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

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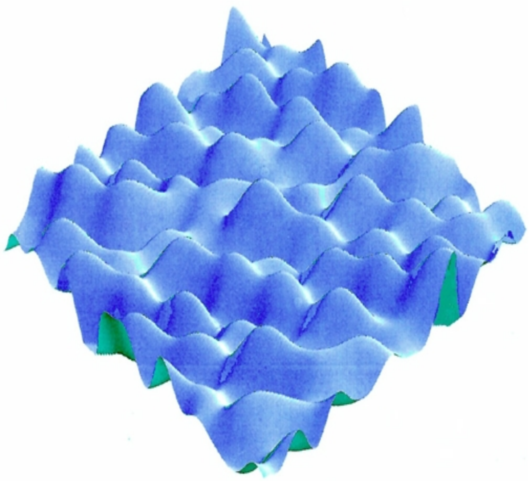
Where does a galaxy cluster come from?

Abell 1689 observed by the Hubble Space Telescope

Formation of large-scale structure in the Universe

Early Universe
(small perturbations)



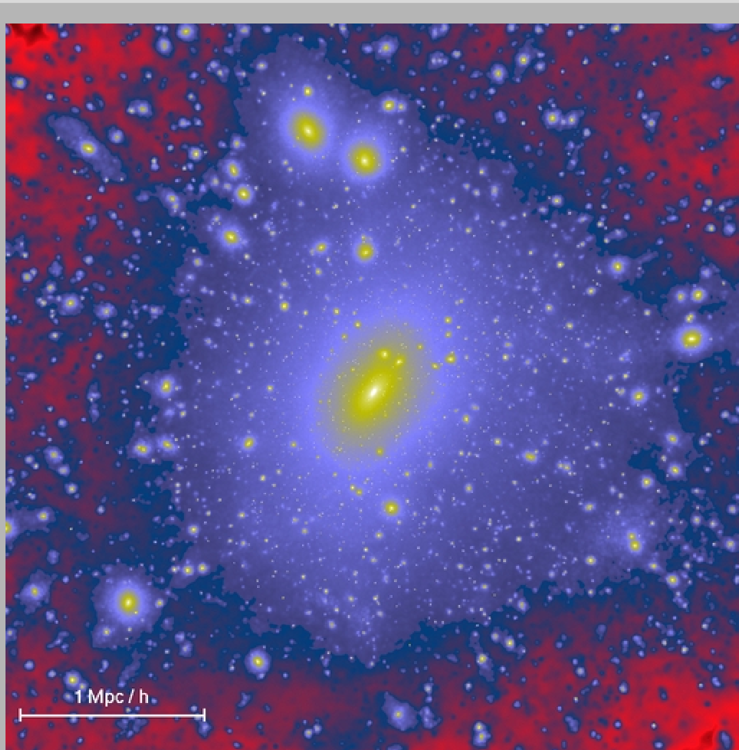
At first the ripples evolve independently

Then they interact with others in non-linear ways

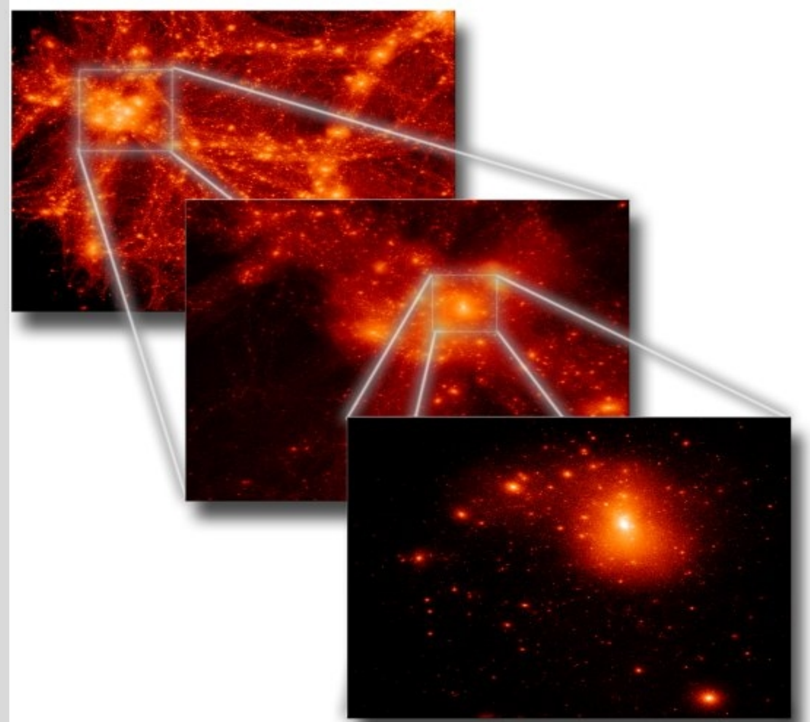
the small over-density fluctuations attract additional mass as the Universe expands

Formation of large-scale structure in the Universe

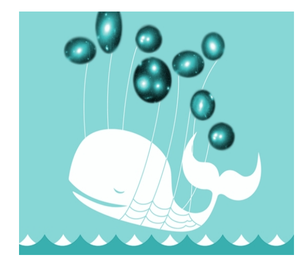
Gravitational instability produces high peaks of the density field → merger of small clumps at the intersection of a filamentary large-scale structure



Millennium Simulation, Volker Springel, 2005



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



GALAXY CLUSTER

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

hundreds
of galaxies

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

largest gravitationally bound
systems in the Universe

Galaxy
clusters

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

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Galaxy clusters

High-mass tail of mass function

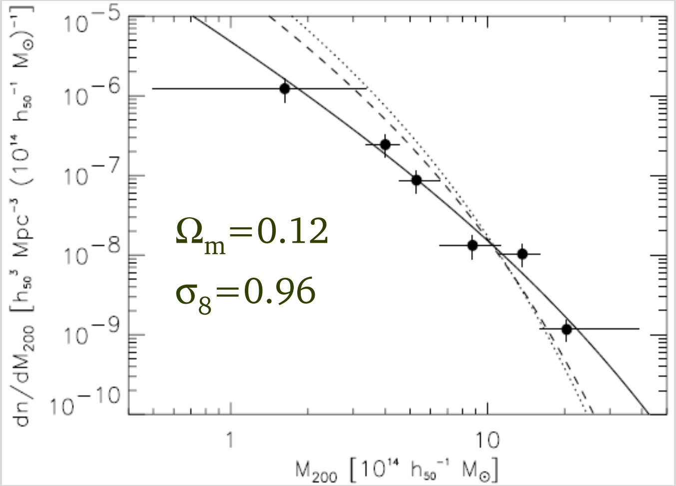
↓

number density

↓

measurement of cosmological parameters

number of systems with a given mass per unit volume



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galaxy-environment connection

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number density
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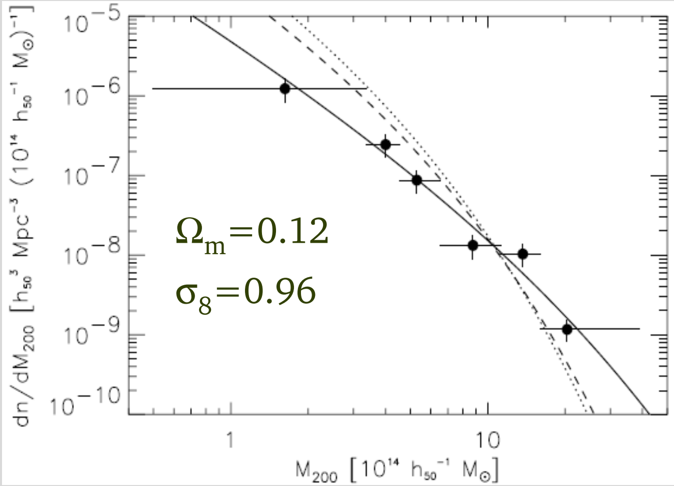

Reiprich & Böhringer 2002

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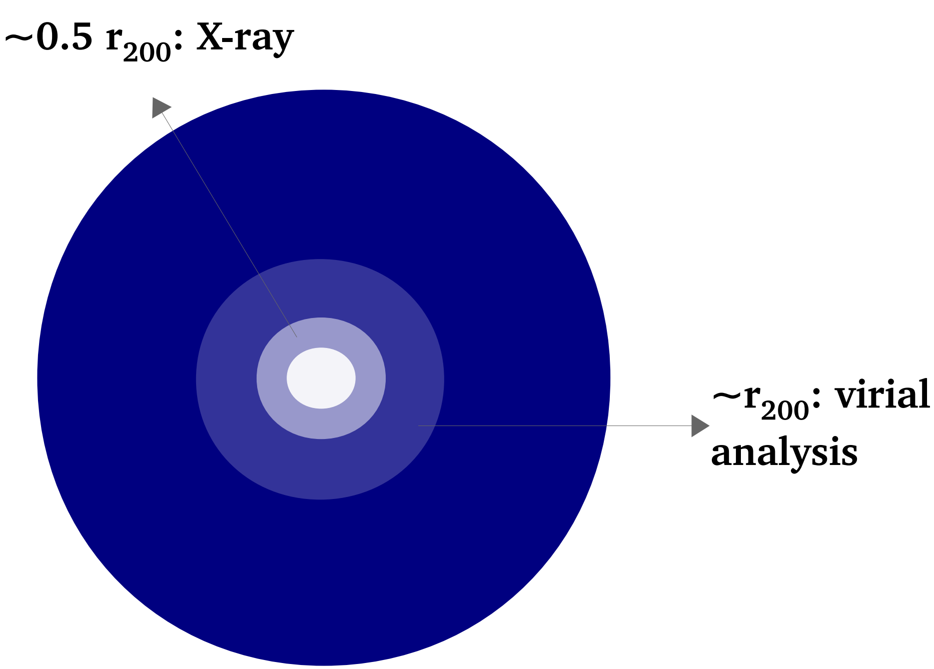
nucleosynthesis
galaxy-environment
matter distribution

How to measure the mass of galaxy clusters ?

- Virial theorem
- Jeans Equation
- Scaling relations
- X-ray temperature

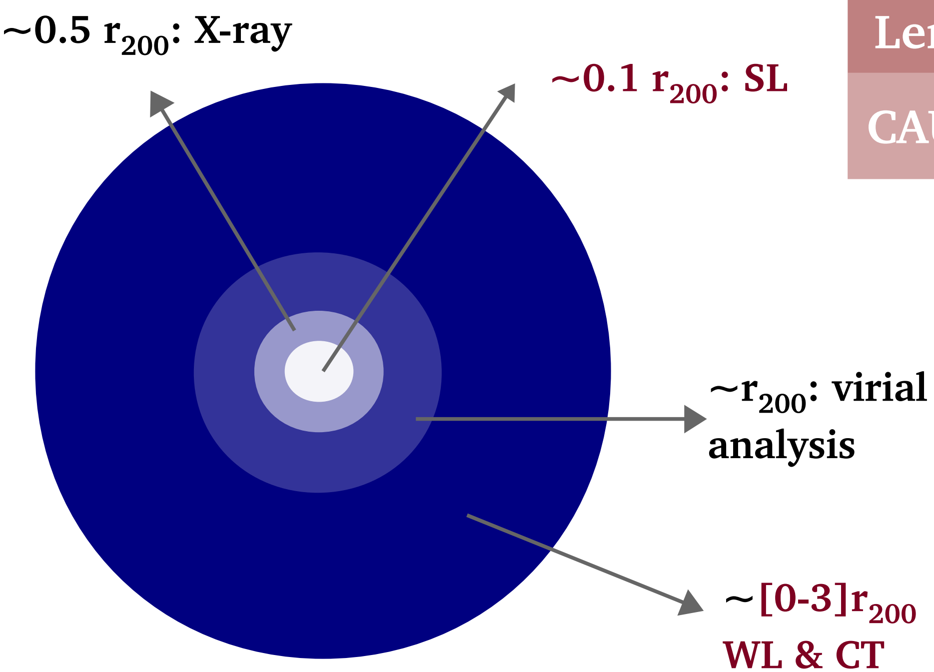


r_{200}: radius enclosing a matter density 200 times the critical density of the Universe $\sim 277.5\ h^2 M_\odot/\mathrm{Mpc}^3$

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



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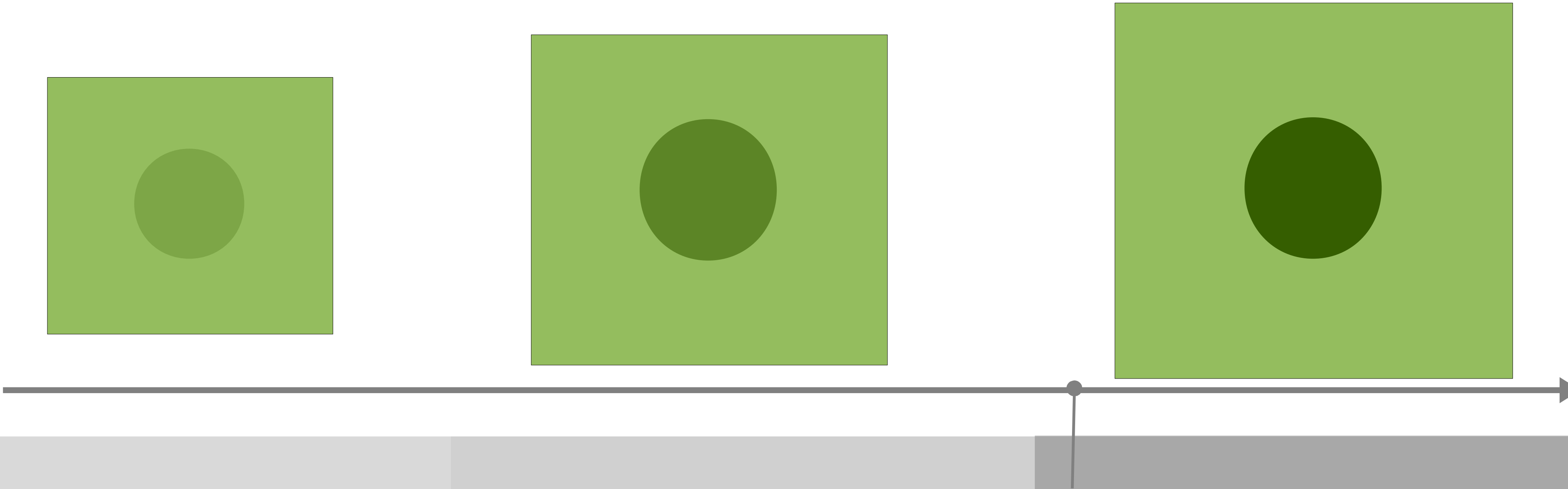
caustic technique – spherical infall model



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)

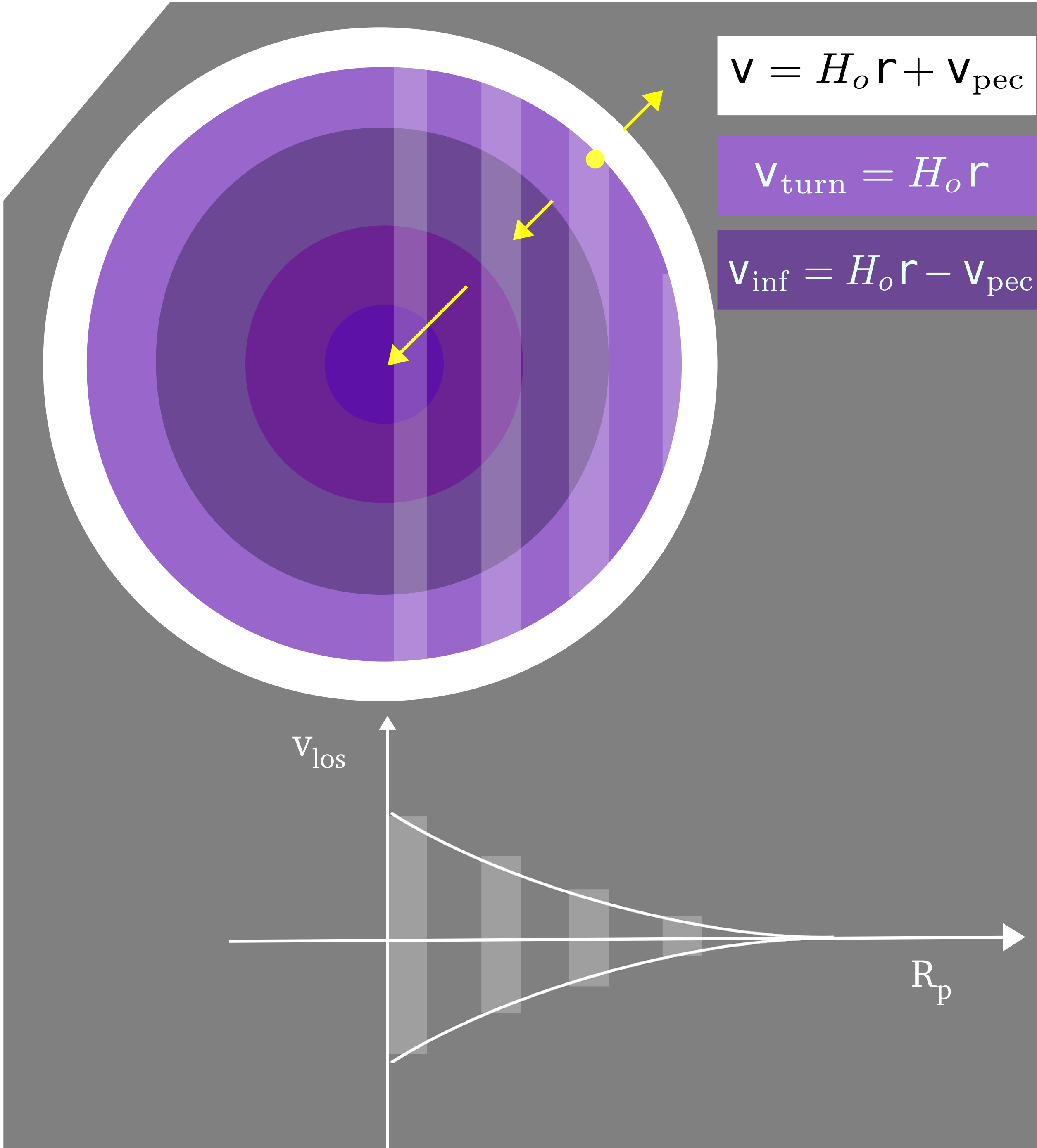
structures will be formed if, at some time, the spherical region ceases to expand with the background universe and begins to collapse

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)

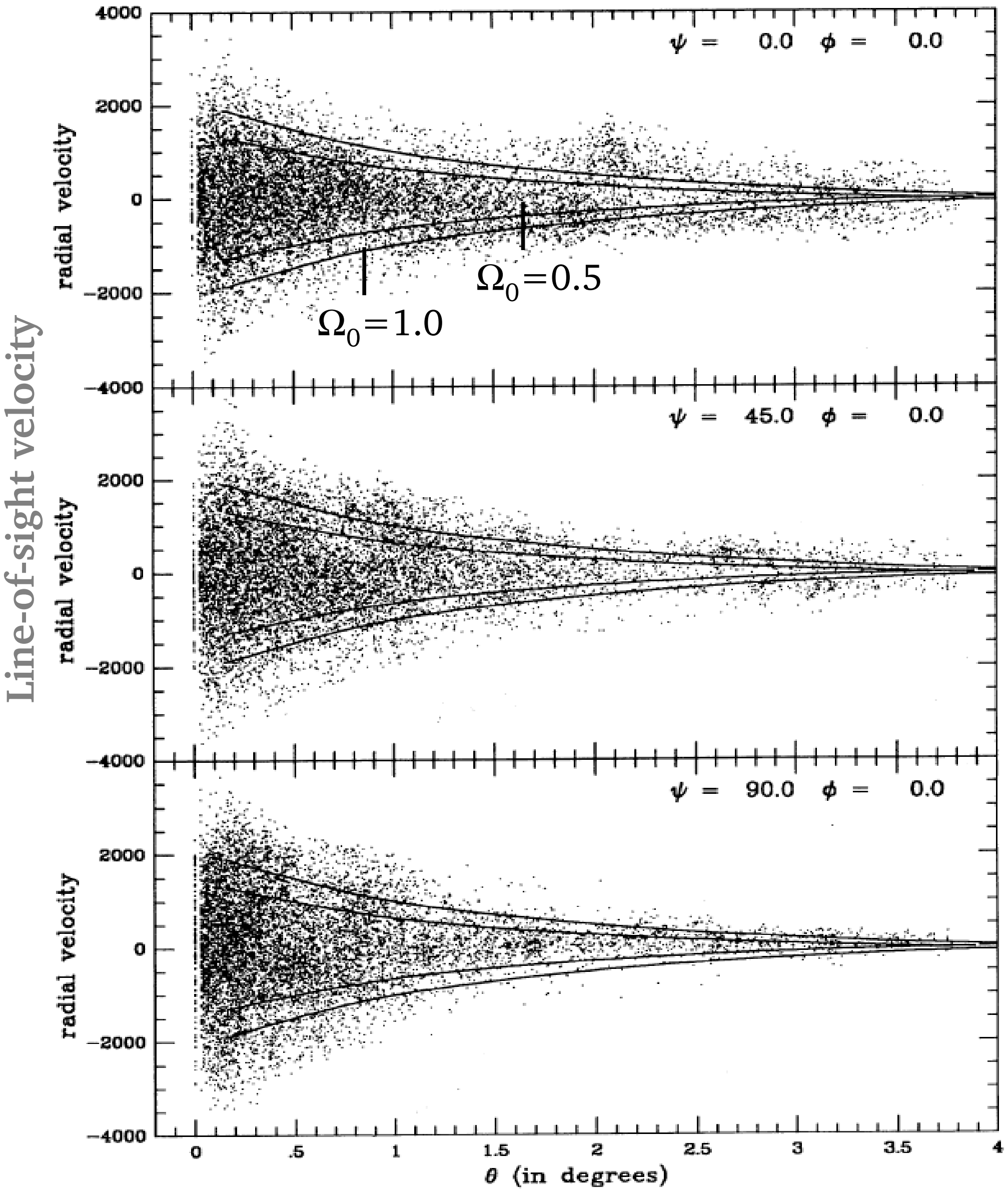
from spherical infall model

(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

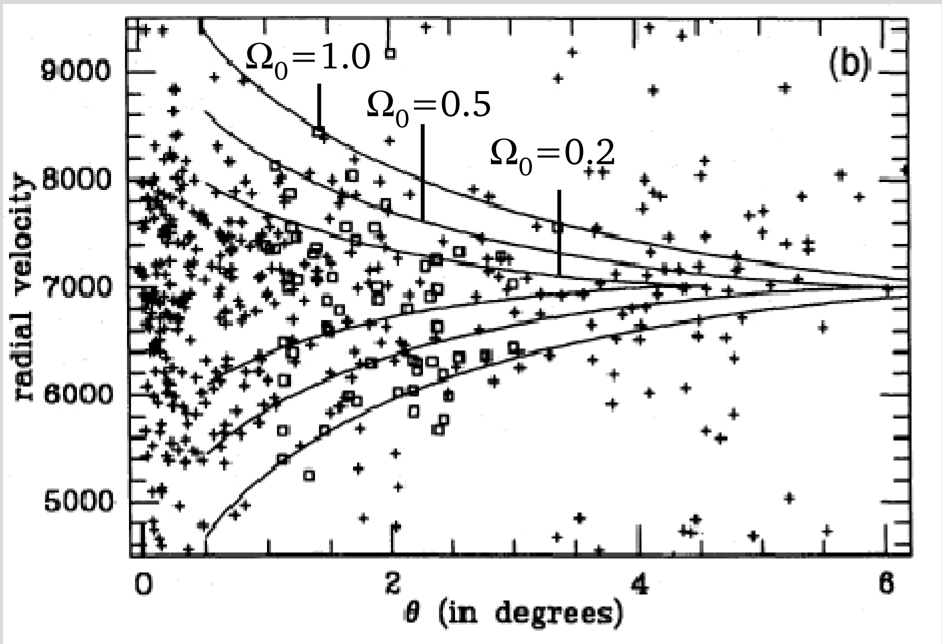


projected distance to the center

van Haarlem & van de Weygaert 1993

Real data

Coma cluster



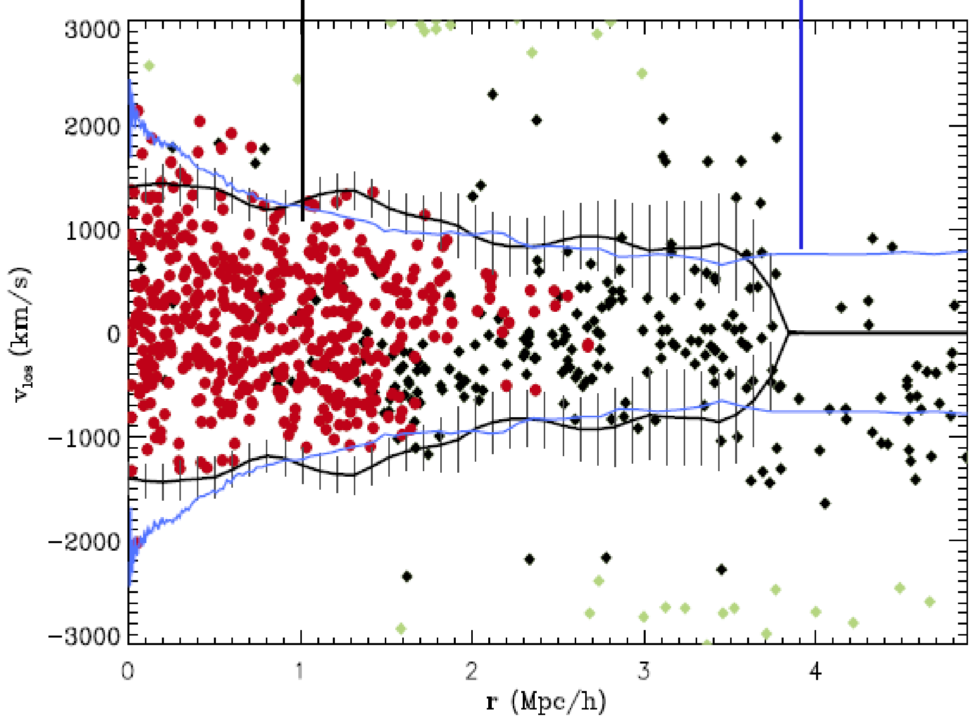
van Haarlem et al. 1993

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

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

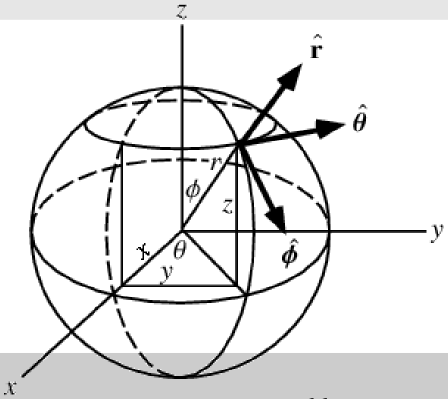
but clusters accrete mass anisotropically
→ the velocity field can have a substantial non-radial random component

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

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

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

$$\beta(r) = 1 - \frac{\langle v^2_\theta \rangle + \langle v^2_\phi \rangle}{2\langle v^2_r \rangle}$$



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HOLDS INDEPENDENTLY OF THE DYNAMICAL STATE OF THE CLUSTER

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

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

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]

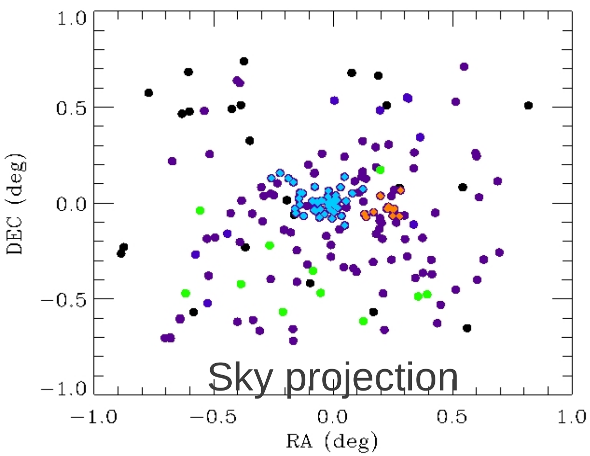
to simulated and real data

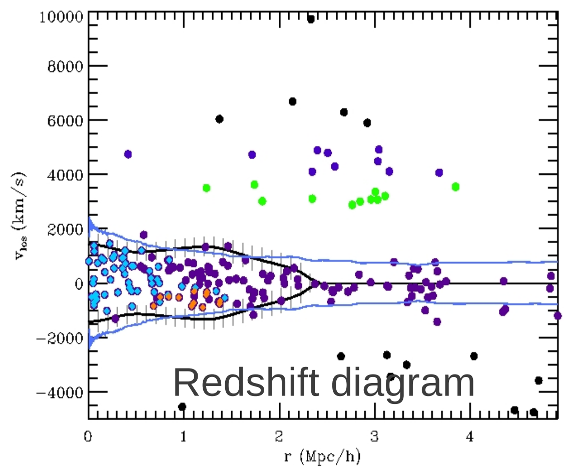
We have applied the caustic technique to 3000 mock catalogs, built from 100 simulated clusters with $M(<r_{200}) \geq 10^{14} h^{-1} M_{\odot}$ (Borgani et al. 2004)

four steps

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

1 Binary tree & σ-plateau



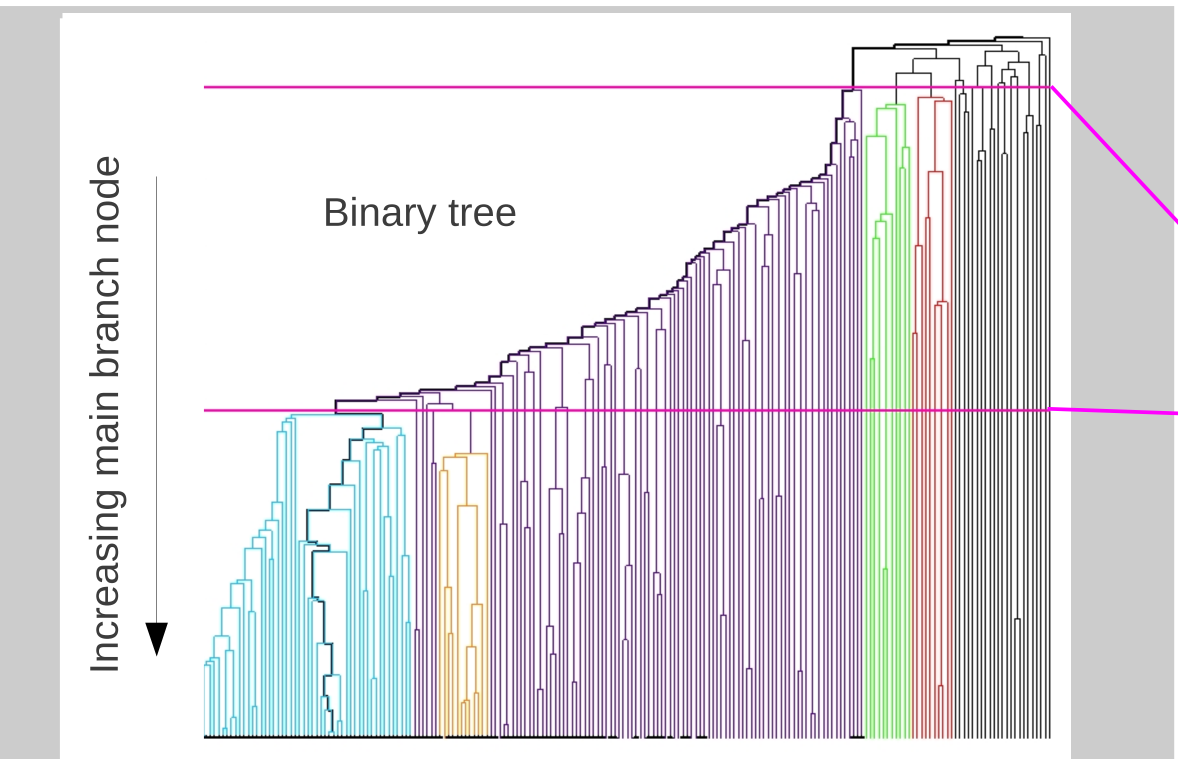


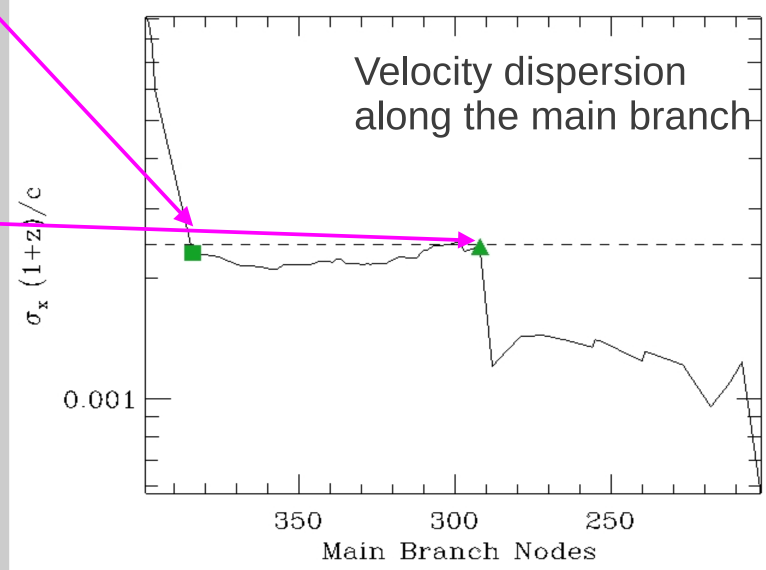
binding energy

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

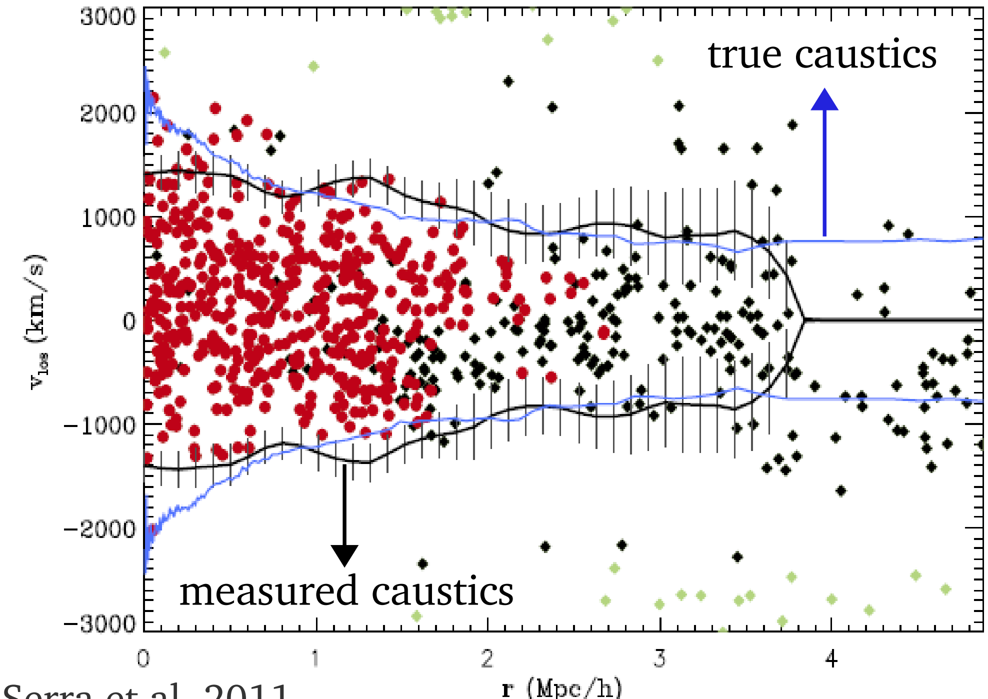
Binary Tree

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

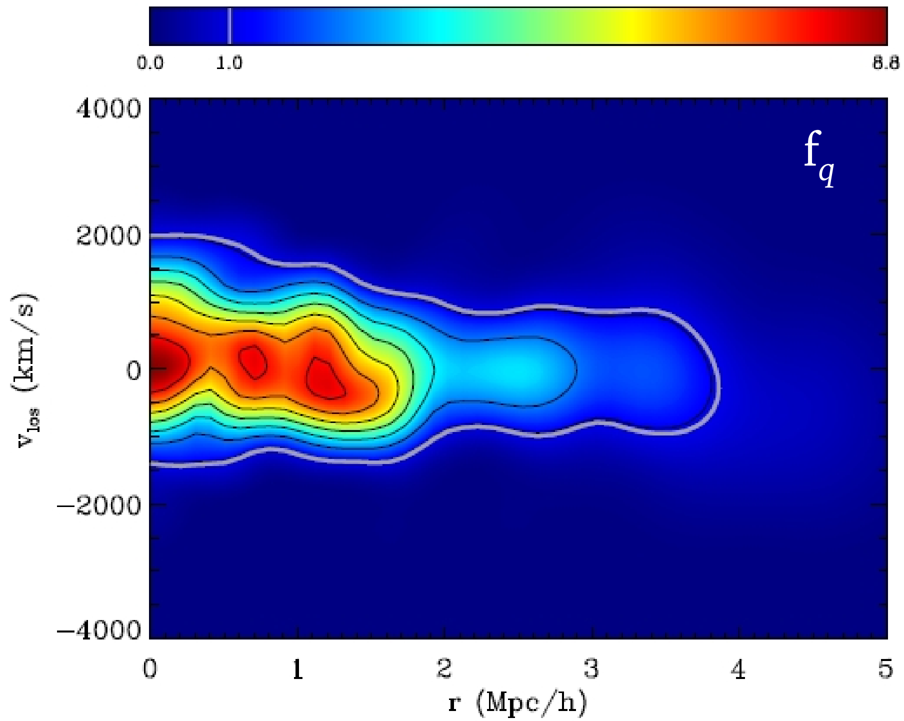




2 Redshift diagram



Serra et al. 2011



3 Caustic location

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

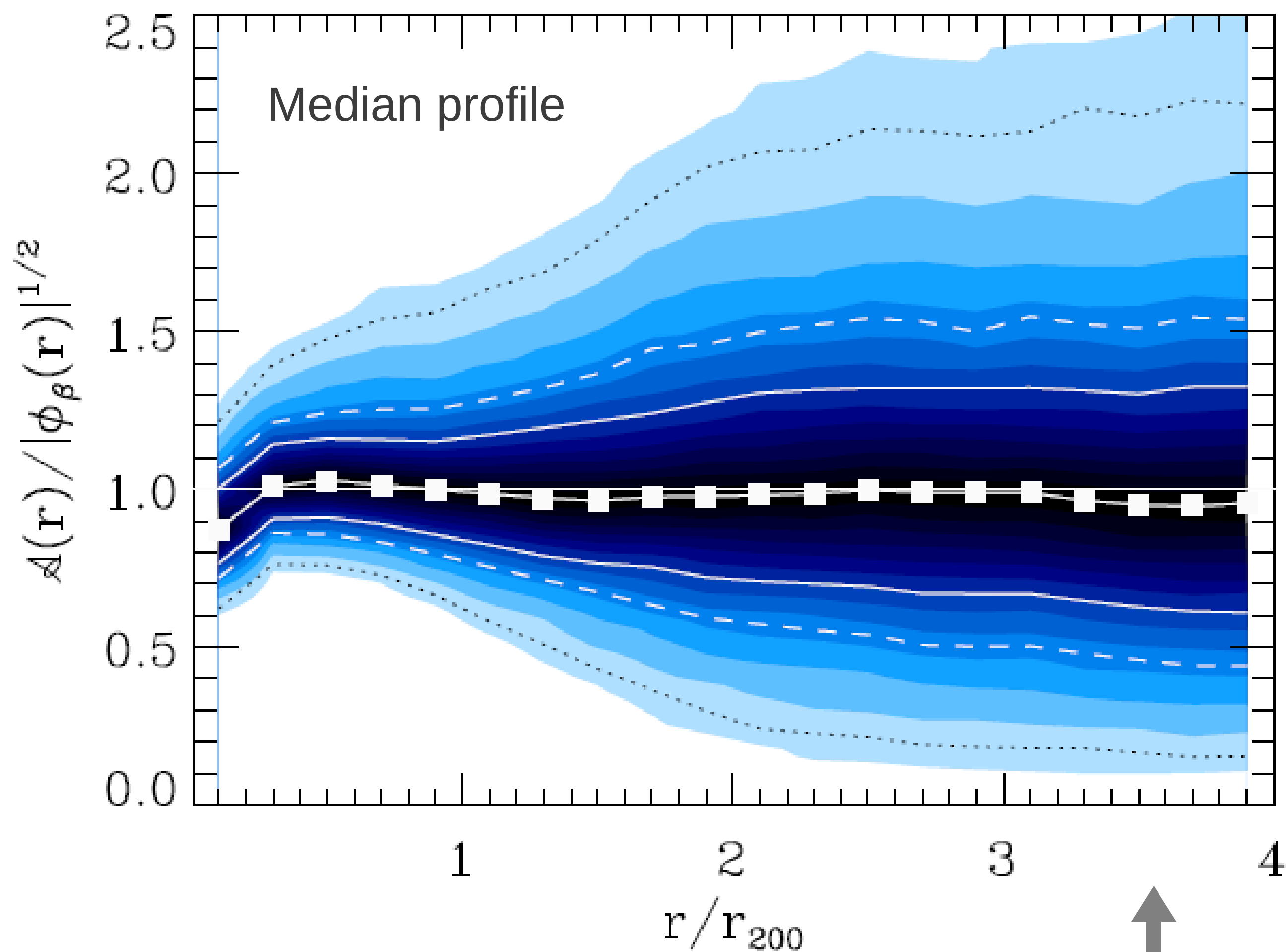
$$S(\kappa) \equiv \langle v^2_{\rm esc} \rangle_{\kappa,R} - 4\langle v^2 \rangle = 0$$

distribution of N galaxies

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

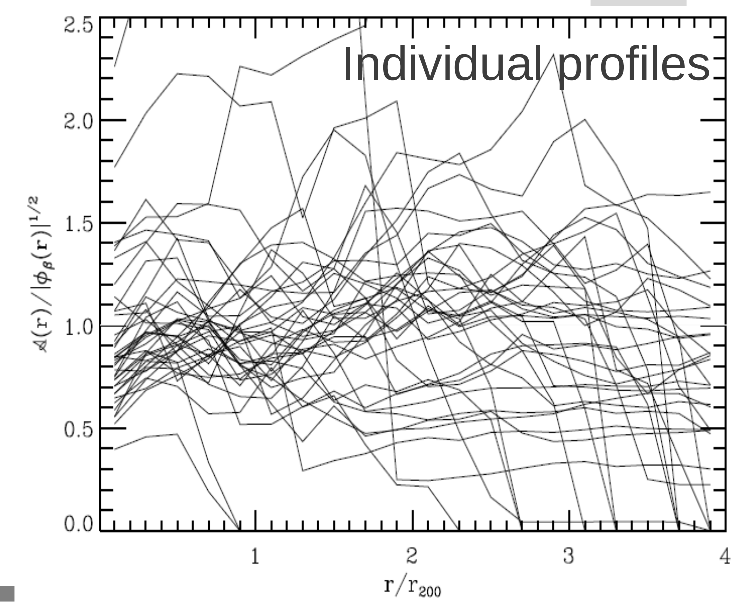
$$\mathsf{x} = (r, v)$$

3 Gravitational potential profiles



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

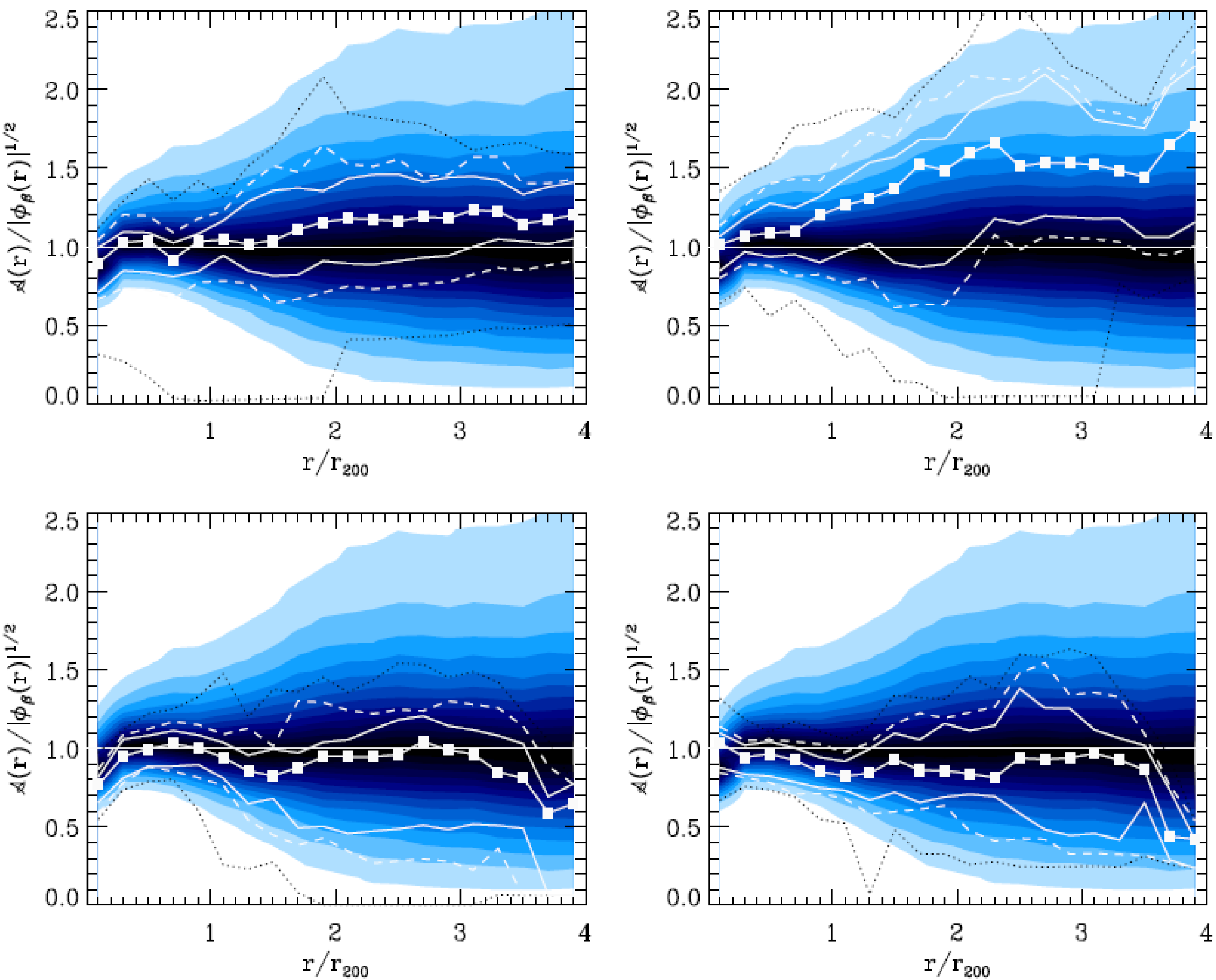
3000 simulated clusters with $M_{200} \geq 10^{14}\ h^{-1} M_\odot$



Serra et al. 2011

Projection effects

Examples of individual clusters



Serra et al. 2011

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

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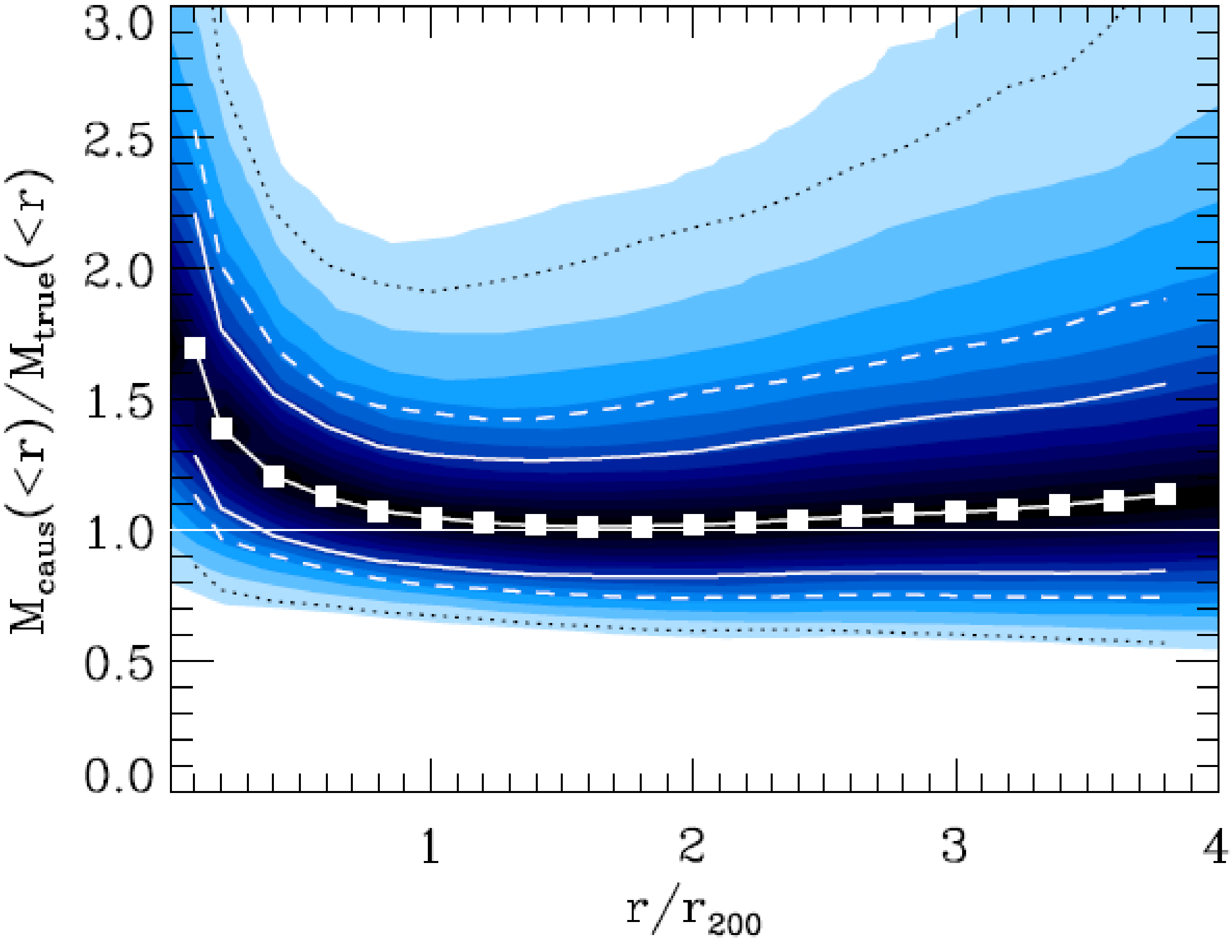
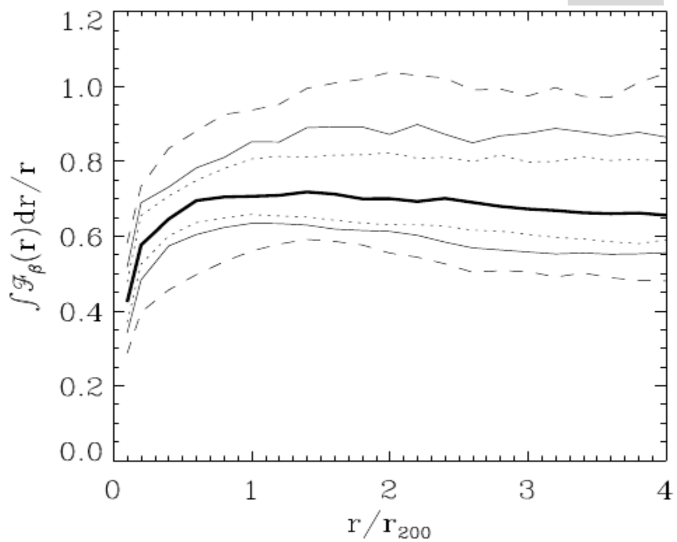
4 Mass profiles



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

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



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

Serra et al. 2011

Stacked cluster

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

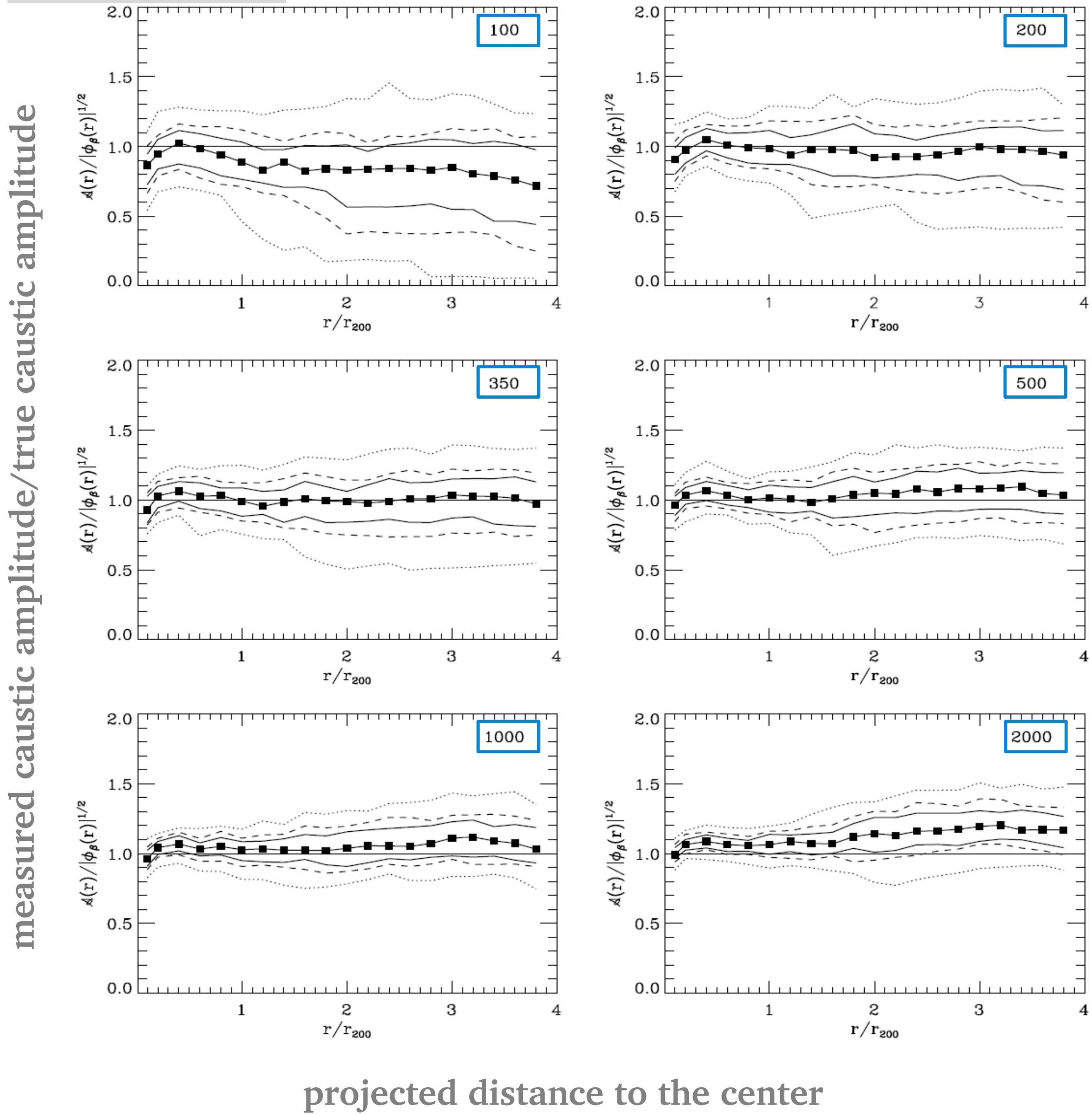
30'

30'

$z^{clus}=0.1$

30' → 2.46 Mpc/h

spread decreases with increasing number of galaxies



Serra et al. 2011

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CAUSTIC TECHNIQUE

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Membership

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

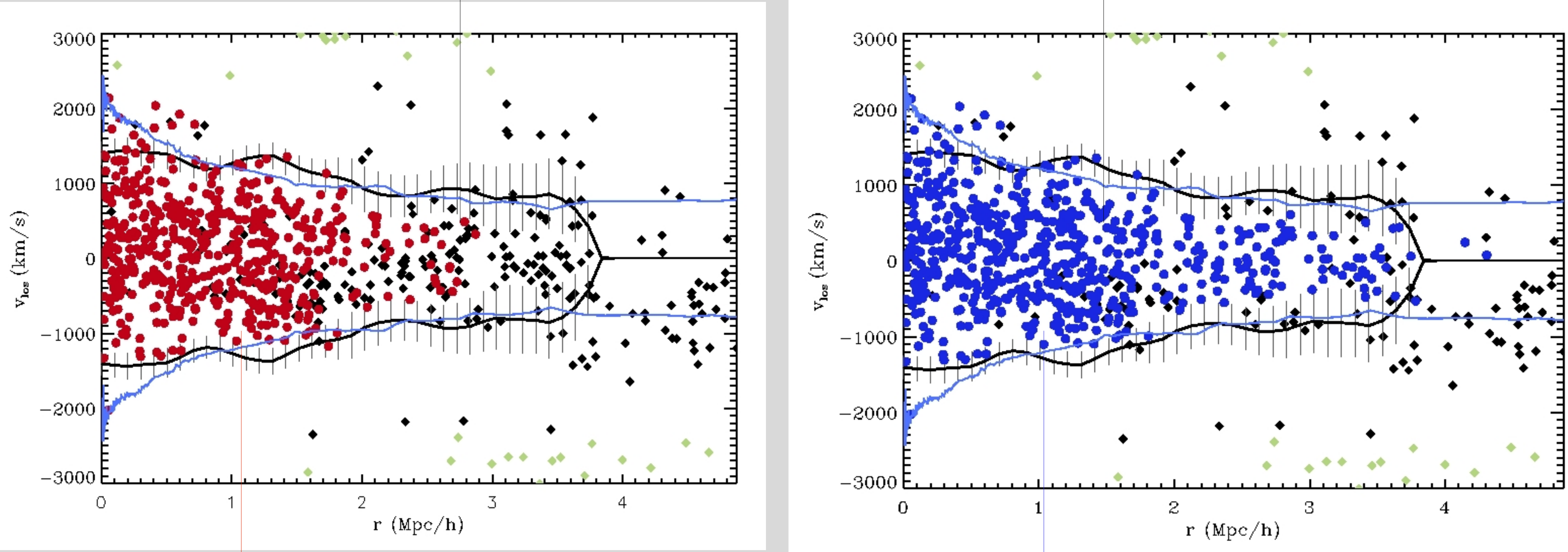
How to define members?

- from 3D information
  - galaxies within $3r_{200}$
  - bound galaxies
- from observations
  - galaxies within caustics
  - galaxies in main group of binary tree

Membership

mock catalogs → identified members

→ **galaxies within the caustics** ←



galaxies with $r \leq 3r_{200}$

bound galaxies

3D data → true members

Serra et al., in prep

Membership

mock catalogs → identified members

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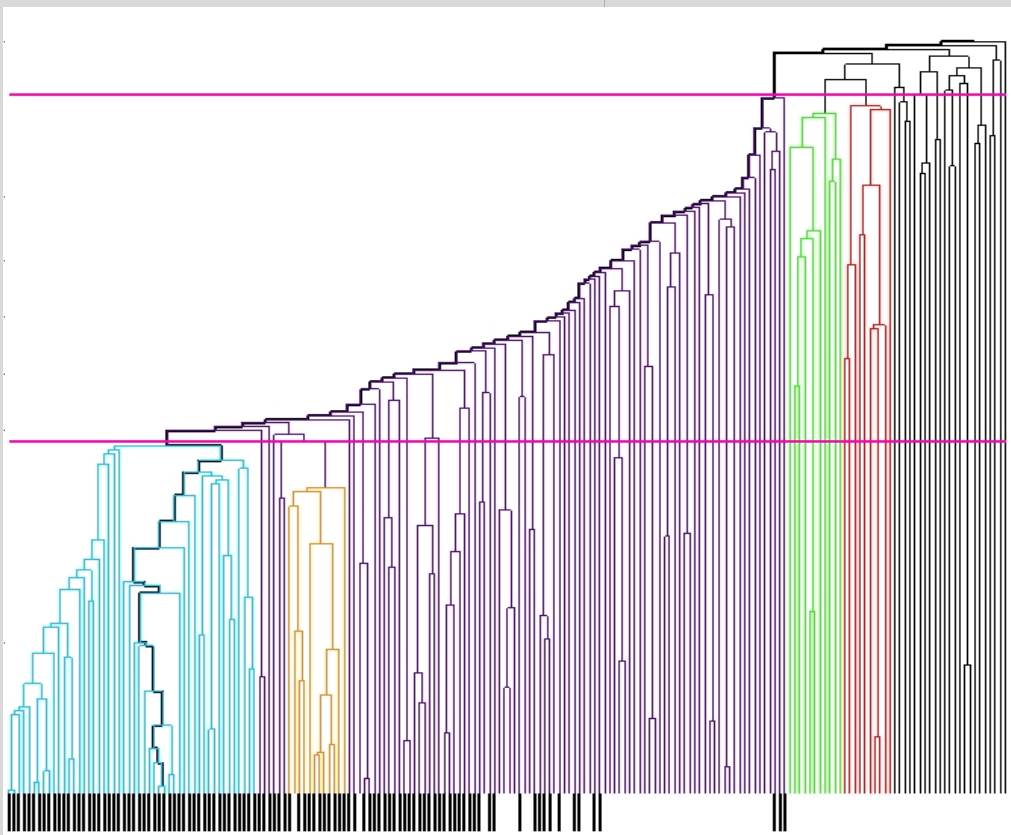

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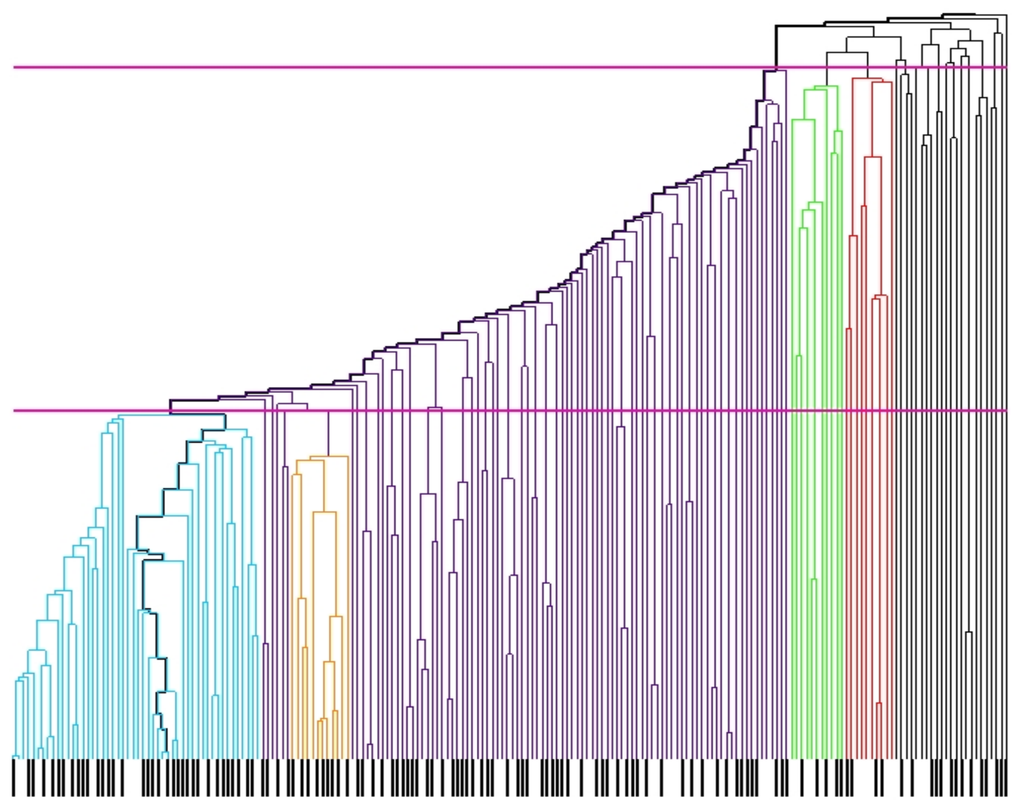


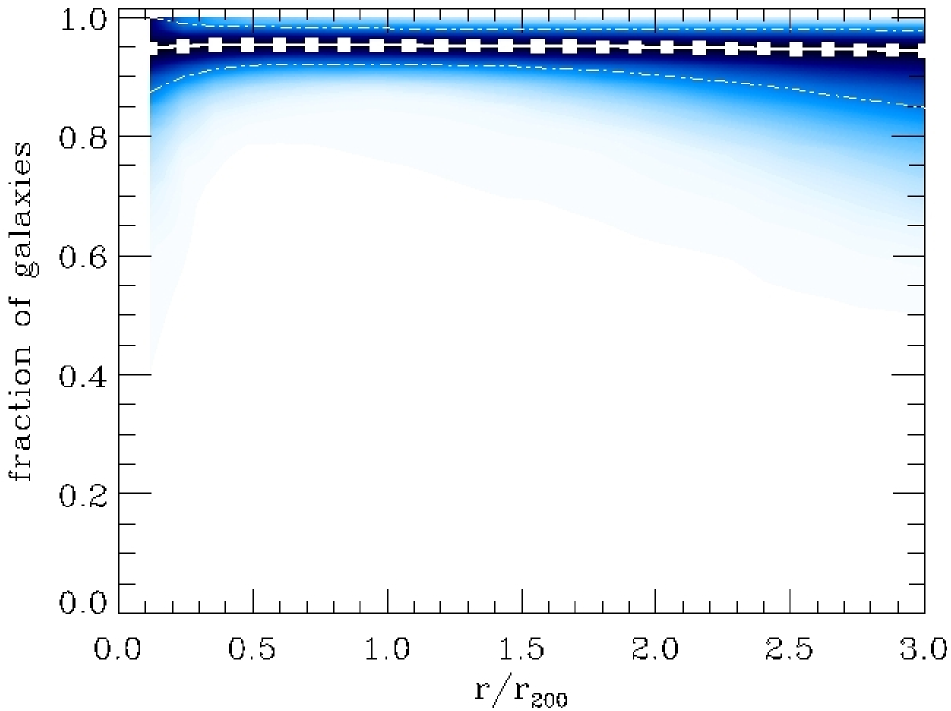
bound galaxies

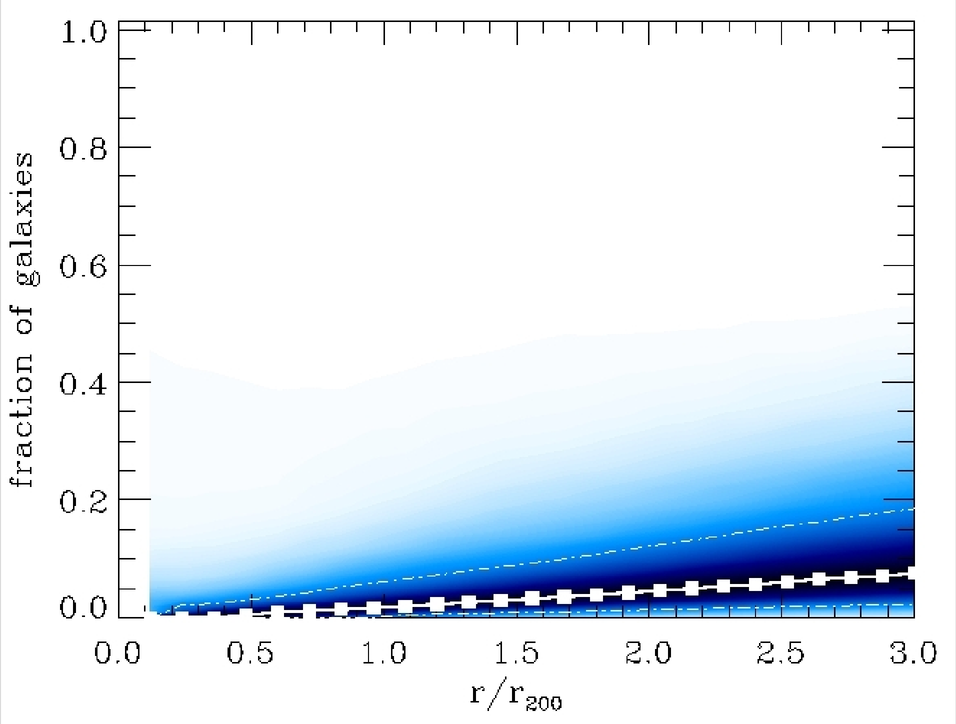
3D data → true members

Serra et al., in prep

galaxies within caustics compared with bound galaxies

Serra et al., in prep

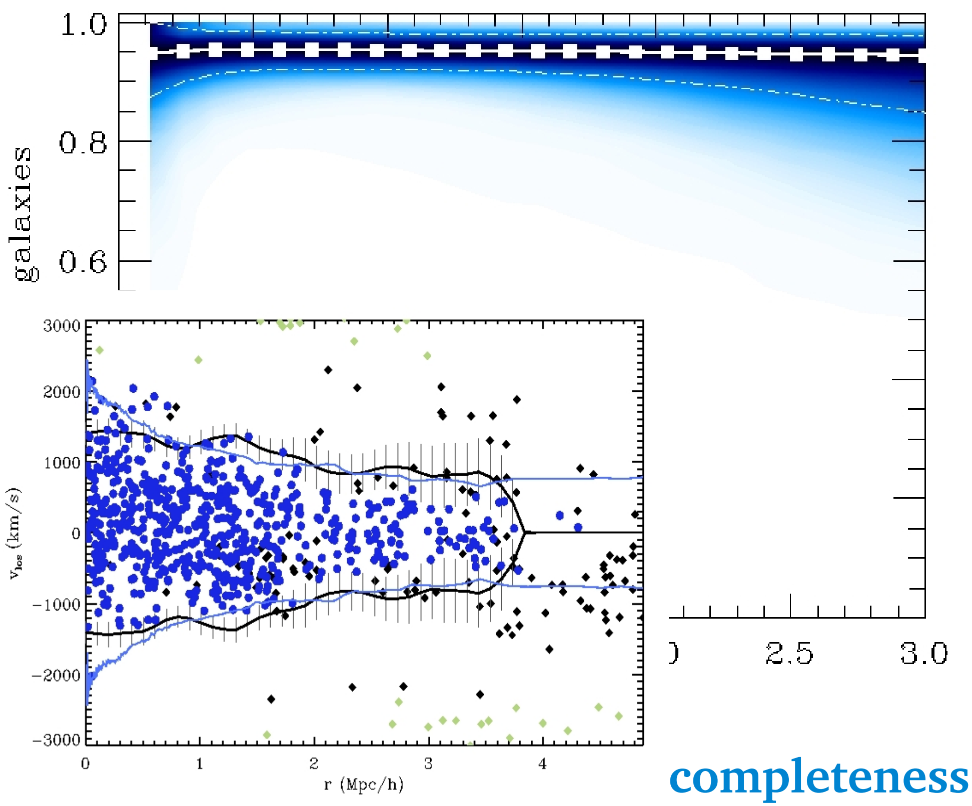




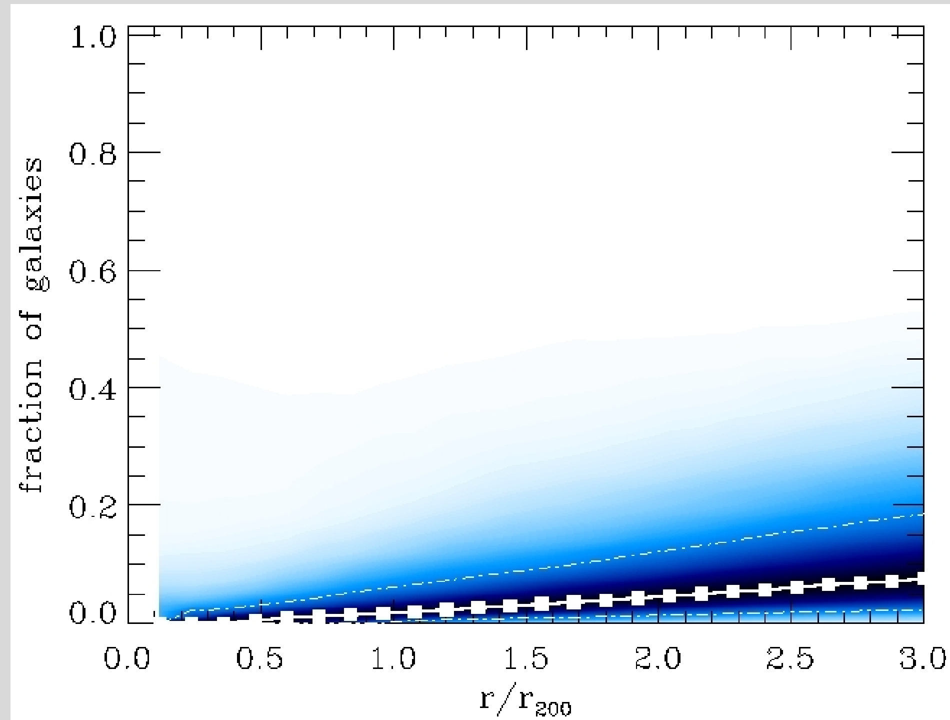
	completeness			contamination		
	-1σ	median	$+1\sigma$	-1σ	median	$+1\sigma$
r_{200}	0.919	0.953	0.981	0.005	0.020	0.066
$2r_{200}$	0.902	0.949	0.979	0.014	0.046	0.124
$3r_{200}$	0.848	0.944	0.978	0.072	0.075	0.186

galaxies within caustics compared with bound galaxies

Serra et al., in prep



completeness



contamination

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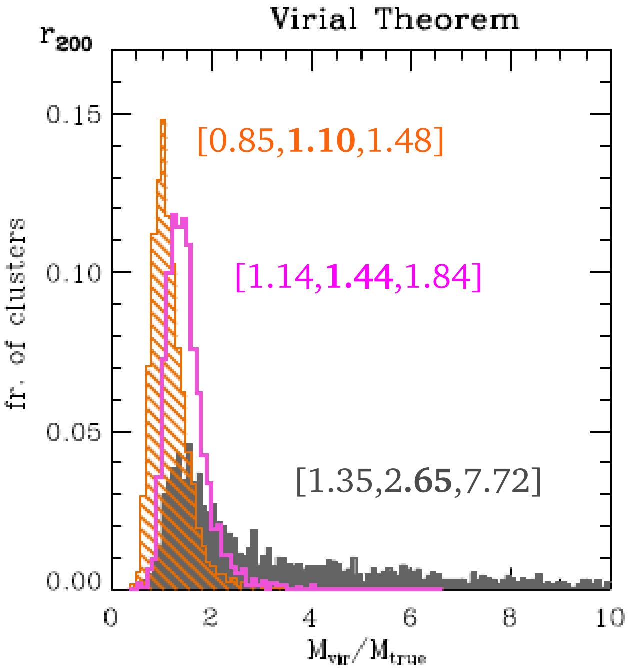
Cluster mass estimates with interlopers removed



caustic location

binary tree algorithm

3σ clipping

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

Can be applied for

- MASS/POTENTIAL ESTIMATES
- IDENTIFICATION OF MEMBERS

CAUSTIC TECHNIQUE

to simulated and real data

Equation of state of dark matter

$$w = \frac{1}{c^2}\frac{p_r + 2p_t}{3\rho}$$

if we do not assume that the pressure profiles are small compared to the mass-energy density

$$\nabla^2\Phi \approx \underbrace{\frac{4\pi G}{c^2}(c^2\rho + p_r + 2p_t)}_{\nabla^2\Phi_N}$$

kinematic mass profile → Φ

lensing mass profile →

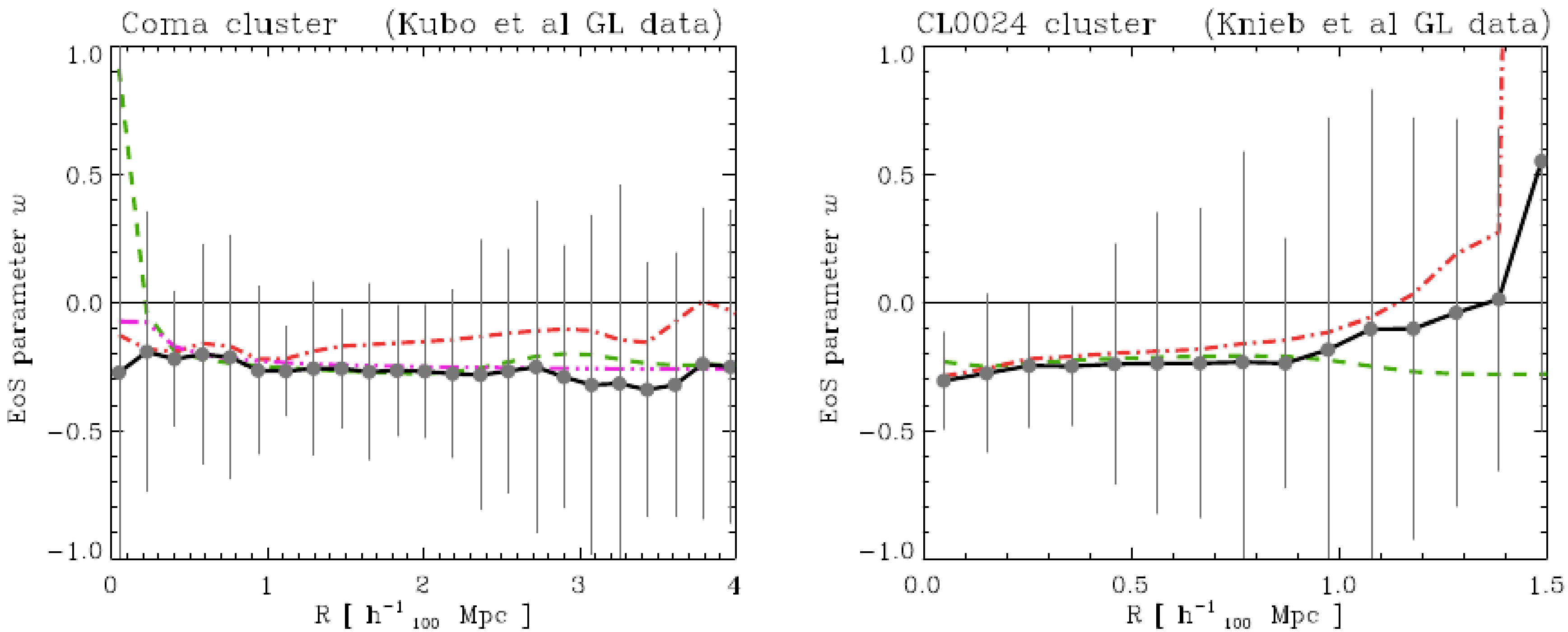
$$\Phi_L = \frac{1}{2}\Phi_N + \frac{1}{2}\Phi$$

density and pressure profiles of dark matter

w_{DM}

Serra & Dominguez, 2011

Equation of state of dark matter



mass from Jeans analysis, β=0

mass from Jeans analysis, β=linear fit from sim. clusters

mass by the caustic technique

mass from Łokas & Mamon, 2003

Escape velocity → members

↓

gravitational potential

ANY

SYSTEM

Galaxy clusters

Dwarf spheroidal galaxies

check the constant M(<300pc)-Luminosity relation found by Strigari et al. 2008 in LCDM

analysis whether we can solve the issue of high M/L in MOND

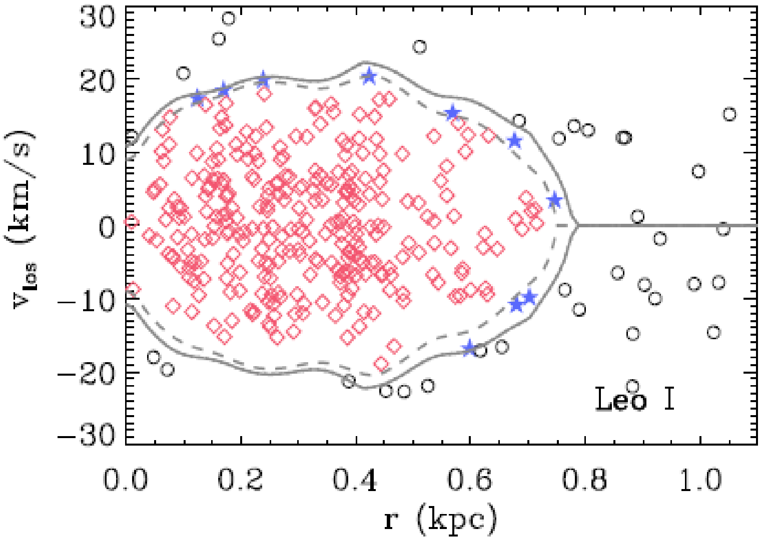
The technique is highly versatile and allows for the detection of interlopers also at small scales

M/L up to 40

↓

CDM dominated systems

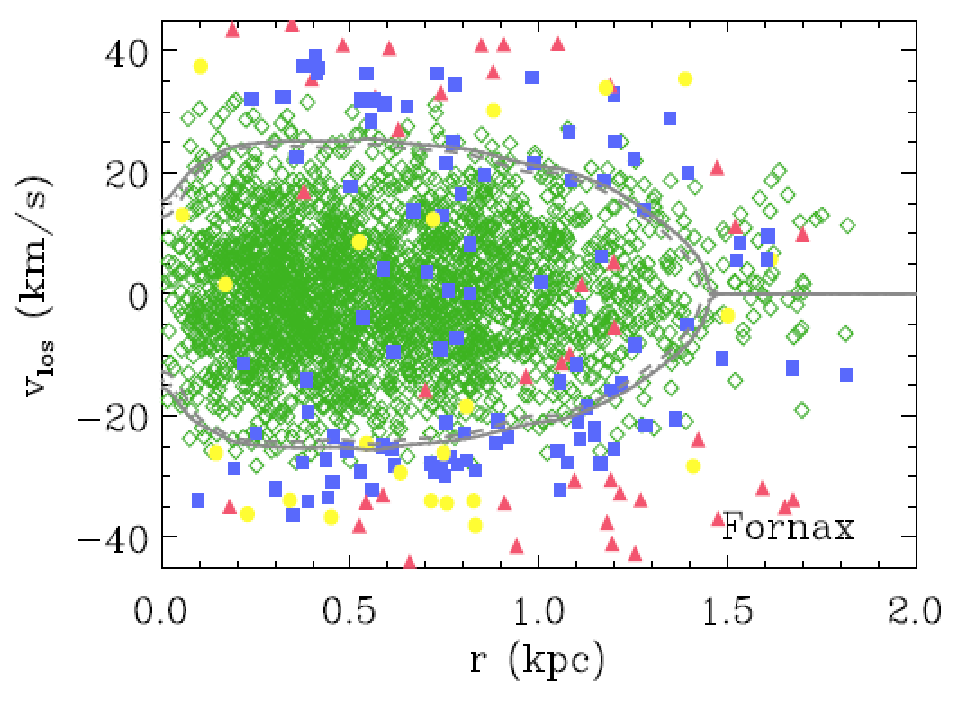
Interlopers: do they bias the velocity dispersion estimate?



Dwarf Spheroidal Galaxies

(Fornax, Carina, Leo I, Sculptor, Sextans)

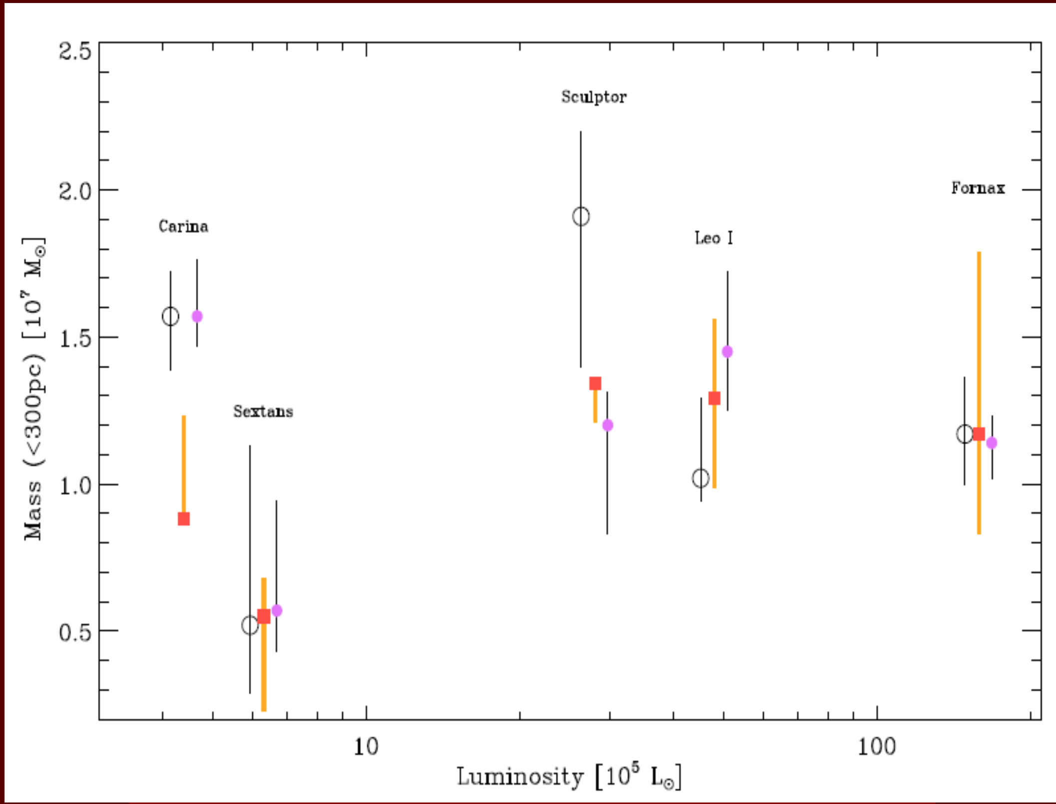
Escape velocity → members



Walker et al. 2007

- ▲ $p \leq 0.5$
- ● $0.5 \leq p \leq 0.7$
- ■ $0.7 \leq p \leq 0.9$
- ◇ $0.9 \leq p$

Mass (<300pc) in ΛCDM



- ● Strigari et al. 2008
- ■ Serra, Angus & Diaferio, 2010
- ○ Angus 2008

Dwarf spheroidal galaxies

ΛCDM

large amount of dark matter

High M/L (up to 40)

MOND

no dark matter?
M/L=1-3

Carina, Sextans and Sculptor have M/L too large

identification of members with caustic location

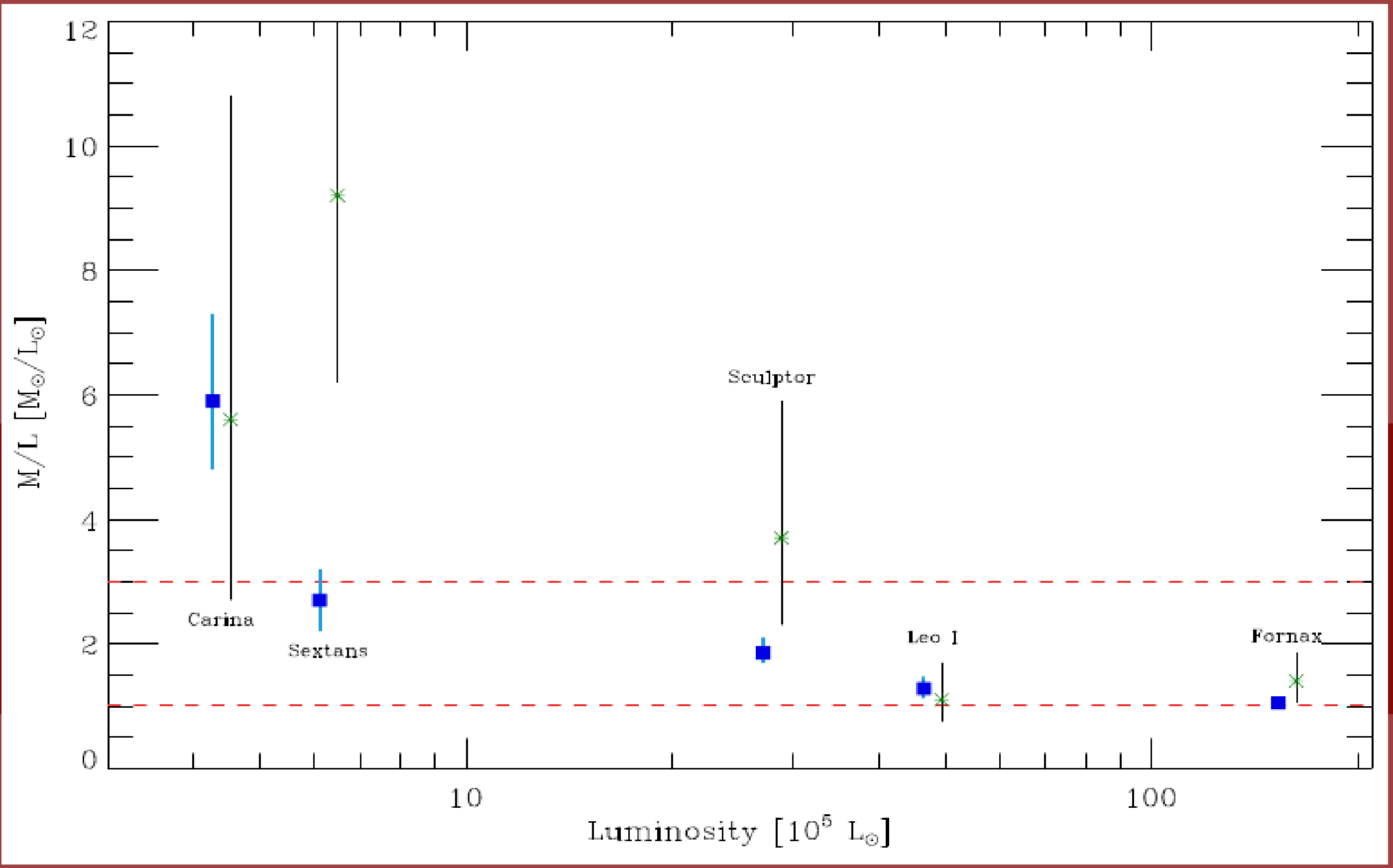
M/L in [1-3]

still a problem

Dwarf Spheroidal Galaxies

(Fornax, Carina, Leo I, Sculptor, Sextans)

Mass-to-light ratios in MOND



■ Serra, Angus & Diaferio, 2010

✳ Angus 2008

Real data

The mass profiles calculated with the caustic technique for two real clusters (CL0024 and Coma), combined with gravitational lensing data, yields slightly negative profiles for the dark matter equation of state, that might be interpreted in the framework of alternative theories of gravity (Serra & Dominguez, 2010).

The membership analysis applied to 5 dSphs has yielded results compatible with previous mass estimates and decreases the mass-to-light ratios in MOND for two dwarfs, which turn out to be consistent with stellar population synthesis models (Serra, Angus & Diaferio, 2010).

Systematics: mass/potential profiles, membership

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

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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 up to $4r_{200}$ (Serra et al. 2011).

The spread mostly originates from the assumption of spherical symmetry the same cluster when looked from another l.o.s. gives different caustics, but the errors account for that

The technique is able to detect true members with a completeness of ~94% and a contamination of ~8% at $3r_{200}$ (Serra & Diaferio in prep.)

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THANK YOU!!!