CLASH-VLT: the dynamics of clusters of galaxies

HST image of the $z=0.44$ CLASH cluster MACS1206 (NASA, ESA, M. Postman)

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...and, in particular,

Barbara Sartoris (Univ. Trieste)

Marianna Annunziatella (Univ. Trieste)
Outline of this talk:

- General introduction on clusters of galaxies
- How to measure cluster masses (and mass profiles)
- CLASH-VLT: the survey
- The internal dynamics of CLASH-VLT clusters:
  - Mass profiles $M(r)$
  - Dark Matter equation of state
  - The pseudo-phase-space density profile $Q(r)$
  - Stellar-to-total mass profile ratio
  - Orbits of galaxies in clusters $\beta(r)$

- Summary and perspectives
General introduction on clusters of galaxies

(I use the Maibaum to set the timing of this talk)
A collection of galaxies that is held together by gravity. Clusters may contain from a few to a few thousand member galaxies. Small clusters, with up to a few dozen members, are referred to as ‘groups’, the Milky Way Galaxy, for example, being a member of the Local Group, which contains at least 25 members. Most galaxies are members of groups or binary pairs. Larger clusters contain hundreds or thousands of members and, typically, have diameters of a few megaparsecs (about 10 million light-years). Rich (densely populated) clusters are divided into regular clusters and irregular clusters.

Introduction

What are clusters of galaxies?

Composition of Galaxy Clusters

Dark Matter

Hot Gas

Stars/Galaxies

(by Mark Whittle
Univ. Viriginia)

The Coma cluster of galaxies, by Lopez-Cruz et al.

G.O. Abell (photo by K. Nordhauser)
Introduction

Why are they important?

Dark Matter:

\[
\text{Die Rotverschiebung von extragalaktischen Nebeln}
\]

von F. Zwicky.

(16. II. 33.)

1. Setzt man voraus, dass das Comasystem mechanisch einen stationären Zustand erreicht hat, so folgt aus dem Virialsatz

\[
\bar{\varepsilon}_k = -\frac{1}{2} \bar{\varepsilon}_p, \tag{4}
\]

wobei \(\bar{\varepsilon}_k\) und \(\bar{\varepsilon}_p\) mittlere kinetische und potentielle Energien, z. B. der Masseneinheit im System bedeuten. Zum Zwecke der Ab-

von Beobachtungen an leuchtender Materie abgeleitete\(^1\)). Falls sich dies bewährten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel größerer Dichte vorhanden ist als leuchtende Materie.
Why are they important?

Dark Matter:

The 'bullet' cluster, Markevitch et al. (NASA & ESO)
Why are they important?

Dark Matter:

Mapping the distribution of mass inside clusters of galaxies help us understand:

- the nature of dark matter
- the way halos formed

Measuring cluster masses is also important because clusters can be used as cosmological probes (the density of clusters above a given mass as a function of redshift)

Simulation of a cluster mass profile [Navarro, Frenk & White 1996]
Why are they important?

Evolution of galaxies:

“The predominance of early types is a conspicuous feature of clusters in general”

The morpholgy-density relation in clusters of galaxies, A. Dressler (1980)
Why are they important?

Evolution of galaxies:

The prevalence of red, early-type, passively-evolving galaxies in clusters inform us about the physical processes that speed up galaxy evolution by removing their gas and changing their internal structure.
How to measure cluster masses
How do we measure cluster masses?

X-ray observations:
assuming the intra-cluster, X-ray emitting gas is in hydrostatic equilibrium
How do we measure cluster masses?

Measuring masses

X-ray observations: assuming the intra-cluster, X-ray emitting gas is in hydrostatic equilibrium

Optical observations: using the deflected and amplified light from background galaxies due to the gravitational lensing effect
How do we measure cluster masses?

**X-ray observations:** assuming the intra-cluster, X-ray emitting gas is in hydrostatic equilibrium.

**Optical observations:** using the deflected and amplified light from background galaxies due to the gravitational lensing effect.

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Andrea Biviano “CLASH-VLT: the dynamics of clusters of galaxies”
How do we measure cluster masses?

X-ray observations: assuming the intra-cluster, X-ray emitting gas is in hydrostatic equilibrium

Optical observations: using the deflected and amplified light from background galaxies due to the gravitational lensing effect

Optical observations: using the spatial and velocity distributions of cluster galaxies

- NASA/Chandra/MIT
- CFHTLens
- Univ. Cincinnati
- Chandra space telescope
- Wendelstein telescope
- Very Large Telescope
Galaxies as tracers of the gravitational potential

Sir James Jeans' equations:

\[ M = \text{total mass profile} \]
\[ \sigma_r = \text{velocity dispersion profile along the radial direction} \]
\[ \nu = \text{number density profile of the tracer (galaxies)} \]
\[ \beta = \text{velocity anisotropy profile of the tracer} \]

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

\[ \beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)} \]

But how do we get \( \nu(r), \sigma_r(r), \beta(r) \) from the observables?
Measuring masses

Phase-space distribution of cluster member galaxies in projection

CLASH-VLT cluster MACS1206

Projected number density profile $N(R)$

I.o.s. velocity dispersion profile $\sigma_{\text{los}}(R)$
Measuring masses

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

\[ \beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)} \]
DEGENERATE SOLUTIONS:

N(R), \( \sigma_{\text{los}}(R) \) observed

\( \nu(r) \), \( \sigma_{\theta}(r) \) and \( \sigma_{r}(r) \) required to solve the Jeans equation for \( M(<r) \)

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

\[
\beta(r) = 1 - \frac{\sigma_{\theta}^2(r)}{\sigma_r^2(r)}
\]
Measuring masses

MAMPOSST

direct maximum likelihood fit to the phase-space distribution of cluster galaxies in projection

projected number density profile N(R)

I.o.s. velocity dispersion profile $\sigma_{\text{los}}(R)$

Modelling Anisotropy and Mass Profiles of Observed Spherical Systems

[Mamon, AB, Boué 2013]
MAMPOSSSt: tested on cluster-size halos from cosmological simulations

Example of MAMPOSSSt solutions for a halo sampled with ~500 particles along one line-of-sight

4 free parameters:
- virial radius $r_{200}$ ($\leftrightarrow$ mass)
- scale radius galaxy distribution
- scale radius mass distribution
- velocity anisotropy
The Caustic technique
[Diaferio & Geller 97; Diaferio 99]

\[ GM(< r) - GM(< r_0) = \int_{r_0}^{r} A^2(x) \mathcal{F}_\beta(x) \, dx \]

\( \mathcal{F}(r) \) depends on \( M(<r) \) itself within the virial region but it is \( \approx \) constant outside.

\( \rightarrow \) can solve the integral.

Use the Jeans equation (MAMPOSSSt) in the virial region and the Caustic technique outside
[AB+Girardi 2003]
CLASH-VLT: the survey
CLASH & CLASH-VLT

CLASH, Cluster Lensing And Supernova survey with Hubble, 
**PI: M. Postman**, (Postman et al. 2012)

524 HST orbits to observe 25 gravitationally lensing clusters of galaxies at 0.18<z<0.90, 
+ Suprime-CAM Subaru follow-up for weak lensing

CLASH-VLT, VLT-VIMOS follow-up 
from the ESO Large Programme 
(Rosati et al. 2014)

225 hours to observe the 14 southern CLASH clusters and obtain redshifts for ≈500 members in each cluster, 
and ~100 lensed images of z≤7 galaxies
An example: MACS 416 [from Rosati et al. 2014]
The survey

CLASH & CLASH-VLT

Abell209, z=0.209

MACS1206, z=0.440

MACS416, z=0.397

~ 1000, 900, 600 spectroscopic members out to radii of ~ 3, 5, 5 Mpc, in Abell 209, MACS 416, MACS1206, resp.

+ Subaru 5-band photometry allowing the determination of the galaxy stellar masses via SED fitting (MAGPHYS, da Cunha et al. 2008) (only 3 bands for MACS416)

Andrea Biviano “CLASH-VLT: the dynamics of clusters of galaxies”
The internal dynamics of CLASH-VLT clusters: mass profiles $M(r)$
Run MAMPOSSt:
must choose models for $M(r)$ and $\beta(r)$

Say: $\gamma \equiv \frac{d \ln \rho}{d \ln r}$, the slope of the mass density profile

5 $M(r)$ models, 2 free parameters, $r_{200}$ and scale radius $r_{-2}$ or $r_{\text{core}}$

1) NFW, characterized by $\gamma(0) = -1$ and $\gamma(\infty) = -3$
2) Einasto, characterized by $\gamma(0) = -2 \left( \frac{r}{r_{-2}} \right)^{1/m}$ (we adopt $m=5$)
3) Hernquist, $\gamma(0) = -1$ and $\gamma(\infty) = -4$
4) Burkert, $\gamma(0) = 0$ and $\gamma(\infty) = -3$
5) Softened Isothermal Sphere, $\gamma(0) = 0$ and $\gamma(\infty) = -2$

5 Velocity anisotropy models, 1 free parameter

1) Constant $\beta$ at all radii
2, 3, 4) Three models always radial, increasingly so with increasing radius
5) $\beta = \beta_{\infty} (r-r_{-2})/(r+r_{-2})$, changing anisotropy sign with radius
The mass profiles

Abell 209 [Sartoris, AB et al. in prep.]

\[ M_{200} = 15.5 \times 10^{14} M_\odot \quad (h=0.7) \]

Best-fit \( M(r) \) model is NFW

Dot: \( r_{200}, M_{200} \) from MAMPOSSt
The mass profiles

Abell 209 [Sartoris, AB et al. in prep.]

Best-fit $M(r)$ model is NFW
The mass profiles

Abell 209 [Sartoris, AB et al. in prep.]

The best-fit M(r) model is NFW.

MAMPOSSt + Caustic recovers the 3D mass profile M(r). We compare to the deprojected lensing determination.

Good agreement between M(r) derived using galaxies as tracers of the gravitational potential and M(r) derived from lensing.

May 27th 2015, USM
Andrea Biviano “CLASH-VLT: the dynamics of clusters of galaxies”
MACS0416 (Balestra et al. in prep.)

The mass profiles

MACS0416

M_{200} = 9.3 \times 10^{14} M_\odot \, (h=0.7)

Best-fit M(r) model is not NFW but SIS

MAMPOSSSt + Caustic recovers the 3D mass profile M(r).
We project it along the l.o.s. to allow comparison with the lensing determination.

Good agreement between M(r) derived using galaxies as tracers of the gravitational potential and M(r) derived from lensing (less good with M(r) from X-ray)

MAMPOSSSt (SIS best-fit)
Weak lensing (Umetsu+14)
Chandra (S. Ettori)

Dots: weak lensing from Jauzac+14

MAMPOSSSt (NFW best-fit)
Strong lensing (Grillo+14)
The mass profiles

\[ M_{200} = 13.7 \times 10^{14} M_\odot \ (h=0.7) \]

MACS1206 (AB et al. 2013)

MAMPOSSSt + Caustic recovers the 3D mass profile \( M(r) \). We project it along the l.o.s. to allow comparison with the lensing determination.

Good agreement between \( M(r) \) derived using galaxies as tracers of the gravitational potential and \( M(r) \) derived from lensing and from X-ray.

Best-fit \( M(r) \) model is NFW

\[ M_{200} = 13.7 \times 10^{14} M_\odot \ (h=0.7) \]

Lensing and X-ray \( M(r) \) from Umetsu et al. 2012

NFW best fit from dynamical analysis (combined Jeans + Caustic analysis)

X-ray (Chandra) hydrostatic mass

Virial radius

May 27th 2015, USM

Andrea Biviano “CLASH-VLT: the dynamics of clusters of galaxies”
The internal dynamics of CLASH-VLT clusters: Dark Matter equation of state
In GR, the cluster potential well $\phi$ is shaped by the whole mass-energy content of the clusters: density and pressure separately.

Galaxies are non relativistic, their velocity distribution depends only on $\phi'(r)$

Light trajectories respond to both $\phi'(r)$ and a relativistic term depending on $m(r)$

$$m(r) = 2m_{\text{lens}}(r) - m_k$$

$$2\Phi_{\text{lens}}(r) = \Phi(r) + \int \frac{m(r)}{r^2} \, dr$$

(Sartoris et al. 2014)
The Dark Matter equation of state

\[ w(r) = \frac{p_r(r) + 2p_t(r)}{3\rho(r)} \approx \frac{2}{3} \frac{m'_K(r) - m'_{\text{lens}}(r)}{2m'_\text{lens}(r) - m'_K(r)} \]

Averaging over all radii
\[ w = -0.00 \pm 0.15 \text{ (stat)} \pm 0.8 \text{ (syst)} \]

(Sartoris et al. 2014; based on a single cluster CLASH-VLT so far)
The internal dynamics of CLASH-VLT clusters: The pseudo-phase-space density profile $Q(r)$
The pseudo-phase-space density profiles of cosmological halos

MACS1206 and Abell 209 are best fitted by the NFW mass profile.

MACS416 is best fitted by the SIS mass profile.

Is there a more fundamental physical quantity that is common to the three clusters?

MACS1206: Ratio of different mass profile best-fitting models

Andrea Biviano “CLASH-VLT: the dynamics of clusters of galaxies”
The pseudo-phase-space density profiles of cosmological halos

Taylor & Navarro 2001: the shape of the PPS density profile of cosmological halos,

\[ Q(r) = \frac{\rho}{\sigma^3} \]

\( \rho \) mass density profile, 
\( \sigma \) velocity dispersion profile

is a universal power-law

**Why?**

A scale-invariant profile may result from violent relaxation, subsequently dynamical equilibrium sets the exponent value (Dehnen & McLaughlin 2005)
The pseudo-phase-space density profiles of cosmological halos

The physical meaning of $Q(r)$: related to the entropy of the system

X-ray observers define the intra-cluster gas 'entropy' $K \equiv kT / n_e^{2/3}$

Taking $kT \sim \sigma_v^2$, $n_e \sim \rho$

$\rightarrow Q \sim K^{-3/2}$

$K(r)$ is not a simple power-law for galaxy clusters, suggesting non-gravitational processes shape $K(r)$ of the gas

What about (presumed) non-collisional matter (DM, galaxies)?
We have $\rho$ (from mass profiles) and $\sigma$ (from l.o.s. velocity dispersion profiles deprojection), so we can determine $Q(r)$ observationally.

Good agreement between observed and theoretically/numerically expected $Q(r)$ profile.
Good agreement between observed and theoretically/numerically expected Q(r) profile.
Good agreement between observed and theoretically/numerically expected $Q(r)$ profile
The same relation also holds at low redshift ($<z>=0.05$).

Stack of 40 relaxed clusters from the WINGS sample, $\approx 4900$ cluster members.

What about $Q(r)$ evolution?

$Q(r)$, $WINGS [AB, Mamon, Cava et al. in prep]$,

- - - theoretical prediction

$Q(r)$ vs. $r/r_{200}$

$Q(r) [M_\odot \text{Mpc}^{-3} \text{km}^{-3} \text{s}^{-1}]$
The same relation also holds at high redshift ($<z>=1.02$)

Stack of 10 clusters from the GCLASS sample, $\approx 400$ cluster members

What about $Q(r)$ evolution?
The internal dynamics of CLASH-VLT clusters: Stellar-to-mass profile ratio
Learning about galaxy evolution in clusters

Abell 209 and MACS 1206: similar total mass profiles

But what about their stellar mass profiles?

They may inform us on processes affecting galaxy evolution in the clusters environment.

Combine the spectroscopic sample with a photometric sample selected in $z_{\text{phot}}$ to achieve 100% completeness.

Fit galaxy spectral energy distributions with MAGPHYS (da Cunha et al. 2008) to get the galaxy stellar masses, $M_*$
Total vs. stellar mass density profiles

[Annunziatella, AB, et al. 2014; Annunziatella, Mercurio, AB et al. in prep.]

stellar mass density profile, \( \rho_*(r) \)
galaxy number density profile, \( n(r) \)
total mass density profile, \( \rho_{\text{tot}}(r) \)

Shading: cosmic value of stellar mass fraction at the cluster \(<z>\)
Total vs. stellar mass density profiles

[Annunziatella, AB, et al. 2014; Annunziatella, Mercurio, AB et al. in prep.]

stellar mass density profile, $\rho_*(r)$
galaxy number density profile, $n(r)$
total mass density profile, $\rho_{\text{tot}}(r)$

Abell 209

MACS 1206

Shading: cosmic value of stellar mass fraction at the cluster $<z>$
Total vs. stellar mass density profiles

[Annunziatella, AB, et al. 2014; Annunziatella, Mercurio, AB et al. in prep.]

**Abell 209**

- Stellar mass density profile, $\rho_*(r)$
- Galaxy number density profile, $n(r)$
- Total mass density profile, $\rho_{\text{tot}}(r)$

- Tidal destruction
- Dynamical friction

**MACS 1206**

- Tidal destruction
- No dynamical friction

Shading: cosmic value of stellar mass fraction at the cluster $<z>$
Total vs. stellar mass density profiles

[Annunziatella, AB, et al. 2014; Annunziatella, Mercurio, AB et al. in prep.]

stellar mass density profile, $\rho_*(r)$
galaxy number density profile, $n(r)$
total mass density profile, $\rho_{tot}(r)$

Shading: cosmic value of stellar mass fraction at the cluster $<z>$
The internal dynamics of CLASH-VLT clusters: Orbits of galaxies in clusters $\beta(r)$

(Got the big brezel in the end!)
Inverting the Jeans equation

Define a fiducial mass profile from the combination of MAMPOSSt, Caustic and lensing $M(r)$ and get a direct, non-parametric estimate of $\beta(r)$ from the inversion of the Jeans equation

[Binney & Mamon 82, Solanes & Salvador-Solé 90]

Compare with MAMPOSSt parametric solutions (cross-check)

Observables

$N(R), \sigma_{\text{los}}(R)$

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

$+ M(r)$

$\rightarrow$

$\beta(r)$
Galaxy orbits

A0209, [Sartoris, AB et al. in prep.]

\[ \beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)} \]

→ tangential component of velocity dispersion

→ radial component of velocity dispersion
Galaxy orbits

MACS416, [Sartoris, AB et al. in prep.]

$\beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)}$ → tangential component of velocity dispersion

→ radial component of velocity dispersion
Galaxy orbits

MACS1206, [AB et al. 2013]

\[ \beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)} \]

→ tangential component of velocity dispersion

→ radial component of velocity dispersion
The $\beta(r)$ of cluster-size halos in cosmological simulations

11 simulated halos, [Mamon, AB, Boué 2013]

\[
\beta(r) = 1 - \frac{\sigma^2_\theta(r)}{\sigma^2_r(r)} \rightarrow \text{tangential component of velocity dispersion}
\]
\[
\rightarrow \text{radial component of velocity dispersion}
\]
What about $\beta(r)$ evolution?

WINGS, stack of 42 relaxed $<z>=0.05$ clusters [Cava, AB, Mamon et al. in prep.]

\[ \beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)} \]

$\rightarrow$ tangential component of velocity dispersion

$\rightarrow$ radial component of velocity dispersion
Galaxy orbits

GCLASS, stack of 10 $z \approx 1$ clusters [AB, van der Burg, Muzzin et al. in prep.]

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

→ tangential component of velocity dispersion

→ radial component of velocity dispersion

radial orbits

tangential orbits
Evolution of $\beta(r)$ of cluster-size halos in simulations

[Munari, AB et al. 2013]

\[ \beta(r) = 1 - \frac{\sigma_\theta^2(r)}{\sigma_r^2(r)} \]

→ tangential component of velocity dispersion

→ radial component of velocity dispersion
Evolution of $\beta(r)$ of cluster-size halos in simulations

[Iannuzzi & Dolag 2012]

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

Galaxy orbits

- tangential component of velocity dispersion
- radial component of velocity dispersion
Summary and perspectives

(Summary of our findings for lazy - or tired - listeners)
Summary (1/2)

- Using 3 (out of 12) clusters from the CLASH-VLT survey with 600-1000 cluster members each

- M(r) traced by cluster galaxies in agreement (and of comparable precision) with M(r) from lensing

- Cmp the two determination of M(r) to constrain DM EoS

- M(r) best-fit model is NFW (2 clusters), SIS (1 cluster)
Summary (2/2)

- Q(r) is remarkably similar and close to the predicted power-law in different clusters and at different redshifts → *rapid dynamical relaxation of the collisionless component*

- Two clusters of similar total mass density profiles have different stellar mass density profiles → *different relevance of different physical processes affecting galaxy evolution (dyn. friction, tidal disruption)*

- Orbits of galaxies are isotropic near the center, increasingly radial outside; variance among clusters. *No evolution?*
Perspectives

➢ Enlarge the sample by factor 4 in next ~12 months
   (most observations completed, data-reduction ongoing,
   thanks Italo Balestra and Amata Mercurio!)
Perspectives

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➢ What makes M(r) different in different clusters? Are these profiles universal for dynamically relaxed clusters?
Perspectives

➢ Enlarge the sample by factor 4 in next ~12 months (most observations completed, data-reduction ongoing, thanks Italo Balestra and Amata Mercurio!)

➢ What makes M(r) different in different clusters? Are these profiles universal for dynamically relaxed clusters? Can we improve M(r) determination for unrelaxed clusters? (ongoing: Sartoris + AB)

MACS0416, one of the three CLASH-VLT clusters analyzed so far, the one with a non-NFW M(r), shows clear evidence of an ongoing merger between two subclusters (Balestra et al. in prep.)
Improving $M(r)$ for bimodal clusters

MACS0416: bimodal velocity distribution, elongated spatial distribution

Choose a similar halo from cosmological numerical simulations – $M(r)$ being known for this halo we try to devise a new method to estimate it correctly.
Improving $M(r)$ for bimodal clusters

Use KMM algorithm (McLachlan & Basford) to fit two Gaussians to the l.o.s. velocity distribution and separate the two merging components. Then run MAMPOSSt separately on the two components.

The total projected mass profile relative to a given center is reconstructed from the sum of two surface mass-density components (this is analog to the procedure adopted in gravitational lensing mass reconstruction)
Perspectives

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➢ What makes $M(r)$ different in different clusters? Are these profiles universal for dynamically relaxed clusters? Can we improve $M(r)$ determination for unrelaxed clusters? (ongoing: Sartoris + AB)

➢ What makes $Q(r)$ so invariant? Cmp. to num. simulations (ongoing: Sartoris + Munari + Planelles + AB)
What makes $Q(r)$ so invariant?

Comparison of $Q(r)$ of observed clusters (from CLASH-VLT and Munari, AB, Mamon 2014) obtained using galaxies as tracers of the velocity field with $Q(r)$ of halos from cosmological num. simulations, using either DM particles or subhalos as tracers of the velocity field.

Different slope found when using subhalos.
Perspectives

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➢ What makes $Q(r)$ so invariant? Cmp. to num. simulations (ongoing: Sartoris + Munari + Planelles + AB)

➢ Determine $\beta(r)$ for different cluster galaxy populations (orbits might be related to galaxy evolution in clusters)
Determine $\beta(r)$ for different galaxy populations

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

Low-z cluster (Munari, AB, Mamon 2014)  
z=0.44 cluster (AB + 2013)
Perspectives

➢ Enlarge the sample by factor 4 in next ~12 months (most observations completed, data-reduction ongoing, thanks Italo Balestra and Amata Mercurio!)

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➢ Determine $\beta(r)$ for different cluster galaxy populations (orbits might be related to galaxy evolution in clusters)

➢ The dynamics of the SPT-SZ clusters (with Raffaella, Alex, Joe, Sebastian, Veronica ...)

May 27th 2015, USM
...and if you just came in, here is

The very short summary

(no need to climb it, get the Maibaum and the brezel at once)