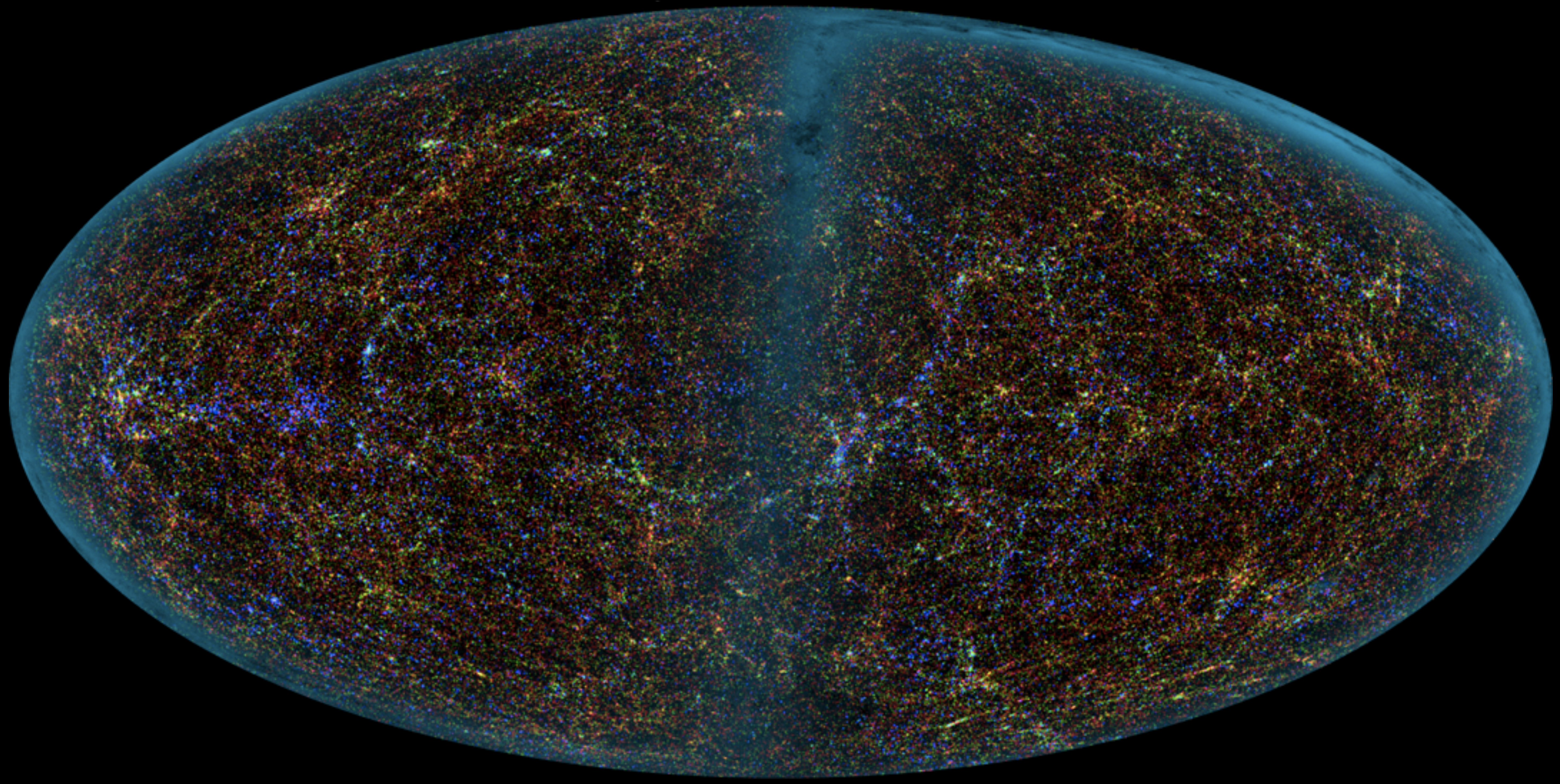
Cosmology

and Large Scale Structure



Today

Measurements of Ω_m

Homework 5 available
Time to pick a project topic

14 November 2024

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

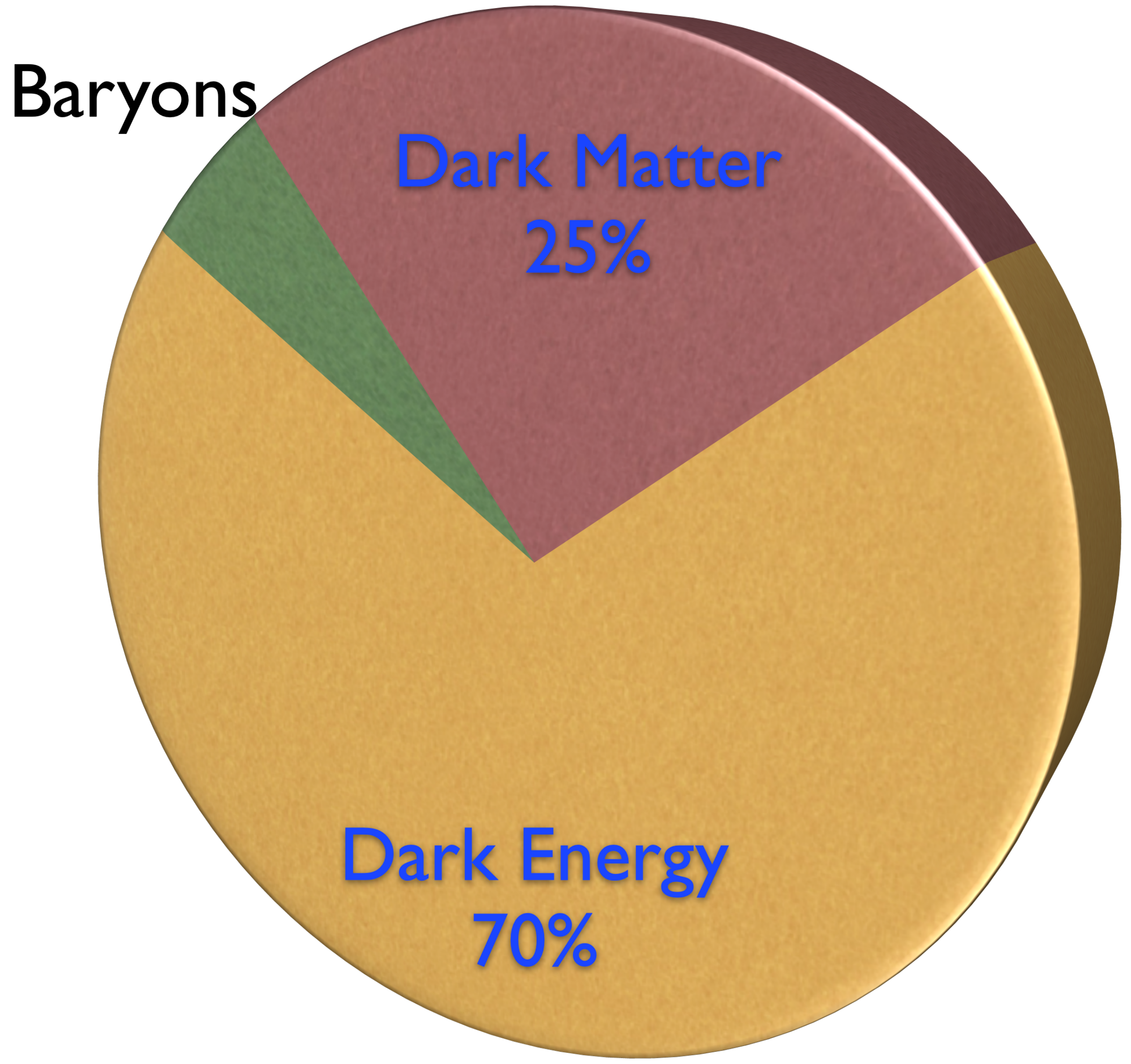
Empirical Pillars of the Hot Big Bang

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



Cosmological Parameters

The search for two parameters has become six, maybe seven

two parameters

- Hubble expansion rate
  - H_0
- Mass density
  - Ω_m

Or simply H_0, q_0
but in the absence of dark energy,
$q_0 = \frac{1}{2}\Omega_m$

six parameters

- Hubble expansion rate
  - H_0
- Power spectrum index and normalization
  - n $[P(k) \propto k^n]$
  - σ_8 (amplitude of mass fluctuations in 8 Mpc spheres)
- Mass-energy density
  - Normal matter (baryon) density Ω_b
  - Dark matter density Ω_{CDM}
  - Dark energy density (cosmological constant) Ω_Λ
  - Neutrino mass density Ω_ν (they're mass as well as energy)

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 plus 4×10^{-5} in neutrinos

neutrinos $0.001 < \Omega_\nu < 0.002$ for 3 neutrino flavors with $0.06 < \sum_{i=1}^{3} m_{\nu_i} < 0.12$ eV

upper limit from cosmic structure formation
lower limit from neutrino oscillations

dark energy Ω_{Λ_0} 0.70 energy density of vacuum

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

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

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

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
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Measurements of the gravitating mass density

- Cluster M/L
  - measure M/L of a cluster, combine with measured luminosity density of universe.
  - Mass from virial theorem

$$M \approx \frac{2.5}{G}\sigma^2 R_e$$

  - luminosity L from observations of *cluster* galaxies
  - j from integrating the luminosity function of *field* galaxies:

$$j = \Phi^* L^* \Gamma(\alpha) \qquad\qquad \rho_m = \left(\frac{M}{L}\right) j$$

Coma cluster

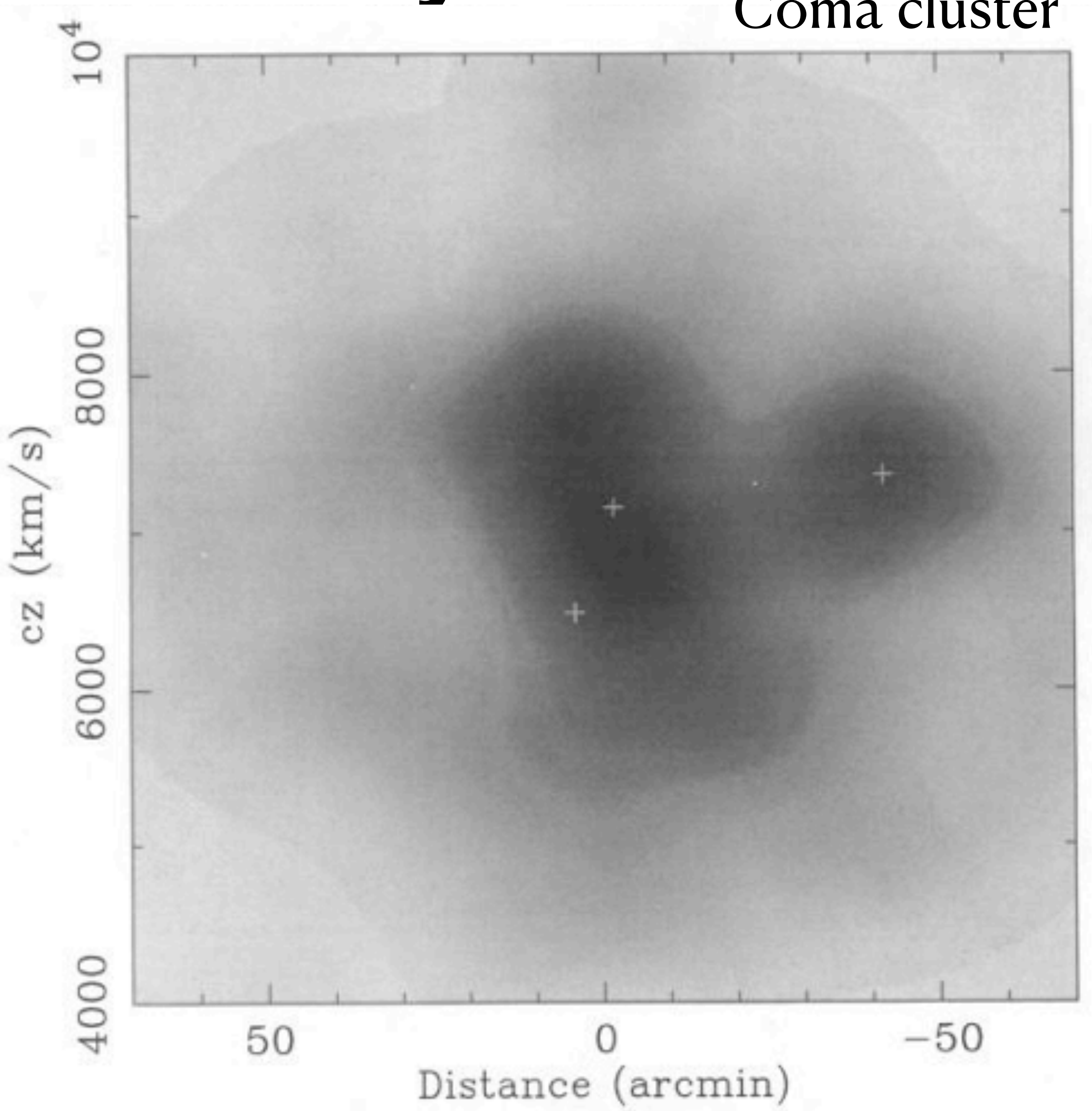


FIG. 10.—Galaxy density distribution projected onto the plane of radial velocity versus projected distance from the cluster center along the NE–SW diagonal (NE positive). The density is smoothed with a Gaussian of dispersion 8′ in the spatial dimension and 300 km s^{-1} in the velocity dimension. The positions of the three dominant galaxies are marked by crosses (*left to right*: NGC 4889, NGC 4874, NGC 4839). The gray scale is linear with density and runs from zero to the maximum.

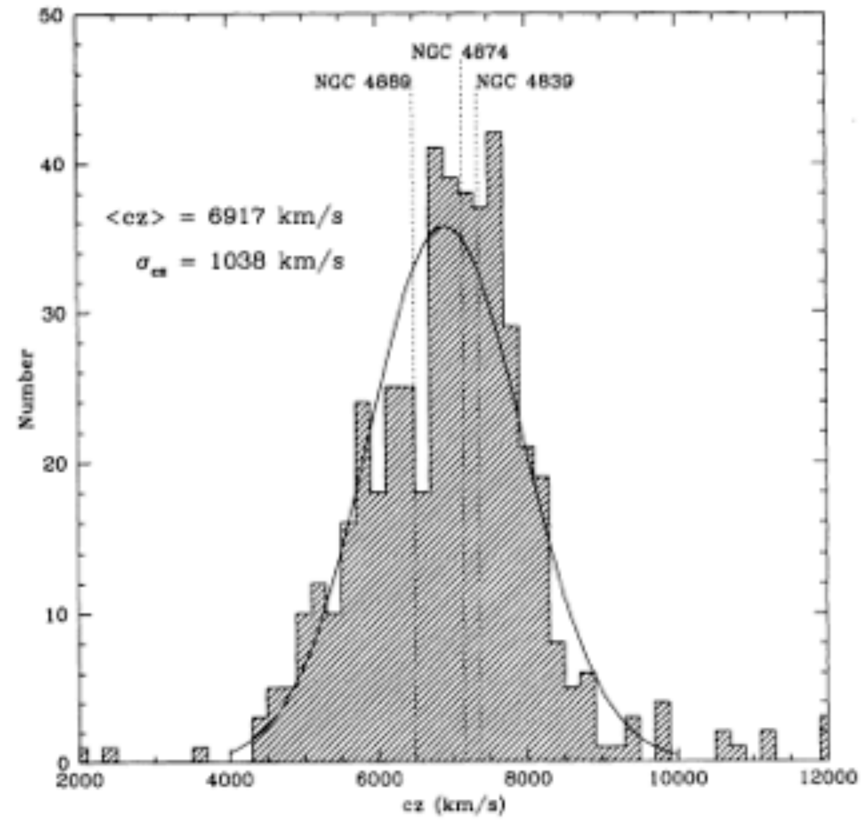


FIG. 5.—Distribution of radial velocities for galaxies in the Coma cluster. The curve is a Gaussian with mean 6917 km s^{-1} and standard deviation 1038 km s^{-1}. The velocities of the three dominant cluster galaxies are indicated.

Measurements of the gravitating mass density

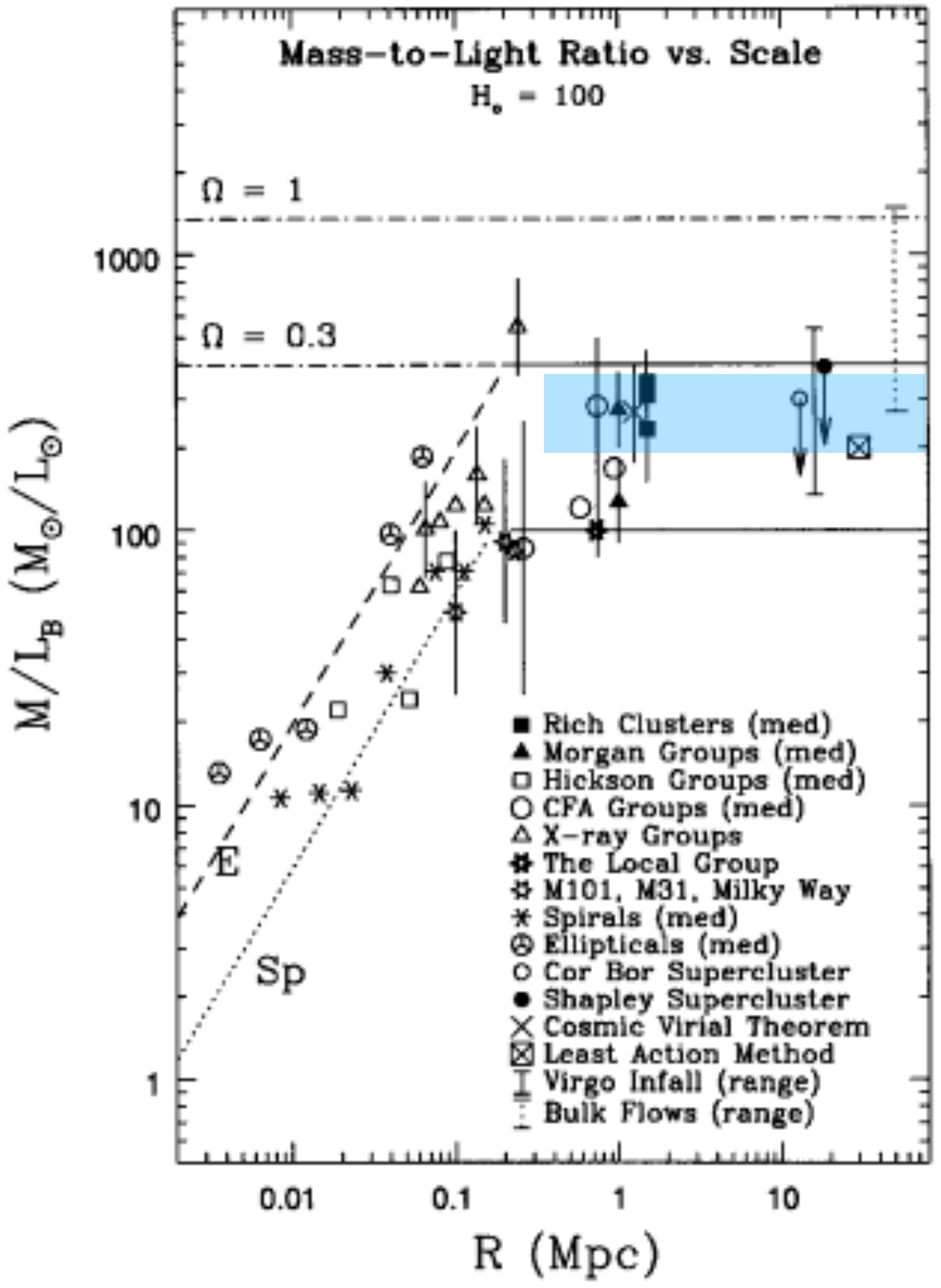
- Cluster M/L
  - measure M/L of a cluster, combine with measured luminosity density of universe.
  - j from integrating the luminosity function of galaxies:

$$j = \Phi^* L^* \Gamma(\alpha) \qquad \rho_m = \left(\frac{M}{L}\right) j$$

  - 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.



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

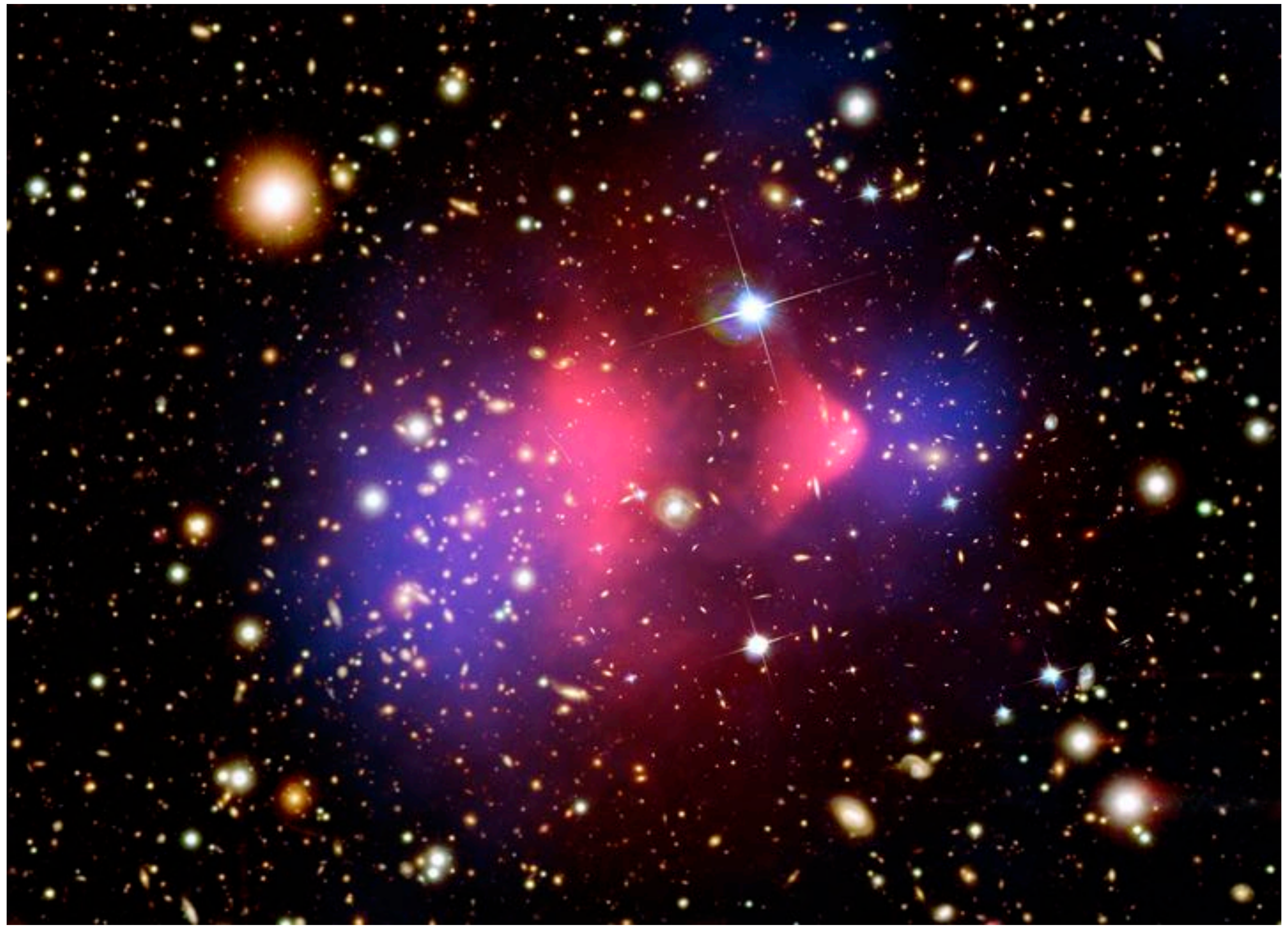
$\Omega_j \approx 10^{-3}$

$\frac{M}{L} \approx 250$

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

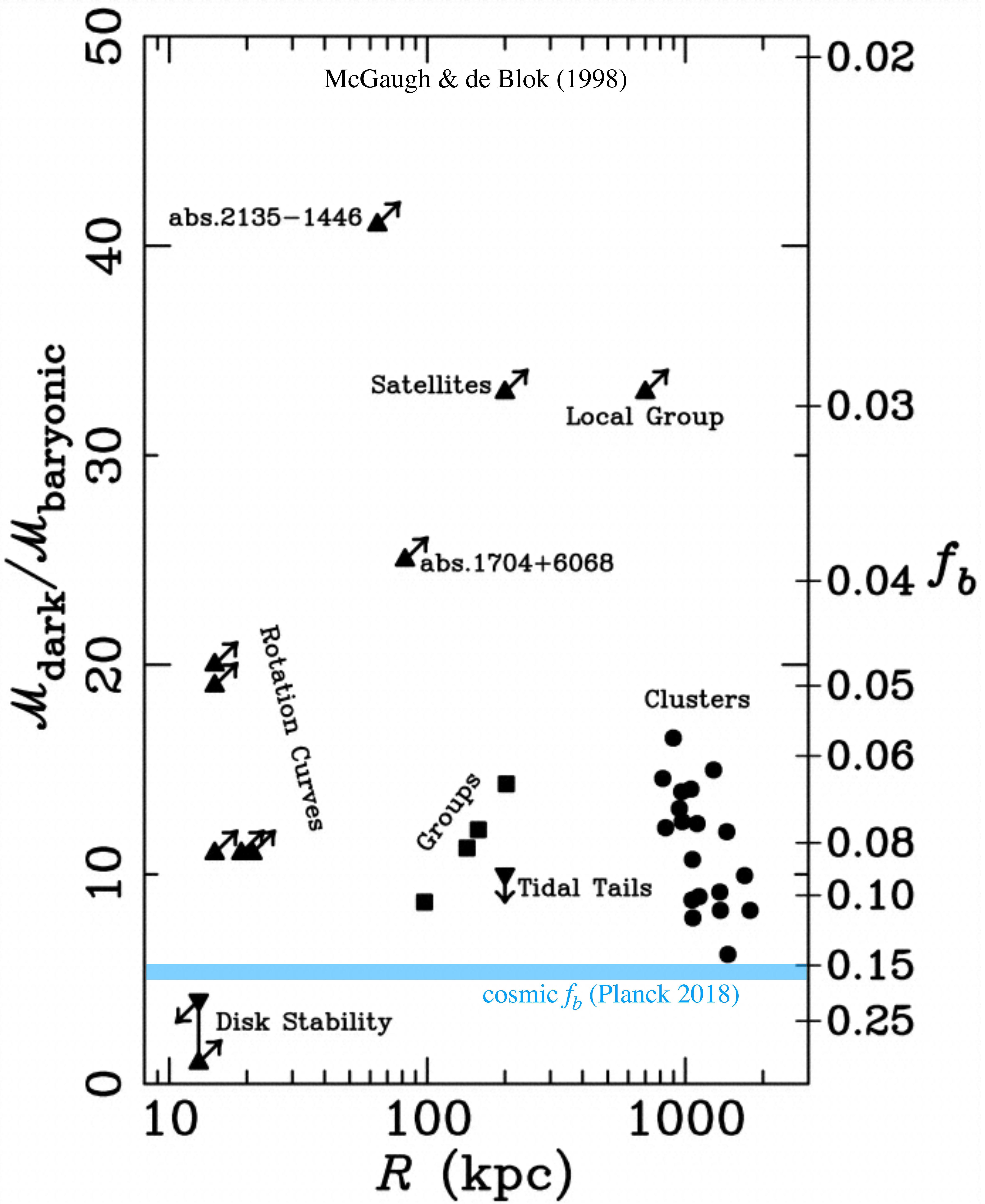


– cluster baryon fractions

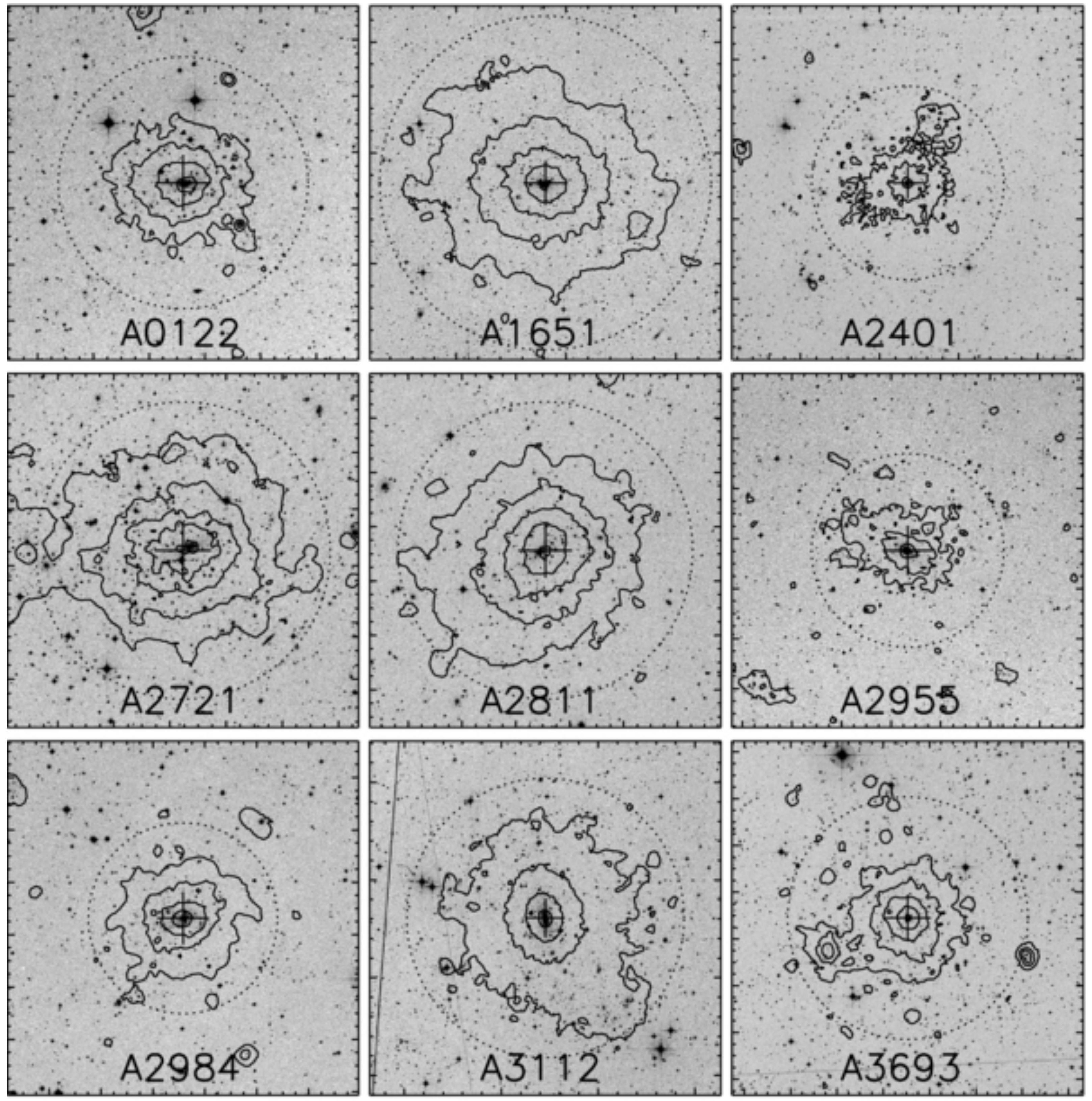
$$f_b = \frac{M_b}{M_{tot}} \quad \circ\!\!\longrightarrow \quad \Omega_m = \frac{\Omega_b}{f_b}$$

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



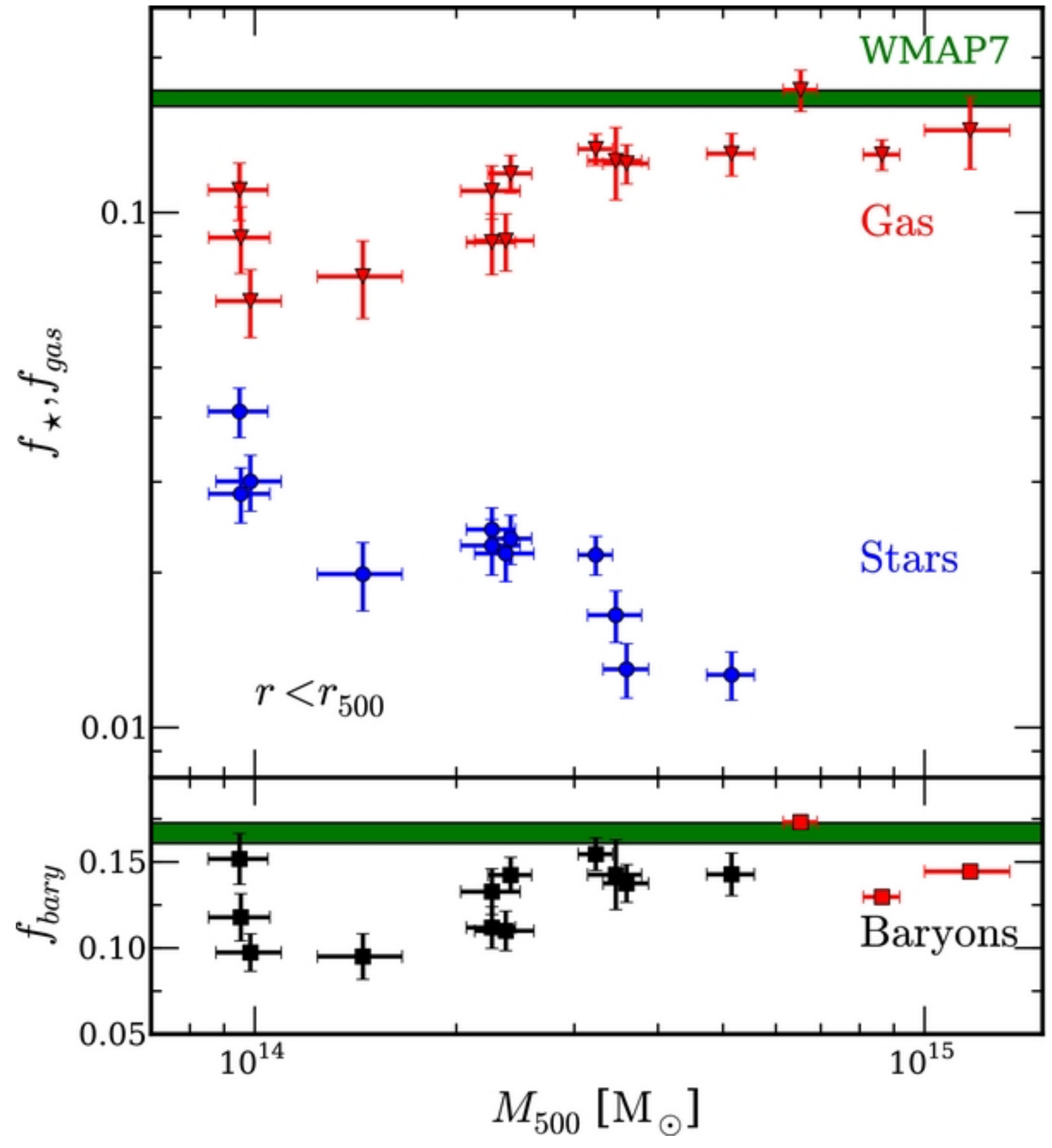
– cluster baryon fractions

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

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

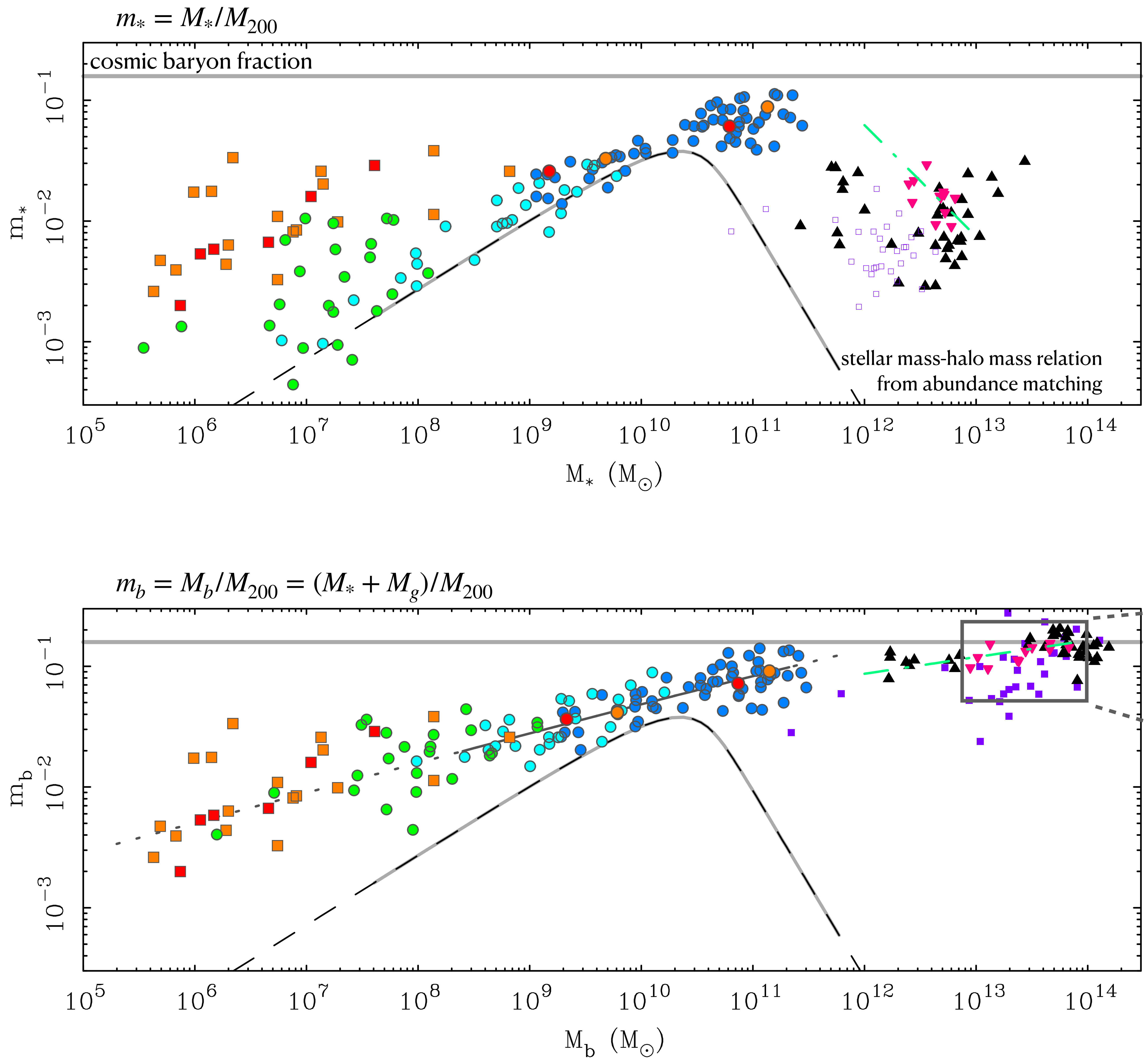
Measure cluster dynamical mass M_{tot} from X-ray temperature (contours) or weak lensing or velocity dispersion

Gonzalez et al. (2013)

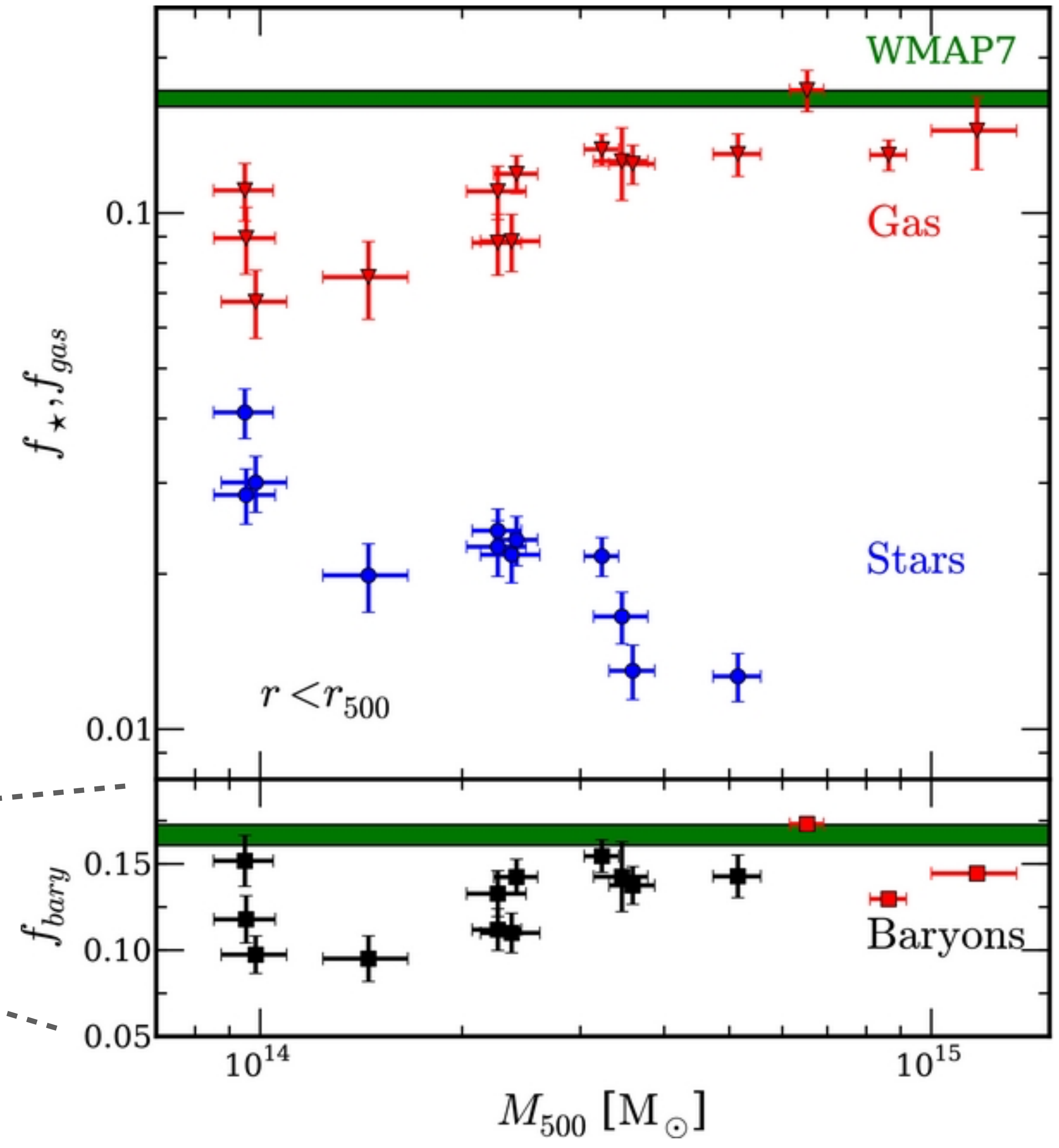


Most of the baryonic mass in rich clusters is in the hot, X-ray emitting gas of the ICM (intracluster medium). Only the most massive clusters approach the cosmic fraction found in fits to the acoustic power spectrum of the CMB. Lower mass clusters suffer a missing baryon problem.

– beyond cluster baryon fractions



Gonzalez et al. (2013)



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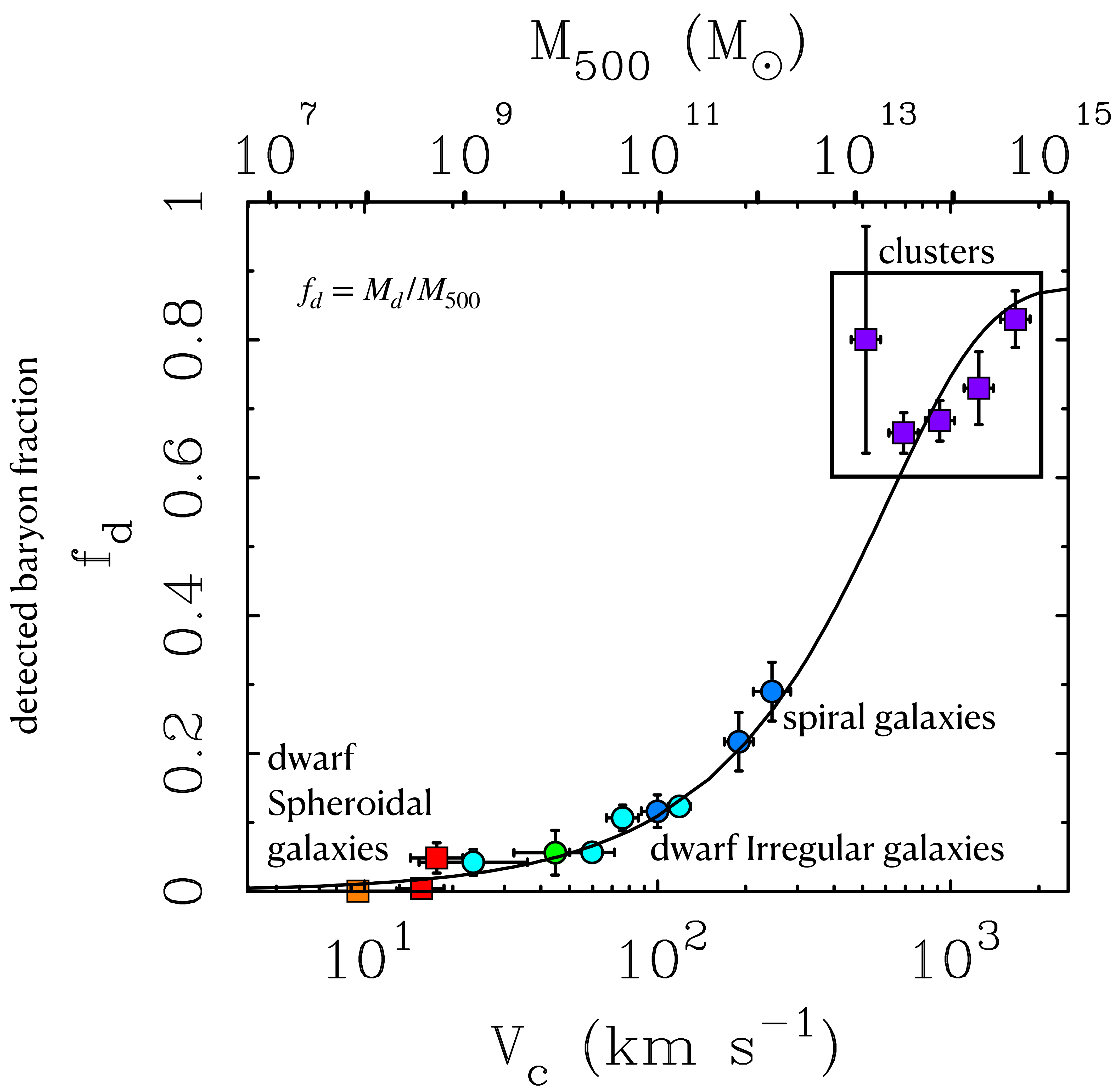
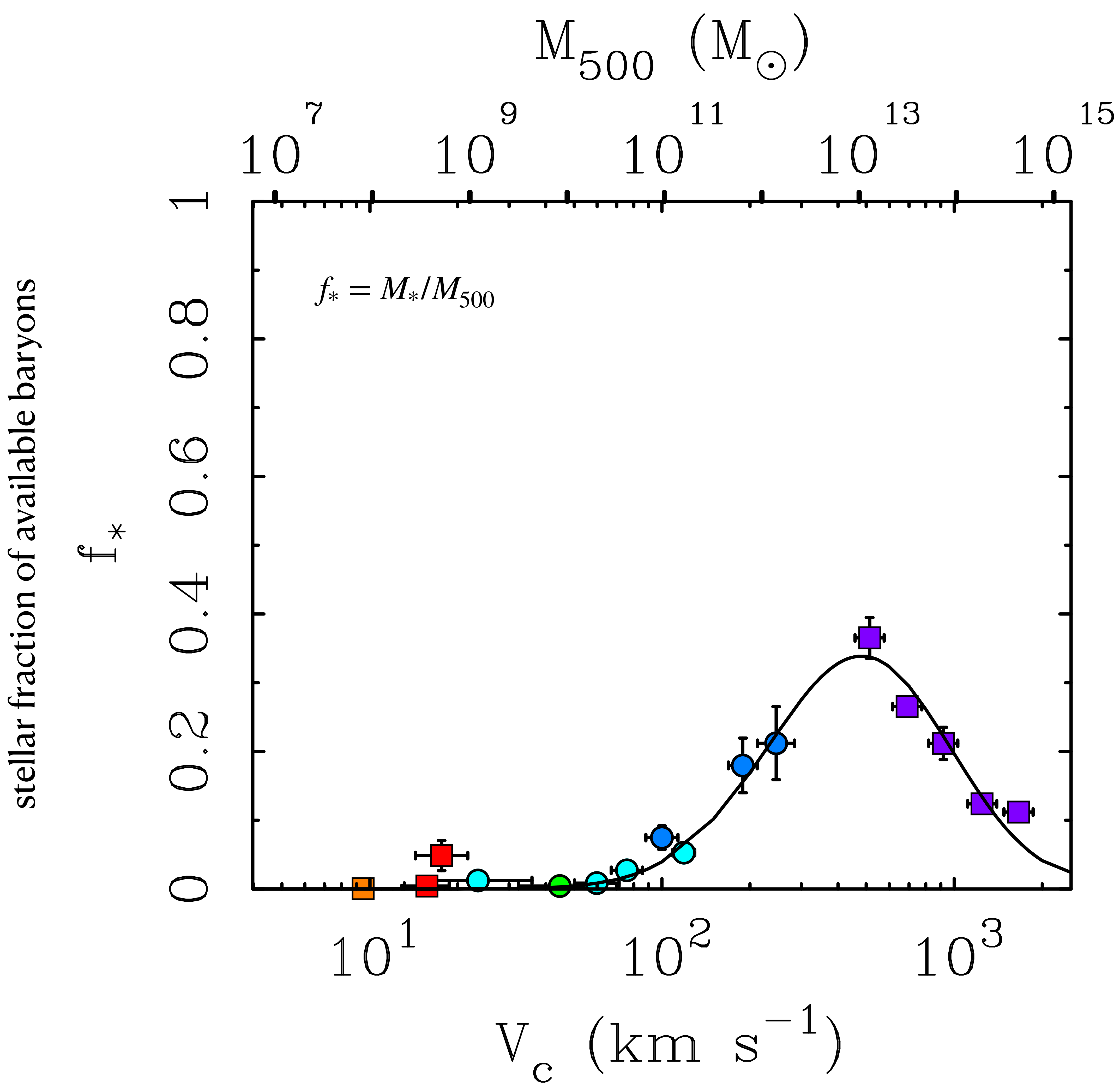
– beyond cluster baryon fractions

McGaugh et al. (2010)





$f_d = M_b/(f_b\, M_{200}) = (M_* + M_g)/(f_b\, M_{200})$

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Measurements of the gravitating mass density

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  – measure shear over large scales

Dark Energy Survey
arxiv:2002.11124

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

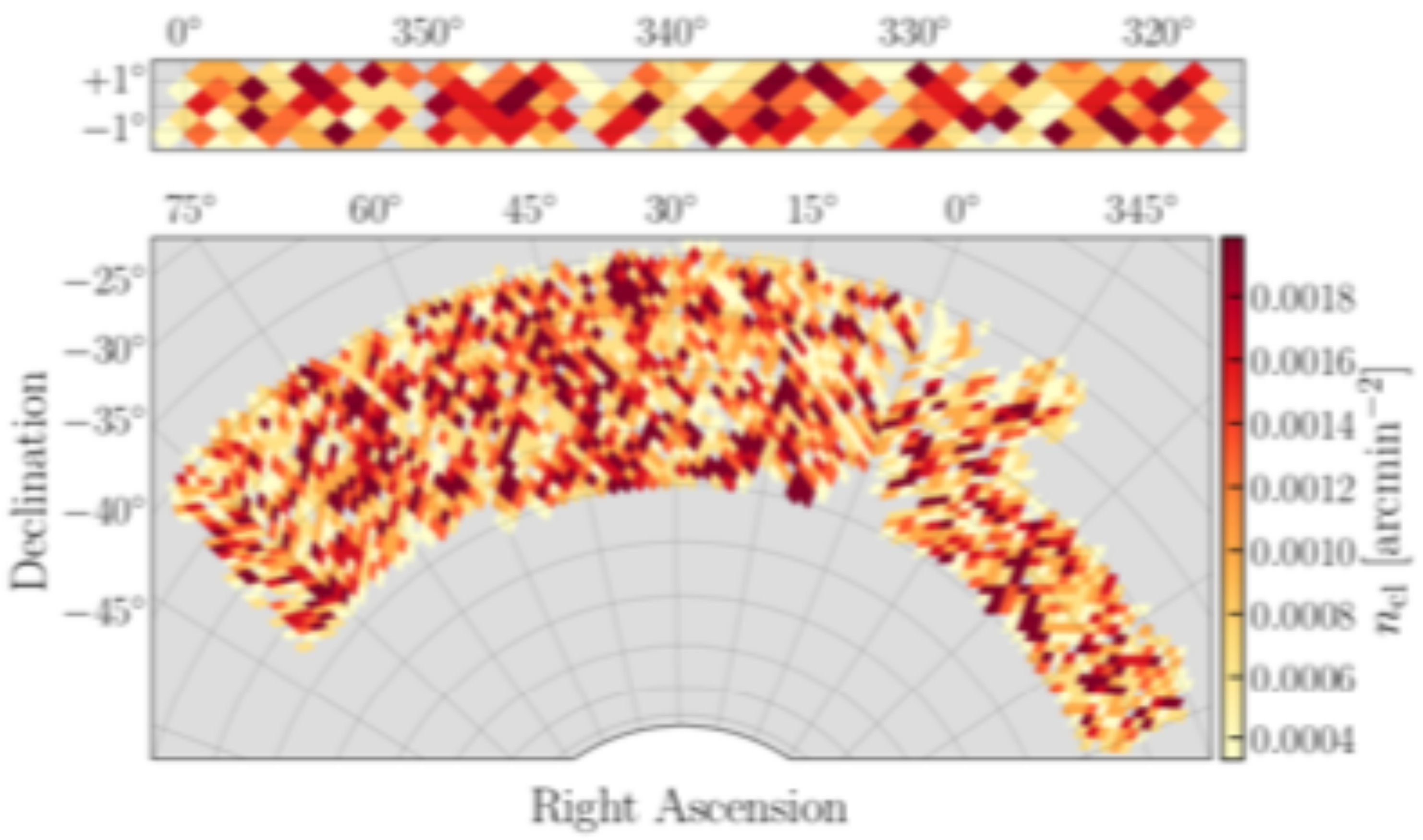
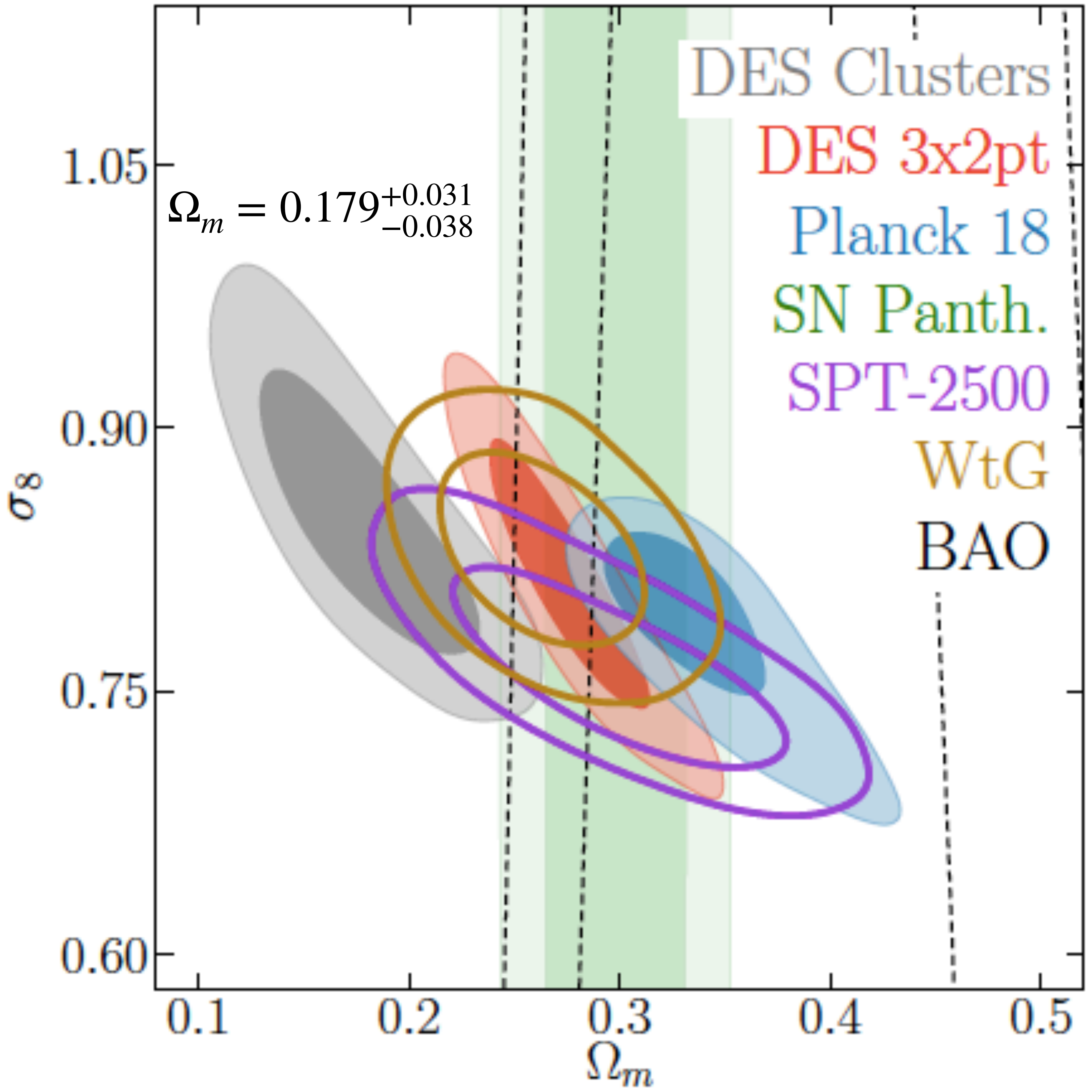


FIG. 1. The DES Y1 redMaPPer cluster density over the two non-contiguous regions of the Y1 footprint: the Stripe 82 region (116 deg^2; *upper* panel) and the SPT region (1321 deg^2; *lower* panel).

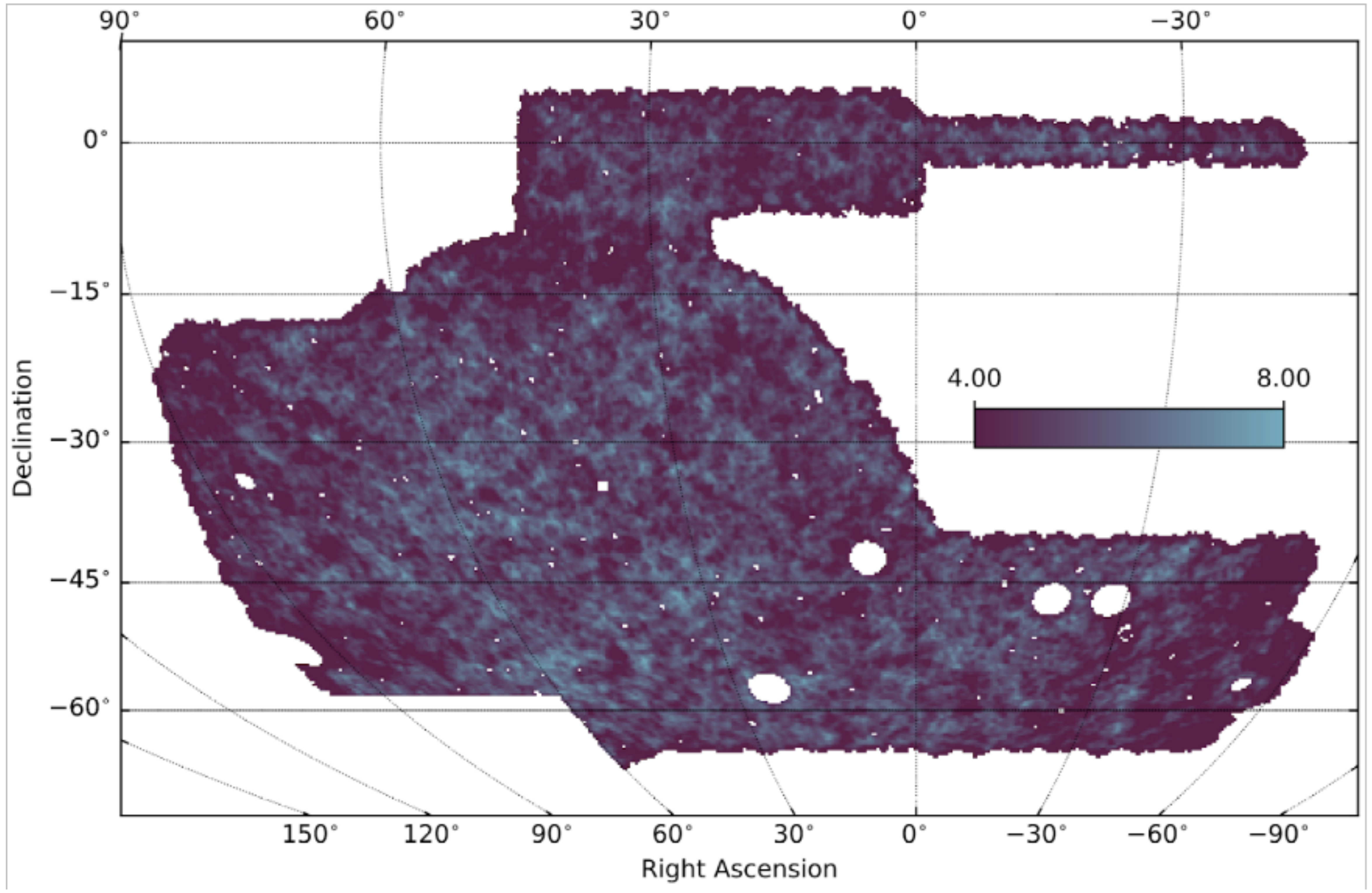


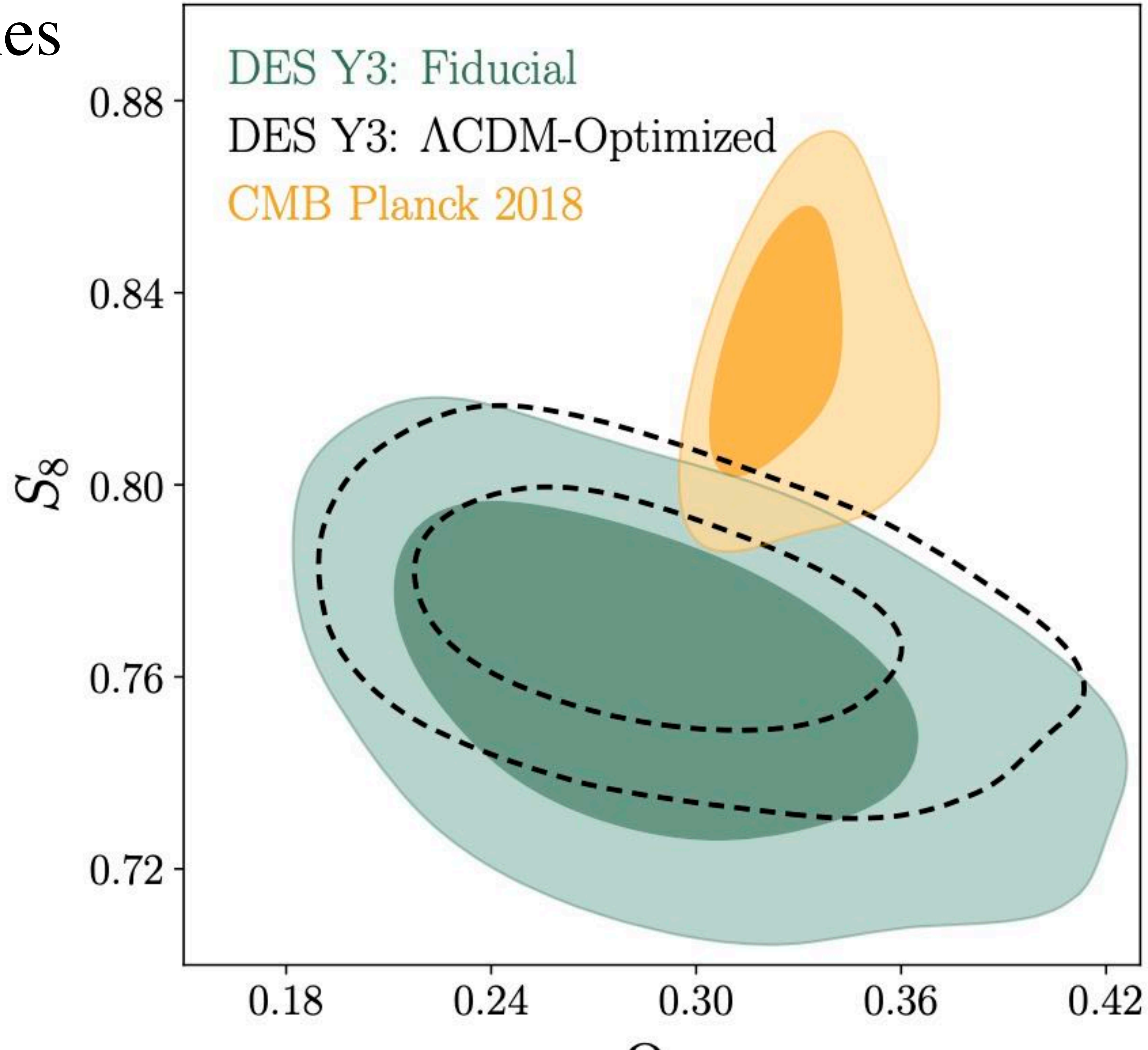
Measurements of the gravitating mass density

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

- Weak lensing
  – measure shear over large scales

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





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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

682 TONRY AND DAVIS

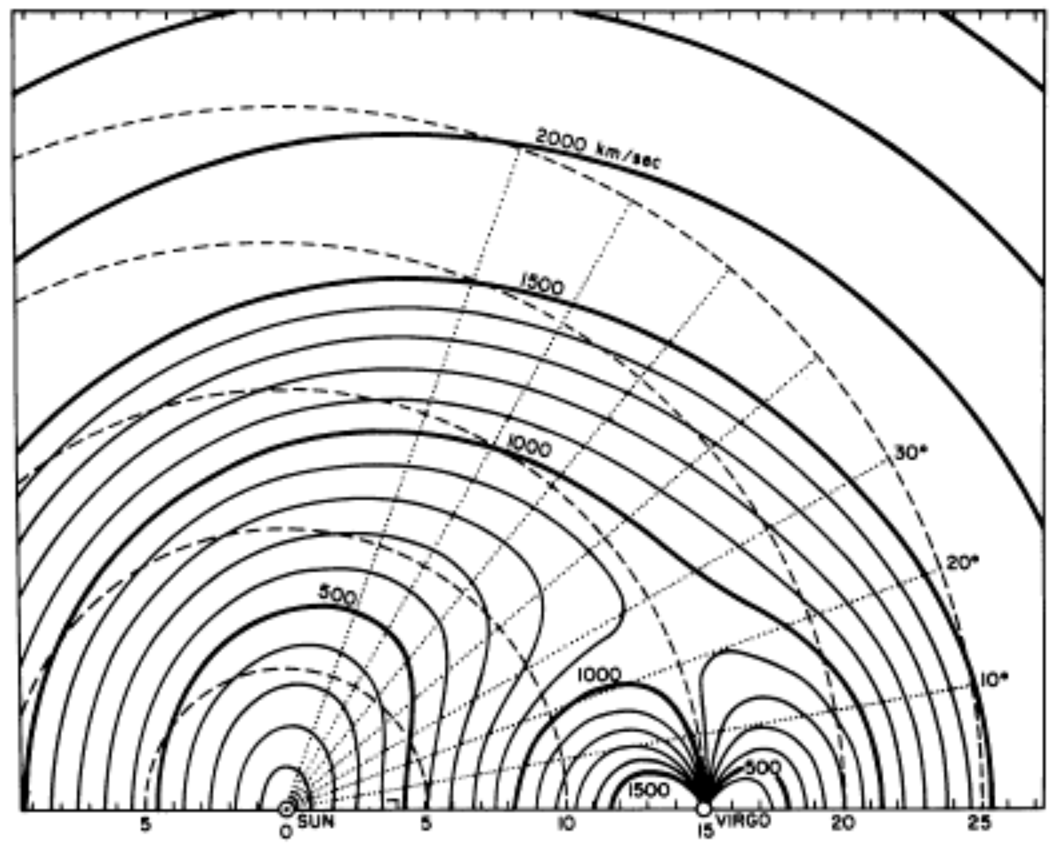


Fig. 1.—On a two-dimensional grid with the Earth and the Virgo cluster on the x axis, redshift contours are plotted for a Hubble flow perturbed by a Virgocentric flow. An infall velocity of 400 km s^{-1} at our position is assumed. A pure Hubble flow would be concentric circles.

$$\Omega_m = 0.25 \pm 0.05$$

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

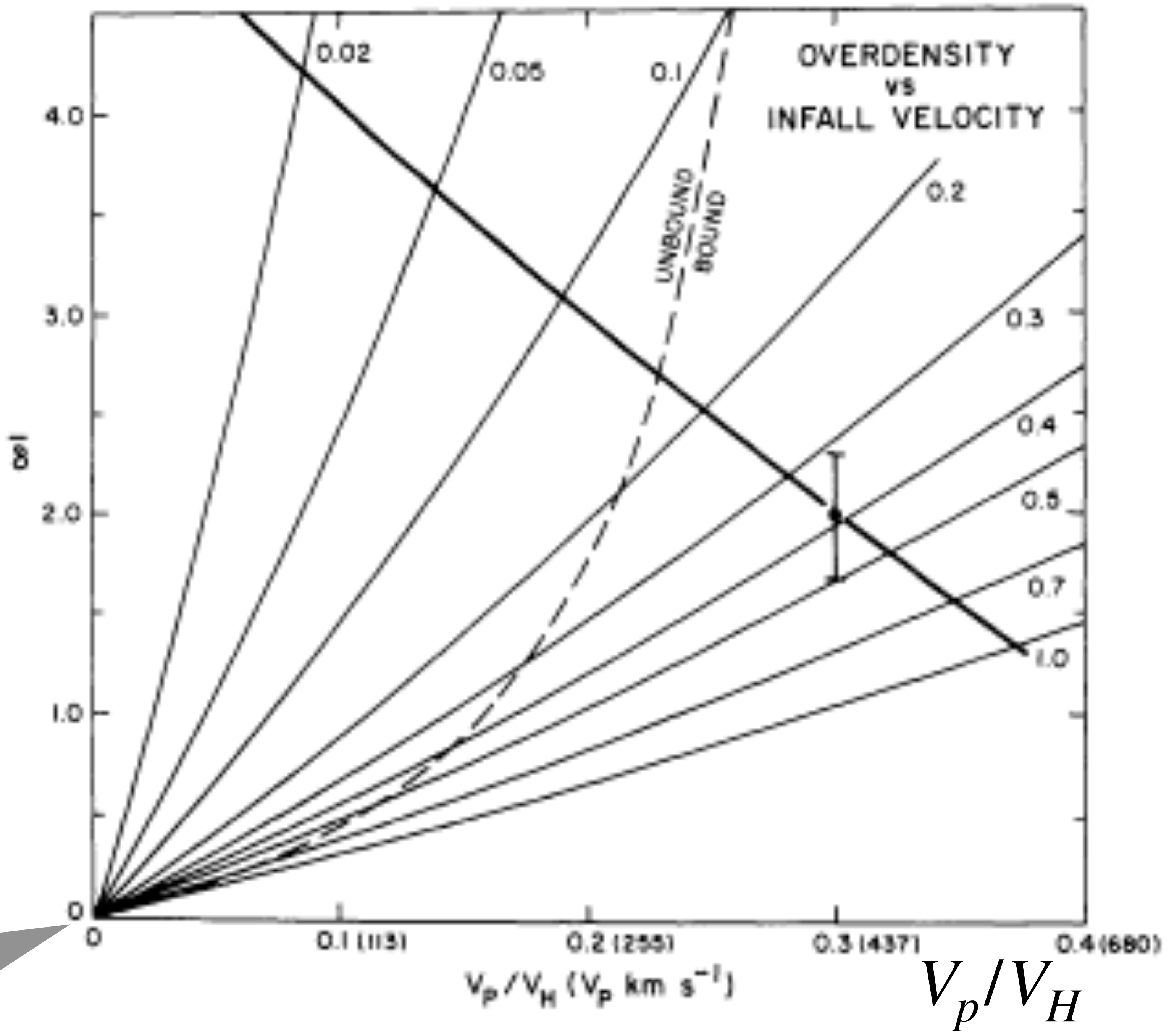
Lines are lines of constant Ω_m

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.

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



V_p/V_H

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 vel
this model will app
which have not yet
Virgo core and wit
km s^{-1} are assume
scale peculiar moti
effect on the comp
100 km s^{-1} Mpc^{-1},
300 km s^{-1} galactic
Aaronson, and Hu
sional velocity of
Table 2 lists the c
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