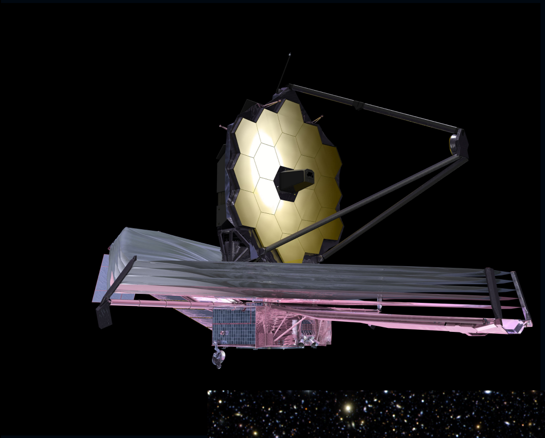
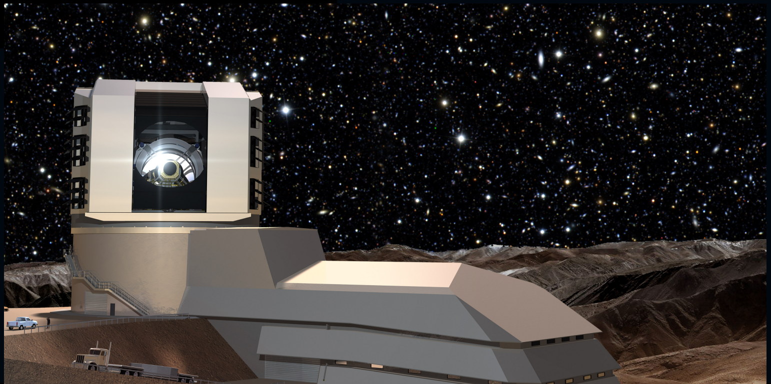
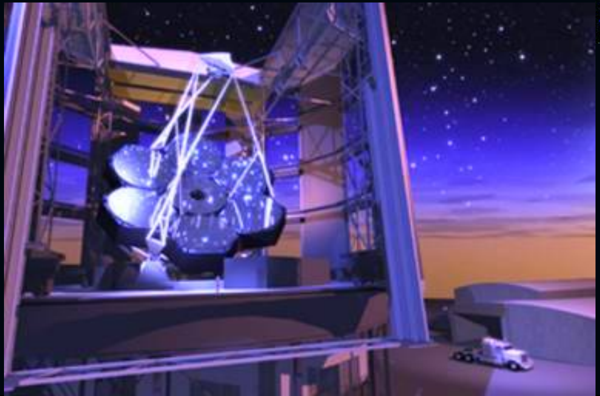
Future Observational Prospects for Small Scale Probes of Dark Matter

Josh Simon
Carnegie Observatories







Current Facilities

- Large (8-10m) ground-based telescopes
  - Simultaneous optical spectroscopy of ~100 targets over ~0.02-0.15 deg^2 field of view
- Hubble Space Telescope
  - Deep imaging and excellent astrometry over small fields
- Gaia
  - Accurate and precise photometry and astrometry over the entire sky

Upcoming Ground-Based Facilities

- Subaru Prime Focus Spectrograph (2021)
  - Simultaneous optical-near IR spectroscopy of 2400 targets over 1.3 deg^2 field of view with an 8m telescope
- LSST (2021)
  - 10-year optical imaging survey over 18000 deg^2 down to 27^{th} magnitude
- Thirty-meter class telescopes (2024)
  - GMT, TMT, ELT
  - Deep spectroscopy, narrow-field astrometry

Upcoming Space-Based Facilities

- James Webb Space Telescope (2020?)
  - Deepest near-IR imaging and spectroscopy ever obtained, narrow-field astrometry
- WFIRST (2027?)
  - 5-year near-IR imaging survey over 2200 deg^2 down to 26^{th} magnitude, good astrometry

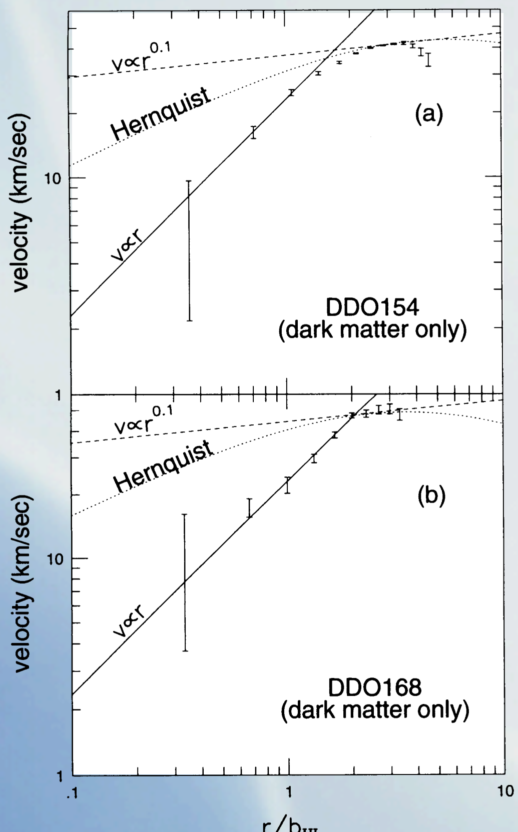
Small-Scale Problems with ΛCDM

- Cusp/core problem
  - Do any galaxies have cuspy density profiles?
  - Why don't all of them?

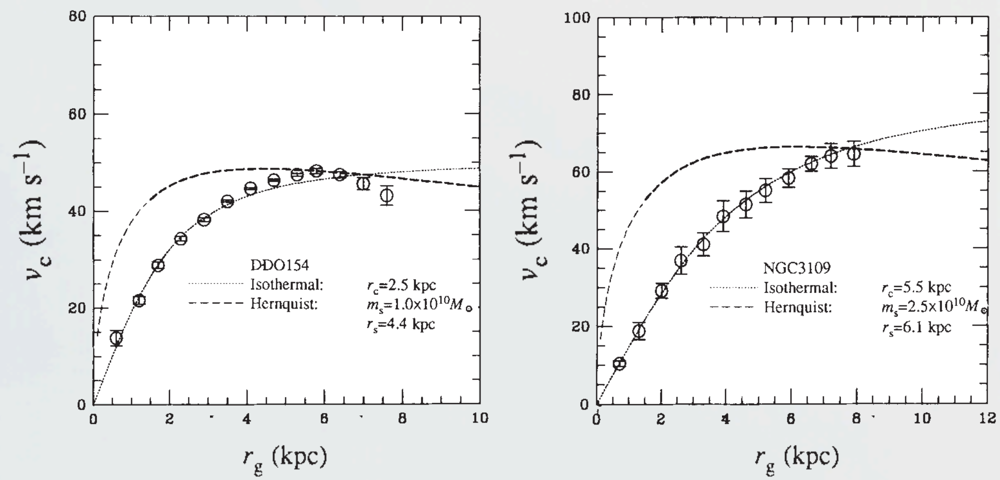
- Missing satellite problem
  - Does the predicted ΛCDM substructure exist?
  - How many satellites does the Milky Way actually have?

The Cusp/Core Problem

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



Flores & Primack (1994)

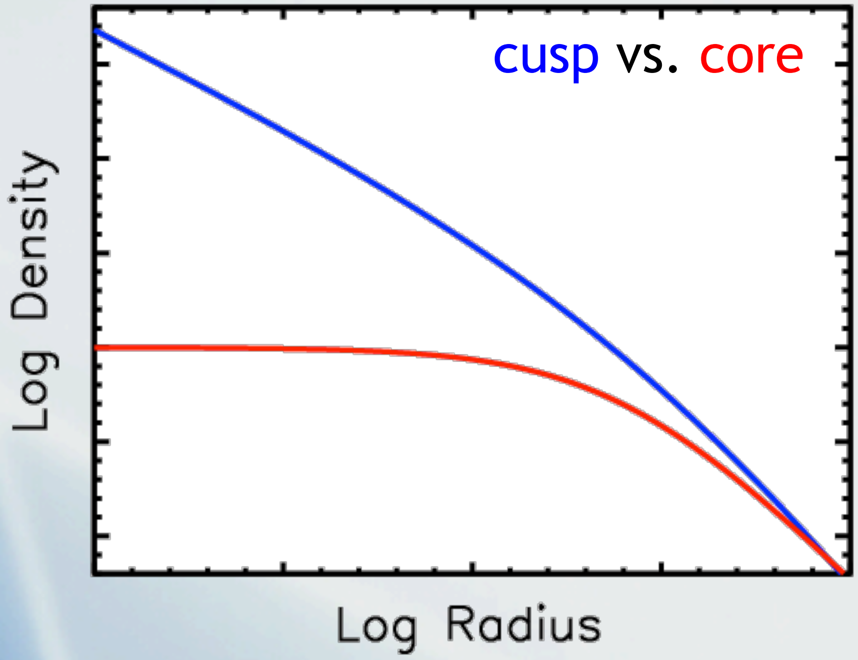


Moore (1994)

The Cusp/Core Problem

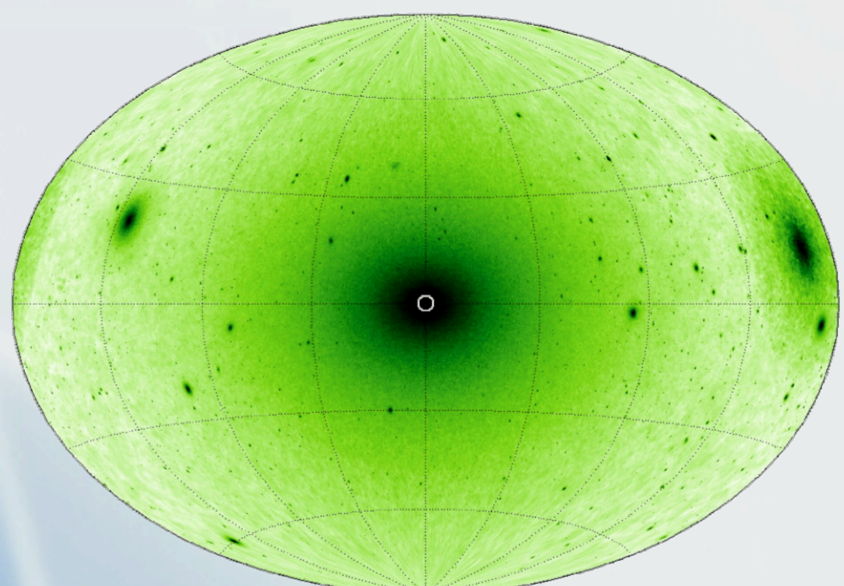
- Navarro, Frenk, & White (1996)

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



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

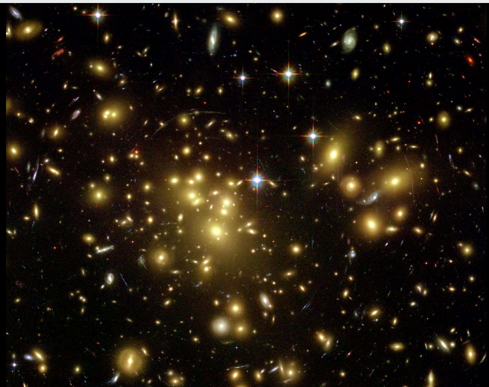


Kuhlen et al. (2008)

Dark Matter Laboratories

- 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



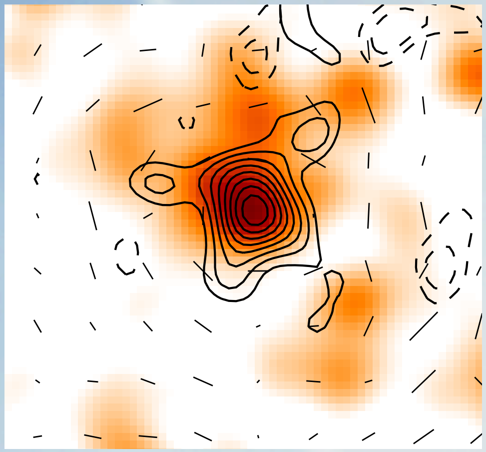



Galaxy Clusters

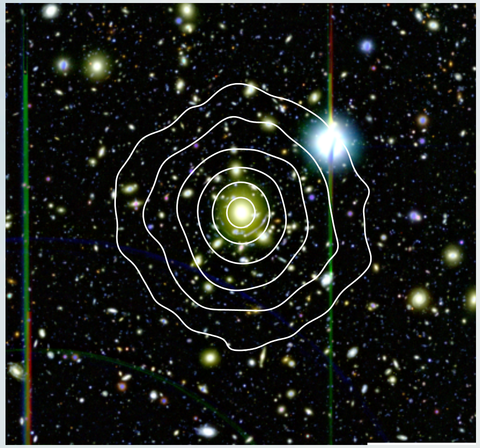
- Most massive collapsed structures in the universe
- Baryonic effects may be easier to model
  - Most of the baryons are in the hot gas
  - Deep potential well is more robust to feedback
- Only systems in which measurements can be made out to the virial radius

Slides kindly contributed by Drew Newman

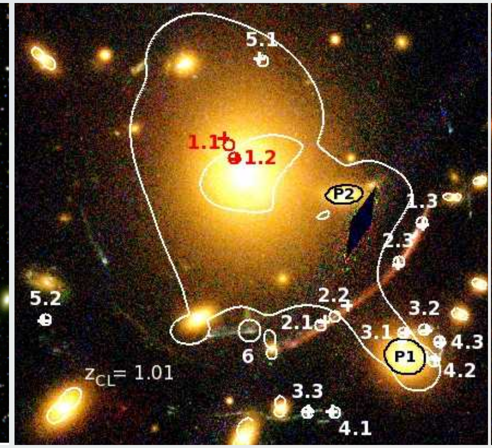
Observations



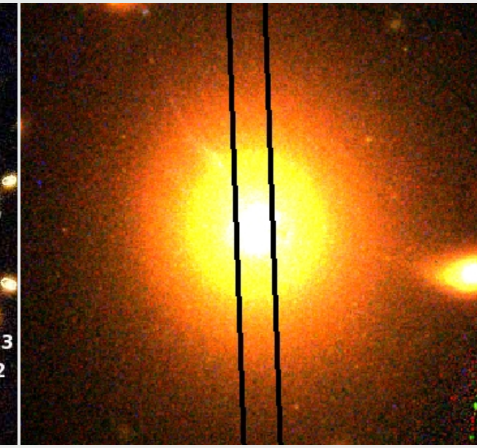
Weak lensing



X-ray

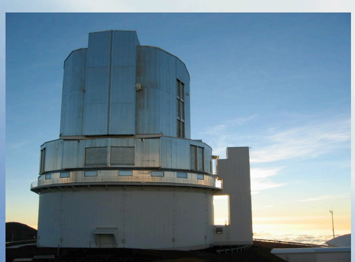


Strong lensing



Stellar dynamics

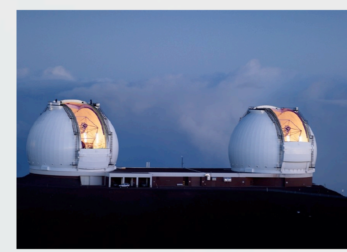
3 Mpc ---------------- 500 kpc -------- 100 kpc ---------- 20 kpc ----------------- 3 kpc



Subaru

Chandra

HST

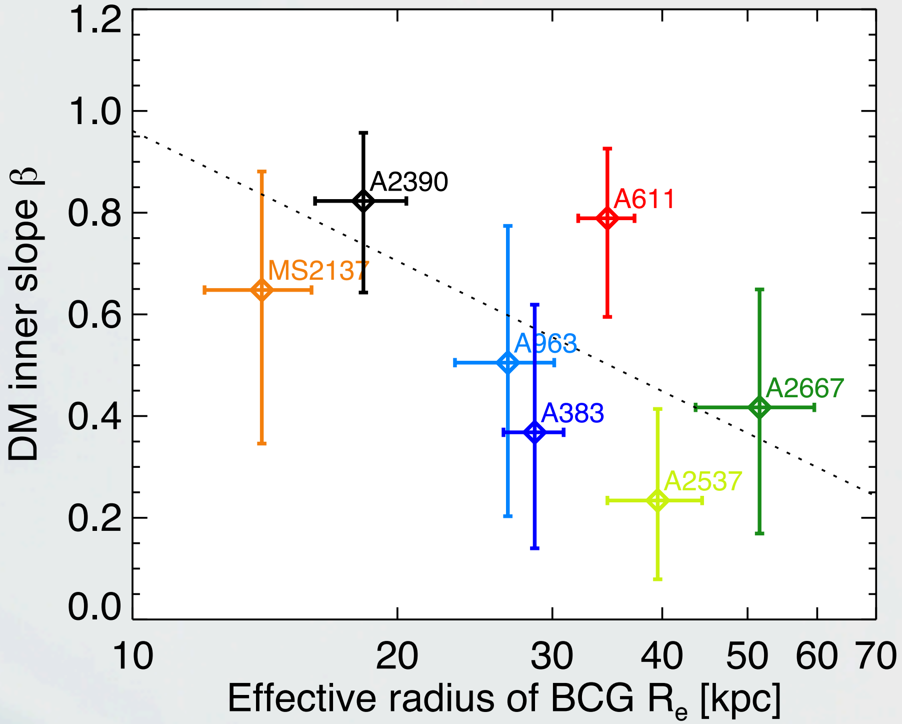


Keck

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

Cluster Inner Density Profile Slopes

- 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)

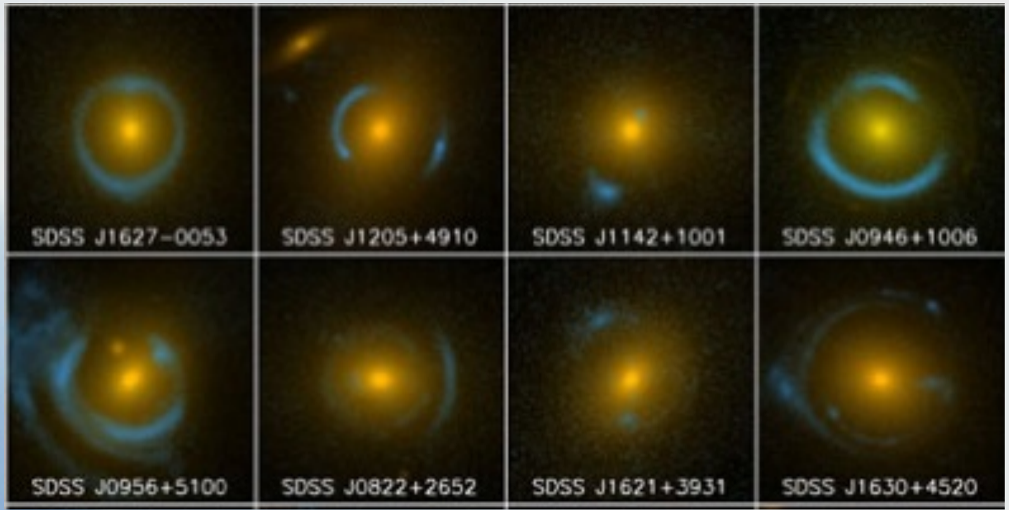
Future Outlook

- HST is providing exquisite data for a larger sample of clusters (CLASH/ Frontier Fields)
- Need to understand the origin of the correlation with BCG properties

See conference talk by Newman

Massive Galaxies

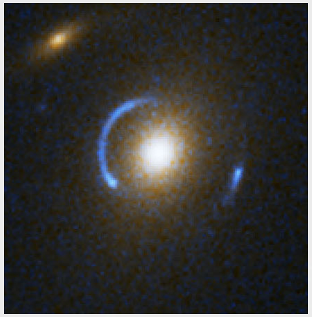
- Pro: Gravitational lensing provides an extremely accurate measurement of enclosed mass
- Con: Only a minority of the mass is in dark matter



Bolton et al. (2008)

Lensed Galaxy Mass Distributions

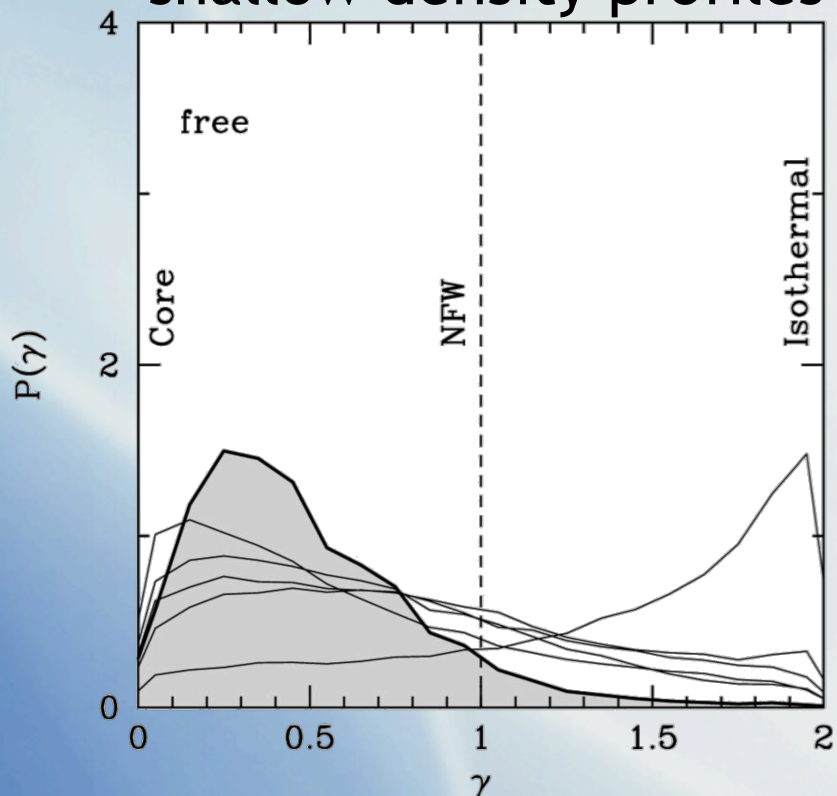
- Lensing determines the total mass contained within $r_{Einstein}$ (~5 kpc)



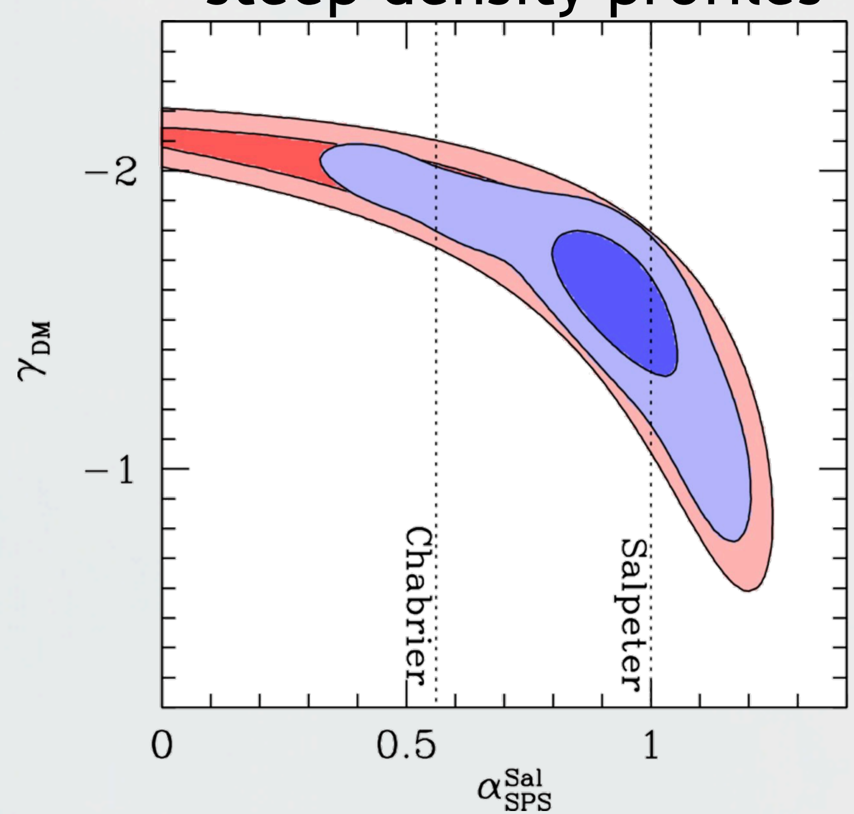
- Add central velocity dispersion: get mass profile at $r_{Einstein}$
- Add additional kinematic or lensing measurements: full mass profile
- Degeneracy with initial mass function

Lensed Galaxy Mass Distributions

5 spiral lenses prefer shallow density profiles



161 elliptical lenses prefer steep density profiles

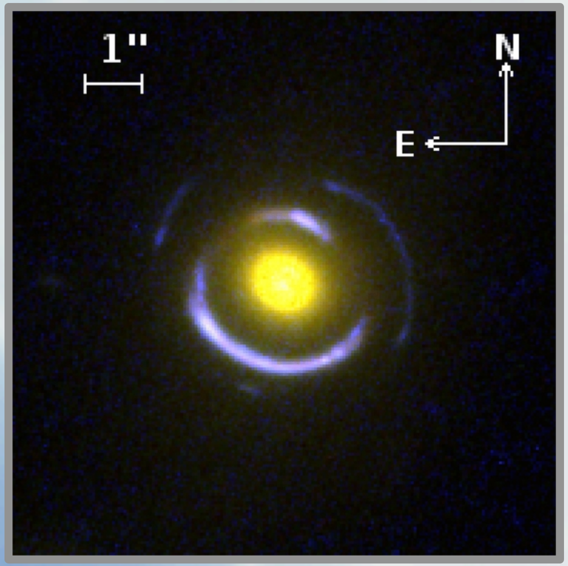


Dutton et al. (2013)

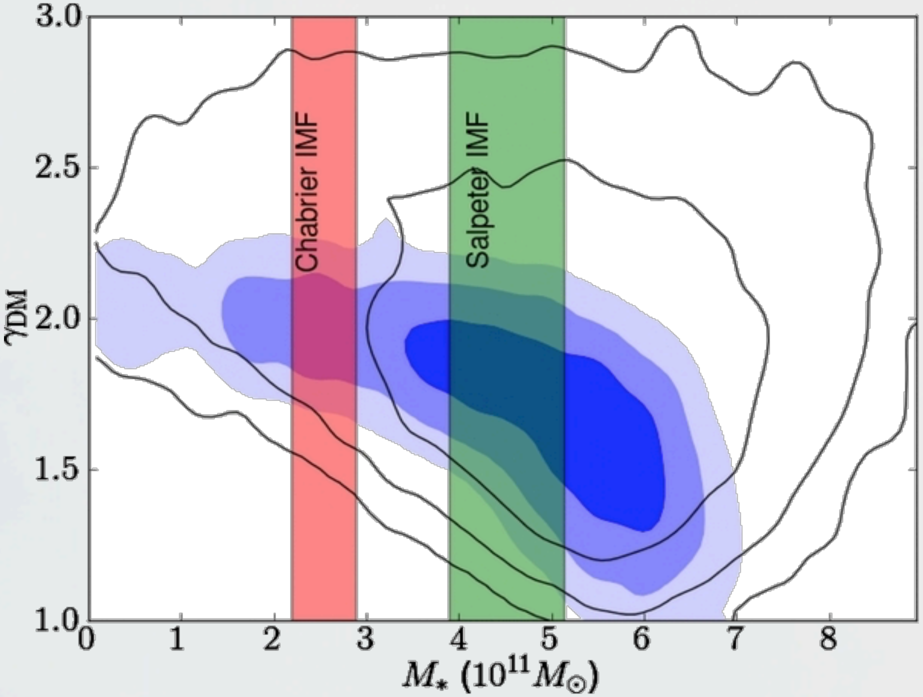
Oguri et al. (2014)

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}

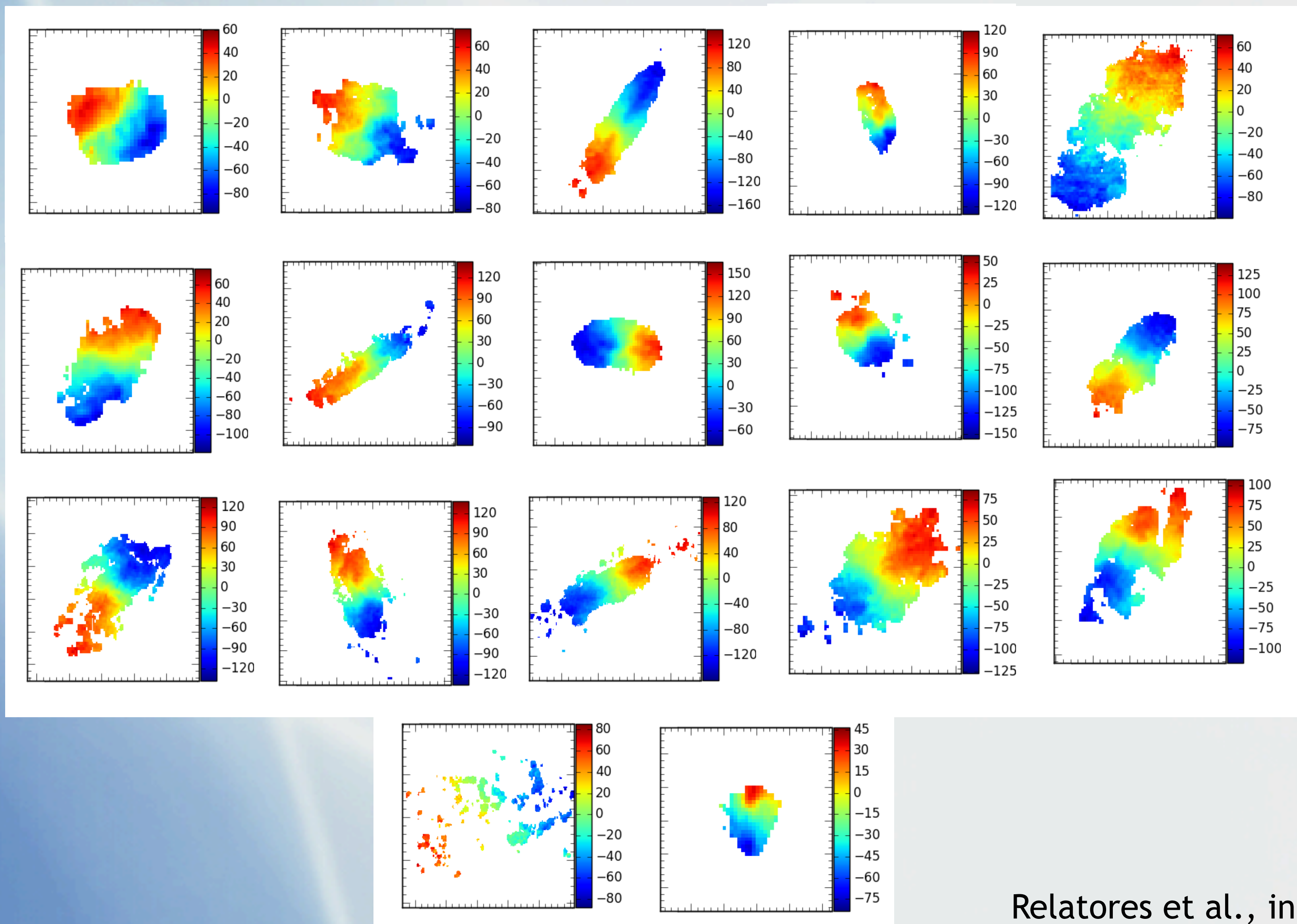
See presentations by Vegetti and Hezaveh

Low-mass Disk Galaxies

- New survey of 26 nearby galaxies
  - Observed with CARMA (CO) and Palomar/CWI ($H\alpha$)
  - Spatial resolution ~3" (CO), 2" ($H\alpha$)
  - Sample chosen to be structurally well-behaved
    - D < 30 Mpc
    - V_{rot} ~ 100 km/s

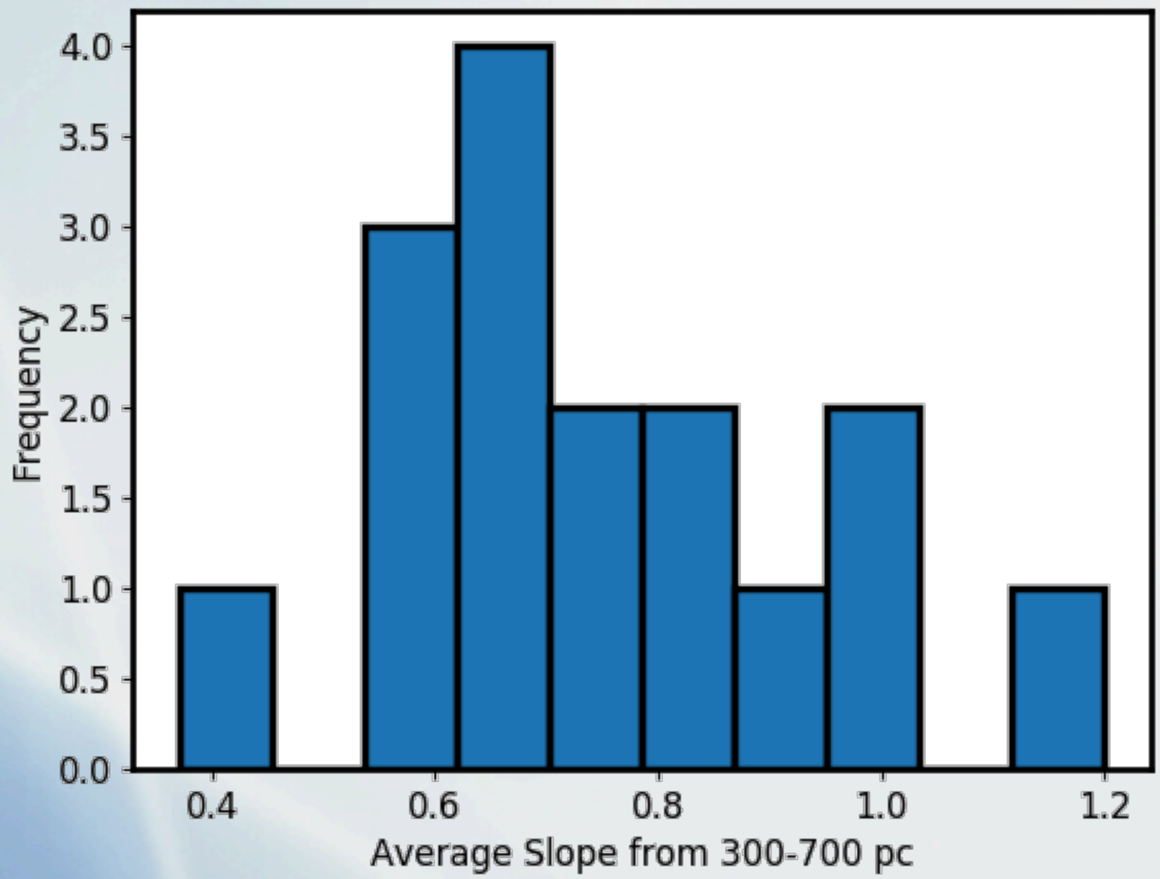
Truong et al. (2017)
Relatores et al., in prep.

Hα Velocity Fields for New Sample



Relatores et al., in prep.

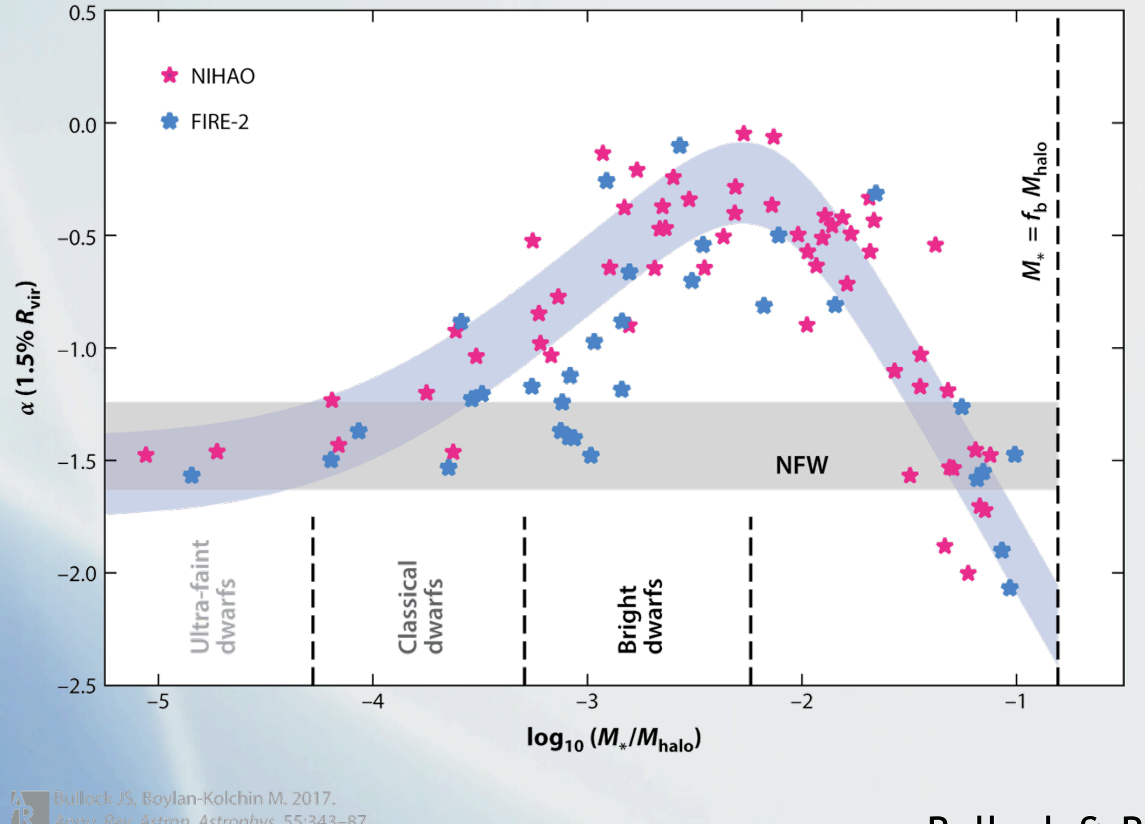
Distribution of Central DM Slopes



Relatores et al., in prep.

Lower Mass Galaxies Are the Key

- Galaxies with $M_{vir} \leq 10^{10}$ $M_\odot$ ($M_* \leq 10^7$ $M_\odot$) should be unaffected by feedback



Bullock & Boylan-Kolchin (2017)

Dwarf Spheroidals as DM Probes

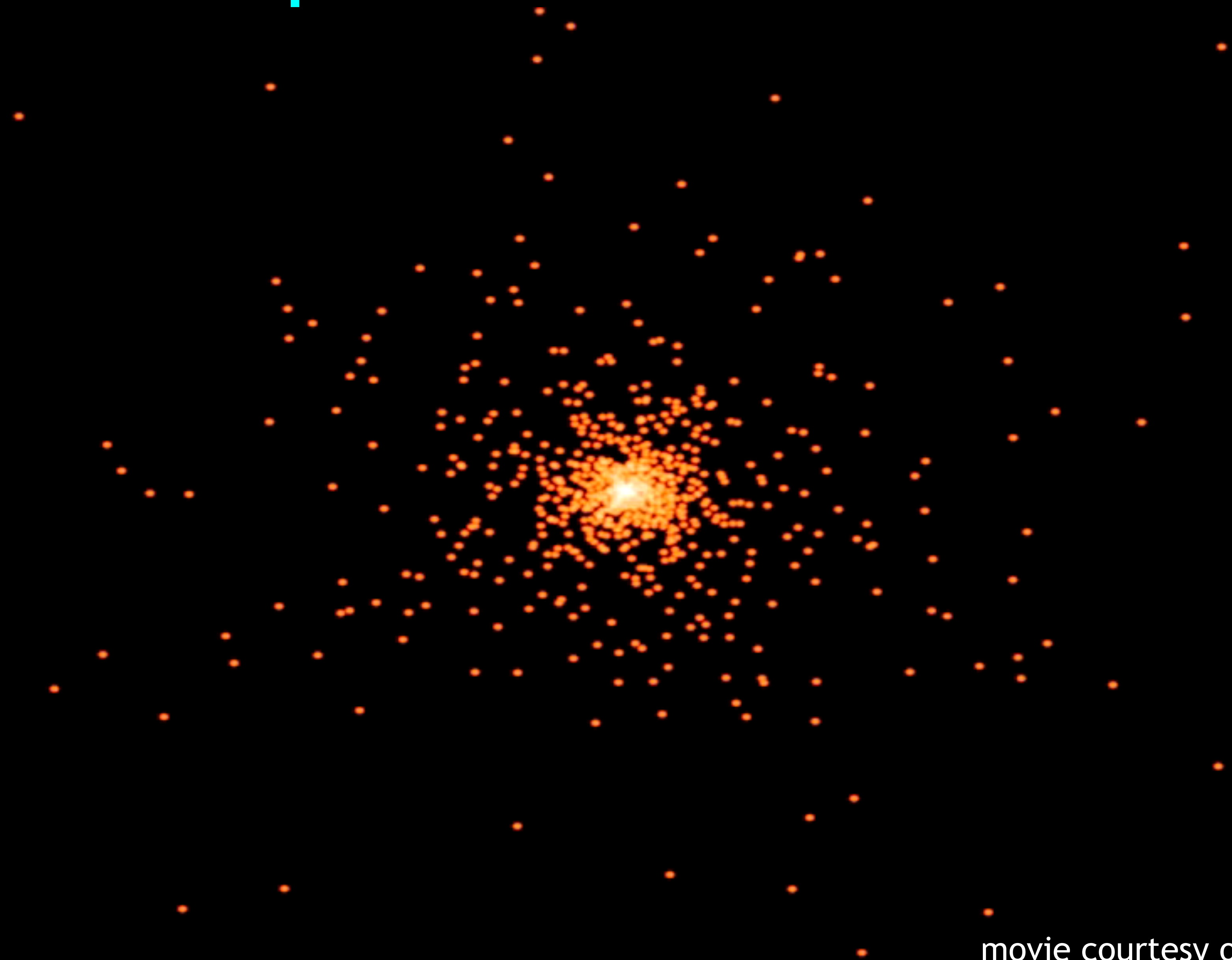
- Closest and most dark matter-dominated galaxies known
  - luminosities from 10^3 to 10^7 $L_\odot$
  - sizes from 30 to 1000 pc
  - (inferred) virial masses of $\sim 10^9$ $M_\odot$

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



movie courtesy of TJ Cox

Dwarf Spheroidal Density Profiles

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

- Jeans equation:

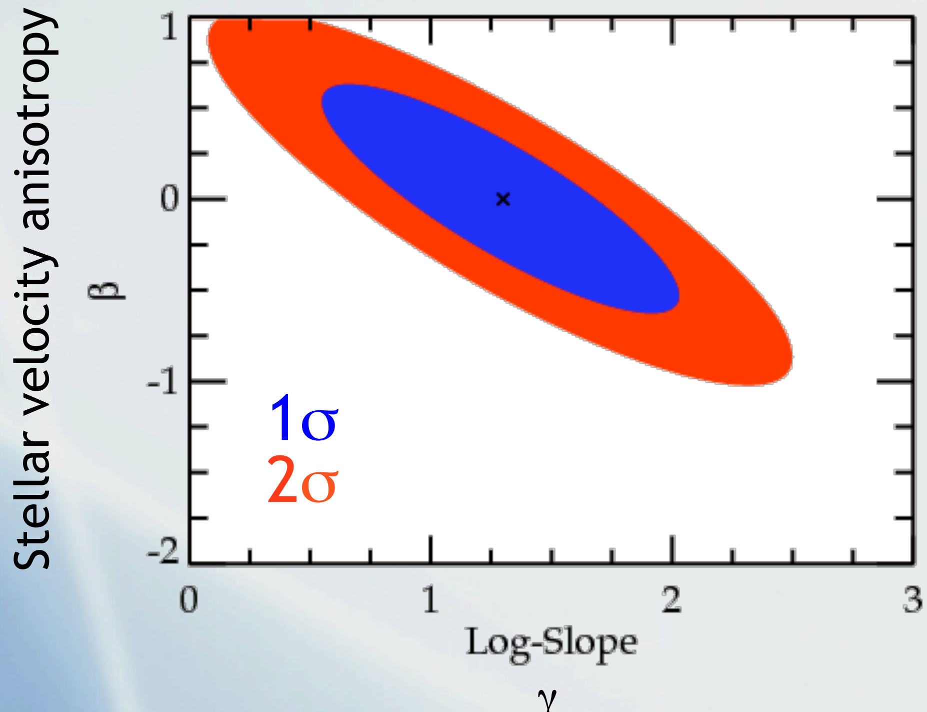
$$r \frac{d(\rho_* \sigma_r^2)}{dr} = -\rho_* \frac{GM(r)}{r} - 2\beta(r)\rho_*\sigma_r^2$$

observed
unknown

M(r) and β(r) are degenerate!

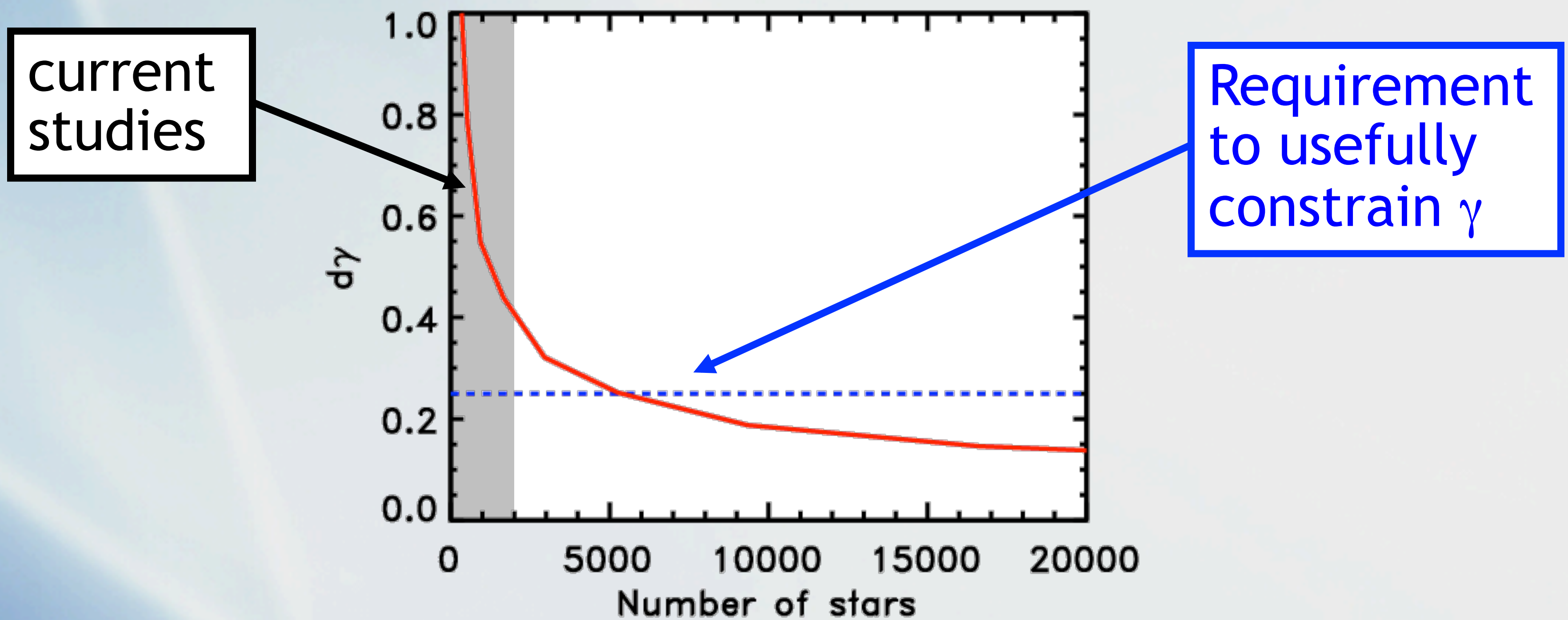
Dwarf Spheroidal Density Profiles

- 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)

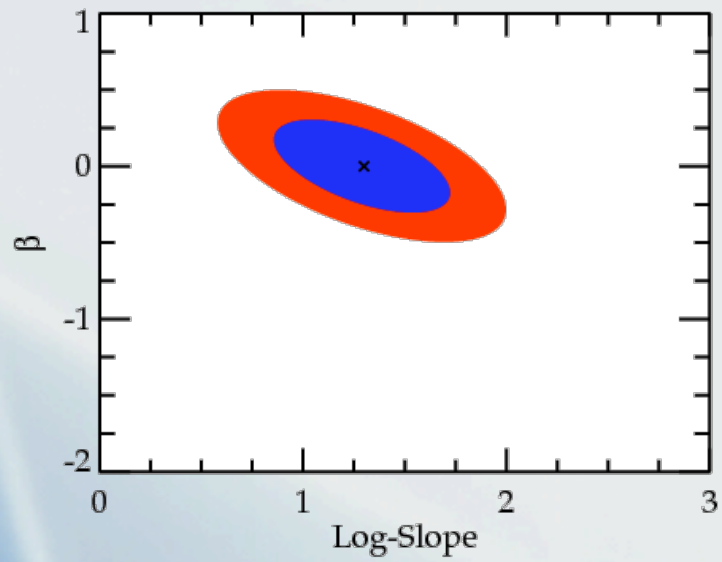
dSph Density Profile Results

- 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}

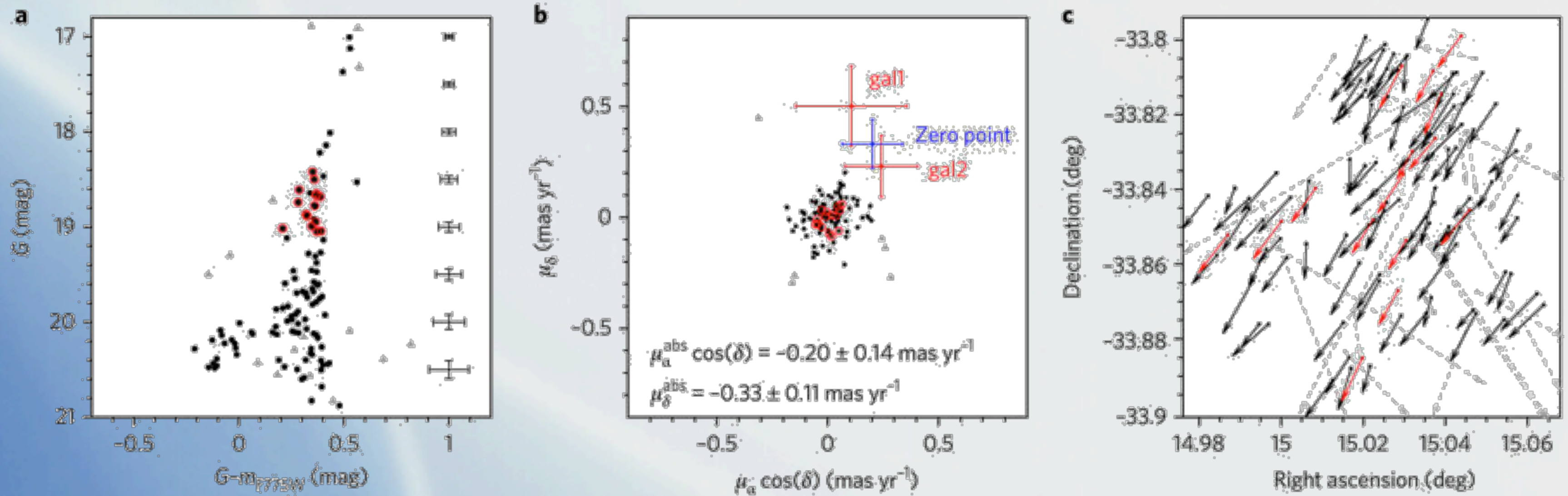
RVs plus proper motions



Strigari et al. (2007)

Internal Proper Motions in Sculptor

- Epoch 1 from archival HST imaging and epoch 2 from Gaia DR1
  - Find predominantly radial orbits
  - PM uncertainties of ~70 μas yr^{-1} per star



Massari et al. (2018)

Future Outlook

- Currently little agreement in derived density profile slopes
- Larger radial velocity samples can be obtained even with current instruments
- Possibility of measuring proper motions with HST, Gaia, JWST, or 30-m telescopes (or all of the above!)

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?

Miss Satellite roblem

- Currentl MW arfs/cand ates
  - 29 of the discov ed in last 3 ars
- redictions for to l p ulation
  - 300-600 (To et a 8)
  - 300 0 (Har et al.)
  - 100 (Newton et al. 2017)

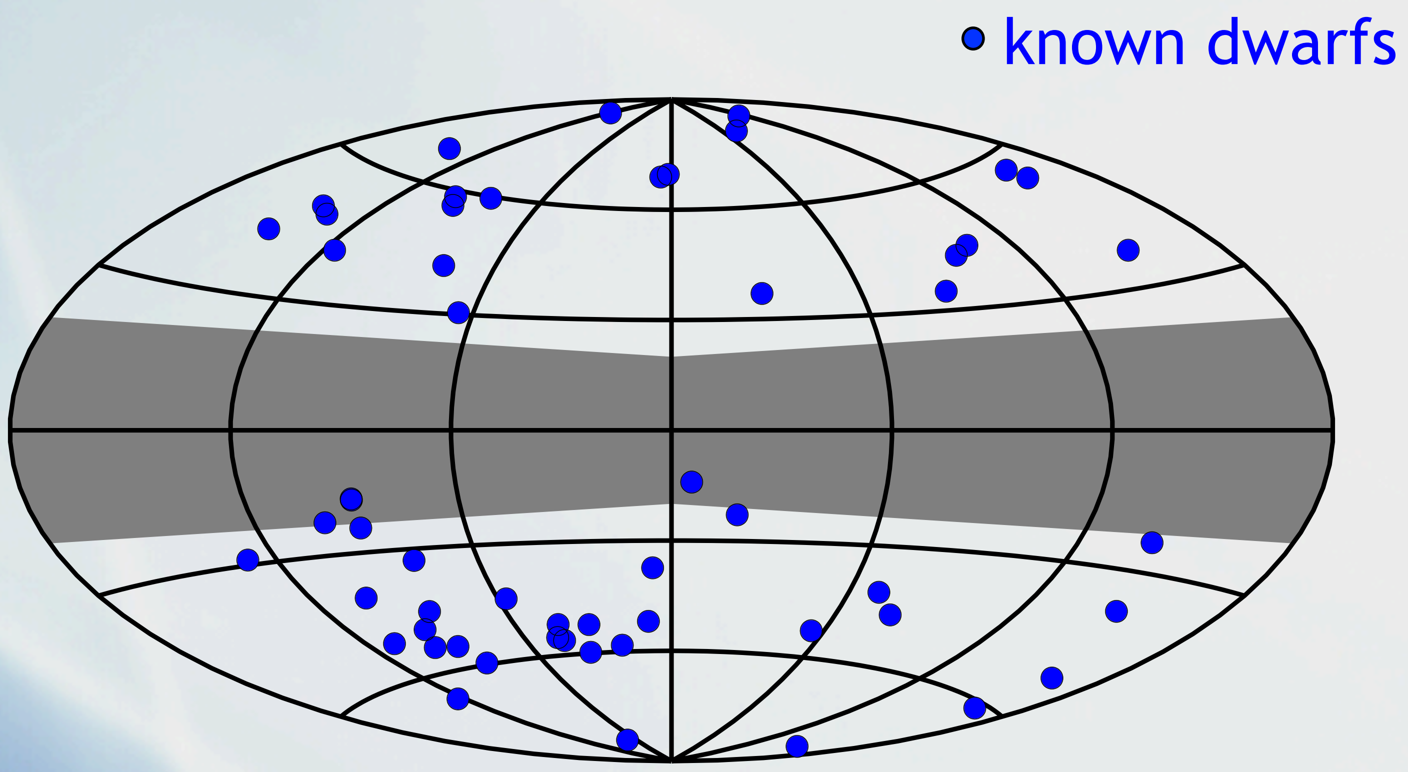




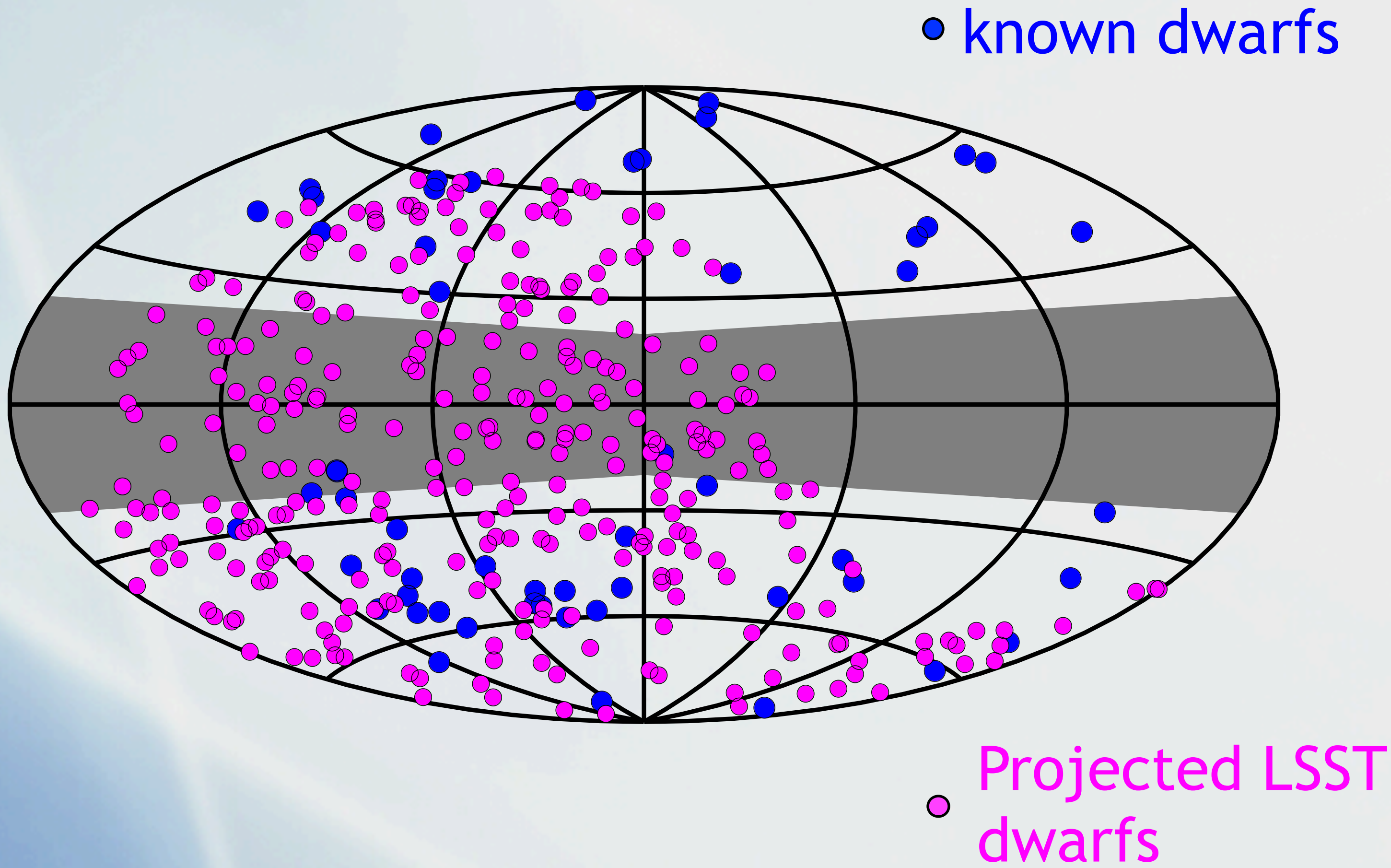

Missing Satellite Problem

- Currently 56 MW dwarfs/candidates
  - 29 of these discovered in last 3 years
- Predictions for total population
  - 300-600 (Tollerud et al. 2008)
  - 300-850 (Hargis et al. 2014)
  - 100-200 (Newton et al. 2017)

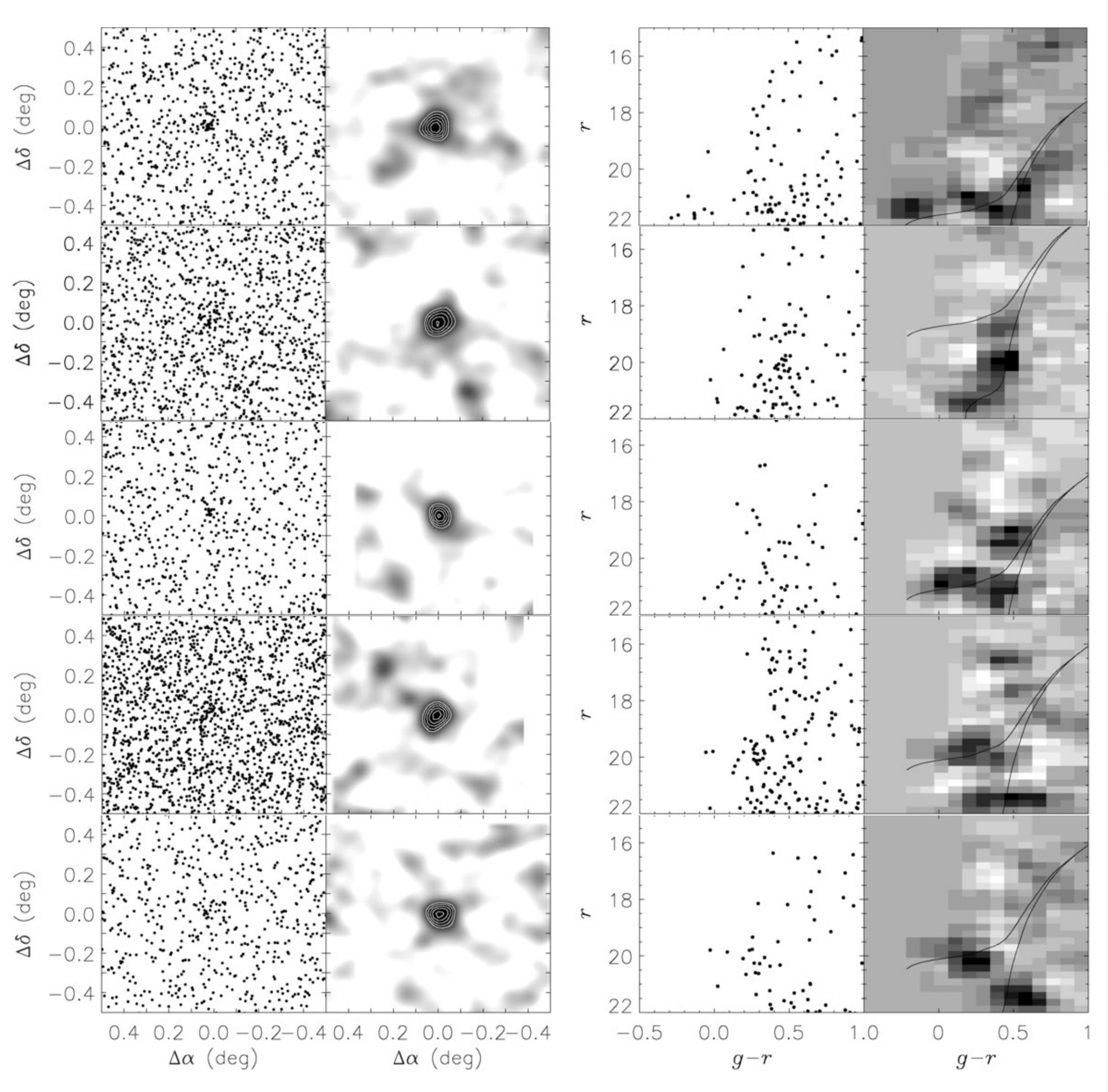
Current Satellite Population



After LSST



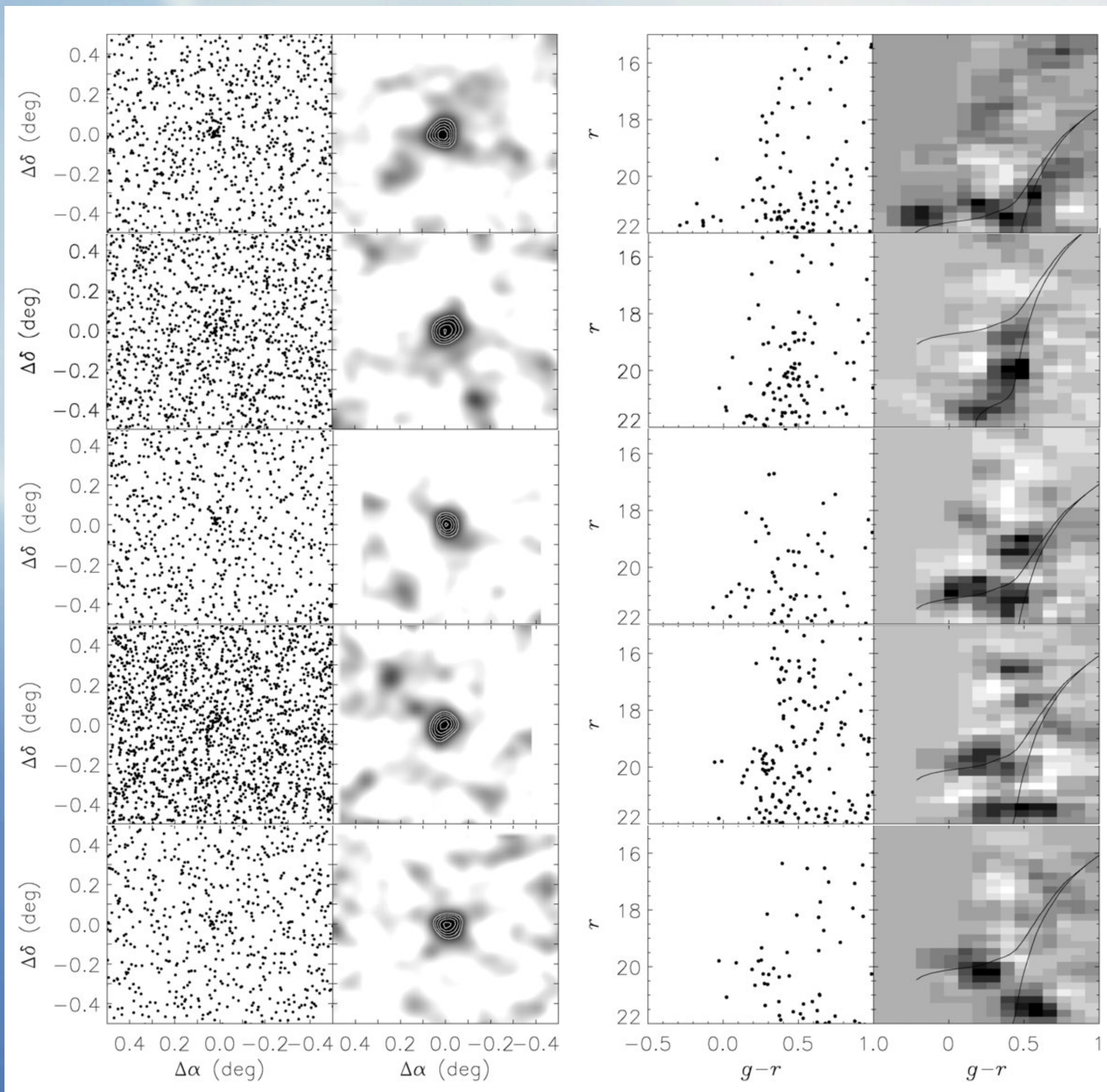
Deep Imaging Surveys Require Spectroscopic Follow-up



LSST will find hundreds of objects like these - which ones are dwarfs?

Walsh et al. (2009)

Deep Ground-Based Surveys Require Intensive Follow-up



Dwarf

Dwarf

Asterism?

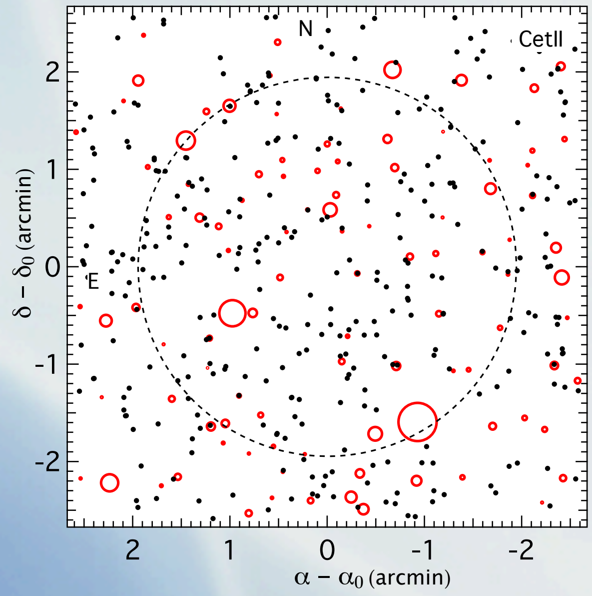
Asterism?

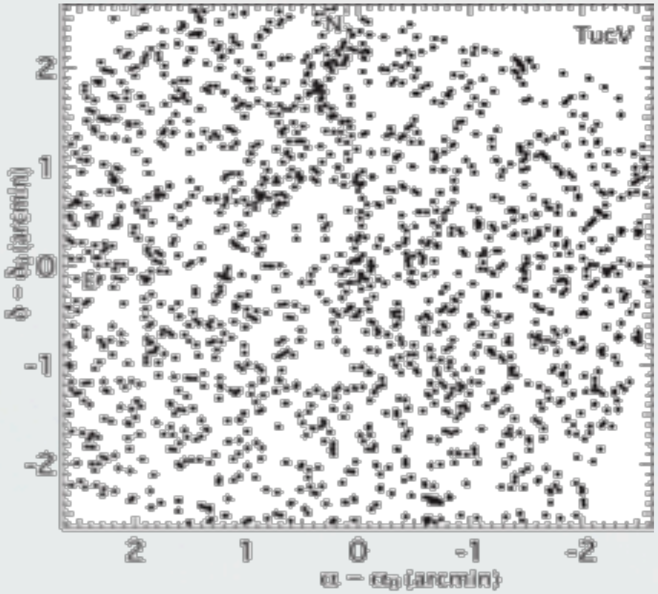
Asterism?

Walsh et al. (2009)

Already a Problem for Current Surveys

- Recent deep Gemini/GMOS imaging studies question 2 DES satellites

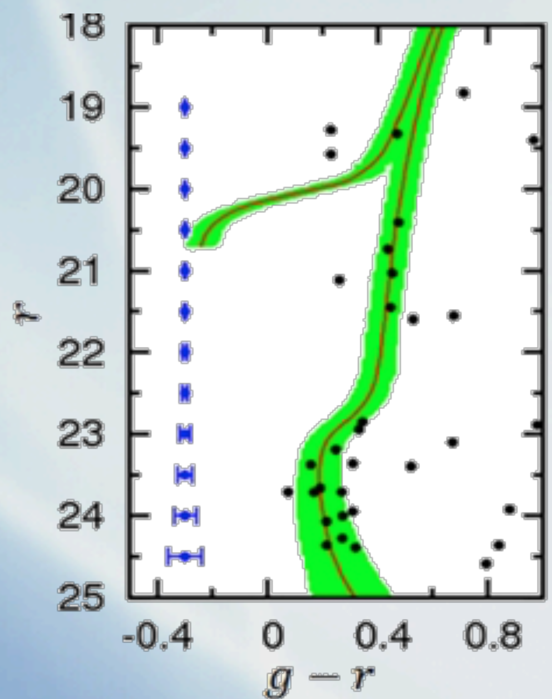




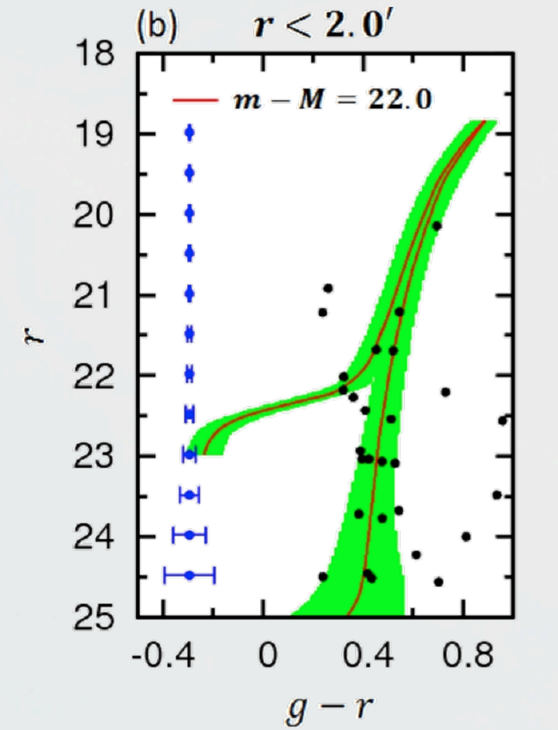
Conn et al. (2018a, 2018b)

LSST analogues

Virgo I: M_V = -0.8, d = 87 kpc



Cetus III: M_V = -2.4, d = 251 kpc



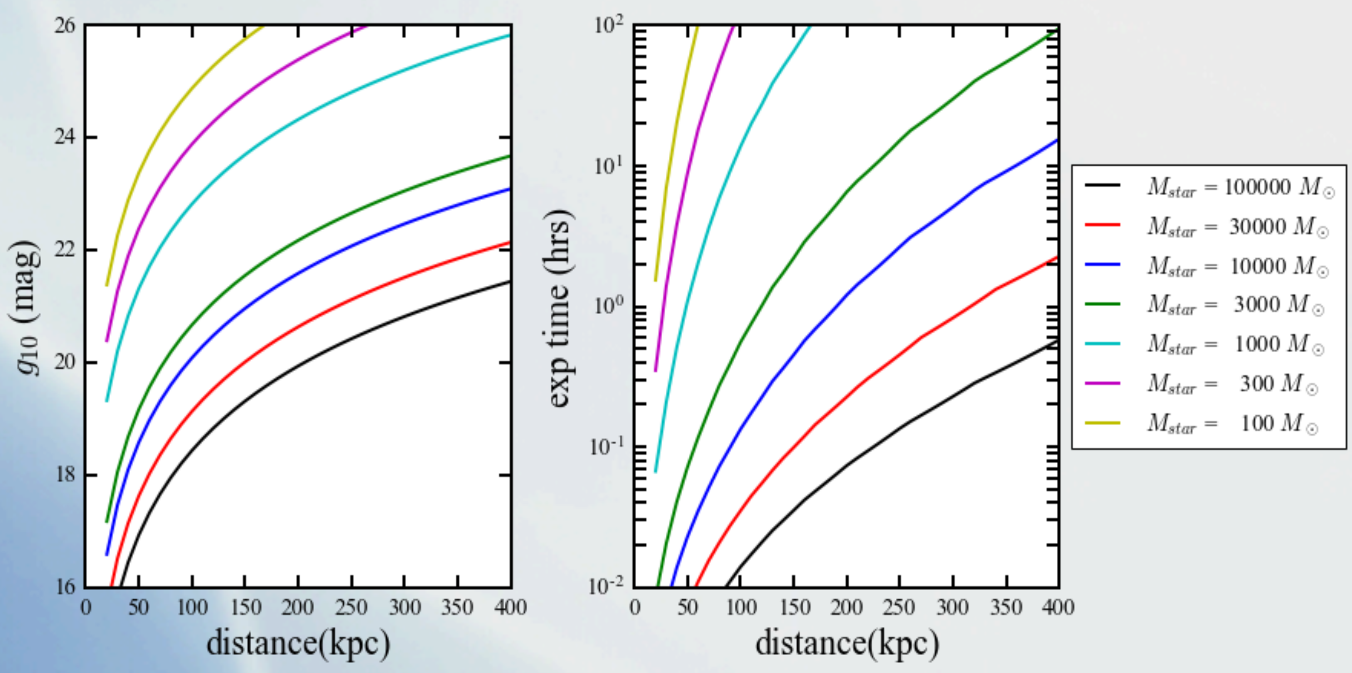
Only 4 stars per dwarf brighter than r=23!

Homma et al. (2016)

Homma et al. (2018)

How Much Spectroscopic Followup?

- Confirming all LSST dwarfs would require:
  - ~3200 hours on an 8m telescope (e.g., Subaru)
  - ~320 hours on GMACS/GMT



Najita et al. (2016)

How Much Spectroscopic Followup?

- Detailed follow-up of ~10 streams would require:
  - ~800 hours on an 8m telescope (e.g., Subaru)
  - ~80 hours on GMACS/GMT (but *only* if the field of view is very large)

Najita et al. (2016)

Critical Facilities

- GMT/TMT/ELT
  - Diffraction-limited AO imager with as large a field of view as possible (30”)
  - Wide-field multi-object optical spectrograph
    - FOV > 10 arcmin
    - Velocity accuracy of 1-2 km s^{-1}
- Wide-field multi-object spectrograph on 8+m telescope
  - FOV > 1 deg
  - Velocity accuracy of 1-2 km s^{-1}

Critical Facilities

- Something in space
  - Provide astrometry over as long a time baseline and at as high an angular resolution as possible

Stellar Streams

- Streams can be used for:
  - Determining the mass (profile) of the Milky Way (e.g., Bonaca & Hogg 2018)
  - Constraining the presence of dark subhalos around the Milky Way (e.g., Erkal et al. 2016)
- Measuring stream kinematics requires multi-object spectroscopy over ~degree scales with ~km s^{-1} accuracy

See presentations by Carlberg (conference), Bozorgnia, and Li

Where Will/Can We Be In 10 Years?

- Kinematics of low-mass disk galaxies
  - Larger samples are possible
- Kinematics of classical dSphs
  - Samples of ~few thousand-10000 stars possible
  - Internal proper motions from HST/Gaia + JWST/WFIRST??
- Ultra-faint dwarfs
  - Likely >100 UFDs known
  - Kinematic samples of ~100 stars possible

Where Will/Can We Be In 10 Years?

- Streams
  - Milky Way mass will be better constrained than it is now (1% uncertainties on halo parameters possible in principle)
  - Kinematics of stars around prominent stream gaps is possible

Where Will/Can We Be In 10 Years?

- Indirect detection
  - Gamma-rays
    - Fermi-LAT sensitivity scales as $t^{1/2}$ and $N^{1/2}$
    - Expected improvement of a factor of ~5
    - CTA sensitivity ~10× better than LAT or current Cerenkov telescopes above 100 GeV
  - X-rays
    - Megasecond+ integrations needed for significant improvements
  - Radio
    - Significant improvements possible with longer integrations and new telescopes

Summary

- In the foreseeable future we will have
  - Full luminosity function of MW dwarfs
  - Best streams (and gaps) for probing MW halo mass and substructure
  - Larger samples of density profile measurements for v_{circ} > 50 km s^{-1} galaxies
  - 3D internal kinematics for dwarf spheroidals???
  - ~10× better indirect detection limits

Is this good enough?