Pseudo phase-space density profiles: a tool to investigate the accretion and evolutionary history of cluster galaxies

Andrea Biviano (INAF/Oss. Astr. Trieste)
+ the CLASH & CLASH-VLT teams
+ E. Munari, G. Mamon
The pseudo phase space density profiles of cosmological halos

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

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

(\( \rho \) is the density profile, \( \sigma \) is the 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

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

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

(\( \rho \) is the density profile, \( \sigma \) is the velocity dispersion profile)

is a universal power-law

Why?

Also confirmed analytically by considering dynamical relaxation processes in the infalling matter, like phase-space mixing associated with shell crossing and collective collisions related to clumpiness (Lapi & Cavaliere 2011)
The pseudo phase space density profiles of cosmological halos

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

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

(\( \rho \) is the density profile, \( \sigma \) is the velocity dispersion profile)

is a universal power-law

**Observational check:**

Use clusters of galaxies: we must determine the mass density profile \( \rho \), and the deprojected velocity dispersion profile of cluster galaxies
The CLASH & CLASH-VLT programs

**CLASH**, Cluster Lensing And Supernova survey with Hubble, *PI: M. Postman.*

524 HST orbits to observe 25 gravitationally lensing clusters of galaxies at $0.18 < z < 0.90$

**CLASH-VLT**, VLT-VIMOS follow-up from the ESO Large Programme


225 hours to observe the 14 southern CLASH clusters and obtain redshifts for $\approx 500$ members in each cluster, and $\sim 100$ lensed images of $z \leq 7$ galaxies
A case study:
the CLASH cluster MACS J1206-0847

Results from Biviano+13
MACS J1206:

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

Mean cluster redshift:

$\langle z \rangle = 0.4398 \pm 0.0002$

Cluster velocity dispersion:

$\sigma = 1087 \pm 54 \text{ km s}^{-1}$
Determine the mass (density) profile

Apply the Jeans equation of dynamical equilibrium to the distribution of cluster galaxies in projected phase-space, rest-frame velocities vs. clustercentric distances

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

Velocity anisotropy \( \Rightarrow \) orbital distribution of the tracers of the gravitational potential

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

Problem: we must solve the \( M(<r) - \beta(r) \) degeneracy
Solve the Jeans eq. degeneracy by a maximum likelihood fit to the full distribution of the tracers of the gravitational potential in projected phase-space, assuming a shape for the 3-d velocity distribution of tracers (galaxies, in our case)

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

[Mamon, Biviano & Boué 2013]
Mass profile of MACS J1206

Different models considered:
NFW, Einasto, Hernquist, Burkert, Softened Isothermal Sphere
Mass profile of MACS J1206

Independent determination from the weak + strong lensing analysis of Umetsu+12

Alternative determination from the projected phase-space distribution of cluster galaxies using the Caustic method of Diaferio+Geller (1997)

Dashed black line: best-fit mass model solution from MAMPOSSt (‘NFW’ model)
The velocity anisotropy profile

Given $M(r)$ and the observables we obtain $\beta(r)$ from the inversion of the Jeans equation

[Binney & Mamon 1982, Solanes & Salvador-Solé 1990]

Observables

$N(R), \sigma_v(R)$

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

Jeans inversion

$\beta(r)$
The velocity anisotropy profile(s)

Dashed black lines are theoretical models, the middle one is a good fit to cluster-size halos from cosmological numerical simulations.

Star-forming and quiescent galaxies have similar orbits within the cluster, isotropic near the center and radially-elongated outside.
Knowledge of $\beta(r)$ is needed to determine the 3-d velocity dispersion, $\sigma$, given the observed velocity dispersion along the line-of-sight:

With the mass density profile, $\rho(r)$, and the 3-d velocity dispersion profile, $\sigma(r)$, we can determine the pseudo phase space density profile, $Q(r) = \rho/\sigma^3$
The pseudo phase space density profile(s)

- **Data & 1-σ intervals:** colored lines and shaded regions
- **Theoretical relation from num. simulations:** dashed black lines

Good agreement between the observed $Q(r)$ and the theoretical prediction

The agreement is acceptable for the star-forming galaxies and good for the quiescent galaxies
The pseudo phase space density profile(s): check for evolution

Use a low-z (0.09) cluster (A2142) with many (>900) spectroscopic members from the literature (Owers+11, MMT/Hectospec) and apply a similar analysis.

NFW is the best-fit mass model.

Inverting the Jeans equation gives these velocity anisotropy profiles.

Red and blue galaxies have different velocity anisotropy profiles.

The pseudo phase space density profile(s)

Results for the low-redshift cluster A2142 (z=0.09)

The theoretical profile is obeyed also at low-z, but only by quiescent galaxies, and not so well by star-forming galaxies

Summing up

Current results indicate:

- $M(r)$ is close to theoretically favored models (NFW, Einasto)
- Orbits are similar to those seen for DM particles in simulated halos \textit{(in the $z=0.44$ cluster, not in the $z=0.09$ one)}
- Theoretical $Q(r)$ power-law relation is confirmed, but star-forming galaxies (SFGs) show some deviation
- $Q(r)$ for quiescent galaxies does not change with time
Discussion

★ Is the power-law behavior of the PPS density profile $Q(r)$ established via violent relaxation?

If yes, why SFGs follow it (at least over some radial range)?

Violent relaxation occurred sufficiently long ago that SFGs present in the cluster at that time should have become quiescent by now.

★ Is the power-law exponent of $Q(r)$ established by dynamical equilibrium?

If yes, the lack of $Q(r)$ evolution for quiescent galaxies from $z=0.44$ to $z=0.09$ requires $z=0.44$ SFGs to reach dynamical equilibrium before they evolve into quiescent galaxies by $z=0.09$
Perspectives

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

- Analysis of distant clusters to investigate $Q(r)$ evolution: CLASH-VLT (12 $<z> \approx 0.4$ clusters, $\approx 500$ members with $z$ per cluster)

- Analysis of a sample of X-ray emitting groups, to see dependence of $Q(r)$ on the mass of the galaxy system

(In collaboration with: G. Mamon, A. Cava, and the CLASH, CLASH-VLT, DAFT/FADA, and WINGS teams)
gas stripping