COSMIC STRUCTURES, CLUSTERS OF GALAXIES, AND THE THEORY OF GRAVITY

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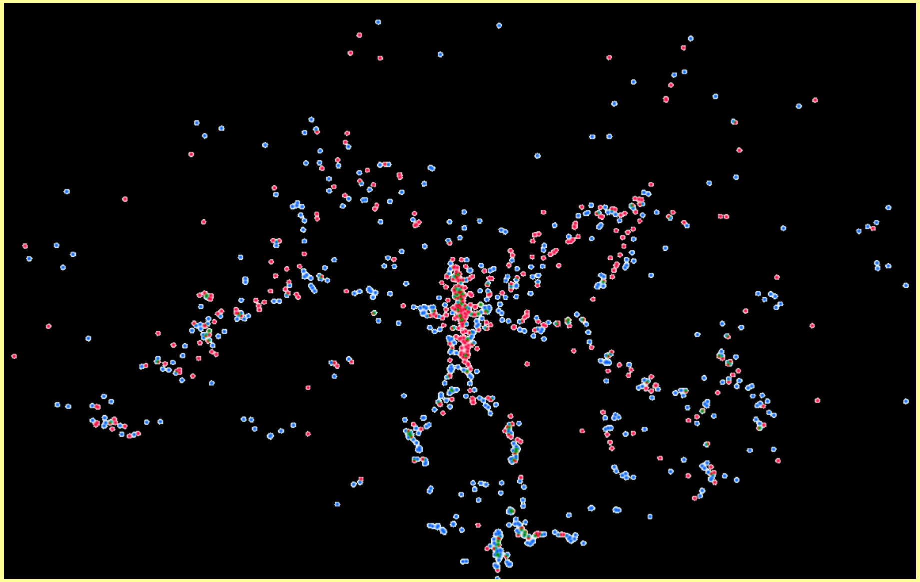
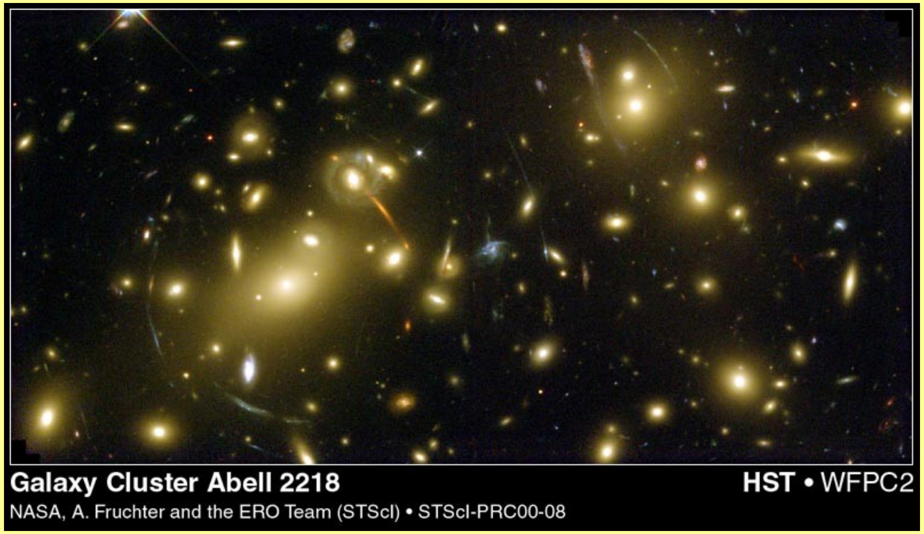
www.dfg.unito.it/ricerca/caustic

Napoli, 21 marzo 2013



- **Redshift surveys:**
  The largest structures and HectoMAP

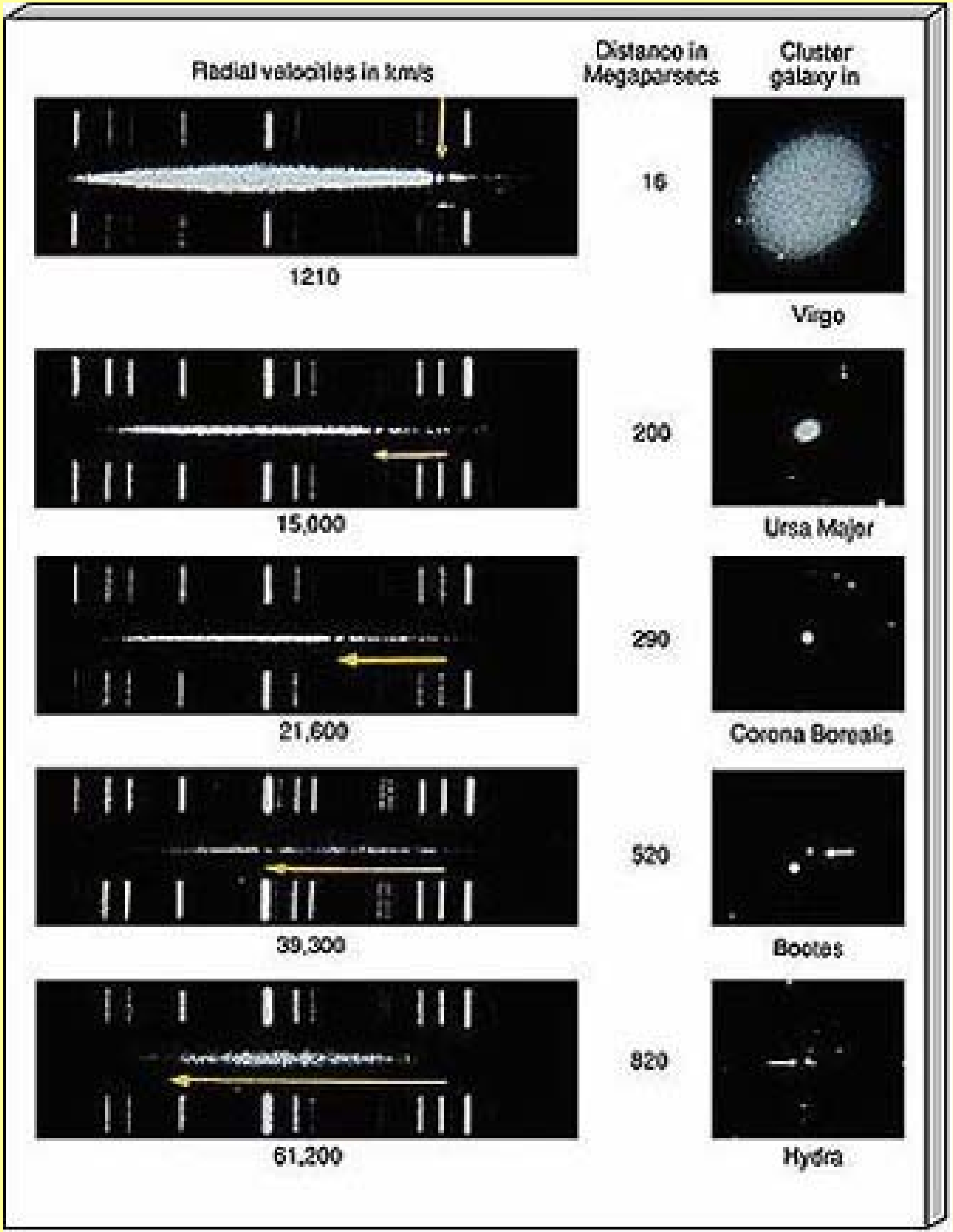
- **Clusters of galaxies:**
  The caustic method, the mass function and MOND



V. Slipher and E. Hubble

Vesto Melvin Slipher
1875-1969

Edwin Powell Hubble
November 20, 1889 – September 28, 1953




(1894-1966)

Georges Lemaître
and
the “Hubble” law

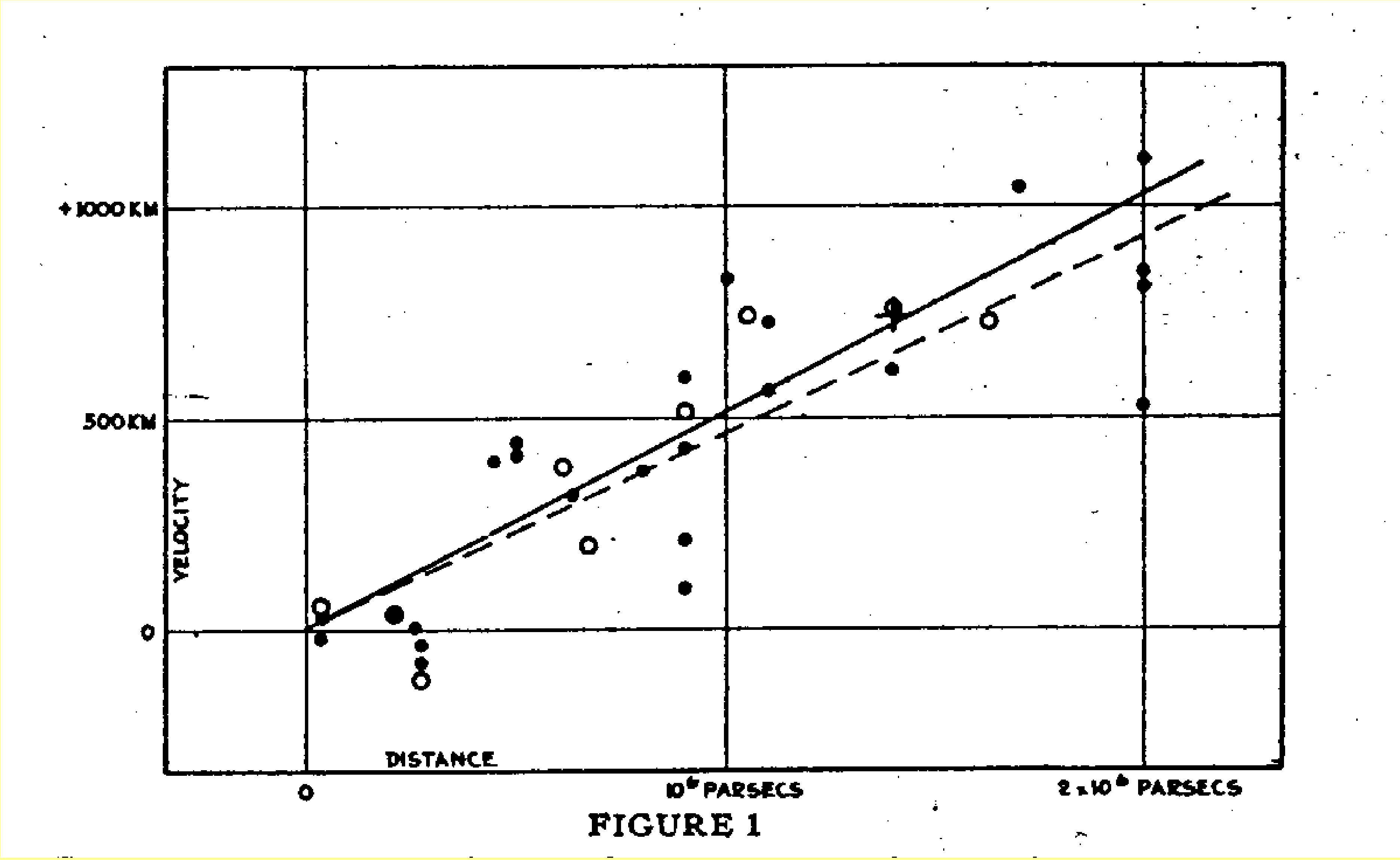
Utilisant les 42 nébuleuses figurant dans les listes de Hubble et de Strömberg ([1]), et tenant compte de la vitesse propre du soleil (300 Km. dans la direction $\alpha = 315°$, $\delta = 62°$), on trouve une distance moyenne de 0,95 millions de parsecs et une vitesse radiale de 600 Km./sec, soit 625 Km./sec à 10^6 parsecs ([2]).

Nous adopterons donc

$$\frac{R'}{R} = \frac{v}{rc} = \frac{625 \times 10^5}{10^6 \times 3{,}08 \times 10^{18} \times 3 \times 10^{10}} = 0{,}68 \times 10^{-27}\ \mathrm{cm}^{-1} \qquad (24)$$

Lemaître 1927

The Redshift-Distance Relation

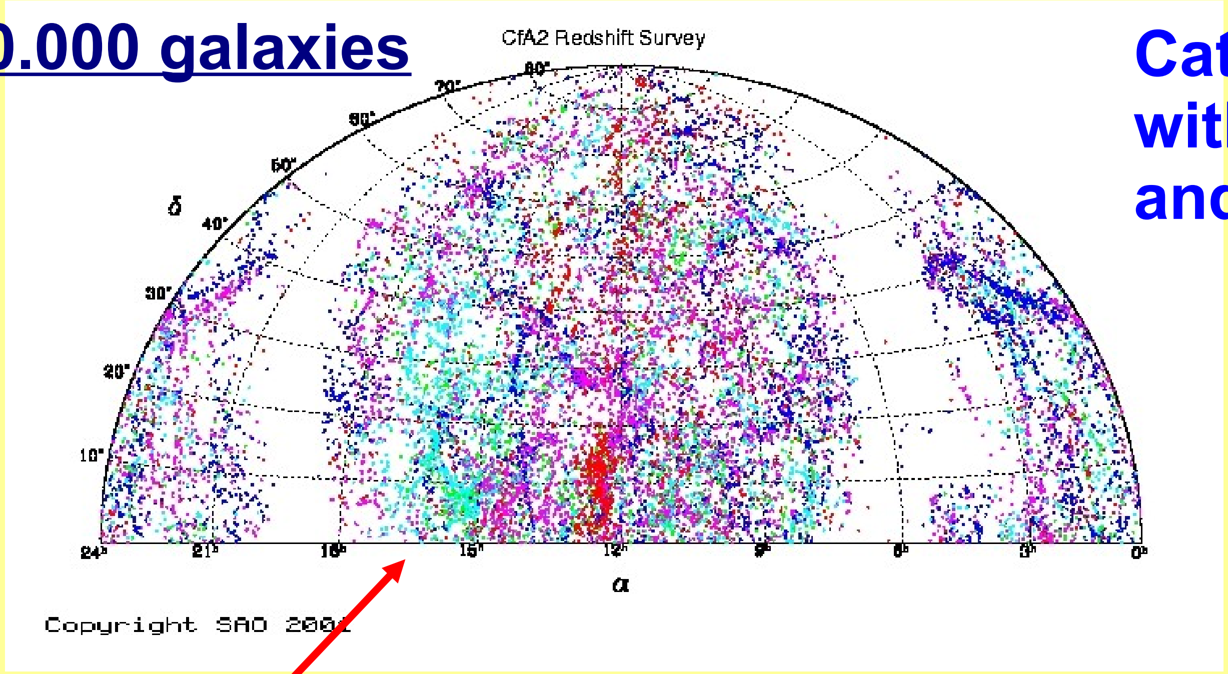


Hubble 1929

(20 out of 24 velocity measurements are from Slipher 1913-17)

THE CENTER FOR ASTROPHYSICS REDSHIFT SURVEY (1978-1999)

20.000 galaxies



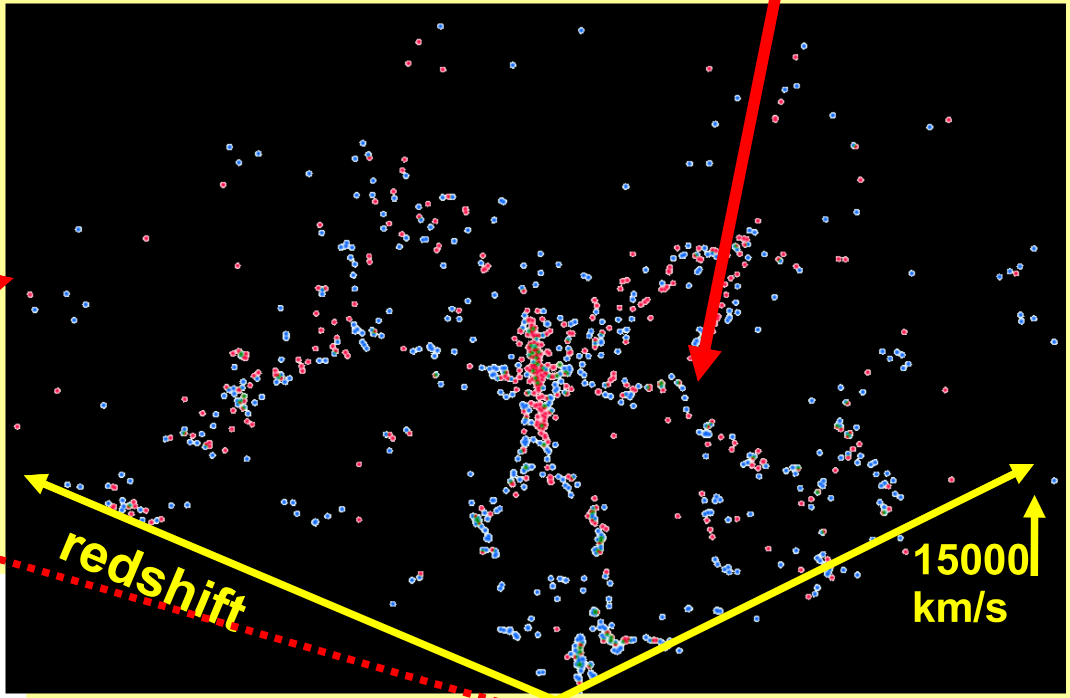
Catalogue of galaxies with measured positions and distance (redshift)

Sky projection

redshift survey

Milky Way

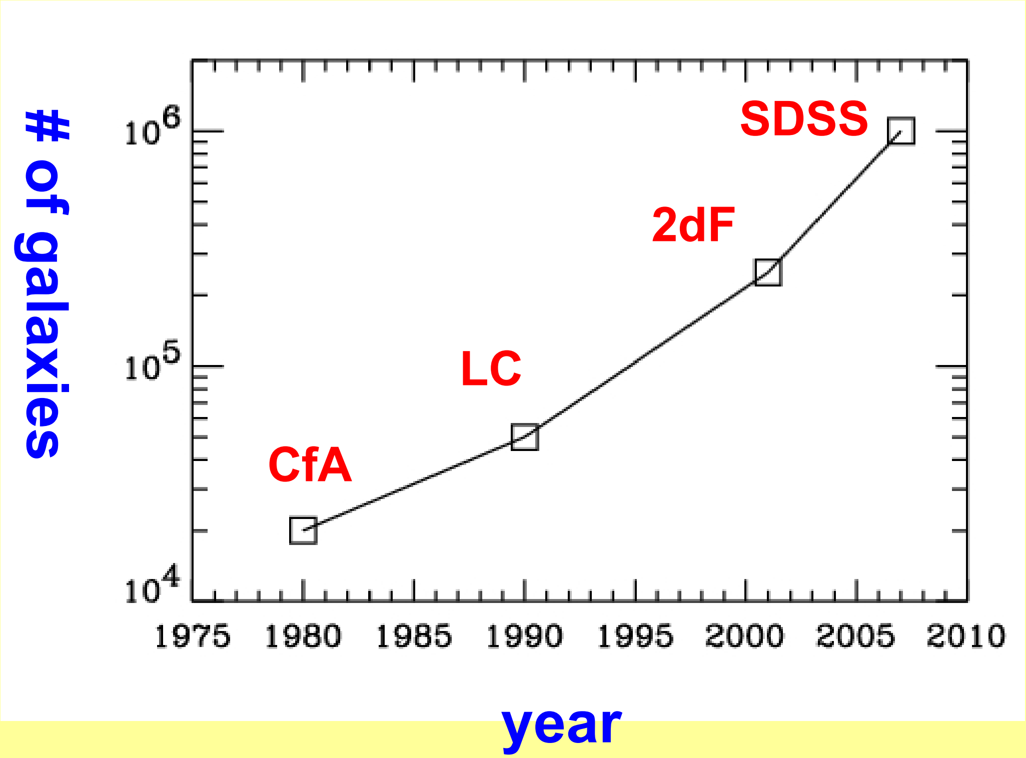
The Great Wall



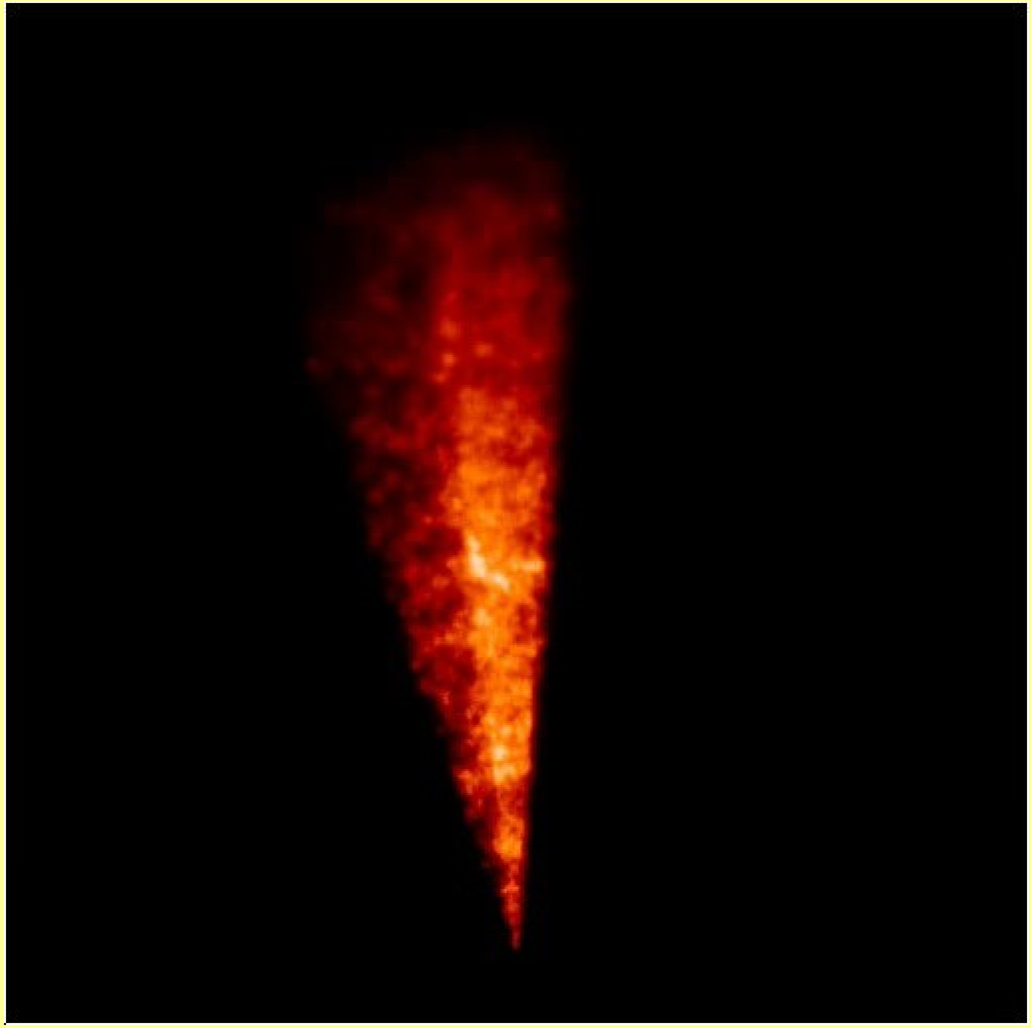
de Lapparent, Geller & Huchra 1986; Falco et al. 1999

INCOMPLETE LIST OF REDSHIFT SURVEYS

- **CfA (1980's): 2 10^4 galaxies, z ~ 0.05 (redshift limit)**
- **Las Campanas (1990's): ~ 5 10^4 galaxies, z ~ 0.2**
- **2dF (2001): 2.5 10^5 galaxies (5% of the sky), z ~ 0.2**
- **SDSS (2001-08): 10^6 galaxies (25% of the sky), z ~ 0.45**

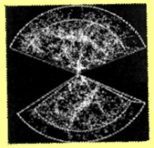


The 2dF REDSHIFT SURVEY



Colless et al 2001

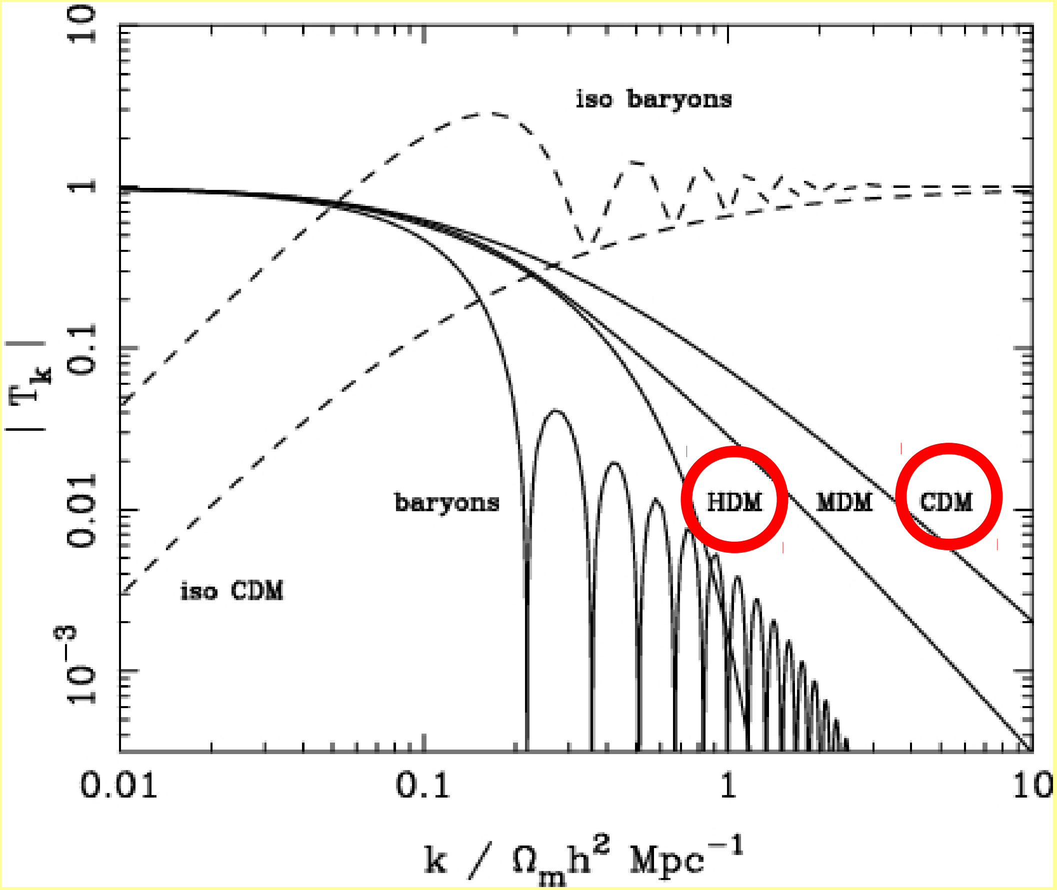
The
CfA RS



How does this large-scale structure form?

Gravitational instability and Inflation

Transfer functions of various models



(Peacock 2003)

Early 80's:

1. *Inflation:* quantum fluctuations set the initial conditions of the mass density field

2. Hypotheses on the nature of DM: *Cold DM* was proposed

Predictions of Inflation:

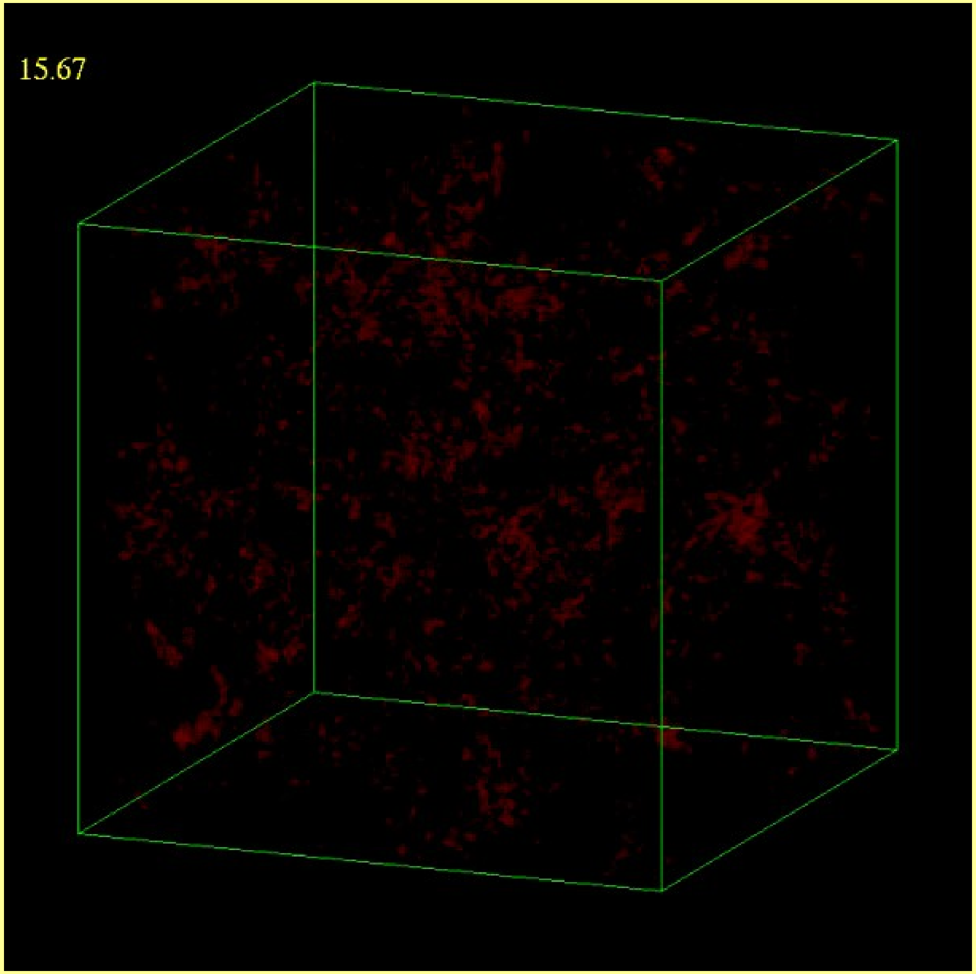
1. The primordial density field is a *Gaussian random field:*

$$P(k)=T^2(k)P_i(k)$$

2. The universe has *flat geometry*

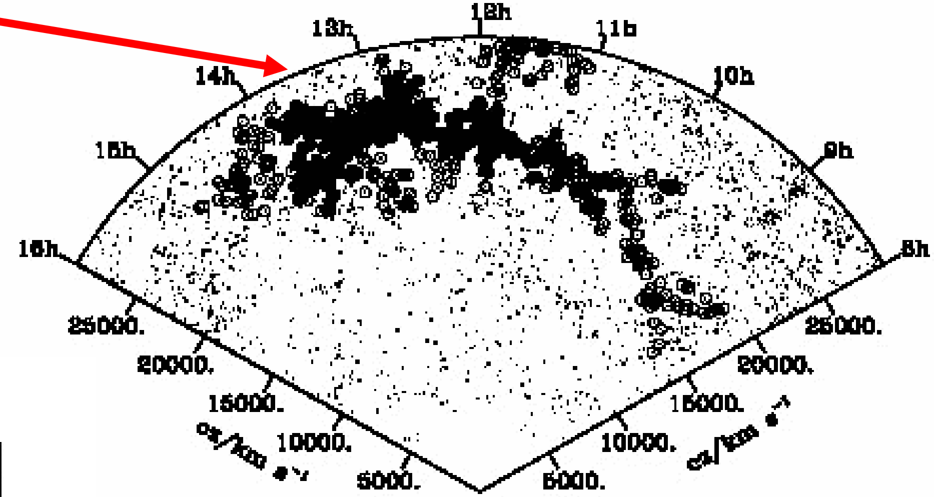
THE FORMATION OF COSMIC STRUCTURES:

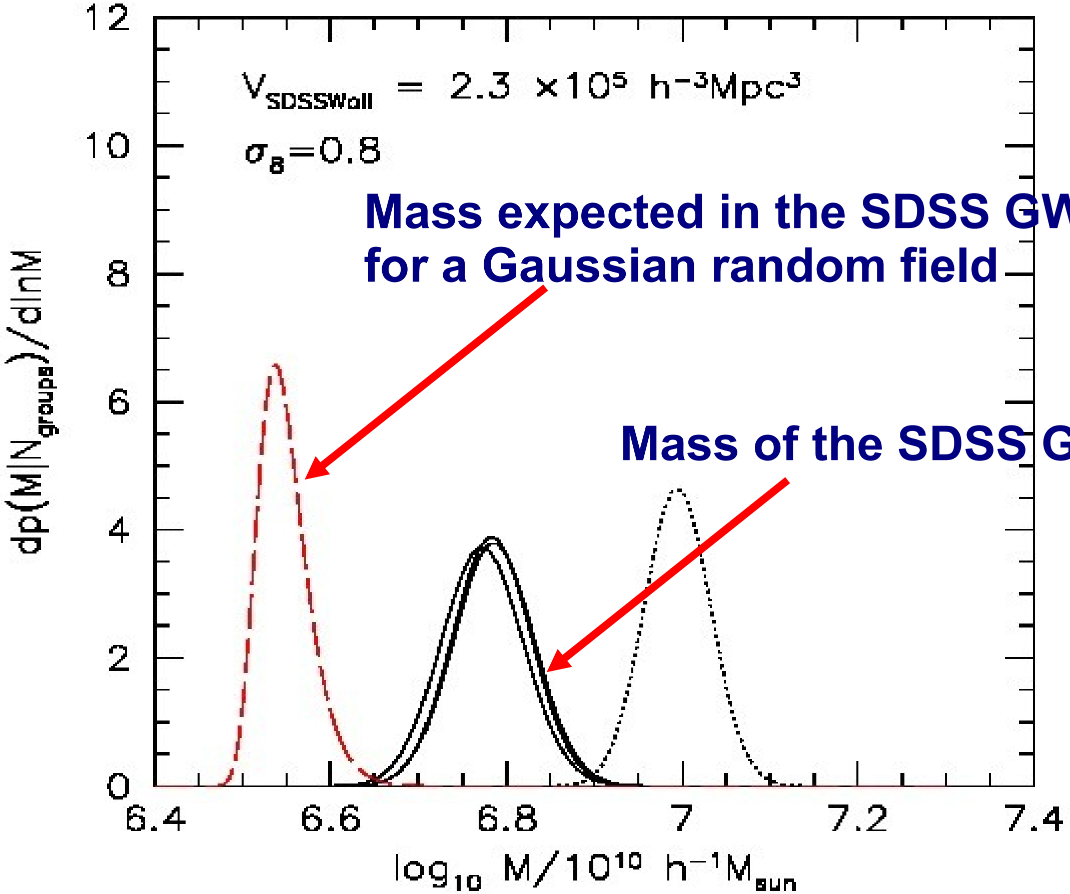
CDM



Courtesy of Ben Moore et al.

The SDSS Great Wall





There should NOT be any other similar system in the Hubble volume!

Sheth & Diaferio 2011

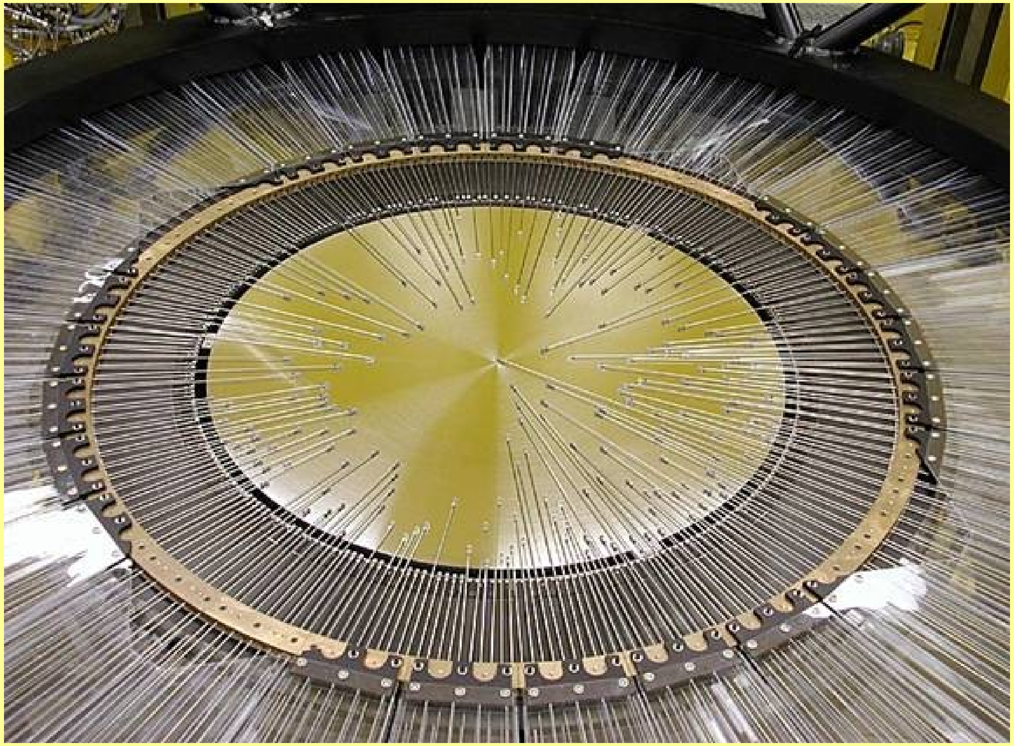
MMT

6.5 m mirror

Smithsonian Institution

THE UNIVERSITY OF ARIZONA

Hectospec



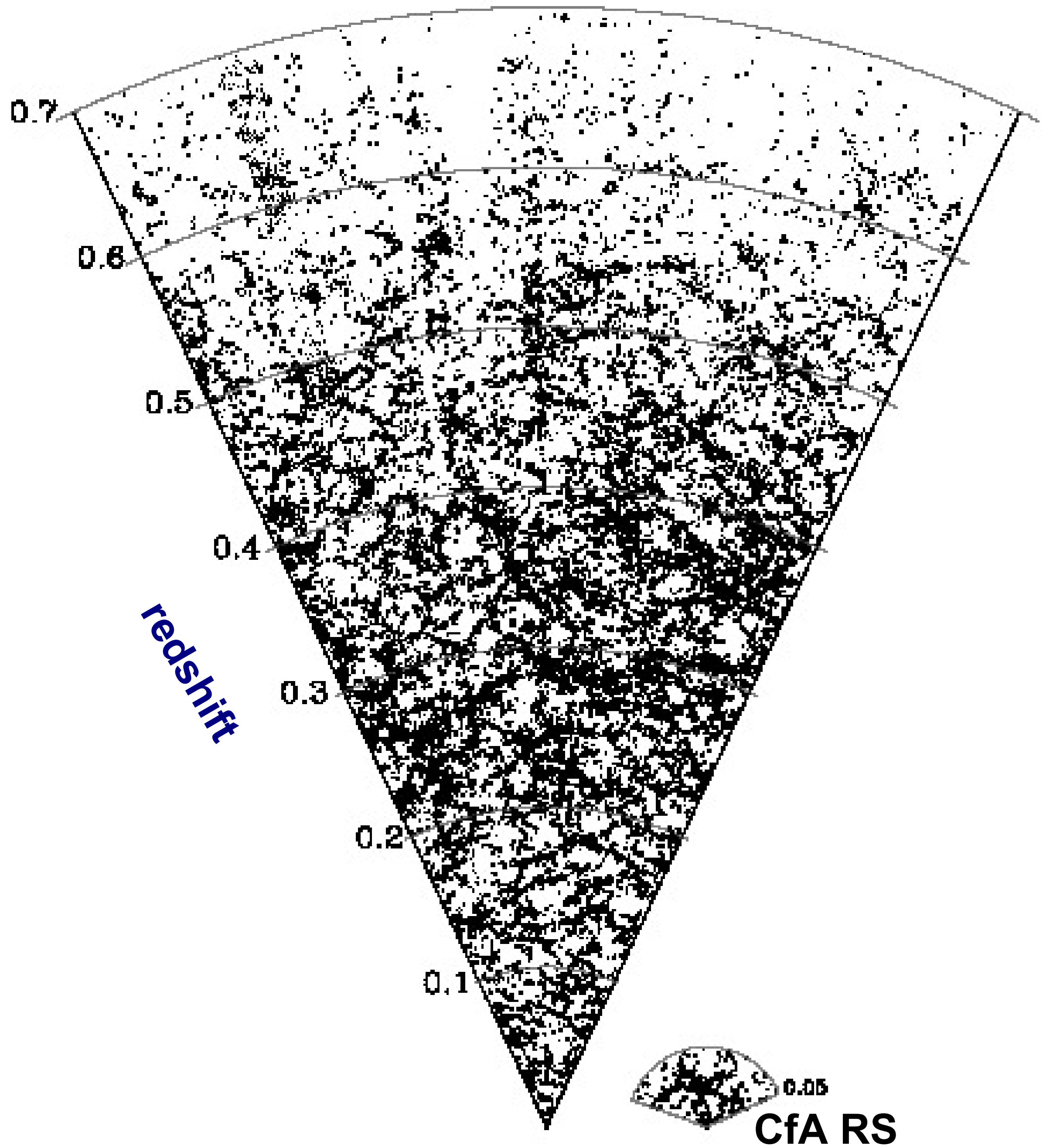
300 optical fibers
350-1000 nm @ 6Å resolution

HectoMAP

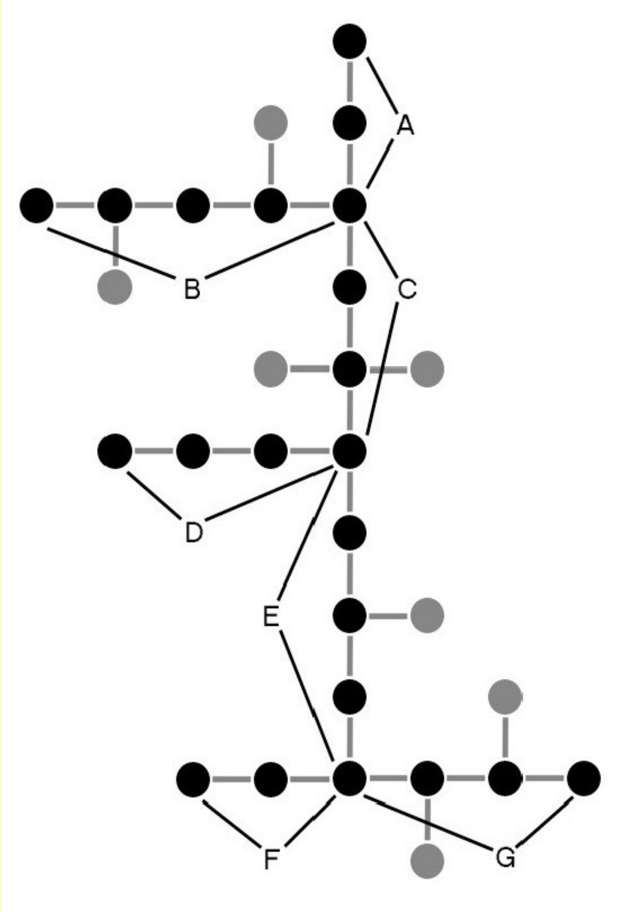
(Geller, Diaferio, Kurtz, Fabricant)

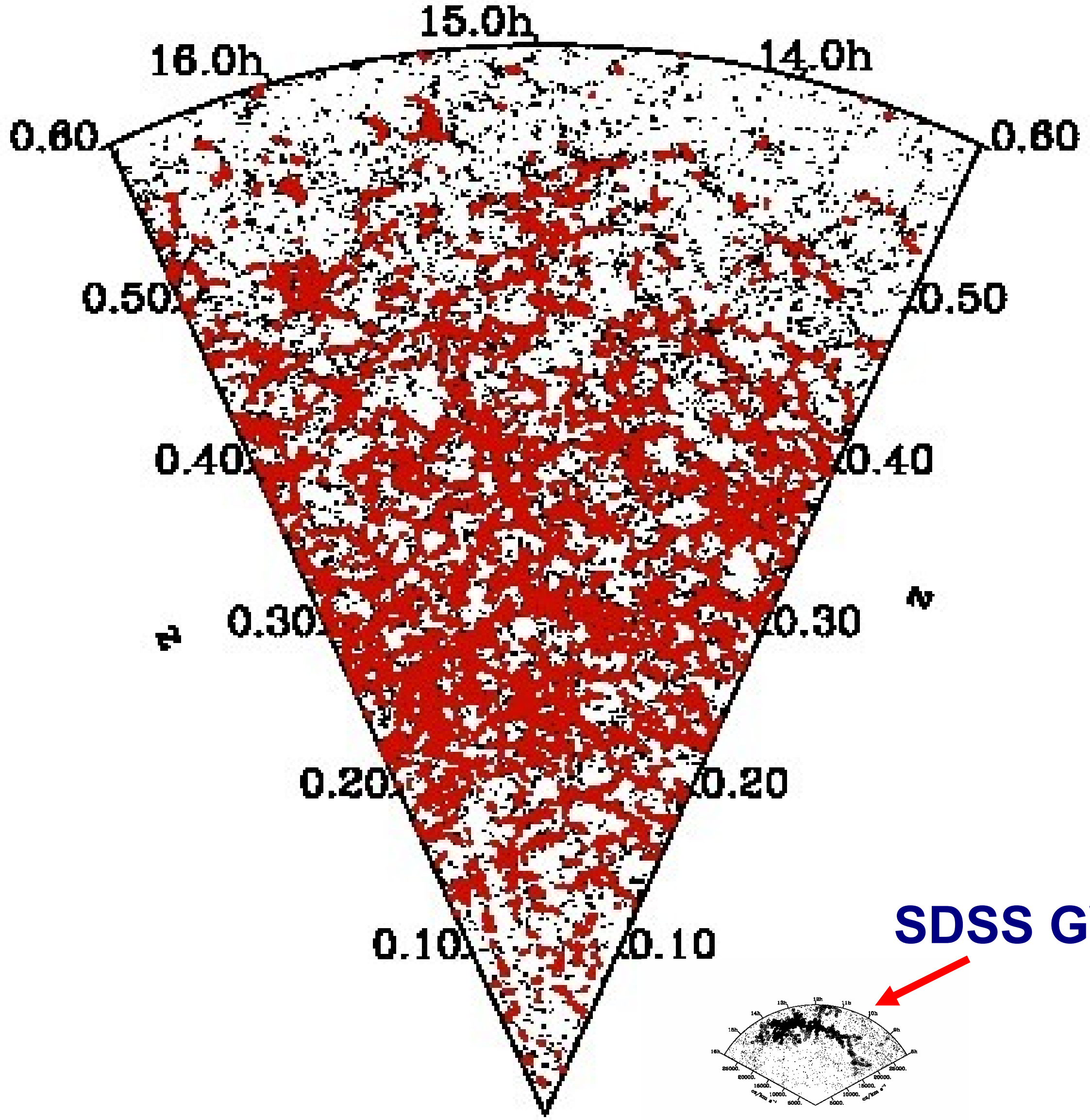
- ~60,000 galaxies
- $r_{petro} < 21$
- 50 deg^2
- median z~0.34

Completion planned by the end of 2013



Minimal spanning tree





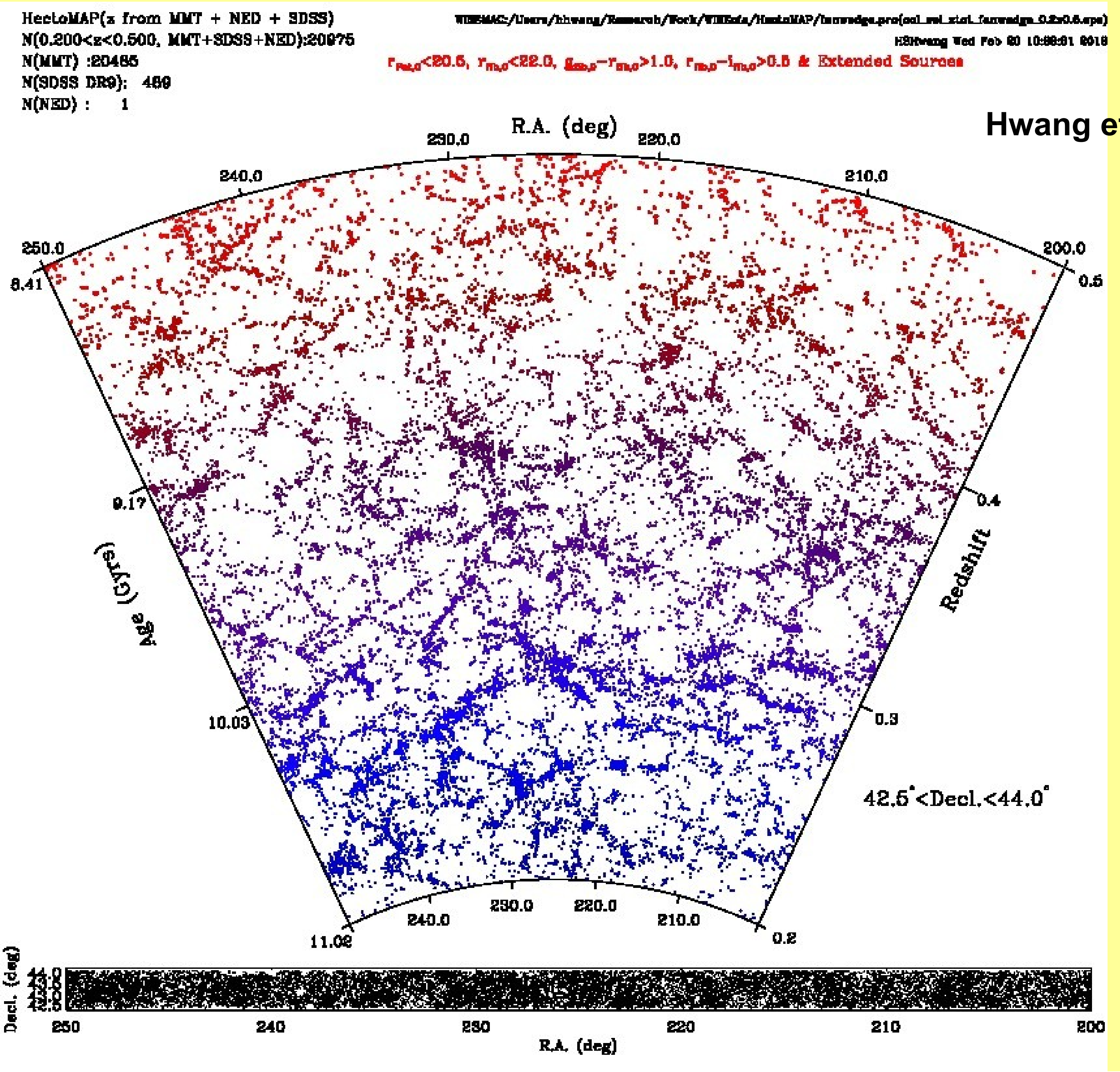
SDSS GW

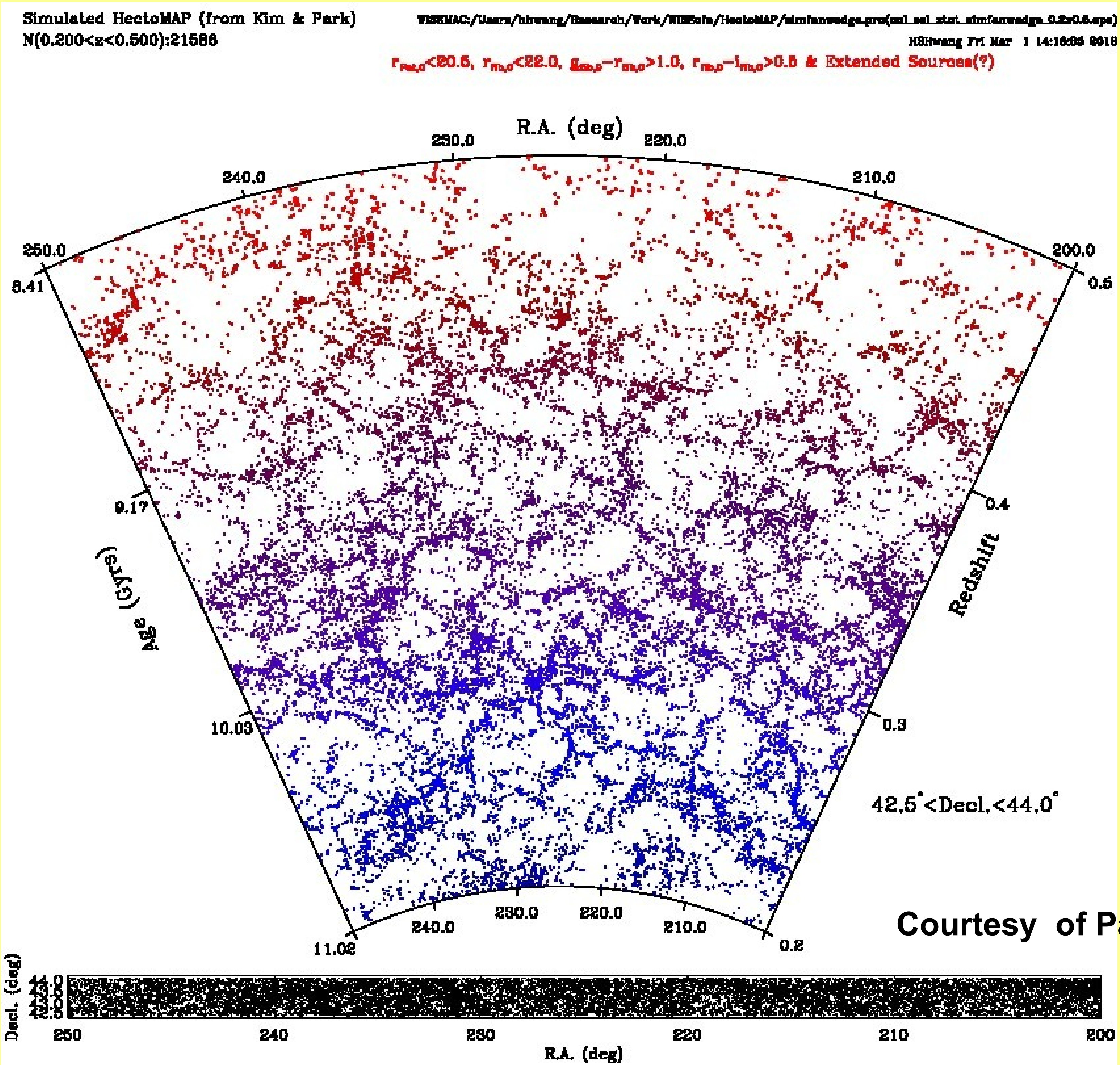
The Relevance of Non-Gaussianities

- **Physical conditions at inflation:**
  single field, slow roll, canonical kinetic energy, initial vacuum state

- **Evolution of cosmic structures and non-linear processes in the “low”-redshift Universe:**
  e.g., non-linear effects at decoupling z~1090, ISW, IGM vs. mass distribution, etc.

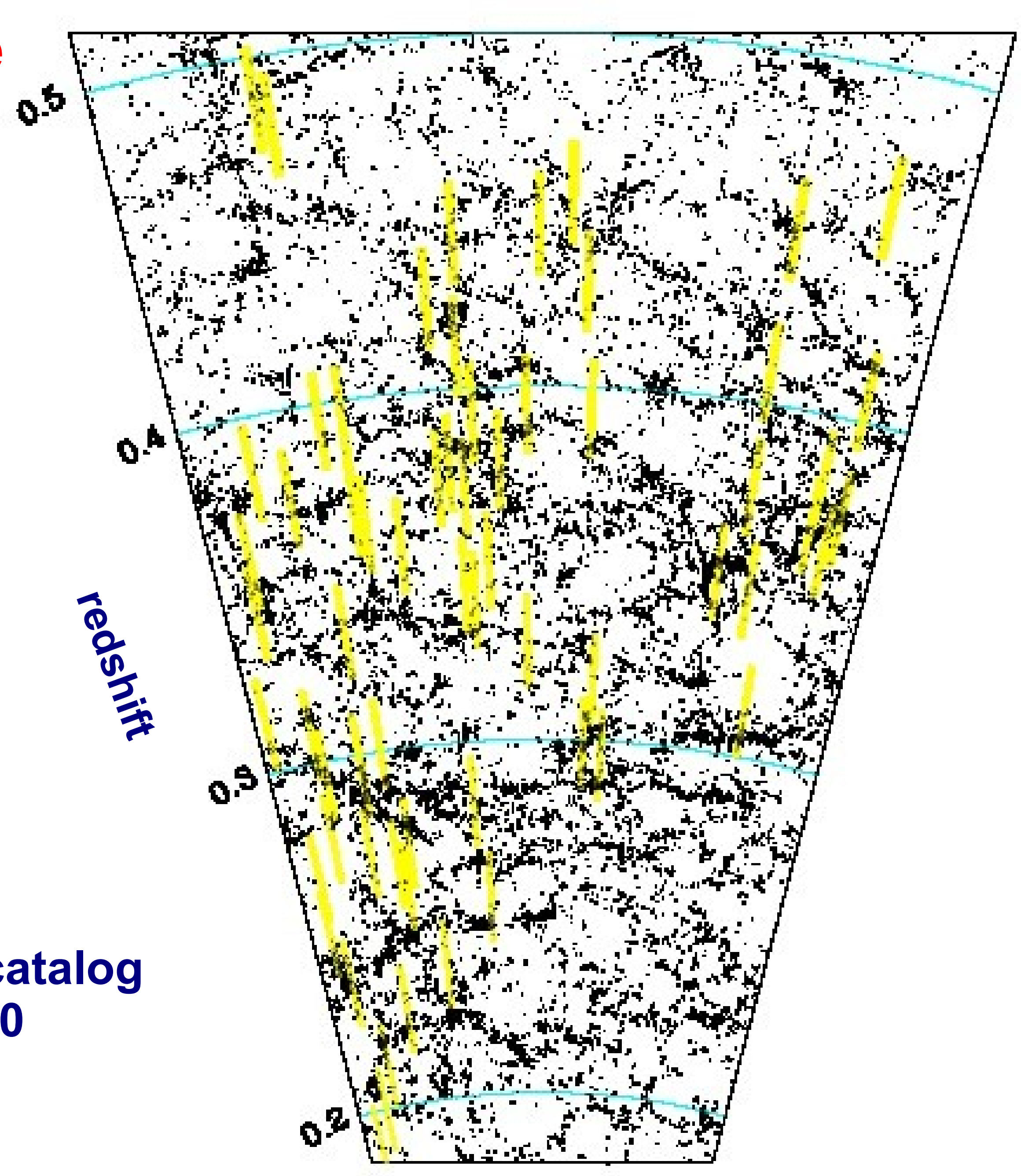
Hwang et al 2013





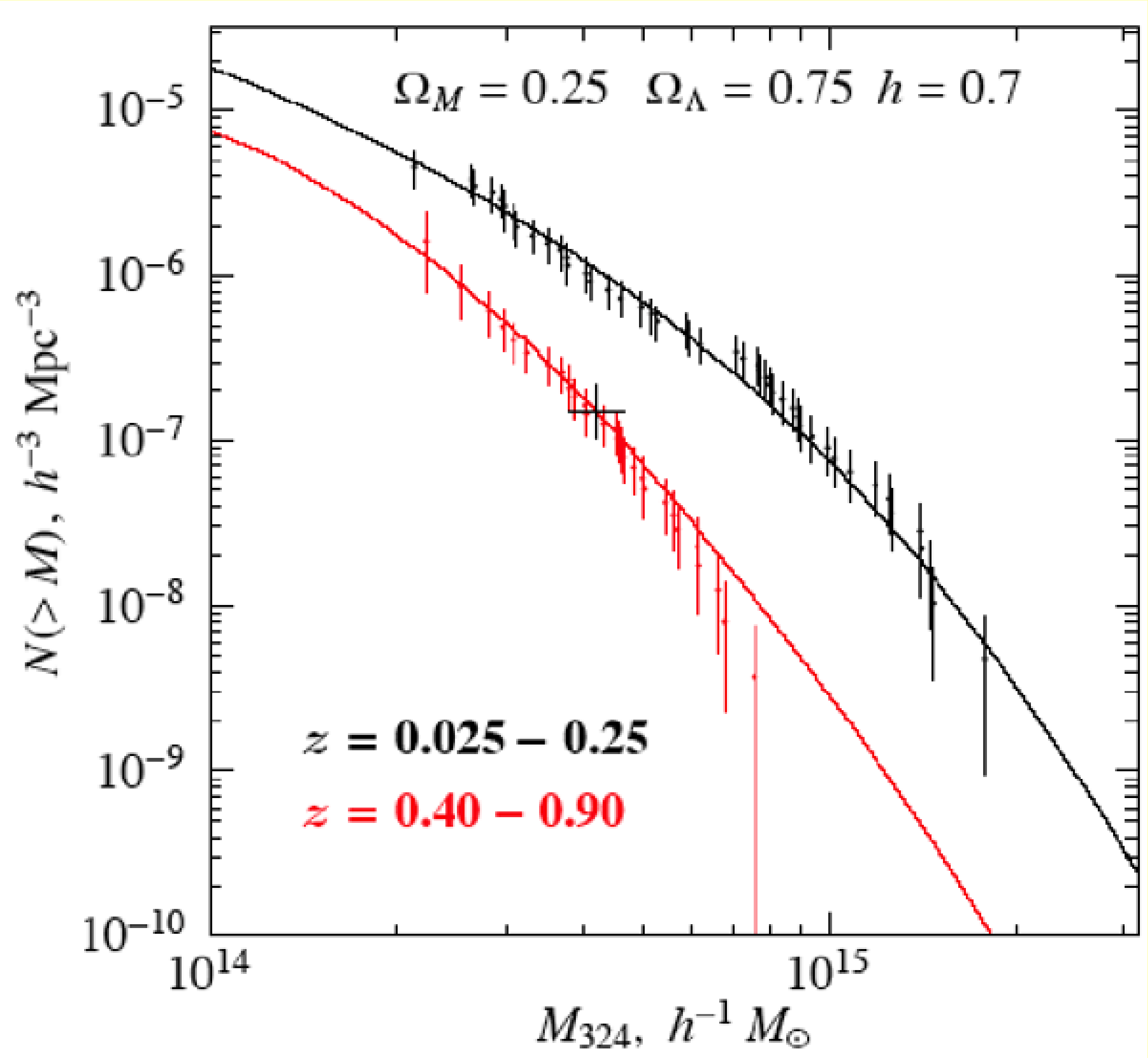
Courtesy of Park 2013

Dense vs. sparse redshift surveys



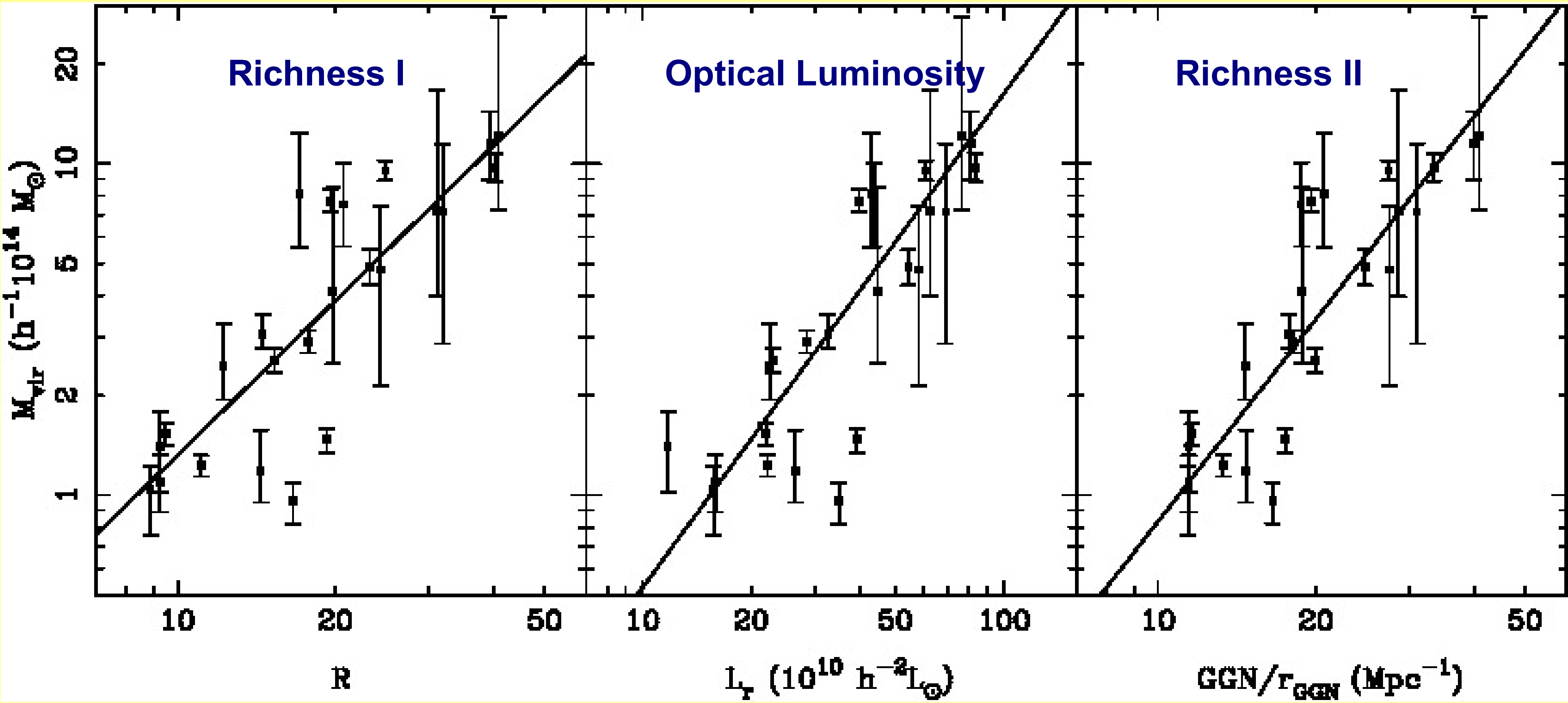
HectoMAP
vs.
the GMBCG cluster catalog
of Hao et al 2010

The cluster mass function as a cosmological probe



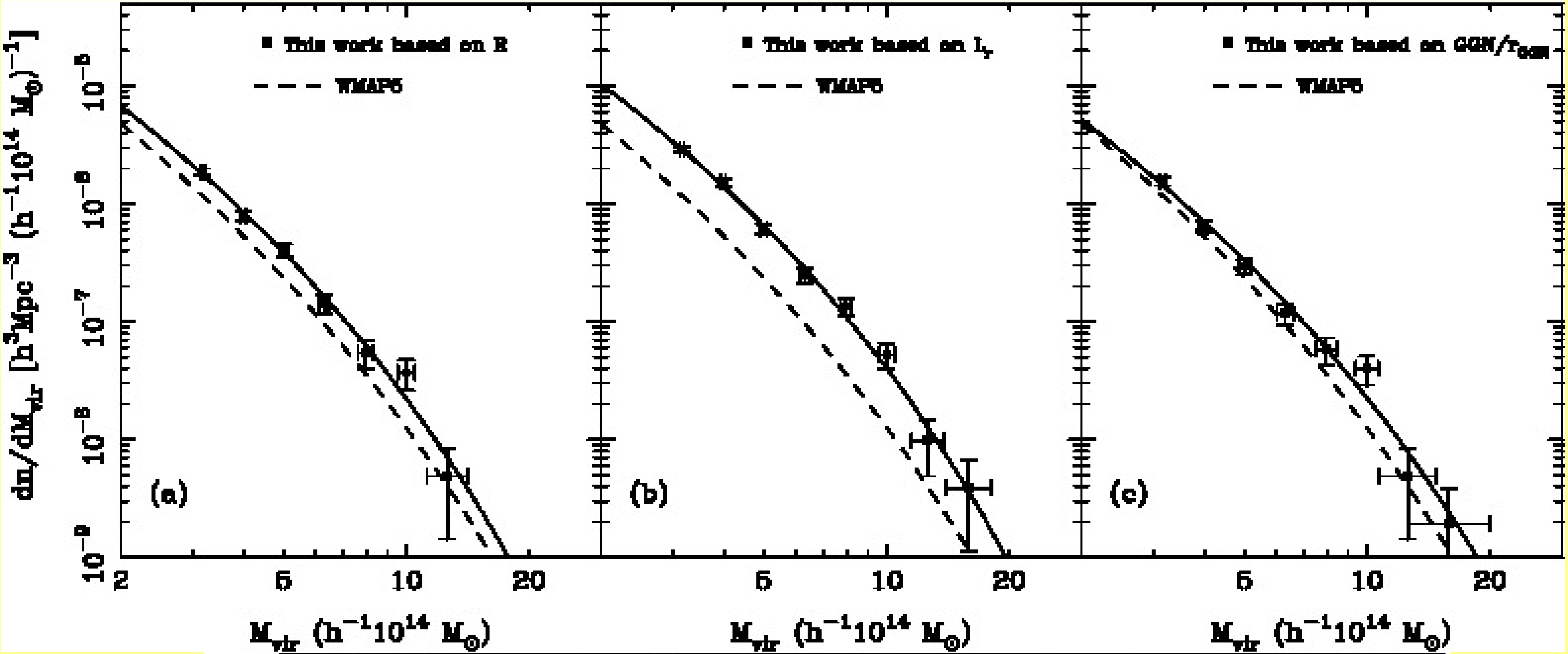
Vikhlinin et al 2007

Cluster mass from scaling relations

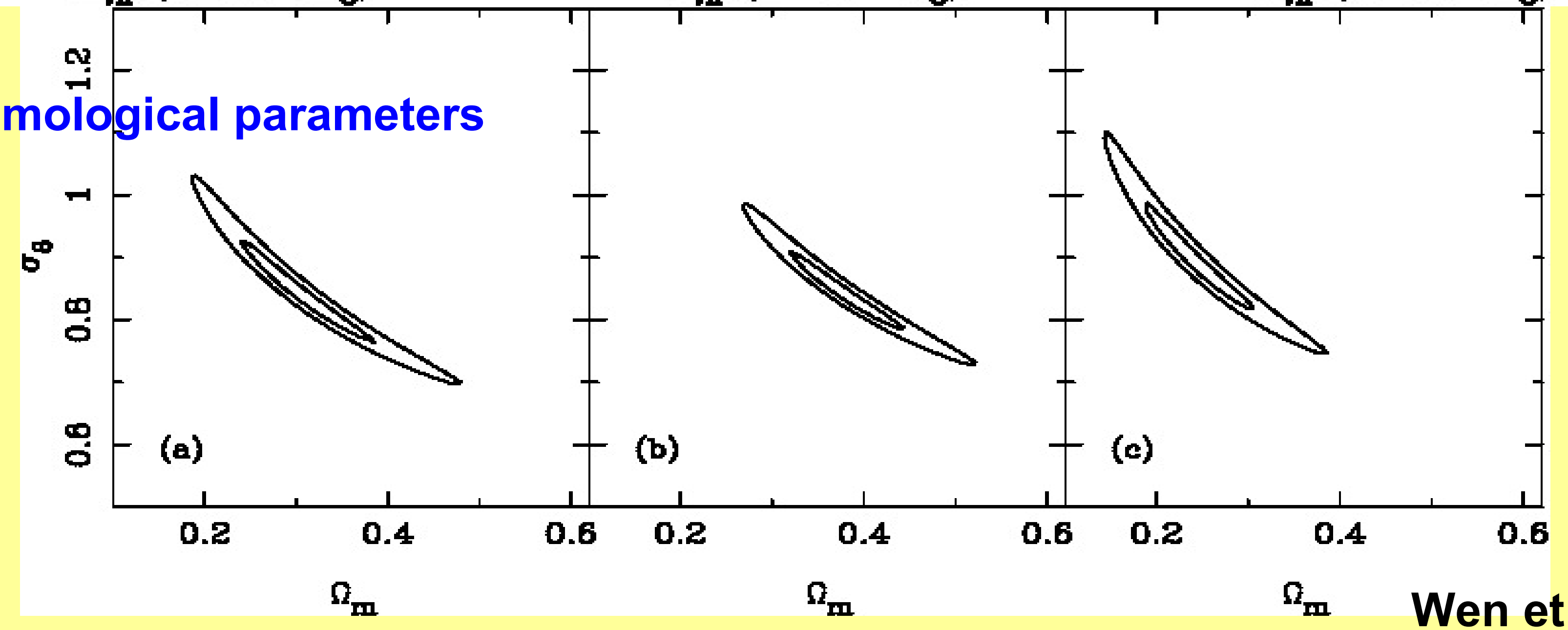


Wen et al 2010

Mass functions



Cosmological parameters



Wen et al 2010

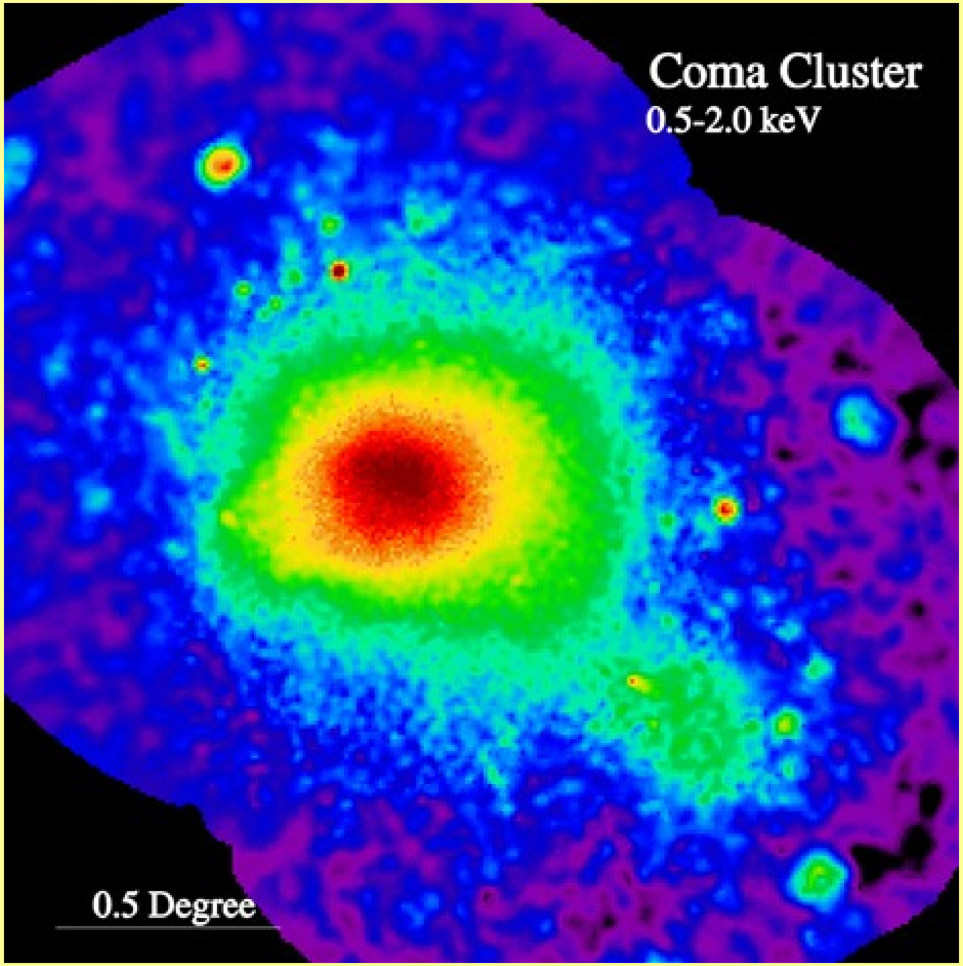
Mass Estimates

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

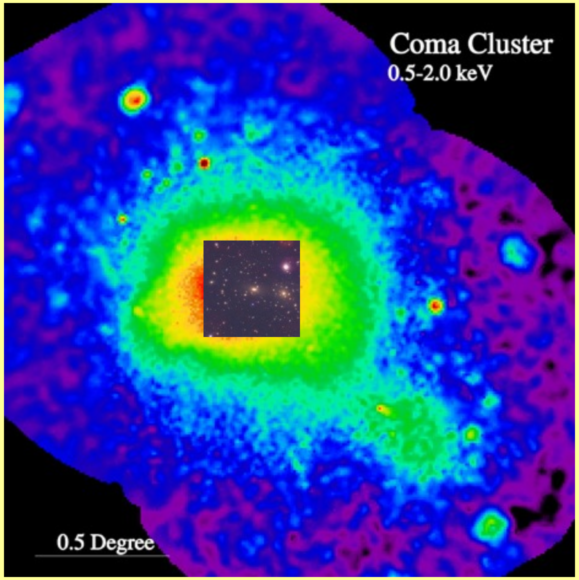
Do not require dynamical equilibrium

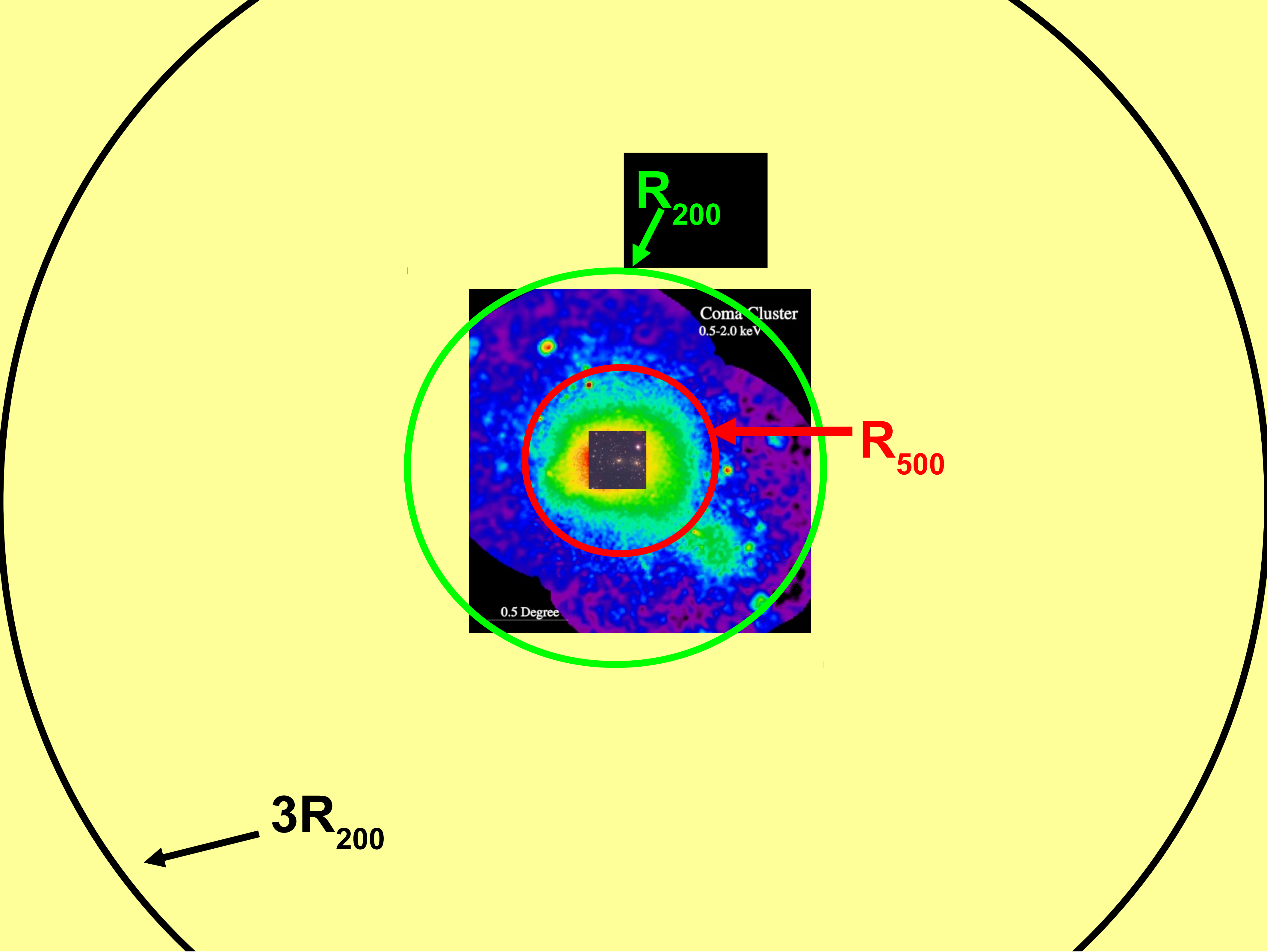
THE COMA CLUSTER



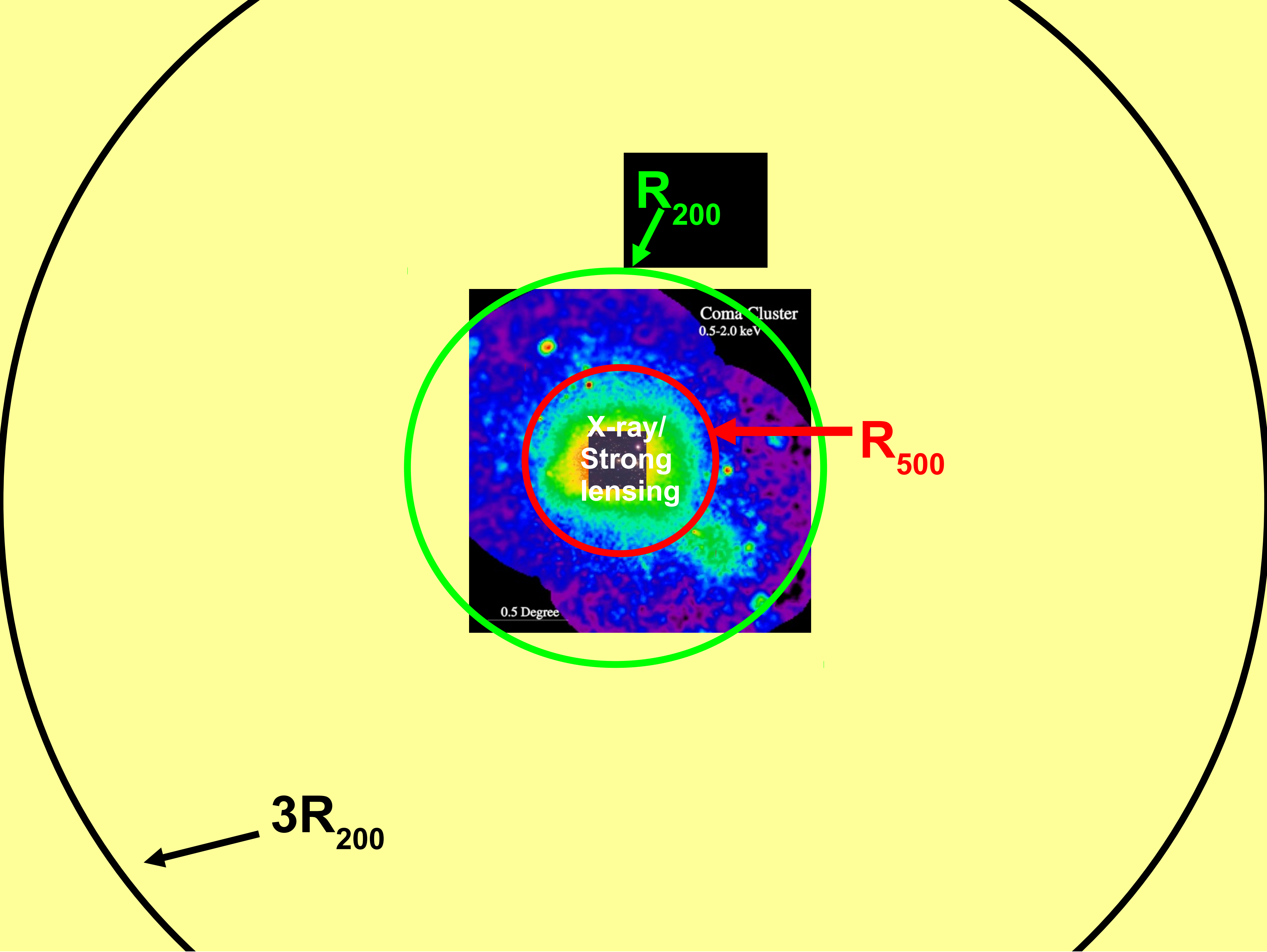
0.35 h^{-1} Mpc

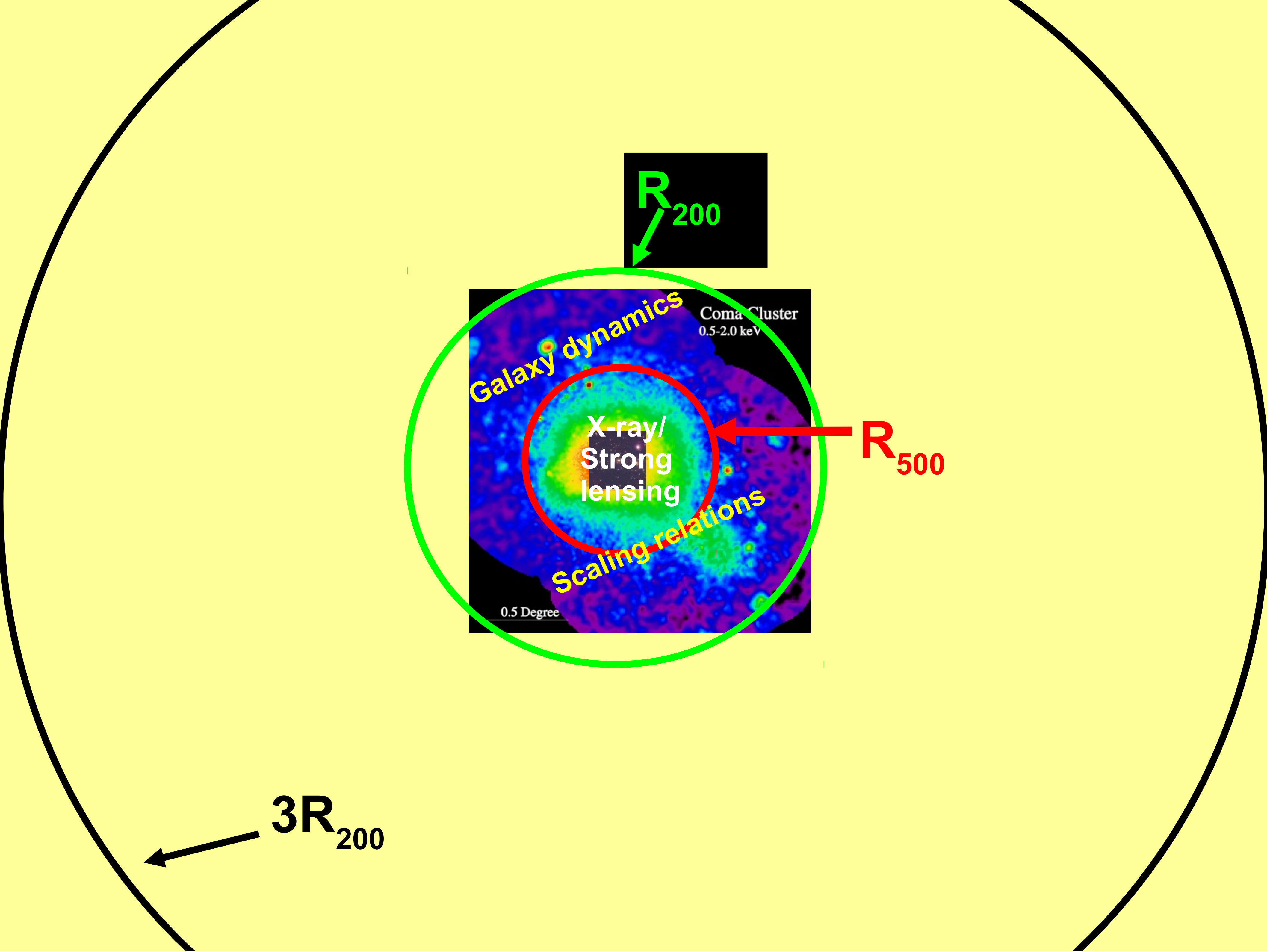
2.5 h^{-1} Mpc


Coma Cluster
0.5-2.0 keV
0.5 Degree

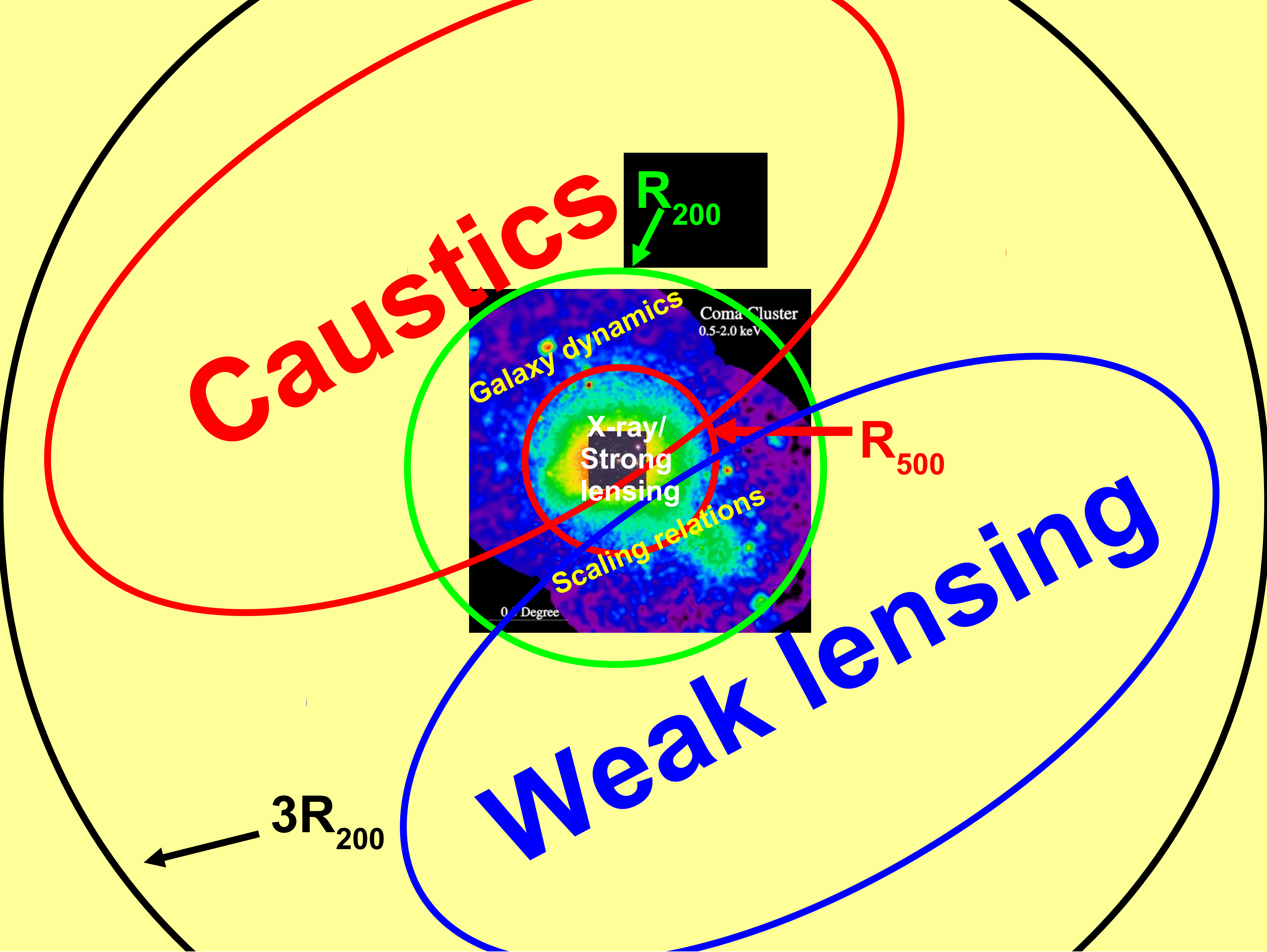


R200
Coma Cluster
0.5-2.0 keV
R500
0.5 Degree
3R200


R200
Coma Cluster
0.5-2.0 keV
X-ray/
Strong
lensing
R500
0.5 Degree
3R200

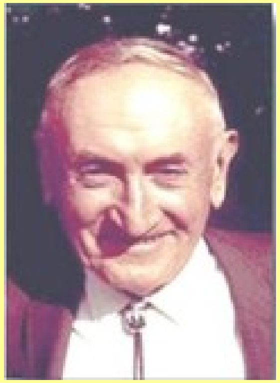


R200
Coma Cluster
0.5-2.0 keV
Galaxy dynamics
X-ray/
Strong
lensing
R500
Scaling relations
0.5 Degree
3R200



Caustics
R_{200}
Coma Cluster
0.5-2.0 keV
Galaxy dynamics
X-ray/
Strong
lensing
R_{500}
Scaling relations
Weak lensing
$3R_{200}$

Early mass estimate: The dark matter problem



Zwicky 1933

Total cluster mass >> sum of masses of individual galaxies

Coma cluster

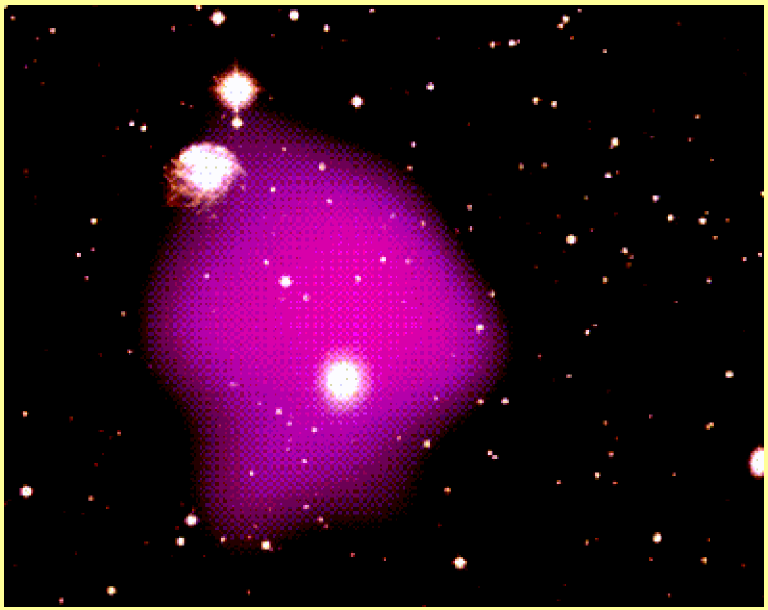
By using Newton
+ virial theorem:

$$GM = 3\sigma^2 R >> 100 \Sigma m_{gal}$$

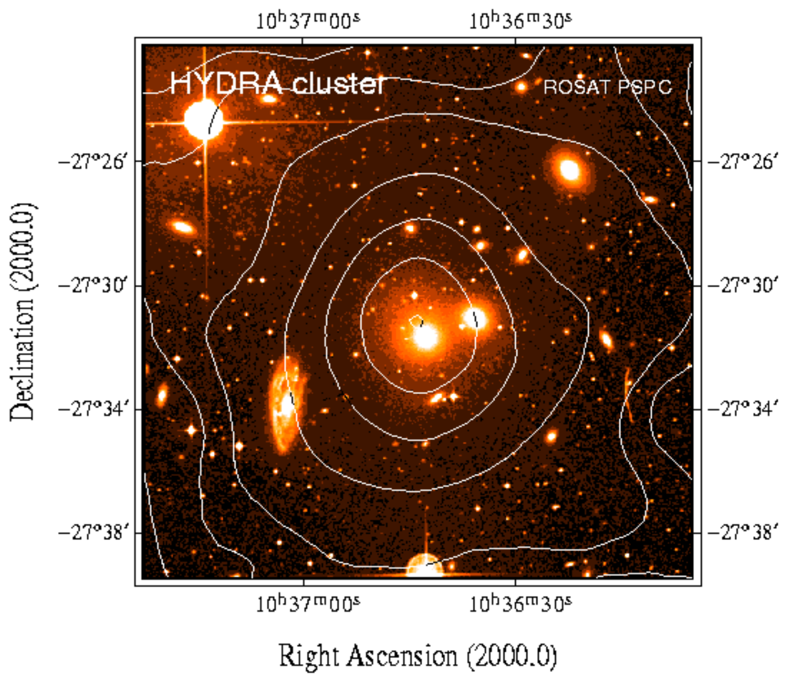
$$R = \frac{\pi}{2} \frac{N(N-1)}{2} \left(\sum_i \sum_{i>j} \frac{1}{r_{ij}} \right)^{-1}$$

The 1980's: X-ray emission

NGC2300 group



Hydra cluster



$GM(<r) \sim k_B T_X r$ (hydrostatic equilibrium)

gas temperature

A MORE SOPHISTICATED APPROACH

From Jeans equations

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

velocity anisotropy parameter $\beta(r) = 1 - (\langle v_\theta^2\rangle + \langle v_\phi^2\rangle)/2\langle v_r^2\rangle$

From hydrostatic equilibrium

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

A MORE SOPHISTICATED APPROACH

From Jeans equations

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

velocity anisotropy parameter

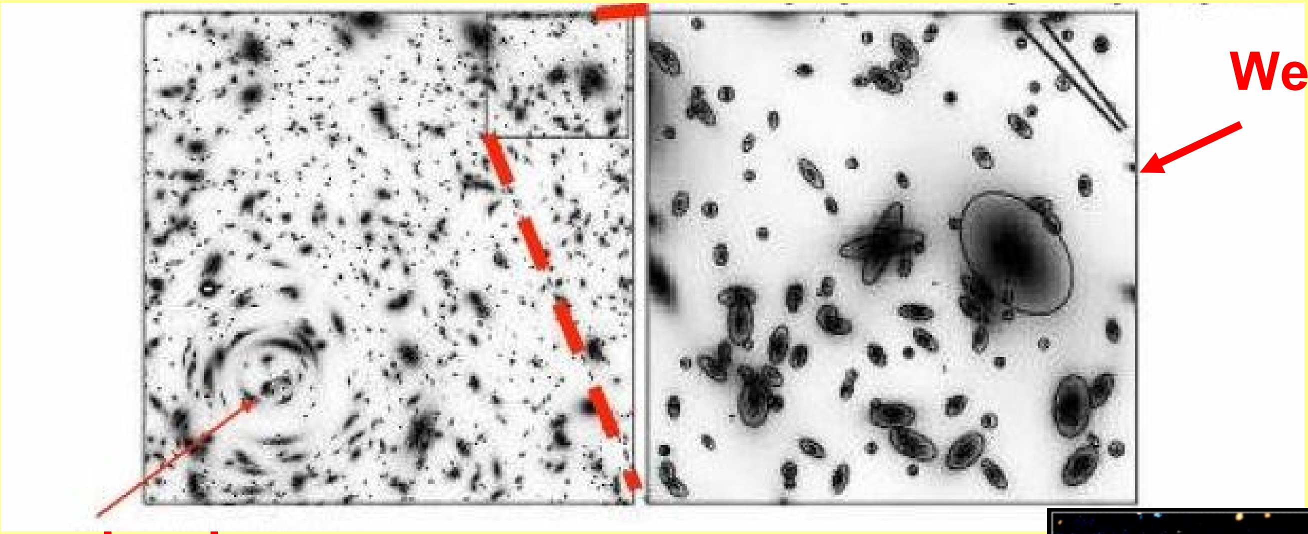
$$\beta(r) = 1 - (\langle v_\theta^2 \rangle + \langle v_\phi^2 \rangle)/2\langle v_r^2 \rangle$$

UNKNOWN!

From hydrostatic equilibrium

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

Dropping the dynamical equilibrium hypothesis. The 1990's: Gravitational lensing



Weak lensing

Strong lensing

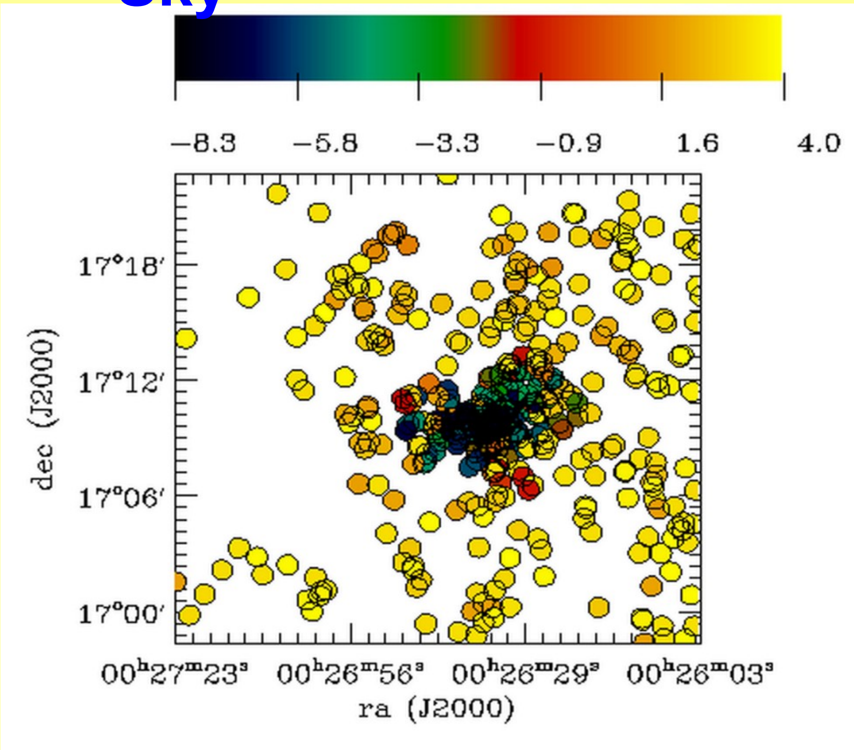
$$GM(<r) \sim \alpha r c^2$$

deflection angle

Dropping the dynamical equilibrium hypothesis. The caustic method

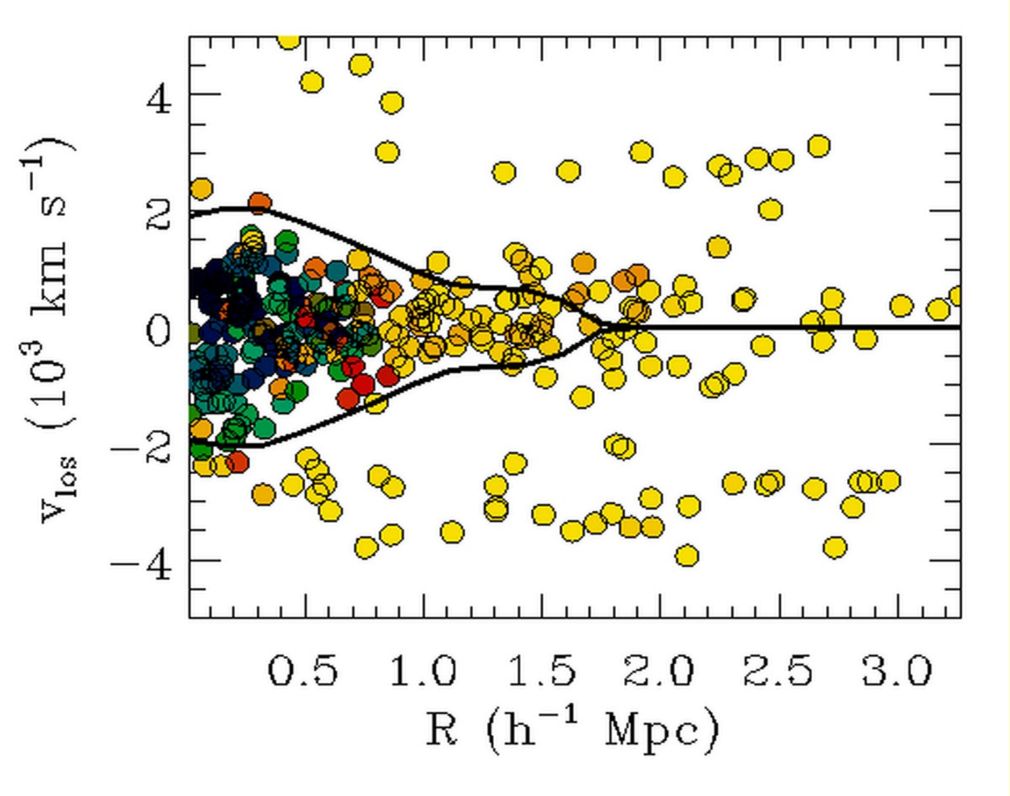
CL0024

Sky



Redshift diagram

line-of-sight velocity

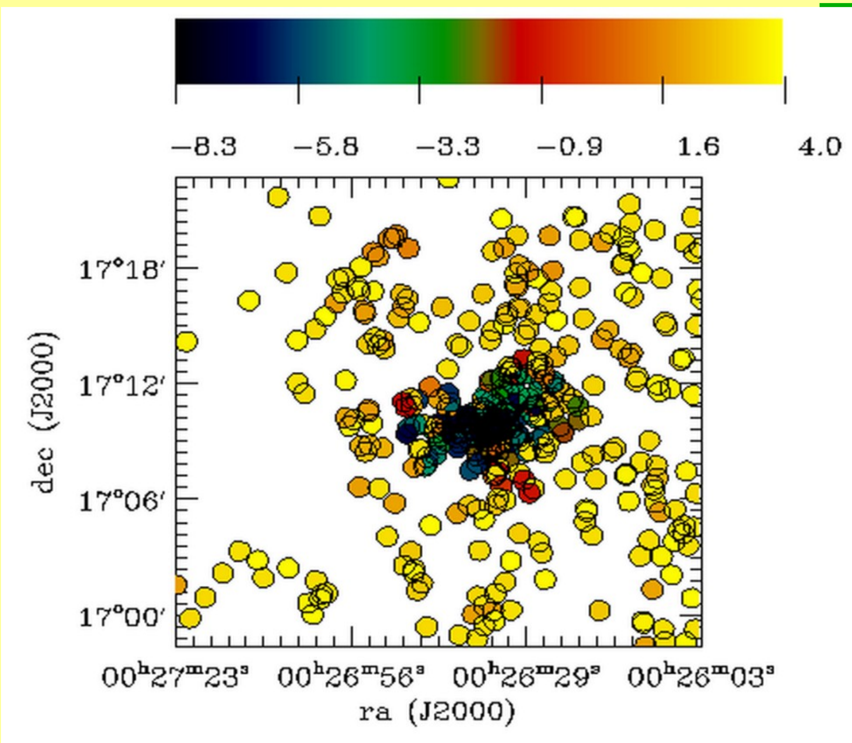


projected distance

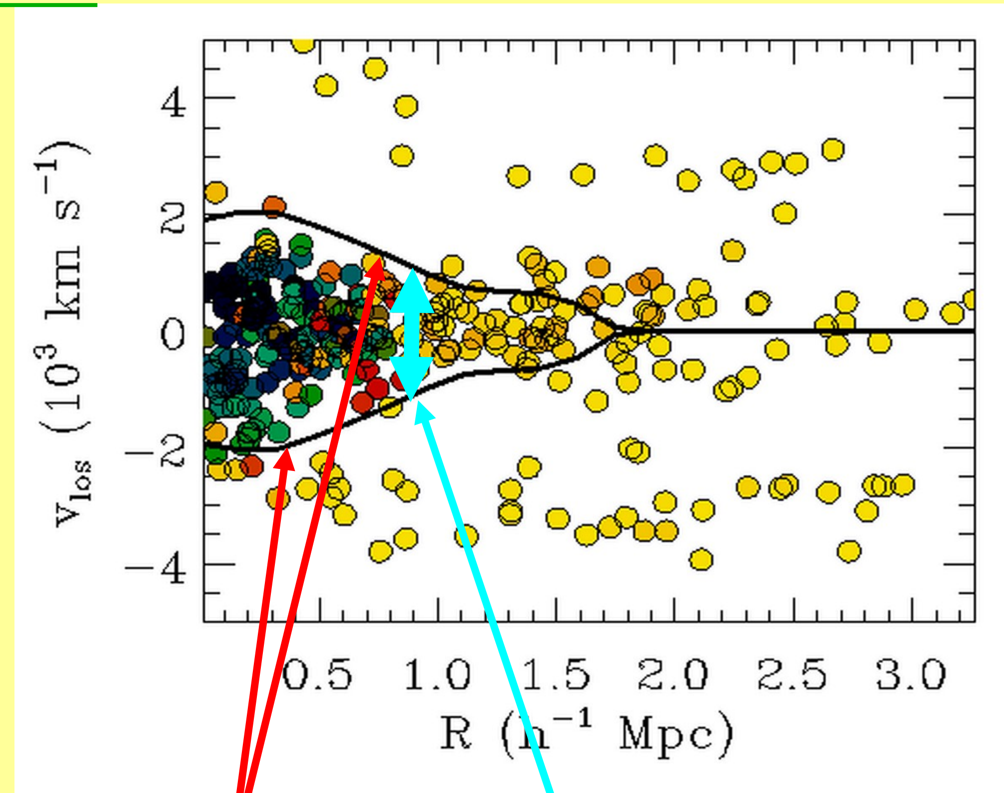
THE CAUSTIC TECHNIQUE

Example: CL0024

Sky



Redshift diagram



Caustics

Caustic amplitude = escape velocity

MASS ESTIMATE:

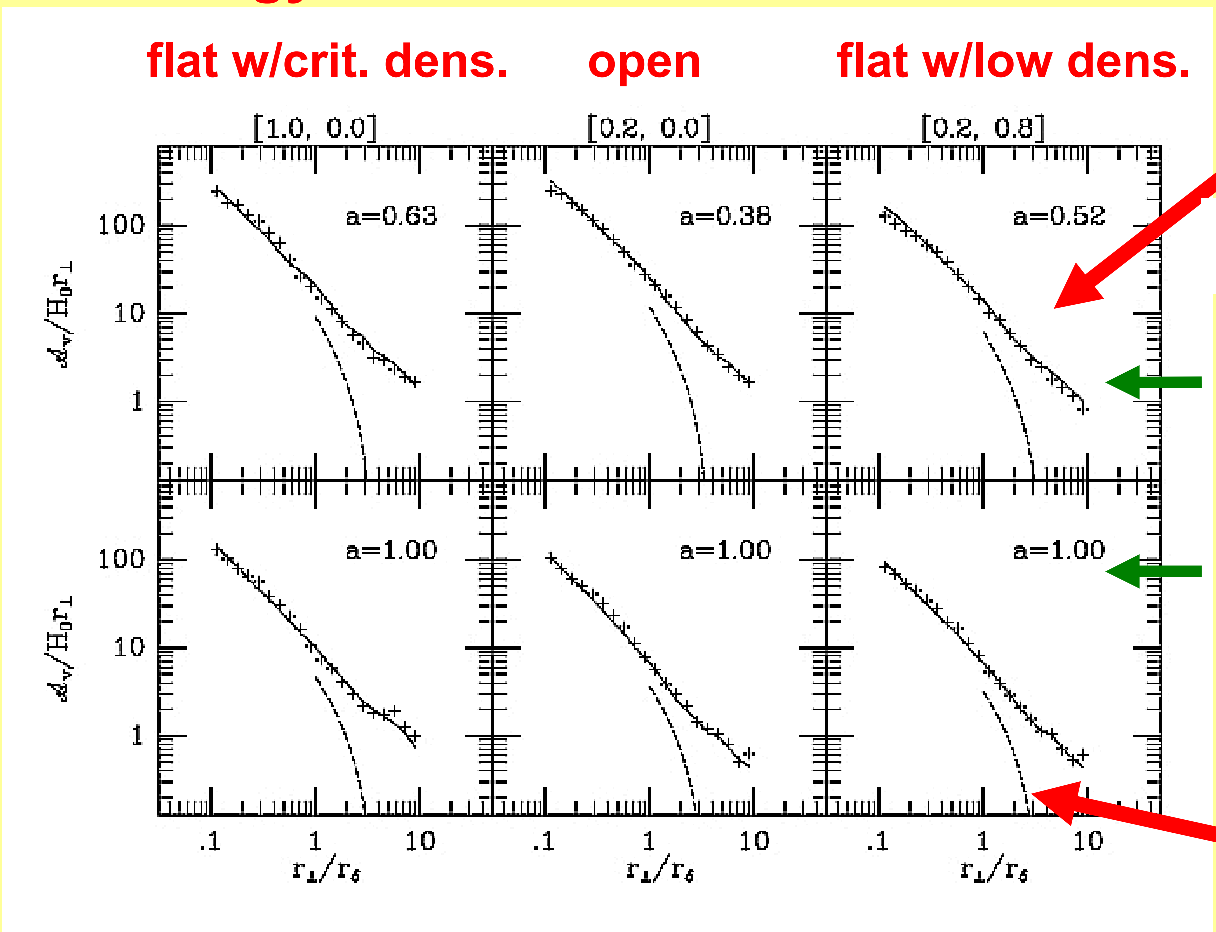
$$GM(<r) = \frac{1}{2}\int_0^r \mathcal{A}^2(x)dx$$

(Diaferio & Geller 1997)

THE CAUSTIC TECHNIQUE

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

cosmology →



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

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

clusters out of equilibrium

clusters in equilibrium

spherical infall model

caustic amplitude

radius

Diaferio & Geller 1997

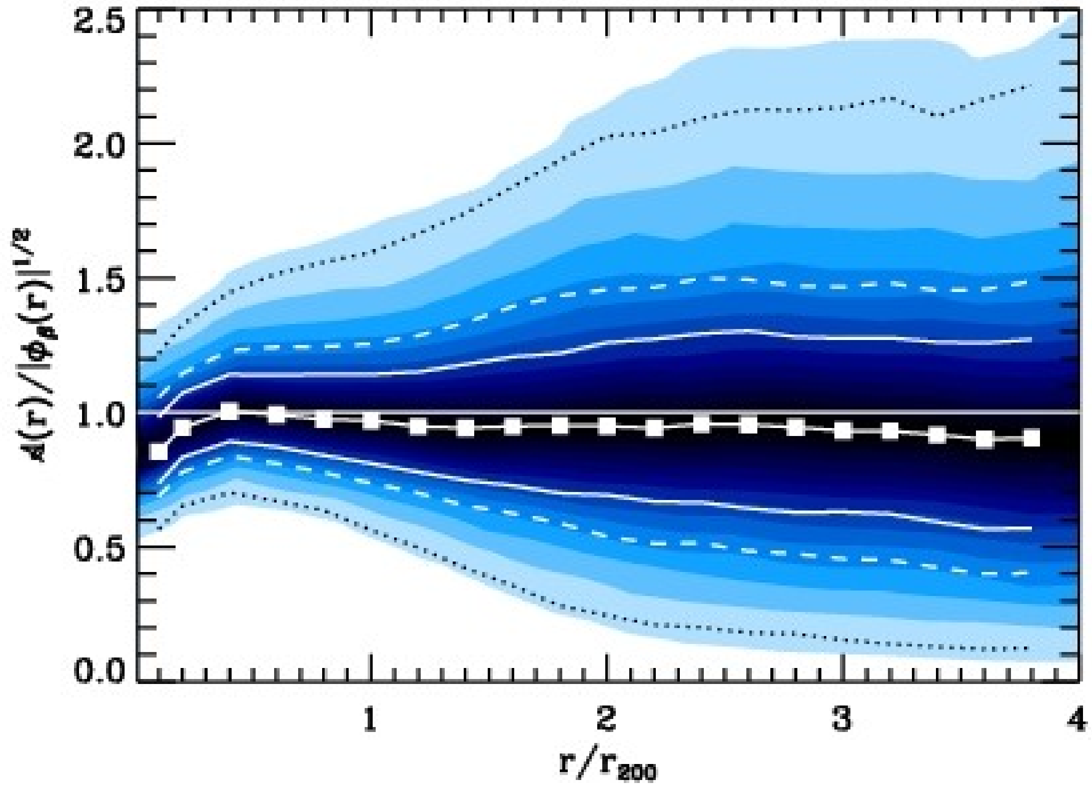
THE GRAVITATIONAL POTENTIAL PROFILE

(unclean sample...!)

3000 synthetic clusters

(ΛCDM model)

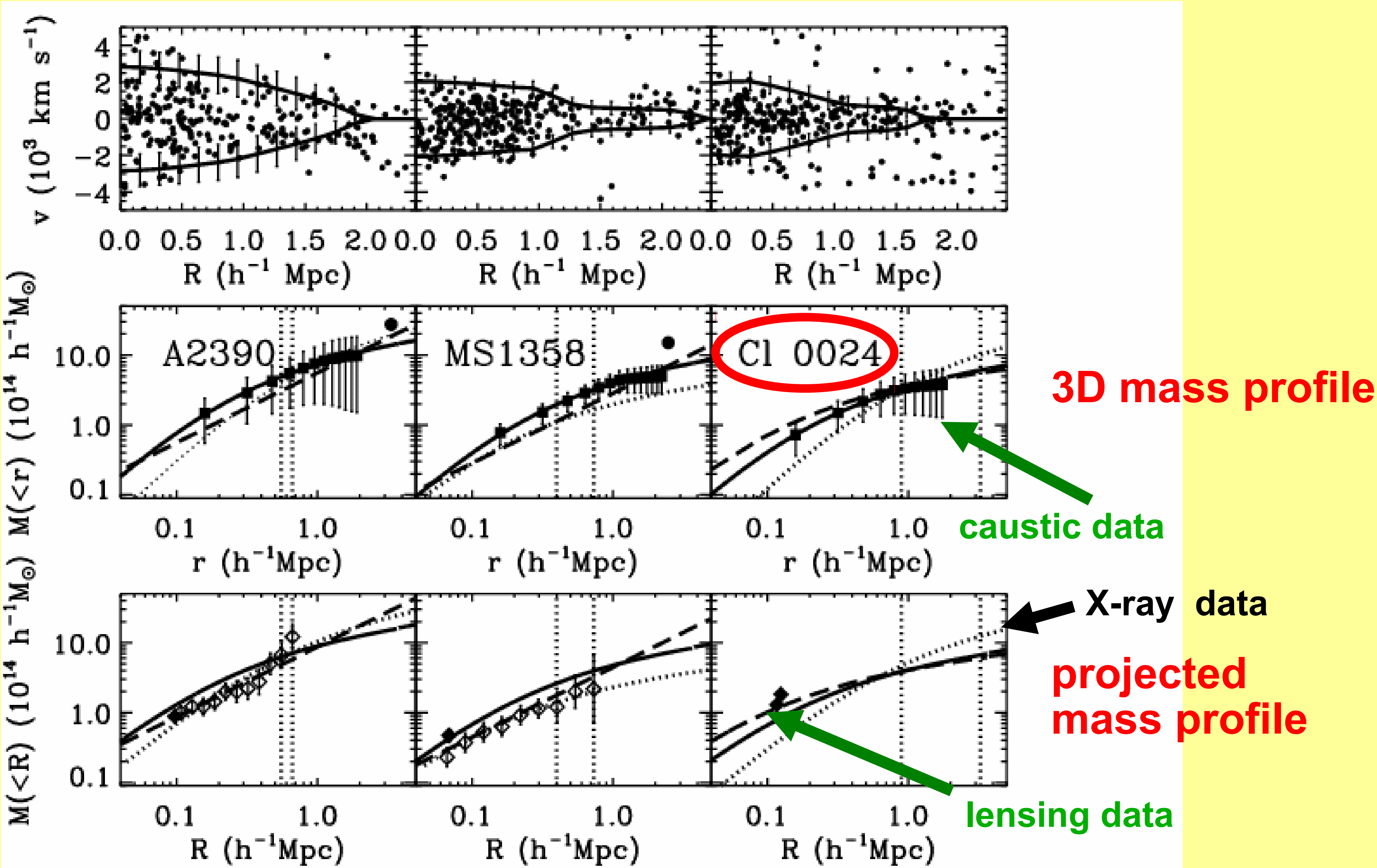
Caustic potential/true potential



68%

Serra et al. 2010

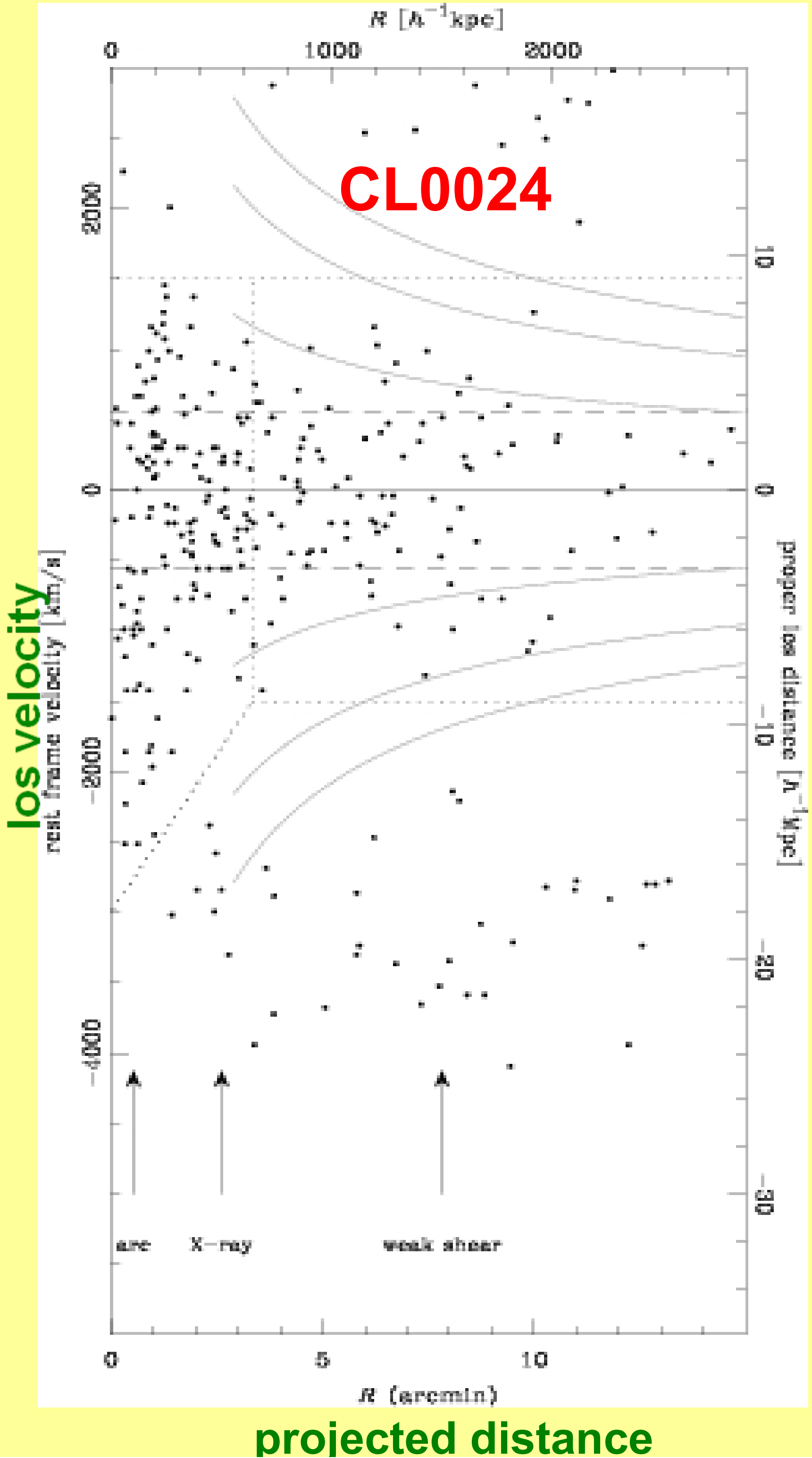
CAUSTIC TECHNIQUE:
CAUSTICS VS. LENSING

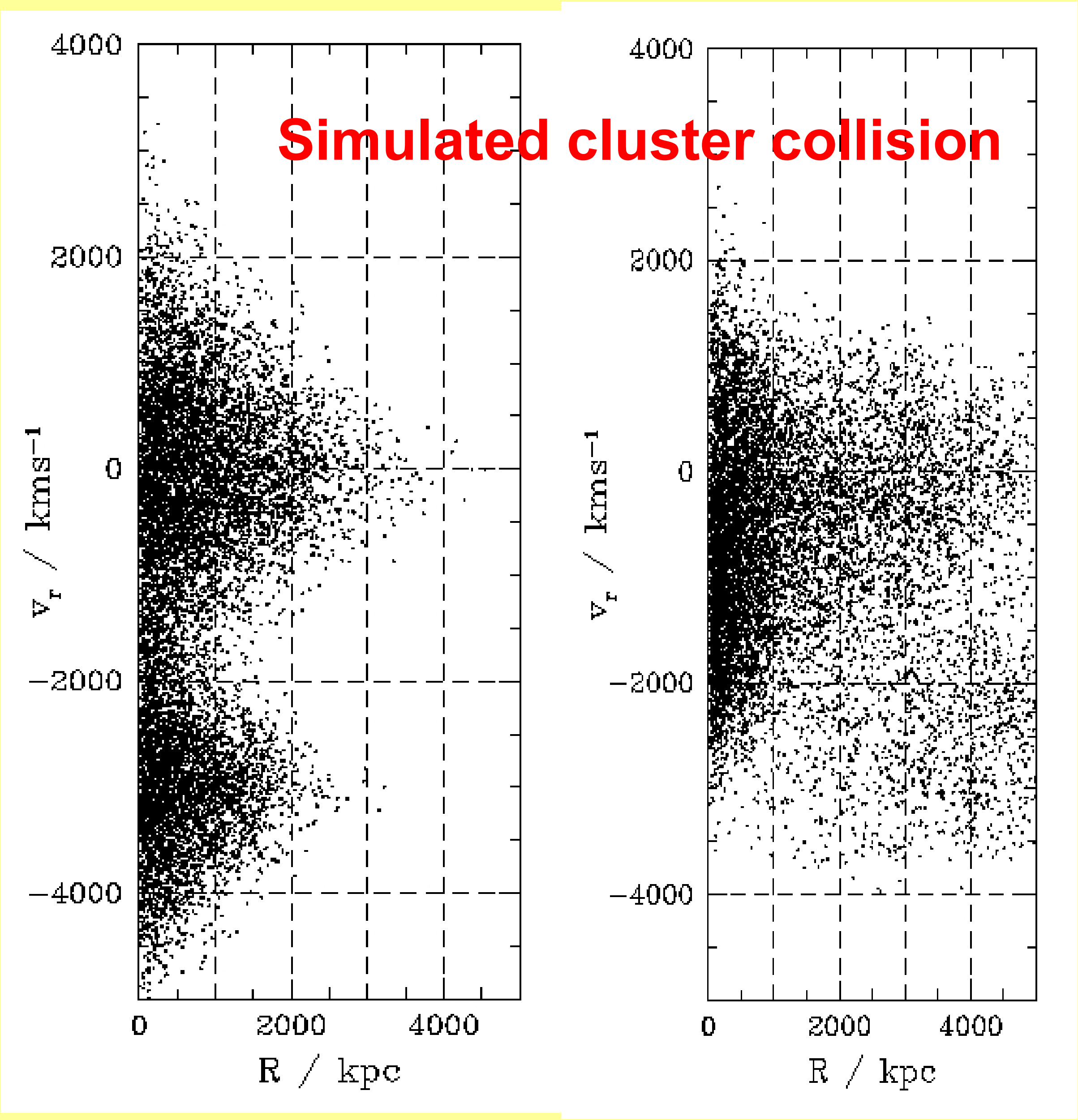


Diaferio et al. 2005

(but for Cl0024 see also Umetsu et al 2010)

CL0024: a head-on 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

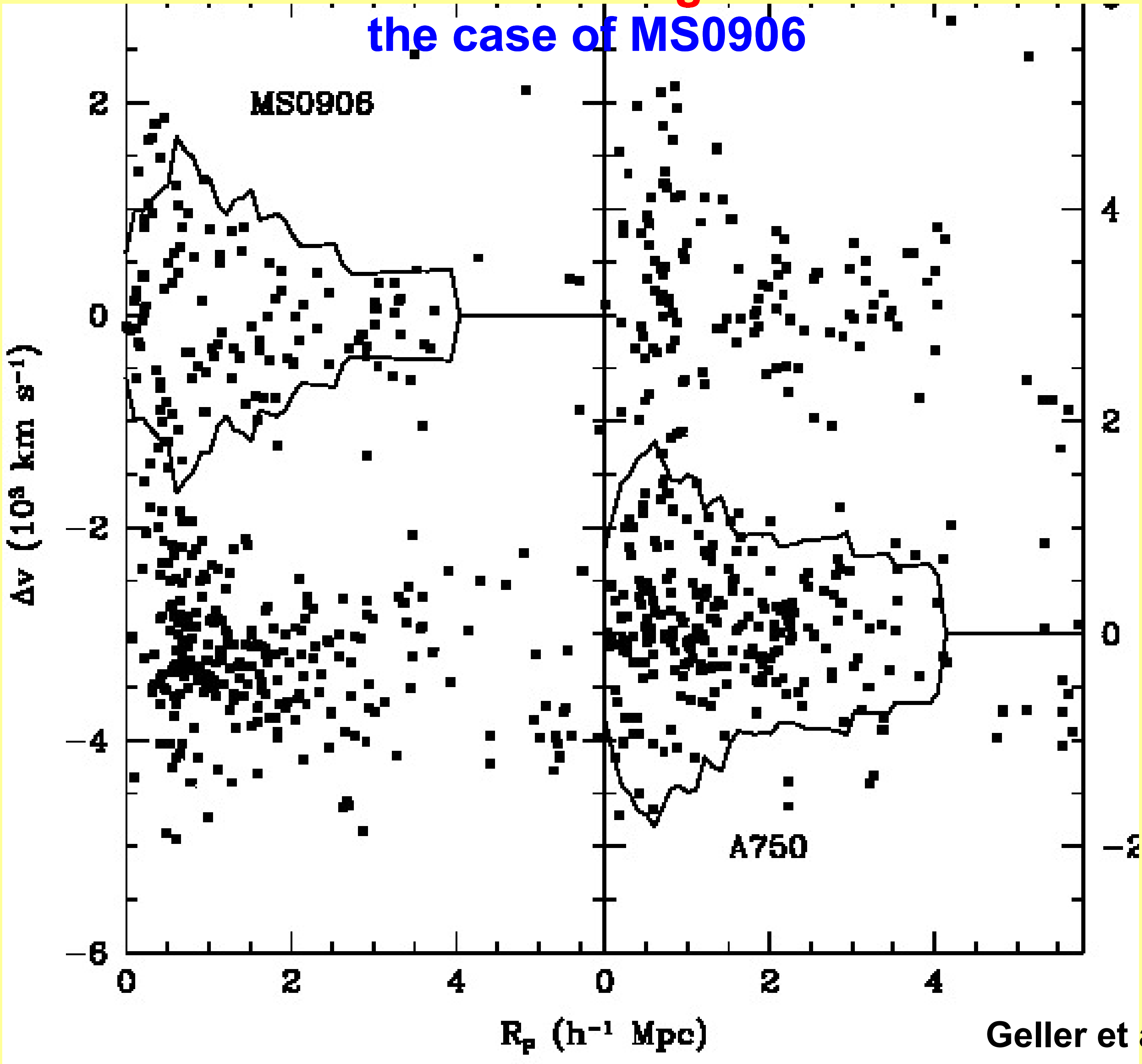
Requires:

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

Yields:

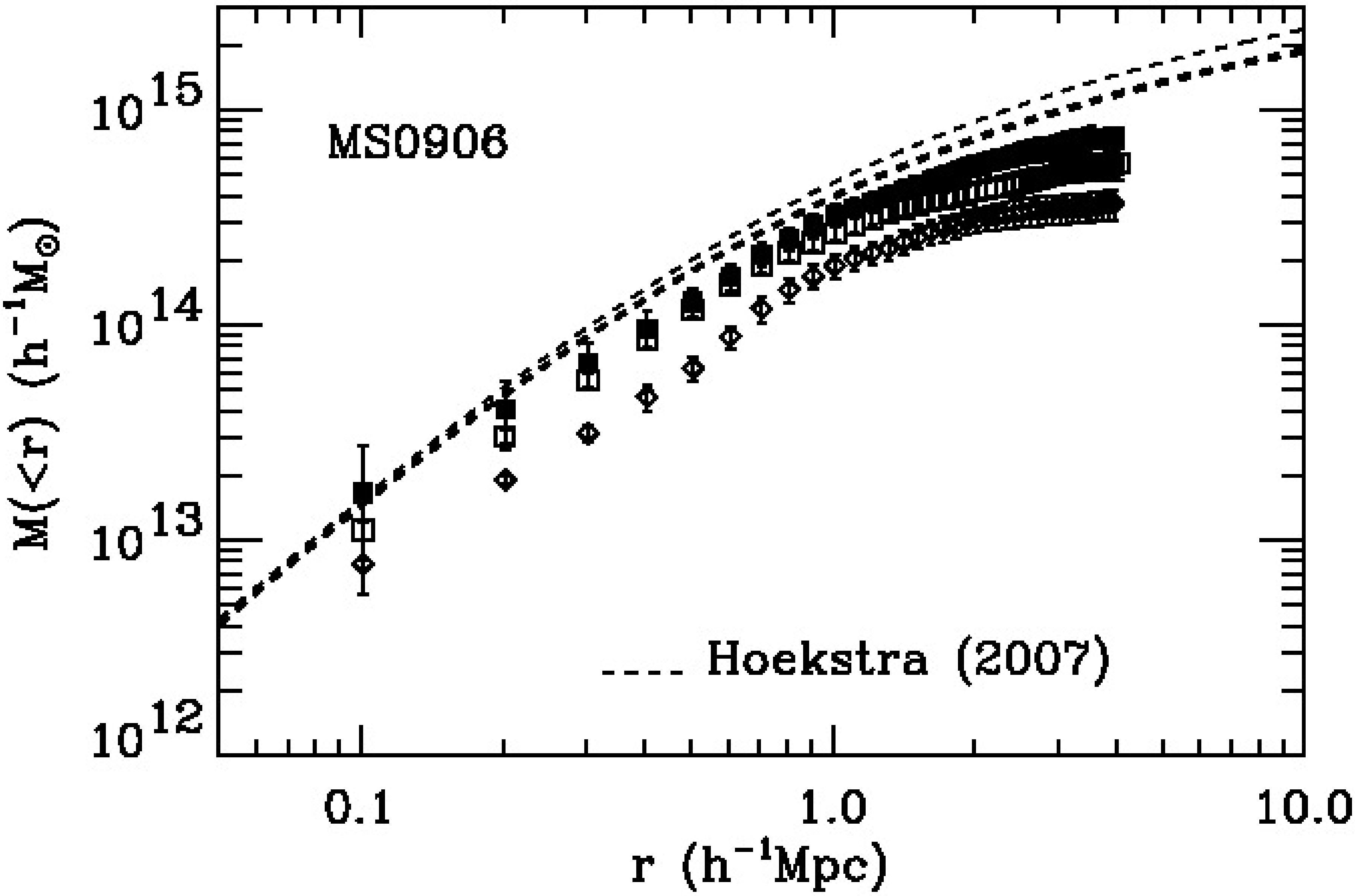
- Mass projected along the line of sight

Caustic vs. Lensing Masses:
the case of MS0906



Geller et al. 2013

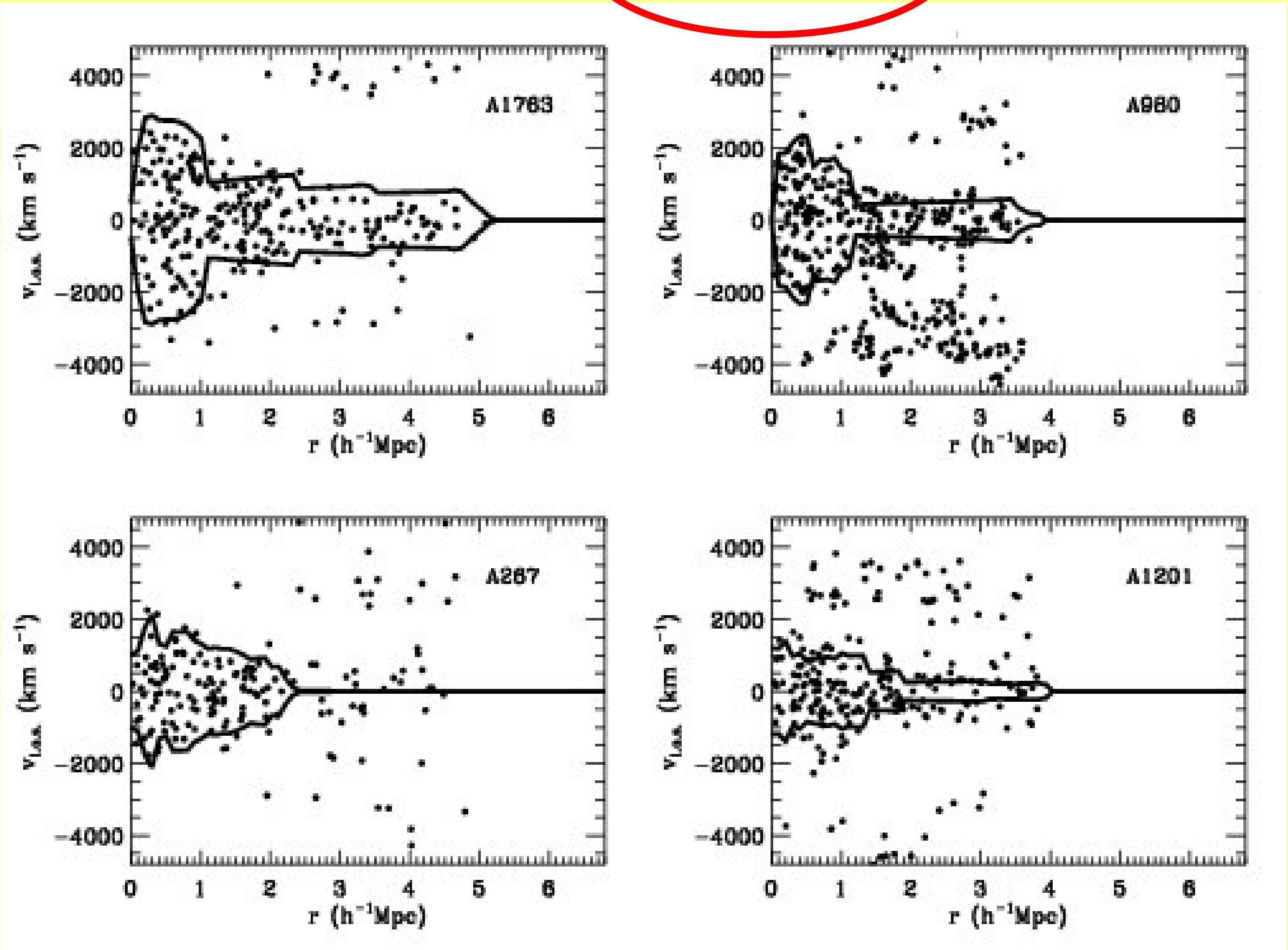
Caustics vs. Lensing Masses:
the case of MS0906



Geller et al. 2013

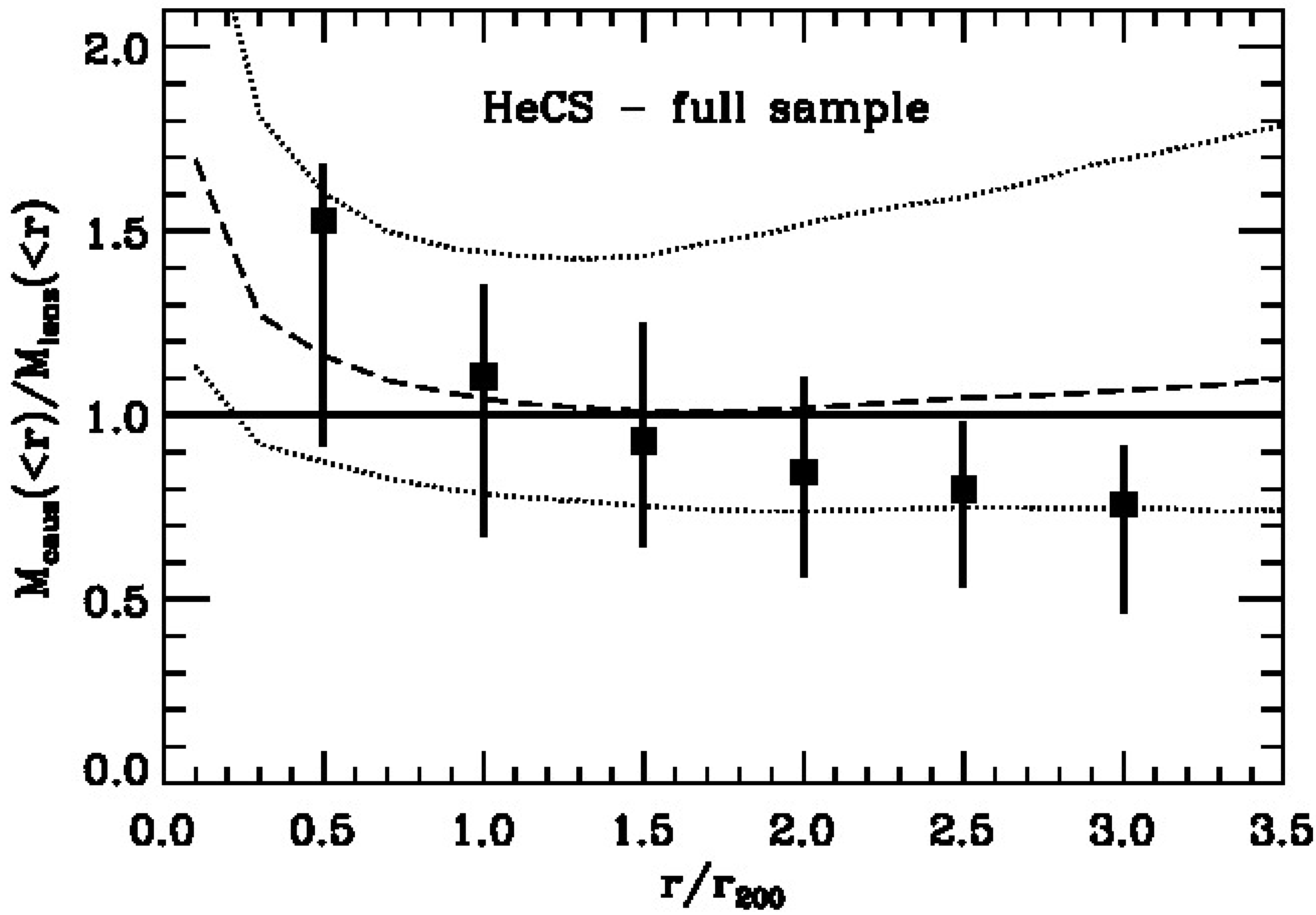
HeCS – Hectospec Cluster Survey

72 clusters @ 0.1<z<0.3



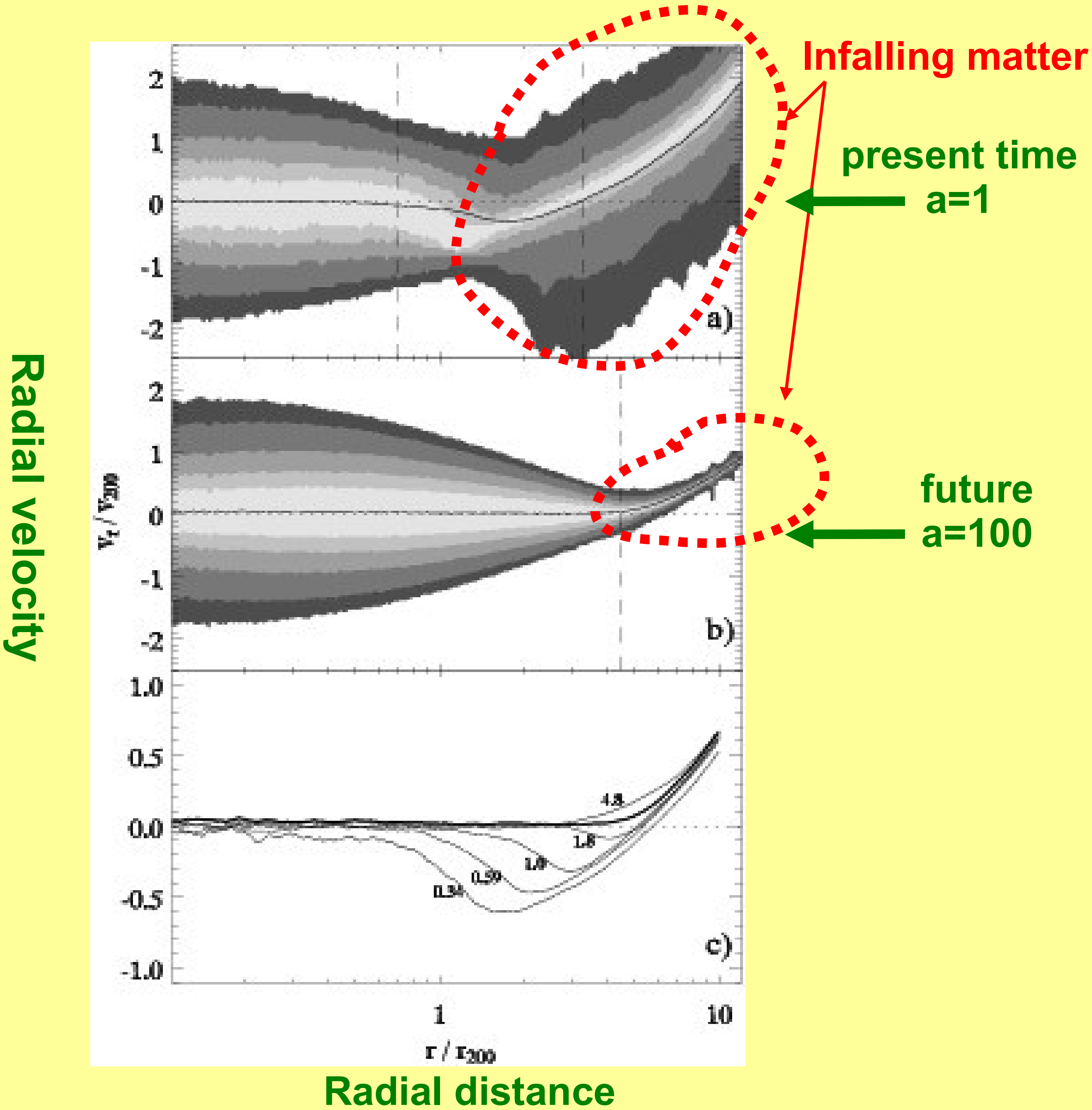
Rines et al. 2013

Caustics vs. Lensing Masses



Geller et al. 2013

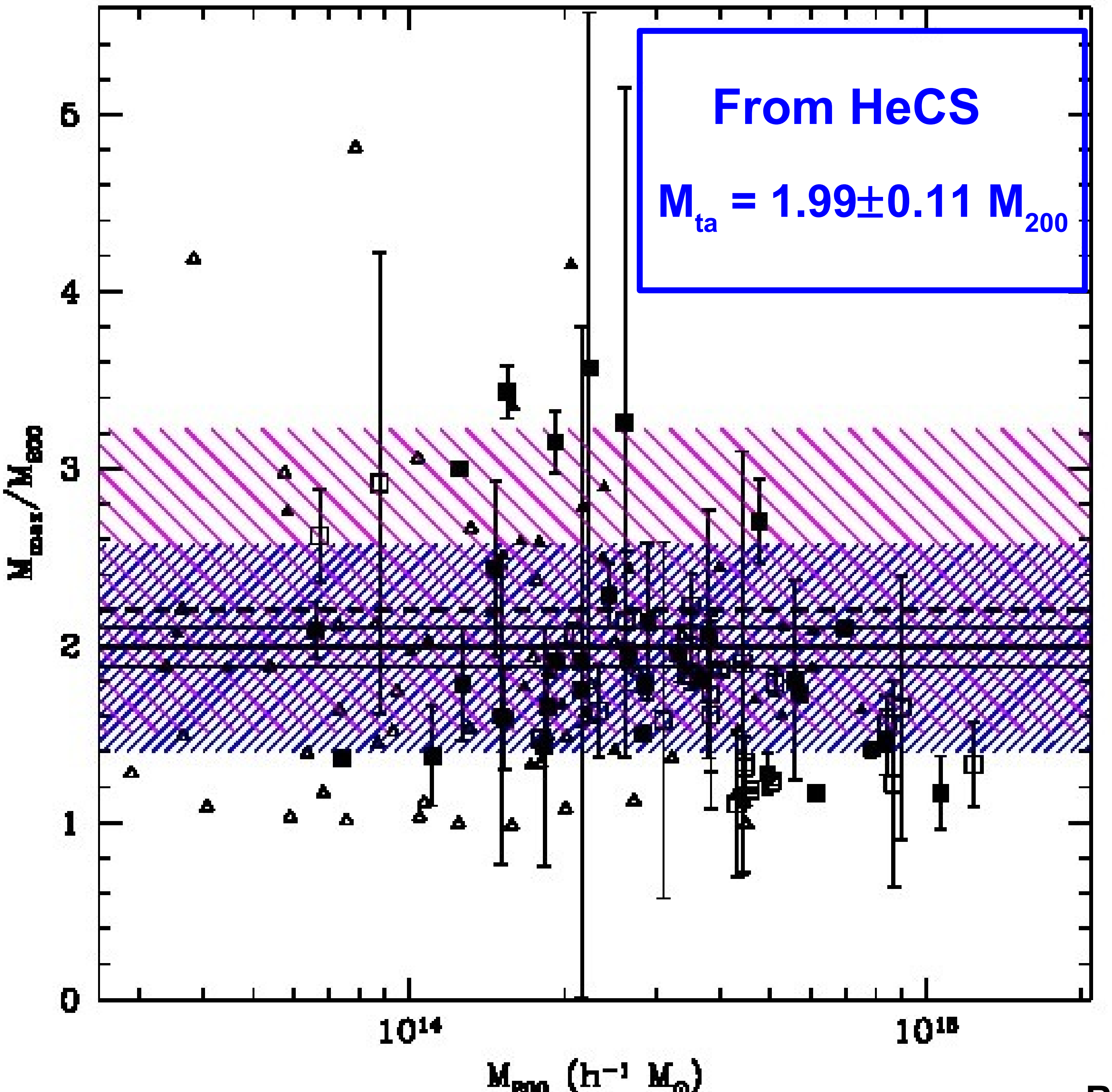
HeCS: The ultimate cluster mass



in ΛCDM

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

Busha et al. 2005



Rines et al 2013

Cosmic structure
in alternative theories of gravity

The case of
MOdified Newtonian Dynamics
(no Dark Matter!)

Standard Poisson equation

$$\nabla\phi = 4\pi G\rho$$

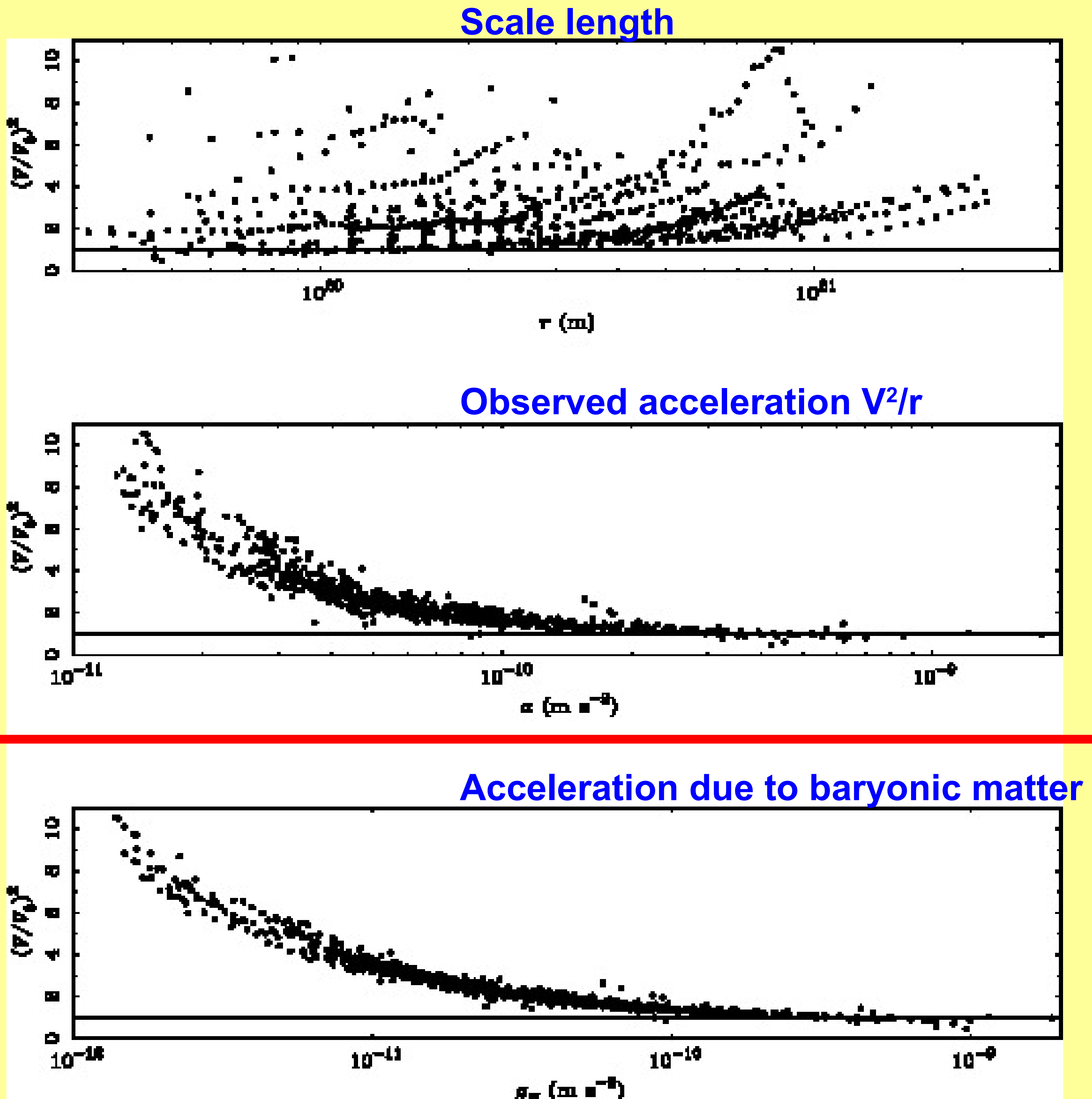
Modified Poisson equation

$$\nabla\cdot[\nabla\phi\ \mu(|\nabla\phi|/a_0)] = 4\pi G\rho$$

$a_0 = 1.2\times10^{-10}$ m s^{-2}

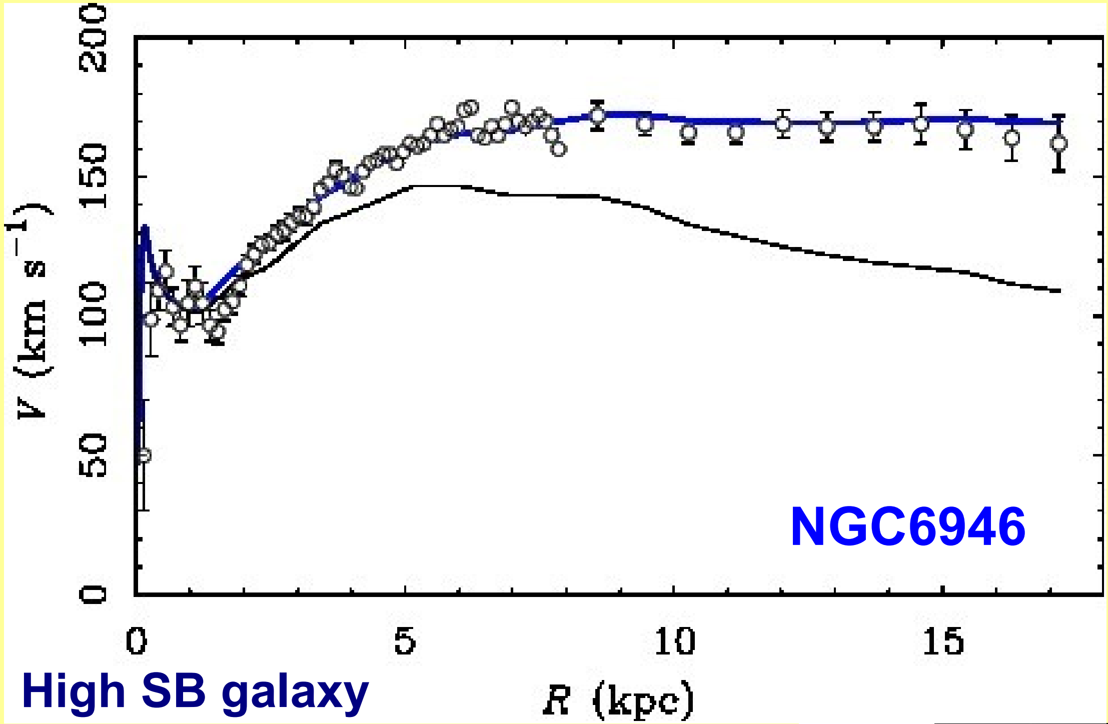
(Milgrom 1983)

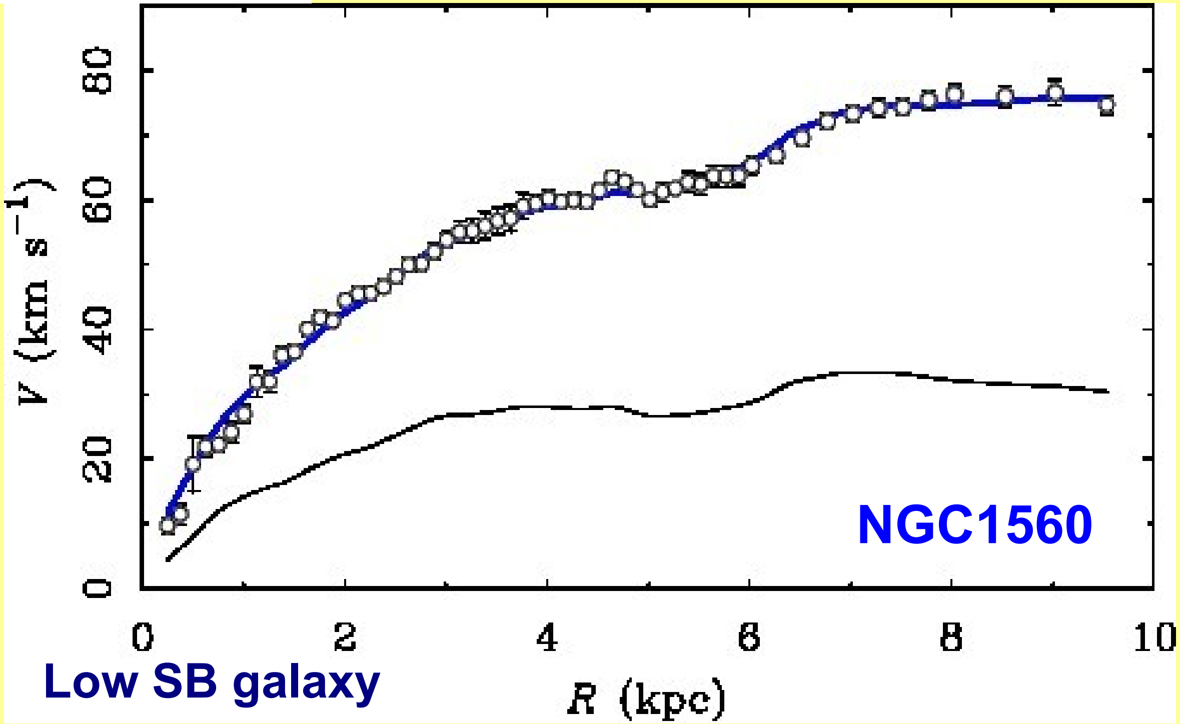
The MOND Acceleration Scale



Famaey & McGaugh 2012

Galaxy Rotation Curves in MOND (no dark matter)



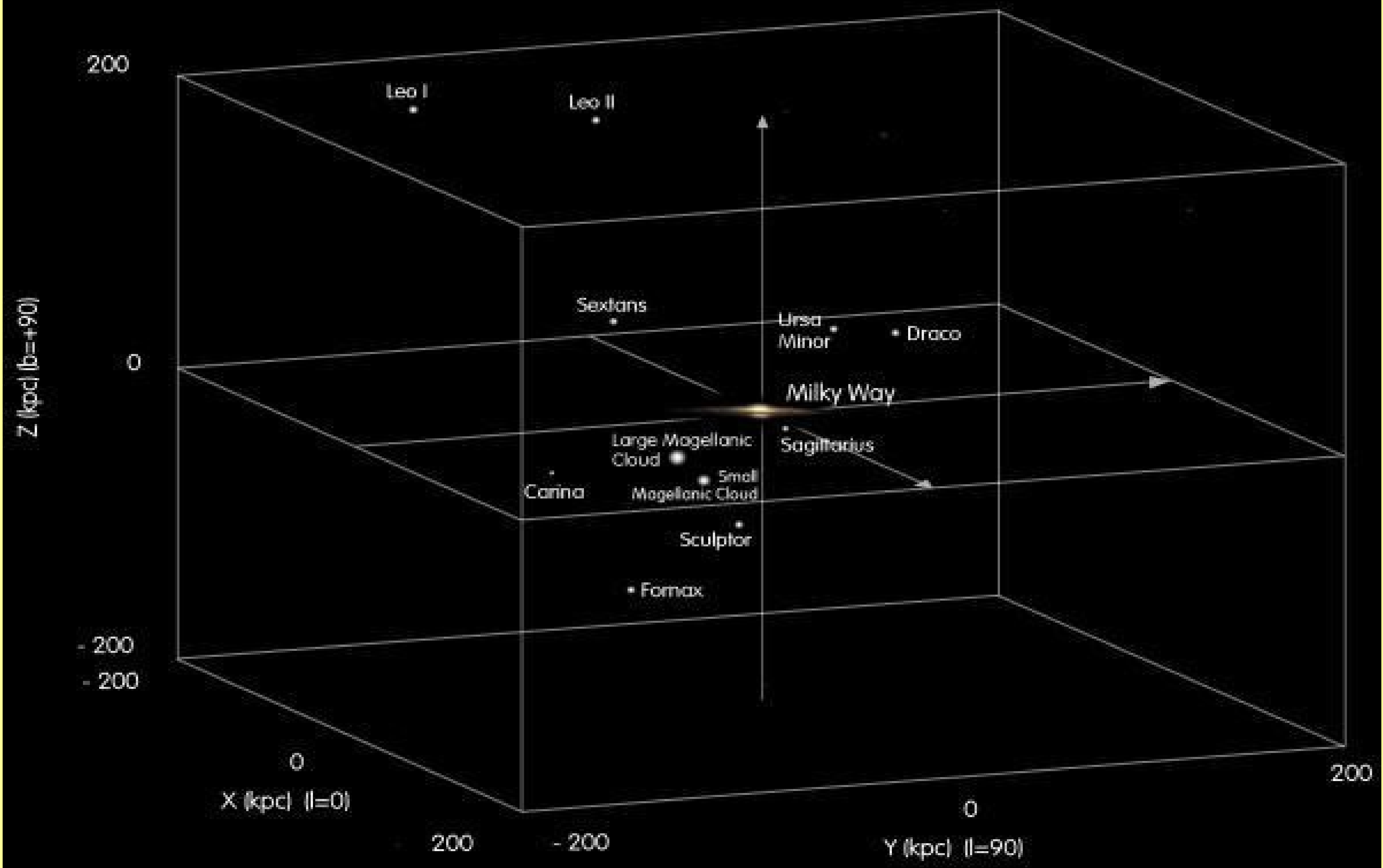


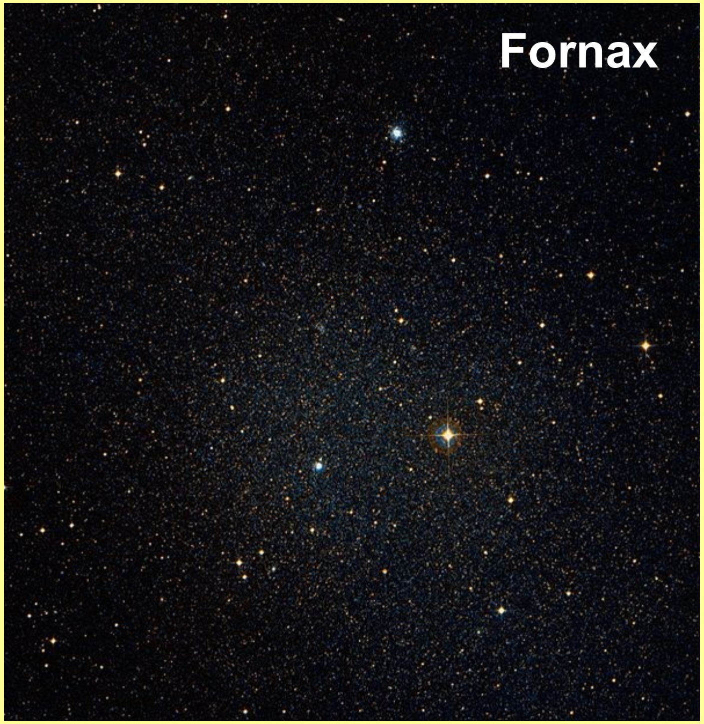
A prediction

4. Effects of the modified dynamics are predicted to be particularly strong in dwarf elliptical galaxies (for review of properties see, e.g., Hodge 1971 and Zinn 1980). For example, those dwarfs believed to be bound to our Galaxy would have internal accelerations typically of order $a_{in} \sim a_0/30$. Their (modified) acceleration, g, in the field of the Galaxy is larger than the internal ones but still much smaller than a_0, $g \approx (8\ \mathrm{kpc}/d)a_0$, based on a value of $V_\infty = 220$ km s^{-1} for the Galaxy, and where d is the distance from the dwarf galaxy to the center of the Milky Way ($d \sim 70$–220 kpc). Whichever way the external acceleration turns out to affect the internal dynamics (see the discussion at the end of § II, the section on small groups in Paper III, and Paper I), we predict that when velocity dispersion data is available for the dwarfs, a large mass discrepancy will result when the conventional dynamics is used to determine the masses. The dynamically determined mass is predicted to be larger by a factor of order 10 or more than that which can be accounted for by stars. In case the internal dynamics is determined by the external acceleration, we predict this factor to increase with d and be of order (d/8 kpc) (as long as $a_{in} \ll g$, $h_{50} = 1$).

Milgrom 1983

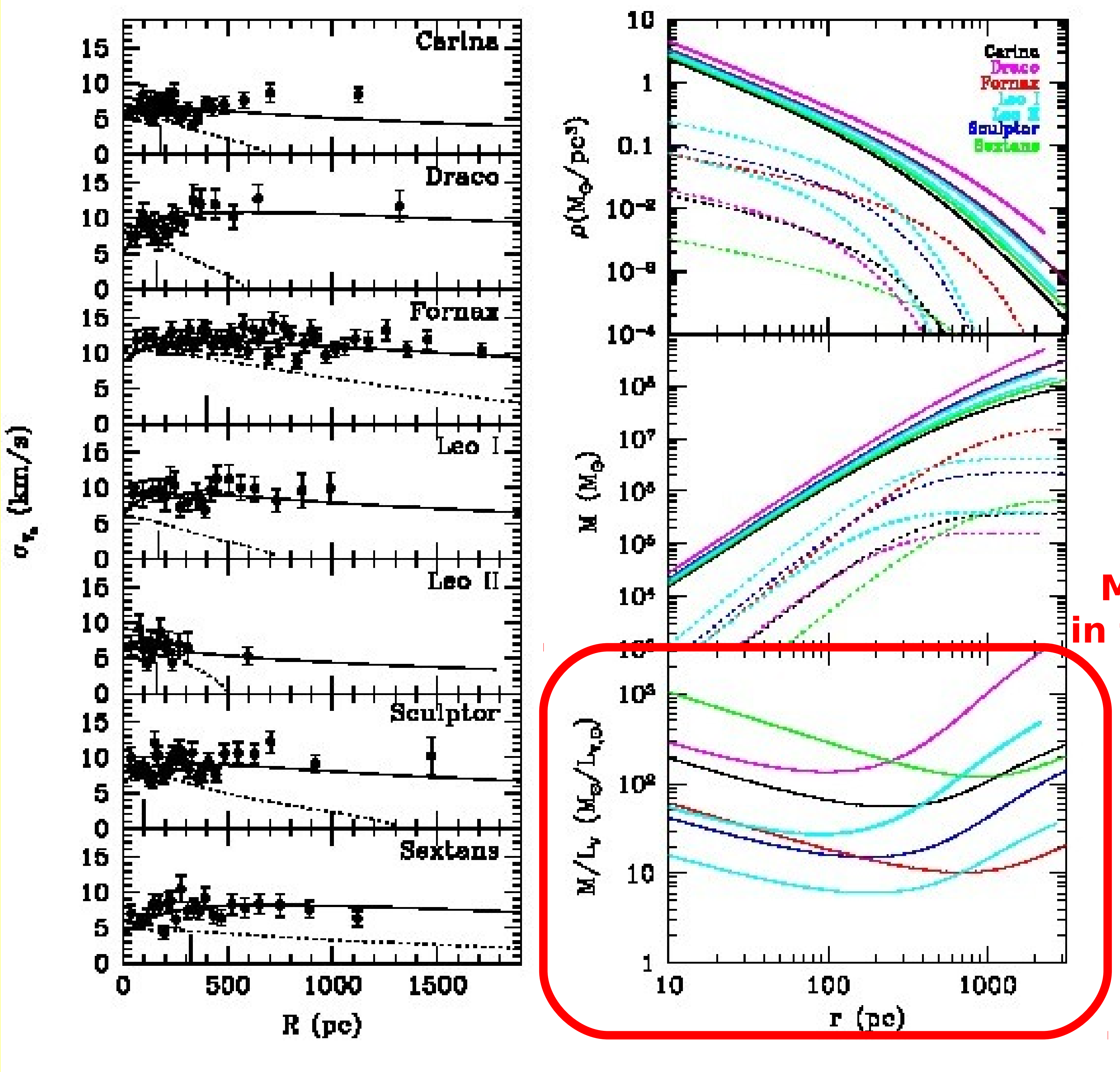
The Case of the Dwarf Spheroidals




Sculptor

Fornax

Leo I
© Anglo-Australian Observatory

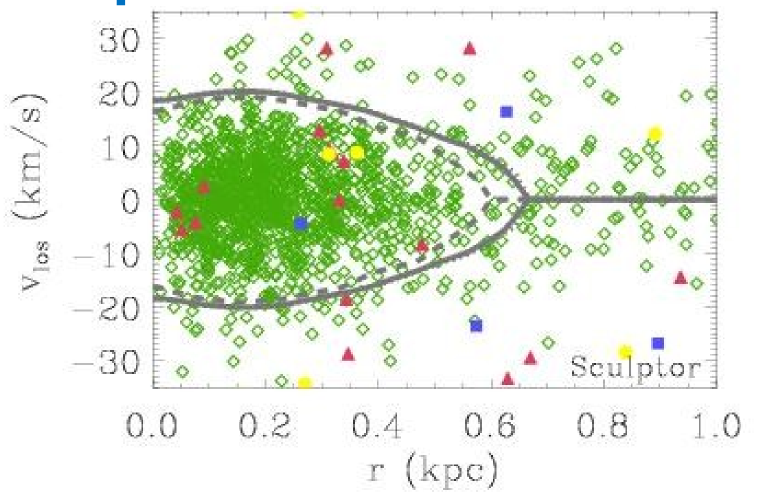
Sextans



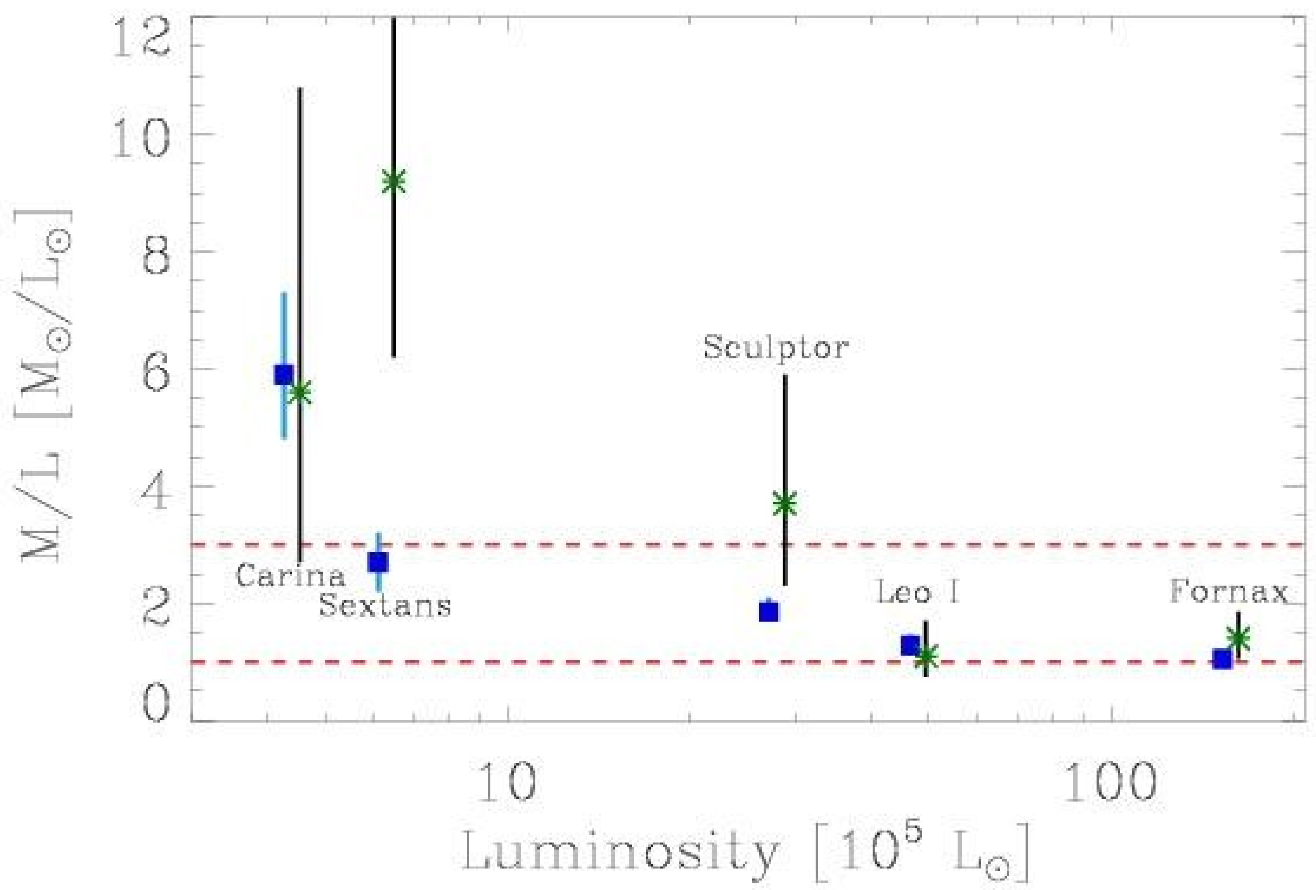
Mass-to-light ratio in the standard model

Walker et al 2007

Sculptor

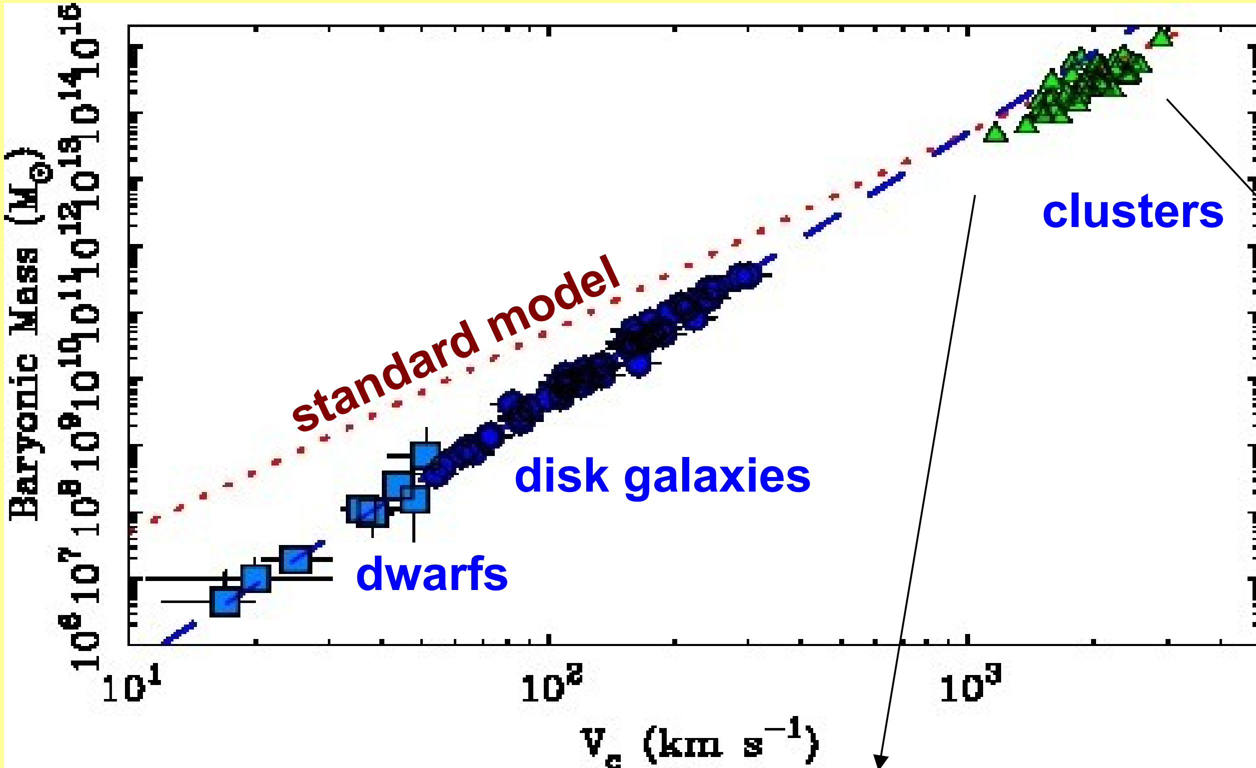


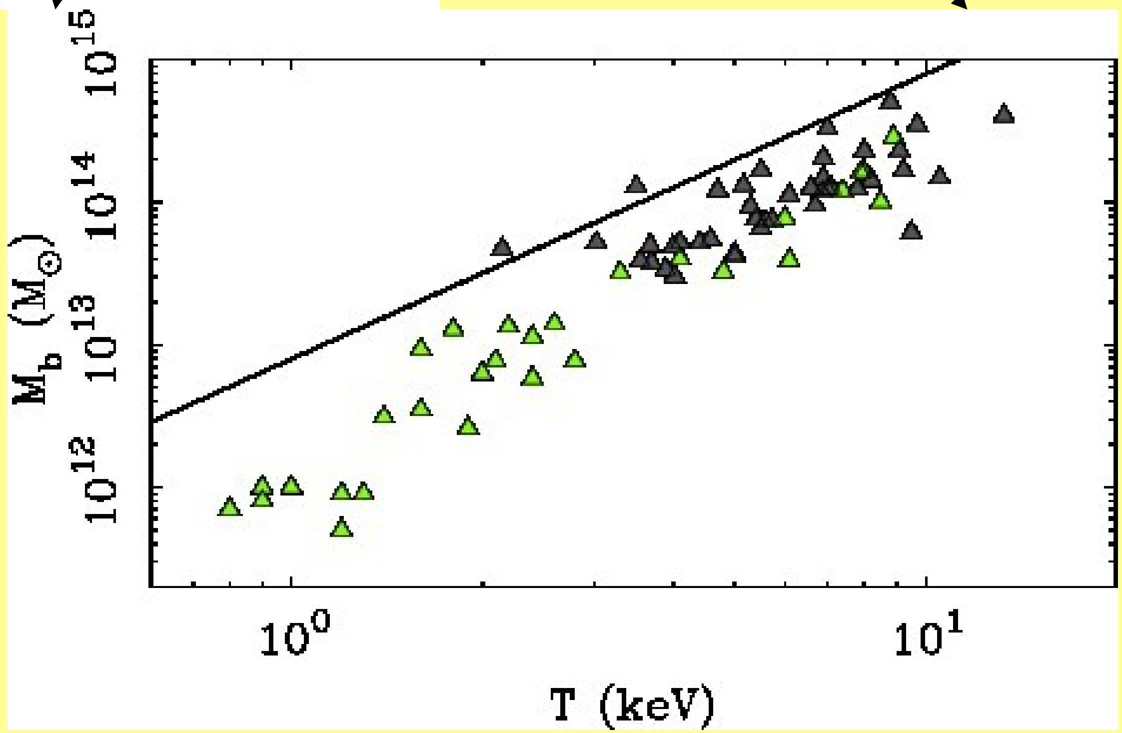
Mass-to-light ratio in MOND



Serra, Angus & Diaferio 2010

The Baryonic Tully-Fisher Relation





McGaugh 2008

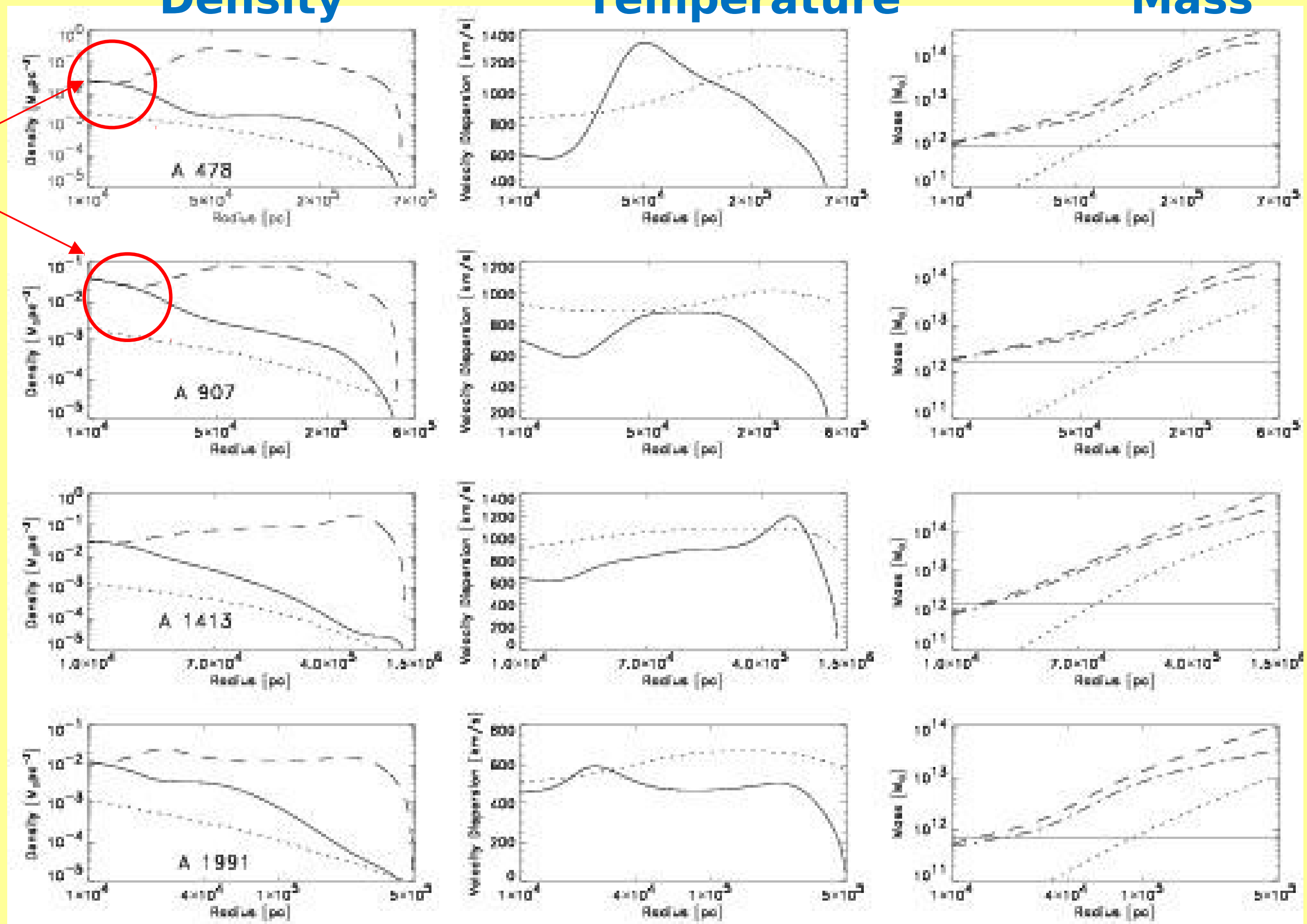
AN ALTERNATIVE COSMOLOGY?

MOND + 11 eV Sterile Neutrino

Equilibrium configurations of 30 clusters and groups:

The Tremaine-Gunn limit

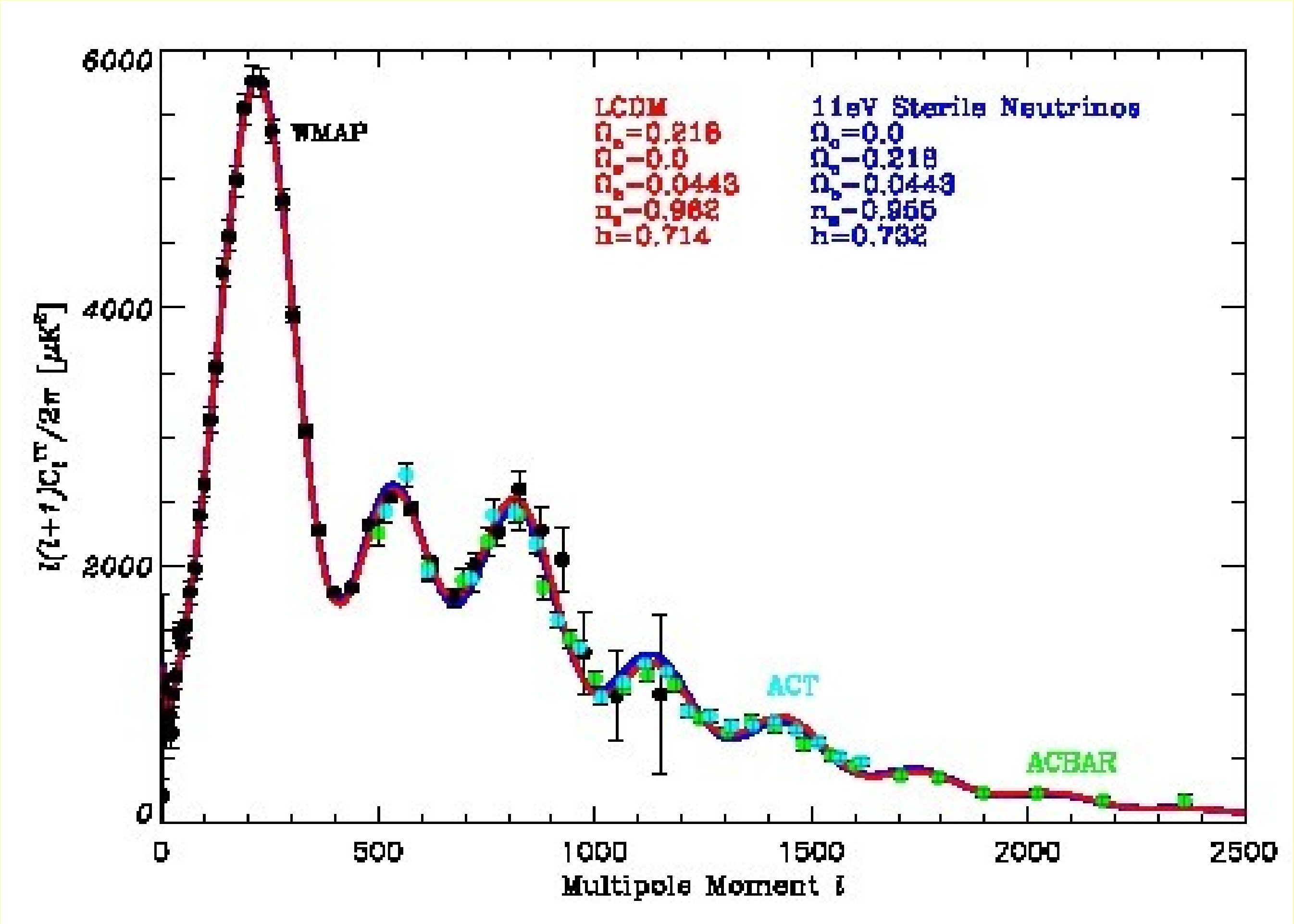
Density **Temperature** **Mass**



radial distance

Angus et al 2010

AN ALTERNATIVE COSMOLOGY?
MOND + 11 eV Sterile Neutrino

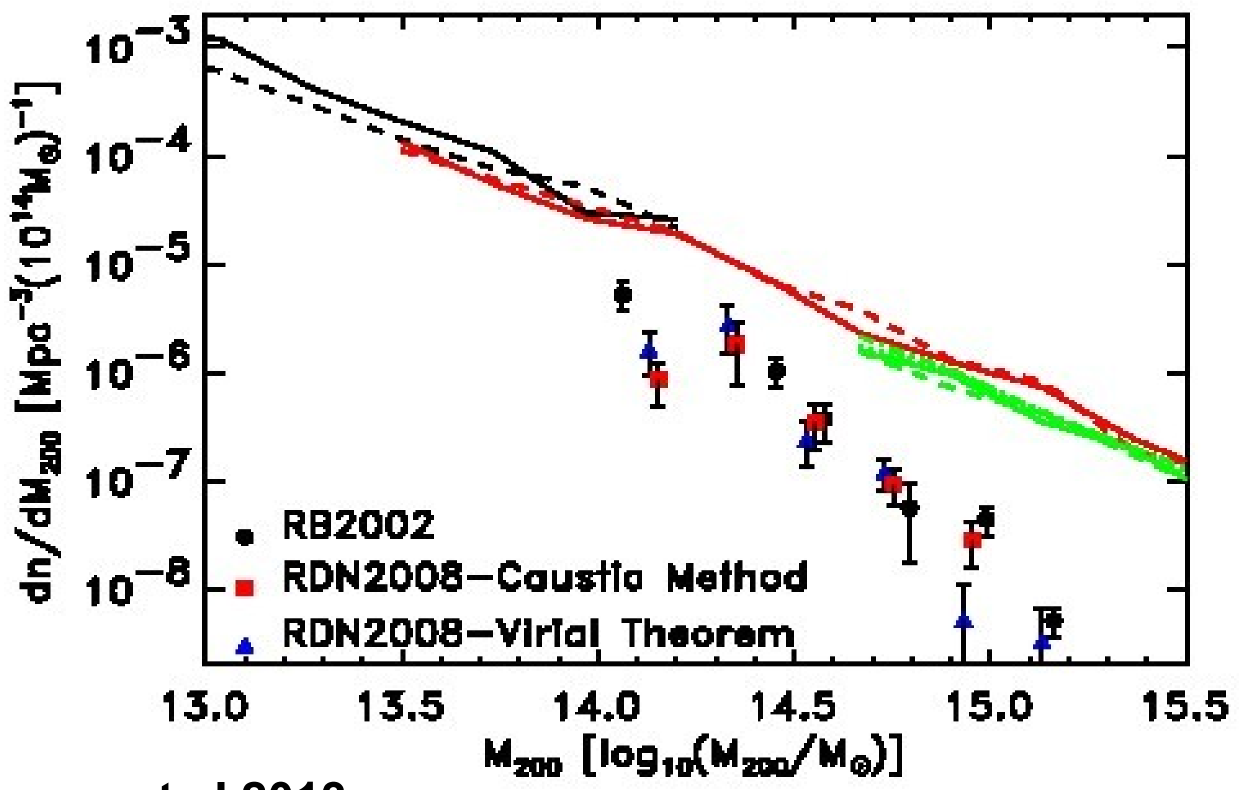


(Angus 2009)

LSS N-body simulations in a MOND+sterile ν^* cosmology

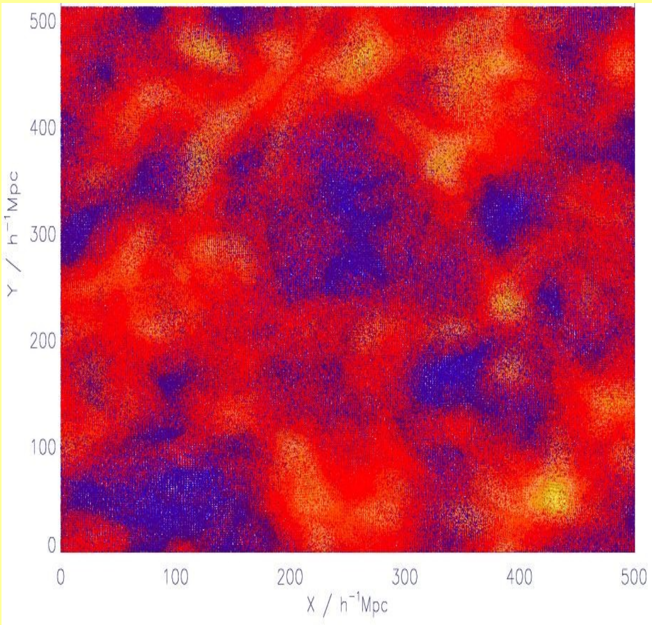
*m=10-300 eV

Cluster mass function

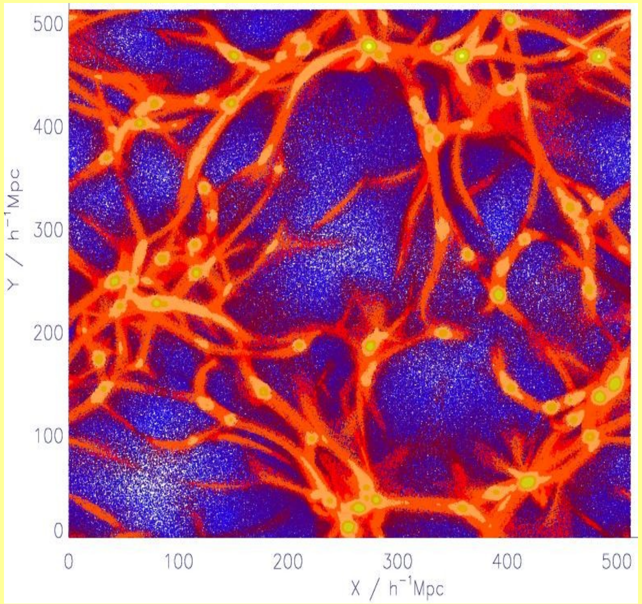


Angus et al 2013

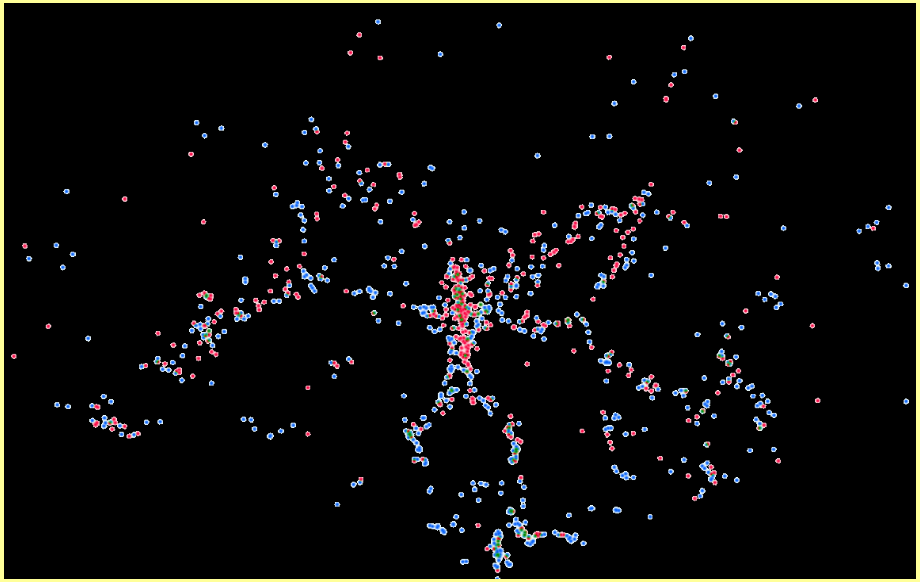
Standard gravity



MOND



Angus and Diaferio 2011



Summing up...

- **Redshift surveys:**
  The largest structures and HectoMAP

- **Clusters of galaxies:**
  The caustic method, the mass function and MOND