Observational Constraints on the Distribution of Dark Matter in Galaxies

Josh Simon
Carnegie Observatories

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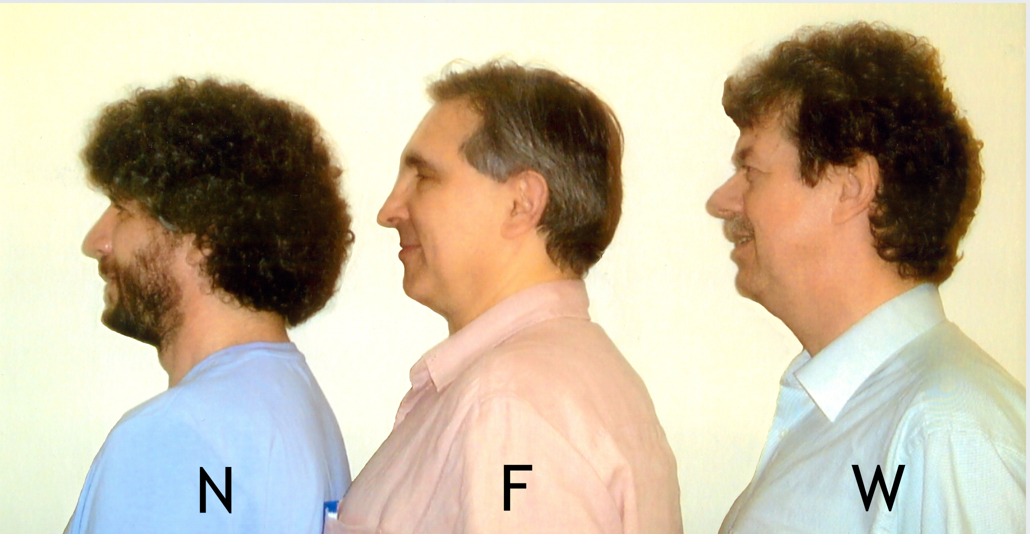
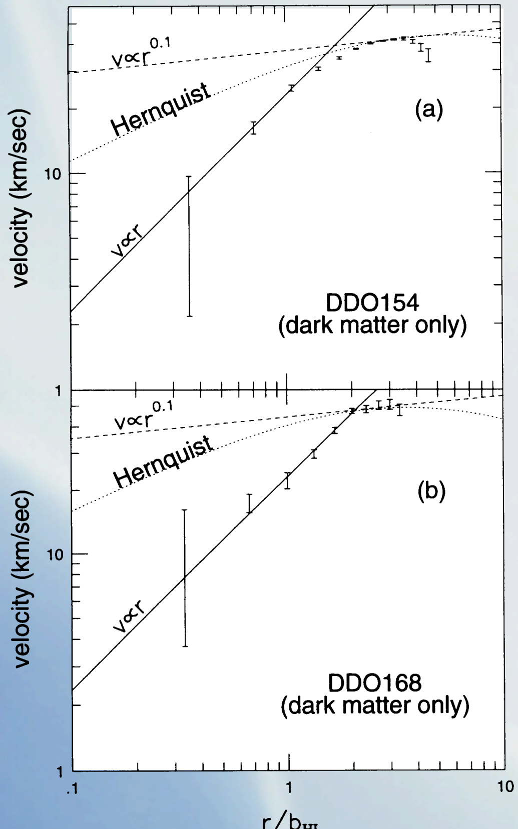
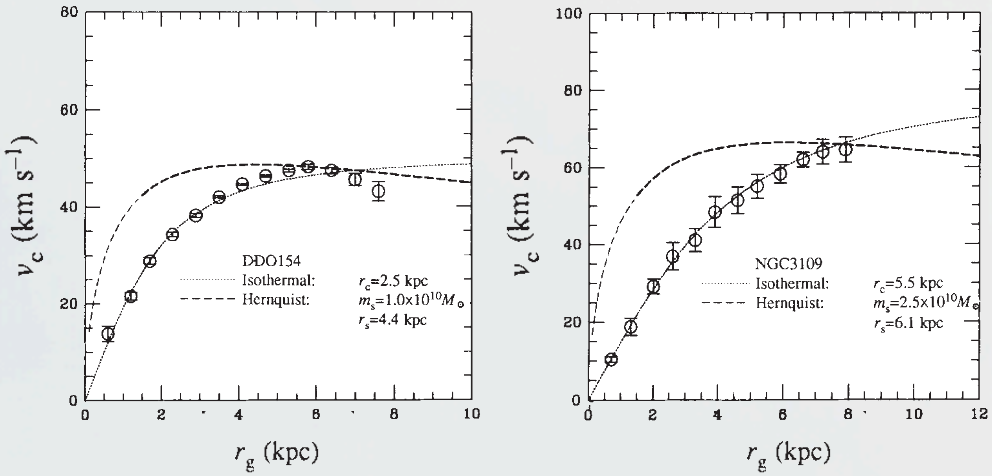


The Cusp/Core Problem

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



Flores & Primack (1994)

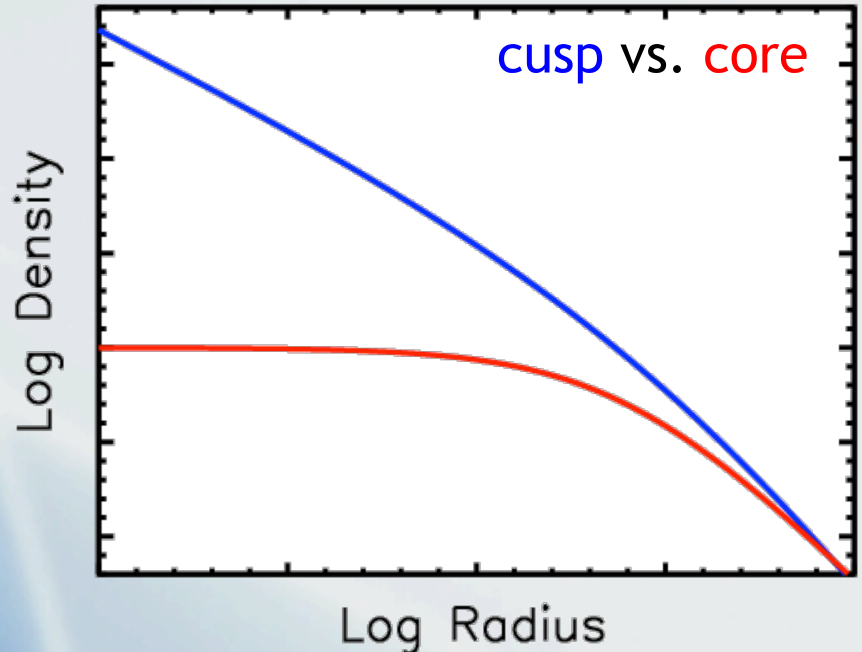


Moore (1994)

The Cusp/Core Problem

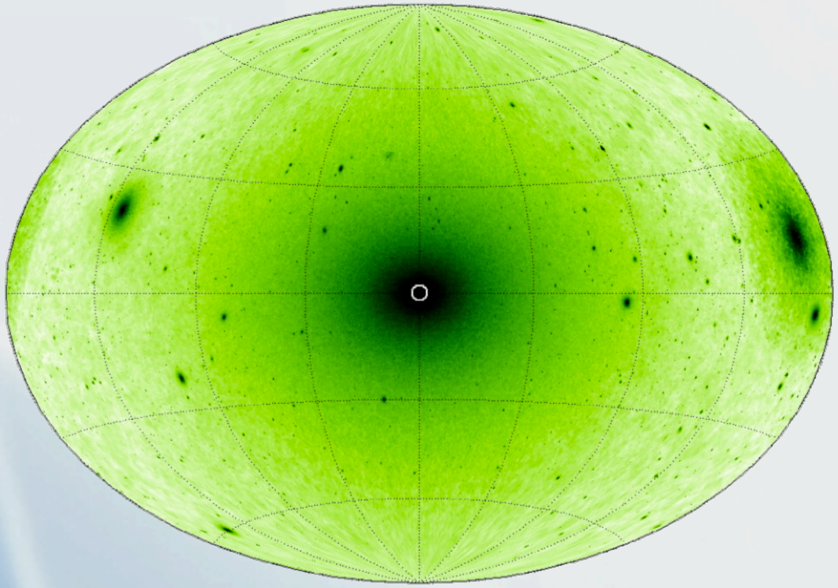
- Navarro, Frenk, & White (1996)

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



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 ρ^2

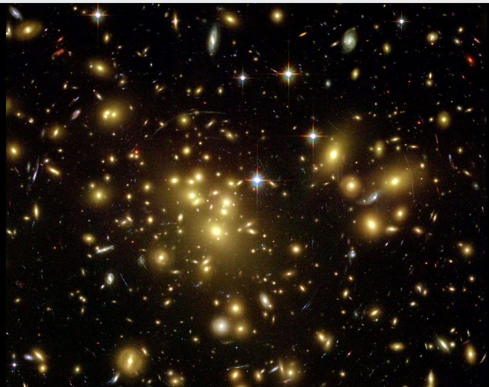


Kuhlen et al. (2008)

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

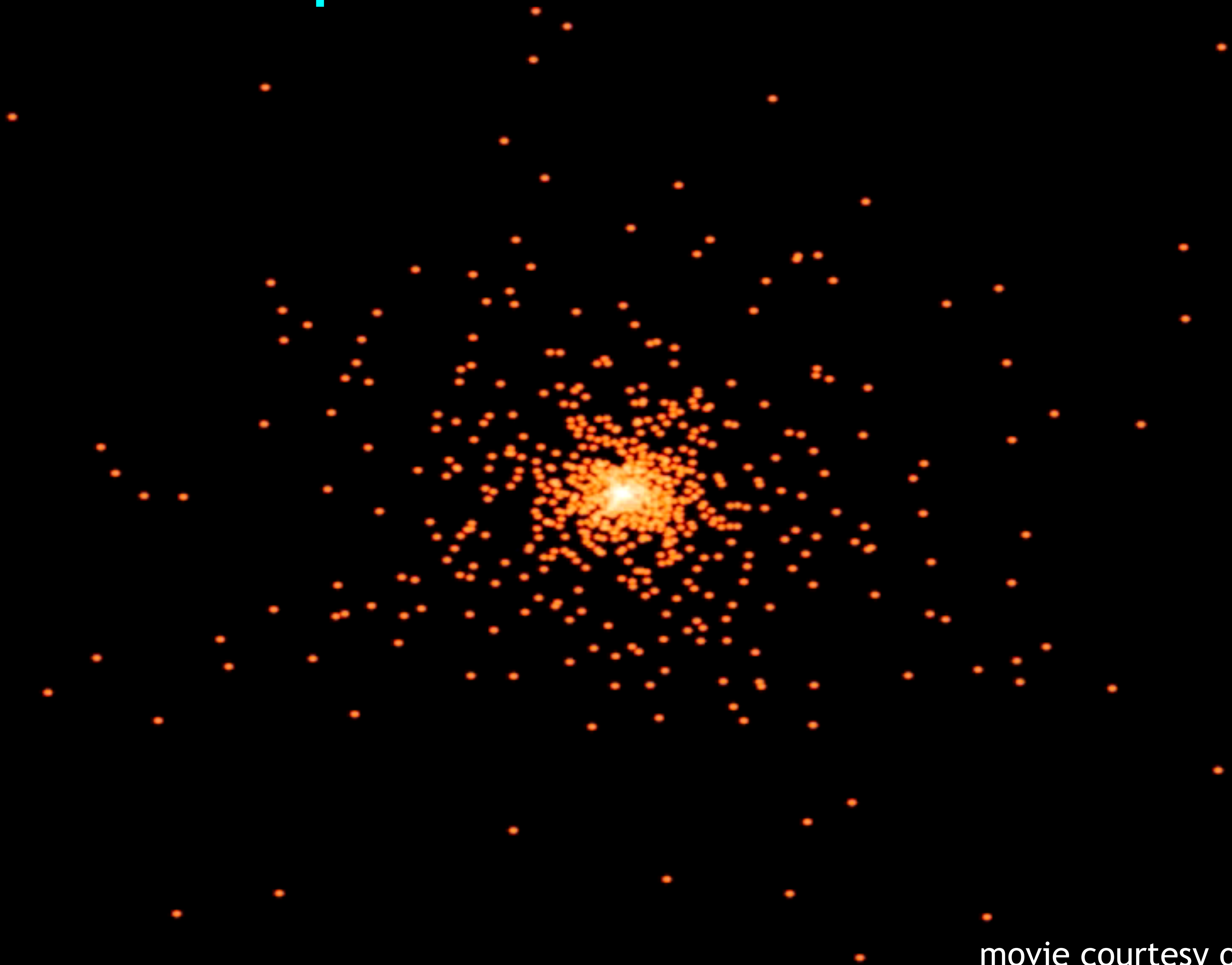
- Closest and most dark matter-dominated galaxies known
  - luminosities from 10^3 to 10^7 $L_\odot$
  - sizes from 30 to 1000 pc
  - masses of ~10^9 $M_\odot$



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



movie courtesy of TJ Cox

Dwarf Spheroidal Density Profiles

- Cleanest systems in principle
  - Baryons of little importance
  - Less interpretation of observations necessary
- Jeans equation:

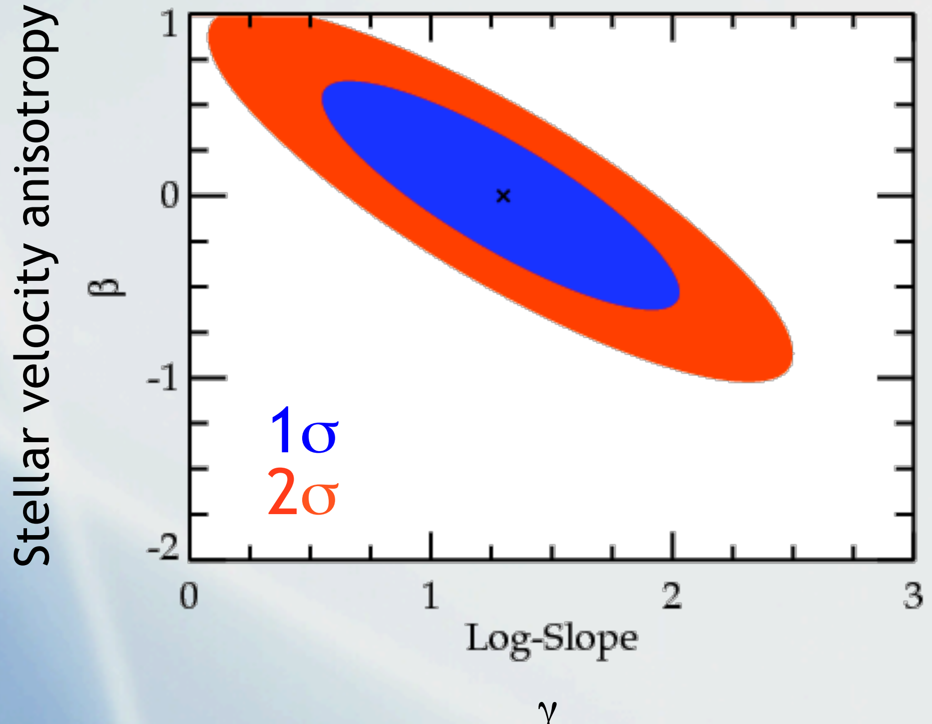
$$r \frac{d(\rho_* \sigma_r^2)}{dr} = -\rho_* \frac{GM(r)}{r} - 2\beta(r)\rho_* \sigma_r^2$$

observed
unknown

M(r) and β(r) are degenerate!

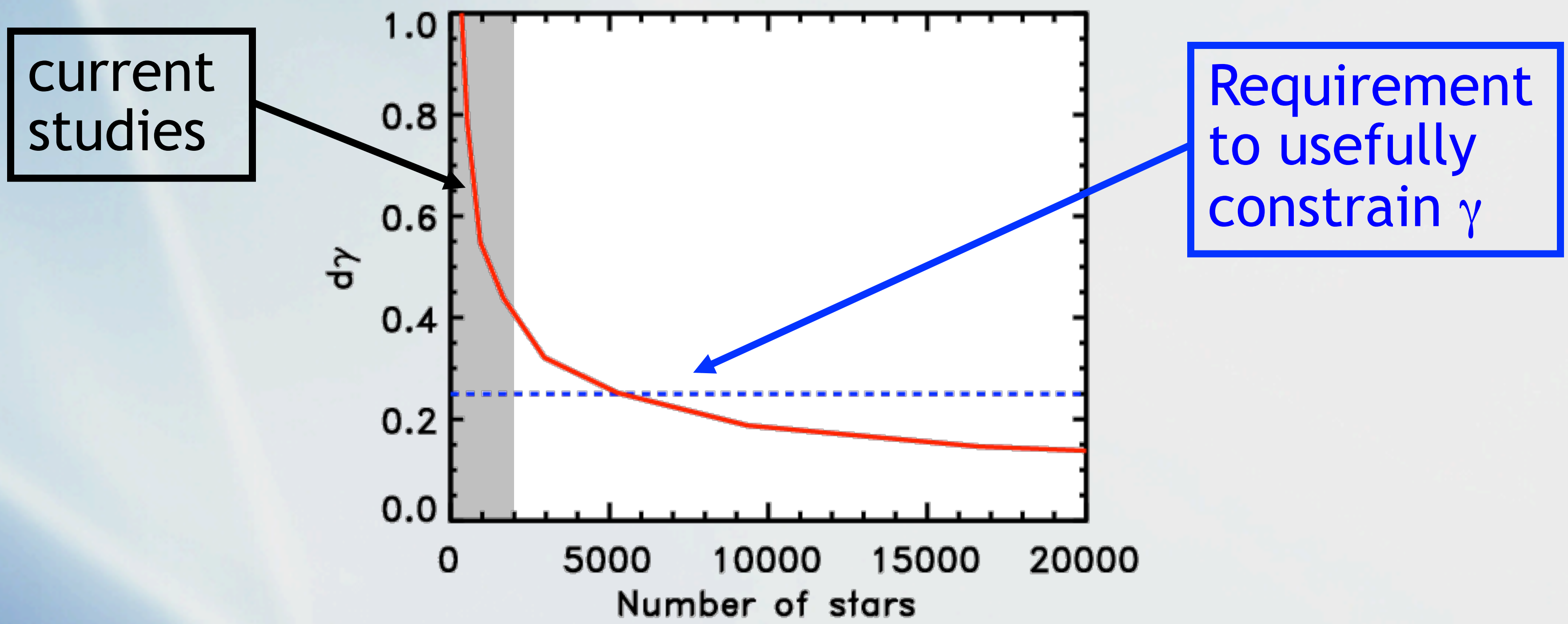
Dwarf Spheroidal Density Profiles

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



Strigari et al. (2007)

How Many Stars Does It Take?



dγ < 0.25 requires 5000 stars

dγ < 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)

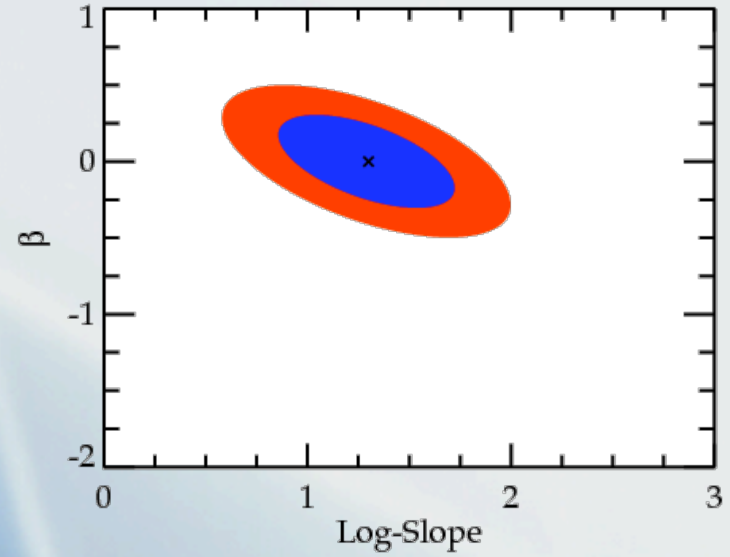
dSph Density Profile Results

- 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 km s^{-1} ~ 11 μas yr^{-1}

RVs plus proper motions



Strigari et al. (2007)

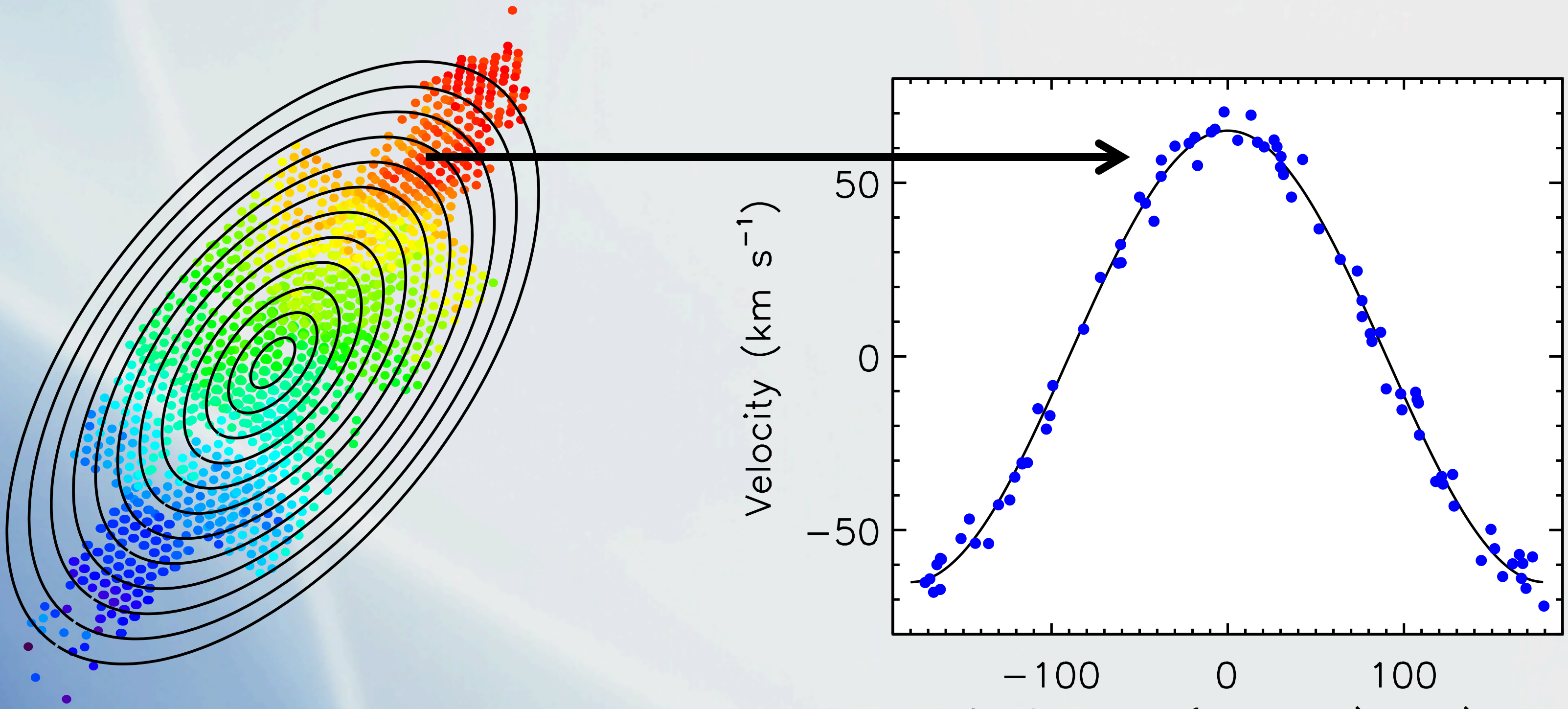
Future Outlook

- 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

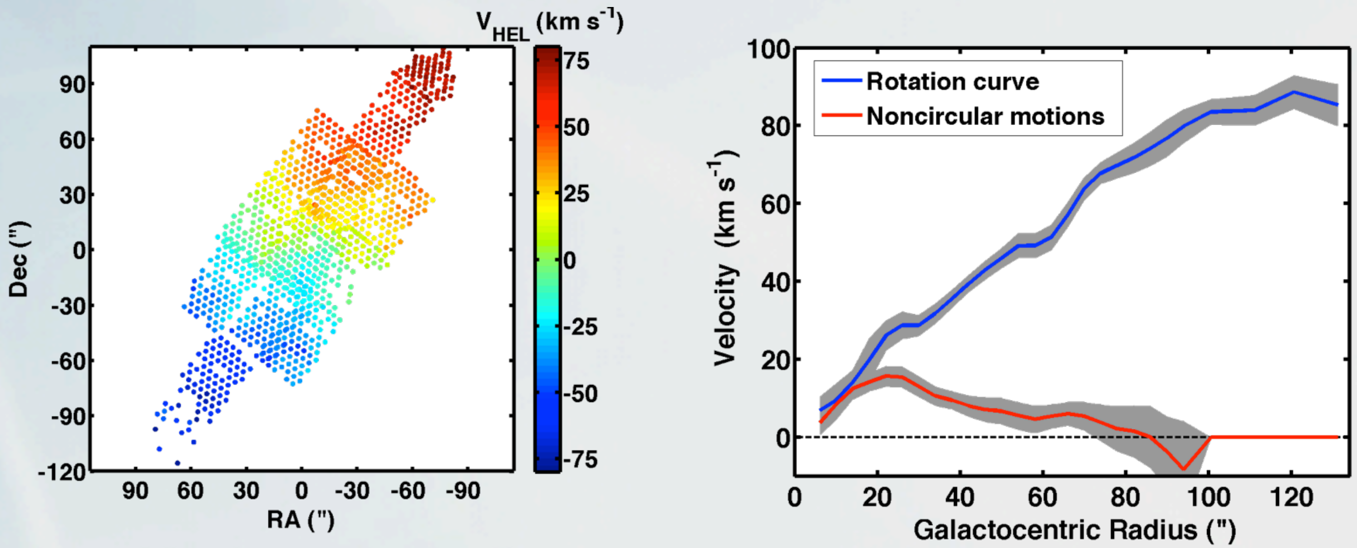
Late-Type Dwarf Galaxies

Tilted Ring Modeling

- Galaxy rotation curve is determined by a harmonic fit: $V_{obs} = V_{sys} + V_{rot}\cos\theta + V_{rad}\sin\theta$



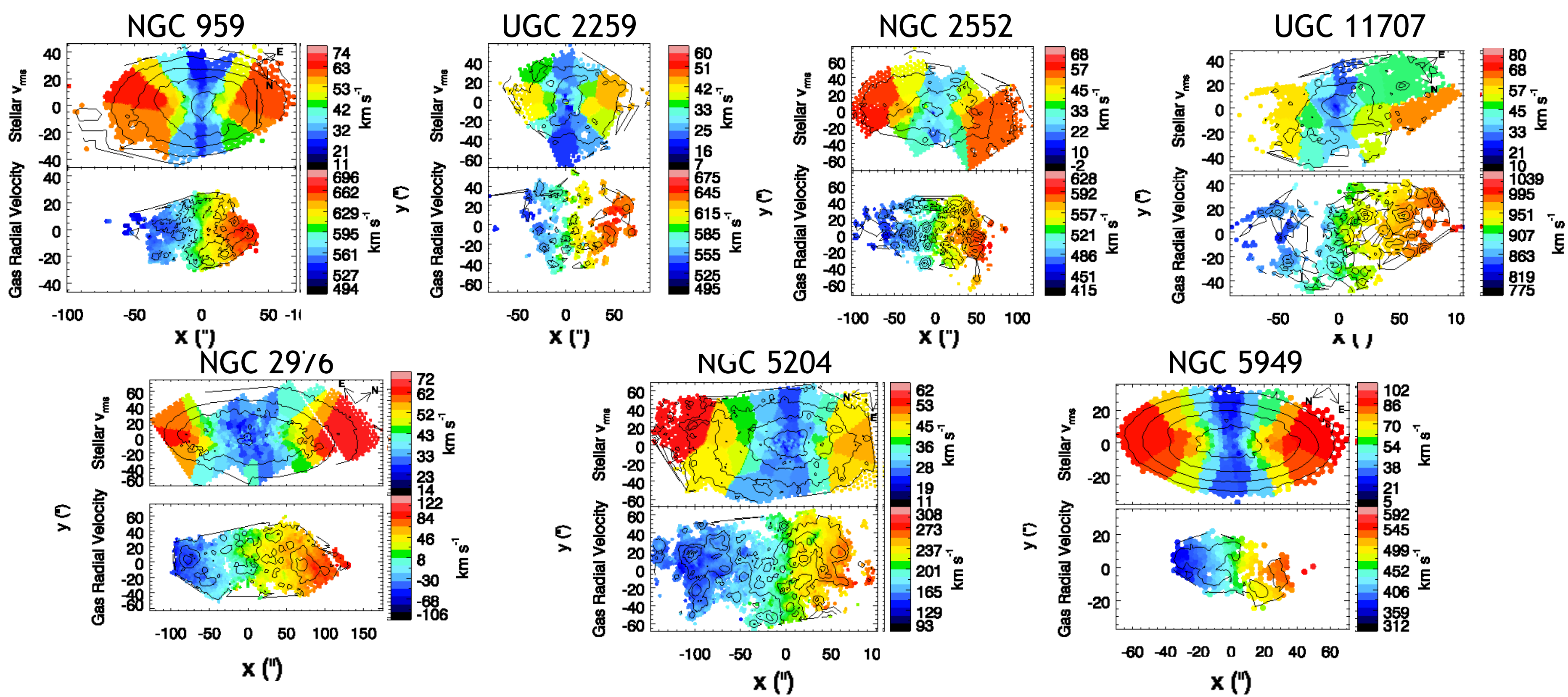
Disk Galaxy Rotation Curves



- 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)

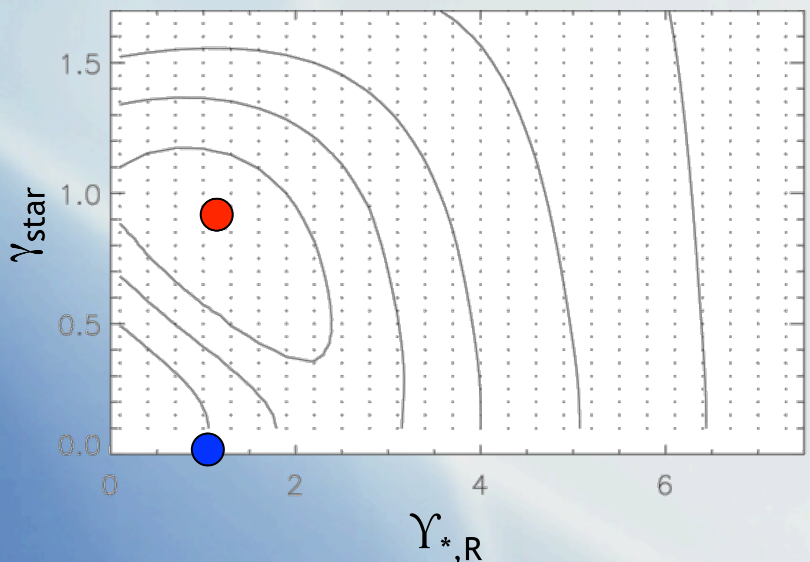
Stellar + Gas Velocity Fields of 7 Dwarfs



Adams et al. (2014)

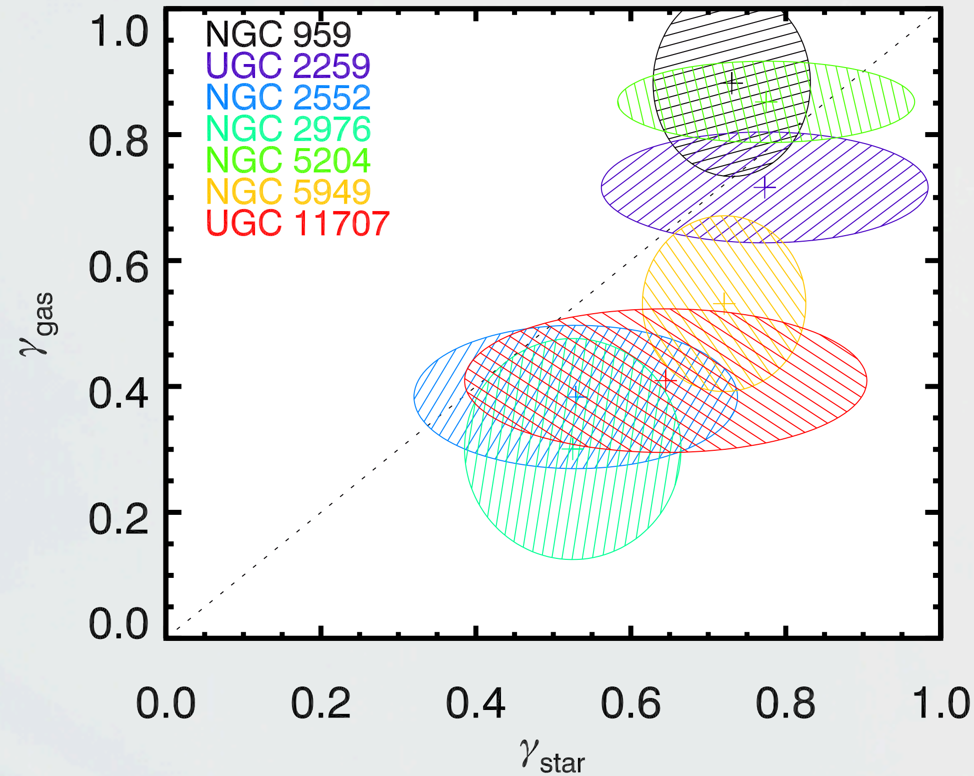
Stars vs. Gas

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



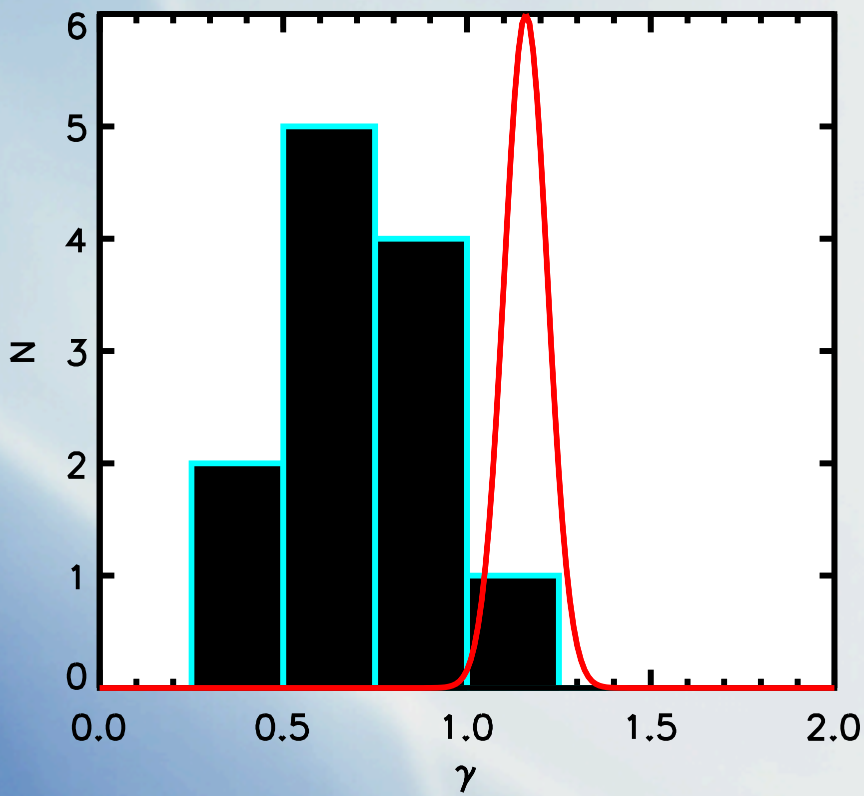
Adams et al. (2012) - stars

Simon et al. (2003) - gas



Adams et al. (2014)

Observed Distribution of Central Slopes



Galaxy sample: Adams et al. (2014) + Simon et al. (2005) + Oh et al. (2011)

Simulations: Diemand et al. (2004)

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

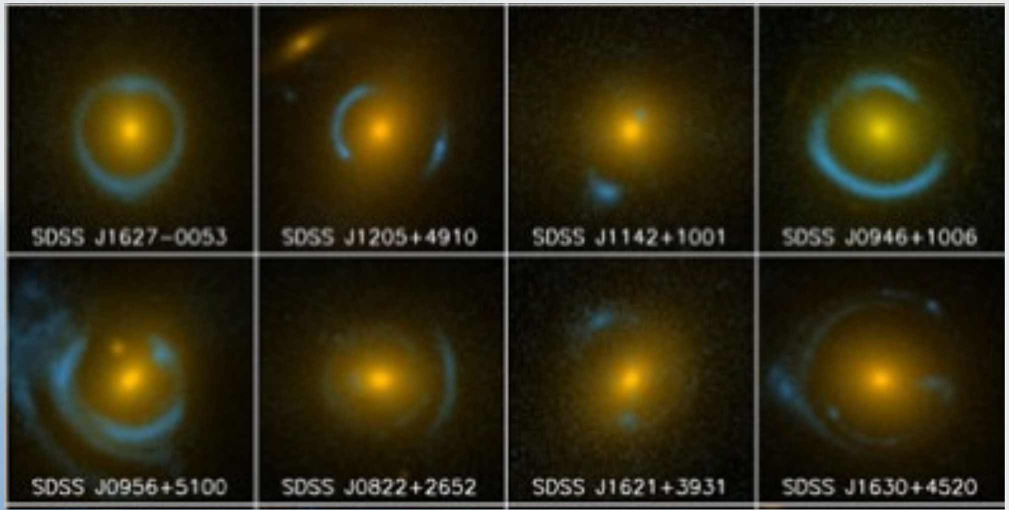
Adams et al. (2014)

Future Outlook

- Survey of 25 galaxies in Hα (Palomar) and CO (CARMA) is underway
  - Will provide best available constraints on distribution of γ
  - 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

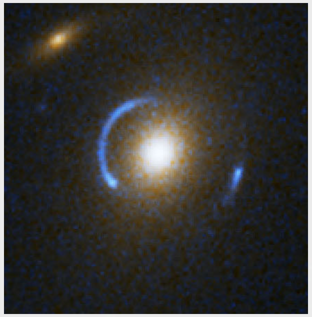
- Pro: gravitational lensing provides an extremely accurate measurement of enclosed mass
- Con: Only a minority of the mass is in dark matter



Bolton et al. (2008)

Lensed Galaxy Mass Distributions

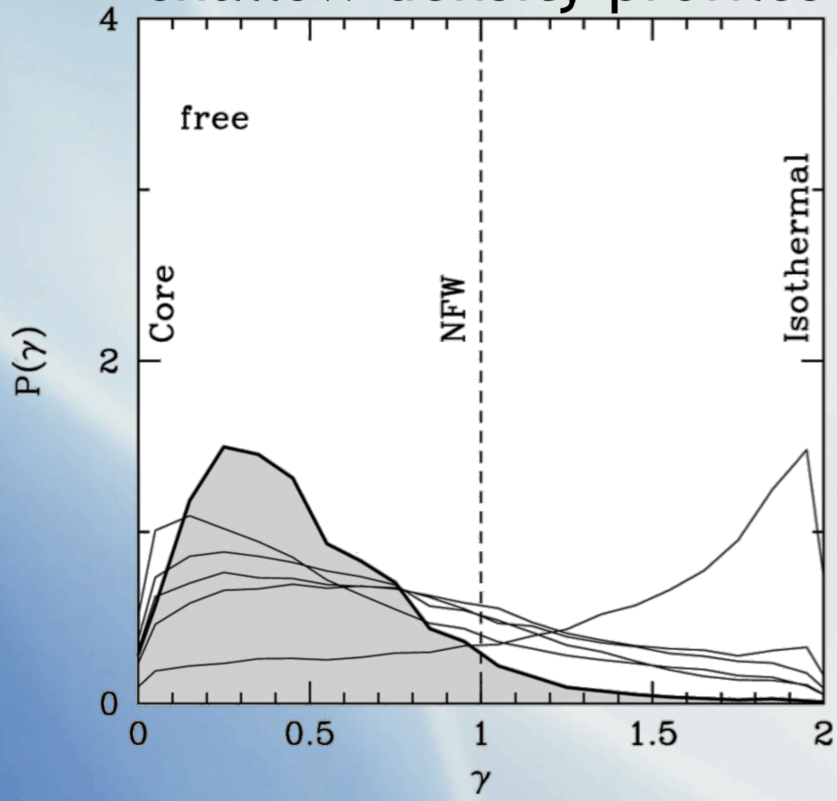
- Lensing determines the total mass contained within $r_{Einstein}$ (~5 kpc)



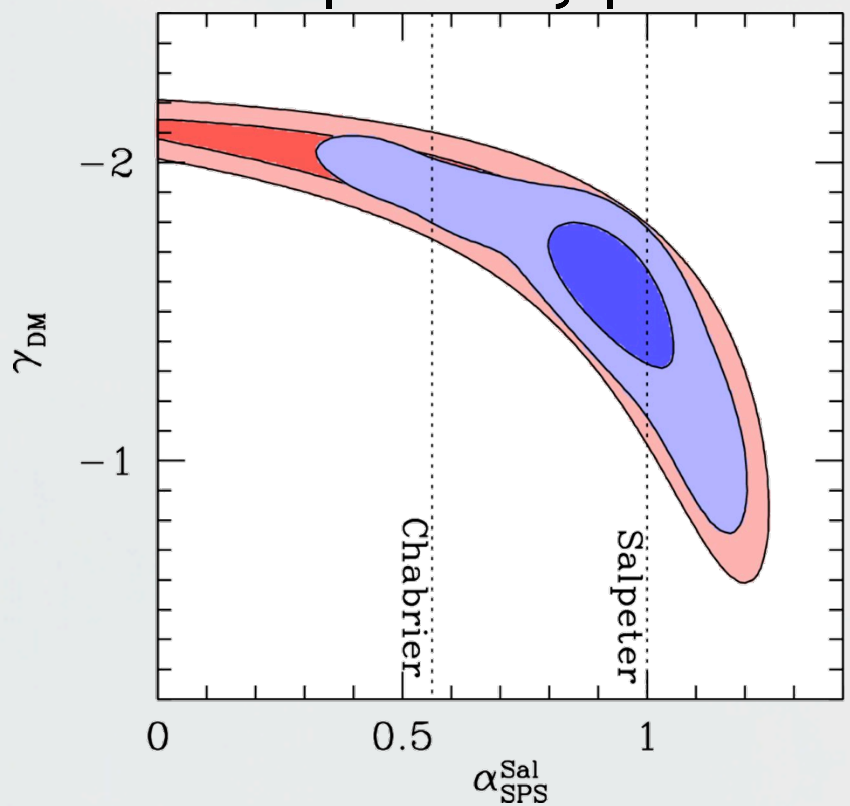
- Add central velocity dispersion: get mass profile at $r_{Einstein}$
- Add additional kinematic or lensing measurements: full mass profile
- Serious degeneracy with IMF

Lensed Galaxy Mass Distributions

5 spiral lenses prefer shallow density profiles



161 elliptical lenses prefer steep density profiles



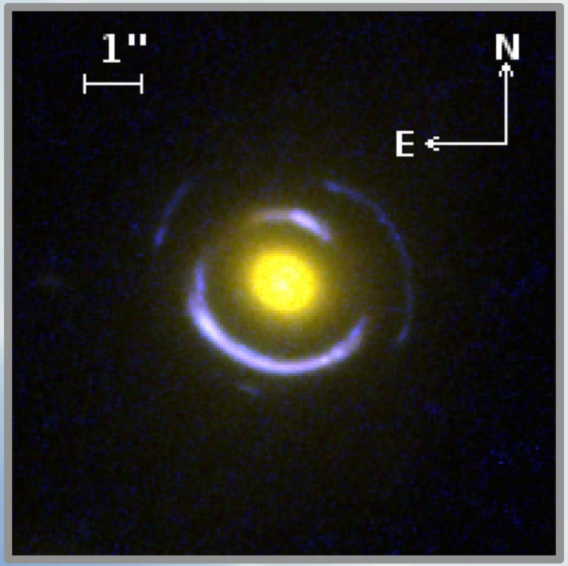
Dutton et al. (2013)

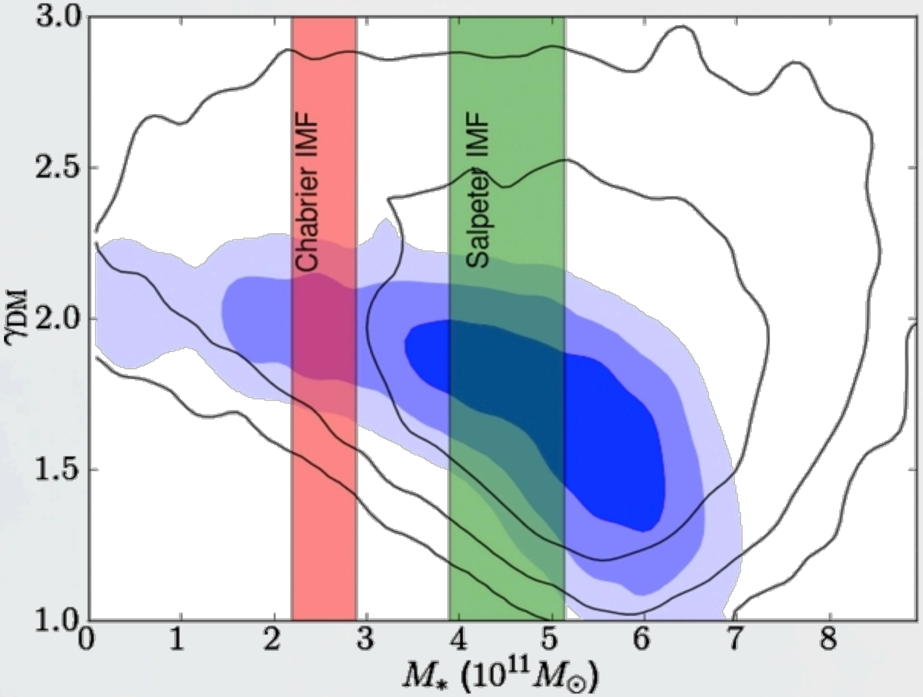
Oguri et al. (2014)

The Jackpot Lens

- Single galaxy lensing two background sources

$\gamma_{DM} = 1.7 \pm 0.2$





Sonnenfeld et al. (2012)

Future Outlook

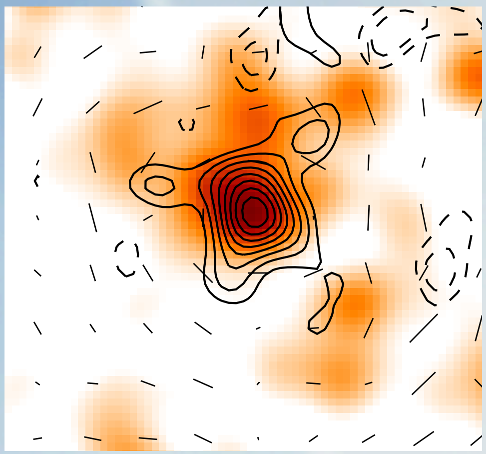
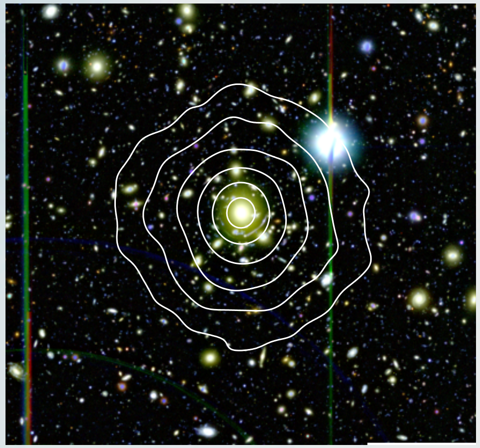
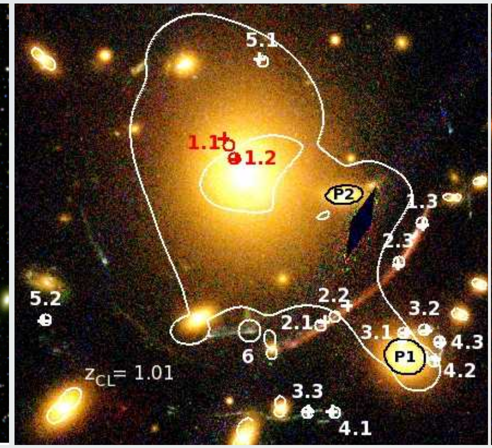
- Larger lens surveys in progress
  - Will include more rare objects like the Jackpot
- Understanding of IMF is improving, but uncertainties in stellar mass will always limit constraints on γ_{DM}

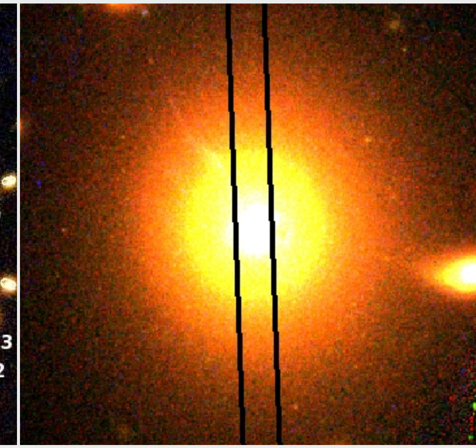
Galaxy Clusters

- 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

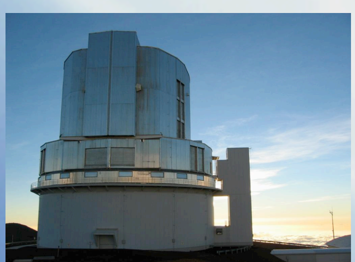
Observations



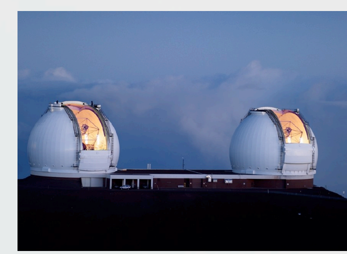
Weak lensing *X-ray* *Strong lensing* *Stellar dynamics*

3 Mpc ---------------- 500 kpc --------- 100 kpc ---------- 20 kpc ------------------ 3 kpc


Subaru

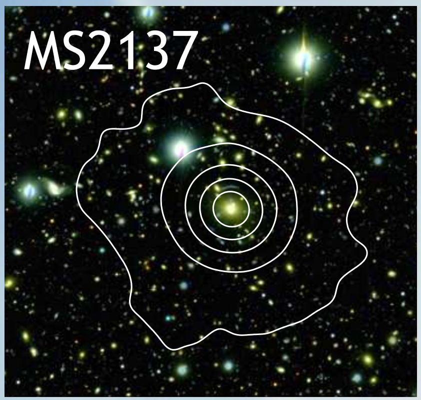

Chandra

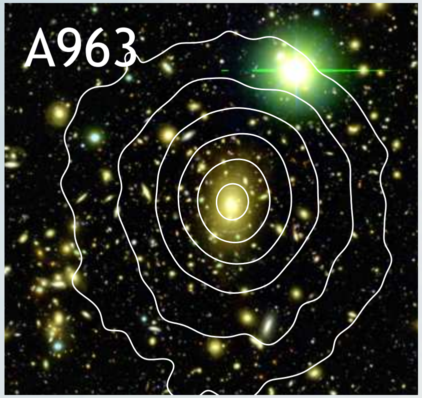

HST

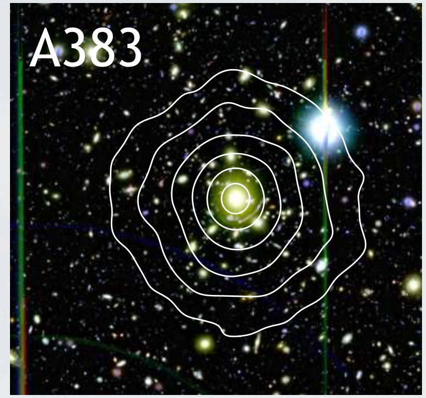

Keck

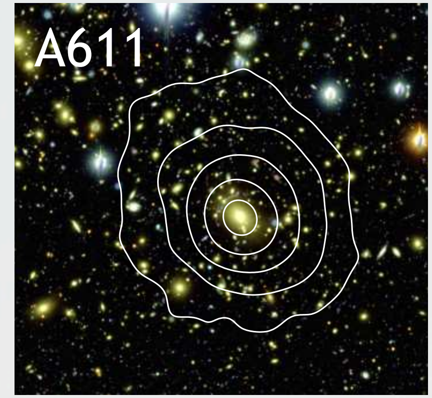
Independent probes span r ~ 3 kpc – 3 Mpc (3 decades in r)

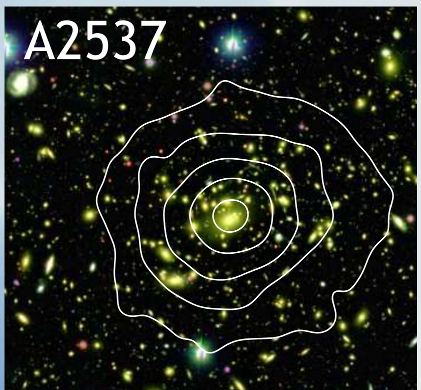
Cluster Sample

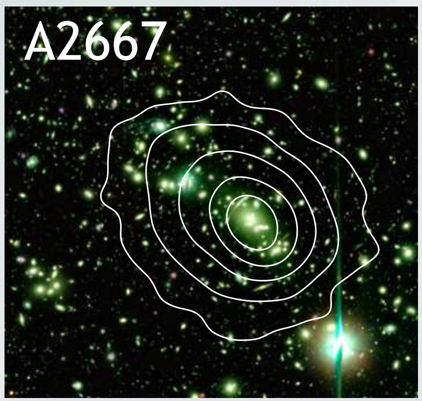


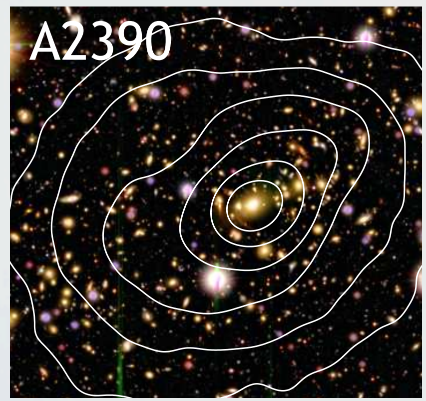










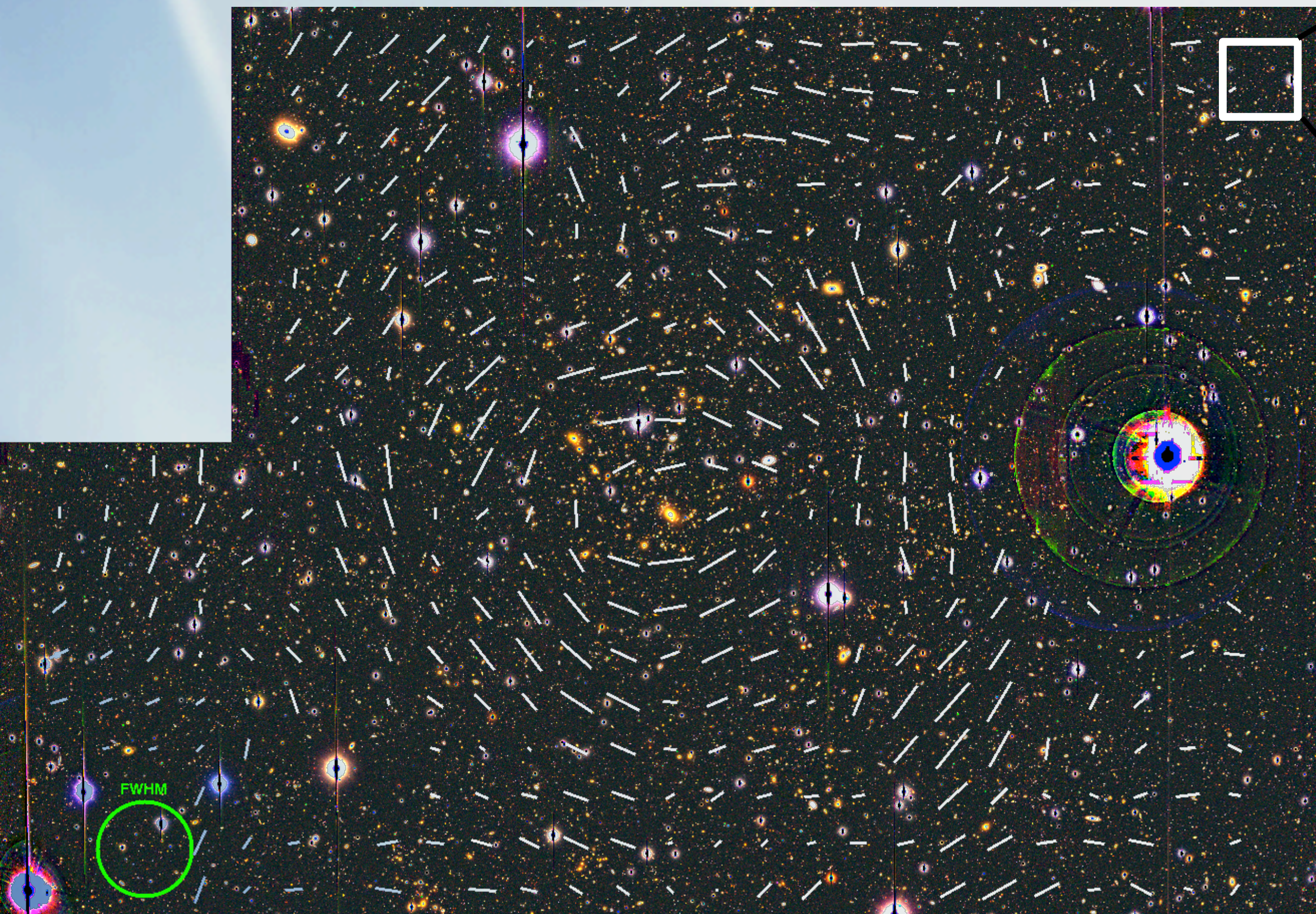


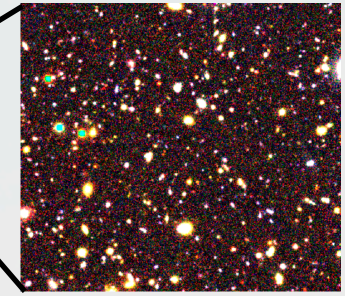
Chandra contours on Subaru images

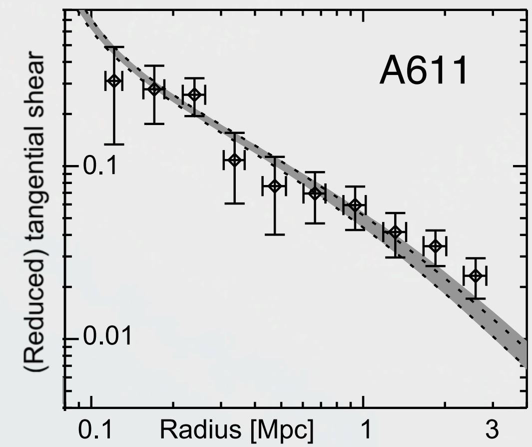
- Clusters are relaxed and symmetric
- BCGs are aligned with X-ray/lensing centroid
- $M_{200} = 0.4 – 2 \times 10^{15}\ M_\odot$
- $z = 0.19 – 0.31$

Newman et al. (2013ab)

Weak Lensing (probes large radii)







Subaru SuprimeCam

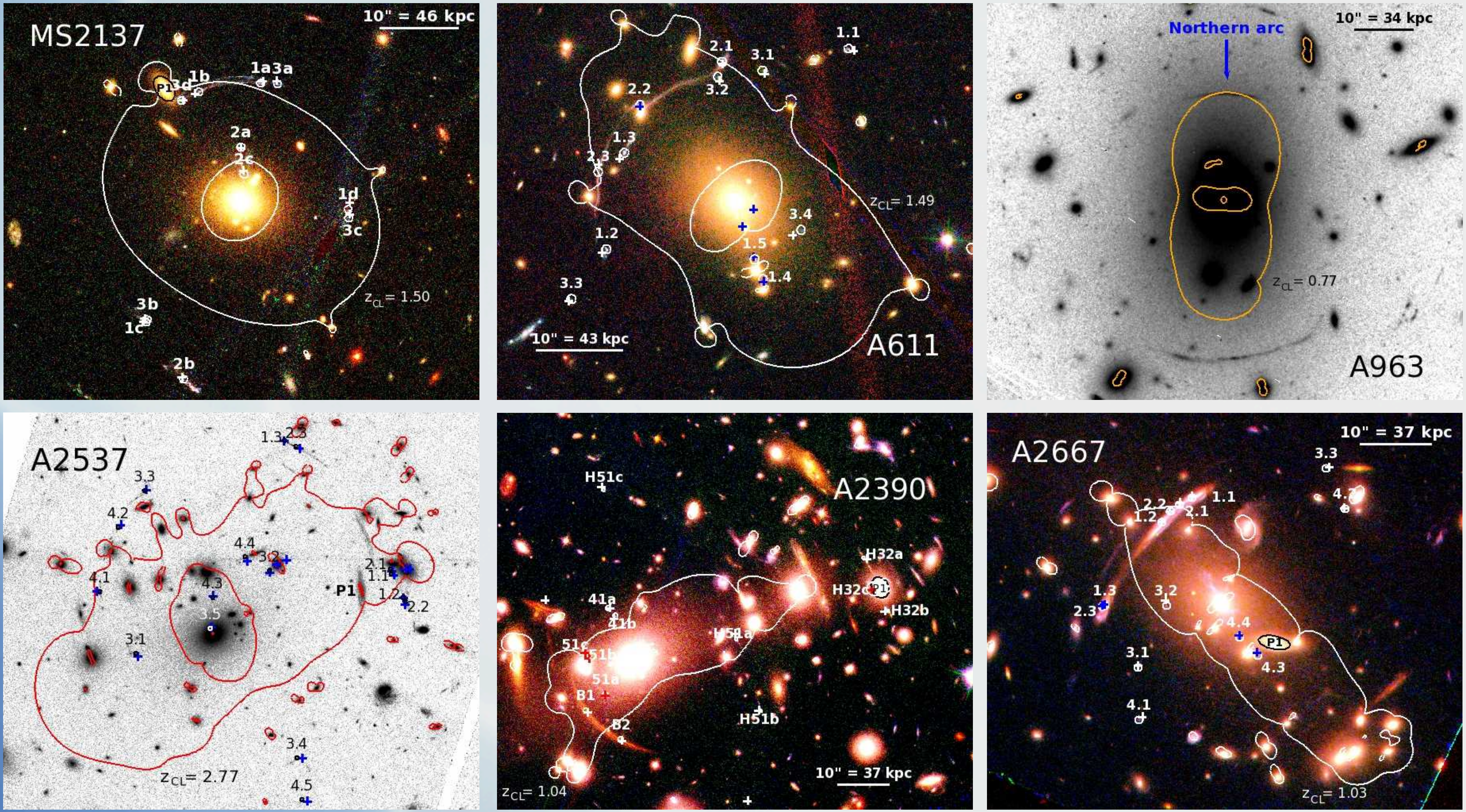
35 arcmin ~ 8 Mpc

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_{spec} of 21 (7 new)

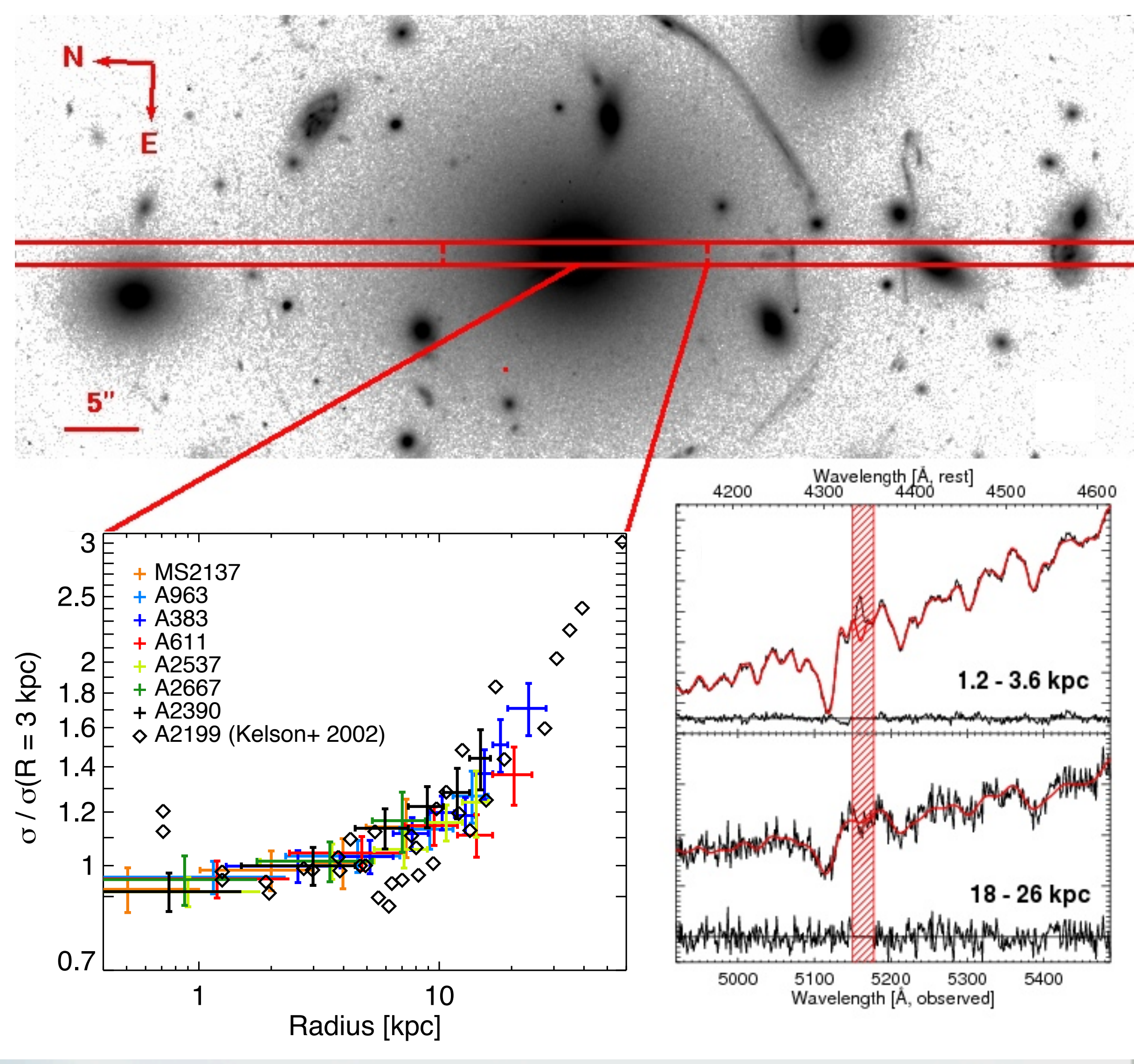


Newman et al. (2013ab)

Stellar Kinematics (probes small radii)

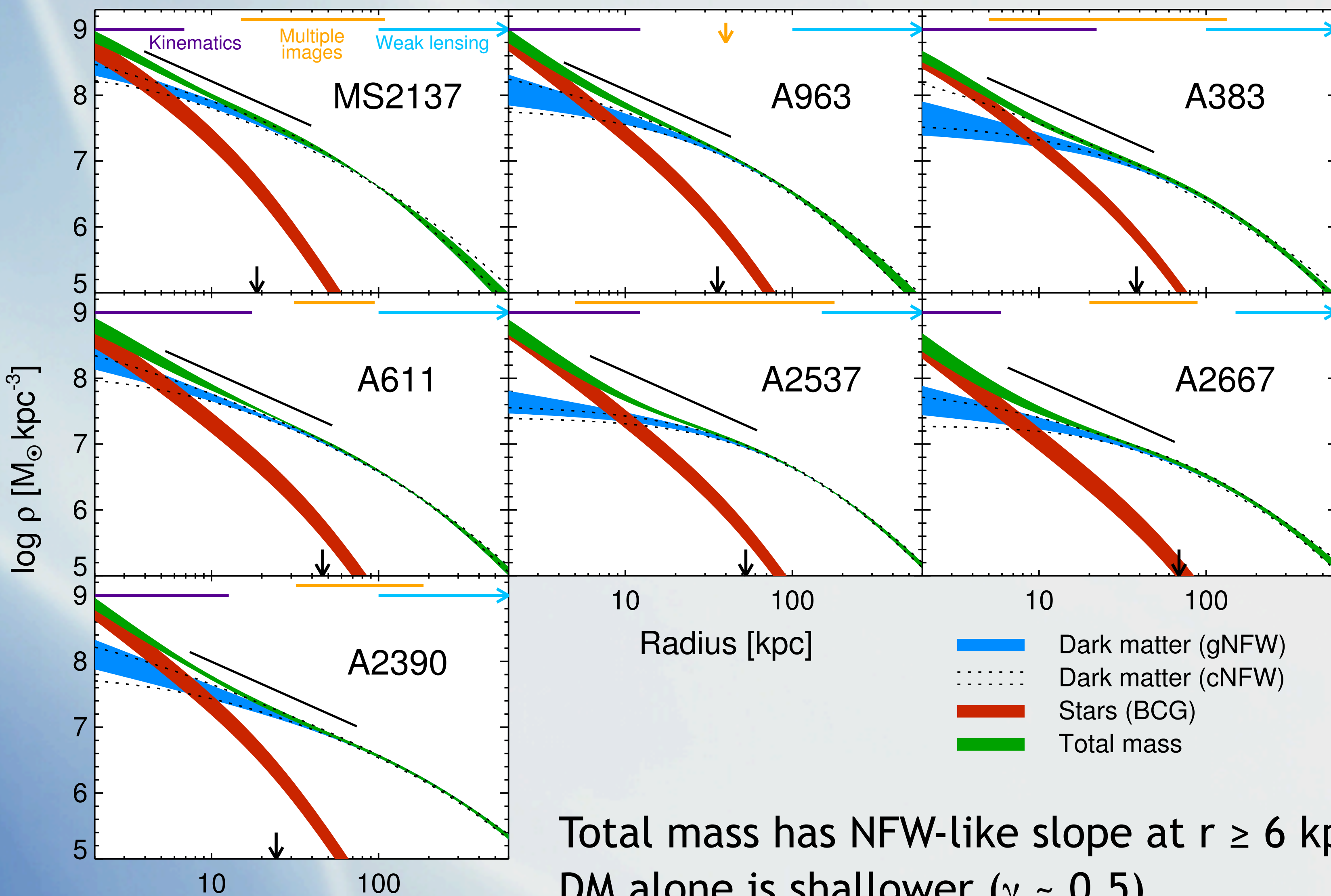
Resolved stellar kinematic measurements in the giant central galaxy provide mass constraints down to ~ 3 kpc.

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



Newman et al. (2012)

Dark Matter and Stars in Cluster Cores

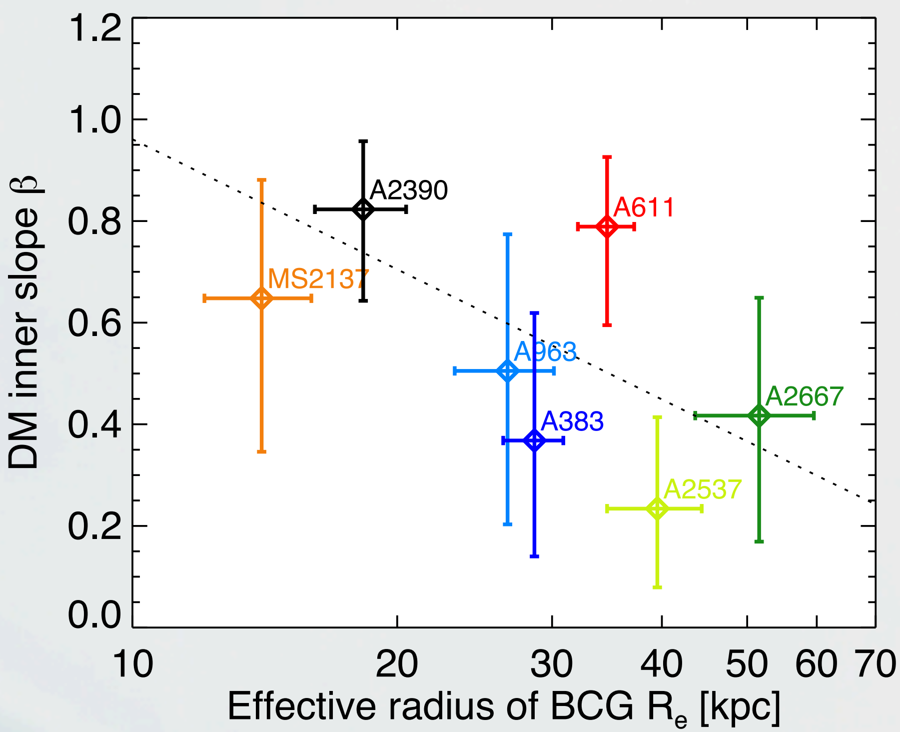


Total mass has NFW-like slope at r ≥ 6 kpc
DM alone is shallower (γ ~ 0.5)

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?