Observational Constraints on the Distribution of Dark Matter in Galaxies

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The Cusp/Core Problem

- First recognized in 1994 that dwarf galaxy rotation curves are too shallow

The Cusp/Core Problem

- Navarro, Frenk, & White (1996)

\[ \rho(r) \propto \frac{1}{(r/r_s)(1 + r/r_s)^2} \]

Log Density vs. Log Radius
The Cusp/Core Problem

- This is important because:
  - Measurements of the mass distribution within galaxies could provide clues to DM physics
  - DM annihilation signals go as $\rho^2$

Kuhlen et al. (2008)
Outline

• Four primary regimes in which dark matter density profiles can be measured
  - Local Group dwarf spheroidals
  - Low-mass spiral/irregular galaxies
  - Massive galaxy lenses
  - Galaxy clusters
Dwarf Spheroidals as DM Probes

- Closest and most dark matter-dominated galaxies known
  - luminosities from $10^3$ to $10^7$ L$_\odot$
  - sizes from 30 to 1000 pc
  - masses of $\sim 10^9$ M$_\odot$
Dwarf Spheroidal Density Profiles

• Cleanest systems in principle
  - Baryons of little importance
  - Less interpretation of observations necessary

• But: radial velocities provide only one component of the 3D motion of each star
Dwarf Spheroidals as DM Probes
Dwarf Spheroidal Density Profiles

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  - Baryons of little importance
  - Less interpretation of observations necessary

- Jeans equation:

\[
\frac{d}{dr} \left( \frac{\rho_r \sigma_r^2}{r} \right) = \frac{GM(r)}{r} - 2\beta(r)\rho_r \sigma_r^2
\]

*observed unknown*

\(M(r)\) and \(\beta(r)\) are degenerate!
Dwarf Spheroidal Density Profiles

• Assume \( \rho(r) \propto r^{-\gamma} \)
  - Want to distinguish \( \gamma \sim 0 \) (CDM is wrong) from \( \gamma \sim 1 \) (DM is cold)

Strigari et al. (2007)
How Many Stars Does It Take?

$\gamma < 0.25$ requires 5000 stars

$\gamma < 0.20$ requires 9000 stars

Strigari et al. (2007)
Published RV Samples

• Fornax: 2483
• Sculptor: 1365
• Carina: 774
• Sextans: 441
• Draco: 210
• Ursa Minor: 182
• Leo I: 827

Walker et al. (2009)
Muñoz et al. (2005)
Kirby et al. (2010)
dSph Density Profile Results

- **Fornax**
  - $\gamma = 0.39^{+0.37}_{-0.43}$ (Walker & Penarrubia 2011)
  - core (Jardel & Gebhardt 2012)
  - core or cusp (Breddels & Helmi 2013)

- **Sculptor**
  - core or cusp (Battaglia et al. 2008)
  - $\gamma = 0.05^{+0.39}_{-0.51}$ (Walker & Penarrubia 2011)
  - core (Amorisco & Evans 2012)
  - $\gamma = 0 \pm 1.2$ (Breddels et al. 2013)
  - core or cusp (Breddels & Helmi 2013)
  - $\gamma = 0$ or $1.2$ (Richardson & Fairbairn 2014)
Dwarf Spheroidal Density Profiles

- Instead of using radial velocities alone, add proper motions
  - Directly determines the velocity anisotropy
  - $5 \text{ km s}^{-1} \sim 11 \mu\text{as yr}^{-1}$
Future Outlook

- Currently little agreement in derived density profile slopes
- Radial velocity sample sizes are still being increased
- Possibility of measuring proper motions with HST, Gaia, JWST, or ELTs
Late-Type Dwarf Galaxies
Tilted Ring Modeling

- Galaxy rotation curve is determined by a harmonic fit: \( V_{\text{obs}} = V_{\text{sys}} + V_{\text{rot}} \cos \theta + V_{\text{rad}} \sin \theta \)
Disk Galaxy Rotation Curves

- Interpretation complicated by:
  - Non-circular motions
  - Bars
  - Unknown stellar M/L
  - Disk geometry (warps, etc.)
  - Adiabatic contraction

Simon et al. (2003, 2005)
Kuzio de Naray et al. (2006, 2008)
Oh et al. (2011)
Stellar + Gas Velocity Fields of 7 Dwarfs

NGC 959

UGC 2259

NGC 2552

UGC 11707

NGC 2976

NGC 5204

NGC 5949

Adams et al. (2014)
Stars vs. Gas

- Initial suggestions of disagreement between stars and gas, now resolved

Adams et al. (2014)

γ_{star}

Adams et al. (2012) - stars
Simon et al. (2003) - gas

γ_{gas}

UGC 2259
UGC 2552
UGC 2976
UGC 5204
UGC 5949
UGC 11707

Adams et al. (2014)
Observed Distribution of Central Slopes

Average DM profile has $\gamma = 0.63 \pm 0.28$


Simulations: Diemand et al. (2004)
Future Outlook

- Survey of 25 galaxies in H\(\alpha\) (Palomar) and CO (CARMA) is underway
  - Will provide best available constraints on distribution of \(\gamma\)
  - Test predictions of different models to explain non-CDM slopes
- Still unclear whether \(\gamma < 1\) is because of DM properties or baryonic physics
Massive Galaxies

- Pro: gravitational lensing provides an extremely accurate measurement of enclosed mass
- Con: Only a minority of the mass is in dark matter

Bolton et al. (2008)
Lensed Galaxy Mass Distributions

- Lensing determines the total mass contained within $r_{Einstein}$ (~5 kpc)
- Add central velocity dispersion: get mass profile at $r_{Einstein}$
- Add additional kinematic or lensing measurements: full mass profile
- Serious degeneracy with IMF
Lensed Galaxy Mass Distributions

5 spiral lenses prefer shallow density profiles

161 elliptical lenses prefer steep density profiles

Dutton et al. (2013)

Oguri et al. (2014)
The Jackpot Lens

• Single galaxy lensing two background sources

\[ \gamma_{\text{DM}} = 1.7 \pm 0.2 \]
Future Outlook

- Larger lens surveys in progress
  - Will include more rare objects like the Jackpot
- Understanding of IMF is improving, but uncertainties in stellar mass will always limit constraints on $\gamma_{DM}$
Galaxy Clusters

- Most massive collapsed structures in the universe
- Baryonic effects may be easier to model
  - Most of the baryons are in the hot gas
  - Deep potential well is more robust to feedback
- Only systems in which measurements can be made out to the virial radius

Slides kindly contributed by Drew Newman
Observations

Weak lensing  X-ray  Strong lensing  Stellar dynamics

3 Mpc  500 kpc  100 kpc  20 kpc  3 kpc

Subaru  Chandra  HST  Keck

Independent probes span $r \sim 3$ kpc - 3 Mpc (3 decades in $r$)
- Clusters are relaxed and symmetric
- BCGs are aligned with X-ray/lensing centroid
- $M_{200} = 0.4 - 2 \times 10^{15} M_\odot$
- $z = 0.19 - 0.31$

Newman et al. (2013ab)
Weak Lensing (probes large radii)

3–5 filters, photo-z selection of bkg. galaxies using P(z) distribution

Newman et al. (2013ab)
Strong Lensing (probes intermediate radii)

Total: 80 images of 25 sources, $z_{\text{spec}}$ of 21 (7 new)
Resolved stellar kinematic measurements in the giant central galaxy provide mass constraints down to ~ 3 kpc.

Joined with strong lensing gives a long lever arm on the inner density profile.
Dark Matter and Stars in Cluster Cores

Total mass has NFW-like slope at $r \geq 6$ kpc
DM alone is shallower ($\gamma \sim 0.5$)

Newman et al. (2013b)
Inner Density Profile Slopes in Clusters

- DM slope correlates with properties of the BCG
  - Connection with the assembly of the central galaxy?
- $\gamma = 0.50 \pm 0.10$

Newman et al. (2013b)
Future Outlook

• CLASH will provide exquisite data for a larger sample of clusters
• Need to understand the origin of the correlation with BCG properties
Summary

- Late-type dwarf galaxies: $\gamma = 0.6$
- Galaxy clusters: $\gamma = 0.5$
- Dwarf spheroidals: no consensus
- Massive galaxies: no consensus

Can a single astrophysical mechanism be responsible for the shallow slopes of both dwarf galaxies and clusters?