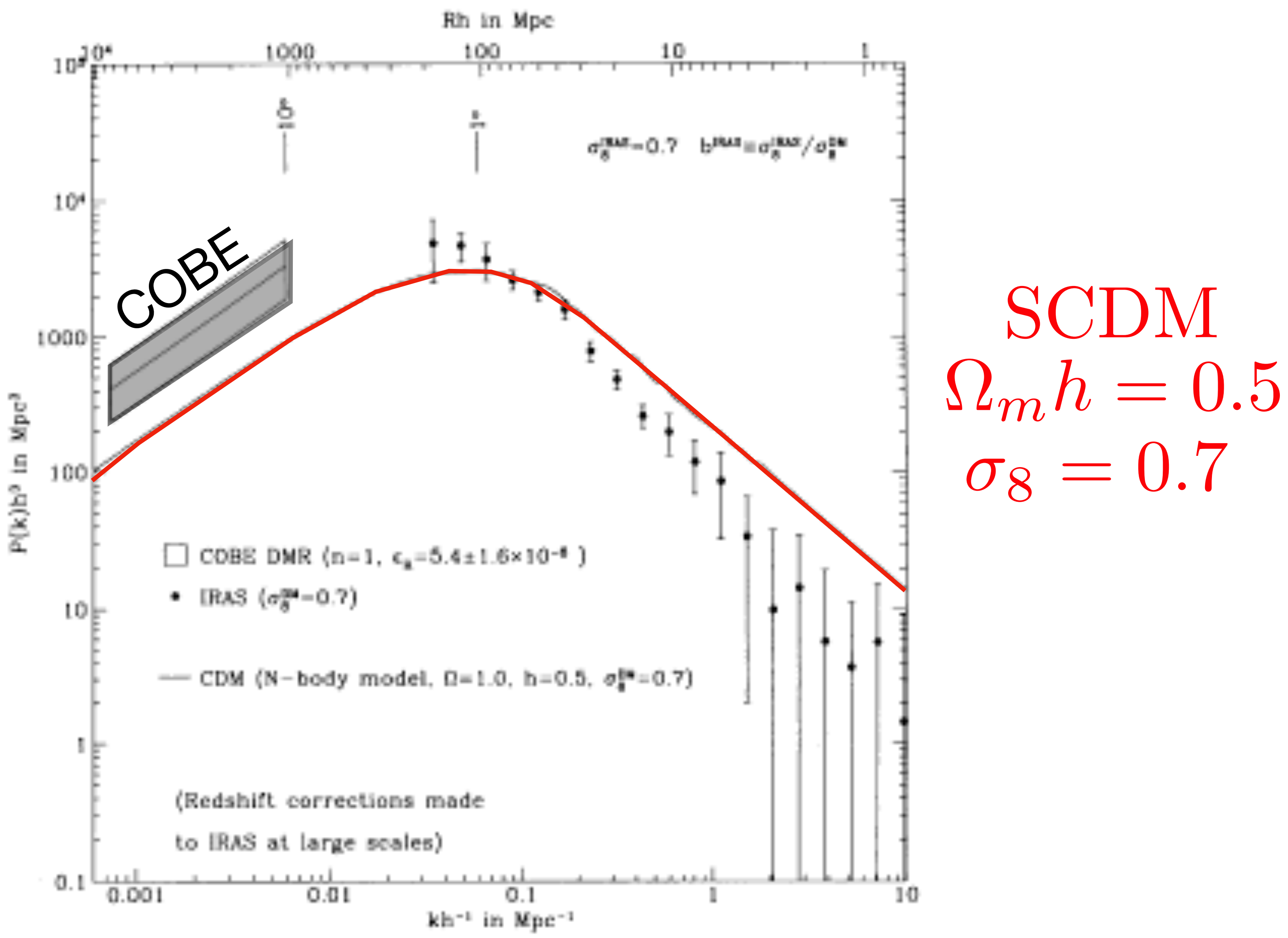
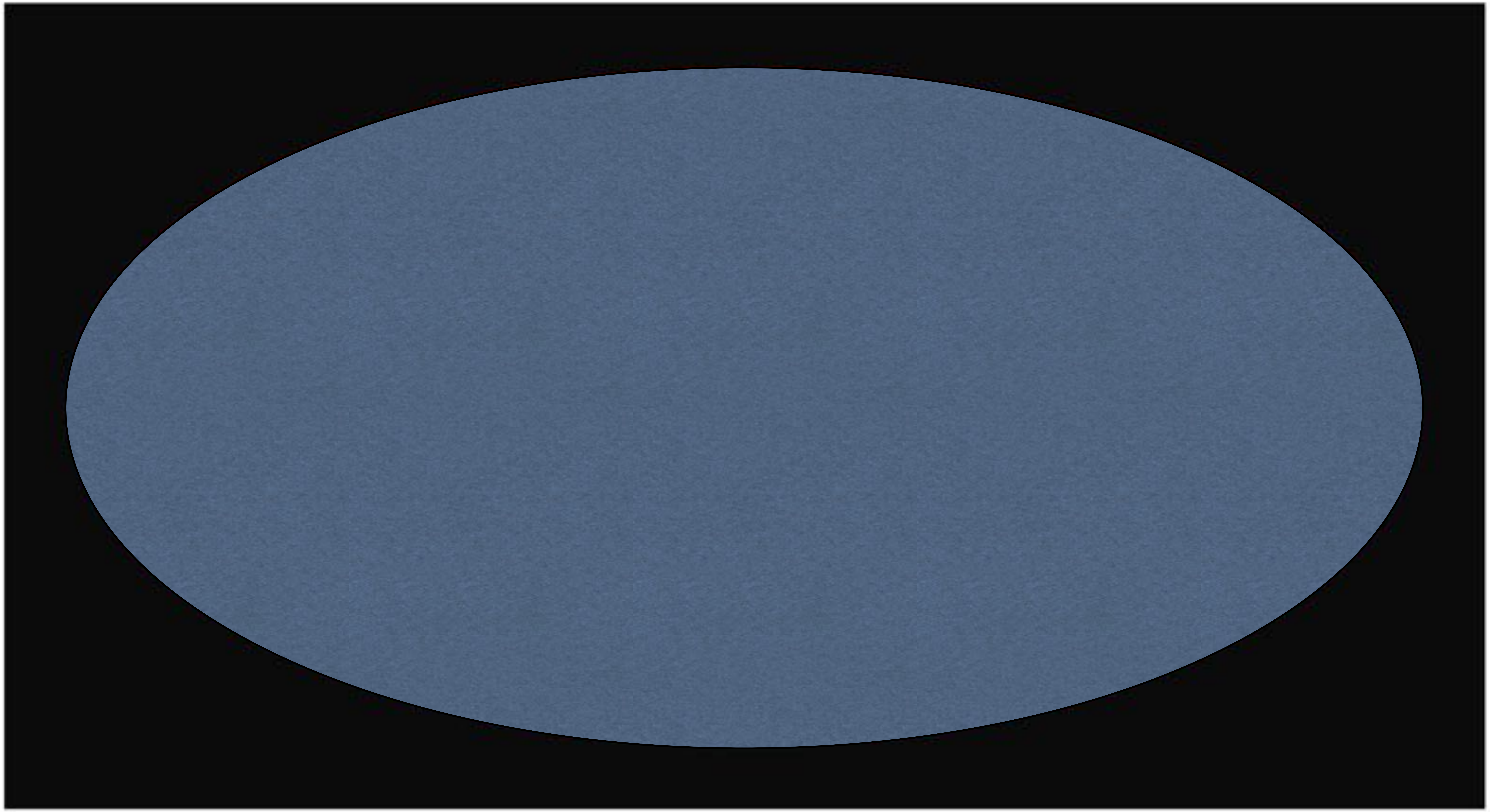


FIG. 10.—Solid curve is the real space power spectrum of the full nonlinear CDM *N*-body simulation (as in Fig. 3) normalized to the real space variance of *IRAS* galaxies ($\sigma_8 = 0.7$). The points are the *IRAS* redshift space $\tilde{P}(k)$ from Fig. 4, rescaled by eq. (17) with $\Omega = 1$ and $b = 1$; this is then, apart from the effects of the convolution in eq. (14), an approximation to the power spectrum of *IRAS* galaxies in *real* space on large scales if the *IRAS* galaxies are unbiased. The box indicates the power spectrum inferred from the *COBE* DMR measurements, assuming a $n = 1$ spectral index and $\epsilon_H = (5.4 \pm 1.6) \times 10^{-6}$ (Smoot et al. 1992; Wright et al. 1992). Note that when the CDM model is normalized to the *IRAS* variance, it produces excessive power on small scales while simultaneously failing to produce sufficient power on large scales to match the *COBE* results.

Fisher et al. (1993) ApJ, 402, 42

CMB: Baby picture of the universe (370,000 years old)



Universe very uniform at z = 1090 (370,000 years old)

CMB temperature fluctuations directly related to density fluctuations

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta\rho}{\rho} \sim 10^{-5}$$

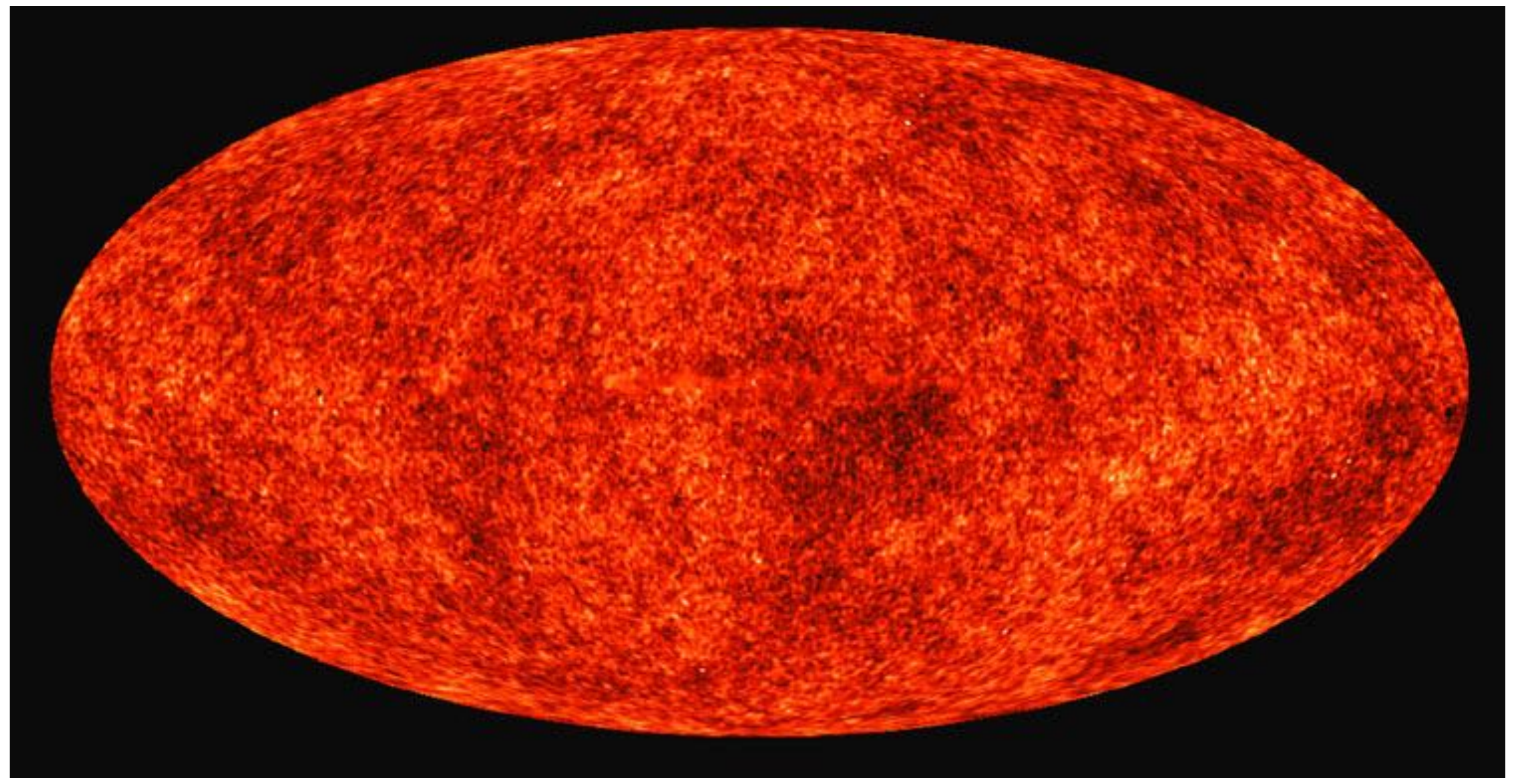
Basic problem:
not enough time for structure to grow.

$$\delta \propto a = 1091 \text{ since } z = 1090$$

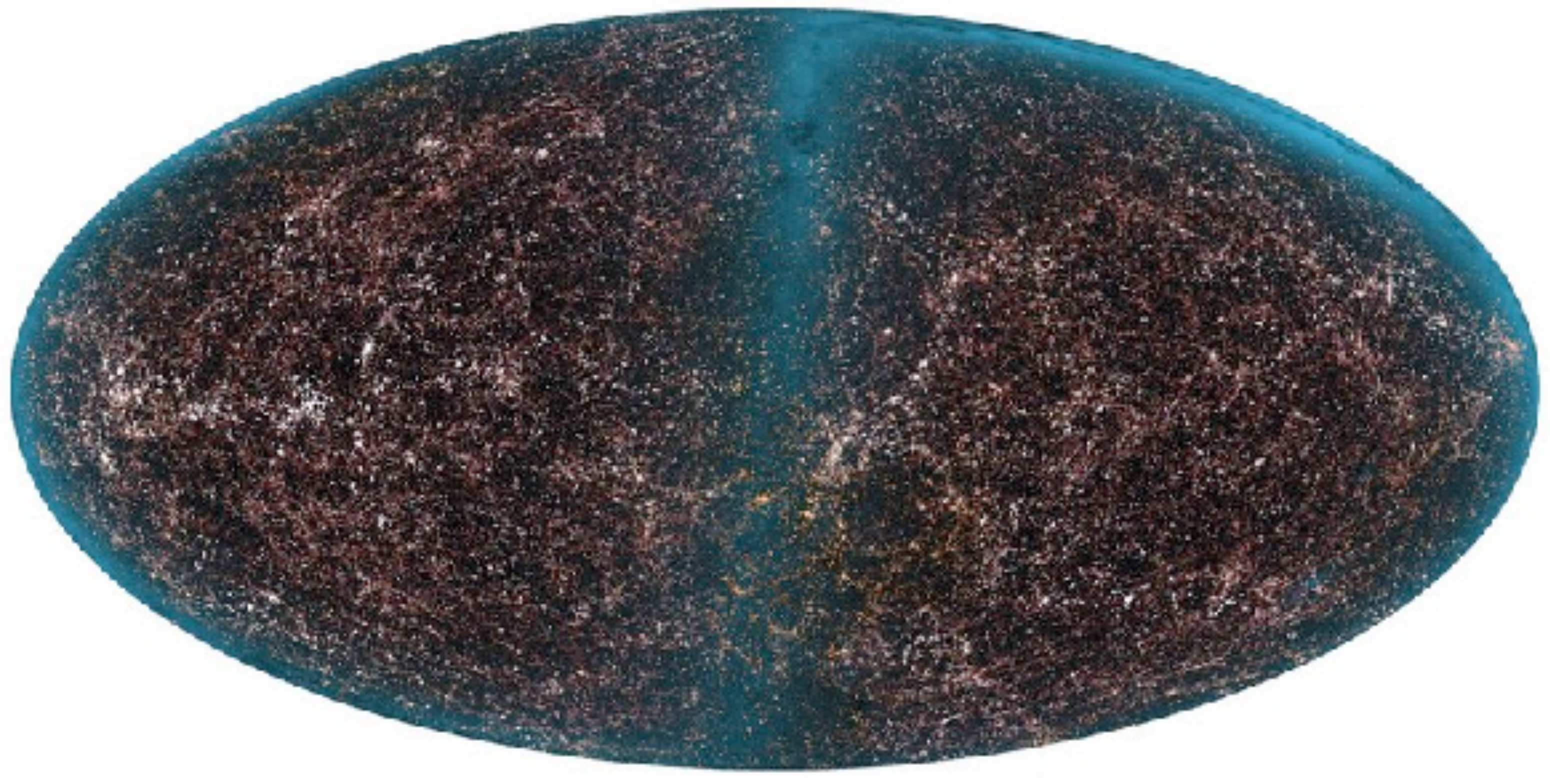
Gravity will grow the observed large scale structure, but it works slowly. Can't get here from there in a Hubble time: need a factor of 100,000 but only get 1,000. Cold dark matter speeds up the process while not overproducing the temperature fluctuations.

There isn't enough time to form the observed cosmic structures from the smooth initial conditions unless there is a component of mass independent of photons.

t = 3.8 x 10^5 yr



t = 1.4 x 10^{10} yr



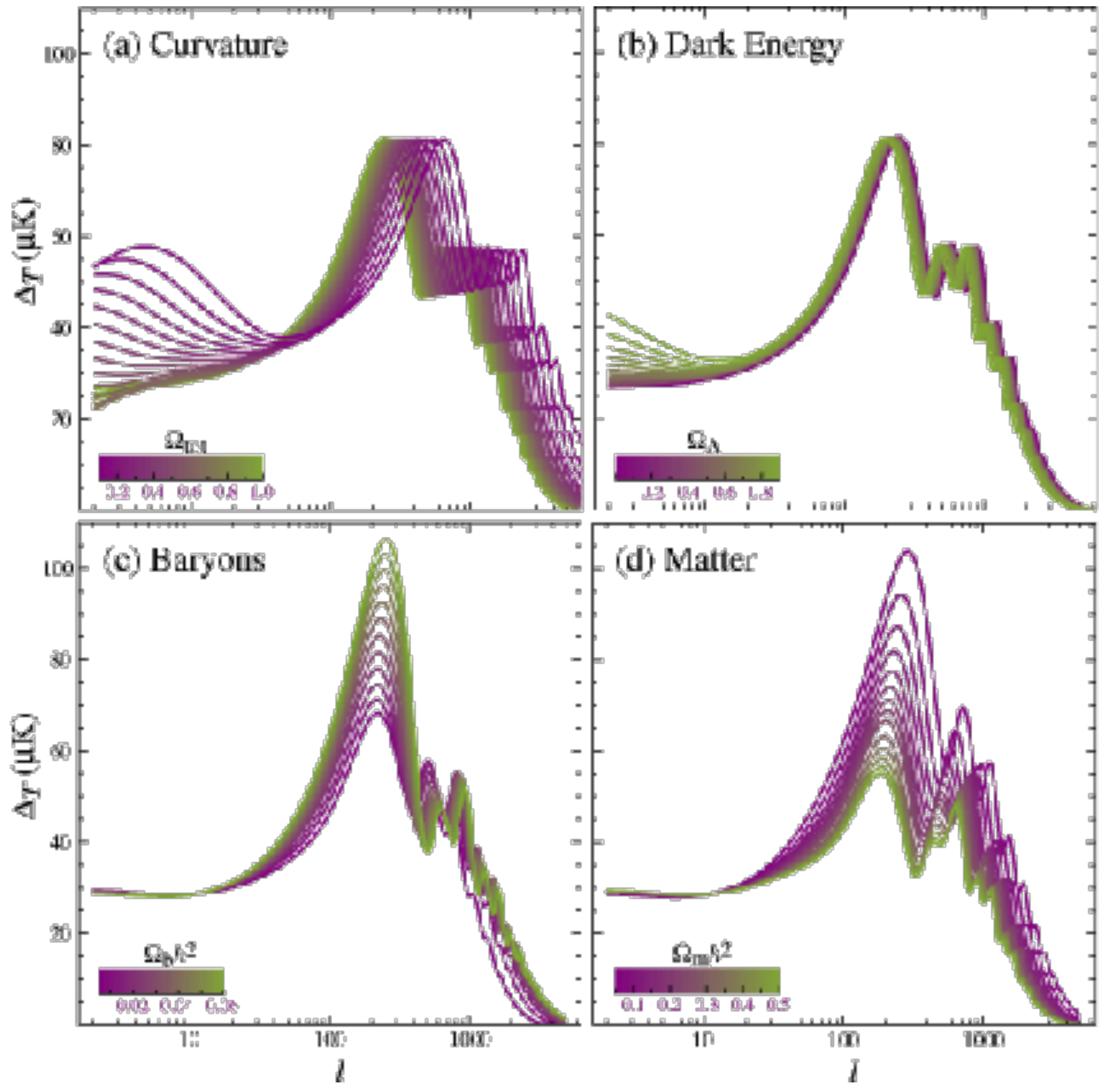
Early universe very smooth: $\delta \sim 10^{-5}$

Current universe very lumpy: $\delta \sim 1$

$\delta \propto a$

$a \propto t^{2/3}$ at early times

Detailed shape of the acoustic power spectrum depends sensitively on cosmic parameters.



Best-fit cosmology obtained from multi-parameter fit. Well constrained, but not unique - lots of parameter degeneracy.

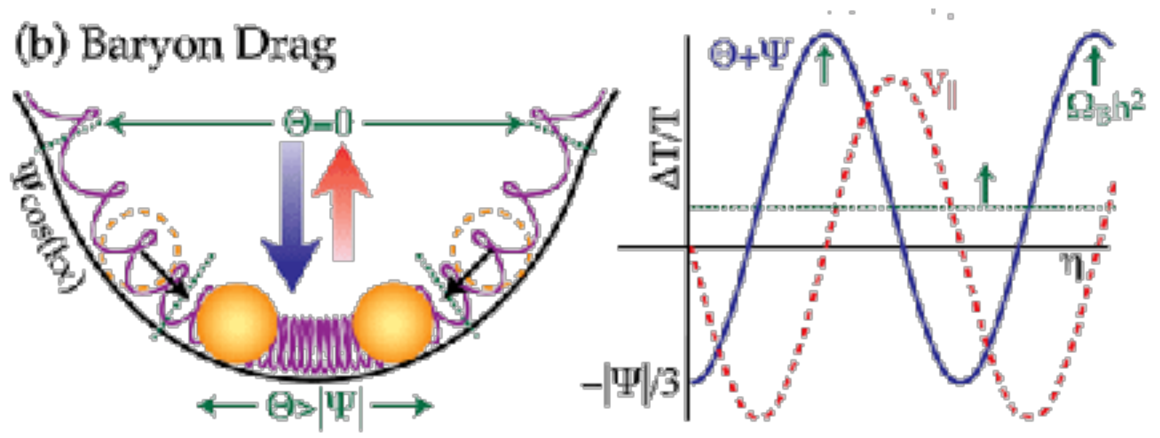
Compression and rarefaction nearly cancel out, but don't quite. Left with

$$\frac{\delta T}{T} = \frac{1}{3}\frac{\delta \rho}{\rho}$$

Damped and driven oscillator

Baryons damp oscillations, like a kid dragging his feet on a swing.
 pure damping spectrum in limit of all baryons

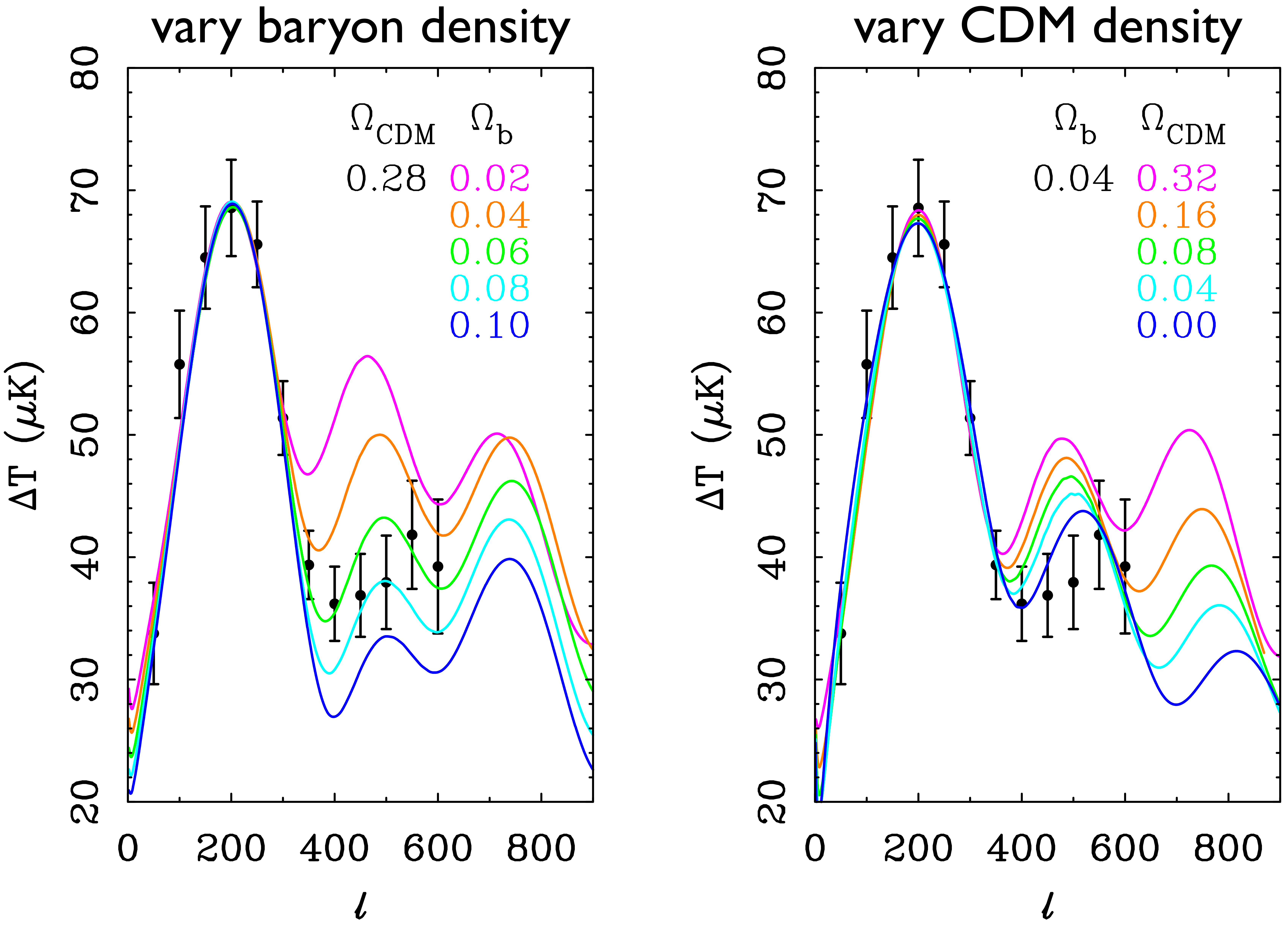
Dark matter helps drive oscillations, like a parent pushing the kid.



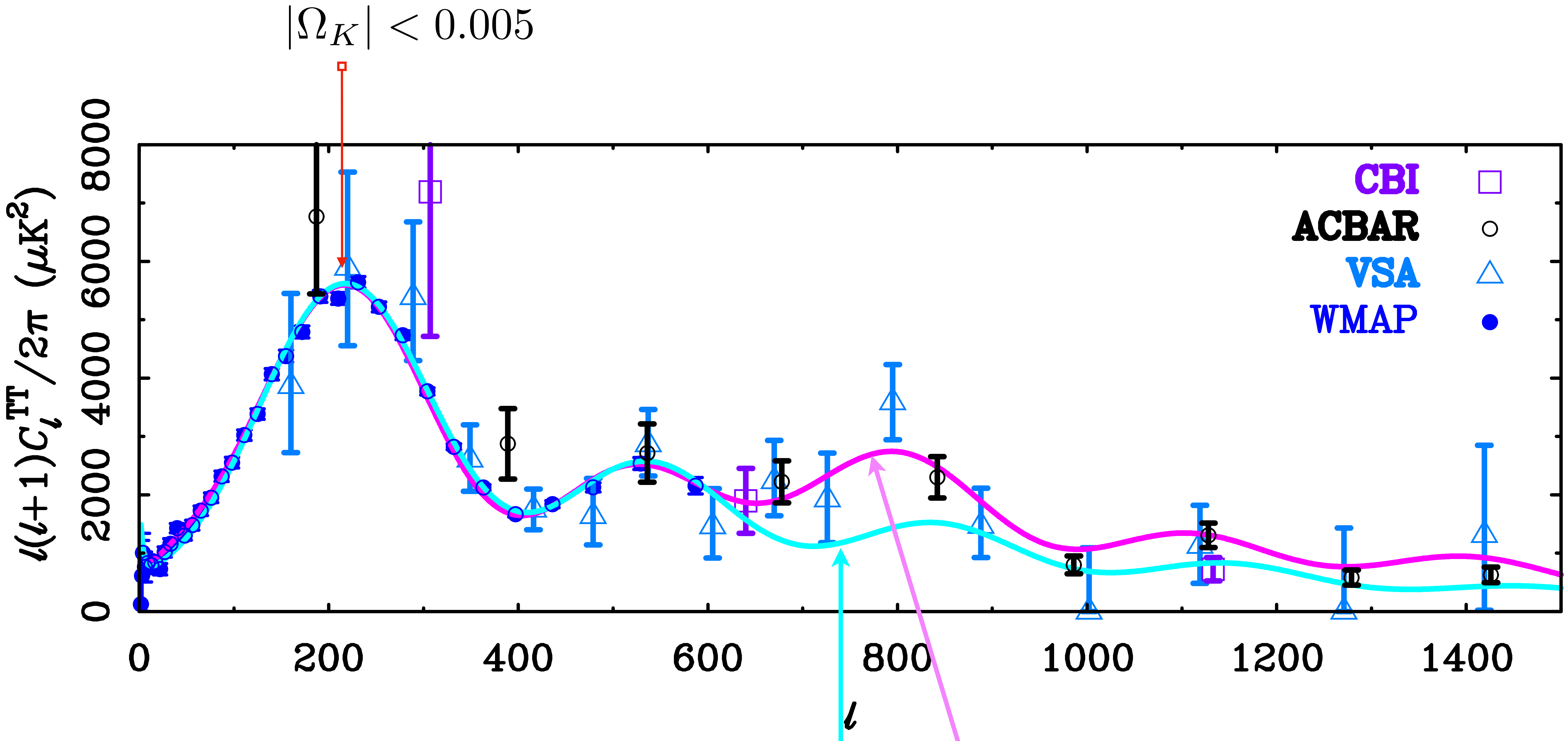
Wayne Hu provides a nice CMB tutorial at http://background.uchicago.edu/index.html

See also the movies of Max Tegmark at http://space.mit.edu/home/tegmark/movies.html

CMB power spectra



artificially normalize first peak to show variation in shape



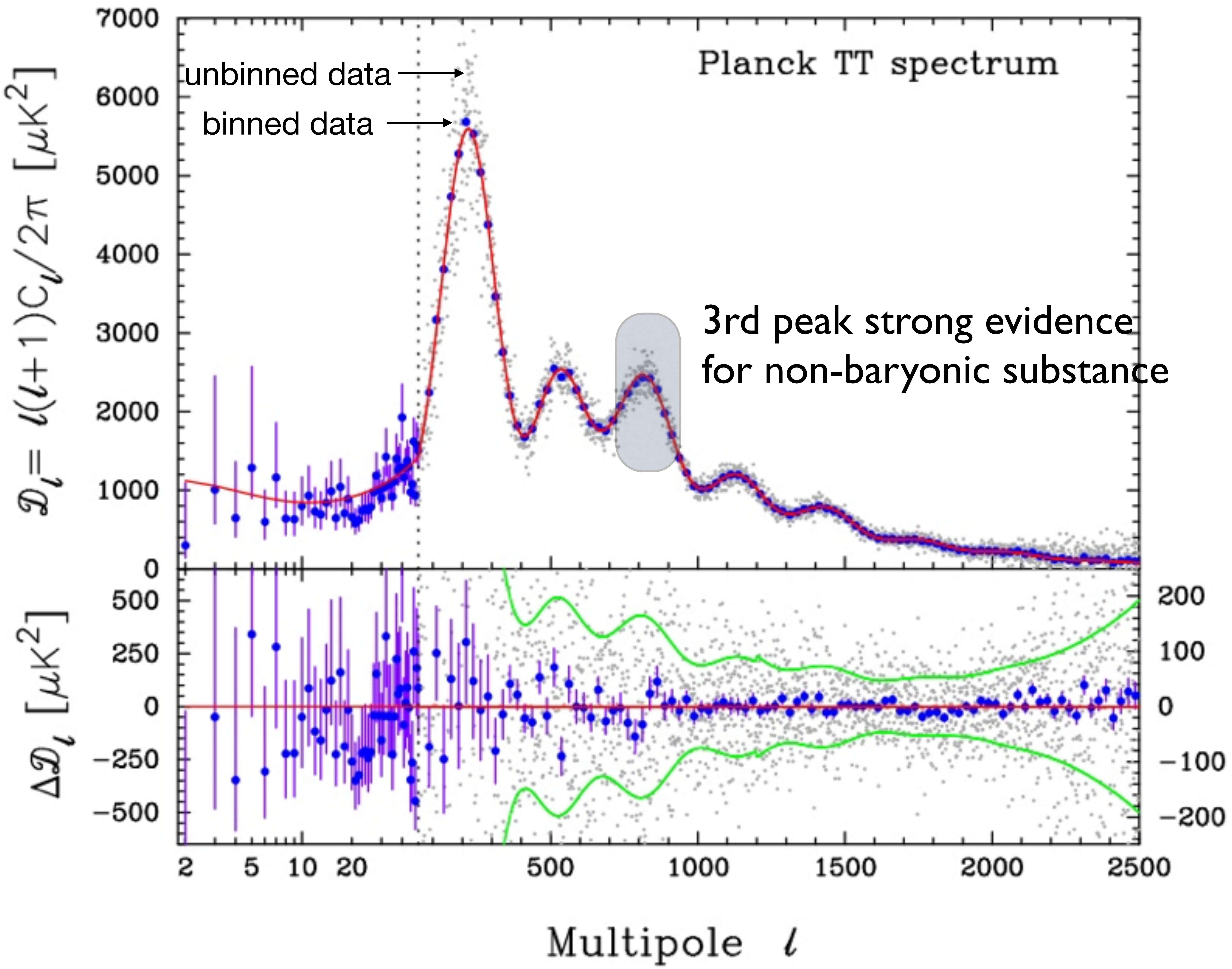
Effective Poisson eqn for mode k

Assume modes are independent - a good assumption in linear regime

$$k^2\Phi = 4\pi G\,(\delta_\gamma\,\rho_\gamma + \boxed{\delta_b\,\rho_b} + \boxed{\delta_{CDM}\,\rho_{CDM}})$$

baryons a net drag

CDM a net forcing term
out of phase with baryons


Planck TT spectrum
unbinned data
binned data
3rd peak strong evidence
for non-baryonic substance
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ
7000
6000
5000
4000
3000
2000
1000
0
500
250
0
−250
−500
200
100
0
−100
−200
2
5
10
20
500
1000
1500
2000
2500

Measurements of the gravitating mass density

- Cluster M/L $\Omega_m \approx 0.25$ Bahcall et al. (1995)
  - measure M/L of a cluster, combine with measured luminosity density of universe.
- Weak lensing $\Omega_m \approx 0.18 \pm 0.04$ Dark Energy Survey arxiv:2002.11124
  - measure shear over large scales
- Peculiar Velocity Field $\Omega_m = 0.25 \pm 0.05$ Tonry & Davis (1980)
  - measure deviations from Hubble flow
- Power spectrum of galaxies
- CMB fits

$$\Omega_m h = 0.213 \pm 0.023$$
$$\Omega_m = 0.3 \text{ for } h = 0.71$$
Tegmark et al. (2004)

$$\Omega_m = 0.315 \pm 0.007$$
also gives $h = 0.674 \pm 0.005$

Planck Collaboration (2018)