# MEASURING THE GROWTH OF GALAXY CLUSTERS


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**www.dfg.unito.it/ricerca/caustic**

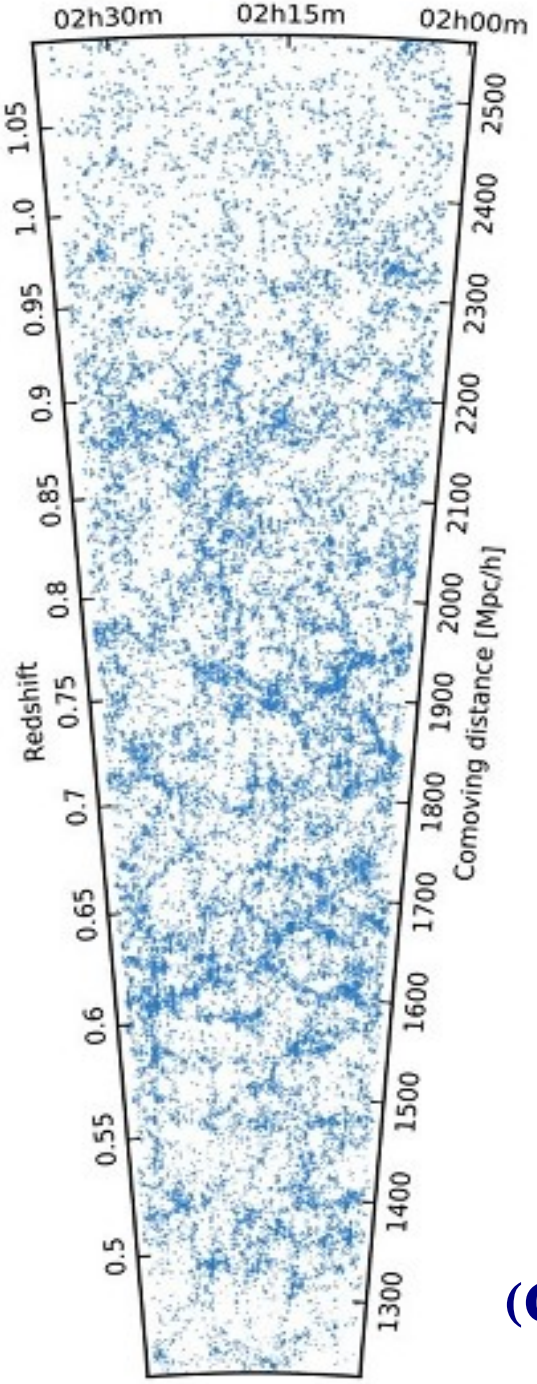
**with Ana Laura Serra, Cristiano De Boni, Heng Yu, Kenneth Rines and Margaret Geller**


**6th KIAS Workshop on Cosmology and Structure Formation**

**Seoul, November 5th 2014**

# OUTLINE

- The growth of structures on linear and non-linear scales
- Mass distribution within and around clusters
- Estimation of the mass in the outskirts of clusters and its connection to the mass accretion rate
- How well we can identify cluster substructures and surrounding groups and their connection with cluster formation
- Identification of cluster members and modified gravity




# TESTING DARK ENERGY AND MODIFIED GRAVITY MODELS

## with lensing and/or redshift surveys

**Measuring the growth factor**

$$f(z)=\frac{d\ln D}{d\ln a}=\Omega_0{}^{\gamma}(z)$$

**with γ=0.55 in GR.**

**Measurable quantity in redshift surveys: redshift distortion**

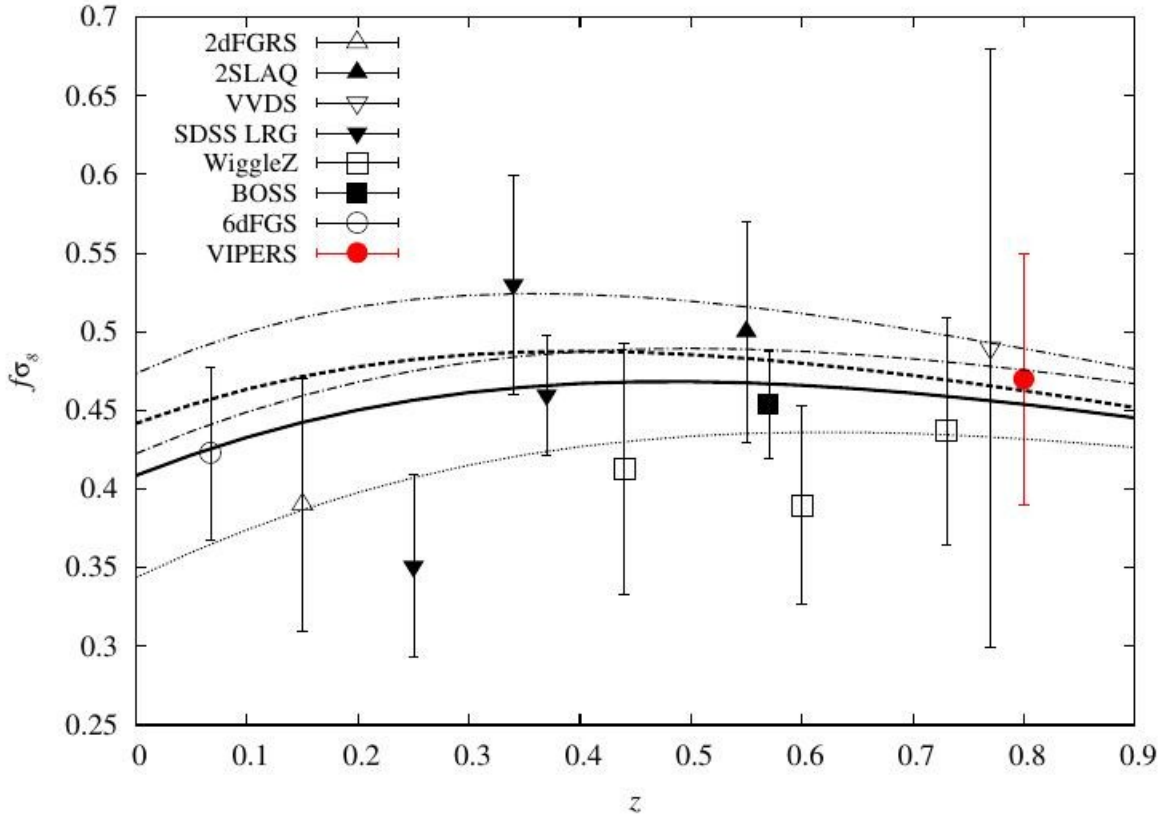
$$\beta=\frac{f(z)}{b}$$

**VIPERS**

**(Guzzo et al. 2014)**

# Growth rate on large scales

**Upcoming surveys (e.g., DES, eBOSS, DESI, PFS, LSST, Euclid, WFIRST)**
**claim 1% accuracy in the redshift range $0<z<2$**
**up to wave numbers $k$~0.2 h/Mpc in the next decade or two**



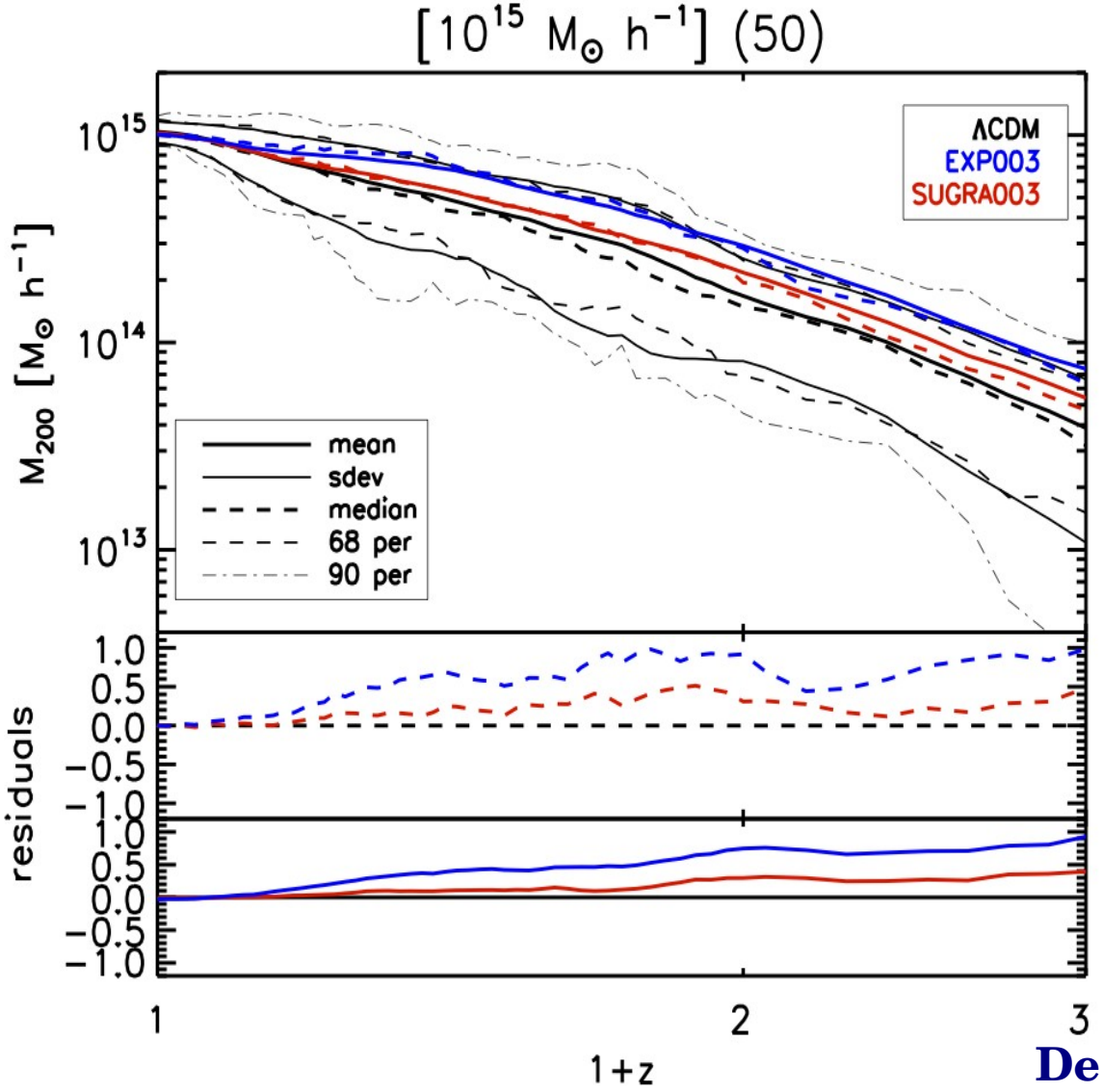

**Current measures have 20-50% accuracy**

**de la Torre et al. 2013**

**Measures to smaller scales, up to $k$~2-3 h/Mpc?**

# STRUCTURE GROWTH ON NON-LINEAR SCALES

**The mass accretion history (MAH)**
**in two interacting dark energy models**

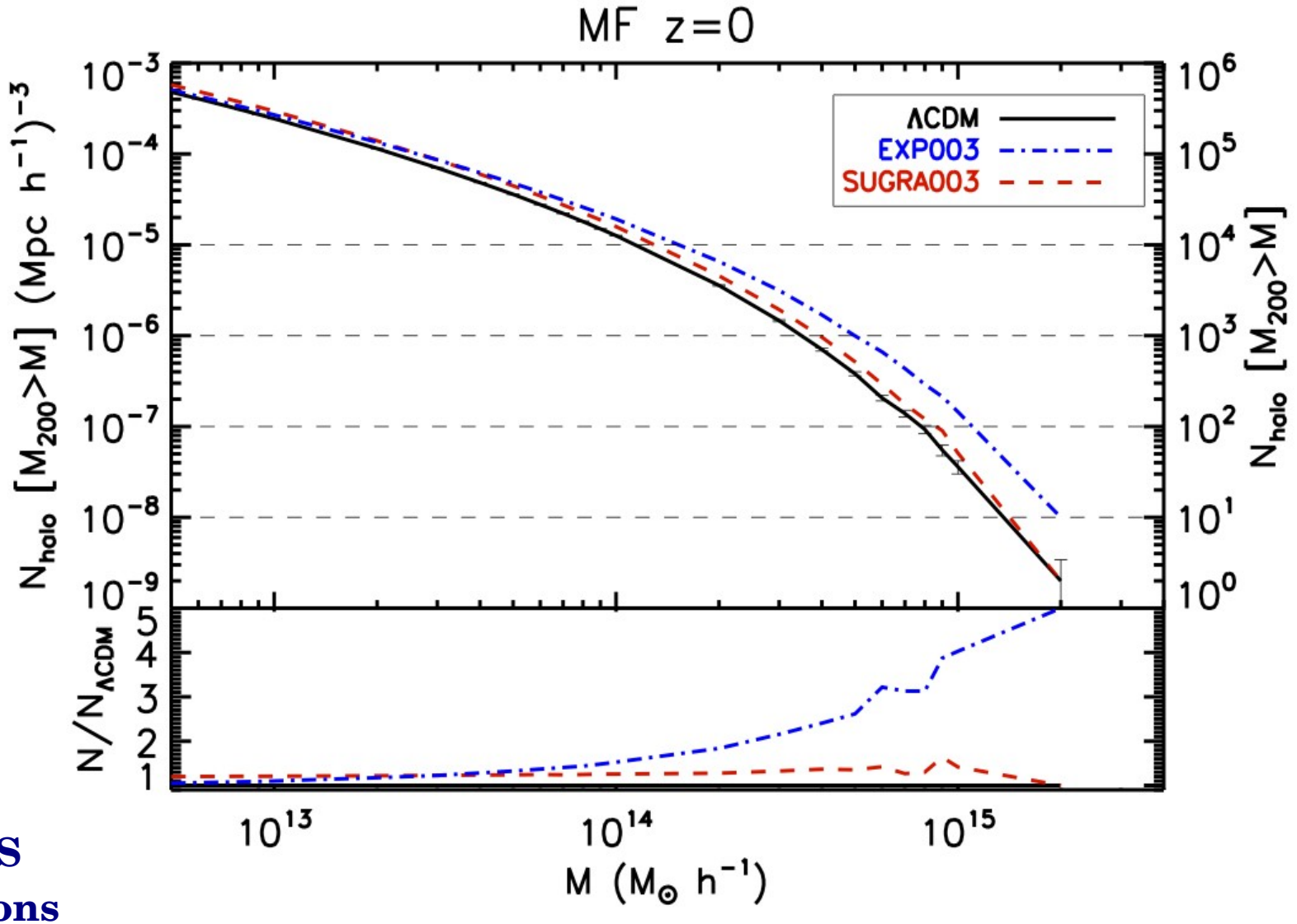



**CoDECS simulations (Baldi 2012)**

**De Boni et al. in prep.**

# STRUCTURE GROWTH ON NON-LINEAR SCALES

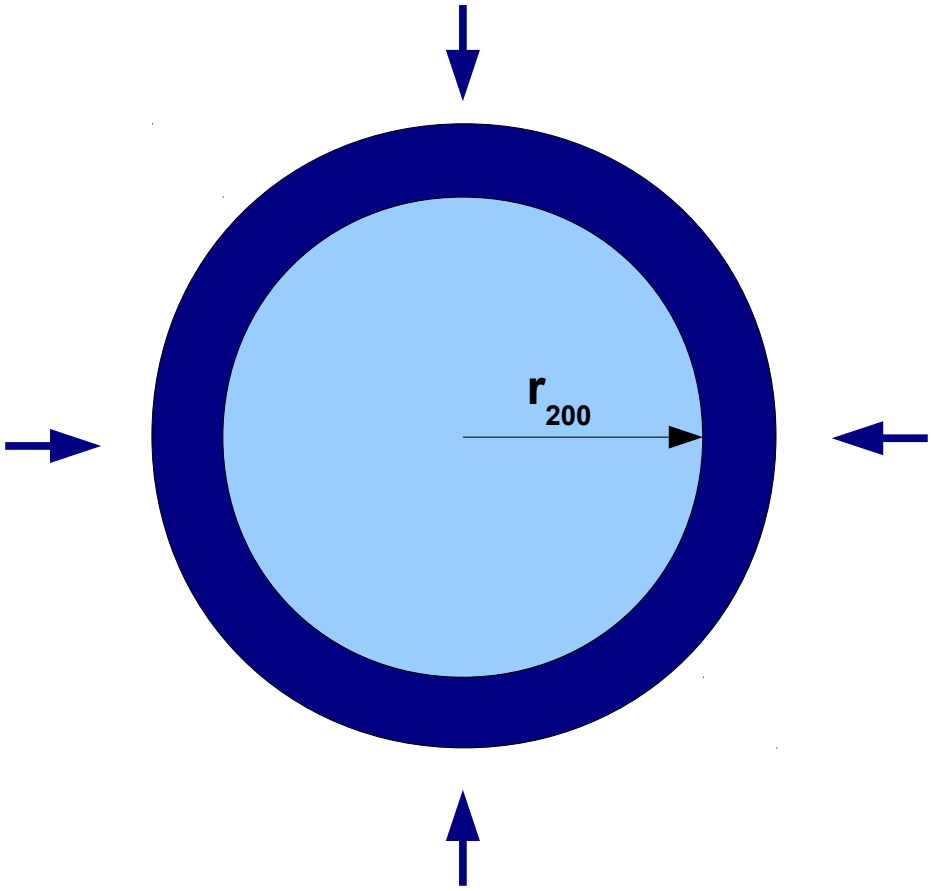
**Different MAH's propagate**
**into different mass functions**




**CoDECS simulations (Baldi 2012)**

**De Boni et al. in prep.**

# Mass Accretion History and Mass Accretion Rate



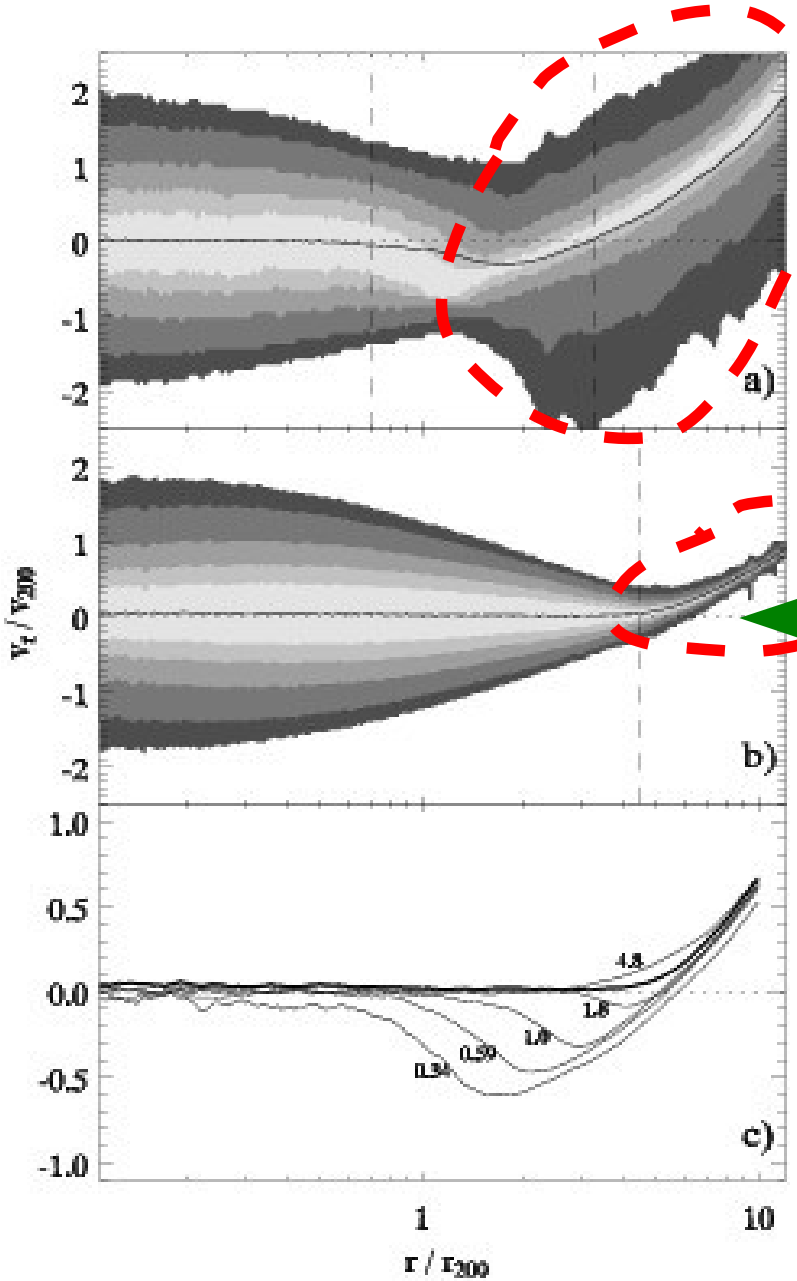

**ΔM,**
**Δt <= Φ**

**Mass profile beyond $r_{200}$:**

**Connection between mass profile and mass accretion rate**

**(Ludlow et al. 2013; Diemer & Kratsov 2013; Correa et al. 2014)**

# The ultimate cluster mass




Infalling matter

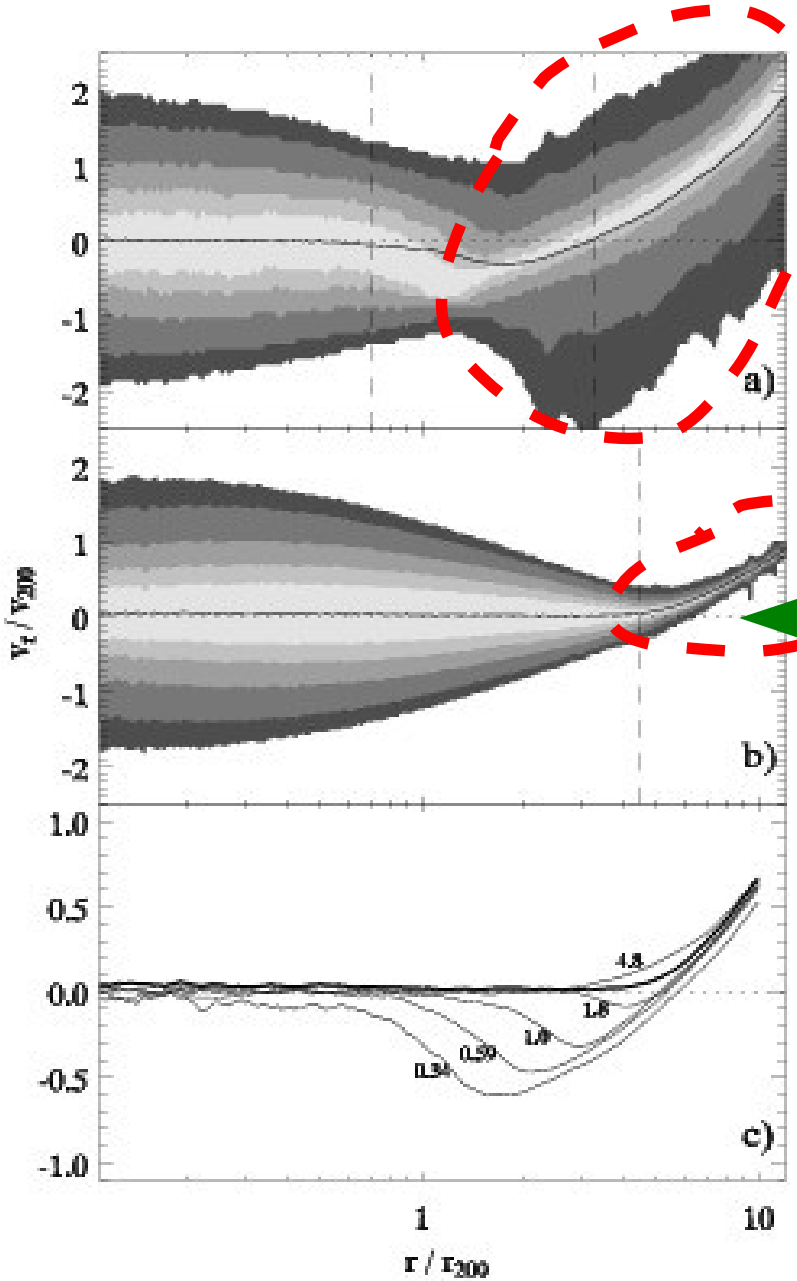
present time
a=1

future
a=100

in ΛCDM
$M_{fin} = 1.9\ M_{200}$

Busha et al. 2005

# The ultimate cluster mass




Infalling matter

present time
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$M_{fin} = 1.9\ M_{200}$

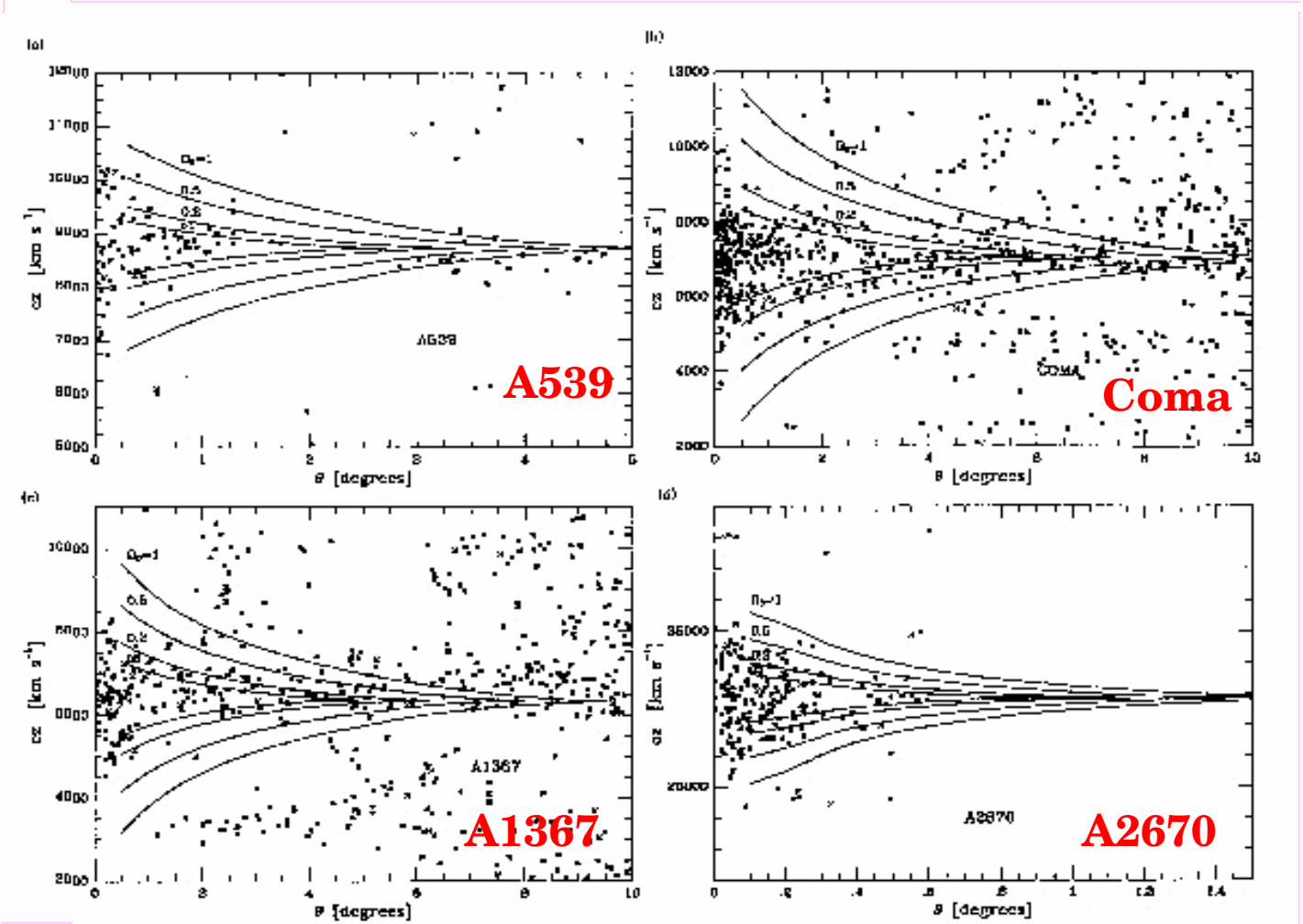
How do we measure this mass?

Busha et al. 2005

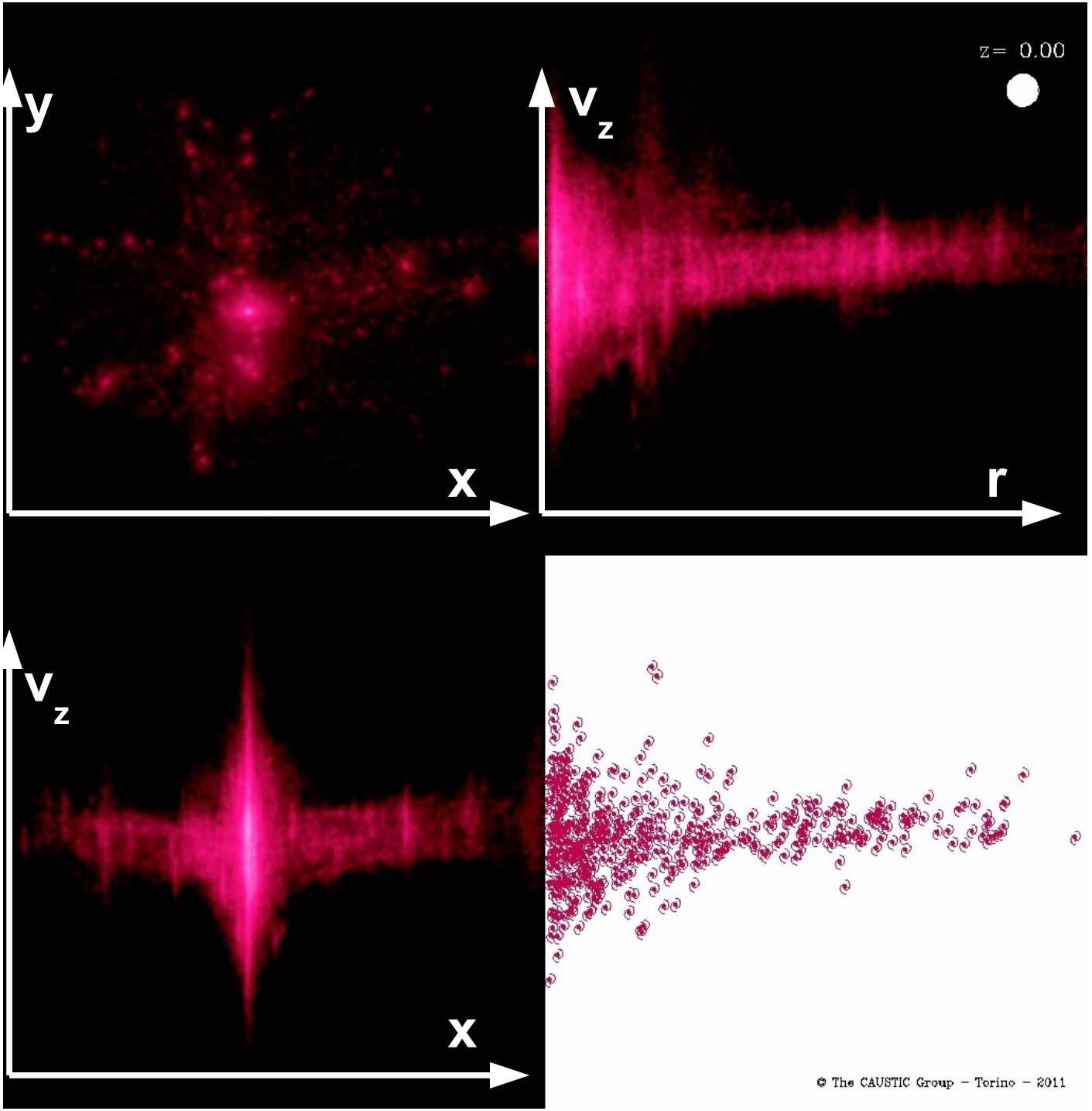
# MASS DISTRIBUTION
# IN THE OUTER REGION OF CLUSTERS

**infall peculiar velocity:**

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




Regös & Geller 1989

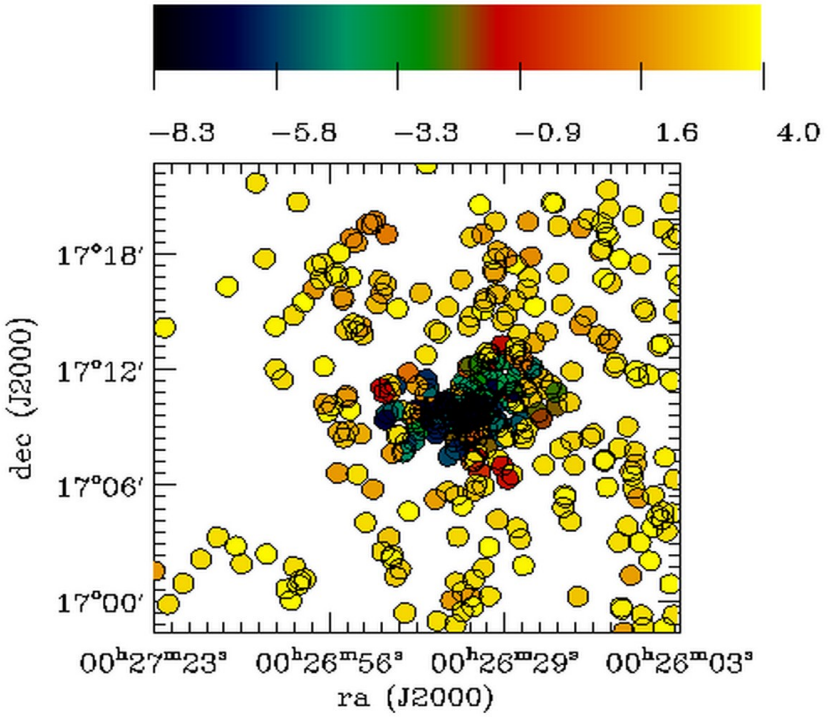

z= 0.00
y
x
$v_z$
r
$v_z$
x
© The CAUSTIC Group – Torino – 2011

# THE CAUSTIC TECHNIQUE

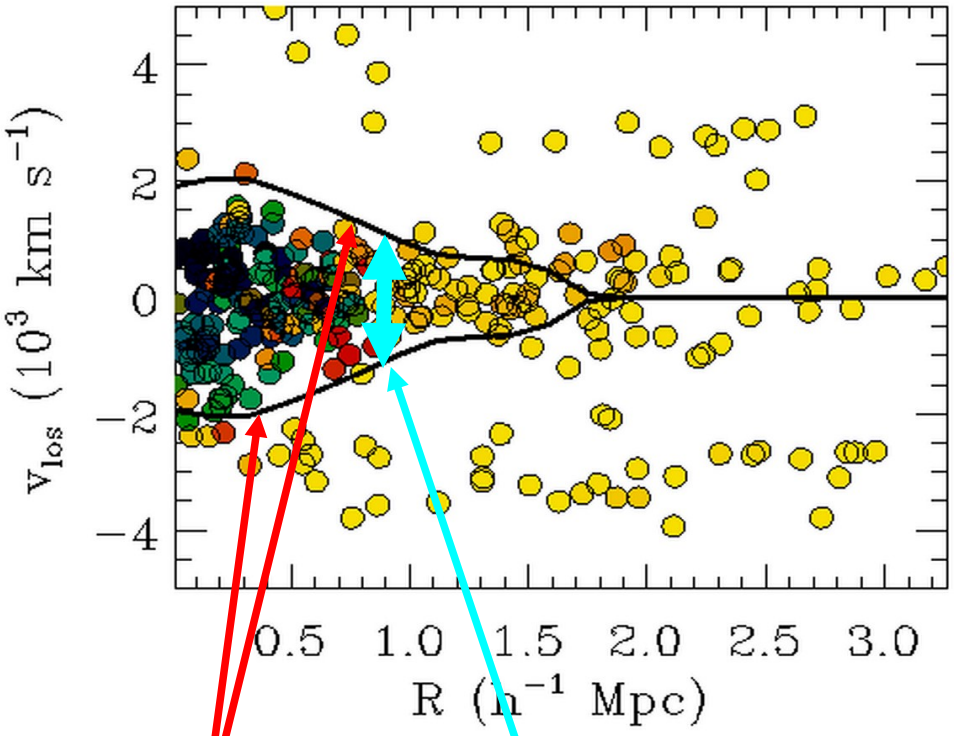
**Example:**

**CL0024**

**Sky**




**Redshift diagram**




**MASS ESTIMATE:**

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

**Caustics**

**Caustic amplitude = Escape velocity**

**Diaferio & Geller 1997**

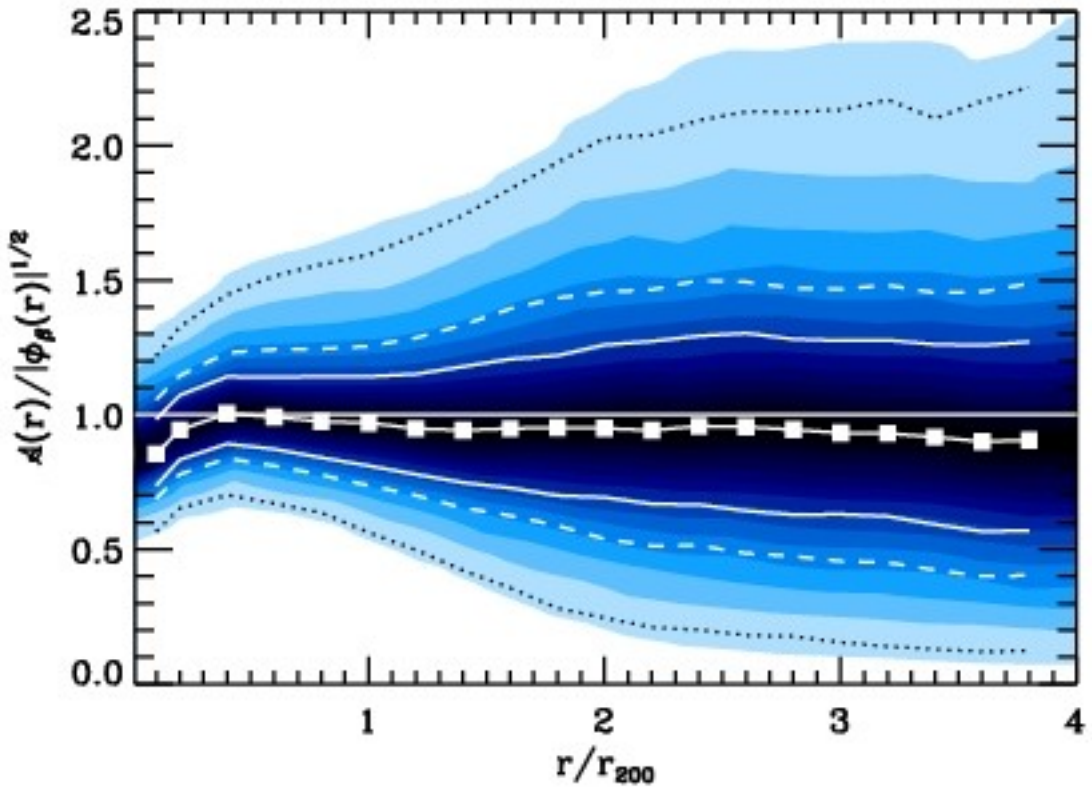
# MEASURING
# THE GRAVITATIONAL POTENTIAL PROFILE

***(unclean sample...!)***

***3000 synthetic clusters***

***(ΛCDM model)***

**Caustic potential/true potential**

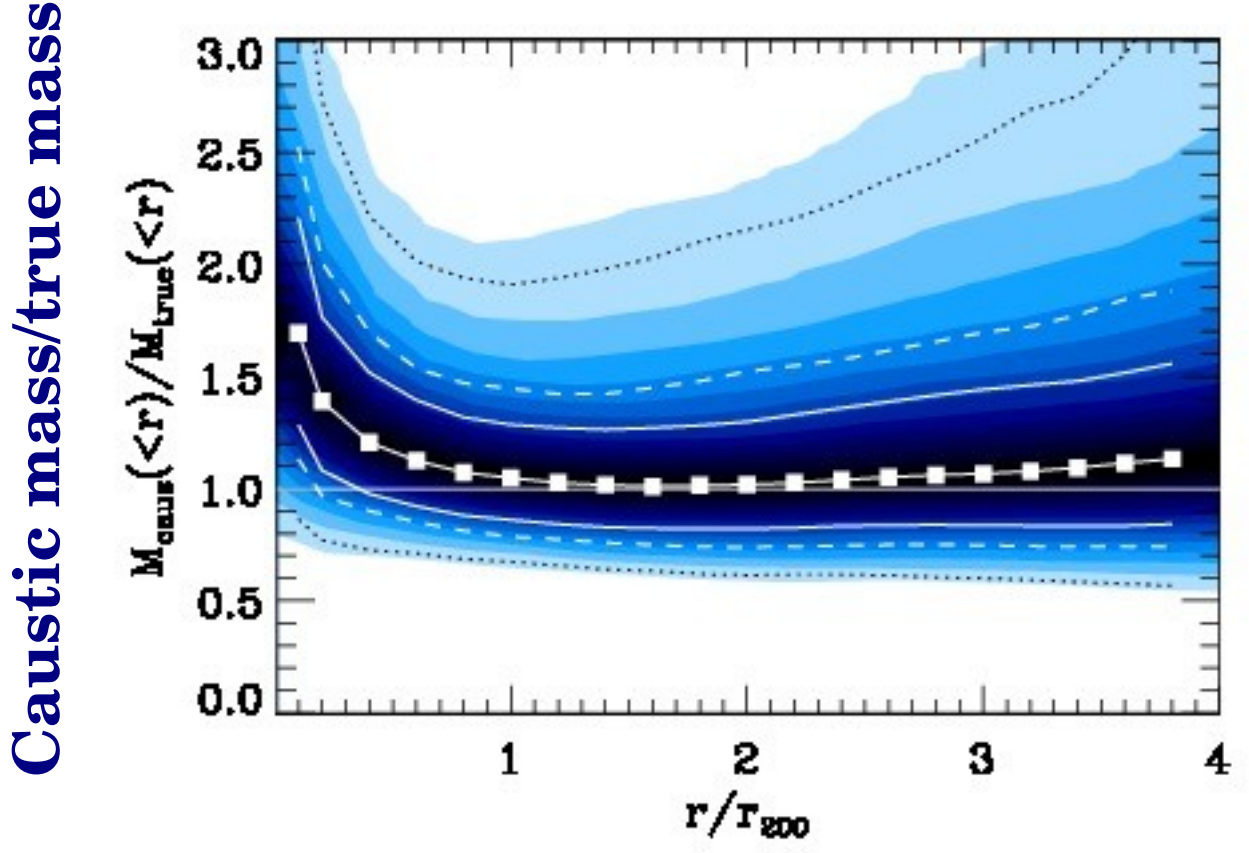



**68%**

**Serra et al. 2011**

# MEASURING
# THE CUMULATIVE MASS PROFILE
## *(unclean sample...!)*

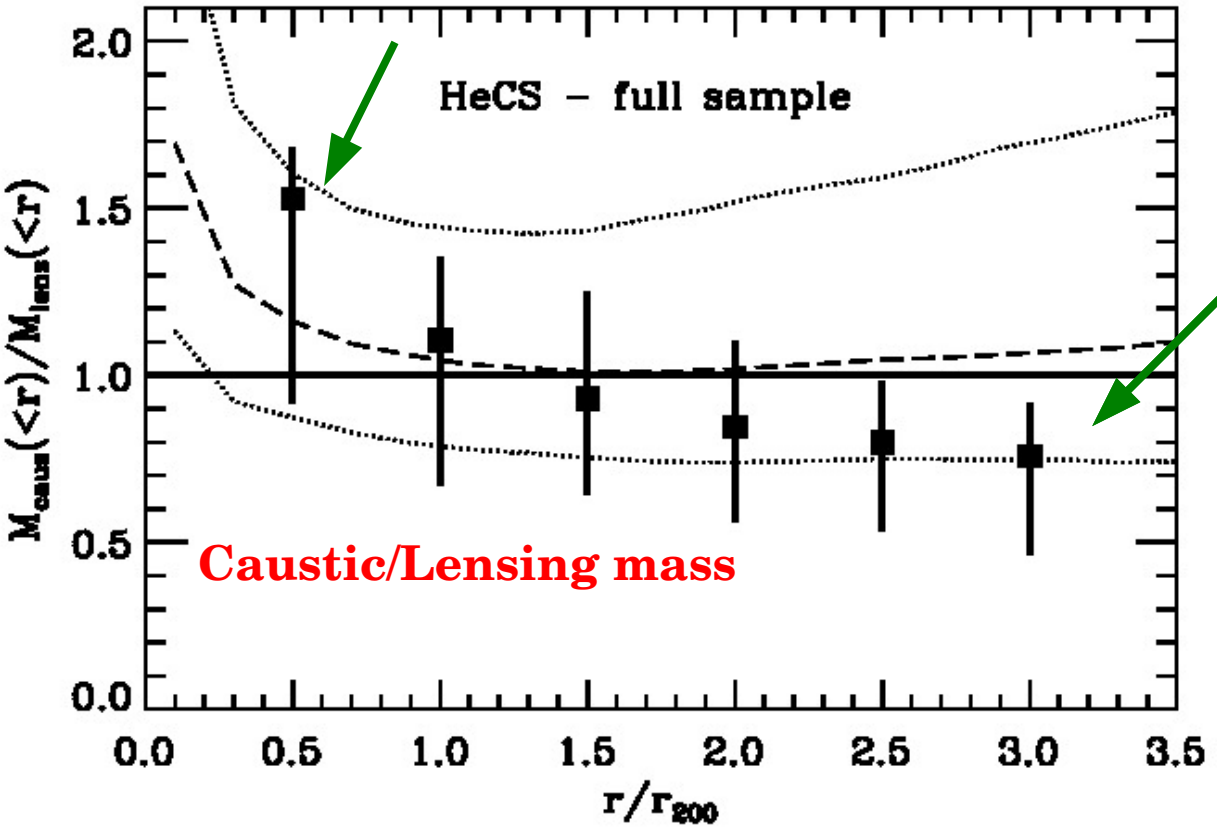
***3000 synthetic clusters***
***(ΛCDM model)***



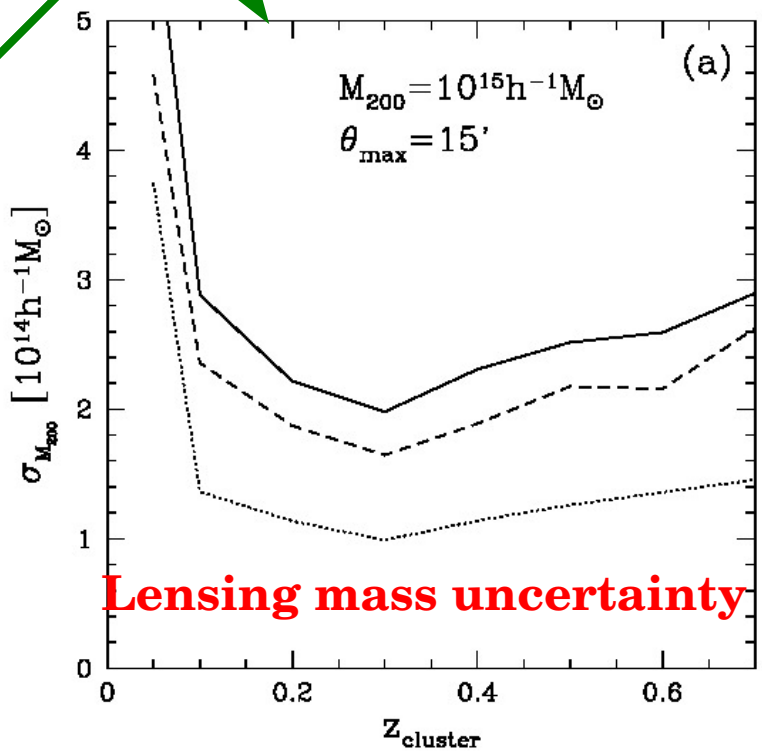

**Serra et al. 2011**

# CAUSTIC vs. LENSING MASS

**Caustic method: systematic overestimate at small r (Serra et al. 2011)**




**Weak lensing: contribution from large-scale structures (Hoekstra 2003)**

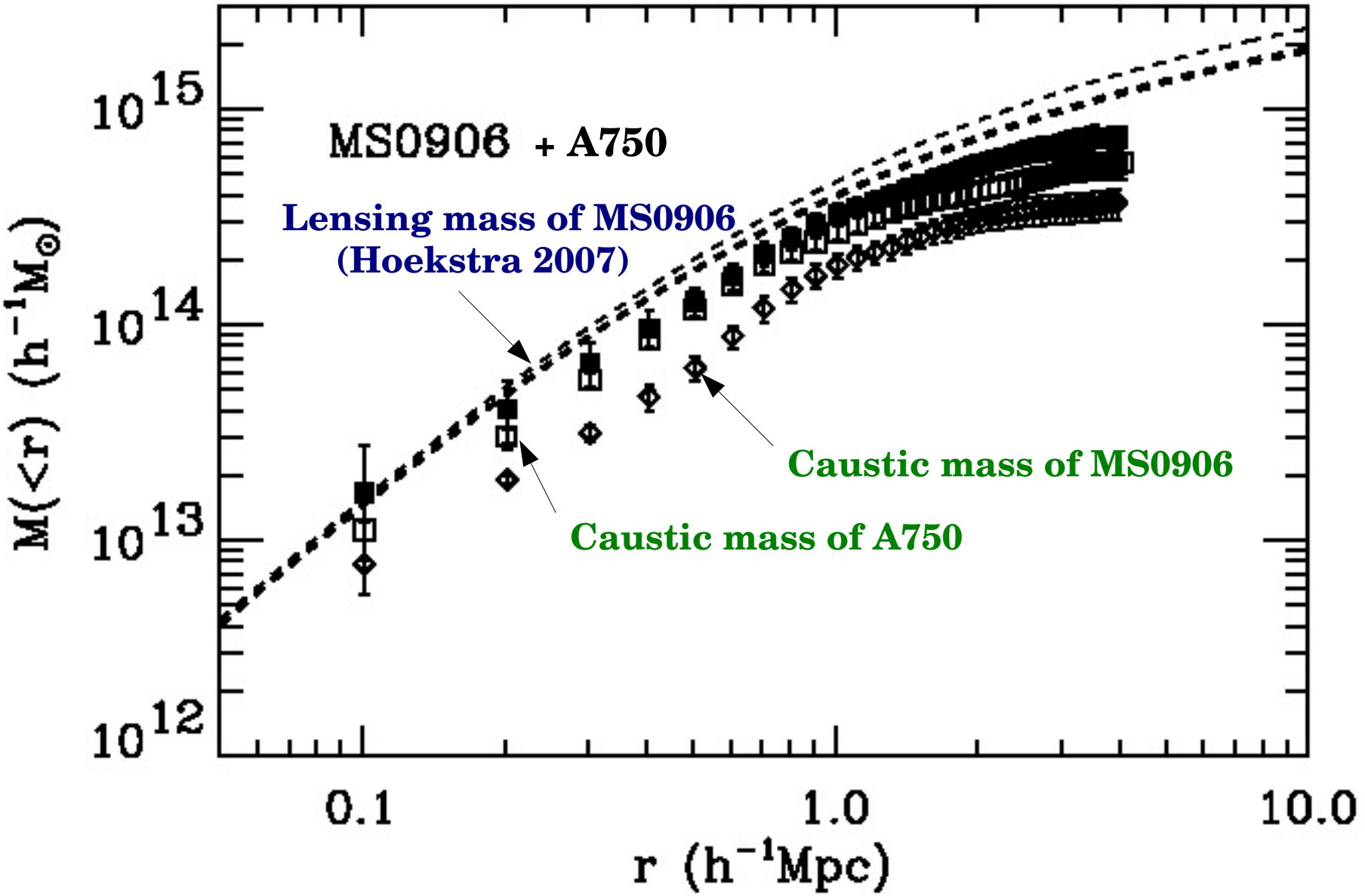



Geller et al. 2013

# THE TWO CLUSTERS MS0906 AND A750

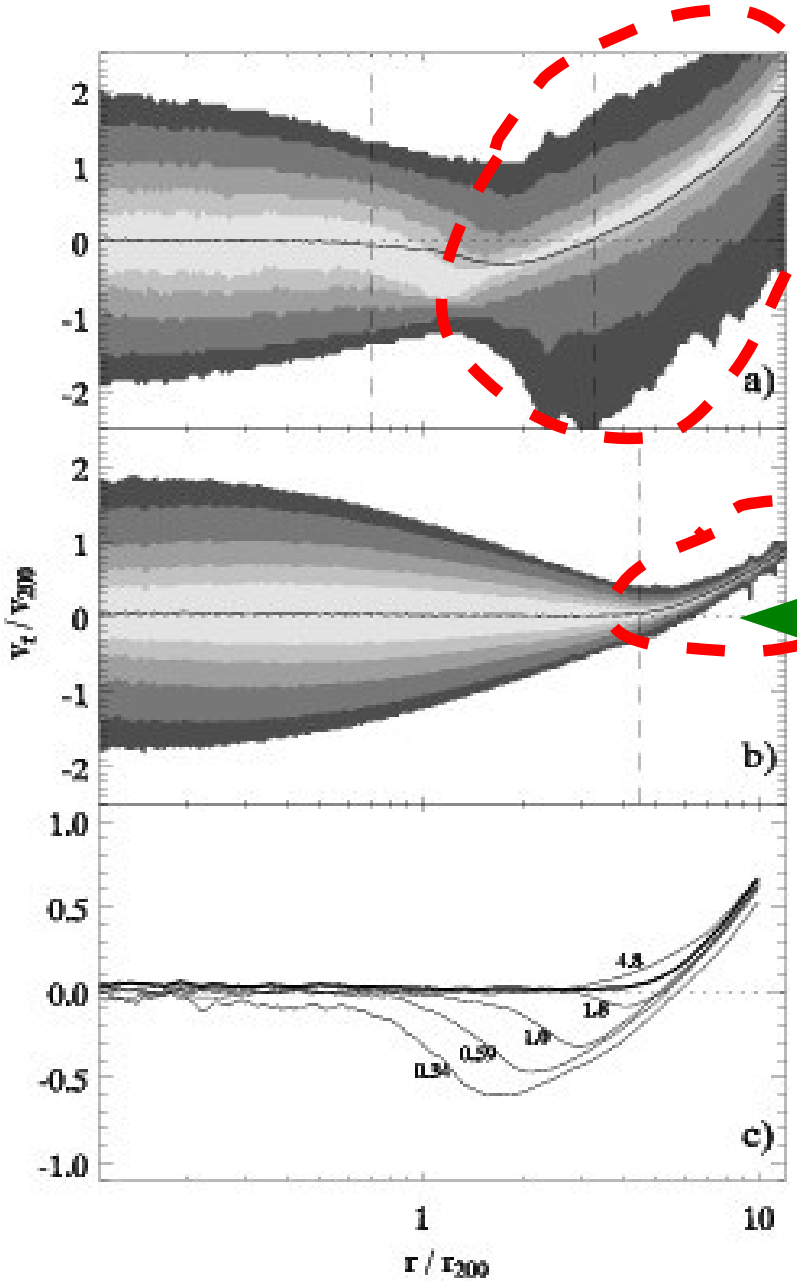
1 Mpc

# Caustics vs. Lensing Masses:
# the case of MS0906




Geller et al. 2013

# The ultimate cluster mass




Infalling matter

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a=100

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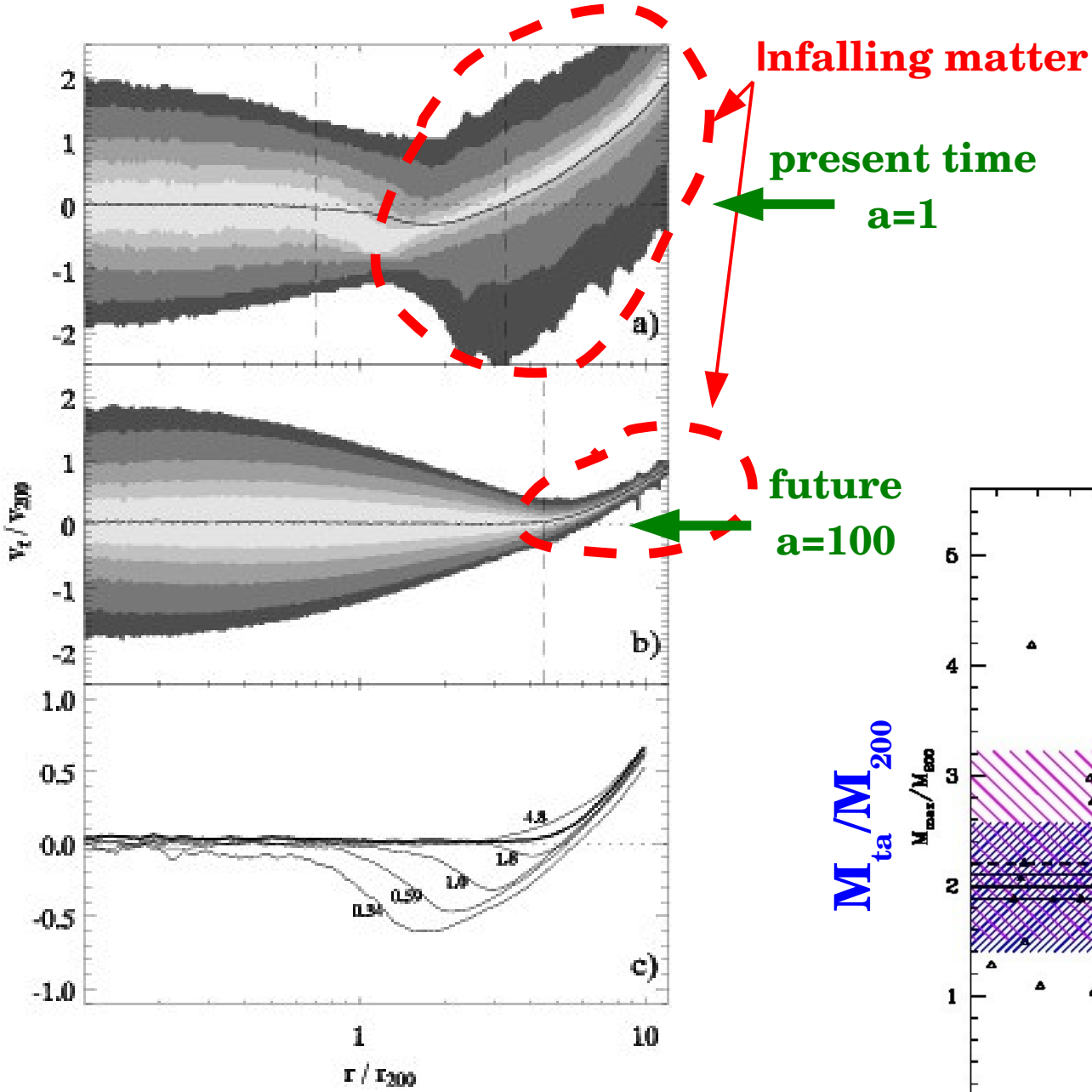
$M_{fin} = 1.9\ M_{200}$

Busha et al. 2005

# HeCS: The ultimate cluster mass



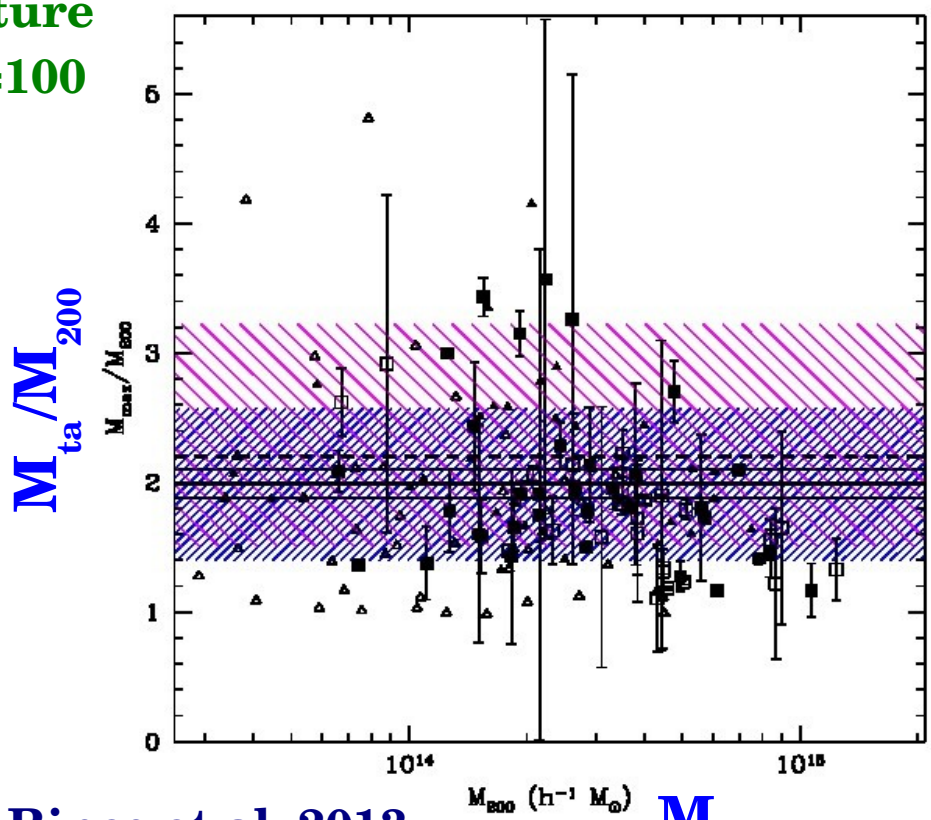

Busha et al. 2005

in ΛCDM

$M_{fin} = 1.9\ M_{200}$

From HeCS

$M_{ta} = 1.99 \pm 0.11\ M_{200}$




Rines et al. 2013

$M_{200}$

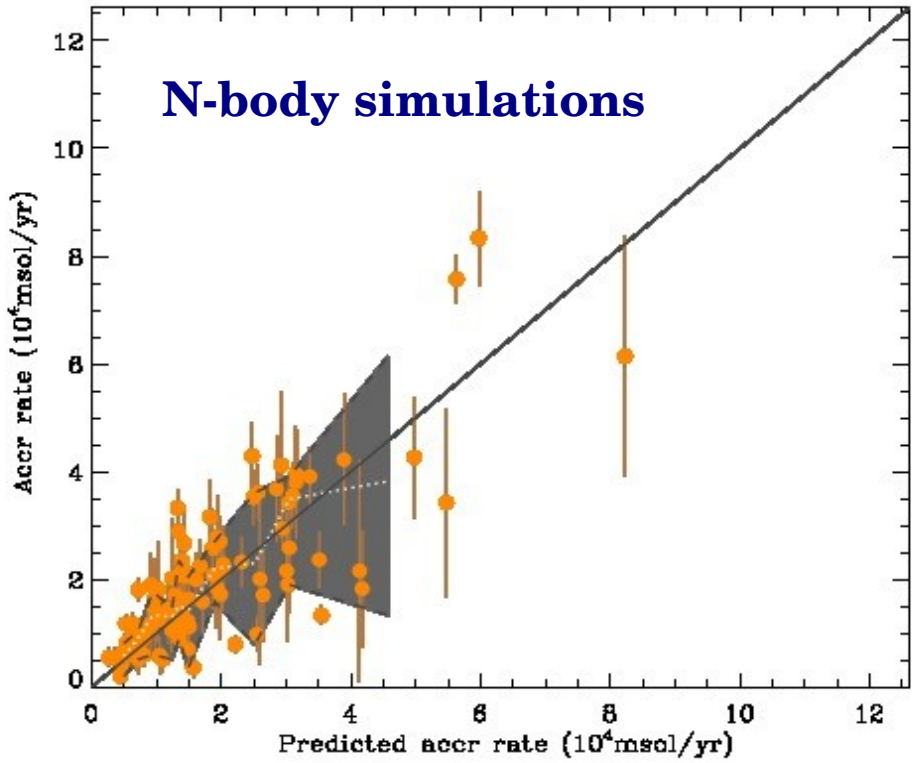
# Measured accretion rate $\Delta M/\Delta t$

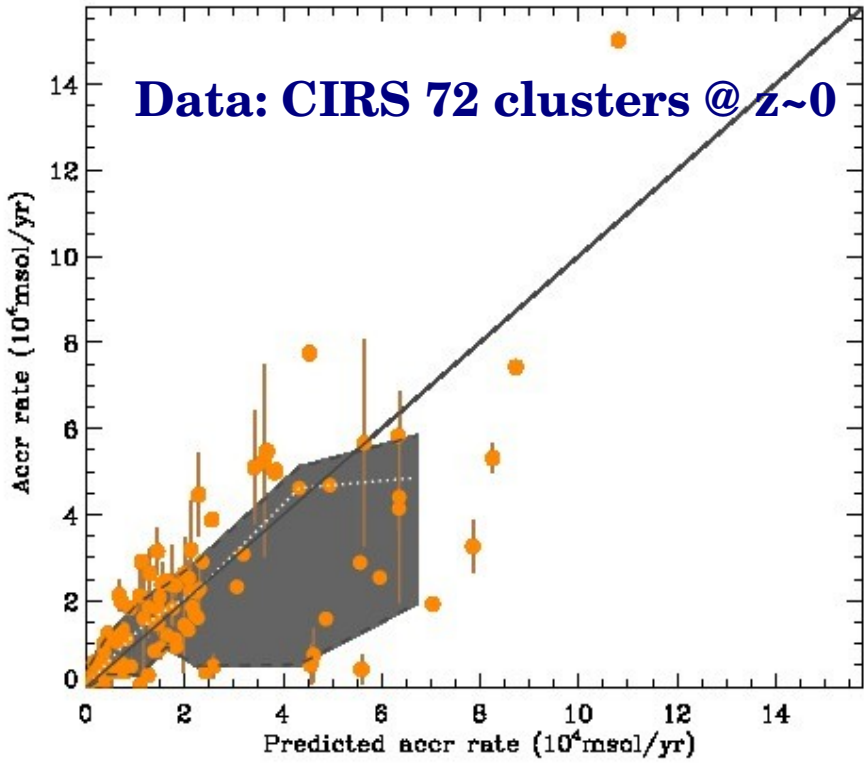
# vs

# Expected accretion rate

# @ z~0

**Measured**




**Expected** **Expected**

$$\langle dM/dt \rangle \propto M^{1.127}(1+1.17z)E(z)$$

***Expected rate from the Millennium Sim. (McBride et al 2009)***

**Serra et al. in prep.**

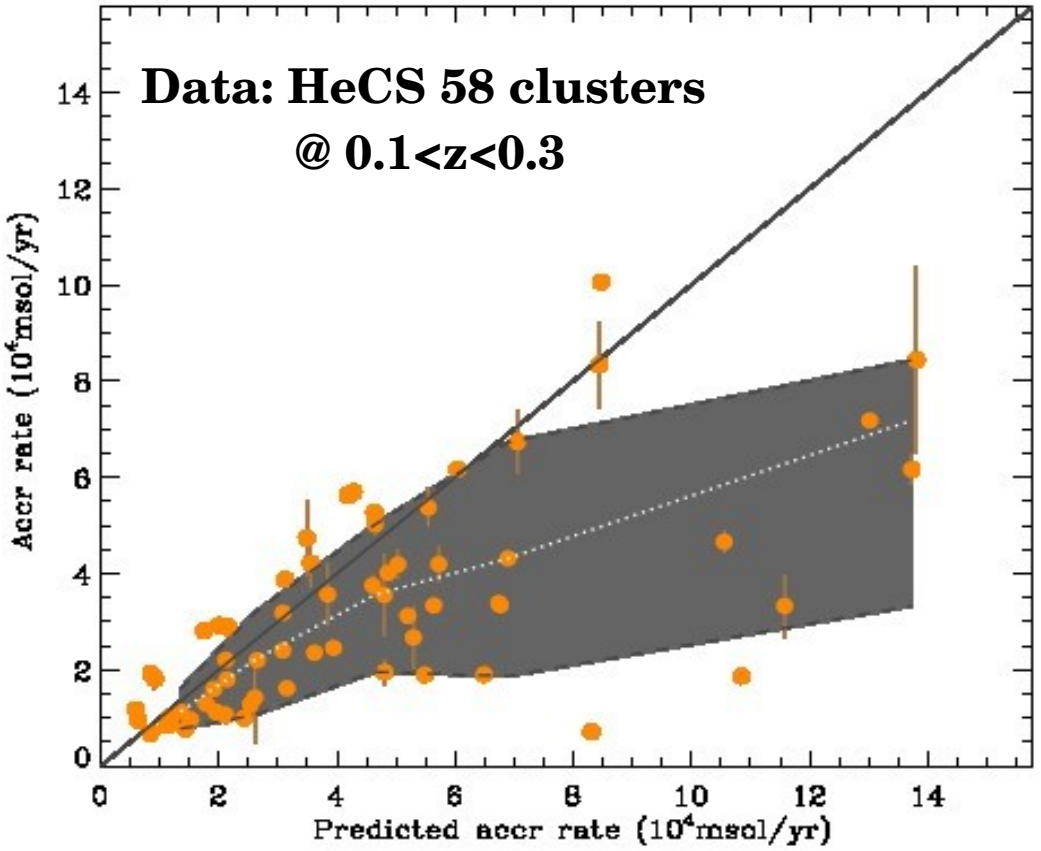
# Measured accretion rate $\Delta M/\Delta t$

# vs

# Expected accretion rate

# @ 0.1<z<0.3

**Measured**

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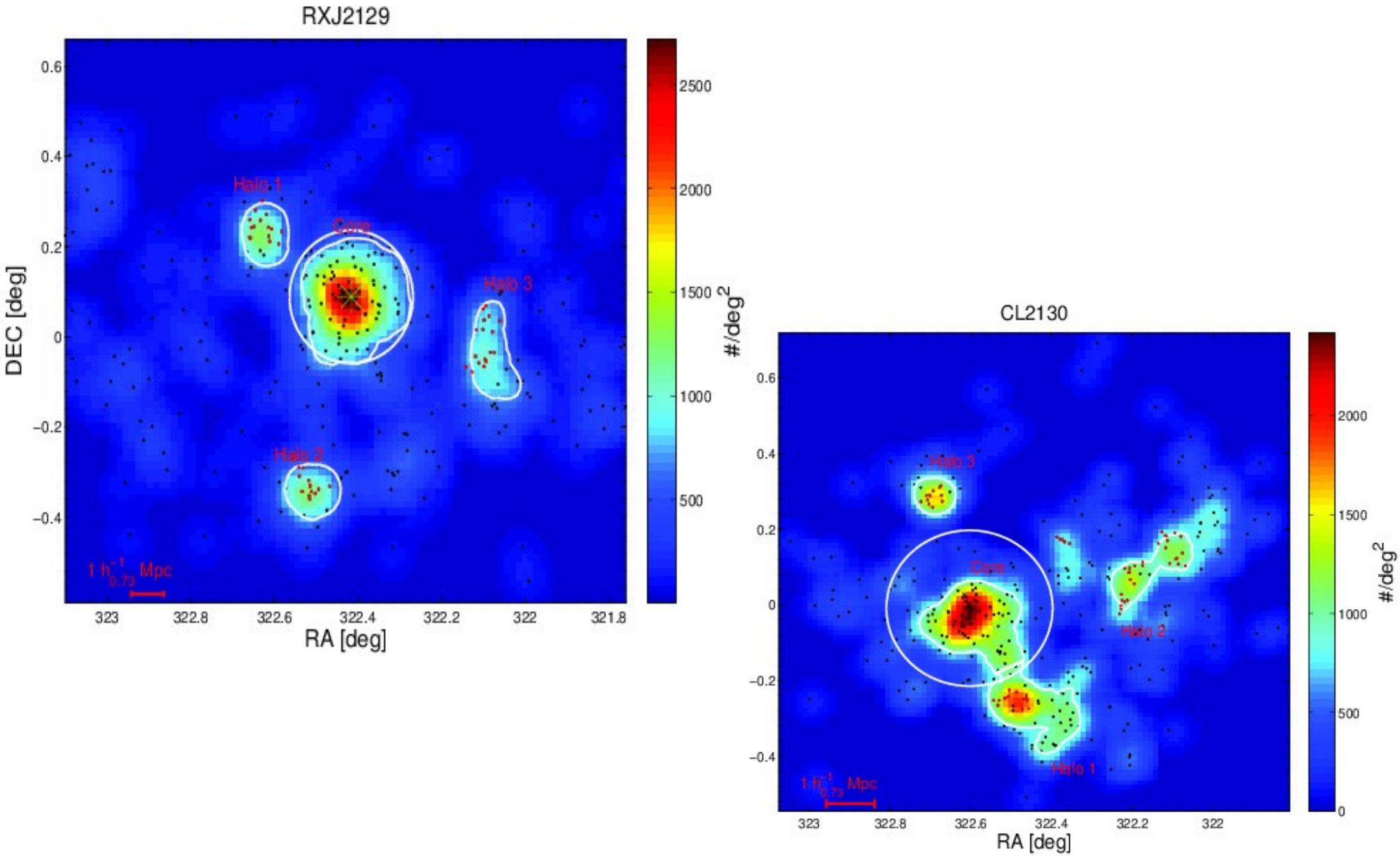
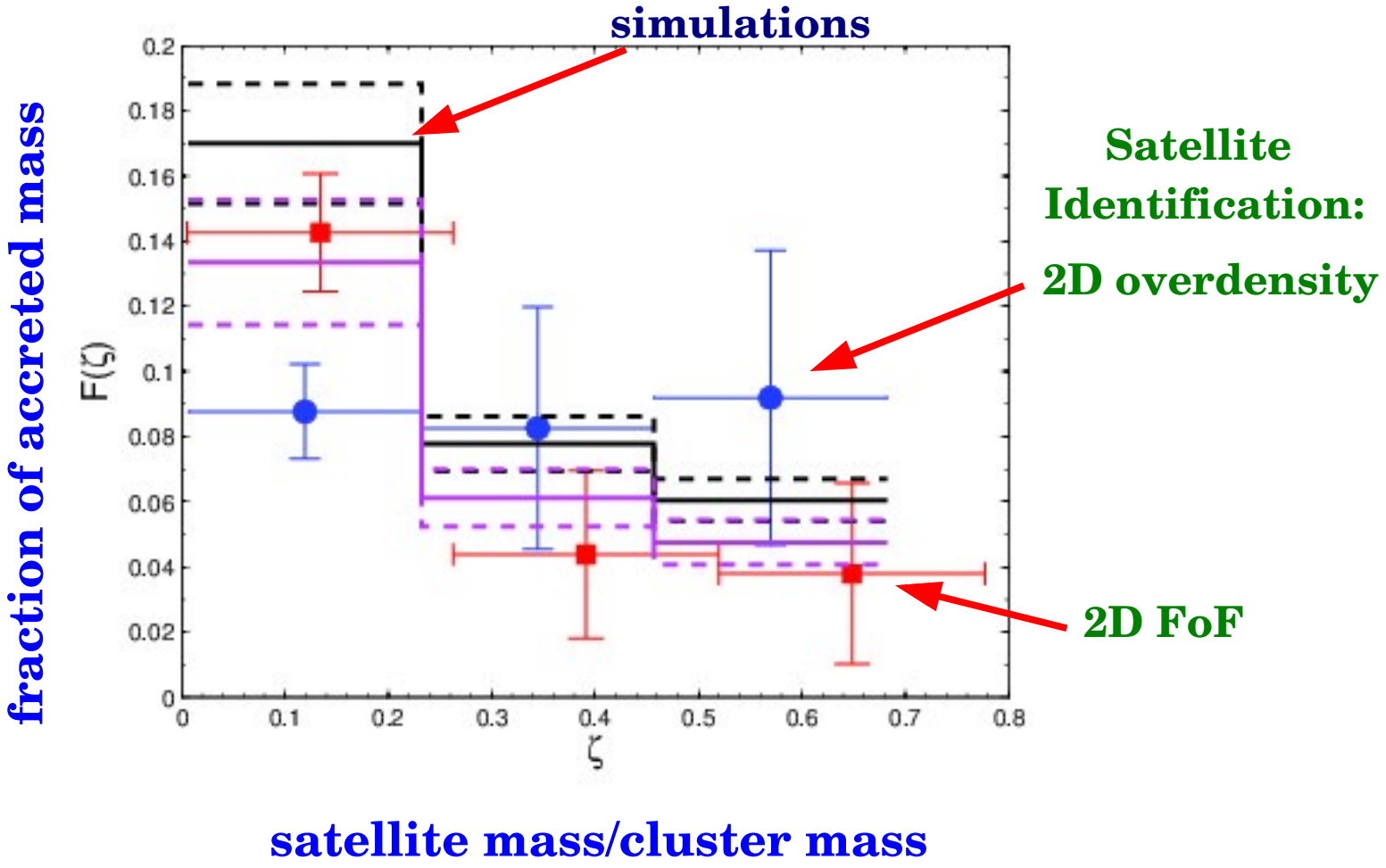
# ACCRETION WITH SURROUNDING GROUPS



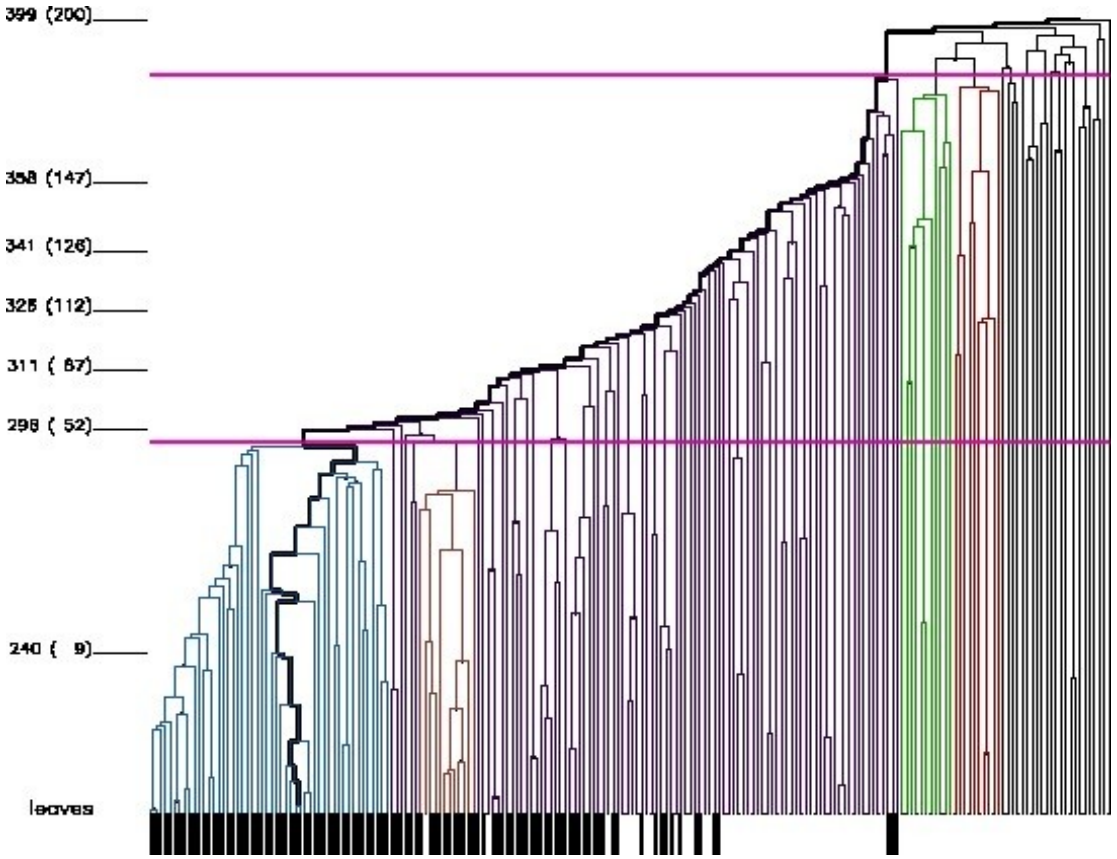

**7 clusters from the CLASH collaboration: Lemze et al. 2013**

# ACCRETION WITH SURROUNDING GROUPS

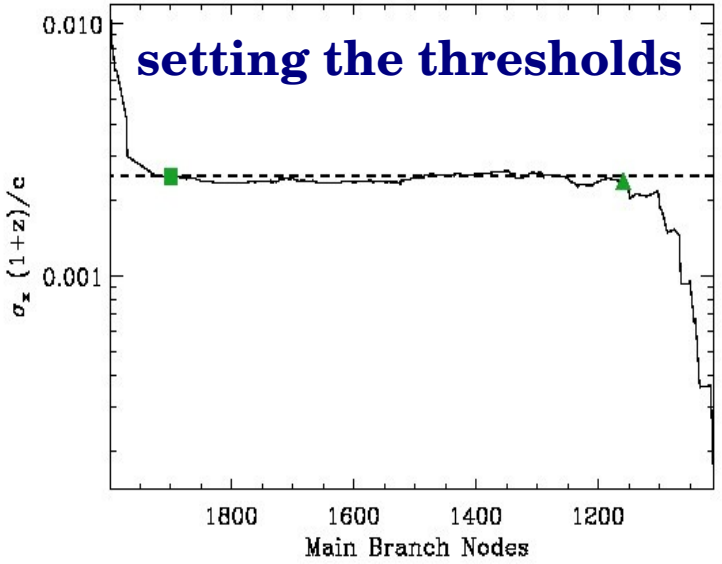


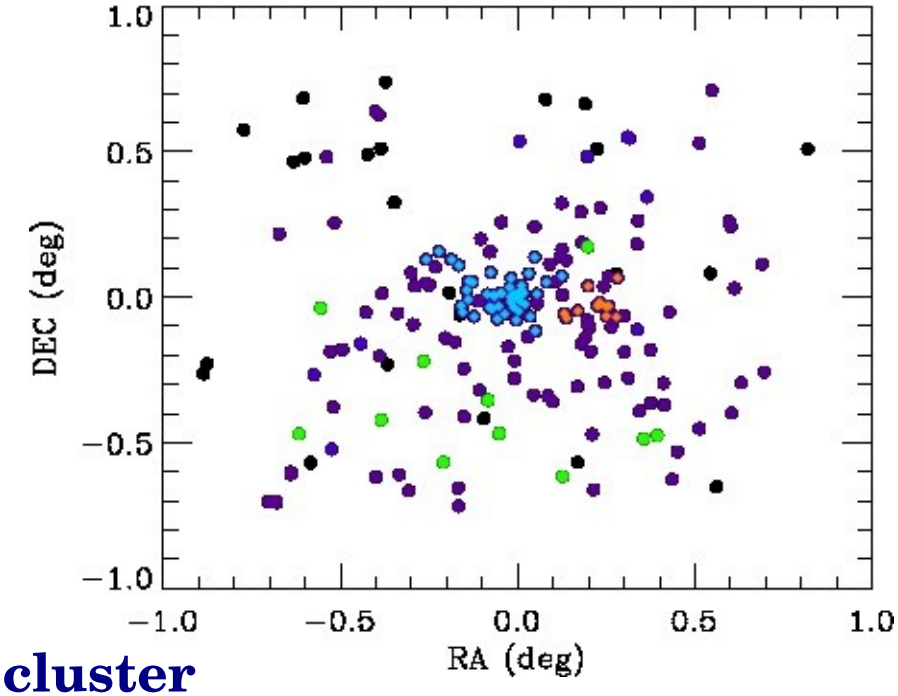

Lemze et al. 2013

# SUBSTRUCTURES AND SURROUNDING GROUPS WITH THE CAUSTIC TECHNIQUE



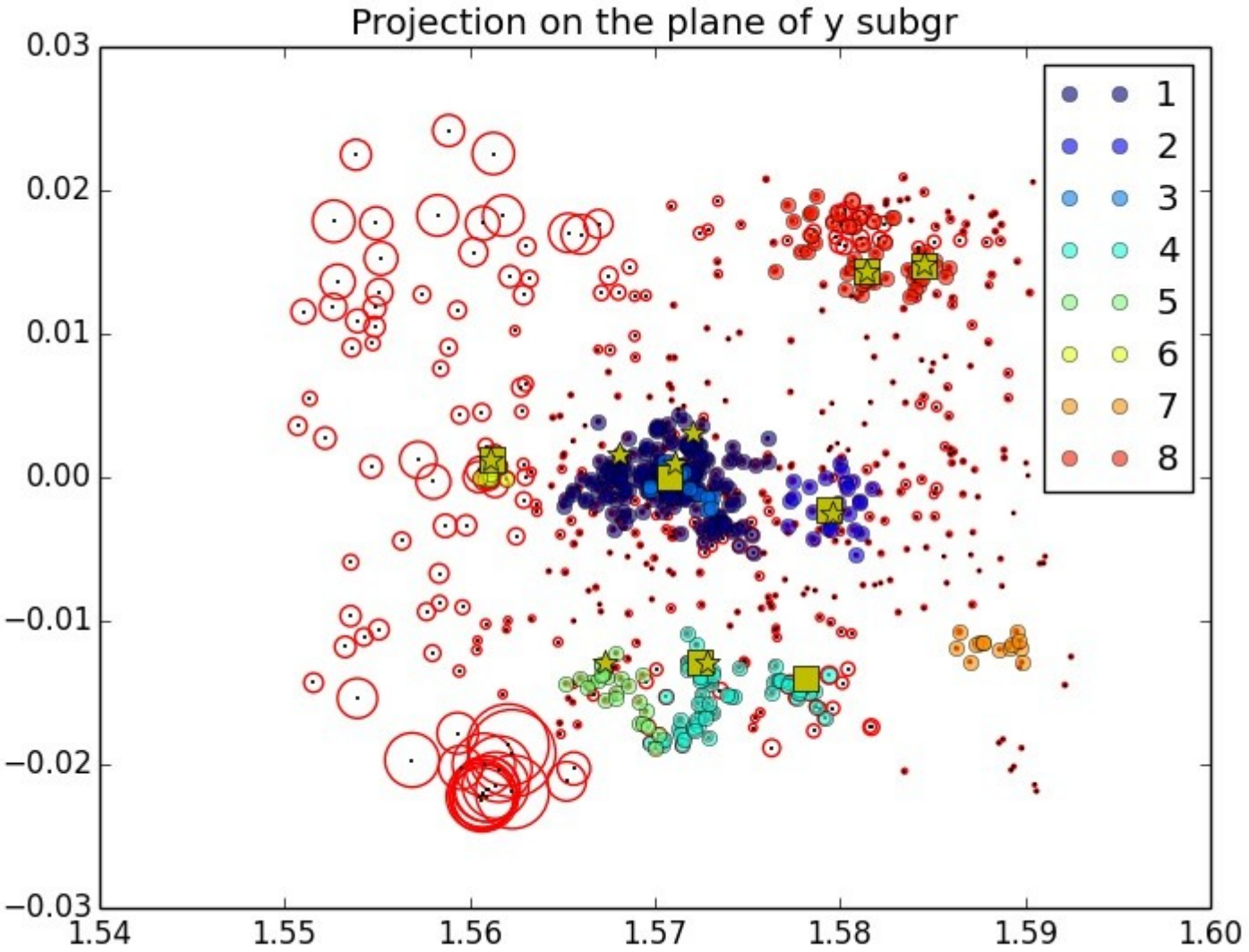

**binary tree**




**simulated cluster**

# SUBSTRUCTURES AND SURROUNDING GROUPS WITH THE CAUSTIC TECHNIQUE

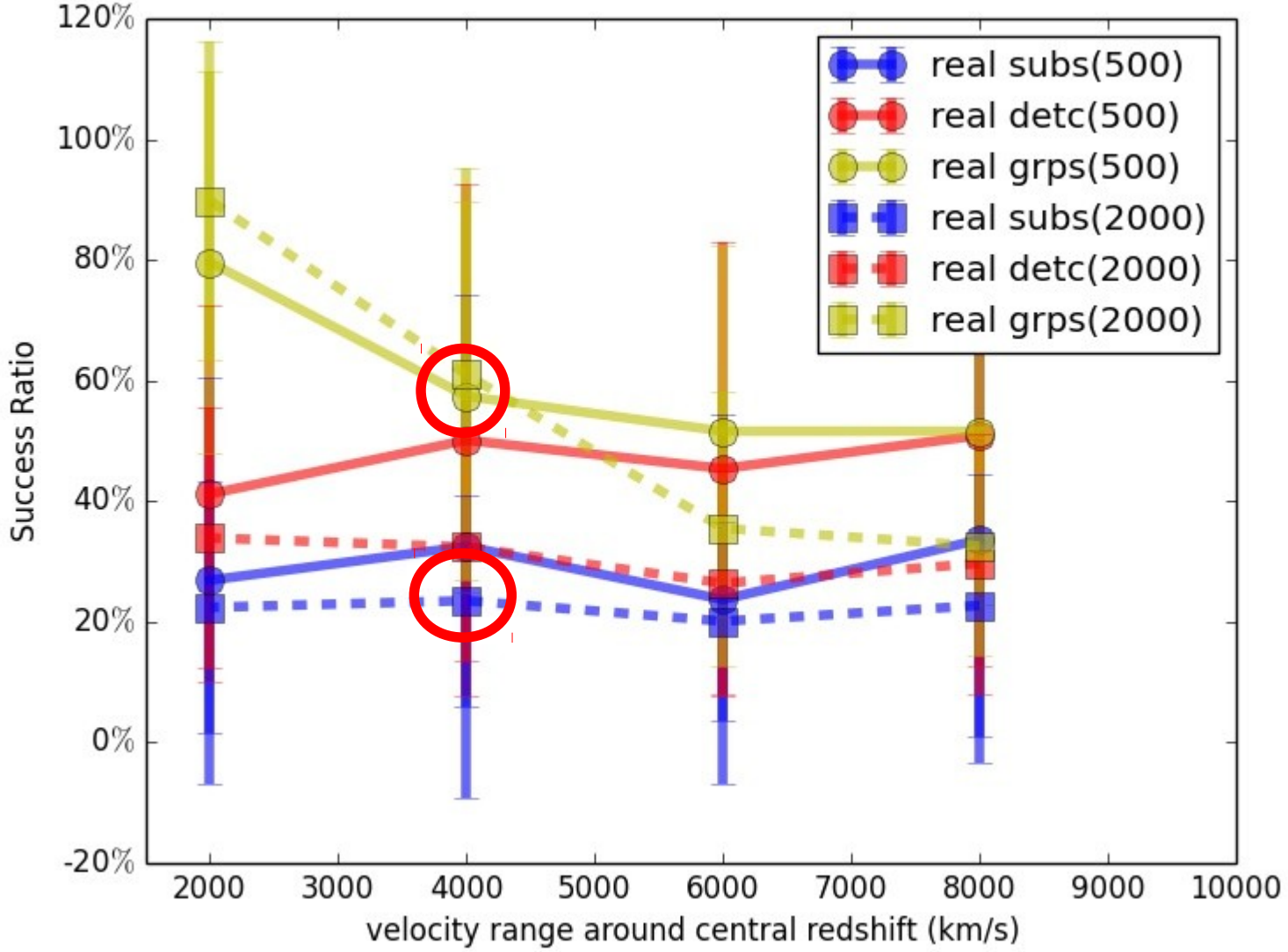



**recovery tests**

**Yu et al. in prep.**

# SUBSTRUCTURES AND SURROUNDING GROUPS WITH THE CAUSTIC TECHNIQUE

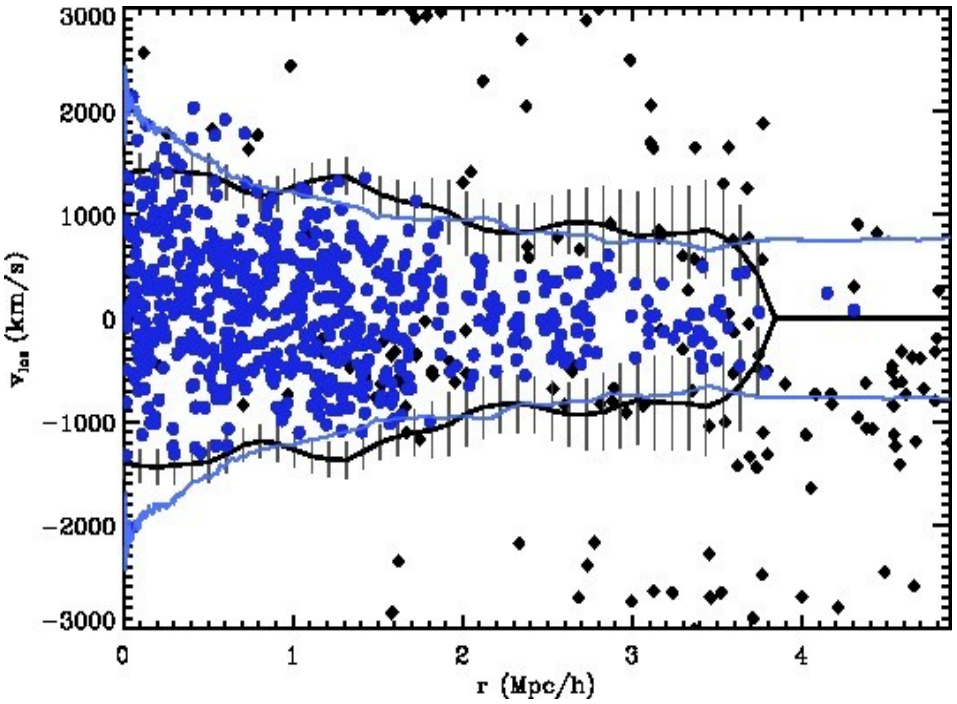
recovery rate



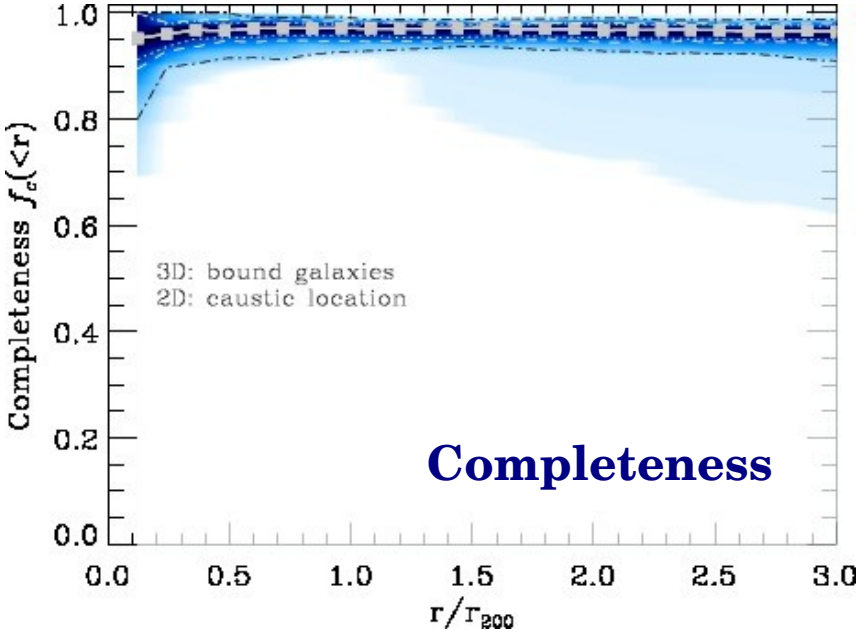

sampling redshift range around the cluster center

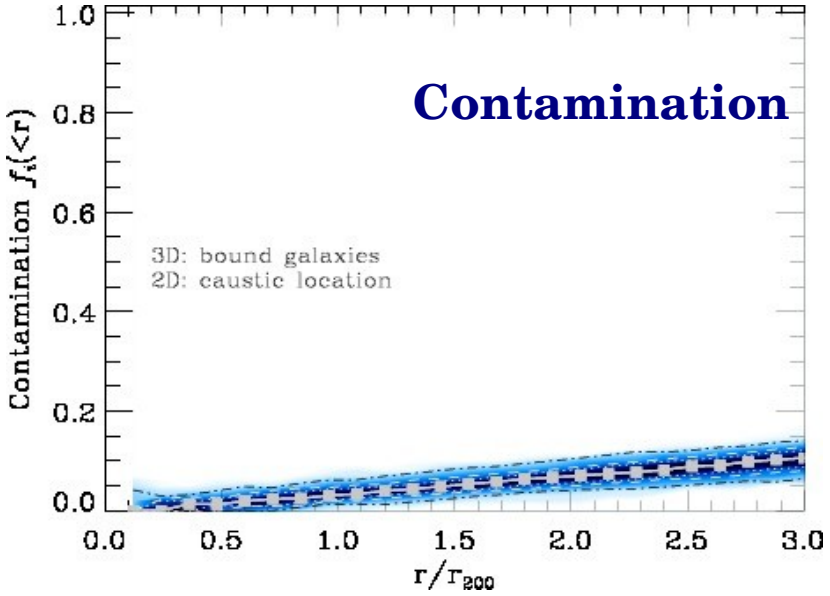
Yu et al. in prep.

# IDENTIFICATION OF CLUSTER MEMBERS WITH THE CAUSTIC TECHNIQUE



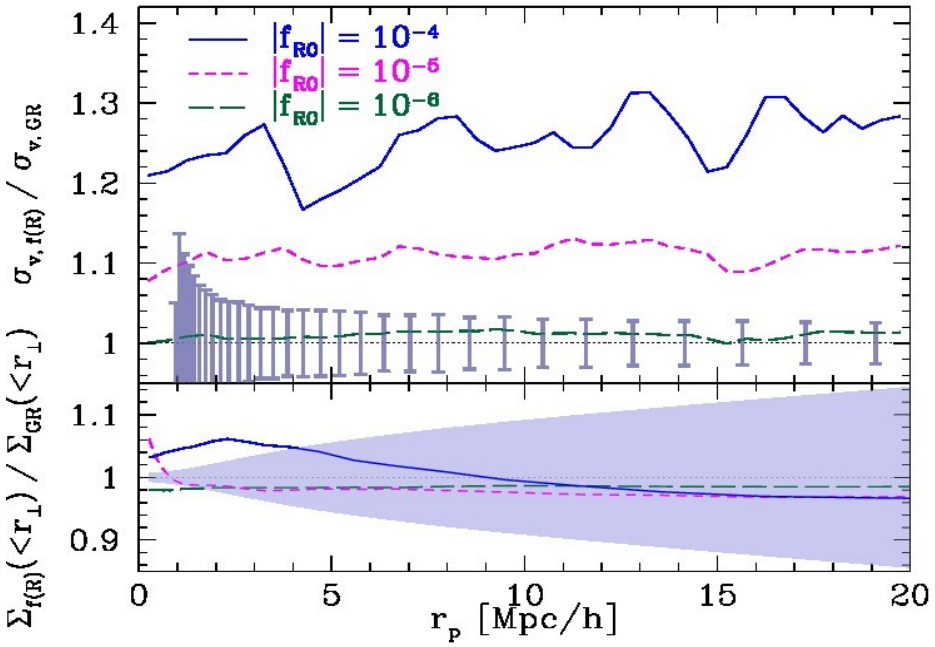

Serra & Diaferio 2013



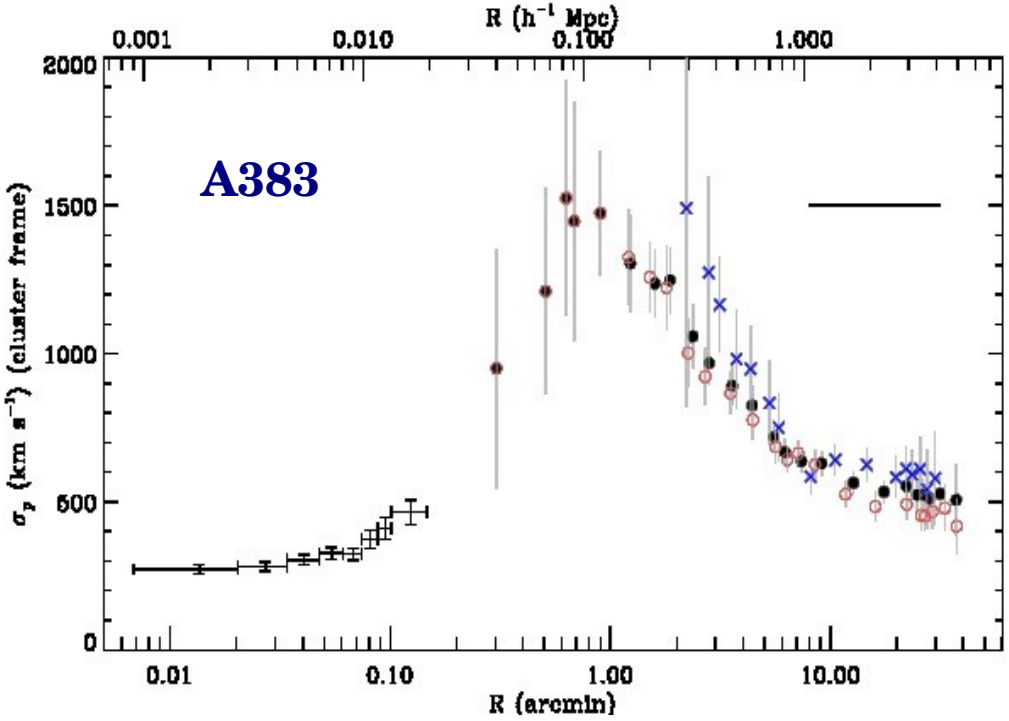
# CLUSTER VELOCITY DISPERSION PROFILE IN MODIFIED GRAVITY

velocity dispersion f(R)/GR




Lam et al. 2012

accurate measurement of velocity dispersion profiles

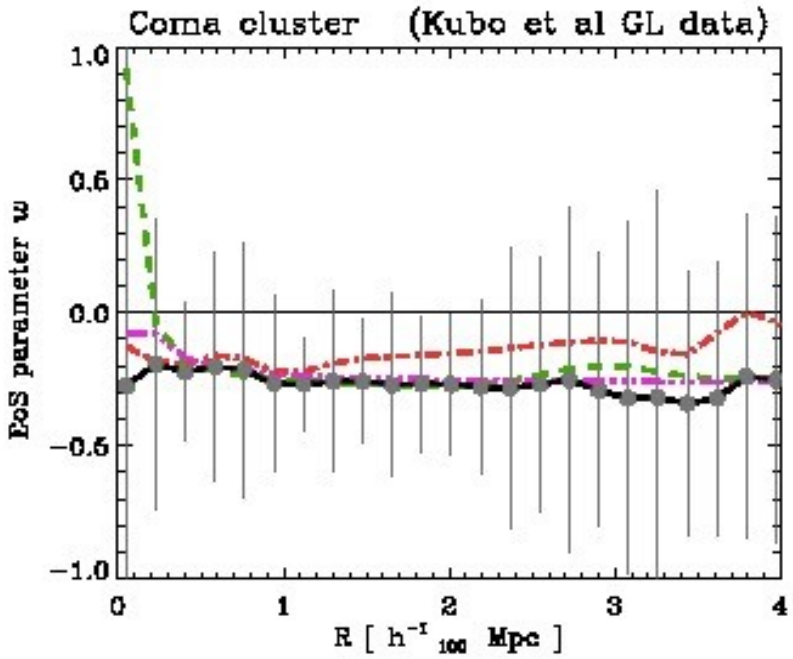


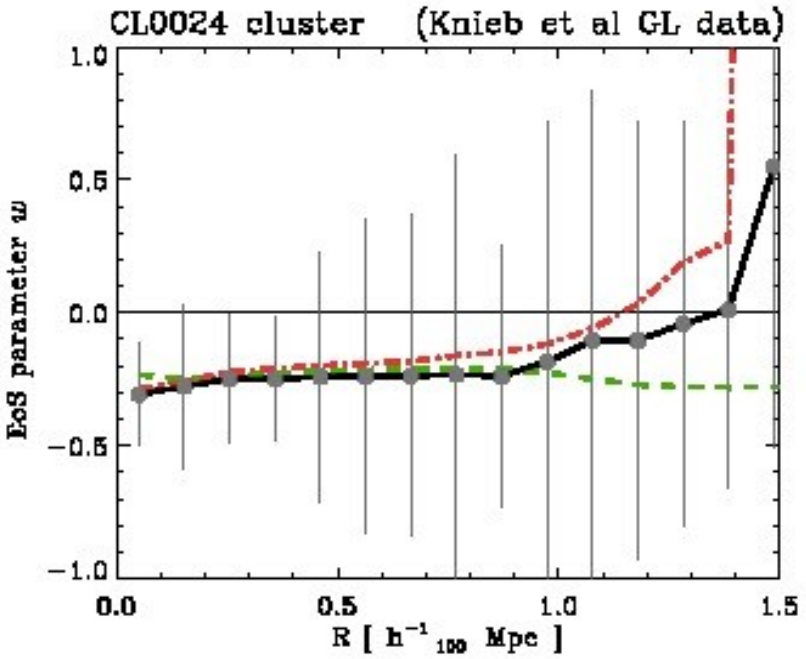

Geller et al. 2014

# THE EQUATION OF STATE OF DARK MATTER

## By combining kinematic and lensing mass estimates (Faber & Visser 2006)

w

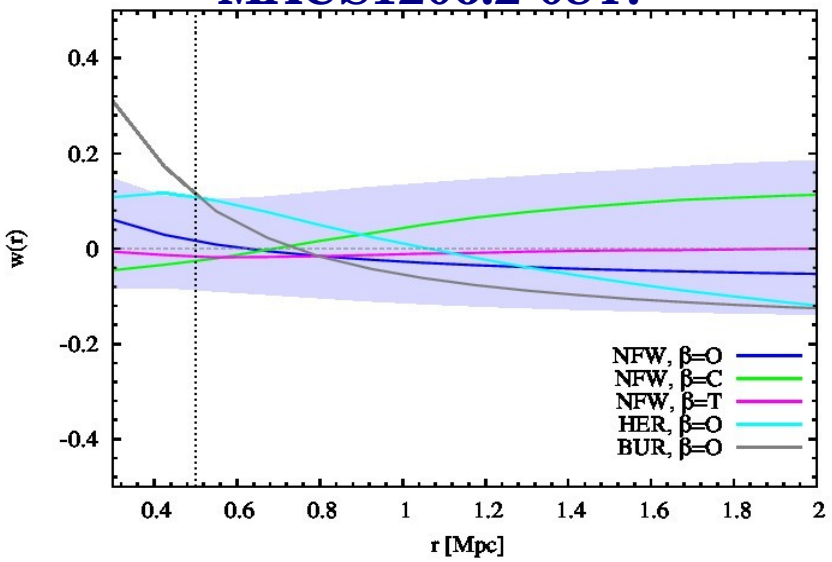



Serra and Domínguez-Romero 2011

MACS1206.2-0847

w



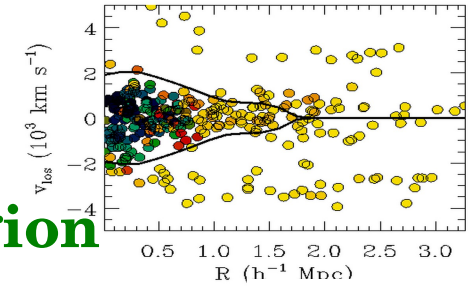

Sartoris et al. 2014

$w = p/\rho$

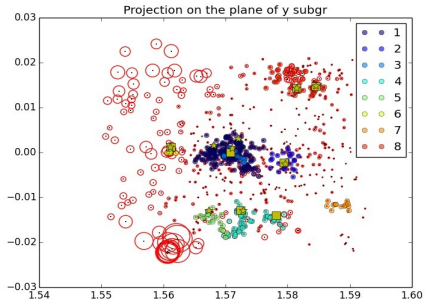
# SUMMING UP

**With the caustic technique we can:**

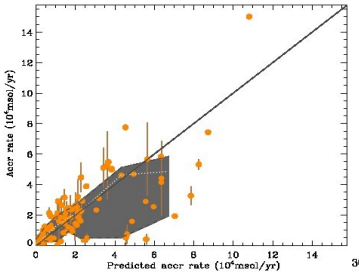
1. **Measure the mass in the cluster infall region**



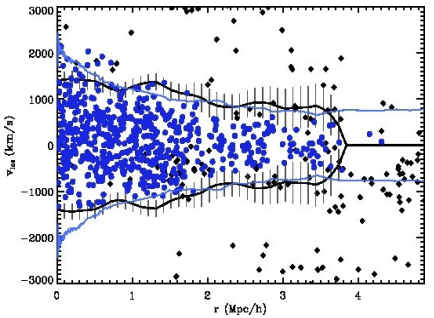

2. **Identify the cluster substructures and surrounding groups**




3. **Measure the cluster accretion rate**




4. **Identify the cluster galaxy members**




**TEST**
**FORMATION OF GALAXY CLUSTERS**
**AND**
**MODIFIED GRAVITY MODELS**