The mass profiles of galaxy clusters using galaxies as tracers

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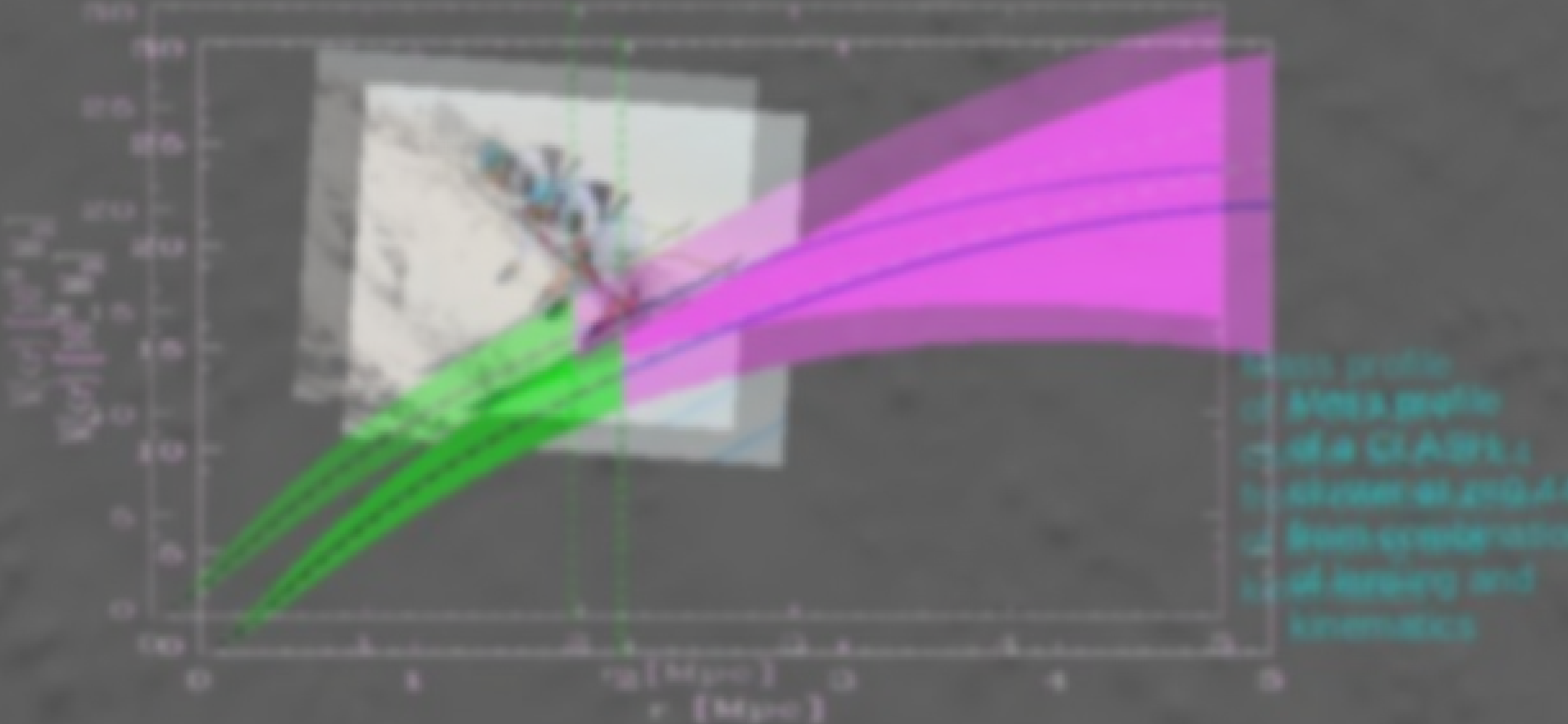

Andrea Biviano (INAF/Osservatorio Astronomico di Trieste)
+ Gary Mamon, Emiliano Munari & the CLASH-VLT team

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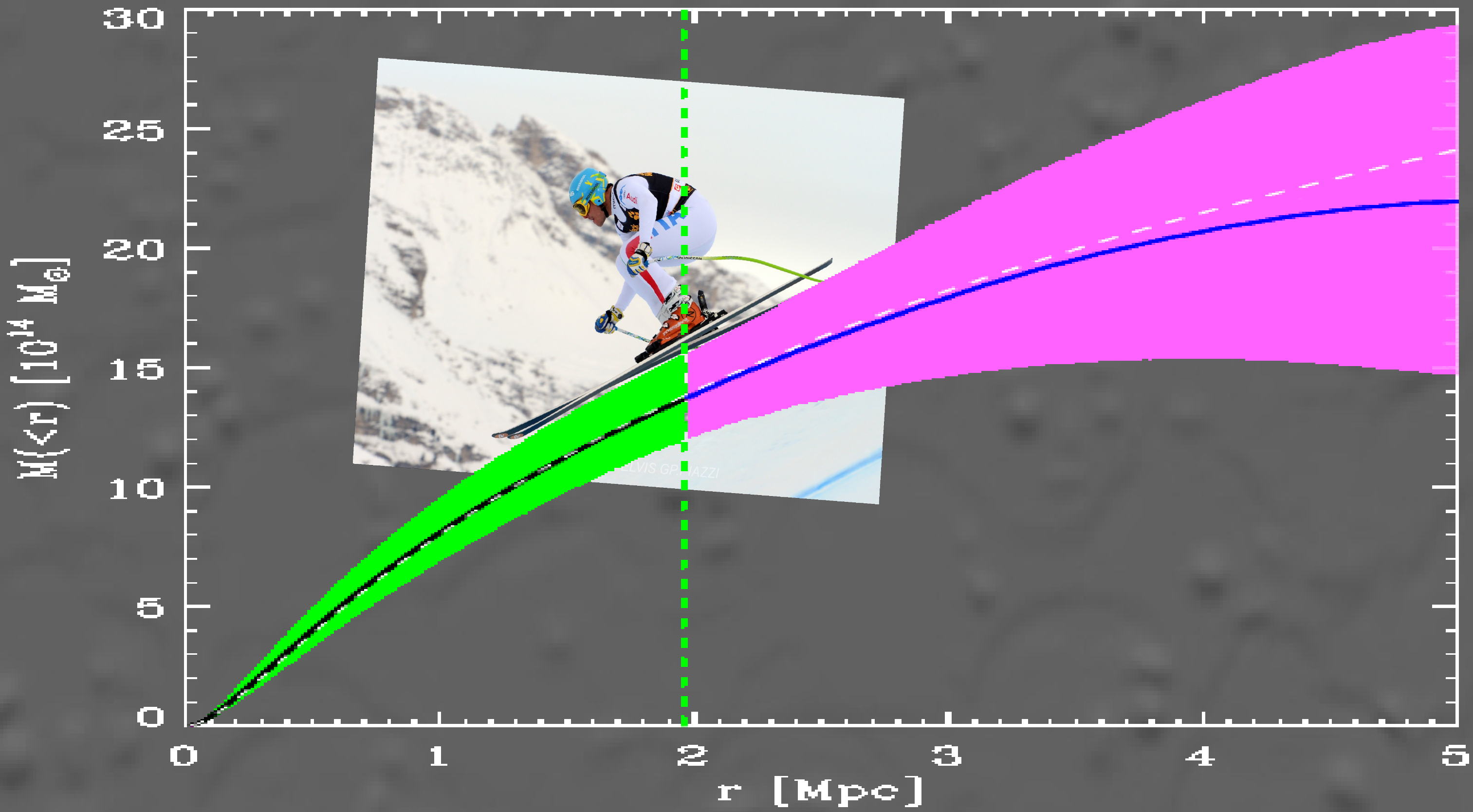

Mass profile of a CLASH cluster at z=0.44 from combination of lensing and kinematics

Andrea Biviano (INAF/Osservatorio Astronomico di Trieste)
+ Gary Mamon, Emiliano Munari & the CLASH-VLT team

Layout of the talk:

1 Problems in using galaxies as tracers

2 Methods of mass profile determination

3 Case-study: CLASH cluster MACS J1206-0847

4 Results: c-M relation
M(r) shape

5 Orbits of galaxies and pseudo-phase space density profiles

6 Summary & perspectives

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Problems
(in using galaxies as tracers)

I) Spatial incompleteness of the spectroscopic sample

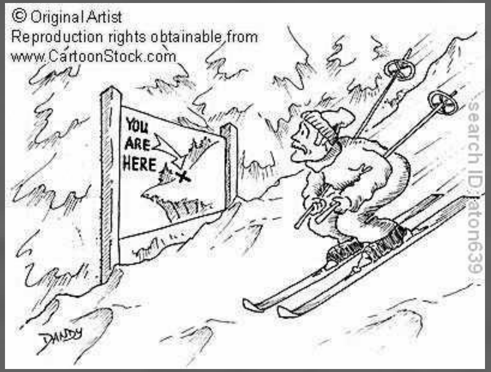
Affects estimates of the spatial distribution of galaxies, like the harmonic mean radius (which enters the virial theorem), the number density profile (which enters the Jeans equation) *[e.g. Carlberg, Yee, Ellingson 1997; Biv. et al. 2006]*

Solutions:

a) Correct the spectroscopic sample for incompleteness
[e.g. Biv. & Poggianti 2009]

b) Use a substitute sample that is complete (e.g. photometric sample with z_{phot} selection of cluster members)
[e.g. Guennou et al. 2013, in prep.]

II) Substructures and deviations from dynamical equilibrium



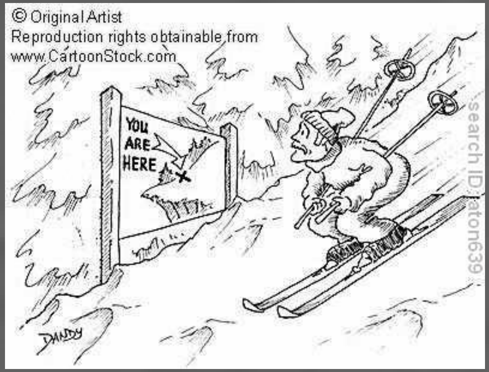
Distort the equilibrium distribution of cluster galaxy velocities, affect most mass (profile) estimates, unless merger is on the plane of the sky *[e.g. Takizawa et al. 2010]*

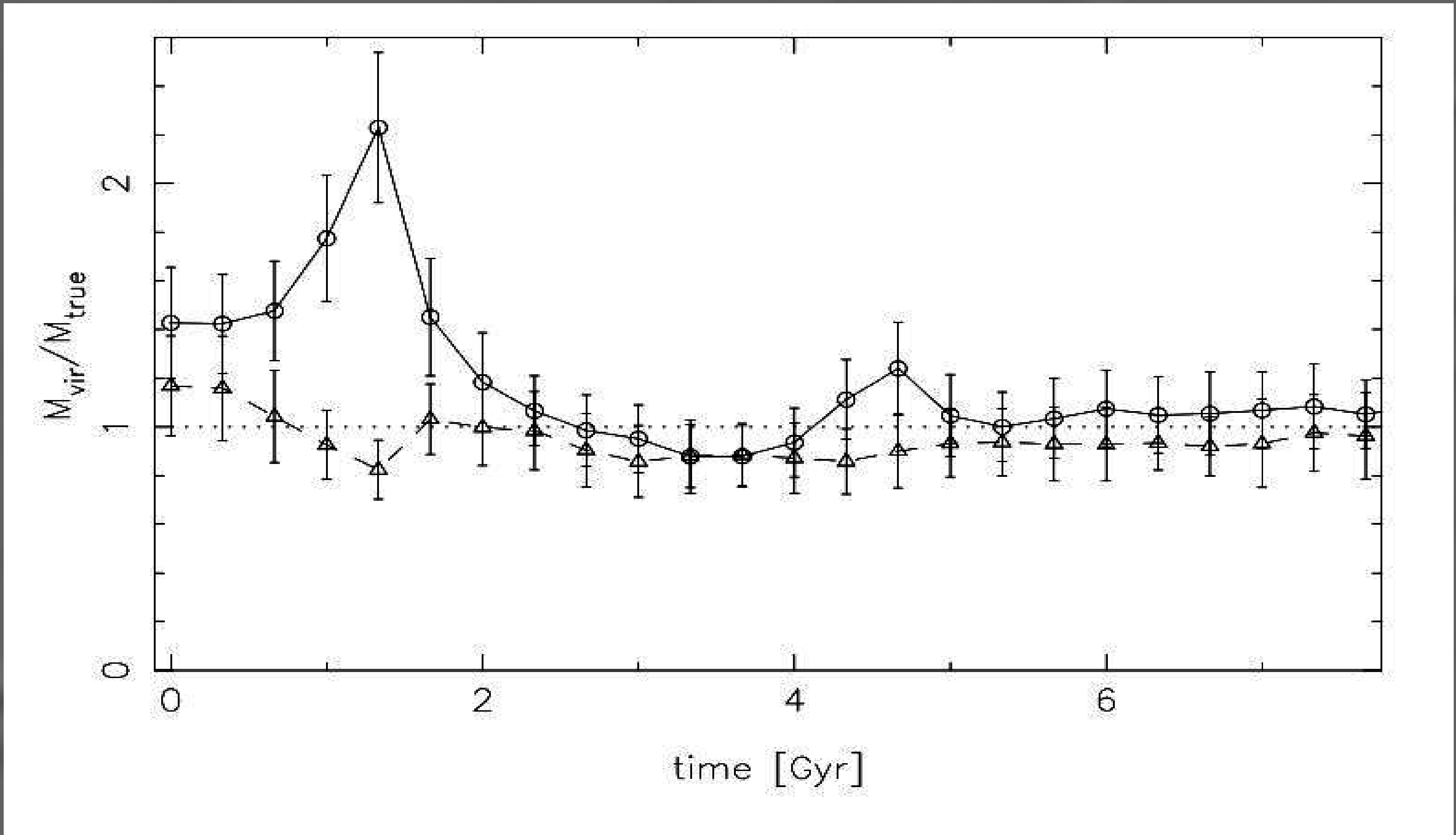
Solutions:

a) If minor merger: identify galaxies in substructures, remove them from sample of tracers *[e.g. Katgert, Biv., & Mazure 2004]*

b) If major merger: use numerical simulations to reproduce observed distribution and infer pre-merger dynamical estimates *[like, e.g., Mastropietro & Burkert 2008]*

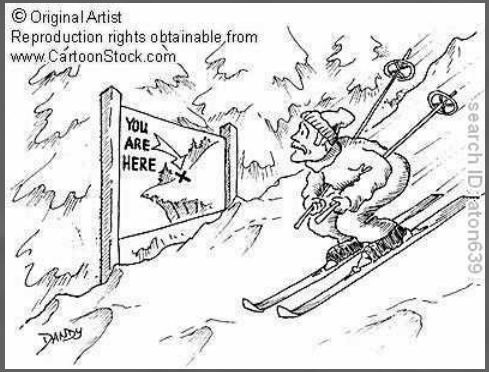
II) Substructures and deviations from dynamical equilibrium

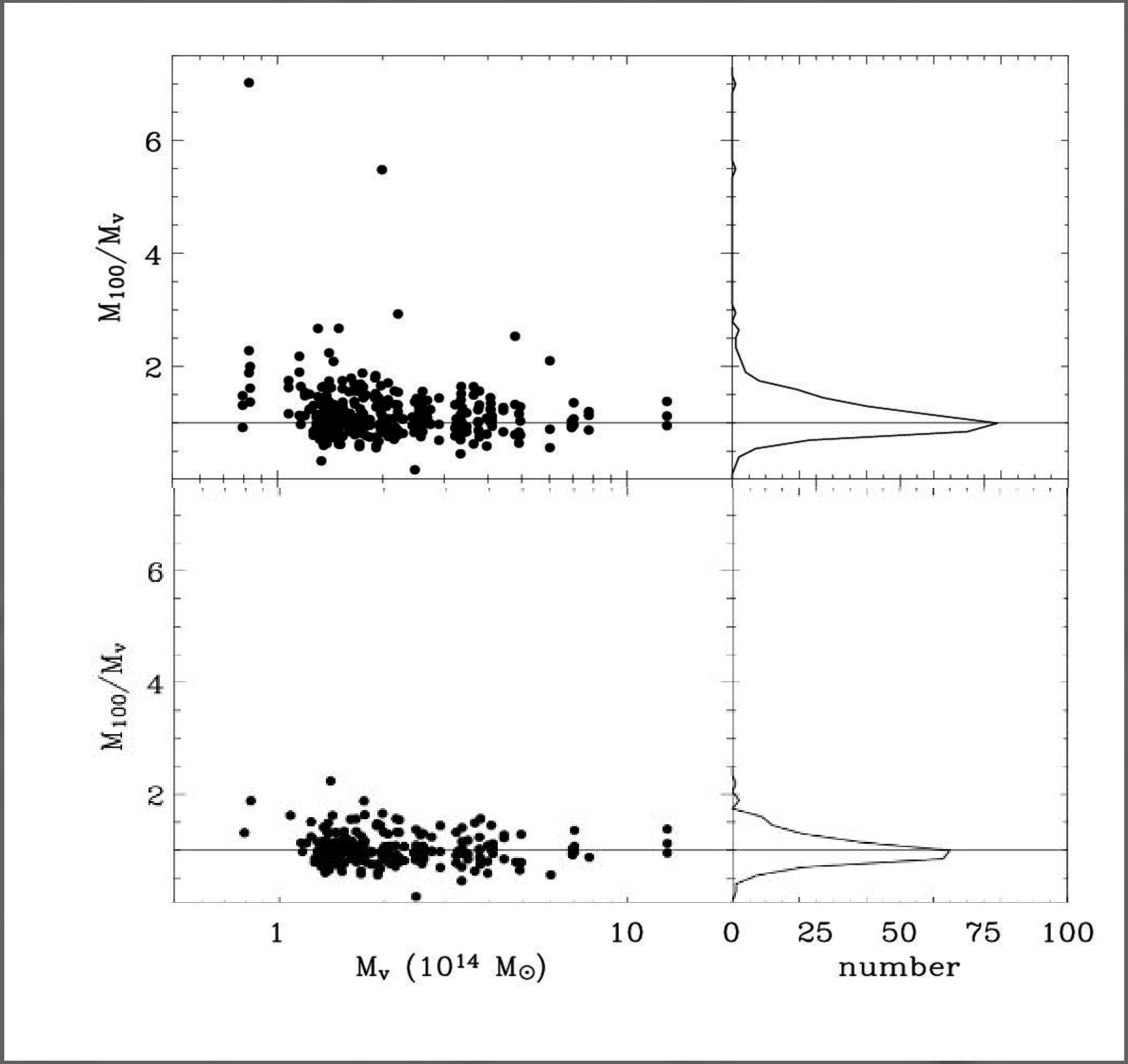




Estimated/True mass vs. time during a merger, along two line-of-sight axes, circles/triangles = parallel/perpendicular to the merger direction *[Takizawa et al. 2010]*

II) Substructures and deviations from dynamical equilibrium



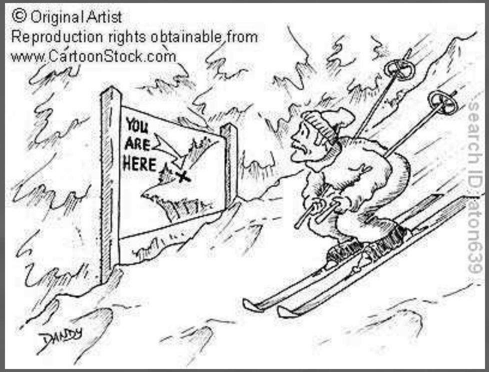


Estimated/True mass for simulated cluster-size halos

As above, clusters with subclusters removed from the sample

[Biv. et al. 2006]

III) Interlopers



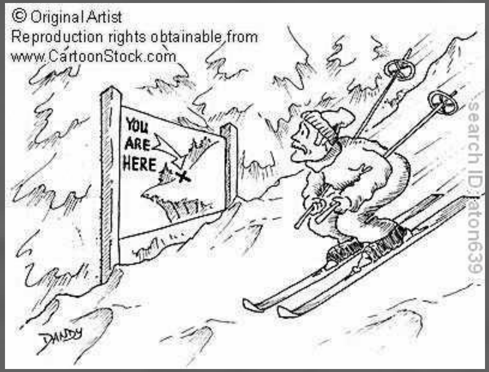
Identification of cluster members among galaxies in the cluster area is not perfect. ~20 % identified “members” within r_{200} are spurious *[Biv. et al. 2006, Wojtak et al. 2007, Mamon, Biv. & Murante 2010]*

Solutions?

a) Use positions of galaxies in projected phase-space, not only their positions in the velocity distribution

b) Use statistical subtraction of interlopers [this only works for stacks of several clusters, because of cosmic variance]

IV) Triaxiality

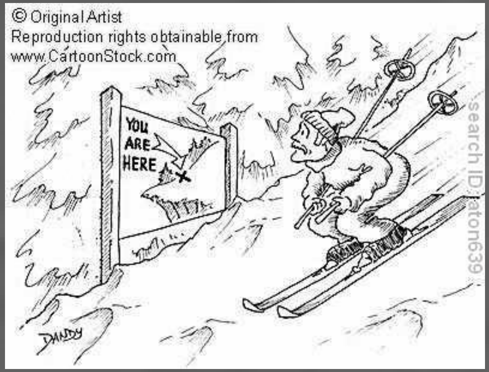


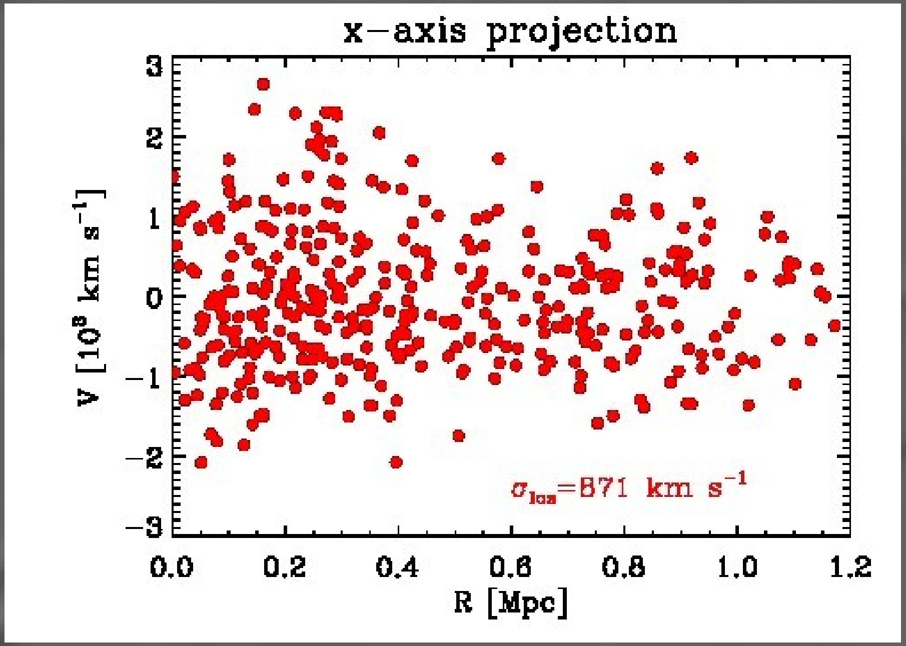
Clusters are triaxial, their velocity distributions are wider along their major axes (alignement of inertia and velocity tensors) *[e.g. Kasun & Evrard 2005; Wojtak, Gottlöber & Klypin 2013].*
When major axis ≡ line-of-sight direction, mass is overestimated

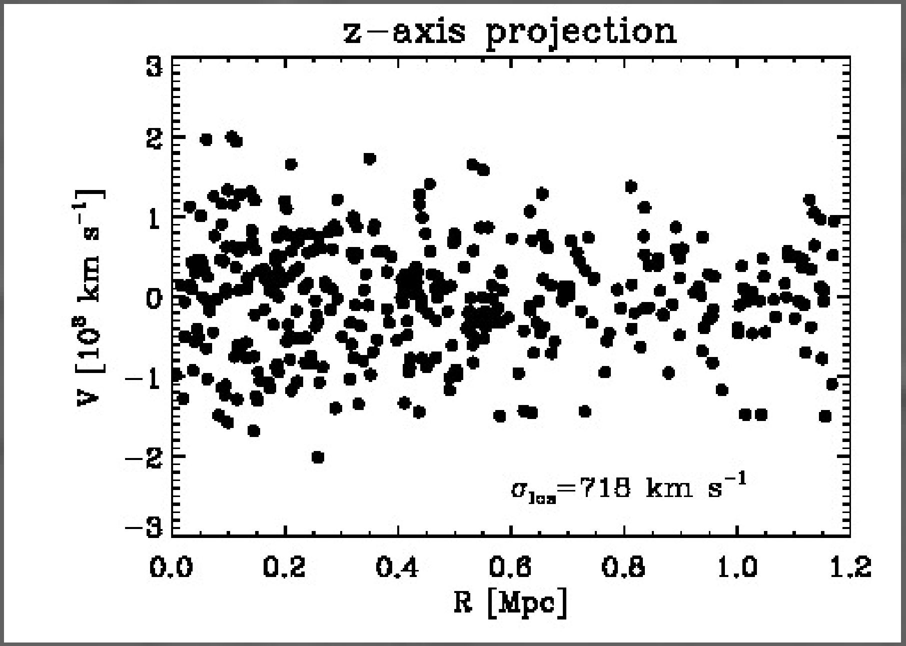
Solutions:

a) Use the elongation of the galaxies distribution and of the BCG to guess if line-of-sight direction is close to major axis [near sphericity hints they are aligned]
b) Stack several clusters, to average out peculiar alignements

IV) Triaxiality



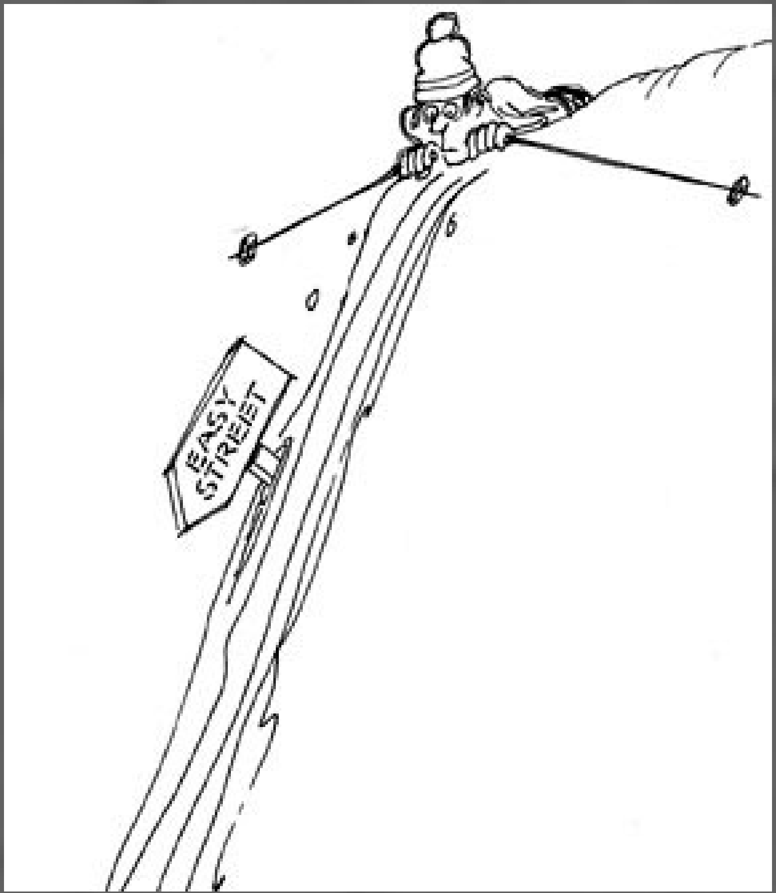




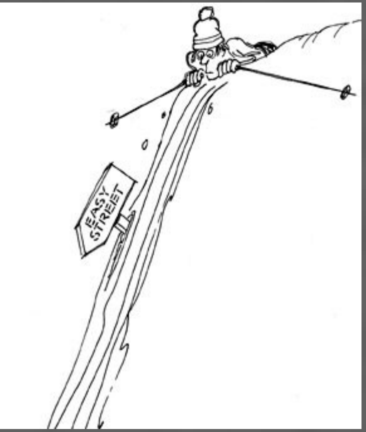
Projected phase-space distribution of particles in the same cluster-size numerically simulated halo, seen along two orthogonal directions

Methods
(of mass profile determination)

I) “Simple”



I) Simple methods



Determine M(r) using the Virial Theorem or the Projected Mass estimator *[Heisler, Tremaine & Bahcall 1985]* in radial bins

But:

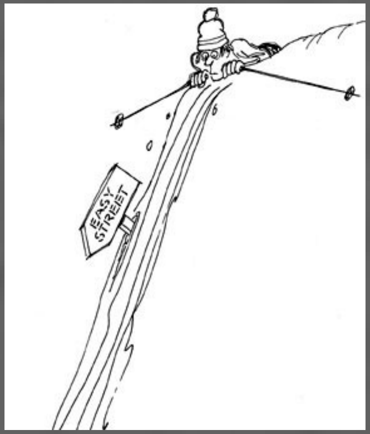
a) Spatial incompleteness affects the VT estimates via the harmonic mean radius *[Biv. et al. 2006]*

b) VT estimates must be corrected for surface-pressure term which depends on unknown velocity anisotropy *[The & White 1986]*

c) Interlopers and subclustering affects the PM estimates *[Perea et al. 1990]*

d) PM tends to overestimate M(r) at small radii and underestimate it at large radii *[Rines & Diaferio 2006]*

I) Simple methods



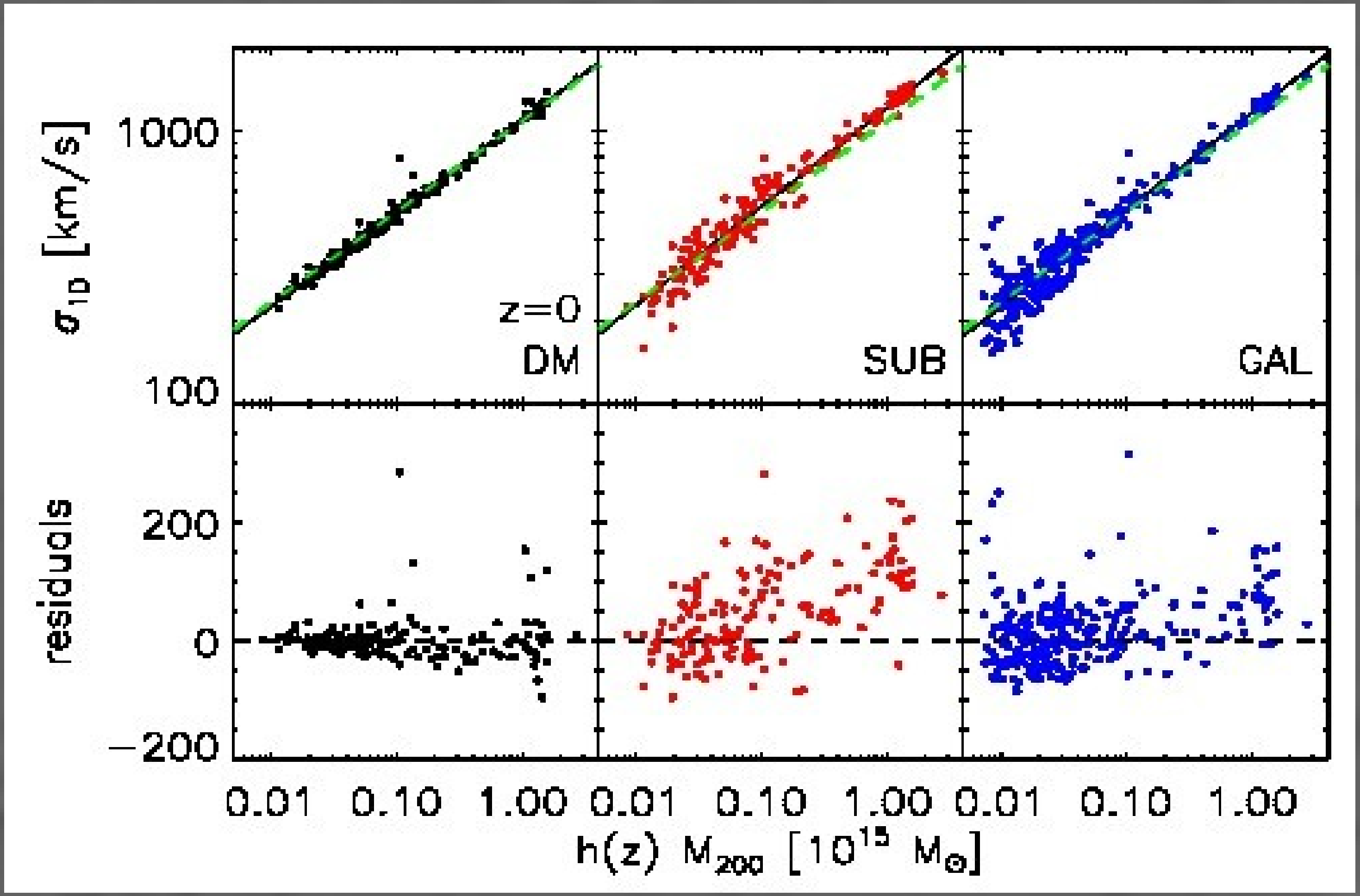
Use velocity dispersion along the line-of-sight, σ_v, as a proxy for the cluster mass

and use the number (or luminosity) density profile of cluster members as a proxy for the cluster mass profile

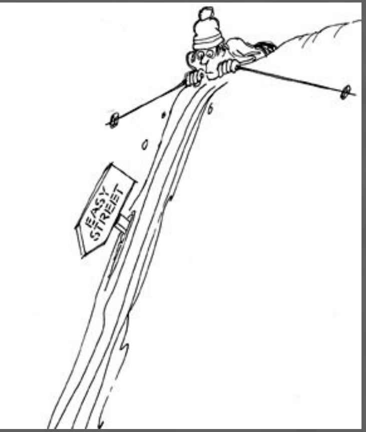
But:

a) How well do we know the scaling relation Mass vs. σ_v?
b) Does light trace mass?

I) Simple methods

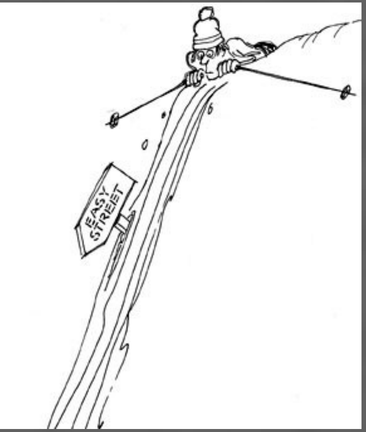


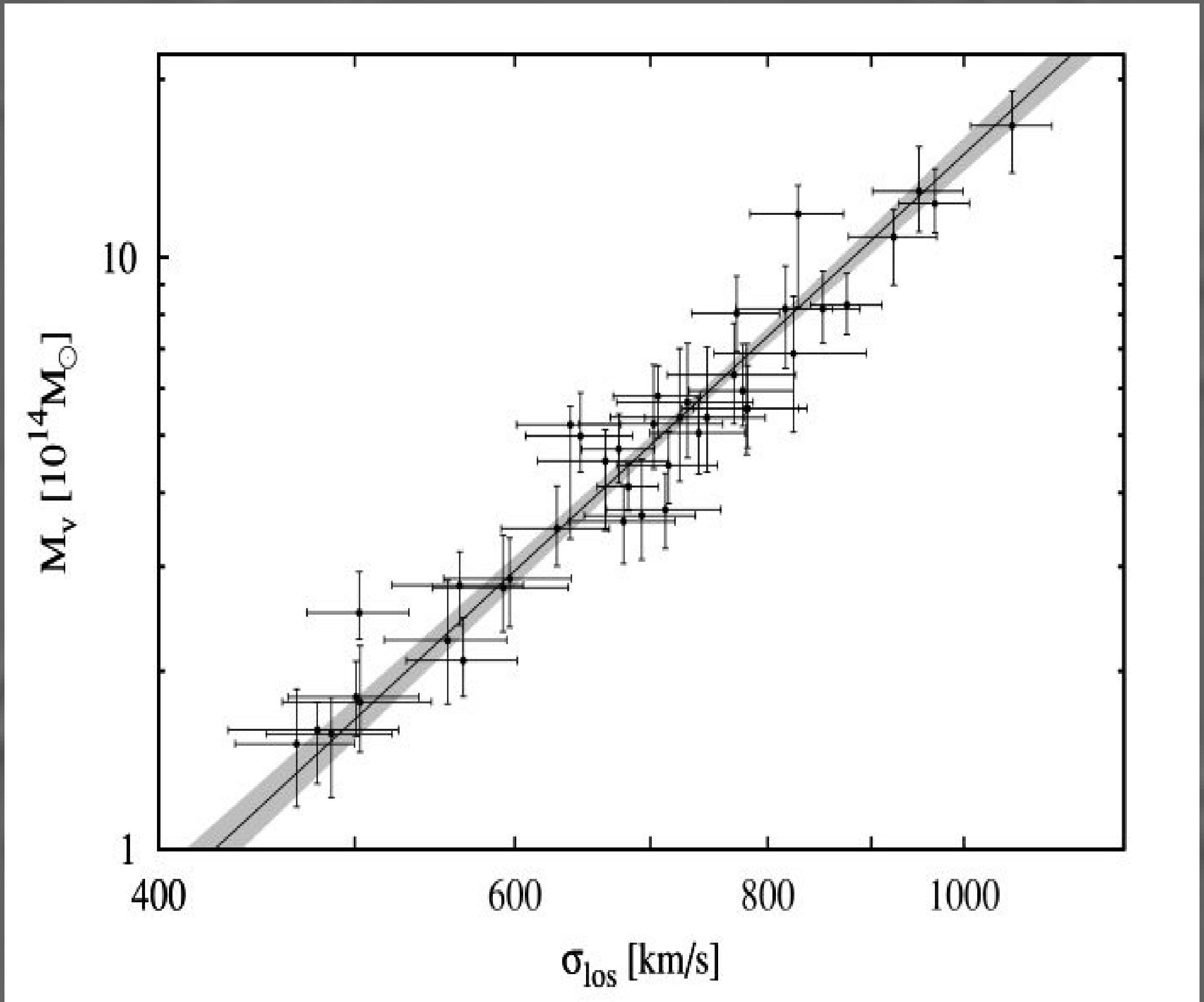
Simulated scaling relation Mass vs σ_v depends on tracer: DM particles, subhalos, “galaxies”



*[**Munari** Emiliano et al. 2013]*

I) Simple methods



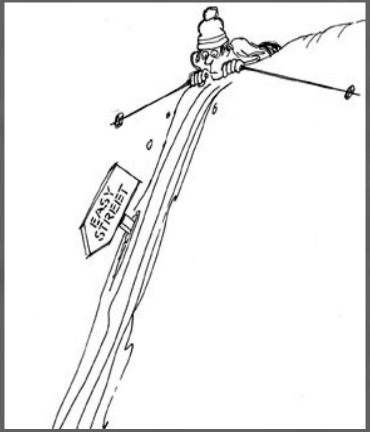


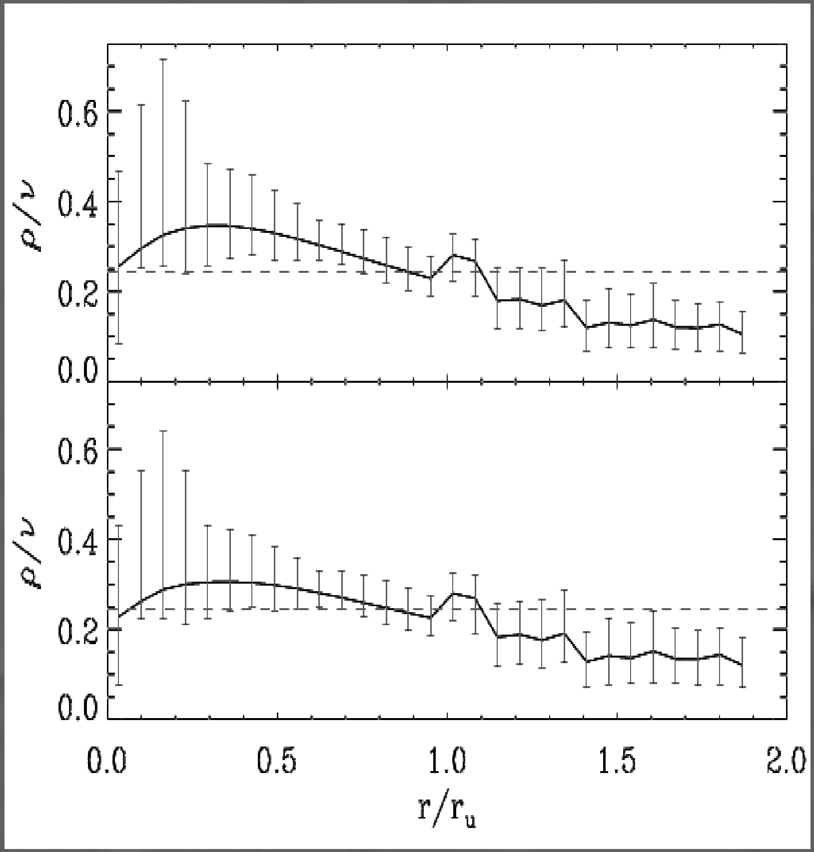
$M_{\rm v} = M_0[\sigma_{\rm los}/(750\,{\rm km\,s^{-1}})]^{\alpha}$ α= 3.17 ± 0.13 M_0= 5.99 ± 0.17

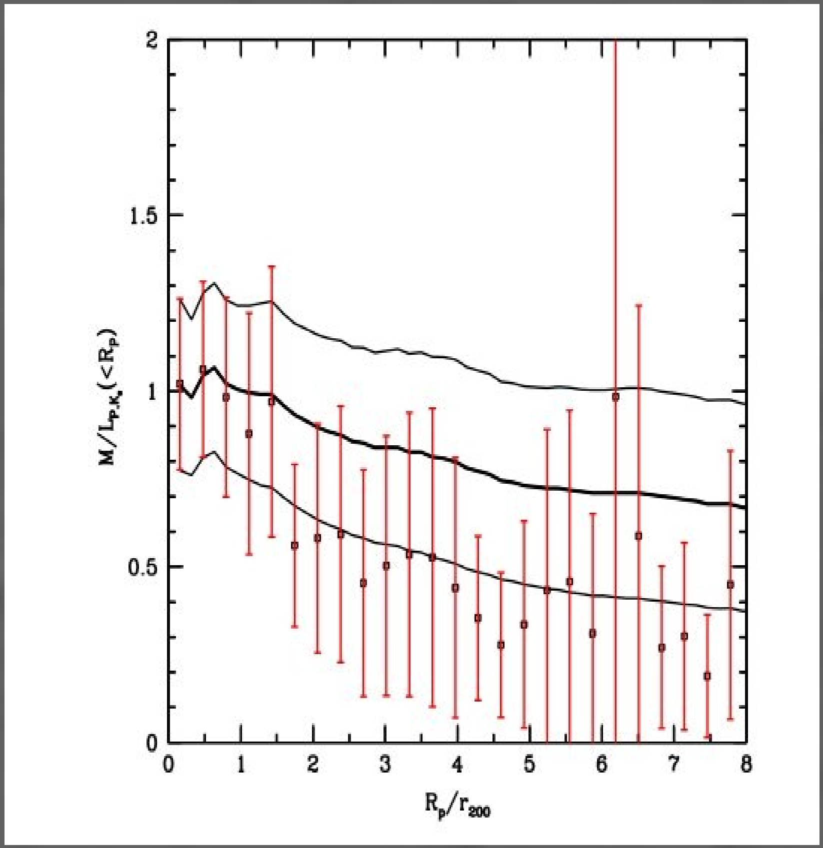
Observed z ≈ 0 scaling relation Mass vs σ_v

[Wojtak & Łokas 2010]

I) Simple methods

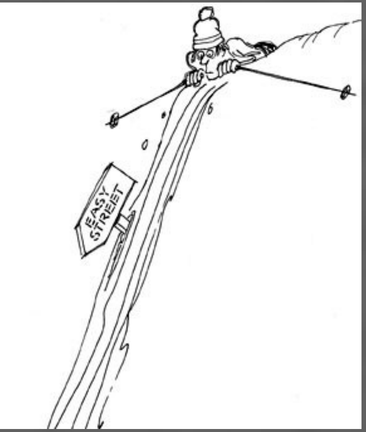






Mass is distributed like passive (or *K*-band selected) galaxies but not exactly so *[Biv. & Girardi 2003; Rines 2004]*

I) Simple methods



The method of the caustics in projected phase-space *[Diaferio & Geller 1997; Diaferio 1999]* is relatively simple but very powerful:

<u>see Ken Rines' talk</u>

Pay attention to the 'filling function' its value is crucial for the mass normalization in this method, and different values have been advocated in the literature:

$$\mathscr{F}_{\beta}(r) = -2\pi G \frac{\rho(r) r^2}{\phi(r)} \frac{3 - 2\beta(r)}{1 - \beta(r)}$$

Diaferio & Geller 1997, *Geller et al. 2013*: F_β(r)=0.5

Serra et al. 2011: F_β(r)=0.7

Biv. & Girardi 2003: F_β(r) variable with r

Methods
(of mass profile determination)

II) More complex

II) More complex methods

Based on the Jeans equation of dynamical equilibrium:

$$M(<r) = -\frac{r\sigma_r^2}{G}\left(\frac{d\ln\nu}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

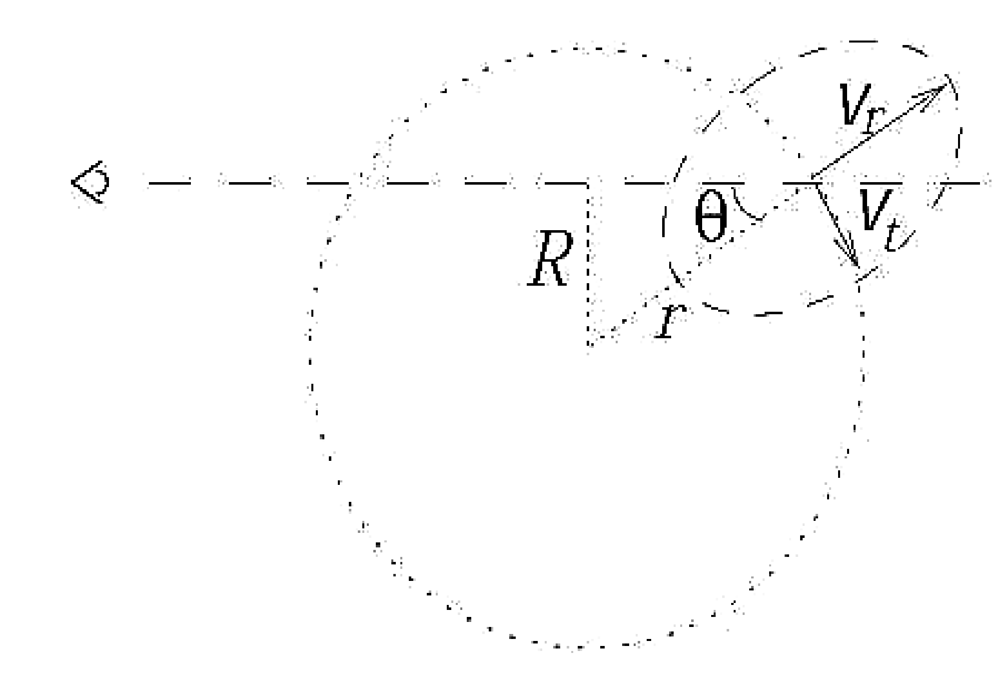
Velocity anisotropy ⇨ orbital distribution of the tracers of the gravitational potential

$$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_\mathrm{r}^2(r)}$$

Problem: we must solve the M(<r) – β(r) degeneracy

II) More complex methods

Knowledge of β(r) is needed to determine the 3-d velocity dispersion given the observed vel.disp. along the line-of-sight:



$$N(R)\sigma_p^2(R) = 2\int_R^\infty \left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu\,\sigma_r^2(r)\,r\,dr}{\sqrt{r^2-R^2}}$$

Only if β=0

$$\sigma_r^2 = -\frac{1}{\pi\nu(r)}\int_r^\infty \frac{d[N\times\sigma_p^2]}{dR}\frac{dR}{\sqrt{R^2-r^2}}$$

II) More complex methods

Breaking the M(r)-β(r) degeneracy:

a) Use external constraints:

a1) M(r) from lensing or X-ray *[e.g. Natarajan & Kneib 1996, Benatov et al. 2006]*

a2) β(r) from numerical simulations *[e.g. Hansen & Moore 2006, Mamon, Biv. & Murante 2010]*

b) Use more tracers separately, e.g. red and blue cluster galaxies *[e.g. Biv. & Katgert 2004, Battaglia et al. 2008, Biv. & Poggianti 2009]*

c) Go beyond the Jeans equation *[e.g. van der Marel et al. 2000, Łokas & Mamon 2003, Wojtak et al. 2009, Mamon, Biv. & Boué 2013]*

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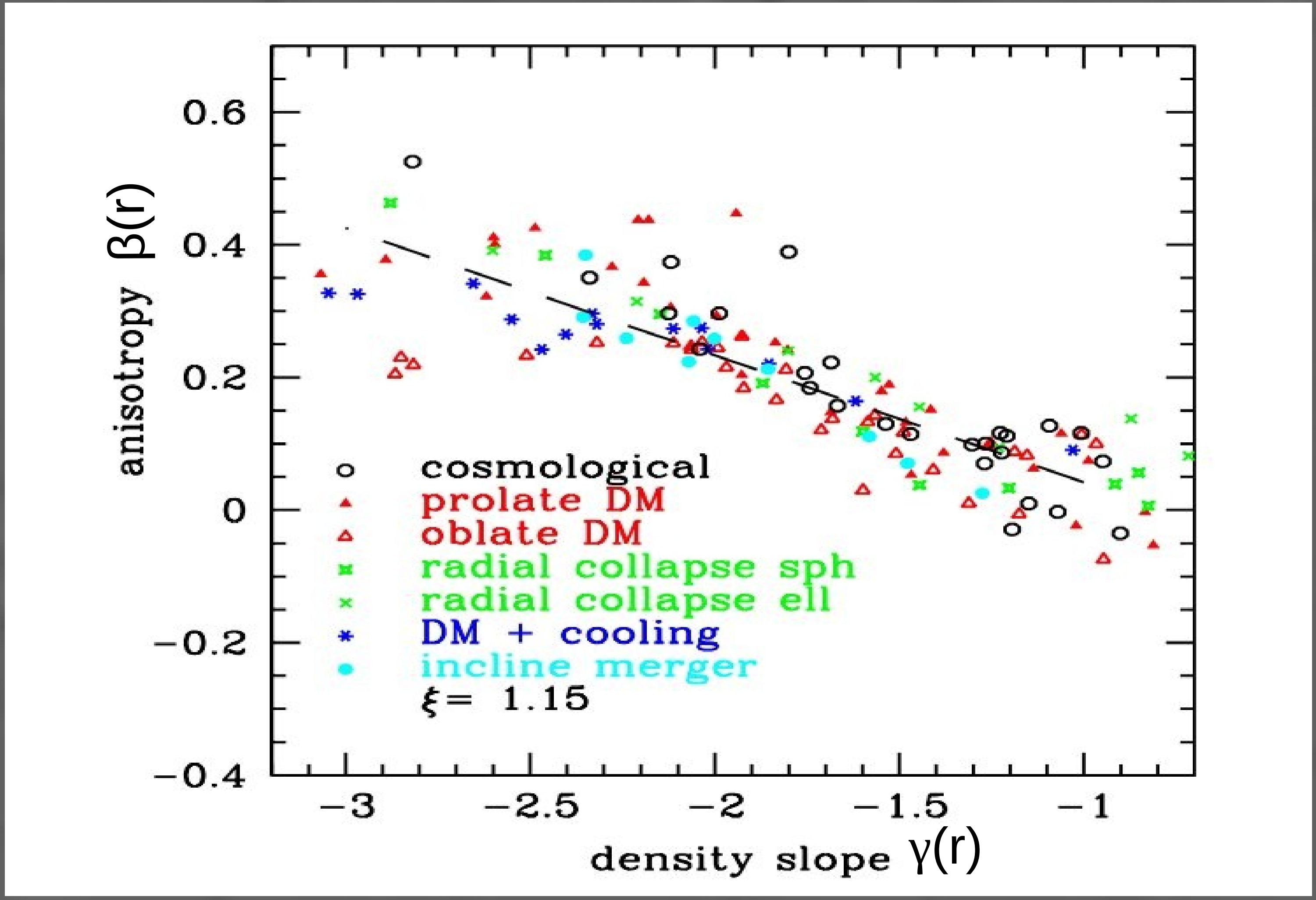
II) More complex methods

The γ(r)-β(r) relation

[Hansen & Moore 2006]

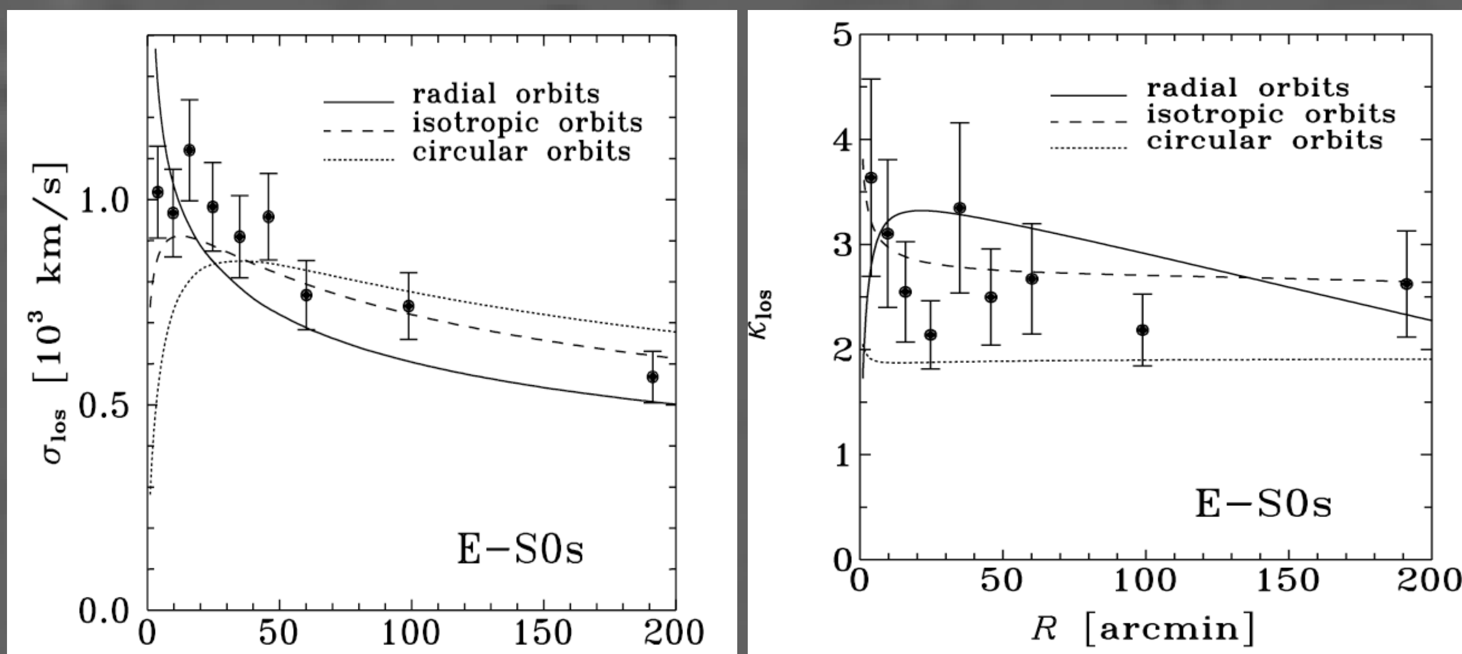


II) More complex methods

Dispersion + Kurtosis (D+K)

[Łokas 2002; Łokas & Mamon 2003]

Solve the Jeans eq. degeneracy by adding the Jeans eq. for the kurtosis: perform a simultaneous fitting to the velocity dispersion and kurtosis profiles:



[Coma cluster data; Łokas & Mamon 2003]

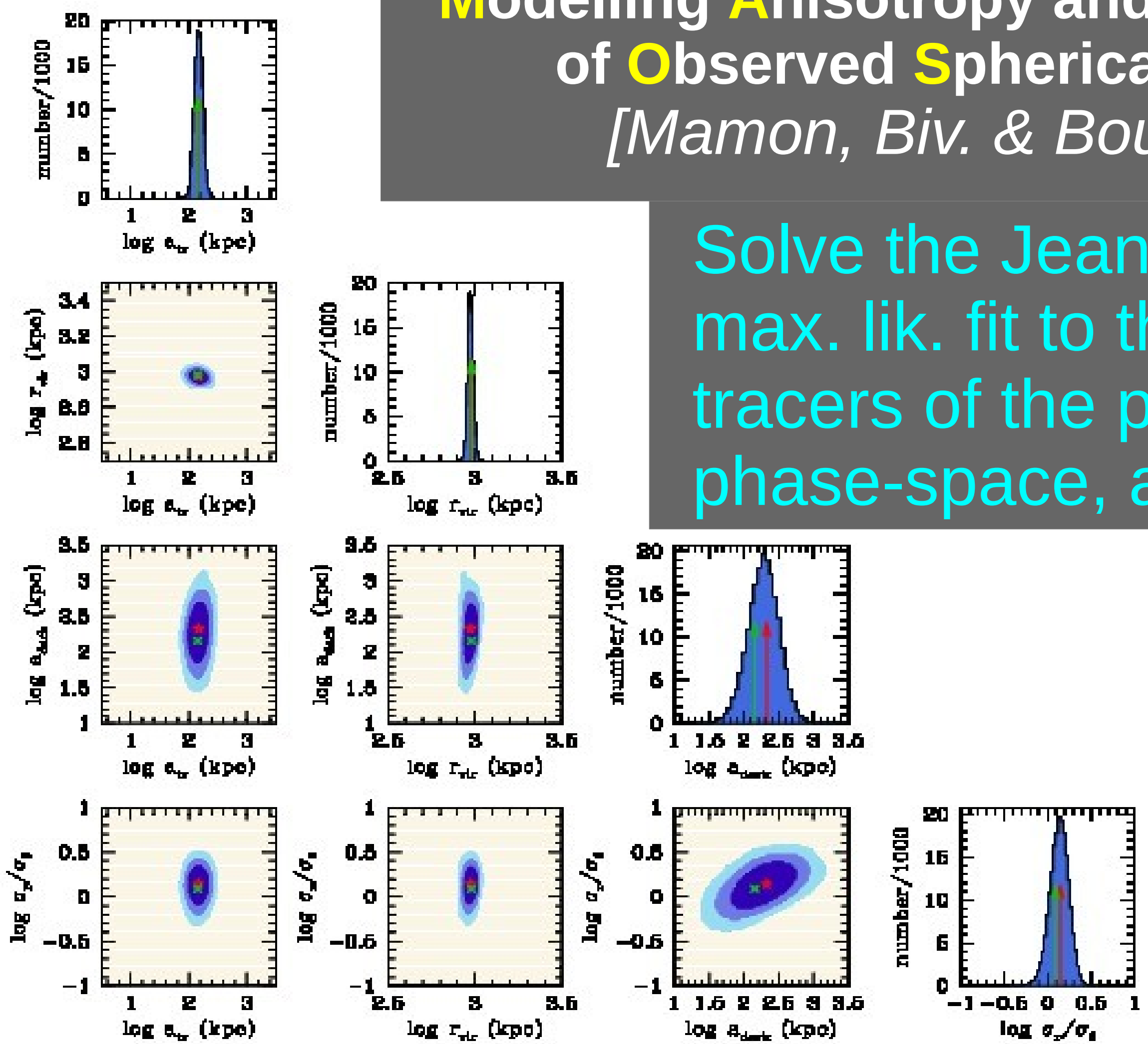
II) More complex methods

MAMPOSSt

Modelling Anisotropy and Mass Profiles of Observed Spherical Systems

[Mamon, Biv. & Boué 2013]

Solve the Jeans eq. degeneracy by a max. lik. fit to the full distribution of tracers of the potential in projected phase-space, assuming a shape for the 3-d velocity distribution of tracers



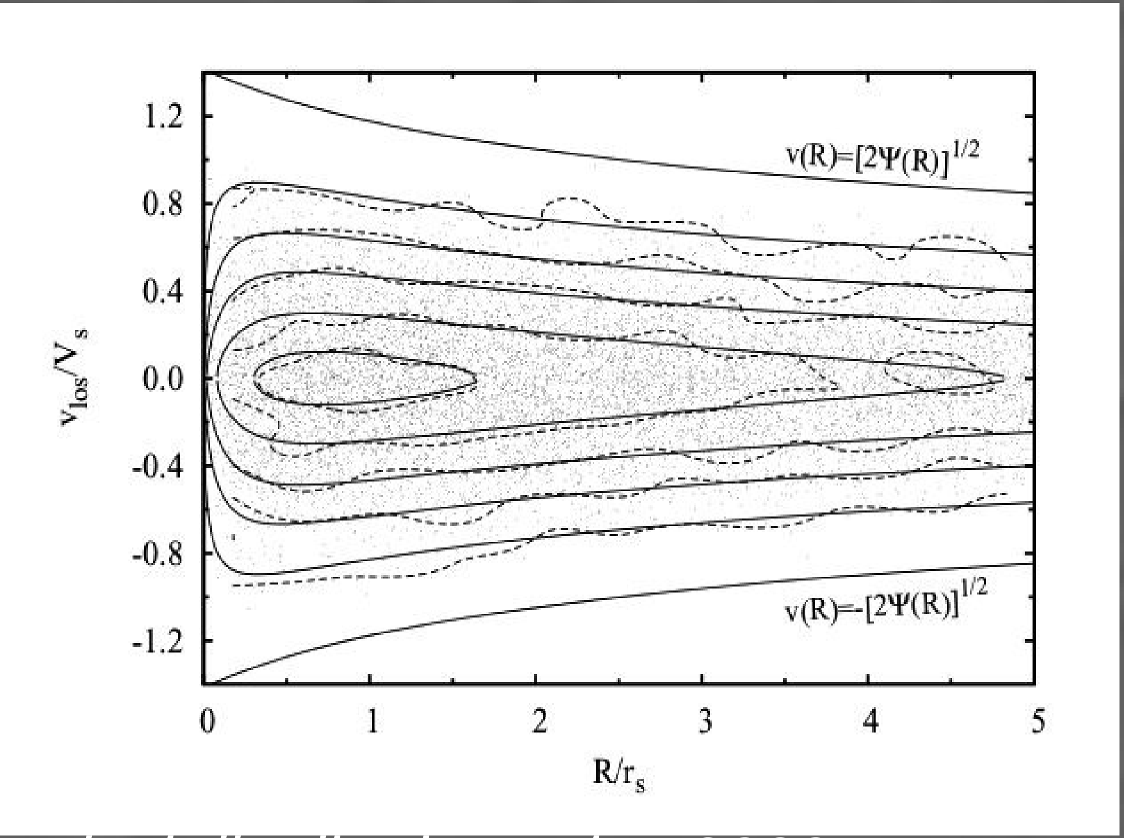
MAMPOSSt analysis of a simulated observation of cluster-size halo in projection, 500 tracers, 4 free parameters

II) More complex methods

Distribution Function (DF) models

[Kent & Gunn 1982; van der Marel et al. 2000; Wojtak et al. 2008, 2009]

Assume a form for the 6-d distribution function of tracers, based on numerical simulations (shown to be separable in energy and angular momentum) then projects in observed phase-space



[recovery of theoretical distribution using 9000 tracers, Wojtak et al. 2009]

II) More complex methods

D+K vs. **MAMPOSSt** vs. **DF**

All use parametric models of M(r) and β(r) or E, L
All use spherical approximation
All require dynamical equilibrium (hence use data within r_{200})

D+K limitation: β constant with radius *(extension of the method to non-constant β just implemented, Richardson & Fairbairn 2012)*

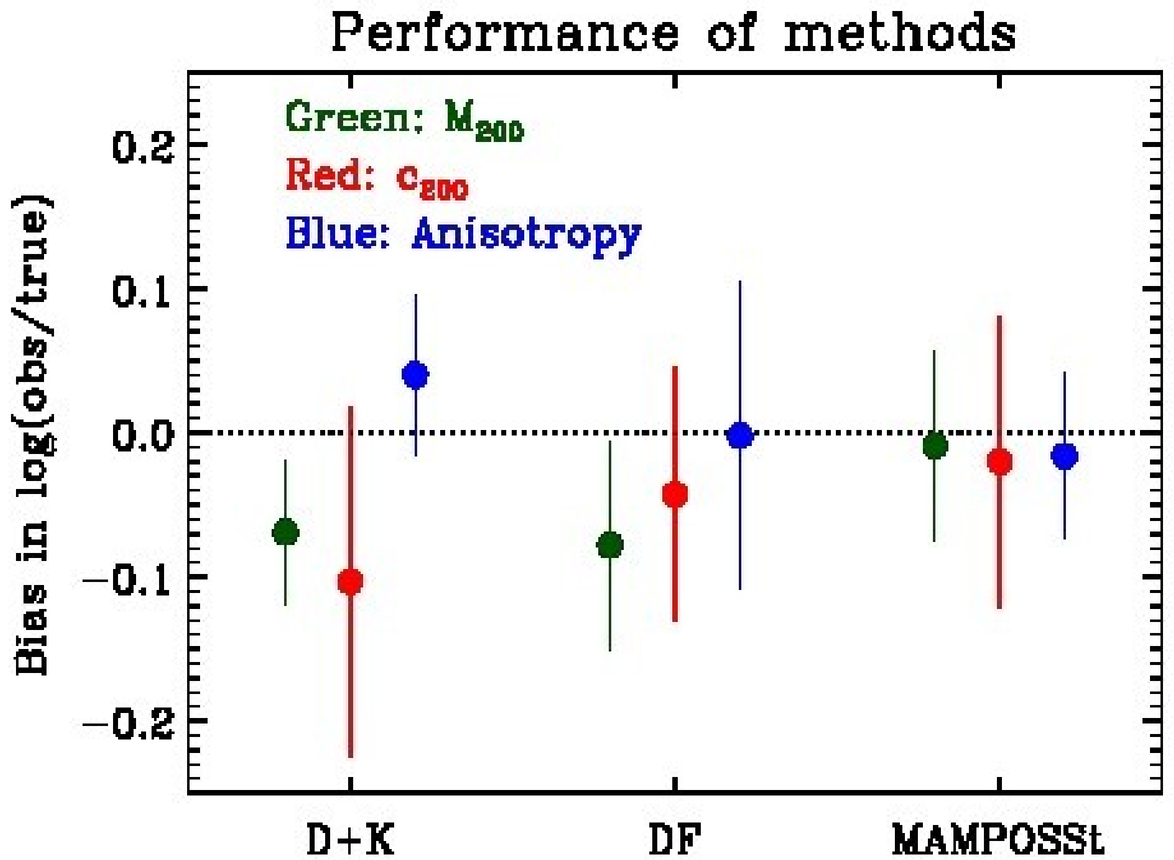
MAMPOSSt limitation: assume 3-d velocity distribution shape *(Gaussian case considered so far: extensions of the method to other distributions – e.g. Tsallis – are in progress)*

DF limitations: it is much slower than previous two. It relies on numerical simulations, but are the ΛCDM halo distribution functions representative of real clusters?

II) More complex methods

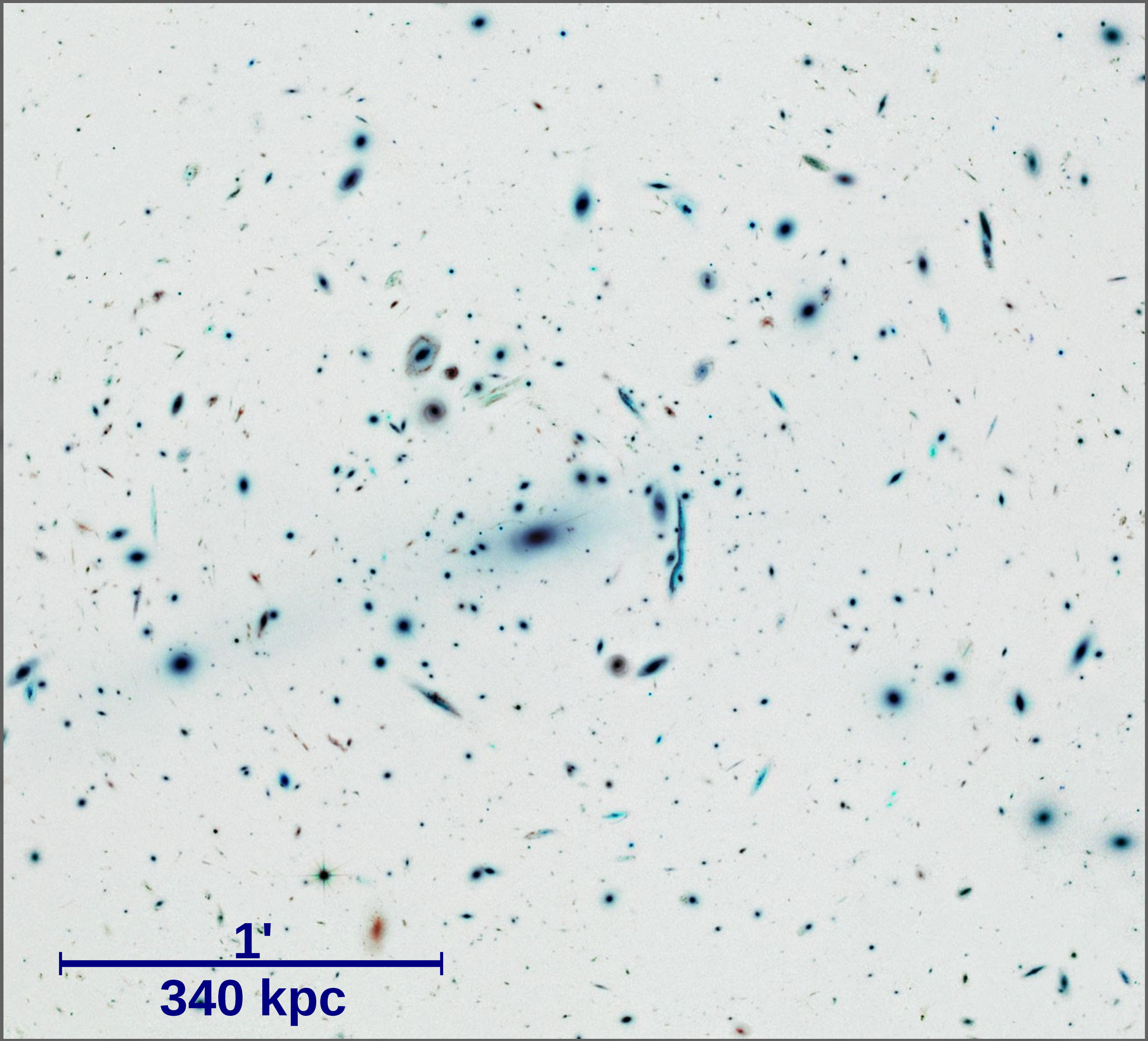
D+K vs. **MAMPOSSt** vs. **DF**

BIas and inefficiency in log (observed/true) for simulated halos in projection, with 300 – 400 tracers, assuming M(r) model is NFW *[Navarro, Frenk & White 1996,1997]*



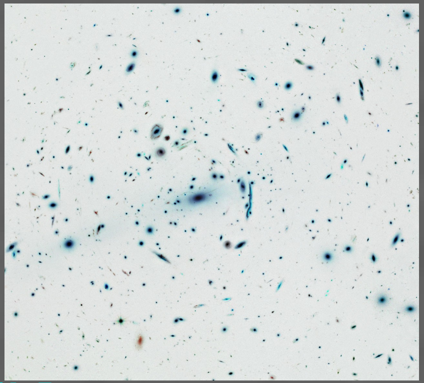
Inefficiency represented by the size of the error bar

Case study:
(CLASH cluster MACS J1206-0847)



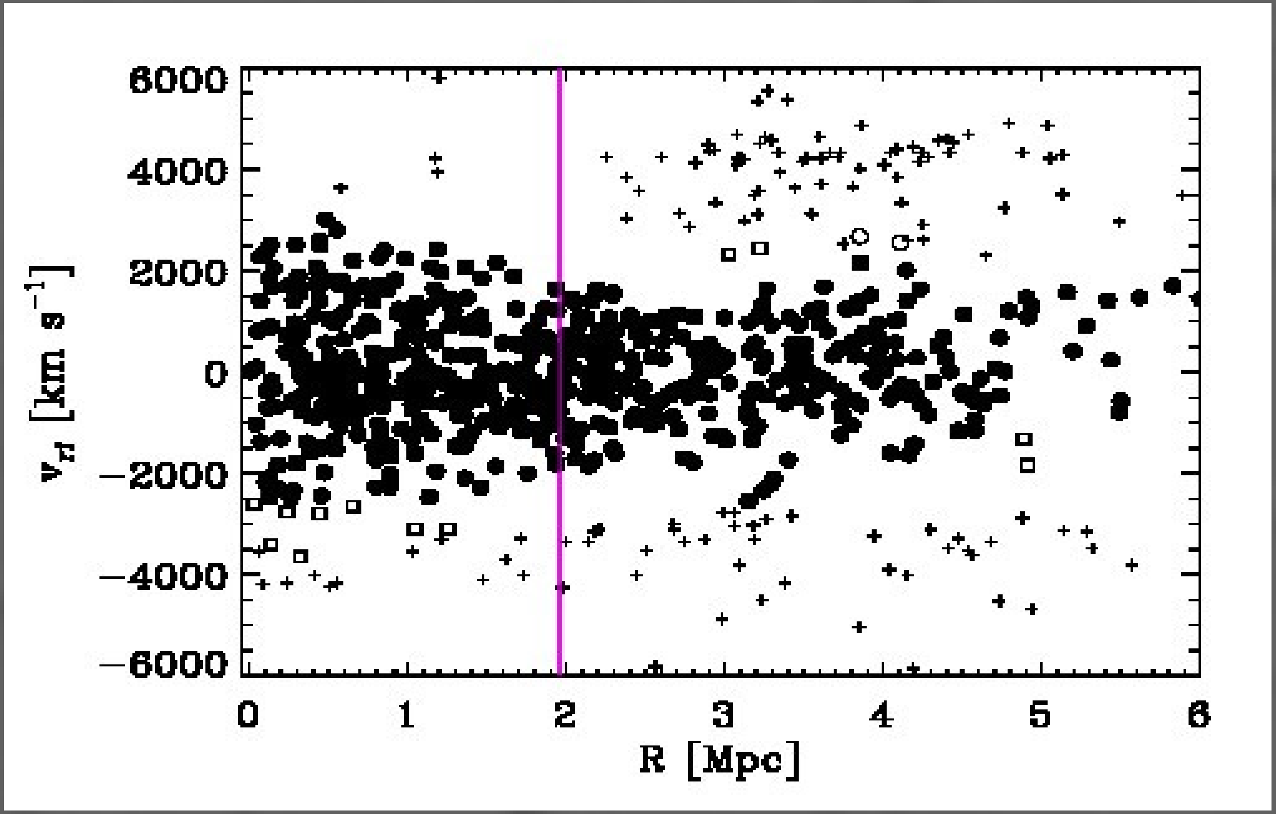
Results from *Biv. et al. (in prep.)*

Case-study cluster

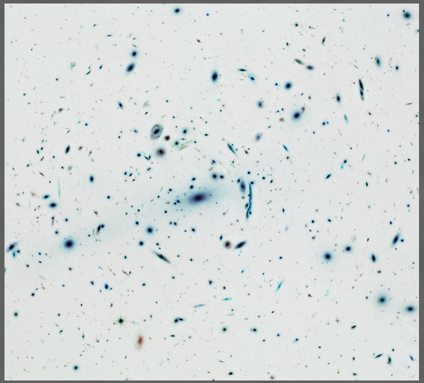


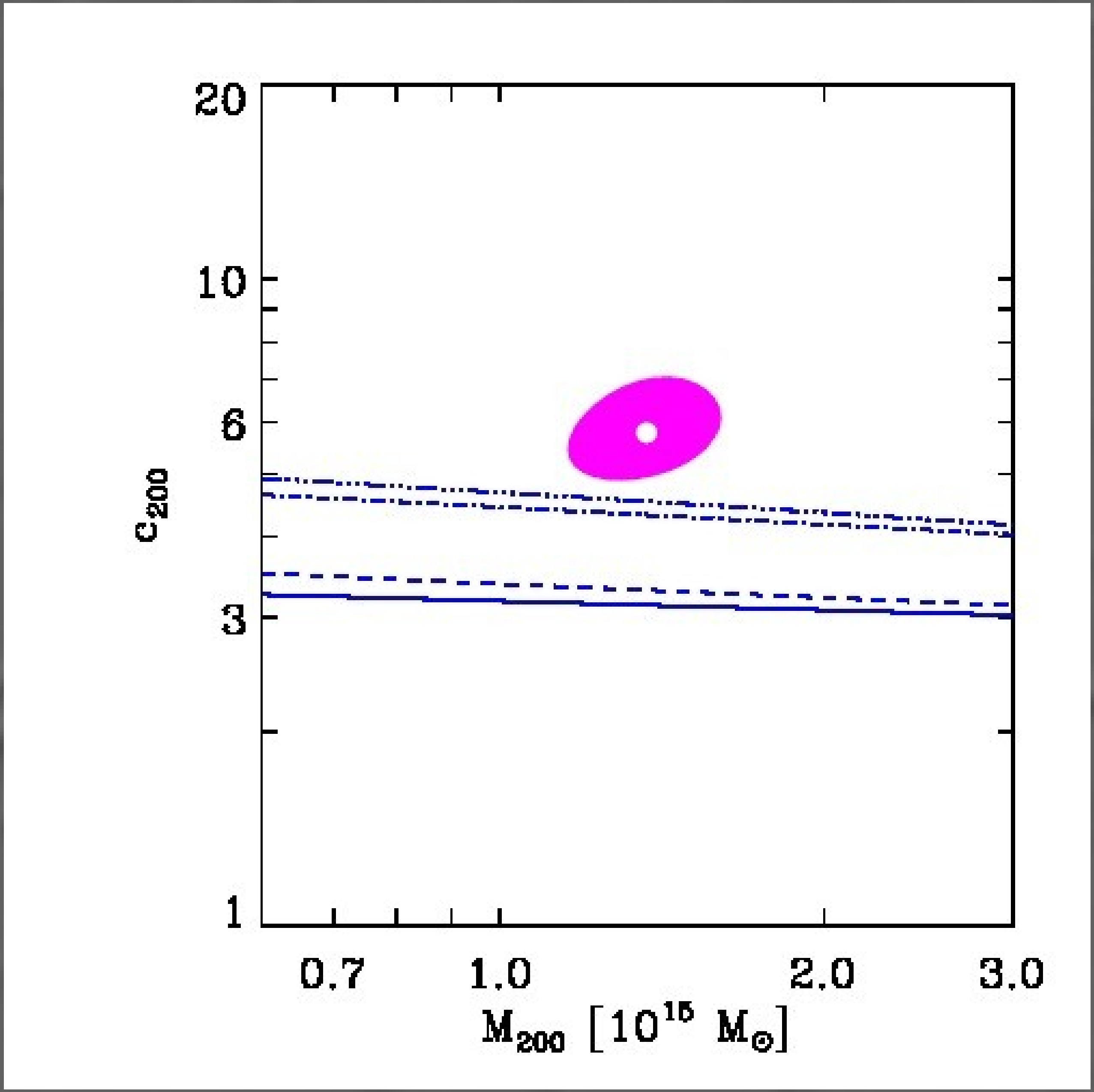
MACS J1206+0847 is a z=0.44 massive cluster, part of **CLASH** *(Cluster Lensing And Supernova survey with Hubble, PI: M. Postman)* sample [see Dan Coe's talk] with VLT-VIMOS follow-up from the ESO Large Programme *"Dark Matter Mass Distributions of Hubble Treasury Clusters and the Foundations of ΛCDM Structure Formation Models", PI: P. Rosati*:

≈ 600 cluster members with accurate ($\Delta z \approx 3 \times 10^{-4}$) redshifts, of which 330 within r_{200}.



Case-study cluster



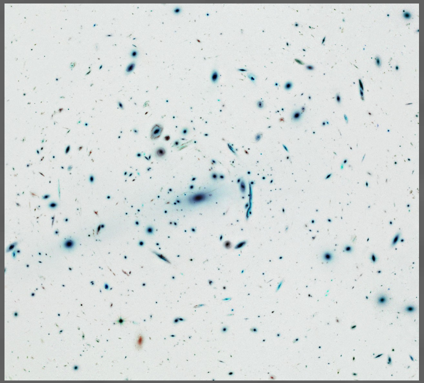


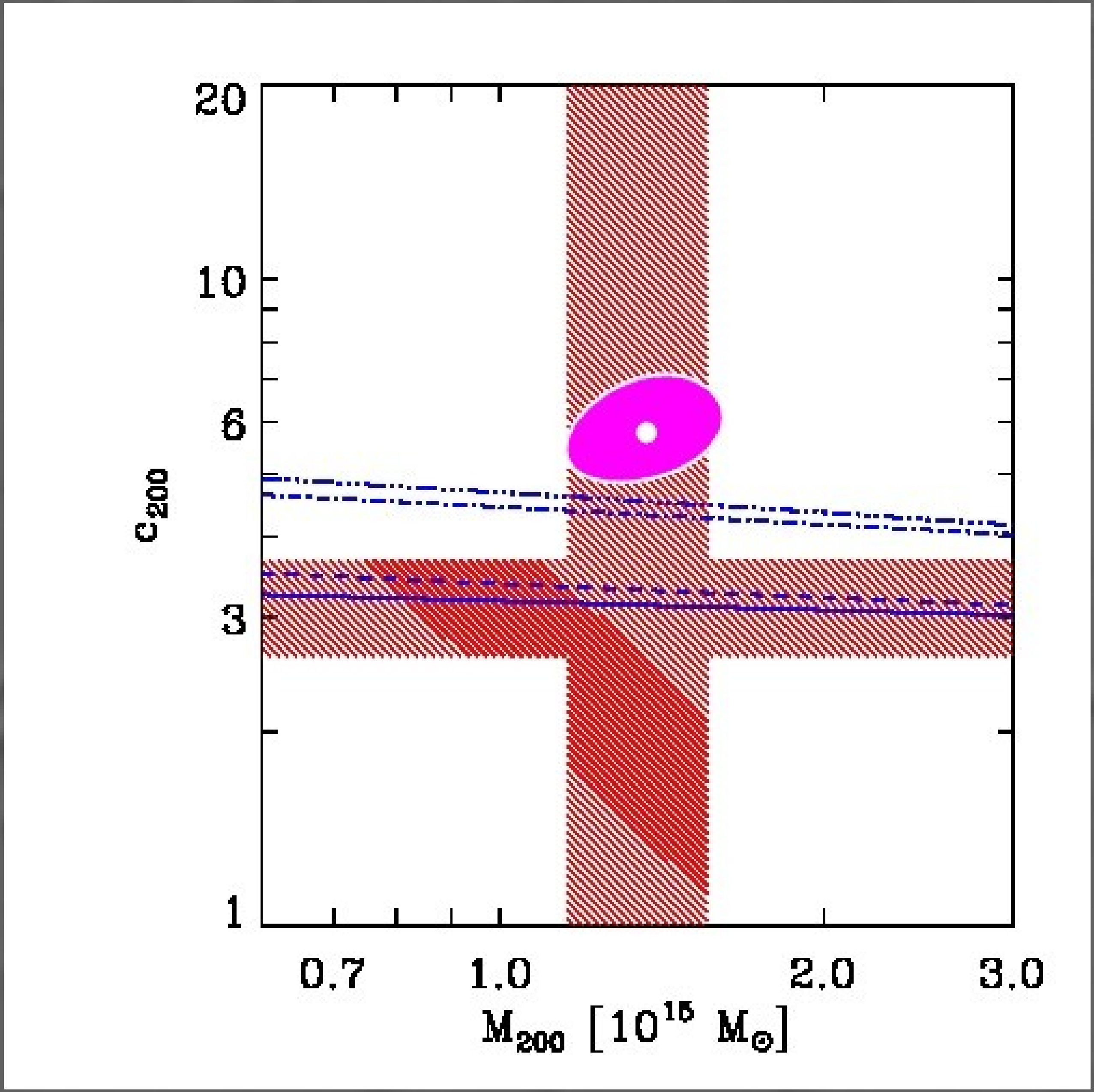
Strong+Weak lensing
[Umetsu et al. 2012]

Theoretical relations
[Bhattacharya et al. 2011, De Boni et al. 2013]

Fit with NFW M(r)

Case-study cluster





Strong+Weak lensing
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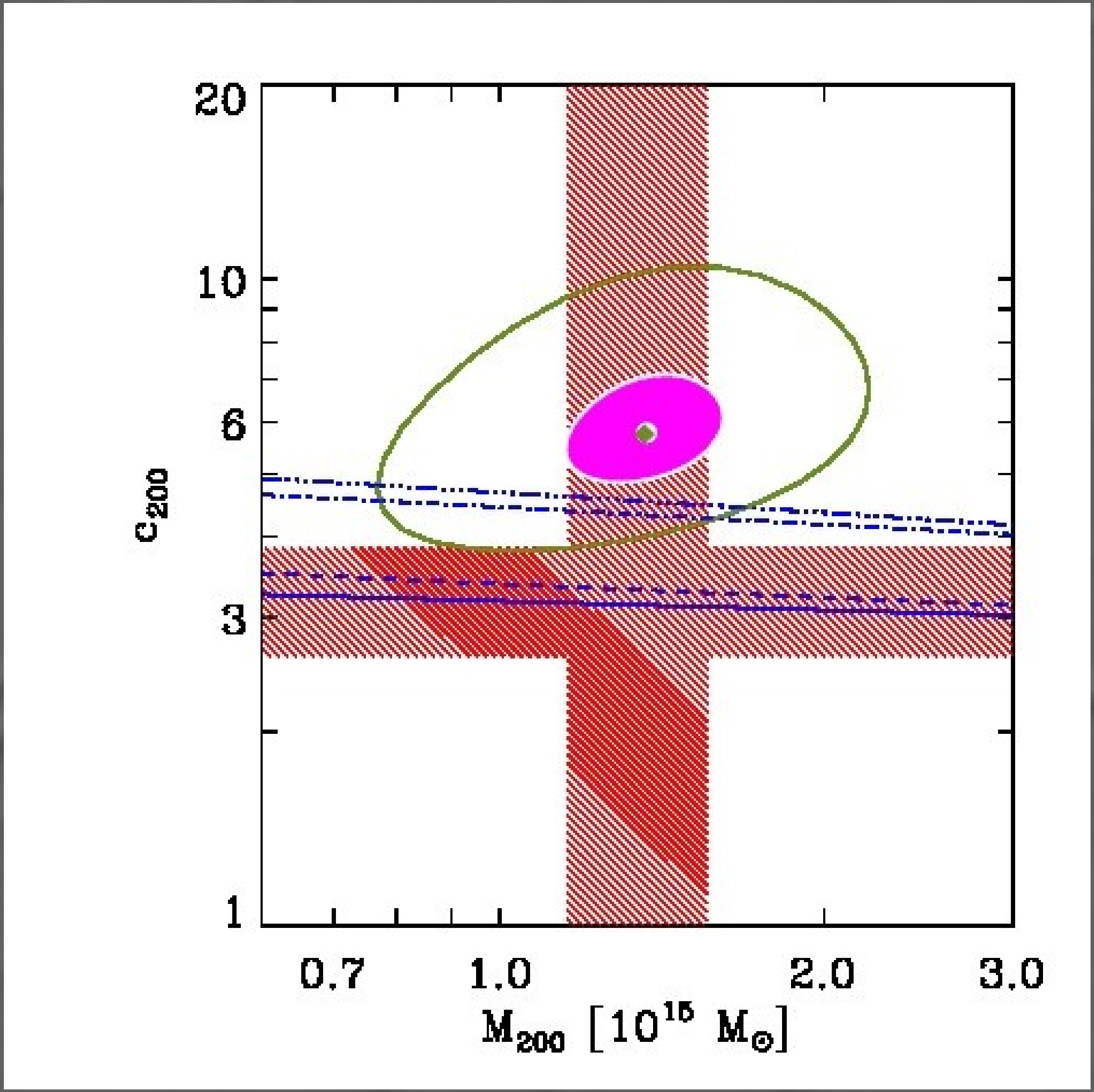
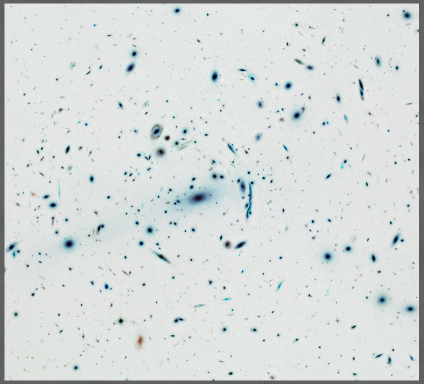
N(R) + σ_v (red gals)

Fit with NFW M(r)

Case-study cluster





Strong+Weak lensing *[Umetsu et al. 2012]*

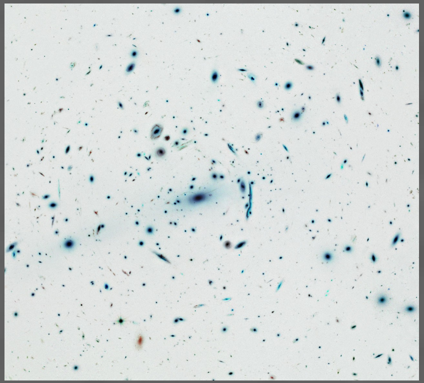
Theoretical relations *[Bhattacharya et al. 2011, De Boni et al. 2013]*

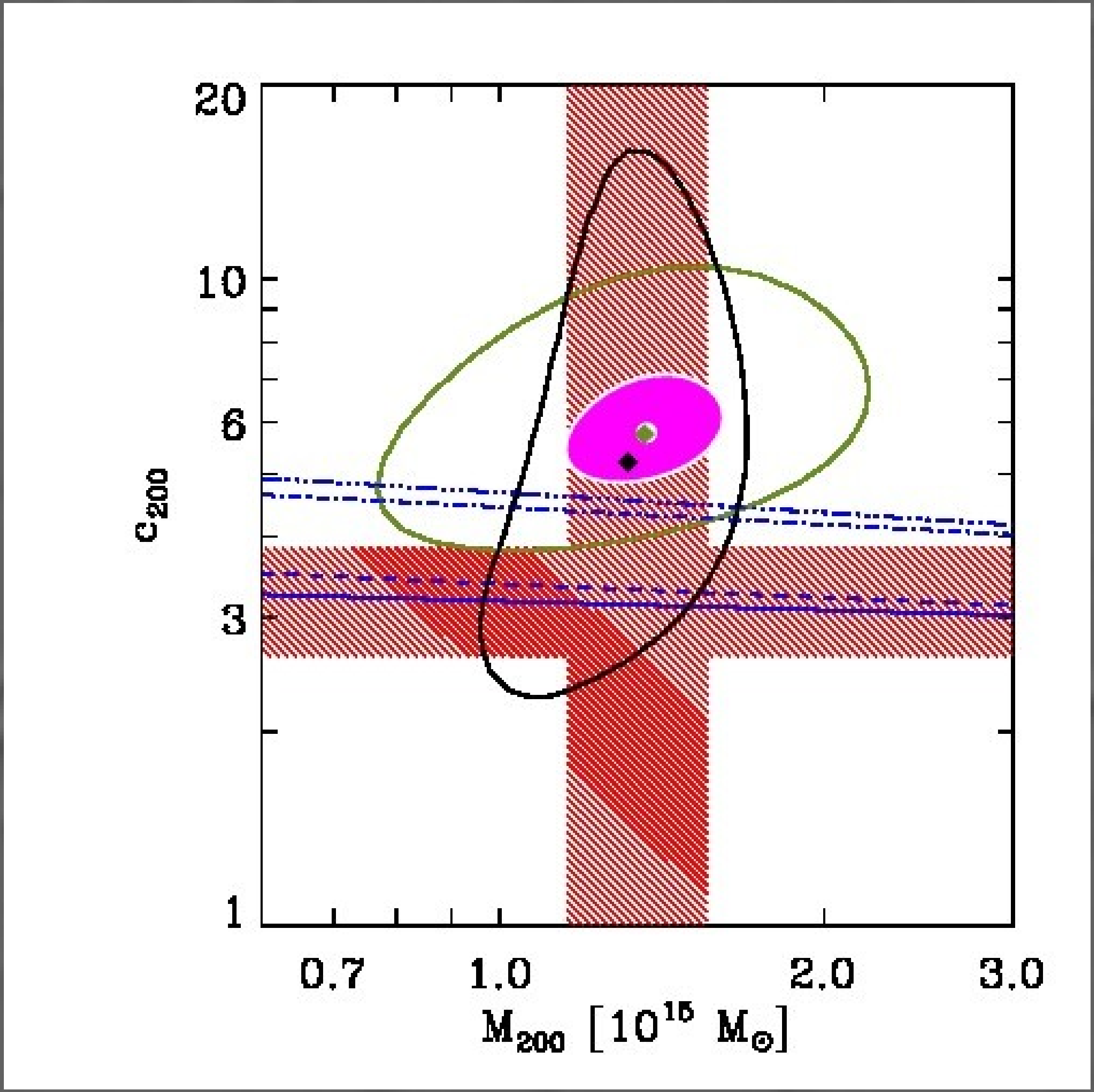
N(R) + σ_v (red gals)

Caustic

Fit with NFW M(r)

Case-study cluster





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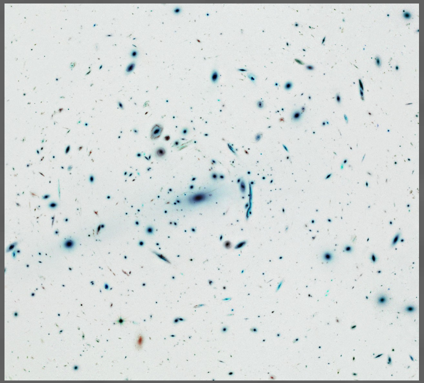
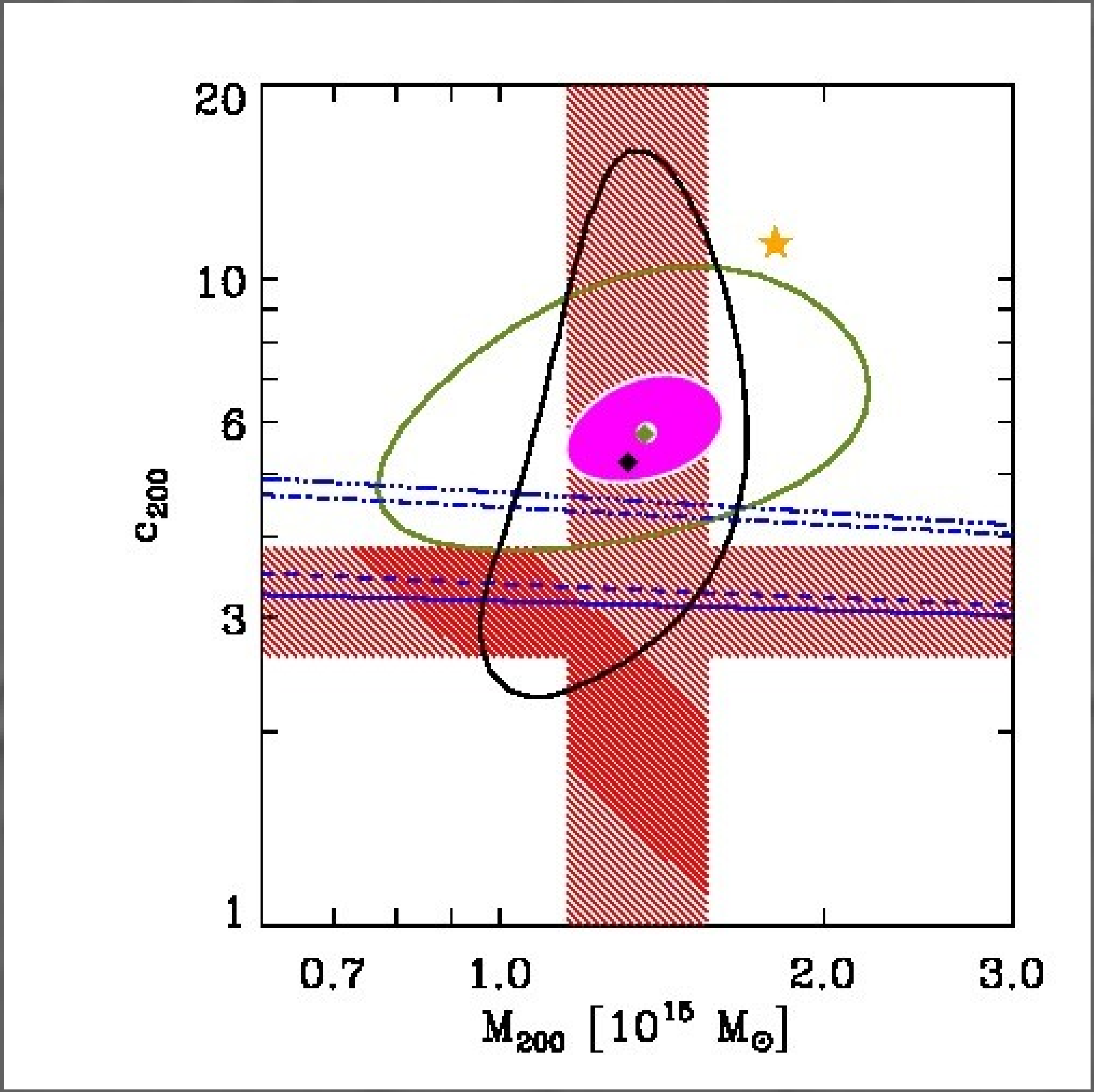
Case-study cluster





Strong+Weak lensing
[Umetsu et al. 2012]

Theoretical relations
[Bhattacharya et al. 2011, De Boni et al. 2013]

N(R) + σ_v (red gals)

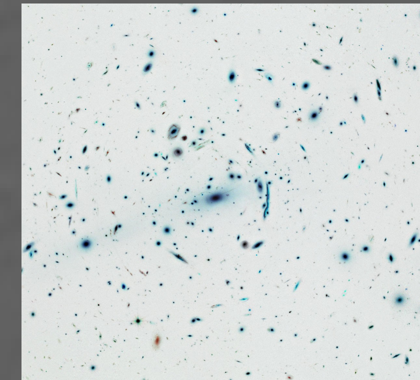
Caustic

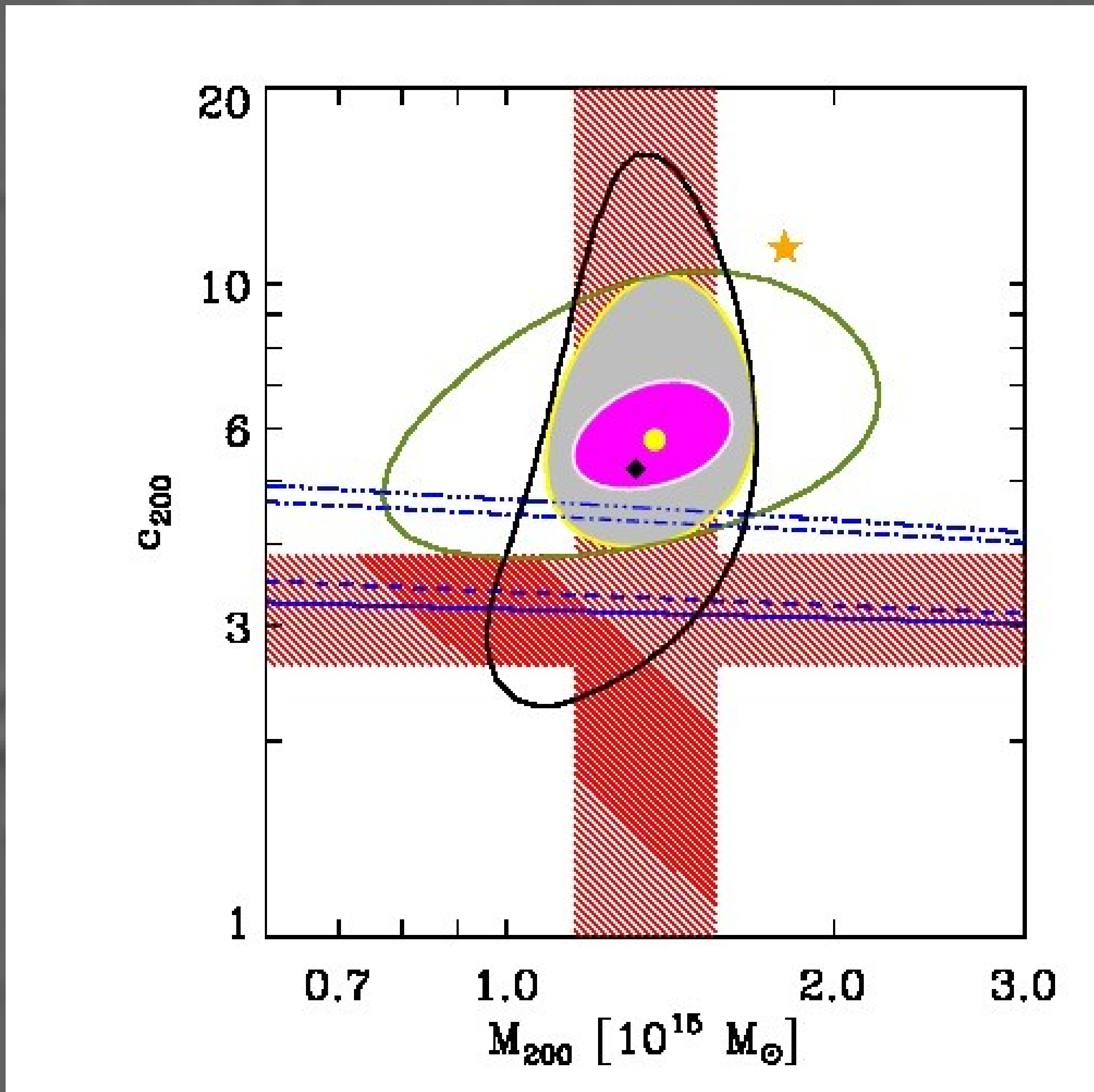
MAMPOSSt

D+K

Fit with NFW M(r)

Case-study cluster





Strong+Weak lensing
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N(R) + σ_v (red gals)

Caustic

MAMPOSSt

D+K

Caustic+MAMPOSSt

Fit with NFW M(r)

Previous results
(concentration – mass relation)

SCI - La "storica,, impresa di Berchtesgaden

I magnifici cinque capofila è GROS

Gli austriaci scrivono: "Valanga italiana,,

NOSTRO SERVIZIO
BERCHTESGADEN, 8 gennaio.

La trionfale giornata dello sci italiano ha trovato vasta eco nei giornali di tutto il mondo. La stampa austriaca è generosa di elogi: «E' un primato mondiale assoluto», si scrive, «accentuato dalla conquista del primato anche nella classifica generale della Coppa del Mondo da parte di Piero Gros».

Nella scia del giovane asso piemontese, applaudito vincitore dello slalom gigante, si sono piazzati Gustavo Thoeni, Erwin Stricker, Helmut Schmalzl e Tino Pietrogiovanna.

Gros ha trionfato in lungo e in largo vincendo entrambe le manches e terminando con oltre due secondi di vantaggio su Thoeni. Il successo gli consente di superare di un punto nella classifica della Coppa del Mondo l'austriaco Franz Klammer.

Questo trionfo, il più grande ottenuto da una rappresentativa nazionale in una gara valevole per la Coppa del Mondo, è stato ottenuto sotto un sole splendente, su una neve molto compatta e dura.

Fra i 111 partenti, diversi dei maggiori quotati della vigilia sono rimasti vittime di cadute: fra questi gli austriaci Thomas Hauser e Hans Hinterseer, nome, quest'ultimo, sul quale si appuntavano molte speranze dello sci d'oltr'Alpe, soprattutto nello slalom.

«Sono sbalordito dalla mia vittoria — ha esclamato Gros dopo avere appreso l'esito della gara —, non credevo di essere sceso così veloce nella seconda manche». Bruno, alto un metro e 83, il trionfatore azzurro era raggiante. L'anno scorso, quando entrò per la prima volta nella massima competizione sciistica, Gros terminò decimo: era l'anno della terza vittoria consecutiva di Gustavo Thoeni. Prima della vittoria di ieri, Gros ha ottenuto una bella serie di successi: primo nello slalom speciale di Sterzing, terzo nello slalom gigante di Val d'Isère, quinto nello slalom gigante di Saalbach.

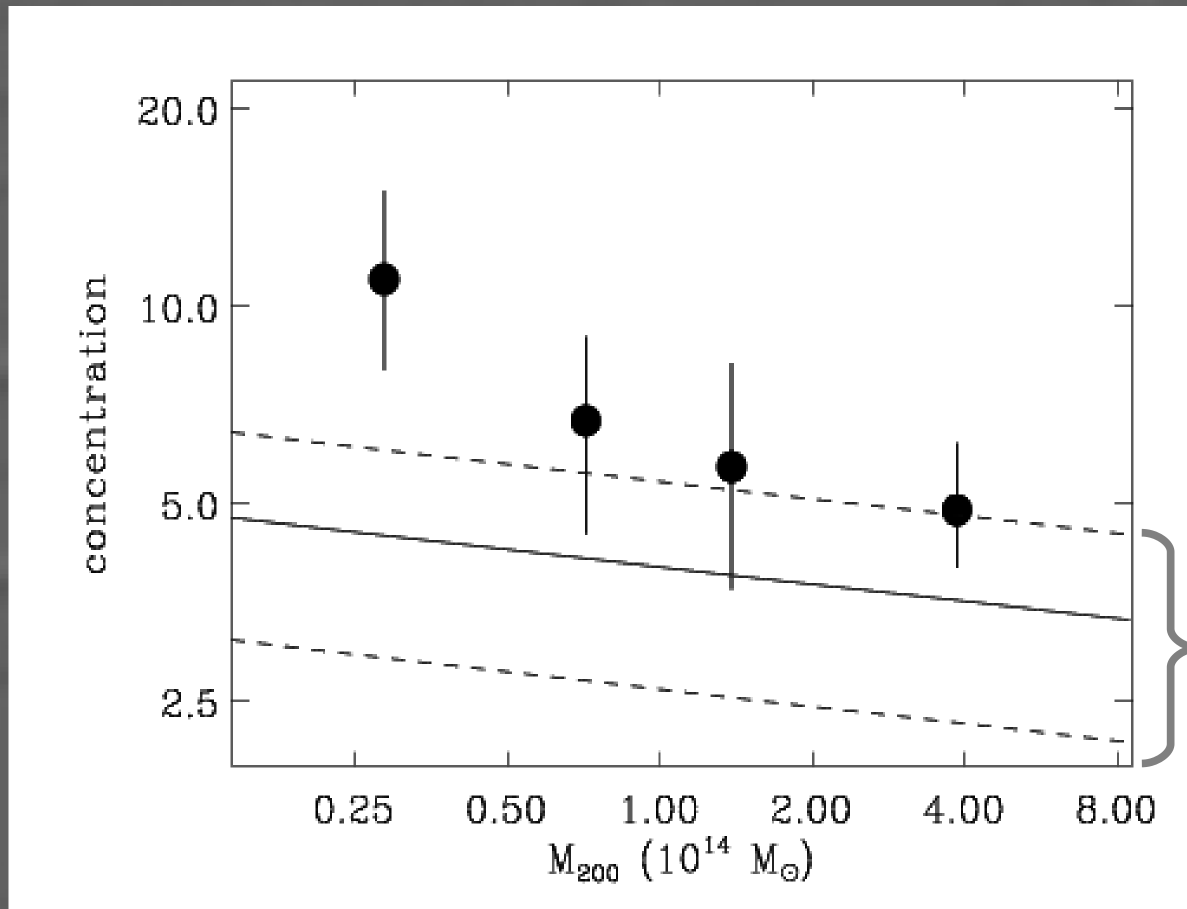
La vittoria azzurra viene sottolineata dal diffuso quotidiano austriaco «Kronenzeitung», sotto un titolo nel quale gli sciatori italiani vengono elogiati per essersi superati gli uni con gli altri, praticamente senza altri avversari. «Qualsiasi altro evento mai verificatosi su questa pista, dice l'articolo, è stato travolto da questa valanga italiana. Gli italiani hanno oscurato tutto il resto». Il loro successo ha assunto le proporzioni di un primato mondiale assoluto. «Sopra Berchtesgaden — conclude il giornale — è stata alzata una grande bandiera bianca, rossa e verde, e la parola Italia si è stagliata nel cielo».

a. p.

Pierino Gros, sulle nevi di Berchtesgaden: è il nuovo mattatore della Coppa del mondo

8 January 1974
World Cup Slalom:
5 italians in the first
5 places
[La Stampa archive]

Previous results



[from Biv. 2008]

Theoretical relation and scatter [Duffy et al. 2008]


SCI - La "storica,, impresa di Berchtesgaden

I magnifici cinque capofila è GROS

Gli austriaci scrivono: "Valanga italiana,,

Compilation of results obtained using galaxies as tracers of the potential for several samples of groups and clusters at low z:
Groups: Biv., Mamon, Ponman, in prep.
Groups & poor clusters: Mahdavi et al. 1999
Poor & rich clusters: Biv. & Girardi 2003, 2dFGRS sample
Rich clusters: Biv. & Salucci 2006, ENACS sample

Previous results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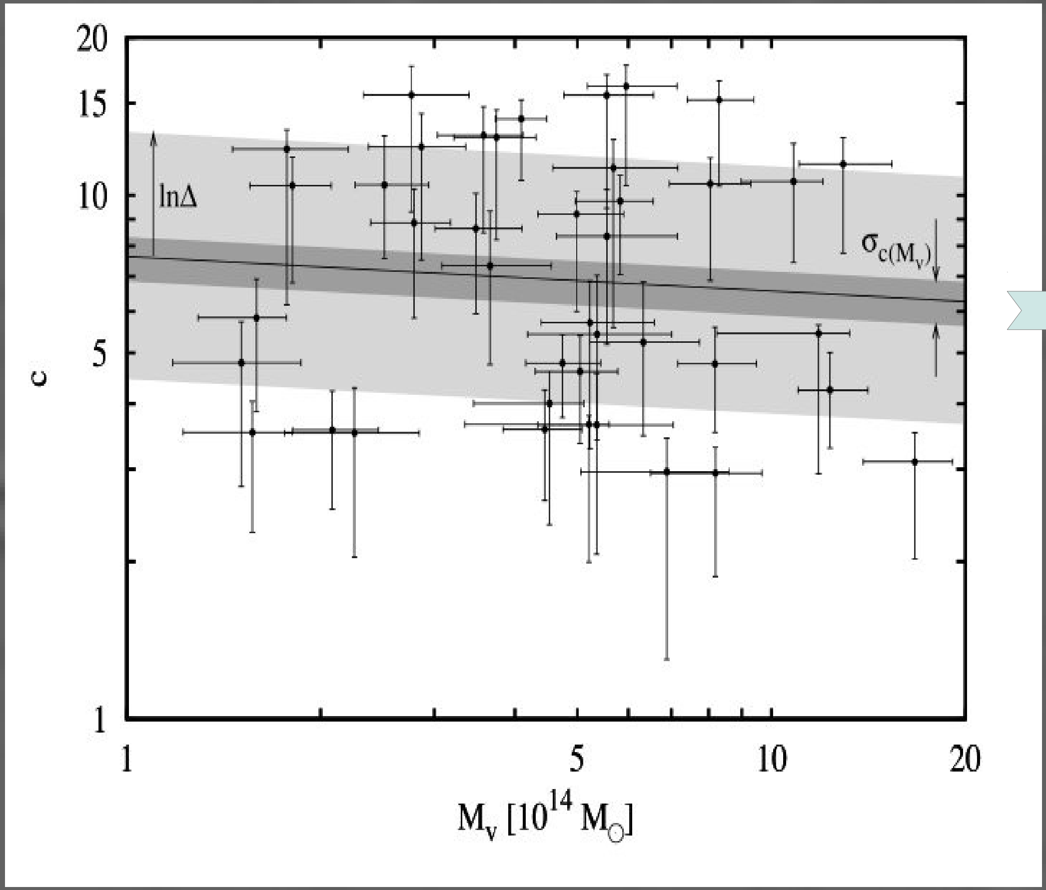
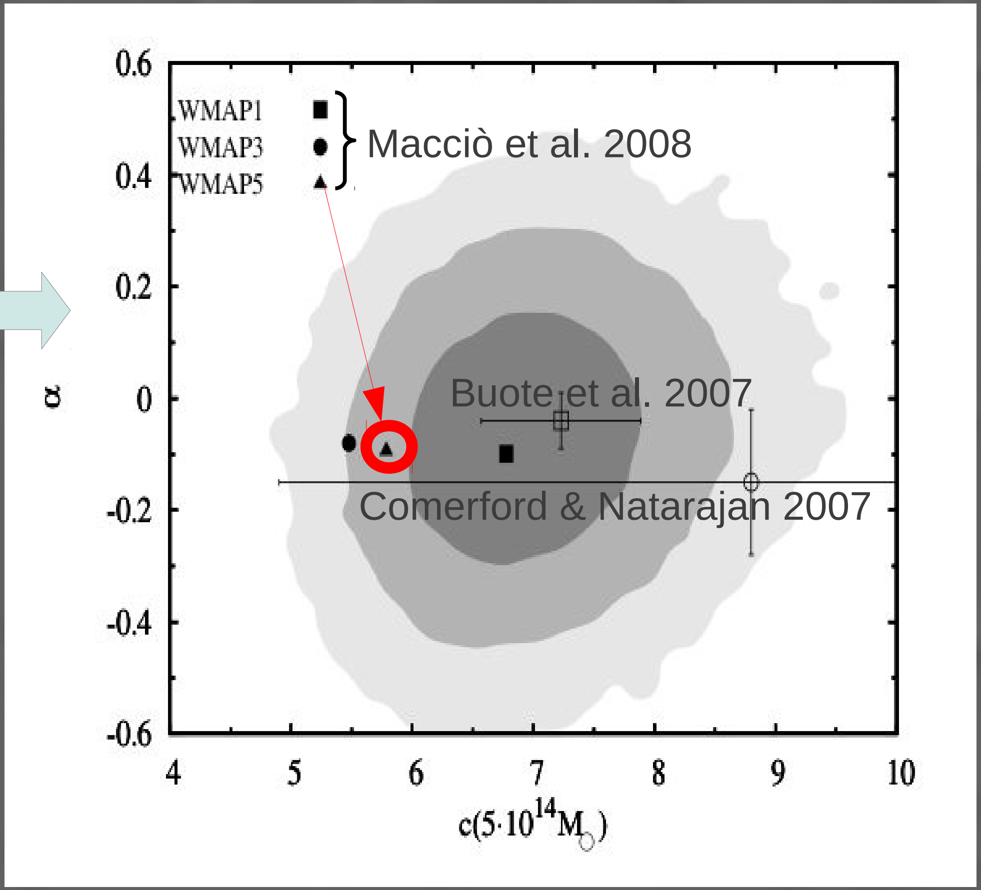
Wojtak & Łokas 2010:
DF analysis of 41 nearby galaxy clusters





Previous results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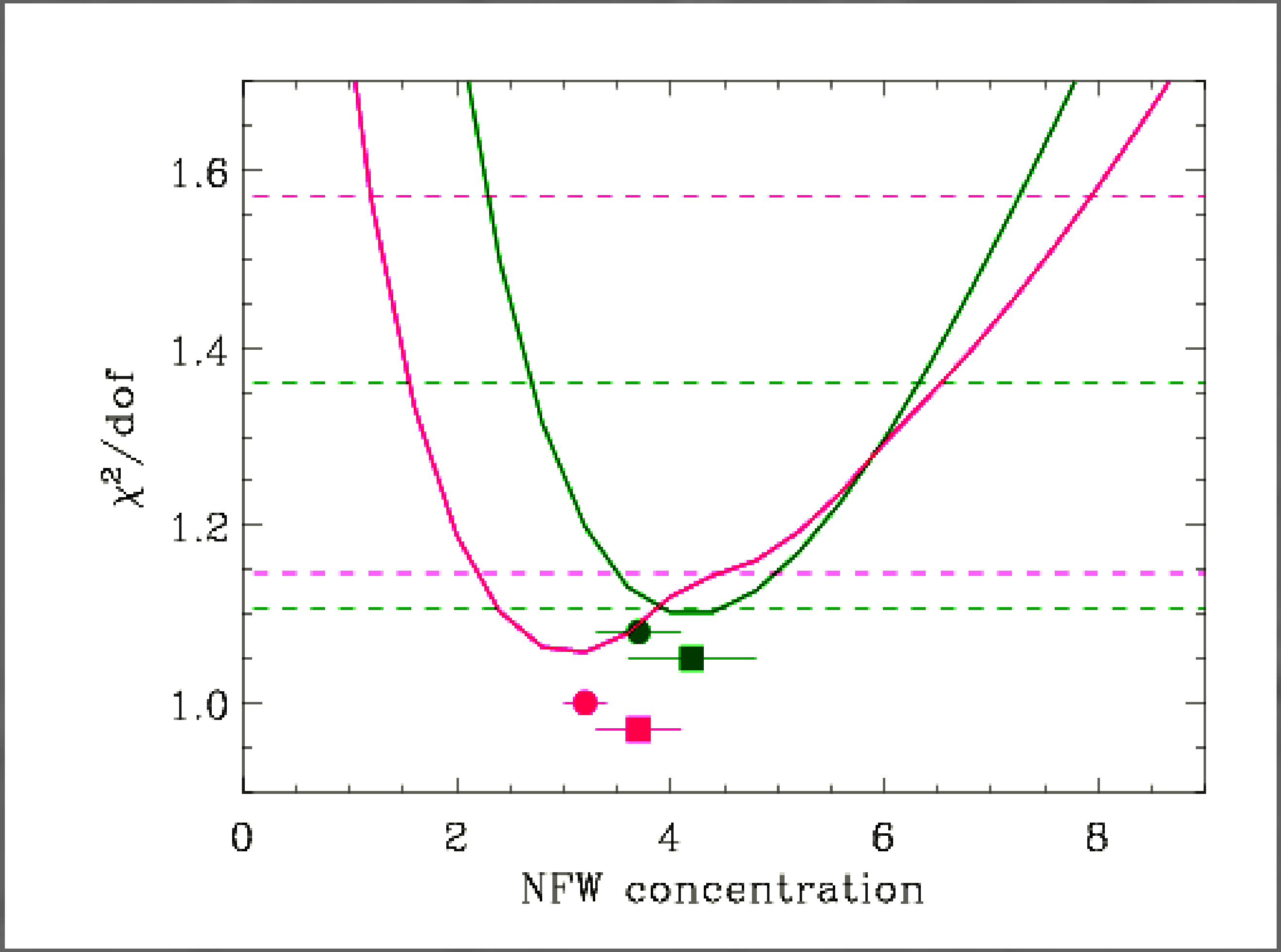
Gli austriaci scrivono: "Valanga italiana„

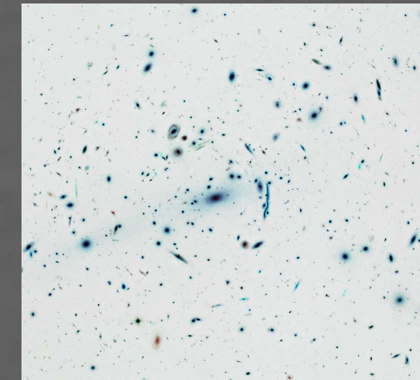
Analysis of the ENACS (**low-z**) and EDisCS (**<z>=0.56**) data-sets by *Biv. & Poggianti 2009,* based on multi-tracer Jeans equation solution



c=c(M,z) predictions from

- ● *Duffy+08* and
- ■ *Gao+08*

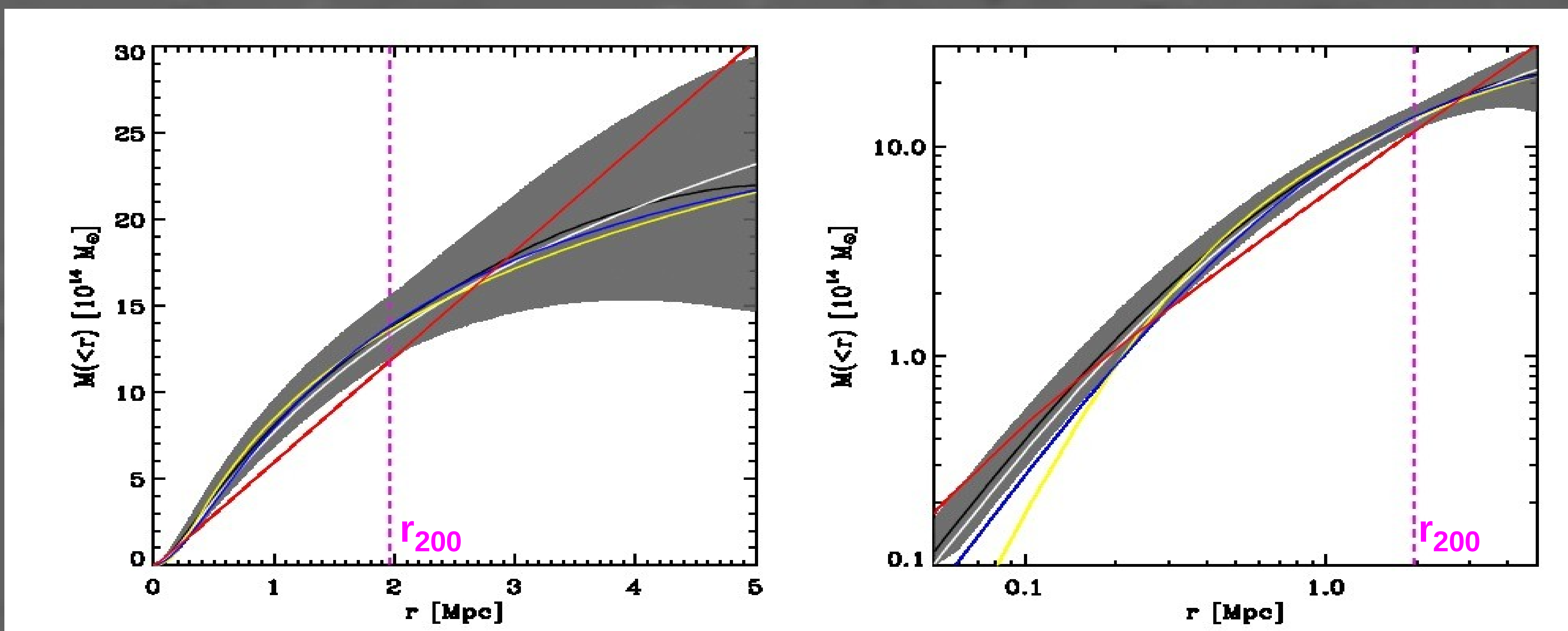
Case-study cluster:
beyond the NFW model



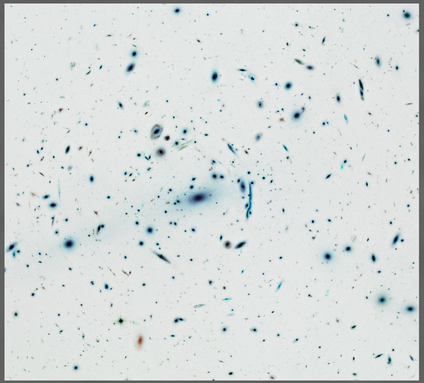
Define **fiducial M(r)** by combining lensing M(r) at r $\leq r_{200}$ and Caustic M(r) at r>r_{200}

Compare with MAMPOSSt solutions for:

NFW, **Burkert**, **Hernquist**, **SIS (softened isothermal sphere)**



Case-study cluster:
beyond the NFW model

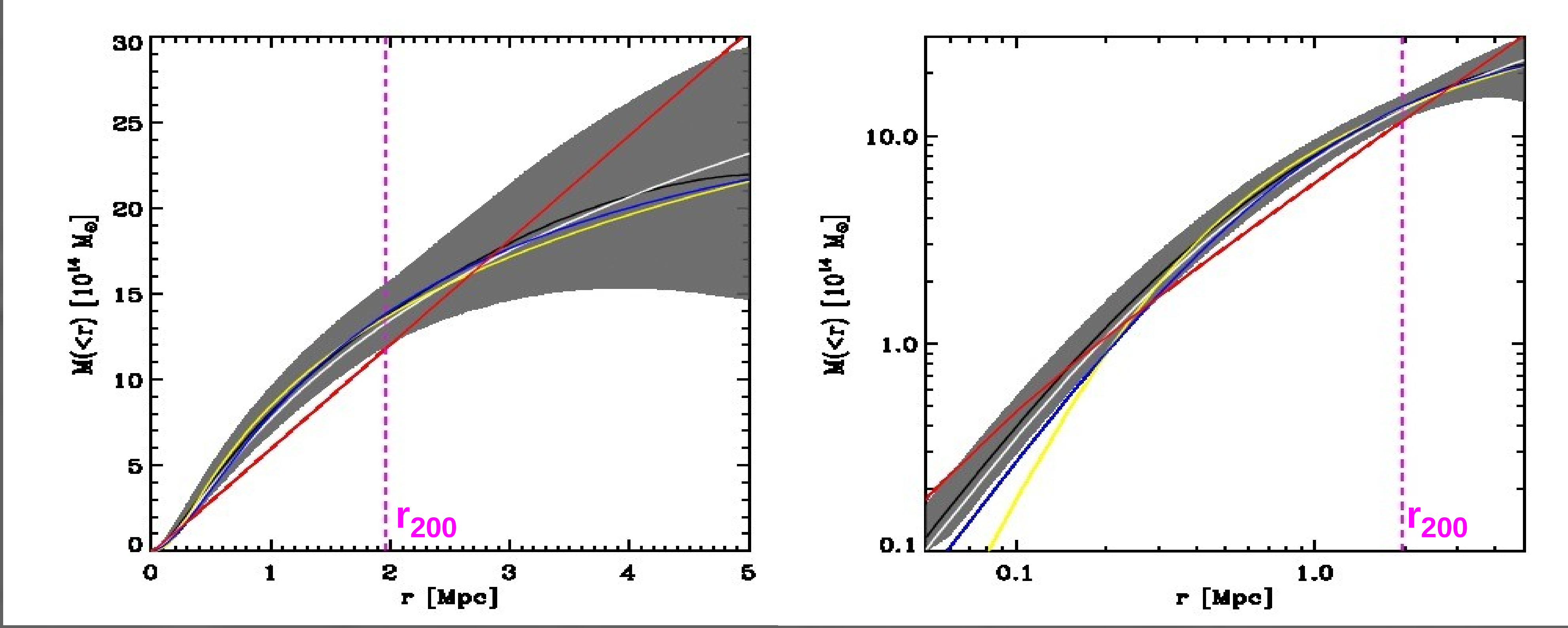


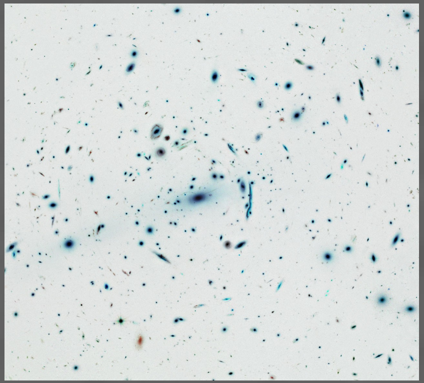
Define **fiducial M(r)** by combining lensing M(r) at $r \leq r_{200}$ and Caustic M(r) at $r > r_{200}$

Compare with MAMPOSSt solutions for:

NFW, **Burkert**, **Hernquist**, **SIS**

→ core size <50 kpc



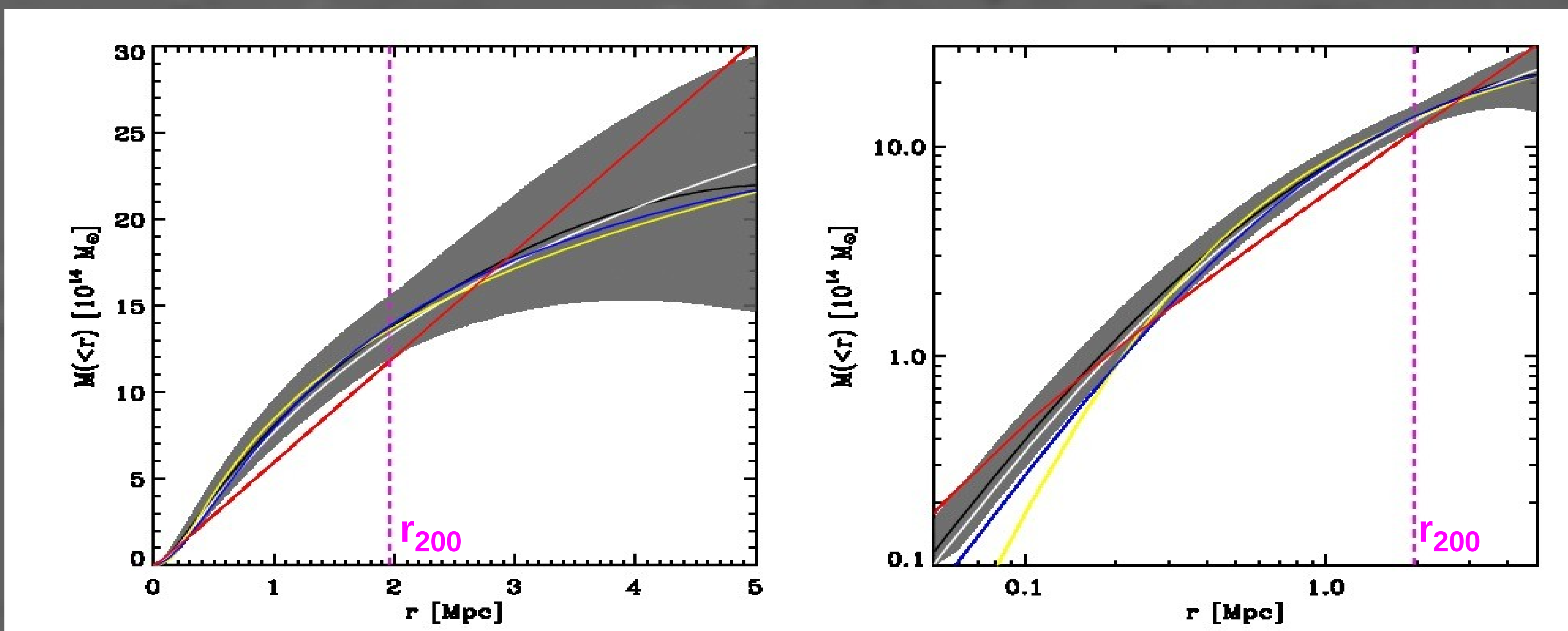


Case-study cluster:
beyond the NFW model

Define **fiducial M(r)** by combining lensing M(r) at r $\leq r_{200}$ and Caustic M(r) at r>r_{200}

Compare with MAMPOSSt solutions for:

NFW, **Burkert**, **Hernquist**, **SIS** → ρ(r) slope not constant



Previous results


SCI - La "storica„ impresa di Berchtesgaden

I magnifici cinque capofila è GROS

Gli austriaci scrivono: "Valanga italiana„

General agreement for clusters:

inner slope consistent with NFW (-1),
outer slope with either NFW or Hernquist (-3 or -4),
Burkert not rejected, but core size must be small
(~size of the central cD), SIS rejected.

Previous results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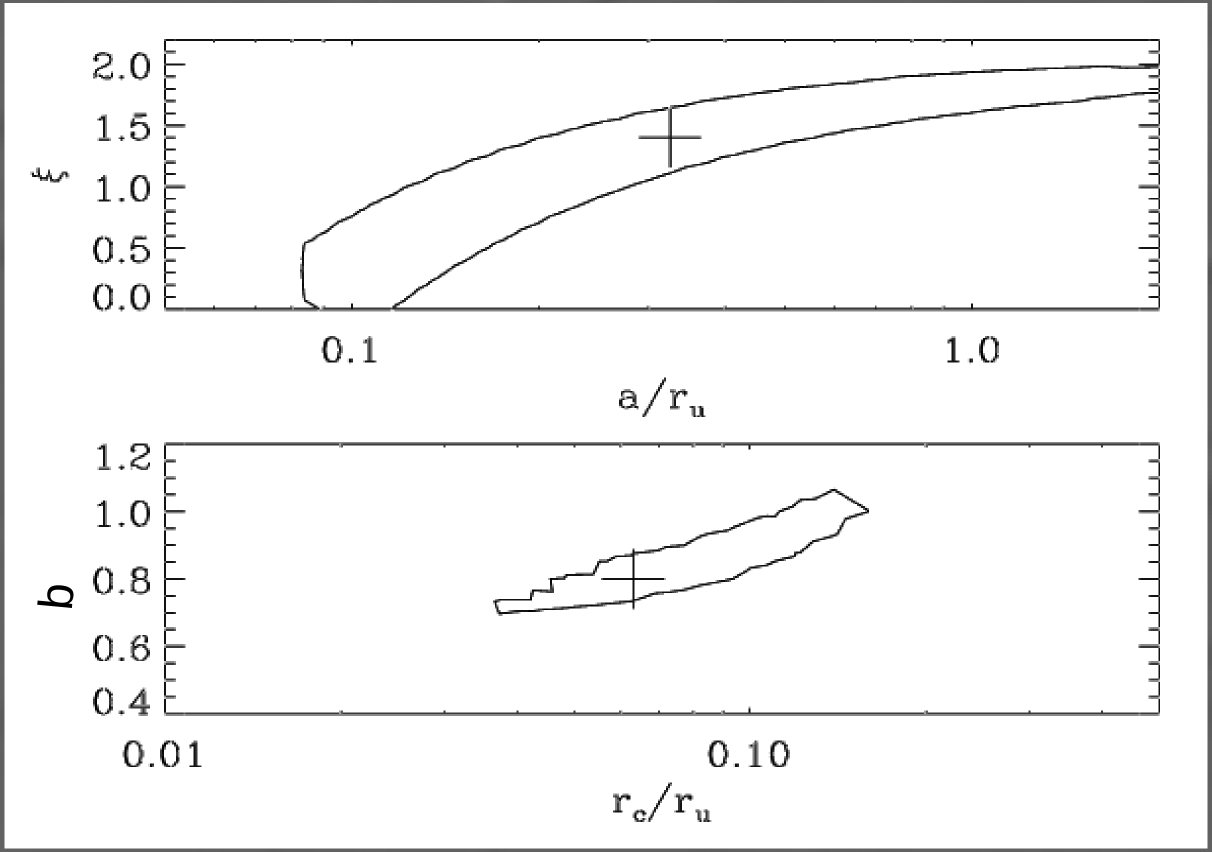
outer slope with either NFW or Hernquist (-3 or -4),
Burkert not rejected, but core size must be small
(~size of the central cD), SIS rejected.

2dFGRS cluster sample:

ξ: inner slope of generalized NFW model
a: scal-radius of NFW model in r_{200} units

b: outer slope of model with an inner core
r_c: core-radius in r_{200} units

[Biv. & Girardi 2003]

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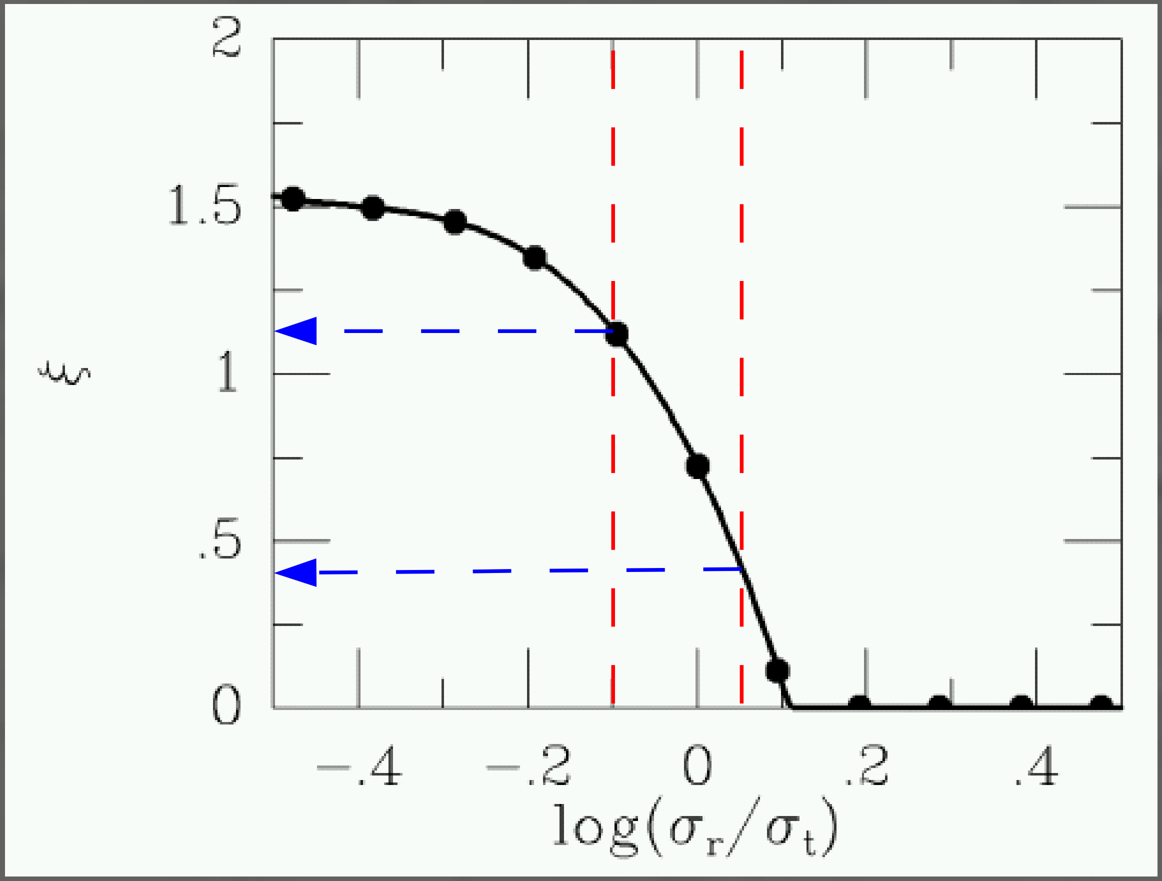
outer slope with either NFW or Hernquist (-3 or -4),
Burkert not rejected, but core size must be small (~size of the central cD), SIS rejected.

CNOC cluster sample:

ξ: inner slope of generalized NFW model vs. velocity anisotropy (found to be ≈0)

[adapted from van der Marel et al. 2000]

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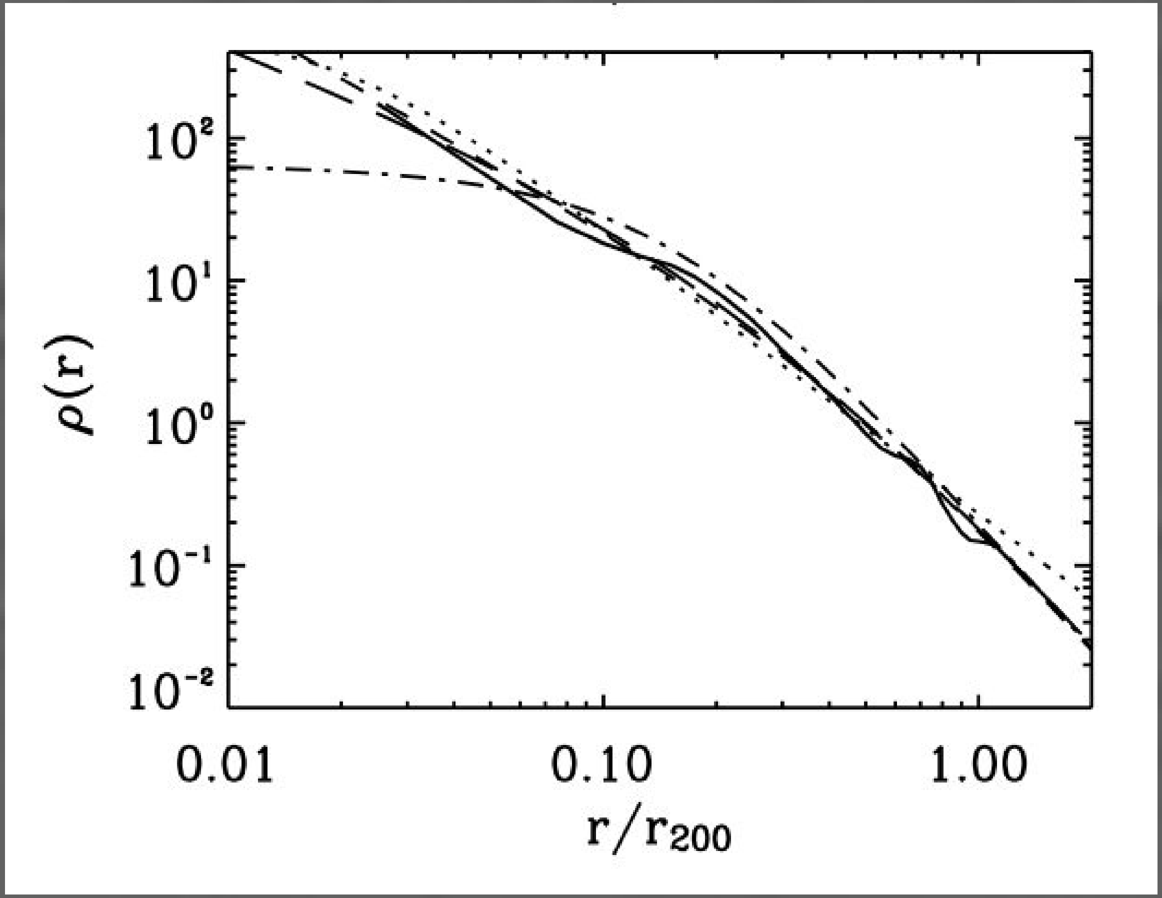
(~size of the central cD), SIS rejected.

ENACS cluster sample:

Solid: non-parametric ρ(r)
Long-dashed: NFW
Short-dashed: Moore et al. 1999
Dash-dotted: Burkert
Dotted: SIS

[Katgert, Biv. & Mazure 2004]

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Previous results

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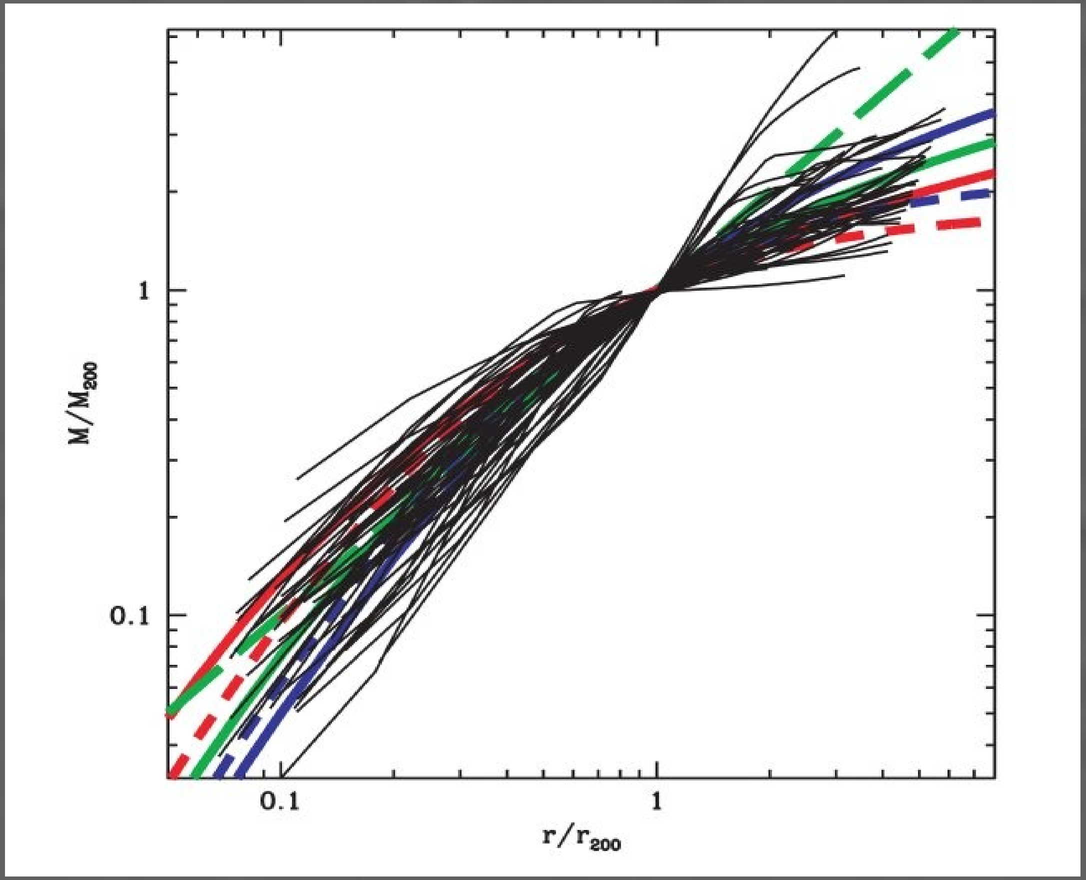
Burkert not rejected, but core size must be small
(~size of the central cD), SIS rejected.

CIRS cluster sample:

Solid: ρ(r) for individual clusters
from the Caustic analysis

Solid colored: NFW, c=3,5,10
Short-dashed: Hernquist
Long-dashed: SIS

[Rines & Diaferio 2006]



Previous results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General agreement for clusters:

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outer slope with either NFW or Hernquist (-3 or -4),
Burkert not rejected, but core size must be small
(~size of the central cD), SIS rejected.

No general agreement for groups:

Mahdavi et al. 1999:
NFW & Hernquist OK,
SIS ruled out

Mahdavi & Geller 2004:
best-fit is provided by SIS

Orbits of galaxies
and Pseudo-Phase Space density profiles

Orbits of galaxies and PPS

Why care about the shape of M(r)?

Taylor & Navarro 2001 suggested that what really matters is the shape of the PPS density profile,

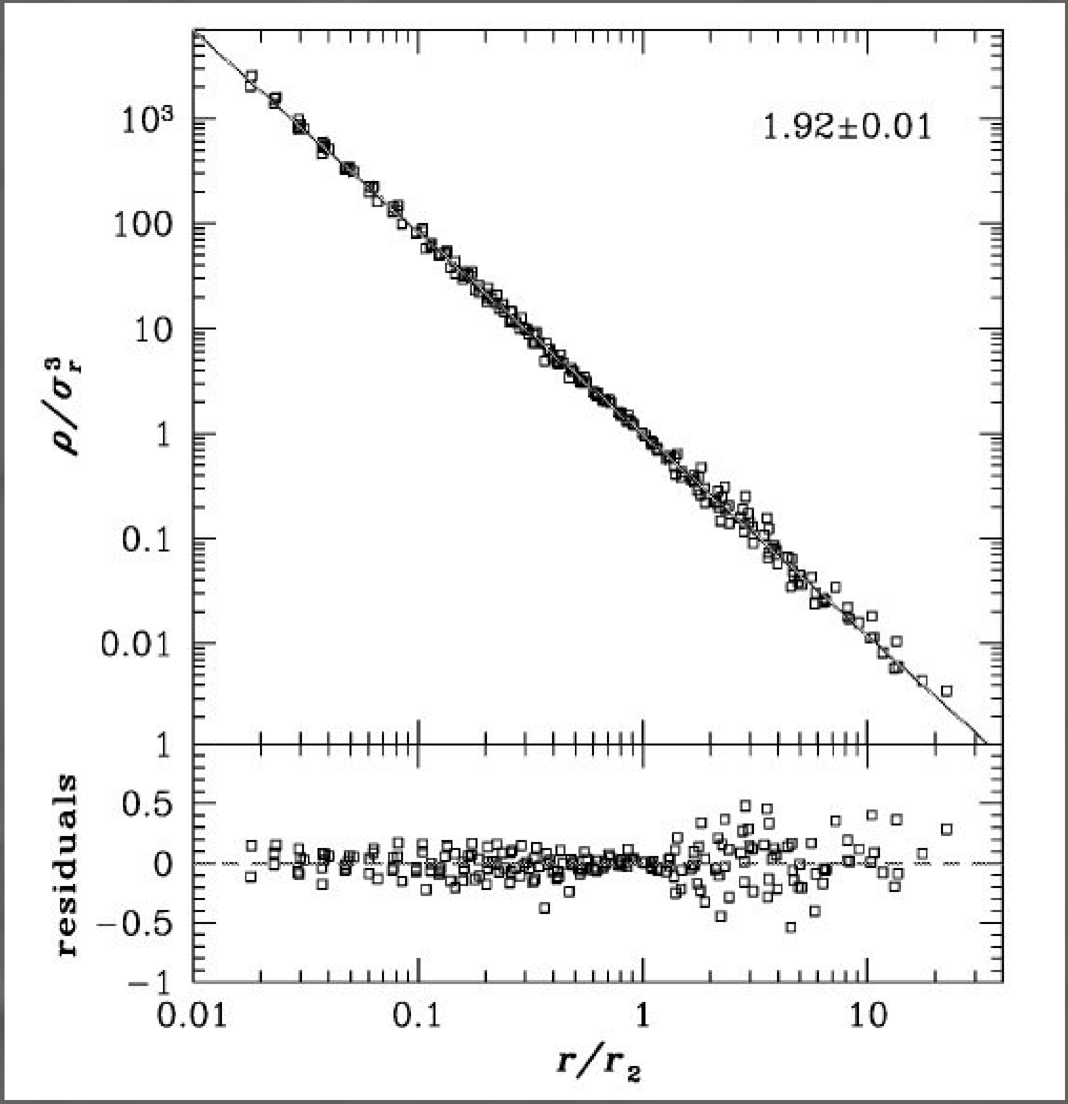
$$Q(r) = \rho/\sigma^3$$

or, perhaps,

$$Q_r(r) = \rho/\sigma_r^3$$

that might be even more fundamental and universal than Q(r) *[Dehnen & McLaughlin 2005]*

Power-law behavior predicted



Orbits of galaxies and PPS

To get $Q(r)$ and $Q_r(r)$ we need $\rho(r)$, $\sigma(r)$, $\sigma_r(r)$
i.e. both Mass and Velocity Anisotropy profiles

Given $M(r)$ and observables can get $\beta(r)$ from the inversion of the Jeans equation
[Binney & Mamon 1982, Solanes & Salvador-Solé 1990]

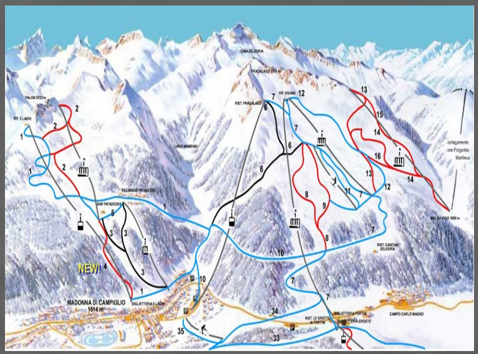
Observables
$N(R)$, $\sigma_V(R)$

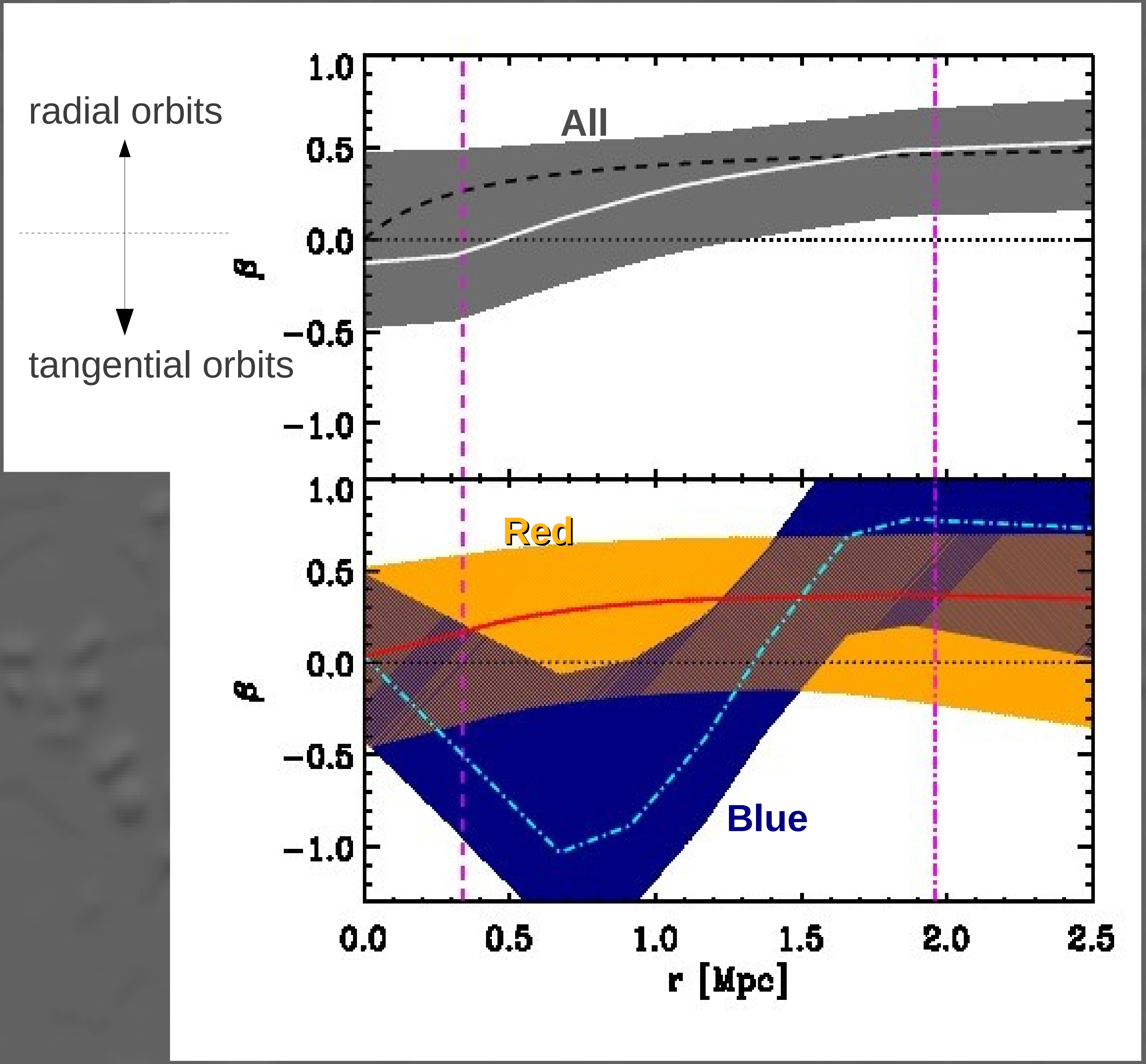
$+M(r)$ →

→ $\beta(r)$

number density profile &
l.o.s. velocity dispersion
profile of cluster members

Orbits of galaxies and PPS





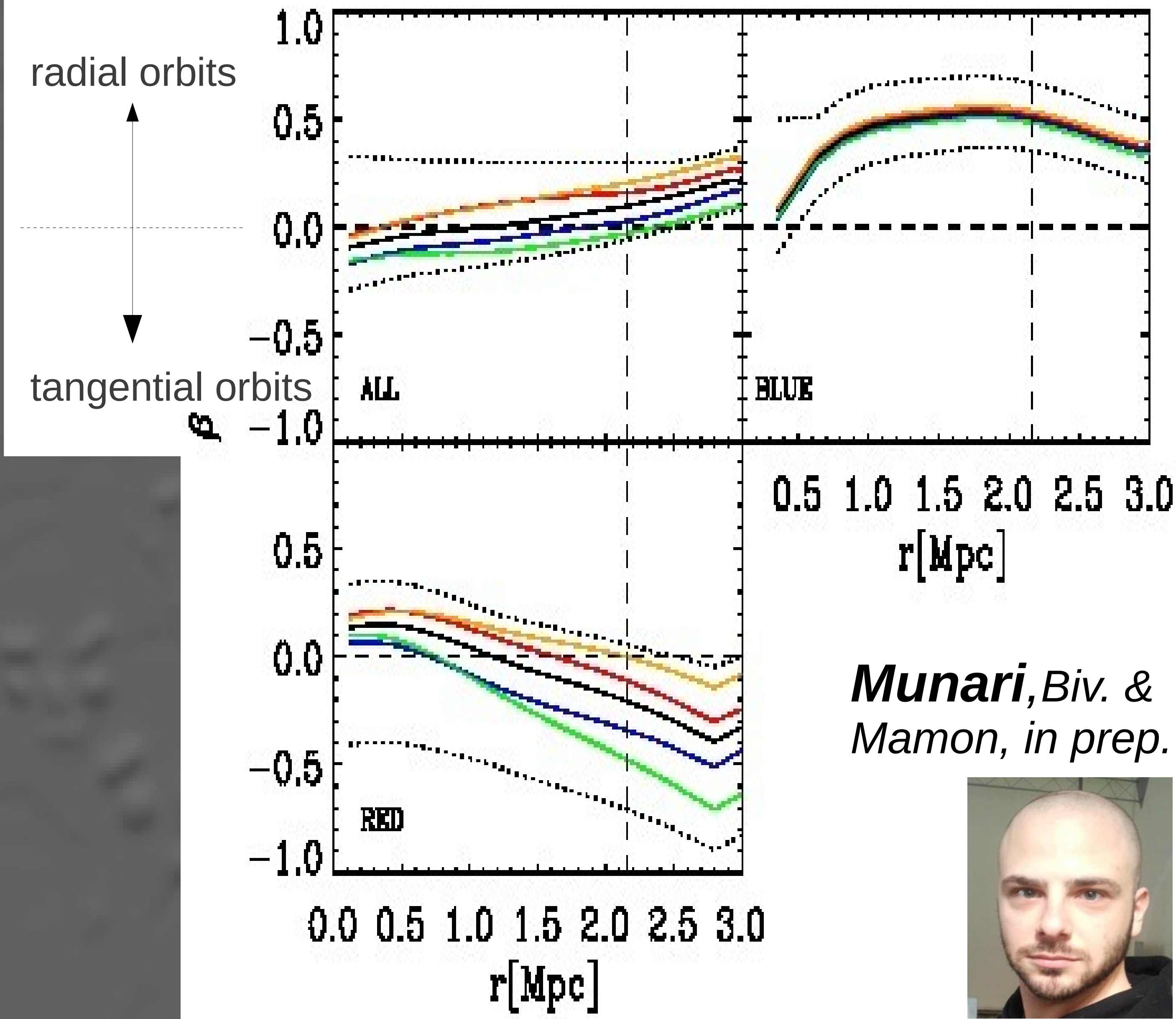
MACS J1206-0847

Velocity anisotropy profiles β(r)

All cluster members (solid white line) and theoretical expectation from numerical sims. (dashed black line)

Red (solid red line) & blue (dash-dotted blue line) members

Orbits of galaxies and PPS



Munari, *Biv. & Mamon, in prep.*

Abell 2142

Rich z=0.09 cluster.

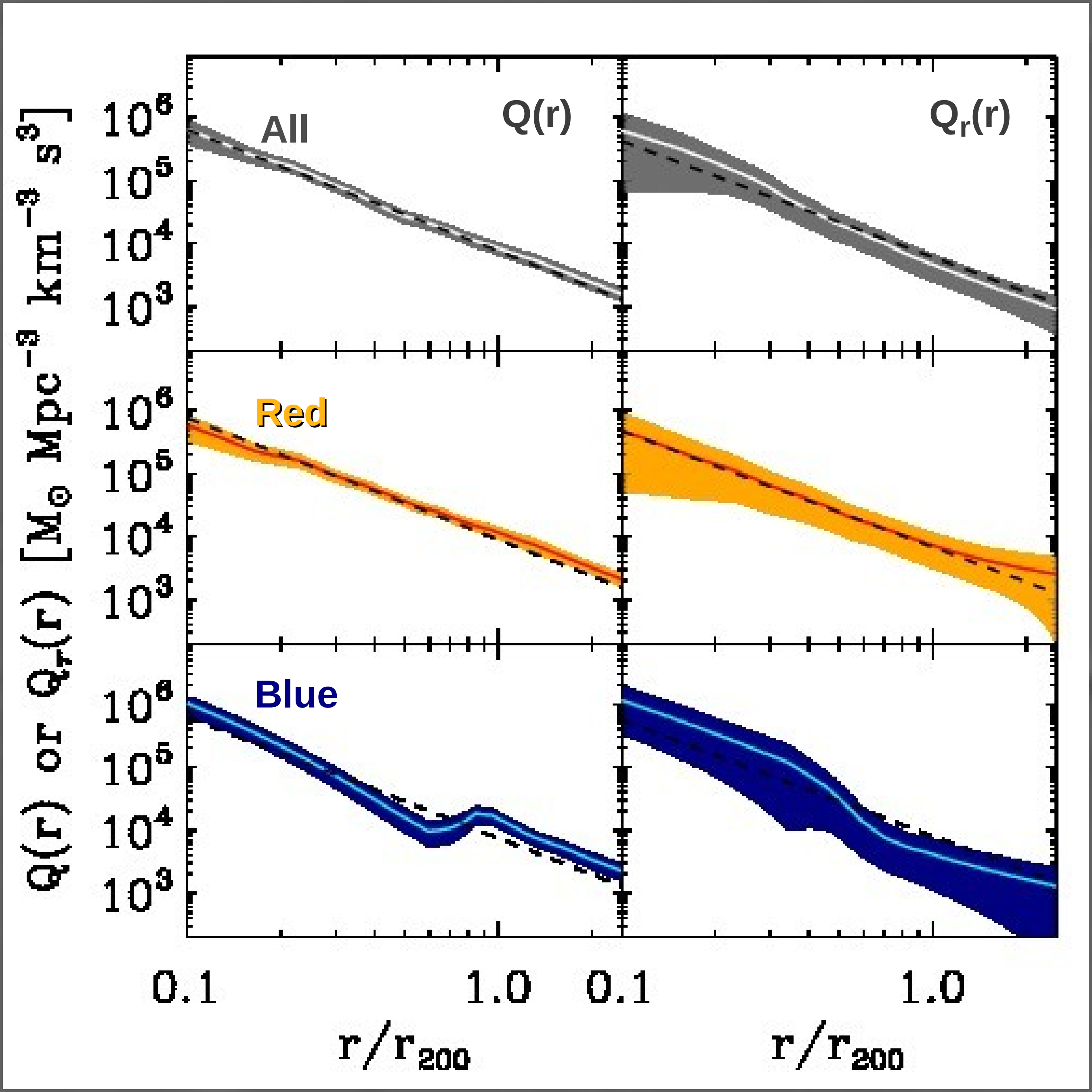
Data from *Owers, Nulsen & Couch 2011*

Velocity anisotropy profiles β(r):

Dashed lines are 1-σ intervals

Lines of ≠ colors are for ≠ M(r) determinations

Orbits of galaxies and PPS



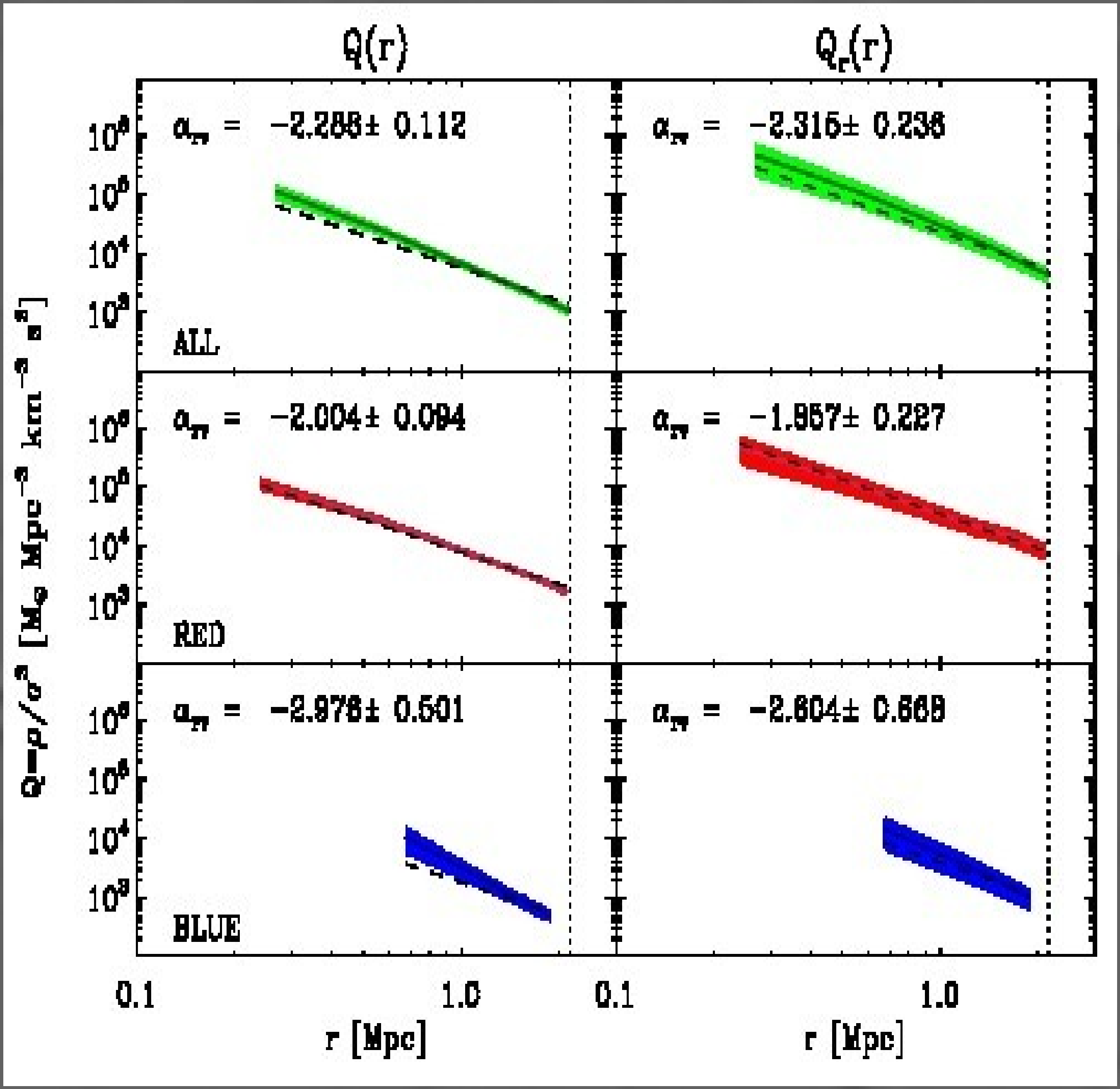
MACS J1206-0847

Pseudo-Phase Space density profiles

Data & 1-σ intervals: colored lines and shaded regions

Theoretical relations from num. simulations: dashed black lines

Orbits of galaxies and PPS



A2142

Pseudo-Phase Space density profiles

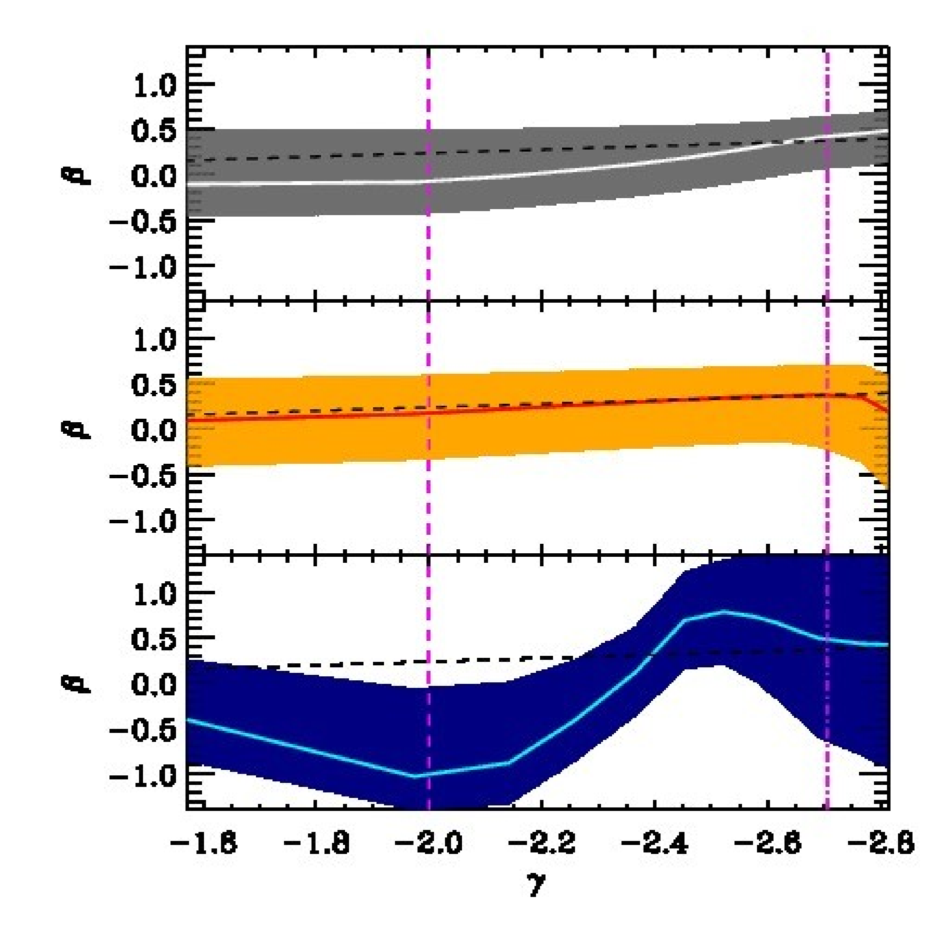
Data & 1-σ intervals: colored lines and shaded regions

Theoretical relations from num. simulations: dashed black lines

Munari, *Biv. & Mamon, in prep.*

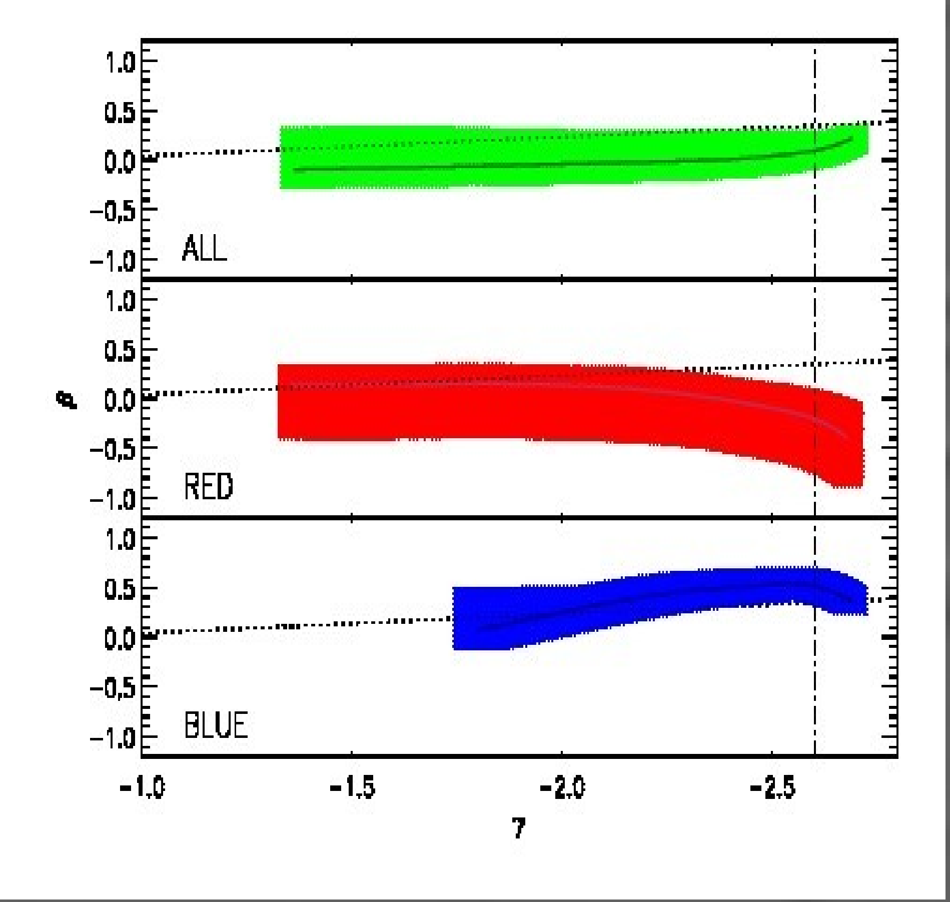
Orbits of galaxies and...
...the $\gamma(r)$-$\beta(r)$ relation

MACS J1206-0847, z=0.44



Abell 2142, z=0.09

*[**Munar**i, Biv. & Mamon in prep.]*



Dashed or dotted lines: theoretical relation of *Hansen & Moore 2006*

Summary & perspectives

Summary & perspectives

Using galaxies as tracers of the potential:

- allows M(r) determinations with competitive accuracy with other methods (given several hundreds tracers)
- allows M(r) determinations over large radial range (0.05 – 3 r_{200})
- allows velocity anisotropy profile β(r), and hence also PPS density profiles Q(r) and Q_r(r) determinations

Summary & perspectives

Current results indicate:

- M(r) is close to NFW, and the Isothermal Sphere is rejected
- Inner slope could be flat, but the core size must be small (<0.05 Mpc)
- Outer slope could be steeper than NFW, perhaps Hernquist-like
- Clusters are slightly more concentrated than expected for their mass
- Theoretical Q(r) and Q_r(r) power-law relations are confirmed...
- ...and so is also the γ(r)-β(r) relation (but not for blue galaxies?)
- Orbits of different cluster galaxy populations are different, and evolve with z ⇒hints to galaxy evolution in clusters

Summary & perspectives

Future developments:

- ✯ Technical developments for MAMPOSSt: beyond the Gaussian 3-d velocity distribution, beyond the spherical assumption, joint analysis with gravitational lensing constraints

- ✯ Analysis of large low-z cluster samples, SDSS, WINGS, to see dependence of M(r) and β(r) on cluster properties (e.g. dynamical status)

- ✯ Analysis of distant clusters to investigate M(r) and β(r) evolution:
  CLASH-VLT (14 <z> ≈ 0.4 clusters, ≈ 500 members with z per cluster)
  DAFT/FADA (9 <z> ≈ 0.6 clusters, ≈ 150 members with z per cluster)

- ✯ Analysis of a sample of X-ray emitting groups, to solve current discrepant results on their M(r)

(In collaboration with: G. Mamon, A. Cava, and the CLASH & DAFT/FADA teams)