Galaxy Clusters Across Cosmic Times: Opening Talk

Andrea Biviano, INAF-OATs

SESSION A: **GALAXY EVOLUTION IN CLUSTERS**

1 : Perturbations on the different components of the ISM (gas, dust, metals)

2 : Quenching of the star formation activity of cluster galaxies

3 : Perturbations on the kinematical properties

4 : Tidal stripping of dark matter haloes

5 : Simulations and model predictions

6 : Identification of the dominant perturbing mechanism

7 : Future surveys

SESSION B: **WHAT IS A GALAXY CLUSTER? FROM THE BCG TO BEYOND THE VIRIAL RADIUS**

1 : Hot gas: physical and chemical properties and distribution

2 : Dark component: distribution and detection methods

3 : Beyond the viral radius : how is the matter accreted ?

4 : Relativistic population and magnetic fields: generation and evolution

5 : Non thermal properties (cosmic rays, annihilation of DM particles)

SESSION C: **HOW AND HOW WELL DO WE MEASURE MASSES?**

1 : X-ray/SZ

2 : Lensing

3 : Kinematics/caustics

4 : Combining probes

5 : Guidance on robustness from simulations

6 : Future instruments

SESSION D: **HOW AND HOW WELL DO WE USE THEM AS COSMOLOGICAL PROBES ?**

1 : Cluster counts and clustering (PS, BAO, RSD)

2 : High-z clusters as cosmological probes

3 : Gas mass fraction and its evolution

4 : Combination of cosmological probes

5 : Impact of baryons on theoretical predictions

6 : Future instruments

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Sorry,
I have no answers,
only questions

?

Galaxy Evolution in Clusters

Odysseus’ crew opens Aeolus’ bag of winds

Galaxy Evolution in Clusters

G=gravitational process; H=hydrodynamical process

G1) galaxy-galaxy tidal stripping
(harassment)

H1) starvation

G2) dynamical friction

G3) galaxy-galaxy mergers

H2) ram-pressure stripping

H3) thermal evaporation

G4) tidal interaction with cluster grav. field

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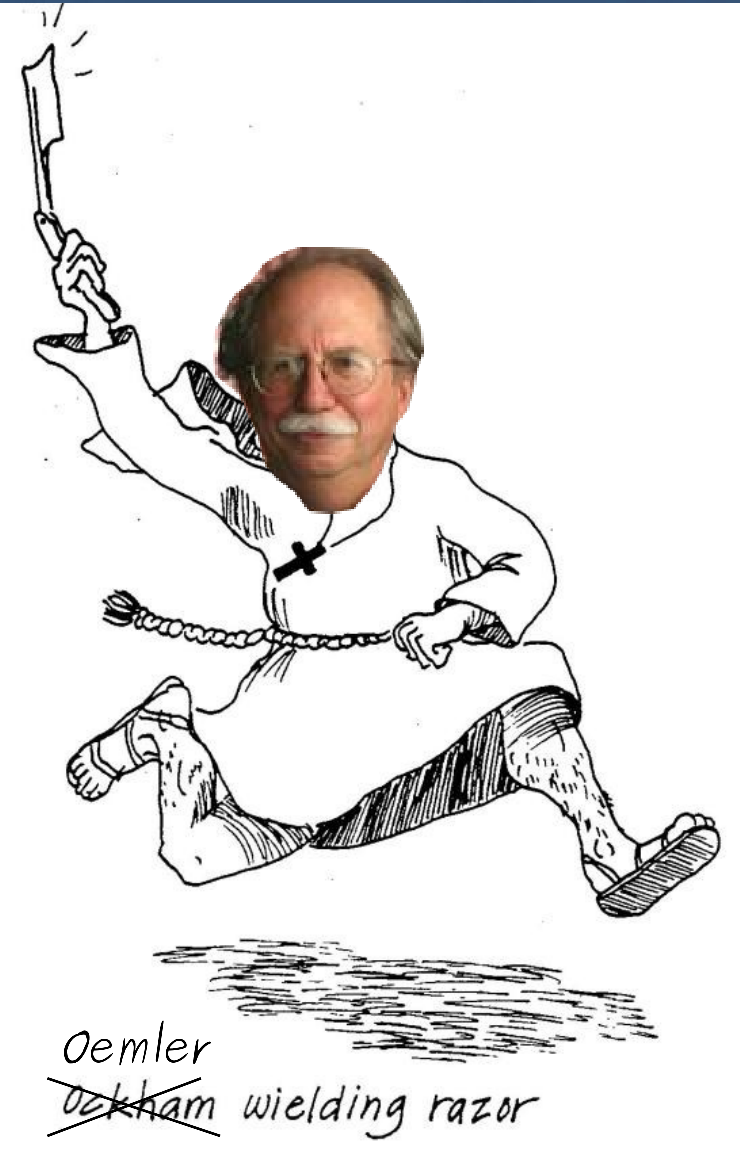
Which is the dominant process?

Galaxy Evolution in Clusters

Ockham's razor:
"Numquam ponenda est pluralitas sine necessitate"
[Plurality must never be posited without necessity]

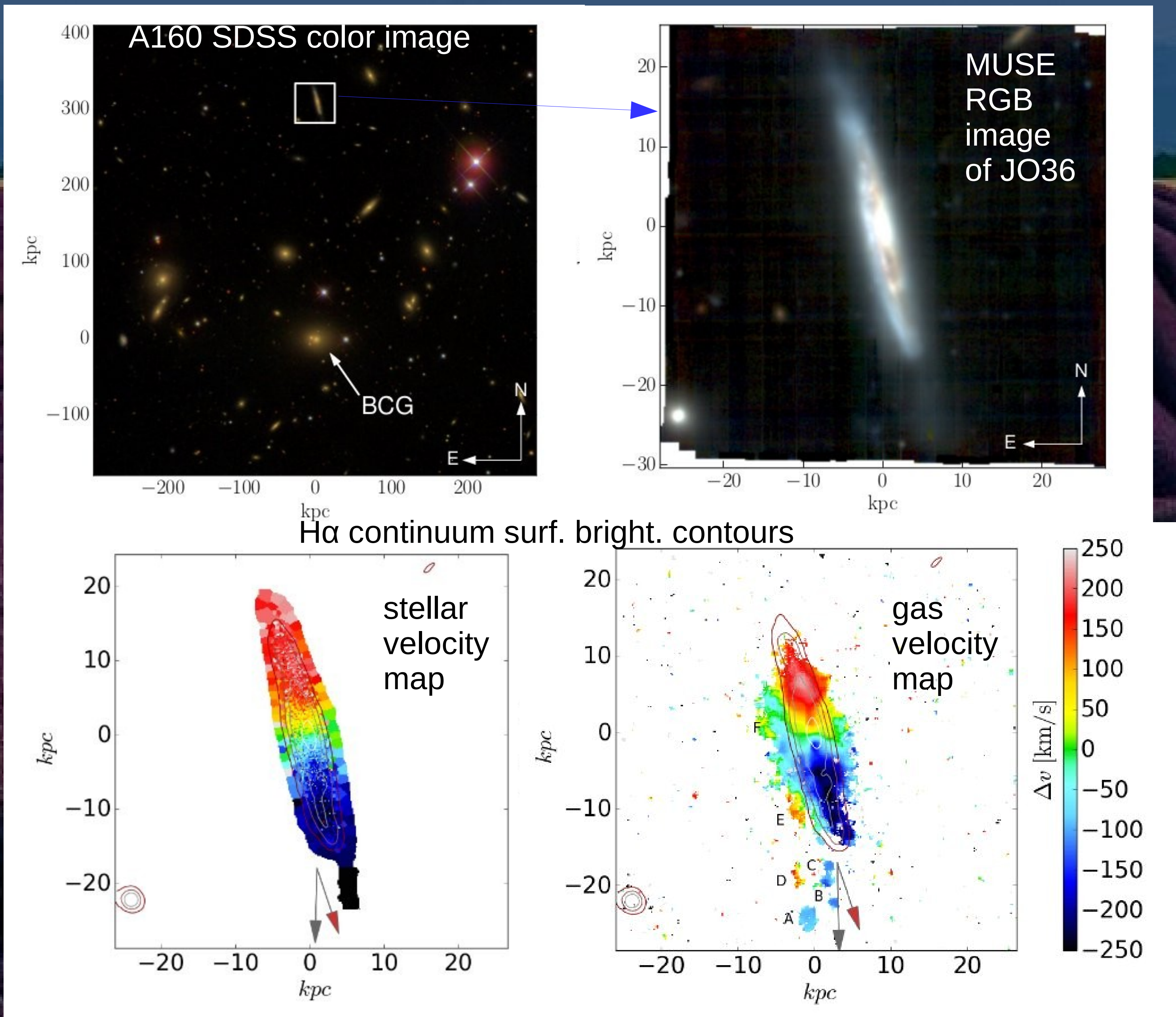
Galaxy Evolution in Clusters



Ockham's razor:
"Numquam ponenda est pluralitas sine necessitate"
[Plurality must never be posited without necessity]

Oemler's razor:
"There is no one dominant process"
[as quoted by S. Baum at the 'Clusters and Superclusters of Galaxies' conference held in Cambridge, UK, July 1991]

Galaxy Evolution in Clusters



GASP survey data (Gas Stripping Phenomena in galaxies with MUSE)
ESO LP,
PI: B. Poggianti
INAF-OAPd

Fritz+17, ApJ submitted:

gas velocity map suggests ram-pressure stripping,

one-side extended stellar trail suggests galaxy-galaxy interaction

Galaxy Evolution in Clusters

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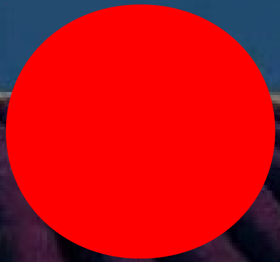
G1) galaxy-galaxy tidal stripping *(harassment)*

H1) starvation



Whole cluster

G2) dynamical friction

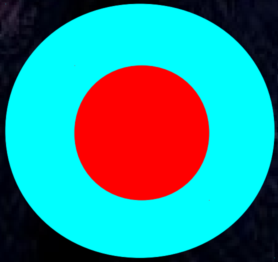
Mostly in the inner regions

G3) galaxy-galaxy mergers

In the outskirts; in the center only if dynamical friction is effective

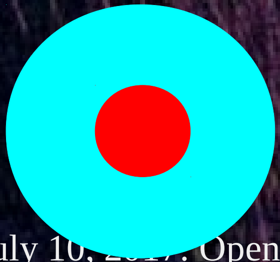
H2) ram-pressure stripping

H3) thermal evaporation



In the inner regions

G4) tidal interaction with cluster grav. field



In the very center

Galaxy Evolution in Clusters

G=gravitational process; H=hydrodynamical process

G1) galaxy-galaxy tidal stripping *(harassment)* → Effective at low velocities

H1) starvation → Effective at high velocities

G2) dynamical friction → Effective at low velocities

G3) galaxy-galaxy mergers → Effective at low velocities

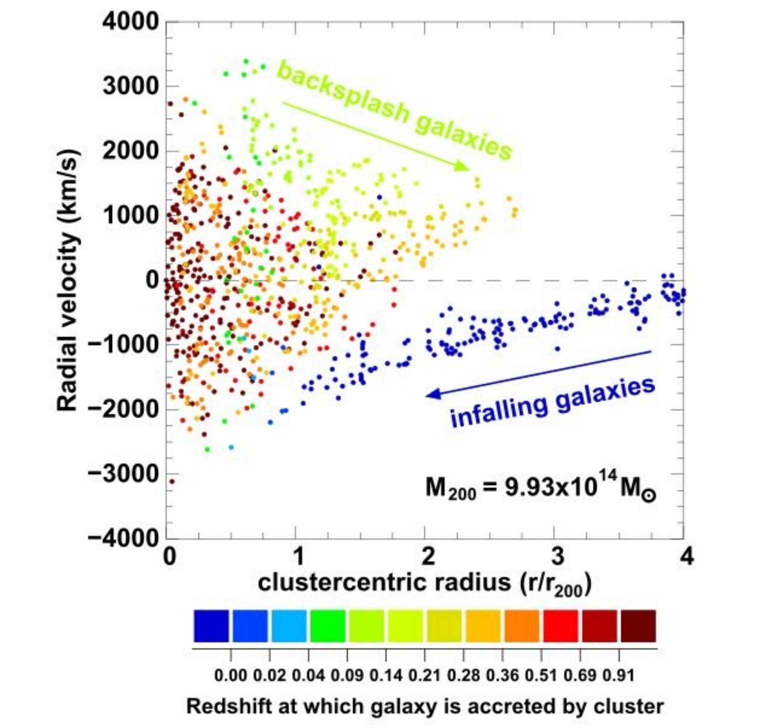
H2) ram-pressure stripping → Effective at high velocities

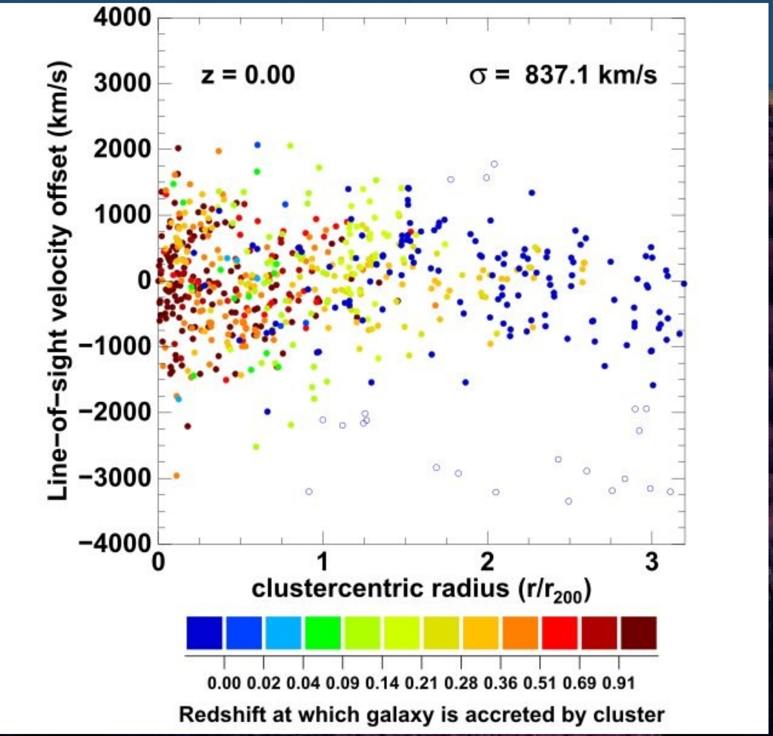
H3) thermal evaporation

G4) tidal interaction with cluster grav. field → Effective at low velocities

Galaxy Evolution in Clusters

A powerful tool of investigation: the phase-space diagram





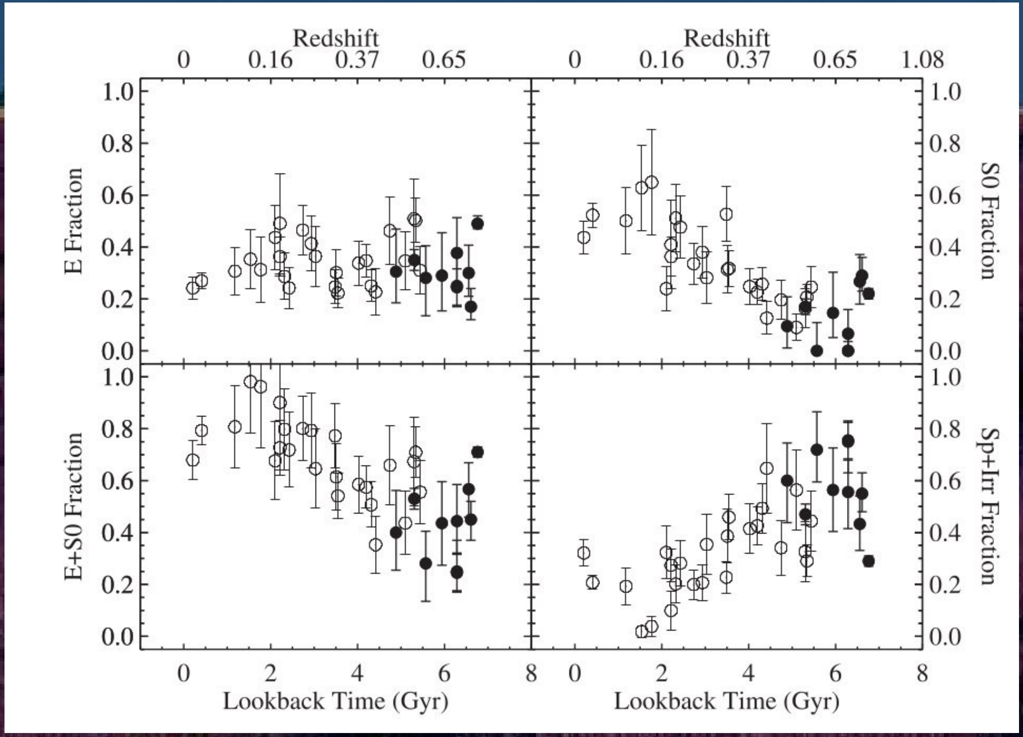
Haines+15: Galaxies in a massive halo from the Millennium simulation.
Simulations cmpd to LoCuSS data suggest Star-Forming galaxies being an infalling population, but one that survives 0.5-2 Gyr after crossing r_{200}.

Muzzin+14: post-starburst galaxies ~1 Gyr quenching after infall

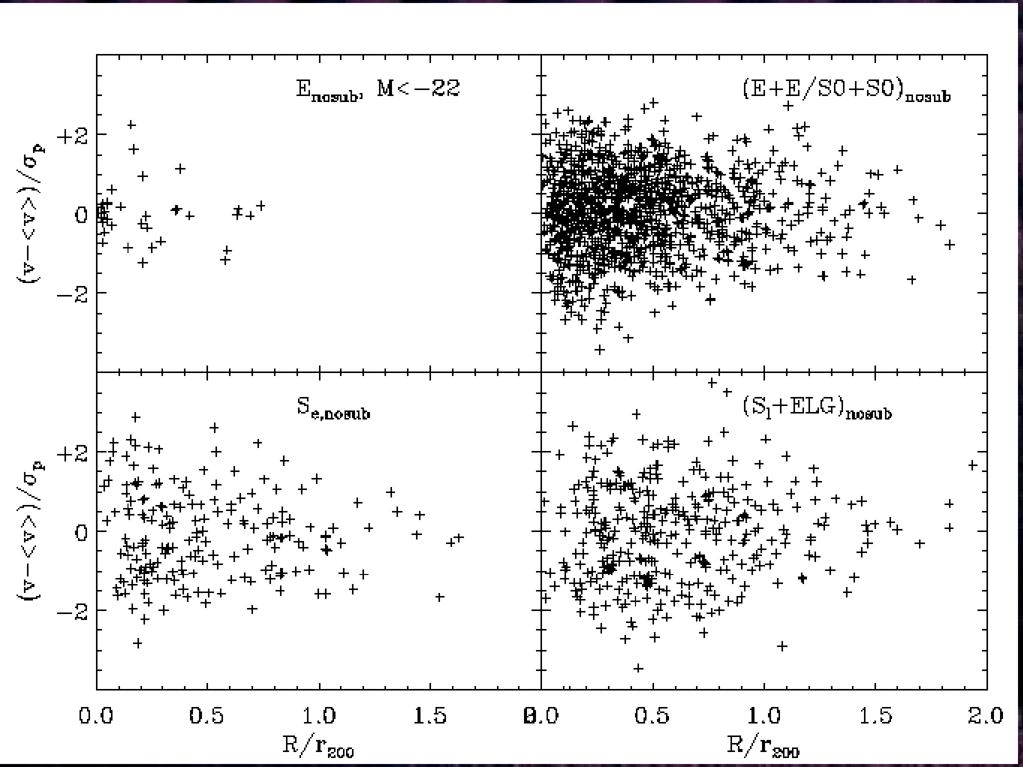
Oman+Hudson 16: satellite quenching on first infall, within ~1 Gyr of 1st pericentric passage

Galaxy Evolution in Clusters

Desai+07 (EdisCS): S0 fraction grows x3 in 2-3 Gyr



AB+ 02: In z~0 clusters (ENACS) S0 and Ellipticals share the same projected phase-space distribution, different from Spirals



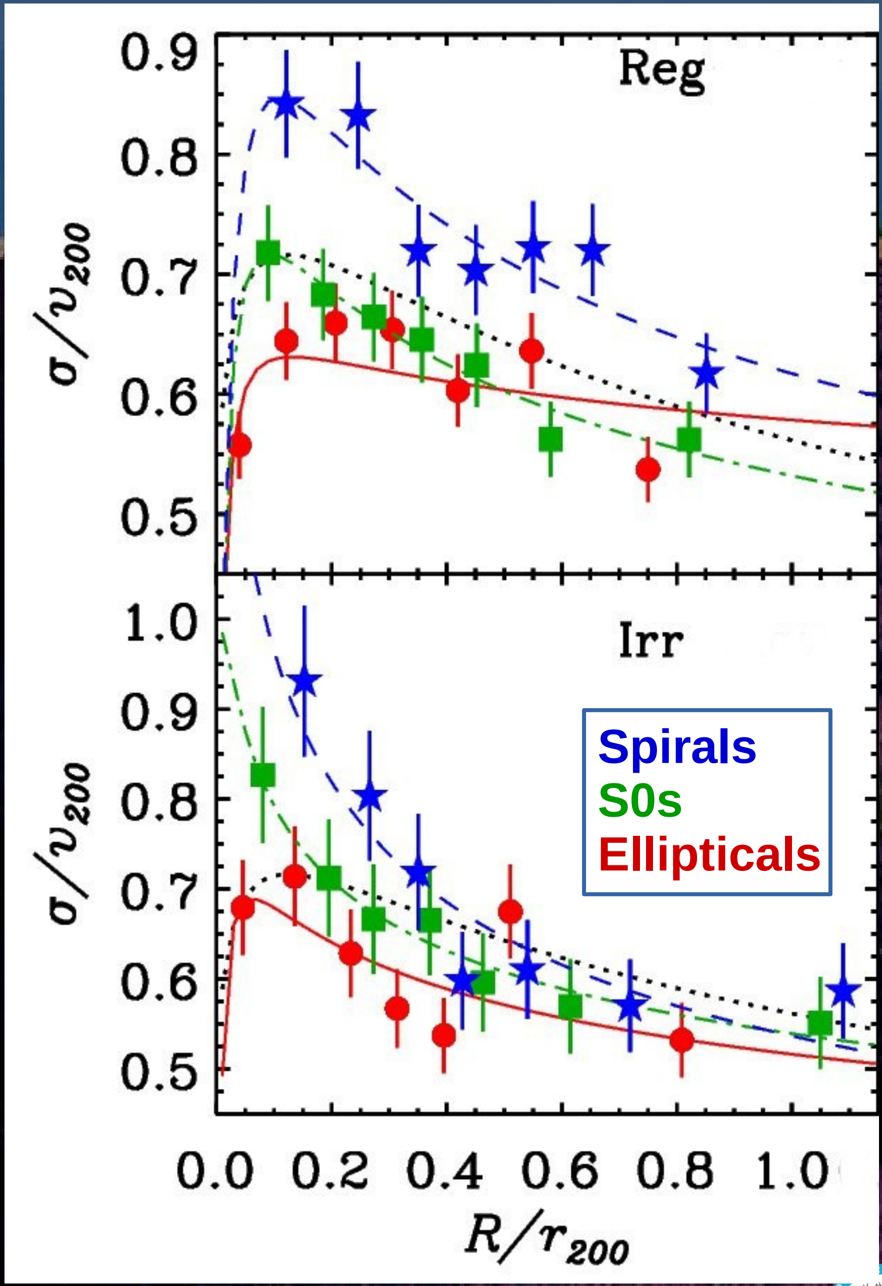
...if S0 form from Spirals how comes S0 and Spirals have different phase-space distributions?

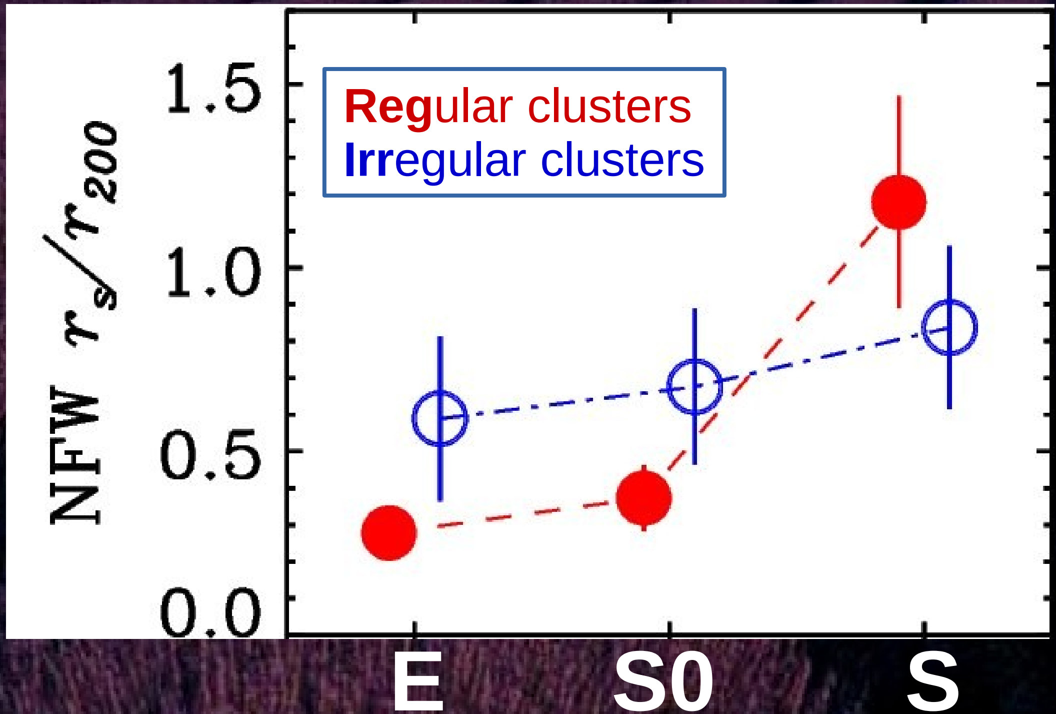
Galaxy Evolution in Clusters

Cava+17, A&A submitted (WINGS data-set, Pis: B. Poggianti & G. Fasano)

S0 projected phase-space distribution similar to E in Regular clusters, intermediate between E and S in Irregular clusters

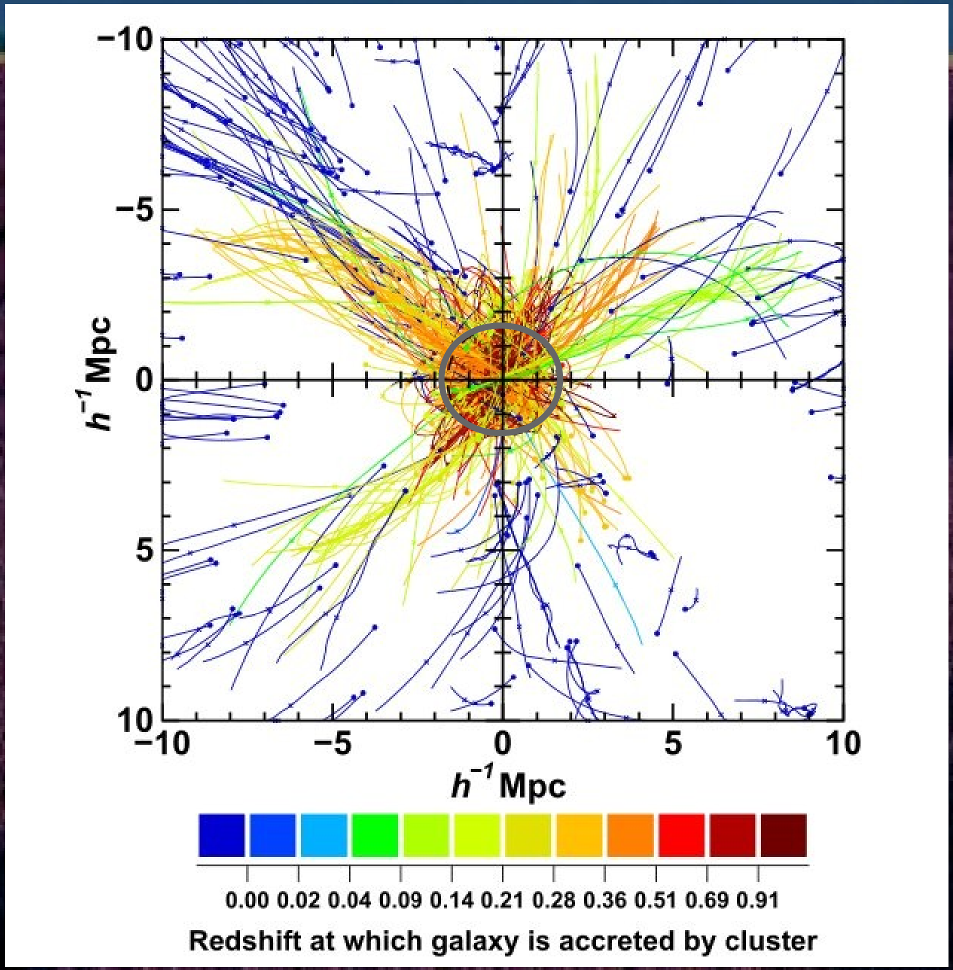
S → S0 transformation process
⇒ evolution in spatial and velocity distribution, fully accomplished in Regular clusters, but still ongoing in Irregular cluster



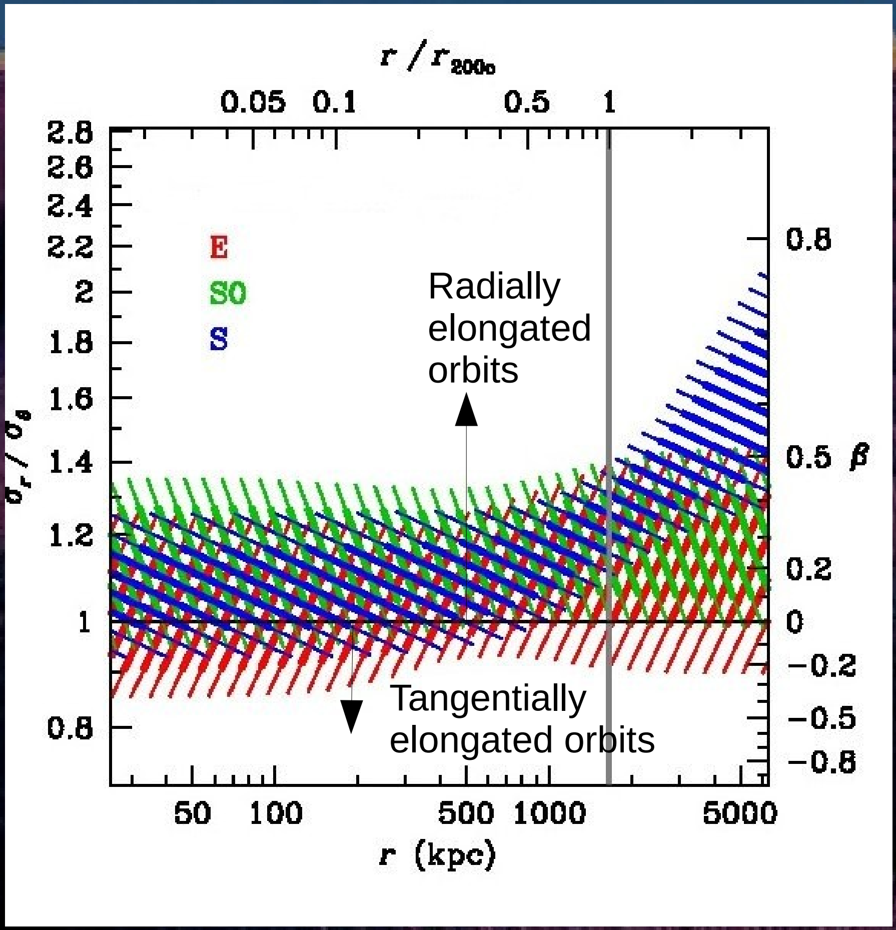


Galaxy Evolution in Clusters

Physical processes depend upon the location within the cluster, but galaxies move...
Distribution in phase-space + gravitational potential = orbits of galaxies in clusters



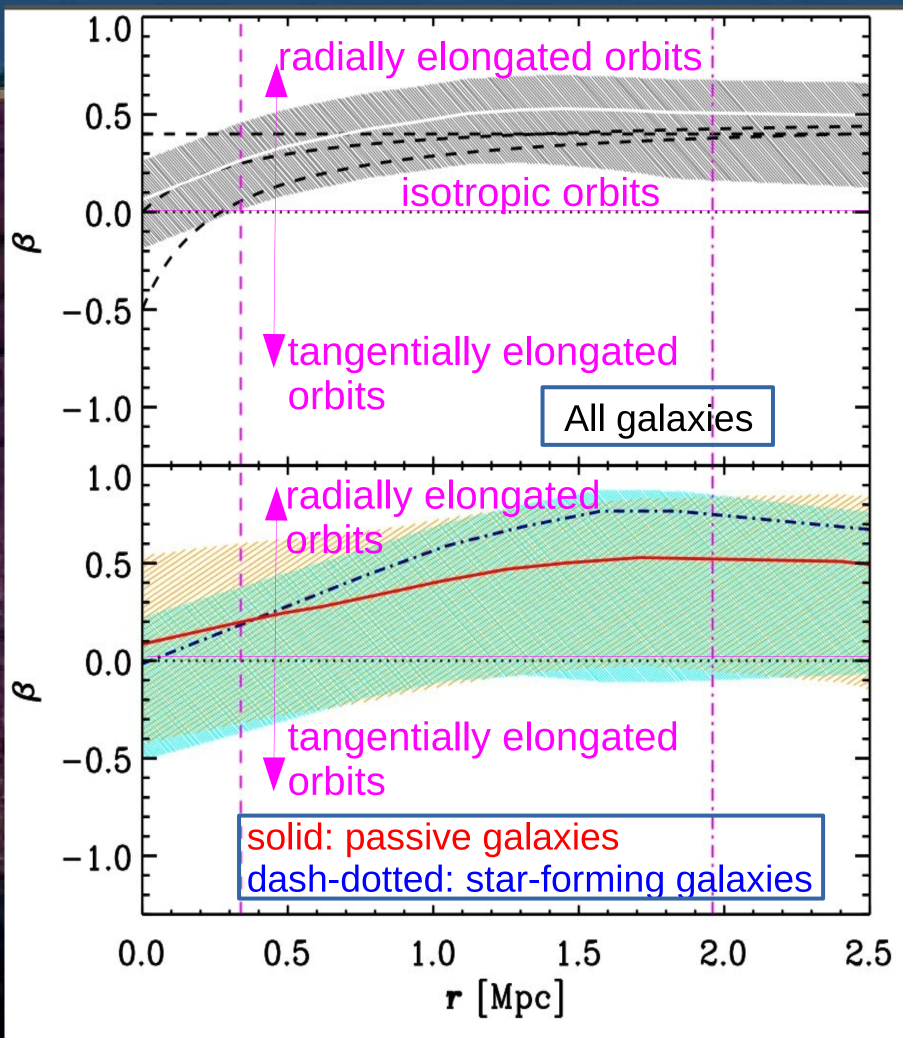
Haines+15:
Individual galaxy orbits in a massive halo from the Millennium simulation



Mamon+ in prep.:
Velocity-anisotropy profiles of WINGS regular cluster galaxies

Galaxy Evolution in Clusters

Evolution of galaxy orbits in clusters



AB+13 (CLASH-VLT):
MACS1206 z=0.440 cluster

The orbits of red/passive galaxies become more radially elongated with z, and more similar to those of blue/star-forming galaxies (that do not evolve).

*This evolution is seen in the CLASH-VLT clusters (**ESO LP, PI: P. Rosati**) at 0.2<z<0.5 (AB+13; Annunziatella+16)*
*and in a stack of 10 GCLASS clusters (**PI: G. Wilson**) at z~1 (AB+16),*
when compared to z<0.1 clusters (from ENACS, AB+Katgert 04; and from WINGS, Mamon+ in prep.)

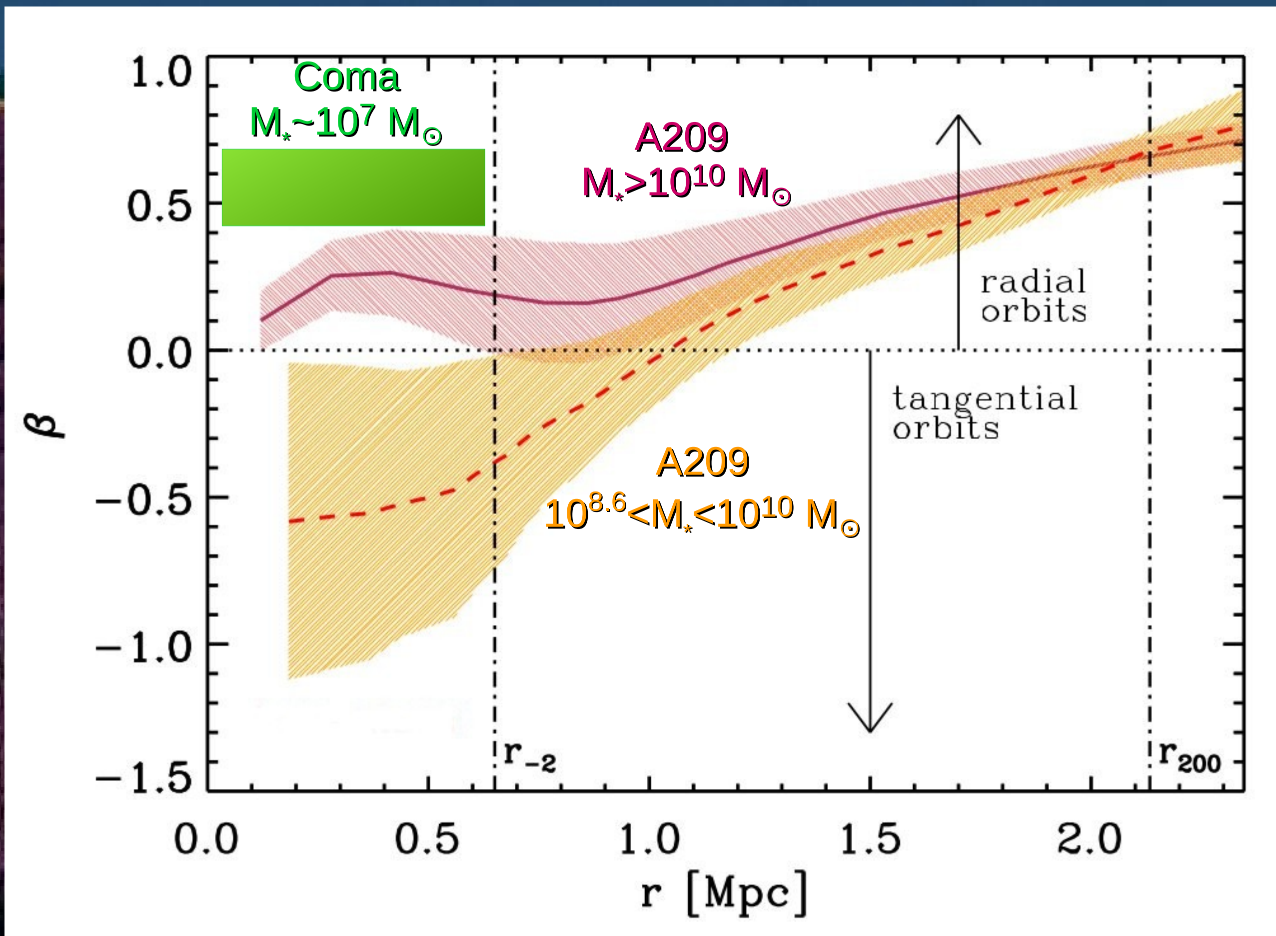
This orbital evolution seems to be recent, over the last ~2 Gyr of cosmic time

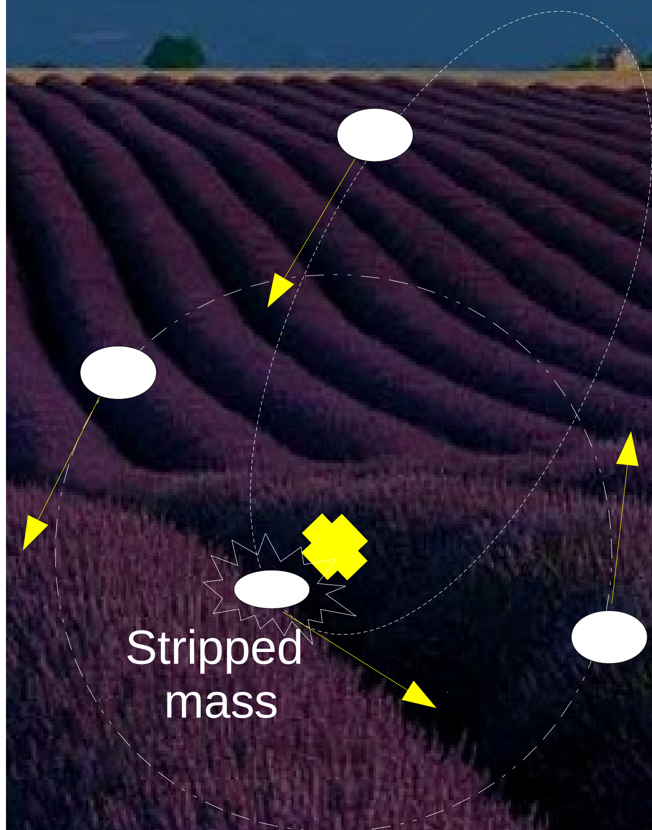
How is it related to quenching and morphological evolution?

Galaxy Evolution in Clusters

Annunziatella+16 (CLASH-VLT data for z=0.21 A209 cluster)
\+ Adami+09 (VIMOS data for dwarfs in z=0.023 Coma cluster)

} Galaxy orbits in clusters depend on galaxy mass





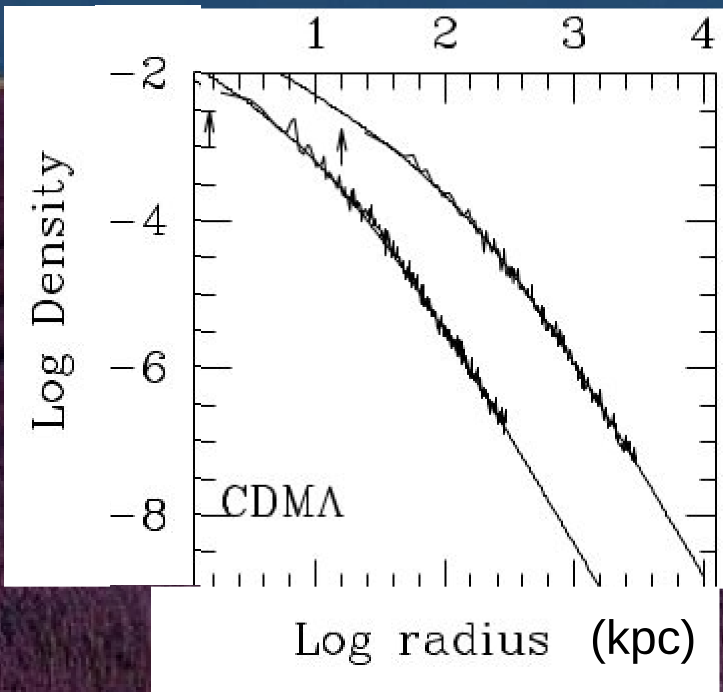
Galaxies on radial orbits have small pericenter, they feel strong tidal field. This field does not affect very massive galaxies. Less massive ones on radial orbits loose part of their mass and drop below the A209 survey limit ($10^{8.6}\ M_\odot$). Those that survive are on more tangential orbits. In Coma, very-low mass galaxies have radial orbits (remnants of stripped ones?)

From the BCG to Beyond the Virial Radius

Opening
René Magritte’s
window

From the BCG to Beyond the Virial Radius

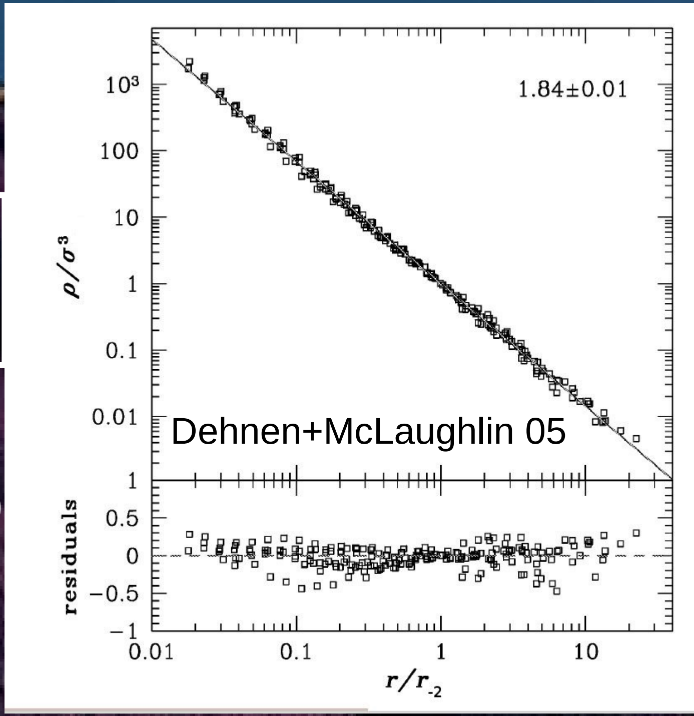
Is there A UNIVERSAL DENSITY PROFILE of clusters?



Navarro, Frenk & White 97: the NFW ρ(r) is universal

Taylor + Navarro 01: Q(r) = ρ/σ^3 is universal power-law

(ρ mass density profile, σ velocity dispersion profile)



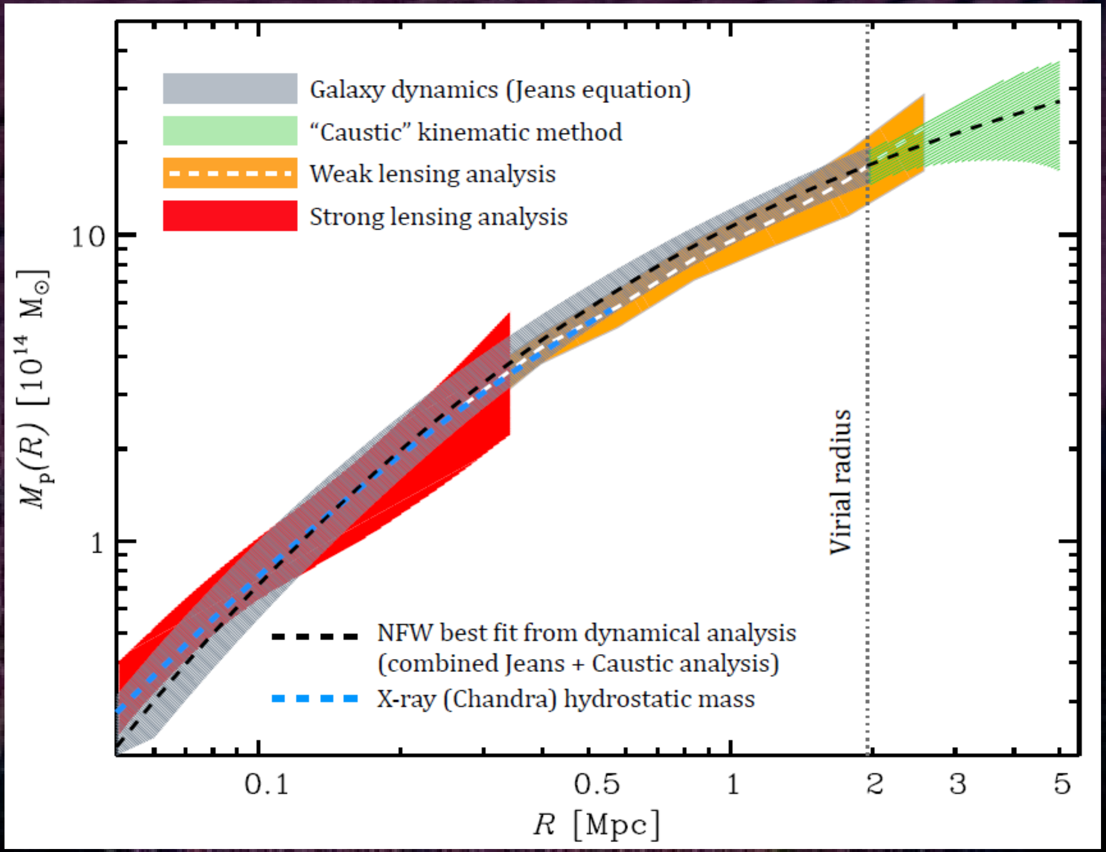
Why is ρ(r) Universal?

- NFW97: result of violent relaxation process (dynamical attractor)
- Syer+White 98: result of halo mass accretion history (itself universal),
  initial fast accretion fixes scale radius
  following slow accretion determines (growing) virial radius
  concentration at given mass depends on z

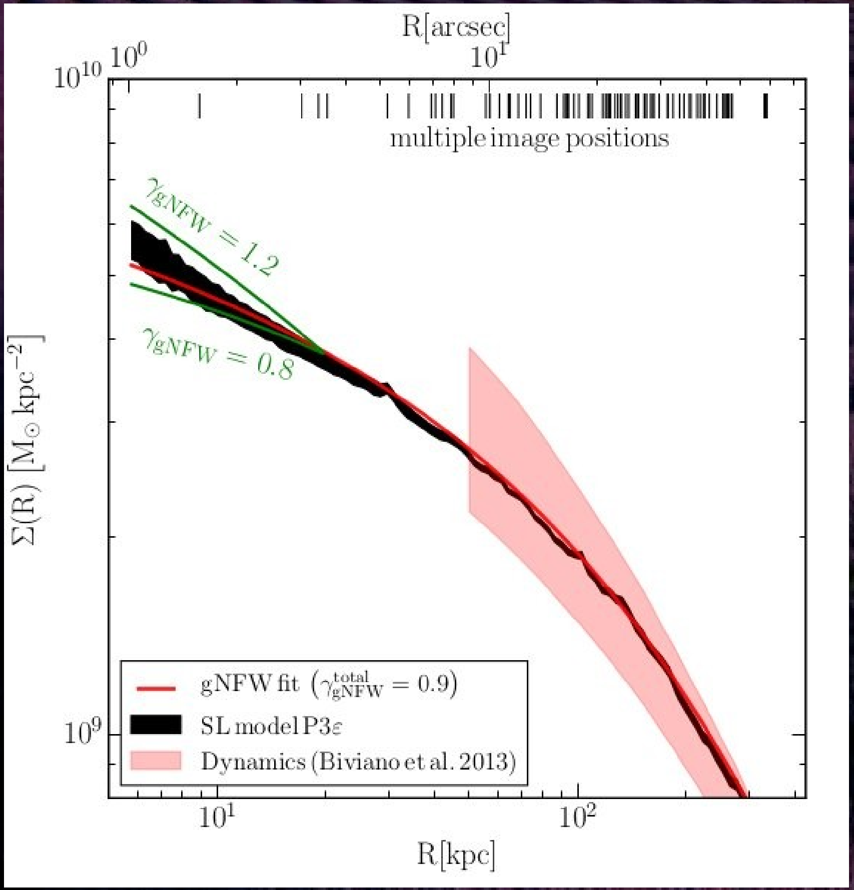
From the BCG to Beyond the Virial Radius

NFW (or Einasto) good fit to observed M(r) } at z≤1
Observed Q(r) is power-law with slope as expected

(low-z: ENACS, Katgert, AB, Mazure 04; z~0.3: CNOC, van der Marel+00; z~0.5: CLASH-VLT, AB+13; z~1: GCLASS, AB+16)



MACS1206, z=0.440, CLASH(VLT) data
Dynamical M(r) from AB+13
Lensing and X-ray M(r) from Umetsu+ 12



MACS1206, z=0.440, CLASH(VLT) data
+ new VLT/MUSE data;
strong lensing M(r) from Caminha+17, (A&A submitted)

From the BCG to Beyond the Virial Radius

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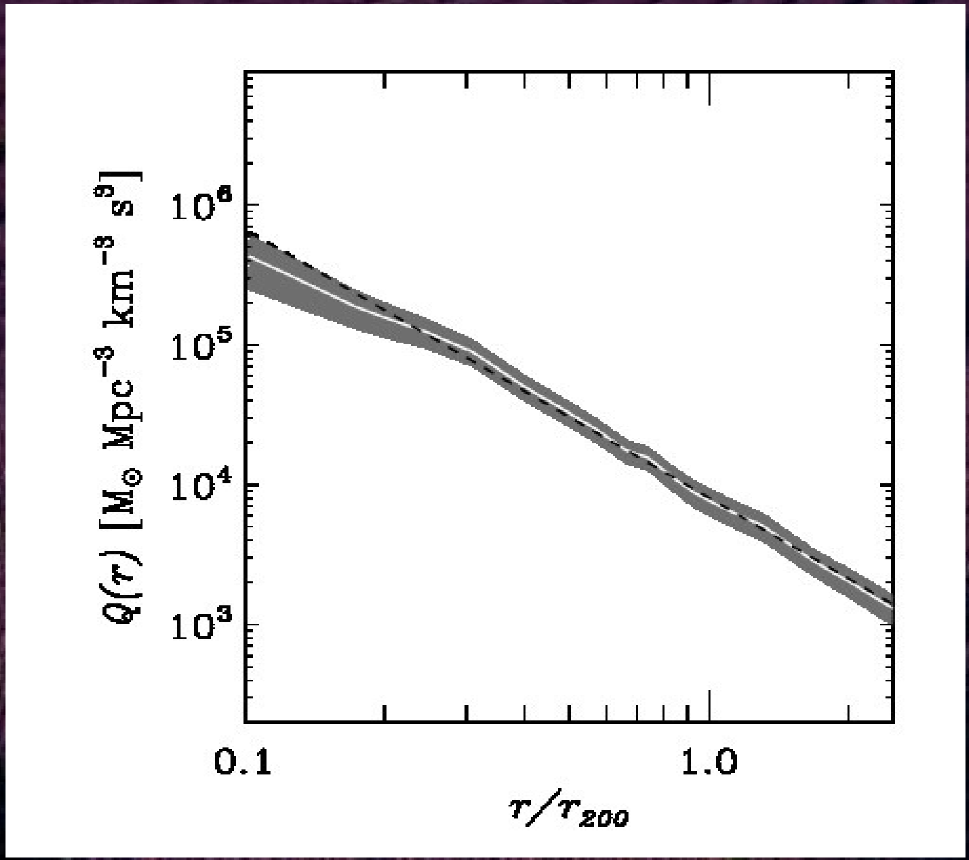
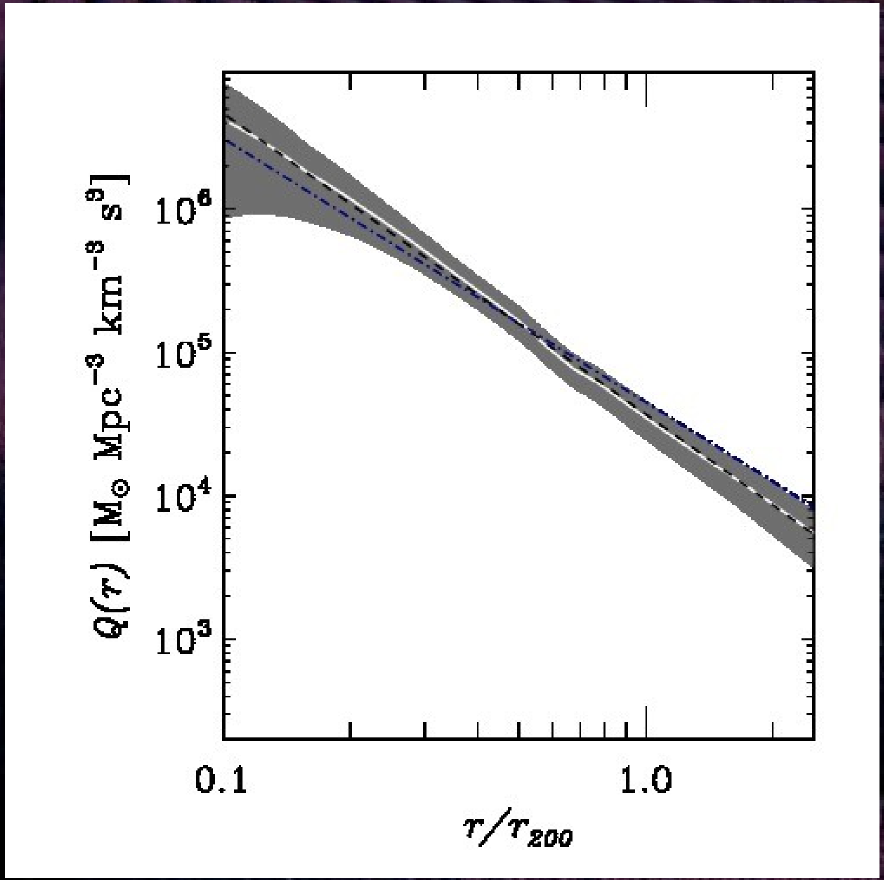


MACS1206, z=0.440, CLASH(VLT) data
Q(r) from AB+13

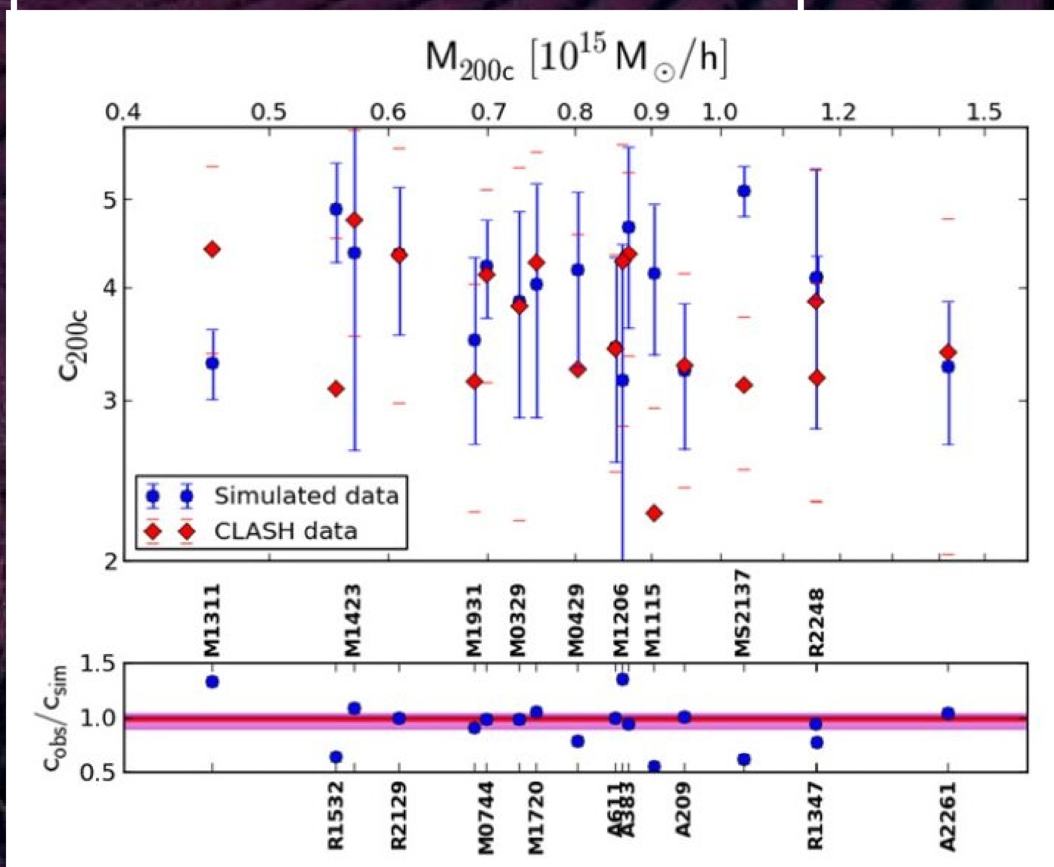


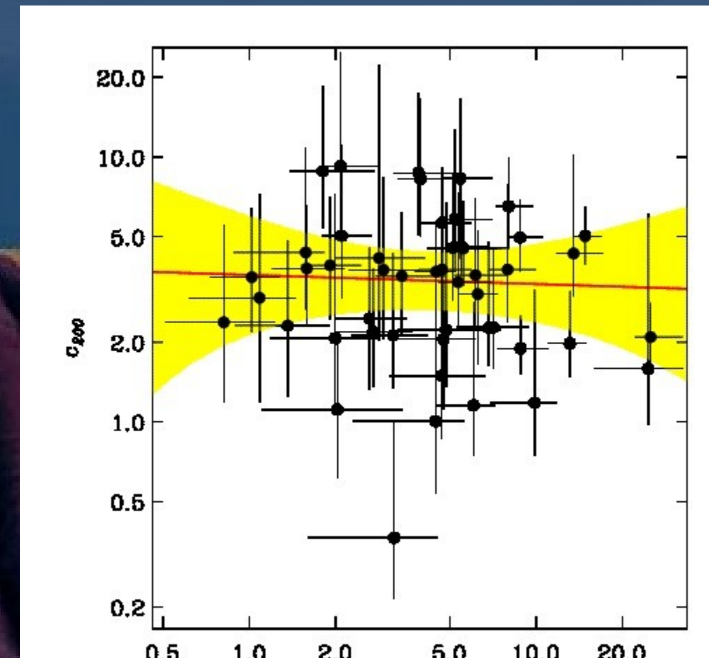
Stack of 10 GCLASS clusters, z~1,
PI: G. Wilson, Q(r) from AB+16

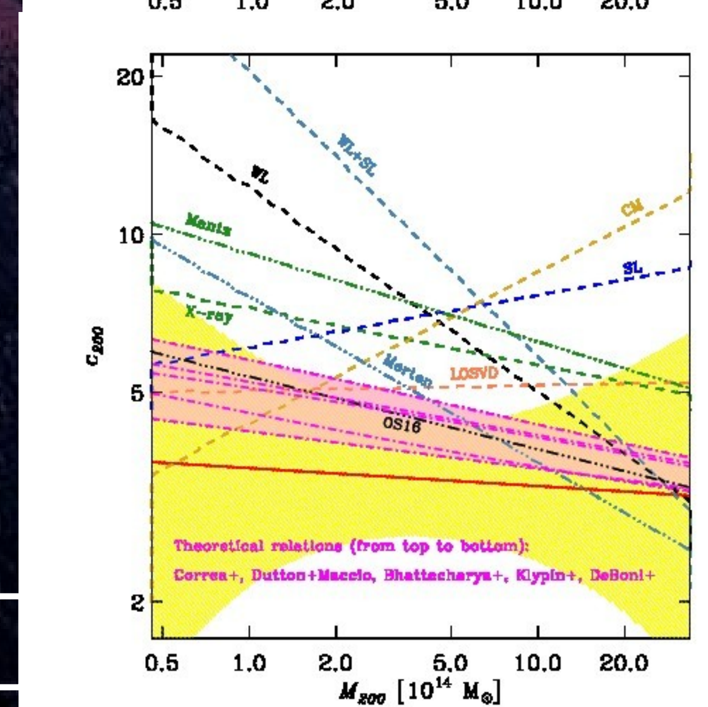
From the BCG to Beyond the Virial Radius

Observed concentration-mass relation as predicted theoretically at cluster scales

Merten+15, CLASH, z~0.5, lensing



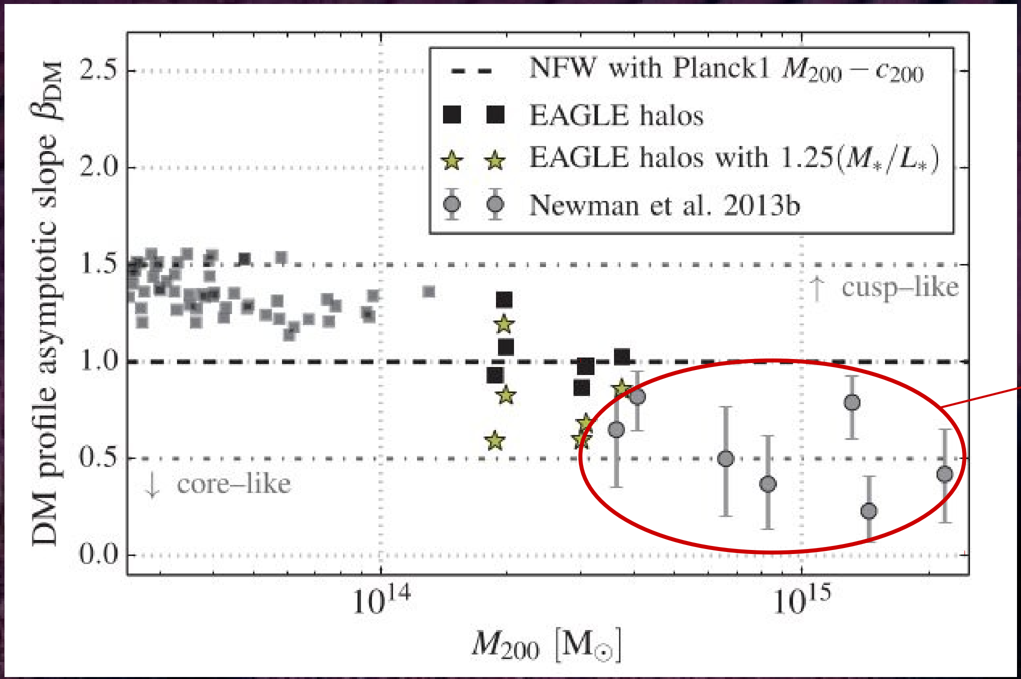


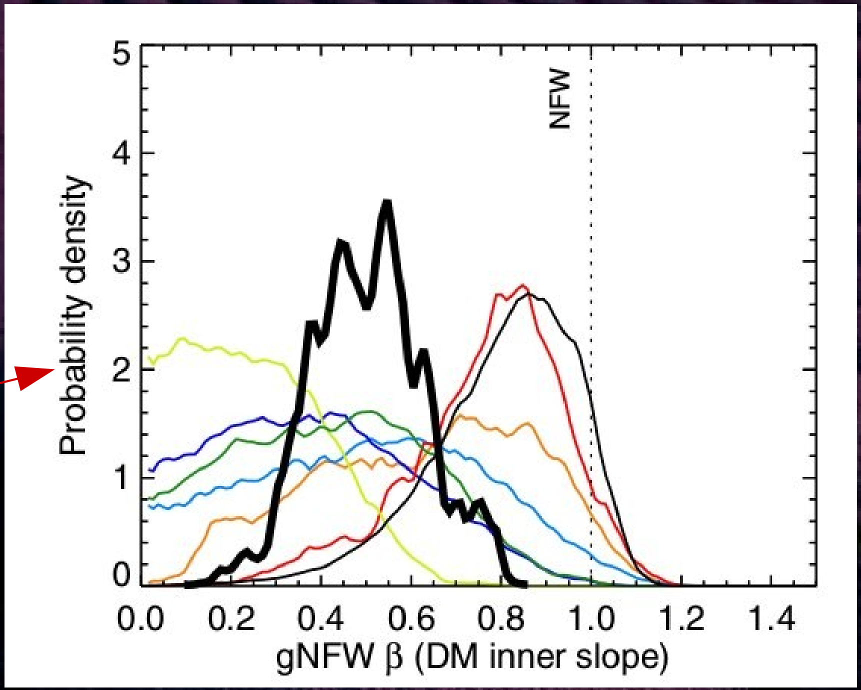


AB+17 submitted, ΩWINGS (PI: B. Poggianti), z~0.1, kin.

From the BCG to Beyond the Virial Radius

NFW fits total ρ(r) of observed clusters, but…
is this really expected from numerical simulations?





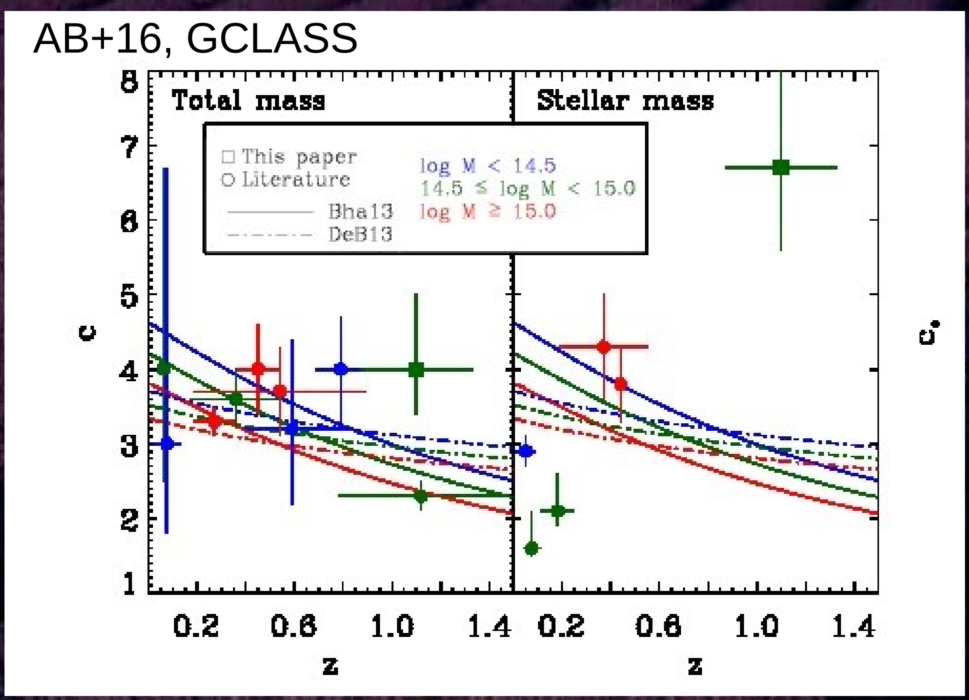
Schaller+15: EAGLE cosmological simulations; including BCG stellar mass makes total ρ(r→0) steeper than NFW; when subtracting the BCG baryons, the DM ρ(r→0) is close to NFW, in disagreement with observations (Newman+13), unless one accounts for a rather extreme super-massive BH component (Smith, Lucey, Edge 17)

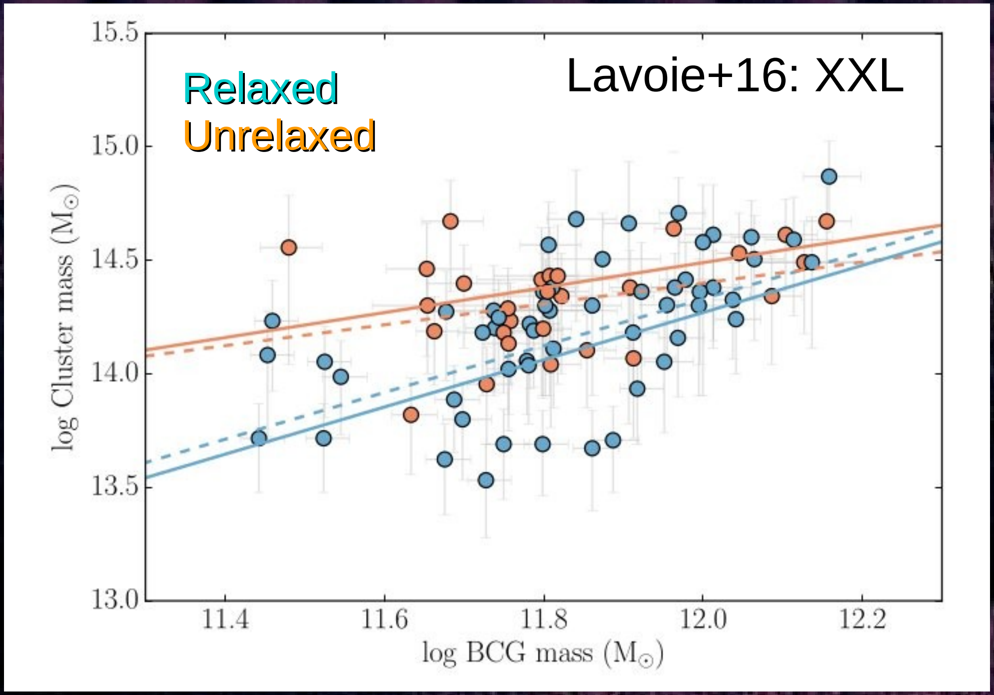
From the BCG to Beyond the Virial Radius

How do baryons affect DM distribution in clusters?

- Adiabatic contraction steepens $\rho_{DM}(r \rightarrow 0)$, opposite of what is observed
- Dynamical friction transfer energy from baryons to DM, flattens $\rho_{DM}(r \rightarrow 0)$
- AGN feedback expels baryons, softens the inner potential and flattens $\rho_{DM}(r \rightarrow 0)$
- Non-standard DM properties (e.g. self-interacting DM) can flatten $\rho_{DM}(r \rightarrow 0)$

Useful to look at total vs. stellar mass distribution z-evolution

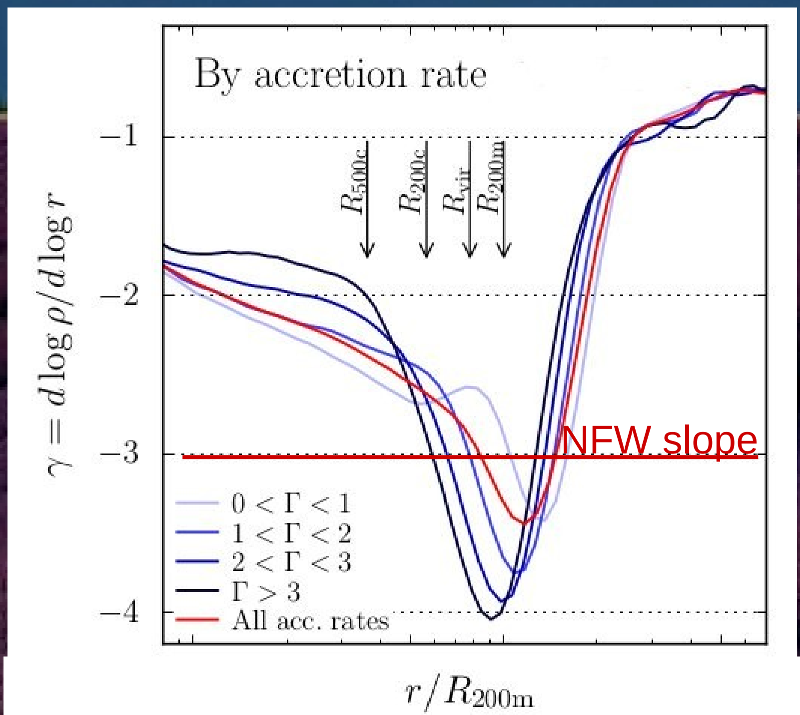




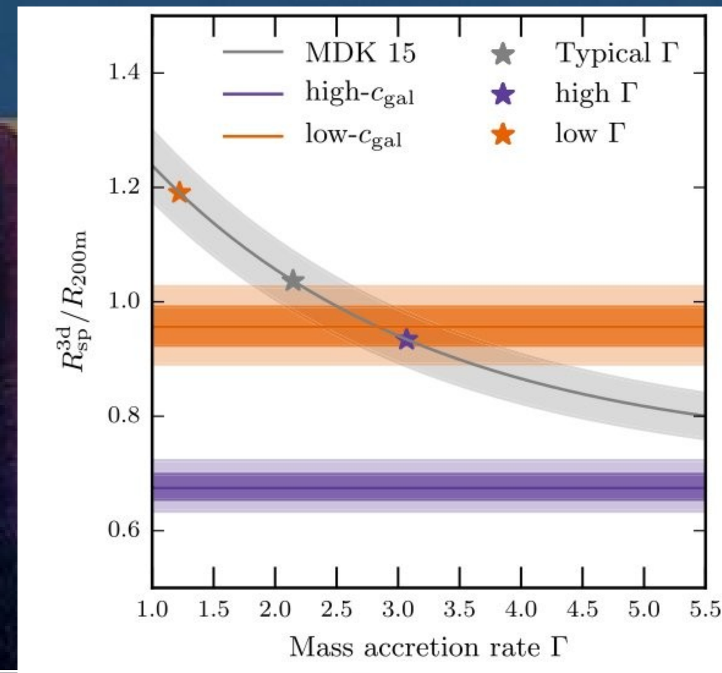
BCG assembly is delayed wrt cluster assembly

From the BCG to Beyond the Virial Radius

Is the external slope γ of ρ(r) different from NFW (γ=3) and why?



Diemer+Kravtstov 14, simulations:
ρ(r) slope vs. radius
for ≠ mass accretion rates



More+16, simulations cfr observations:
splashback radius where ρ(r) slope is steepest
vs. mass accretion rate

ρ(r) becomes very steep at 'splashback' radius, the outermost radius attained by particles following their collapse into halos. This radius is smaller for higher accretion rates.
Current observational constraints use number density profiles of cluster galaxies;
to directly probe $\rho_{DM}(r)$ use kinematics of CLASH-VLT clusters (Sartoris+, in progress)

How and How Well Do We Measure Masses

How to open a can

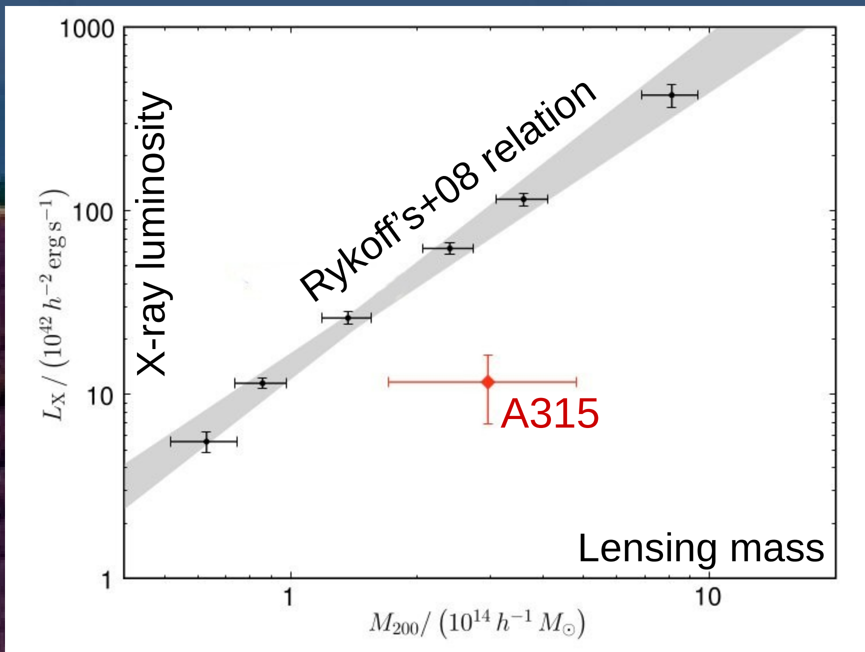
The hard way

The ‘easy’ way

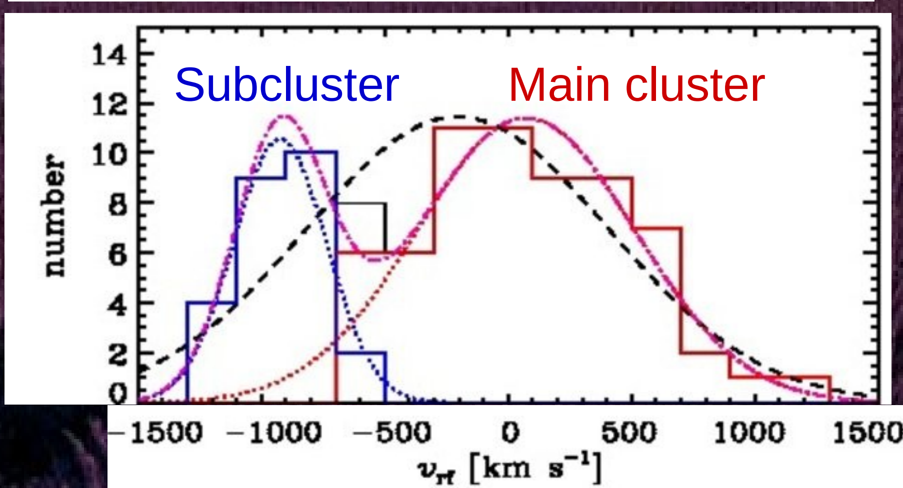
...f**k!

How and How Well Do We Measure Masses

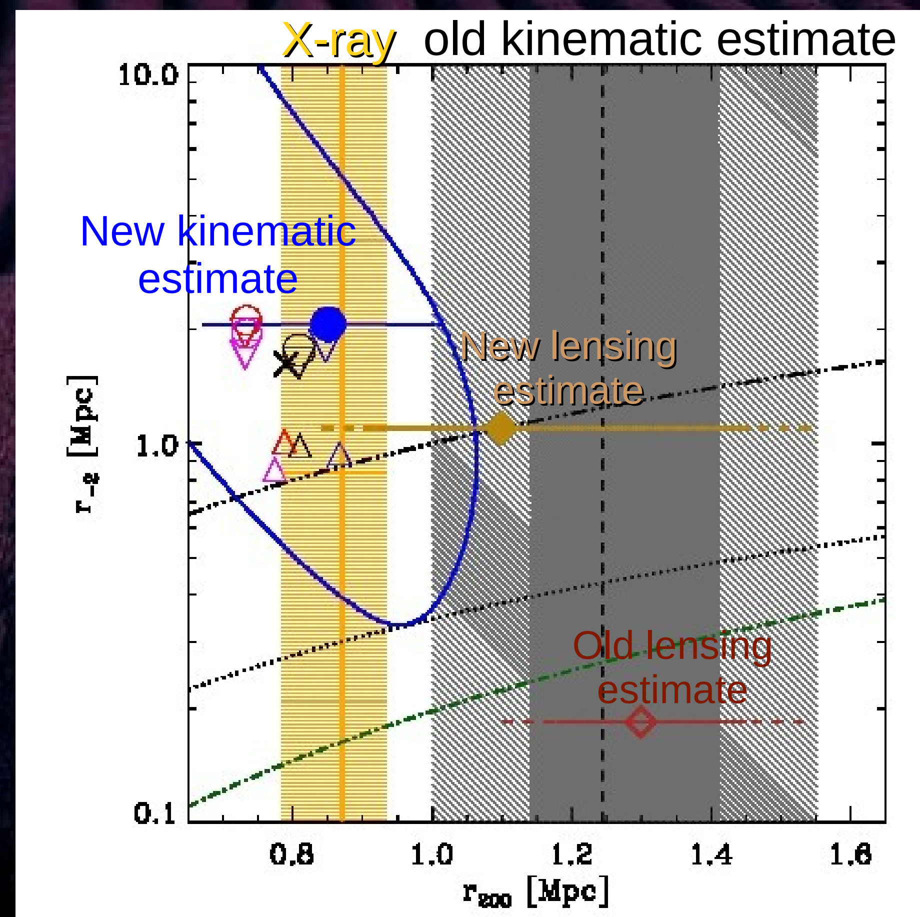
Dietrich+09



When data are not so good, biased mass estimates can occur. Example: Abell 315, initially thought to be X-ray underluminous for its mass, no longer it is when bimodality in velocity distribution and low mass concentration are identified and accounted for.



AB+17

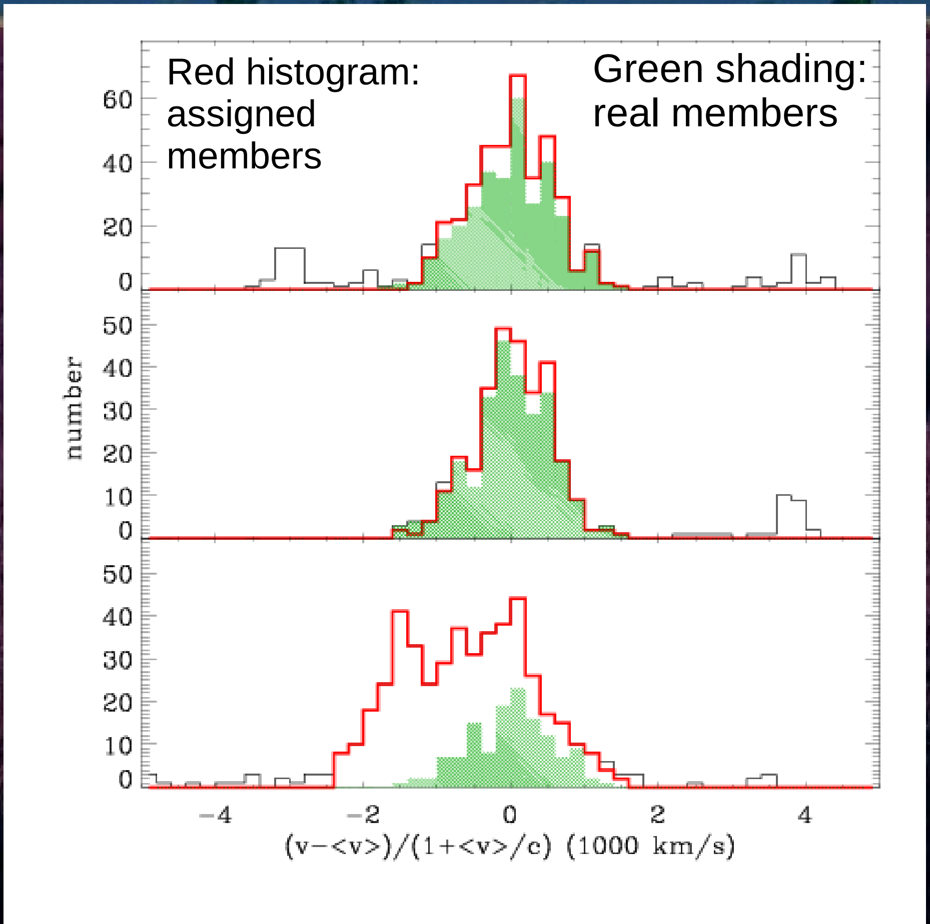


AB+17

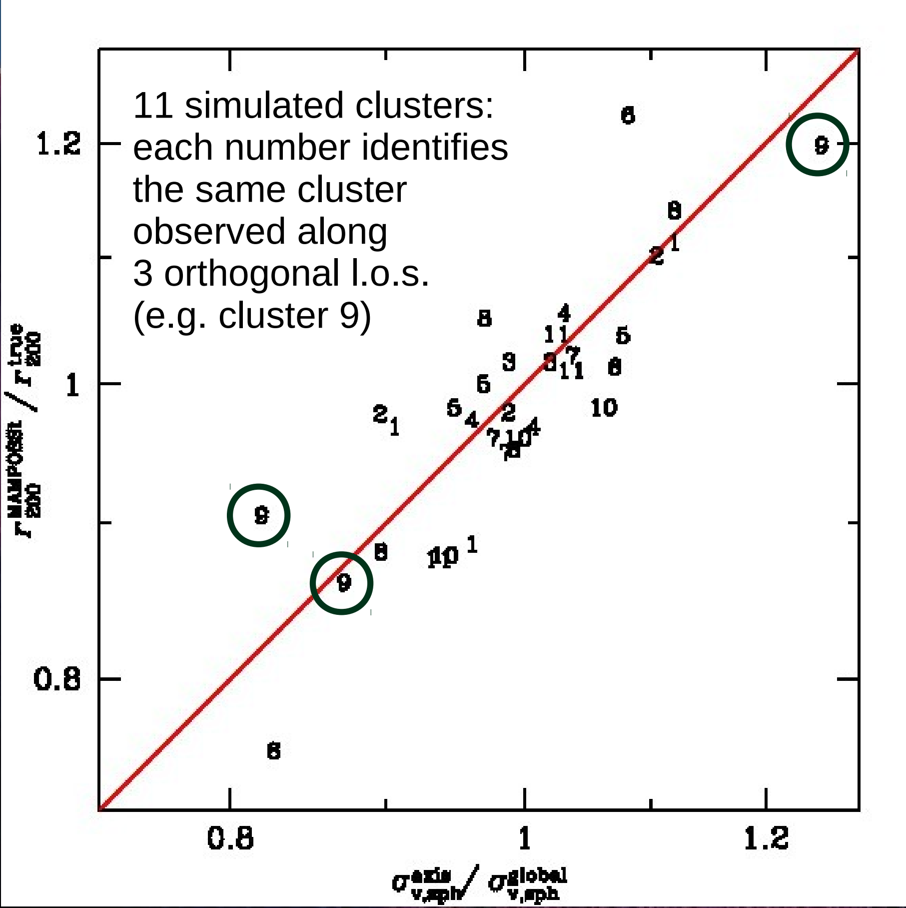
How and How Well Do We Measure Masses

Estimates from kinematics; main problems are:

- poor data-sets: undetected multiple structures (substructures) along the l.o.s.
- rich data-sets: triaxiality



AB+06: a simulated cluster observed along 3 orthogonal l.o.s.



Mamon, AB, Boué 13: error in mass estimate related to ratio of σ_v along l.o.s. axis and global σ_v, itself related to triaxiality

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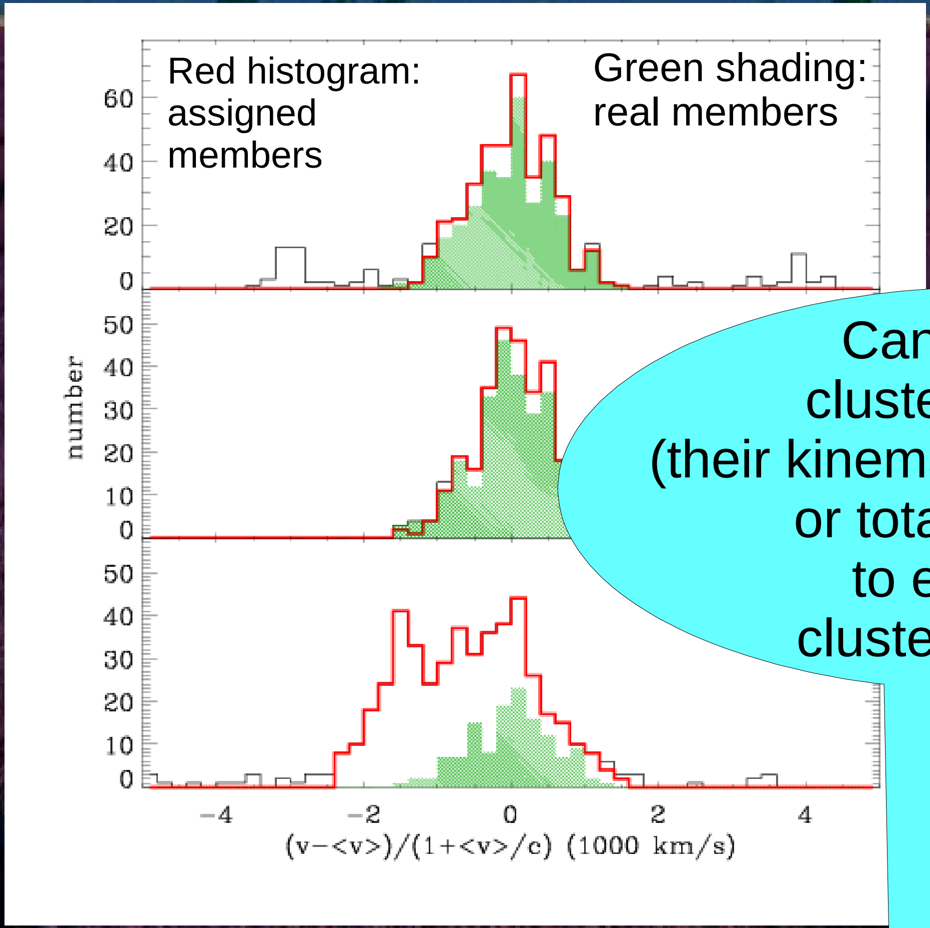

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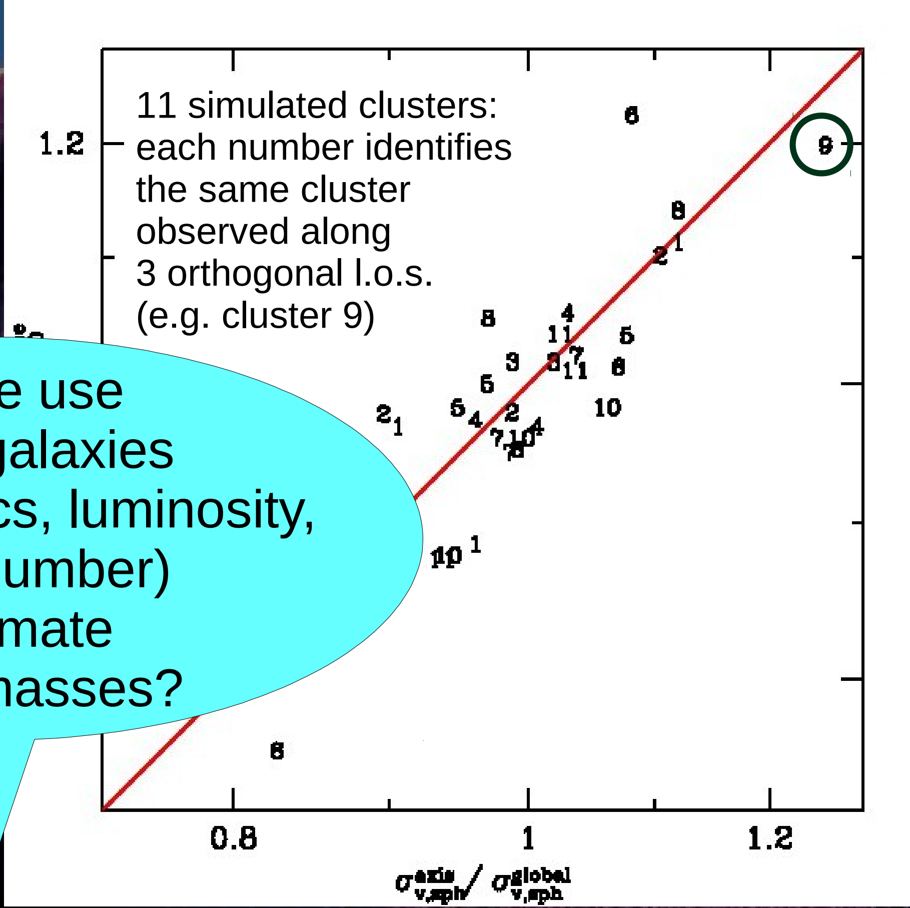
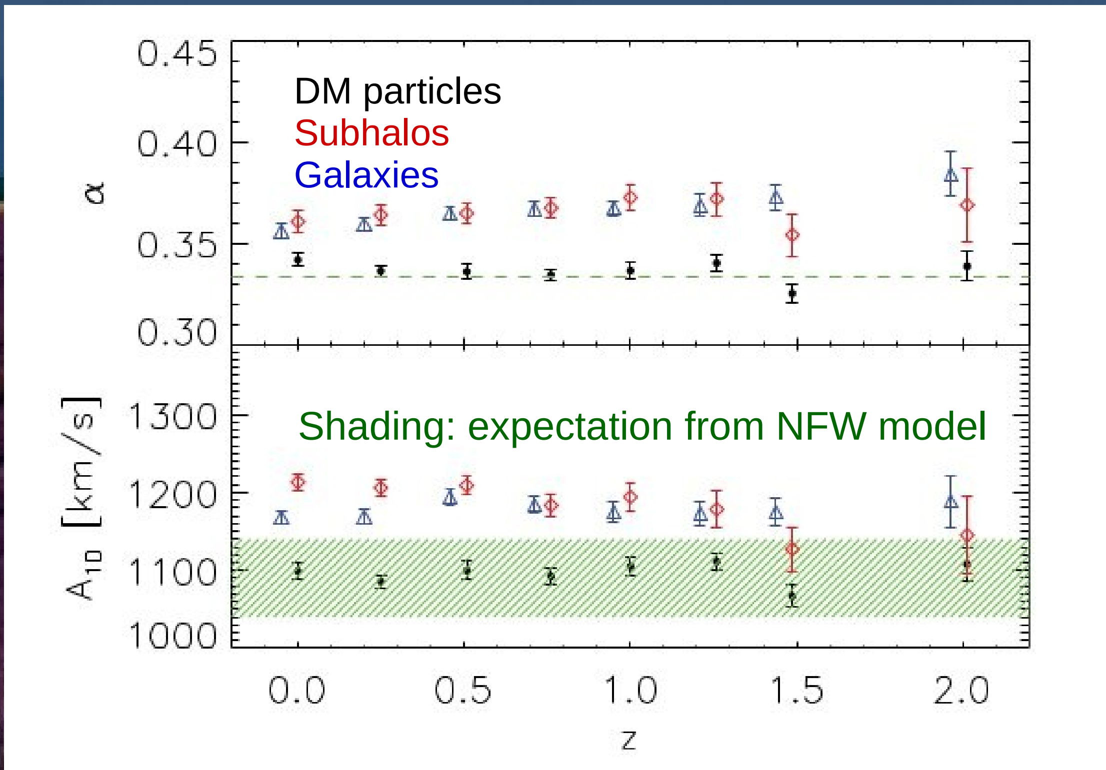
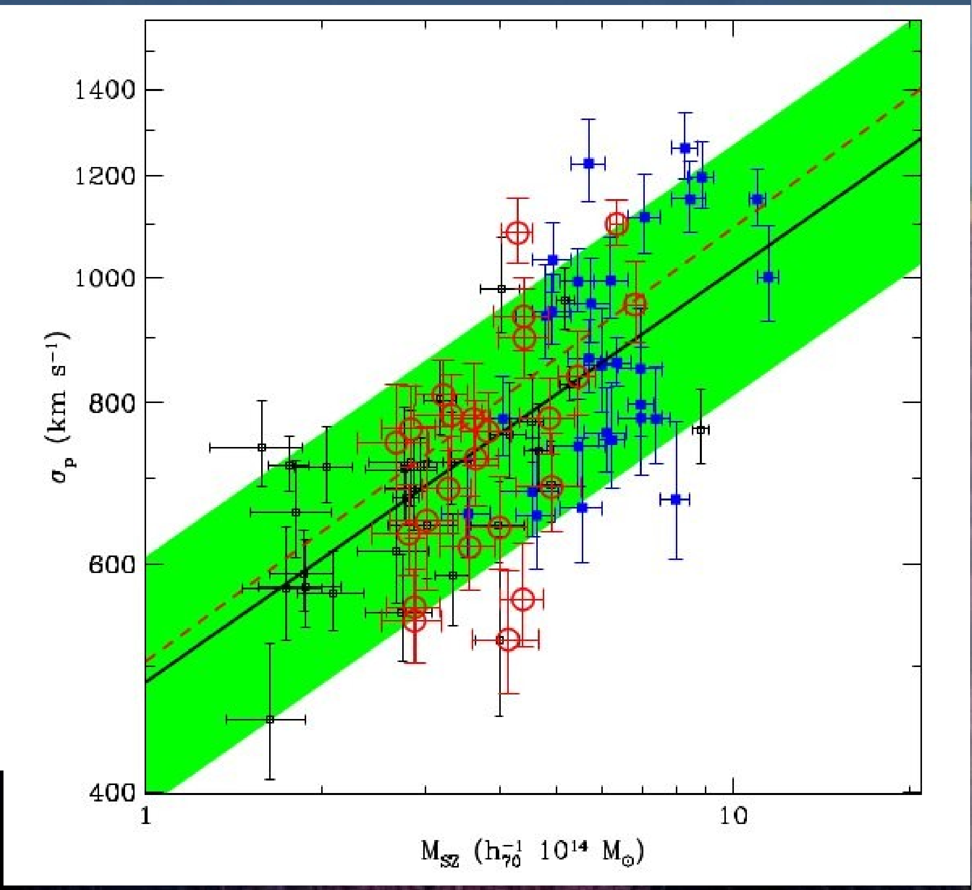


Can we use cluster galaxies (their kinematics, luminosity, or total number) to estimate cluster masses?

Mamon, AB, Boué 13: error in mass estimate related to ratio of σ_v along l.o.s. axis and global σ_v, itself related to triaxiality

How and How Well Do We Measure Masses





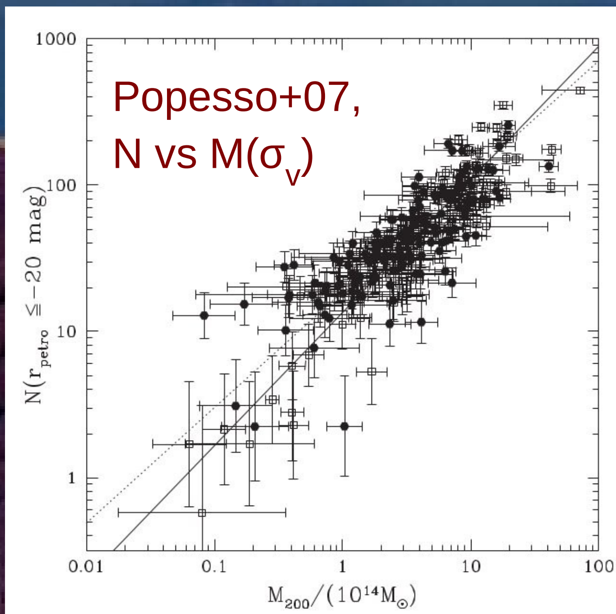
Munari+13 simulations:
$\sigma_v = A_{1D} \times M^\alpha$ depends on z and the tracer (DM particles/subhalos/galaxies), and the physics in the simulations
⇒ difficult to calibrate.

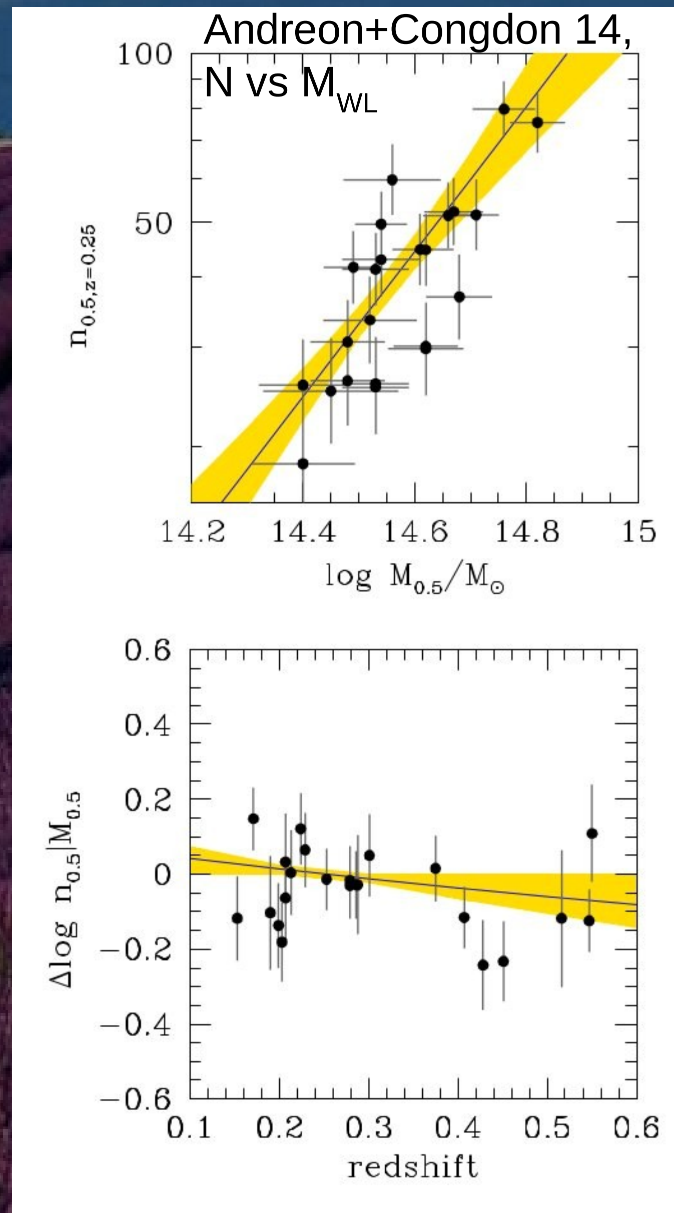
Intrinsic scatter is ~0.06 dex at all z

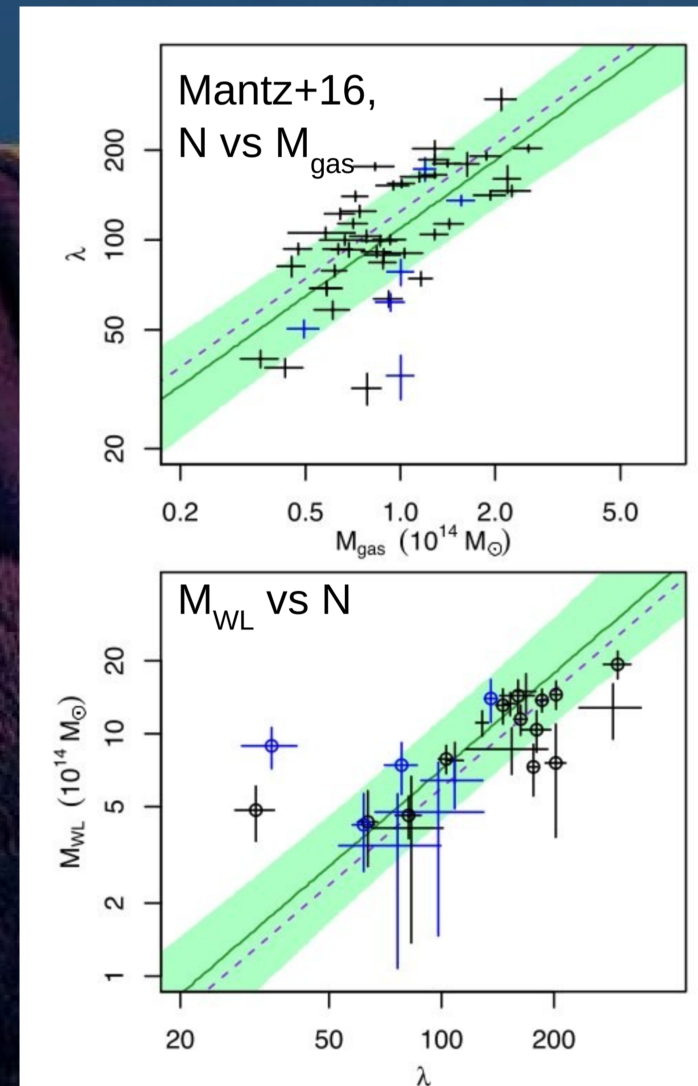
Rines+16: σ_v vs M_{SZ} as expected from virial scaling ⇒low bias in M_{SZ} unless M_{kin} is similarly biased

How and How Well Do We Measure Masses

When kinematics cannot be used, count galaxies (or their luminosities)



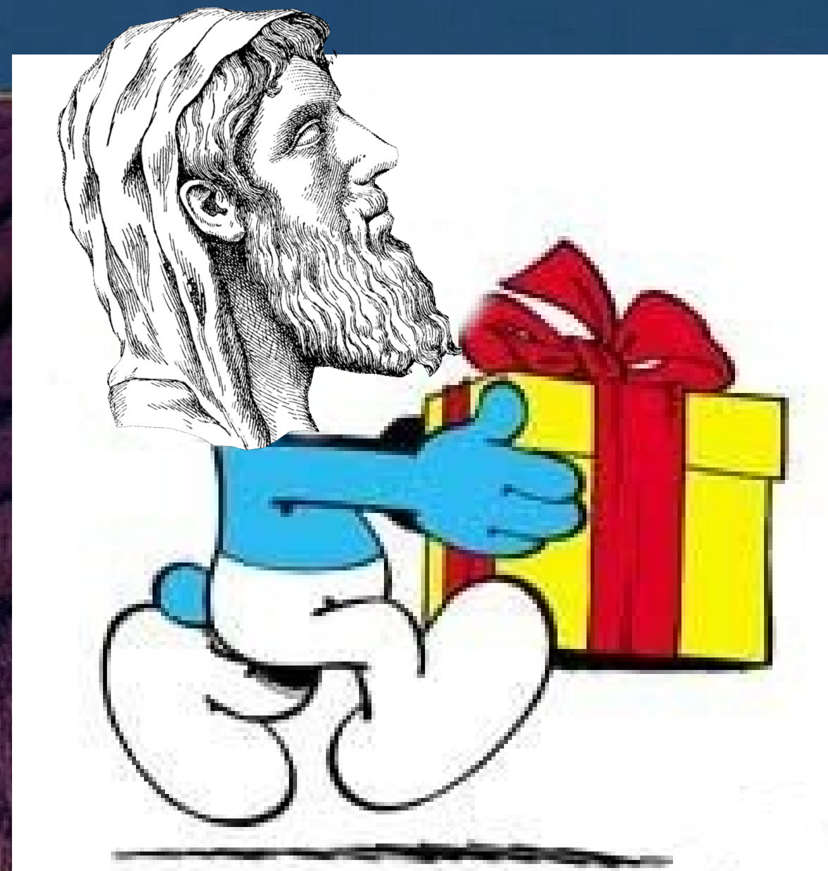




Mass vs. richness relation close to linear ($N \propto M^{0.7\text{-}1.3}$) and not evolving.

Intrinsic scatter for the richness mass proxy is 0.13 ± 0.04 dex

Clusters as Cosmological Probes



The gift pack from Euclid is still to be opened,
full of (hopefully good) surprises!

Clusters as Cosmological Probes

Ongoing and forthcoming surveys (that will be) used for cluster cosmology:

CCAT, DES, eBOSS,eROSITA, KiDS, LSST, Pan-STARRS, Planck-SZ, SPT-3G, SPT-SZ…

15,000 deg^2, imaging photometry: 550-900 nm 24.5 mag$_{AB}$ + 920-2000 nm 24.0 mag$_{AB}$ + slitless spectroscopy 1100-2000 nm 2 10^{-16} erg/cm^2/s

Aims:

- FoM=400 for DE EoS (i.e. measure {w_p,w_a} with {0.02,0.1} precision)
- Measure growth factor to distinguish GR from modified gravity
- Measure sum of neutrino masses with 0.03 eV precision
- Measure primordial perturbation index n, probe inflation models via non-Gaussianity
- Legacy…

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Euclid

What will Euclid do for clusters?

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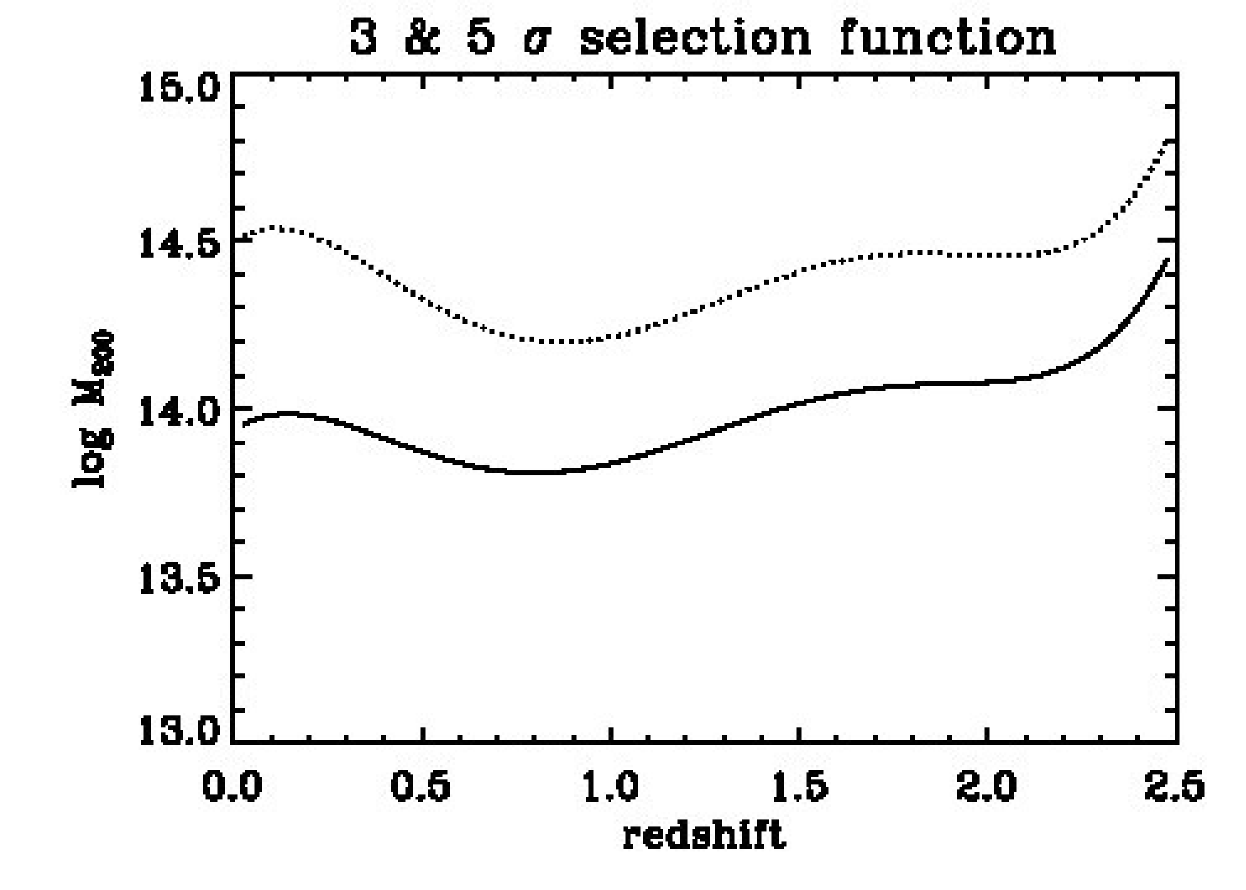
Clusters as Cosmological Probes

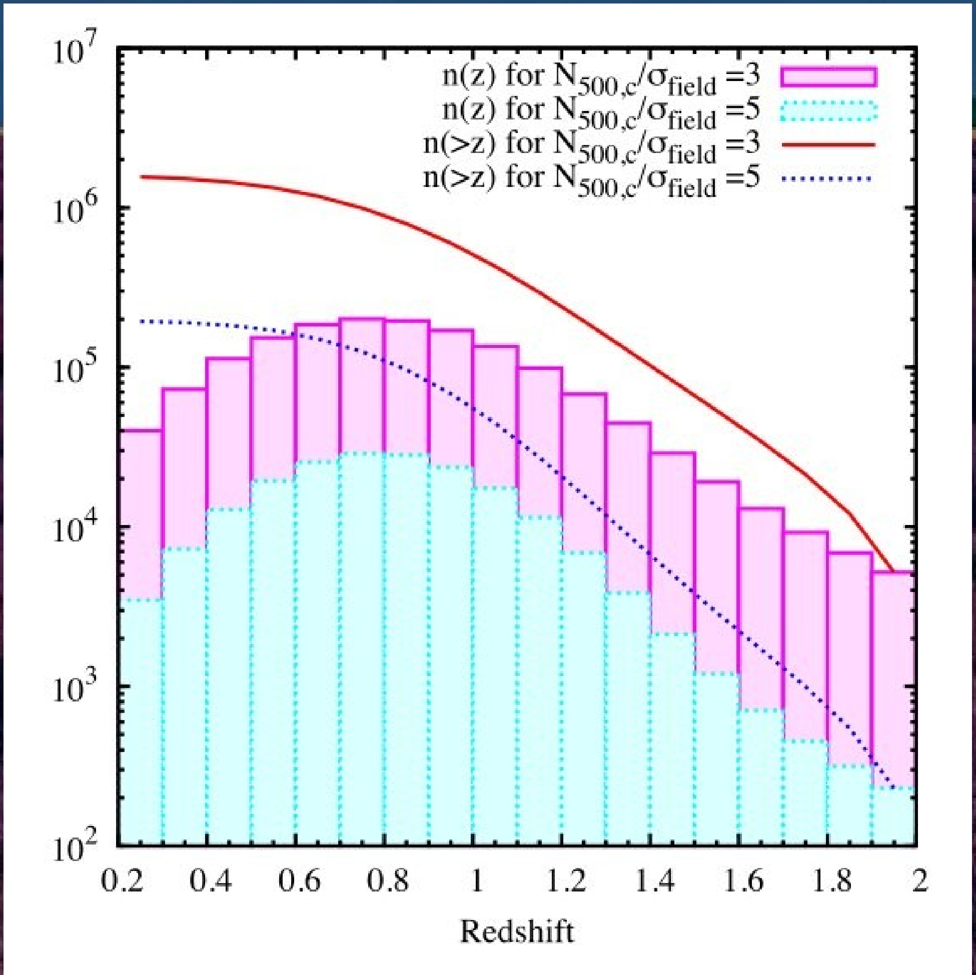
Clusters of galaxies: “additional” cosmology probes for Euclid



Sartoris+16: selection function: limiting mass M_{200} for clusters to be detected with 3σ and 5σ significance in Euclid (analytical estimate)

Clusters as Cosmological Probes

Clusters of galaxies: “additional” cosmology probes for Euclid



Sartoris+16: number of clusters that will be detected with 3σ and 5σ significance in Euclid (from selection function)

Clusters as Cosmological Probes

Clusters of galaxies: “additional” cosmology probes for Euclid

Science Working Group on clusters of galaxies, lead by
J. Bartlett, L. Moscardini, J. Weller *(114 members)*

Ground Segment Work Packages:

Implementation of algorithms, lead by **AB, S. Maurogordato**
(91 members, of which 41 active, 30 passive, and 20 in the green valley)

Validation of algorithms, lead by **B. Hoyle, R. Pelló** *(22 members)*

Clusters as Cosmological Probes

Clusters of galaxies: “additional” cosmology probes for Euclid

Implementation of algorithms Ground Segment Work Package

Processing Functions (and leads):

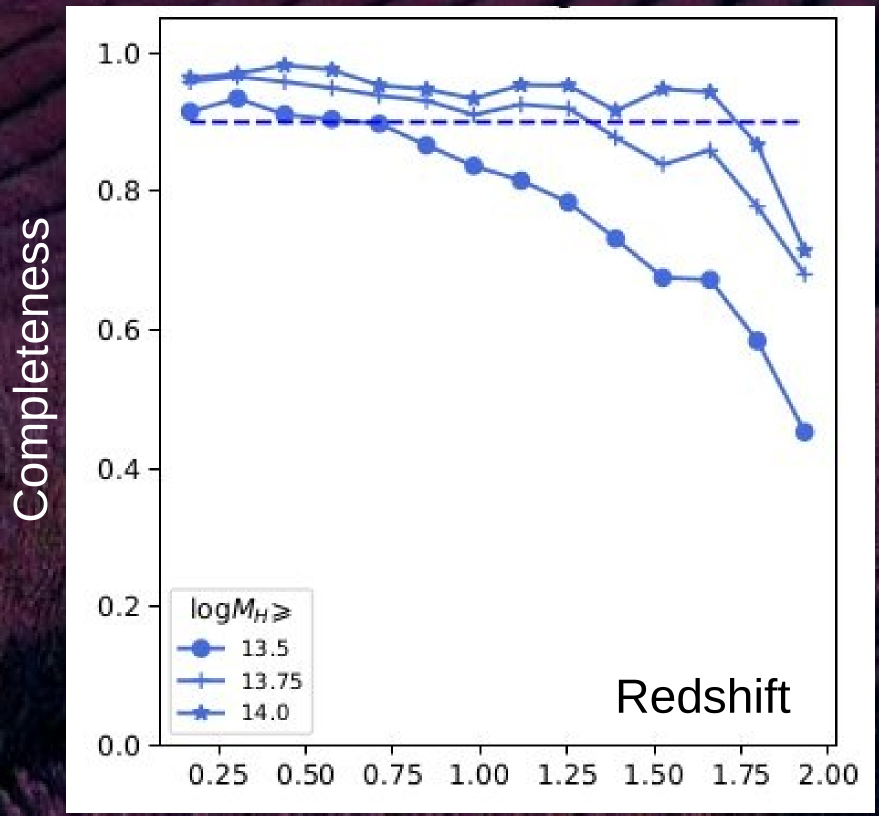
Detection	F. Bellagamba, A. Gonzalez + E. Munari, M. Vannier	
Selection Function	S. Maurogordato, B. Sartoris	
Mean redshift	O. Cucciati, A. Iovino	
Richness	C. Benoist, A. Gonzalez	
Weak lensing	A. Peel	mass calibration
Velocity dispersion	M. Girardi, A. Iovino	
Density profile	C. Adami, G. Mamon	
Luminosity function	M. Bolzonella, E. Zucca	
Mass function	M. Bolzonella, S. Mei	
Cluster clustering	F. Marulli + S. della Torre, M. Moresco, C. Porciani	
Covariance matrices	B. Hoyle	

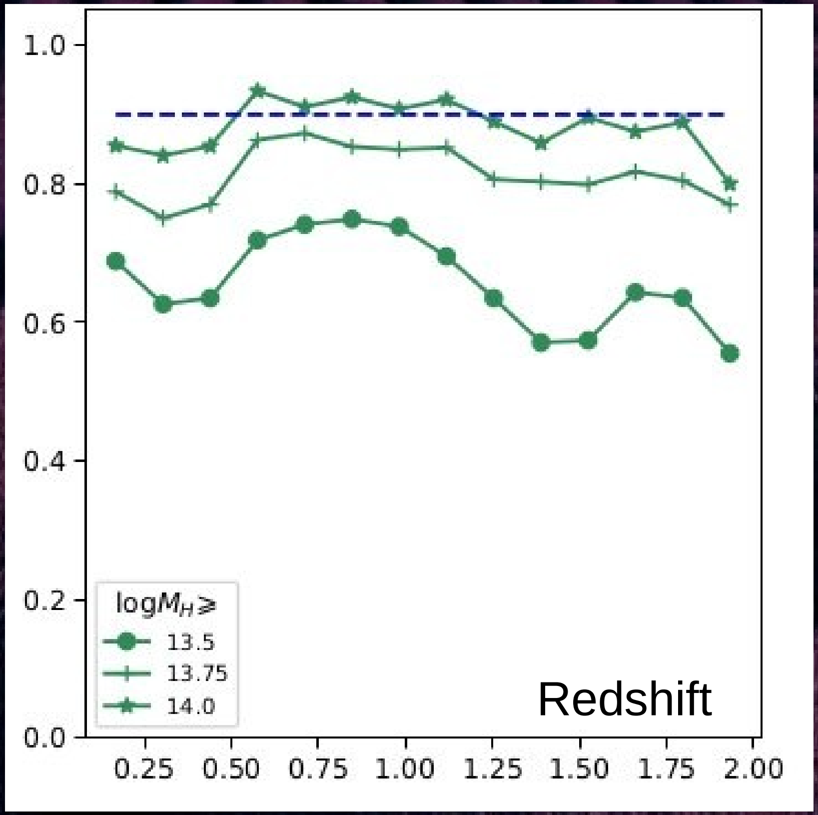
Clusters as Cosmological Probes

Clusters of galaxies detection: two algorithms chosen (out of 8) after 4 challenges (find clusters in blind mock Euclid surveys):

AMICO (matched filter) by F. Bellagamba, M. Maturi, M. Roncarelli

PZWAV (wavelet overdensity) by A. Gonzalez





(figures from the Euclid internal report by Vannier, Adam, Rocci, Maurogordato et al.)

Clusters as Cosmological Probes

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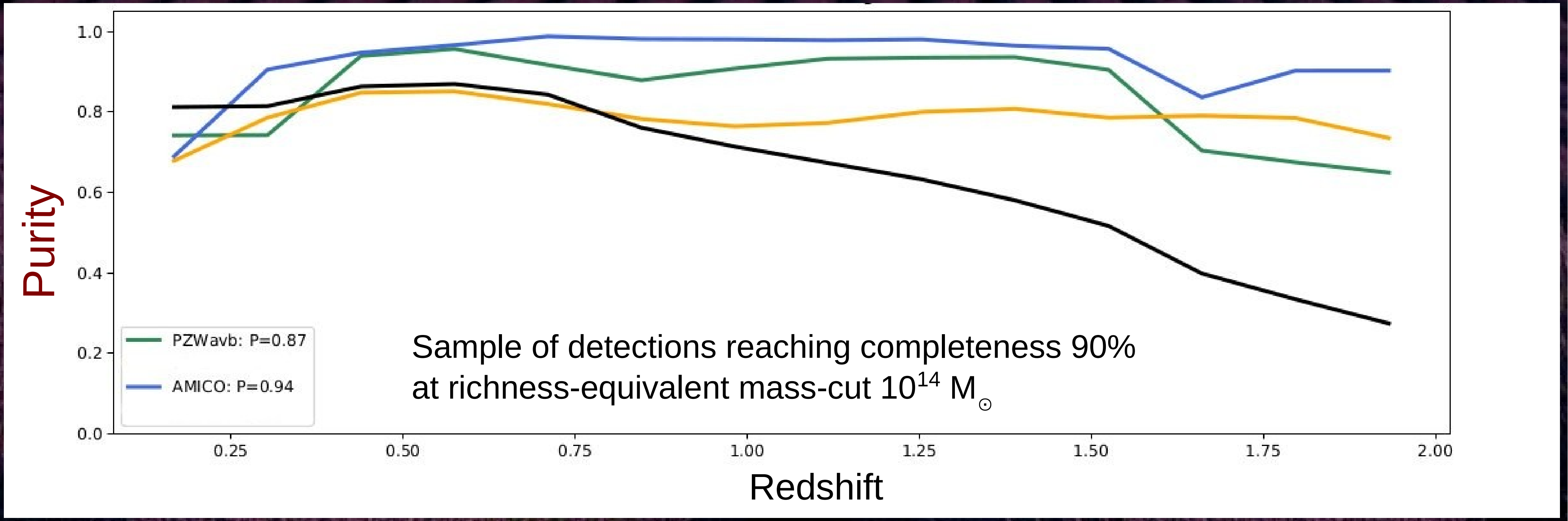

(figure from the Euclid internal report by Vannier, Adam, Rocci, Maurogordato et al.)

Opening Talk: conclusions

Opening Talk: conclusions

"A conclusion is the place where you get tired of thinking"
(Arthur Bloch)

...and tired I am, so refer to Craig for more conclusions (next Thursday, 4:40 PM)