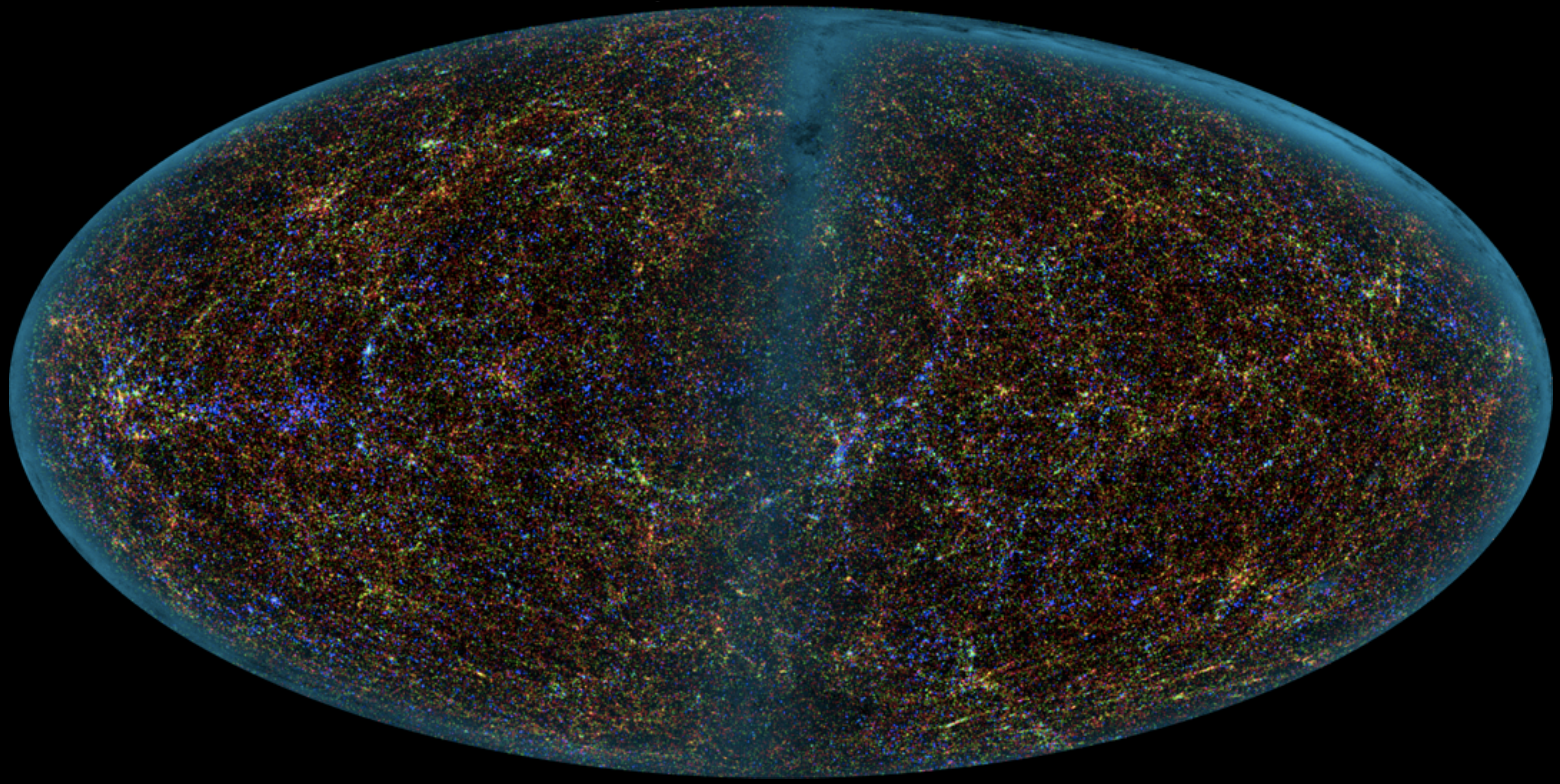
Cosmology
and Large Scale Structure



Today
Power Spectra
LCDM genesis

Homework 4 due

12 November 2024

http://astroweb.case.edu/ssm/ASTR328/

Large Scale Structure

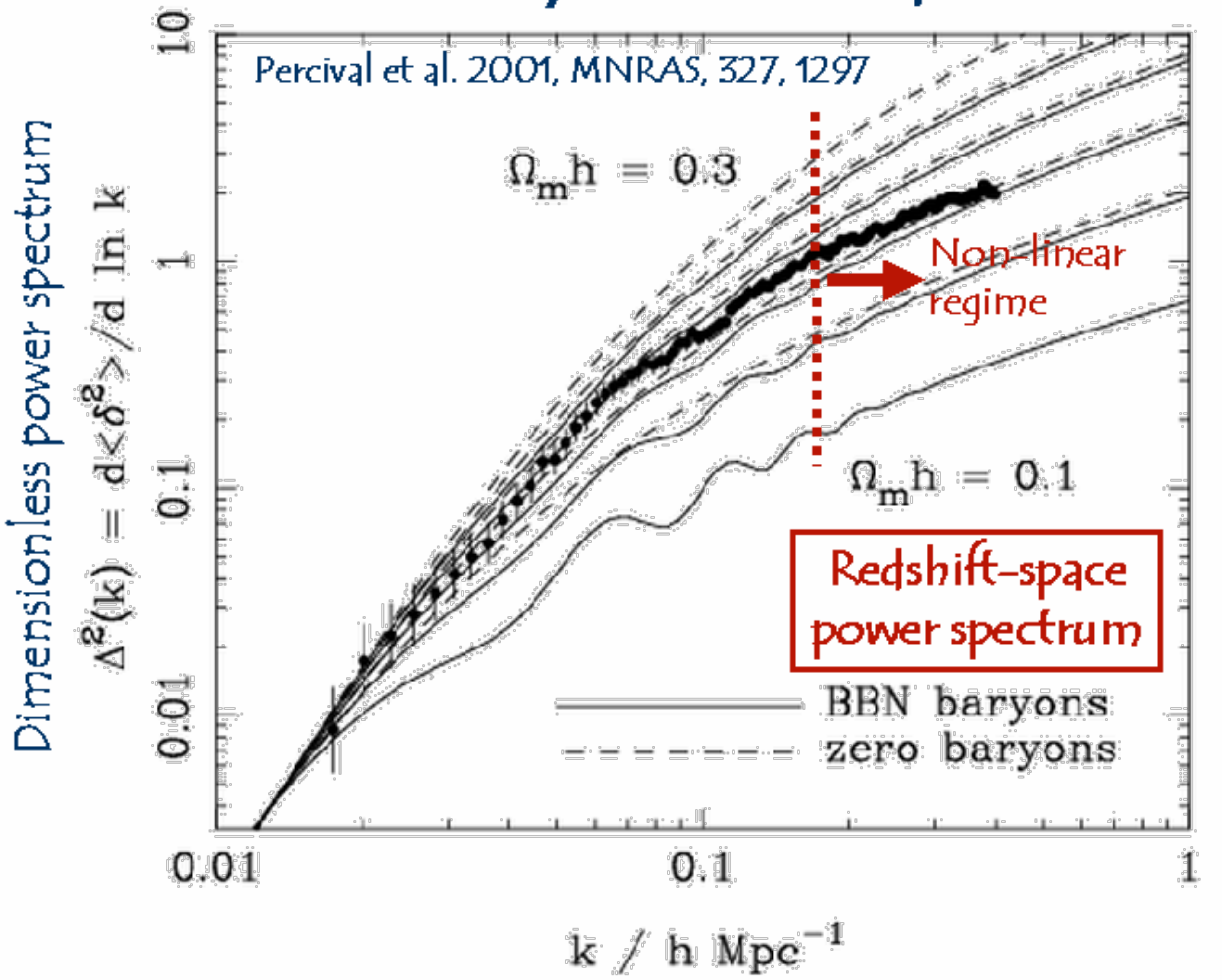
Quantified with the **correlation function** $\xi(r)$ which is the Fourier transform of the **power spectrum** $P(k)$.

The galaxy power spectrum primarily depends on the *shape parameter*
$\Gamma \approx \Omega_m h$

In detail,

$$\Gamma = \Omega_m h \, e^{-\left(\Omega_b + \sqrt{2h}\frac{\Omega_b}{\Omega_m}\right)} - 0.32\left(\frac{1}{n} - 1\right)$$

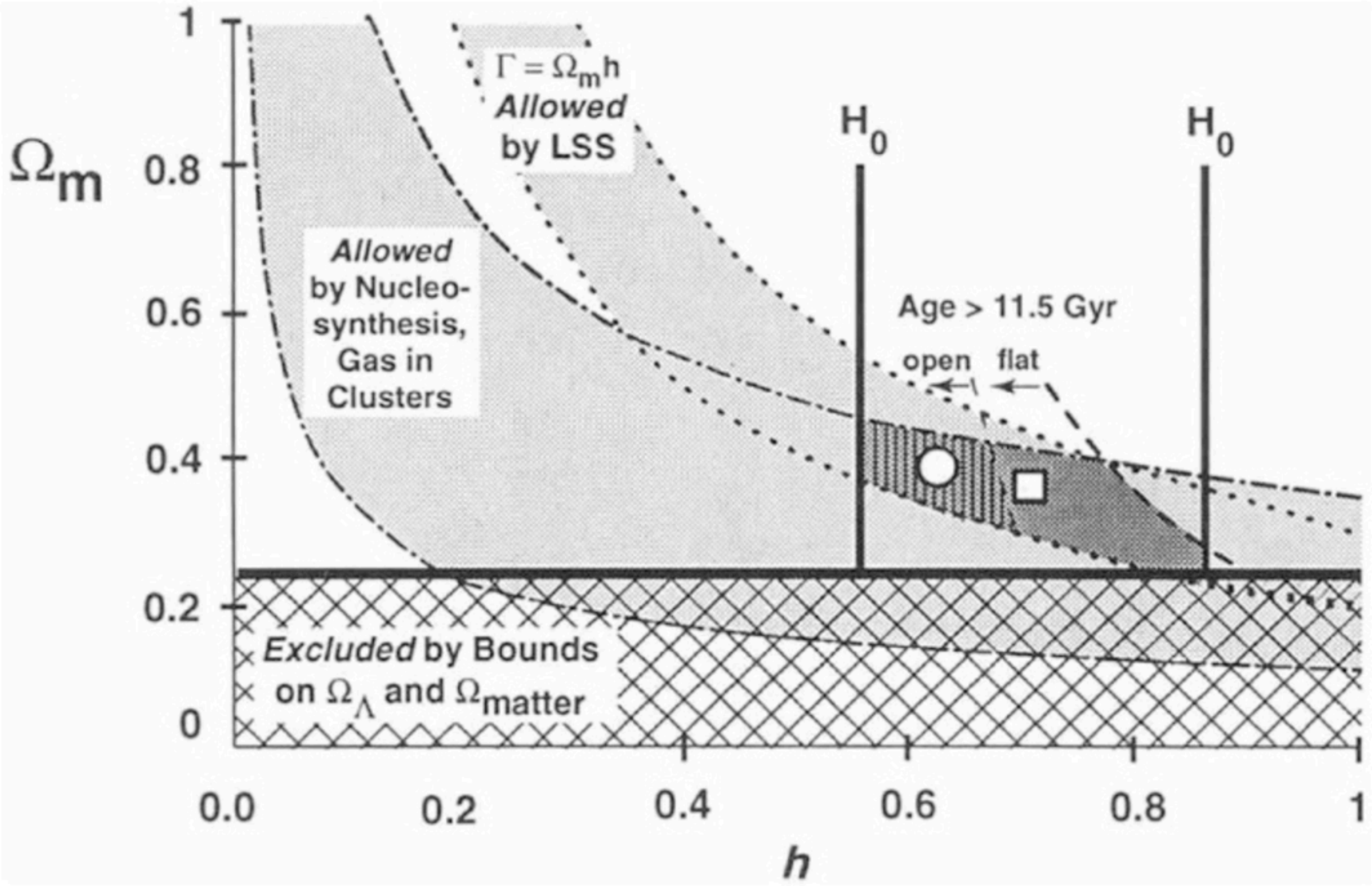
The Galaxy Power Spectrum



How we got LCDM

as it applies to the first problem of Homework 4

Fig. 1 of Ostriker & Steinhardt (1995, Nature, 377, 600)



In addition to the 3 empirical pillars, we now have 2 auxiliary hypotheses

- Dark matter
- Dark Energy

Each of the given constraints

- $t_0 = 13.5 \pm 0.15$ (stat) ± 0.5 (sys) Gyr
- $H_0 = 75.1 \pm 0.2$ (stat) ± 3 (sys) km/s/Mpc

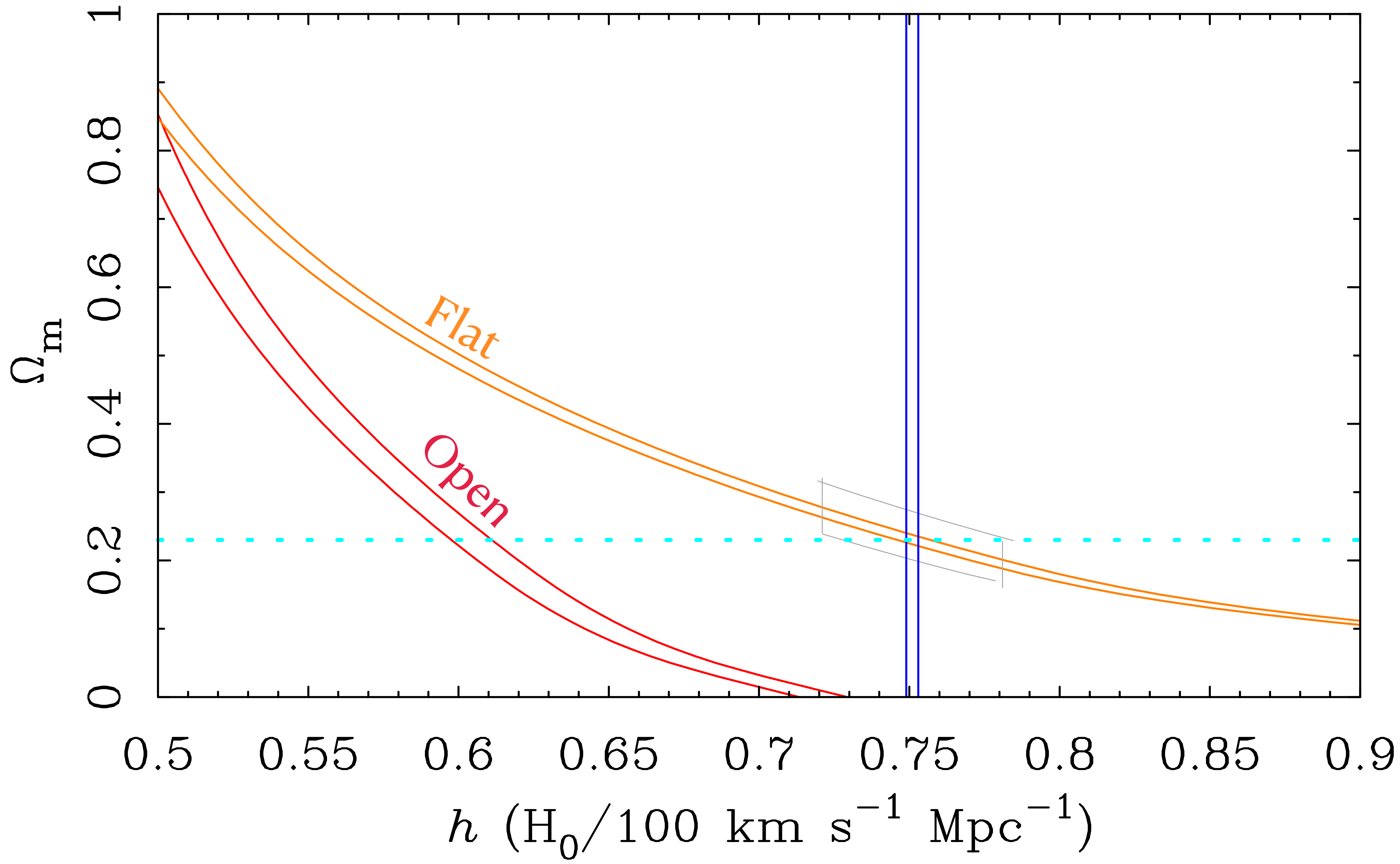
trace out a locus of allowed values in this diagram.
Find where they intersect.

For a short history, see https://tritonstation.com/2019/01/28/a-personal-recollection-of-how-we-learned-to-stop-worrying-and-love-the-lambda/

How we got LCDM

as it applies to the first problem of Homework 4

The age problem was one important driver of the acceptance of the cosmological constant.



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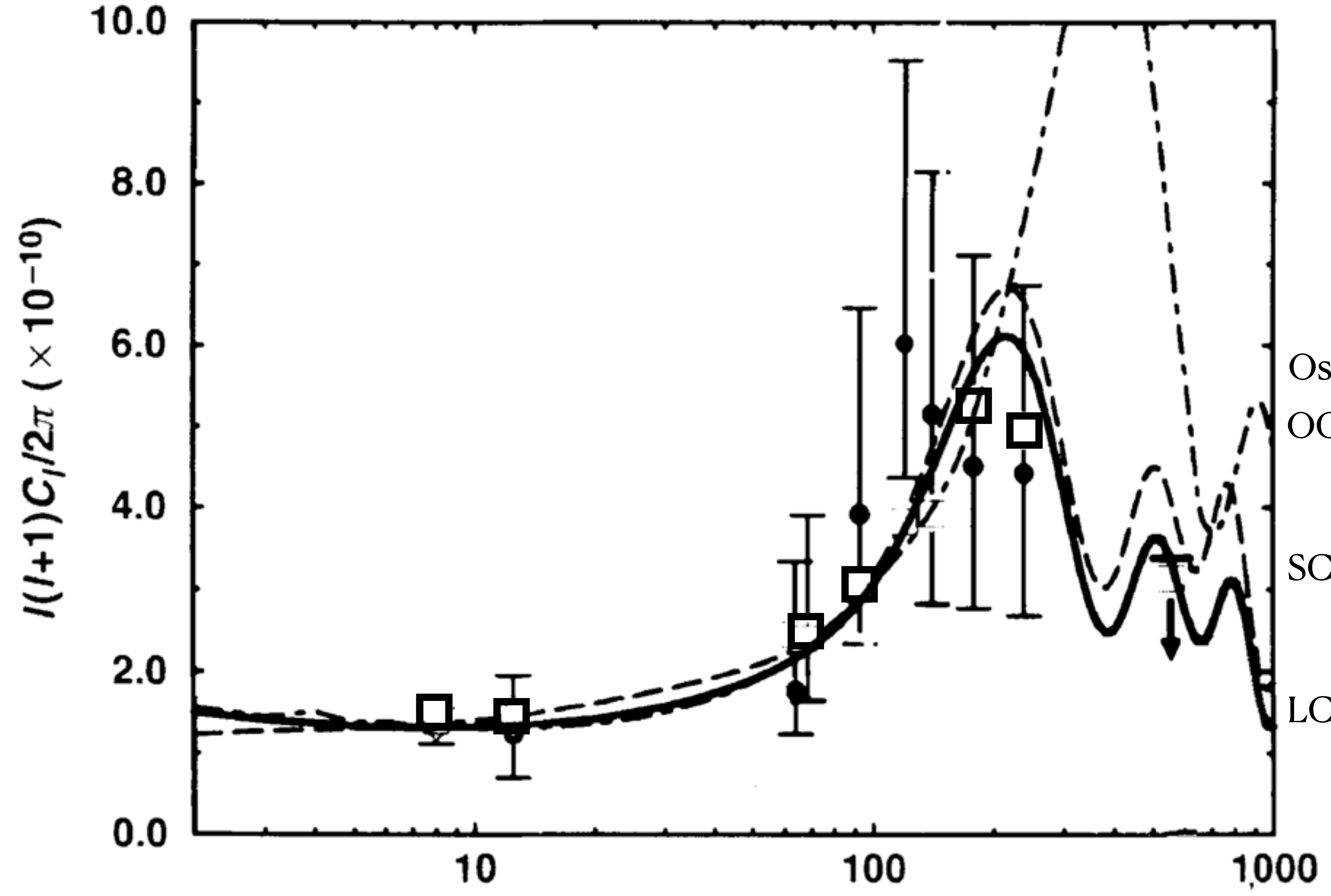
How we got LCDM

as it applies to the first problem of Homework 4

Fig. 2 of Ostriker & Steinhardt
(1995, Nature, 377, 600)

Acoustic power spectrum of the CMB at z = 1090



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Early prediction for the acoustic power spectrum of the cosmic microwave background.

Ostriker & Steinhardt tried

OCDM: $\Omega_{m_0} = 0.375$; $H_0 = 62.5$ (dash-dot line)

SCDM: $\Omega_{m_0} = 1.0$; $H_0 = 50$ (dashed line)

LCDM: $\Omega_{m_0} = 0.35$; $H_0 = 65$; $\Omega_{\Lambda_0} = 0.65$ (solid line)

These are very close to Planck values 20 years later.

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Large Scale Structure

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

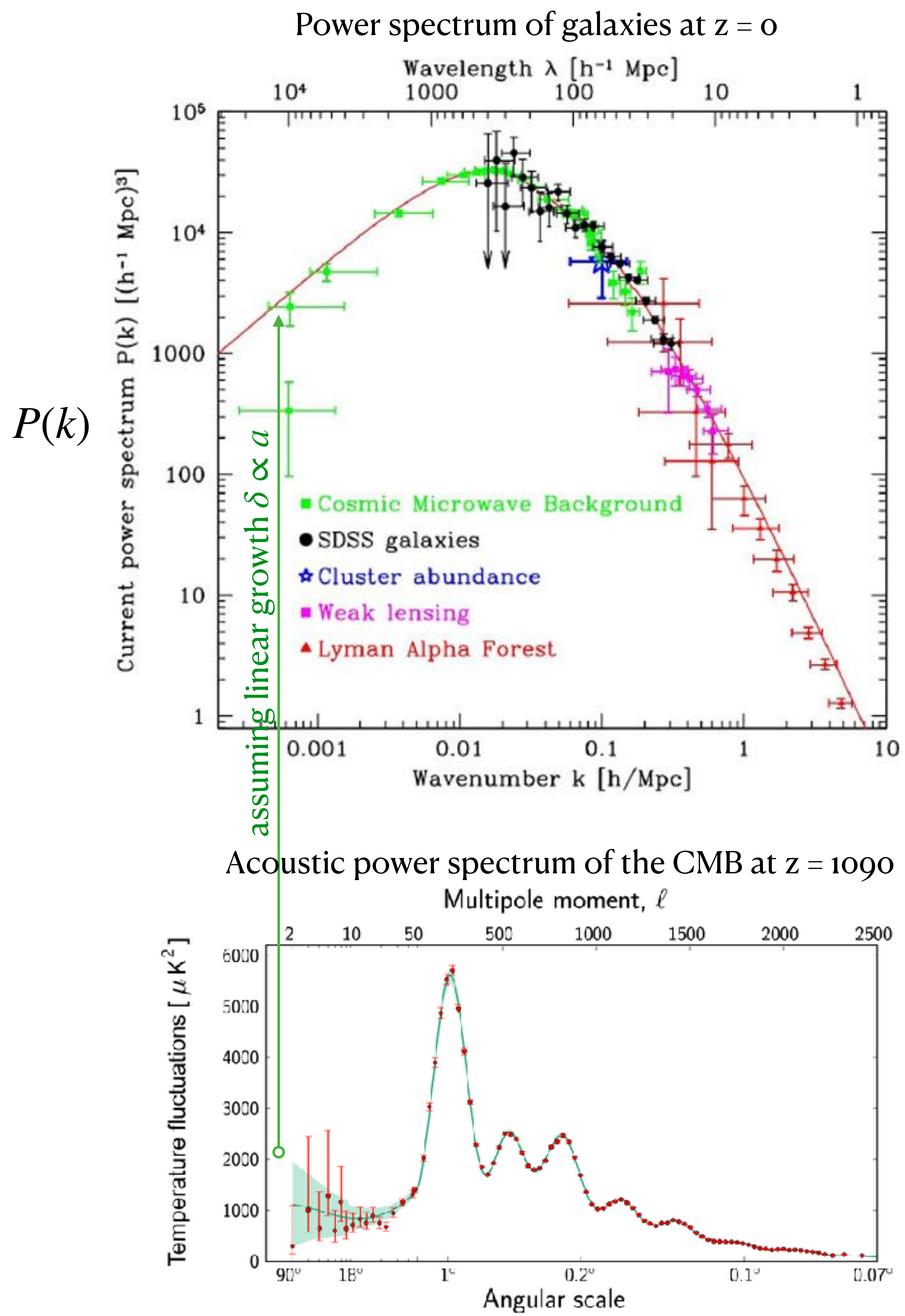
The correlation function is the excess probability of finding a galaxy near another galaxy over that in a random distribution.

$$\frac{dN}{N} = [1 + \xi(r)]dV$$

$$\xi(r) = \frac{V}{(2\pi)^3} \int P(k) e^{-\vec{k}\cdot\vec{r}}\, d^3k$$

$$P(k) \propto |\delta(k)|^2 \propto |\frac{\Delta T}{T}|^2 \propto k^n$$

with $n \approx 1$ (scale free) initially.



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

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

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 λ

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

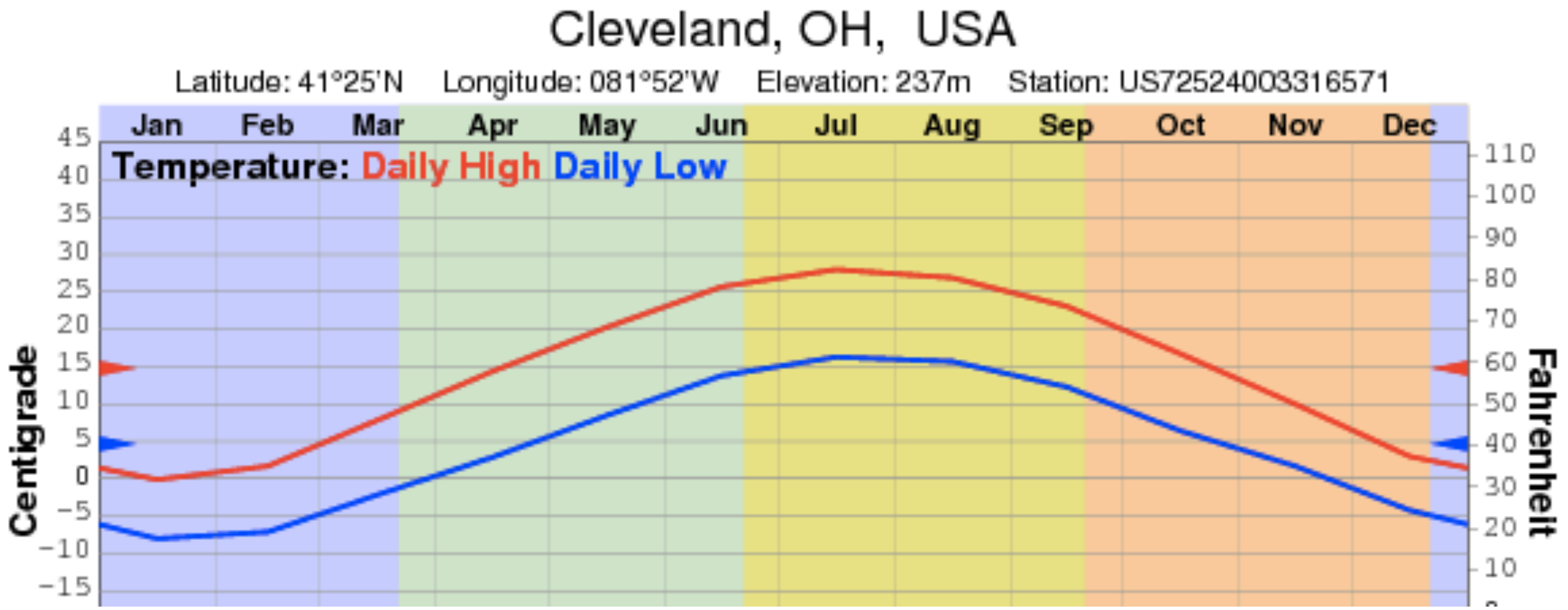
There is more rms variance on small scales, so more power there.
[On very large scales, the universe is homogeneous, so no variance.]

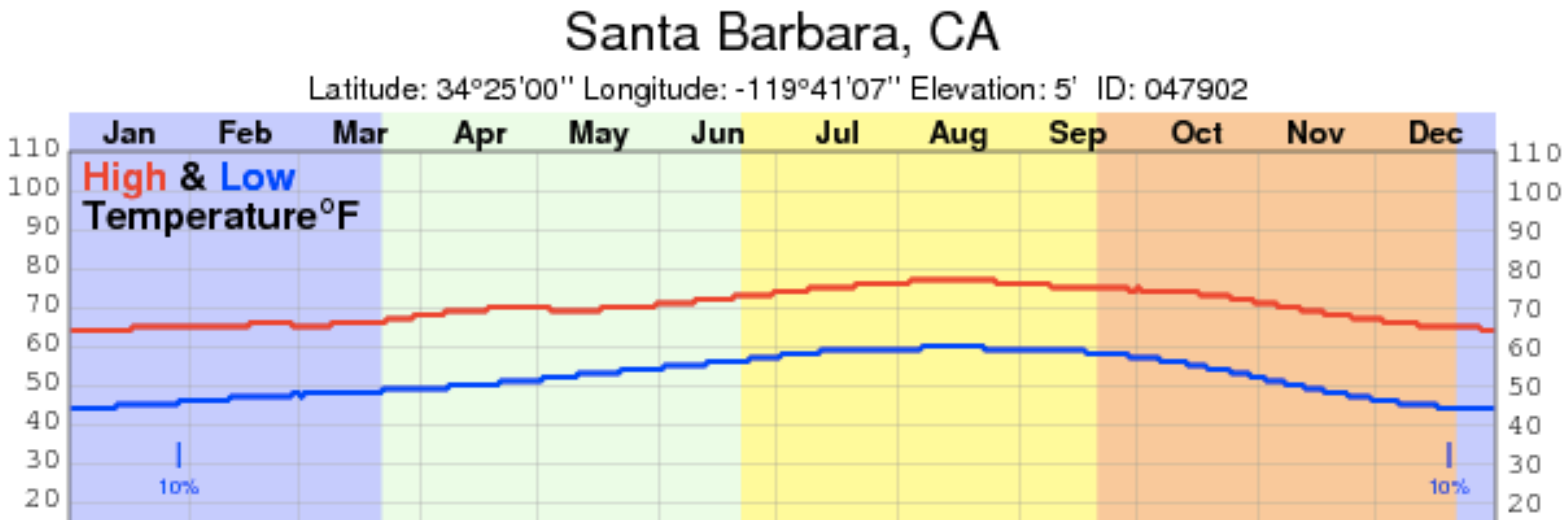
By convention, the normalization is set on a scale of 8 Mpc, where

$$\frac{\delta N_{gal}}{N_{gal}} = 1$$ with corresponding mass variance σ_8

Power Spectrum

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

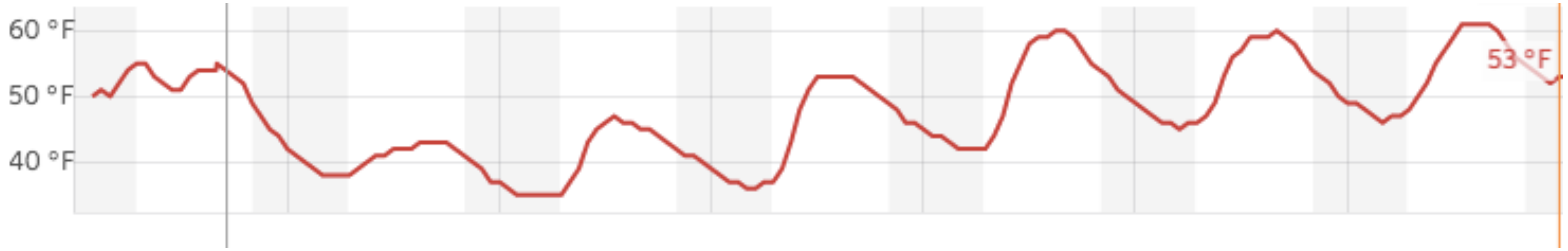




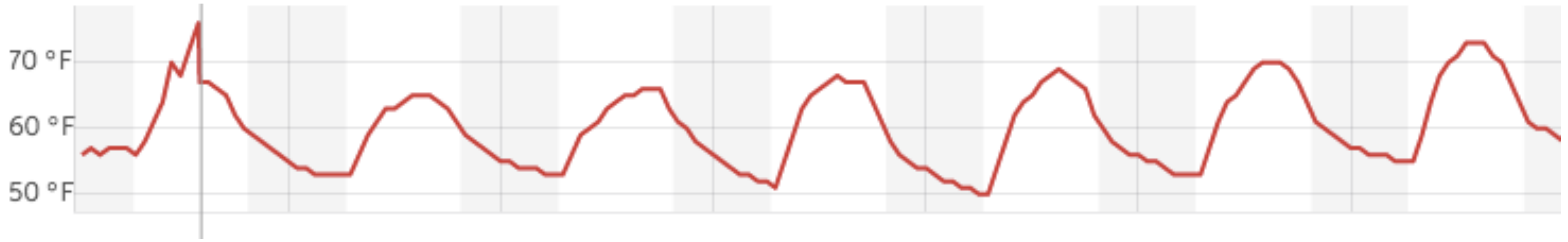
Power Spectrum

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

Cleveland forecast

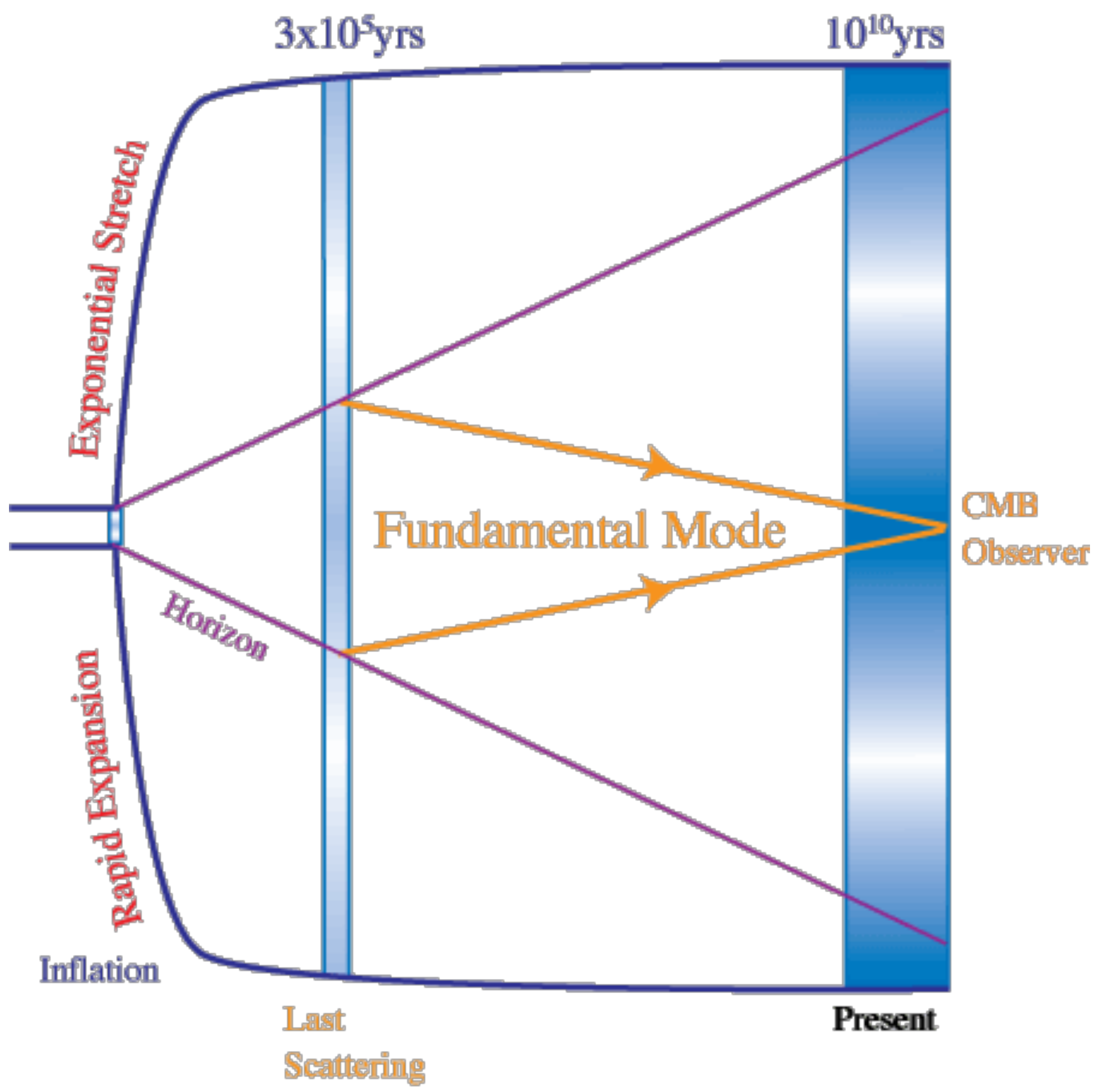


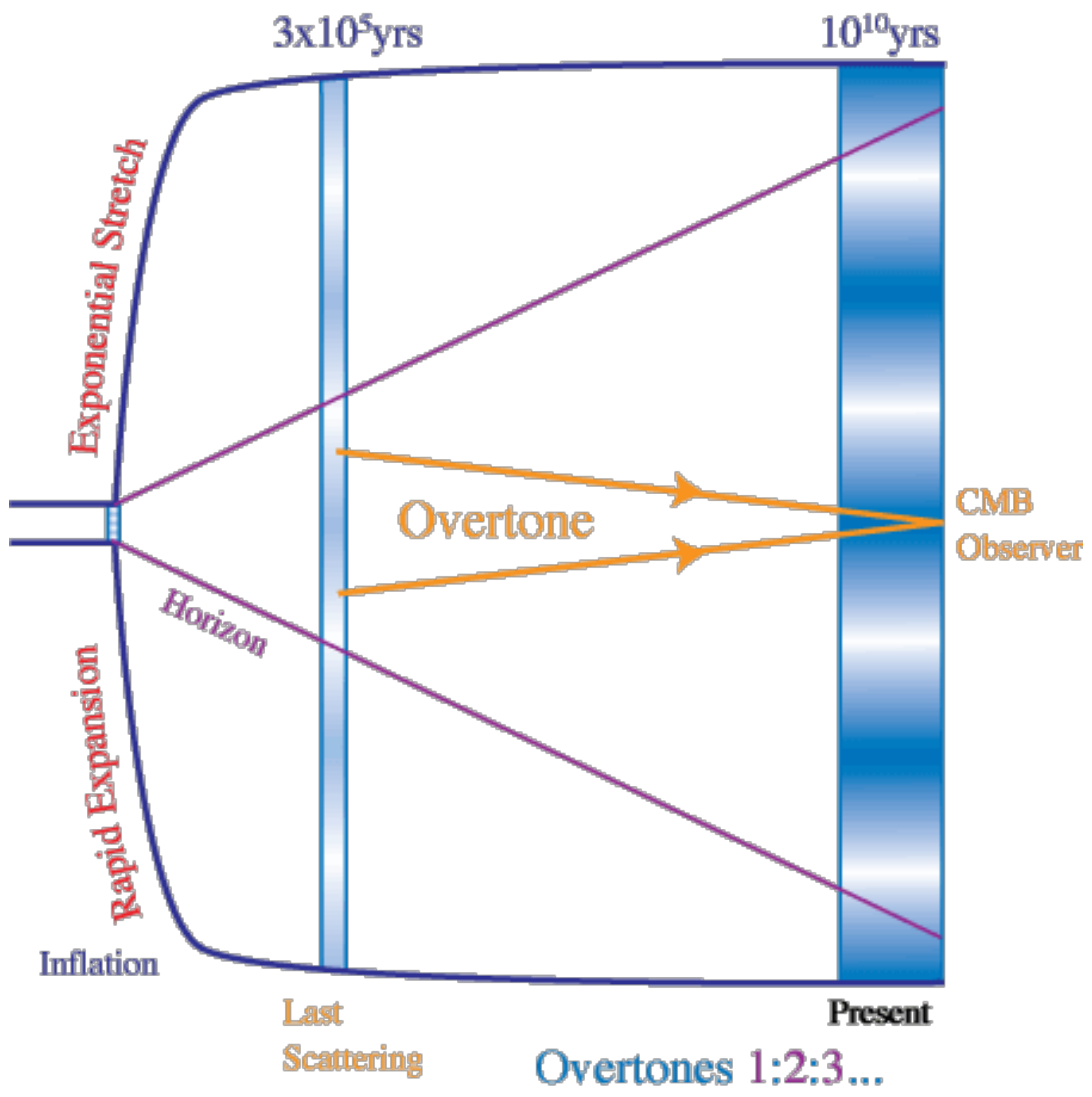
Santa Barbara forecast



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

Detailed shape of the acoustic power spectrum depends sensitively on cosmic parameters.
First and foremost, the location of the first peak measures the angular diameter distance to the surface of last scattering. This is the best evidence that the universe is very nearly flat: $\Omega_k = -0.011 \pm 0.006$ (Planck X 2018)





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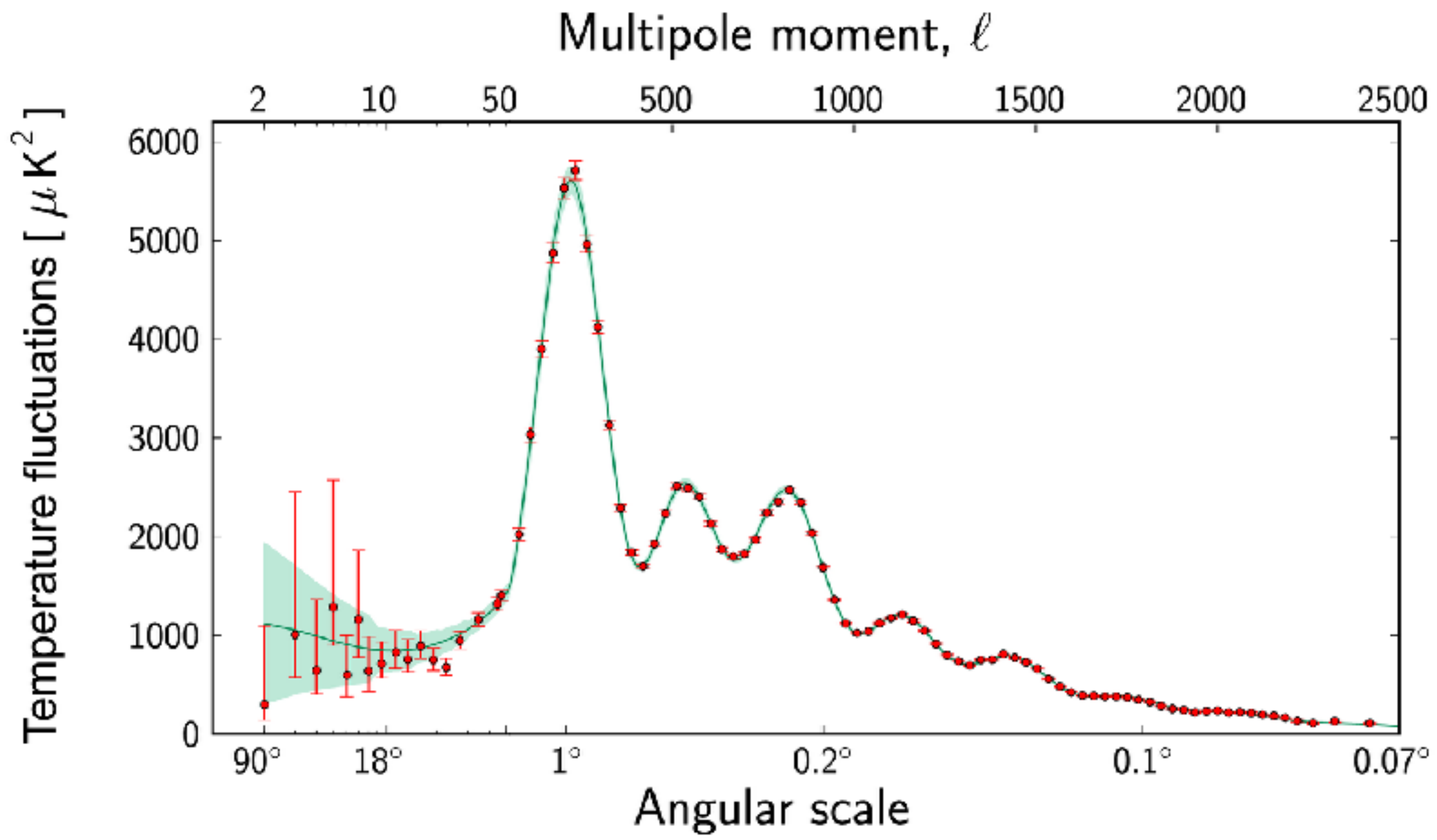
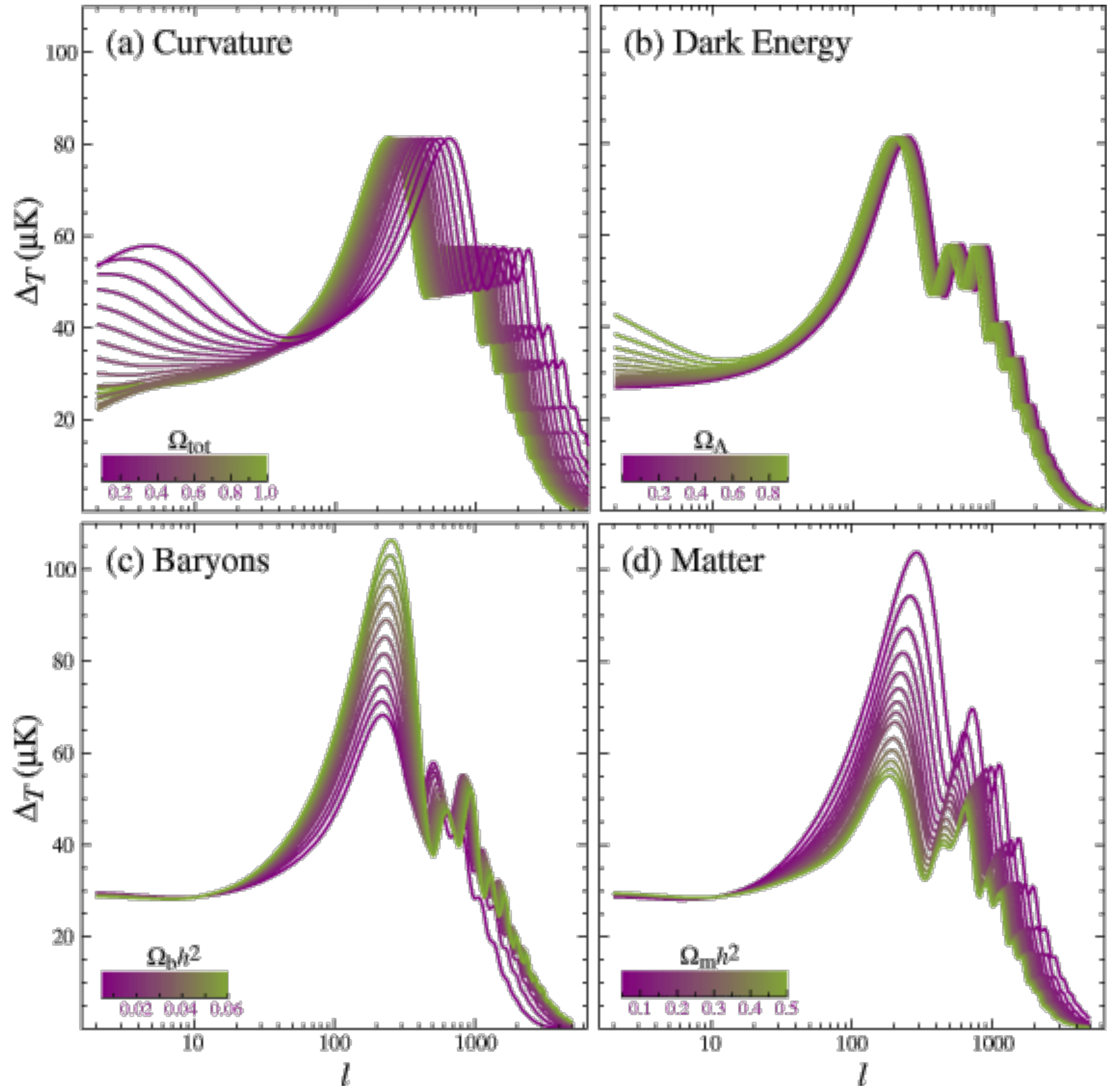
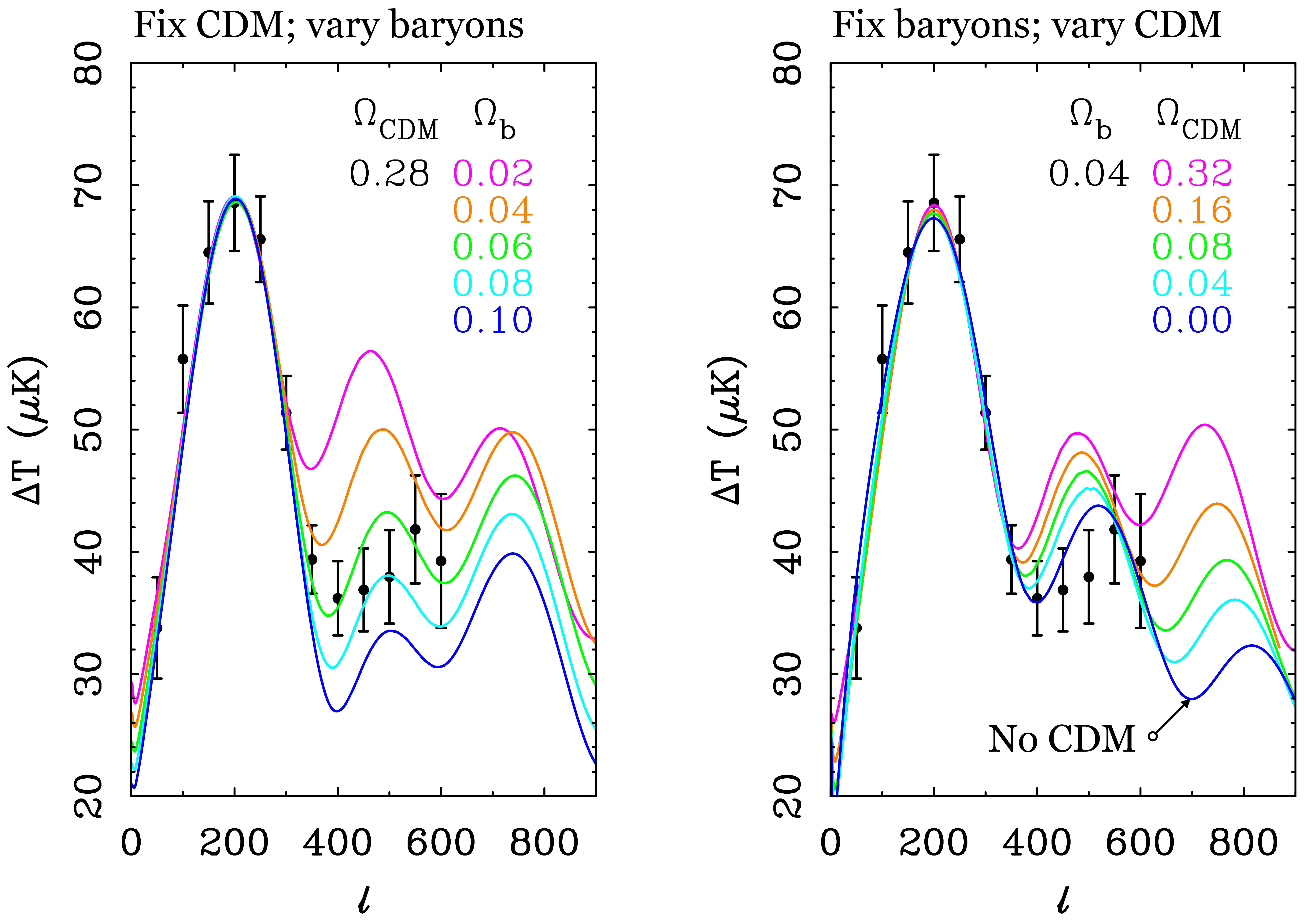




Best-fit cosmology obtained from multi-parameter fit. Well constrained, but not unique - lots of parameter degeneracy.

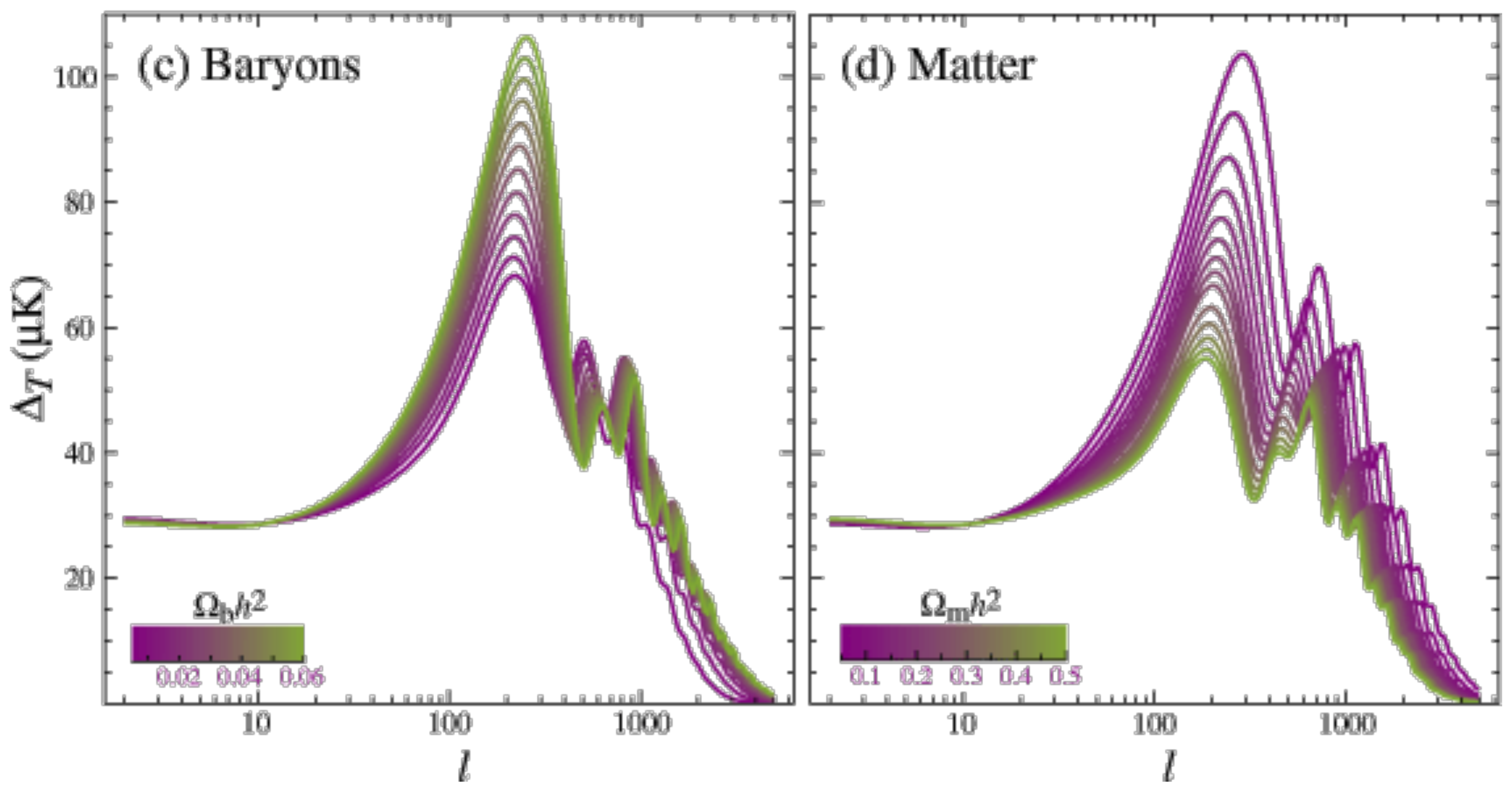
CMB dependence on the density of baryonic and non-baryonic matter



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.



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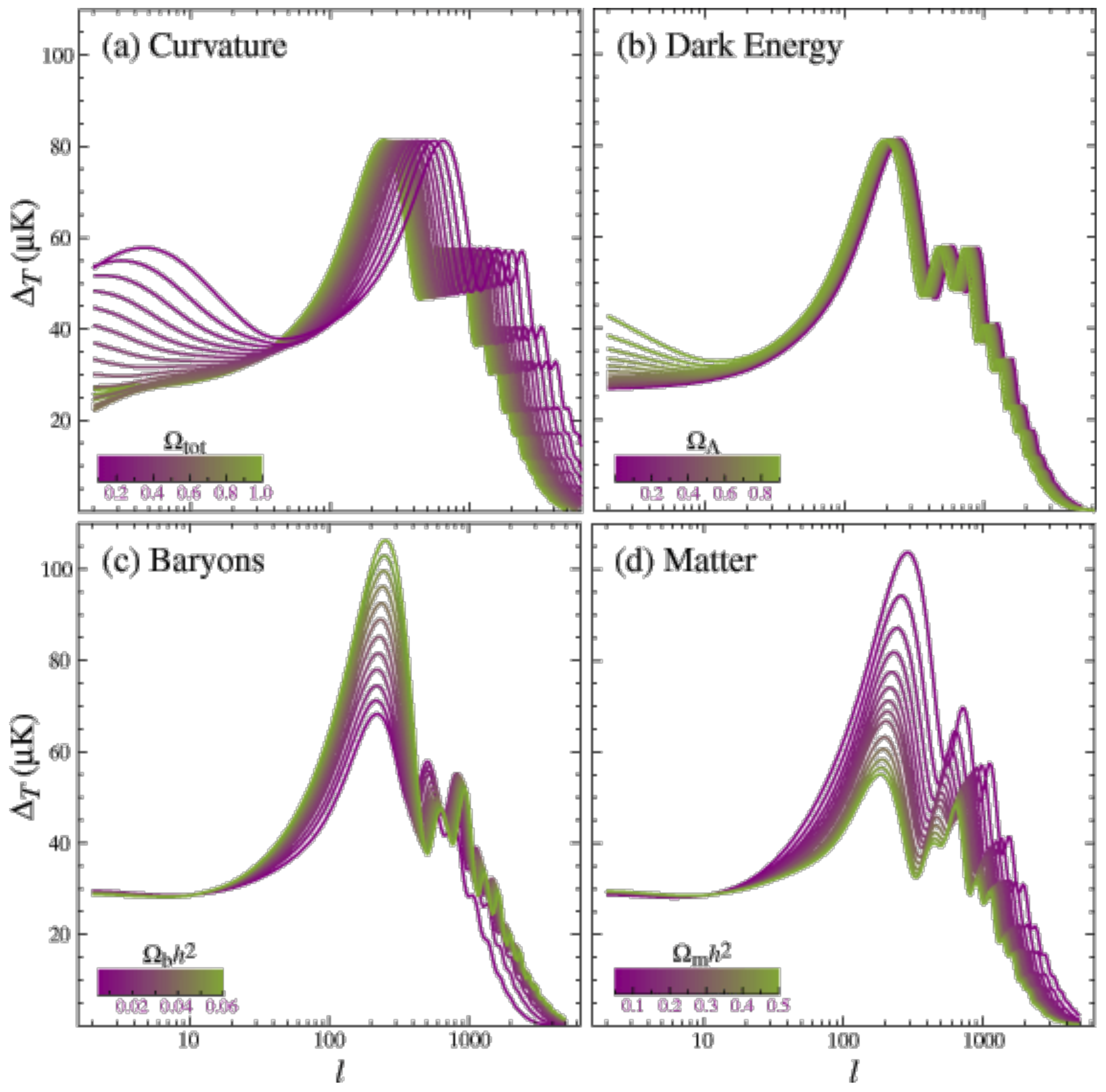

Best-fit cosmology obtained from multi-parameter fit. Well constrained, but not unique - lots of parameter degeneracy.

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

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

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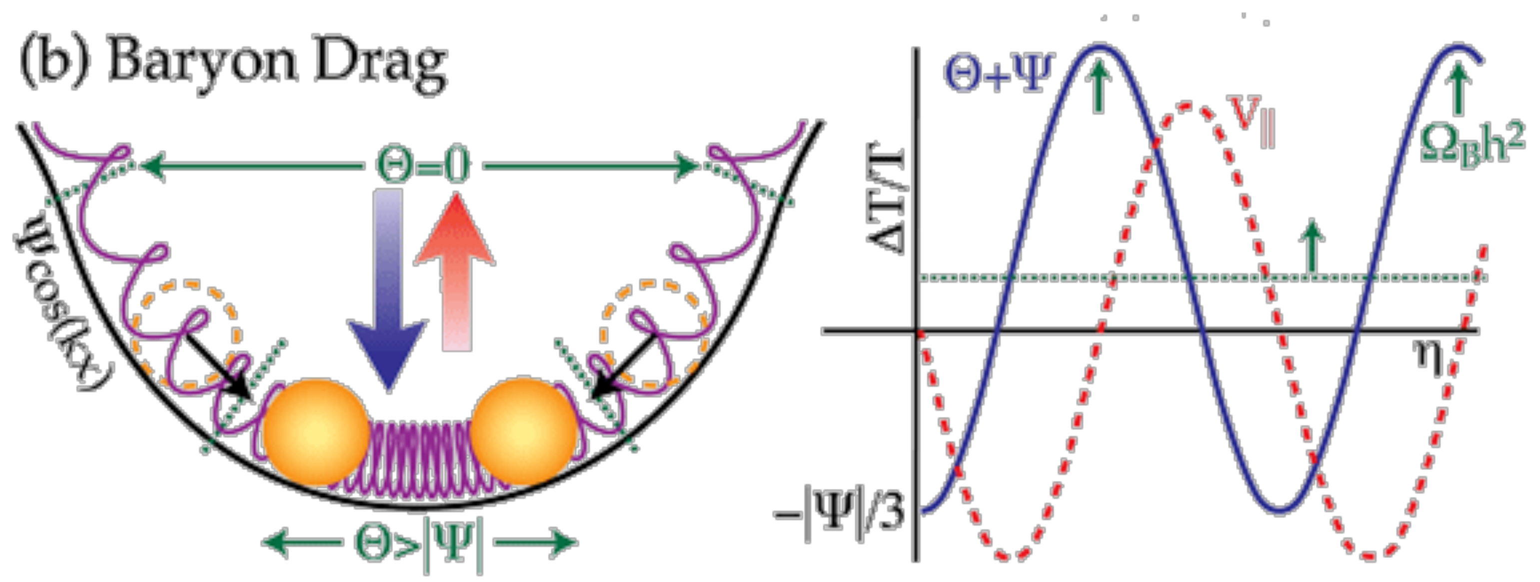

Wayne Hu provides a nice CMB tutorial at http://background.uchicago.edu/index.html