New insights on the dSph from orbit-based dynamical modeling

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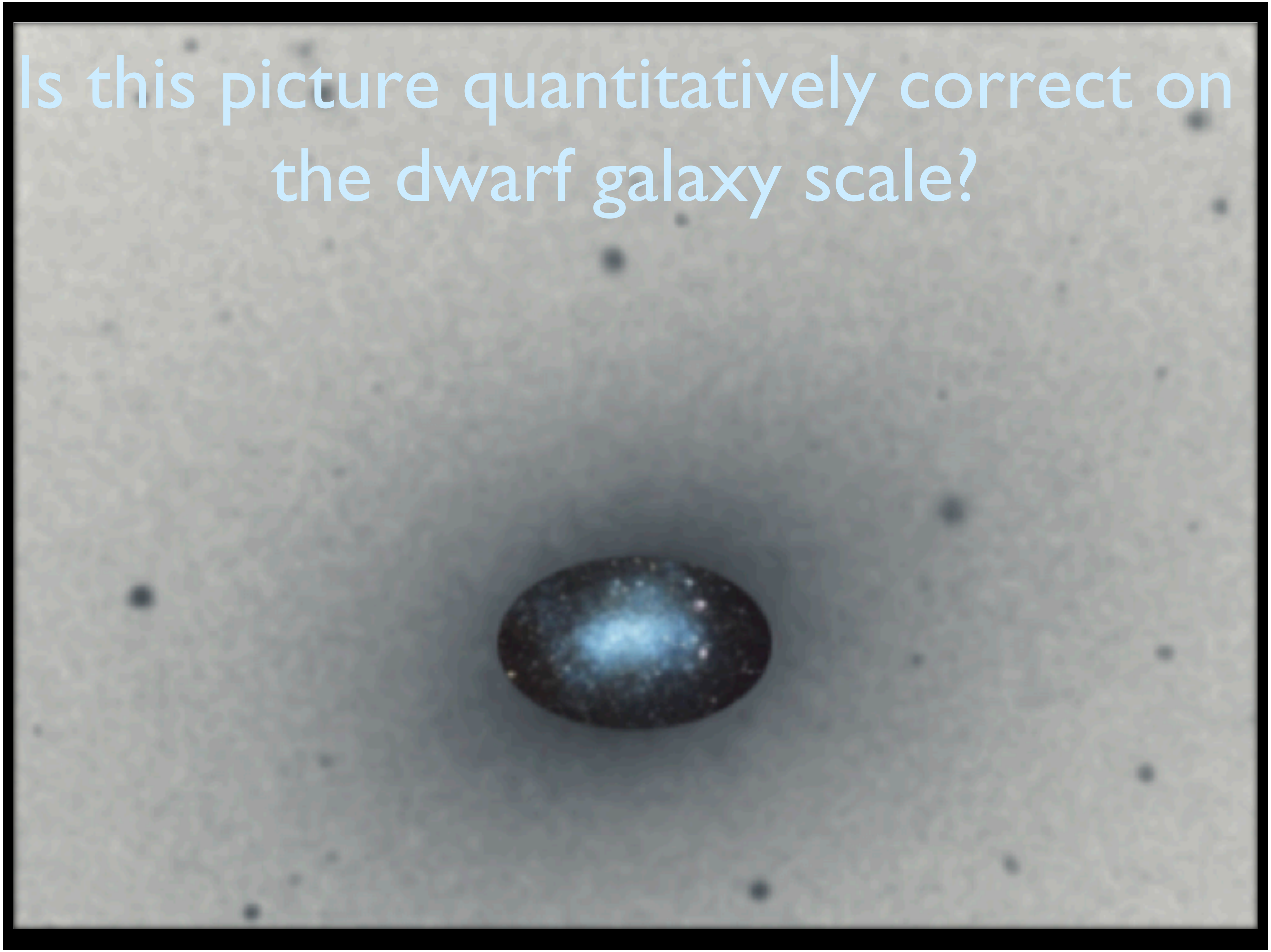
Outline

- Introduction: cosmological predictions/relevance to DM nature
  - Density profiles and shapes
- Dynamical modeling of dwarf galaxies
  - Recent lessons
  - Dynamical modeling with Schwarzschild's method
  - Comparison to LCDM simulations
- Conclusions

Special thanks to: Carlos Vera-Ciro
and Maarten Breddels


Is this picture quantitatively correct on
the dwarf galaxy scale?

Why care?

- Pure N-body CDM simulations make definitive predictions about structure of halos
  - density profiles a la NFW/Einasto; cuspy near the centre
  - halo shapes triaxial; axis ratios change with radius

- These predictions depend on nature of dark matter particle
  - WDM have lower average densities
  - Depending on implementation/particle properties simulations show
    - NFW form (Busha et al. 2007; even for HDM Wang & White 2008)
    - A core (of varying size; Maccio et al. 2012,2013)

- We can use large kinematic datasets for the dwarf galaxies to measure these
  - To shed light on the nature dark matter
  - To constrain physics of baryons on small scales, e.g. SN feedback (strength)

The satellites of the Milky Way: dwarf spheroidal galaxies

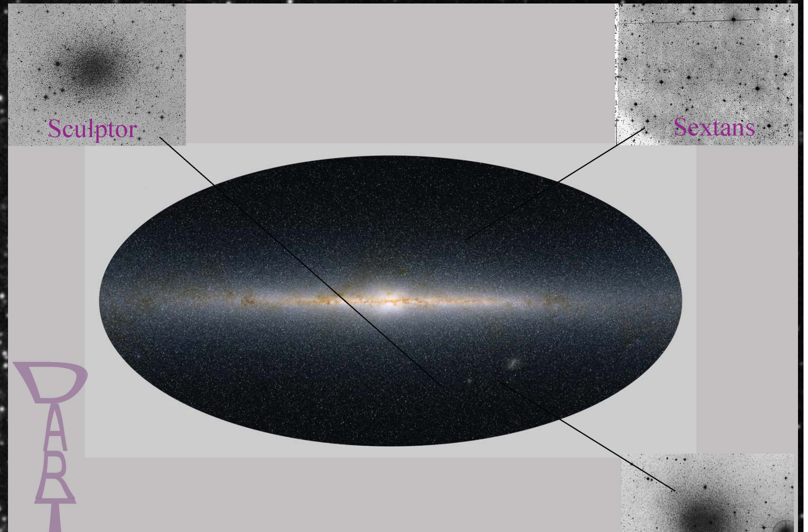
Very faint systems: 100 – 10^7 Lsun

Dynamical mass estimates: 10^7 – 10^9 Msun

- Most DM dominated systems known, and all the way to center

- Large MOS spectrographs on 8m class telescopes (MIKE on Magellan – Walker et al. 2007++; FLAMES on VLT – Battaglia et al. 2008++; Gilmore et al. 2007++) led to large samples of stars with
  - radial velocities
  - metallicities

- Dynamical and chemical modeling



Tolstoy et al.

Kinematics of MW dSph satellites

Fairly flat velocity dispersion profiles

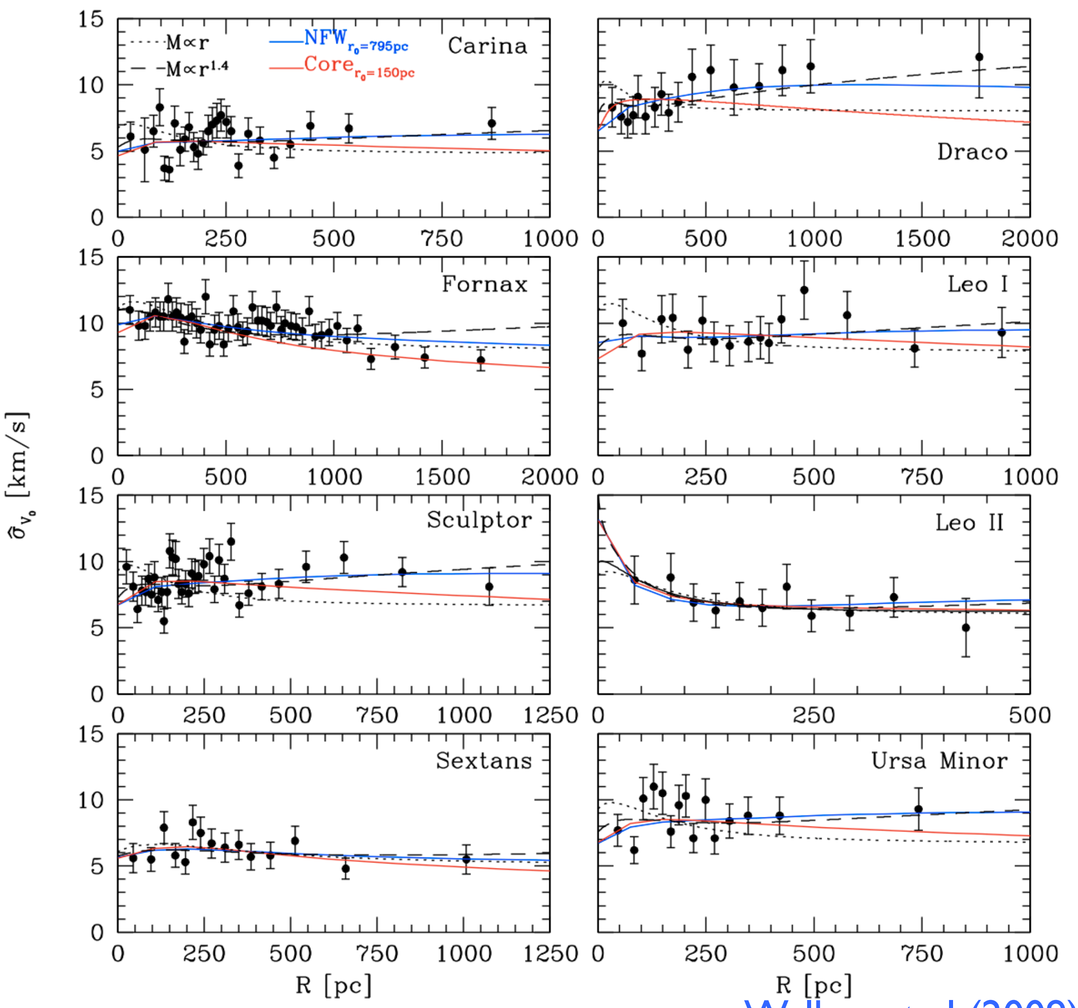
<u>Implications for dark halos?</u>

Modeling often based on Jeans Eq:

- Fit veloc. disp. (2nd and 4th mom)
- parametric (dark halo profile)
- assumptions on orbital structure

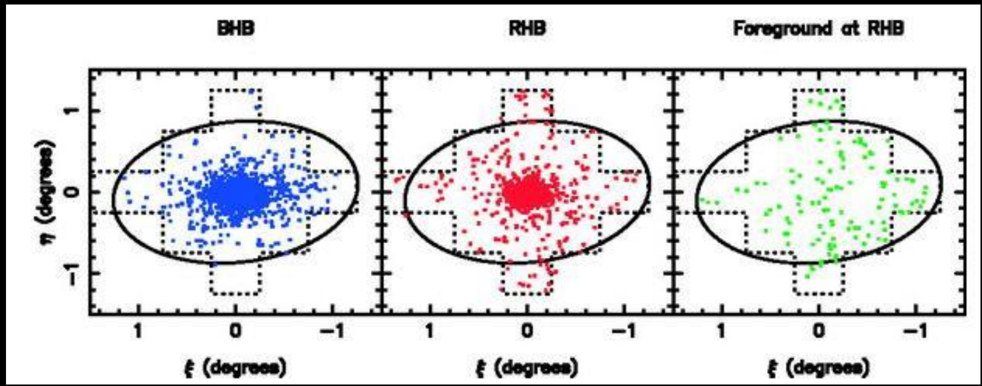
No agreement on cusp or core because of degeneracies

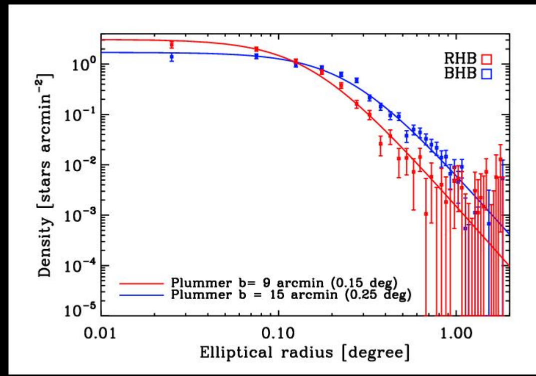
Need more robust modeling technique (fewer assumptions)



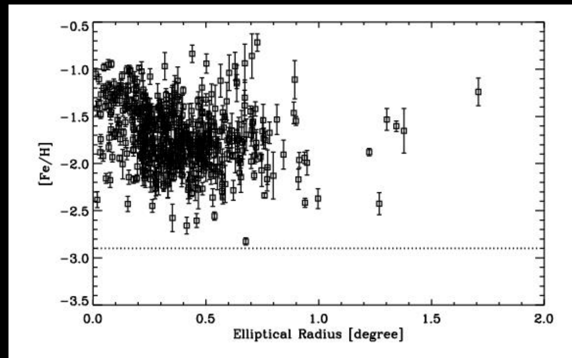
Walker et al (2009)

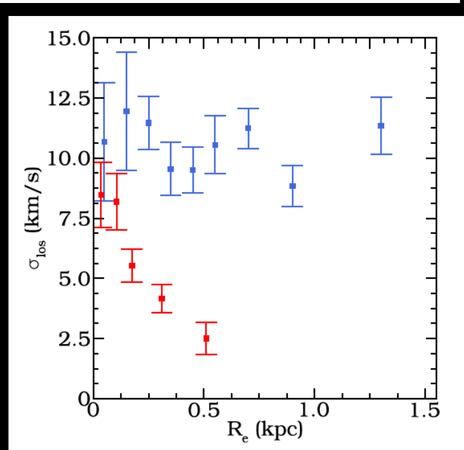
Multiple stellar/kinematical components: Scl





Tolstoy et al. 2004





Battaglia et al. 2008, 2013

- Strong variation of stellar populations with distance
- Also reflected in the metallicity and kinematic distribution

- Metal-rich stars centrally concentrated, colder population
- Metal-poor stars: extended and hotter

- Present in Sculptor, Fornax, Carina, Sextans

Recent results and open questions

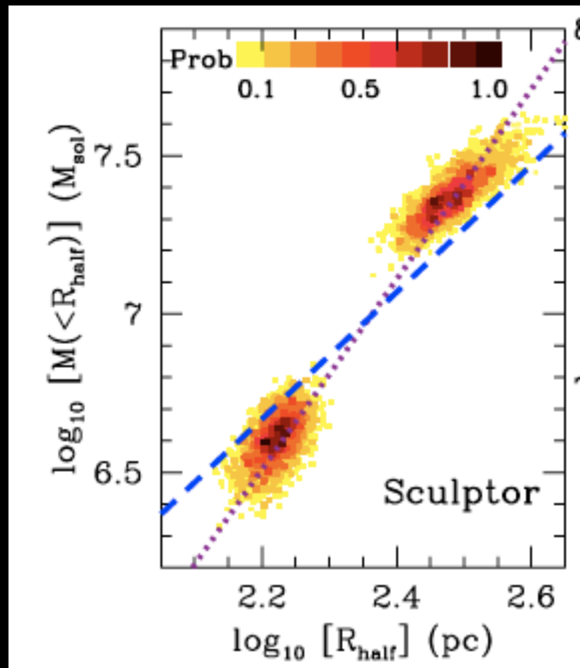
- Possible to measure reliably a mass at a scale close to half-light:

$$M(r_{-3}) = 3\frac{\langle\sigma^2_{\rm los}\rangle r_{-3}}{G}$$

M_{300} (Strigari et al. 2007)
M_{half} ,(Walker et al. 2009)
$M_{1/2}$(Wolf et al. 2010)

- Multiple component nature of dSph:
  - slope measurement in Scl rules out steep NFW at 99% c.l. (Walker & Peñarrubia, 2011, but Strigari et al. 2014)
  - similarly for virial theorem arguments (Agnello & Evans 2012)

Need to model components separately? How about non-parametric modeling?



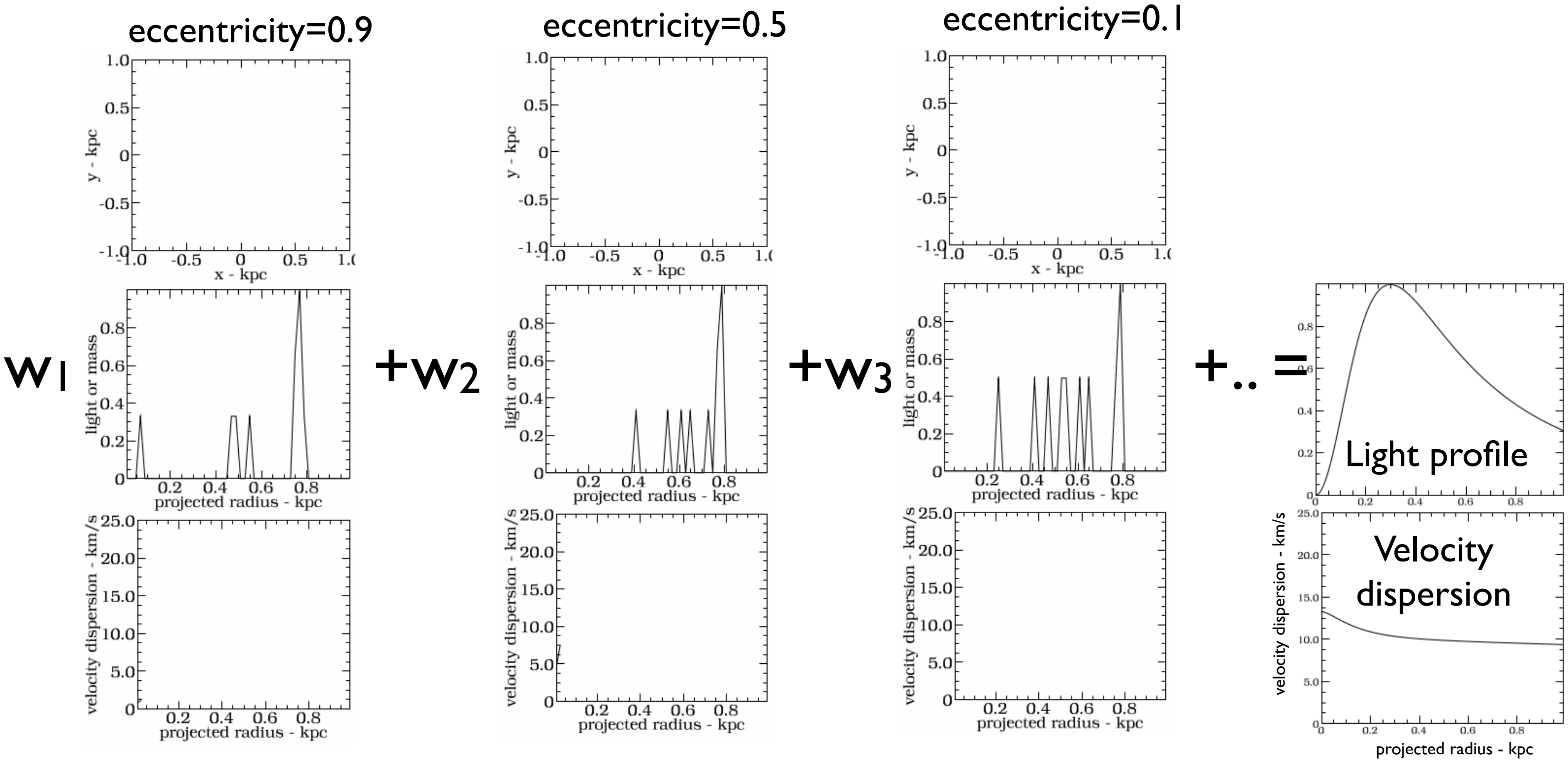
Walker & Peñarrubia (2011)

Dynamical modeling using orbit-based methods

Schwarzschild method

(Martin Schwarzschild 1979)

Assume a potential, integrate different orbits, reproduce observables by adding them: weights

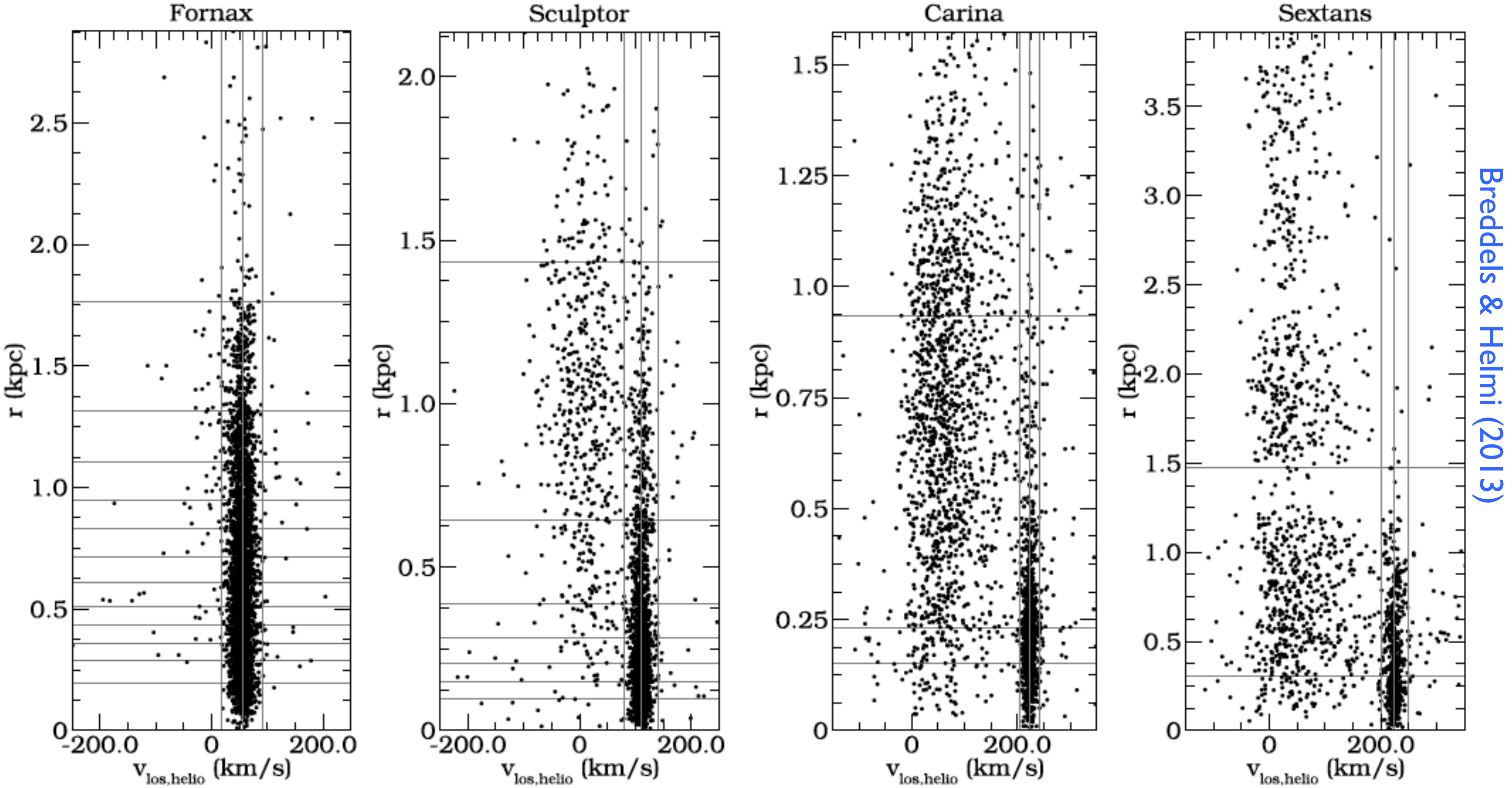


•Best model via max likelihood, gives best fit parameters of gravitational potential, and distribution function (orbital structure)

•Compared to Jeans: less assumptions & always a physical solution

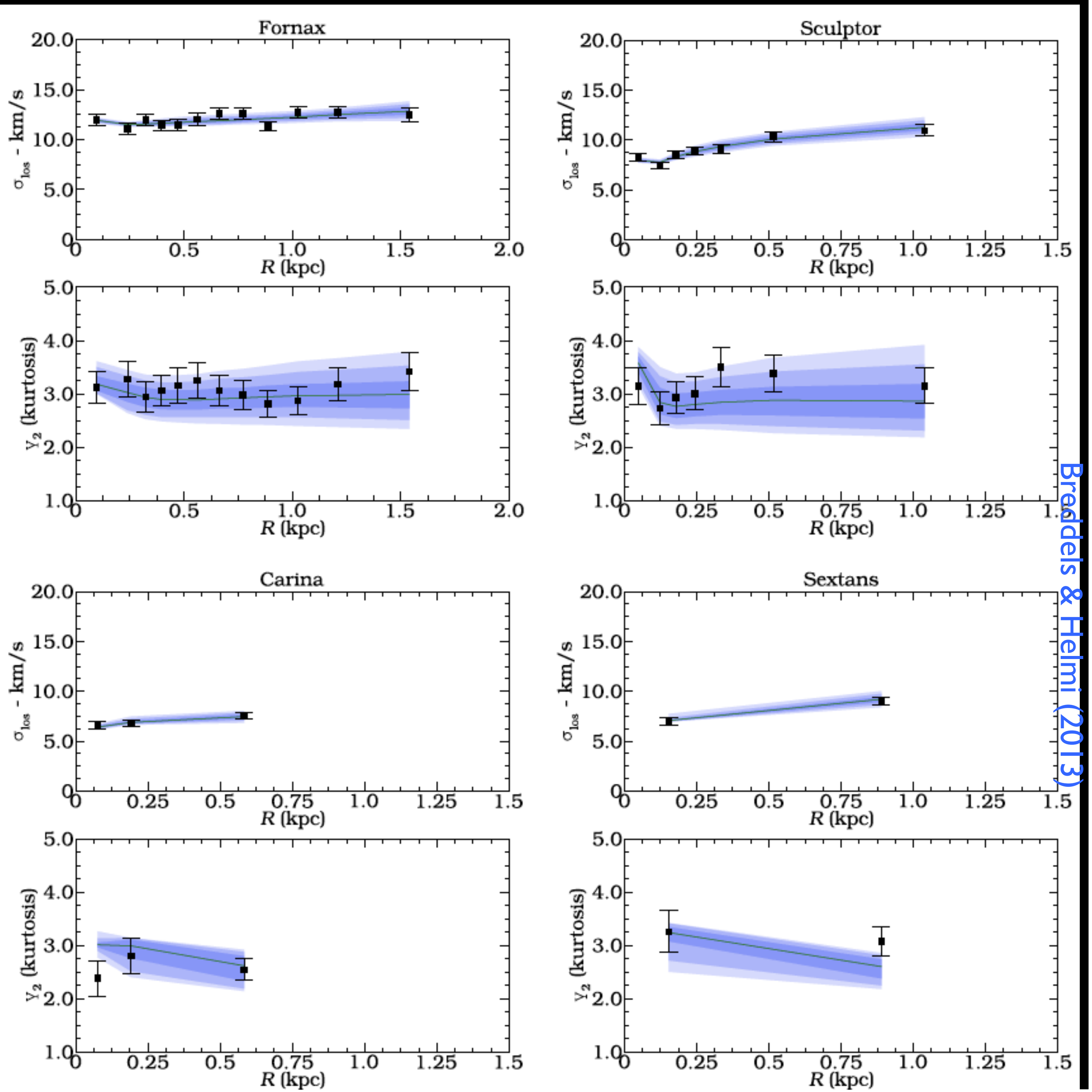
Observables

- Measurements for individual stars: los-velocity and position from galaxy's centre
- Determine membership (contamination by foreground Milky Way stars)



Observables

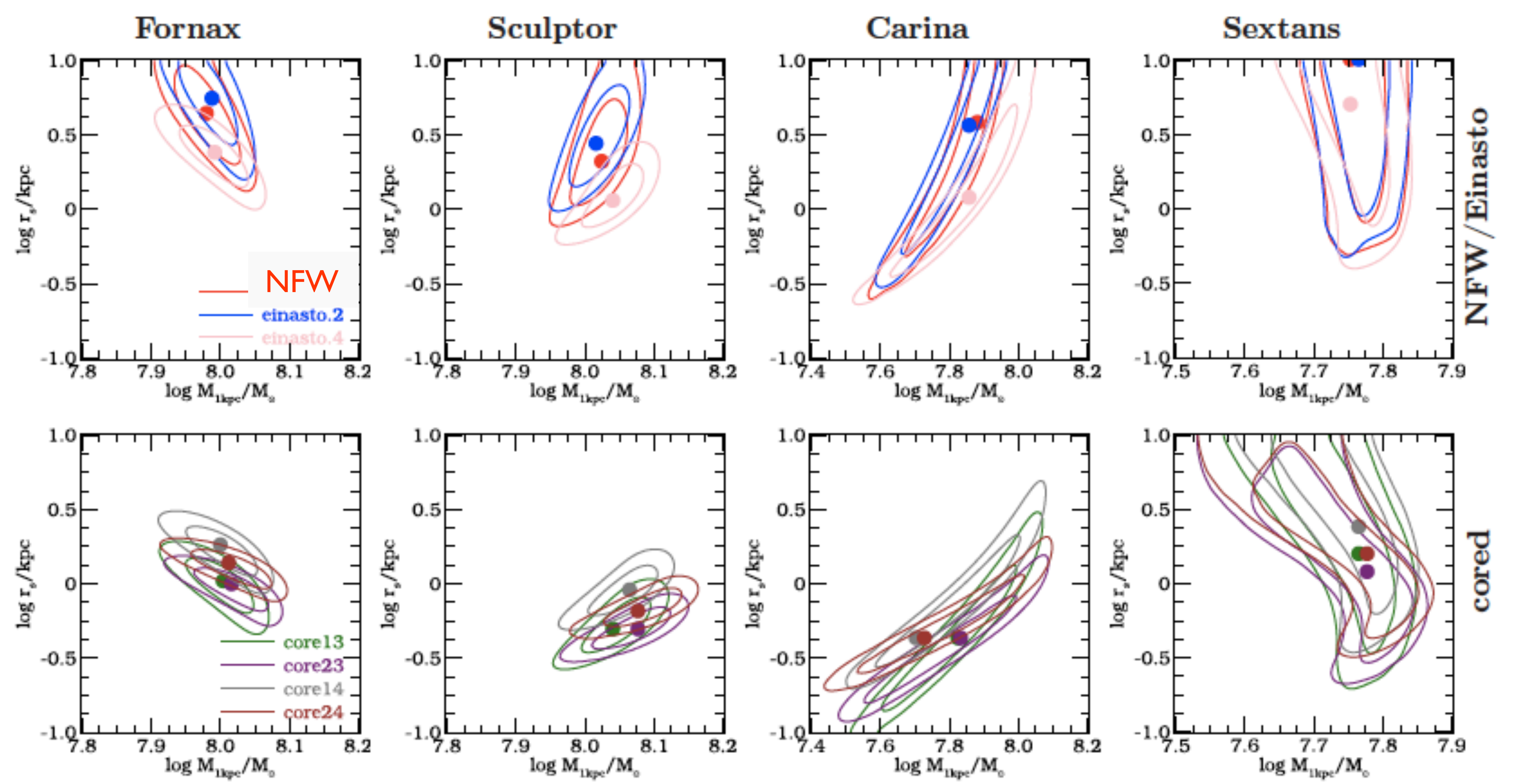
- Moments of the l.o.s. velocity distribution
- 2nd moment, Dispersion σ
- 4th moment (Kurtosis; needed to constrain anisotropy/types of orbits)



Breddels & Helmi (2013)

Models: mass and scale radius

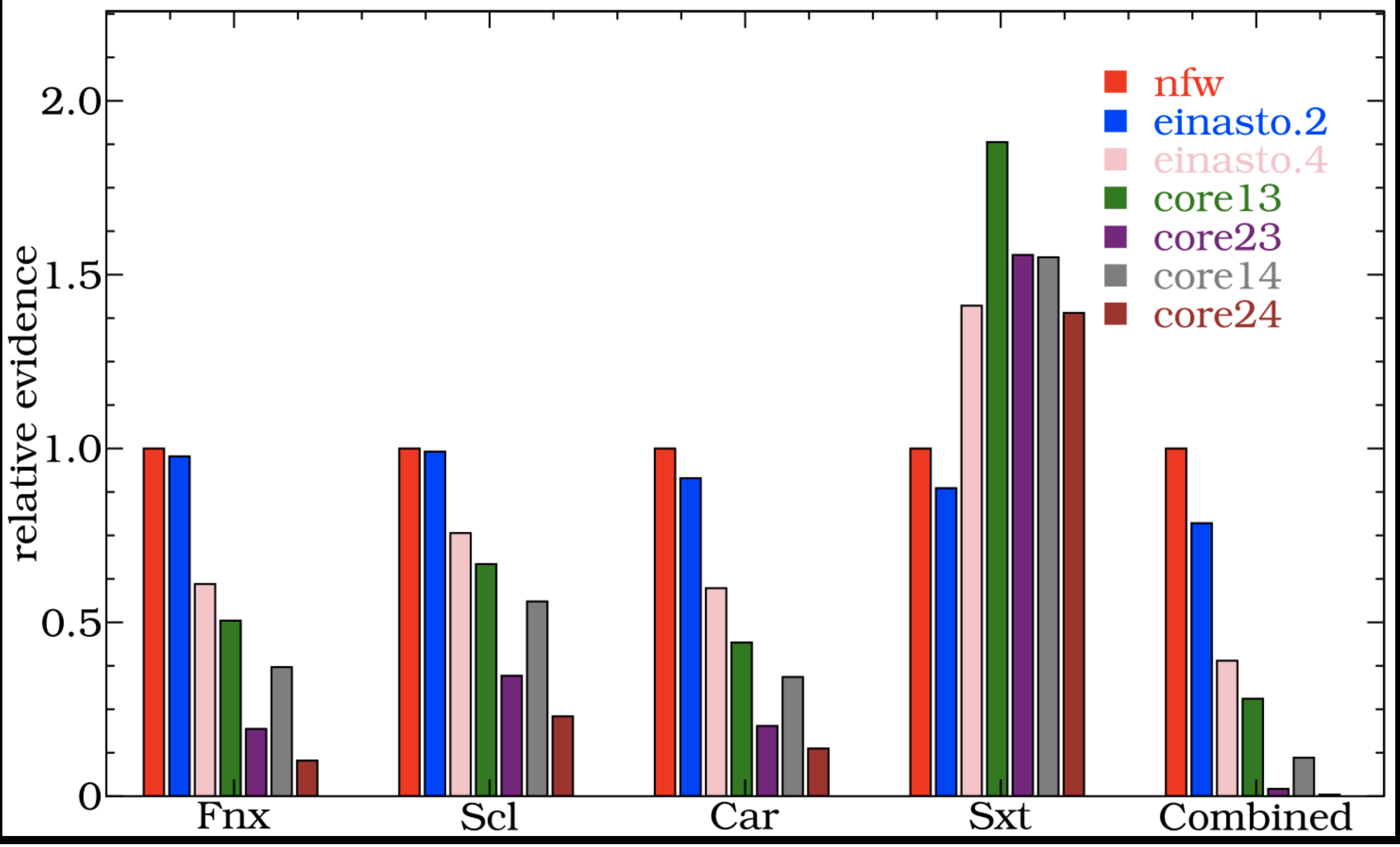
- Specify halo potential, e.g. NFW, integrate orbits
  - Vary parameters (Mass, scale radius) until χ^2 is minimized
- Vary halo potential/density $\rho(r) = \frac{\rho_0}{(1+x^\gamma)^{\beta/\gamma}}$ β = 3, 4 and γ = 1, 2
  - Fit again …



Breddels & Helmi (2013)

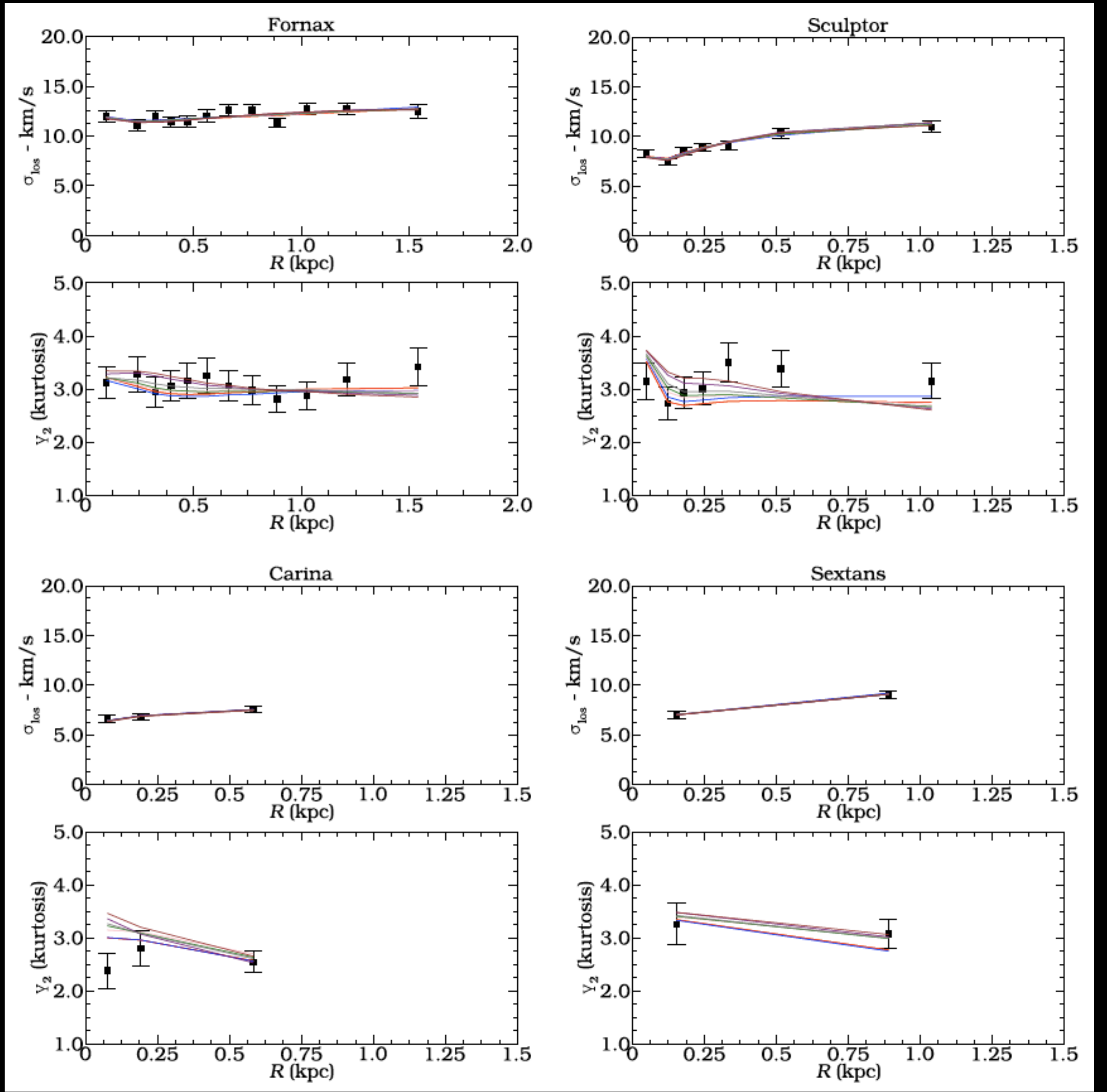
Bayesian evidence: Which give better fits?

- In Bayesian framework, determine evidence: $p(M_1|\text{data})/p(M_2|\text{data})$
- Comparing different models for same galaxy: no one is preferred
- Are all galaxies are embedded in same profile? cored $1/(1+r^2)^{\{3/2,2\}}$ are disfavored



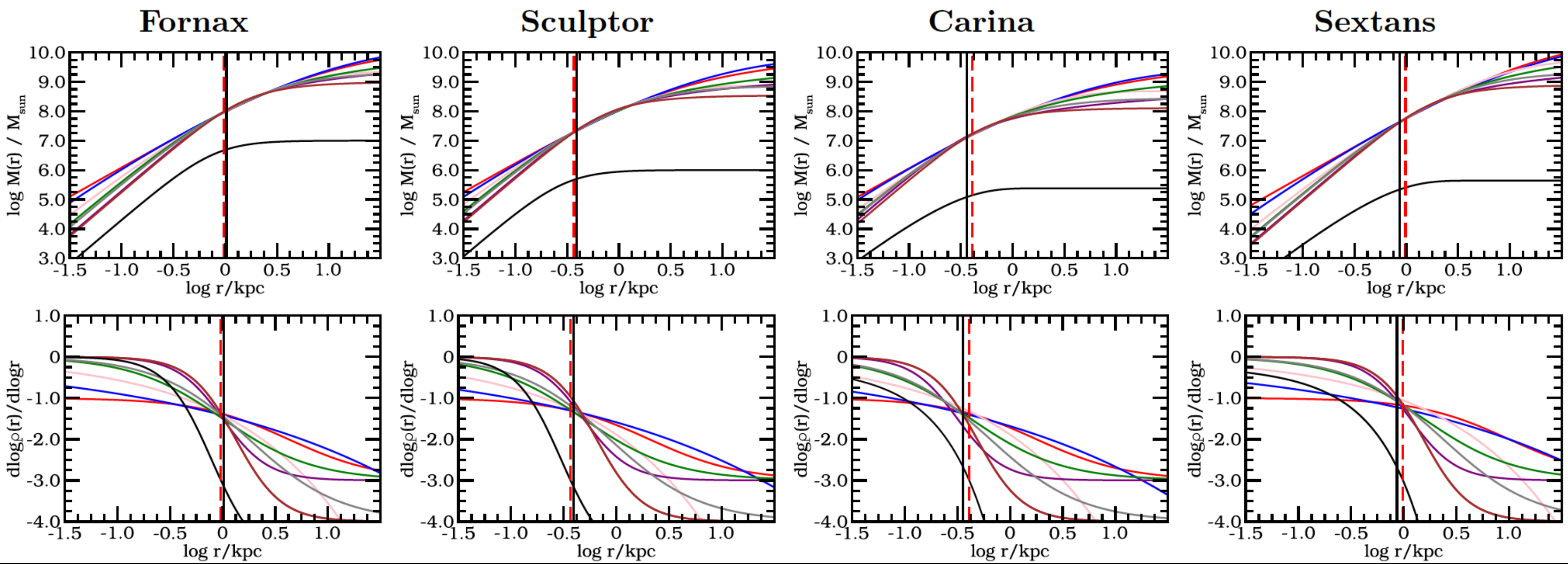
Breddels & Helmi (2013)

The best fit models found give fits that are effectively indistinguishable



Breddels & Helmi (2013)

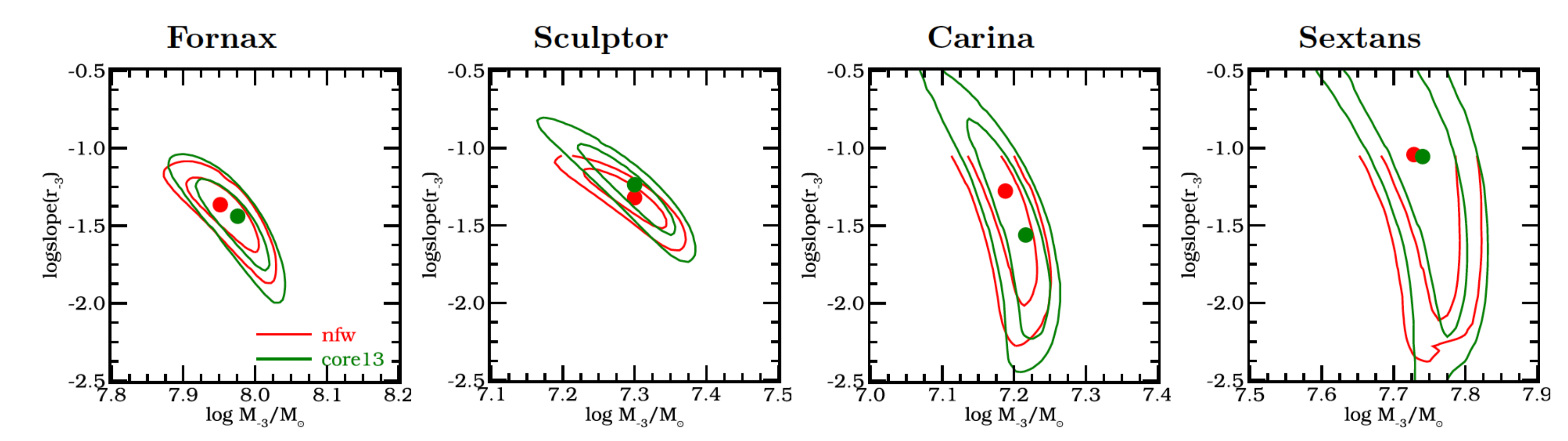
Resulting mass profiles



Breddels & Helmi (2013)

- For each galaxy, finite region where all profiles conspire to give same mass distribution
  - From r_{-3} to last measured data point

Measurement of the slope of the dark halo density profile



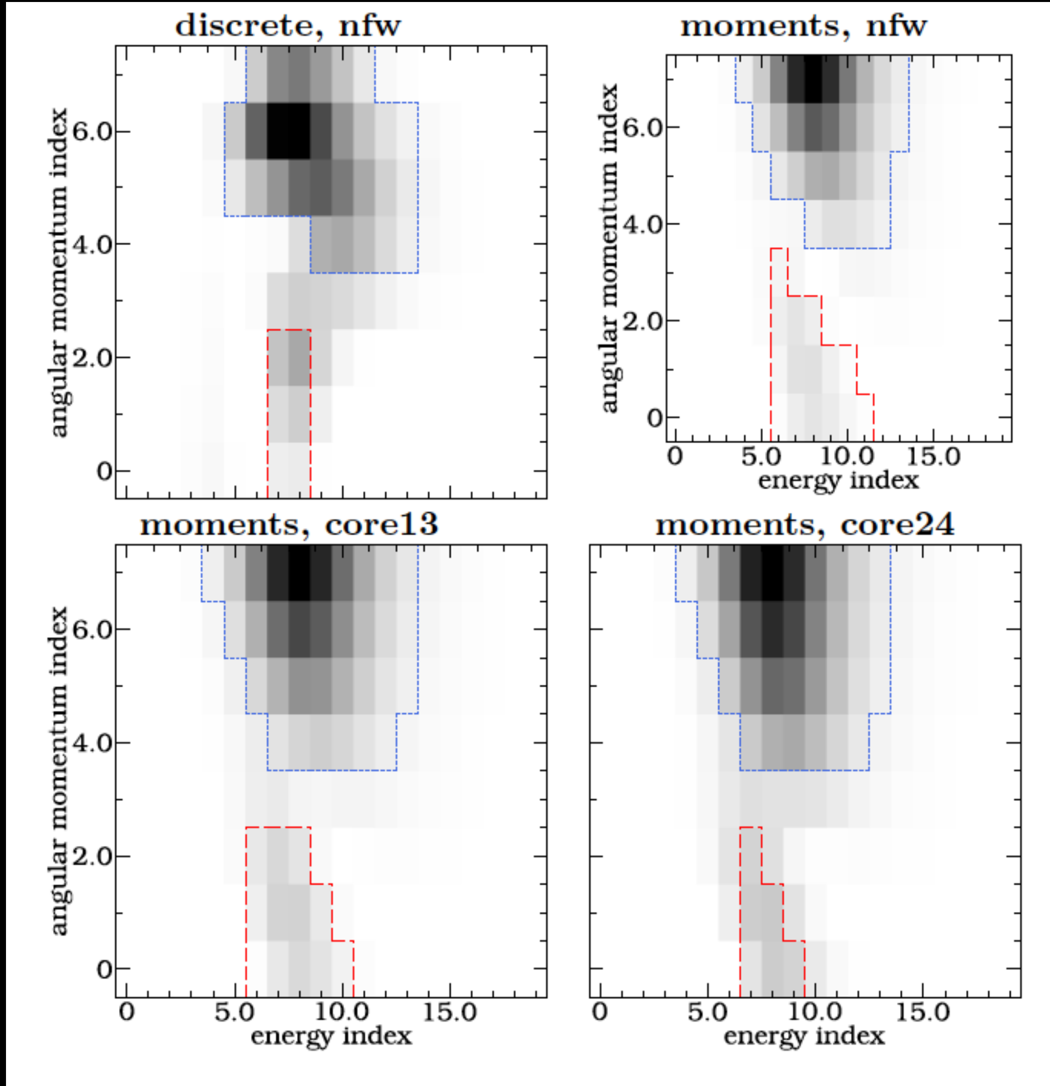
Breddels & Helmi (2013)

- Model-independent measurement of slope of dark halo density profile at ~r_{-3}

- We find $\gamma(r_{-3})$ ~ -1.1 (Sextans) to -1.5 (Fornax) at ~ 1 kpc
    - the large uncertainties for Carina and Sextans are due to size of sample

Distribution function of Sculptor

- From weights we obtain orbital structure and df of these models
- Resulting df has two dynamical components!!
    - Low angular momentum (radial orbits)
    - High-angular momentum (tangential orbits)
- Bimodality present in all models
    - for discrete and moment fitting
    - NFW and cored potentials



Breddels & Helmi (2014)

Distribution function of Sculptor

•Multiple components in Scl are truly physically different

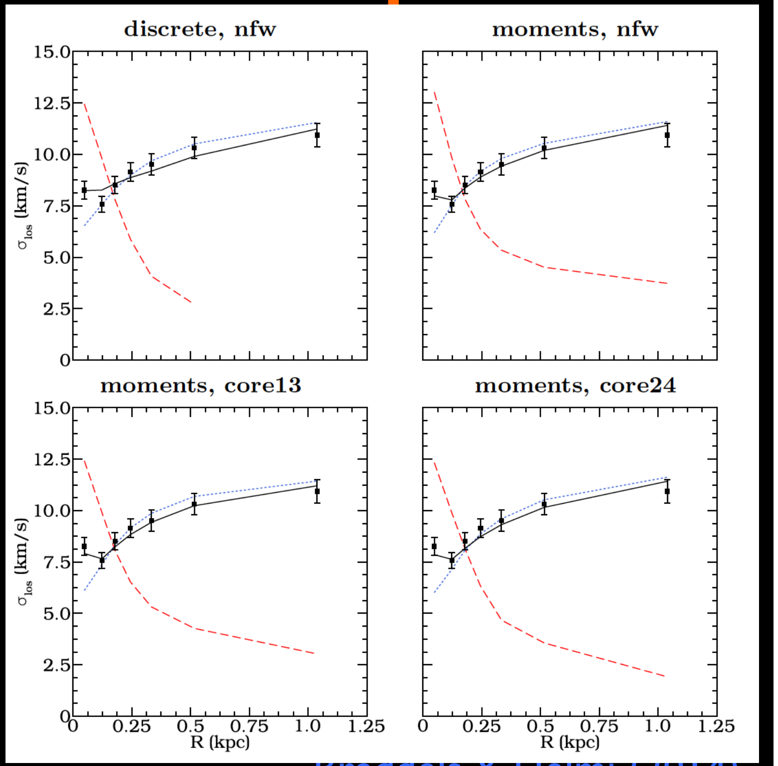
Not gradient of stellar pops from "metal-rich" to "metal-poor"

•No need to assume multiple components: an output of Schwarzschild non-parametric method

•Low angular momentum component is more centrally concentrated, velocity dispersion profile decreases with radius

•High angular momentum component is more extended, velocity dispersion profile is more constant with radius

•Resemblance to metal-rich (Fe/H > -1.5) and metal-poor (Fe/H < -1.7) kinematics



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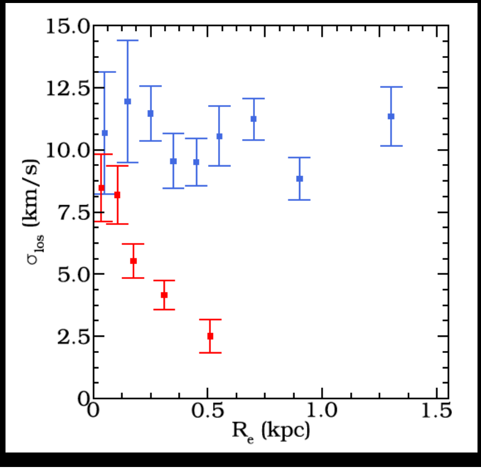


Distribution function of Sculptor

•Correspondance between the df components and those in photometry, or via metallicity, is not perfect

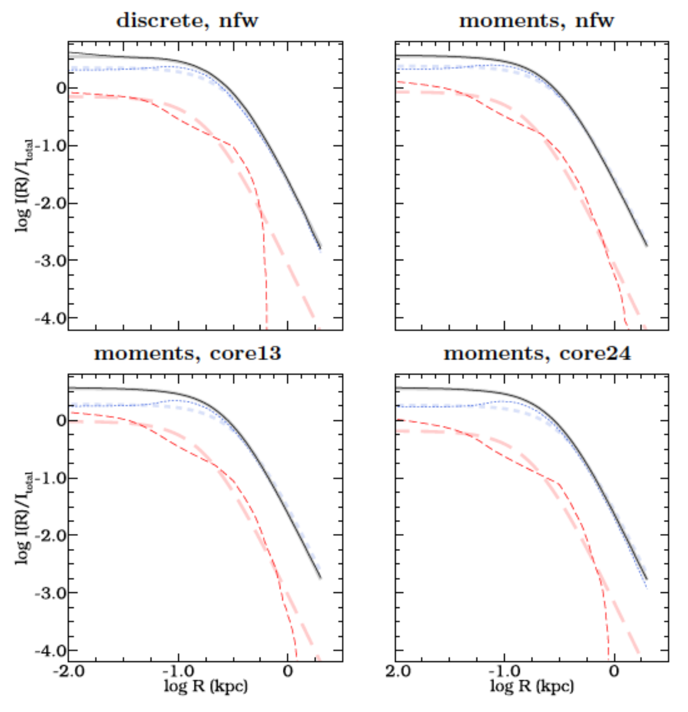
•Plummer fits to model light profiles give a ratio of scale radii ~ 0.6, very comparable to observed

•However, Plummer is not a good fit to innermost component.

•Tension with Walker & Peñarrubia (2011), and Agnello & Evans (2012) might be related

•model MR and MP pops separately but could not fit NFW…

•Uncertainties in characterization of these components too large?



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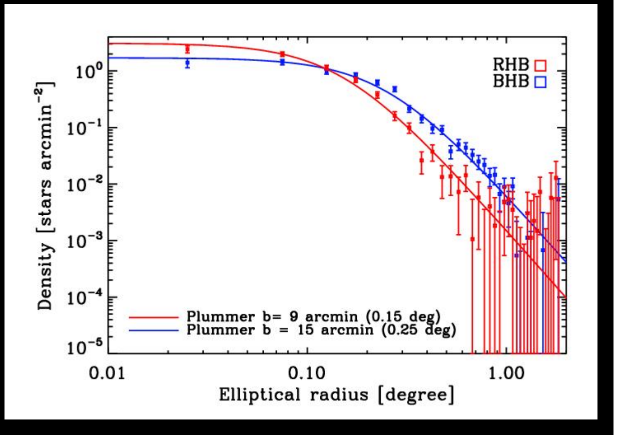

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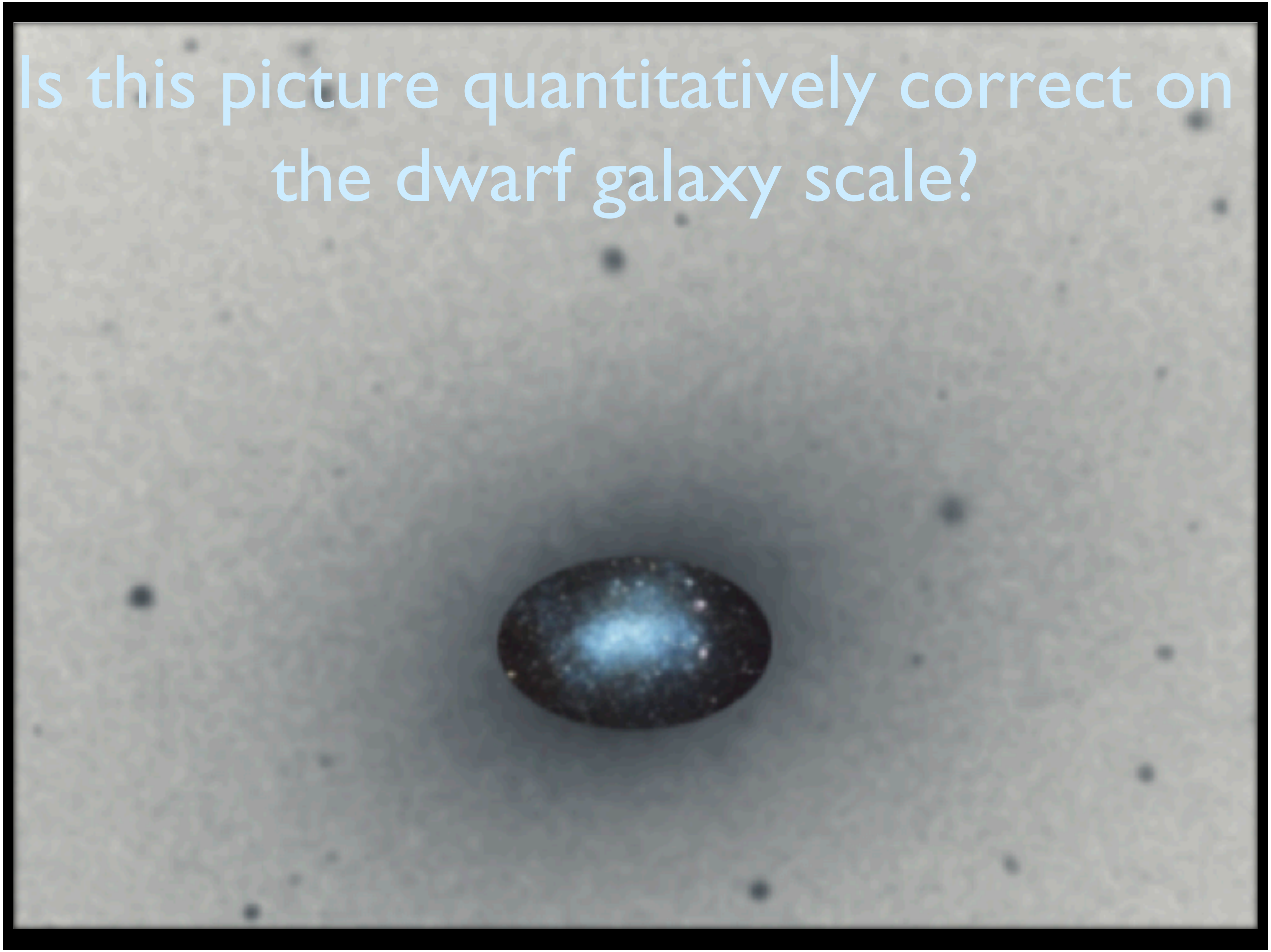
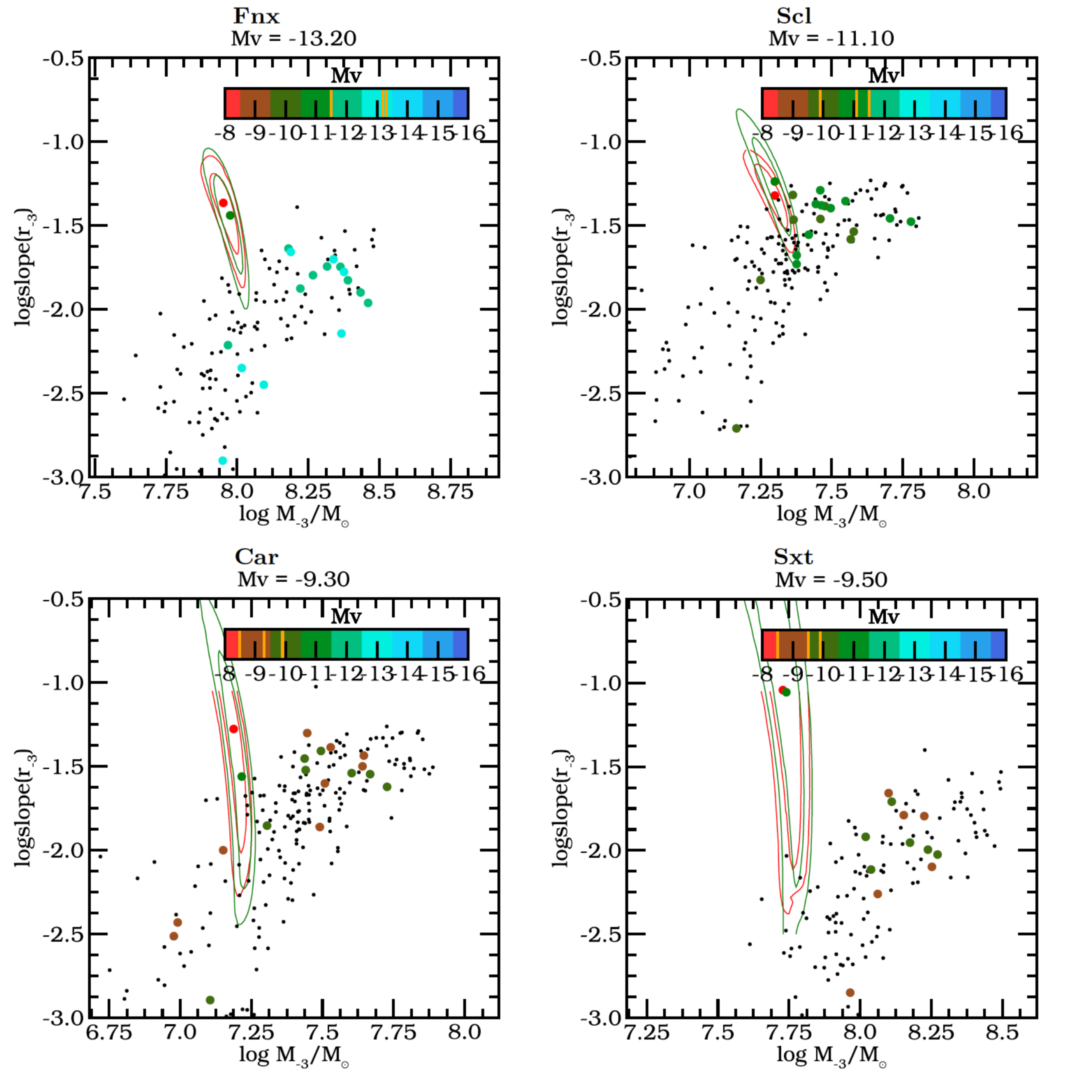


Comparison to subhalos in LCDM simulations

- Selected subhalos in Aquarius simulations
    - Aq-hosts scaled to the same mass, 8 x 10^{11} Msun
    - Luminosities from SA models (Starkenburg et al. 2013)

- Determined $M(r_{-3})$ and $\gamma(r_{-3})$ for subhalos at r_{-3} of each dSph
    - by fitting Einasto profiles

- Some subhalos show overlap with region allowed by observations (Scl)
- Typically they are offset (Fnx, Sxt)



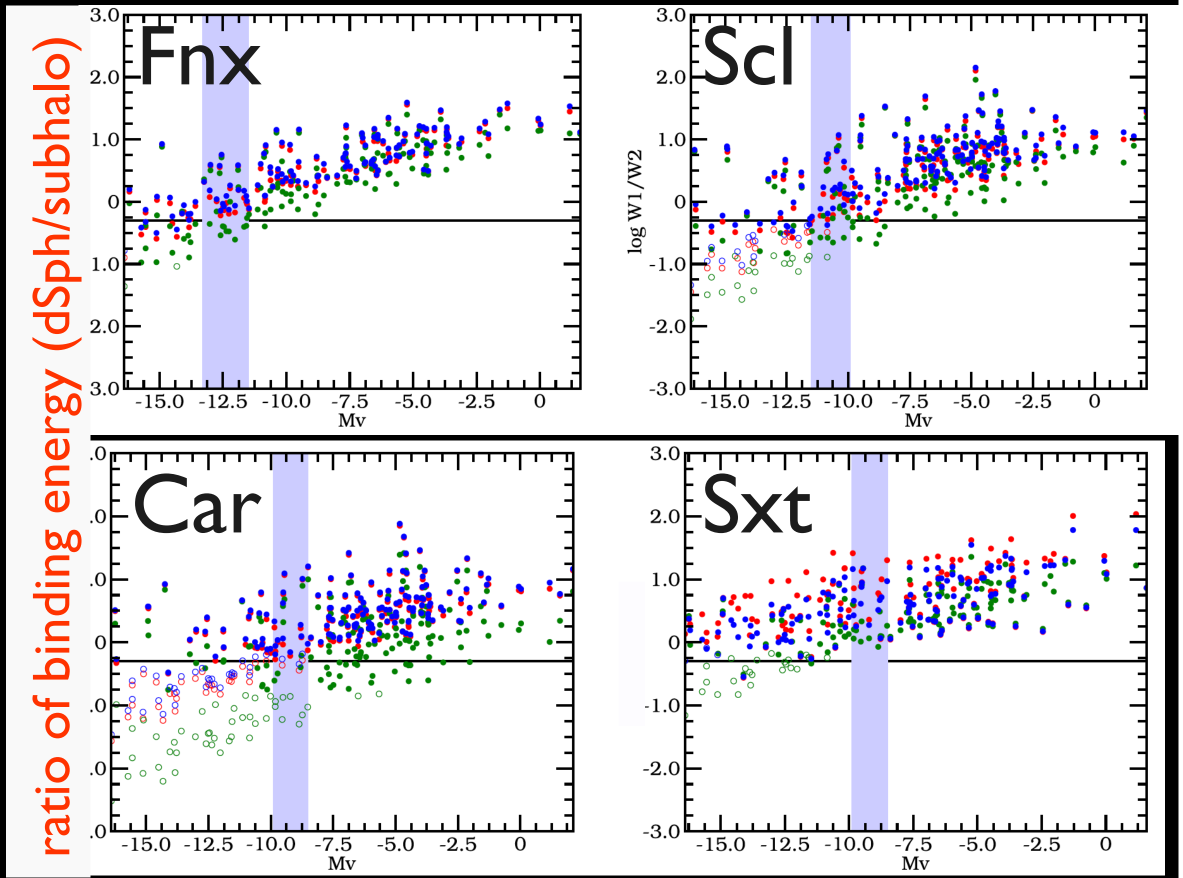
Breddels, Vera-Ciro in prep

Energetic arguments

- For each galaxy, compute binding energy of the best fitting models W_1
    - for different profiles
- Compare to binding energy of the subhalos W_2

- $W_1 = W_2$ implies no energy is required to transform from one system to the other
- $W_1/W_2 > 1/2$ transformation can take place, and energy must be injected into a subhalo
- $W_1/W_2 < 1/2$ subhalo must loose energy

- Ratio takes plausible values



Breddels, Vera-Ciro in prep

Energetic arguments

- SN energy budget given stellar mass of each dwarf: E_{SN} (Peñarrubia et al. 2012)

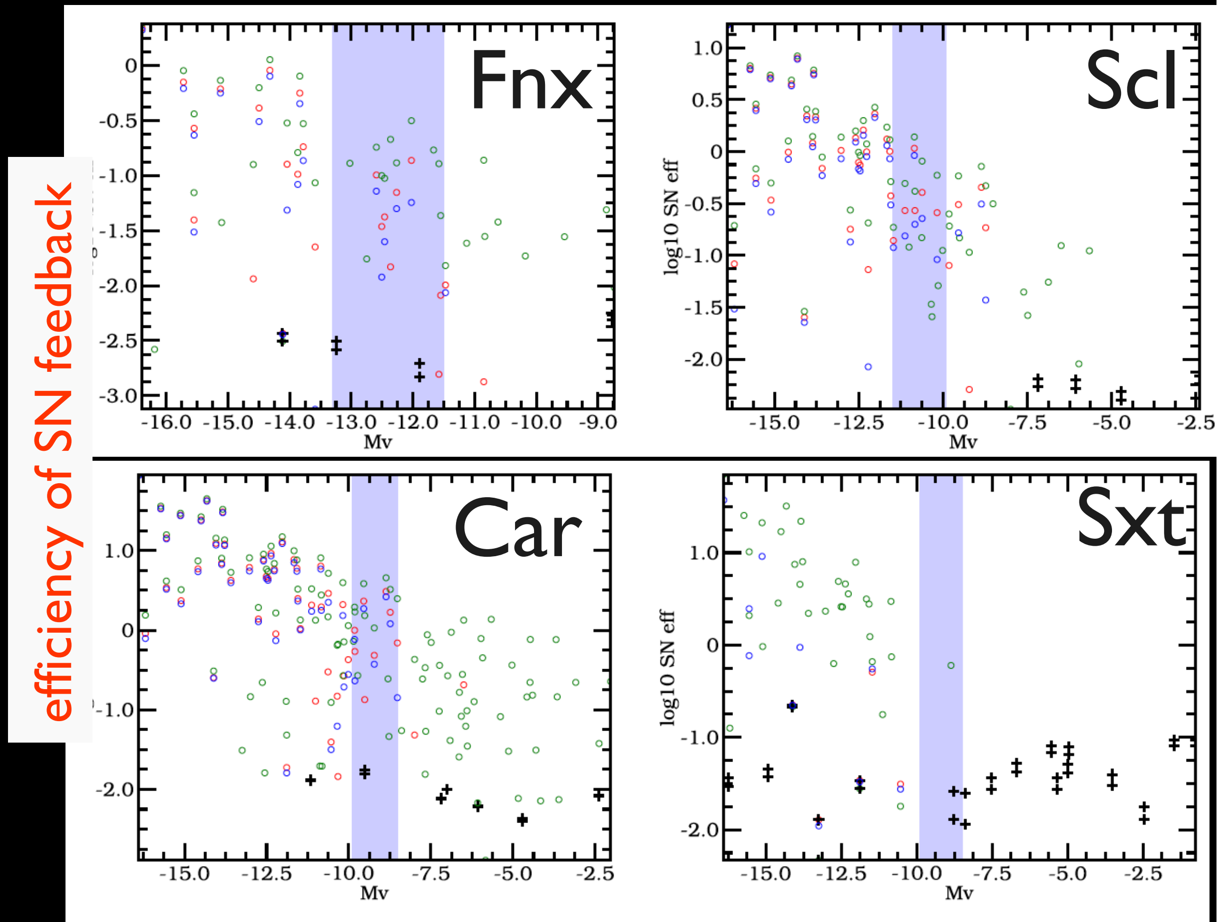
- Efficiency of SN feedback

$$\varepsilon_{SN} = \delta E / E_{SN}$$

$$\delta E = 1/2\,(W_1 - W_2)$$

- If $\varepsilon_{SN} < 1$, then energy change δE is lower than the available SN feedback energy

- For Fnx and Scl, efficiencies are plausible and < 100%.
- For Car it is possible, issues for Sextans



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Summary

- Schwarzschild modeling shows that different dark halo profiles give equally good fits to the dSph kinematic data

- Models conspire to give all the same mass distribution within region ~ 1 kpc in extent

- Slopes can be measured in model independent way
    - These new constraints are not directly consistent with properties of subhalos in LCDM
    - But energetics show it is possible to transform them into dSph halos, except for Sextans (which has large uncertainties)

- Non-parametric modeling of Sculptor reveals multiple dynamical components
    - Linked to the MP and MR populations: physically distinct
    - And demonstrates that NFW halos are still allowed by the data