The Dark Matter Profile in Brightest Cluster Galaxies

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The dark matter profile in massive galaxies

- What is the shape of the DM density profile on small scales?
- Is it universal, or does it vary between galaxies?
- How does the DM distribution compare to the canonical CDM profile?
- If differences are apparent, what do they tell us about the interplay between baryons and DM? About the DM particle?
Challenges

- Precise mass measures covering a wide radial baseline with dense sampling needed
- Must overcome degeneracies inherent to individual probes (e.g., velocity anisotropy)
- Need to separate baryonic and dark mass

⇒ Multiple observational mass probes are key
Observational tools in galaxy clusters

- Weak lensing
- X-ray
- Strong lensing
- Stellar dynamics

3 Mpc 500 kpc 100 kpc 20 kpc 3 kpc

Subaru  Chandra  HST  Keck

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The sample

MS2137  A963  A383  A611
A2537  A2667  A2390

Chandra contours on Subaru images

$M_{200} = 0.4 - 2 \times 10^{15} \, M_\odot$  \hspace{1cm}  $z = 0.19 - 0.31$

Generally relaxed clusters

BCGs aligned with X-ray/lensing centroid
Weak lensing

Subaru SuprimeCam 35 arcmin ~ 8 Mpc

3—5 filters, photo-z selection of bkg. galaxies
Strong lensing

Spectroscopic redshifts

- $z_{\text{spec}} = 6.03$
  - Richard+ 2011
- $z_{\text{spec}} = 1.01$
  - Smith+ 2002, Sand+ 2004
- $z_{\text{spec}} = 2.55$
  - ABN+ 2012
  (all at Keck)

Multiple arc positions and redshifts $\Rightarrow$ precise projected mass distribution on $\sim 10$-100 kpc scales

Arc modeling with Lenstool code
  - Kneib+ 93, Jullo+ 07
Stellar kinematics in the BCG

Resolved stellar kinematics in the BCG extend constraints from inner stellar-dominated to dark matter-dominated regime → rising $\sigma(r)$.

Joined with strong lensing gives a long lever arm on the inner density profile.

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ABN+ 2012
Modeling the mass distribution

Dark matter halo
Generalize the NFW profile at small $r$ with free inner slope $\beta$:

$$\rho_{DM}(r) = \frac{\rho_0}{(r/r_s)^\beta (1 + r/r_s)^{3-\beta}}$$

3 free parameters, plus projected ellipticity and P.A.

Stars in BCG
Stellar mass follows light profile with constant $M_\star/L$ (free parameter)

(Other cluster members also included for strong lensing analysis.)

Simultaneously fit shear, multiple image positions, and velocity dispersion data.

$$\chi^2 = \chi^2_{SL} + \chi^2_{WL} + \chi^2_{Vel. Disp}$$
The total inner density slope
The total inner density slope

Compared to CDM-only Phoenix simulations (Gao+ 2012)

\[ r / r_{200} = 0.003 - 0.03 \]
The total inner density slope very close to CDM-only simulations in the inner regions.

Observed: \( \langle \gamma_{\text{tot}} \rangle = 1.16 \pm 0.05^{+0.05}_{-0.07} \)

CDM-only simulations: \( \langle \gamma_{\text{tot}} \rangle = 1.13 \pm 0.03 \)

Intrinsic scatter < 0.13 (68% CL)
Dark matter and stars in cluster cores

The sum of DM and stars has an NFW-like slope at $r > 6$ kpc; the slope of the DM is shallower.
Stellar mass-to-light ratio of BCGs

Stellar population synthesis

Lensing + dynamics

(9% scatter)

Consistent with results from dwarf-sensitive absorption line studies (e.g., Conroy & van Dokkum 2013), local elliptical resolved kinematics (ATLAS-3D), SLACS galaxy-scale lenses

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The mean inner DM slope $\langle \beta \rangle = 0.50 \pm 0.10$ (rand.) $^{+0.14}_{-0.13}$ (syst.) is significantly shallower than an NFW-type cusp.
The dark matter inner density slope

The DM slope appears to correlate with the properties of the BCG – suggesting a connection with the assembly of the central galaxy.
Physics of the dark matter cusp

1. Adiabatic contraction

Steepening of DM slope due to central build-up of cooling gas.

*Not* main effect except possibly at $r < 5$ kpc.

2. Dynamical friction of satellites on the halo
3. AGN
4. Mildly collisional dark matter
Physics of the dark matter cusp

1. Adiabatic contraction
2. Dynamical friction of satellites on the halo

Dynamical friction of satellite galaxies “heats” DM halo and lowers the central density.

3. AGN
4. Mildly collisional dark matter

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Physics of the dark matter cusp

1. Adiabatic contraction
2. Dynamical friction of satellites on the halo
3. AGN
   
   ![](chart.png)

Martizzi, Teyssier & Moore (2012)

AGN feedback in high-res. hydro. simulations creates cores in the stellar and DM distributions of order ~10 kpc.

4. Mildly collisional dark matter
Physics of the dark matter cusp

1. Adiabatic contraction
2. Dynamical friction of satellites on the halo
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4. Mildly collisional dark matter

Self-interacting DM with allowed cross-sections $\sigma/m \sim 0.1 \text{ cm}^2/\text{g}$ produce ~20 kpc cores.

Spergel & Steinhardt 2000; Yoshida+ 2000; Davé+ 2001; Rocha+ 2012; Peter+ 2012
Summary

• Weak + strong lensing combined with stellar kinematic data can constrain cluster density profiles from ~3 kpc – 3 Mpc.

• Total density profiles are well-matched by collisionless CDM at radii > 5—10 kpc – well within the half-light radius of the BCG where its stellar mass is significant.

• The inner DM profile is shallower than CDM, but correlated with the BCG properties, suggesting a connection between the assembly of stars and the DM core.

• Improving simulations and observations over a wider range of halo mass will help disentangle possible physical origins of the DM cusp flattening.
X-ray vs. Lensing

$M_{\text{lens}} / M_X$ vs. Radius [kpc]

$M_{\text{lens}}$ and $M_X$ are typically within $\approx 15\%$.

Exception A383: Elongated near line of sight, ellipticity $\approx 0.5$

ABN+ 2011; Morandi & Limousin 2012
Simple models achieve good fits

Weak lensing

Strong lensing

~0.5" fidelity in image positions

Stellar kinematics

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Progress in $M_\odot/L$ of early-type galaxies

**Lensing + dynamics**
This work: BCGs
\[
\log \alpha_{\text{SPS}} = 0.27 \pm 0.05
\]
Chabrier IMF = 0, Salpeter IMF = 0.25

**SLACS “field” ellipticals**
Auger+ 2010, Treu+ 2010
\[
\log \alpha_{\text{SPS}} = 0.28 \pm 0.03
\]

**IFU kinematics (ATLAS}^{3D})**
(Cappellari+ 2012a,b,c)
\[
\log \alpha_{\text{SPS}} = 0.25 \text{ at high } \sigma
\]

**Detailed stellar population spectral models**
(van Dokkum & Conroy 2010,2012; C & vD 2012)
Find ~Salpeter IMF for luminous ellipticals.
Cores and cusps

Dwarf disks and Milky Way satellites often have shallow inner slopes or low central densities.
Due to baryonic physics or problem with CDM?
e.g., Moore+ 94, Simon+ 2005, de Blok+ 2008, Walker+ 2009-11, Oh+ 2011, …

“This program

“But clusters are okay!”
Down to what radius?
With what scatter?
Counting dark matter only? Total mass?

Umetsu et al 2011