

# ESTIMATING THE GRAVITATIONAL POTENTIAL AND MASS PROFILES IN THE OUTER REGIONS OF GALAXY CLUSTERS

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*&*

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*A celebration of Vera Rubin's career*

**UNVEILING THE MASS**

Extracting and Interpreting Galaxy Masses

June 15-19 2009

Kingston, Ontario – A UNESCO World Heritage Destination

Kingston, June 18<sup>th</sup>, 2009



# OUTLINE

- **Mass estimators**
- **Historical prologue: The spherical infall model**
- **The caustic technique**
- **Achievements**

# Mass Estimates

Technique	Scale	$R_{500}$	$<R_{200}$	$>R_{200}$
X-ray		X		
Galaxy dynamics		X	X	
Scaling relations		X	X	
Strong lensing		X		
Weak lensing		X	X	X
Caustics		X	X	X

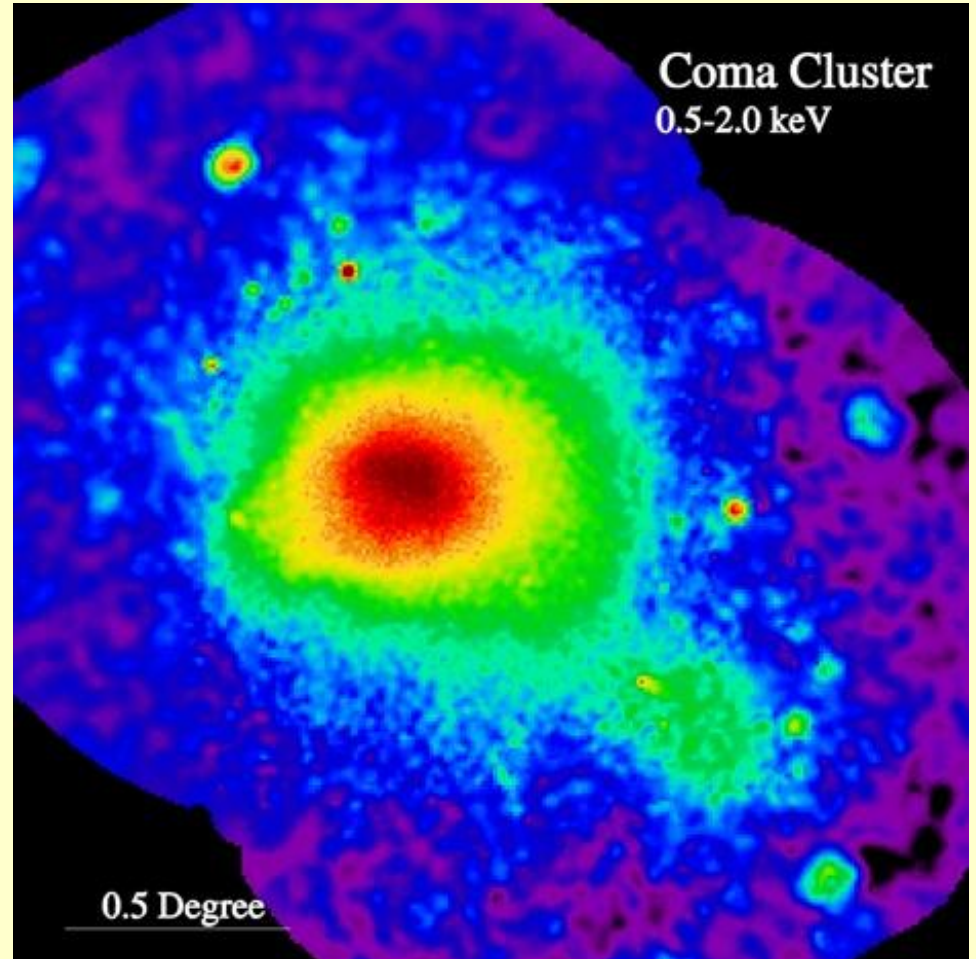
Require dynamical equilibrium

Do not require dynamical equilibrium

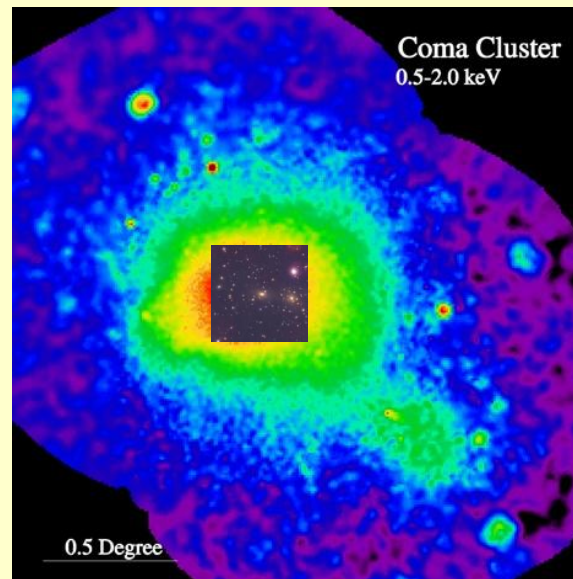
# THE COMA CLUSTER

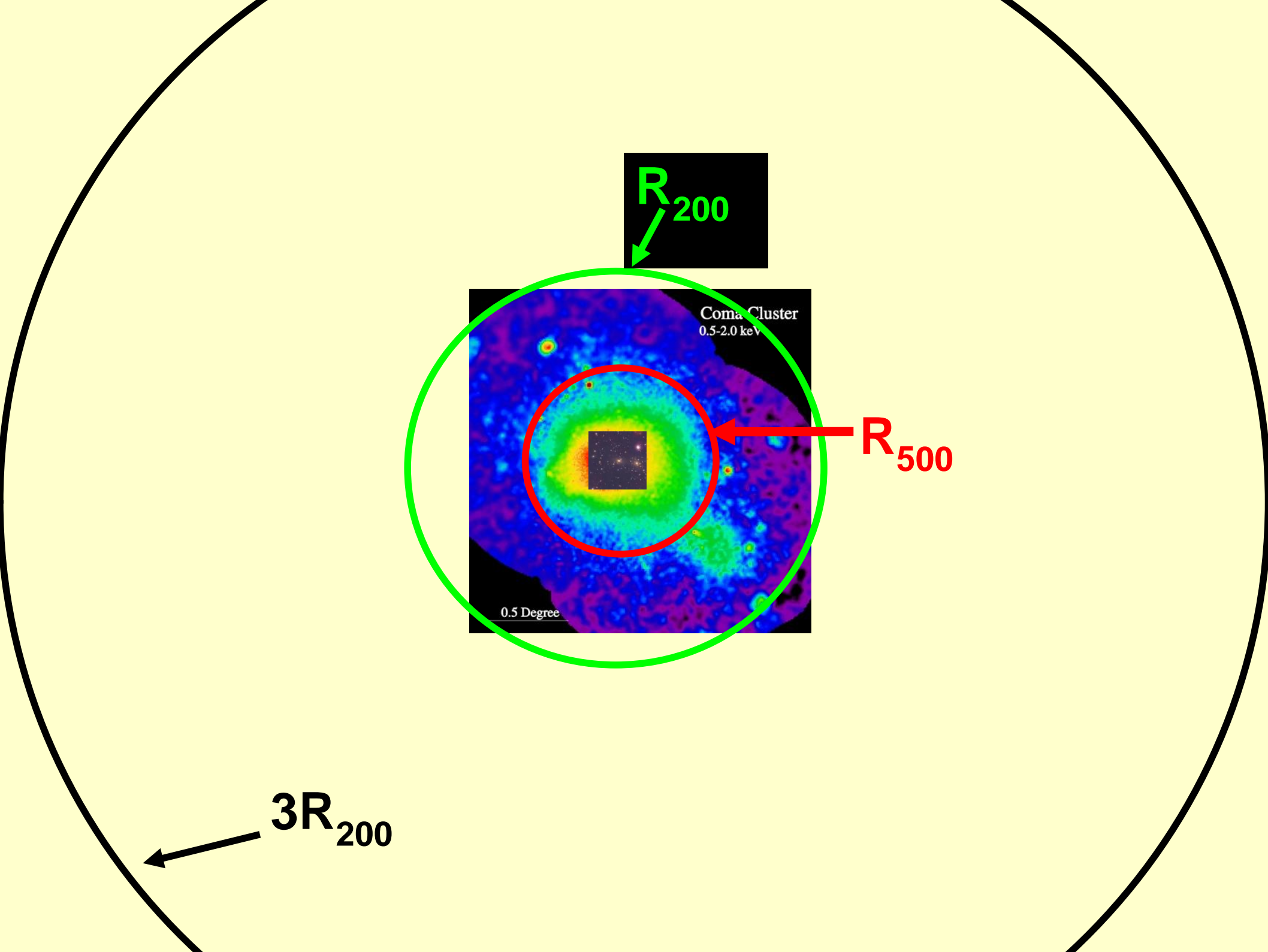


$0.35 h^{-1} \text{ Mpc}$

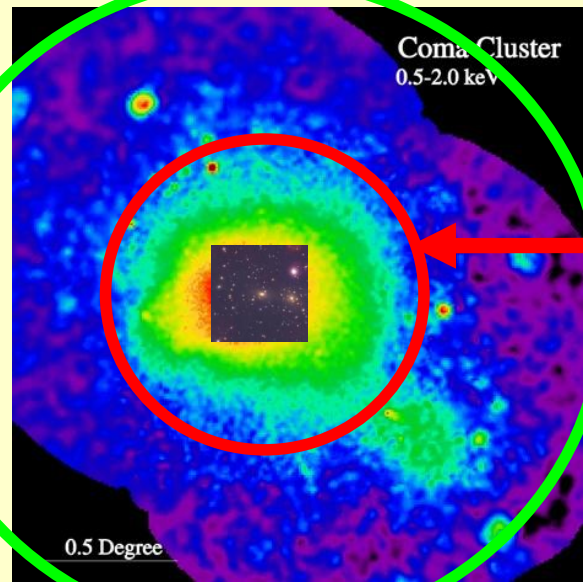


$2.5 h^{-1} \text{ Mpc}$



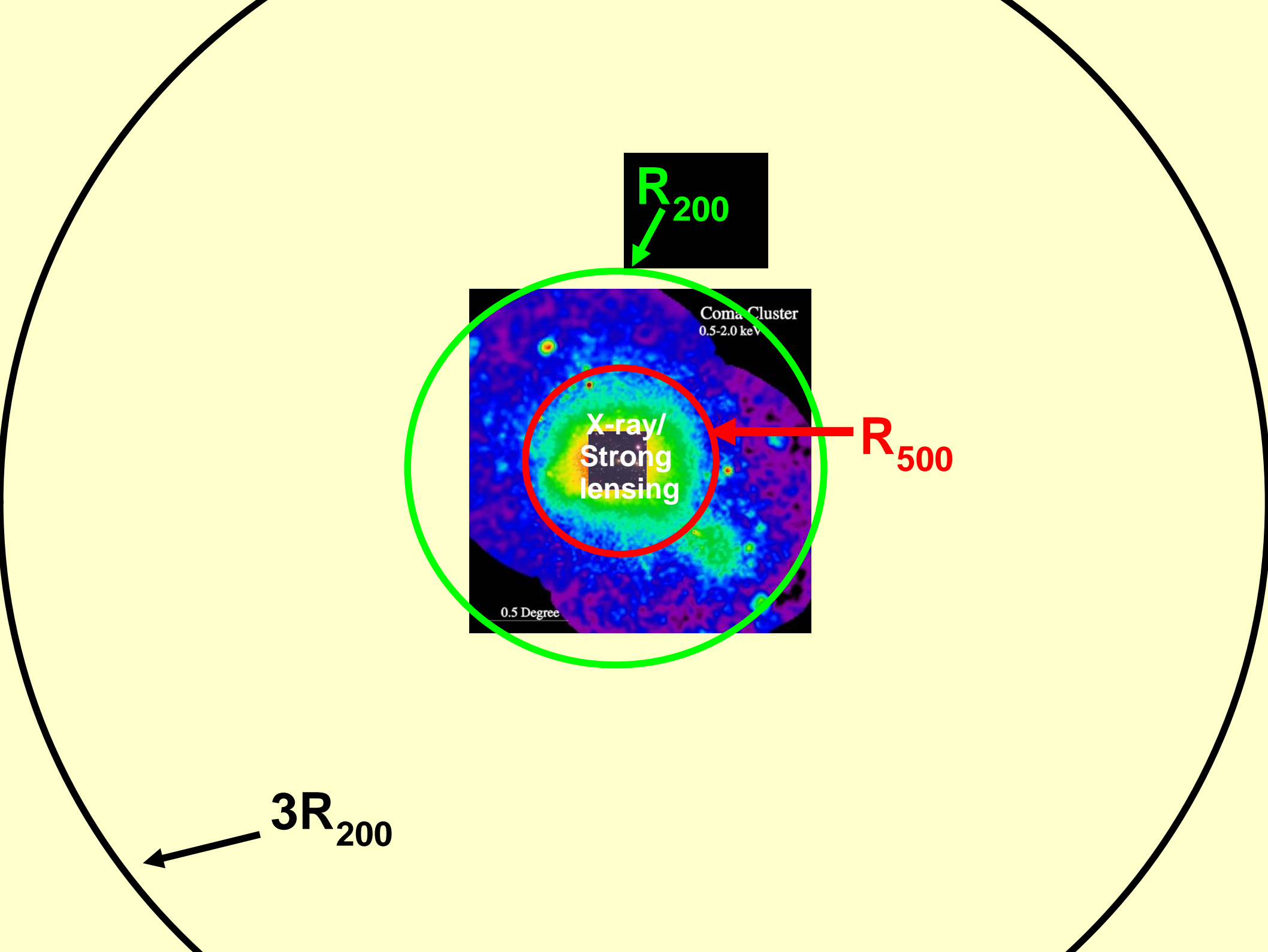


$R_{200}$

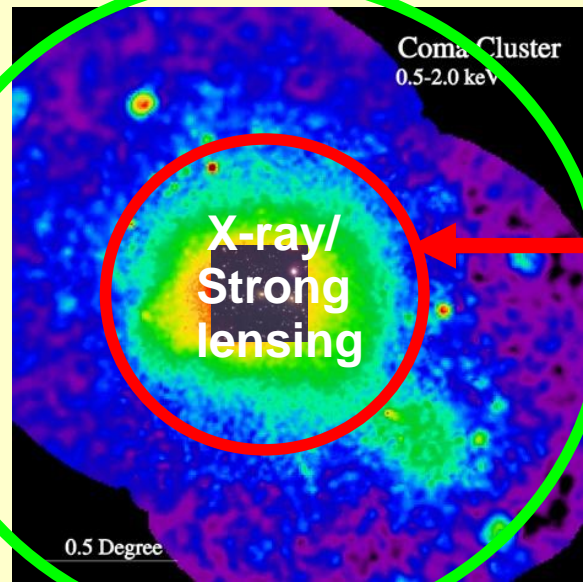


$R_{500}$

$3R_{200}$

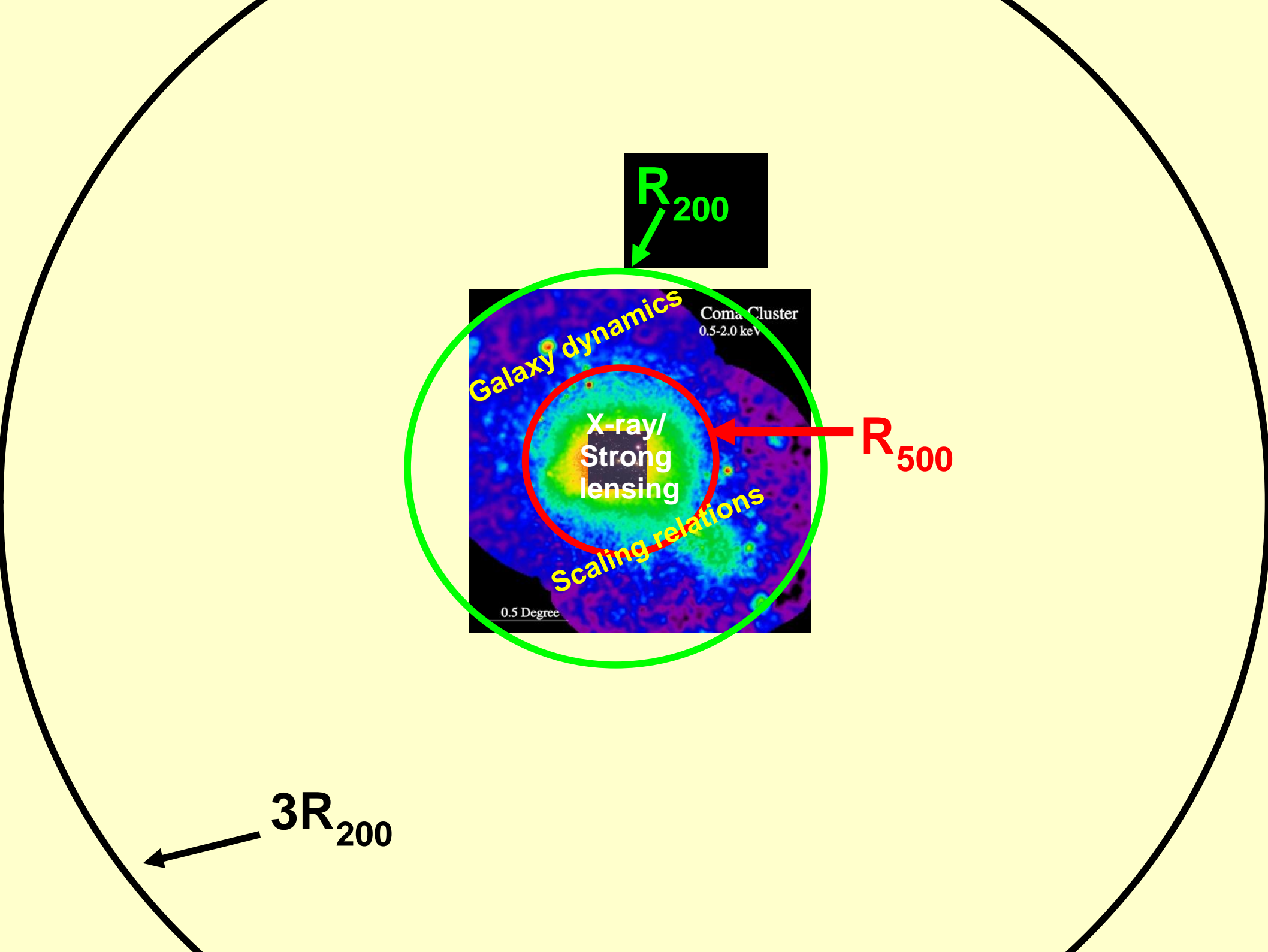


$R_{200}$

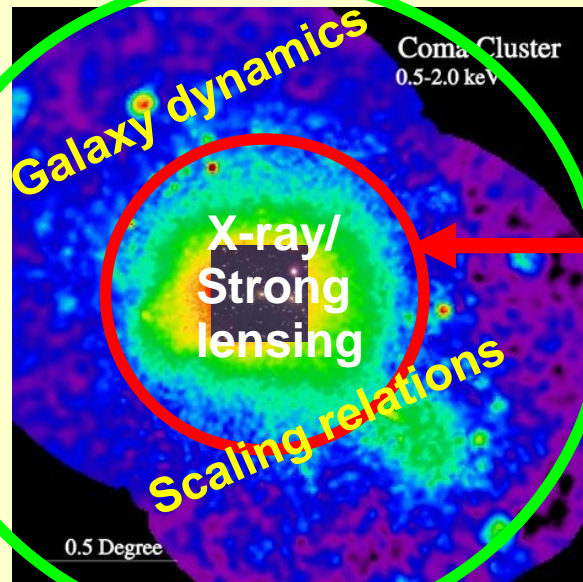


$R_{500}$

$3R_{200}$



$R_{200}$

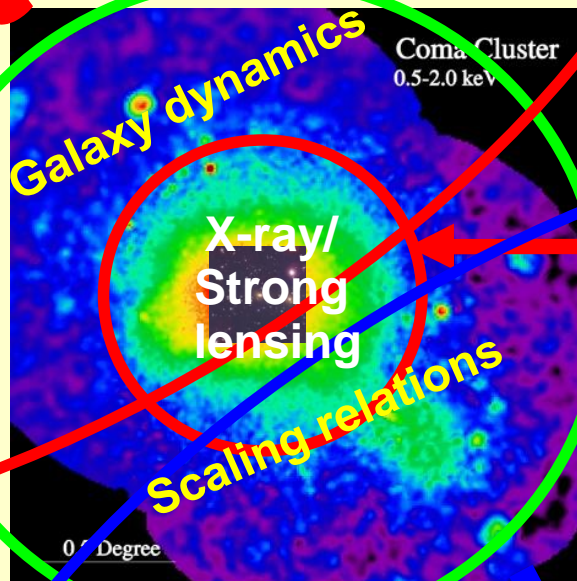


$R_{500}$

$3R_{200}$

**Caustics**

$R_{200}$



$R_{500}$

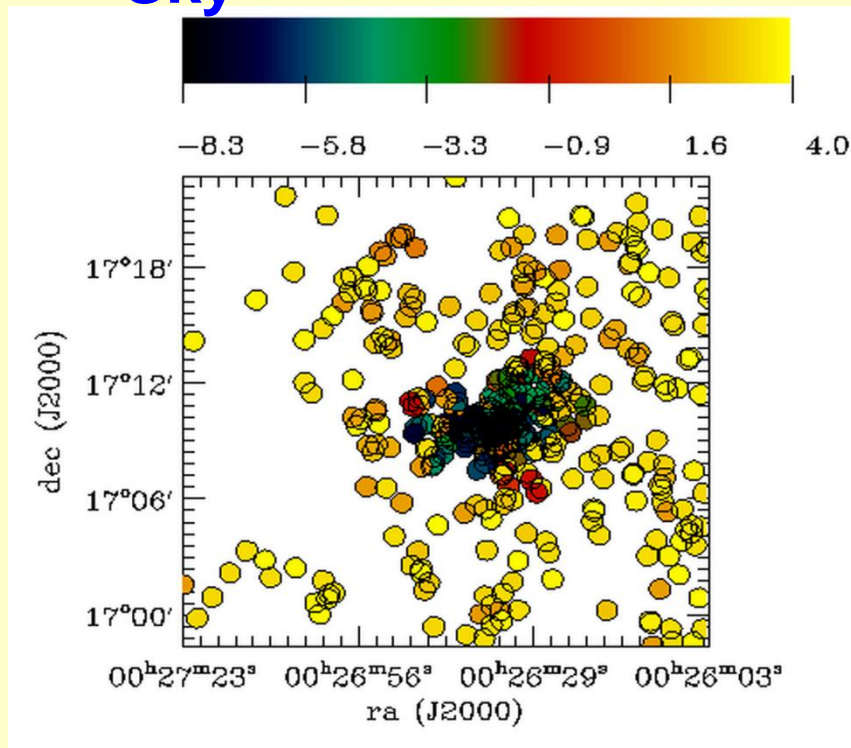
**Weak lensing**

$3R_{200}$

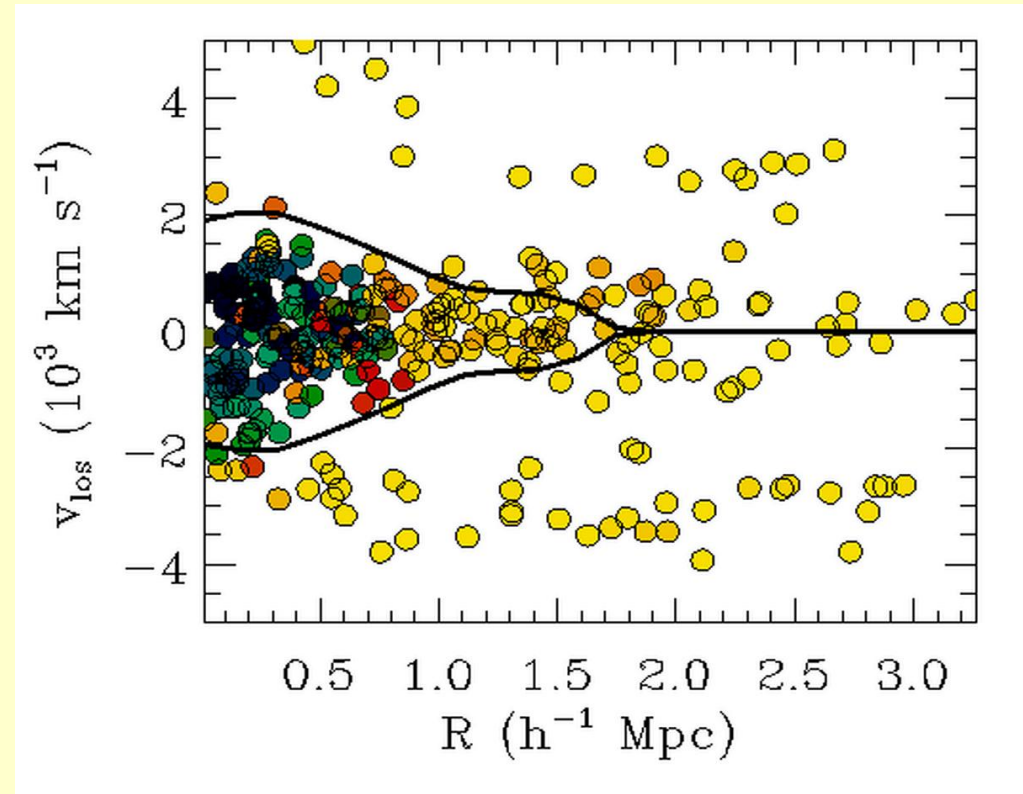
# Dropping the dynamical equilibrium hypothesis. The caustic method

CL0024

Sky



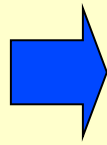
Redshift diagram



# INFALL REGIONS OF CLUSTERS: Prologue (1)

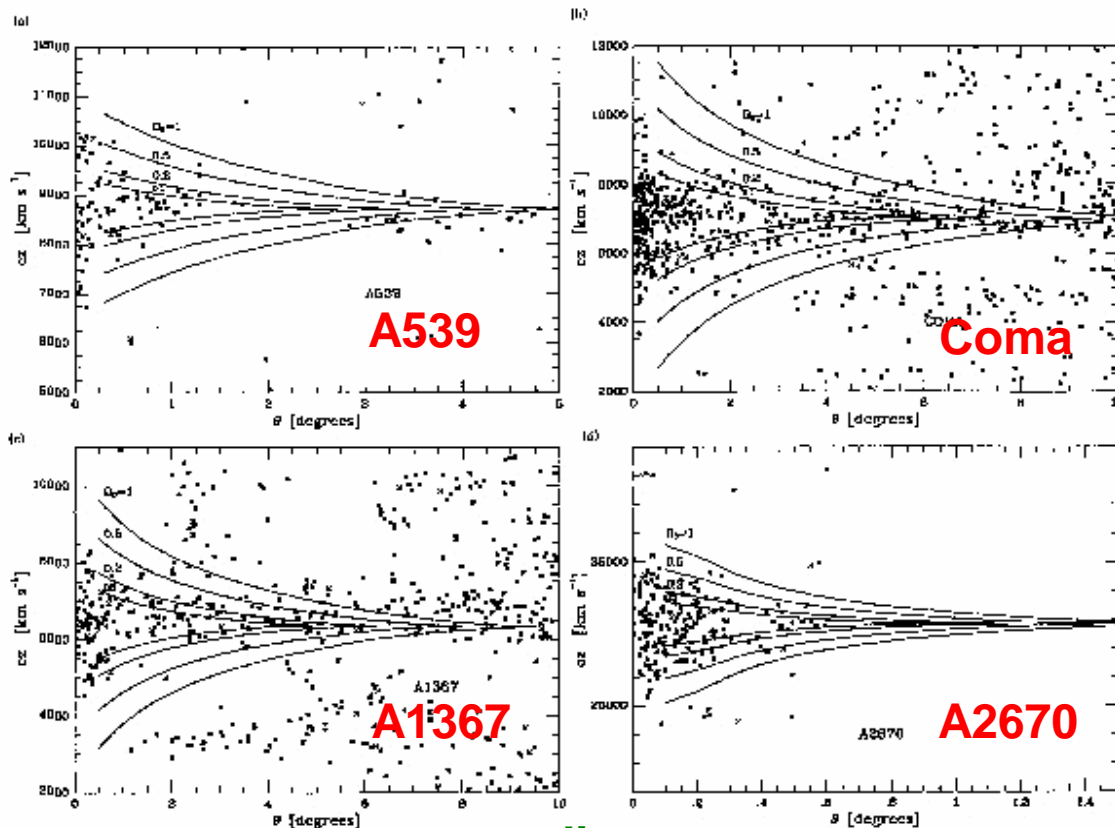
linear scales

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

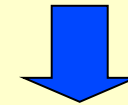


$$\frac{v_{pec}(r)}{H_0 r} = \frac{H_0^s}{H_0} - 1 \simeq -\frac{1}{3} \Omega_0^{0.6} f[\delta_m(r)]$$

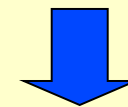
mildly non-linear scales



Caustic amplitude



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



Measure of  $\Omega_0$

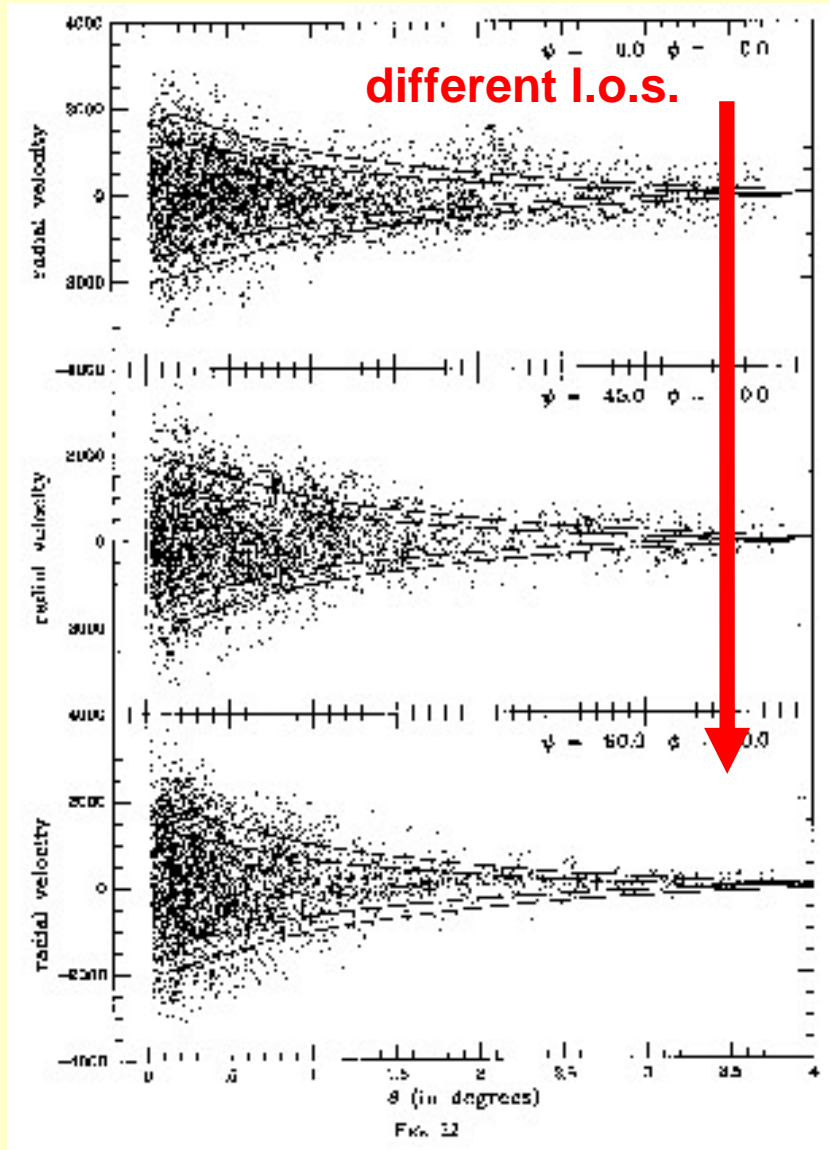
Regös & Geller 1989

CZ

radius

# INFALL REGIONS OF CLUSTERS: Prologue (2)

CZ



Simulated cluster in a SCDM model

Merging and substructures  
affect the velocity field  
AND  
the caustic amplitude

van Haarlem & van de Weygaert 1993

radius

# INFALL REGIONS OF CLUSTERS: Prologue (3)

The caustic amplitude IS the escape velocity

cosmology  $\longrightarrow$

flat w/crit. dens.      open      flat w/low dens.

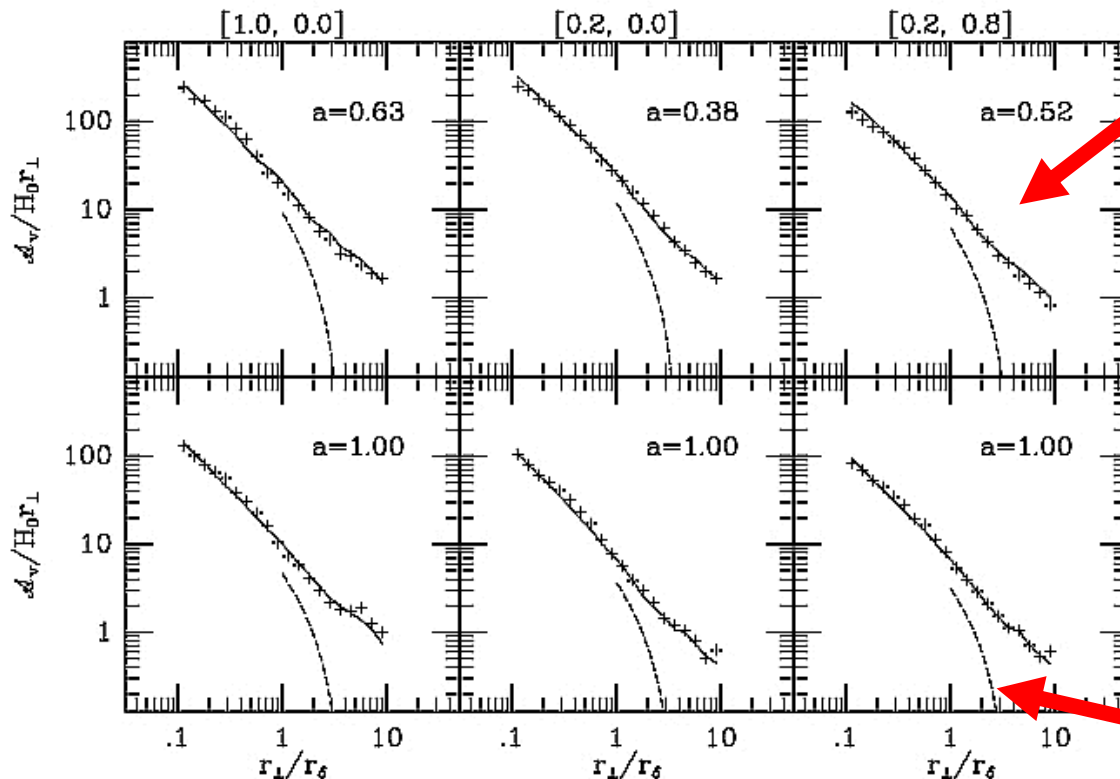
$$\mathcal{A}^2(r) = v_{\text{esc}}^2(r) \frac{1 - \beta(r)}{3 - 2\beta(r)}$$

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

clusters out of equilibrium

clusters in equilibrium

spherical infall model



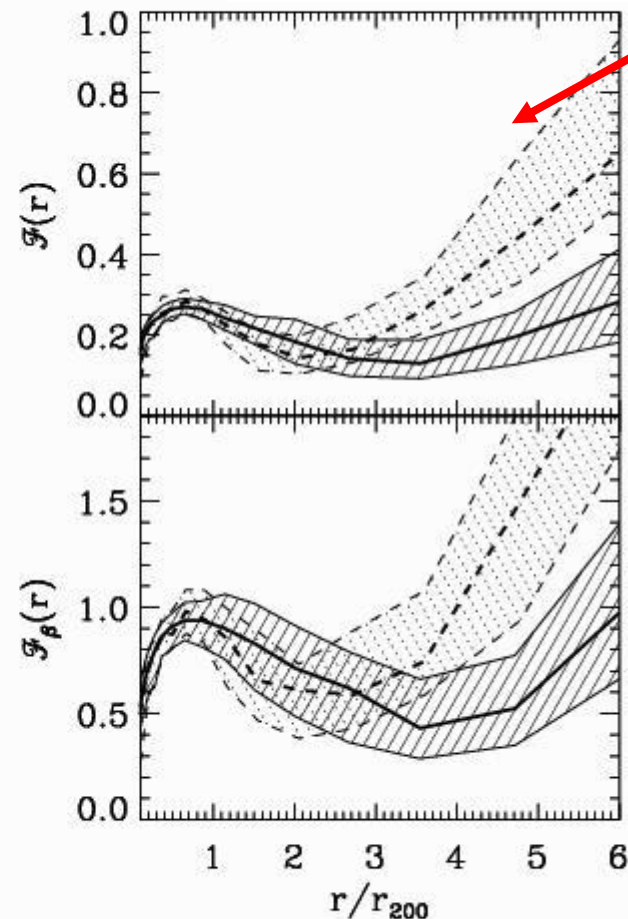
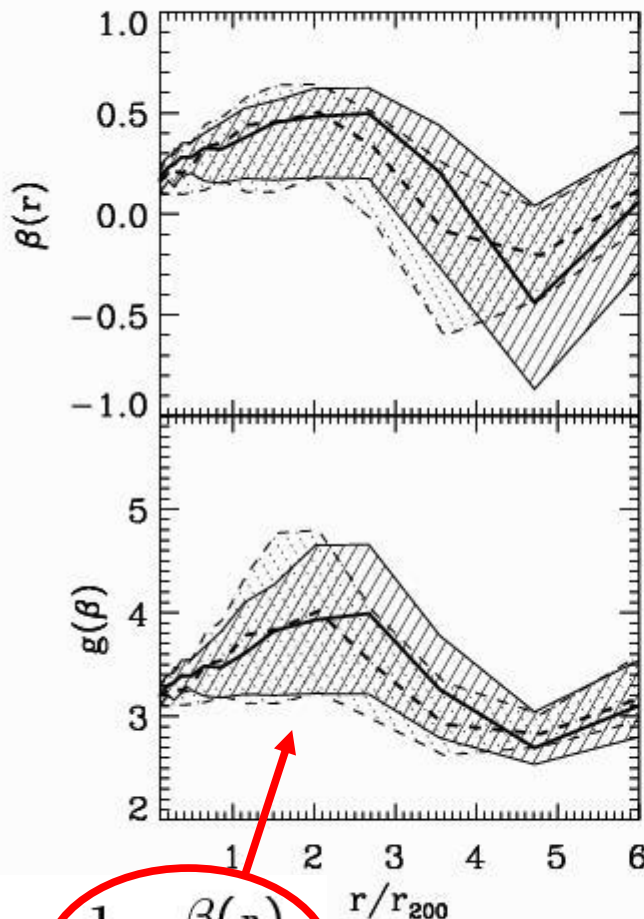
caustic amplitude

radius

# INFALL REGIONS OF CLUSTERS: Prologue (4)

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

Relevant functions from simulated clusters



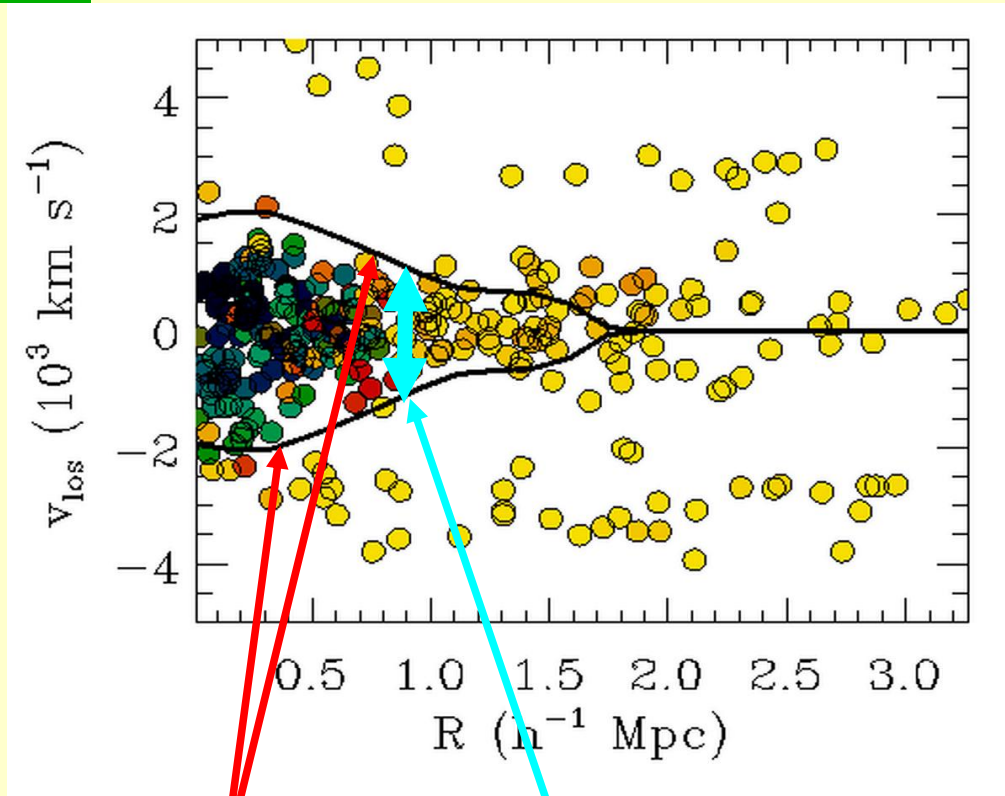
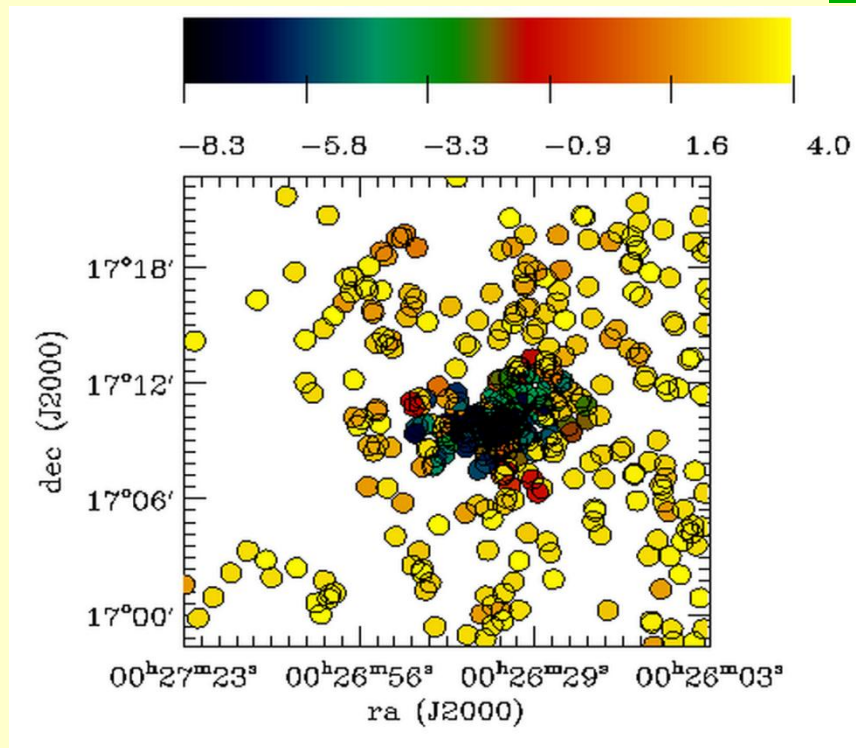
$$\mathcal{A}^2(r) = v_{\text{esc}}^2(r) \frac{1 - \beta(r)}{3 - 2\beta(r)}$$

# CAUSTIC TECHNIQUE: BASICS

Example:  
CL0024

Sky

Redshift diagram



**MASS ESTIMATE:**

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

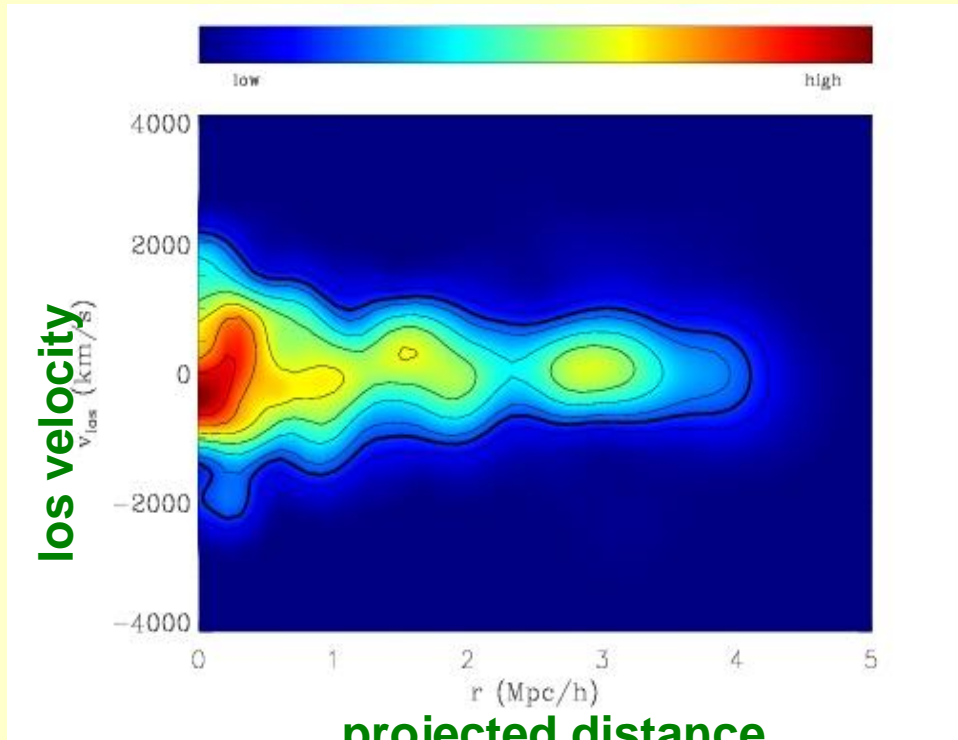
(Diaferio & Geller 1997)

Caustics

Caustic  
amplitude  
=  
escape velocity

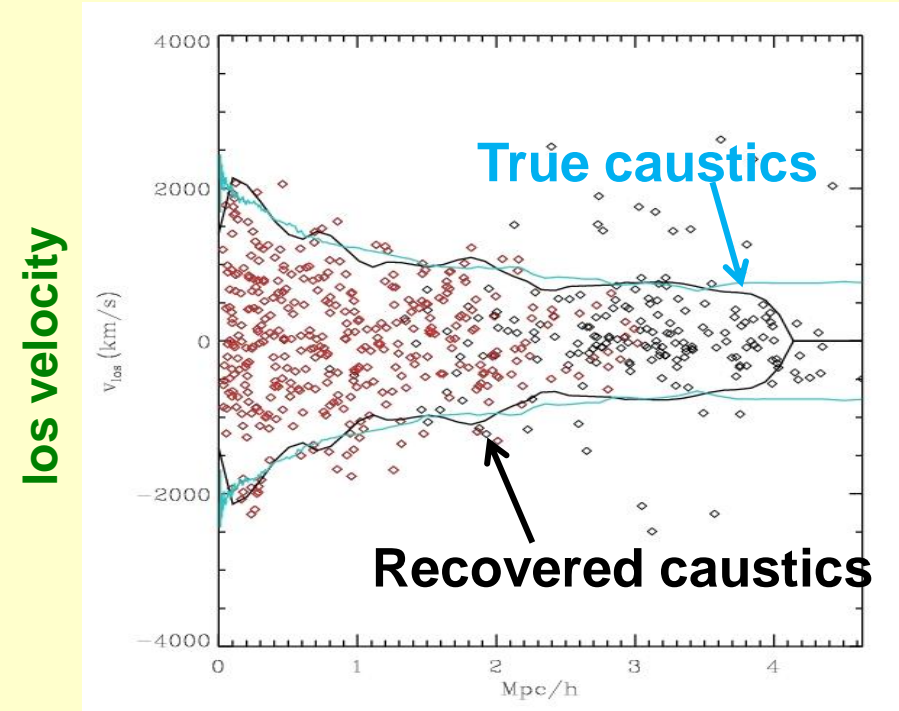
# CAUSTIC TECHNIQUE: LOCATION

map of  $f_q(r,v)$



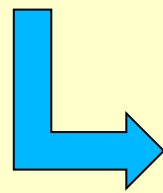
projected distance

Caustic location

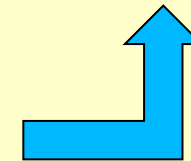


los velocity

projected distance



$$f_q(r, v) = \kappa$$



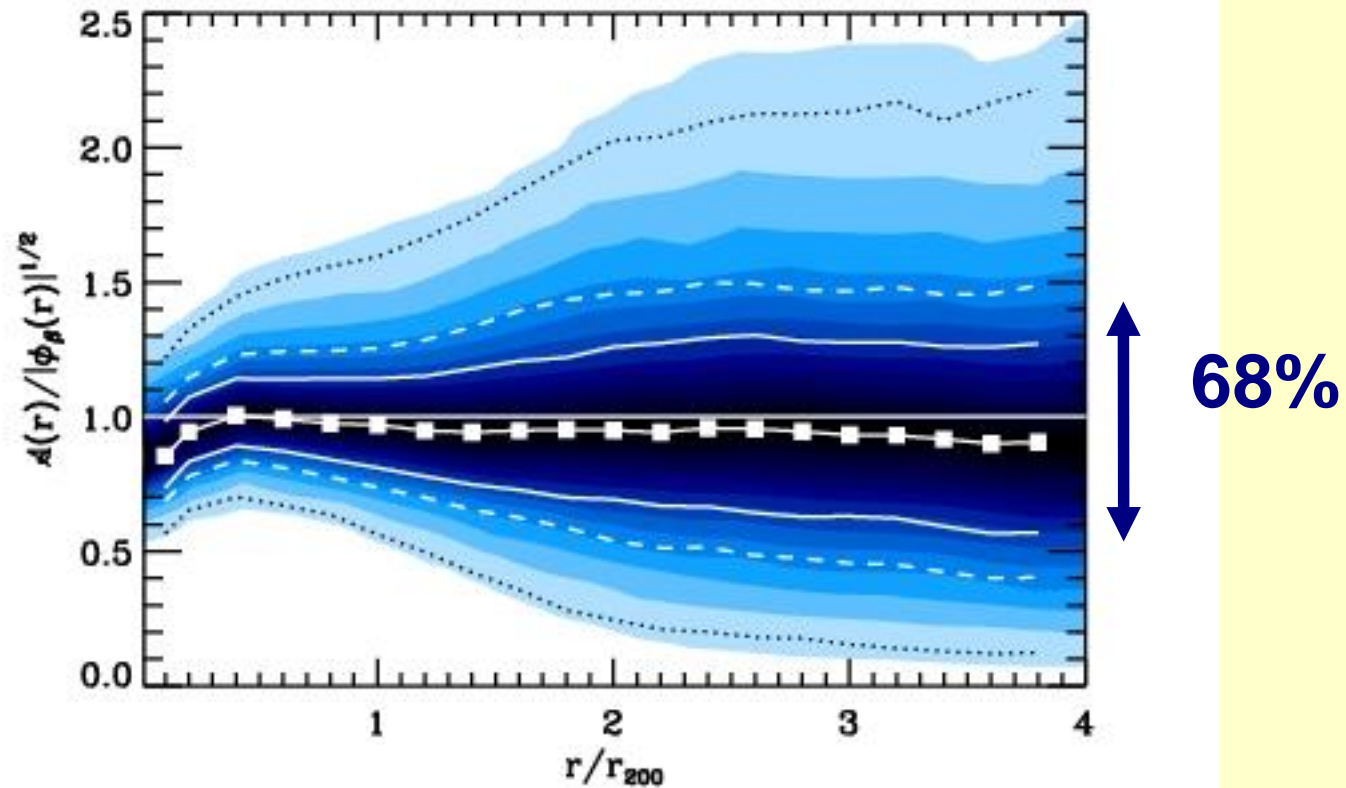
$$S(\kappa, R) = \langle v_{esc}^2 \rangle_{\kappa, R} - \langle v^2 \rangle_R$$

# THE GRAVITATIONAL POTENTIAL PROFILE

*(unclean sample...!)*

**3000 synthetic clusters**  
*( $\Lambda$ CDM model, Borgani et al. 2004)*

Caustic potential/true potential

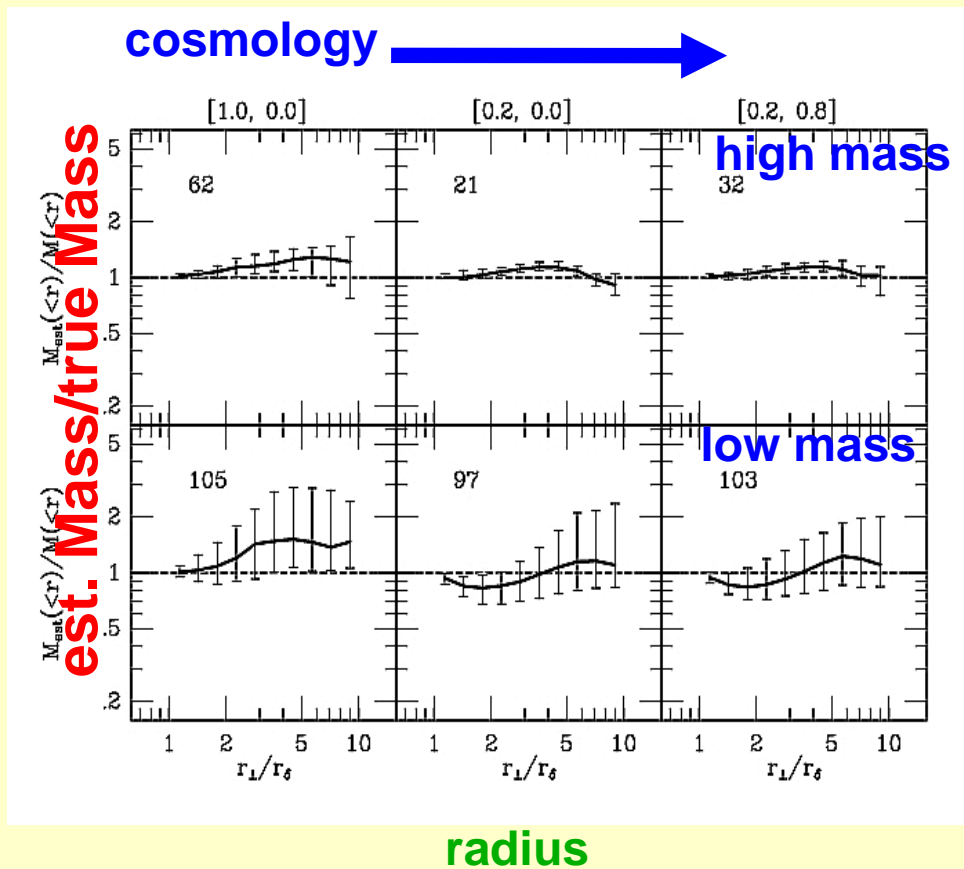


Serra et al. 2009

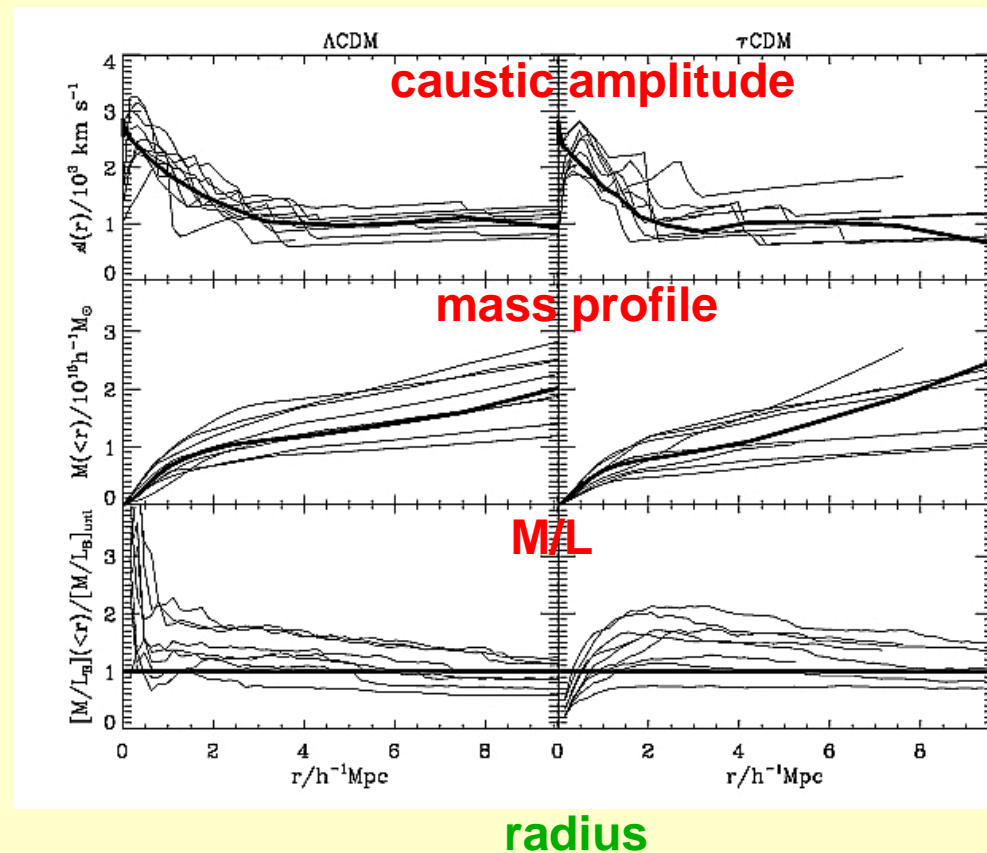
# CAUSTIC TECHNIQUE: MASS PROFILE

## DOES IT WORK?

### Comparison with N-body simulations

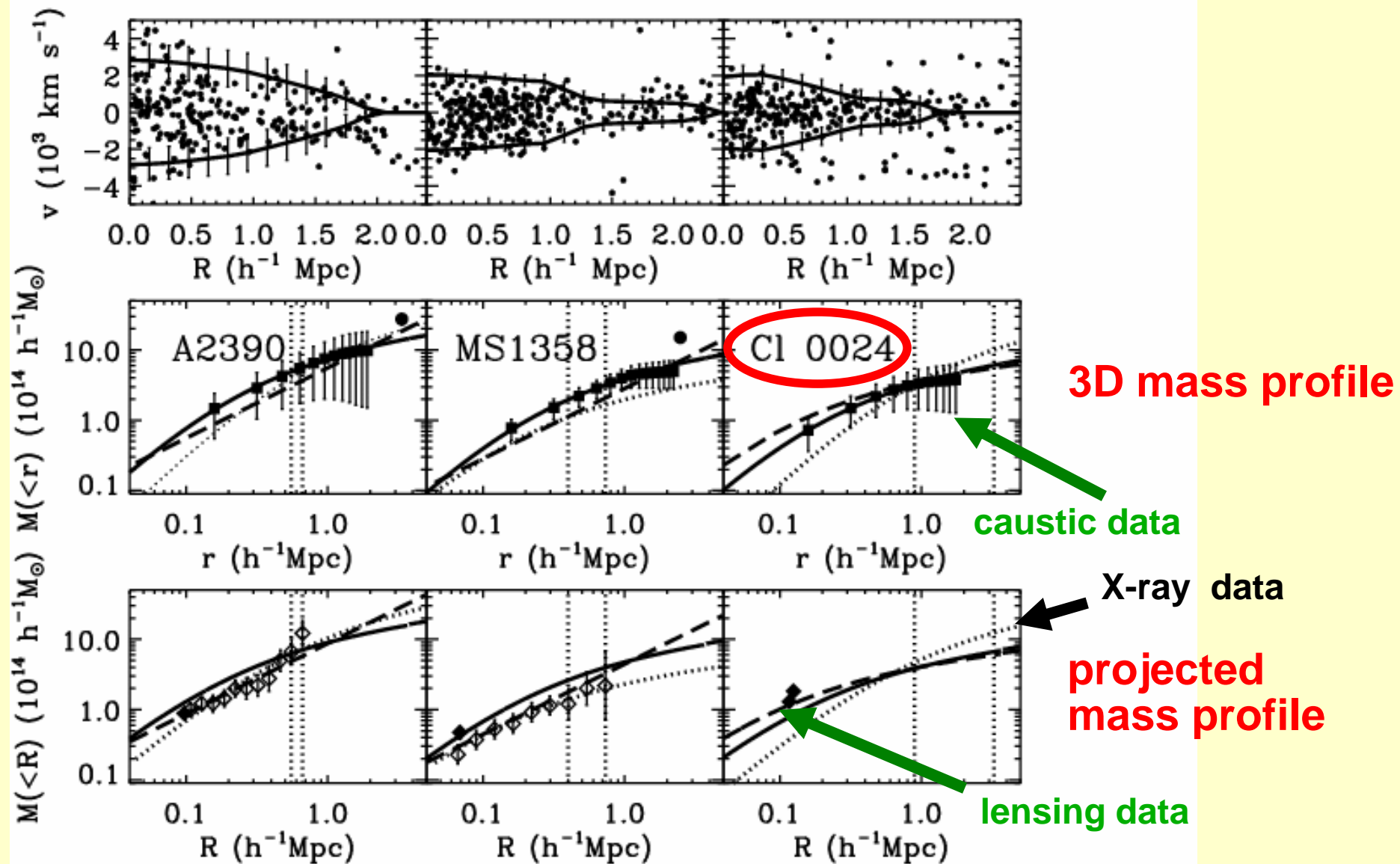


Diaferio & Geller 1997

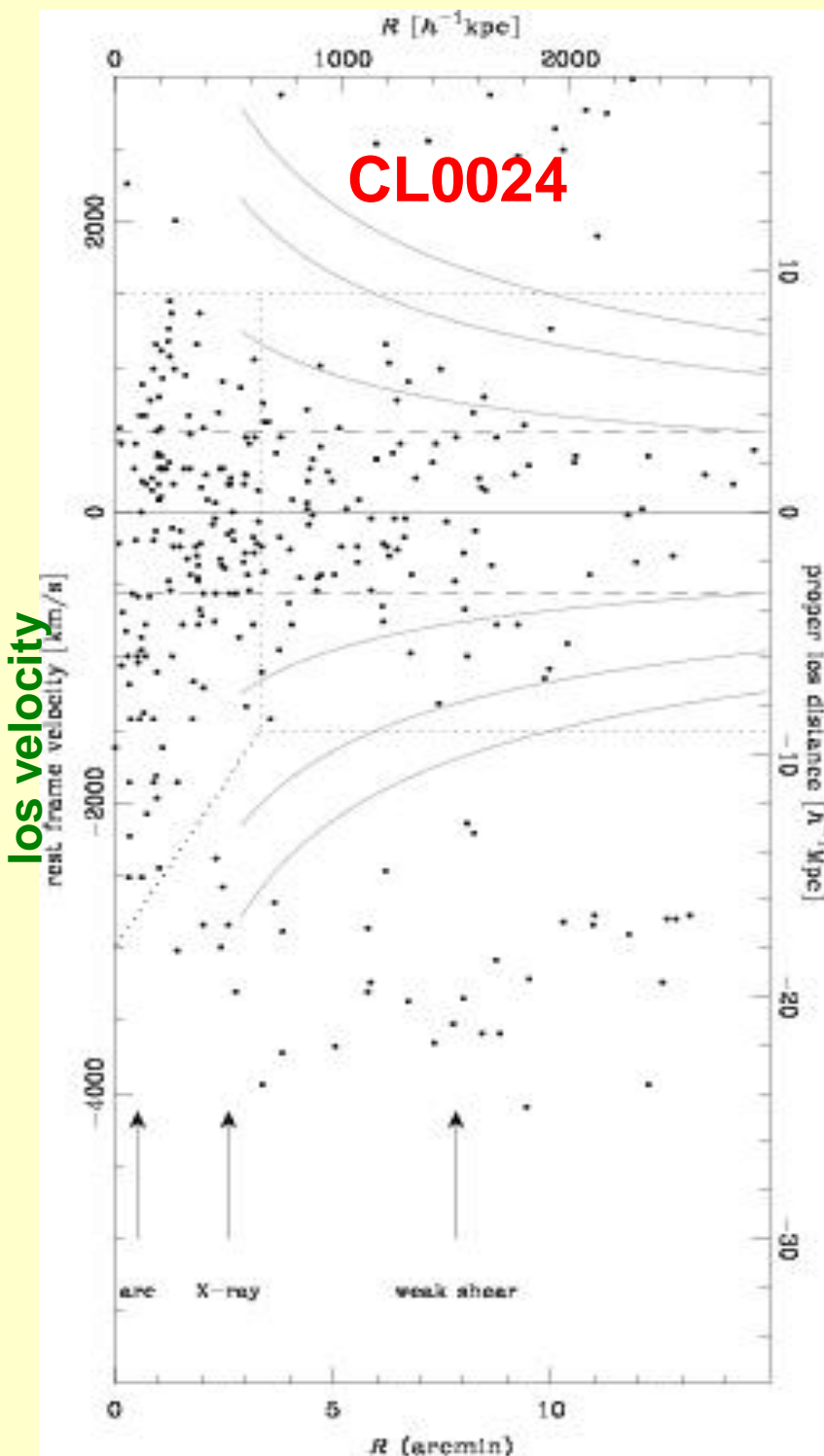


Diaferio 1999

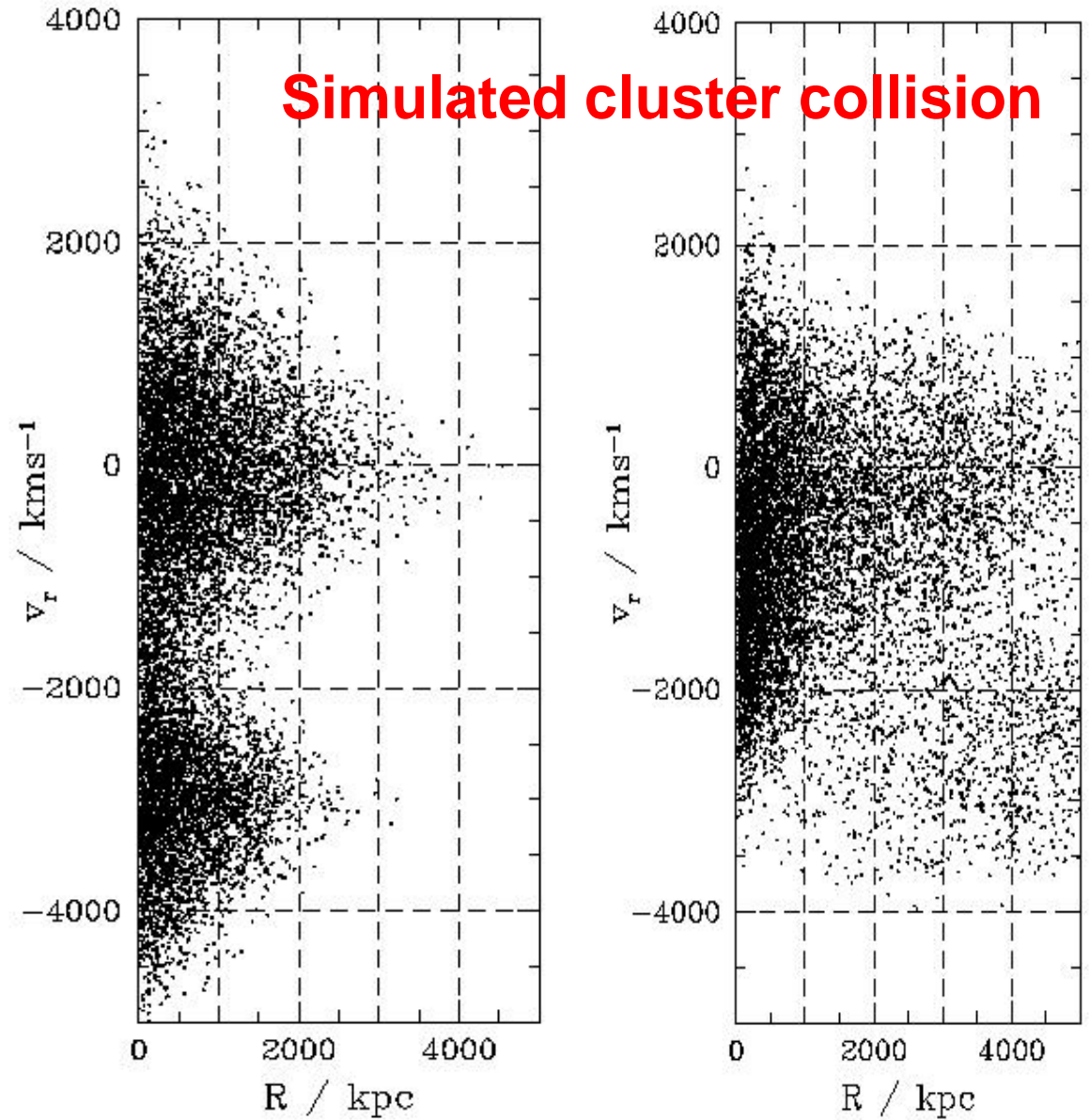
# CAUSTIC TECHNIQUE: CAUSTICS VS. LENSING



# CL0024: a head-on collision



# Simulated cluster collision



Czoske et al. 2002

# 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:

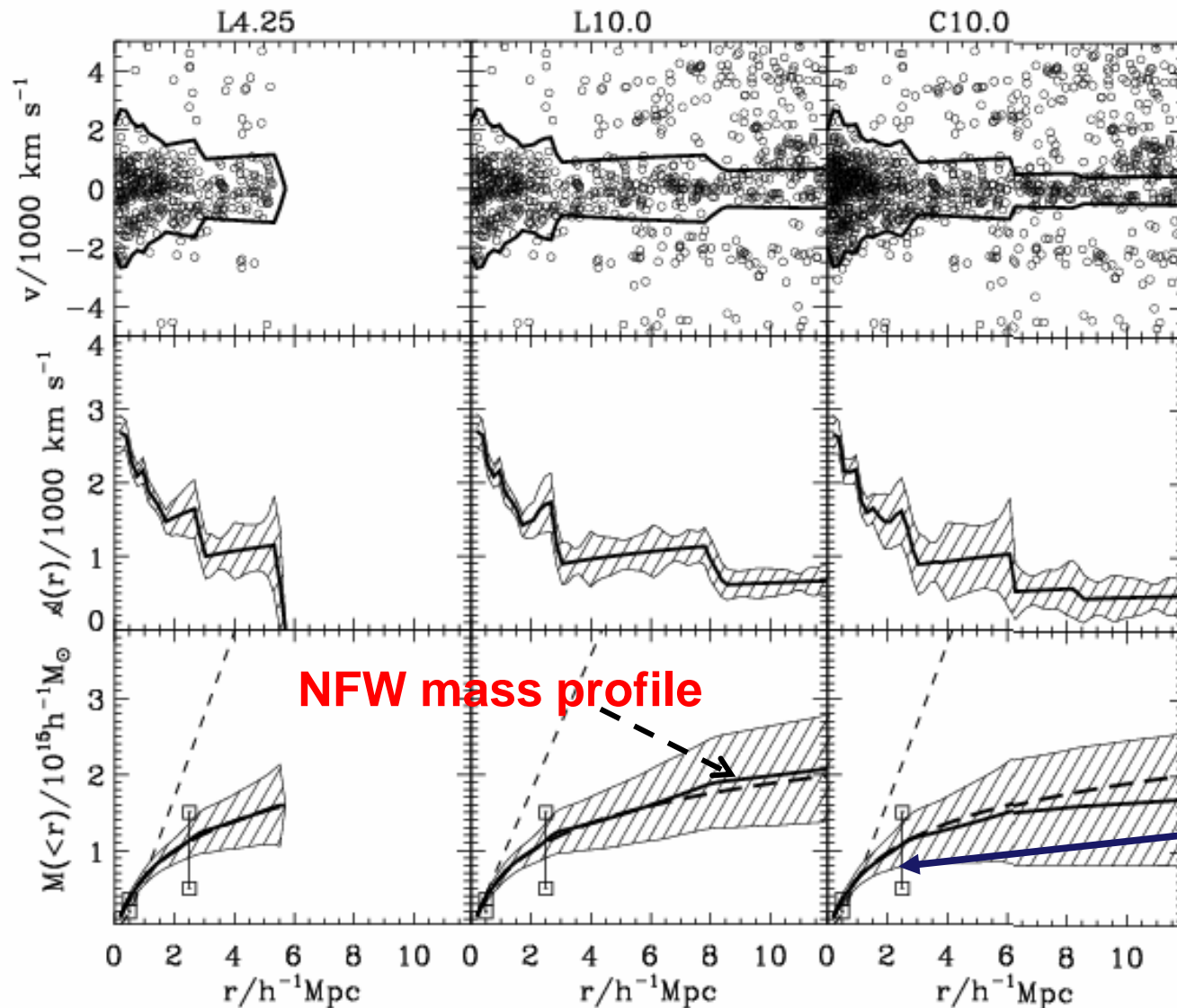
- Mass projected along the line of sight

# Application of the caustic technique

- **Coma** (Geller et al. 1999)
- **Shapley** (Reisenegger et al. 2000)
- **Fornax** (Drinkwater et al. 2001)
- **2dF – 43 clusters** (Biviano & Girardi 2003)
- **CAIRNS – 9 clusters** (Rines et al. 2003)
- **CIRS – 72 clusters** (Rines & Diaferio 2006)
- **400d – 16 groups** (Rines & Diaferio 2009)
- **Bullet Cluster** (Gonzalez et al **TODAY!**)

# CAUSTIC TECHNIQUE

## THE NFW PROFILE AT LARGE RADII

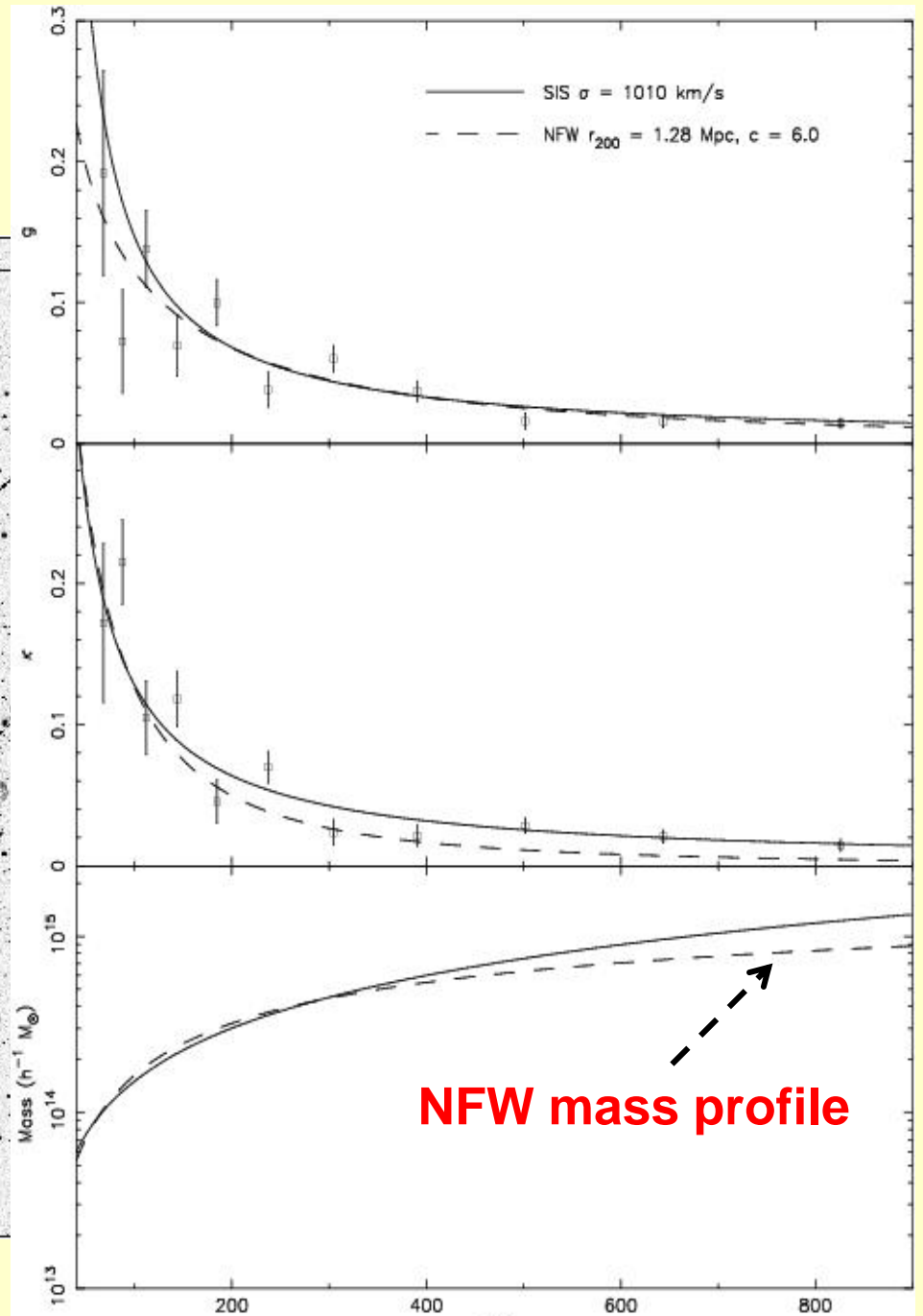
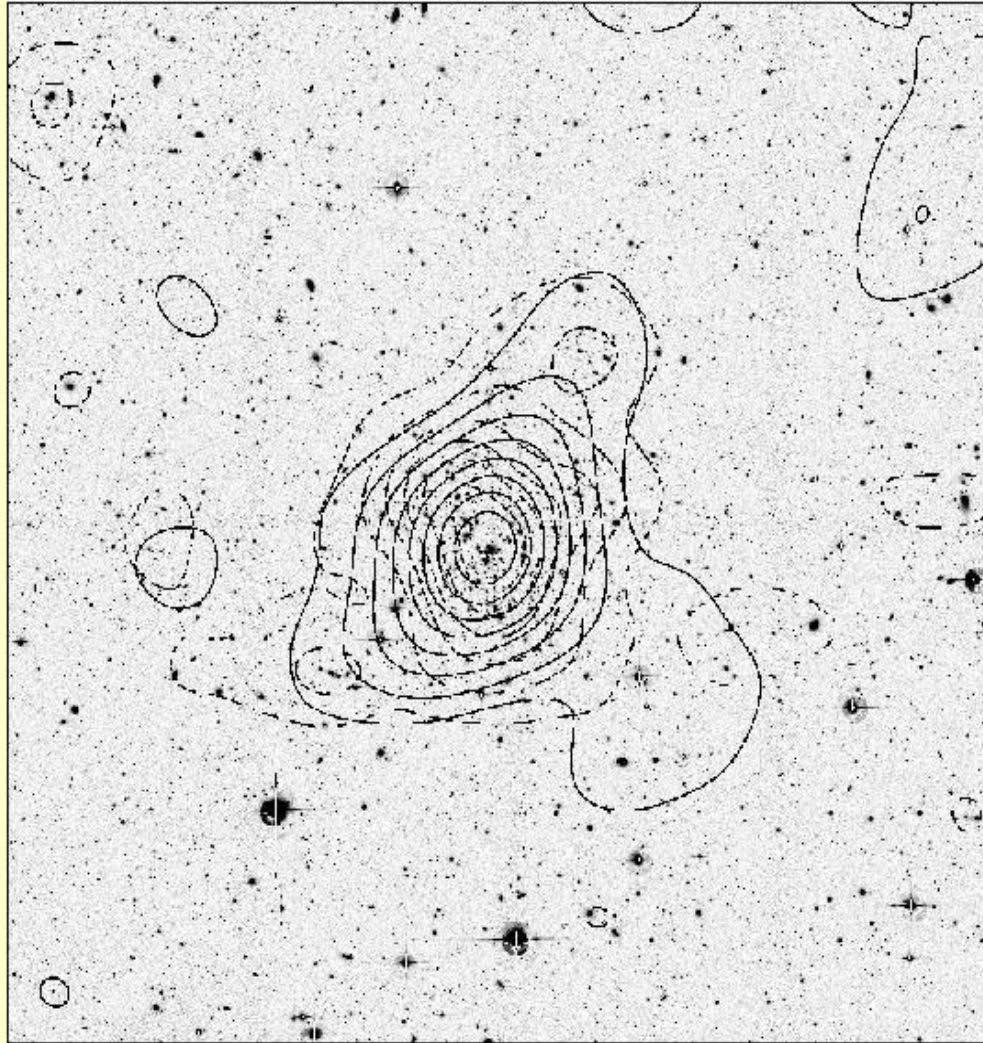


Coma

X-ray  
estimate  
range

Geller et al. 1999

# Weak lensing of A1689

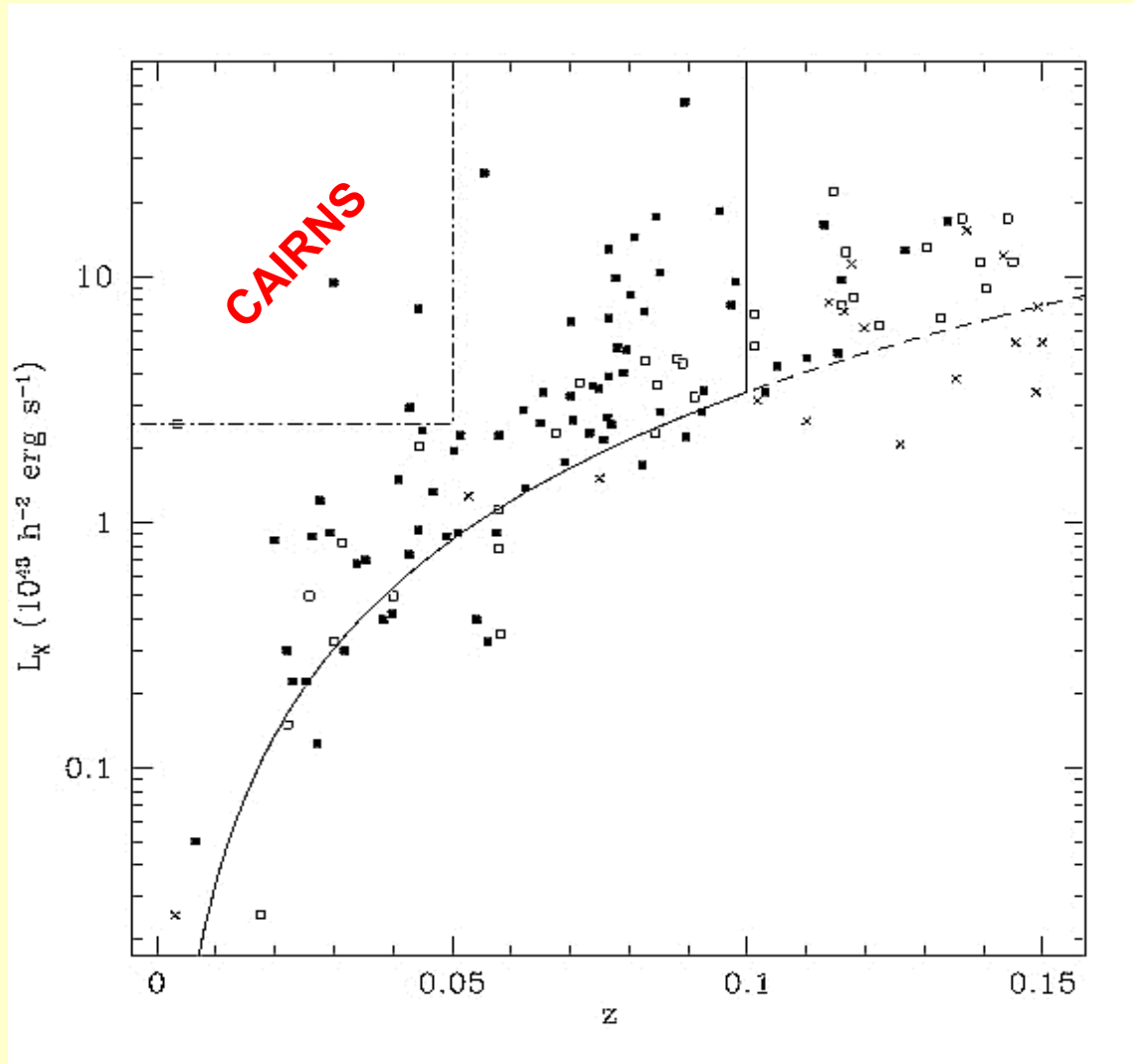


**NFW mass profile**

# CIRS: *Cluster Infall Regions in the SDSS*

72 X-ray selected clusters combined with the 4<sup>th</sup> SDSS data release

X-ray luminosity

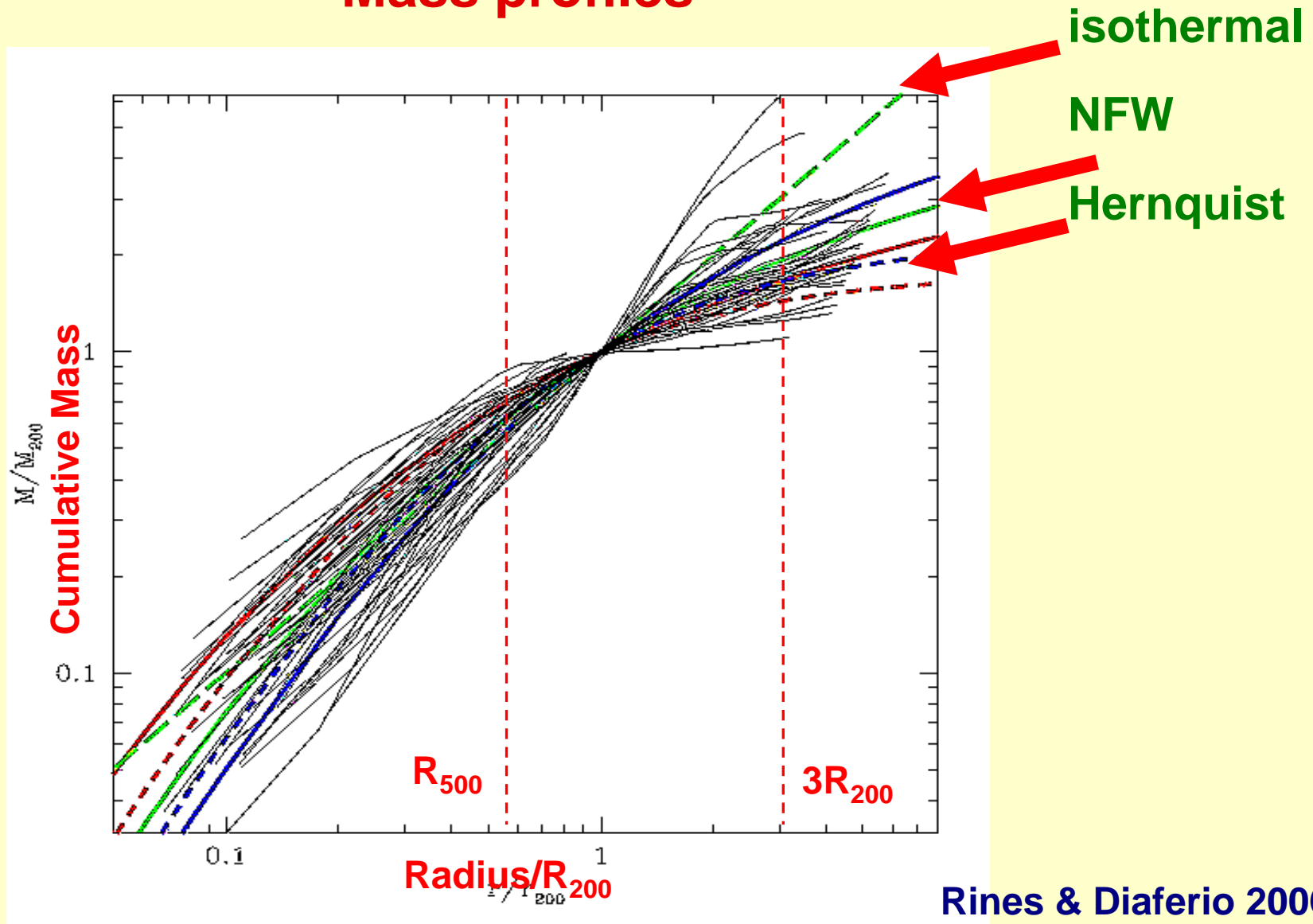


redshift

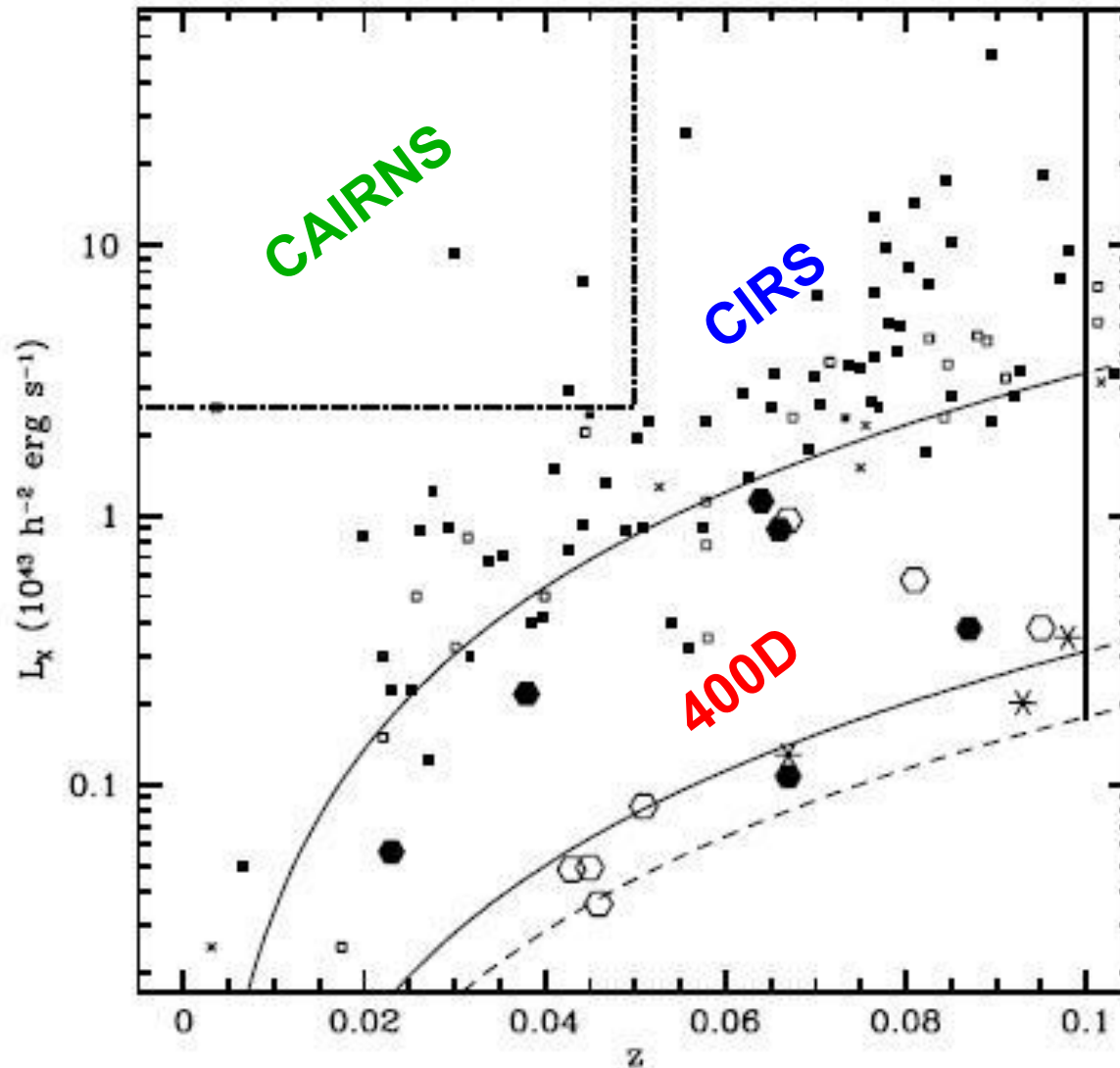
Rines & Diaferio 2006

# CIRS: *Cluster Infall Regions in the SDSS*

## Mass profiles

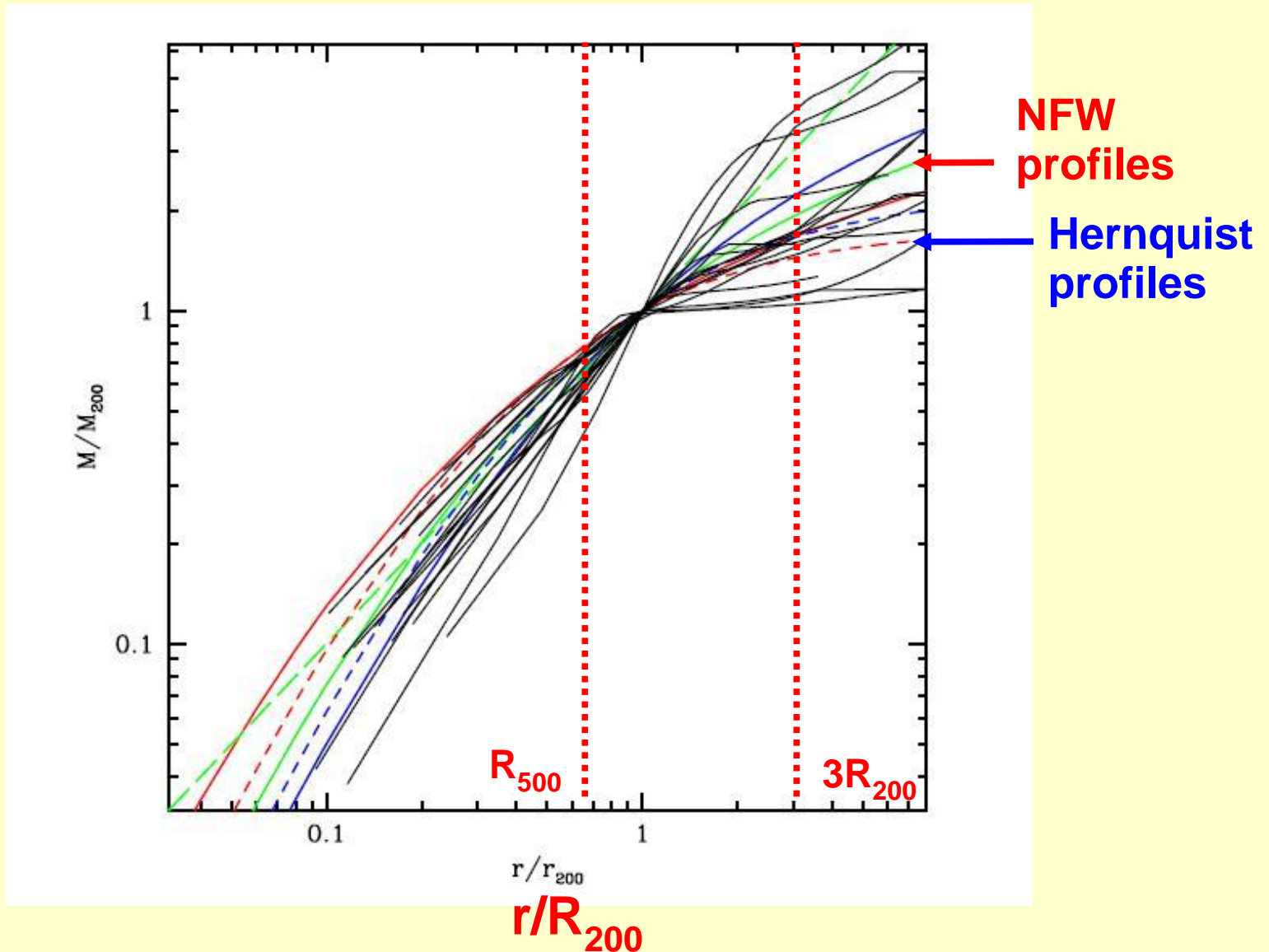


# The 400D Survey: 16 Low Mass Systems



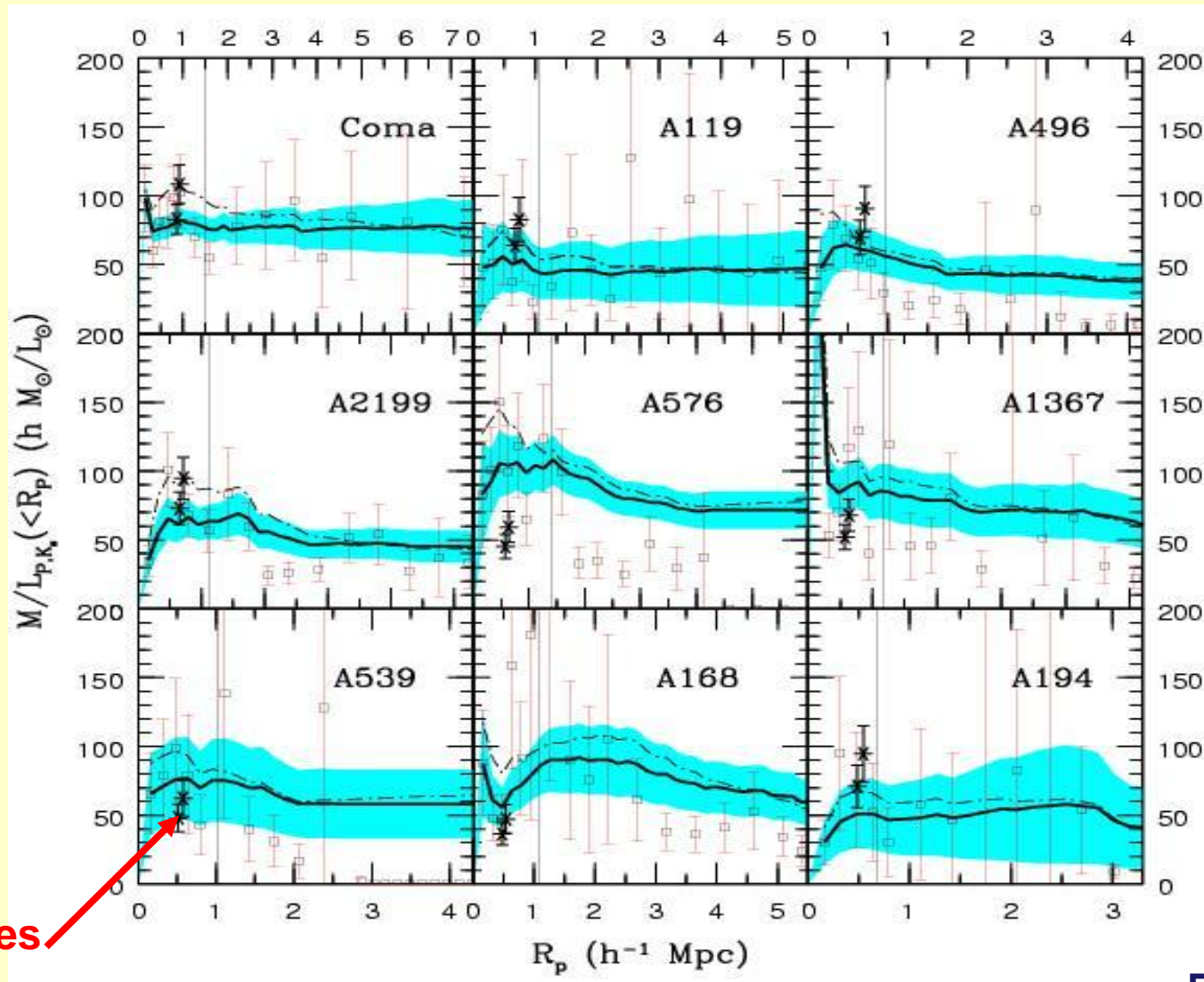
# The 400D Survey

## Mass profile models



# CAIRNS: *Cluster And Infall Region Nearby Survey*

## Mass-to-light ratio profiles



X-ray estimates

# THE CAUSTIC PERFORMANCE AND ADVANTAGES

- 1) 50% accuracy on the gravitational and mass profiles out to  $\sim 3-4 R_{200}$
- 2) Independent of dynamical state
- 3) Any redshift (provided you get enough telescope time...)
- 4) (Insensitive to the cluster mass)

# THE CAUSTIC ACHIEVEMENTS

- 1) First mass profile estimates well beyond  $R_{200}$
- 2) First test of the goodness of the NFW/Hernquist density profiles beyond  $R_{200}$
- 3) First estimate of M/L in the outskirts of clusters
- 4) Absence of velocity bias in CIRS clusters

# THE CAUSTIC DISADVANTAGES

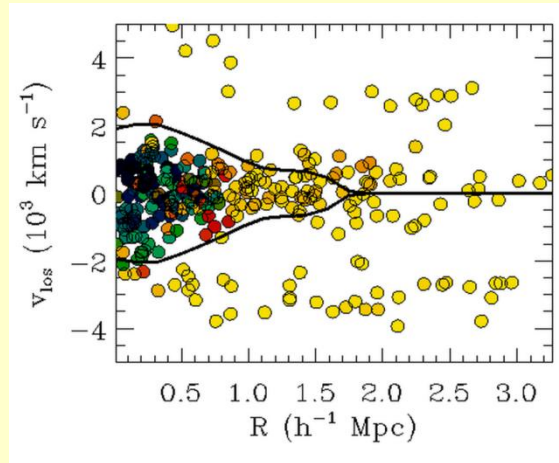
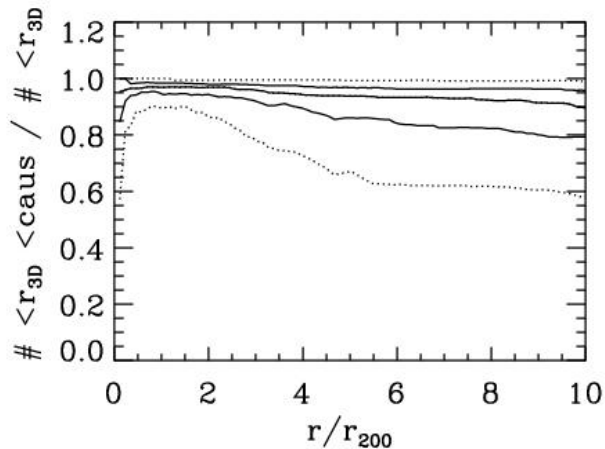
**PROJECTION EFFECTS...**

# PERSPECTIVES

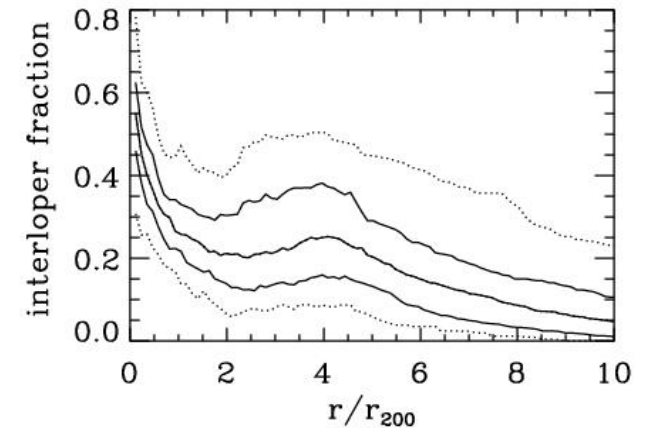
- Hectospec clusters (Rines et al.)
- SPIDER clusters (de Carvalho et al.)
- member identifier
- substructure identifier

# The caustic technique as a member identifier

Fraction of real members within the caustics



Fraction of interlopers within the caustics



It also applies to stars in dwarf galaxies...!

Have you already seen the poster by A. L. Serra?

Further updates coming soon on the Caustic Group site

<http://www.dfg.unito.it/ricerca/caustic/caustic.html>