Dwarf galaxies and dark matter

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PEOPLE

MARIE CURIE ACTIONS

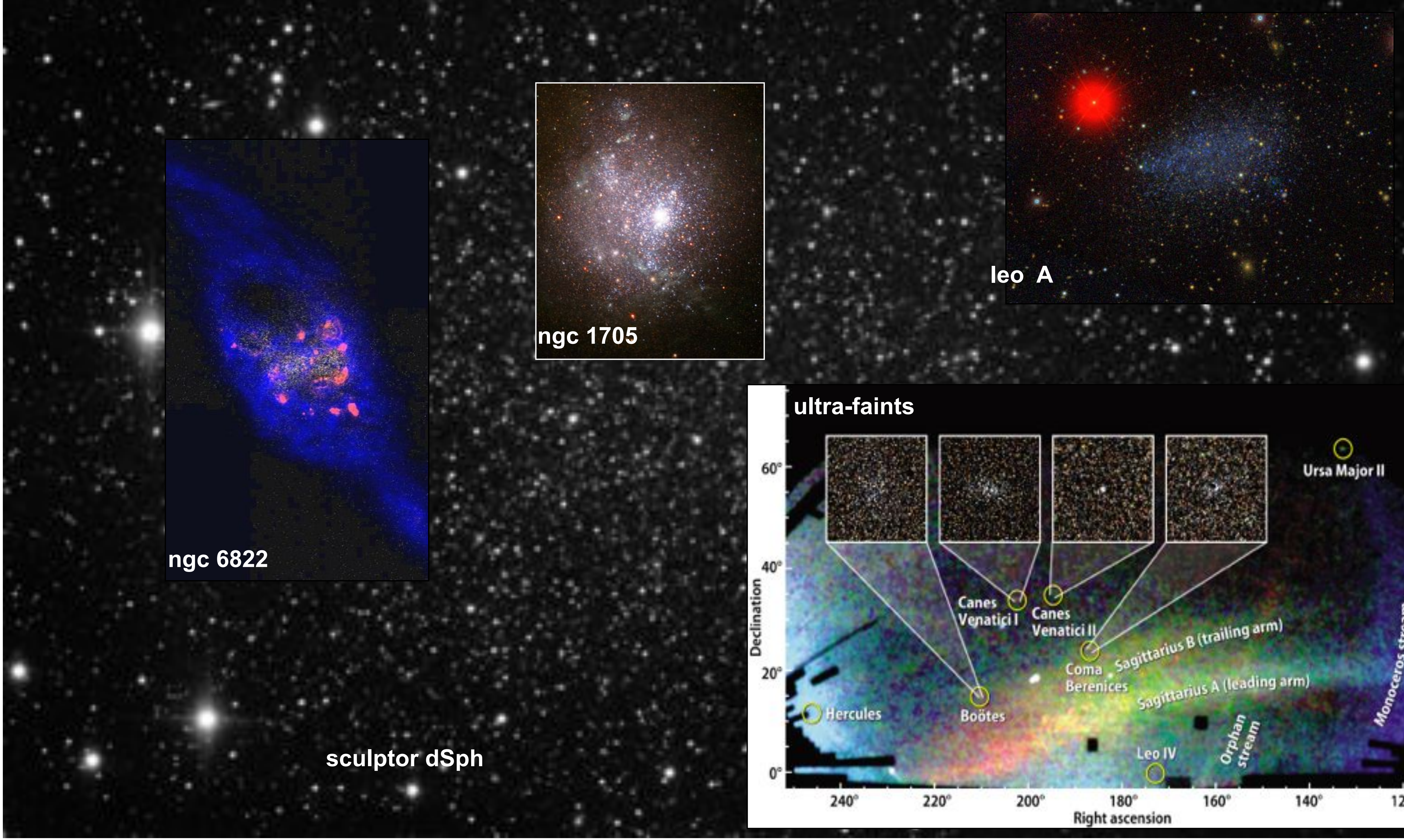
Outline

- Introduction: cosmological relevance and recent findings
  - ΛCDM specific predictions: density profiles, overwhelming amounts of substructure
- Properties and Internal dynamics
  - Comparison to ΛCDM
- Dynamical evolution
  - The morphologies of dwarfs in ΛCDM
- Conclusions

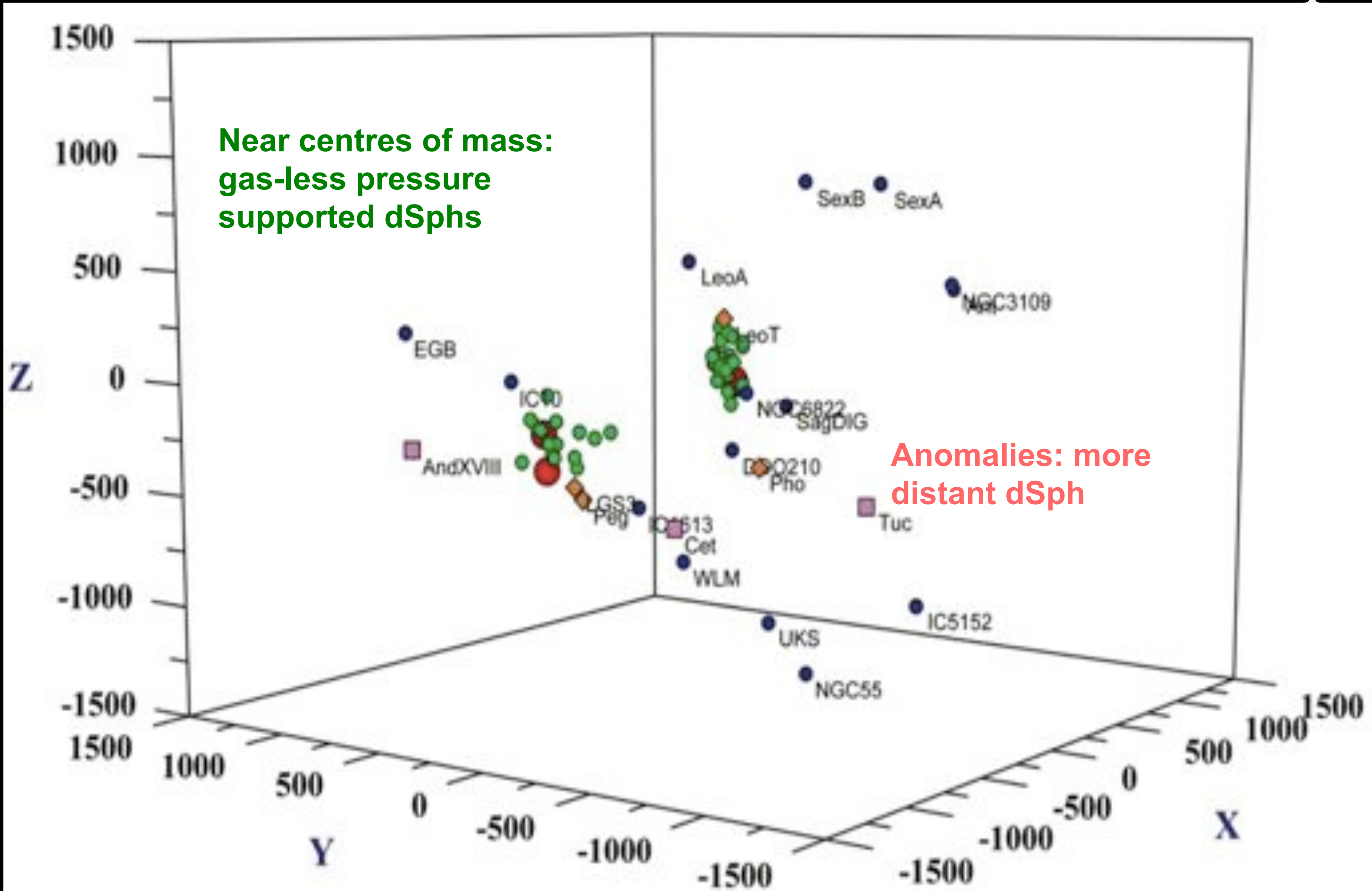
Special thanks to:

Maarten Breddels & Tjitske Starkenburg

Nearby Dwarf Galaxies: <u>variety</u>



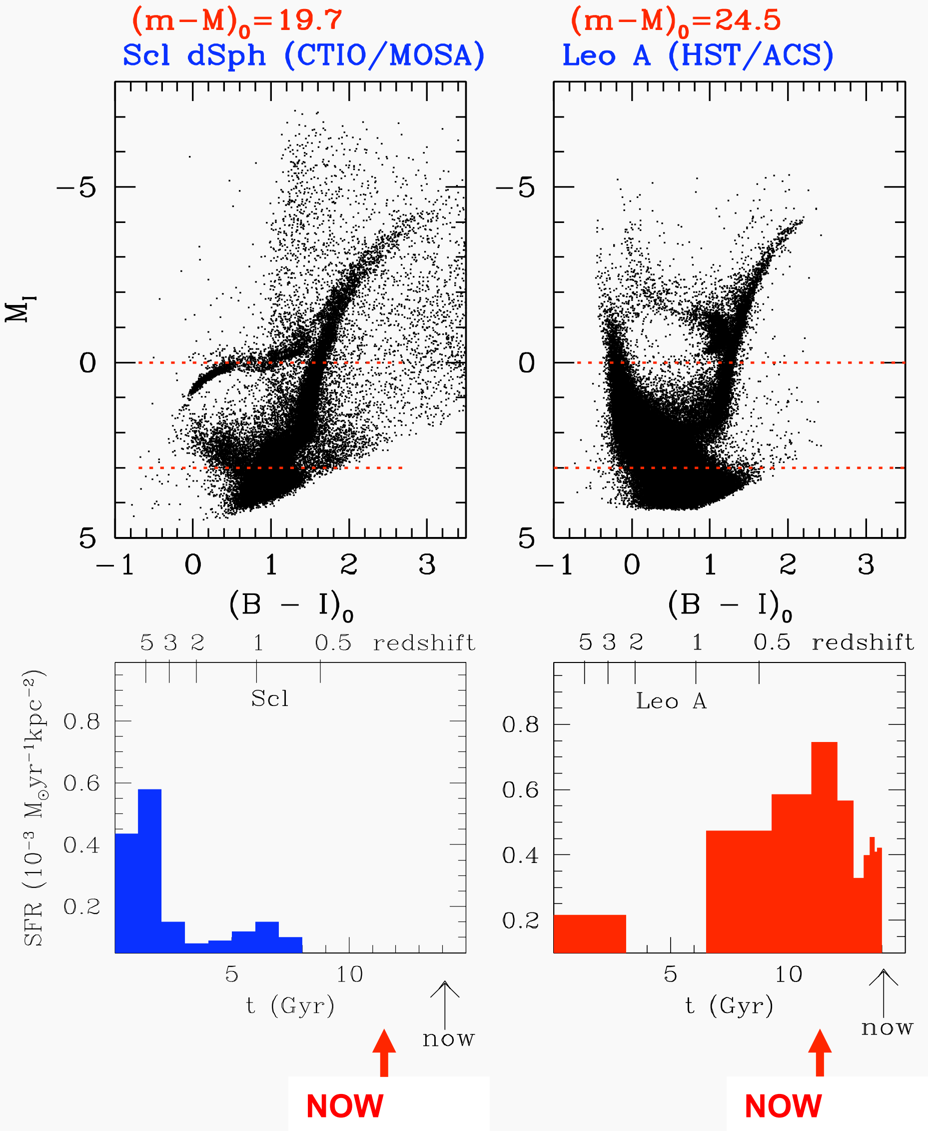
Dwarf Galaxies: distribution in Local Group



Outer regions: dominated by gas rich quiescently evolving dwarf irregulars

Mateo 2008, Garching workshop

Photometry



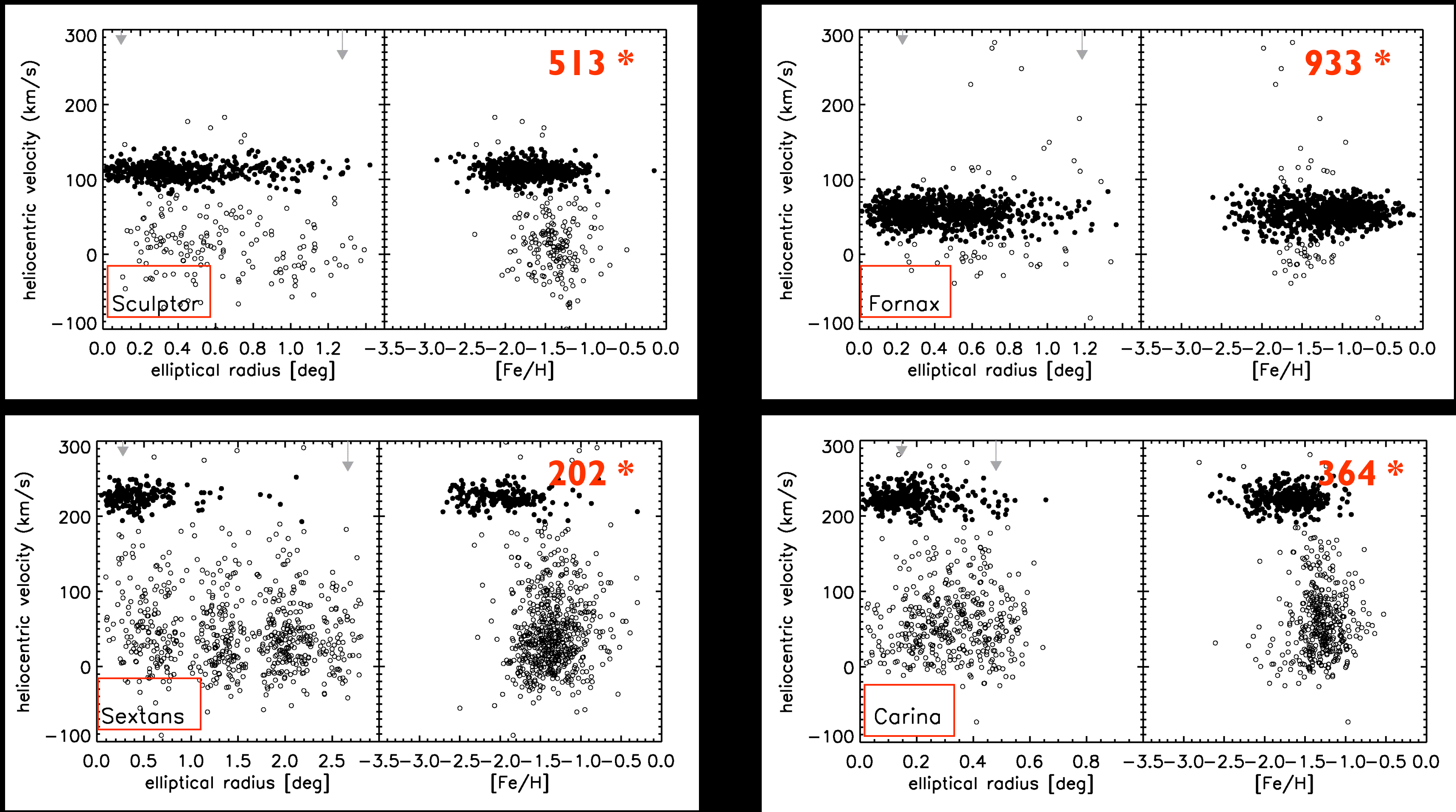
de Boer et al. 2010

Cole et al. 2007

We obtain star precise formation histories from CMDs, often to very early times

Spectroscopy of nearby dSph

- Obtain radial velocities and metallicities using CaT
- S/N > 10 allows δ[Fe/H] ~ 0.1 dex; δv_r ~ 2 km/s
- Dynamical mass estimates, metallicity distribution functions, chemo-dynamics



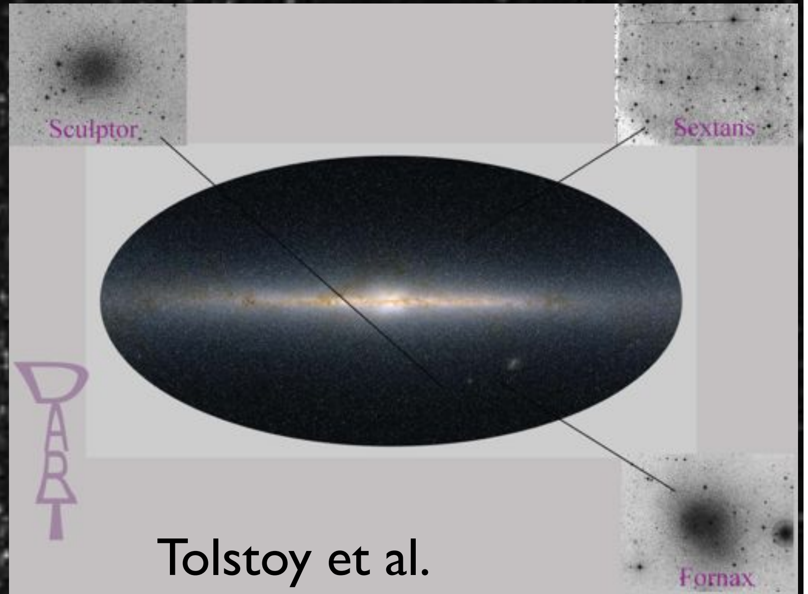
Helmi et al. 2006

The satellites of the Milky Way: dwarf spheroidal galaxies

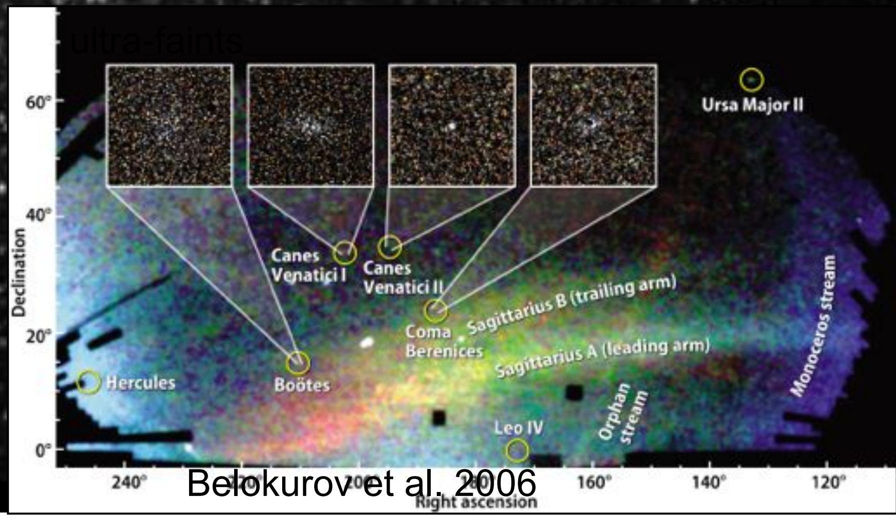
Very faint systems: 100 – 10^7 Lsun

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

- Most DM dominated systems known
    - Dynamical modeling can neglect effect of baryons
    - Probe innermost regions (constraints on cusps vs cores)
    - Nature of dark matter



Tolstoy et al.



Belokurov et al. 2006

Kinematics of MW dSph satellites

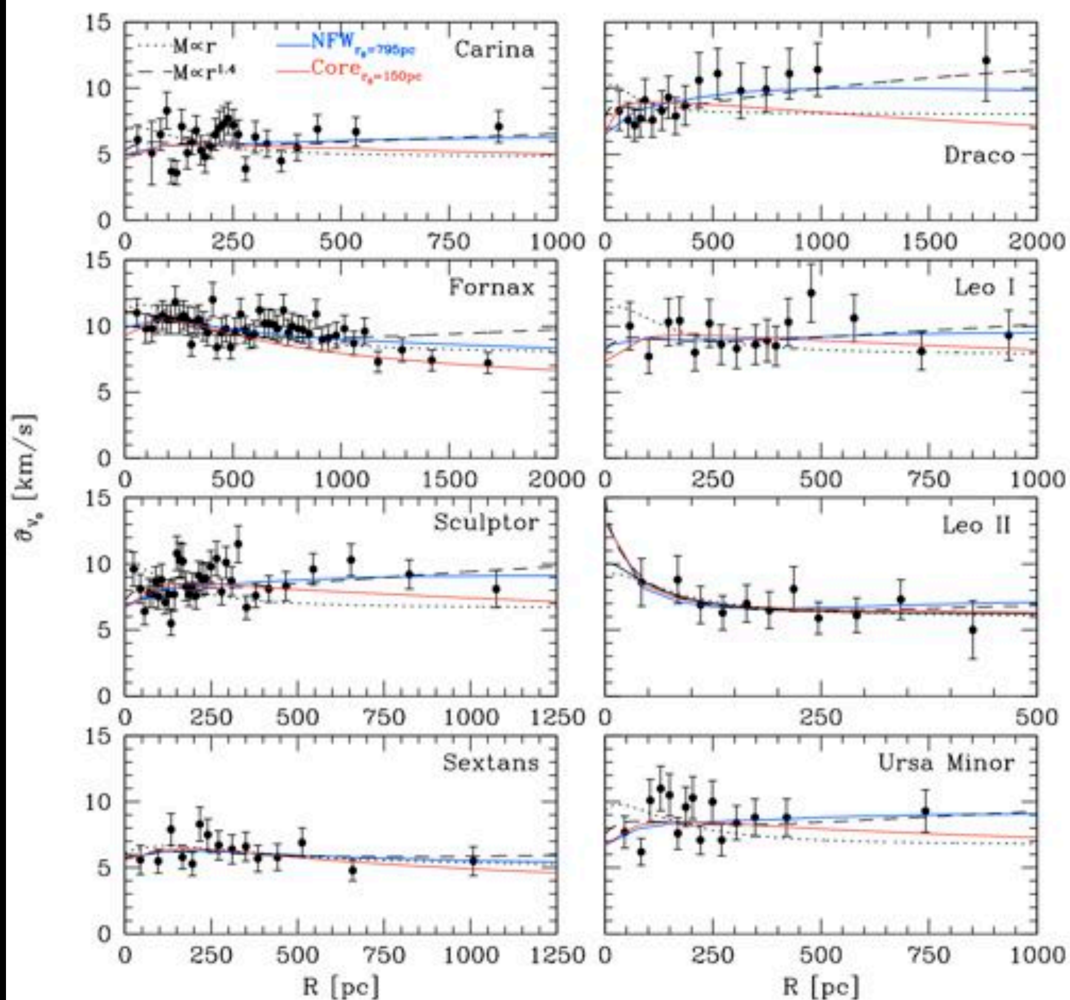
Fairly flat velocity dispersion profiles

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

Modeling often based on Jeans Eq:

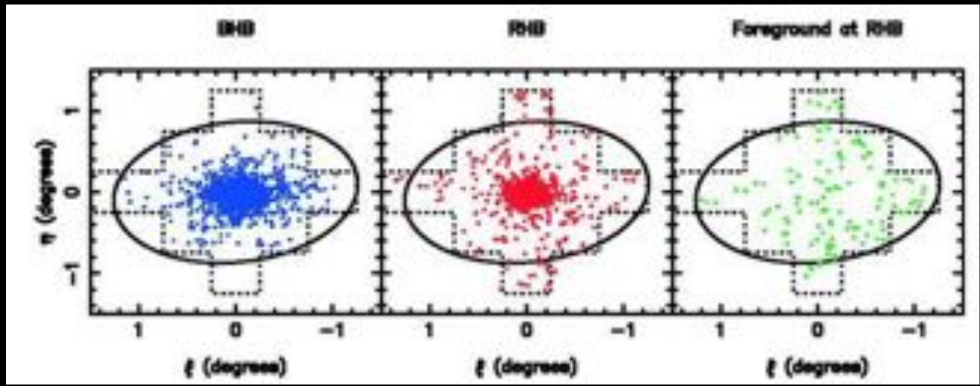
- Fit veloc. disp. (2nd and 4th mom)
- parametric (dark halo prof.)
- assumptions on orbital structure

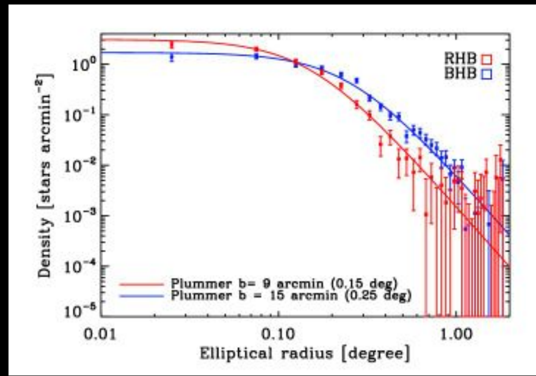
No agreement on cusp or core bc of degeneracies



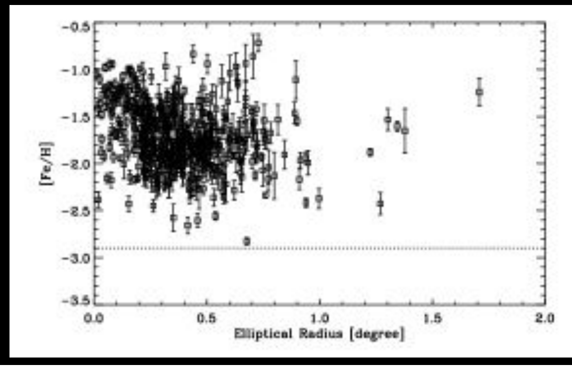
Walker et al (2009)

Multiple stellar/kinematical components: Scl





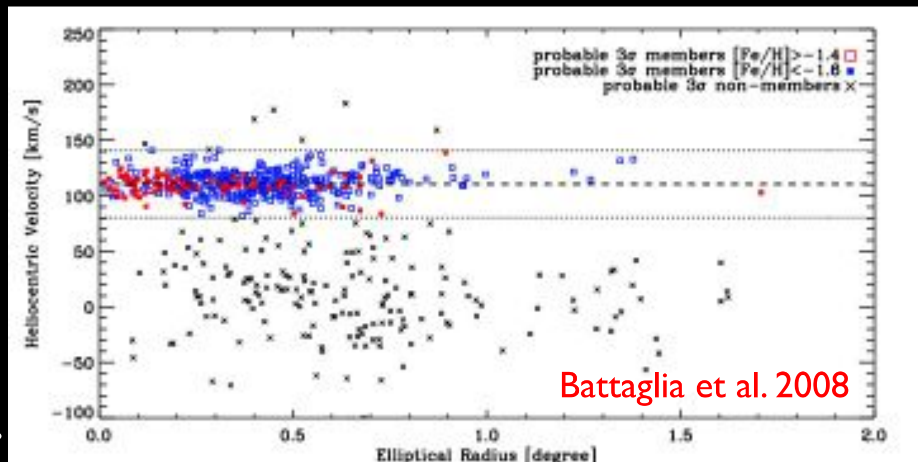
Tolstoy et al. 2004



- 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, Sext.



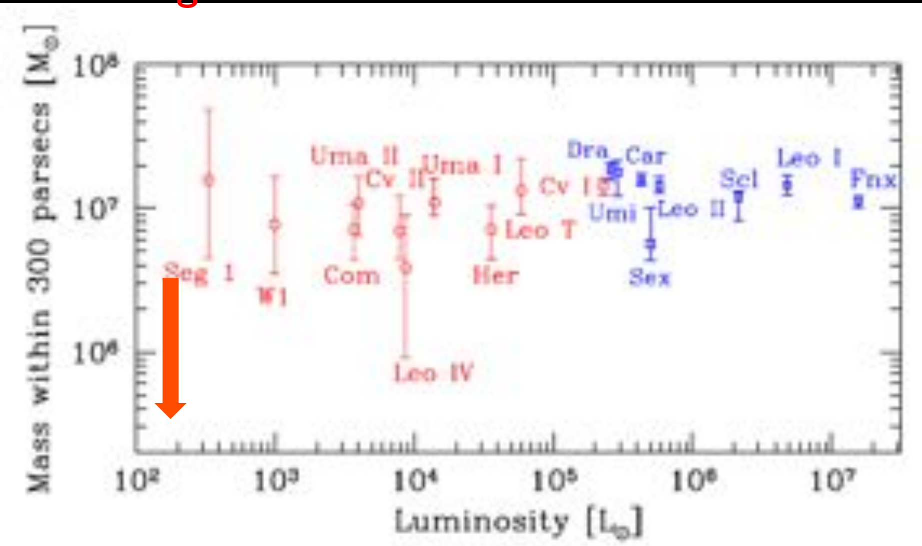
Recent results and open questions

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

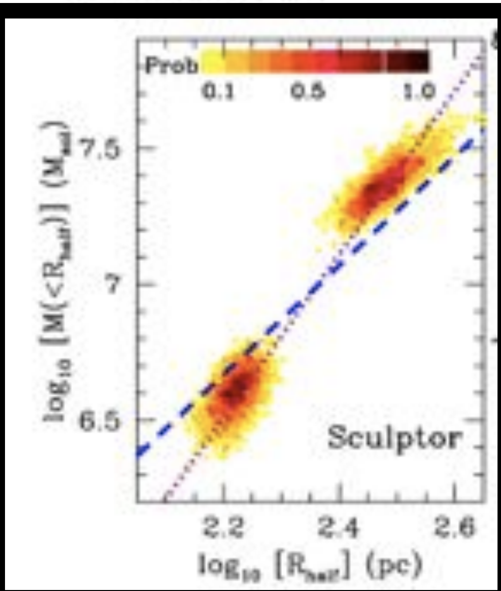
$$M(r_{-3}) = 3\frac{\langle\sigma_{\rm los}^2\rangle r_{-3}}{G}$$

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

Strigari et al. 2008: common mass scale



- Multiple component nature of dSph: slope measurement in Scl rules out steep NFW



Walker & Penarrubia (2011)

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

Questions

- How consistent are the properties of the satellites with the predictions of the LCDM model?

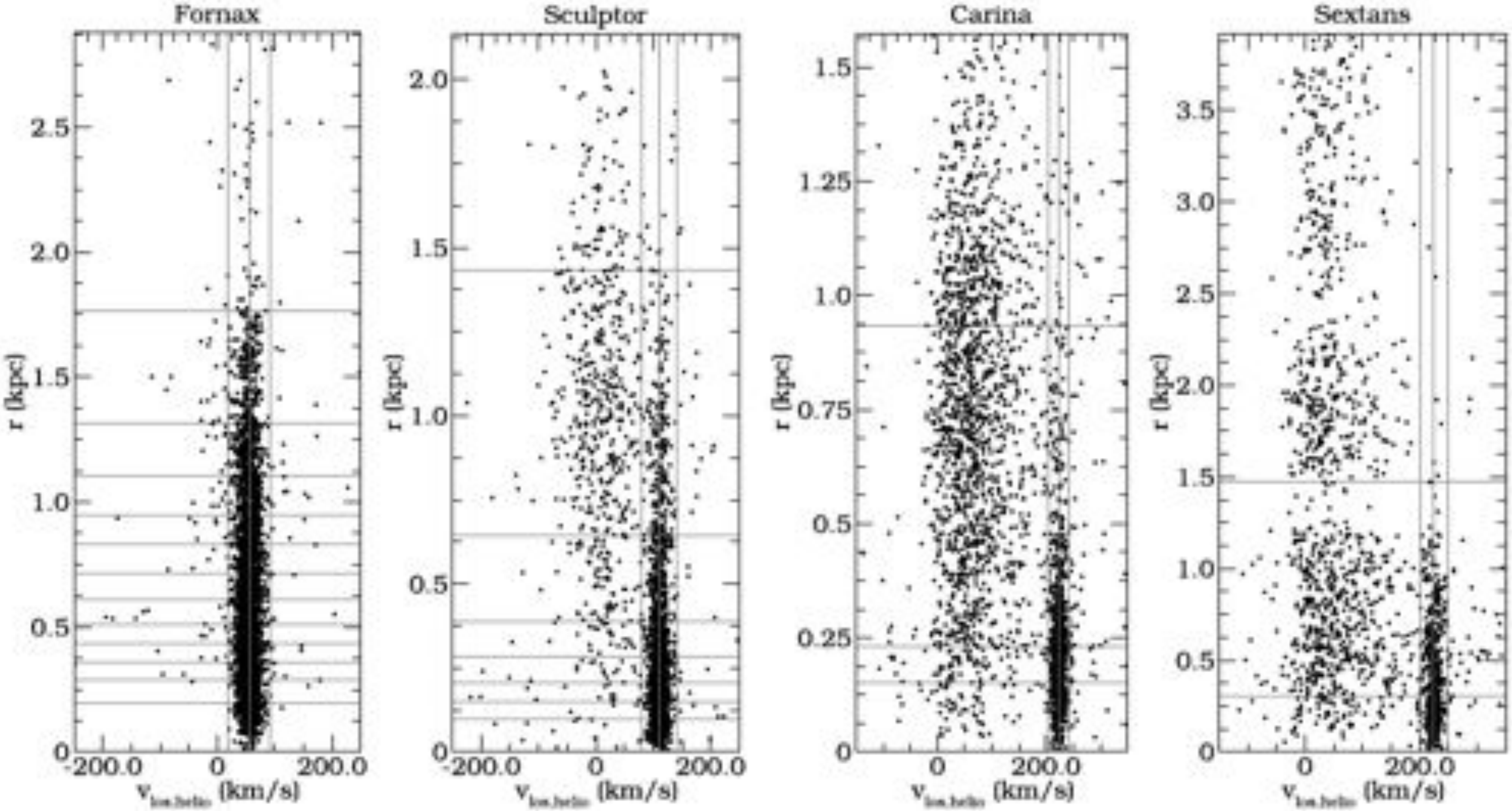
- What are possible formation or evolutionary paths for these systems?
  - Is there a relation between dIrr and dSph galaxies, despite different morphology (disky vs spheroidal); SFH; gas content…
  - Can we explain isolated dSph in the field?

Internal Dynamics

Maarten Breddels

Observables

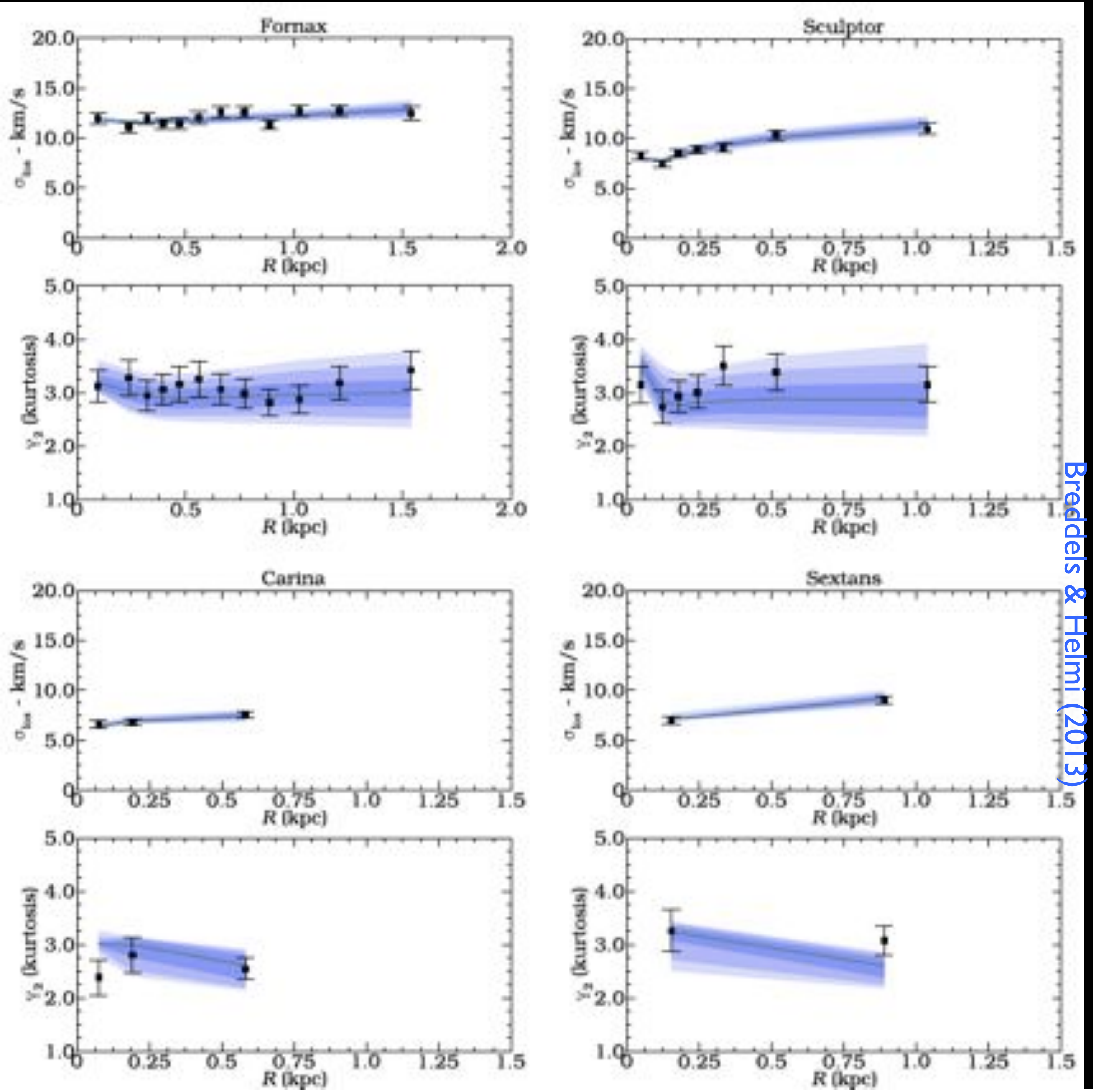
- Measurements for individual stars: los-velocity and position from galaxy's centre
- Determine membership (contamination by foreground Milky Way stars)



Breddels & Helmi (2013)

Observables

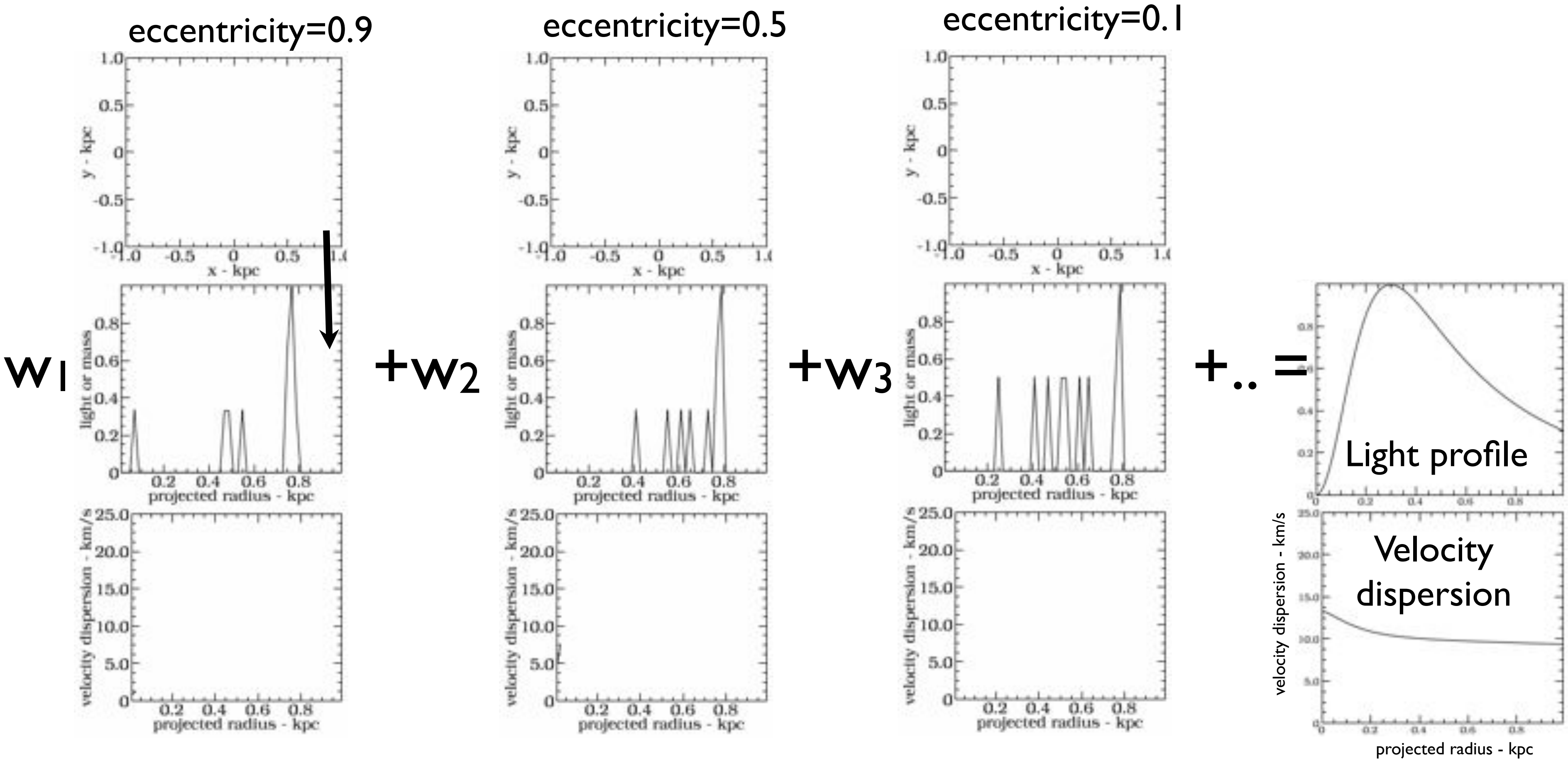
- Moments of the l.o.s. velocity distribution
- 2nd moment, Dispersion σ
- 4th moment (Kurtosis; needed to constrain anisotropy/types of orbits)



Breddels & Helmi (2013)

Schwarzschild method (Martin Schwarzschild 1979)

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

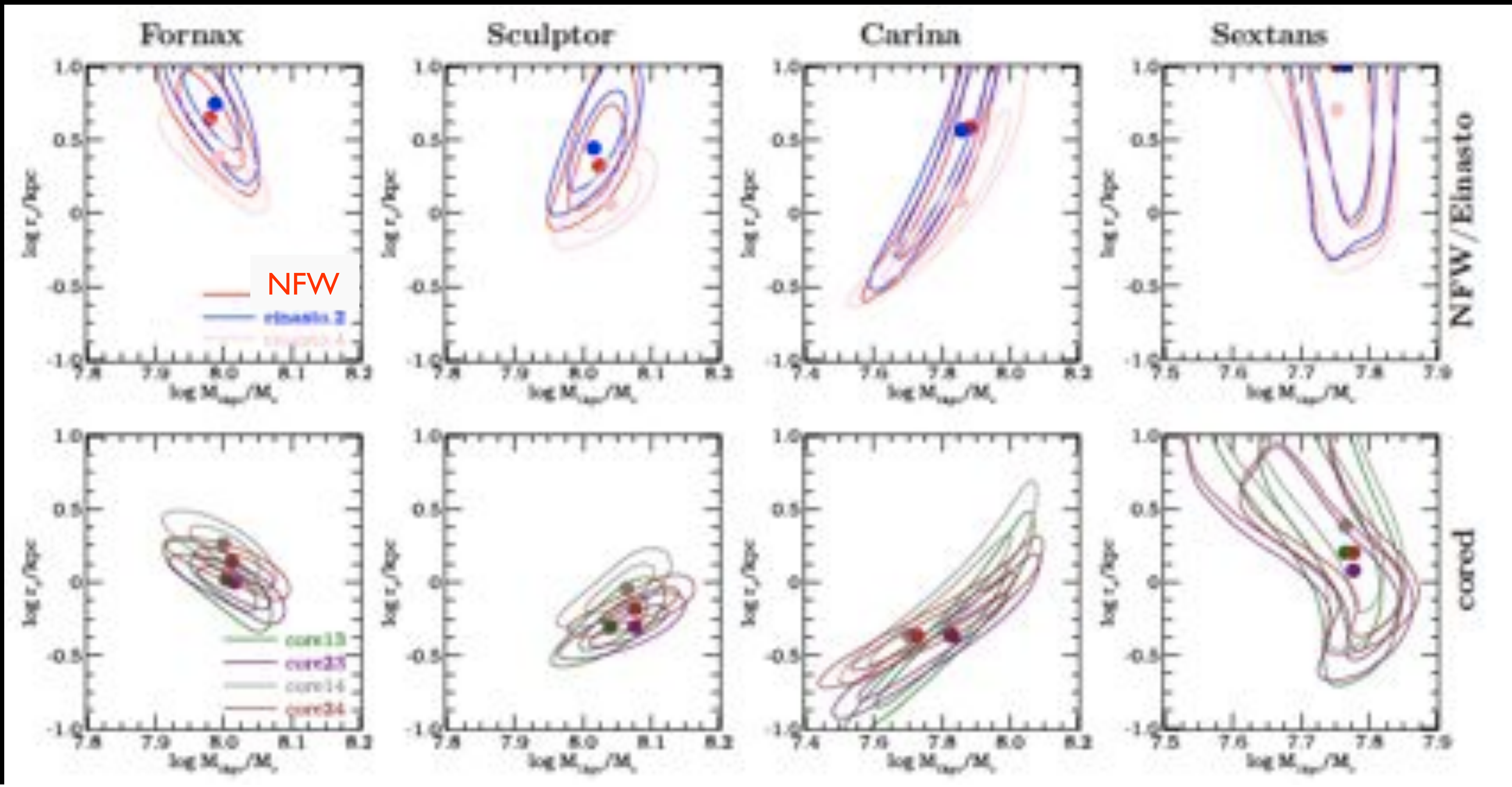


•Best model via max likelihood, gives best fit parameters of gravitational potential, and distribution function (orbital structure)

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

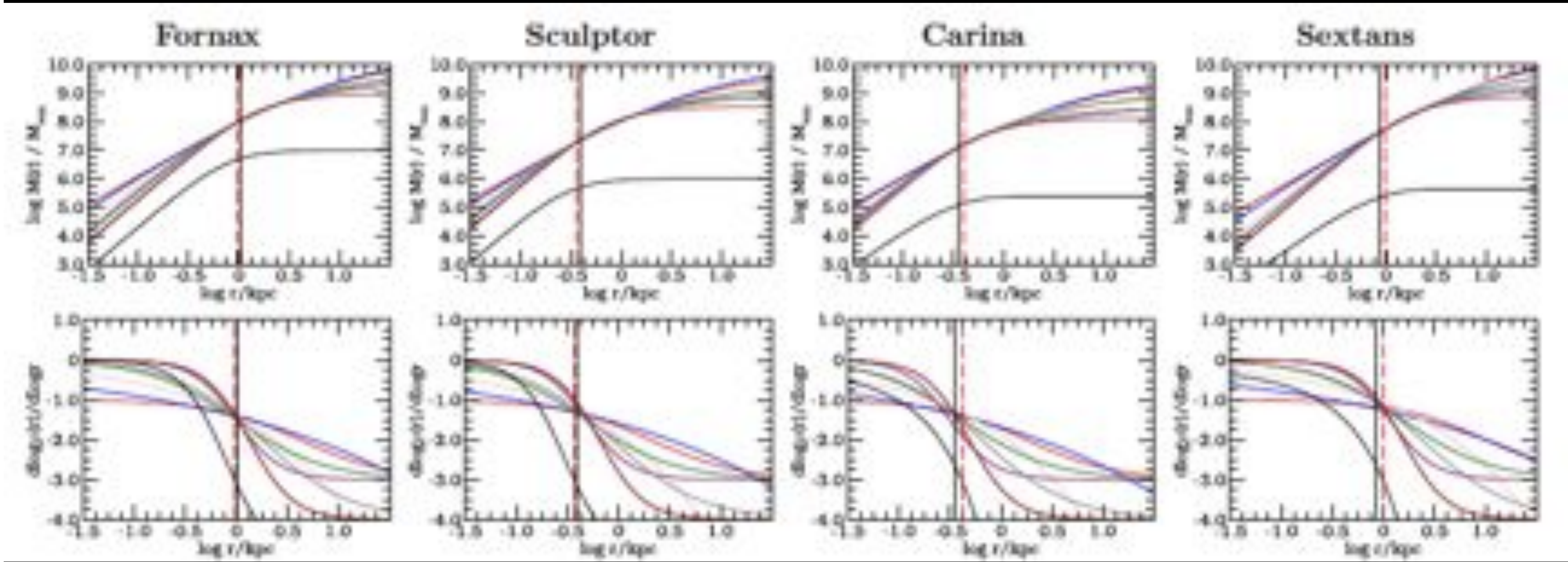
Models: mass and scale radius

- 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)

Resulting mass profiles



Breddels & Helmi (2013)

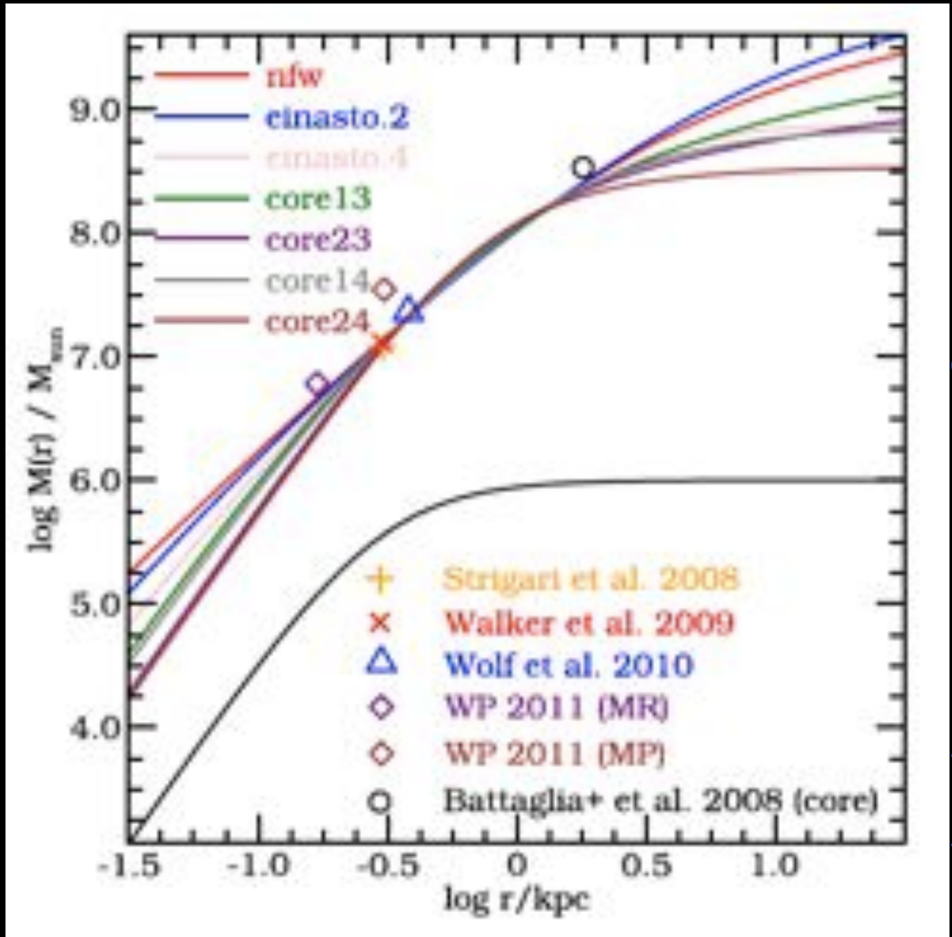
•For each galaxy, finite region where all profiles conspire to give same mass distribution

- •From r_{-3} to last measured data point

•Model-independent measurement of slope of dark halo density profile at $\sim r_{-3}$

•We find $\gamma(r_{-3}) \sim -1.1$ (Sextans) to -1.5 (Fornax) at ~ 1 kpc

Comparisons for Sculptor



Battaglia, Helmi & Breddels (2013)

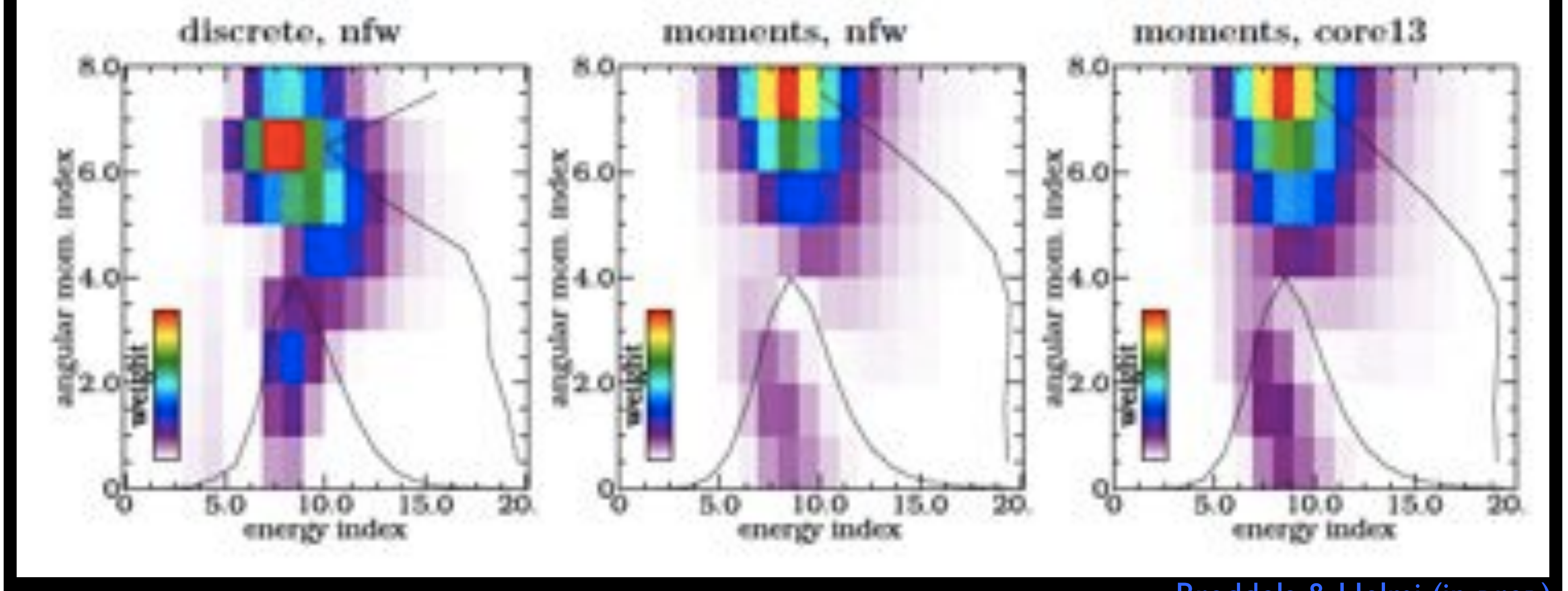
•Consistent with M_{half} modeling of single components, and Jeans modeling based on multiple components

•Walker & Peñarrubia's 2011 method: M_{half} (metal-poor) more overestimated than for M_{half}(metal-rich). Could explain why NFW disfavoured?

Distribution function of Sculptor

- From weights we obtain orbital structure and df of these models
- Resulting df has two <u>dynamical</u> components!!
  - Low angular momentum (radial orbits)
  - High-angular momentum (tangential orbits)

- Bimodality present in all models (for moment fitting, NW and cored potentials)



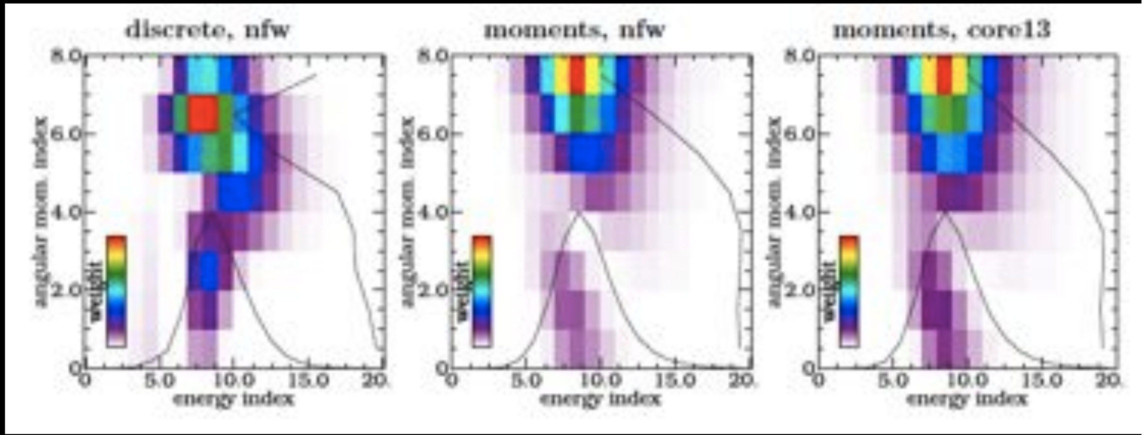
Breddels & Helmi (in prep)

Distribution function of Sculptor

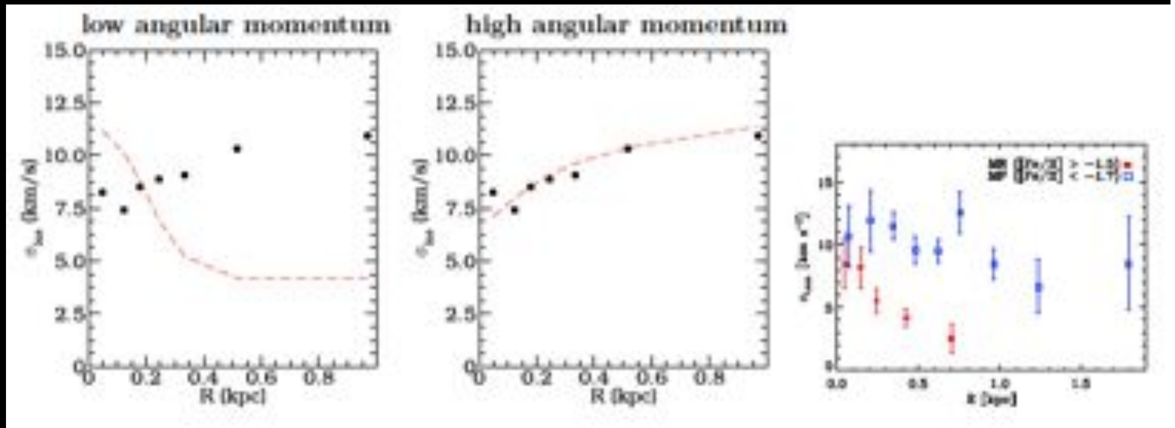
•Multiple components in Sculptor are truly physically different

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

•Schwarzschild non-parametric gives multicomponent Scl



•We find that NFW are allowed and consistent with the data



Tension with Walker & Peñarrubia (2011), model MR and MP pops separately but could not fit NFW…

•Uncertainties in characterization of these components too large?

Breddels & Helmi (in prep)

Summary

•Different dark halo models give equally good fits to our data

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

•Slopes can be measured in model independent way

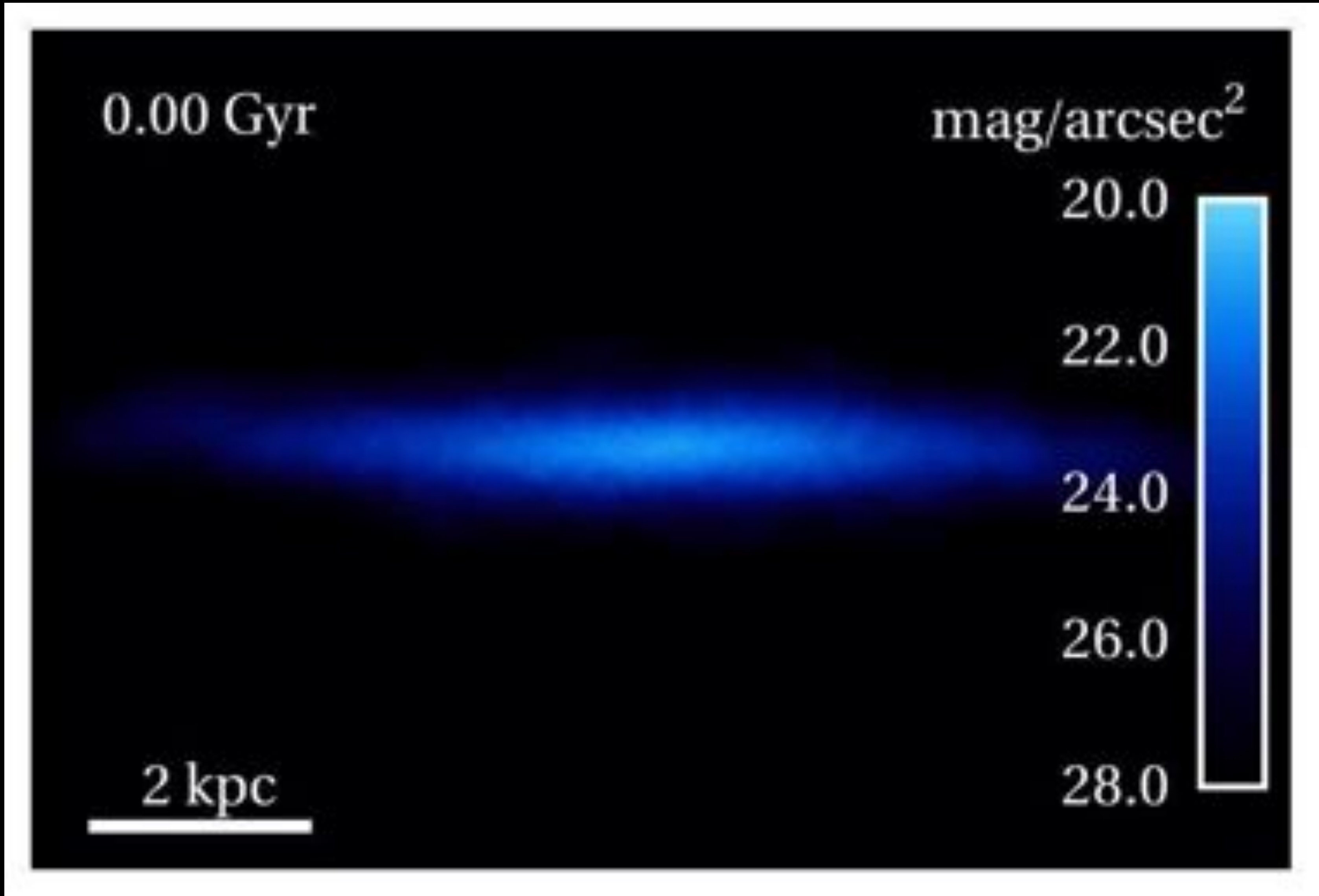
- •Remains to be seen if new constraints are consistent with properties of subhalos in LCDM

•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

Dynamical evolution of dwarf galaxies in LCDM

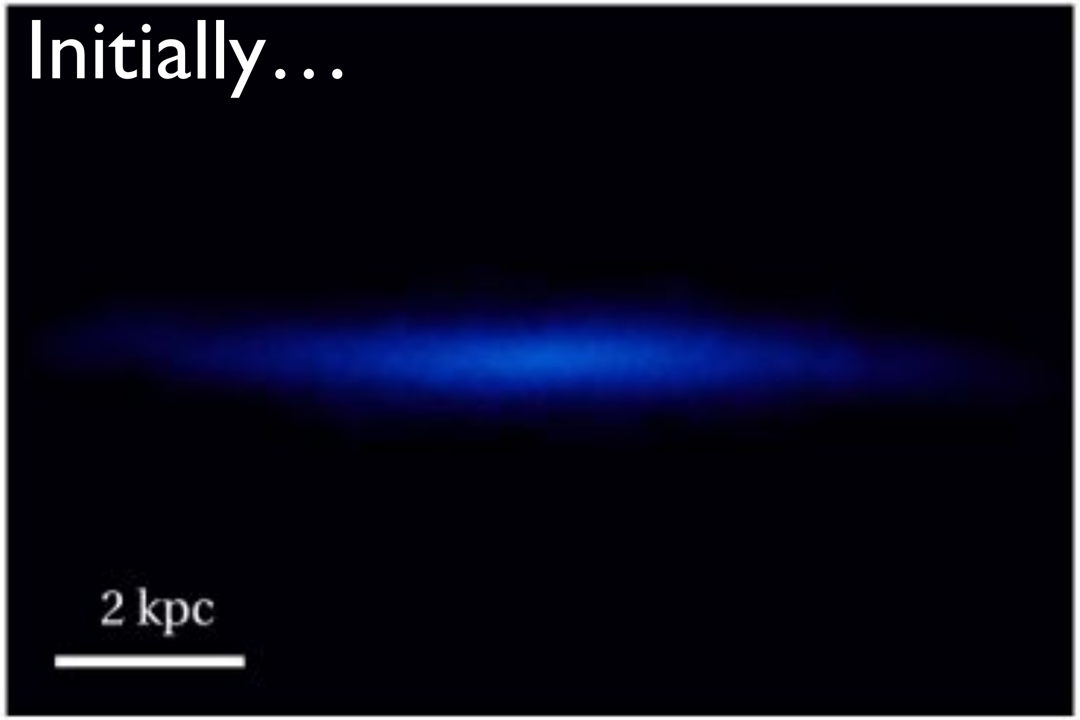
Tjitske Starkenburg

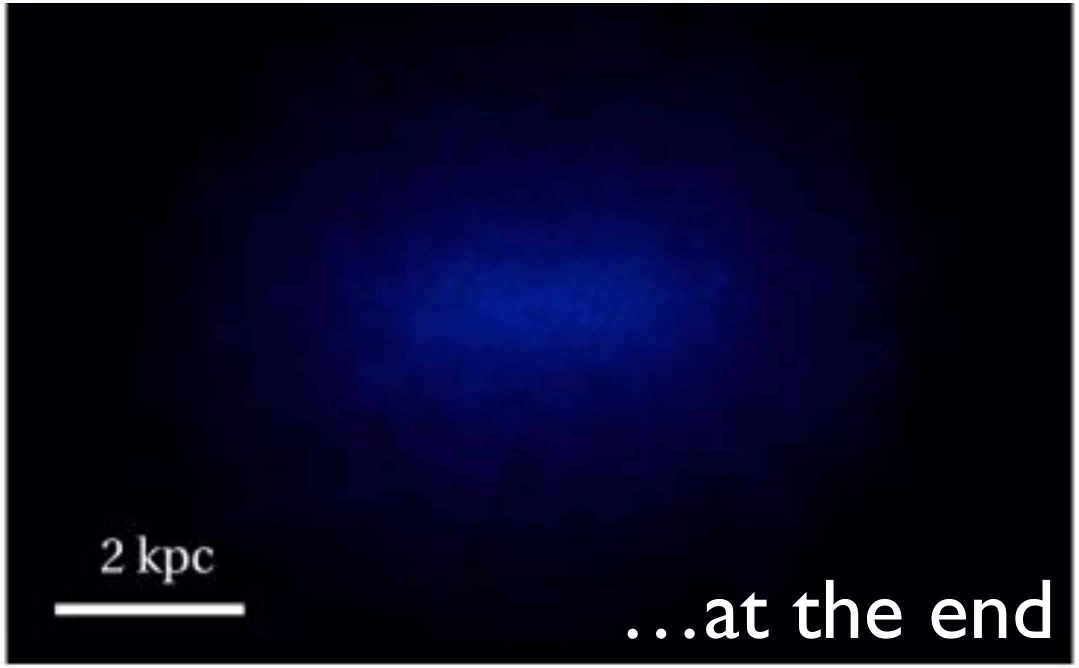


0.00 Gyr
mag/arcsec^2
20.0
22.0
24.0
26.0
28.0
2 kpc

What happened??

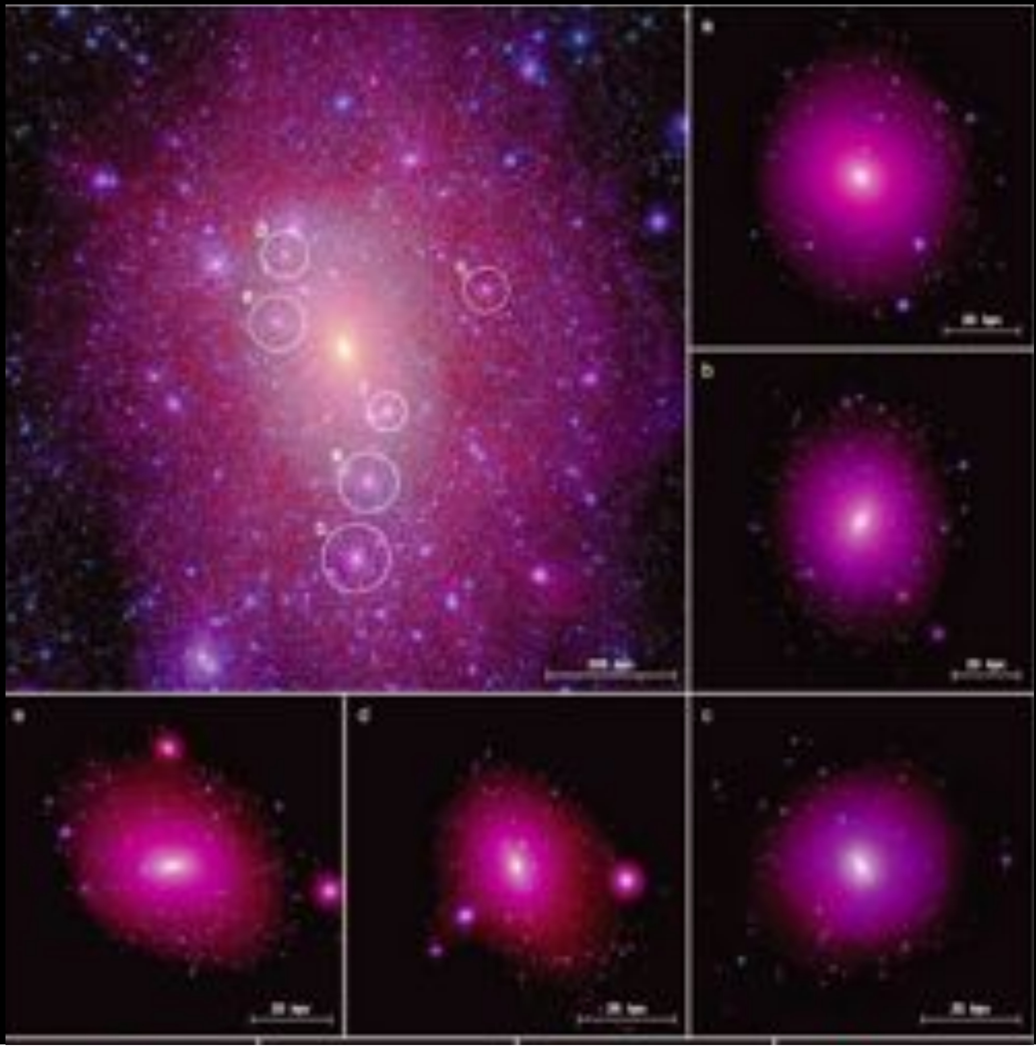
It merged with a dark satellite!



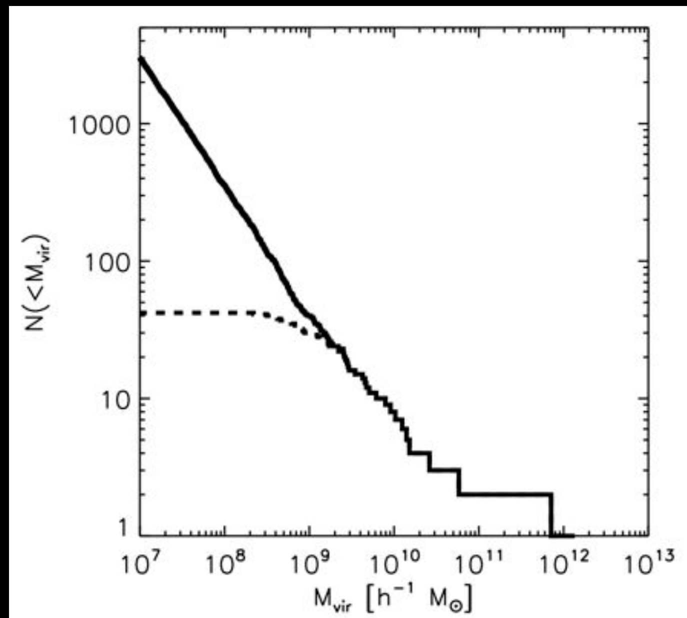


Galaxies and dark satellites

- In LCDM all objects are surrounded by substructures
- Below a given mass, these must be dark



they are predicted out-there and will have an effect of dwarfs



Dark satellites and the morphologies of dwarf galaxies

- Substructure mass function in LCDM is scale-free
  - All galaxies expected to be surrounded by dark matter satellites
- Galaxy formation is not self-similar
  - Dwarf galaxies are inefficient at forming stars; have very high M/L
  - Their satellites (M < 5 x 10^8 Msun) will be dark
    - Gas cooling inefficient and inhibited because of e.g. reionization
- (Dark) satellites dynamically perturb disk galaxies
- Dynamical perturbations by dark satellites are 100x more dramatic on disky dwarf than on giant galaxy with the same gas content

  - Merger with Msat/Mvir = 0.2 is a major merger for the disk dwarf: Msat/Md ~ 20!

Estimation of the structural changes

- Accretion of satellite onto disk leads to its puffing and heating, and increase in scale-height $\Delta H/R_d \sim M_{sat}/M_{disk}$ (Toth & Ostriker 1992)

- Case w/gas, and using galaxy efficiency $\eta_{gal} = M_{disk} / (fb \times M_{vir})$, the relative change

$$\boxed{\Delta H/R_d = \alpha \ (1 - f_{gas})/\eta_{gal} \ (M_{sat}/M_{vir})}$$

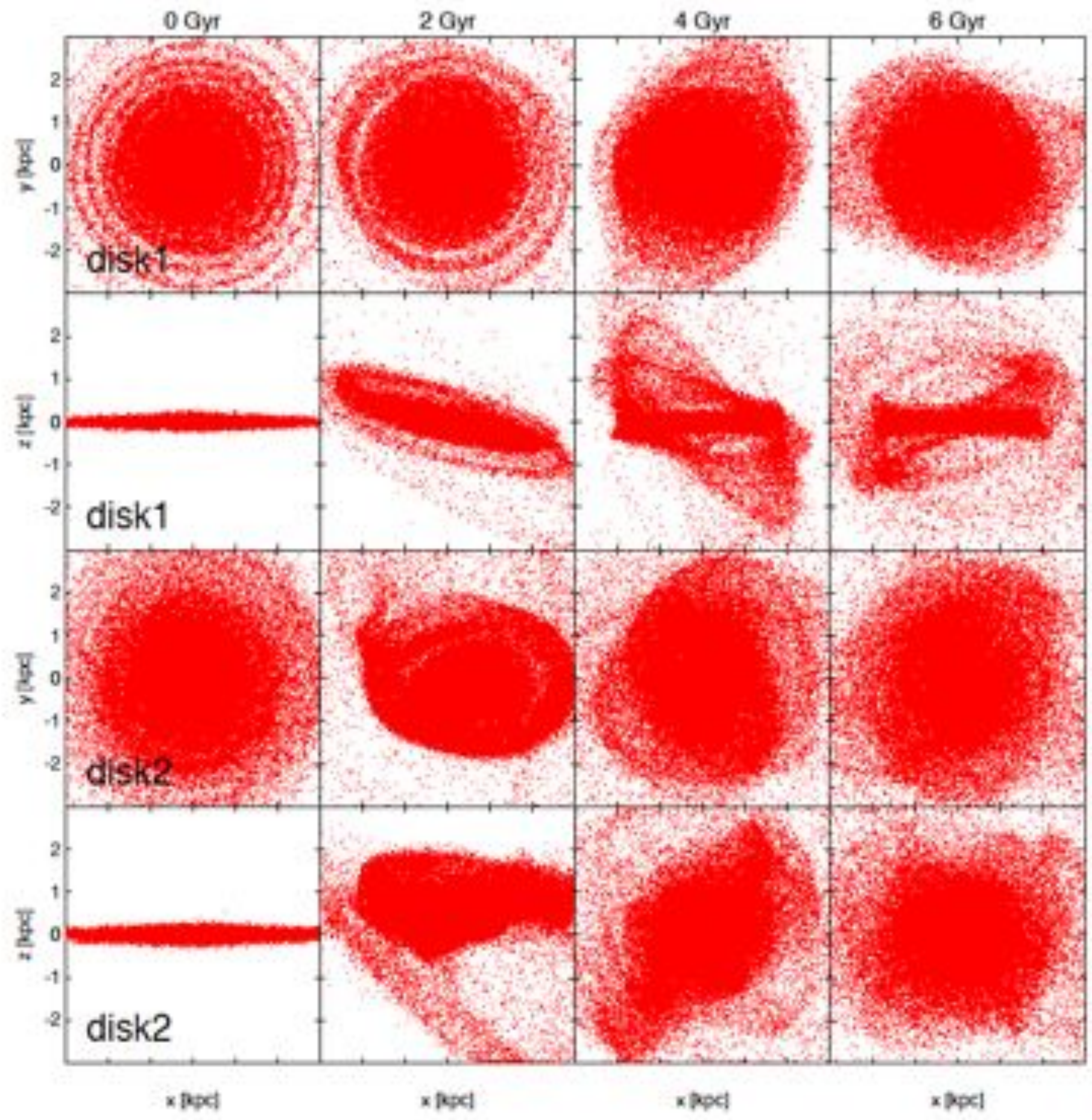
- Important factors:
  - Gas fraction: f_{gas}
  - Galaxy efficiency: η_{gal}
  - Spectrum of satellites/perturbers: M_{sat}/M_{vir}

Simulations of dark satellites with dwarfs

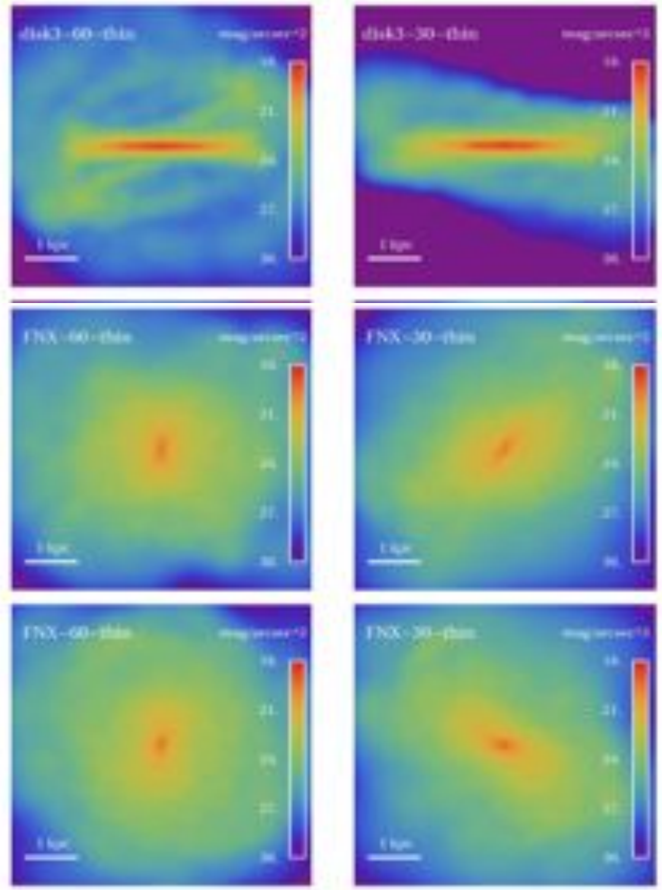
Suite of N-body simulations

- Disky dwarfs with different M_{disk}; dark halos of 10^{10} M_o and 10^9 M_o (Fnx)
  - Also different thickness for disks
- Orbits from Aquarius simulations
  - Eccentric orbit (apo/peri = 25/5), and different inclinations
- Satellite with 0.2 M_{host} (only DM)

Simulations of dark satellites with dwarfs



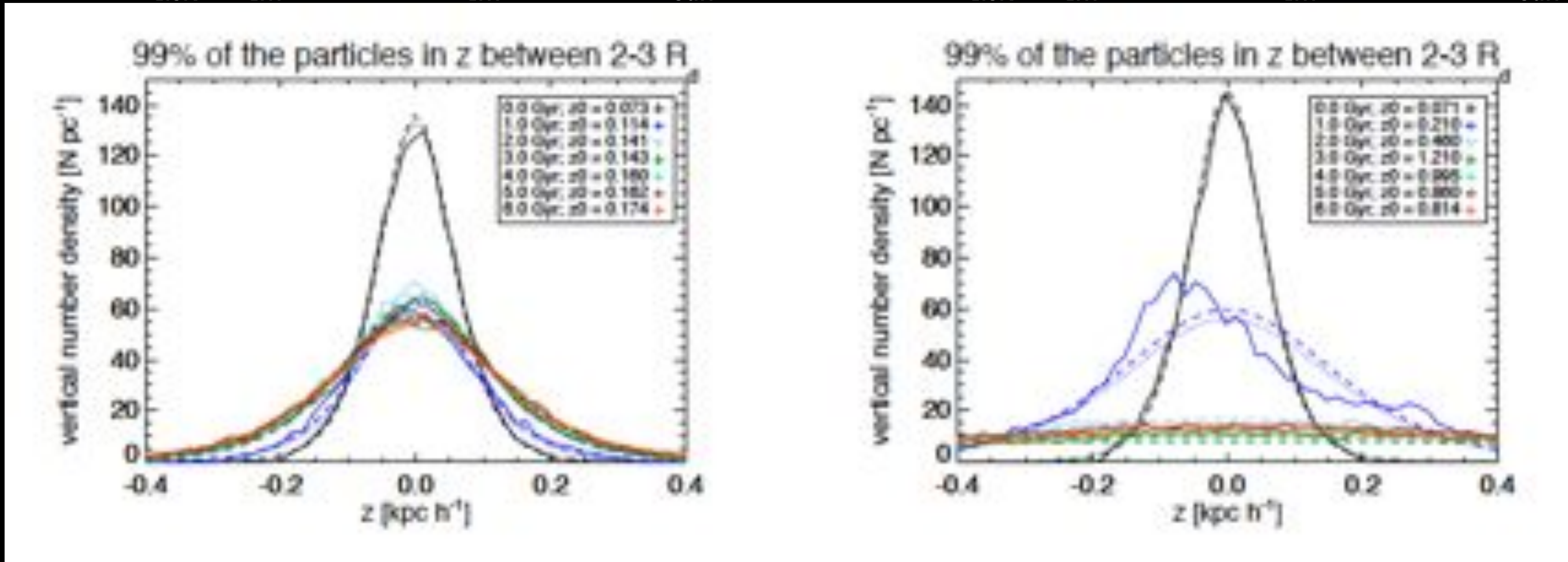
The smaller the disk, the more important the effect



Change in morphology

$M_{disk}/M_{dm} = 0.04; M_{dm} = 10^{10}\ M_{sun}$

$M_{disk}/M_{dm} = 0.01; M_{dm} = 4\times10^{9}\ M_{sun}$

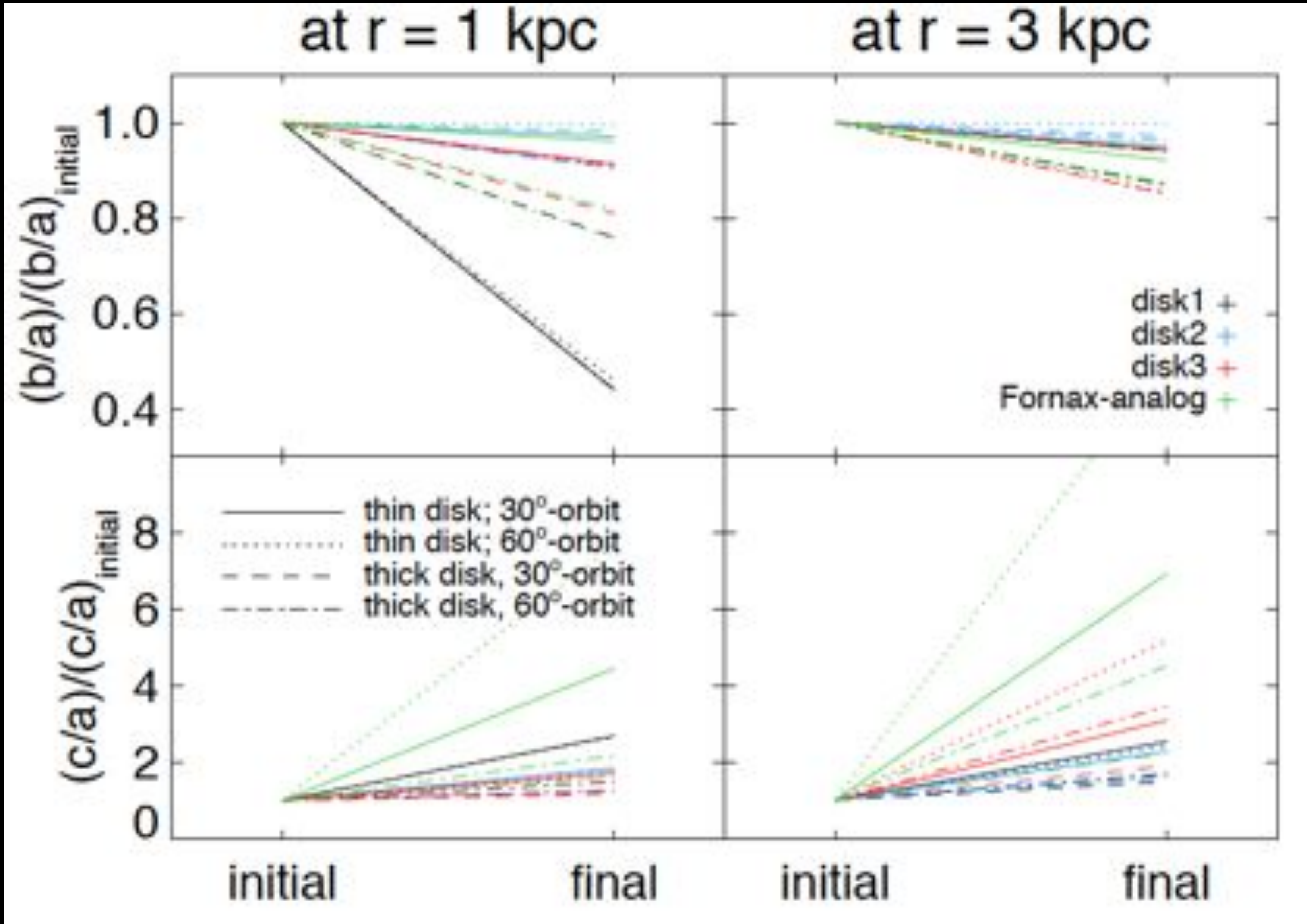


Starkenburg & Helmi (2014)

The bigger disk changes only slightly its morphology (it develops a bar)

The smaller the disk cannot longer be fit by an exponential

Change in shapes: rounder/more triaxial



Starkenburg & Helmi (2014)

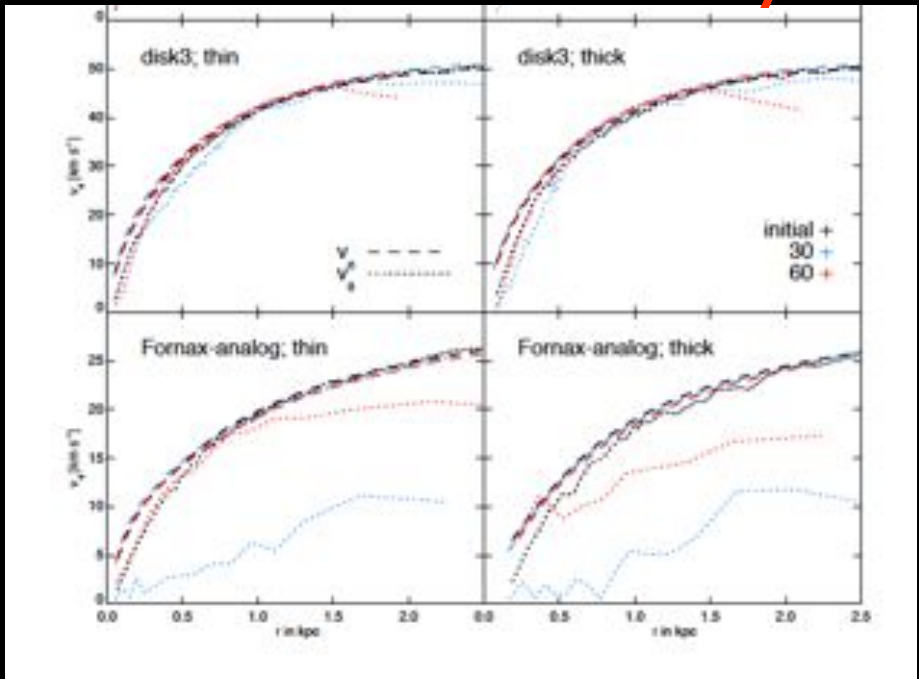
The smaller the disk, the thicker the remnant

Change in kinematics: less (to no) rotational support

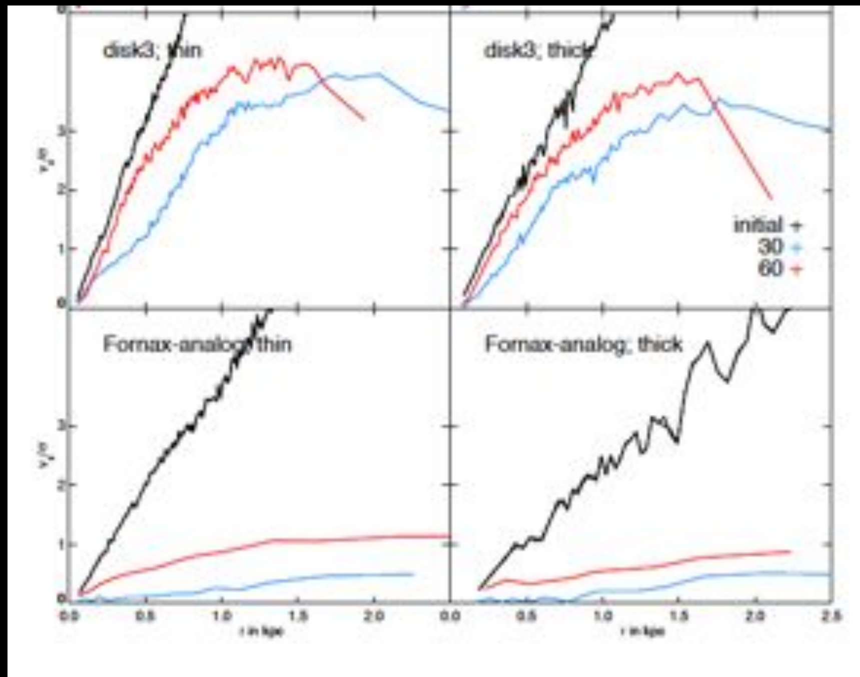
•(some) Rotational velocity lost to random motions

•Almost no rotation for Fnx-like dwarf, especially inner regions

Rotational velocity

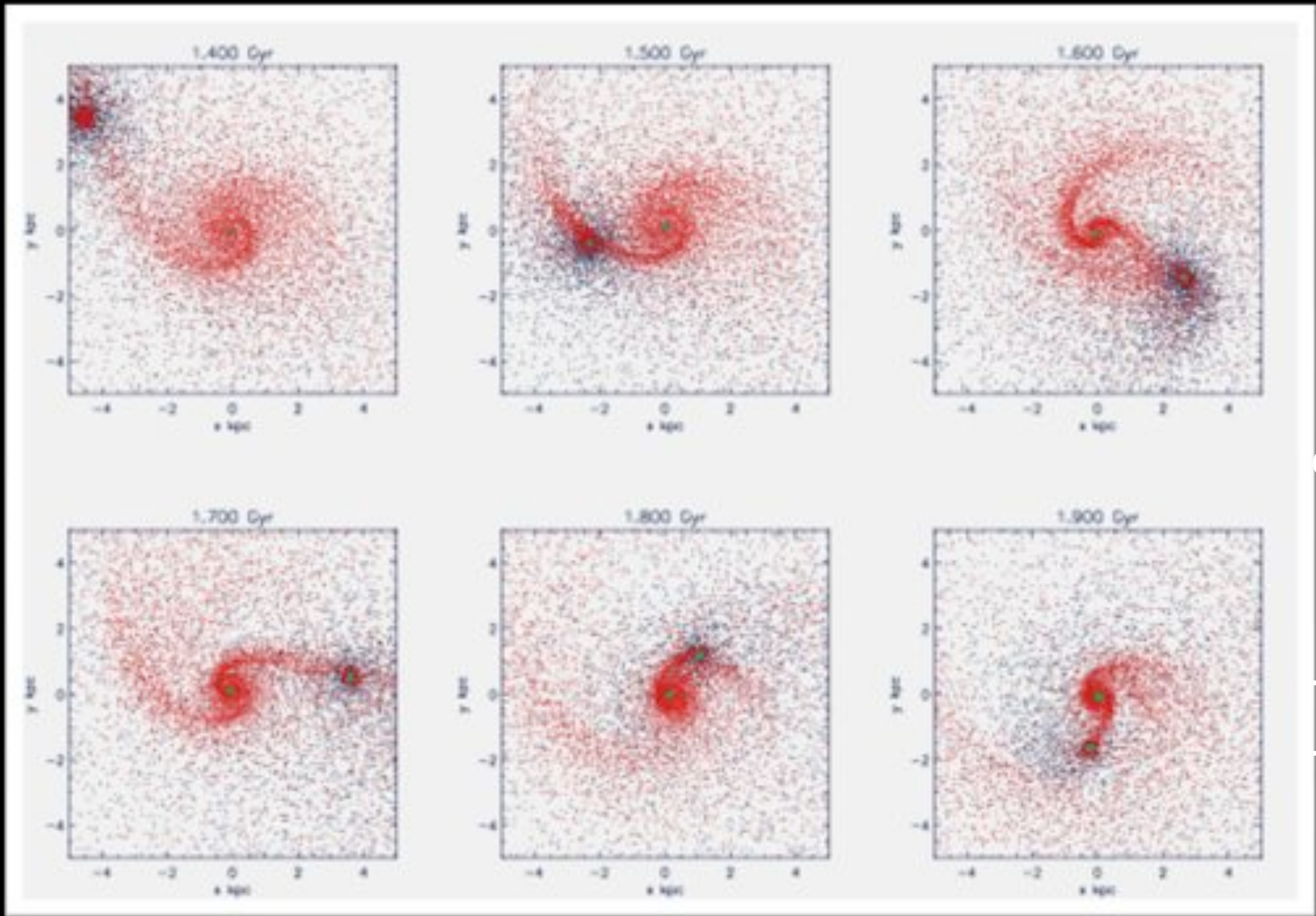


V/σ



Starkenburg & Helmi (2014)

Gas and the interactions with dark galaxies



Starkenburg et al., in prep

SPH simulation of merger

Black: DM

Red: stars

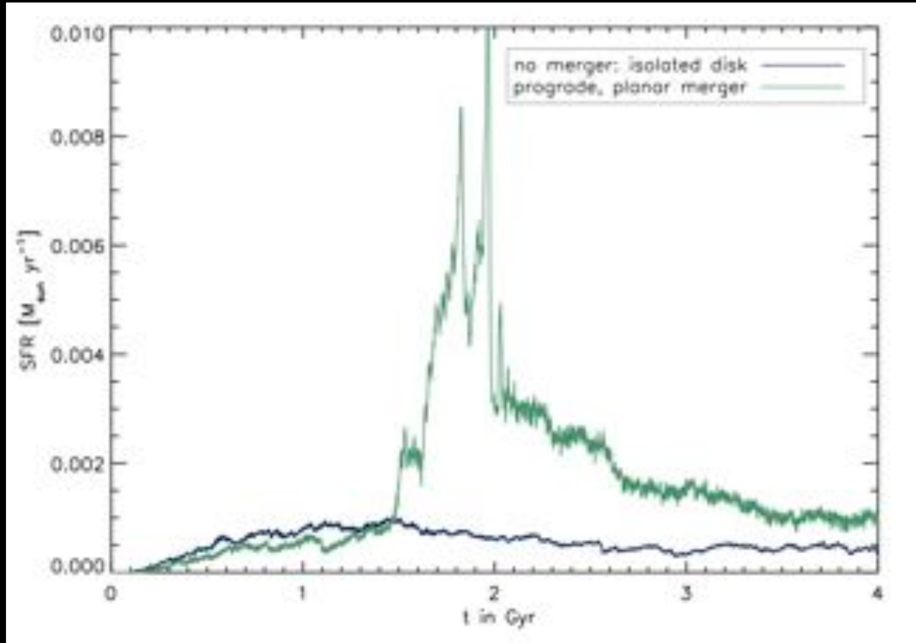
Green: gas

Host is a gas-rich dwarf (fgas = 50%); Satellite is dark on a co-planar and elongated orbit

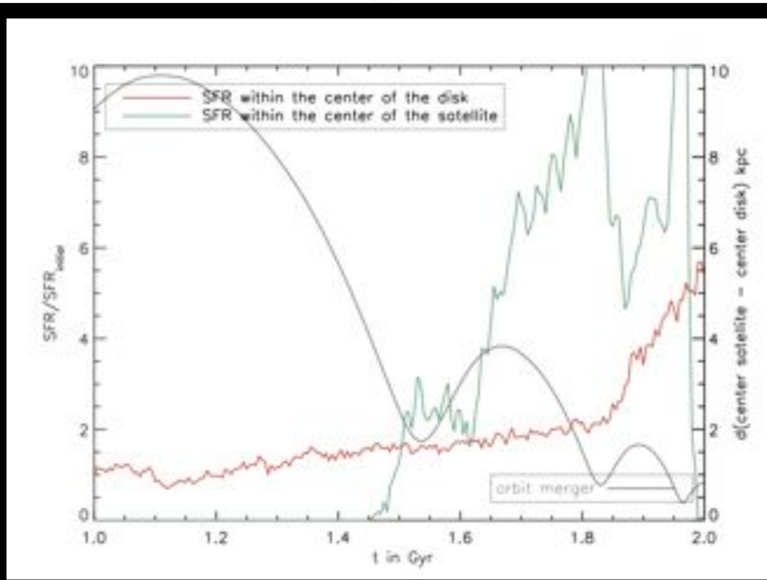
- Satellite accretes gas from dwarf galaxy and lights up!
- The nuclei eventually merge

Starbursts induced by dark galaxies

- The system experiences starburst
- SFR increases by factor > 10
- Most intense during close approach



- Strongest starburst occurs in satellite
- Dwarf galaxy experiences SFR doubles



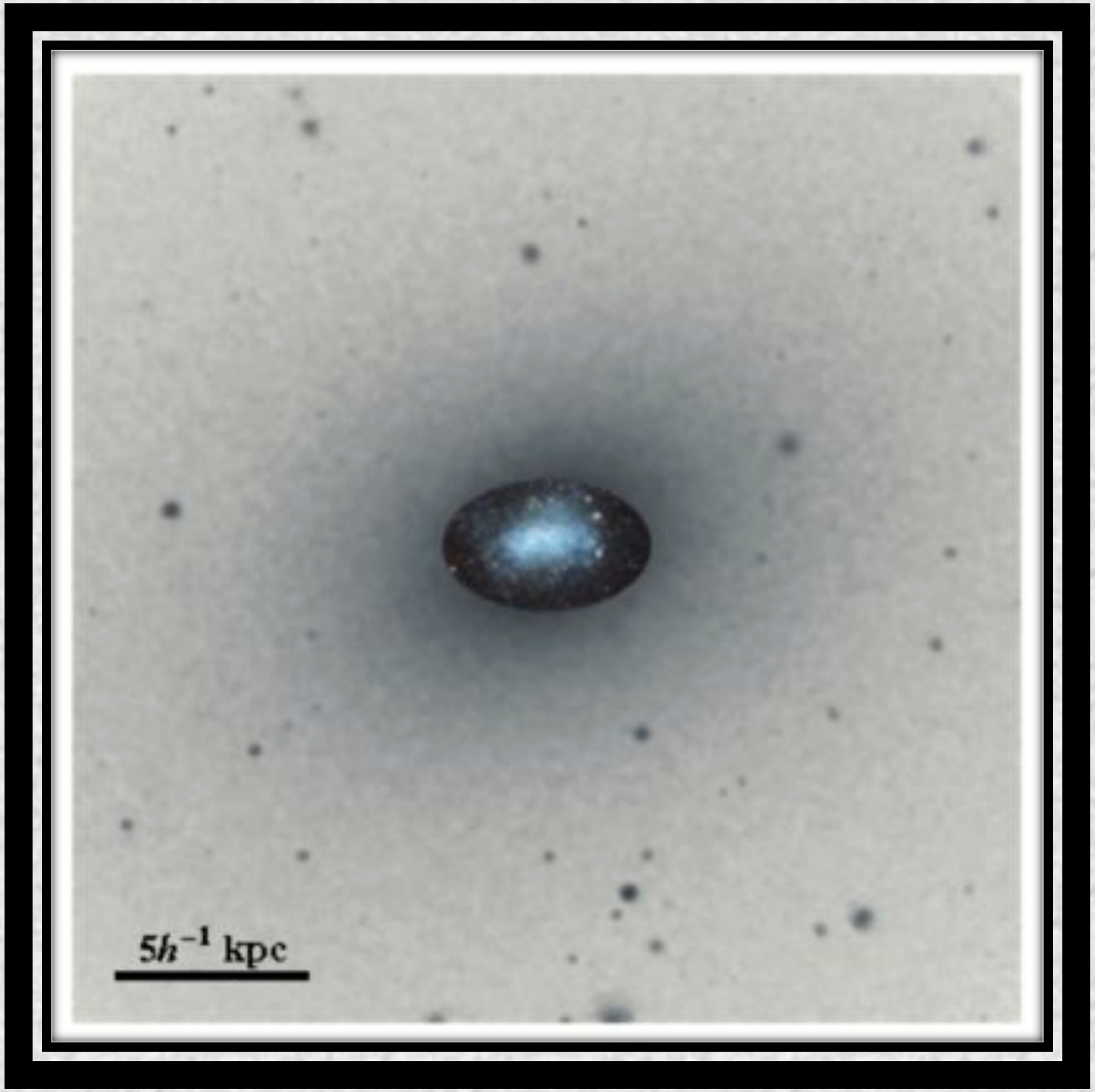
Starkenburg et al., in prep

Implications/Summary

- The satellites of dwarf galaxies will be mostly dark
  - Inefficient SF in dwarf implies lower Md, more often comparable to Msat
- For objects like Fornax, a 20% merger turns
  - a disky morphology into a spheroid
  - internal motions supported by rotation into random
- Gas rich systems also evolve morphologically
- Isolated starbursting dwarf galaxies: could result merger of a gas rich dwarf with a dark satellite

Depending on orbital parameters, mass-ratio, the increase in SFR can be very significant

In LCDM, dark satellites may be partly responsible for the rich variety of morphologies, and for the different types, of dwarf galaxies



Thank you!