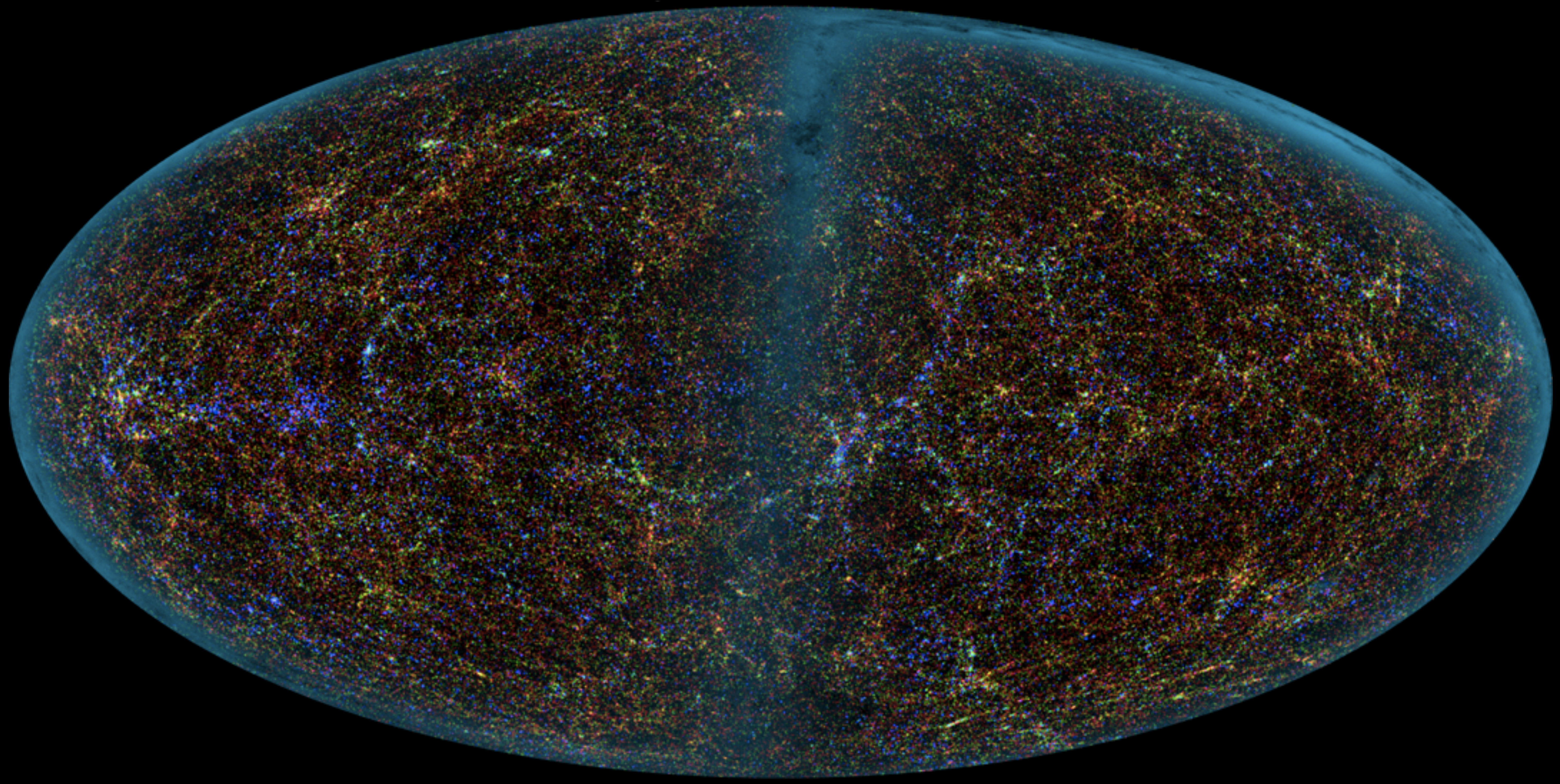
Cosmology

and Large Scale Structure



Today

Large Scale Structure

The Power Spectrum

Measurements of Ω_m

17 November 2022

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

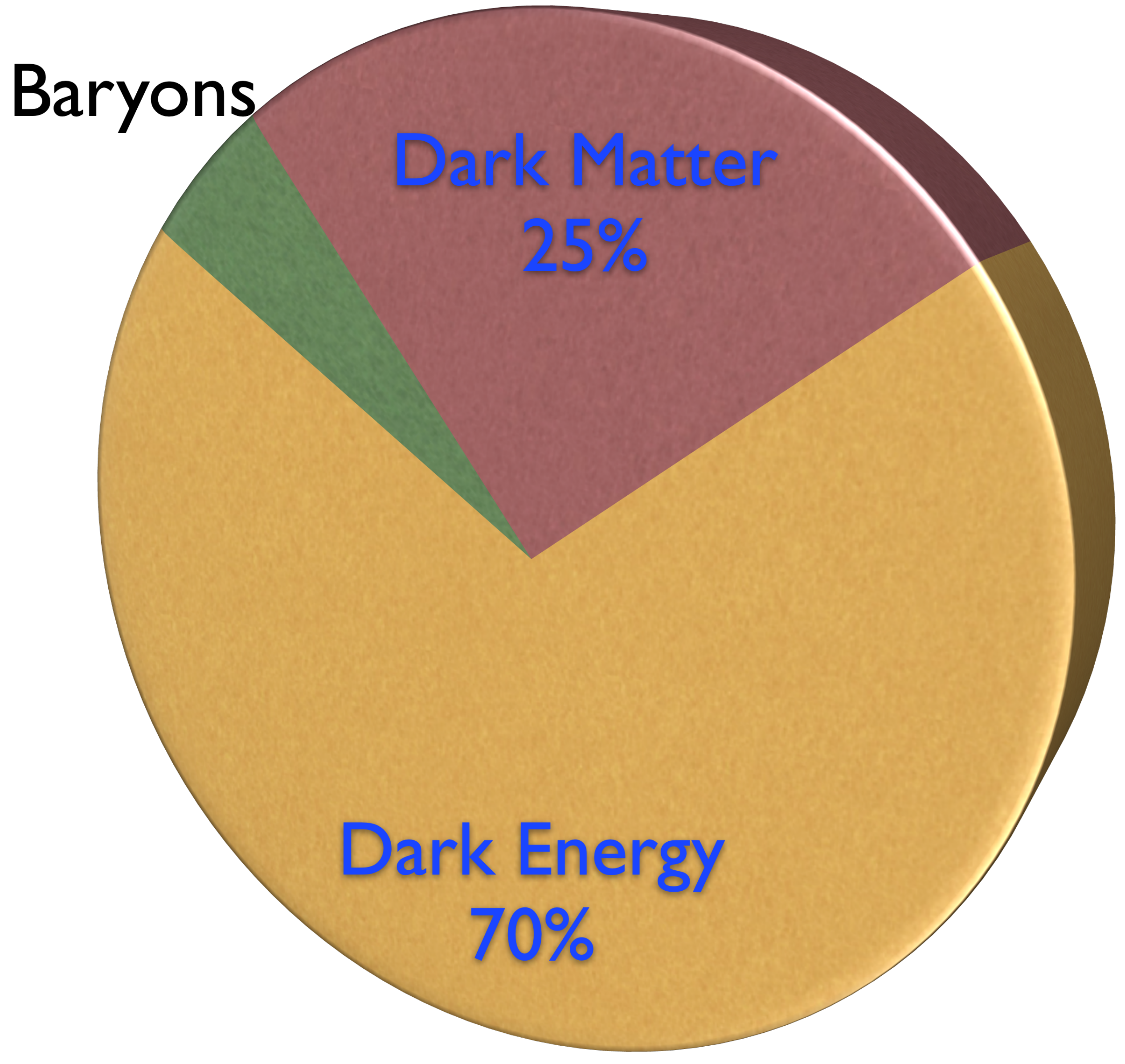
Empirical Pillars of the Hot Big Bang

1. Hubble Expansion
2. Big Bang Nucleosynthesis Ω_b
3. Cosmic Microwave Background

$$\Omega_m = \Omega_b + \Omega_{DM}$$

Auxiliary Hypotheses

- Dark matter Ω_{DM}
- Dark Energy Ω_Λ



Current mass-energy content of the universe

"Vanilla LCDM"

mass density Ω_{m_0}		0.30	give or take a bit
normal matter	Ω_b	0.05	baryons - from BBN
mass that is *not* normal matter	Ω_{CDM}	0.25	cold dark matter
cosmic background radiation	Ω_r	5×10^{-5}	photons
neutrinos	$0.001 < \Omega_\nu < 0.002$		for 3 neutrino flavors with $0.06 < \sum_{i=1}^{3} m_{\nu_i} < 0.12$ eV
dark energy Ω_Λ		0.70	energy density of vacuum

upper limit from cosmic structure formation

lower limit from neutrino oscillations

e.g, $\Omega_\nu = \frac{\sum m_\nu}{93 \text{ eV}}$

since $n_\nu = \frac{9}{11} n_\gamma$

$$\Omega_x = \frac{\rho_x}{\rho_{crit}} \qquad \rho_{crit} = \frac{3H_0^2}{8\pi G}$$

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

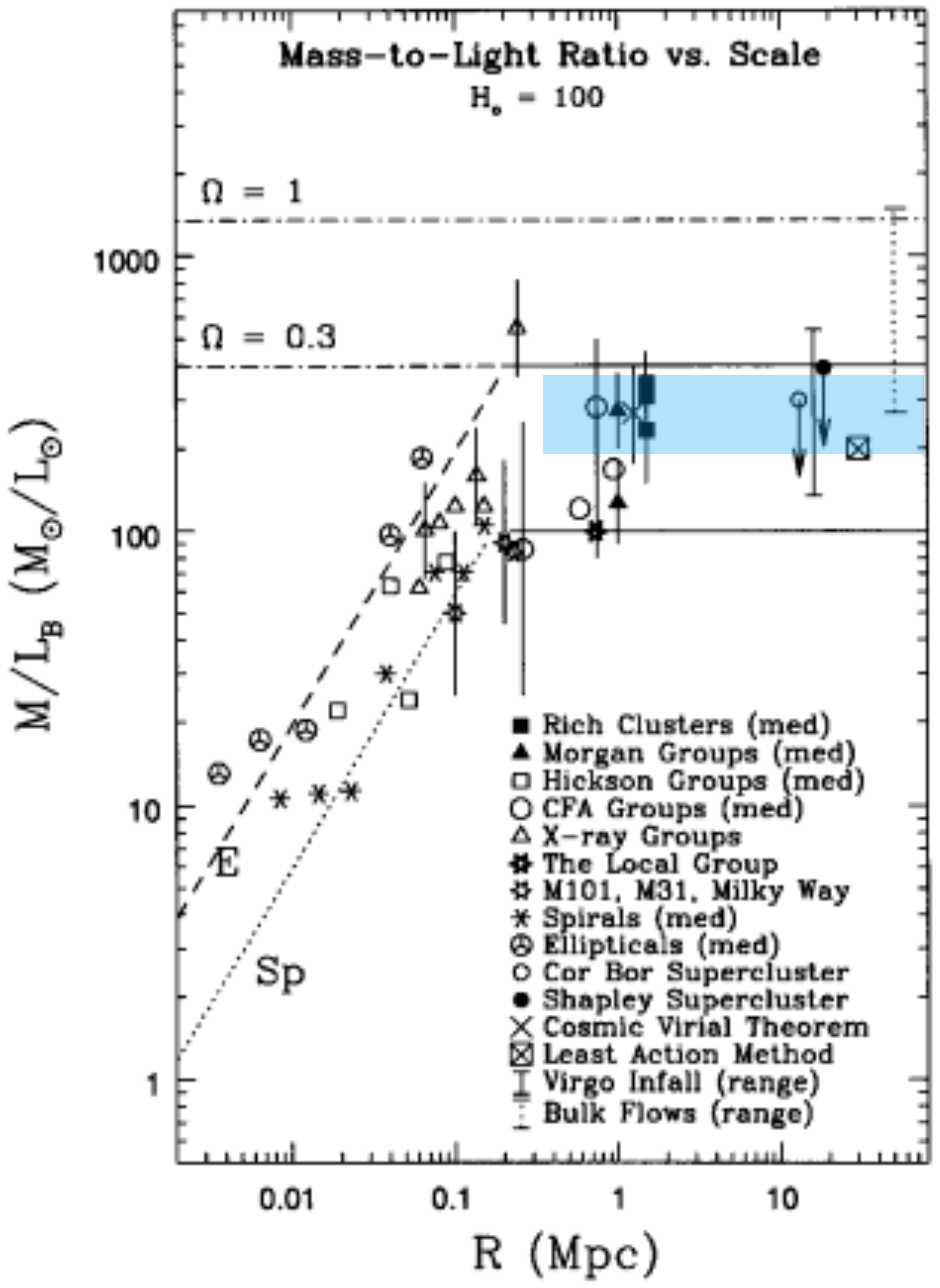
- Cluster M/L
  - measure M/L of a cluster, combine with measured luminosity density of universe.
  - j from integrating the luminosity function of galaxies:

$$\rho_m = \left(\frac{M}{L}\right) j$$

  - Also, cluster baryon fractions:

$$f_b = \frac{M_b}{M_{tot}} \longrightarrow \Omega_m = \frac{\Omega_b}{f_b}$$

  - both assume clusters are representative of the whole.

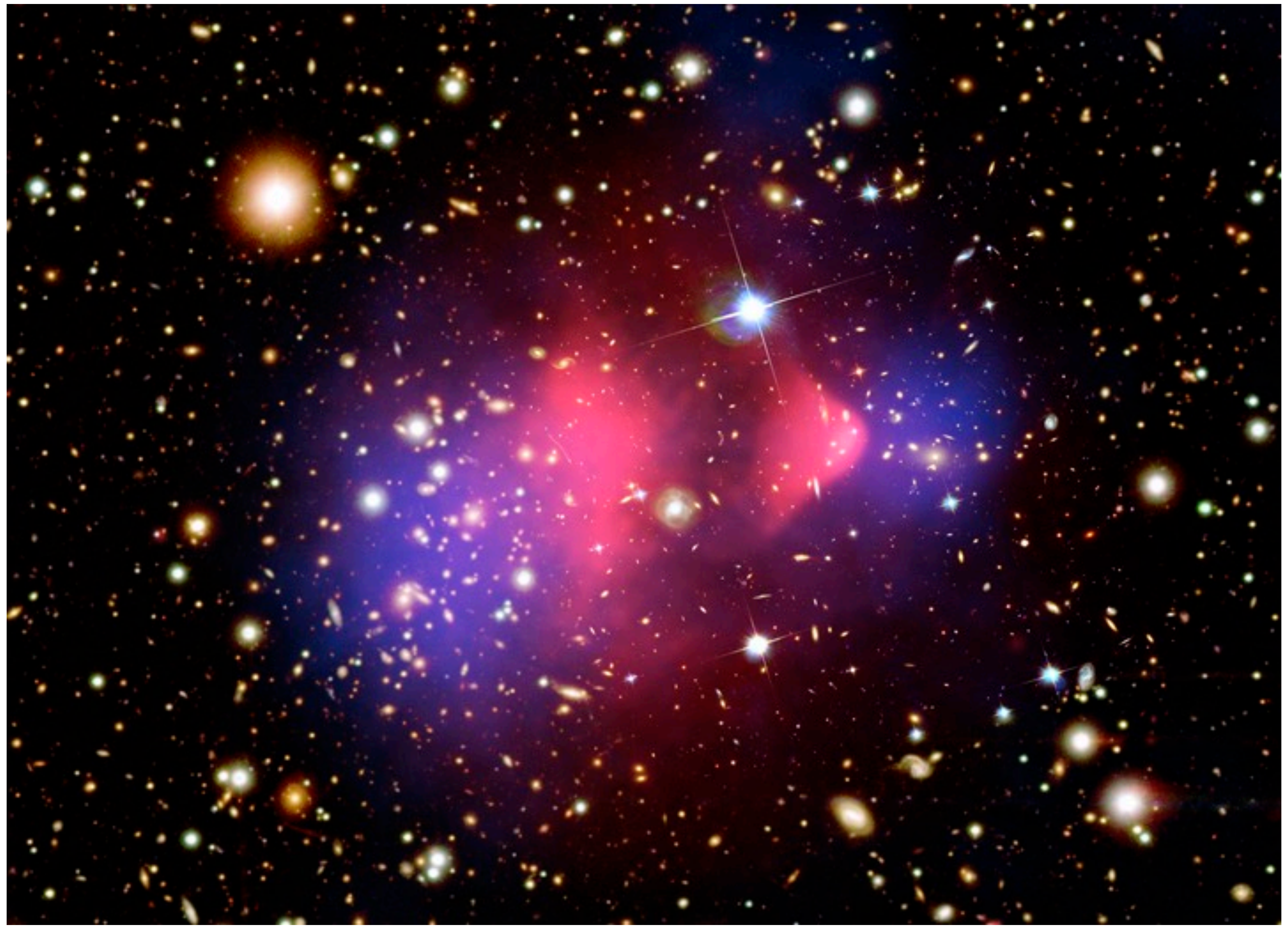


$$\Omega_m \approx \frac{1}{4}$$

FIG. 2.—Composite mass-to-light ratio of different systems—galaxies, groups, clusters, and superclusters—as a function of scale. The best-fit $M/L_B \propto R$ lines for spirals and ellipticals (from Fig. 1) are shown. We present median values at different scales for the large samples of galaxies, groups and clusters, as well as specific values for some individual galaxies, X-ray groups, and superclusters. Typical 1 σ uncertainties and 1 σ scatter around median values are shown. Also presented, for comparison, are the M/L_B (or equivalently Ω) determinations from the cosmic virial theorem, the least action method, and the *range* of various reported results from the Virgocentric infall and large-scale bulk flows (assuming mass traces light). The M/L_B expected for $\Omega = 1$ and $\Omega = 0.3$ are indicated.

Bahcall, Lubin, & Dorman (1995)

Bullet cluster

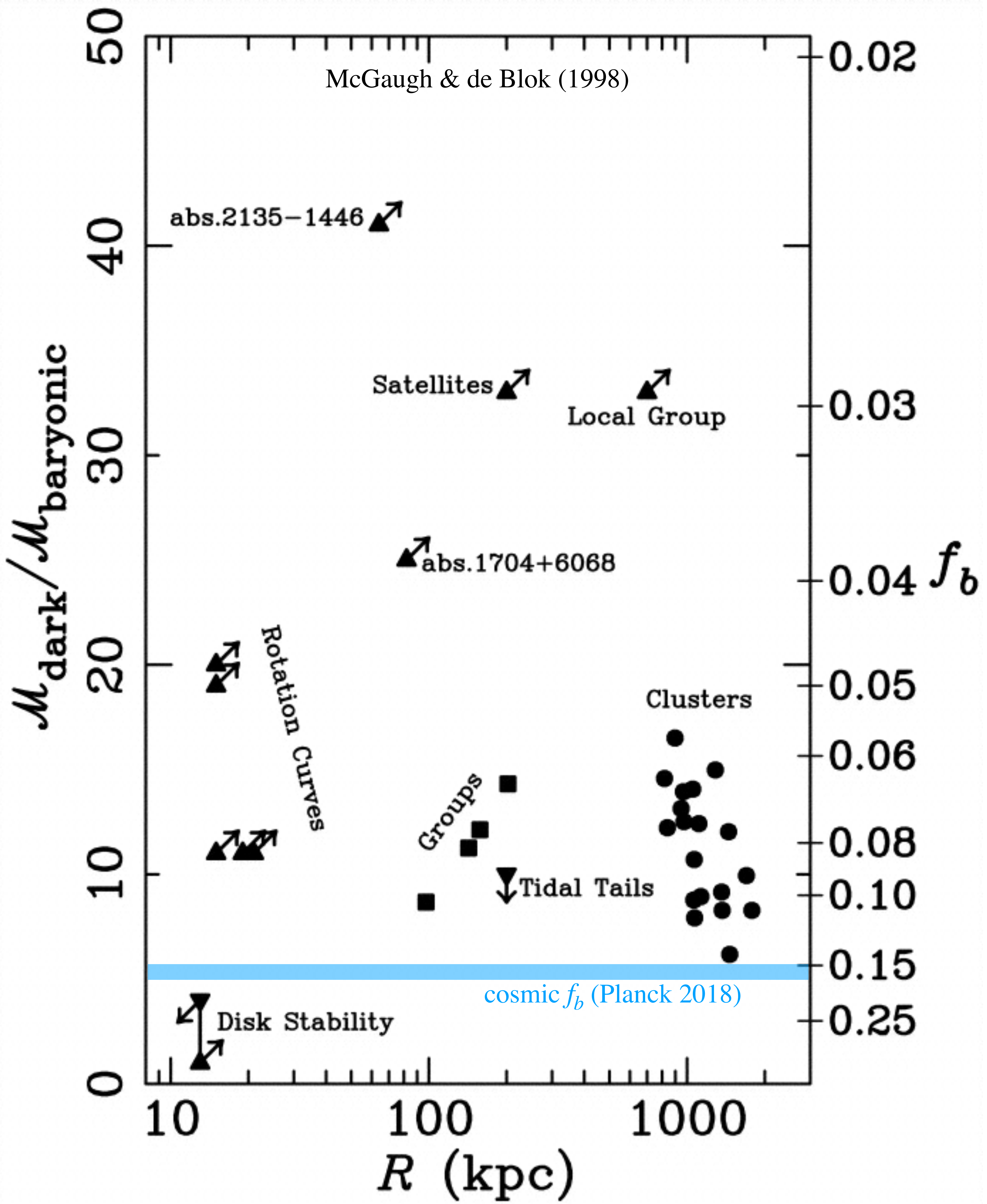


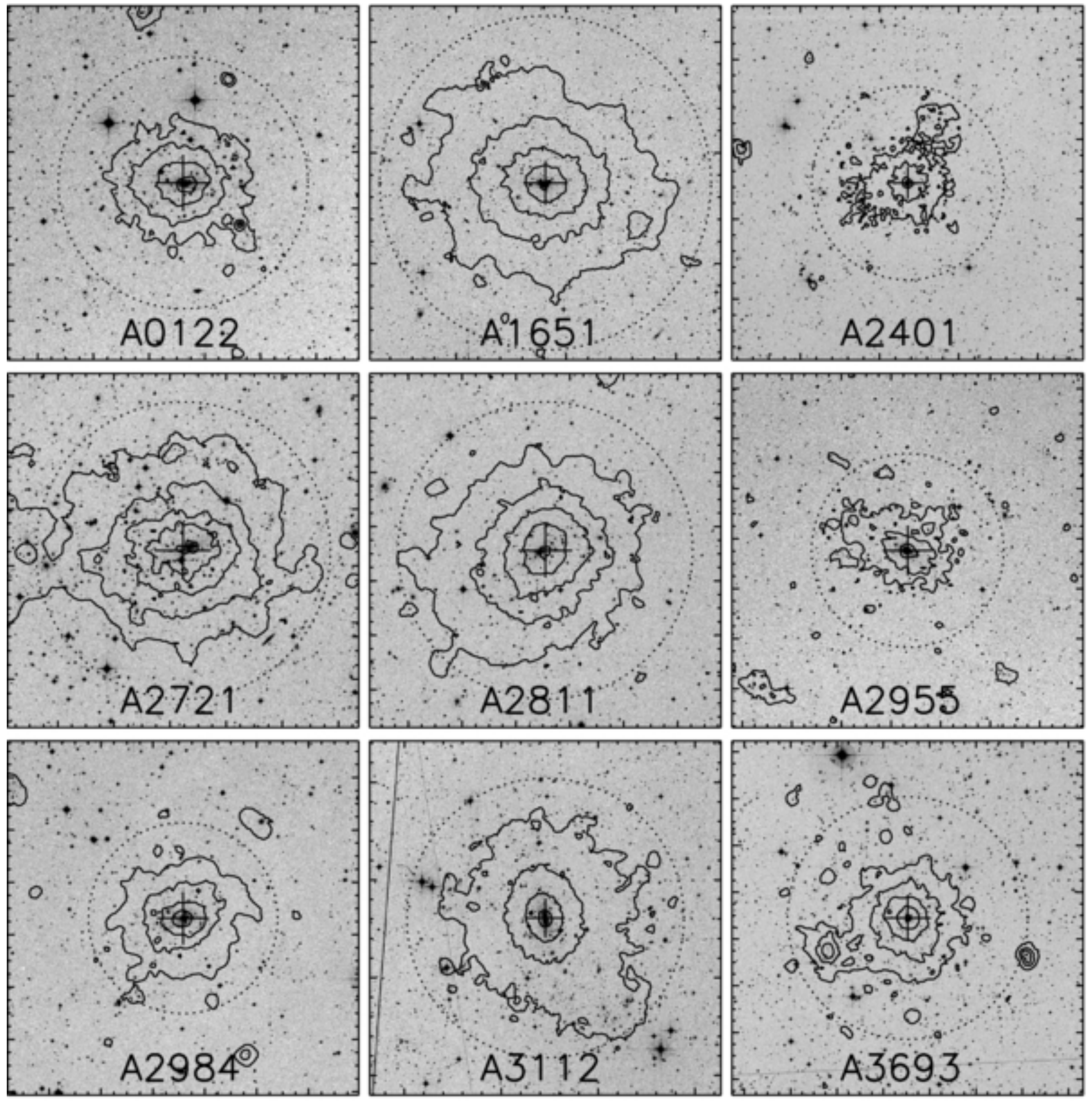
– cluster baryon fractions

$$f_b = \frac{M_b}{M_{tot}} \quad \circ\!\!\longrightarrow \quad \Omega_m = \frac{\Omega_b}{f_b}$$

Measure cluster baryonic mass M_b from luminosity of X-ray gas (pink) plus stars in galaxies (yellow)

Measure cluster dynamical mass M_{tot} from X-ray temperature (pink) or weak lensing (blue) or velocity dispersion





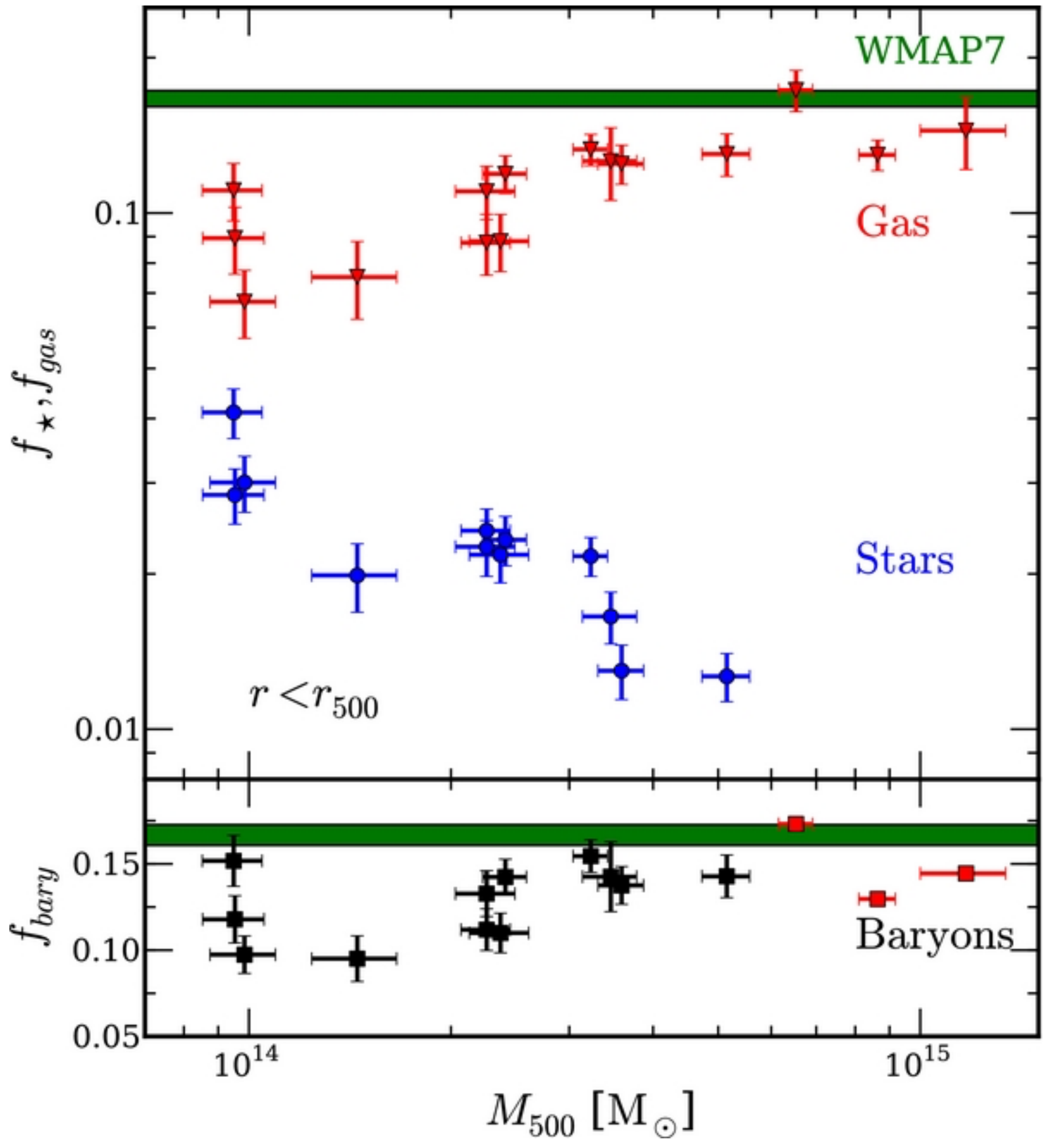
– cluster baryon fractions

$$f_b = \frac{M_b}{M_{tot}} \longrightarrow \Omega_m = \frac{\Omega_b}{f_b}$$

Measure cluster baryonic mass M_b from luminosity of X-ray gas (contours) plus stars in galaxies (black)

Measure cluster dynamical mass M_{tot} from X-ray temperature (contours) or weak lensing or velocity dispersion

Gonzalez et al. (2013)



Most of the baryonic mass in rich clusters is in the hot, X-ray emitting gas of the ICM (intracluster medium). Only the most massive clusters approach the cosmic fraction found in fits to the acoustic power spectrum of the CMB. Lower mass clusters suffer a missing baryon problem.

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Measurements of the gravitating mass density

- Weak lensing
  – measure shear over large scales

Dark Energy Survey
arxiv:2002.11124

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

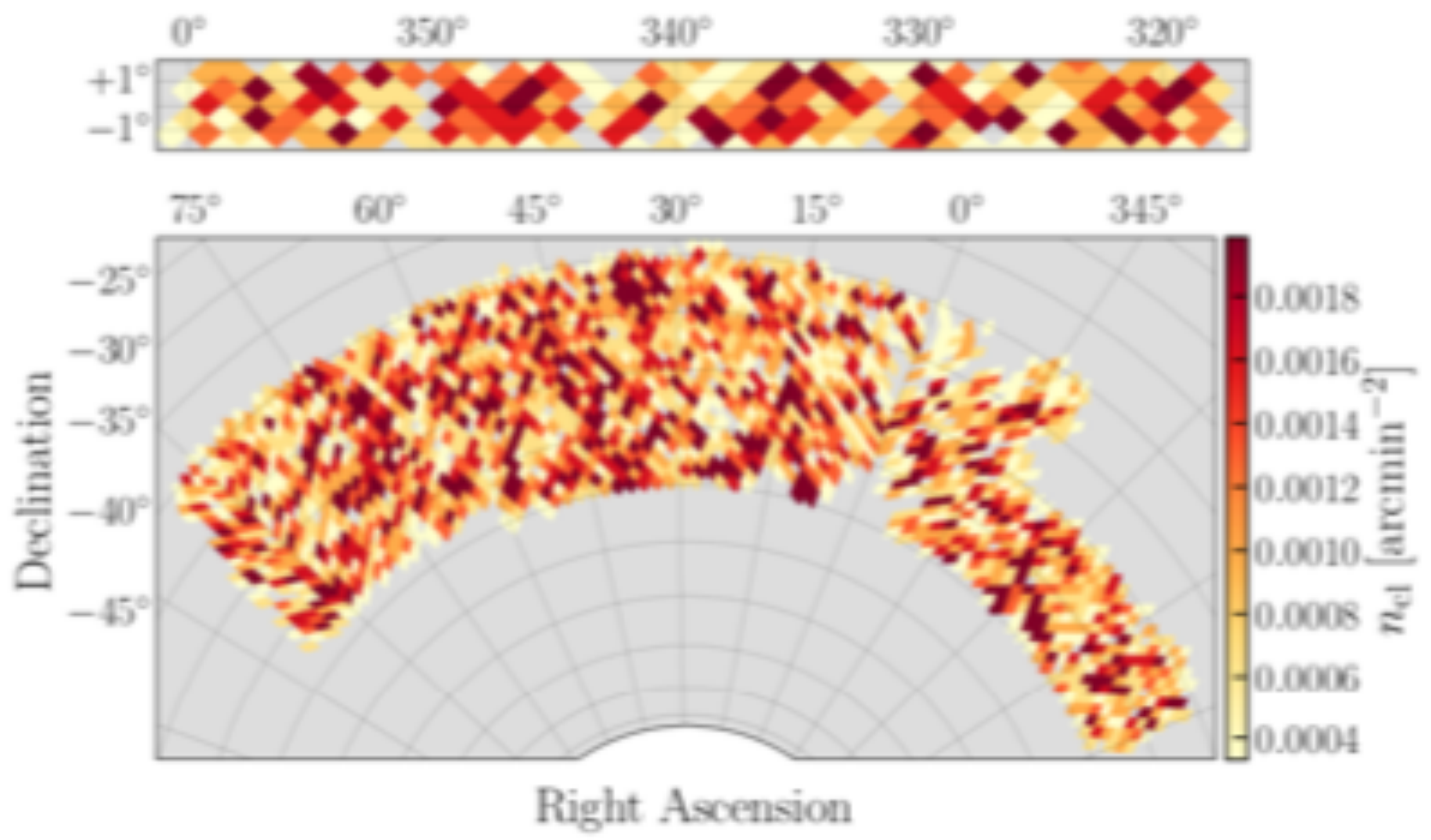
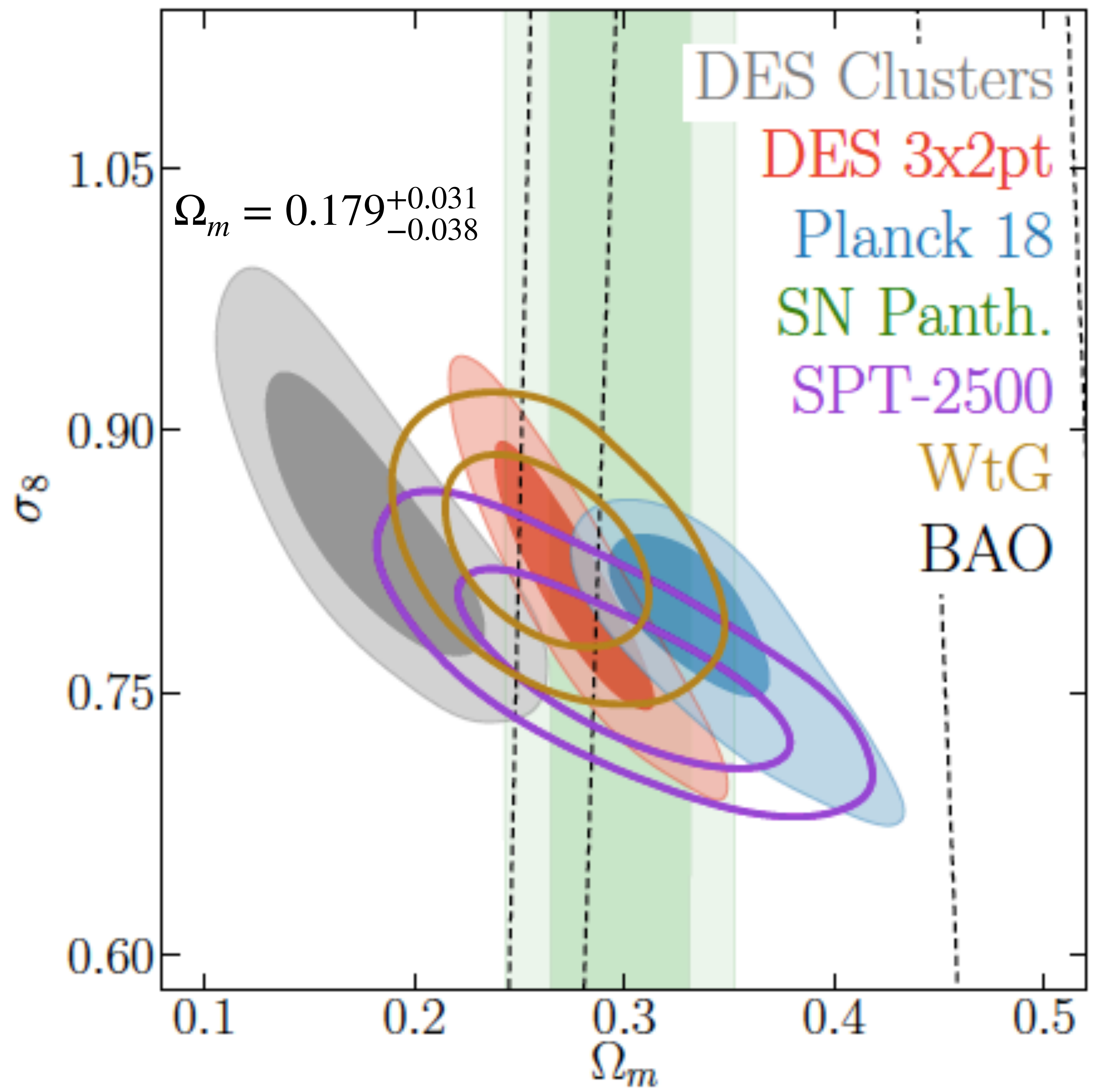


FIG. 1. The DES Y1 redMaPPer cluster density over the two non-contiguous regions of the Y1 footprint: the Stripe 82 region (116 deg^2; *upper* panel) and the SPT region (1321 deg^2; *lower* panel).

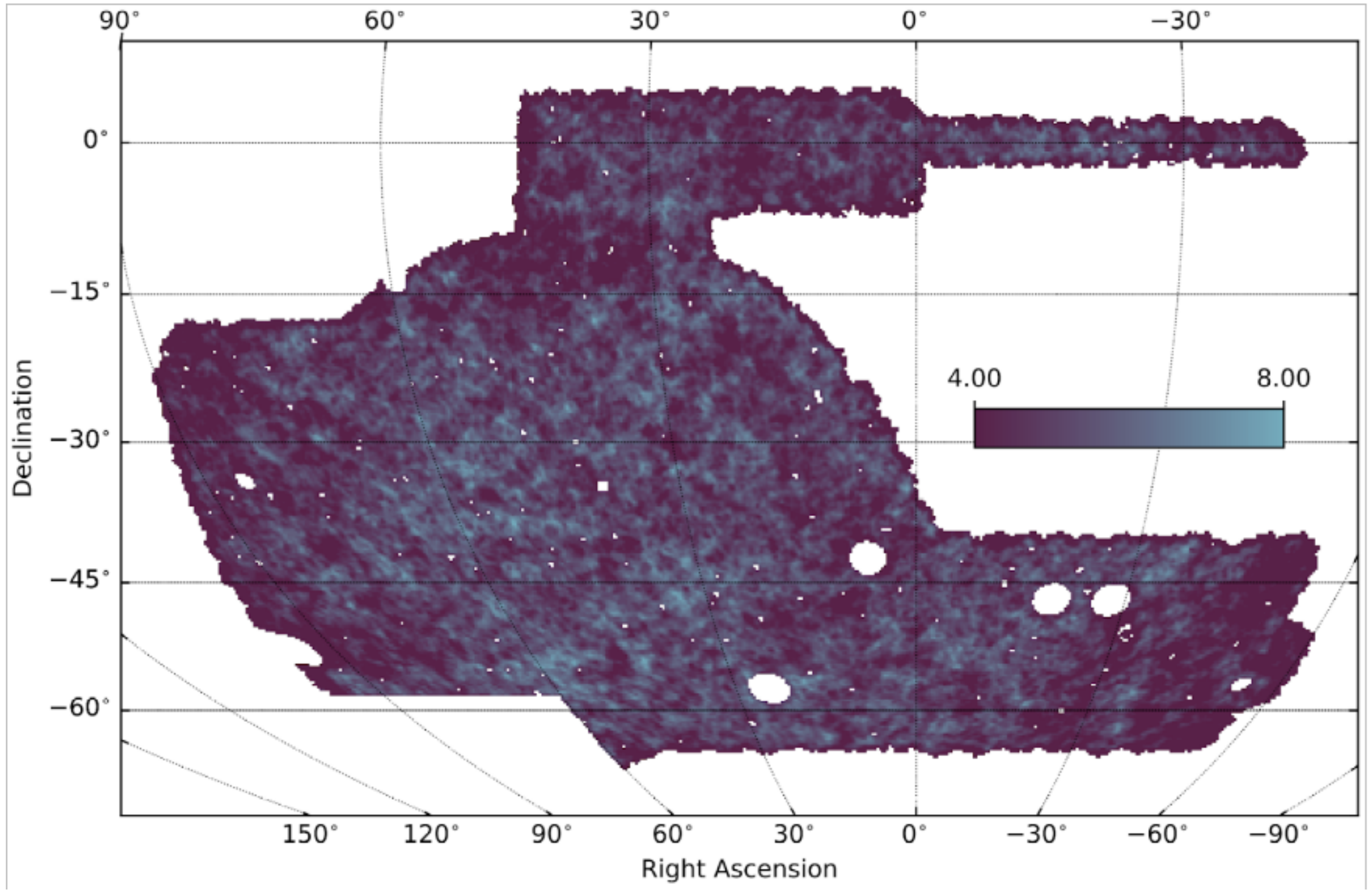


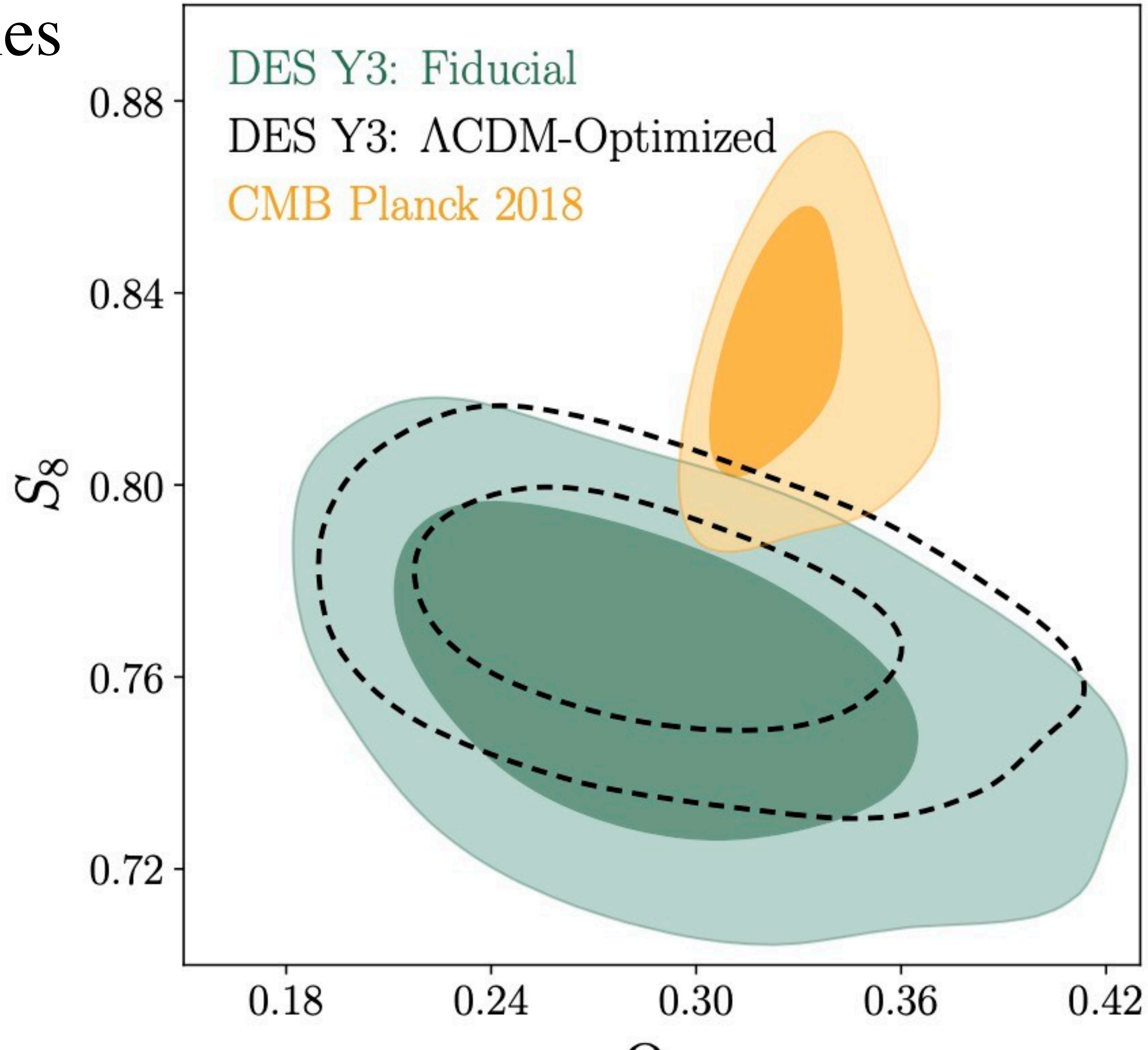
Measurements of the gravitating mass density

$$S_8 = \sigma_8 \left(\frac{\Omega_m}{0.3}\right)^{1/2} = 0.759^{+0.025}_{-0.023}$$

- Weak lensing
  - – measure shear over large scales

Dark Energy Survey
Amon et al. (2022, PRD, 105, 023514)





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Virgocentric infall

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

682 TONRY AND DAVIS (1981)

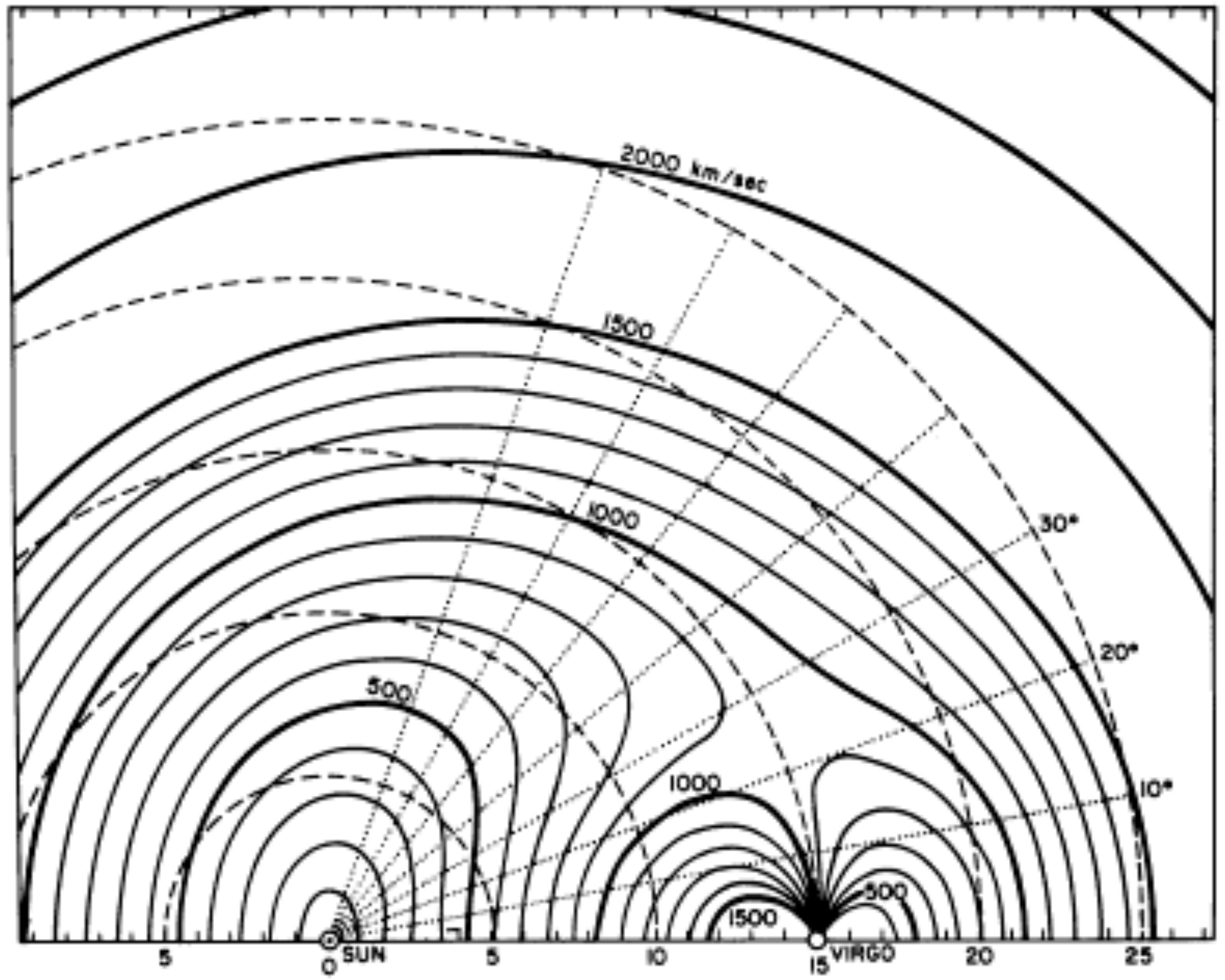


FIG. 1.—On a two-dimensional grid with the Earth and the Virgo cluster on the x axis, redshift contours are plotted for a Hubble flow perturbed by a Virgocentric flow. An infall velocity of 400 km s^{-1} at our position is assumed. A pure Hubble flow would be concentric circles.

Measurements of the gravitating mass density

- Peculiar Velocity Field
  – measure deviations from Hubble flow

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

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

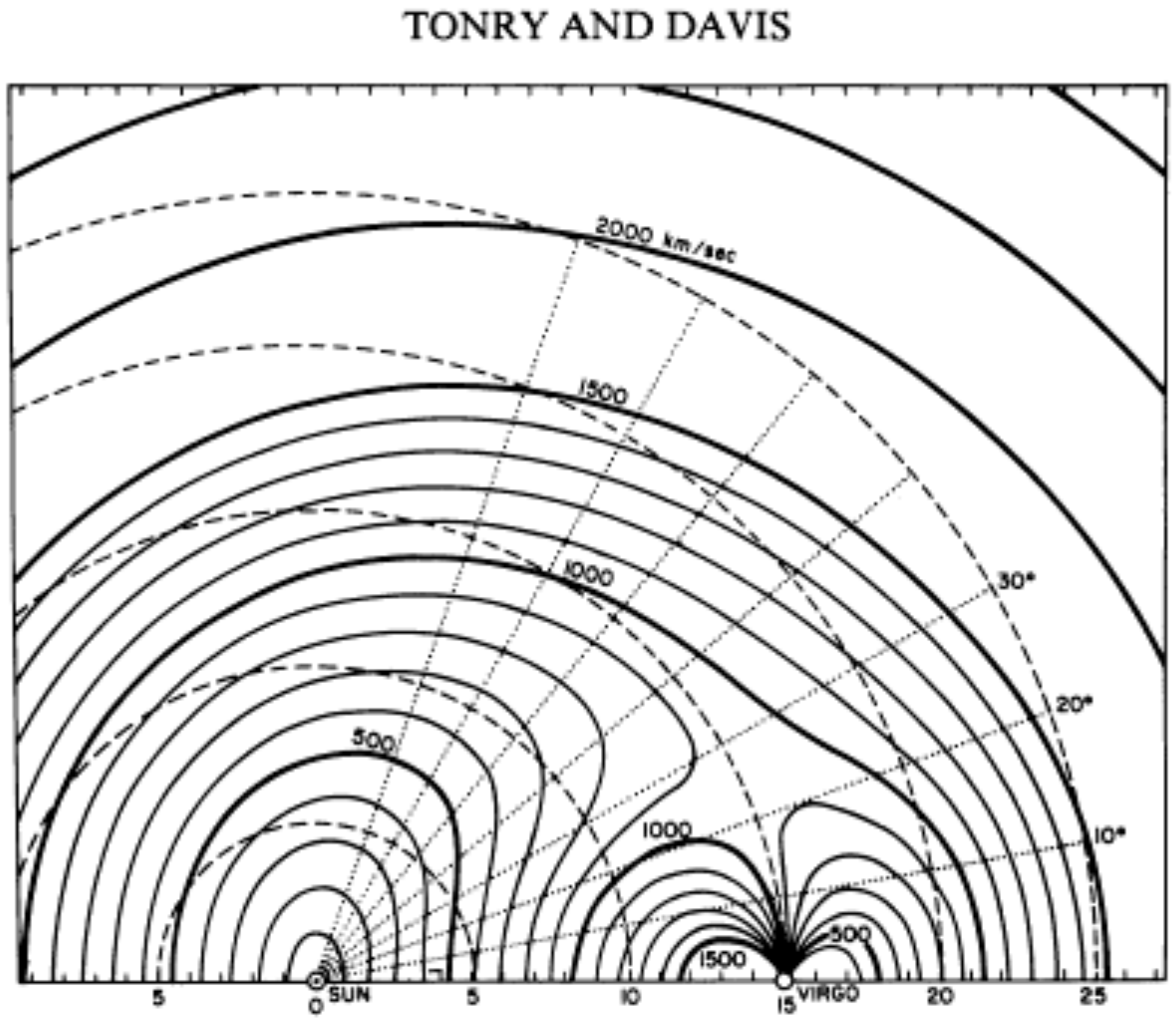
peculiar velocity

distortion in Hubble flow induced by

mass over-density

bias

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

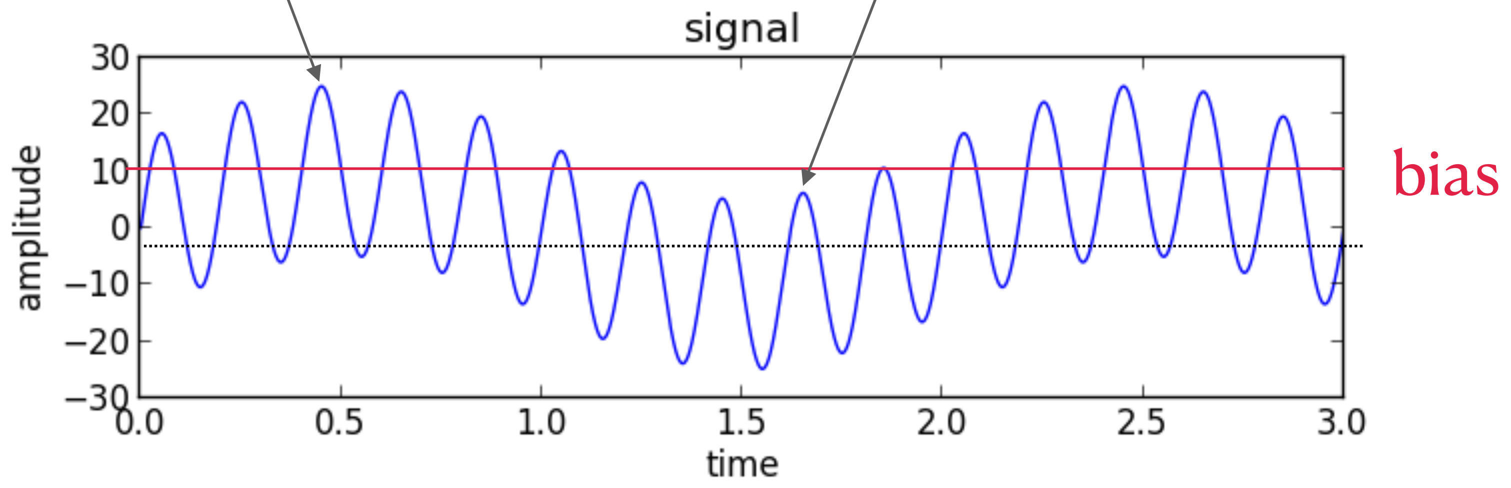


$$\Omega_m = 0.25 \pm 0.05$$

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

Peaks above line make a galaxy

Peaks below line do not



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

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

Davis et al. (1980) found

$$\Omega_m = 0.4 \pm 0.1$$

with a modern distance scale this becomes

$$\Omega_m = 0.25 \pm 0.05$$

basically unchanged for over 40 years

Lines are lines of constant Ω_m

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.

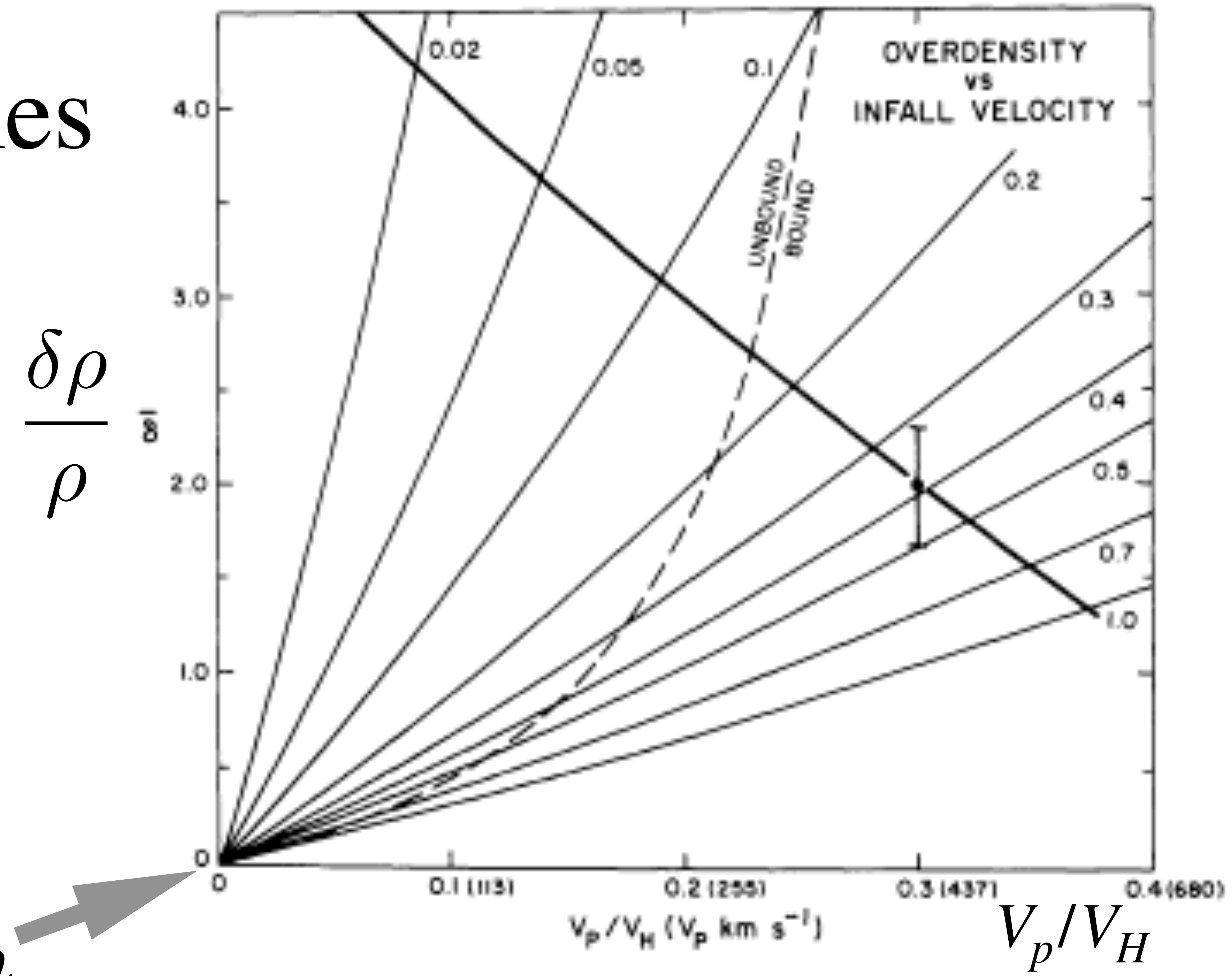


FIG. 1.—The mean overdensity of Virgo vs. v_p/v_H for various values of Ω. The *x*-axis is also labeled with v_p, using a recessional velocity to Virgo of 1020 km s^{-1}. The measured overdensity is prescribed by the heavy line, and is marked at the favored position as given by the anisotropy of the 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.

mated, roughly by
density of galaxies
as r^{-2}; if the mas
duced peculiar velo
this model will app
which have not yet
Virgo core and wit
km s^{-1} are assumed
scale peculiar moti
effect on the comp
100 km s^{-1} Mpc^{-1},
300 km s^{-1} galactic
Aaronson, and Huc
sional velocity of
Table 2 lists the co
dom sample when b
assumed here v_p/v_H
The mean overd
not at all sensitive

VIRG

Distance[a] (Mpc)
0–5. . . . . .
5–10. . . . .
10–15. . . .
15–20. . . .
20–25. . . .
25–30. . . .
30–35. . . .
$\bar{\delta}$. . . . .

[a] Assumes
tance and H
[b] 600 obje
[c] Within l

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$z = 0$

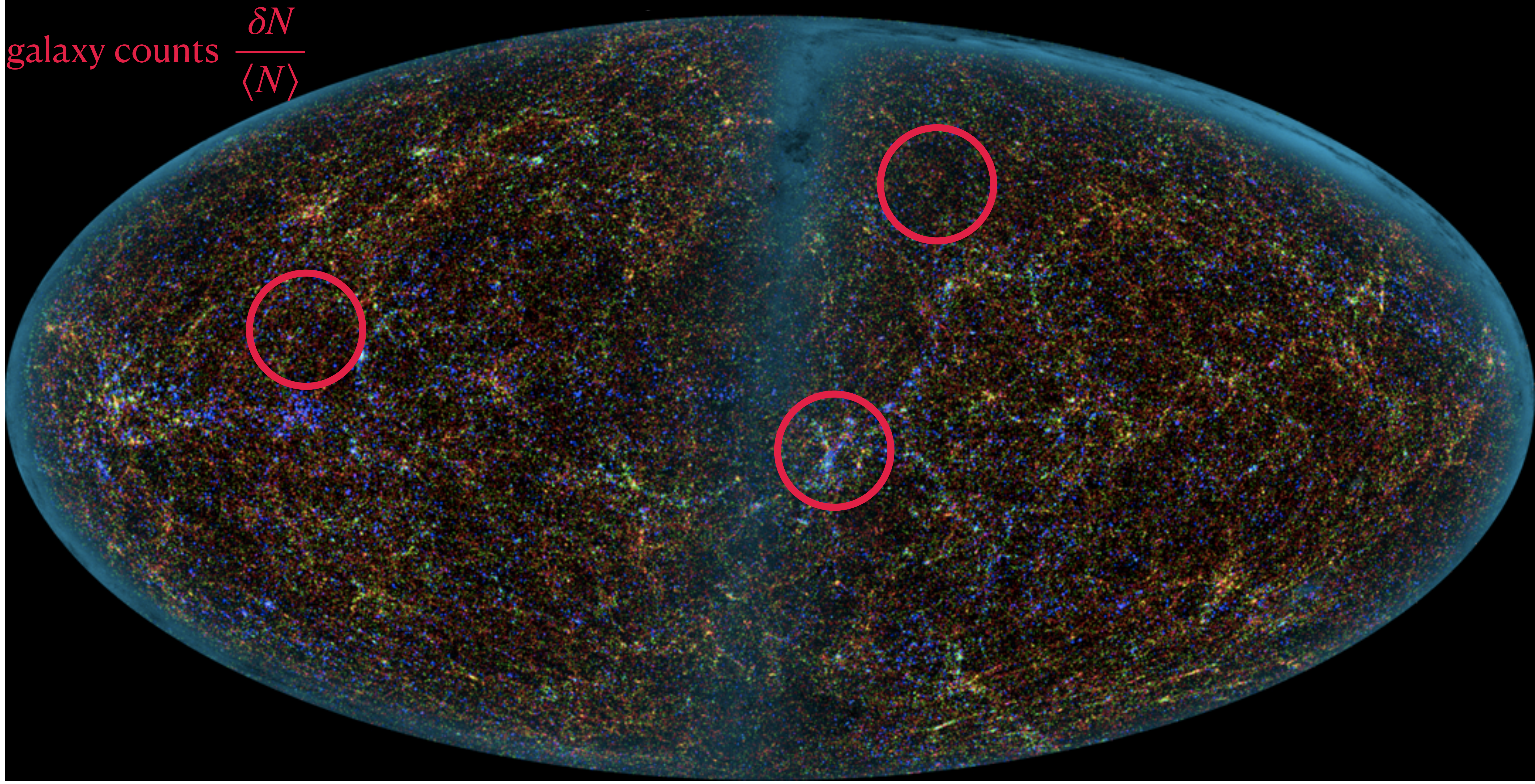
$z = 1090$

Structure formation basics:

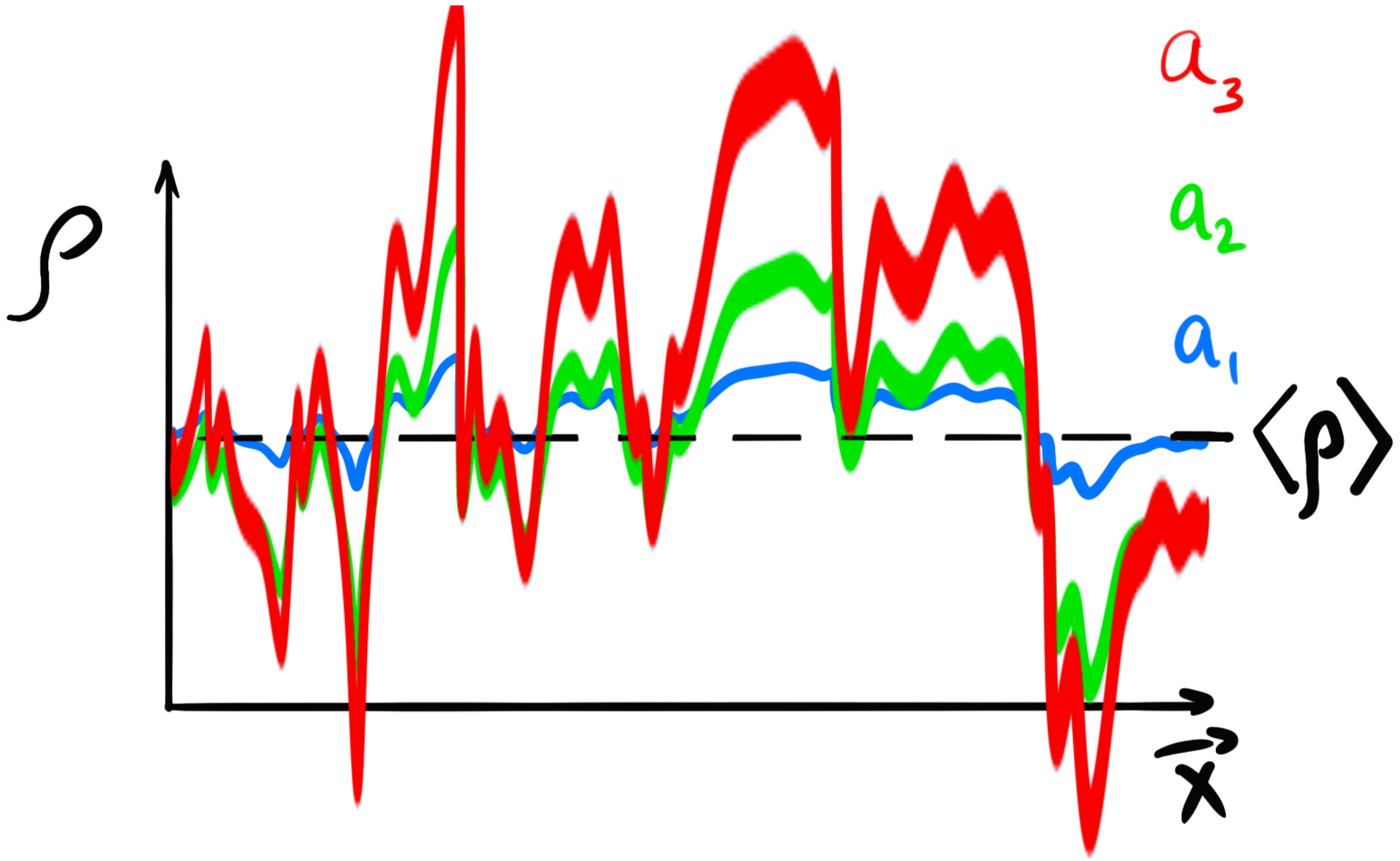
Density perturbations $\delta = \dfrac{\rho - \langle\rho\rangle}{\langle\rho\rangle}$

grow as $\delta(t) \sim a(t)$.

In the early universe, $\langle\rho\rangle = \rho_{\text{crit}}$.



over-density δ
grows with time



You can't get here from there

The factor of 100 offset in density and temperature fluctuations is a prime motivation for non-baryonic **cold dark matter** — a substance for which perturbations δ can grow sufficiently large while not leaving an imprint of corresponding magnitude on the CMB.

Radiation and baryon plasma tightly coupled at recombination, so a fluctuation in density is reflected by one in temperature: $\dfrac{\delta\rho}{\rho} \propto \dfrac{\Delta T}{T}$.

Large Scale Structure

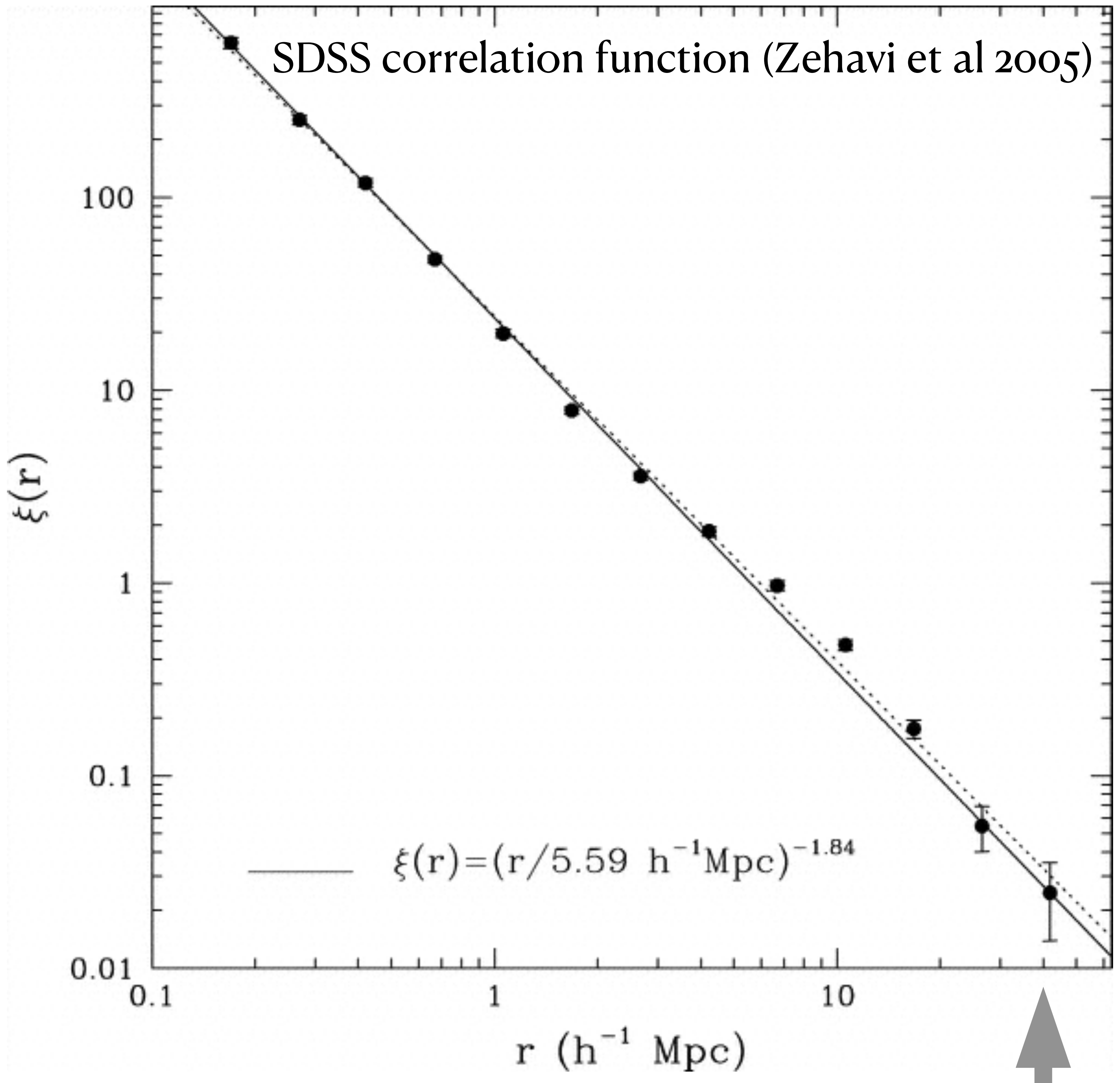
Quantified with the **correlation function** $\xi(r)$ which is the Fourier transform of the **power spectrum** $P(k)$.

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

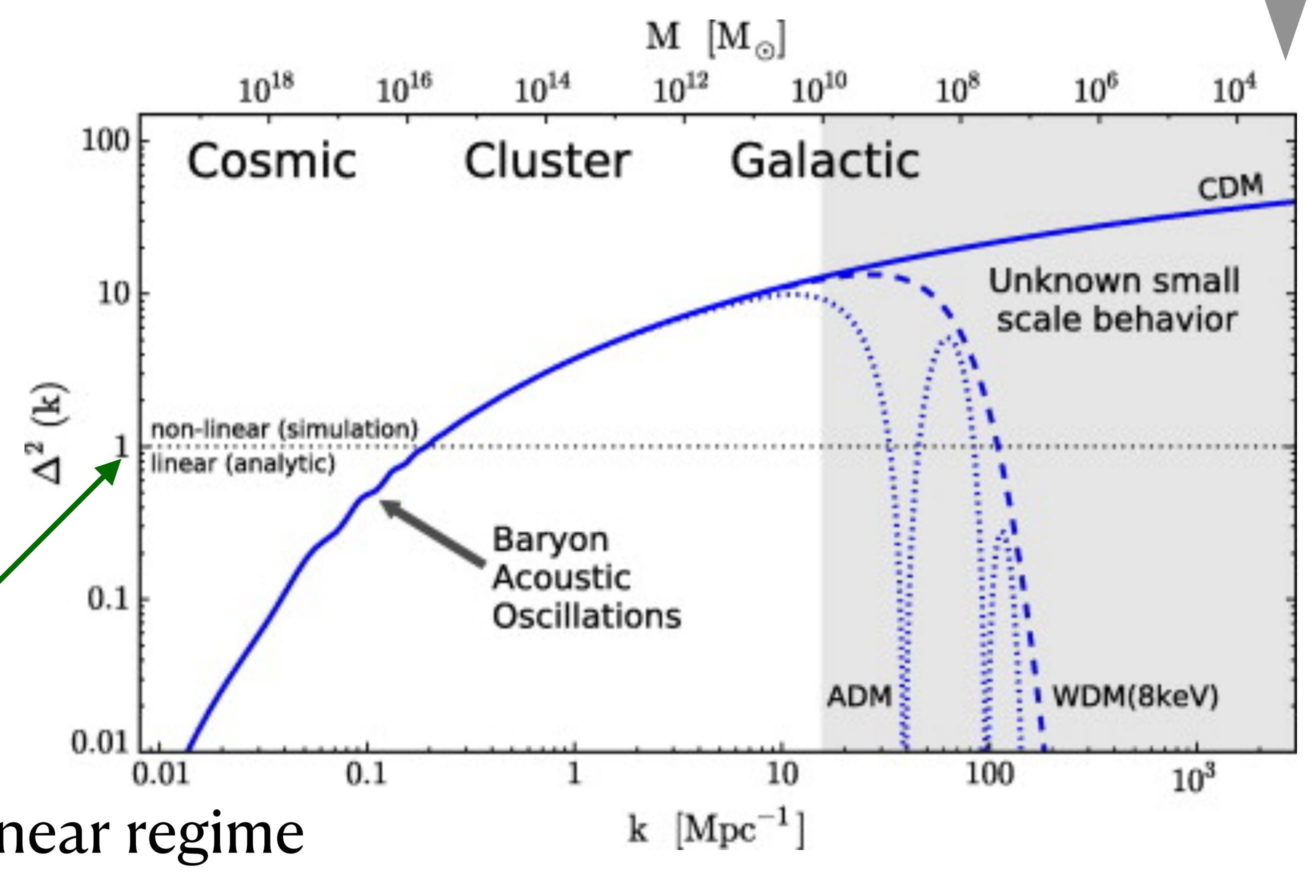
$$\frac{dN}{N} = [1 + \xi(r)]dV \qquad \xi(r) = \frac{V}{(2\pi)^3}\int P(k)e^{-\vec{k}\cdot\vec{r}}\, d^3k$$

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

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 $n = 0.965 \pm 0.004$



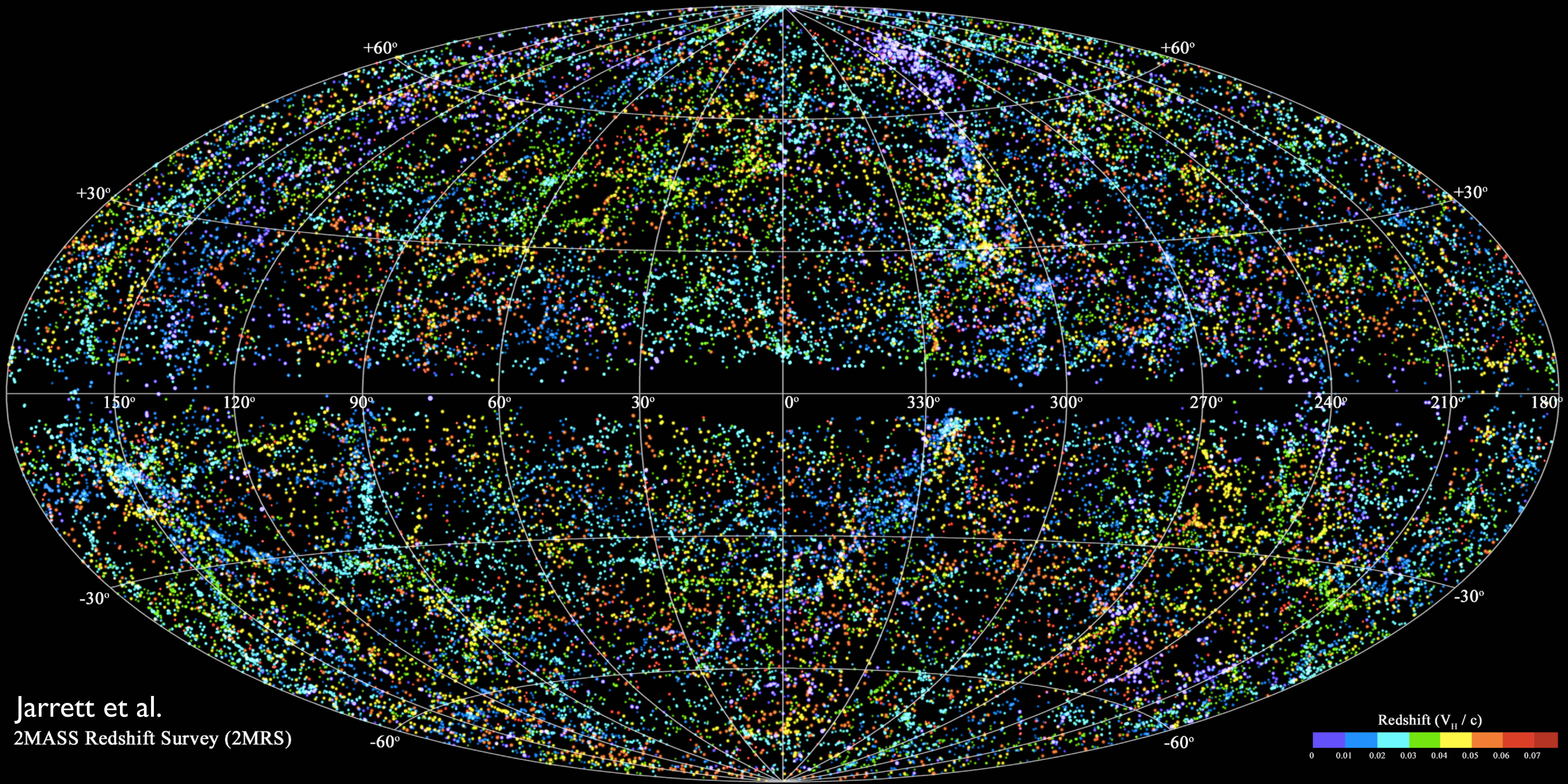
Power Spectrum



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

Measurements of the gravitating mass density

- Power spectrum of galaxies



Jarrett et al.
2MASS Redshift Survey (2MRS)

- # 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: $$\xi(r) = \langle \delta(\vec{x}) \cdot \delta(\vec{x} + \vec{r}) \rangle$$

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 $$k = \frac{2\pi}{\lambda}$$

where k is the wavenumber corresponding to the scale λ

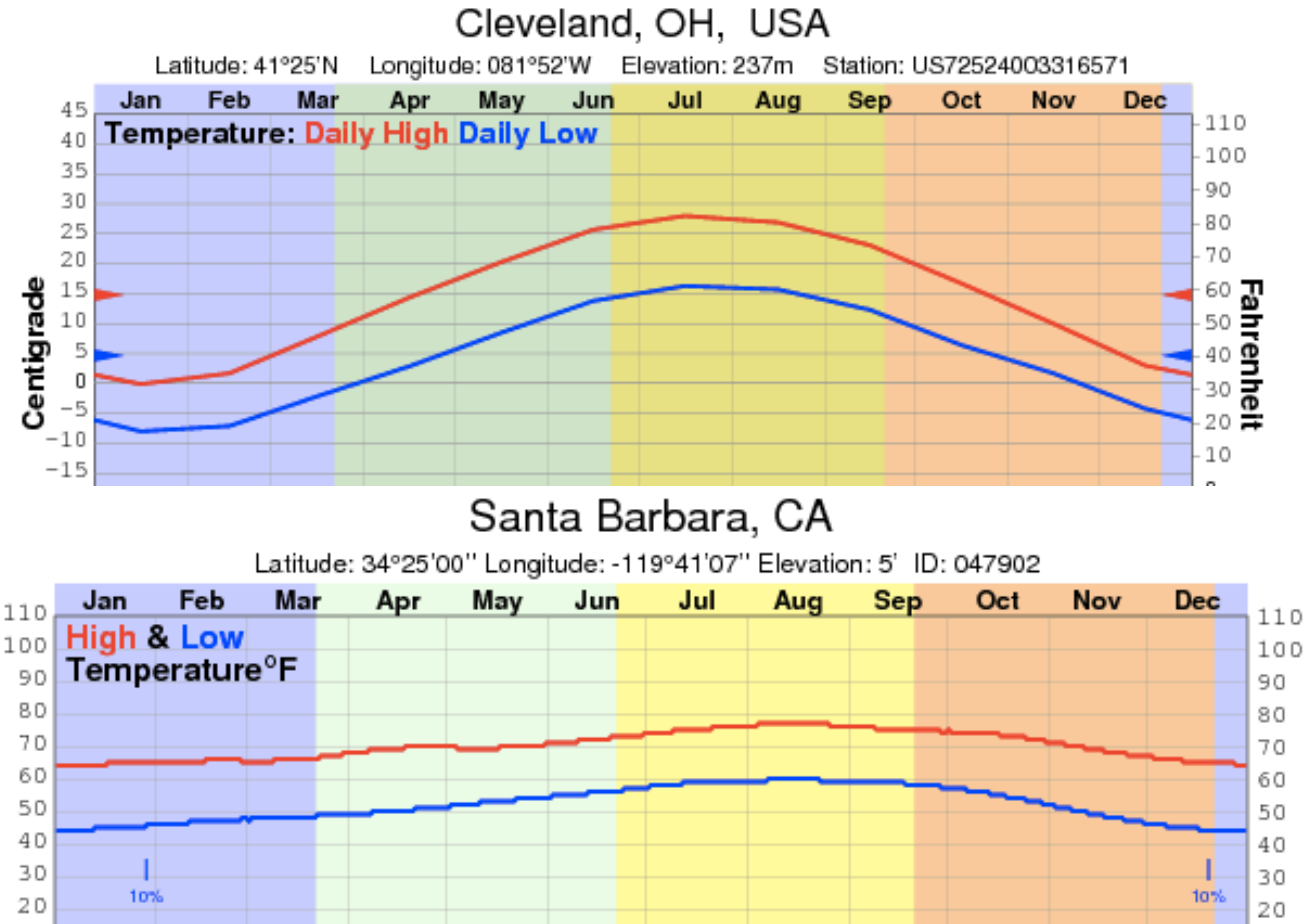
Fourier transform:

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

($|\delta_k|^2 \rightarrow P(k)$)

Power Spectrum

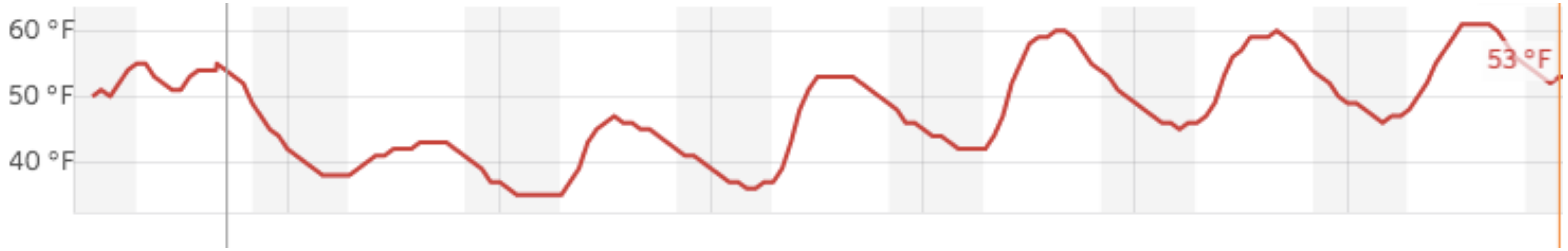
Example: weather in Cleveland and Santa Barbara
More power on long time scales in Cleveland (seasonal variation)



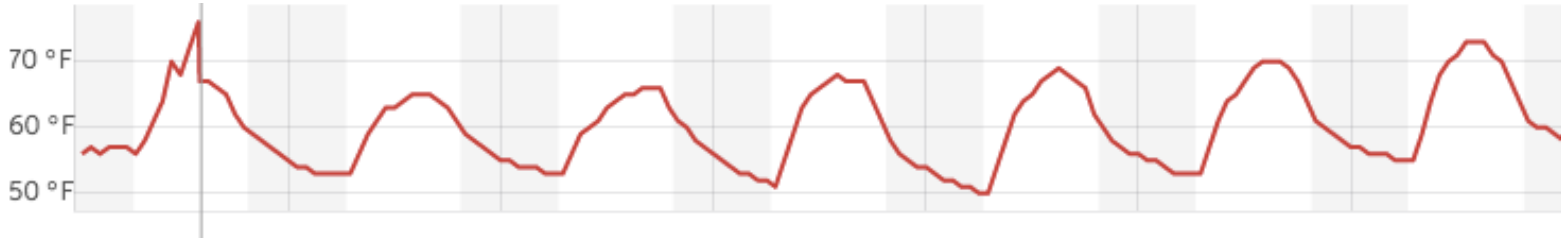
Power Spectrum

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

Cleveland forecast



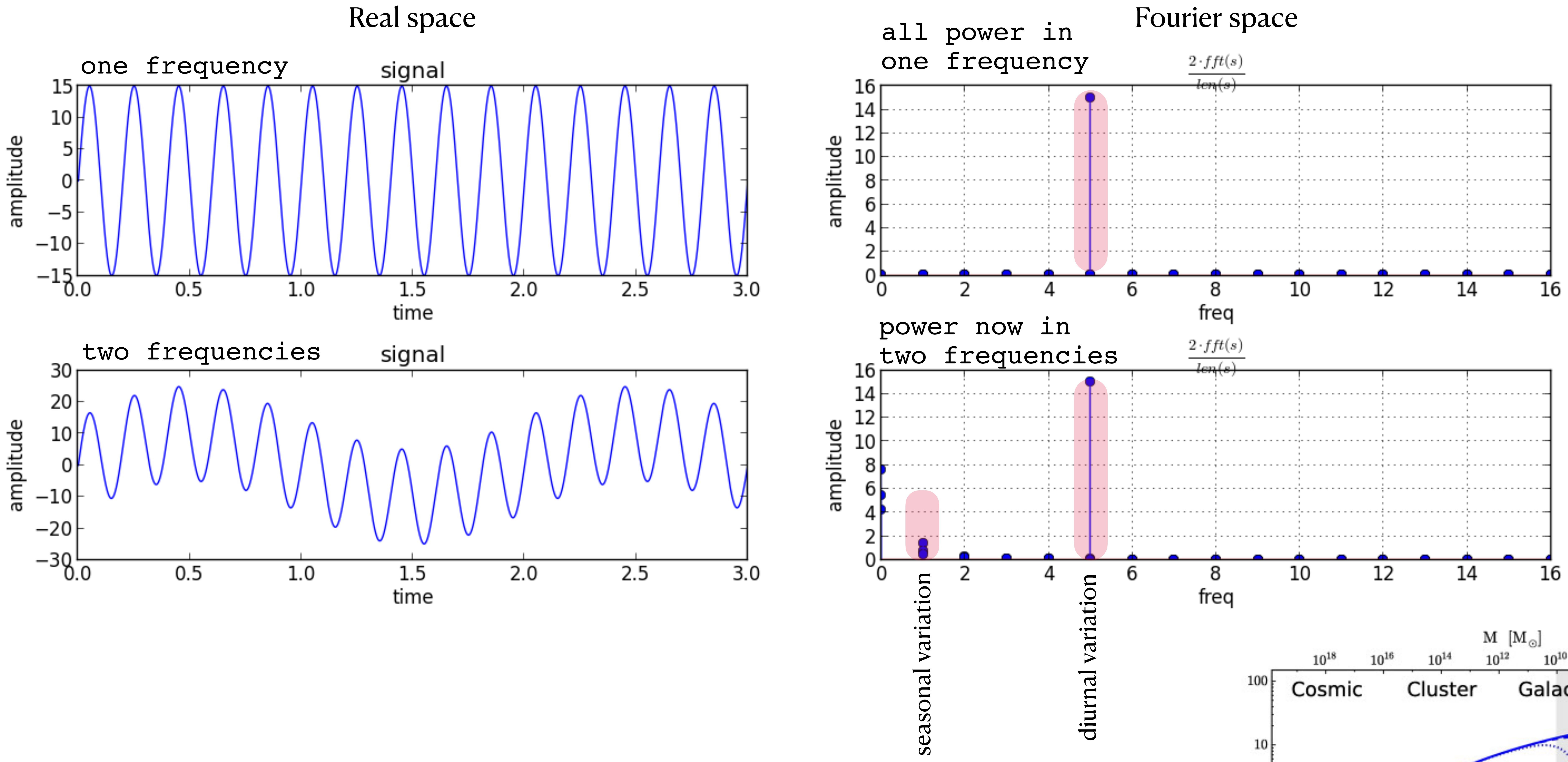
Santa Barbara forecast



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

Superposition of two sinusoids

(e.g., diurnal and annual temperature variation)



So a smooth power spectrum has contributions from all frequencies, but also picks out which are more common.