Measuring the dynamical properties of self-gravitating systems in their outer regions through the caustic technique

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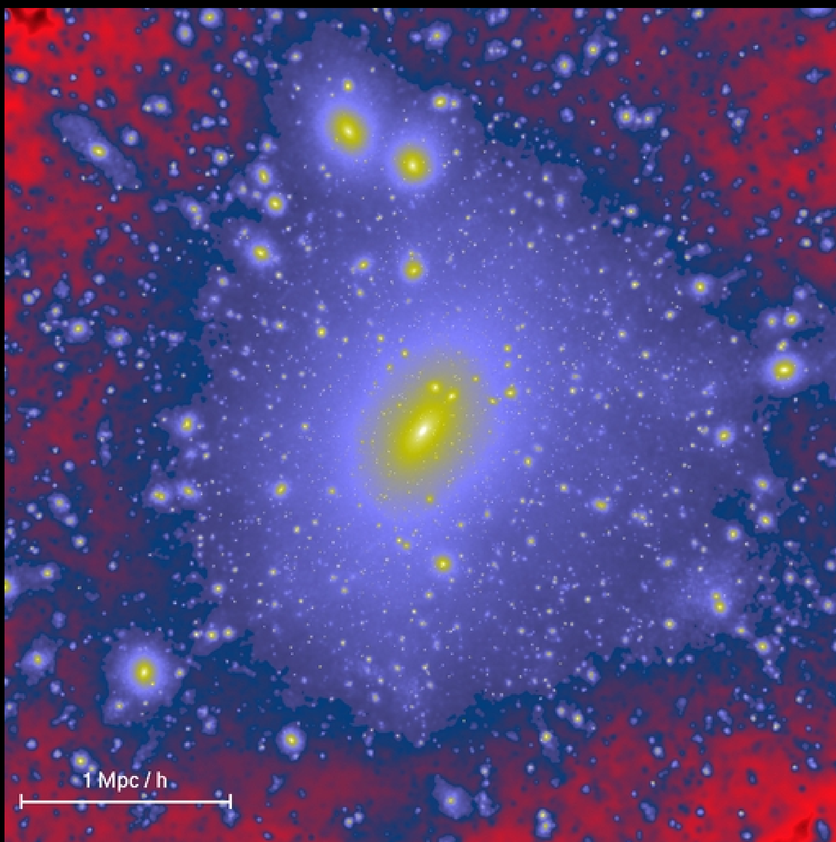
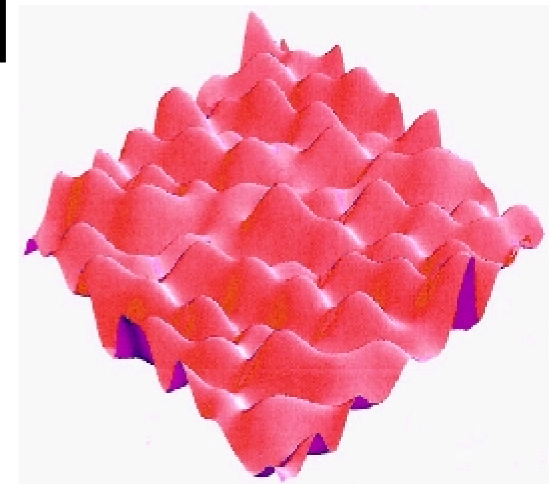
Trieste, September 26th, 2012

Abell 1689 observed by the Hubble Space Telescope

Formation of large-scale structure in the Universe



Millennium Simulation, Volker Springel, 2005

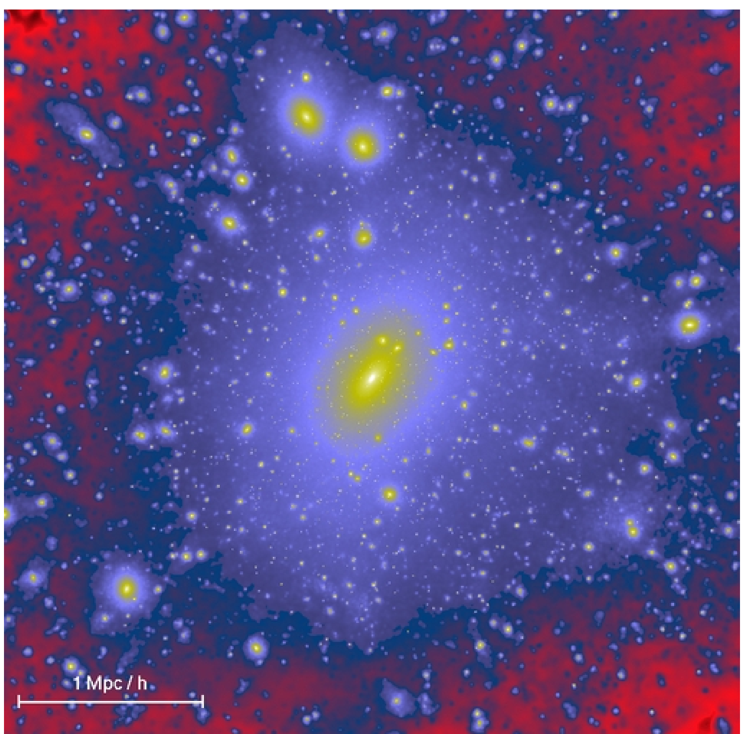


Early Universe
(small perturbations)

- ripples evolve independently
- they interact with others in non-linear ways
- the small over-density fluctuations attract additional mass as the Universe expands

Formation of large-scale structure in the Universe

Gravitational instability produces high peaks of the density field → merger of small clumps at the intersection of a filamentary large-scale structure



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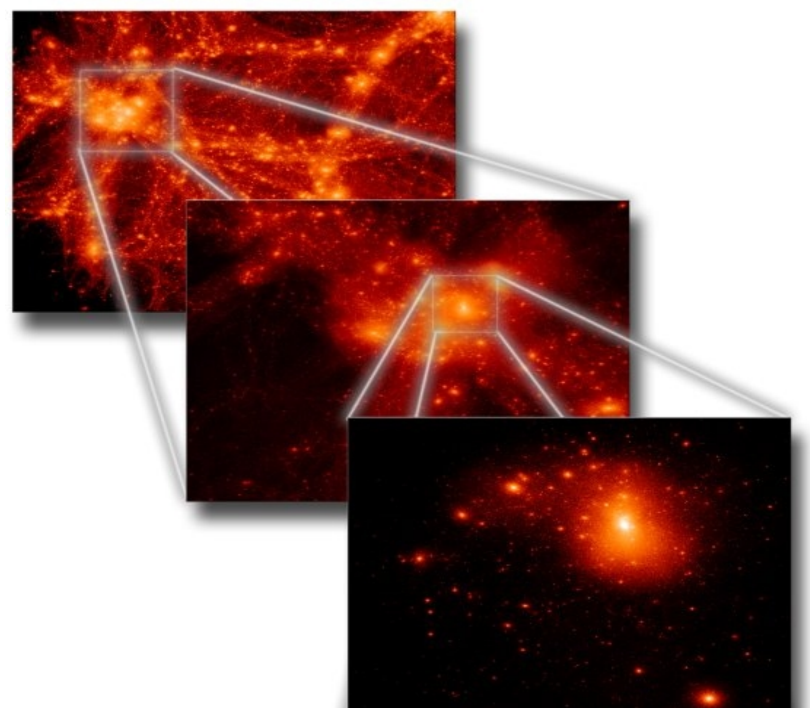
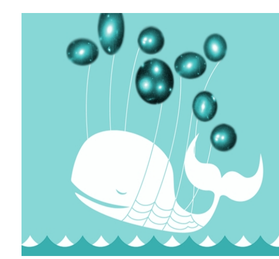


Simulation by Gauss Centre for Supercomputing
Gottlöber, Khalatyan, Klypin, 2008



GALAXY CLUSTER

large-scale *nucleosynthesis*
cosmological
structure **galaxy-environment**
matter distribution
galaxy formation

~80% - DM
~20% - hot diffuse plasma
- stars, dust, cold gas

parameters

largest gravitationally bound systems in the Universe

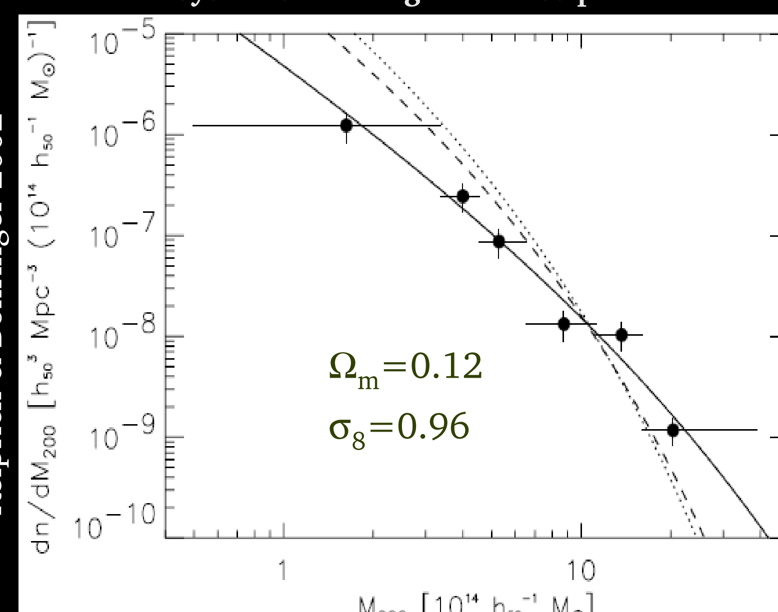
a few Mpc
$\sim 10^{14\text{-}15} M_{sun}$

hundreds of galaxies

galaxy-environment connection

High-mass tail of mass function
↓
number density
↓
measurement of cosmological parameters

number of systems with a given mass per unit volume



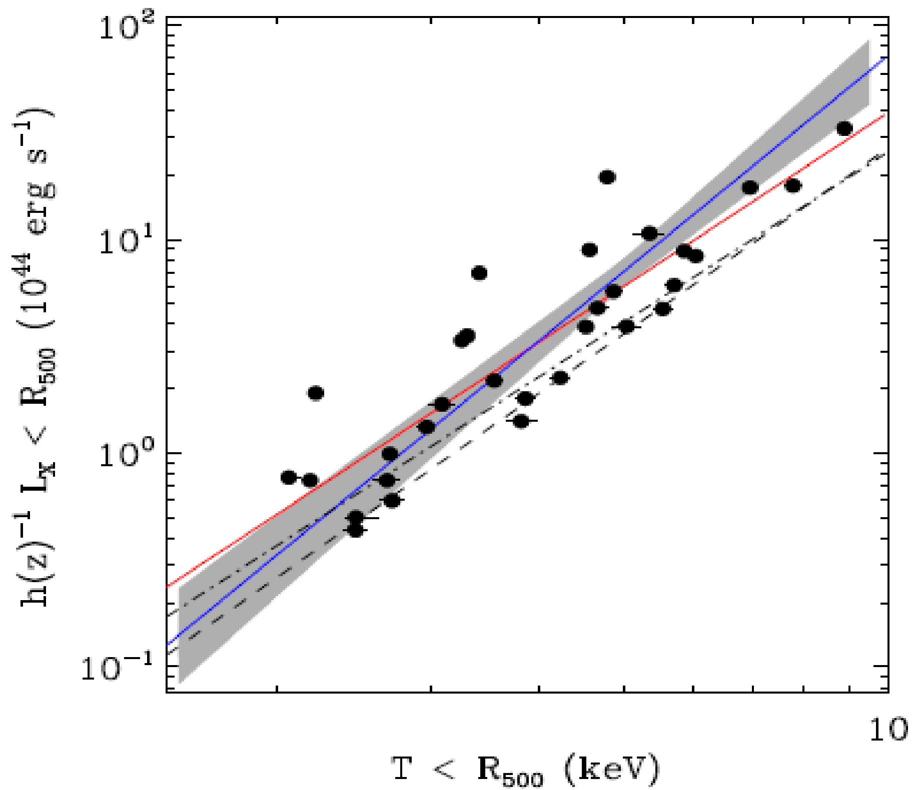
Reiprich & Böhringer 2002

mass distribution

- small scales → assumption of dynamical equilibrium
- Intermediate scales (1-10 Mpc/h)
- large scales → small over-densities → linear theory

can we assume dynamical equilibrium?

from scaling relations... ~yes



Pratt et al. 2009

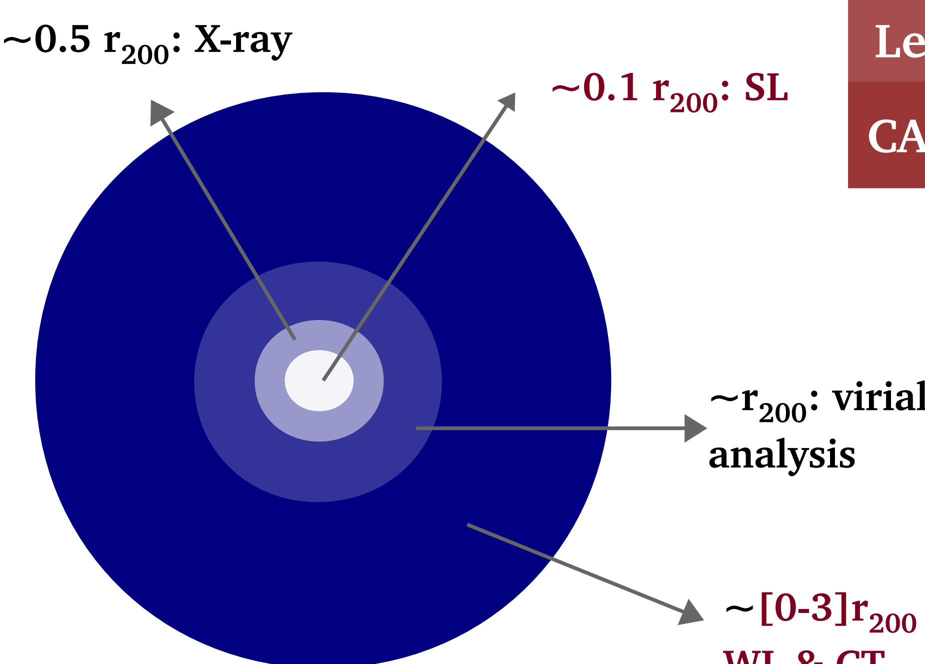
however there are...

spatially inhomogeneous thermal and non thermal emission	kinematic and morphological segregation of galaxies

how to measure the mass of galaxy clusters ?

- Virial theorem
- Jeans Equation
- Scaling relations
- X-ray temperature
- Strong and Weak Lensing
- CAUSTIC TECHNIQUE

No assumption of dynamical equilibrium



r_{200}: radius enclosing a matter density 200 times the critical density of the Universe ~ 277.5 $h^2 M_\odot/\mathrm{Mpc}^3$

total mass within a radius

mass profile

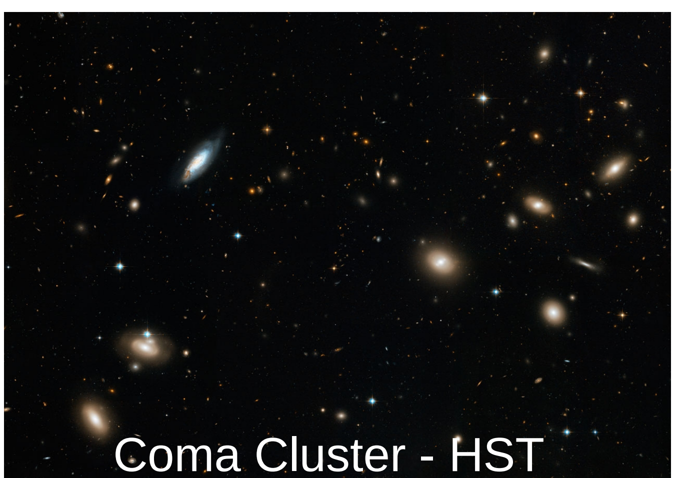
from l.o.s. velocities and position

virial theorem

$$M = \frac{3\sigma^2 R}{G}$$

$$R = \frac{\pi}{2}\frac{N(N-1)}{2}\left(\sum_i \sum_{i>j} \frac{1}{r_{ij}}\right)^{-1}$$

scaling relations



Coma Cluster - HST

Jeans equation

$$M(<r) = \frac{\langle v_r^2 \rangle r}{G}\left[\frac{\mathrm{d}\ln\rho_m}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln\langle v_r^2\rangle}{\mathrm{d}\ln r} + 2\beta(r)\right]$$

$$\beta(r) = 1 - \frac{\langle v_\theta^2 \rangle + \langle v_\phi^2 \rangle}{2\langle v_r^2 \rangle}$$

mass-anisotropy degeneracy
assumption of relation between the galaxy density profile and the mass density profile

dynamical equilibrium + sphericity

total mass within a radius

mass profile

from X-ray

X-ray temperature

isothermal ICM → important departure from assumption in some clusters

scaling relations

the complex thermal structure of the ICM can bias the estimate.

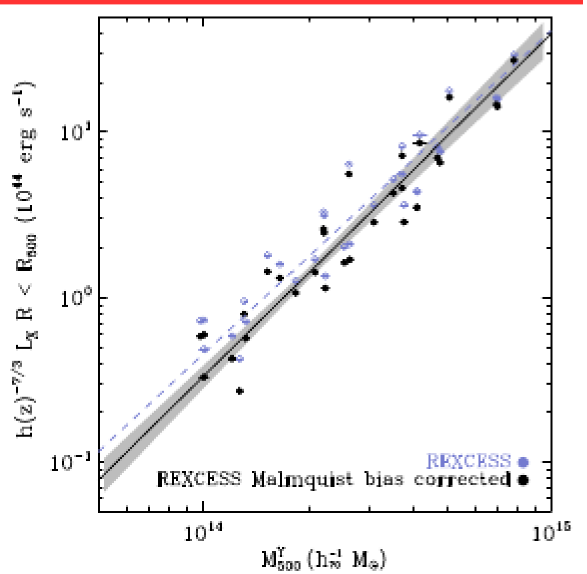
X-ray spectrum

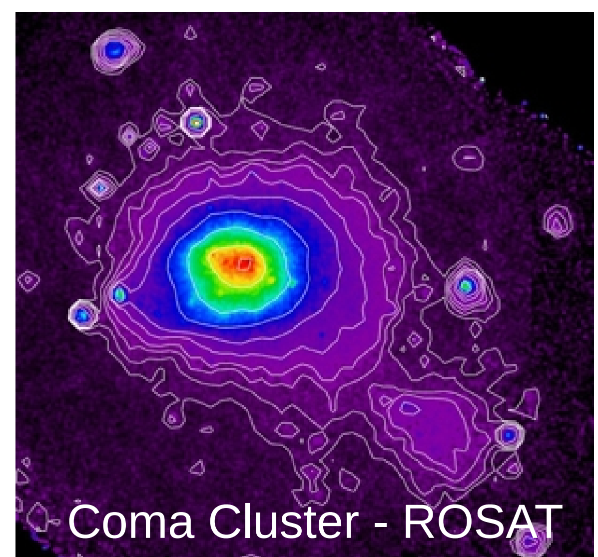
$$M(<r) = \frac{kTr}{G\mu m_p}\left[\frac{\mathrm{d}\ln\rho_{gas}}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln T}{\mathrm{d}\ln r}\right]$$

no β → the ICM pressure is isotropic

dynamical equilibrium + sphericity

Pratt et al. 2009





total mass within a radius

mass profile

from lensing signal

Strong lensing

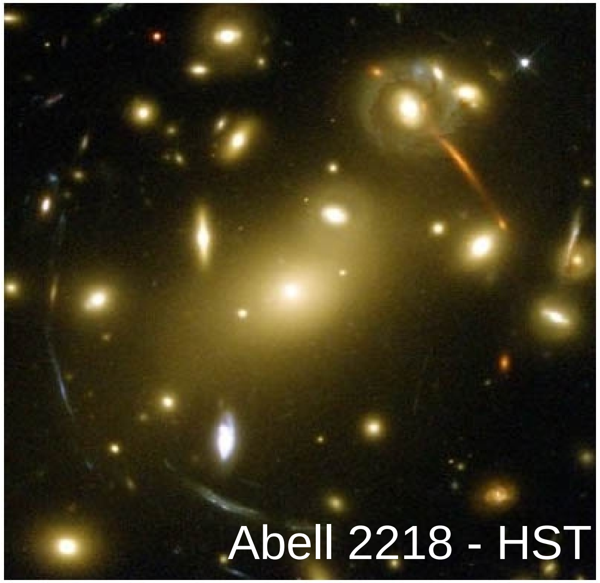
multiple images, arcs

$$M(<r) = \frac{rc^2}{4G}\alpha$$

Weak lensing

tangential distortion of the shape of galaxies

disadvantage: the signal intensity depends on the distances between observer, lens and source



from l.o.s. velocities and position

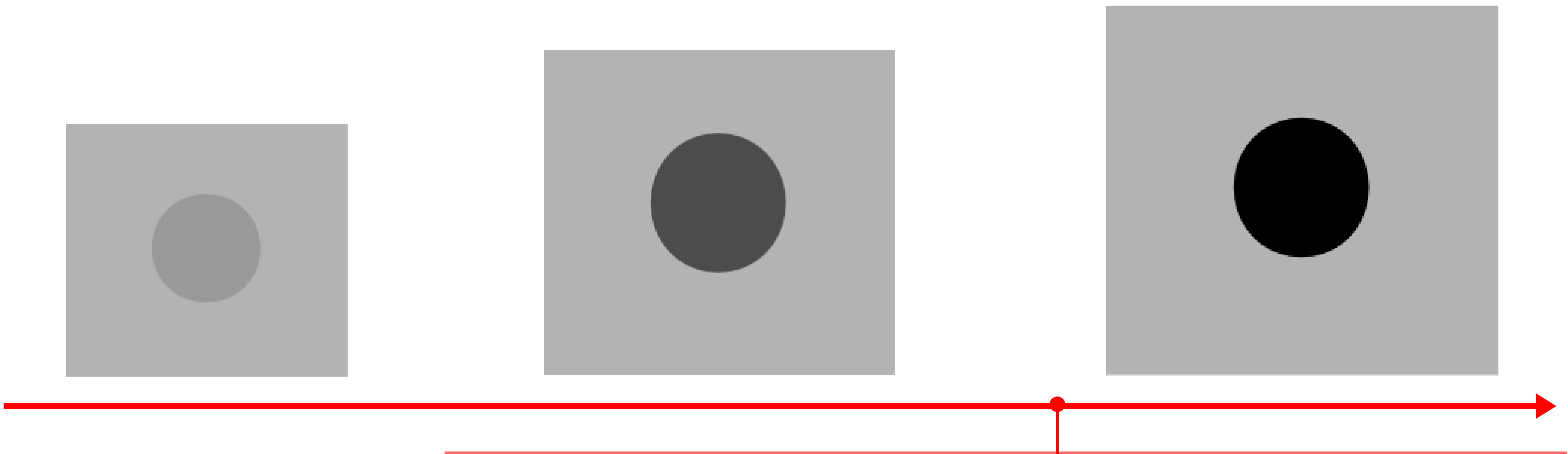
Caustic technique

in hierarchical models of structure formation, the velocity field surrounding the cluster is not perfectly radial, as expected in the spherical infall model

↓

it is possible to extract the escape velocity of galaxies from the redshift diagram

dynamical equilibrium + sphericity



evolves like a Friedmann model (expanding medium)

for any small density perturbation there will be a competition between its self-gravity (which is attempting to increase the density) and the general expansion of the universe (which decreases the density)

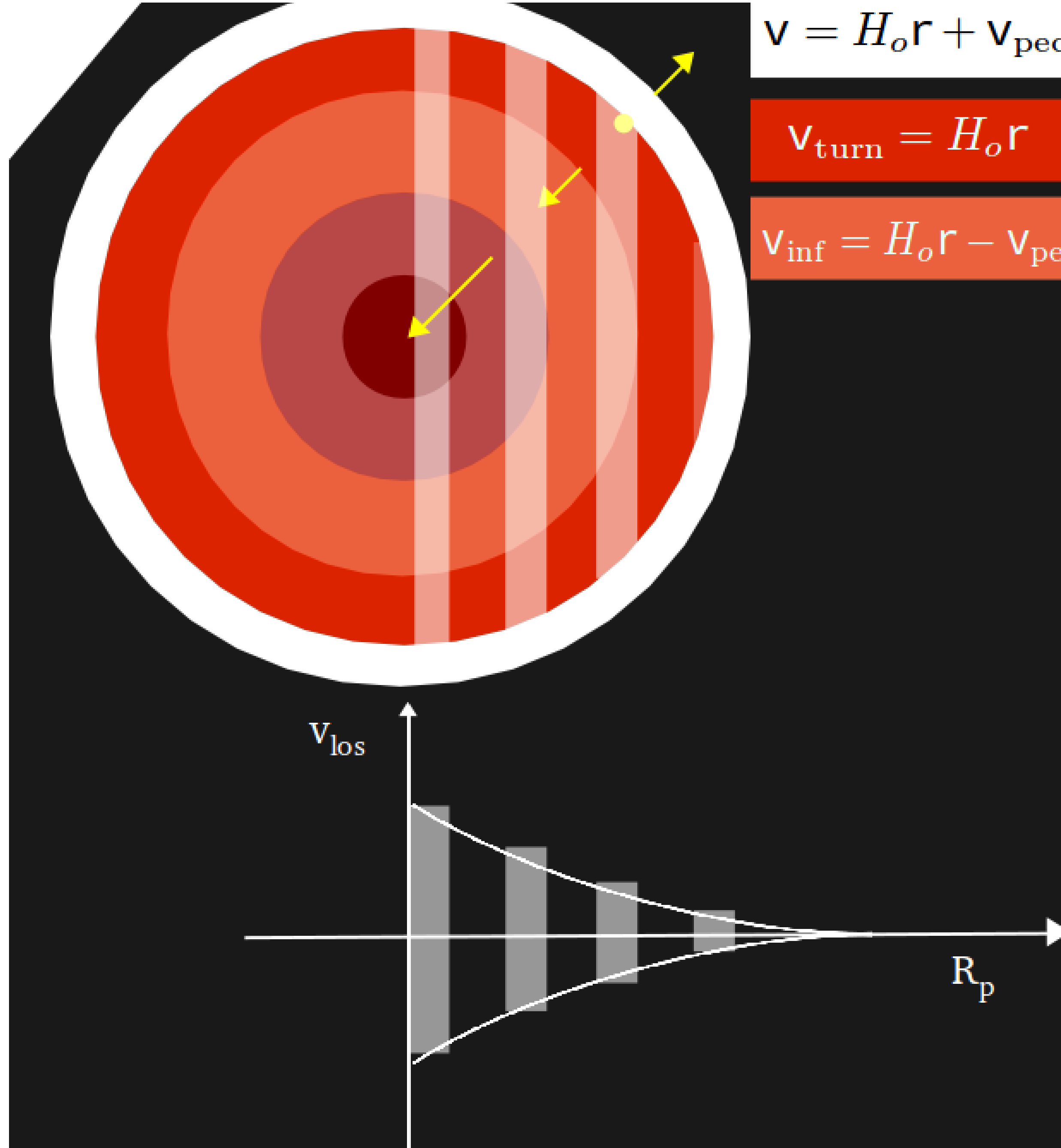
structures will be formed if, at some time, the spherical region ceases to expand with the background universe and begins to collapse

When observed in redshift space, the infall pattern around a rich cluster appears as a “trumpet” whose amplitude $\mathcal{A}(\theta)$ decreases with θ (Kaiser, 1987)

from spherical infall model

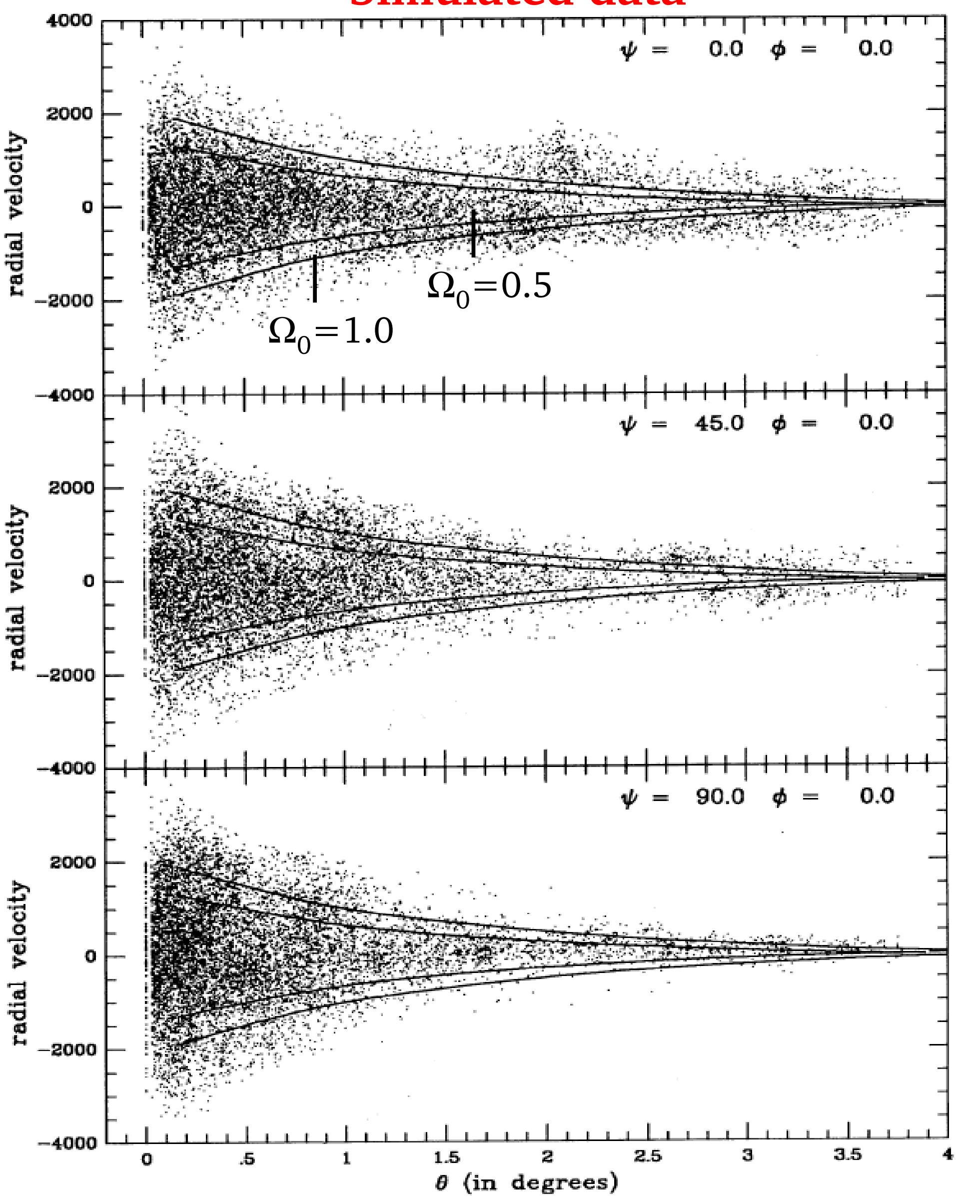
(Regös & Geller, 1989)

$$\mathcal{A}(\theta) \sim \Omega_0^{0.6} r f(\delta) \sqrt{-\frac{\mathrm{d}\ln f(\delta)}{\mathrm{d}\ln r}}$$



Simulated data

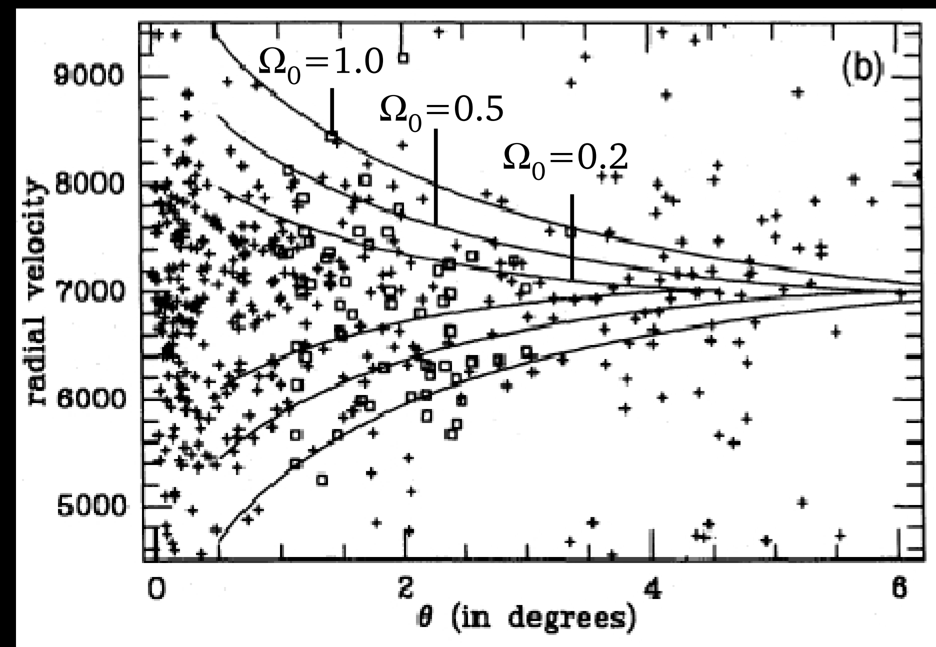
Line-of-sight velocity



projected distance to the center

van Haarlem & van de Weygaert 1993

Real data Coma cluster



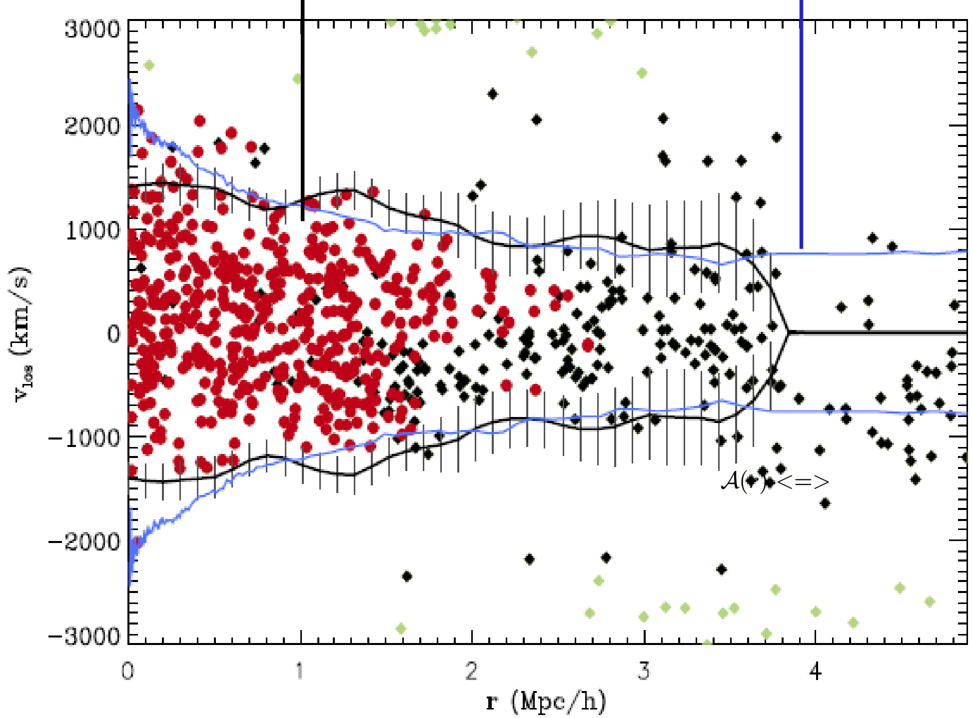
van Haarlem et al. 1993

but clusters accrete mass anisotropically
→ the velocity field can have a substantial non-radial random component

$\mathcal{A}(r) <=>$ **escape velocity**

Caustics located by the caustic technique

Caustics determined by the escape velocity

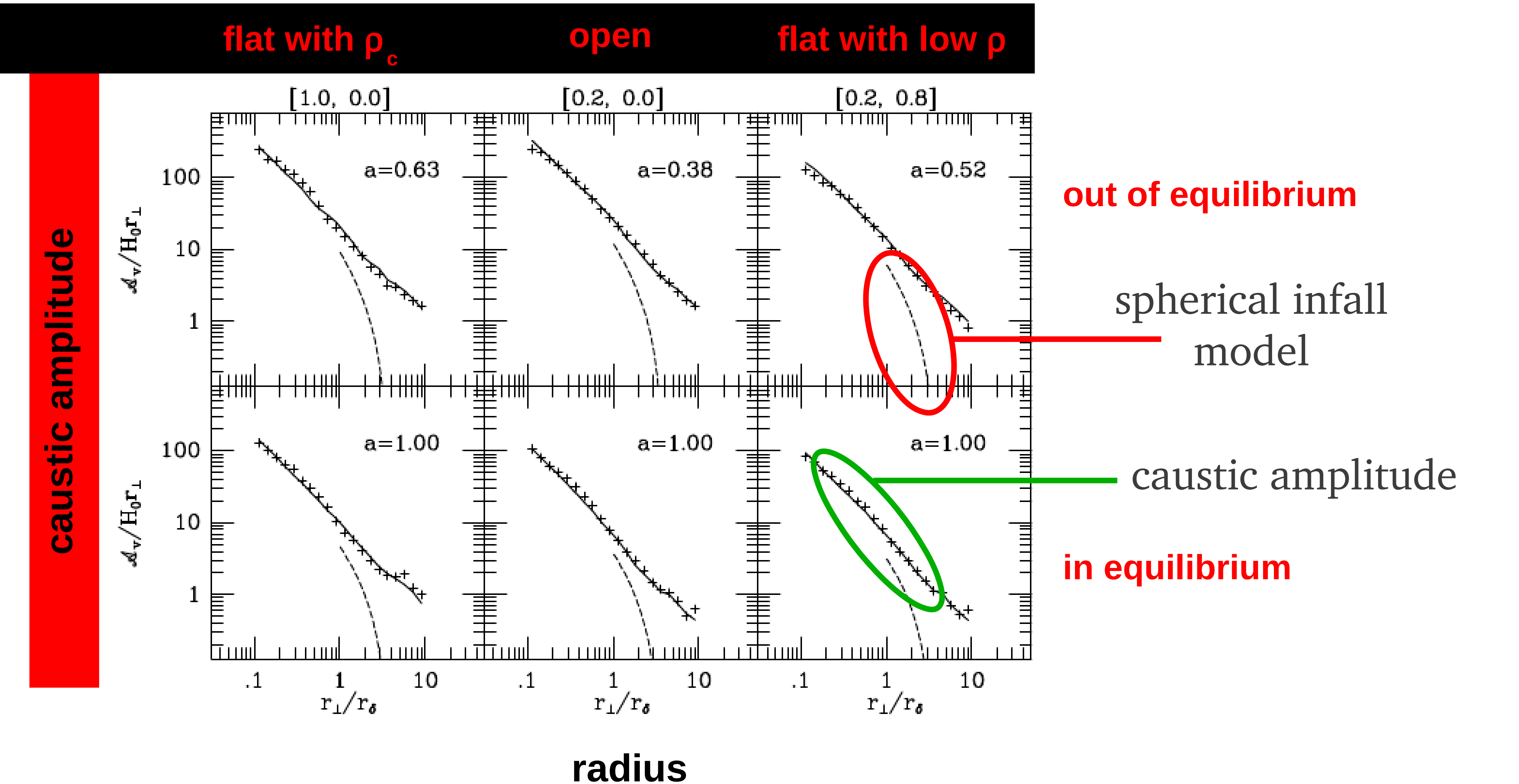


The random components increase the caustic amplitude when compared to the spherical model

but clusters accrete mass anisotropically
→ the velocity field can have a substantial non-radial random component

$$\mathcal{A}_{\rm infall\,model} < \mathcal{A}_{\rm non-radial}$$

$\mathcal{A}(r)$ <=> escape velocity



Diaferio & Geller 1997

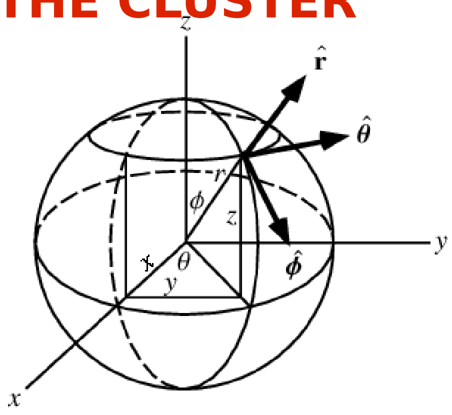
Interpretation: $\mathcal{A}(\theta)$ is the average over a volume $d^3\mathbf{r}$ of the square of the l.o.s. component of the escape velocity

$$\mathcal{A}^2(r) = \langle v^2_{esc,los} \rangle$$

$$\langle v^2_{esc,los} \rangle = -2\phi(r) g^{-1}(\beta)$$

$$\beta(r) = 1 - \frac{\langle v_\theta^2 \rangle + \langle v_\phi^2 \rangle}{2\langle v_r^2 \rangle}$$

HOLDS INDEPENDENTLY OF THE DYNAMICAL STATE OF THE CLUSTER



$$\mathcal{A}_{\text{infall model}} < \mathcal{A}_{\text{non-radial}}$$

Mass estimate

$$\mathcal{A}^2(r) = \langle v^2_{esc,los} \rangle$$

$$\langle v^2_{esc,los} \rangle = -2\phi(r) g^{-1}(\beta)$$

mass of an infinitesimal shell

$$G\,\mathrm{d}m = -2\phi(r)\mathcal{F}(r)\,\mathrm{d}r = \mathcal{A}^2(r) g(\beta)\mathcal{F}(r)\,\mathrm{d}r$$

where $\mathcal{F}(r) = \dfrac{-2\pi G\rho(r) r^2}{\phi(r)}$ and

$\mathcal{F}_\beta(r) = \mathcal{F}(r) g(\beta)$ is a slowly changing function of r

theoretical framework of the

CAUSTIC TECHNIQUE

$$GM(<r) = \mathcal{F}_\beta \int_0^r \mathcal{A}^2(r)\,\mathrm{d}r$$

Developed in the '90s
(Diaferio & Geller, 1997;
Diaferio, 1999)
Problem: it requires hundreds of galaxy redshifts

nowadays the required data are easily collectable

CAUSTIC TECHNIQUE

Can be applied for

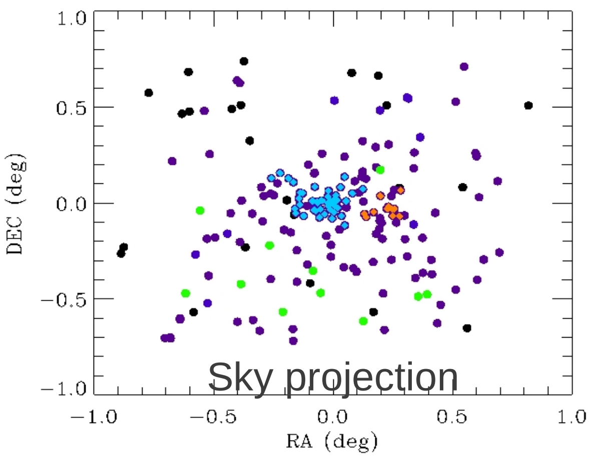
- MASS/POTENTIAL ESTIMATES
- IDENTIFICATION OF MEMBERS
- [IDENTIFICATION OF SUBSTRUCTURES]

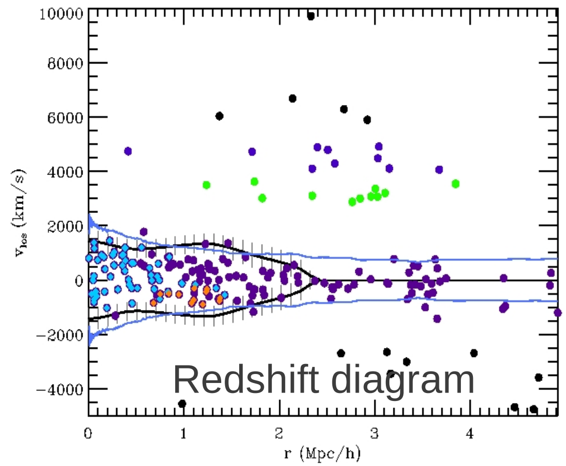
to simulated and real data

1. arrange the galaxies in a binary tree according to a hierarchical method
2. select two thresholds to cut the tree: the largest group obtained from the upper-level threshold identifies the cluster candidate members
3. build the redshift diagram of all the galaxies in the field; locate the caustics, and identify the final cluster members
4. the caustic amplitude determines the escape velocity and mass profiles

four steps

1 Binary tree & σ-plateau



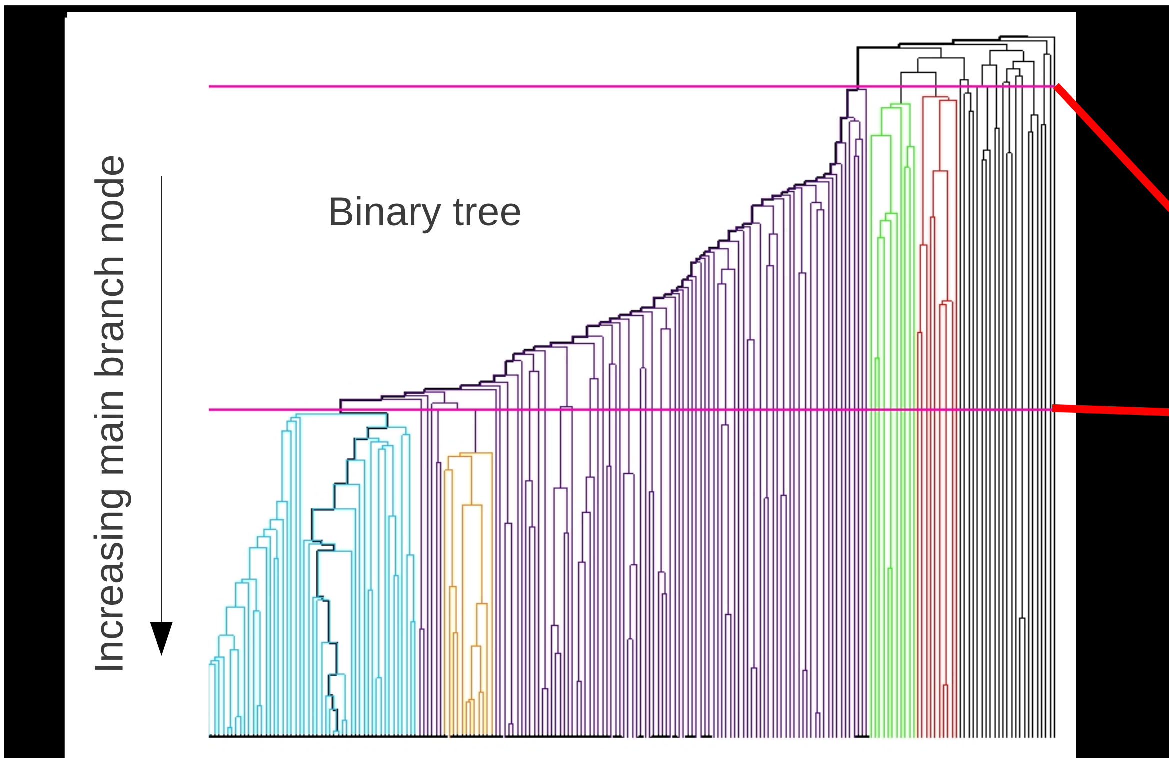


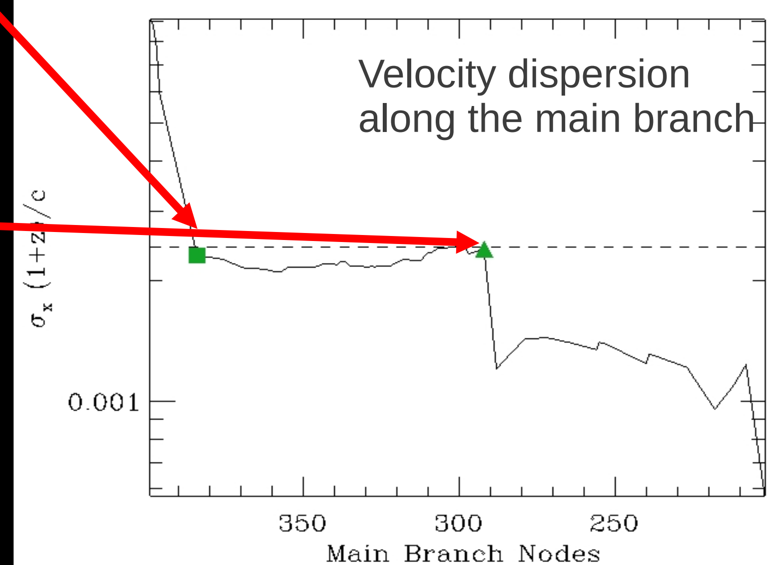
binding energy

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

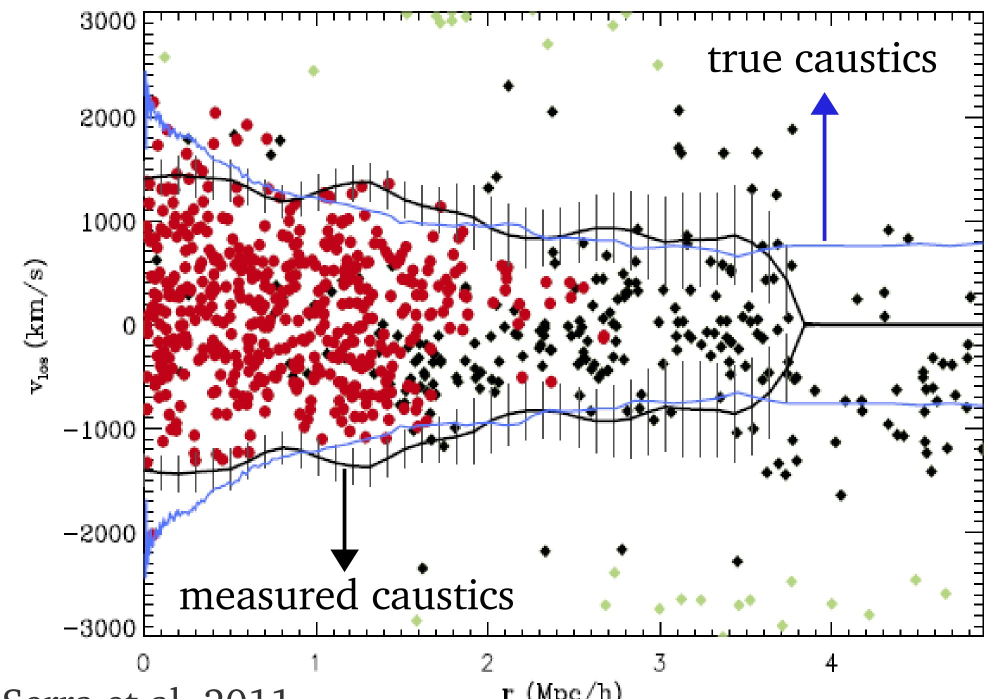
Binary Tree

- **σ plateau**
- **main group members**
- **size R, center**

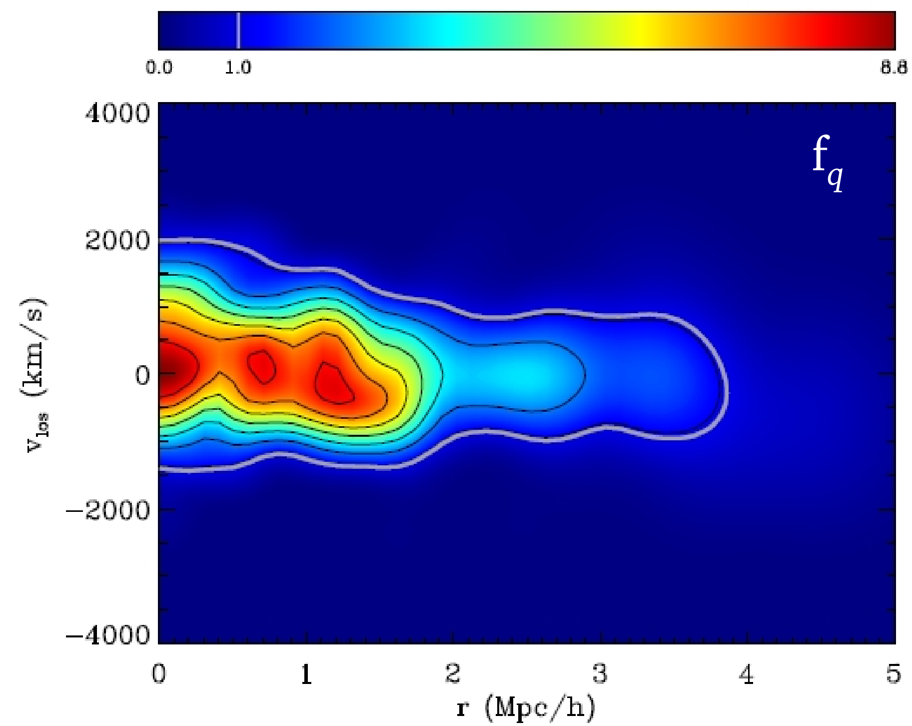




2 Redshift diagram



Serra et al. 2011



3 Caustic location

we choose the parameter κ that determines the correct caustic location as the root of the equation

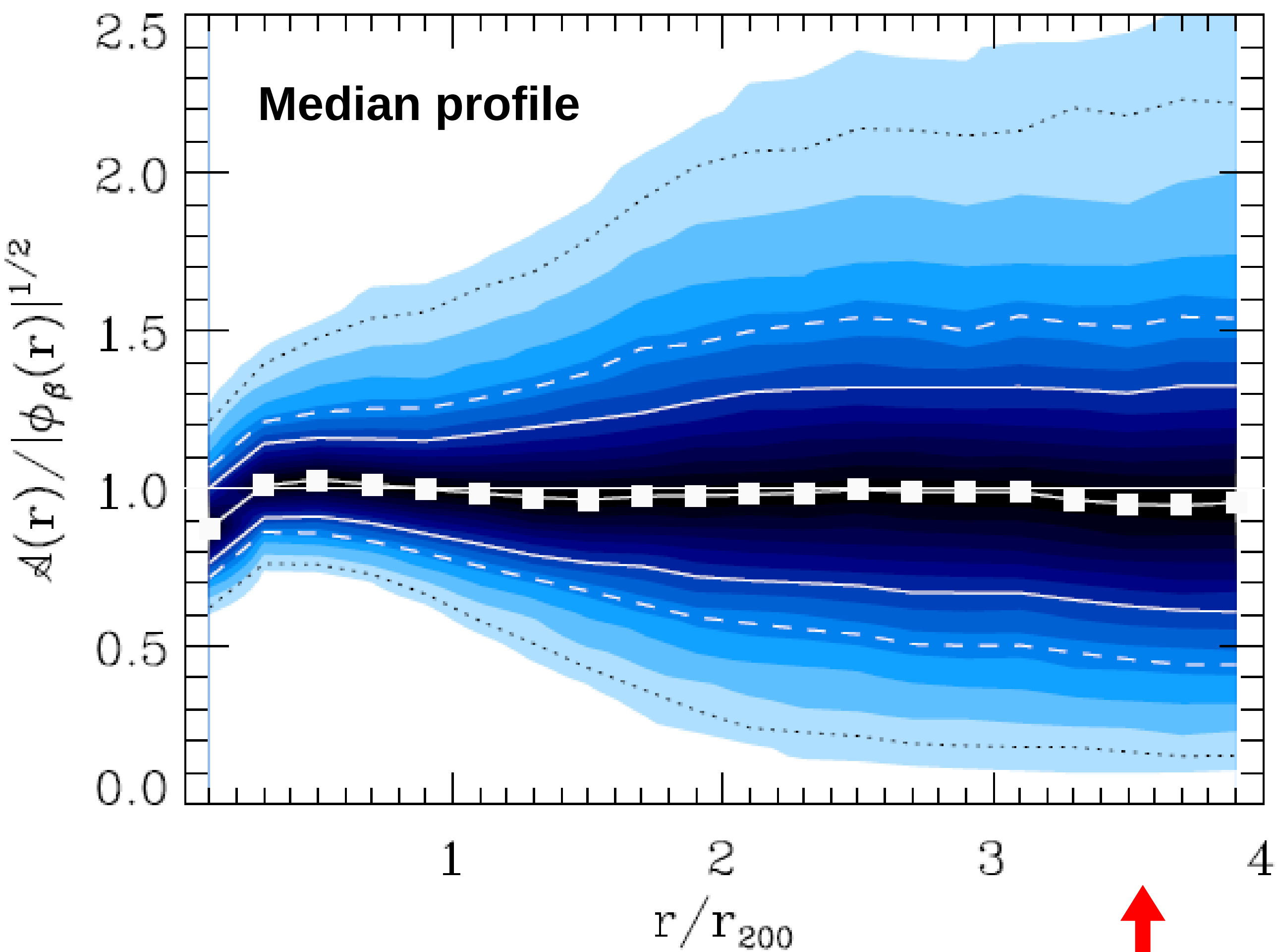
$$S(\kappa) \equiv \langle v_{\rm esc}^2 \rangle_{\kappa,R} - 4\langle v^2 \rangle = 0$$

distribution of N galaxies

$$f_q(\mathsf{x}) = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{h_i^2}K\left(\frac{\mathsf{x}-\mathsf{x}_i}{h_i}\right)$$

$$\mathsf{x} = (r, v)$$

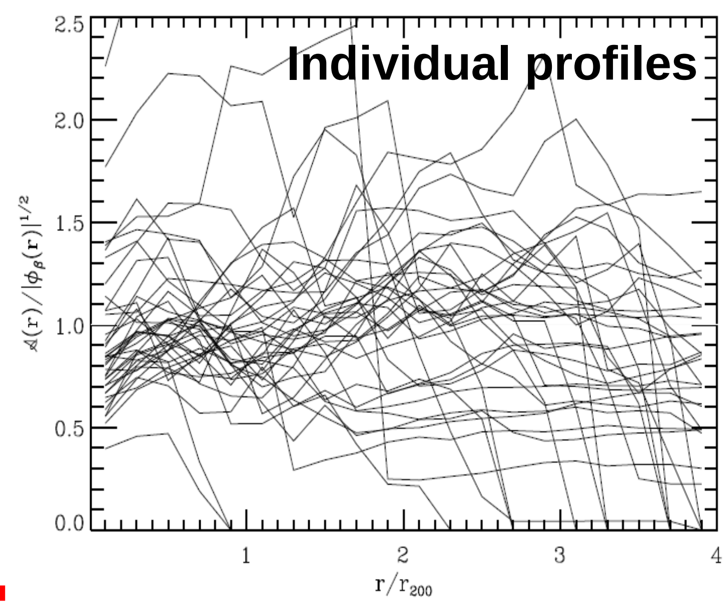
3 Gravitational potential profiles



Escape velocity: better than 10% up to $r \sim r_{200}$

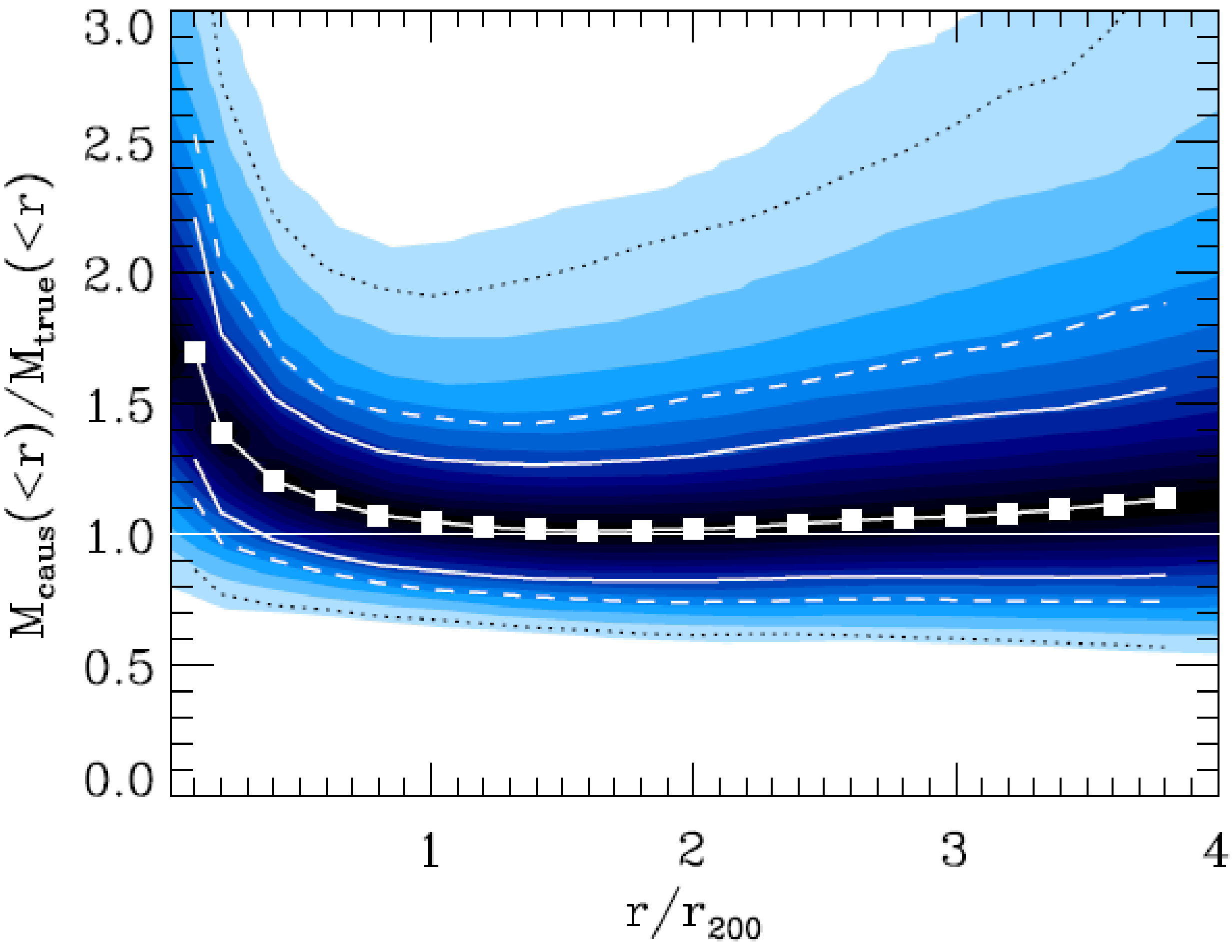
3000 simulated clusters with $M_{200} \geq 10^{14}\ h^{-1} M_\odot$

from simulation by Borgani et al. 2004



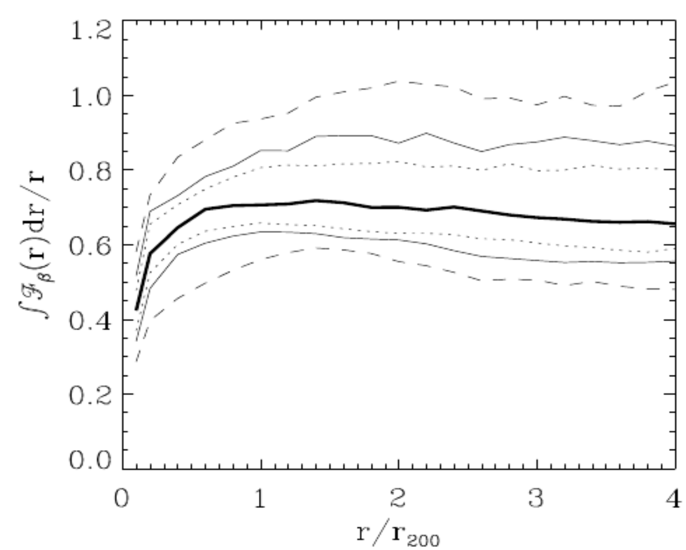
Serra et al. 2011

4 Mass profiles



- (0.6-4) r_{200}→ better than 15%
- $r<0.6\ r_{200}$→ overestimation of the mass up to 70%

3000 simulated clusters with $M_{200} \geq 10^{14}\ h^{-1} M_{\odot}$



Serra et al. 2011

$$GM(<r) = \mathcal{F}_\beta \int_0^r \mathcal{A}^2(r)\,\mathrm{d}r$$

Stacked cluster

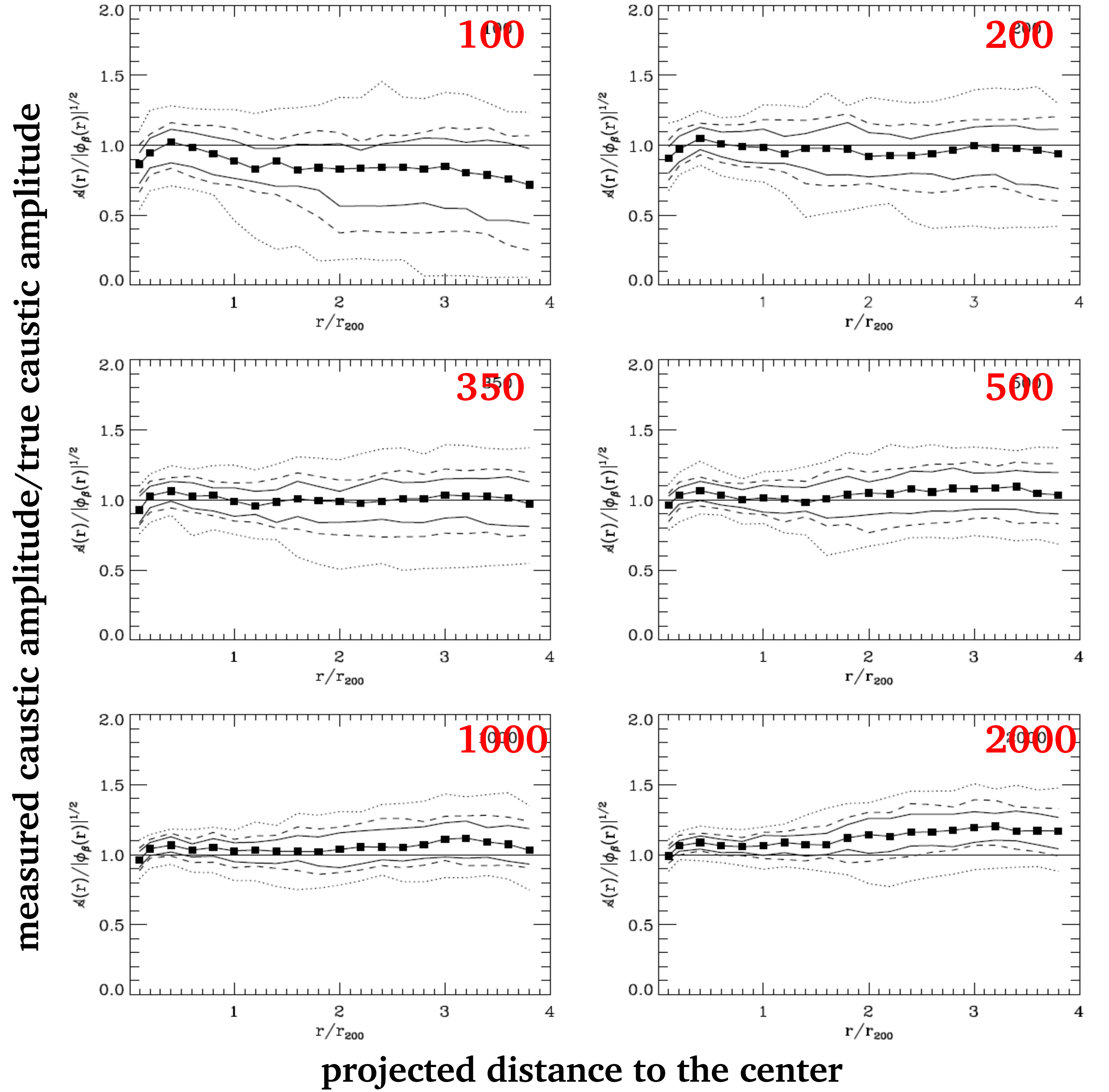
$|v^{x}_{los} - v^{clus}_{los}| = 2000$ km/s

30' × 30'

$z^{clus} = 0.1$

30' → 2.46 Mpc/h

spread decreases with increasing number of galaxies



Serra et al. 2011

Applications to real systems

Coma (Geller et al. 1999) → NFW profile fits cluster density profile

Cluster and Infall Region Nearby Survey (CAIRNS) (Rines et al. 2003)

CIRS (Rines & Diaferio, 2006): 72 X-ray selected clusters with galaxy redshifts extracted from DR4-SDSS. Largest sample of clusters have been measured out to $\sim 3r_{200}$ → virial mass function → cosmological parameters consistent with WMAP (Rines et al. 2007, 2008)

Groups of galaxies: 16 groups – NFW profile confirmed (Rines & Diaferio, 2008)

43 stacked clusters from 2dF (Biviano & Girardi, 2003)

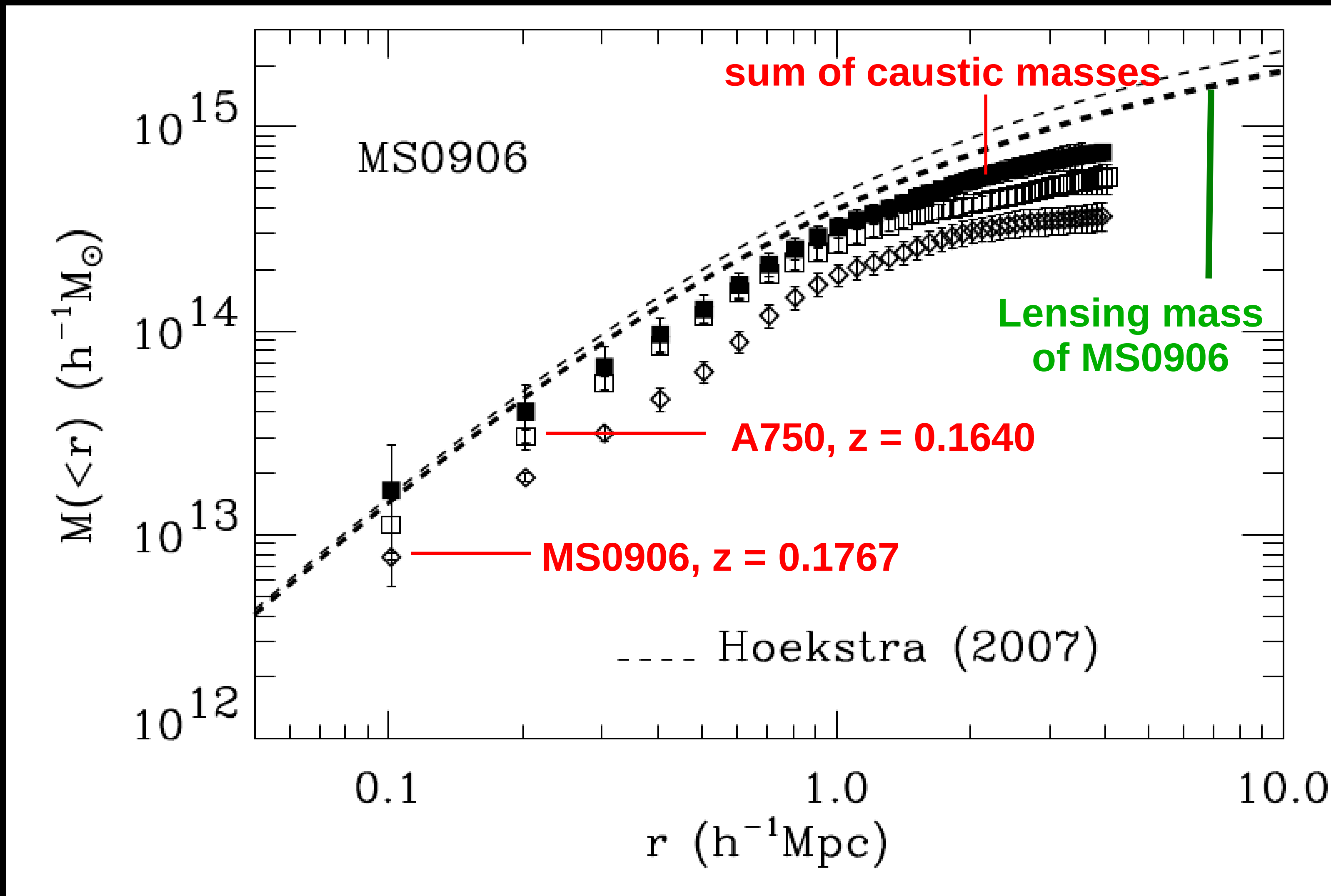
Unrelaxed systems: Shapley superclusters (Reinsenegger et al. 2000, Davidzon et al. in prep), Fornax cluster (Drinkwater et al. 2001), A2199 (Rines et al. 2002)

Coma and CL0024 to measure w_{DM} (Serra & Dominguez, 2011)

Individual systems (Mahdavi et al. 2005; Lemze et al. 2009; Lu et al. 2010)

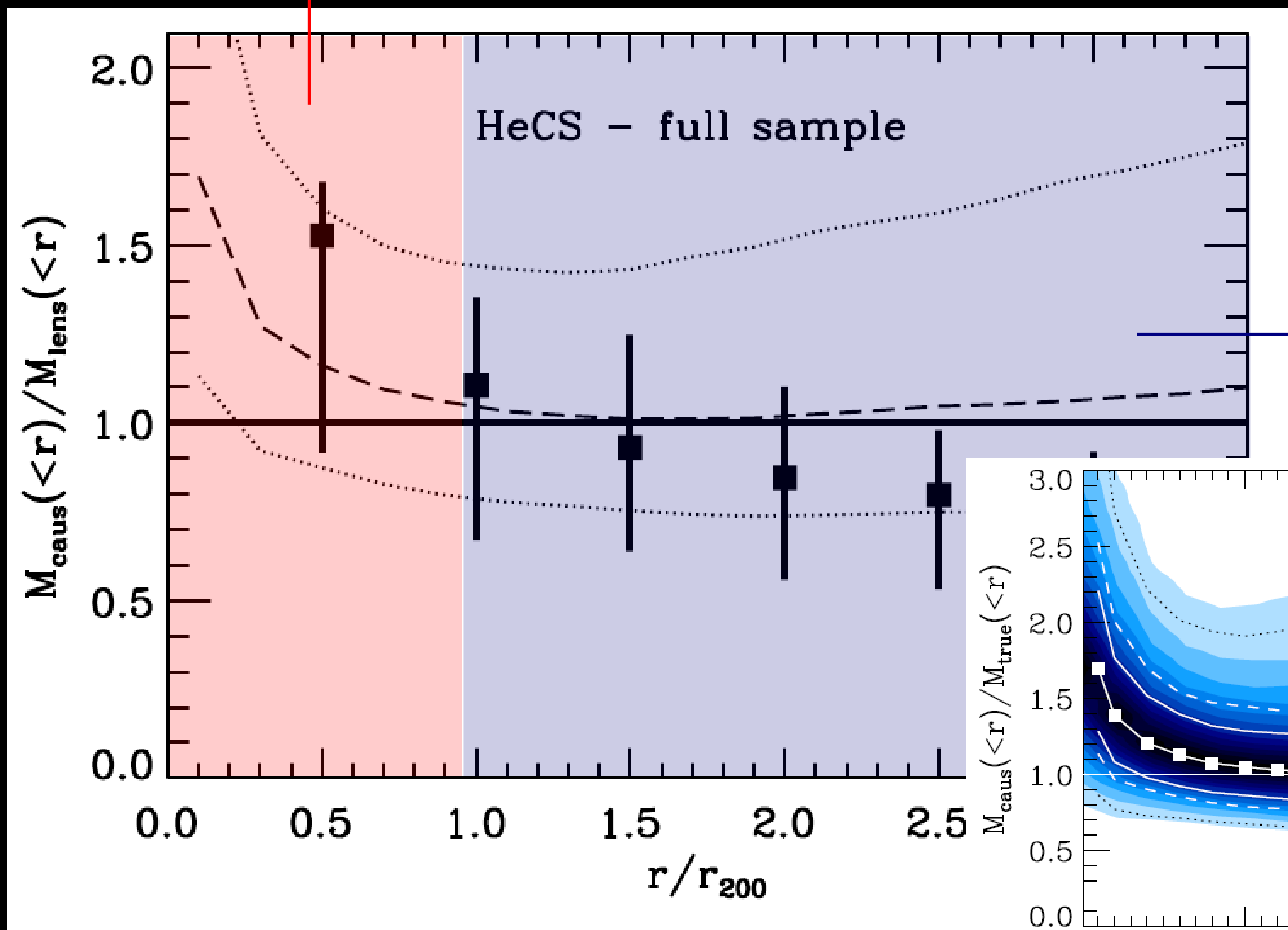
HeCS (Hectospec Cluster Survey; Rines et al. 2012): clusters in the redshift range $0.1 < z < 0.3$; more than 20,000 new redshifts; 17 clusters with WL mass profiles

caustics	lensing
requires	
wide-field redshift survey sufficiently dense survey	wide-field photometric survey redshift where signal is sufficiently strong
yields	
3D mass profile affected by projection	projected mass profile along the line of sight

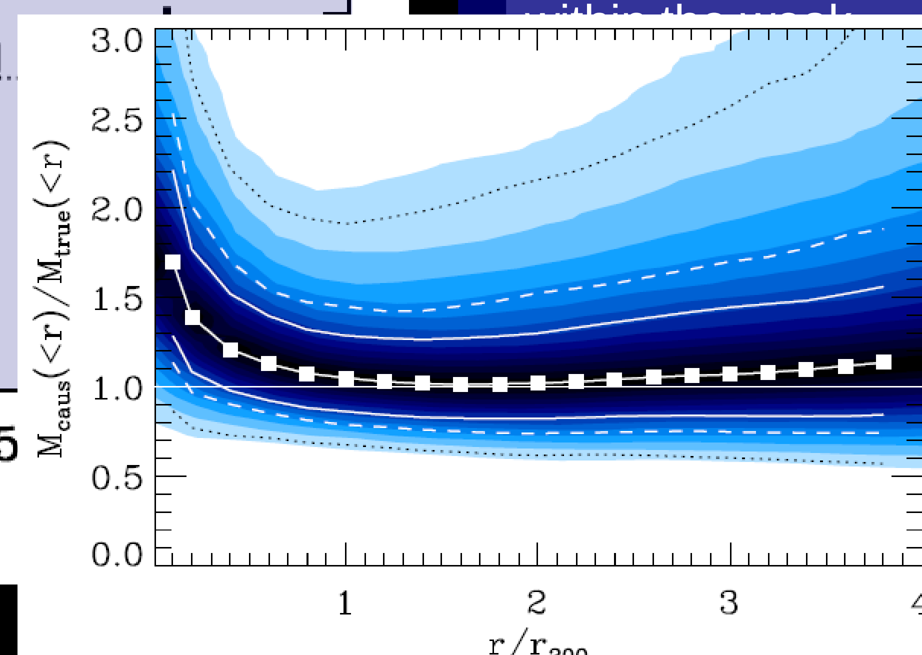


Geller et al. submitted

the caustic technique overestimates the mass in the inner regions



potential biases produced by large-scale structure superposed



Geller et al. submitted

Membership

To study the dependence of properties on the environment we need to know whether a galaxy is member of a cluster

line-of-sight velocity

3σ clipping (Yahil & Vidal 1977): velocity distribution close to gaussian

gap method (Zabludoff et al.1990; Beers et al. 1990)

adaptive kernel method (Pisani 1993) probability density underlying the data

gaussian plus a constant function: fit to the velocity distribution (McKay et al. 2002)

+ projected radius

velocity of a galaxy depends on the gravitational potential profile of the cluster

escape velocity profiles → caustic technique

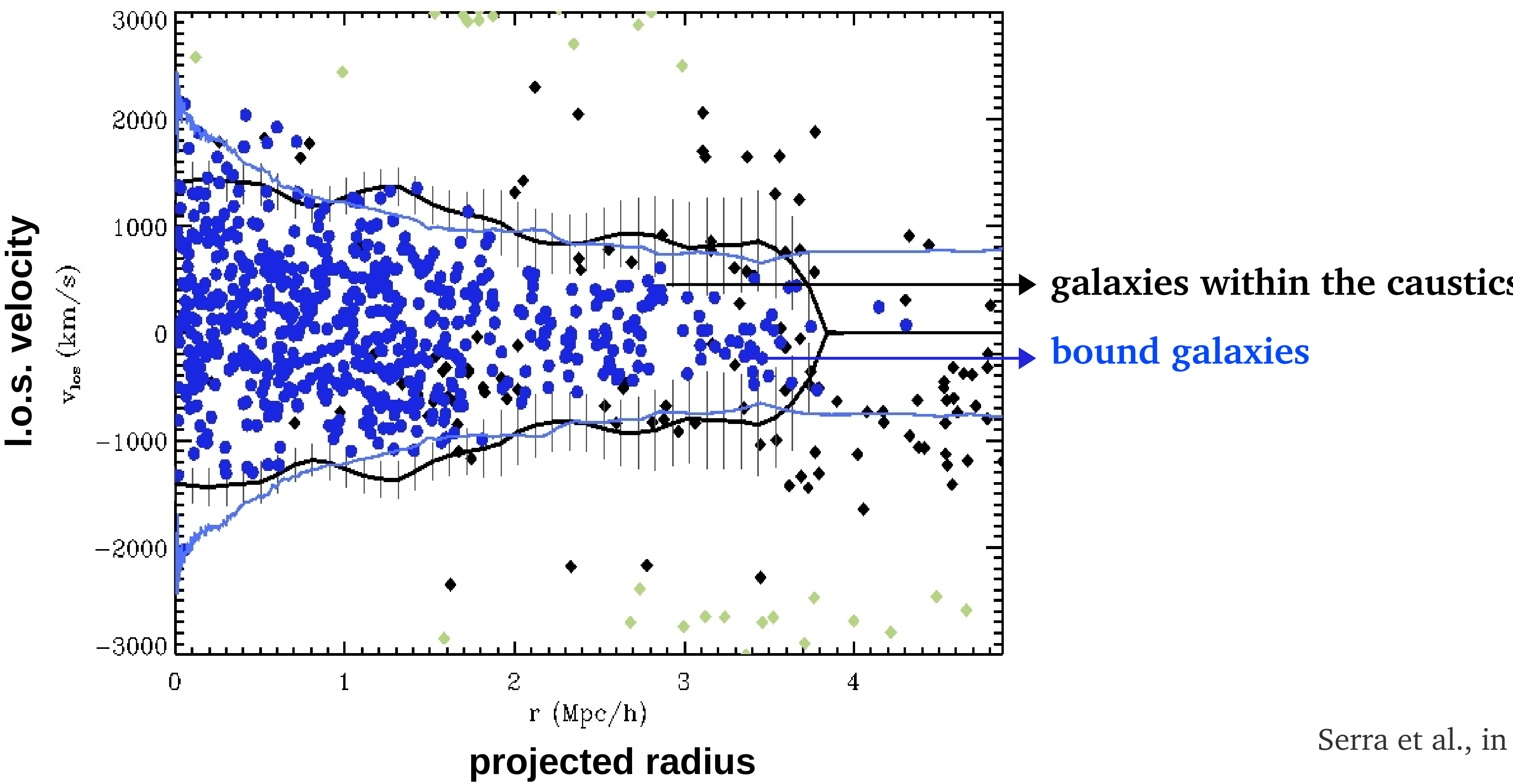
+ dependence of the VD on the projected distance to the center (Prada et al. 2003)

fit to σ_{los} according to the Jeans formalism ($\beta = 0$) (Lokas et al. 2006)

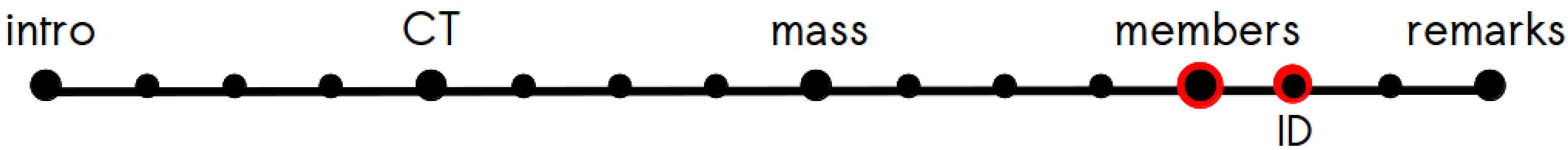
$v_{max}(R)$ from the mass distribution (den Hartog & Katgert, 1996)

boundary lines $\pm v_{lim}(R)$ on the velocity diagram (Wojtak et al. 2007)

Membership

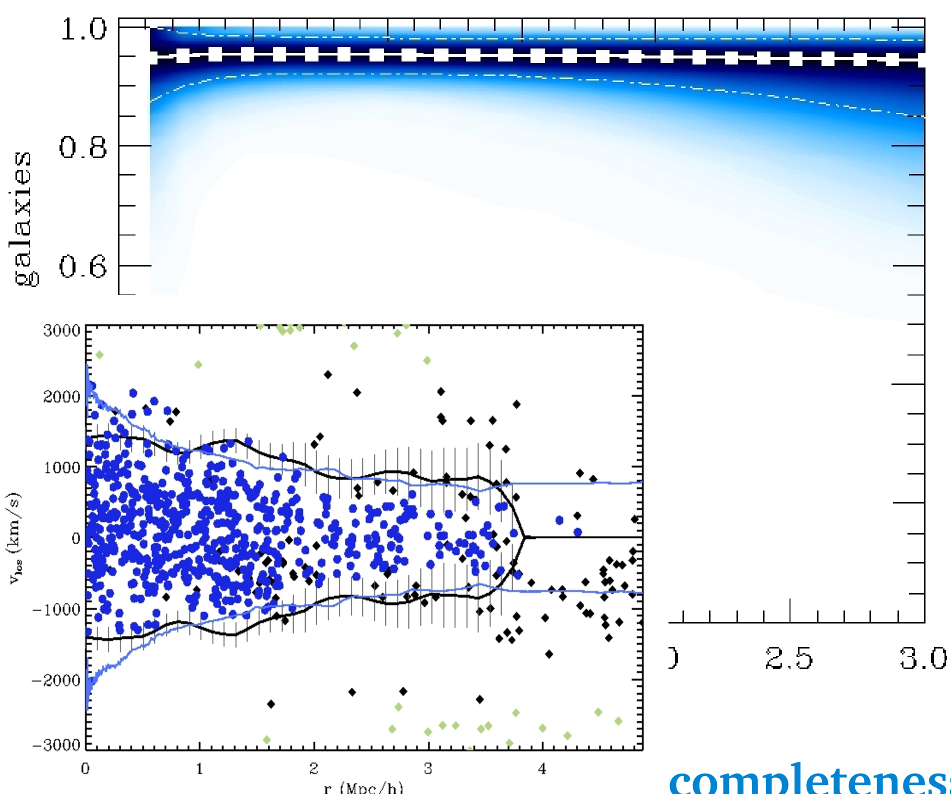


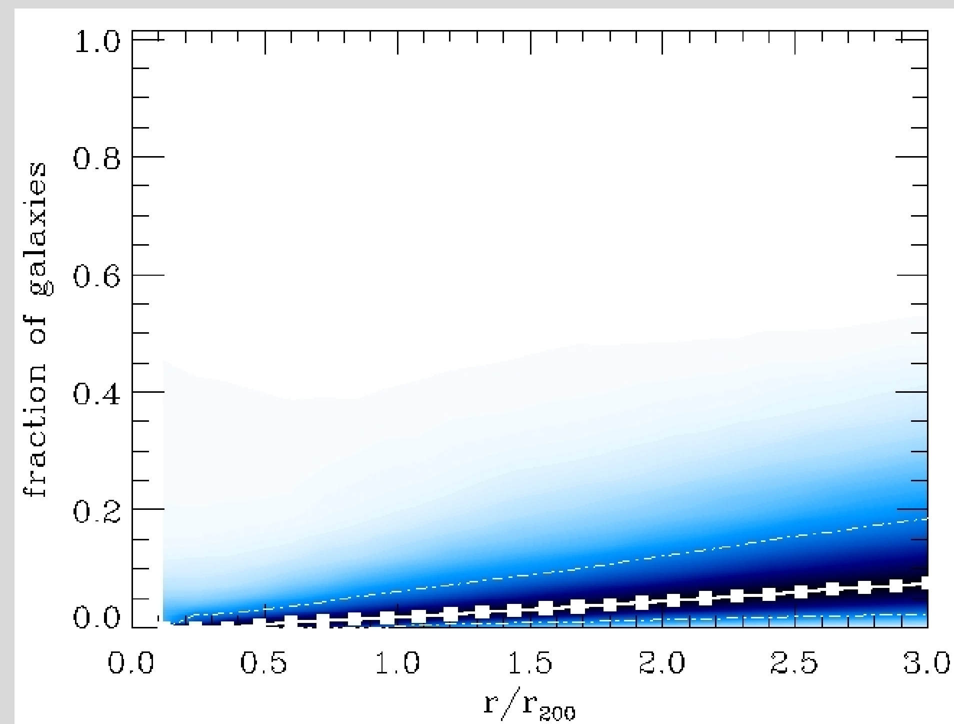
Serra et al., in prep



galaxies within caustics compared with bound galaxies

Serra et al., in prep

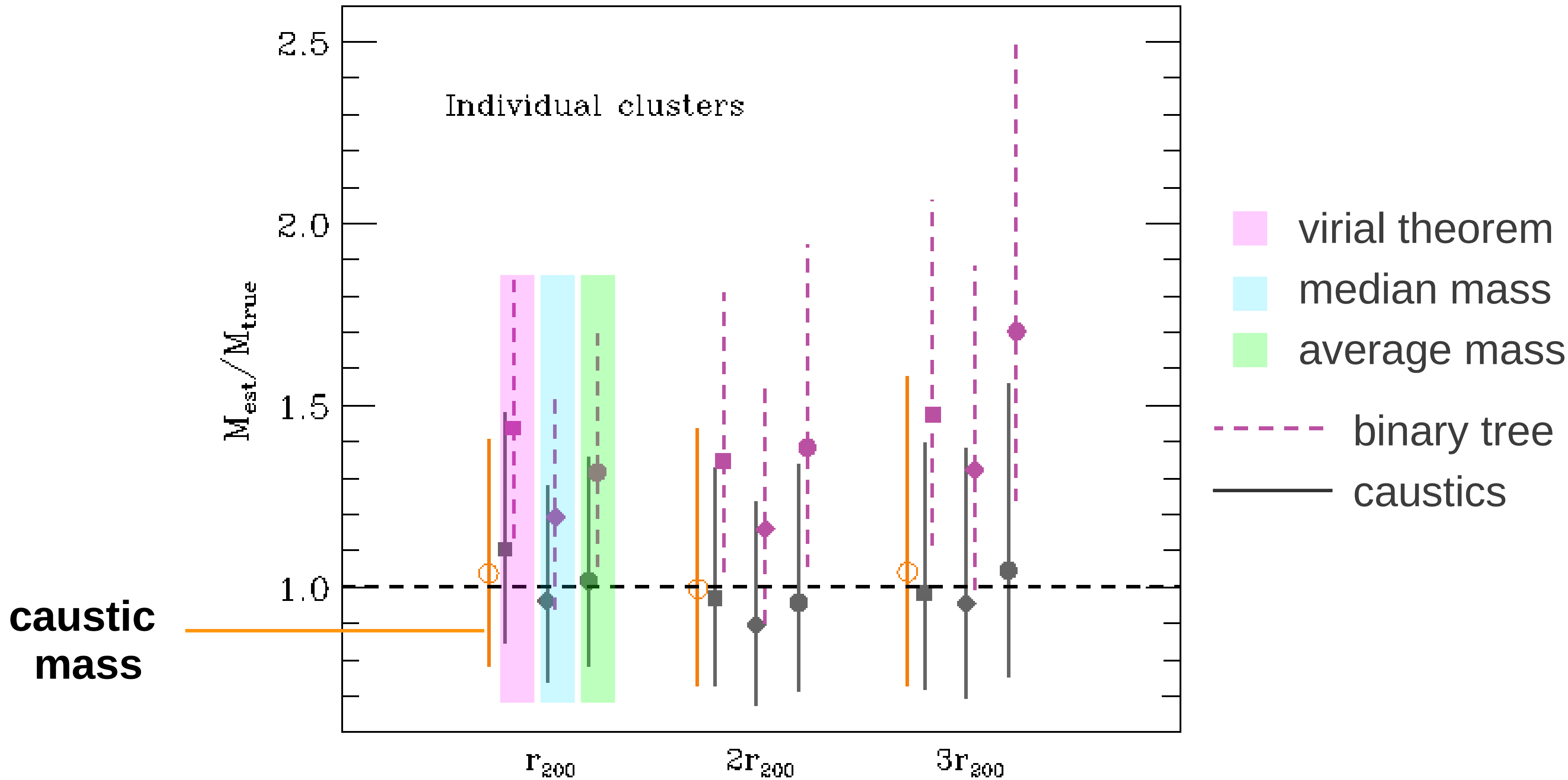




	completeness			contamination		
	-1σ	median	$+1\sigma$	-1σ	median	$+1\sigma$
r_{200}	0.921	0.956	0.984	0.005	0.020	0.066
$2r_{200}$	0.908	0.951	0.981	0.015	0.047	0.126
$3r_{200}$	0.875	0.947	0.980	0.027	0.080	0.193

Serra et al., in prep

Mass estimates



The caustic location performs systematically better in removing interlopers and, on average, the bias in the mass estimate is minimized

Serra et al., in prep

Remarks

the caustic technique and gravitational lensing are the only two methods available to measure the mass profile of clusters beyond the virial radius without assuming dynamical equilibrium

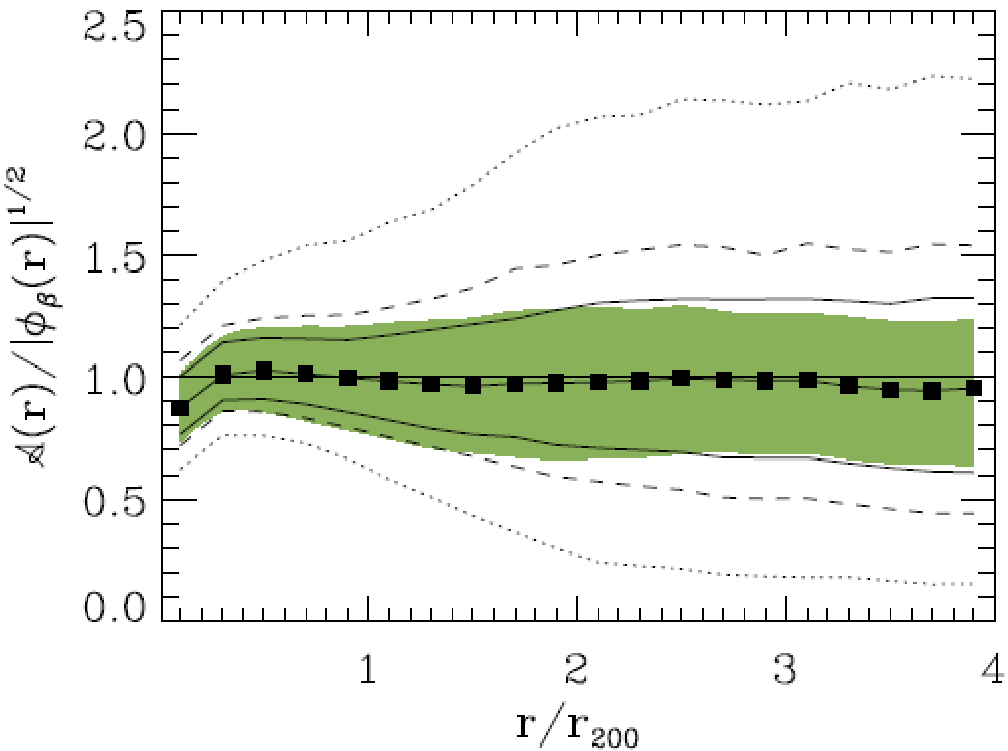
~200 gxs in a field of 2.46 Mpc/h x 2.46 Mpc/h are enough to have an accurate escape velocity profile

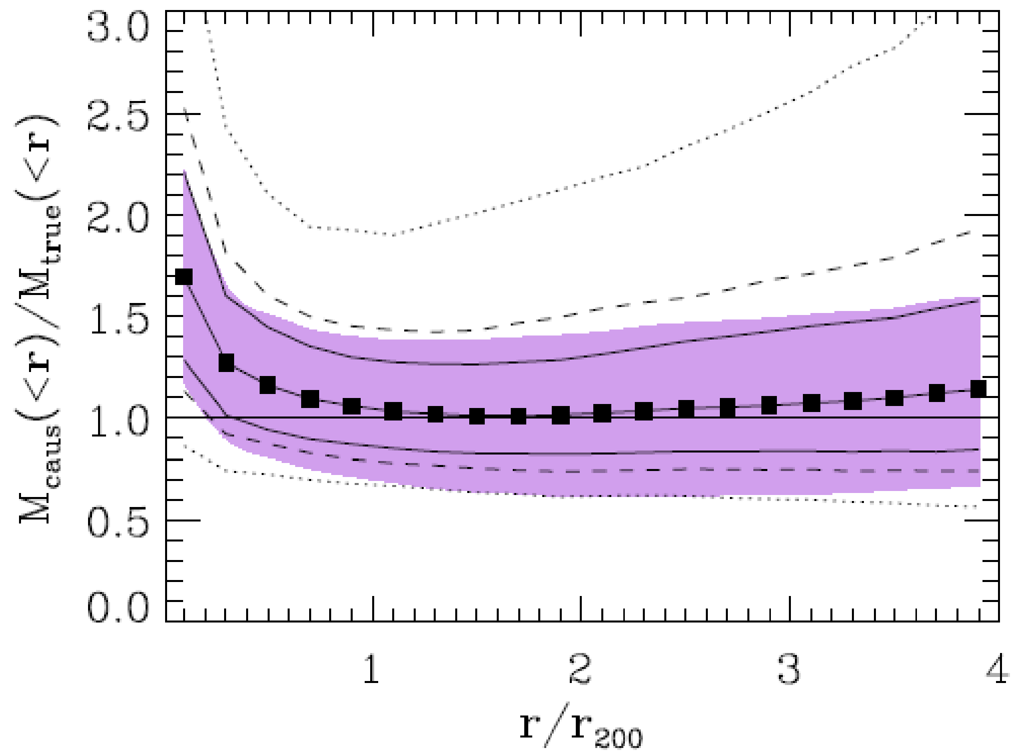
$F_\beta(r)$ is not constant in the inner parts of the cluster → overestimation of the mass

spread due to projection → but the formal errors account for that

$$\delta M_i = \sum_{j=1,i} |2 m_j \delta \mathcal{A}(r_j) / \mathcal{A}(r_j)|$$

Remarks





$$\delta M_i = \sum_{j=1,i} |2 m_j \delta \mathcal{A}(r_j)/\mathcal{A}(r_j)|$$

Remarks

the applications of the caustic technique to a large sample of simulated clusters demonstrated that the escape velocity is recovered with ~25% 1-σ uncertainty and the mass profile with ~50% 1-σ uncertainty

the median ratio of the caustic and weak lensing mass profile in the 19 HeCS clusters is within the 68% confidence limits of the ratio between the true and caustic mass profiles derived from N-body simulations. At radii $< r_{200}$, the caustic approach overestimated the mass. Near the virial radius ($\sim 1.3 r_{200}$) the profiles agree to ~ 30%.

thank you!