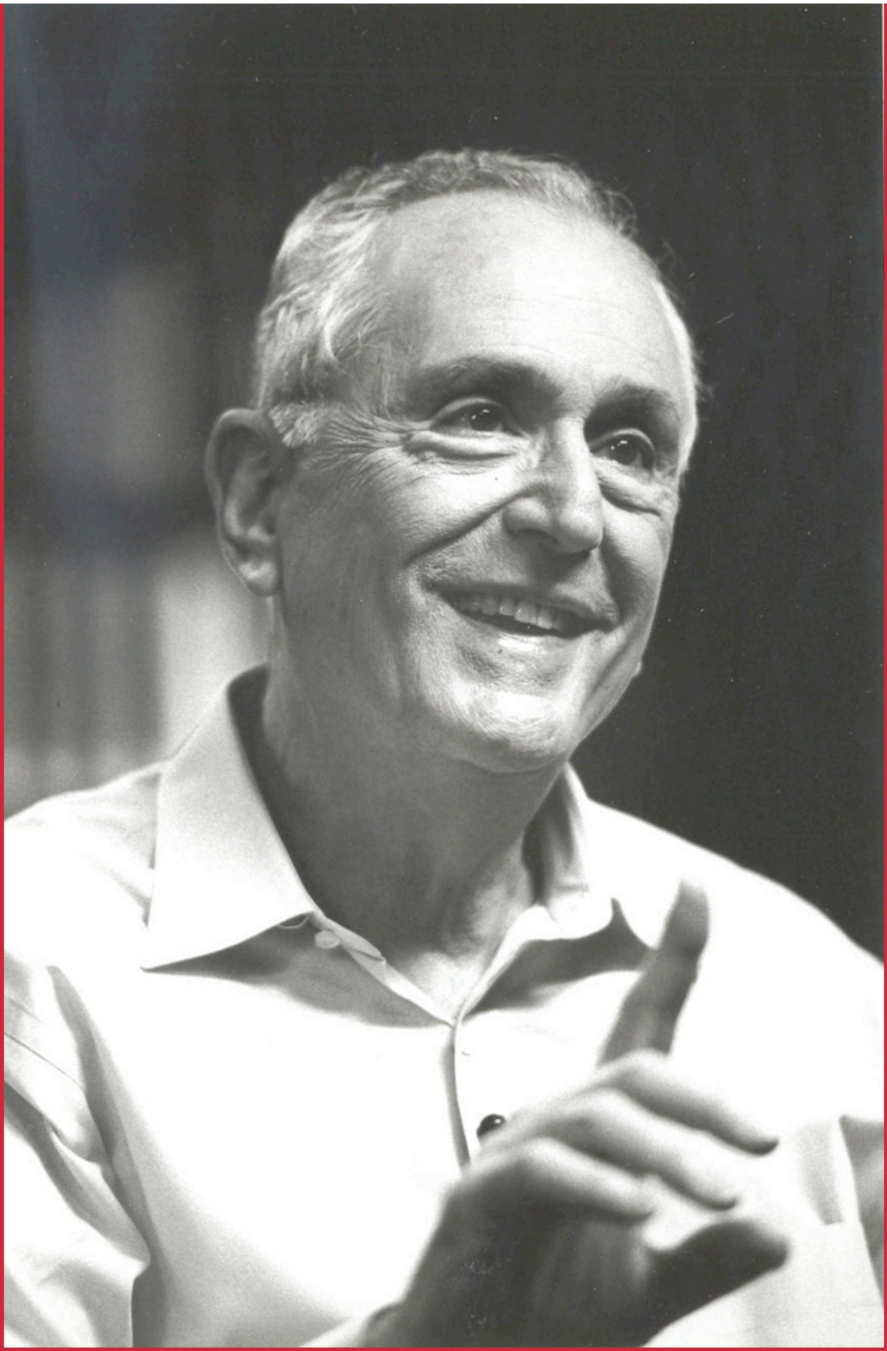
“ The most important discoveries will provide answers to questions that we do not yet know how to ask and will concern objects we have not yet imagined.”

John N. Bahcall

"We want to do extragalactic neutrino astronomy because it is truly an exploration of the universe We do solar neutrino astronomy to test fundamental theories of physics and astronomy. But, perhaps solar neutrino research and extra-galactic neutrino research may in the end share a fundamental characteristic: surprise. Remember, that we undertook solar neutrino research to test stellar evolution and unexpectedly we found evidence for new neutrino physics."

John N. Bahcall



Tracing Dark Matter in the Universe

OR

Where is the Dark Matter?

Neta A. Bahcall
Princeton University

Mass-to-Light Function

M/L(R)

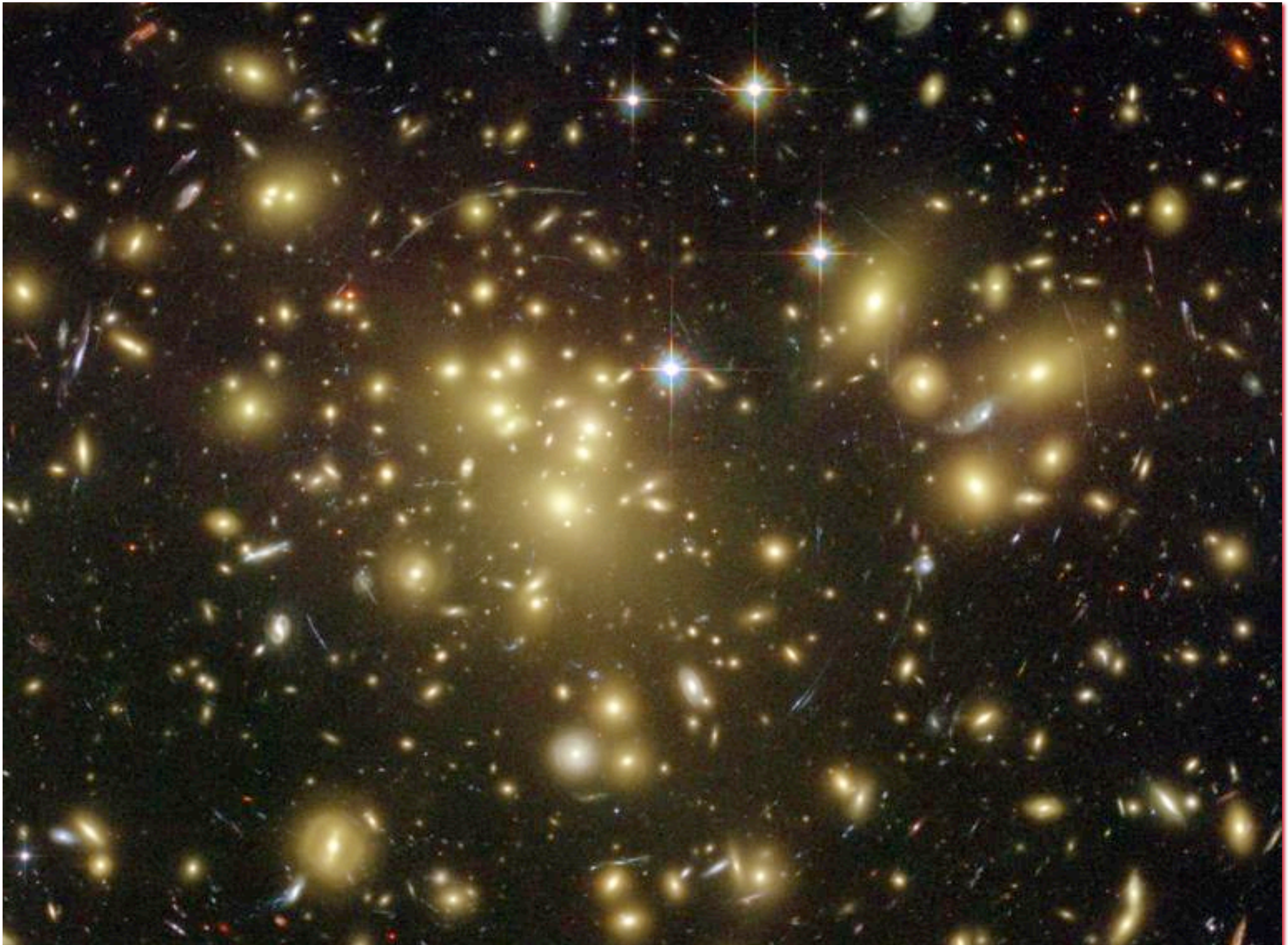
- *How and where is the mass distributed?*
- *How does M/L depend on scale?*
- *How use it to weigh Universe?*

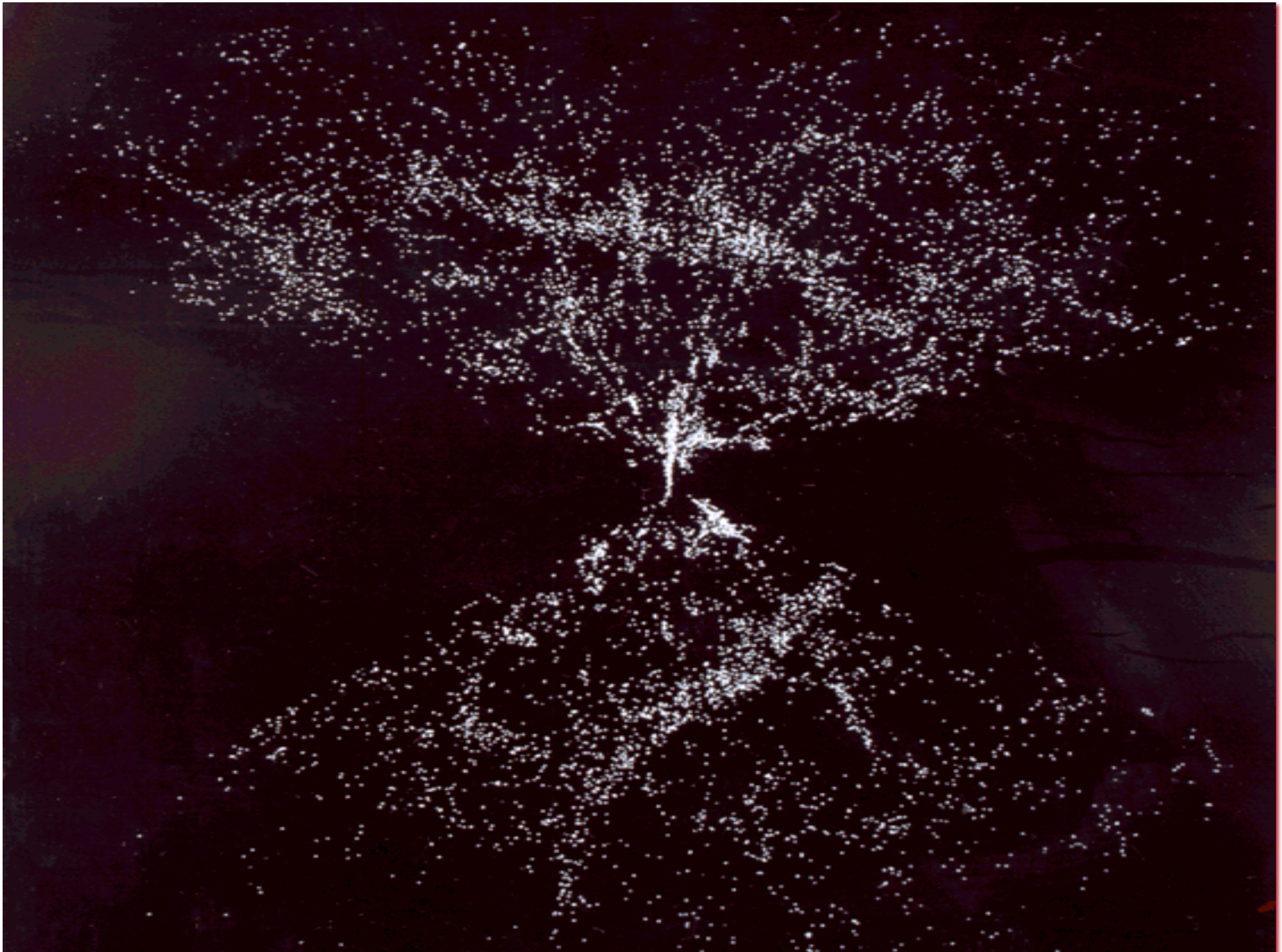
◆ $\mathcal{L}_{univ}(L_o/Vol) \times \langle M/L \rangle_{rep} = \quad {}_{m}(M_o/Vol)$

◆ Determine M, <M/L> of clusters, SCs, LSS

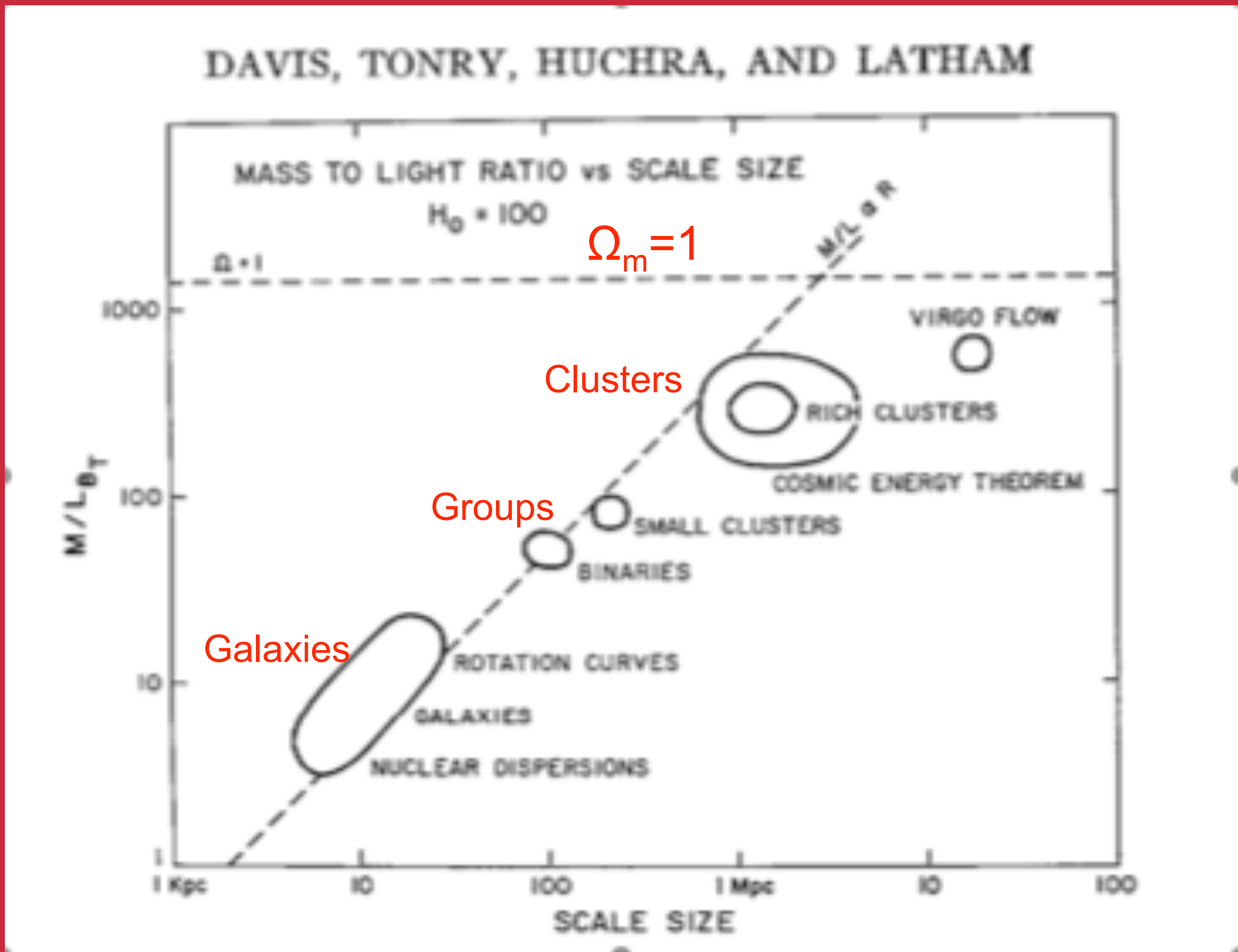
➔ $\langle M/L \rangle_{rep}$ [≈ 300h]

◆ ➔ ${}_{m} \sim 0.2 \pm 0.05$



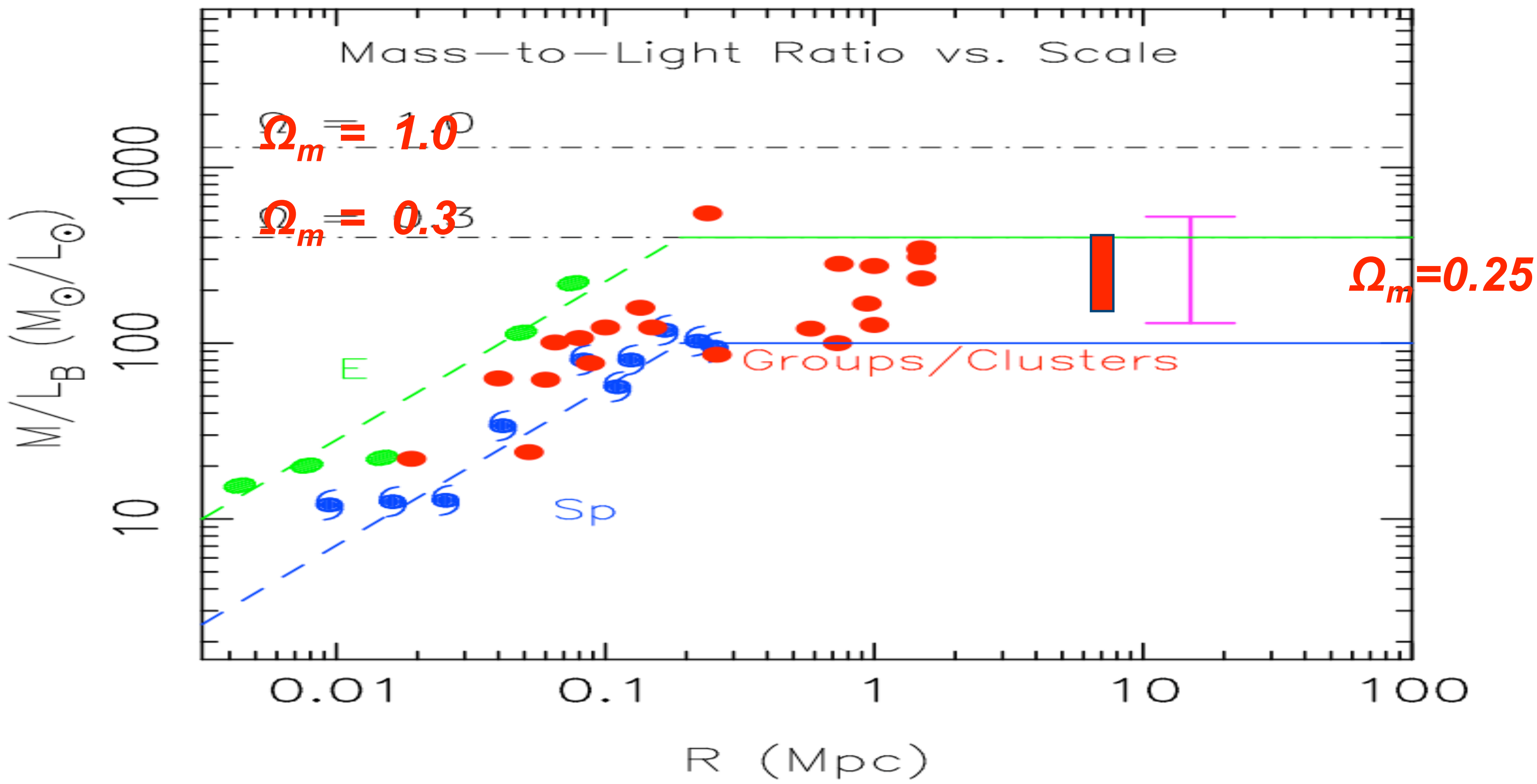


M/L(R) (Davis etal 1980)



Mass-to-Light Function

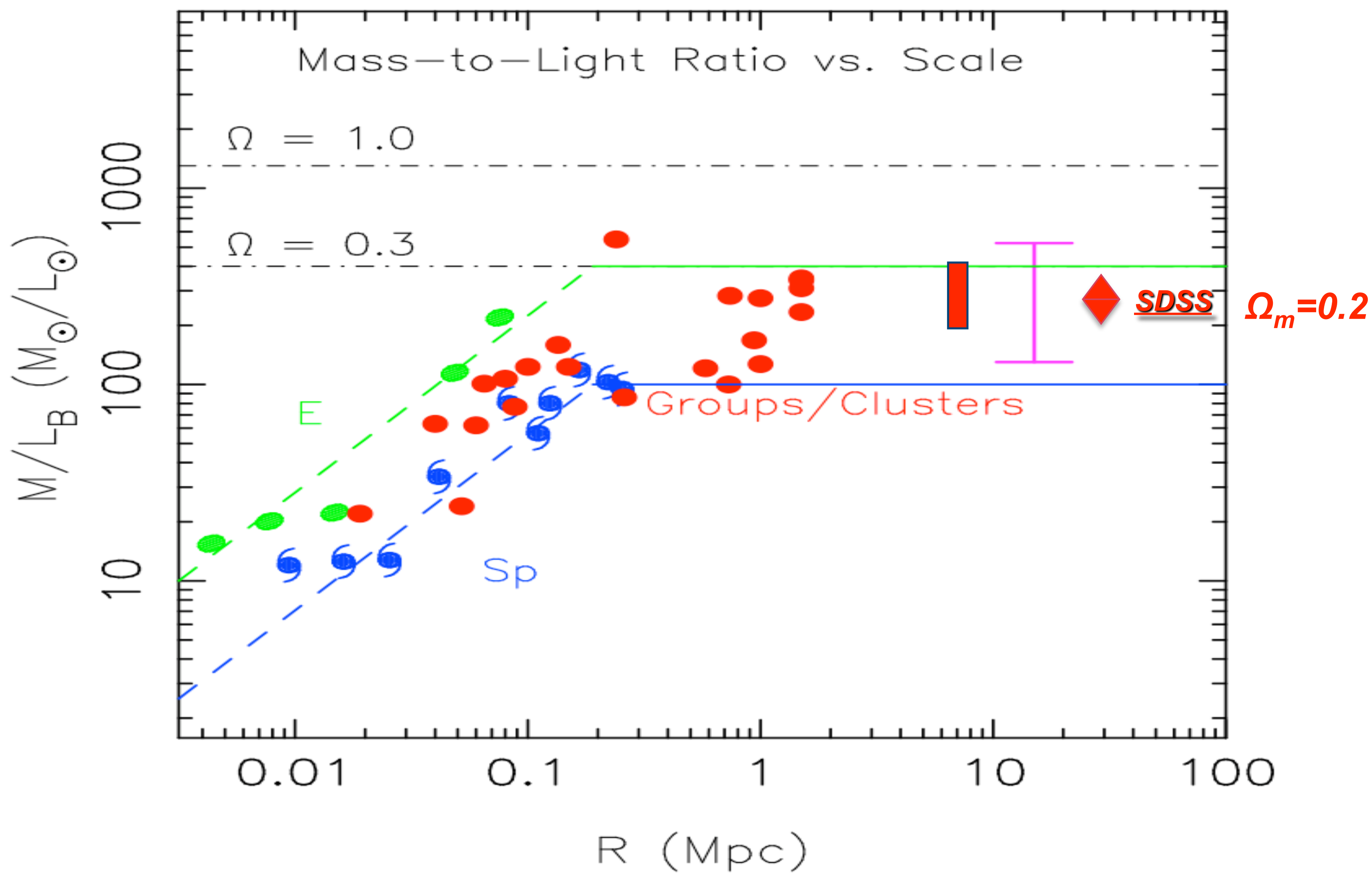
(Bahcall, Lubin & Dorman ‘95; Bahcall and Fan ‘98)



1. M/L flattens on large-scales: M ~ L. End of Dark Matter.
2. Sp + E produce M/L of groups, clusters; Clusters have no excess DM !
3. Most of the DM is in huge halos around galaxies (few-100 Kpc)

Mass-to-Light Function

(Bahcall, Lubin & Dorman ‘95; Bahcall and Fan ‘98)



Tracing Mass and Light to 30 Mpc!

10^5 Sloan Survey groups + clusters (lensing mass)

==============================

- 165,000 groups+clusters N_g >~ 3 to >200 (richest)
- z = 0.1 – 0.3
- Mass from weak-lensing of stacked subsamples;

  R ~ 0 to 30 Mpc!
- Mass: $\Delta M(R)$ [lensing: $\rho(R) - \rho_0$]
- Luminosity: $\Delta L_i(R)$ [$L(R) - L_0$] (L_i)
- $\Delta M/\Delta L_i(\leq R)$ [for all systems, N_g ~ 3 to >200]

Cluster $M/L_i(R)$ Profile (SDSS)

1.6×10^5 clusters N= 3 to 220 (Sheldon etal 2009)

Flat >~ 1Mpc
M ~ L

X=R(vir)

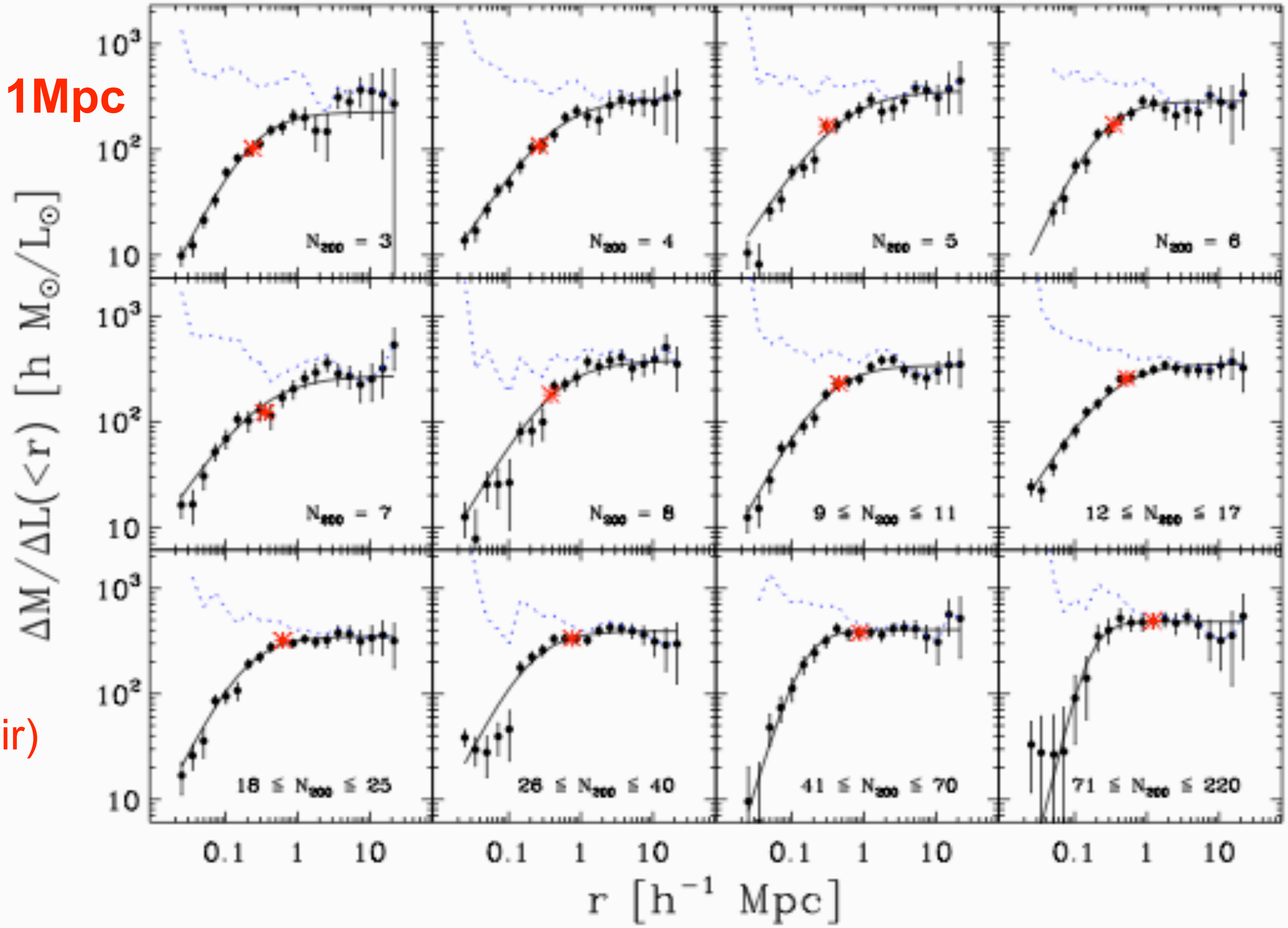


FIG. 8.— Excess mass to excess light ratio profiles for each of the N_{200} bins. Light is measured in the ${}^{0.25}i$ bandpass. These curves are the ratio of the curves shown in Figures 6 and 7. The points with error bars include the mean BCG luminosity, while the dotted curves exclude the luminosity of the BCG. The asterisk marks r_{200}^{mass}. The curve through the data is a simple descriptive model as discussed in §8.6.

M/L$_i$(≤R) (Bahcall and Kulier 2010)

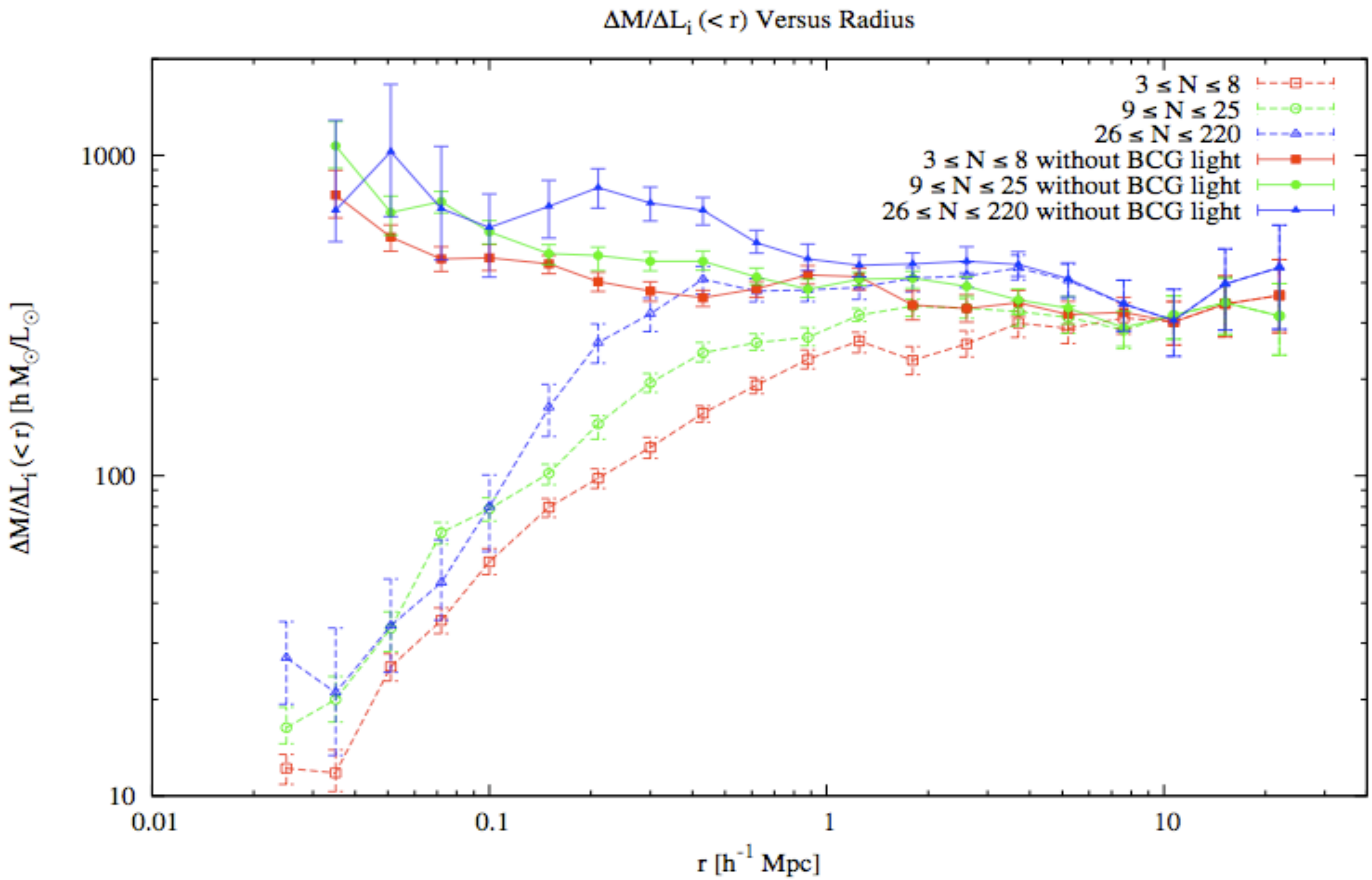


FIG. 1.— Ratio of cumulative excess mass to cumulative excess light as a function of cluster radius. Light is measured in the $^{0.25}i$ bandpass. Different plot symbols represent different cluster richness bins, created by averaging points at the same r from the data of Sheldon et al. 2008. Dashed curves include the mass and light of the BCG, while solid curves include the mass but not the light.

$M/L_i(\leq R)$

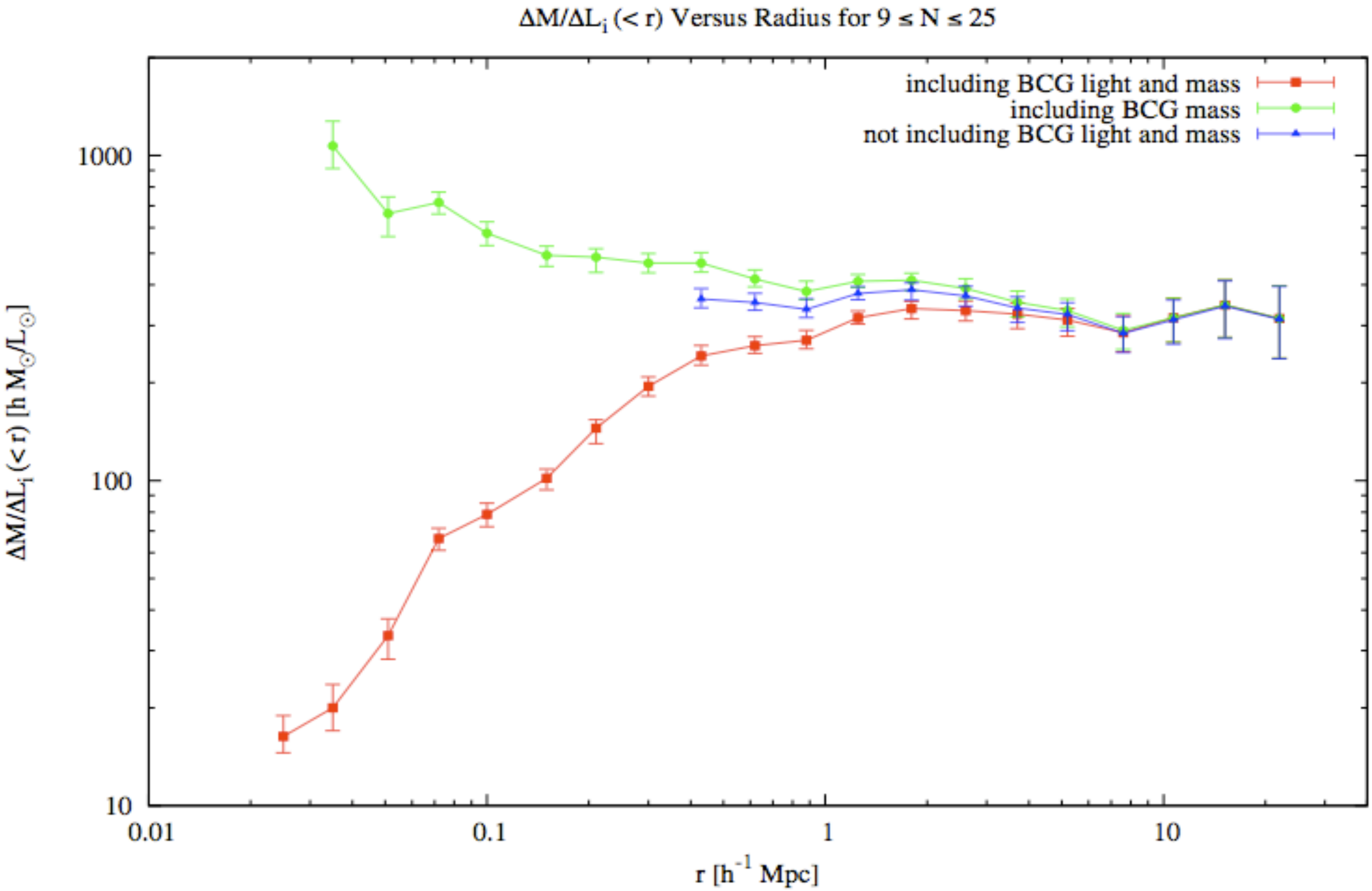


FIG. 2.— $\Delta M/\Delta L$ for $9 \leq N_{200} \leq 25$ showing the effect of subtracting the BCG mass.

M/L(≤R) vs. Richness (no BCG)
(Bahcall & Kulier 2010)

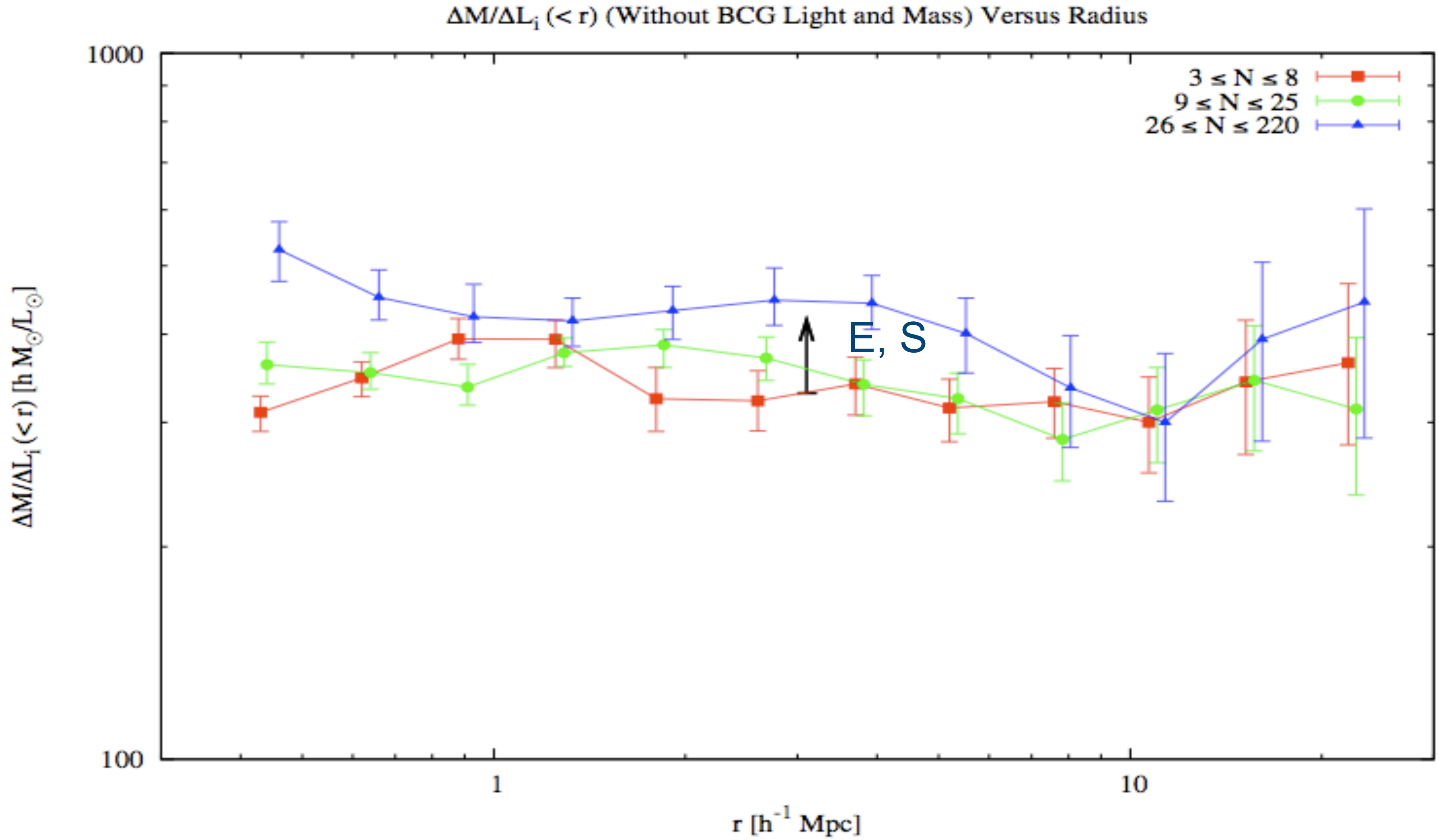


FIG. 4.— $\Delta M/\Delta L$ with the mass and light of the BCG subtracted. Different plot symbols represent different cluster richness bins, created by averaging points at the same r from the data of Sheldon et al. 2008. The black arrow shows the predicted effect on $\Delta M/\Delta L$ due to the difference in stellar population between poor and rich clusters. Points have been shifted slightly in r to show differences between richness bins.

$M/L_i(\leq R)$ vs. R/R_{200} (vs. Richness)

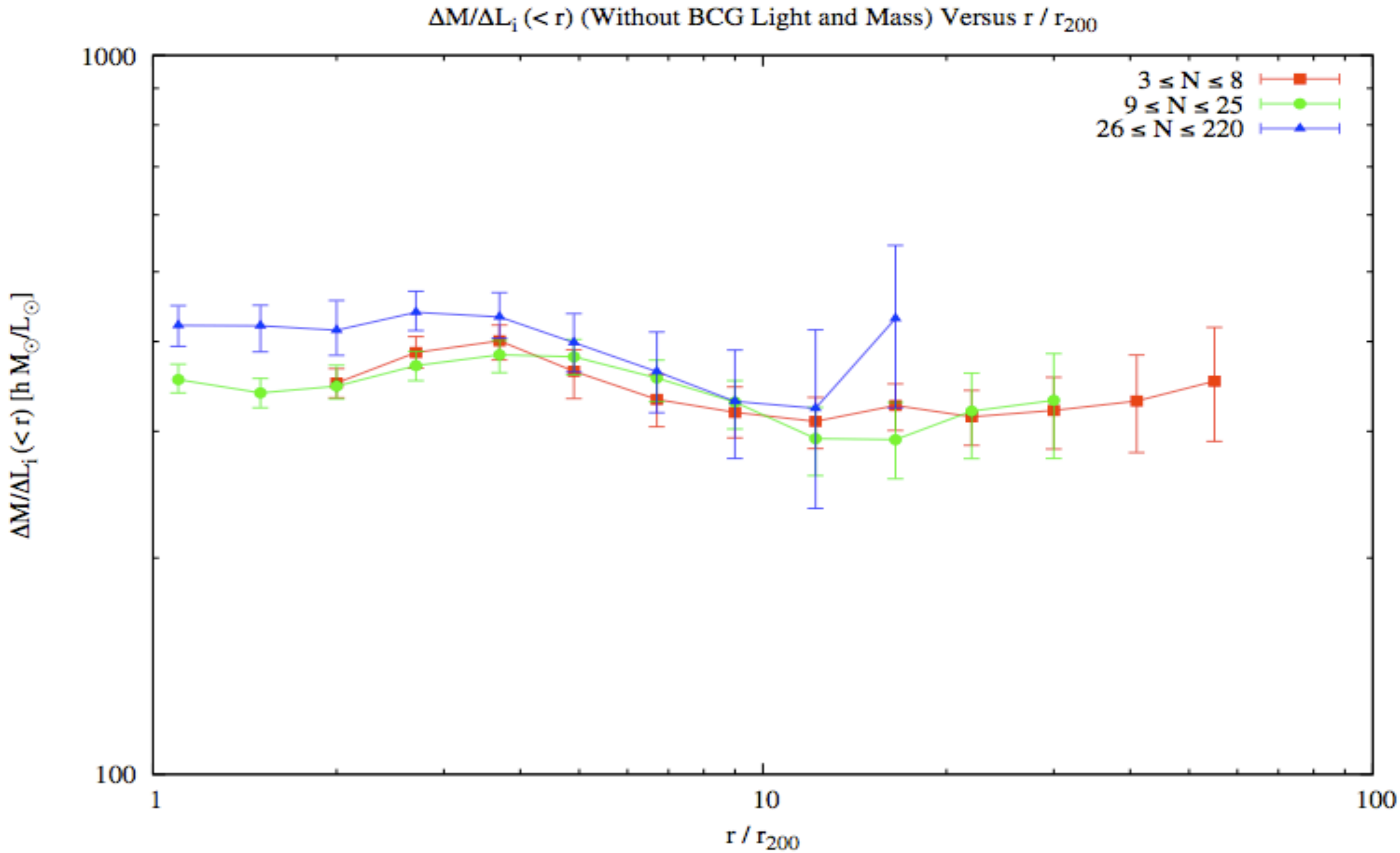
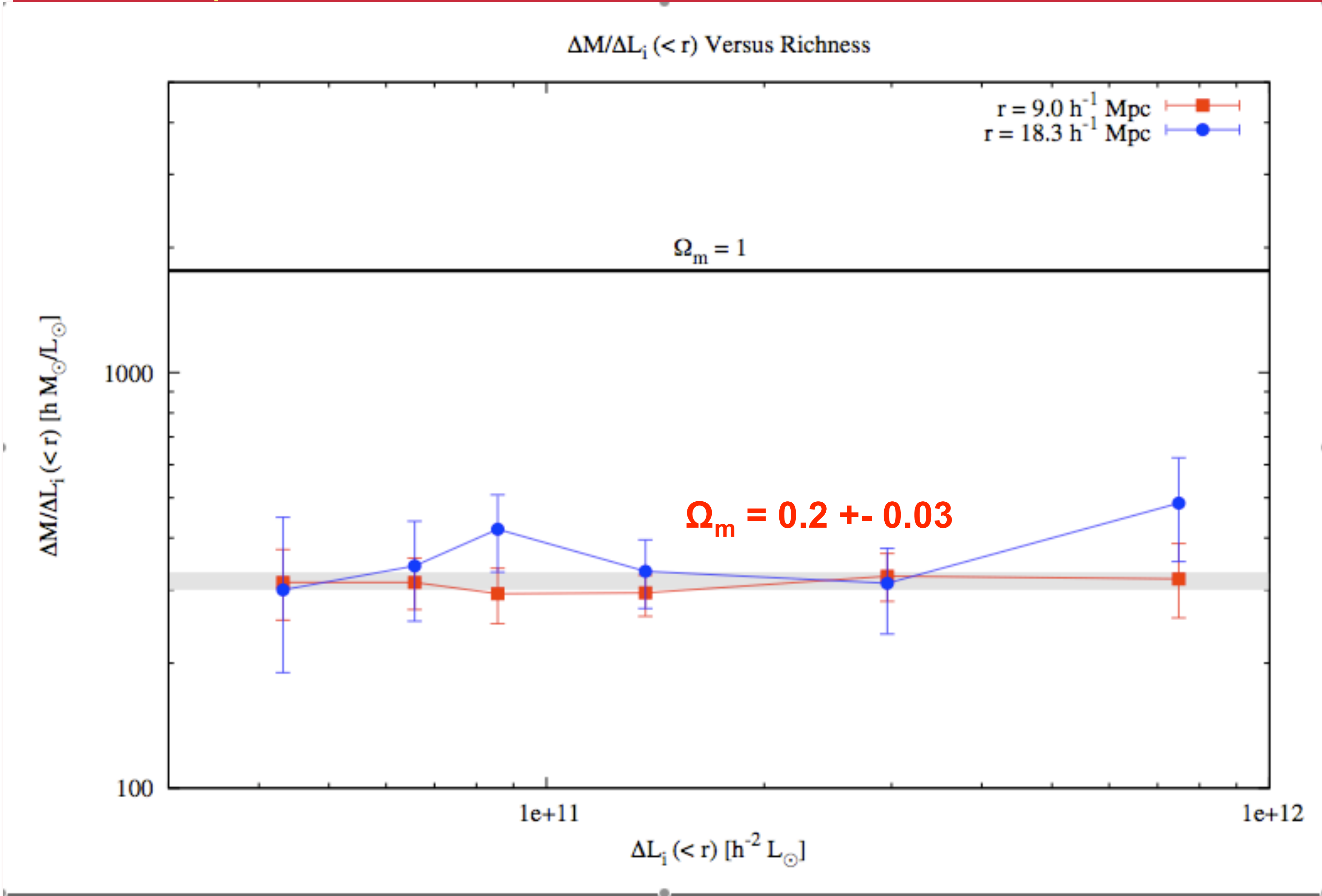


FIG. 5.— $\Delta M/\Delta L$ with the mass and light of the BCG subtracted. Different plot symbols represent different cluster richness bins, created by averaging points at the same r/r_{200} from the data of Sheldon et al. 2008.

M/L_i(≤R) vs. Mass (Bahcall and Kulier 2010)



Tracing Mass and Light
Conclusions (I)

- Mass follows Light [i.e., M/L(<R) flat] on all scales from few-100 Kpc to 30 Mpc (no BCG)

- M/L(<R) similar in all environments – from tiny groups to richest clusters (except BCG). BCG dominant in Groups.

- Small increase of M/L with M (from groups to richest clusters): mostly due to Stellar Population (increasing mix of E vs. Sp galaxies, thus increasing M/L_i due to the older pop with lower L_i). [Other effects such as ICL, gas, mergers, may contribute to this small trend.]

- Most of the Dark Matter located in huge halos around Galaxies; NOT much additional DM on large scales

Conclusions: Cosmology

- M/L_i on large scales (~10 – 30 Mpc):

$$M/L_i = 320 \pm 54 \; (h_{70})$$

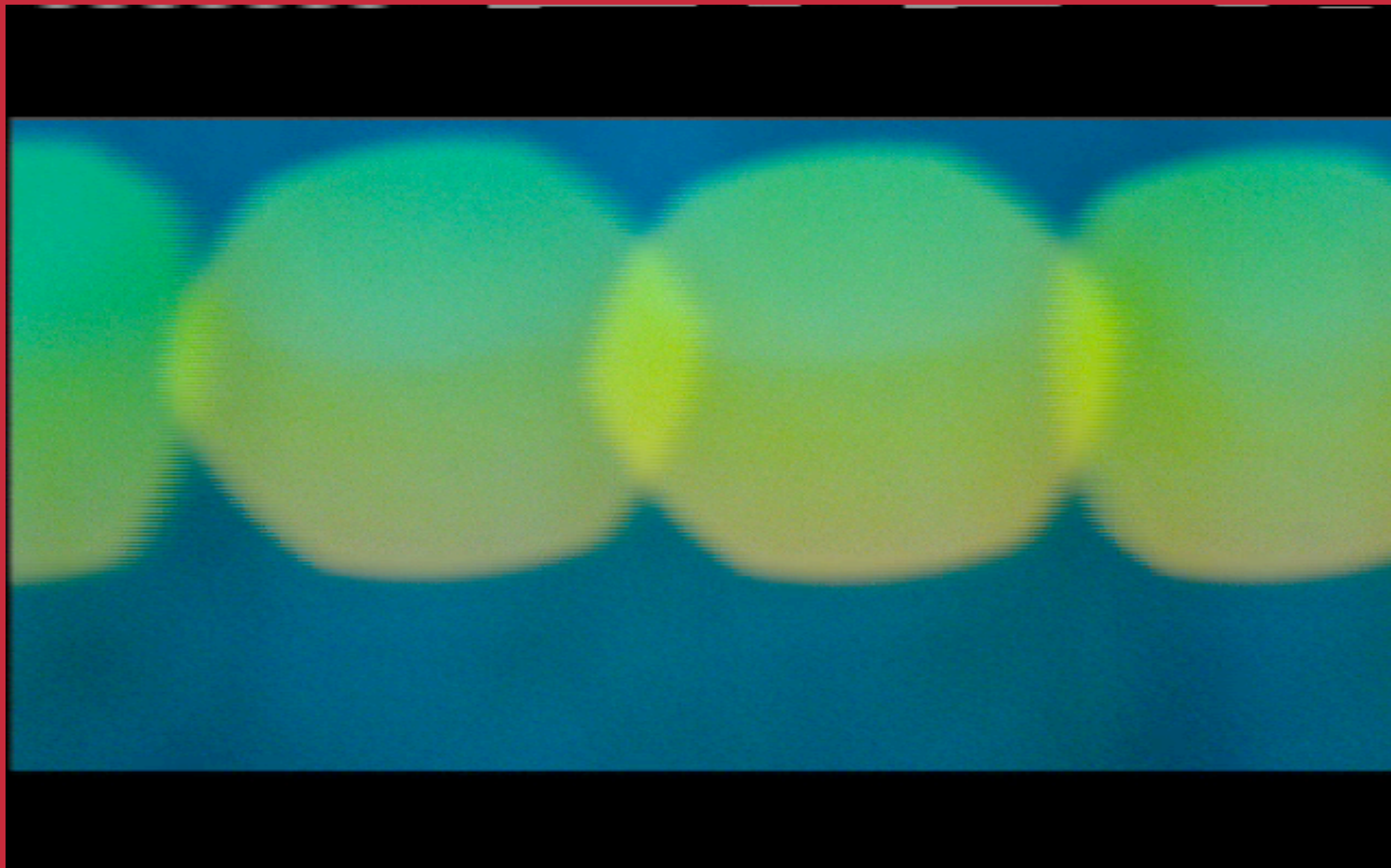
➔ $\Omega_m = 0.2 \pm 0.03 \; [\times \; b^2_{m/l} \sim 1]$

Weighing the Universe

- *M/L Function* — $_m$ = 0.2 +- 0.05
- *Baryon Fraction* — 0.25 +- 0.03
- *Cluster Abundance* — 0.2 +- 0.05
  and Evolution — [$_8$ = 0.9 +- 0.1]
- *Supernovae Ia + Flat* — 0.25 +- 0.05
- *CMB + LSS + h + Flat* — 0.27 +- 0.03

➔ $_m \approx$ 0.25 +- 0.03

- ***4% Baryons***
- ***Mass ~ Light*** ***(R >~ 1Mpc)***



"Amazing" John Bahcall

I find it amazing, almost incredible, that the century and a half long chain of reasoning about how the Sun shines and how neutrinos get to us from the Sun could be tested on the basis of an experiment in the bottom of a mine.

I am amazed that so many people, speaking so many different languages and living at such different times, have collaborated in so many different ways to make it possible that flashes of light in the bottom of a mine could be used to determine the temperature in the interior of the Sun and the properties of exotic subatomic particles.

I am amazed that flashes of light in a mine, the temperature of the Sun, and the properties of neutrinos are linked in such a beautiful way.