Mass and Light in the Outskirts of Galaxy Clusters

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OUTLINE

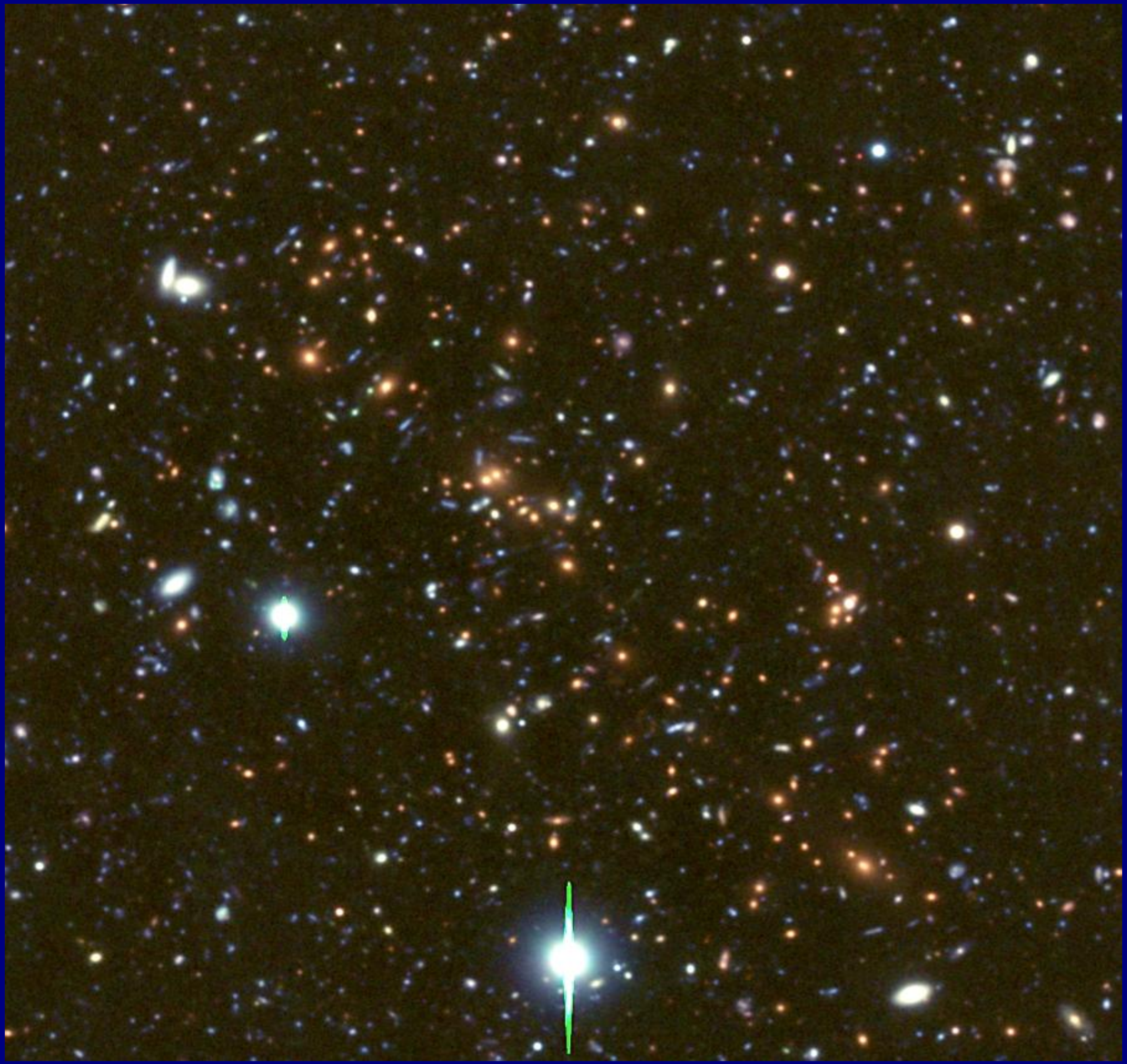
- **Cosmic structure: Do galaxies trace mass?**
- **The bias ancestor: The mass-to-light ratio.**
- **The problem: Measuring the mass.**
- **Outskirts of galaxy clusters: The caustic technique.**
- **Results, links and outlook.**

COSMIC STRUCTURES:
Observations

e.g. PISCES
(*Panoramic Images and Spectroscopy of Cluster Evolution with Subaru*, Kodama et al. 2005)

RX J0152.7-1357 (z=0.83)

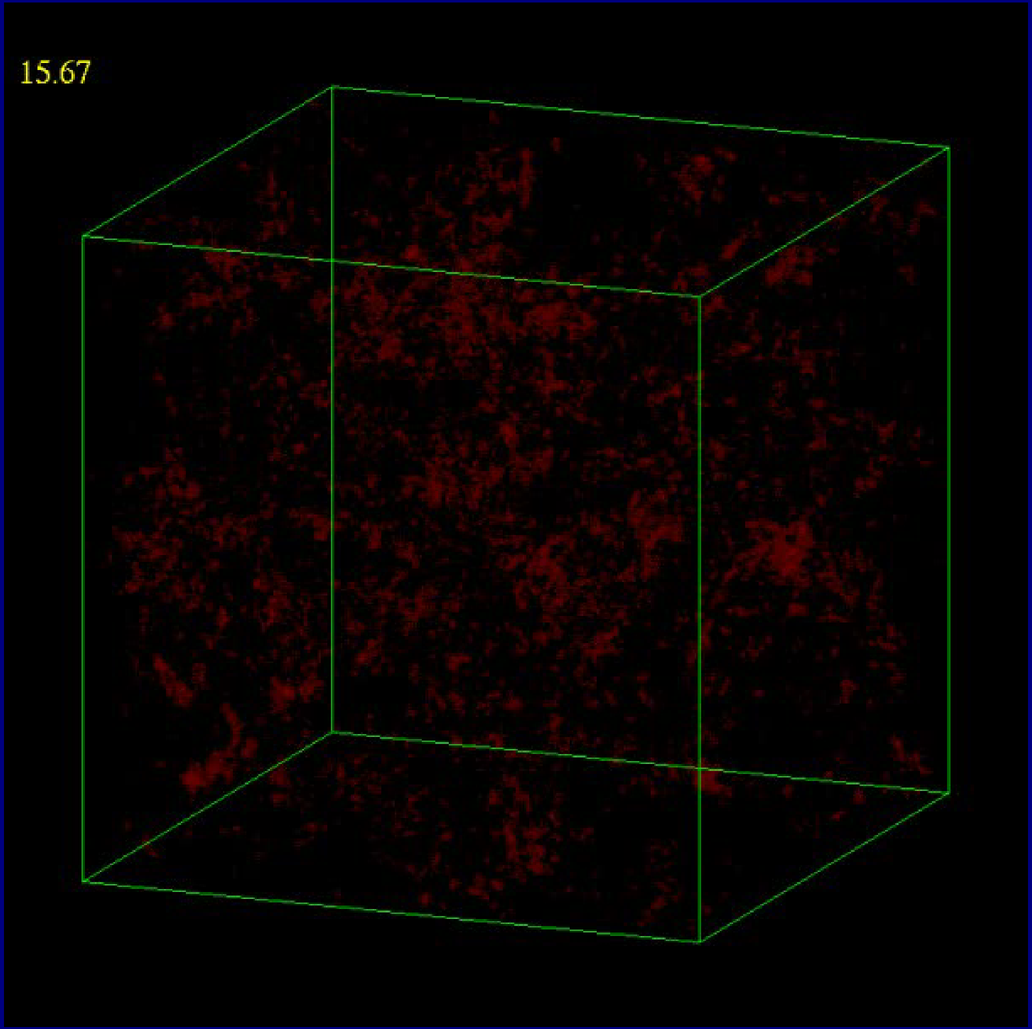
V+R+i'



3 arcmin

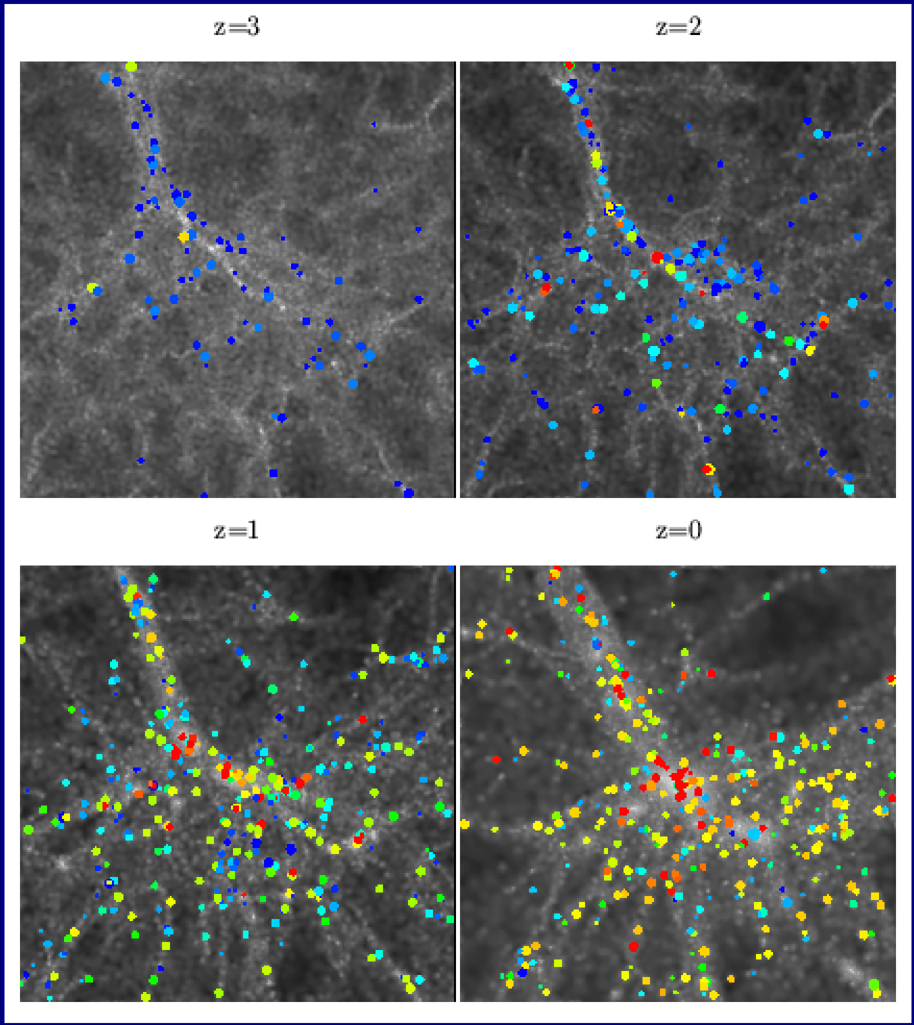
COSMIC STRUCTURES: models (1)

DM



Courtesy of Ben Moore et al.

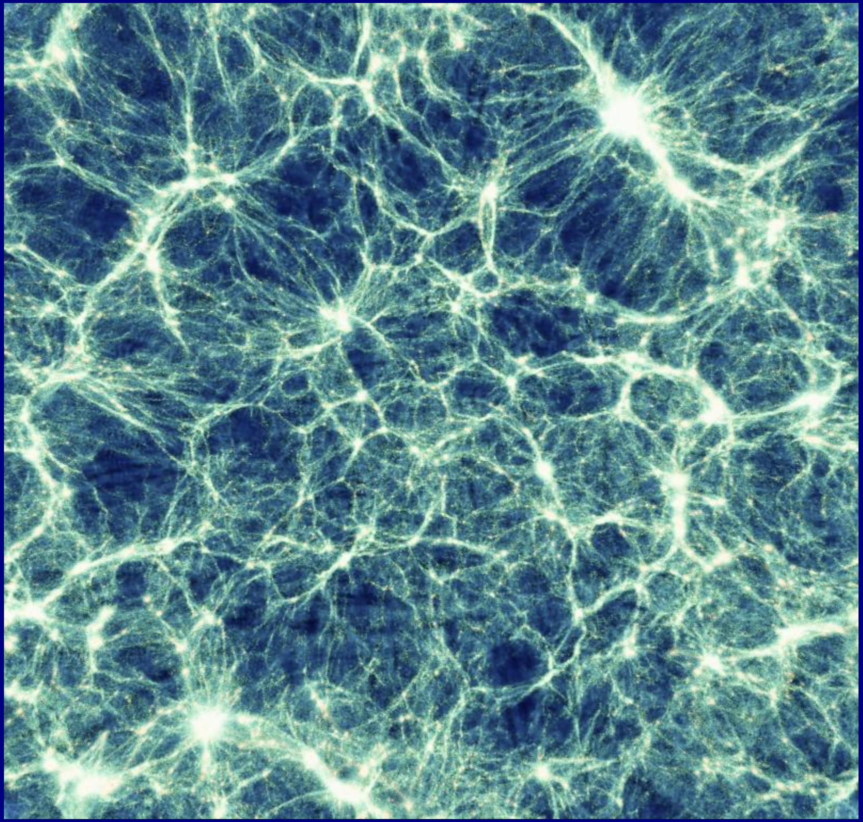
DM+Galaxies (semi-analytic modelling)



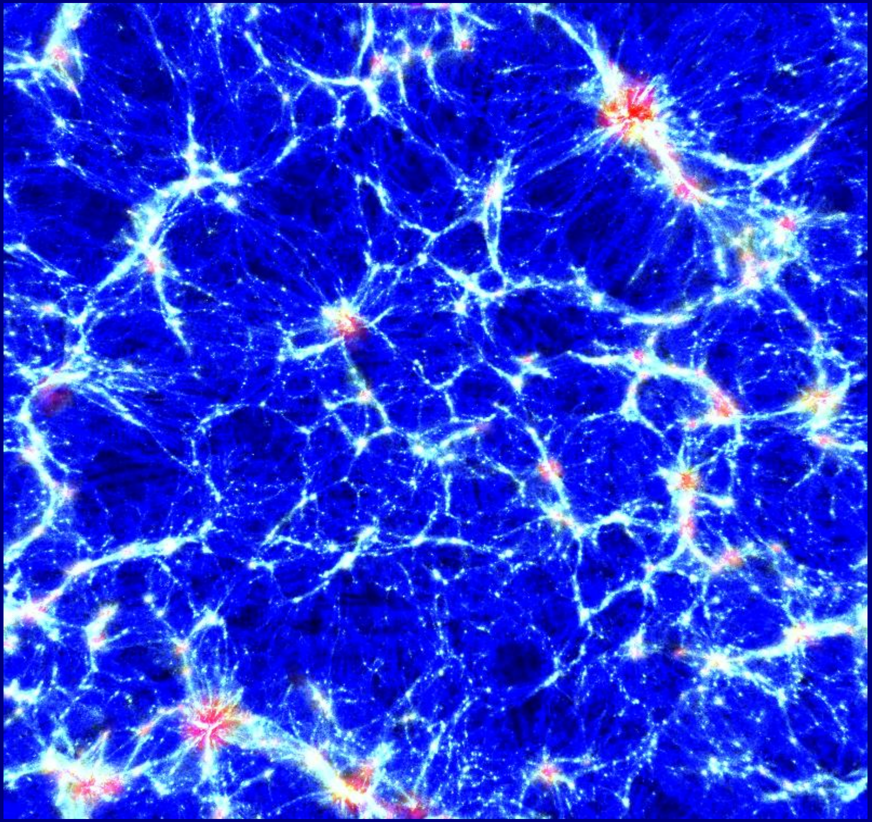
Kauffmann et al. 1999 (GIF sims.)

COSMIC STRUCTURES:
models (2)

N-body/hydro-simulations



gas density

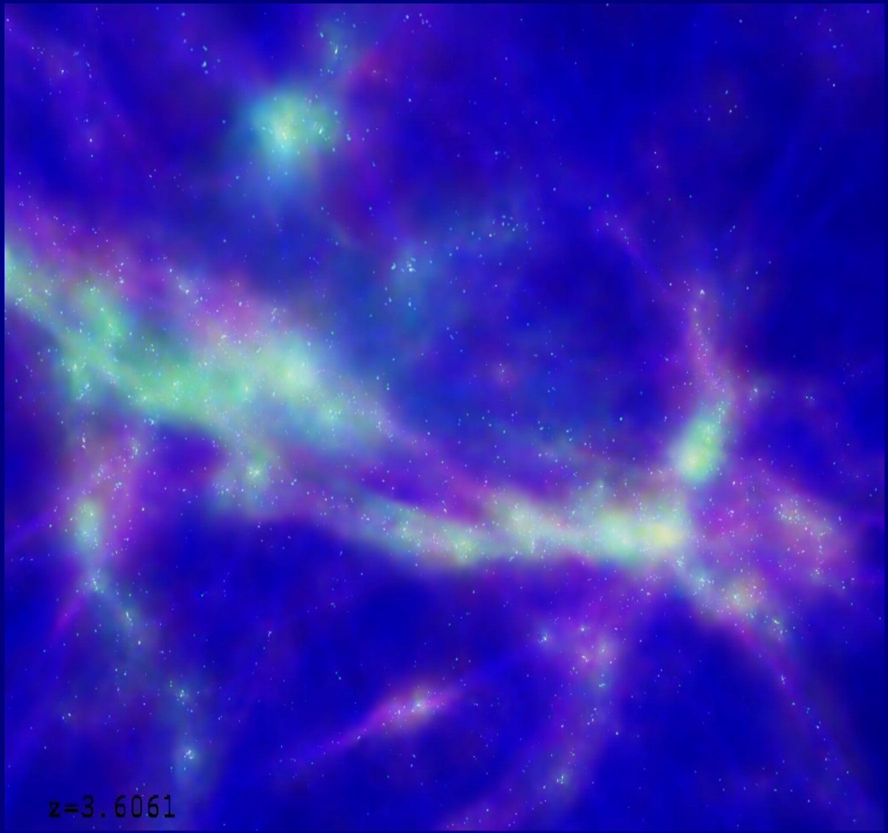


gas temperature

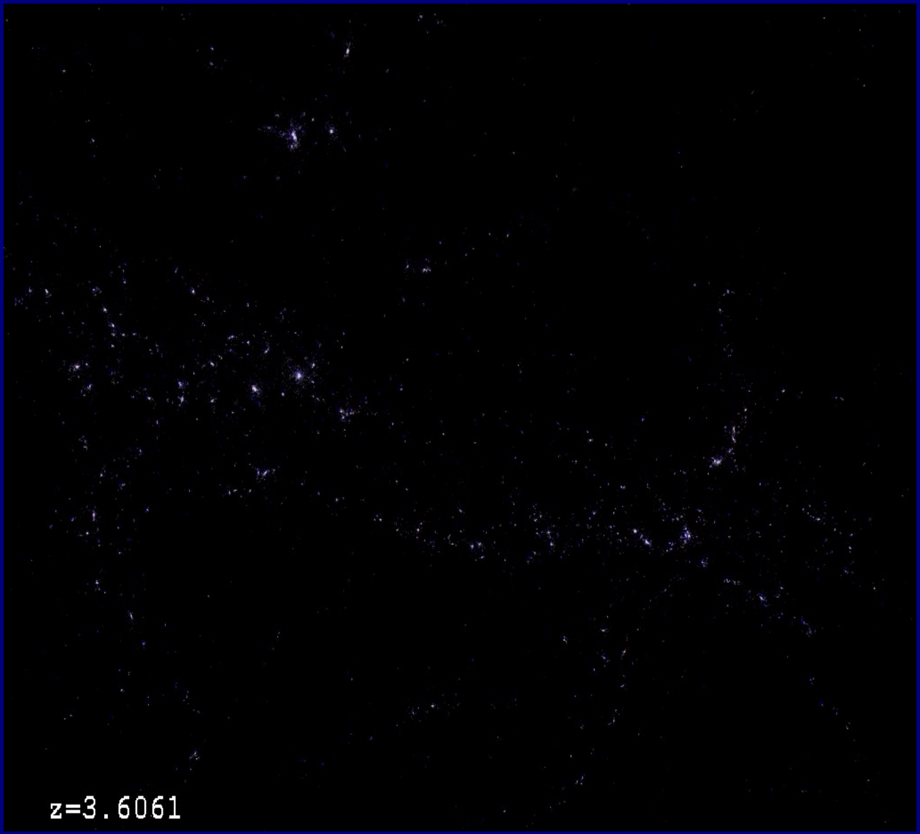
Borgani et al. 2004

COSMIC STRUCTURES: models (3)

Forming a cluster



gas density



stars

Courtesy of Klaus Dolag

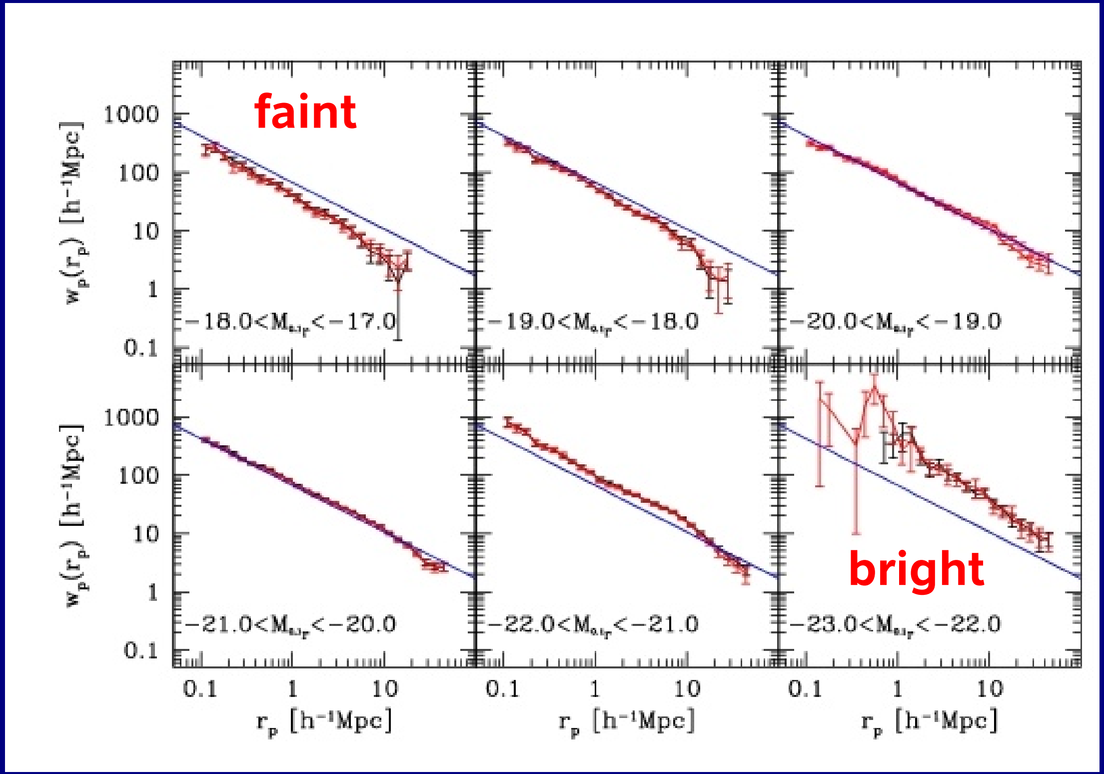
ARE GALAXIES FAITHFUL TRACERS OF MASS?

EVIDENCE OF BIAS:
correlation functions of galaxies

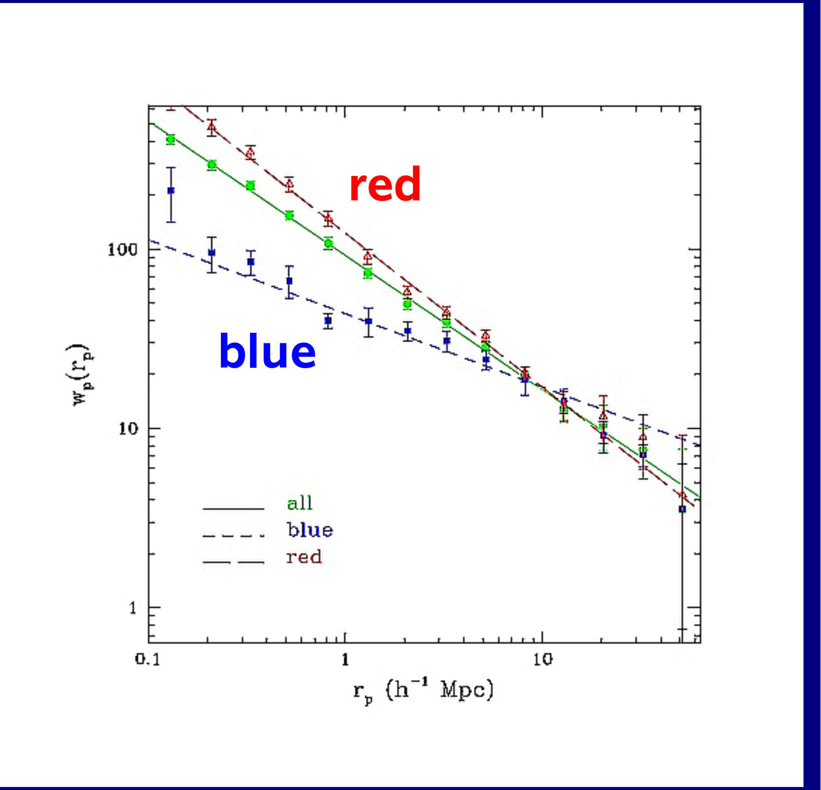
$$\xi_1(r) = b^2(r)\xi_2(r)$$

Luminosity

Color



Li et al. 2006 (SDSS)



Zehavi et al. 2005 (SDSS)

BIAS: MEASURE
linear scales (1)

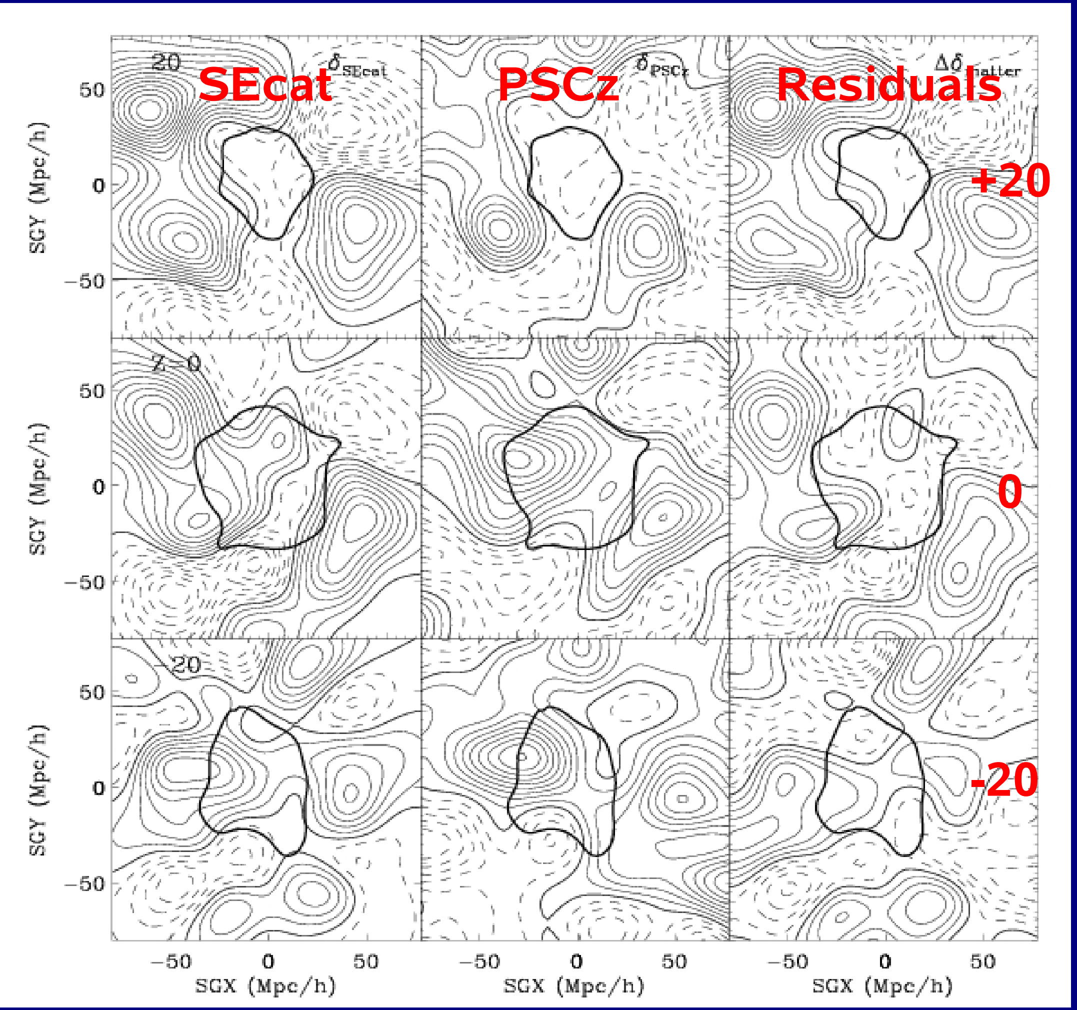
velocity field — density field

$$\nabla \cdot \mathbf{v} = -\Omega_0^{0.6}\delta_{\rm m}$$
$$= -(\Omega_0^{0.6}/b)\delta_{\rm gal}$$

$$\beta = \Omega_0^{0.6}/b$$

$$\beta = 0.57^{+0.11}_{-0.13} \quad \text{d-d}$$
$$\beta = 0.51 \pm 0.06 \quad \text{v-v}$$

Mass density in the SG plane

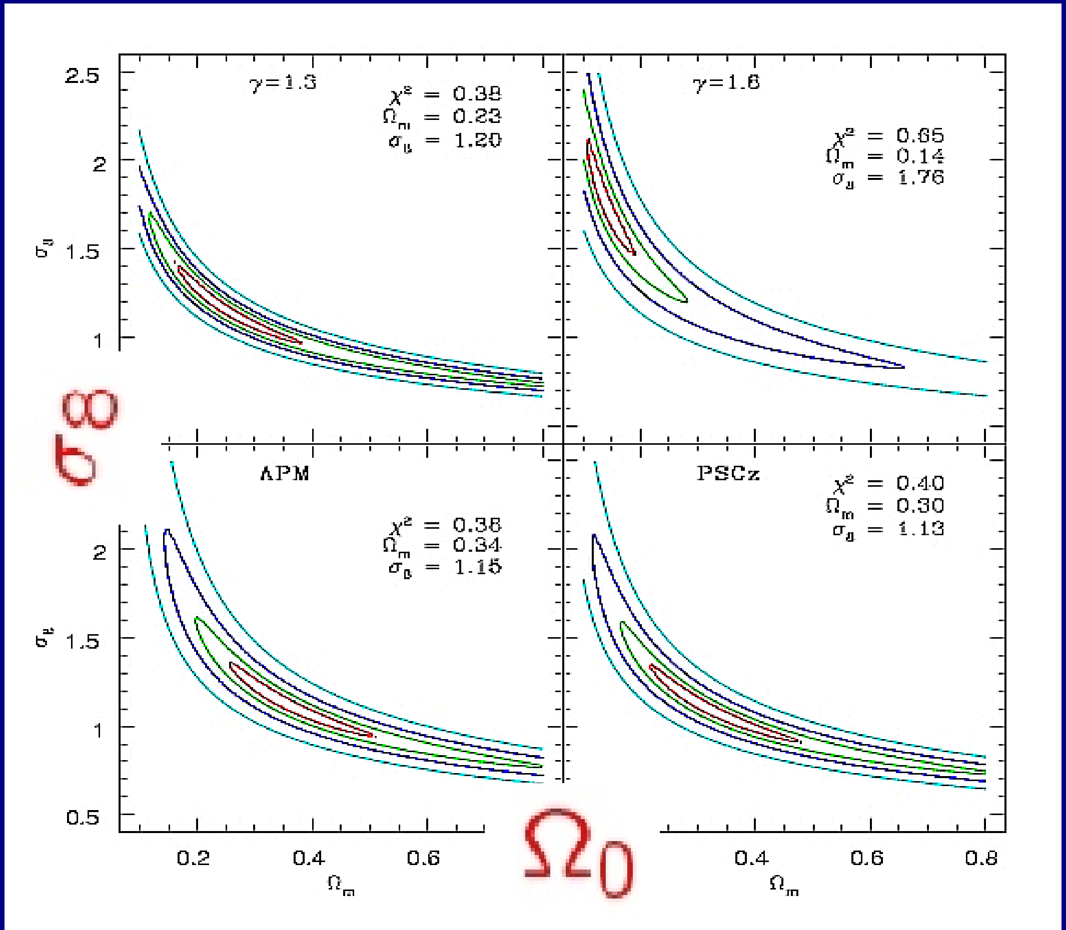


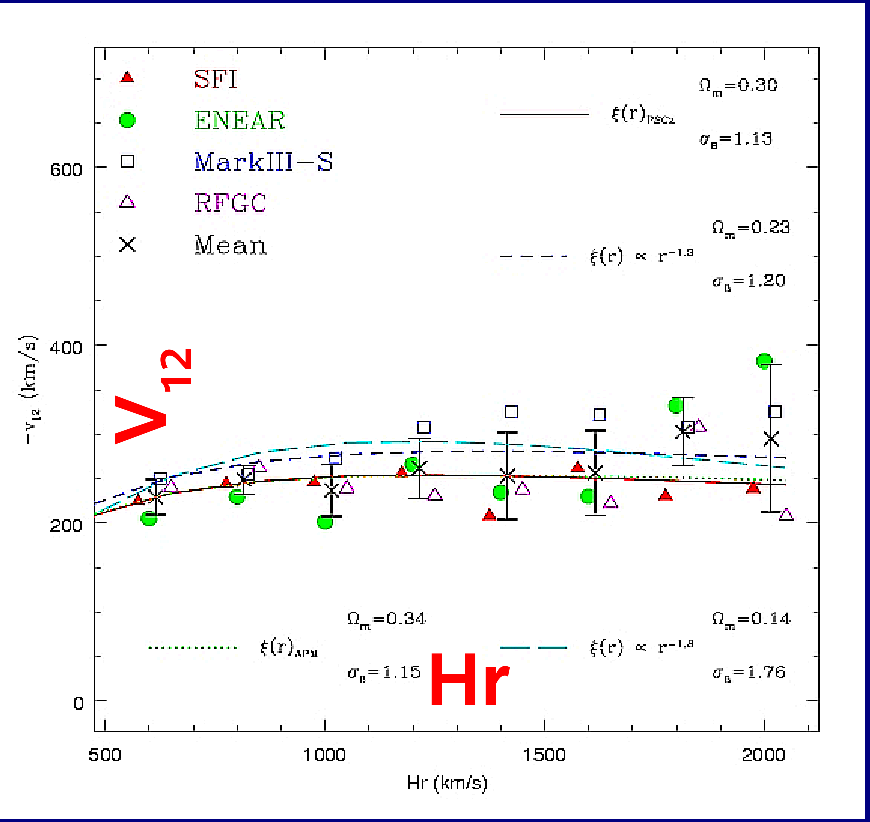
Unbiased Minimal Variance (UMV) estimator on SEcat-PSCz (Zaroubi et al. 2002)

BIAS: MEASURE
linear scales (2)

Pairwise mean relative velocity (Juszkiewicz et al. 1999)

$$v_{12}(r) = -\frac{2}{3} H r \Omega_0^{0.6} \bar{\xi}(r)[1 + \alpha \bar{\xi}(r)]$$



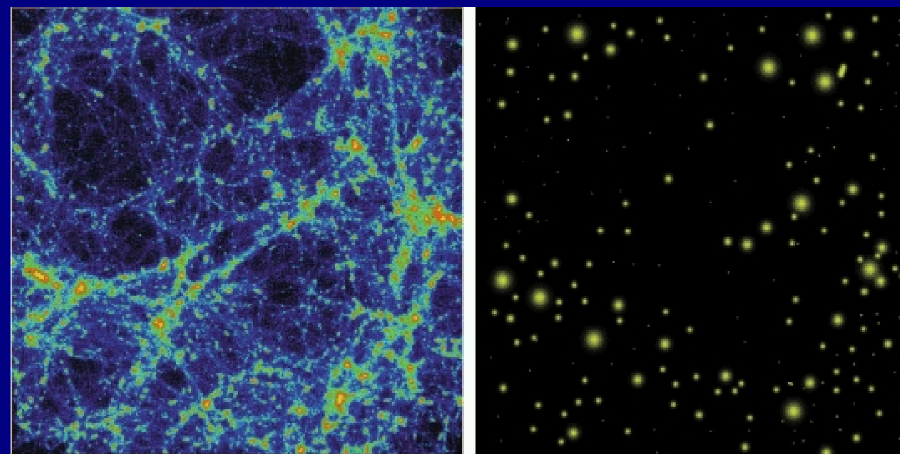


Feldmann et al. 2003

BIAS: MODELLING

The halo model

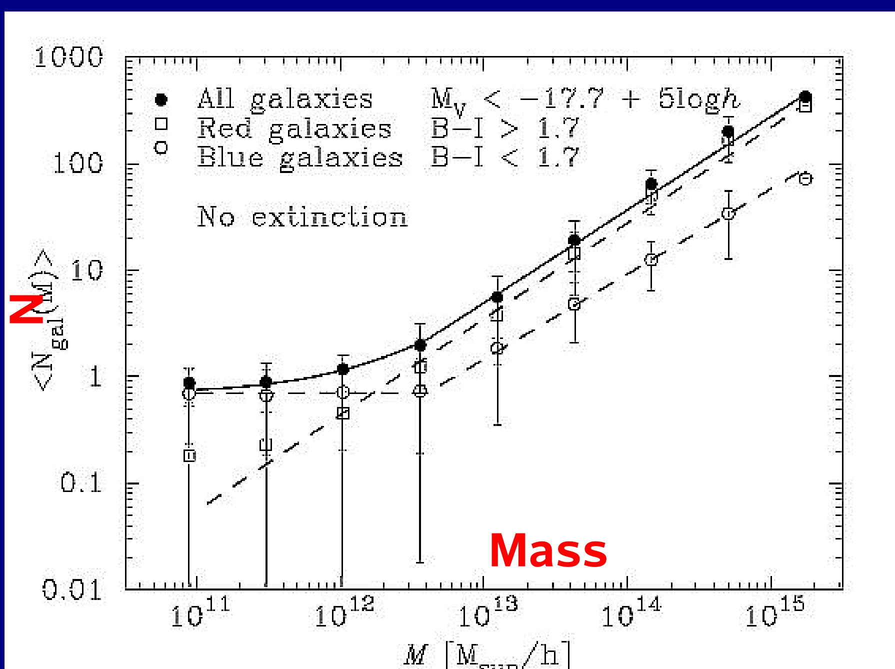
DM density field



Halo distribution

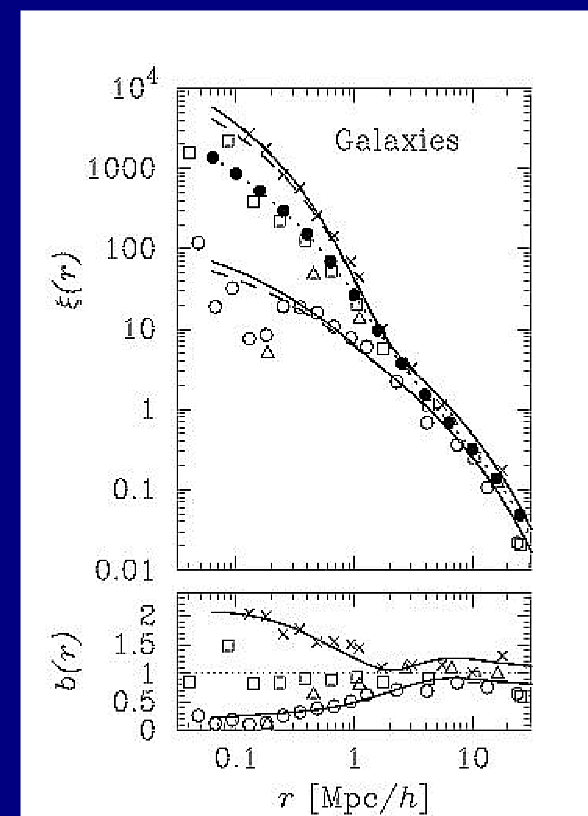
(Cooray & Sheth 2002)

Halo Occupation Number



Sheth & Diaferio 2001

Correlation function



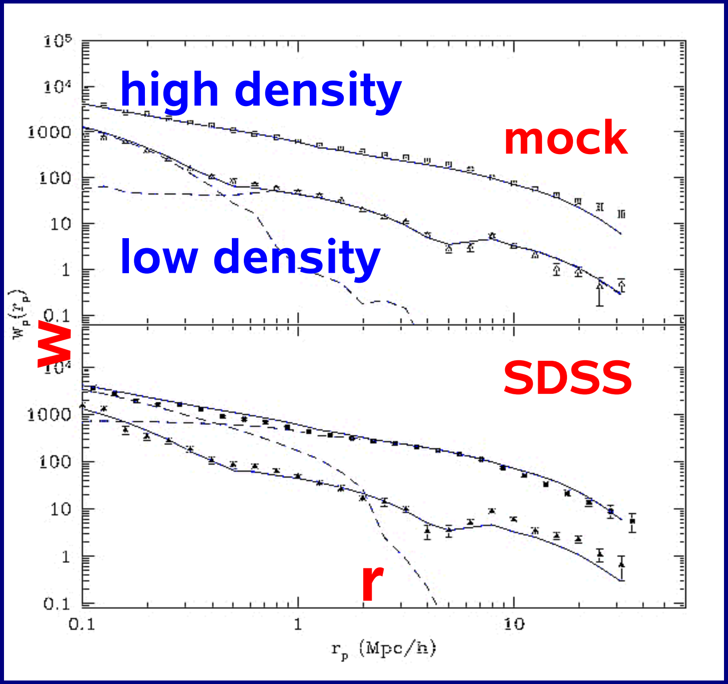
Sheth et al. 2001

BIAS: MODELLING
The halo model new generation:
Towards the galaxy-environment connection

"marked" statistics
(galaxies mirror the
halo-environment connection)
(Sheth 2005)

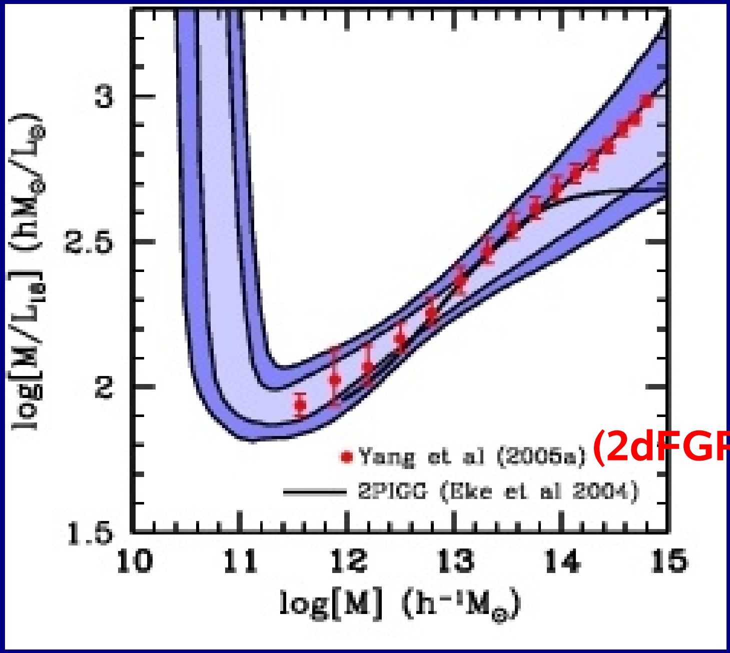
conditional luminosity function
(constrained to yield the LF and the CF)
(van den Bosch et al. 2004)

projected correlation function



Abbas & Sheth 2006

mass-to-light ratio



van den Bosch et al. 2006

RELEVANCE: M/L + CMB

Conditional Luminosity Function

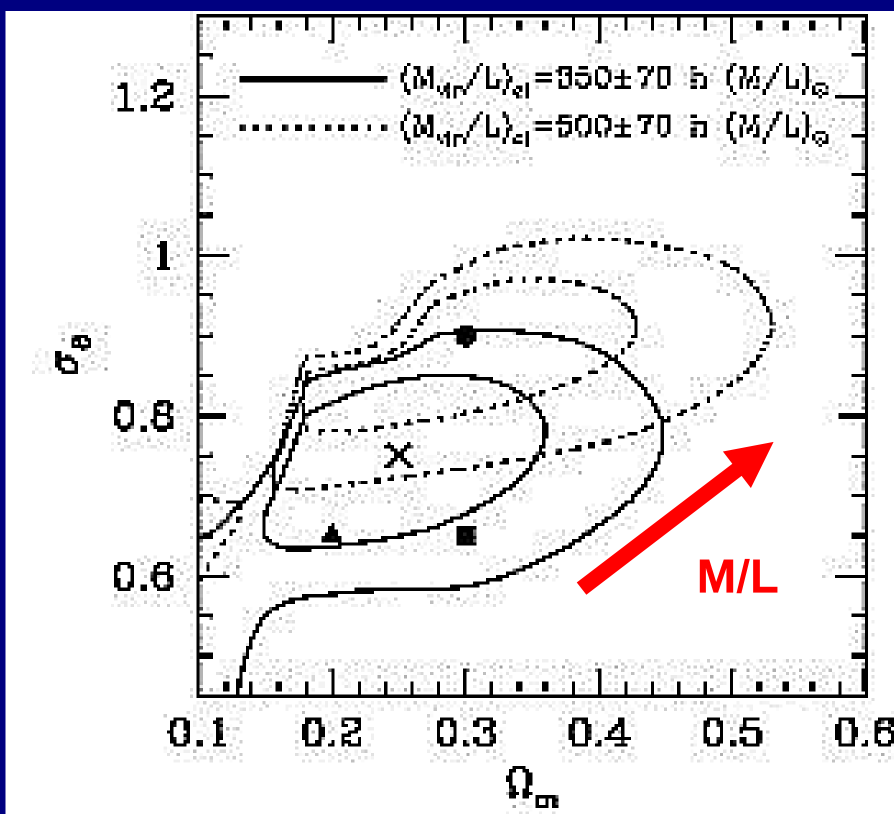
$$\Phi(L) = \int_0^{\infty} \Phi(L|M)\, n(M)\, dM$$

Galaxy two-point correlation function

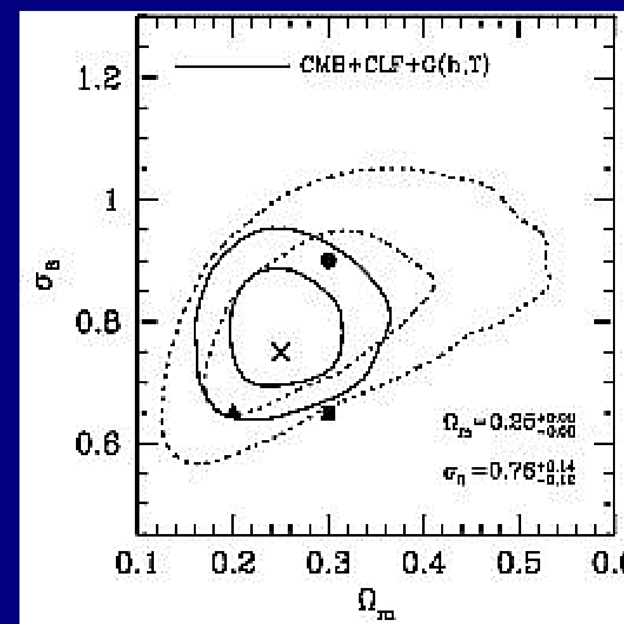
$$\xi_{gg}(r, L) = \tilde{b}^2(L)\, \xi_{dm}(r)$$

Constrained to match observations

M/L alone



M/L+CMB



van den Bosch et al. 2003 with 2dFGRS

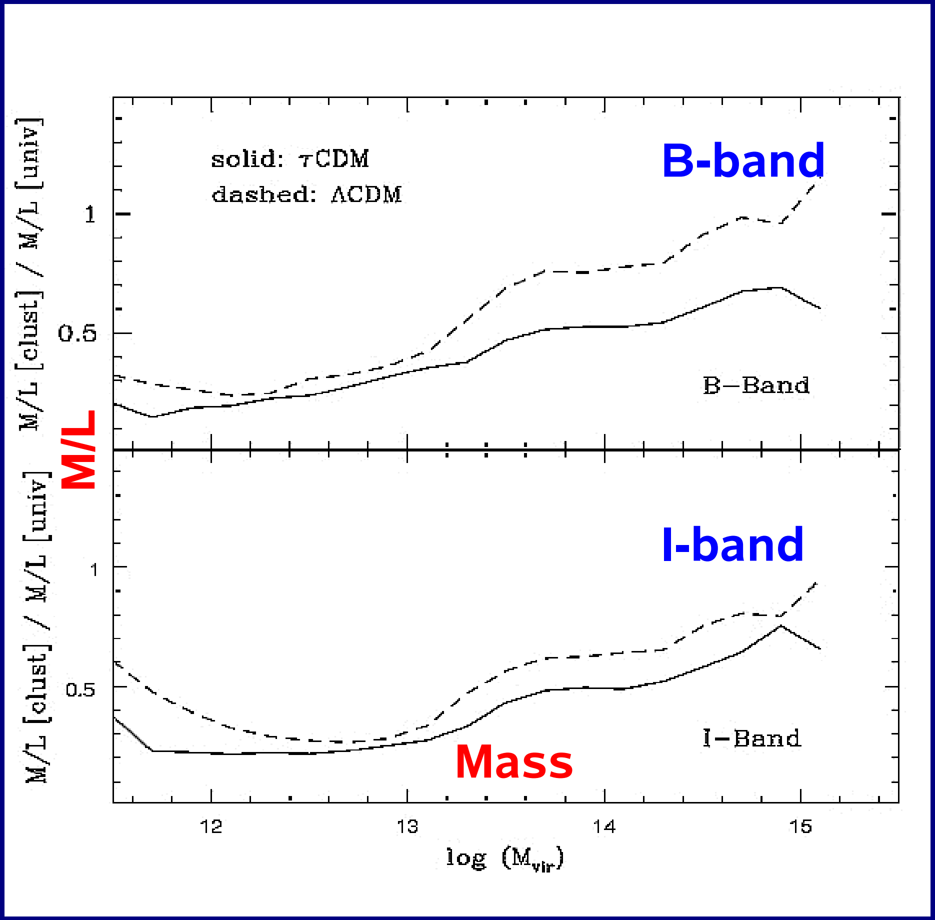
(Agrees with Tinker et al. 2005 with SDSS)

THE BIAS ANCESTOR:
THE MASS-TO-LIGHT RATIO

$$\Omega_0 = \left\langle \frac{M}{L_B} \right\rangle \frac{j_B}{\rho_{crit}}$$

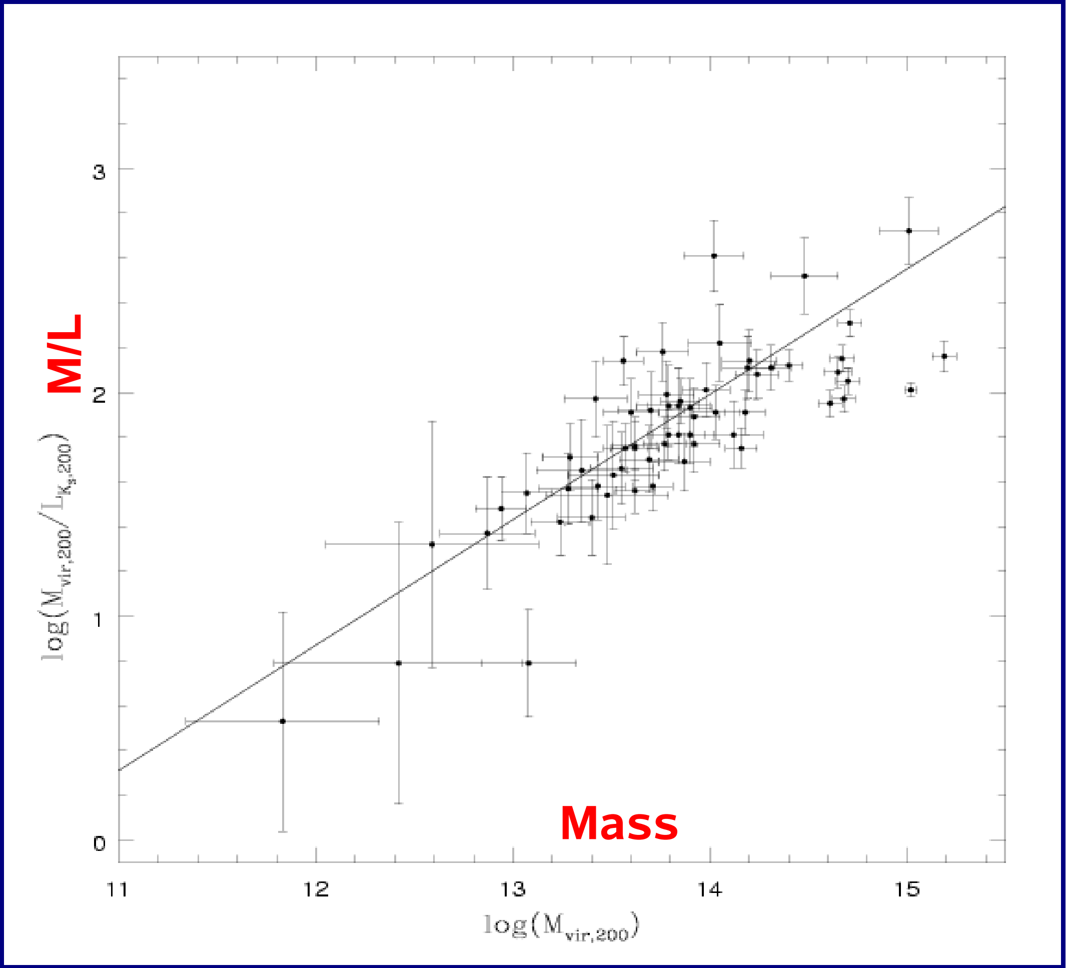
M/L increases with scale

Simulations



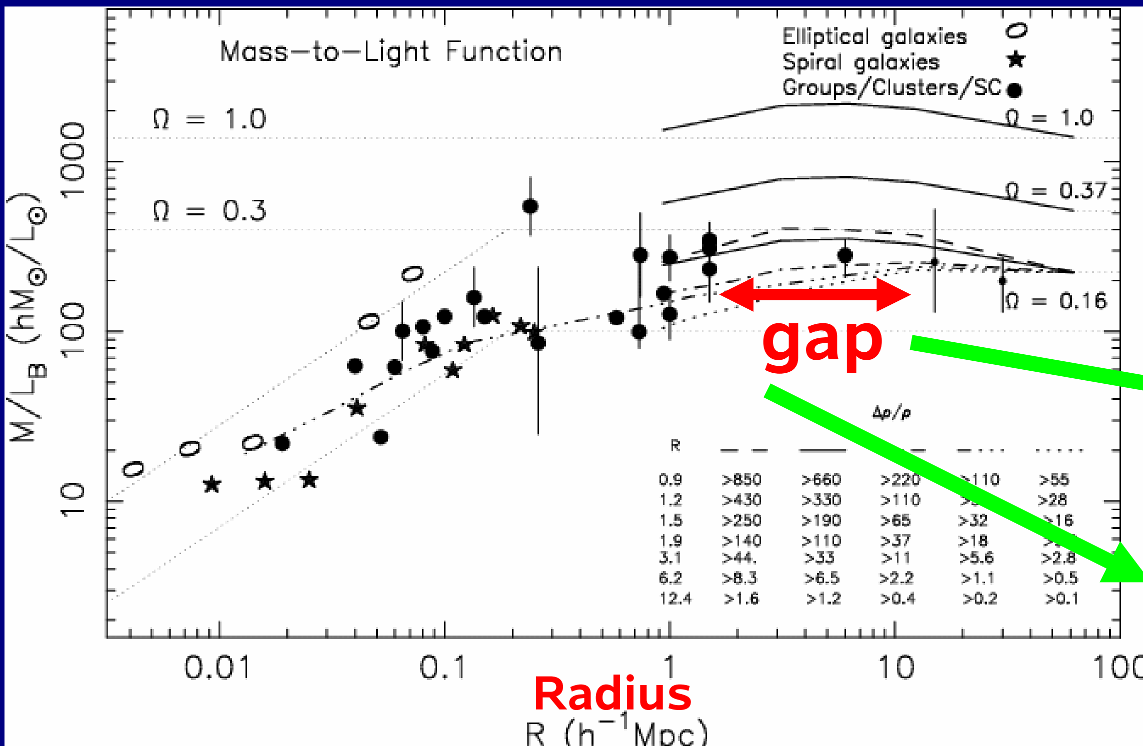
Kauffmann et al. 1999 (GIF sims.)

Observations

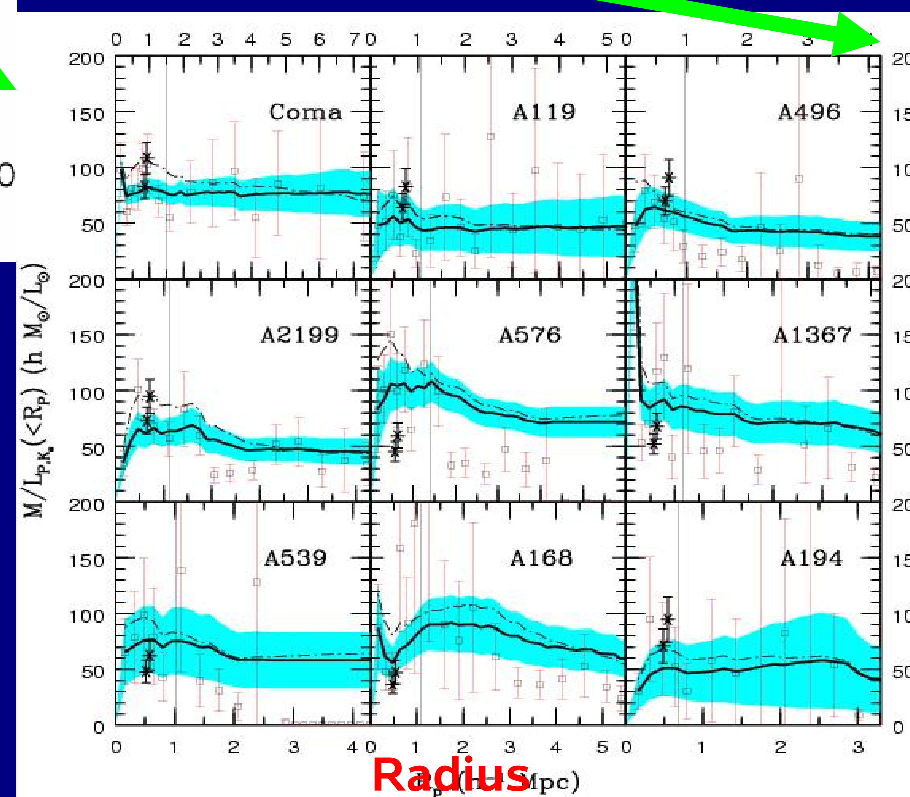


Ramella et al. 2004 (2MASS groups)

M/L: MEASURES



Bahcall et al. 2000



Rines et al. 2004

MEASURING MASS AND LIGHT

MASS:

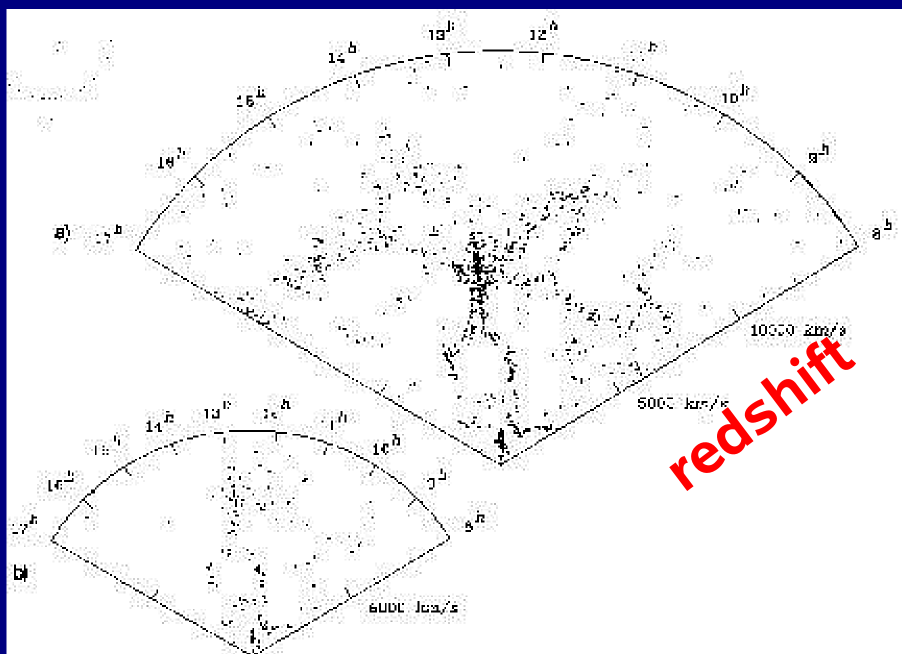
- **Non-linear scales: virial equilibrium**
- **Mildly non-linear scales: weak lensing & caustics in redshift space**
- **Linear scales: peculiar velocity fields**

LIGHT:

- **accurate photometry**
- **completeness**
- **diffuse light (i.e. intergalactic stars)**

INFALL REGIONS OF CLUSTERS: Prologue (1)

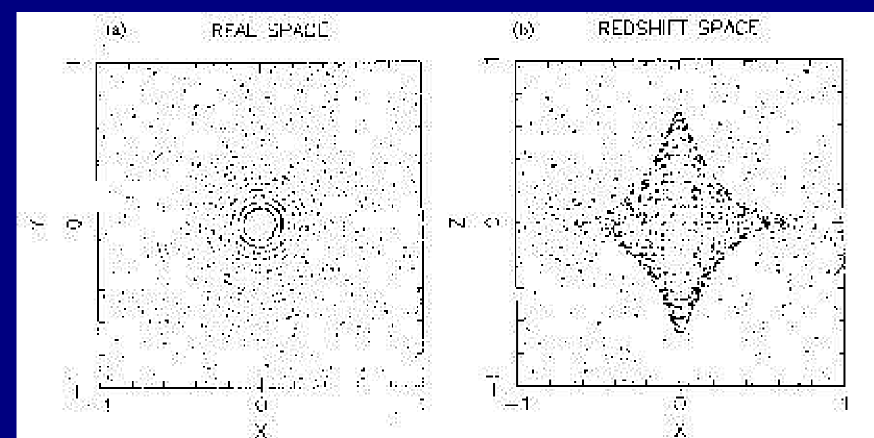
CfA slice



de Lapparent et al. 1986

redshift space distortion and the spherical infall model

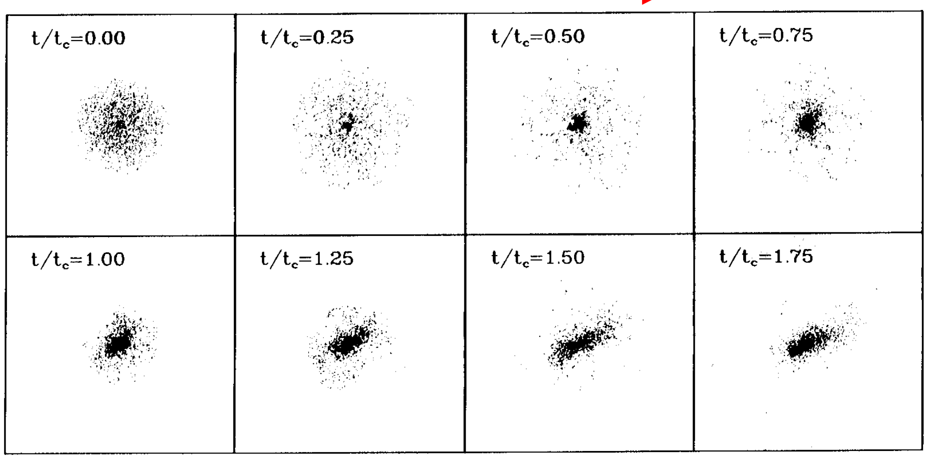
Real space **Redshift space**



Kaiser 1987

INFALL REGIONS OF CLUSTERS:
Prologue (2)

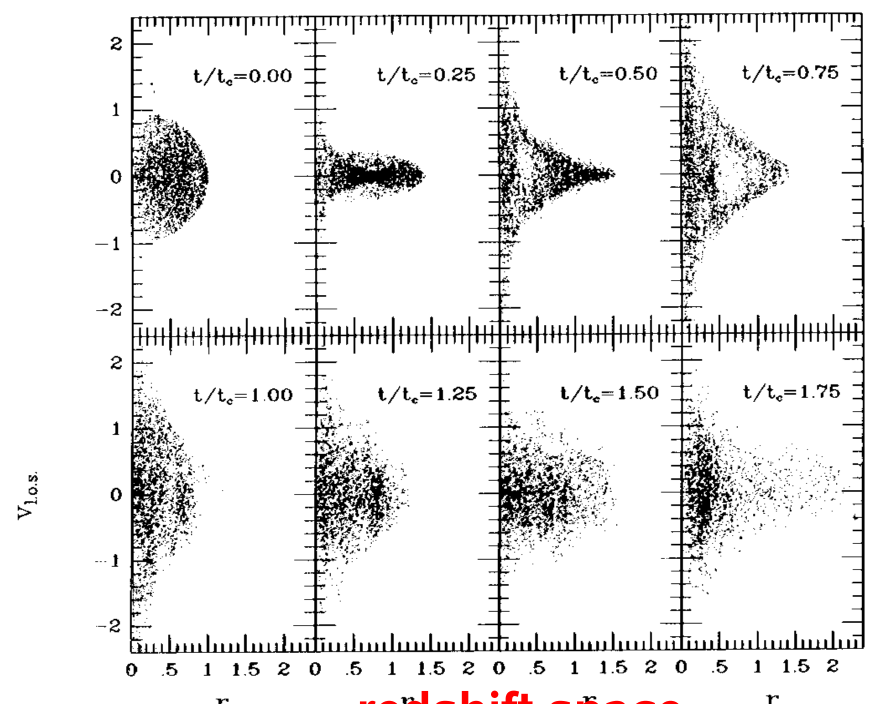
time



real space

Spherical infall model:
A primitive toy simulation

time



redshift space

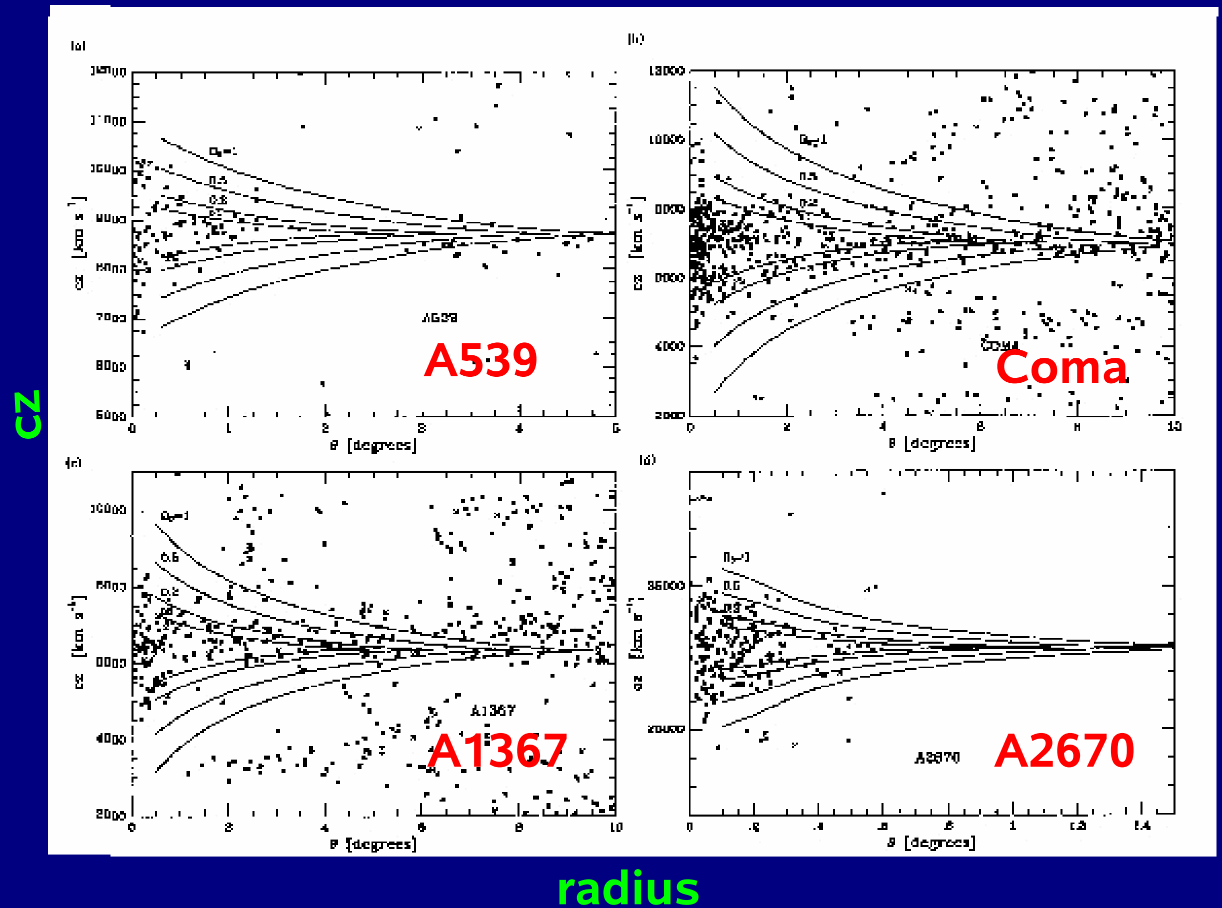
INFALL REGIONS OF CLUSTERS: Prologue (3)

linear scales

$$\frac{v_{\rm pec}(r)}{H_0 r} = -\frac{1}{3}\Omega_0^{0.6}\delta_m(r)$$

mildly non-linear scales

$$\frac{v_{\rm pec}(r)}{H_0 r} = \frac{H_0^s}{H_0} - 1 \simeq -\frac{1}{3}\Omega_0^{0.6} f[\delta_m(r)]$$



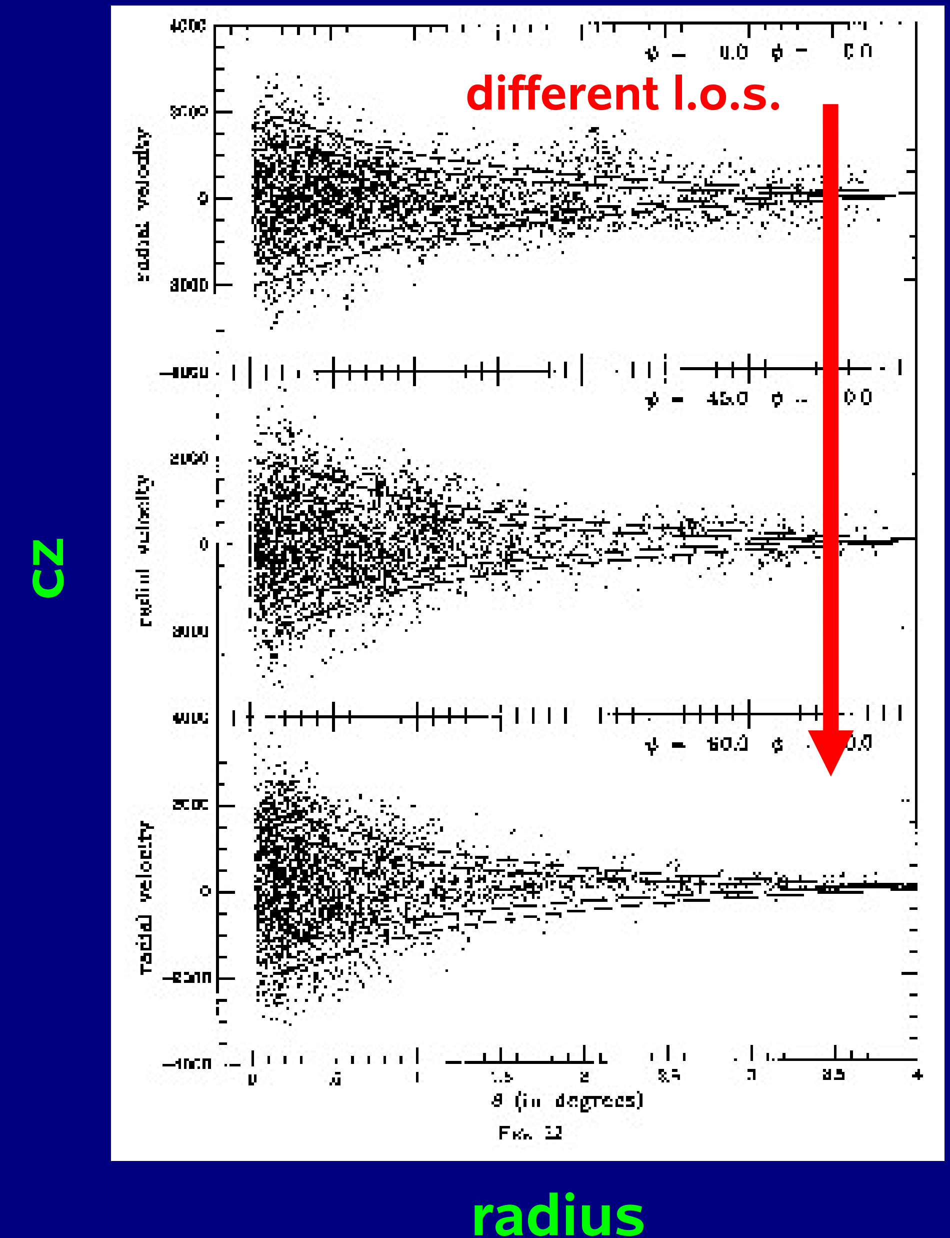
Caustic amplitude

$$cz - \langle cz \rangle \cos\theta \propto \Omega_0^{0.6}\theta^{-\mu[\delta_m(r)]}$$

Measure of Ω_0

Regös & Geller 1989

INFALL REGIONS OF CLUSTERS:
Prologue (4)

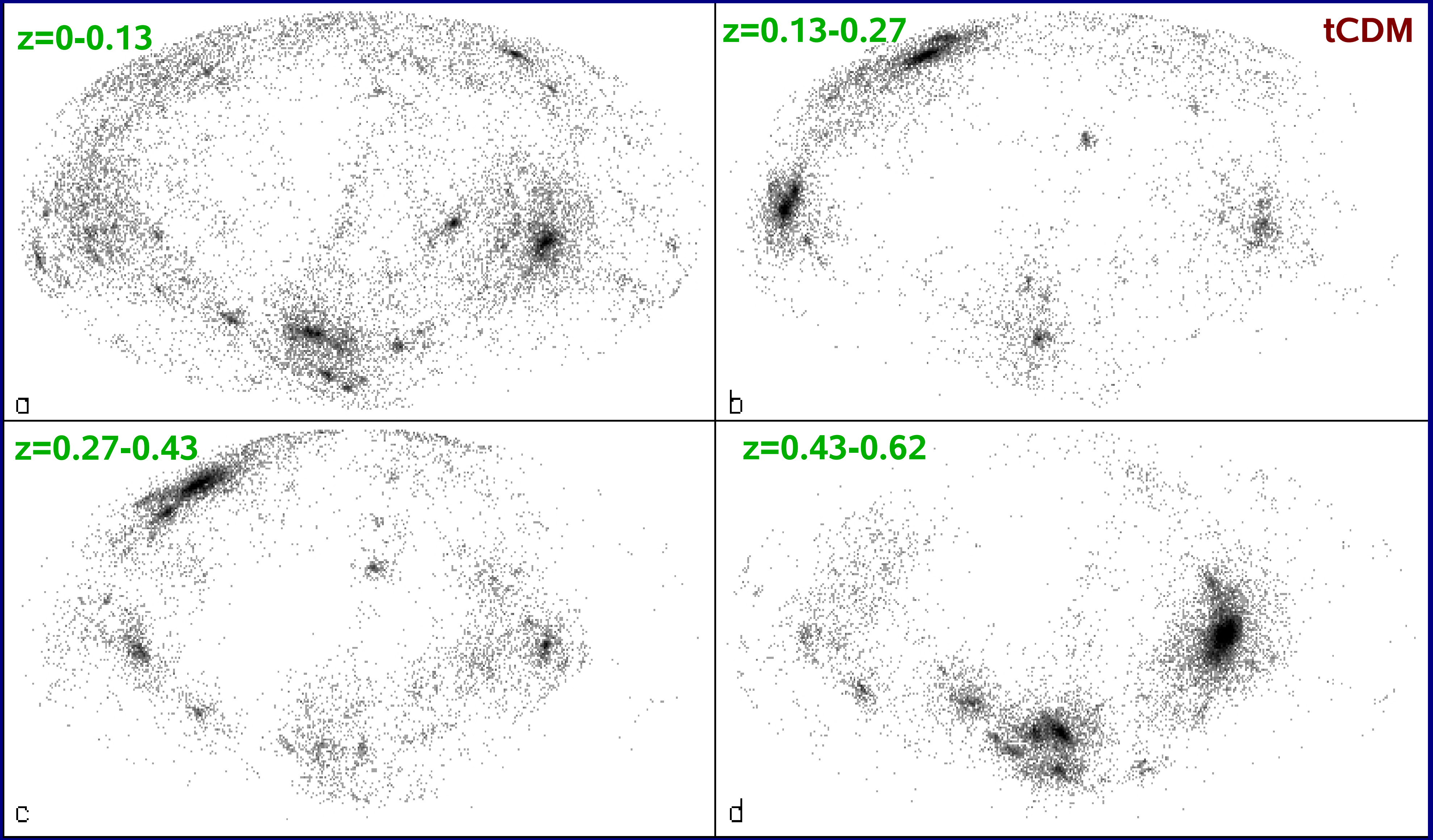


Simulated cluster in a SCDM model

Merging and substructures affect the velocity field
AND
the caustic amplitude

van Haarlem & van de Weygaert 1993

Hierarchical clustering models:
anisotropic and episodic accretion

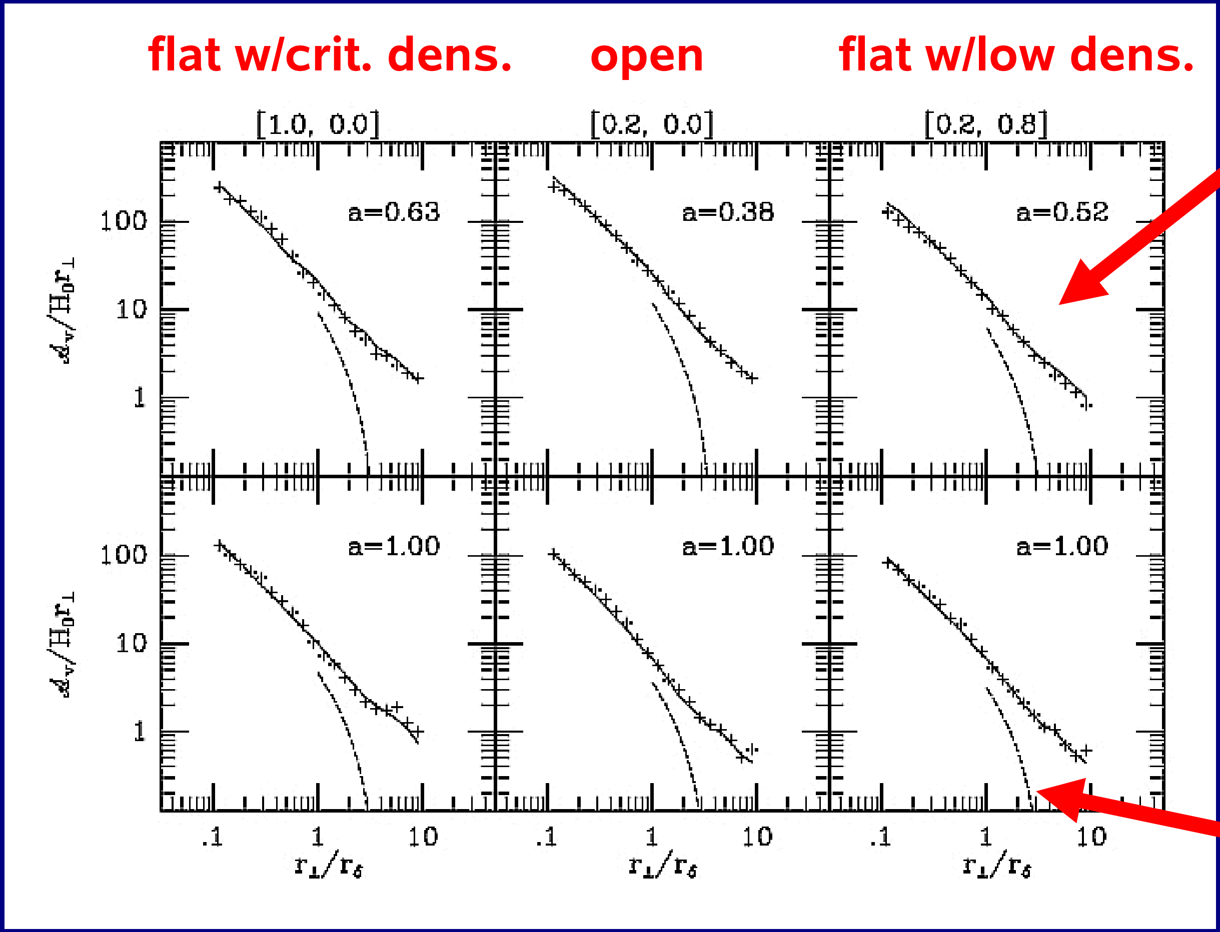


Colberg et al. 1999

INFALL REGIONS OF CLUSTERS:
Prologue (5)

The caustic amplitude <u>IS</u> the escape velocity

cosmology →



$$\mathcal{A}^2(r) = v_{esc}^2(r)\frac{1-\beta(r)}{3-2\beta(r)}$$

clusters out of equilibrium

clusters in equilibrium

spherical infall model

caustic amplitude

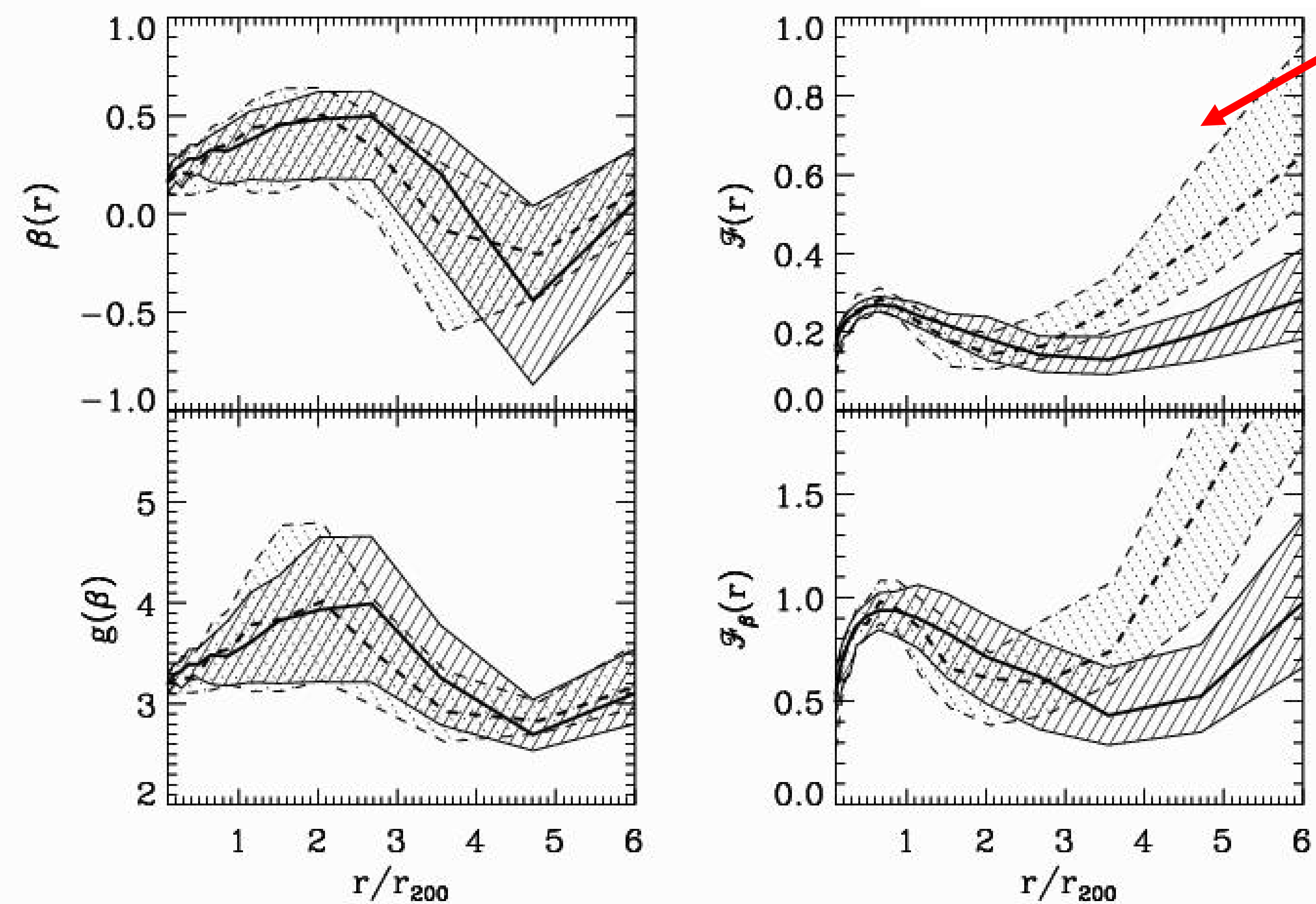
radius

Diaferio & Geller 1997

INFALL REGIONS OF CLUSTERS:
Prologue (6)

$$dm = -2\pi \langle v_{esc}^2 \rangle \frac{\rho(r) r^2}{\phi(r)} dr$$

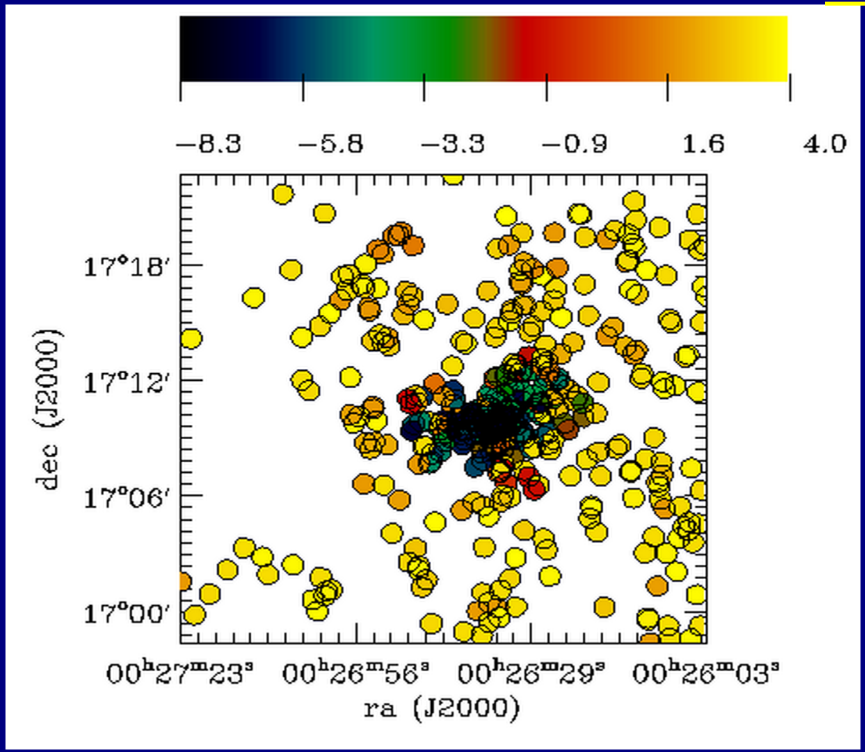
Relevant functions from simulated clusters



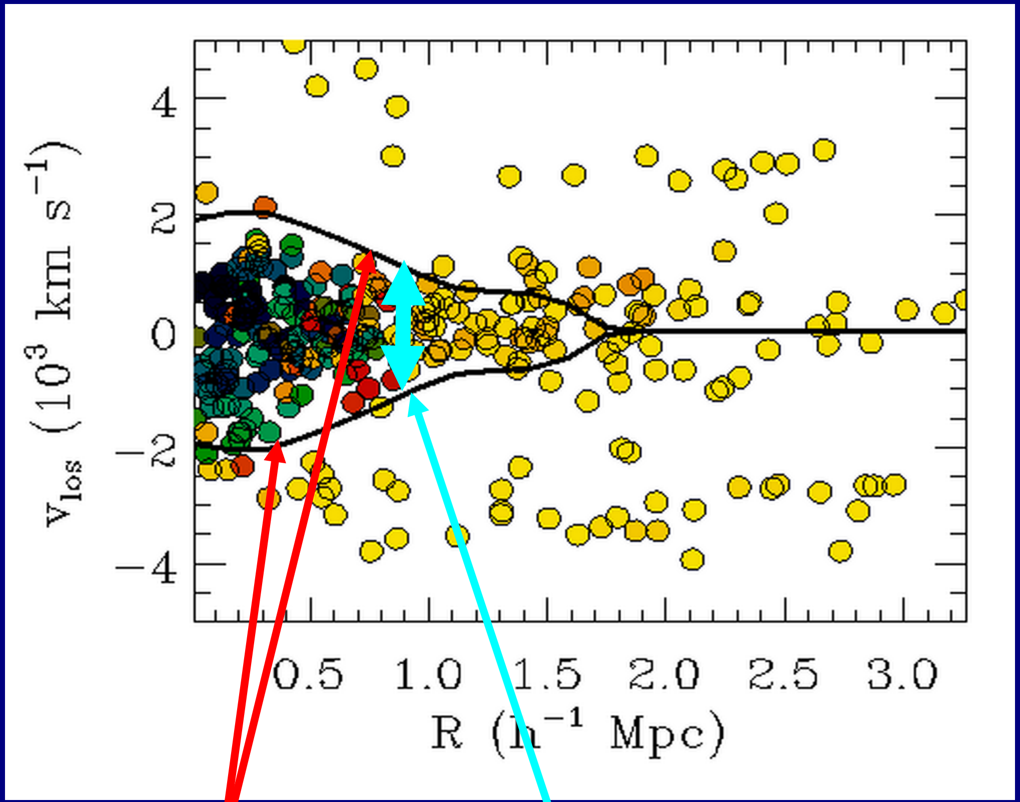
CAUSTIC TECHNIQUE: BASICS

Example: CL0024

Sky



Redshift diagram



Caustics

MASS ESTIMATE:

$$GM(<r) = \frac{1}{2}\int_0^r \mathcal{A}^2(x)dx$$

(Diaferio & Geller 1997)

Caustic amplitude = escape velocity

THE CAUSTIC TECHNIQUE

1. Binary Tree
2. Cut the Tree: Thresholds
3. Galaxy Members: Caustic Location
4. Mass Profile

CAUSTIC TECHNIQUE (1): BINARY TREE

THE HIERARCHICAL METHOD

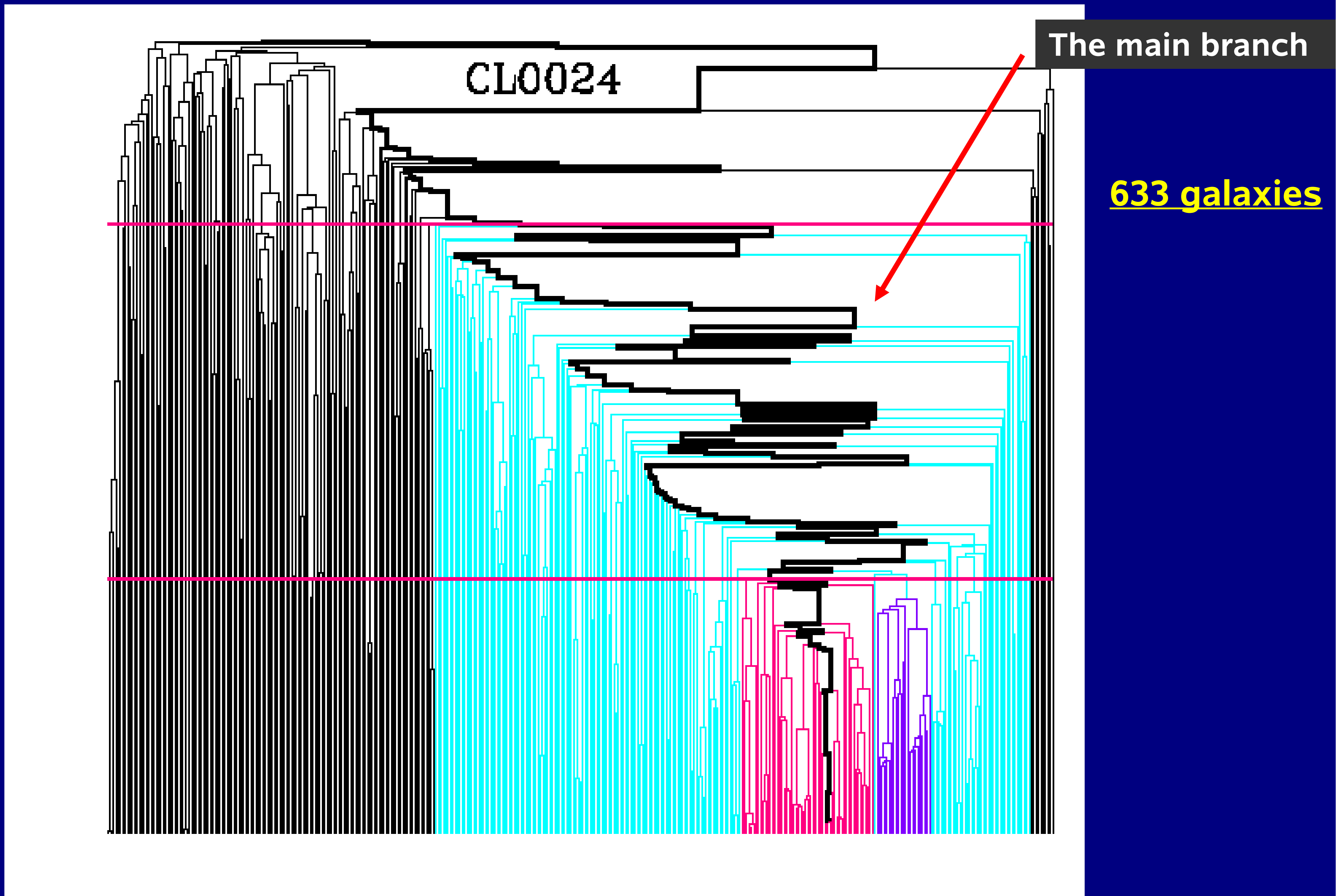
1. Arrange the galaxies in a binary tree based on the pairwise "projected" energy:

$$E_{ij} = -G\frac{m_i m_j}{R_p} + \frac{1}{2}\frac{m_i m_j}{m_i + m_j}\Pi^2$$

Projected separation

Line-of-sight velocity difference

THE BINARY TREE OF THE CL0024 FIELD



633 galaxies

CAUSTIC TECHNIQUE (2): THRESHOLDS

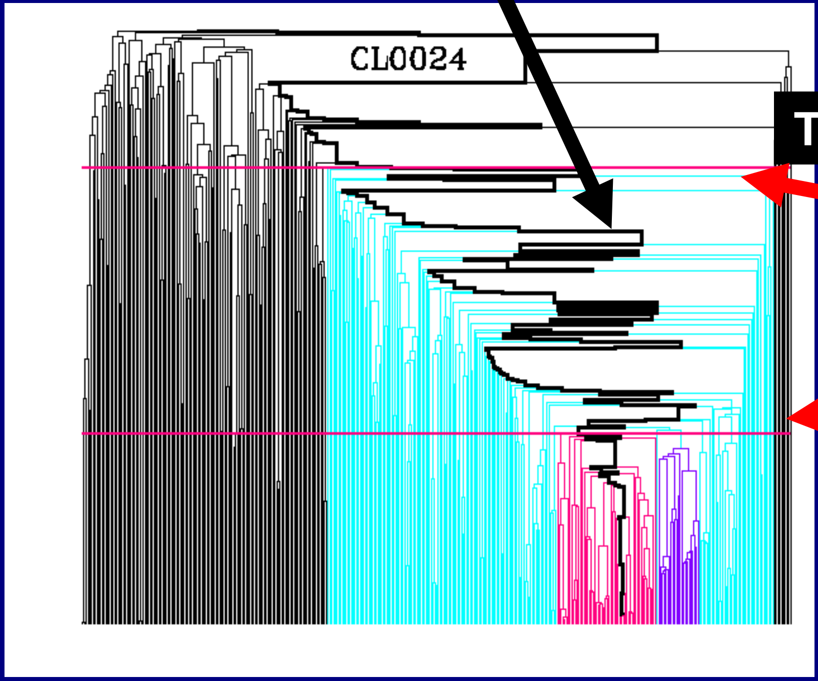
THE HIERARCHICAL METHOD

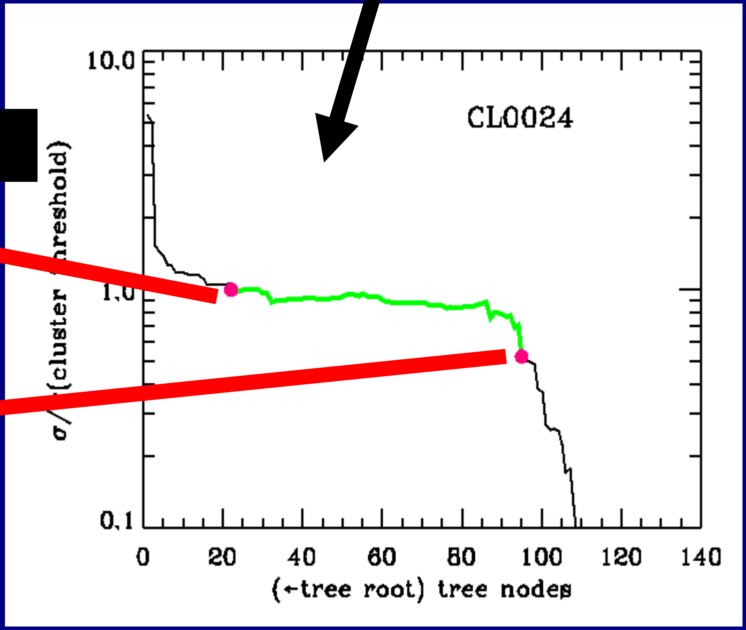
2. Move along the main branch and compute the galaxy velocity dispersion:

Main branch

Velocity dispersion along the main branch

Thresholds





CAUSTIC TECHNIQUE (3): LOCATION

Candidate cluster members determine:

1. the <u>cluster centre</u> → redshift diagram

Galaxy number density in the redshift diagram → $f_q(r, v) = \kappa$ ← <u>CAUSTIC EQUATION</u>

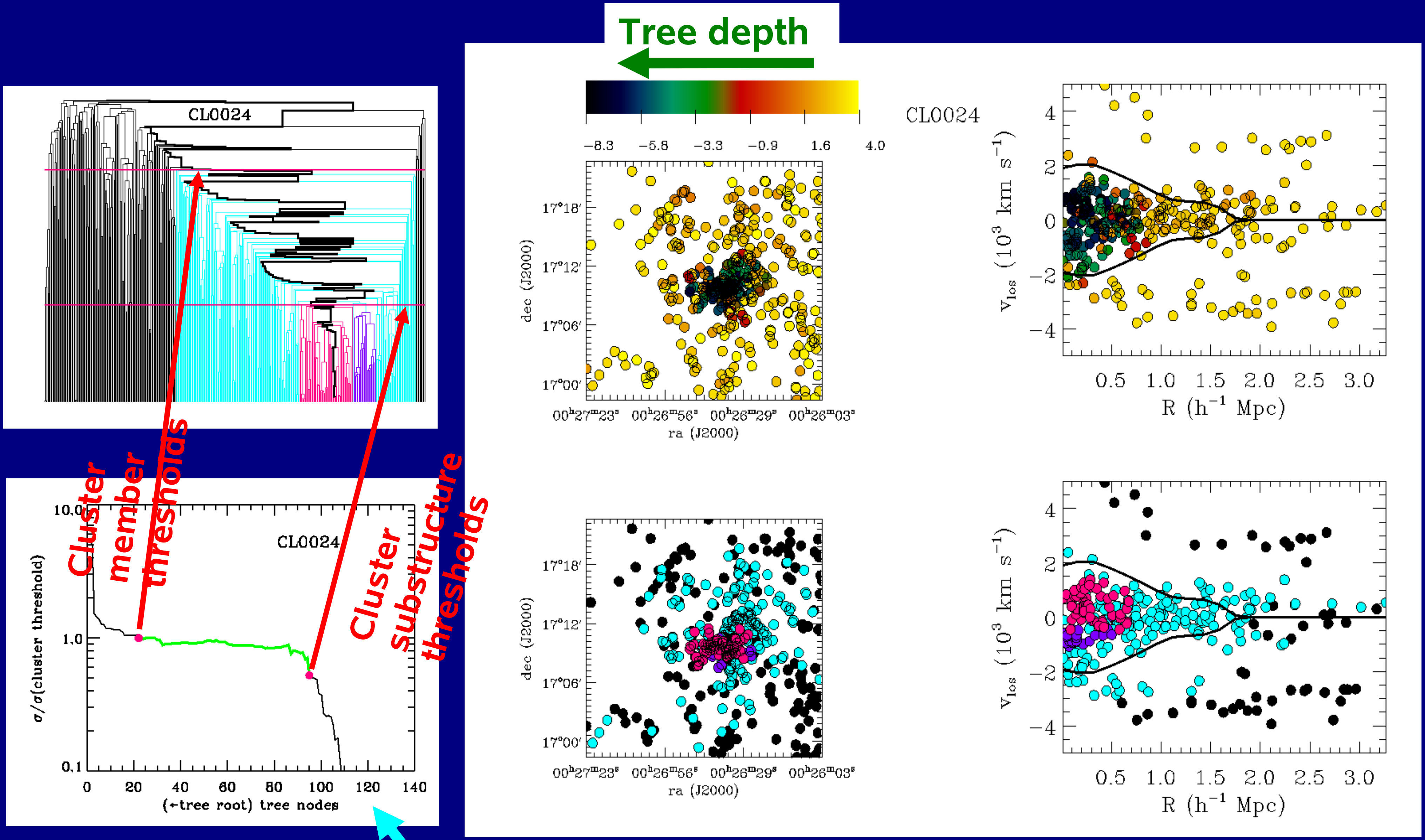
<u>Caustics from the zero of the function:</u>

$$S(\kappa, R) = \langle v^2_{esc} \rangle_{\kappa,R} - \langle v^2 \rangle_R$$

2. the <u>cluster radius</u>

3. the <u>cluster velocity dispersion</u>

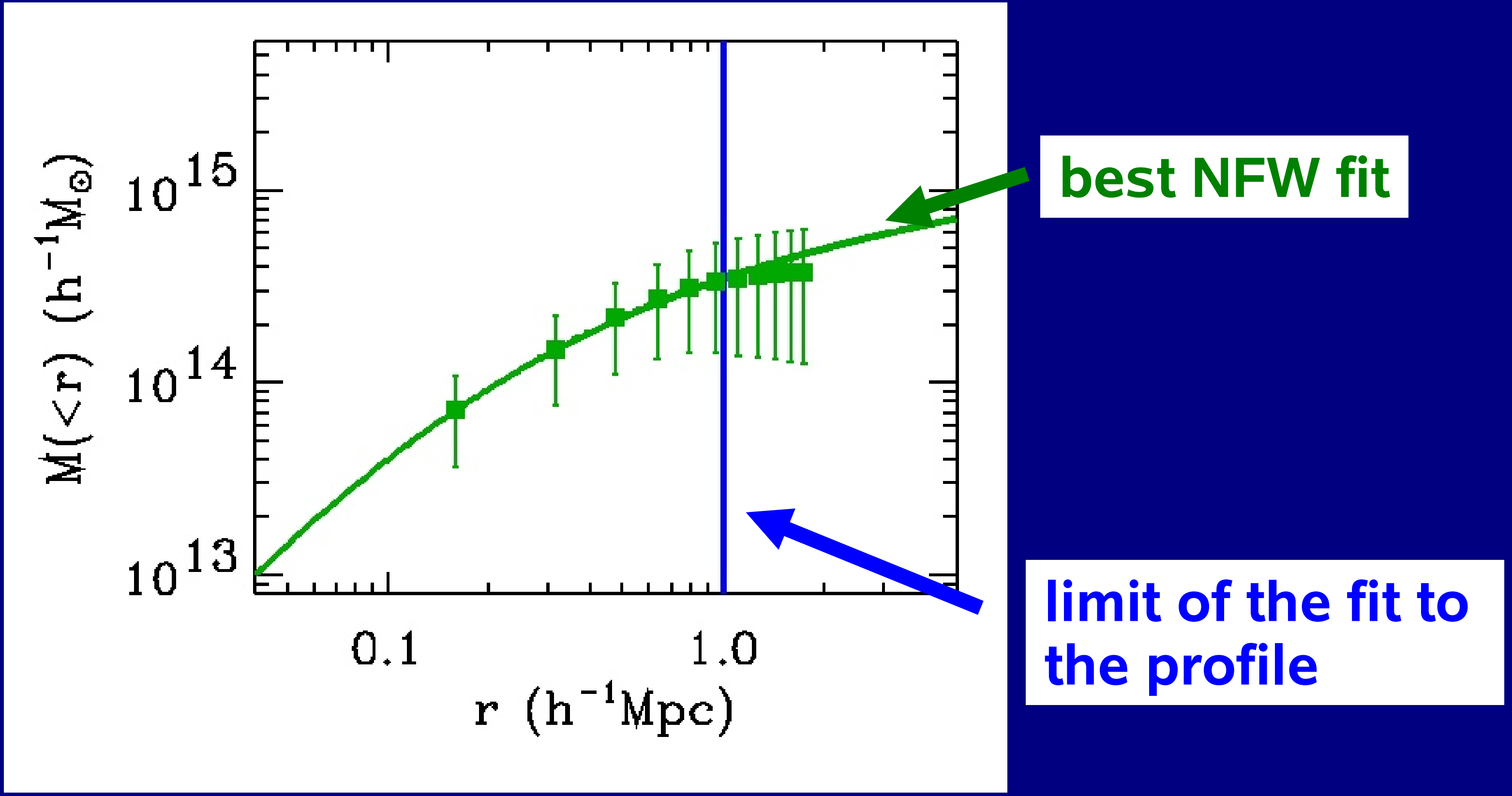
Members and substructures of CL0024



Galaxy velocity dispersion along the main branch

CAUSTIC TECHNIQUE (4):
MASS PROFILE OF CL0024

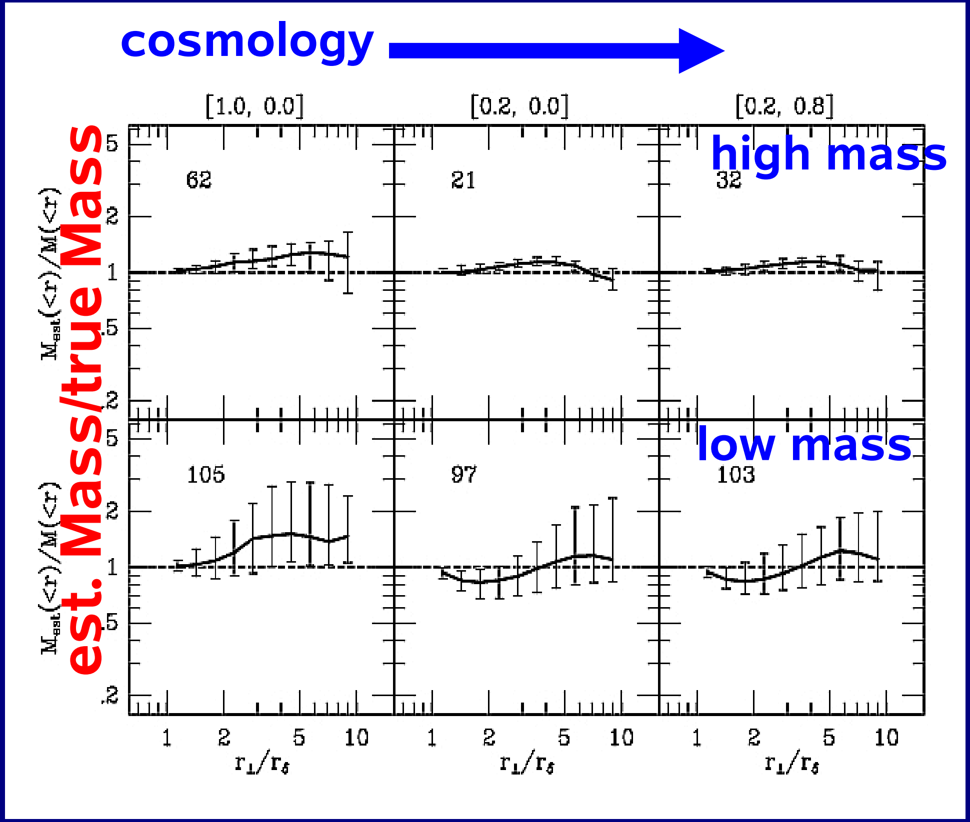
$$GM(<r) = \frac{1}{2}\int_0^r \mathcal{A}^2(x)\,dx$$



CAUSTIC TECHNIQUE (6): MASS PROFILE

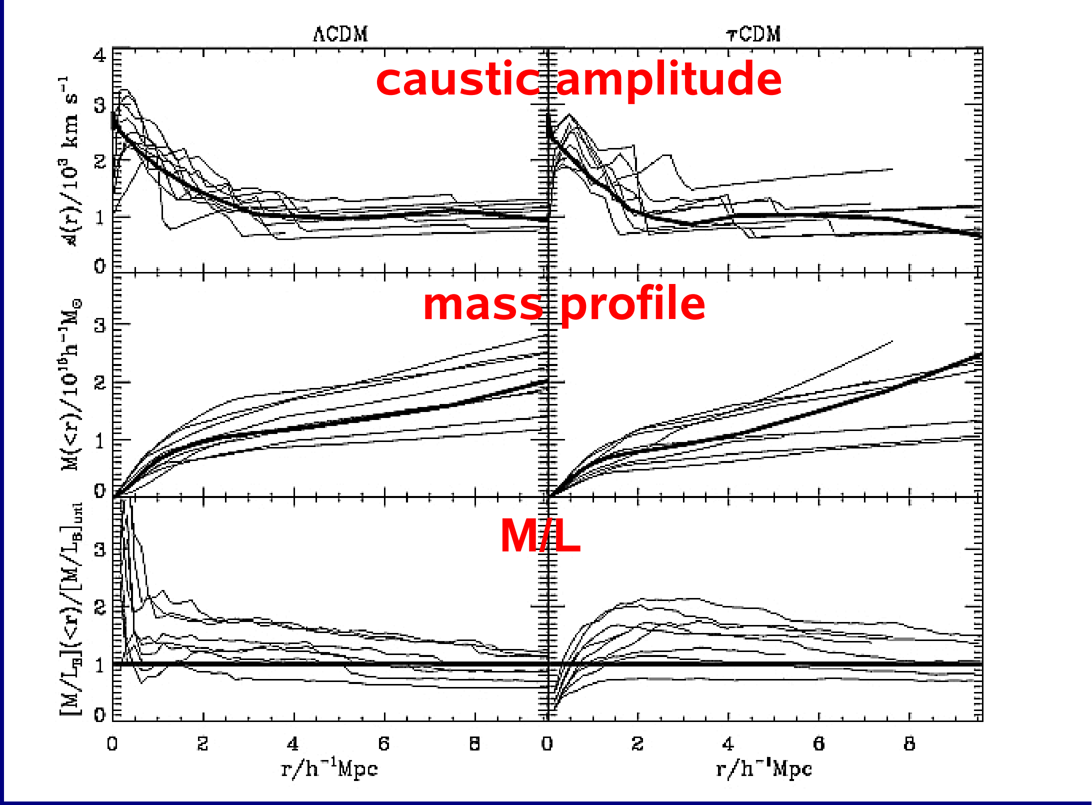
DOES IT WORK?

Comparison with N-body simulations



radius

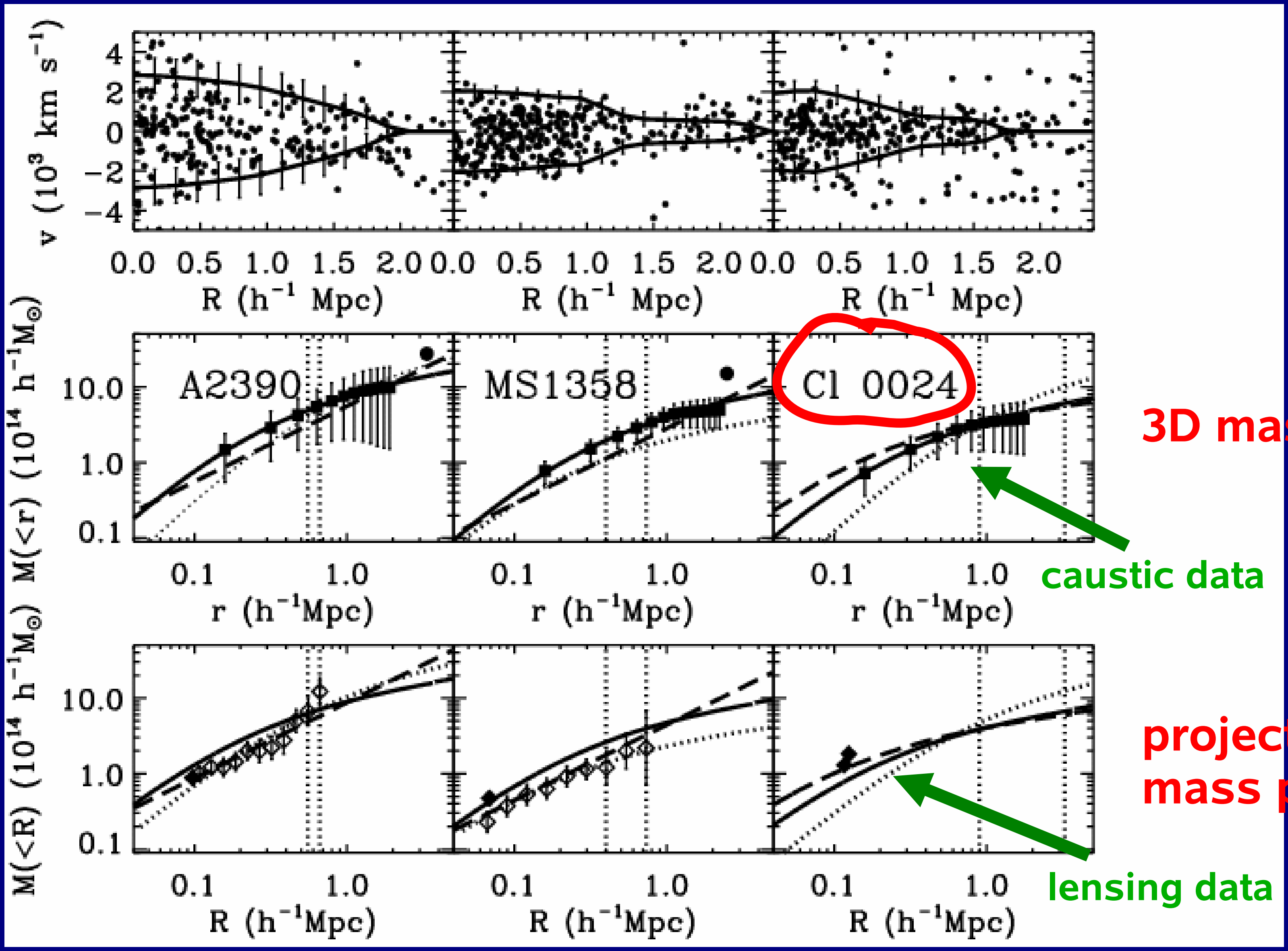
Diaferio & Geller 1997



radius

Diaferio 1999

CAUSTIC TECHNIQUE (5): CAUSTICS VS. LENSING



3D mass profile

caustic data

projected mass profile

lensing data

Diaferio et al. 2005

CAUSTICS VS. LENSING

CAUSTICS

Requires:

- Wide-field redshift survey
- Sufficiently dense survey

Yields:

- 3D mass profile (affected by projection effects)

LENSING

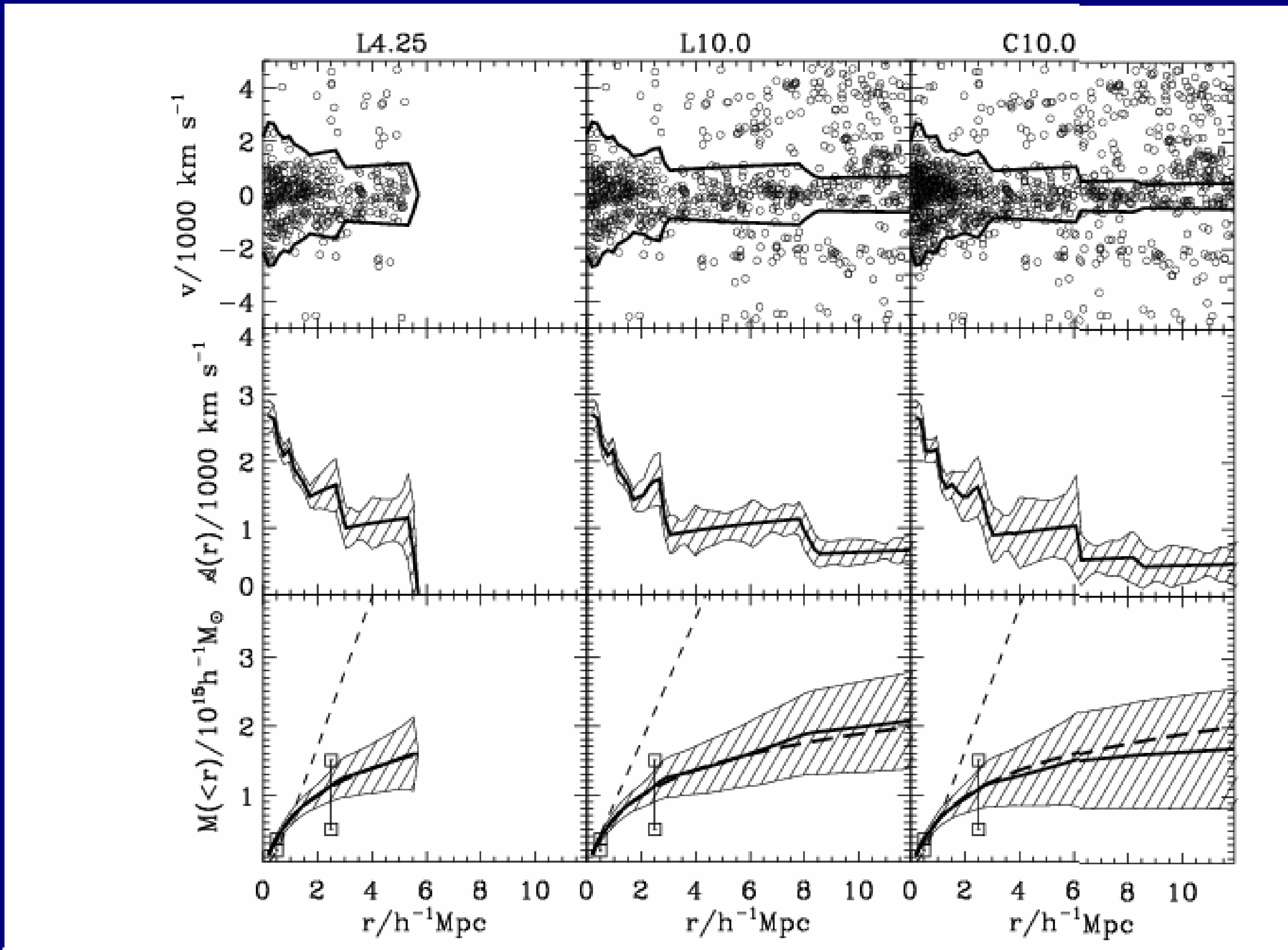
Requires:

- Wide-field photometric survey
- Redshift where signal is sufficiently strong

Yields:

- Mass projected along the line of sight

CAUSTIC TECHNIQUE (6): APPLICATIONS

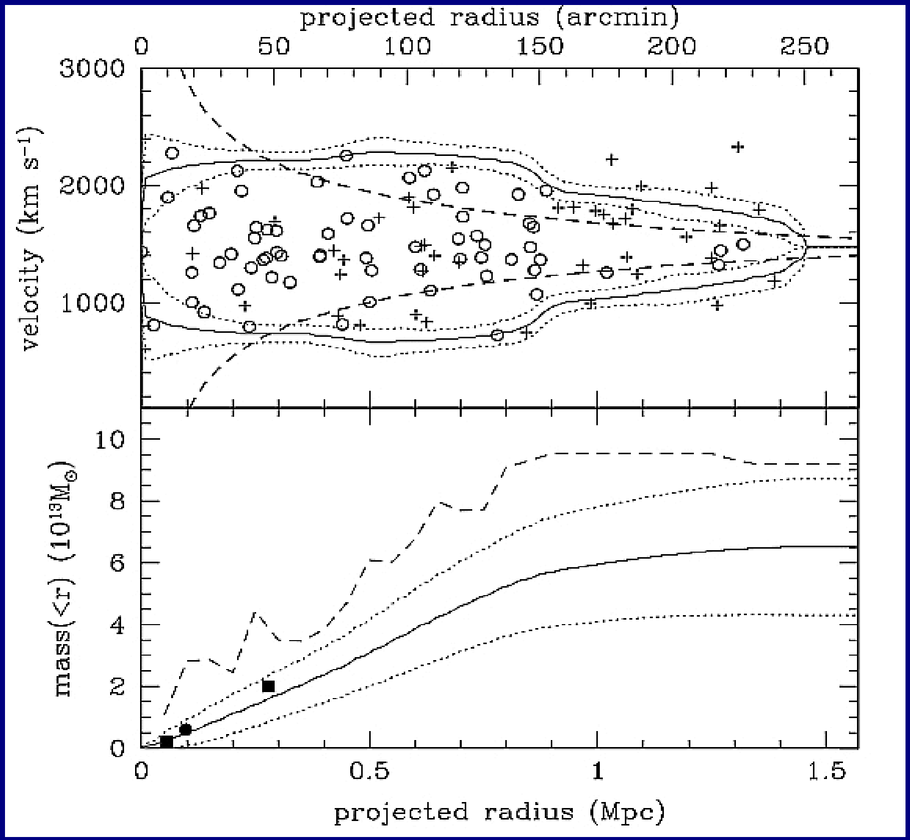


Coma

Geller et al. 1999

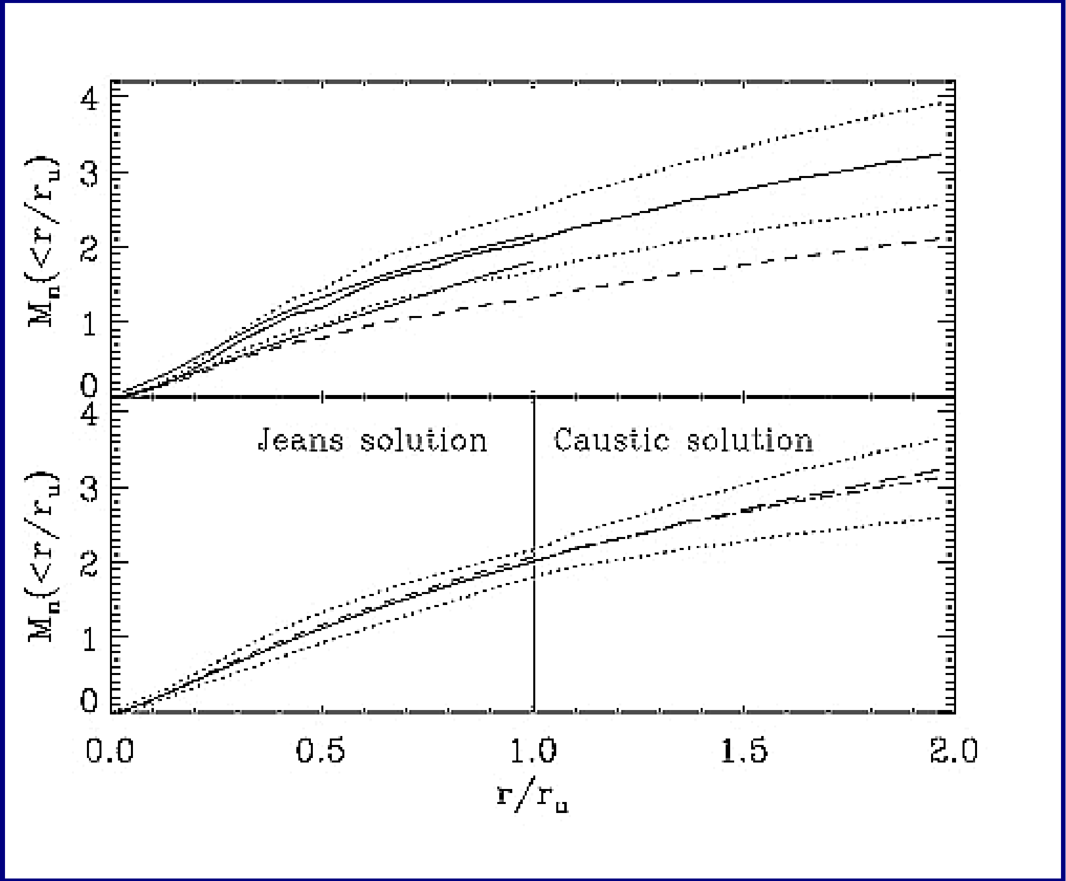
CAUSTIC TECHNIQUE (7): APPLICATIONS

Fornax cluster



Drinkwater et al. 2001

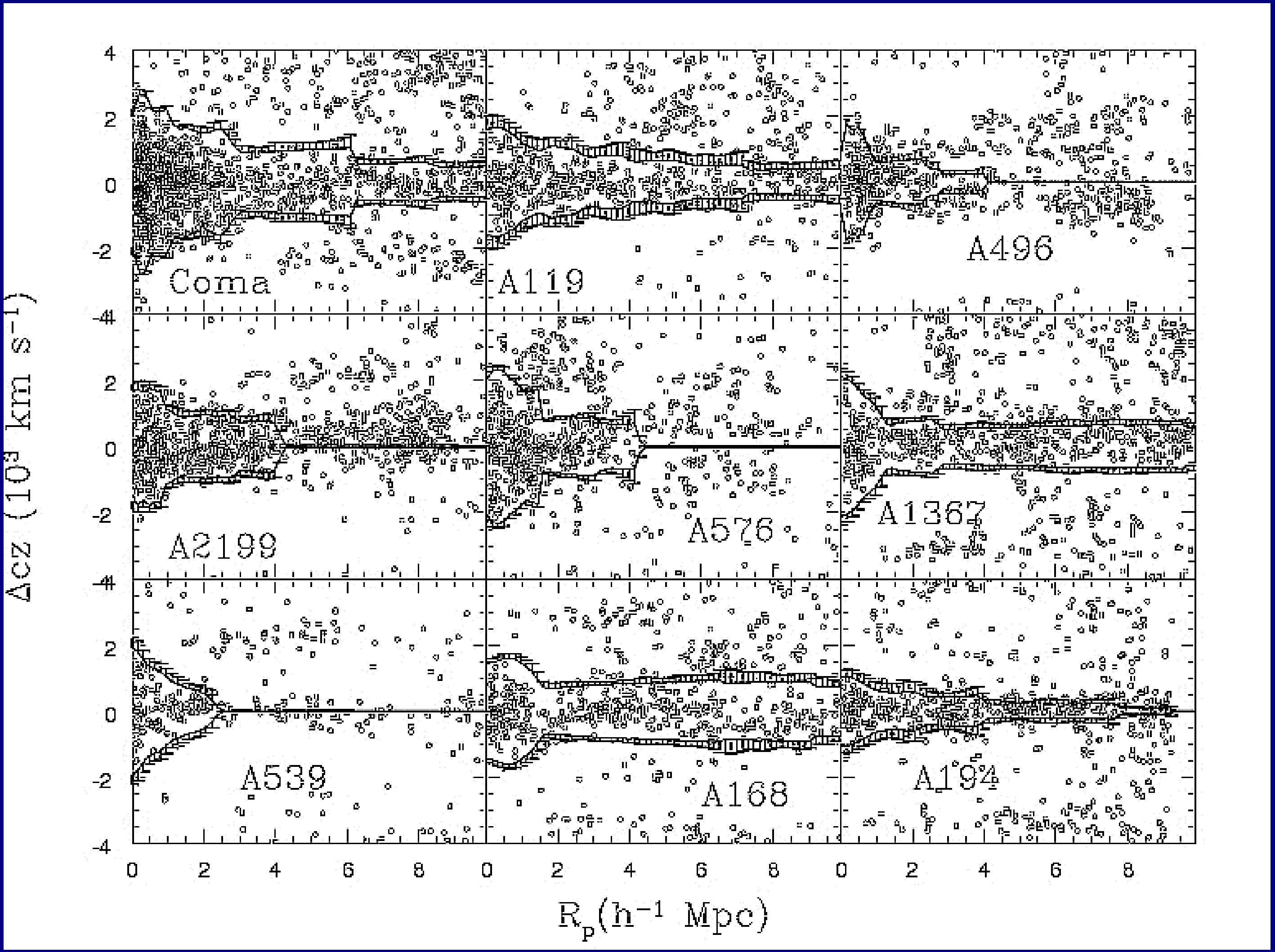
43 stacked clusters from the 2dF



Biviano & Girardi 2003

CAIRNS:
Cluster And Infall Region Nearby Survey

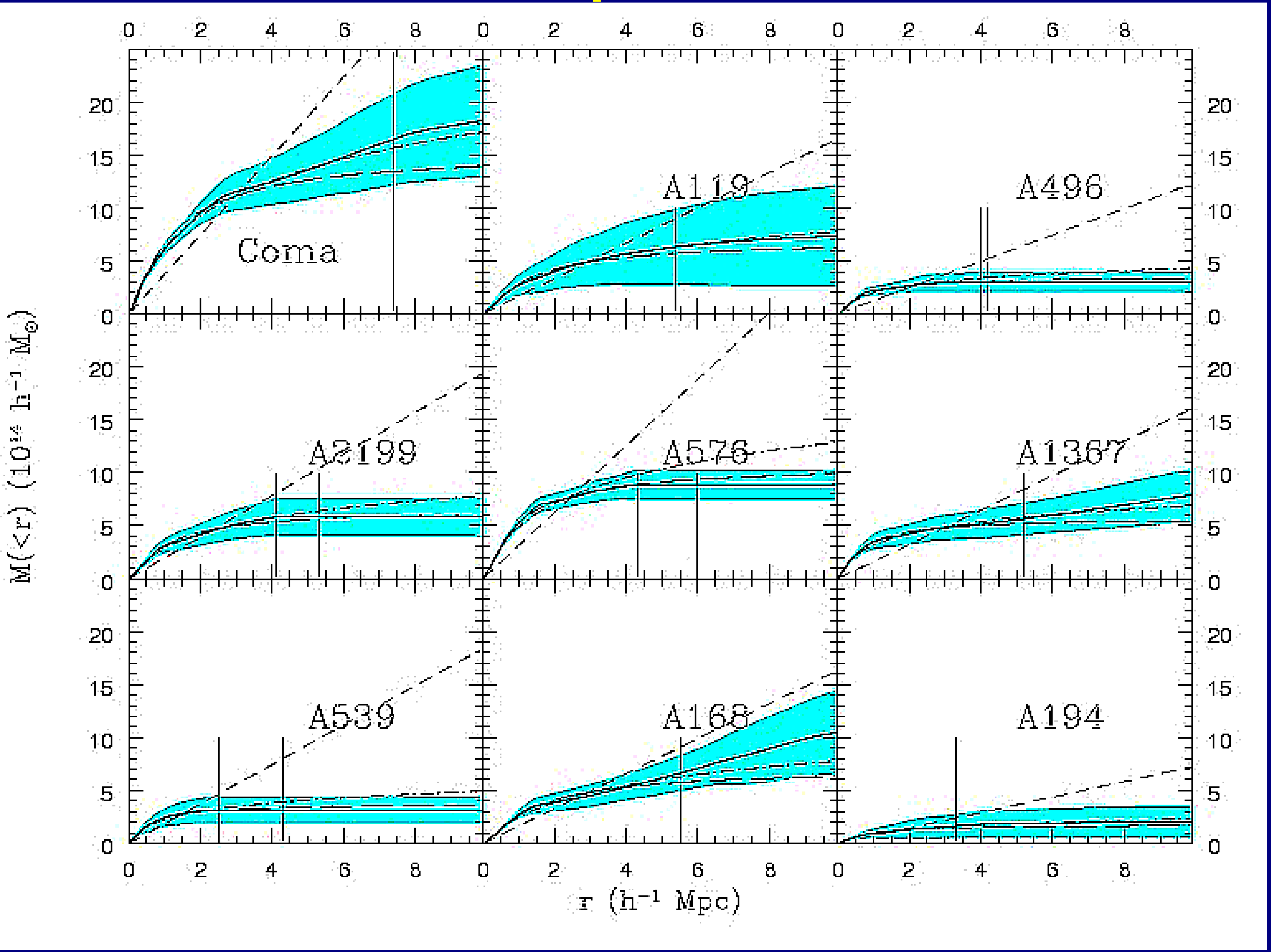
8+1 nearby clusters (cz<15,000 km/s), 15,654 galaxy redshifts



Rines et al. 2003

CAIRNS:
Cluster And Infall Region Nearby Survey

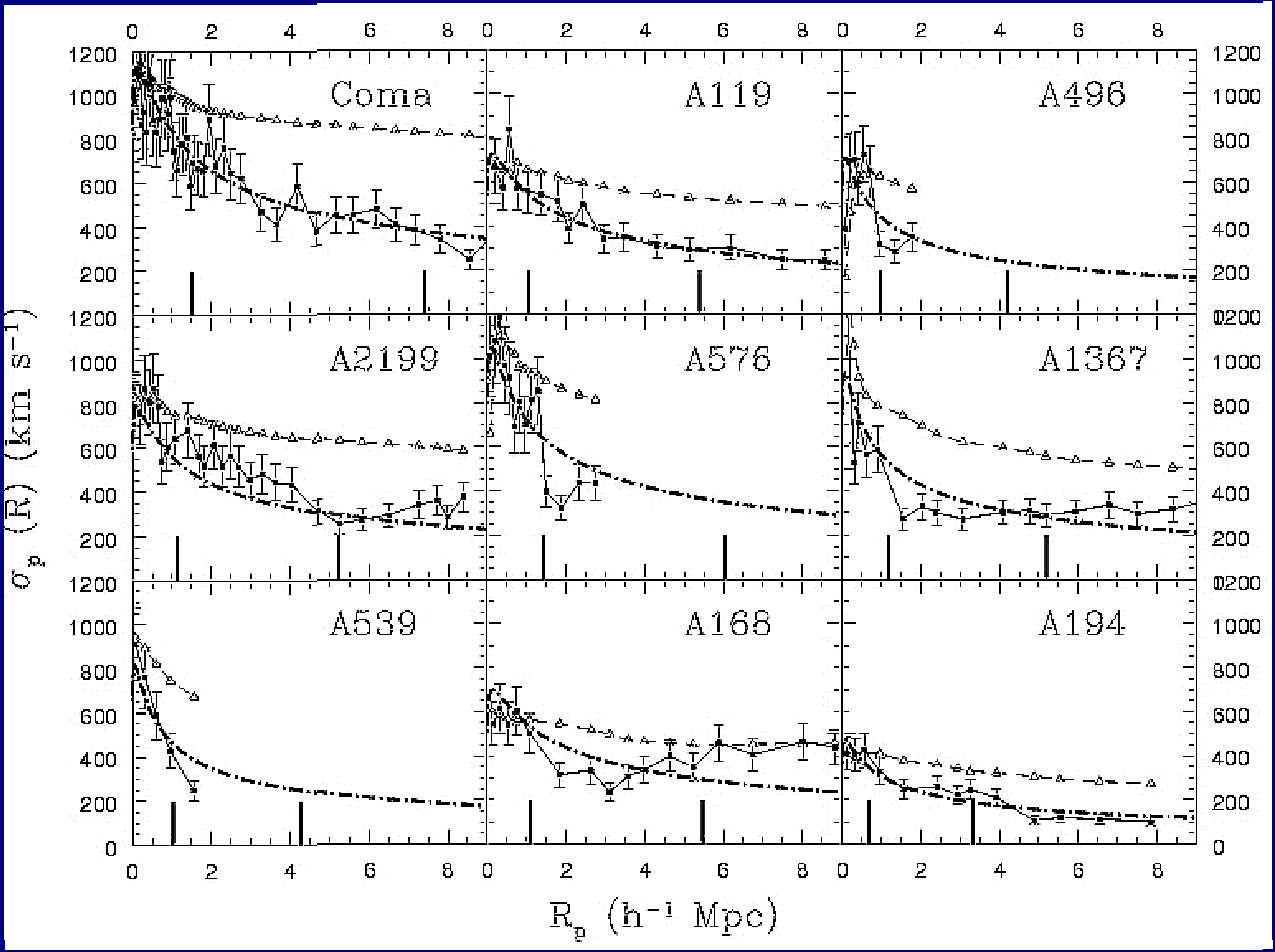
Mass profiles



CAIRNS:

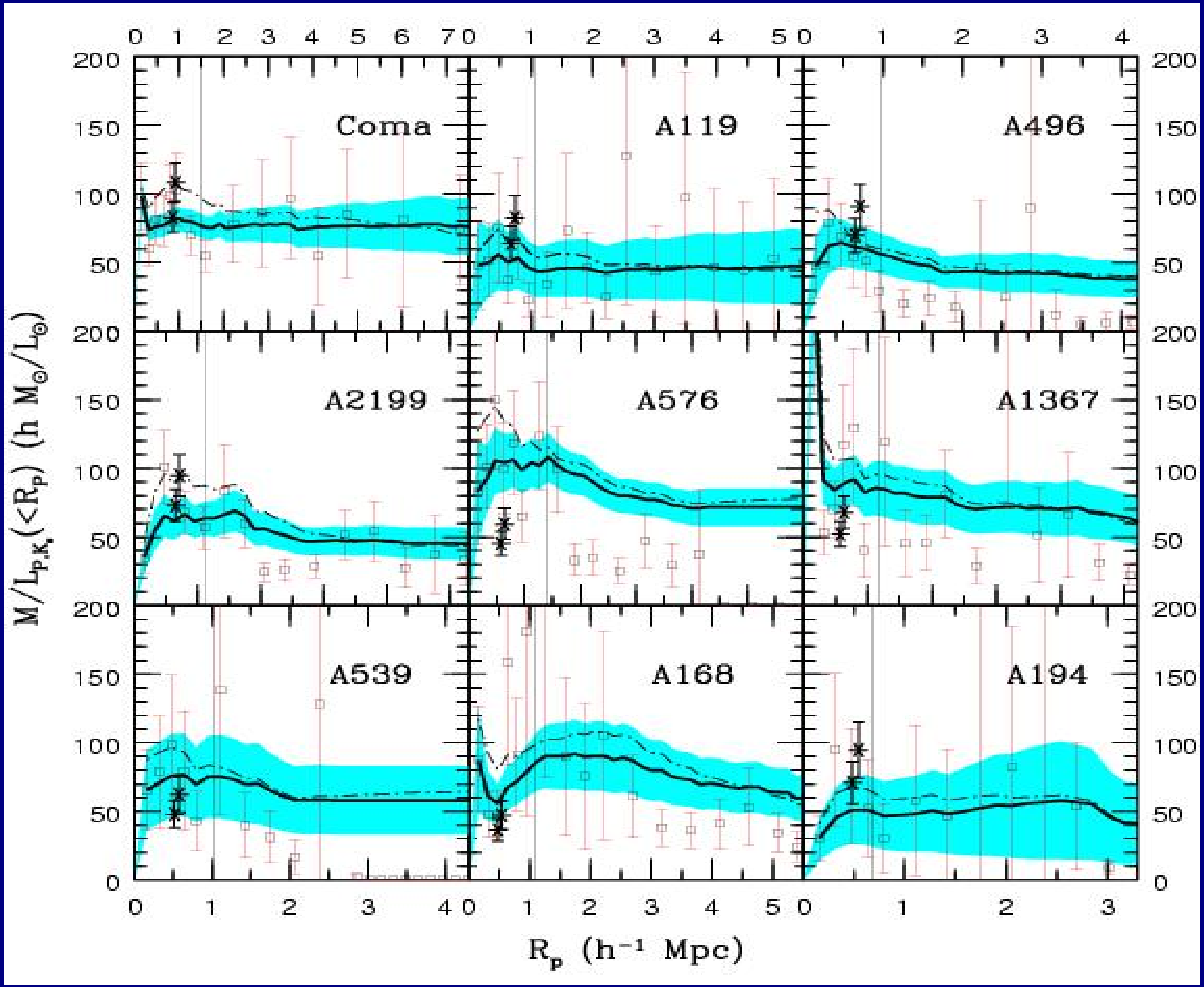
Cluster And Infall Region Nearby Survey

Velocity dispersion profiles



CAIRNS:
Cluster And Infall Region Nearby Survey

Mass-to-light ratio profiles



Ω_m FROM M/L

$$\Omega_0 = \left\langle \frac{M}{L_B} \right\rangle \frac{j_B}{\rho_{\rm crit}}$$

Carlberg et al. 1996 (CNOC1) → $\Omega_m = 0.24 \pm 0.05 \pm 0.09$

Bahcall et al. 2000 → $\Omega_m = 0.16 \pm 0.05$

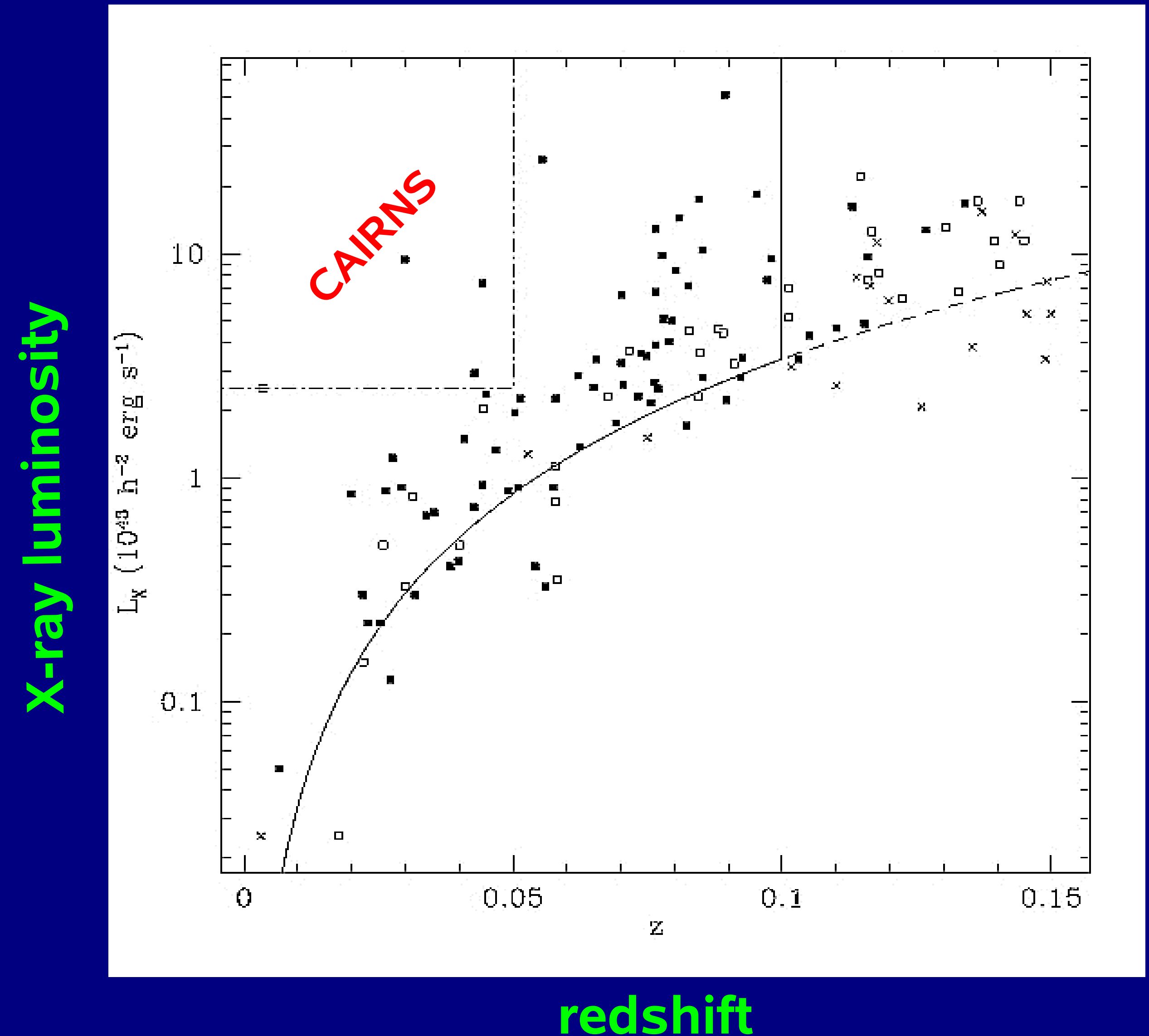
Lin et al. 2003 (2MASS) → $\Omega_m = 0.19 \pm 0.03$

CAIRNS, 2004 (2MASS) → $\Omega_m = 0.18 \pm 0.03$

CIRS:

Cluster Infall Regions in the SDSS

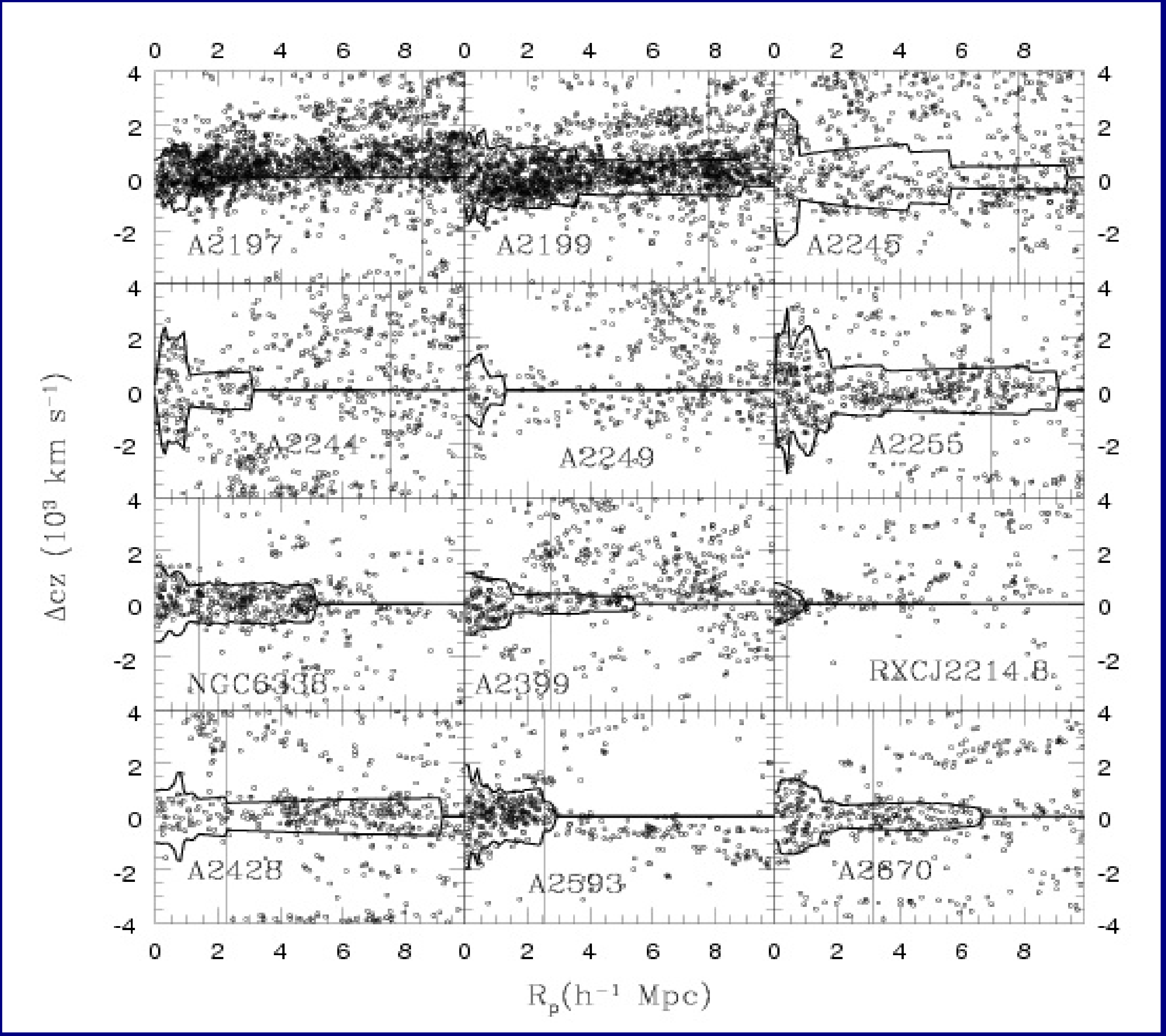
72 X-ray selected clusters combined with the 4th SDSS data release



Rines & Diaferio 2006

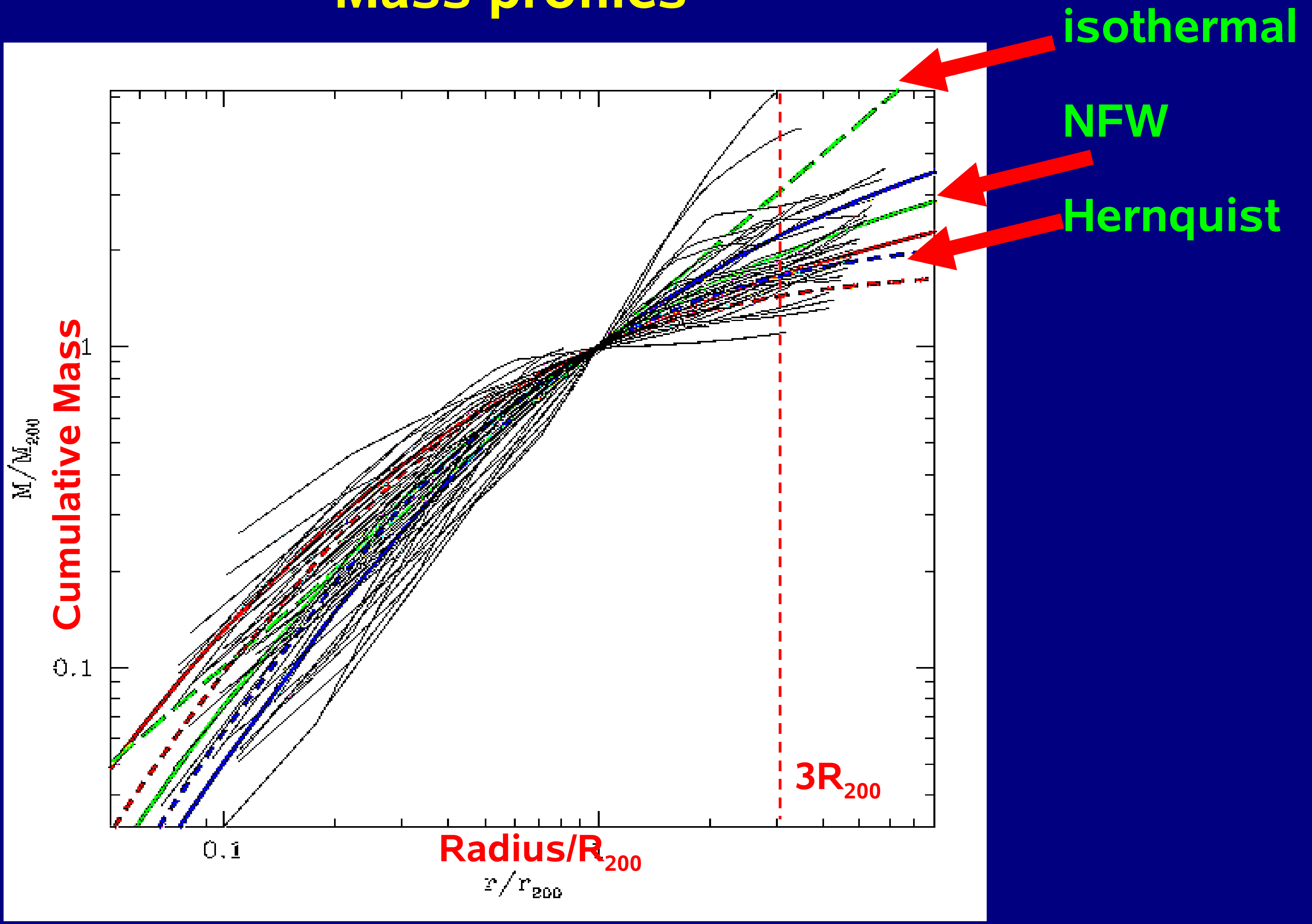
CIRS:
Cluster Infall Regions in the SDSS

Redshift diagrams (12 out of 72)



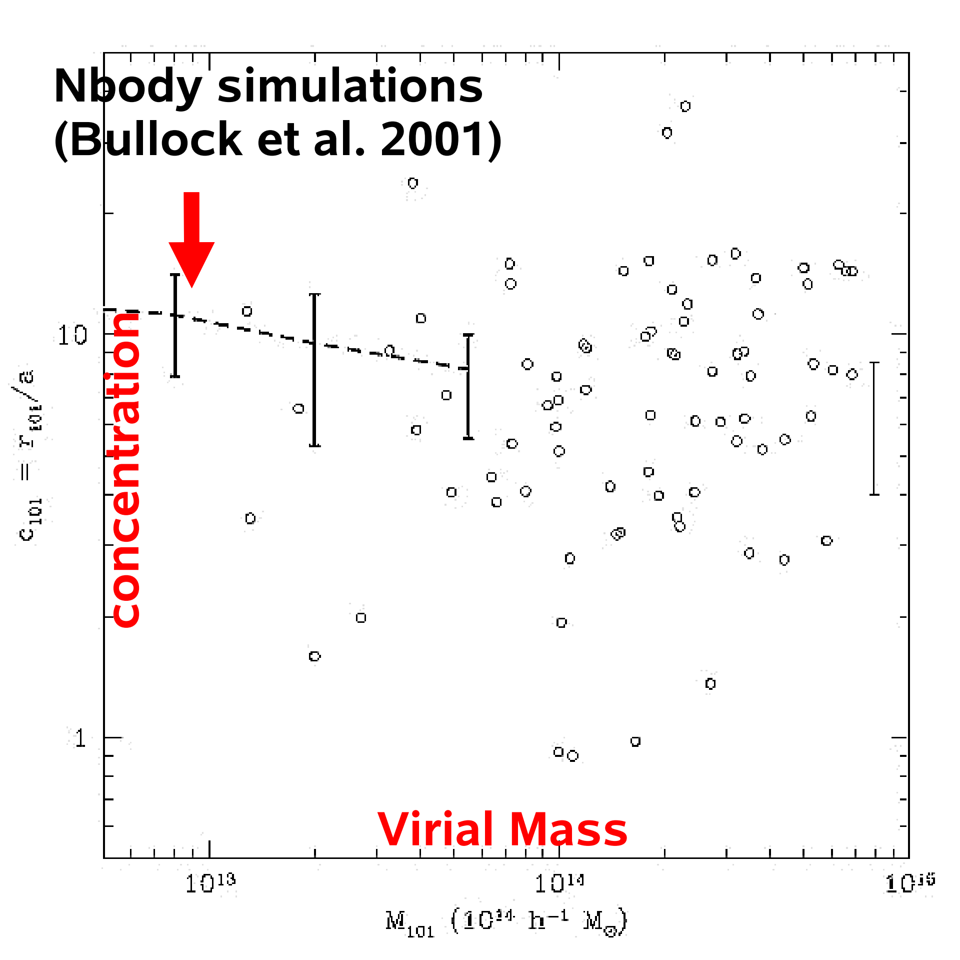
CIRS:
Cluster Infall Regions in the SDSS

Mass profiles

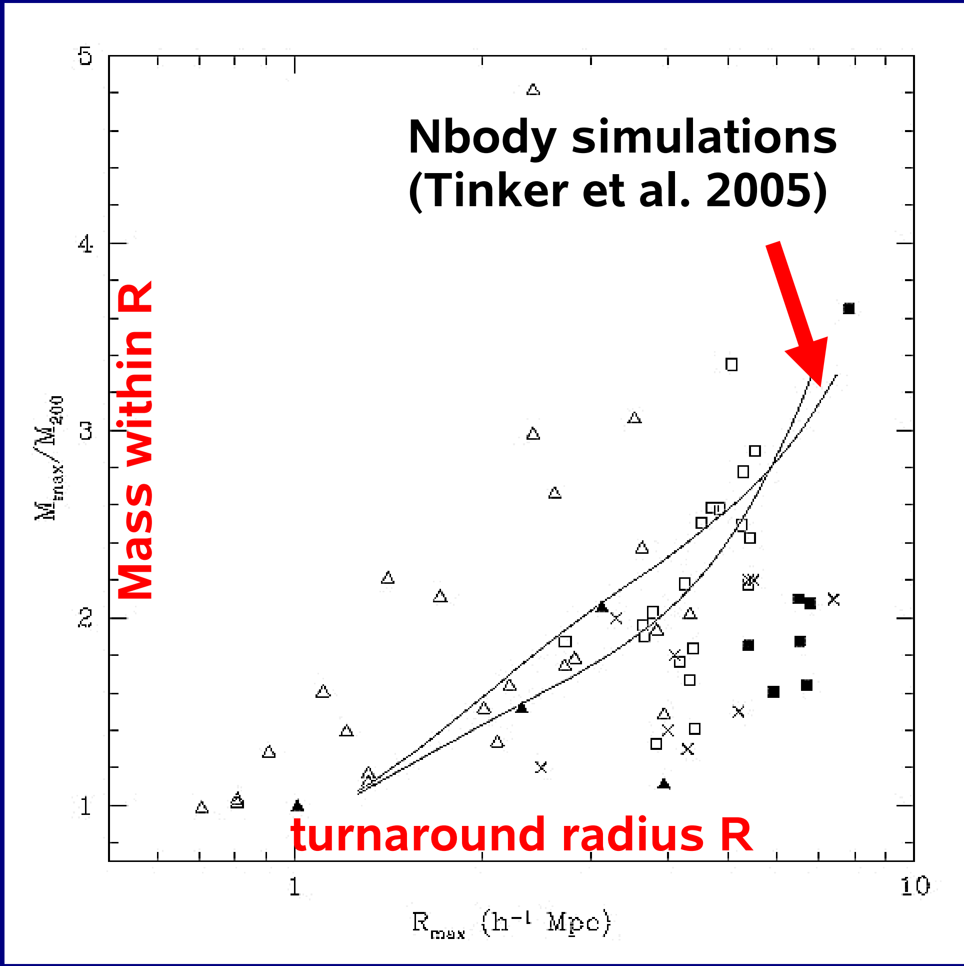


CIRS:
Cluster Infall Regions in the SDSS

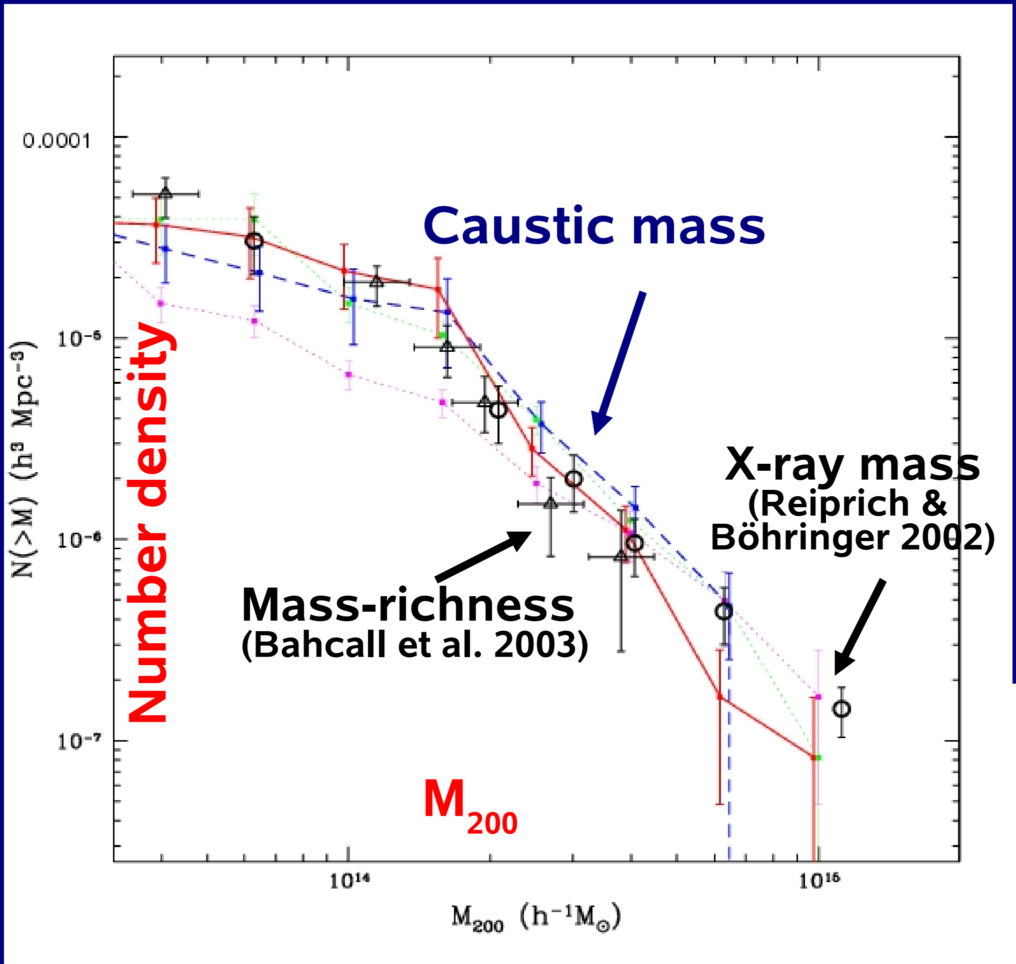
Concentrations



Mass in the infall region



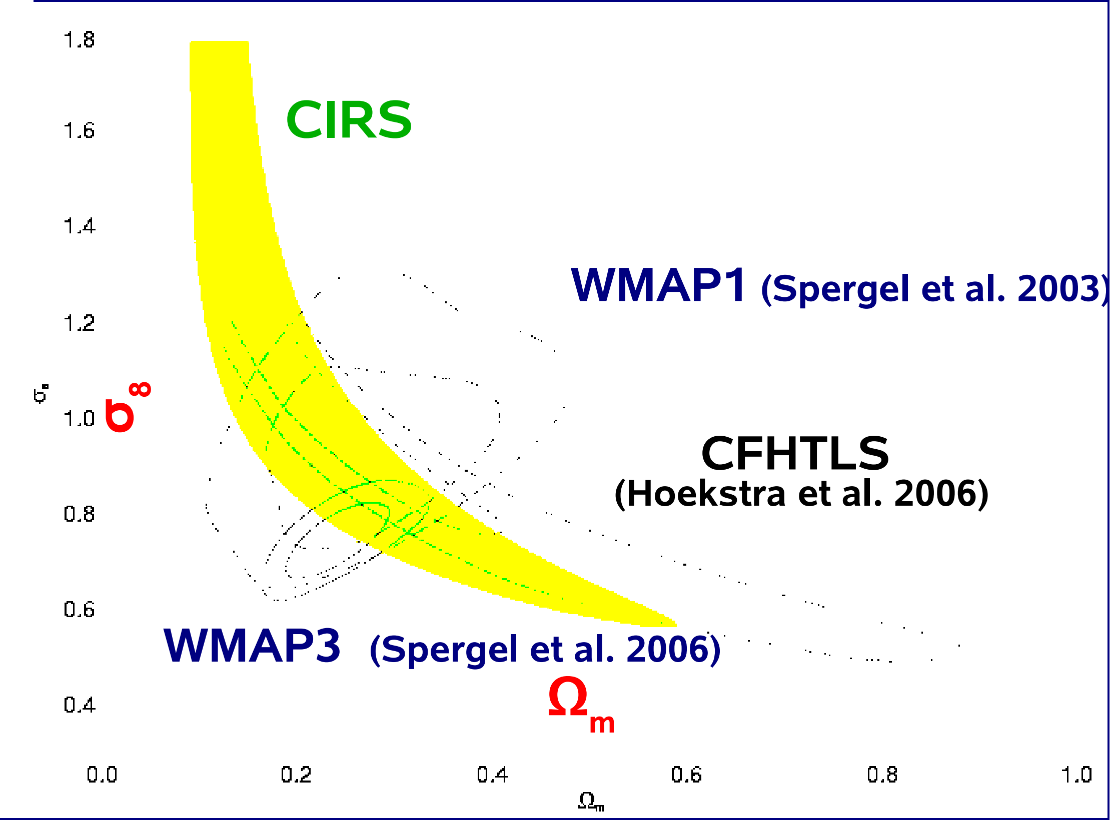
THE CIRS MASS FUNCTION AND THE COSMOLOGICAL PARAMETERS



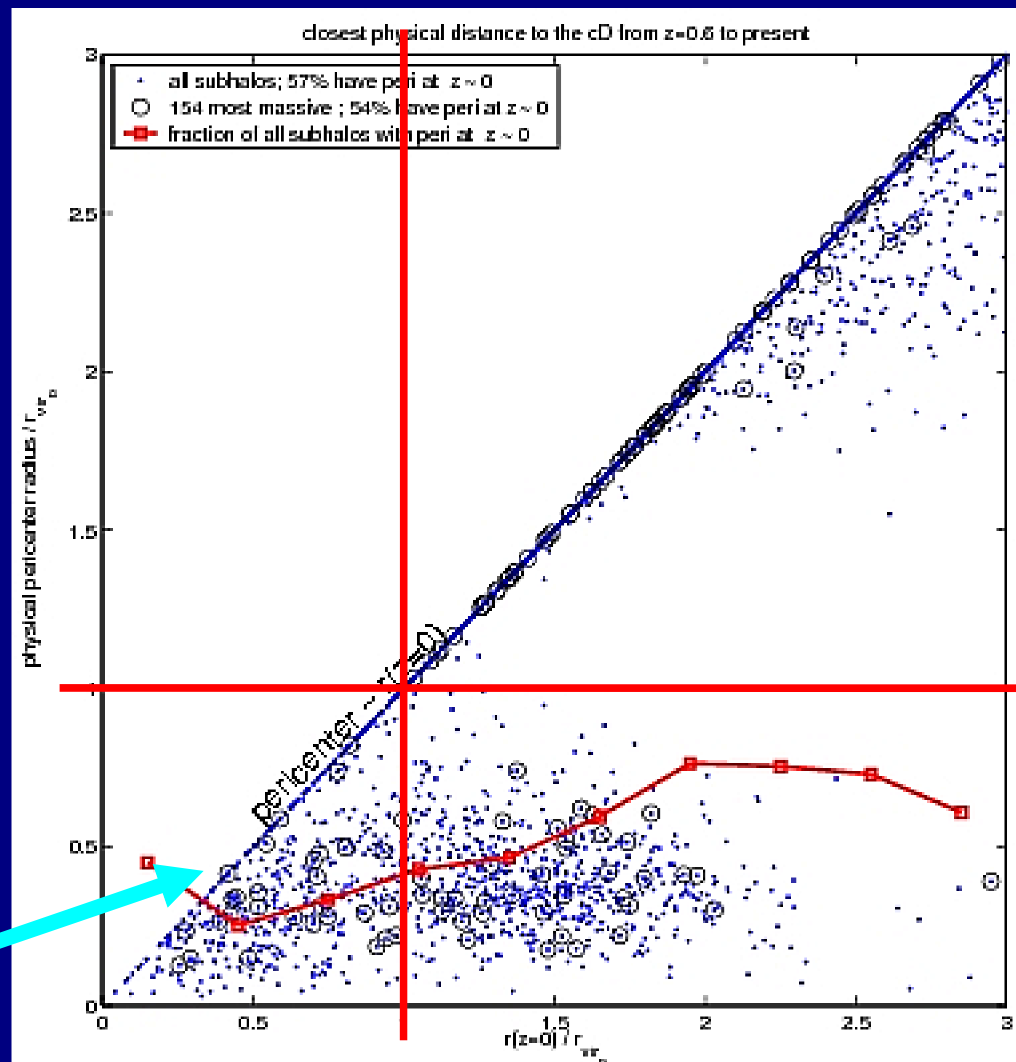
$\Omega_m = 0.24^{+0.14}_{-0.09}$

$\sigma_8 = 0.92^{+0.24}_{-0.19}$

Rines et al. 2006



THE GALAXY-LSS CONNECTION



pericenter

virial region

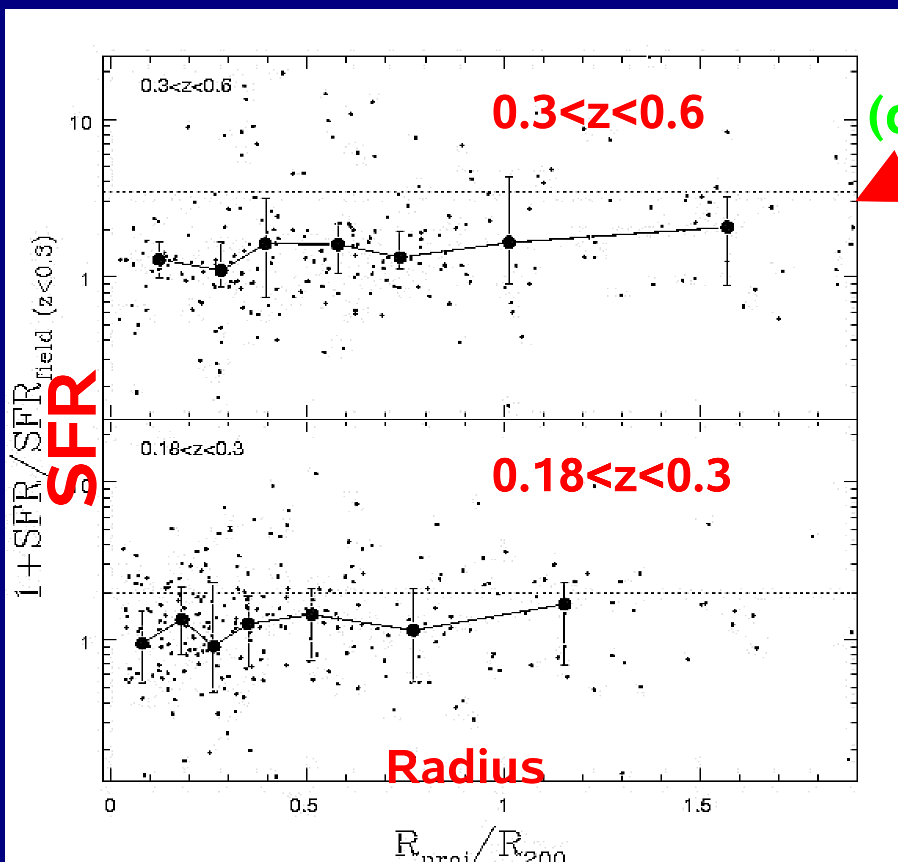
position at z=0

Moore et al. 2004

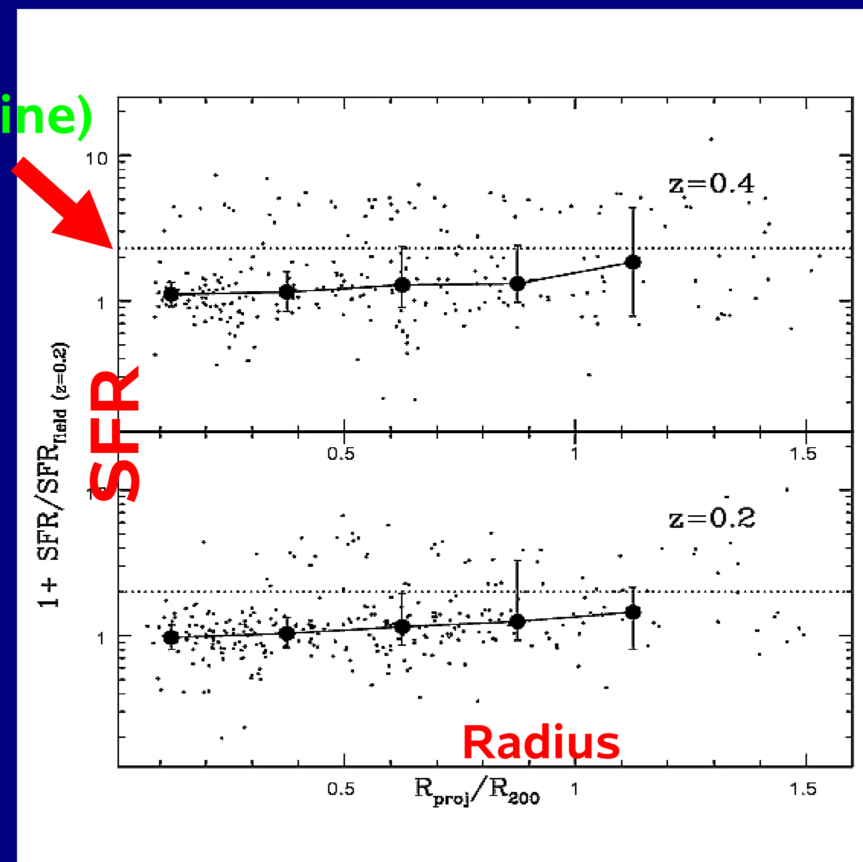
SFR vs. RADIUS

CNOC

N-body+semi-analytic model

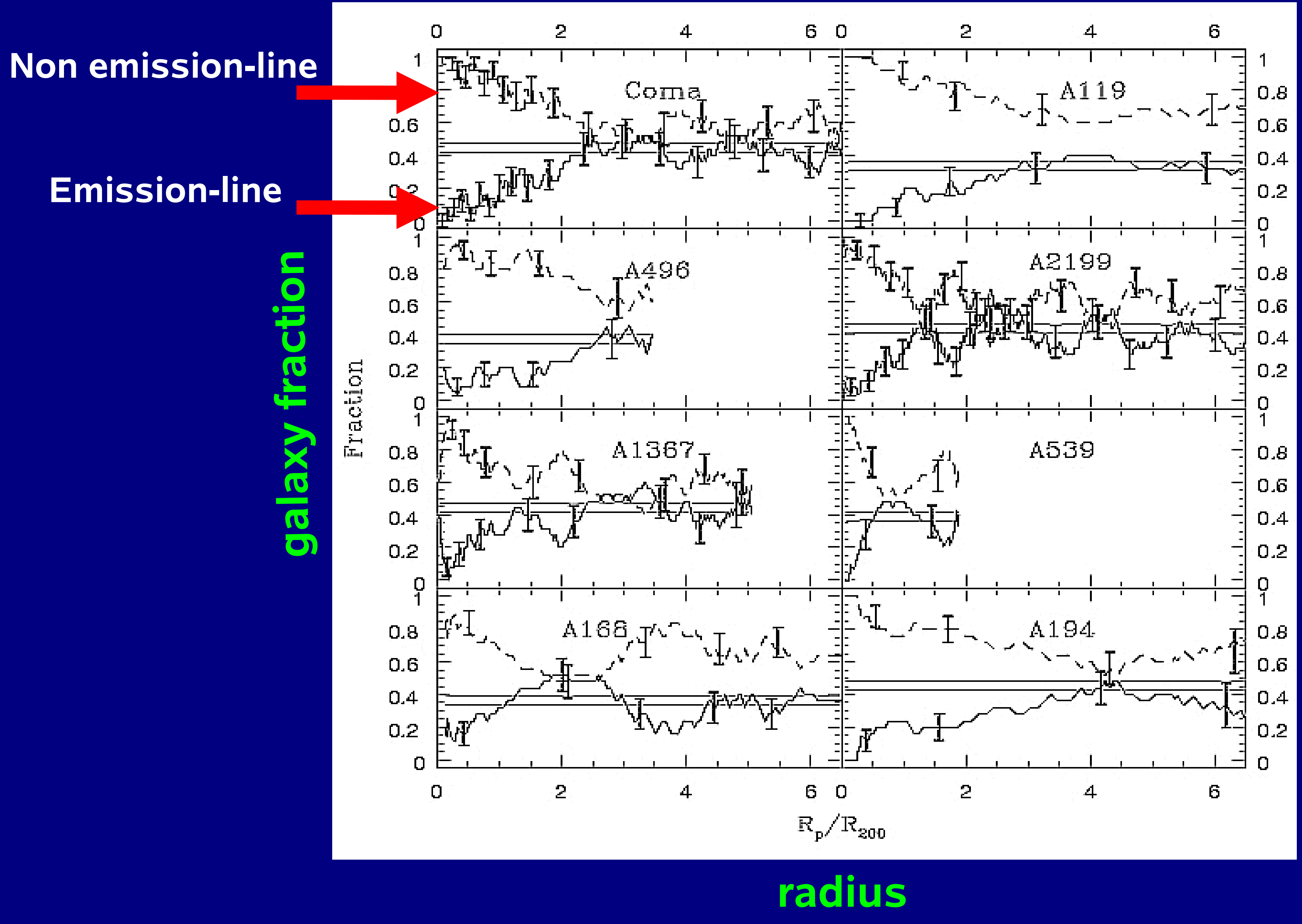


Field
(dotted line)

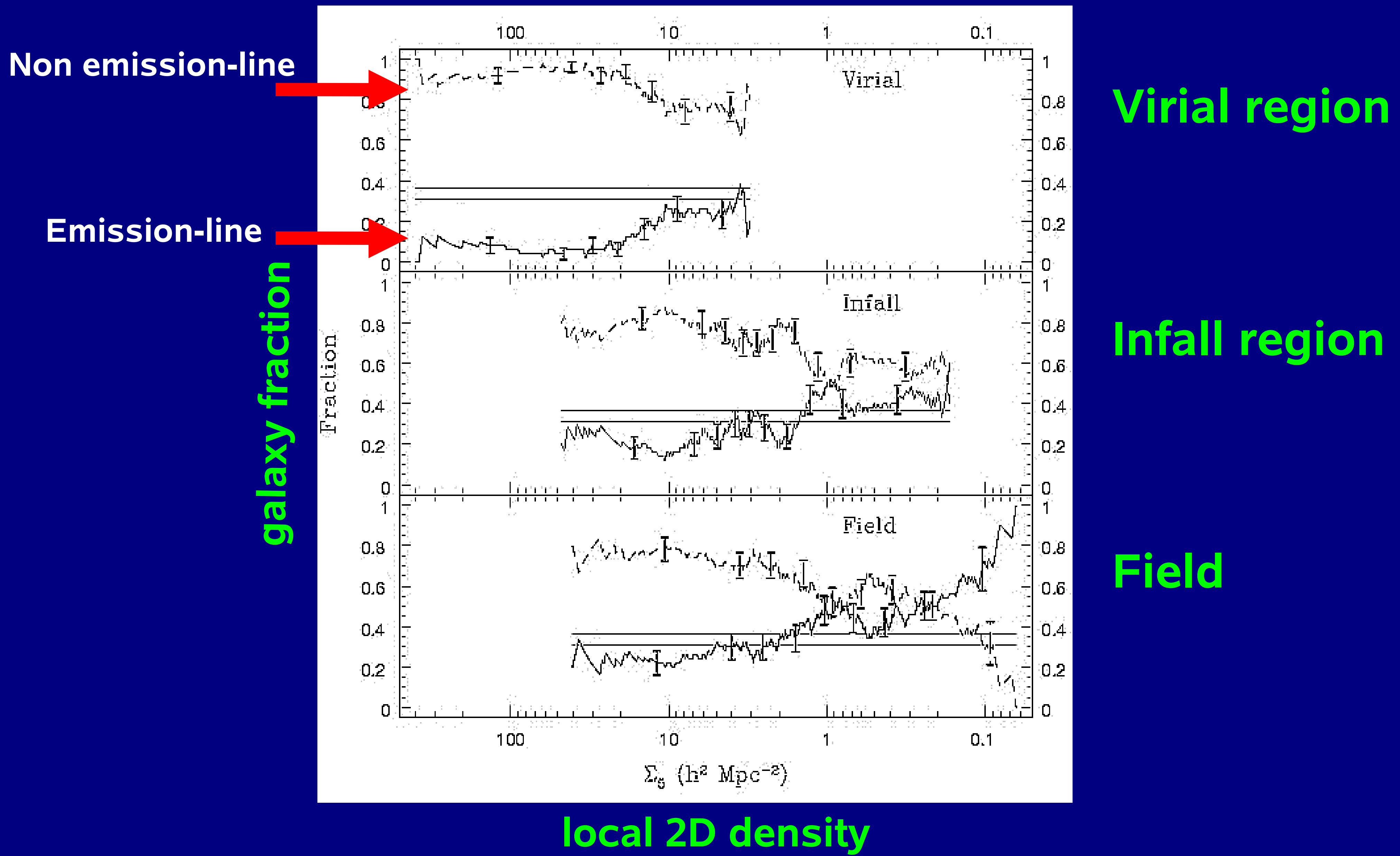


Diaferio et al. 2001

CAIRNS:
Hα vs. radius

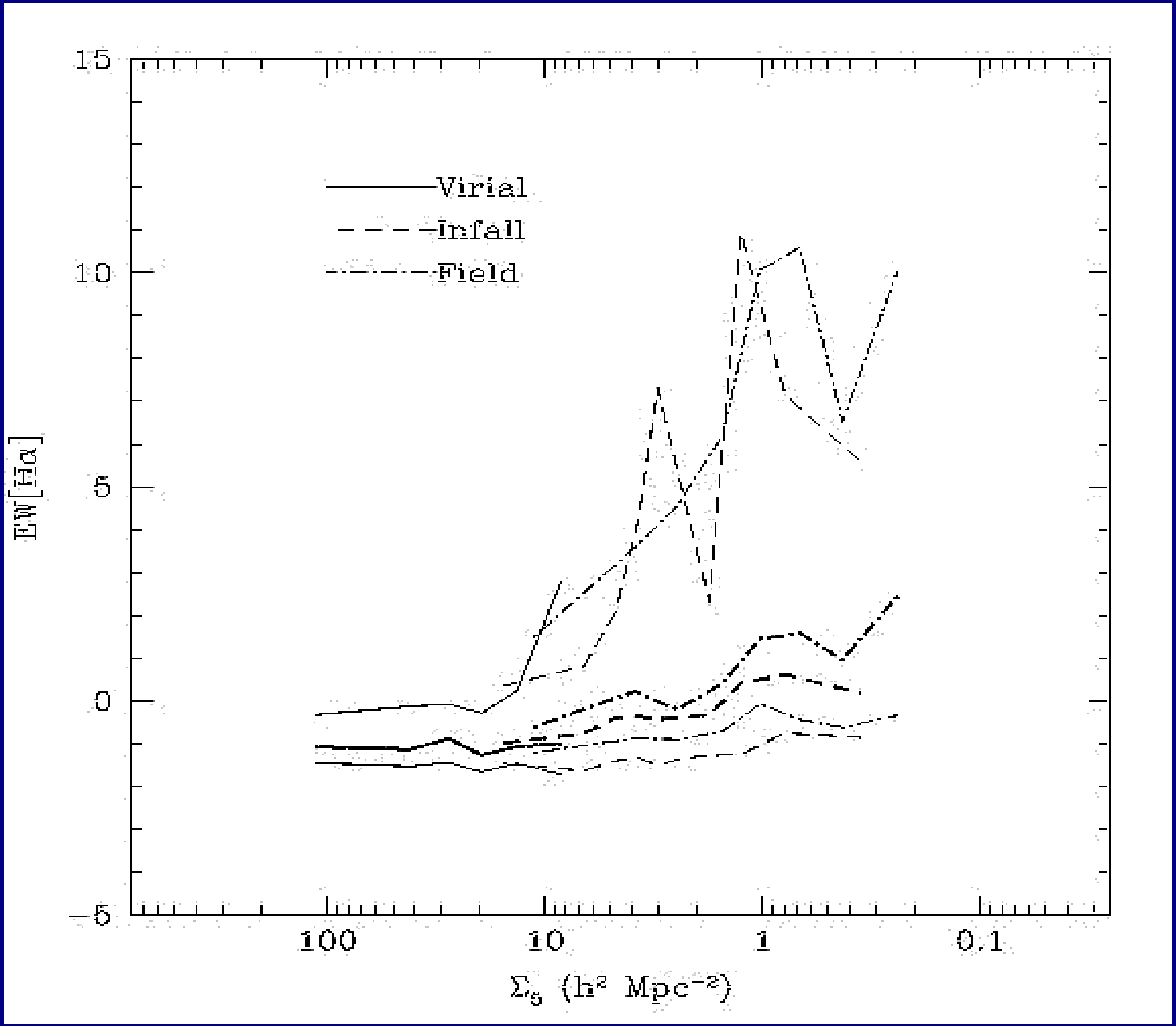


CAIRNS:
Hα vs. local density



CAIRNS:
EW[Hα] distribution vs. density

Equivalent width



local 2D density

CONCLUSION

- The relevance of the mass-to-light ratio

- The caustic technique: A mass estimator for the outer regions of clusters

- Results from the CAIRNS and CIRS cluster surveys

- Mass-to-light ratio profiles out to ~4 R_{200} for 9 clusters

- NFW/Hernquist best fits to the mass profiles out to 4-5 R_{200} for ~80 clusters!

- Mass function yields Ω_m-σ_8 consistent with other estimates

- The galaxy-environment connection: local density