Dwarf galaxies: probes of cosmology on small scales

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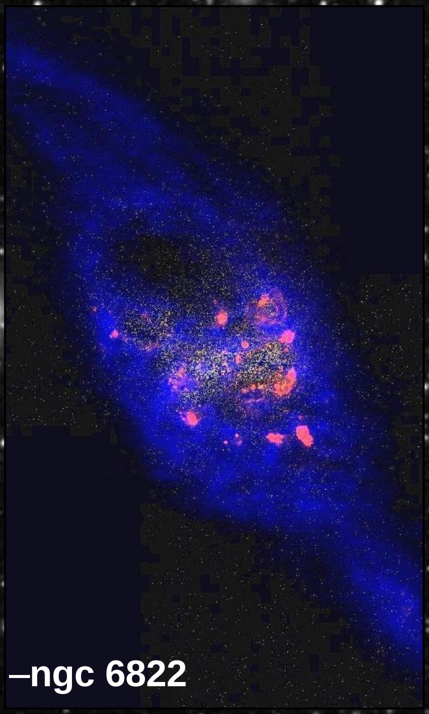
Outline

- Introduction: cosmological relevance and recent findings
- Internal dynamics:
  - Schwarzschild Modeling of Sculptor
- Dynamical evolution
  - The morphologies of dwarfs in ΛCDM
- Conclusions

Special thanks to:

The "dream" team @ Groningen… some now elsewhere

Nearby Dwarf Galaxies



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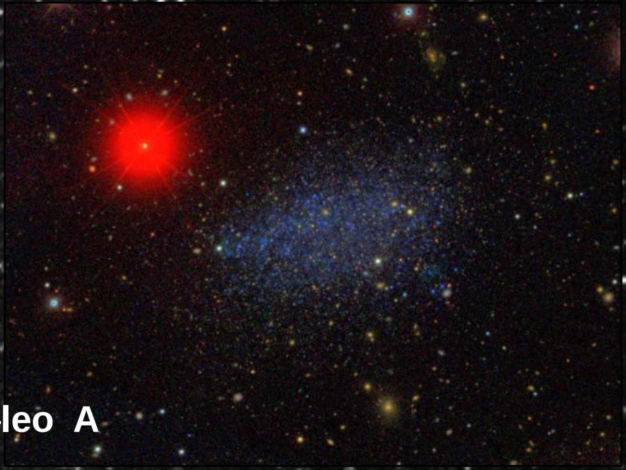
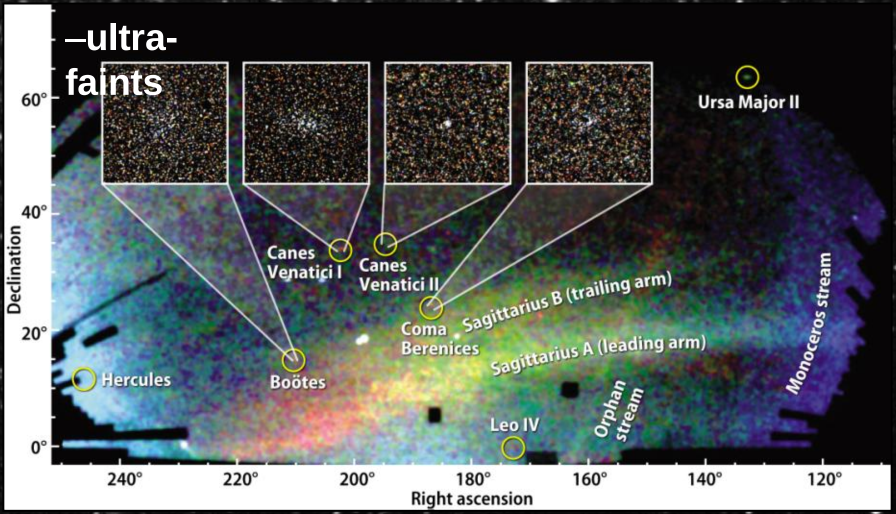


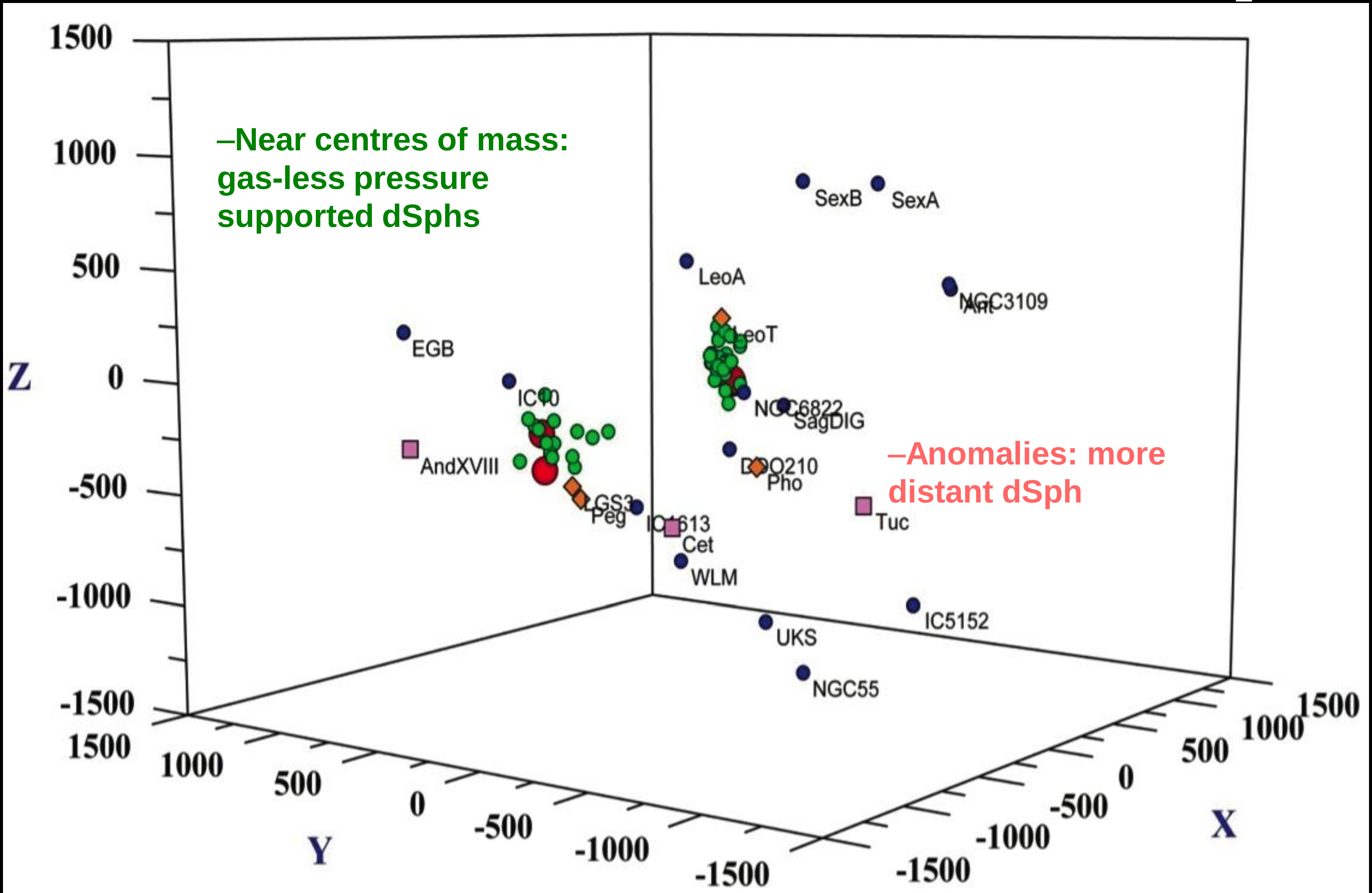
–leo A



–ultra-faints

–sculptor dSph

Dwarf Galaxies in the Local Group



–Near centres of mass: gas-less pressure supported dSphs

–Anomalies: more distant dSph

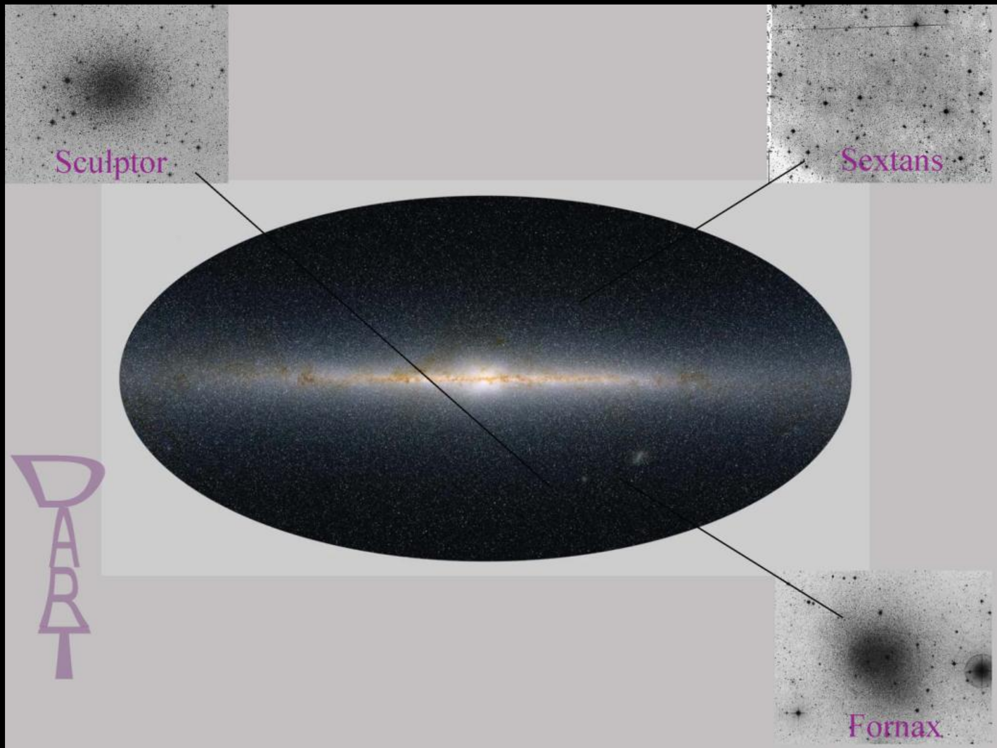
–Outer regions: dominated by gas rich quiescently evolving dwarf irregulars

–Mateo 2008, Garching workshop

The nearest dwarf 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 the effect of baryons
  ➢ Probe the innermost regions (constraints on cusps vs cores)



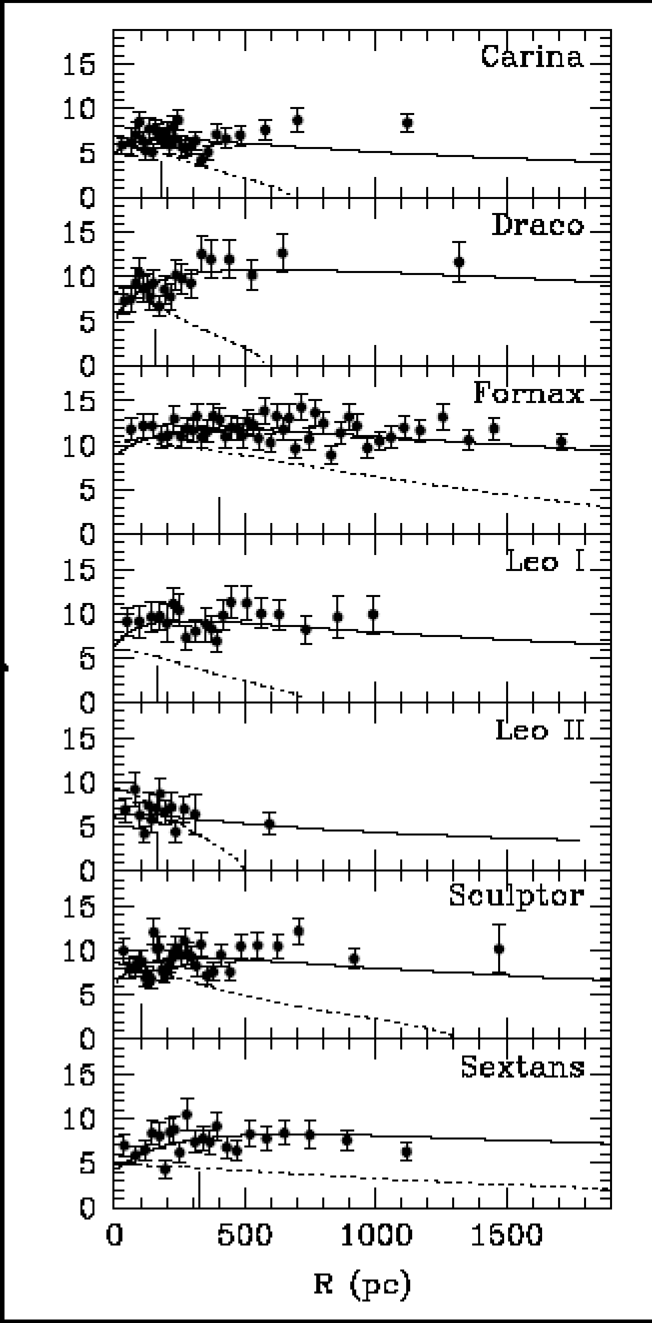
- Contain very old populations
  - windows into the early universe
  - Reionization
  - Relation to galactic building blocks?

MW satellites

- Recent years huge data growth: MOS on 4m & 8m-class telescopes

  WHT: Kleyna et al (Draco, Umi); VLT: Battaglia et al (Scl, Fnx, Sex) - Koch et al. (Leo I, Leo II); Magellan & MMT: Walker et al (7 dSph); Munoz et al (Carina)

- Latest results:
  - Fairly flat velocity dispersion profiles



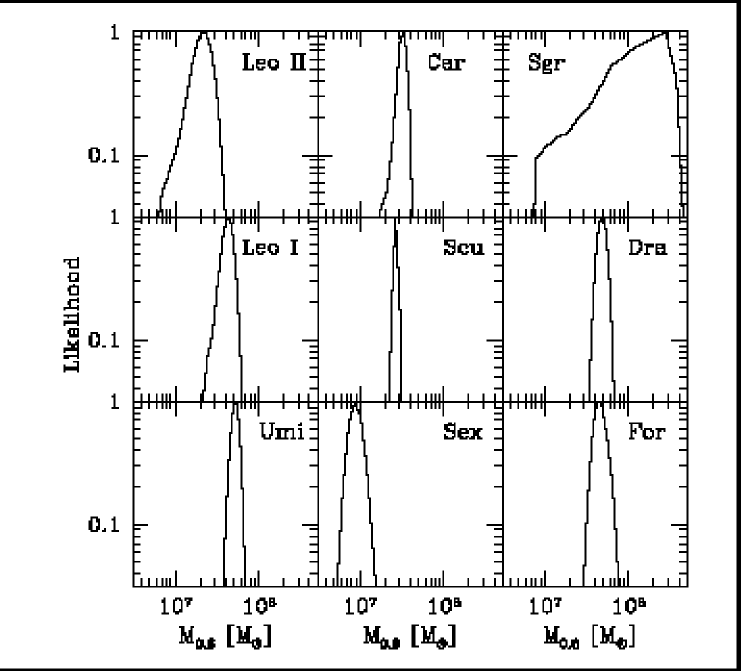
Walker et al (2007)

MW satellites

Latest results:

– mass scale within 0.3 kpc similar (also inside $r_{1/2}$; Wolf et al 2010)

– Indicative of a common (minimum or fundamental) mass scale?
  - Expected in LCDM?

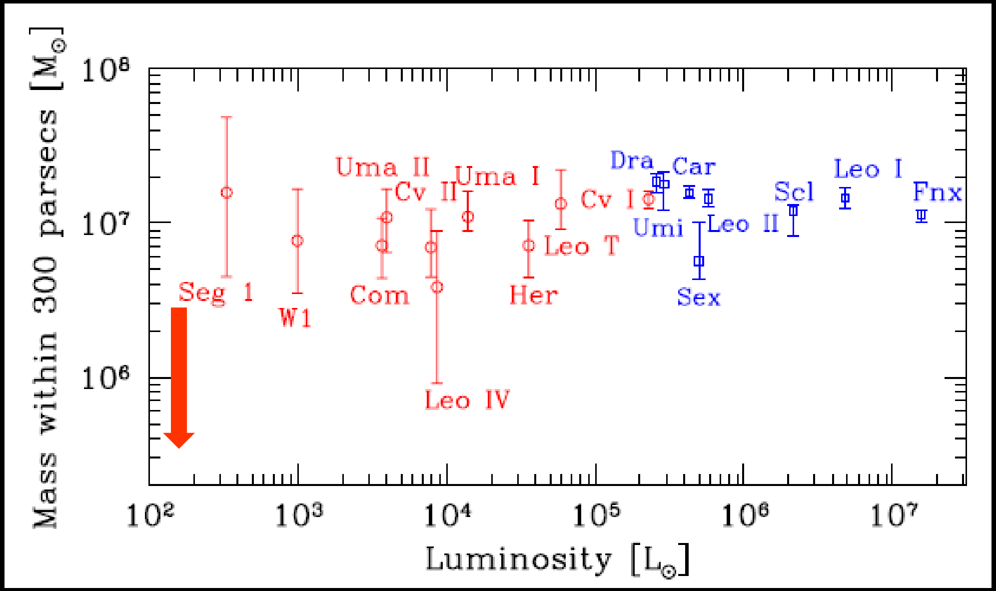


Strigari et al (2007)

– Too massive to be dark? / V_{max} of satellites too low? (Koylan-Bolchin et al. 2011a,b; Strigari, Frenk & White 2010)

– Inner slope and overall density profile?

– Dynamics and formation path?



Strigari et al (2008)

Internal Dynamics

Dynamical Modeling: Jeans Equation

For stationary and spherically symmetric systems

$$\frac{\mathrm{d}}{\mathrm{d}r}(\nu\sigma_{\mathrm{r}}^2) + \frac{2\beta}{r}\nu\sigma_{\mathrm{r}}^2 = \nu g$$

•Density of tracer population: $\nu(r)$; velocity anisotropy β

$$\beta = 1 - \sigma_{\theta}^2(r)/\sigma_{\mathrm{r}}^2(r)$$

•Underlying potential: $\phi(r)$

$$g = -\,\mathrm{d}\Phi/\mathrm{d}r$$

Observations give projection of the velocity ellipsoid along the l.o.s

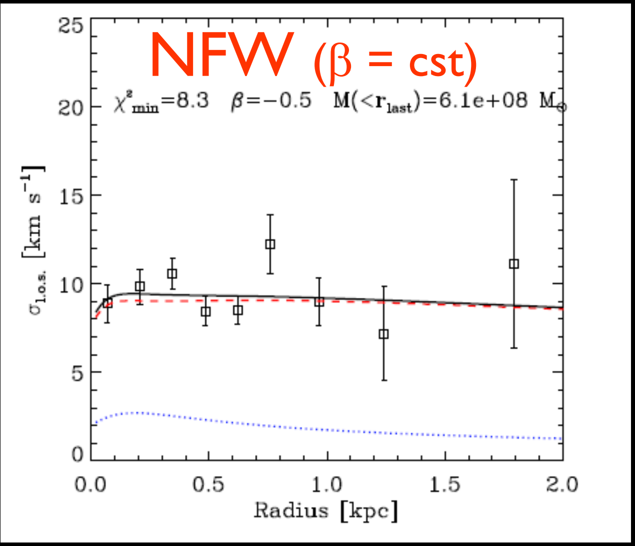
$$\sigma_{\mathrm{los}}^2(R) = \frac{2}{I(R)}\int_R^{\infty}\left(1 - \beta\frac{R^2}{r^2}\right)\frac{\nu\sigma_{\mathrm{r}}^2 r}{\sqrt{r^2 - R^2}}\,\mathrm{d}r$$

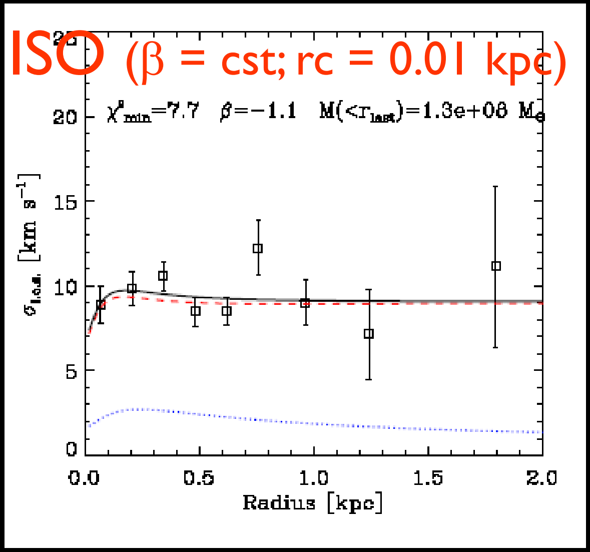
•Surface brightness profile of the tracer population: I(R)

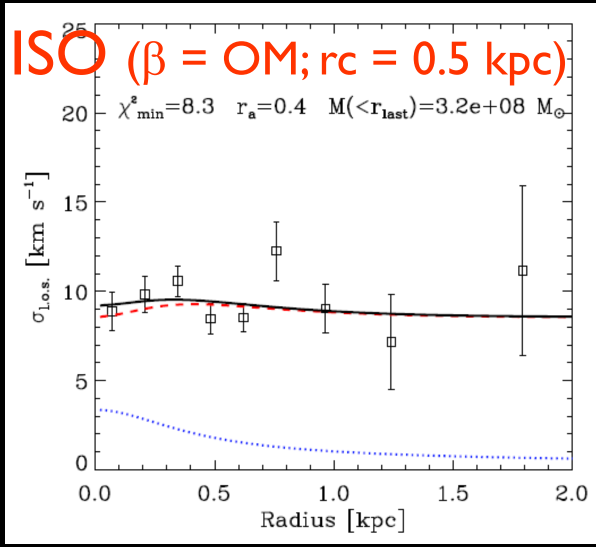
MW satellites: Jeans dynamical modeling

- (Most) Jeans modeling:
  - uses 2nd moment only (see Lokas et al (2005) w/4th moment on Draco)
  - Requires assumption of velocity anisotropy profile

- Strong degeneracies:
  - cannot distinguish between core & cusp





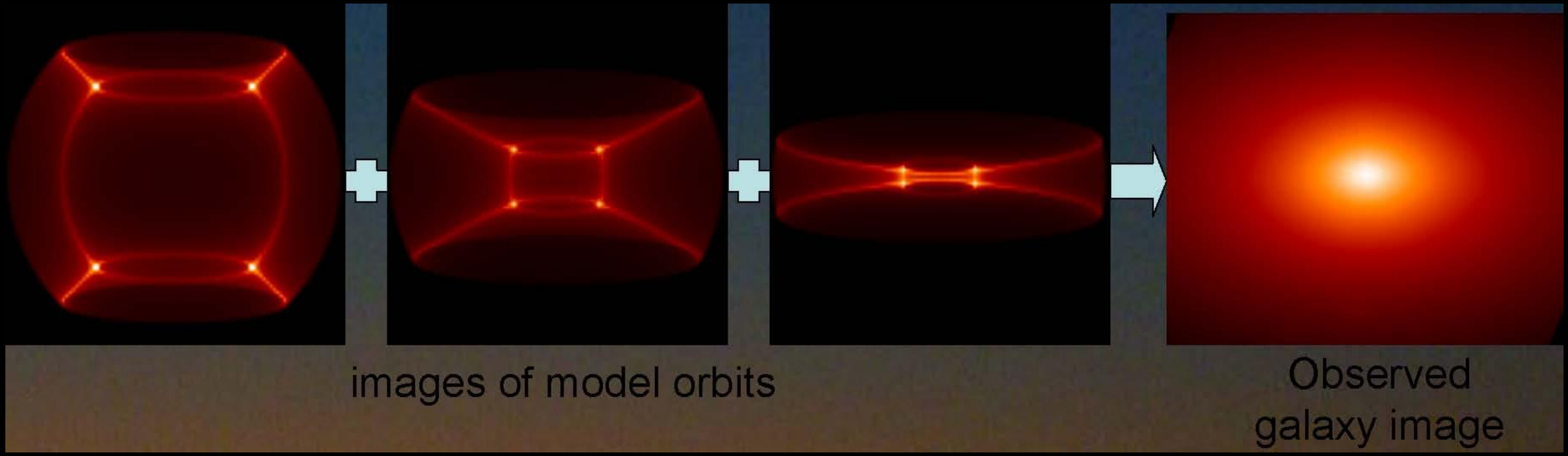


Battaglia et al. 2007

Schwarzschild models

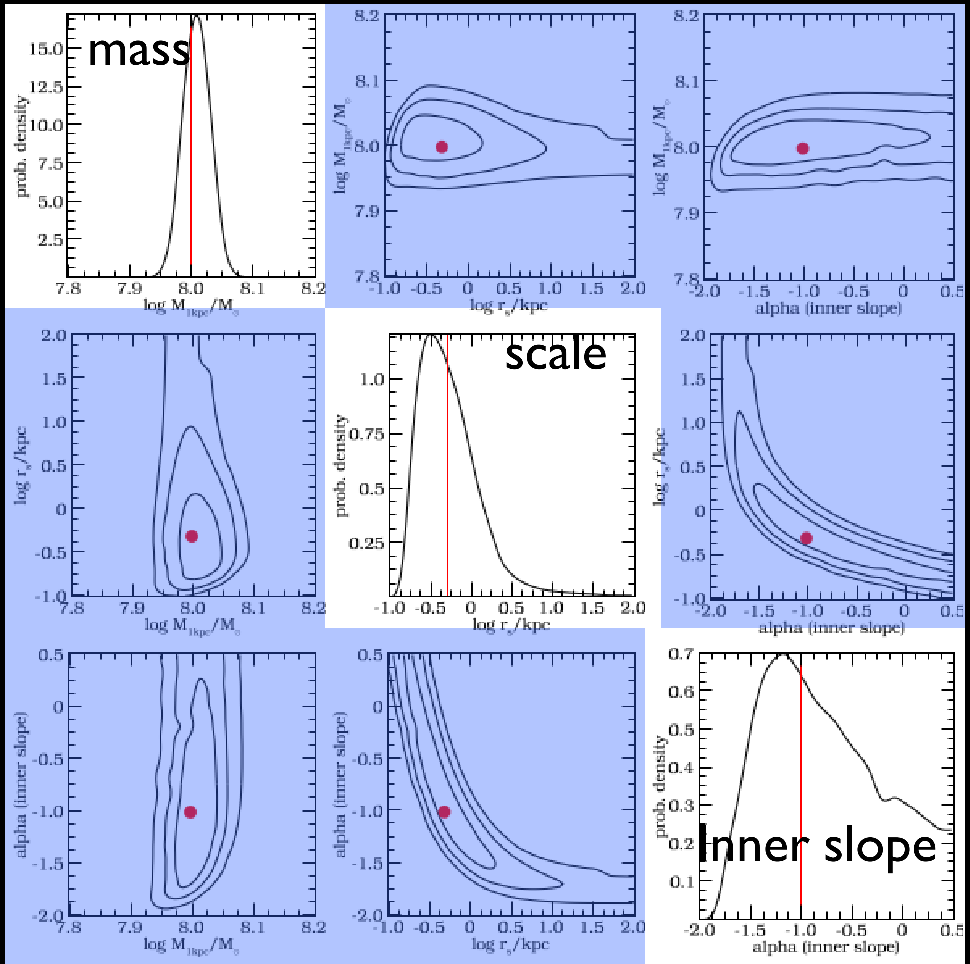
- Integrate orbits in a given potential, and find their weights such that the observables (surface brightness, 2nd and 4th velocity moments) are reproduced

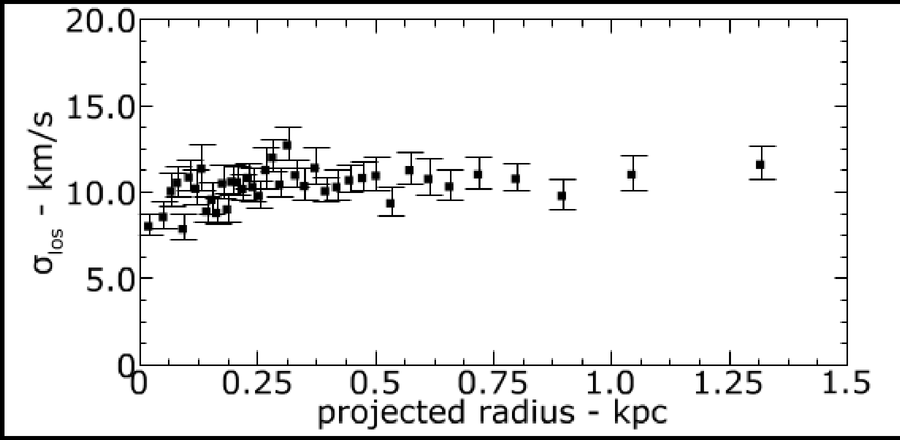
- Best model obtained via max likelihood, and this gives best fit parameters of the gravitational potential, as well as distribution function (anisotropy) of the model



Testing the modeling

- Mock Sculptor: same # of stars, similar velocity dispersion, assumed tangential anisotropy in an NFW DM halo

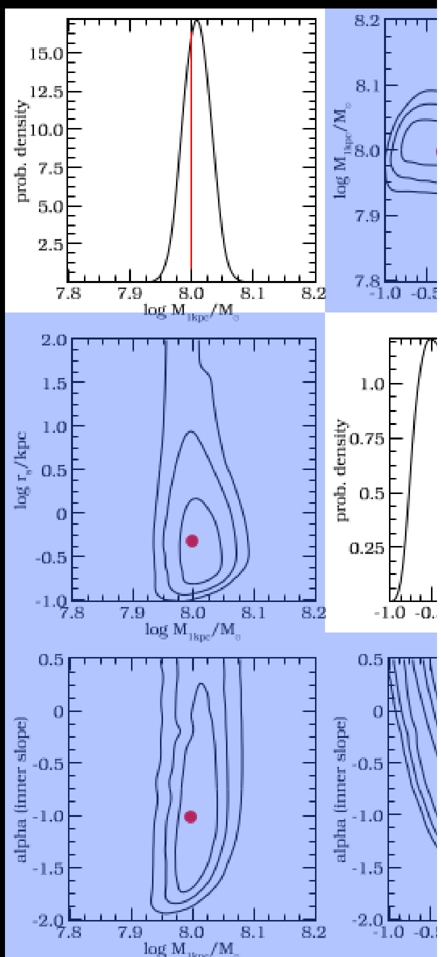


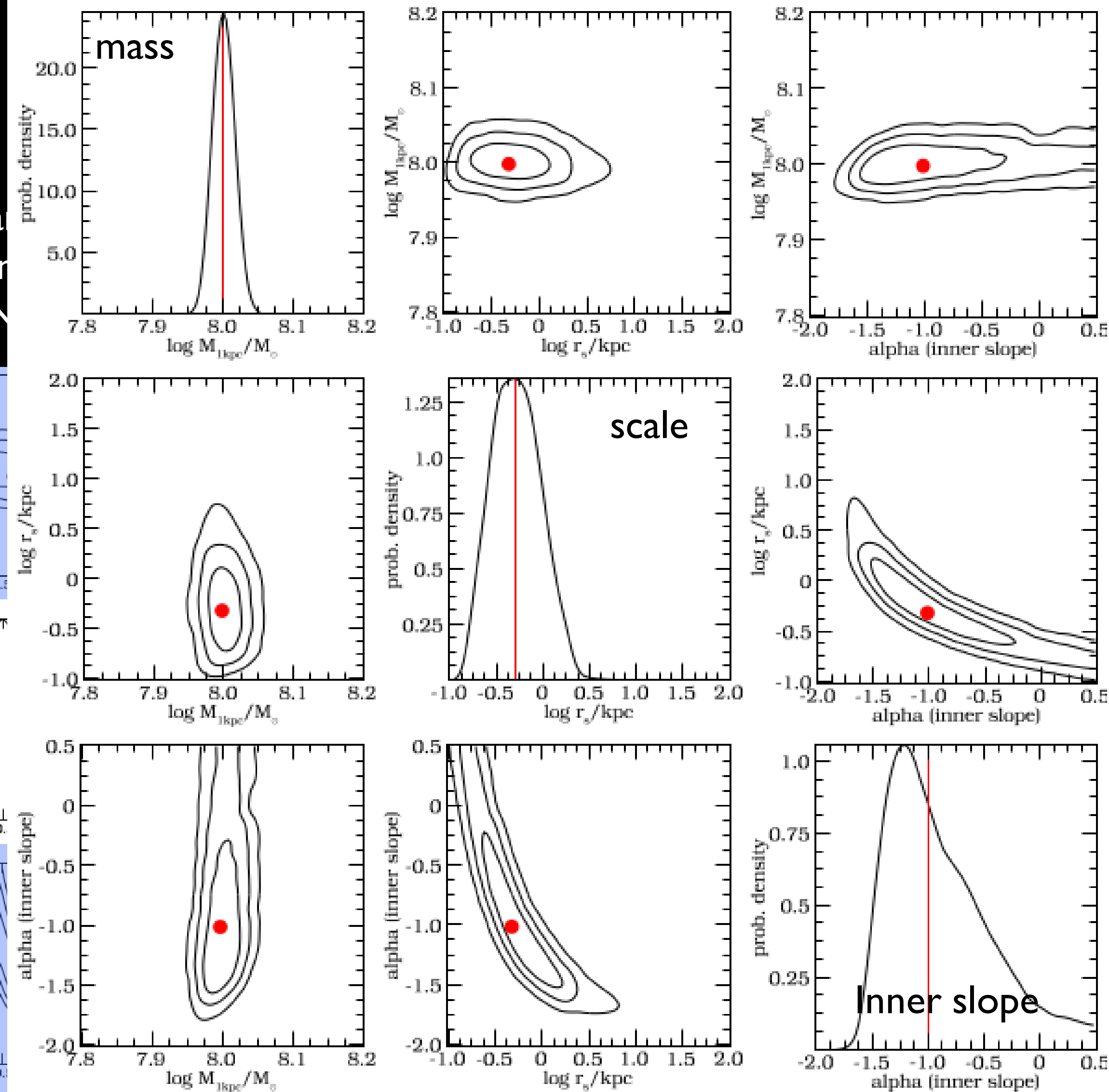


Breddels et al. 2012

- Recover input values
- Inner slope is not so well-constrained but larger samples help

- Mock Sculptor: sa
velocity dispersion
anisotropy in an N

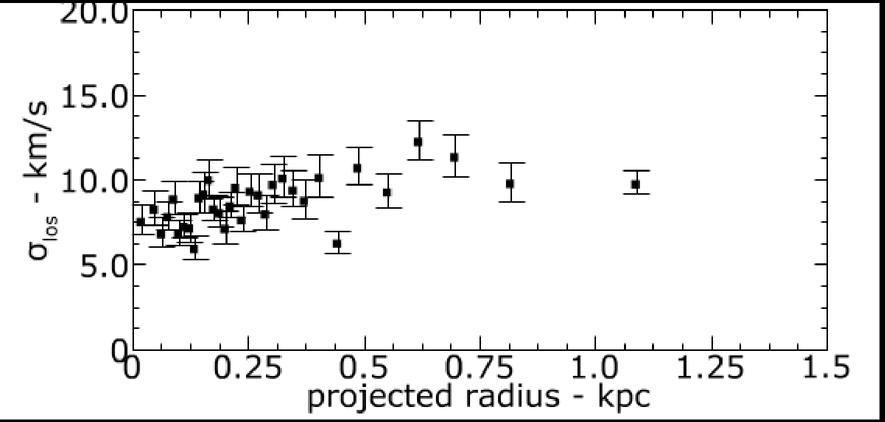




Schwarzschild model of Sculptor

- For Sculptor we assume first NFW profile and derive the mass within 1kpc and the scale radius
    - i.e. we vary systematically these parameters, and find the combination of orbits that minimizes the chi-sq

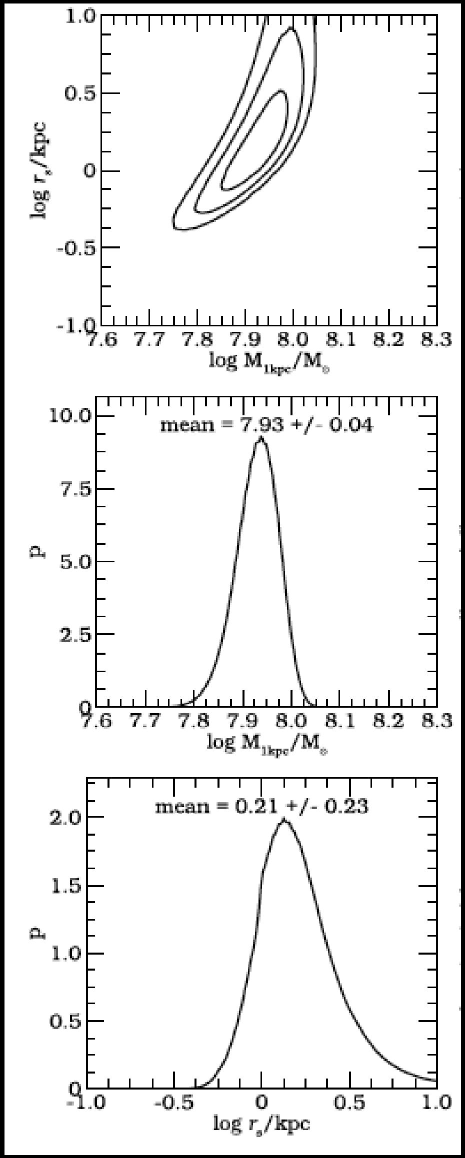
- Data are from Battaglia et al. (2008) and Walker et al (2009); ~ 2400 member stars

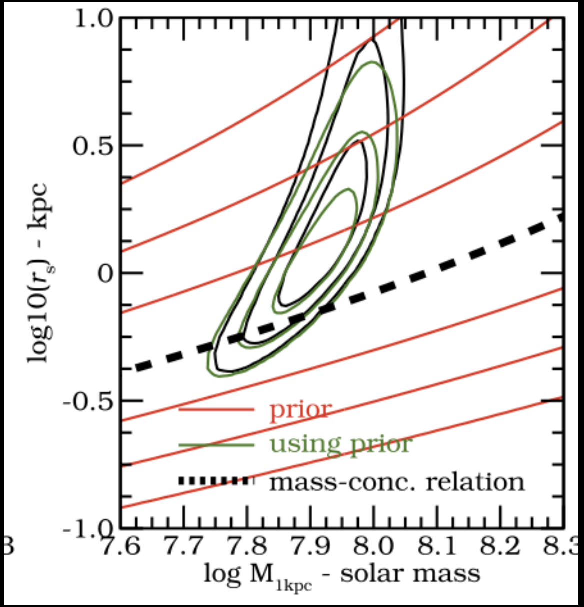


Breddels et al. (2012)

Sculptor's dynamical model. I

- The mass within 1 kpc is very well constrained:
  $8.5^{+0.82}_{-0.75} \times 10^7$ Msun
- The scale radius is more uncertain: $1.62^{+1.13}_{-0.67}$ kpc
- The implied concentration ~ 15
- We can use a prior on mass-concentration, and this restricts possible values of r_s

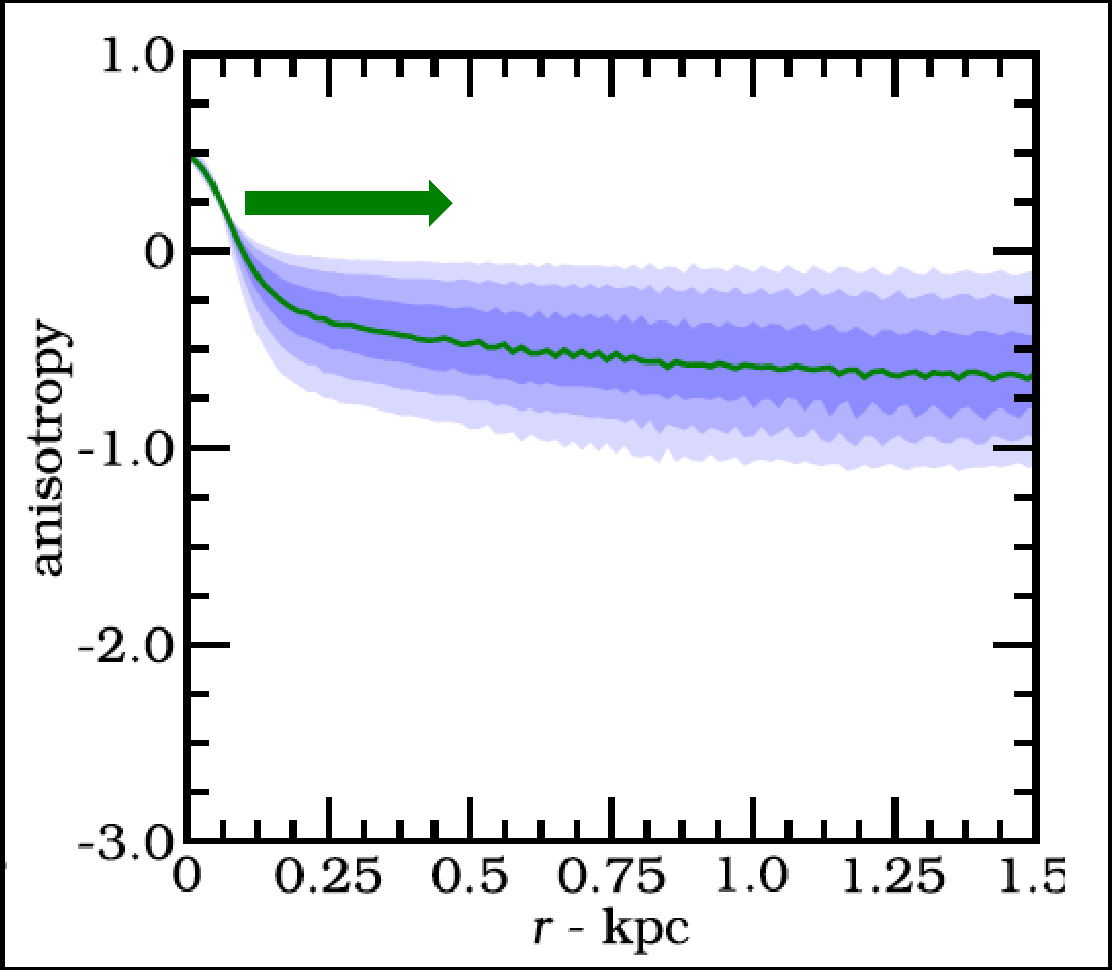




Breddels et al. 2012

Sculptor's anisotropy profile

- The anisotropy is nearly flat and tangentially biased

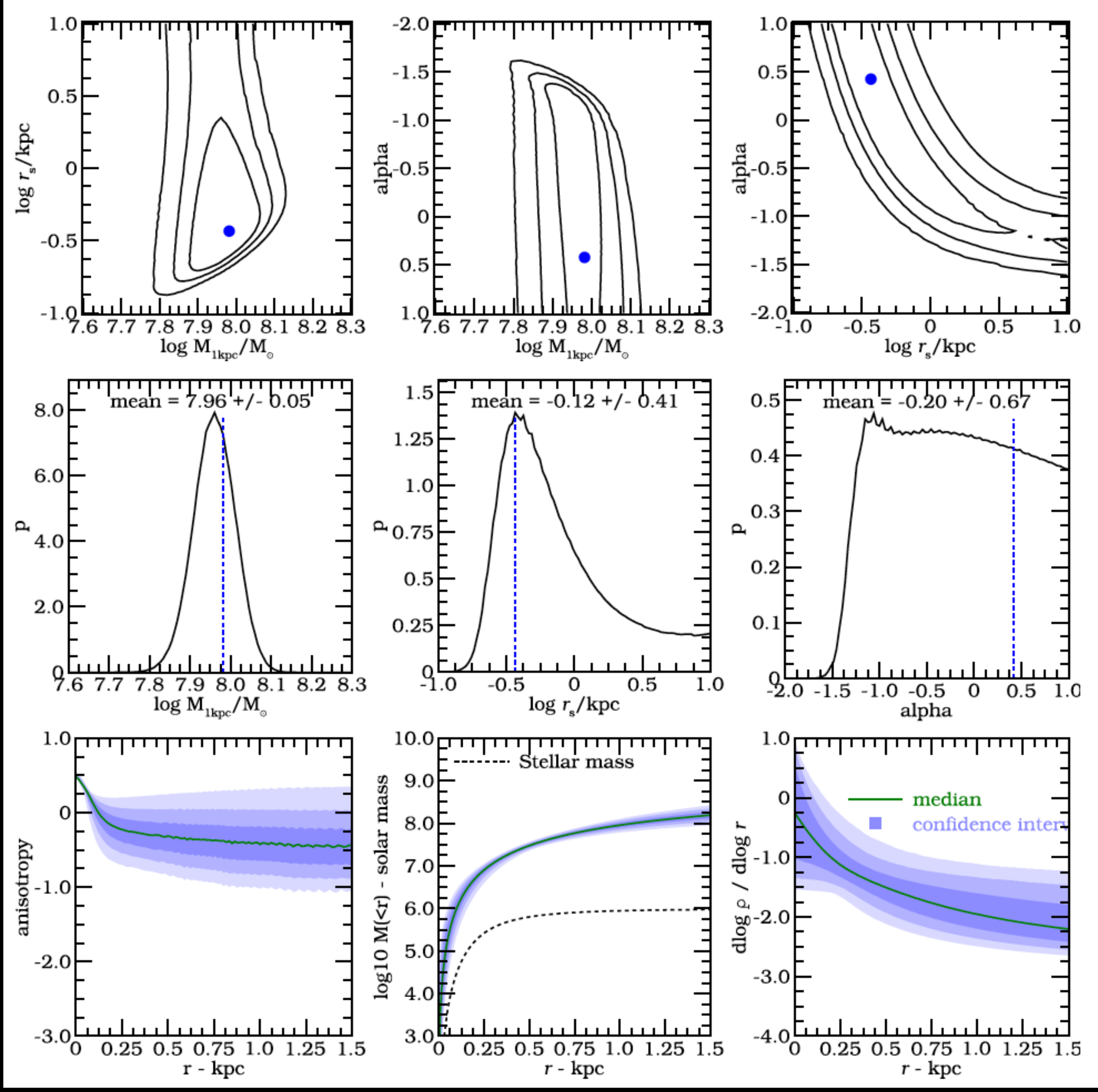


Breddels et al. (2012)

Sculptor's dynamical model. II

If we allow the inner slope to vary:

- Very steep cusps are ruled out ($\alpha < -1.5$)
- The logarithmic slope of the density is -2 at ~ 1 kpc
- The anisotropy profile is similar (beta ~ cst < 0)

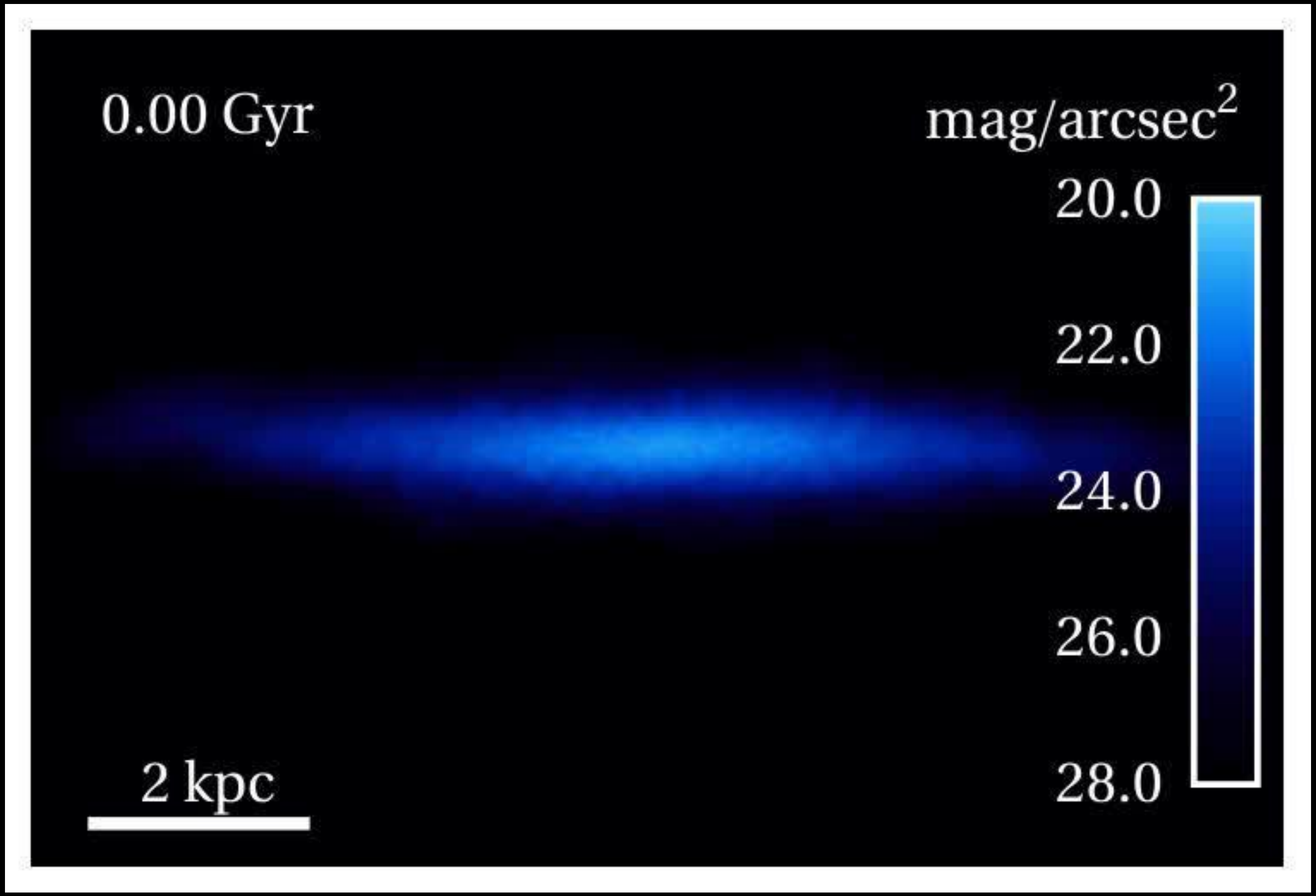


Breddels et al. (2012)

Results from Schwarzschild model of Sculptor

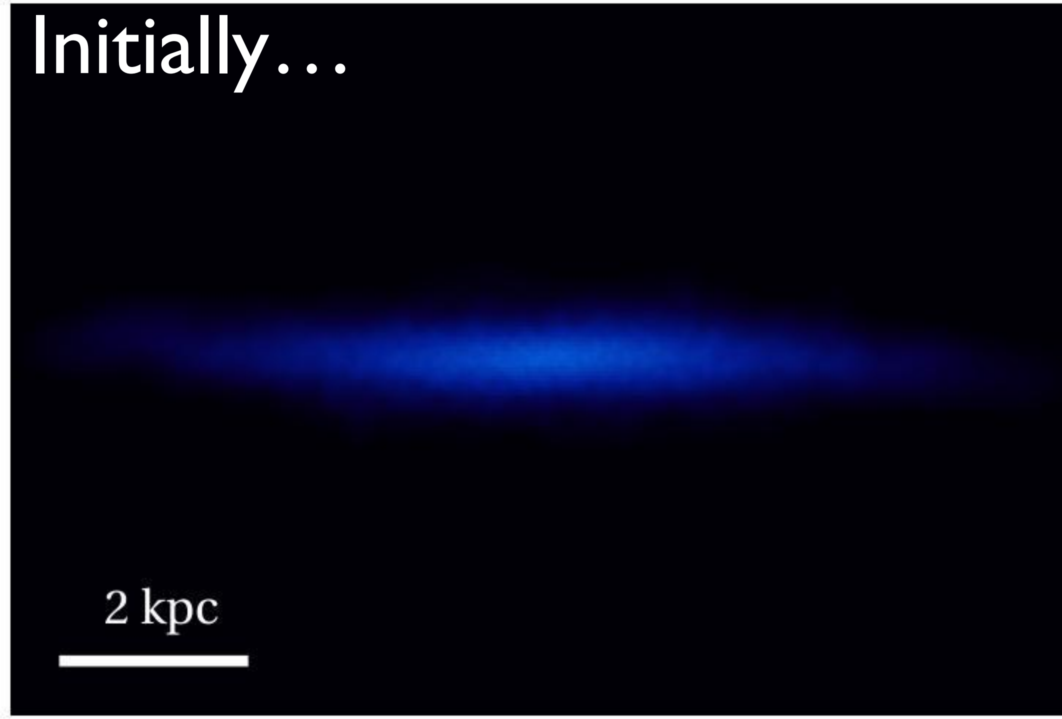
- NFW profiles fit well; M(< 1kpc) determined within 10%, concentration c ~ 15
- Orbital structure: anisotropy is tangentially biased (formation?)
- gNFW we are able to rule out very cuspy (< -1.5) inner slopes.
  - Larger samples (at least 10k stars) would be very helpful
  - Possible to distinguish core and cusp

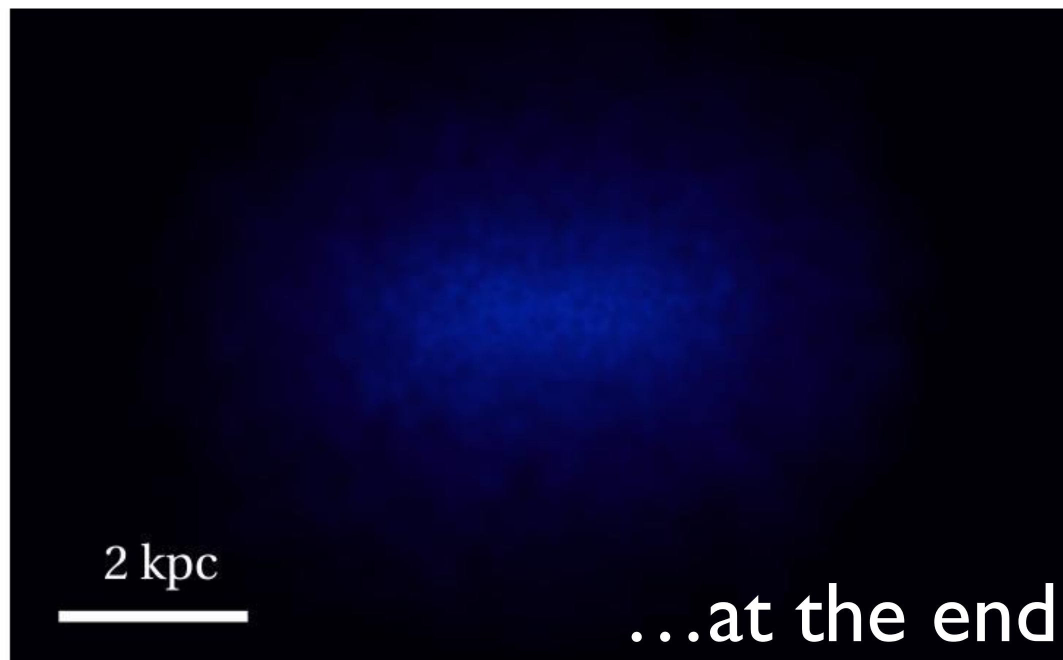
Dynamical evolution of dwarf galaxies in LCDM


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!





Dark satellites and the morphologies of dwarf galaxies

- (Dark) satellites dynamically perturb disk galaxies
  - E.g heating of "disks", thick disk formation, etc
  - Most focus so far on Milky Way-like 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 ($M < 5 \times 10^8$ Msun) will be dark
    - Gas cooling inefficient and inhibited because of e.g. reionization

- Dynamical perturbations by dark satellites are 100x more dramatic on disky dwarf than on giant galaxy

  - 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)

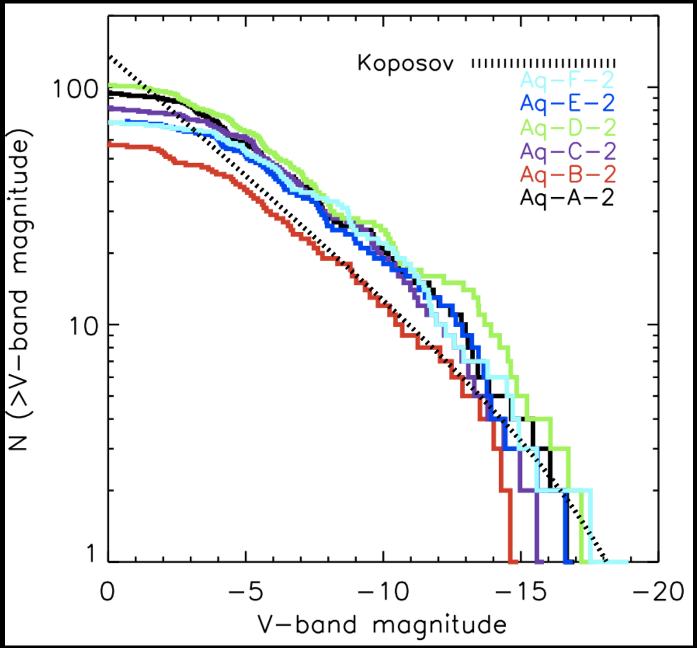
- Case w/gas, and using galaxy efficiency $\eta_{gal} = M_{disk} / (fb \times M_{vir})$, the relative change

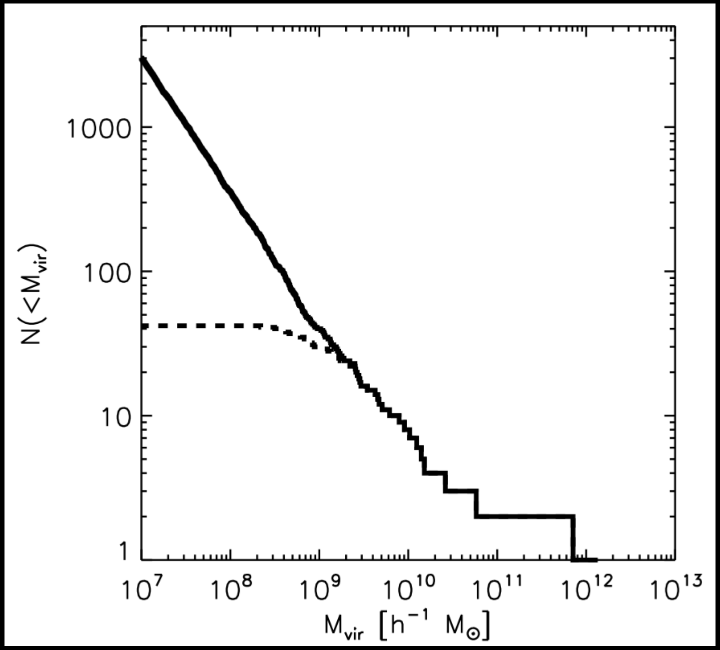
$$\Delta H/R_d = \alpha \ (1 - f_{gas})/\eta_{gal} \ (M_{sat}/M_{vir})$$

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

Modeling galaxies

- SA model + Aquarius simulations to study properties of galaxies from dwarfs to giants (De Lucia & Helmi 2008; Li et al. 2010; Starkenburg 2011)
  - Good agreement in LF of Milky Way satellites; internal properties (scaling relations, SFHs…); galaxies of given luminosity in the right dark matter mass halos
  - Relevant (here) physical processes: feedback, reionization, no cooling in halos below atomic H limit





Starkenburg et al. 2012

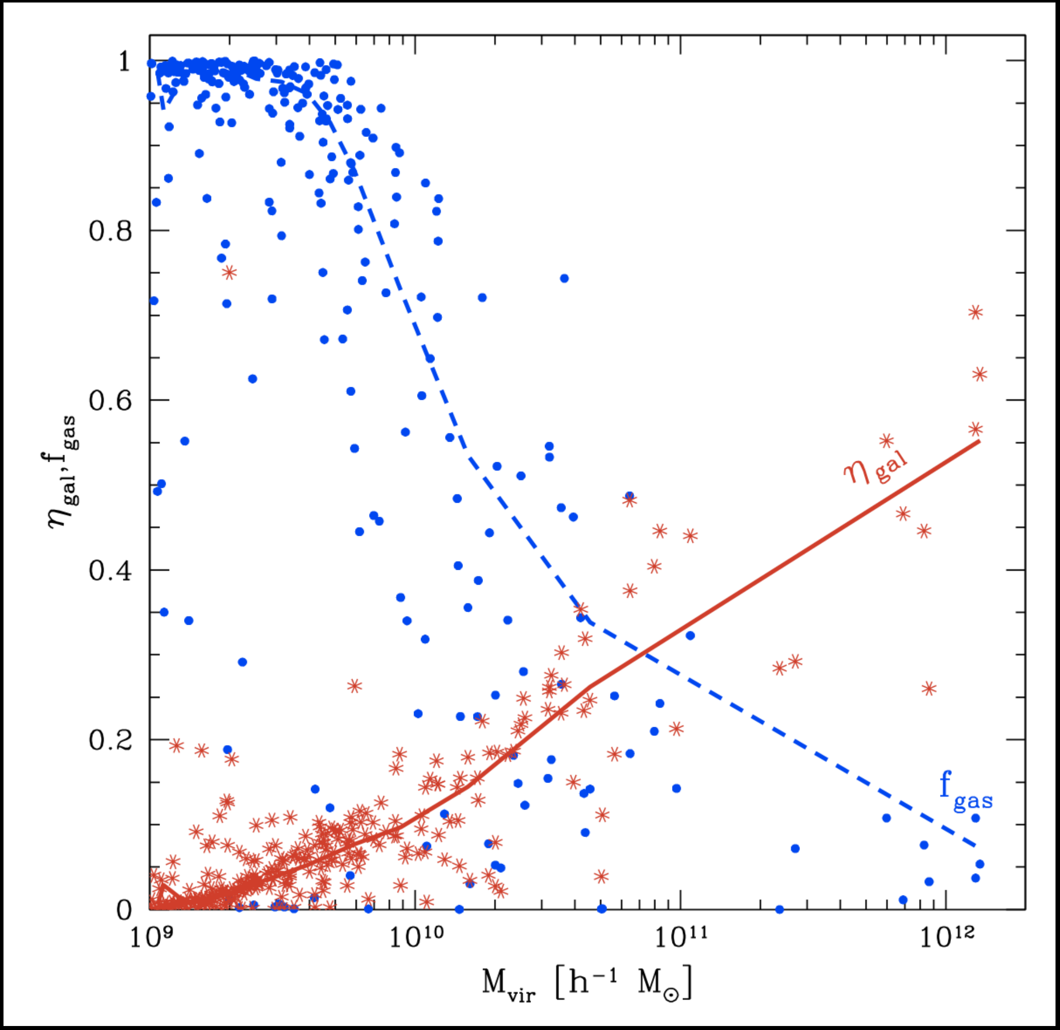
Factors affecting changes. I

- Gas fraction:
  - Cold gas content increases with decreasing virial mass
  - Isolated dwarfs tend to be more gas-rich than field giants

    (More inefficient in SF)

- Galaxy efficiency:
  - Low mass objects are more inefficient at collecting baryons

    (UV background, feedback, …)
  - For L* ➔ η_{gal} ~ 30 – 60%
  - For dwarfs ➔ η_{gal} ~ 1 – 5%
  - Dwarfs have higher M/L

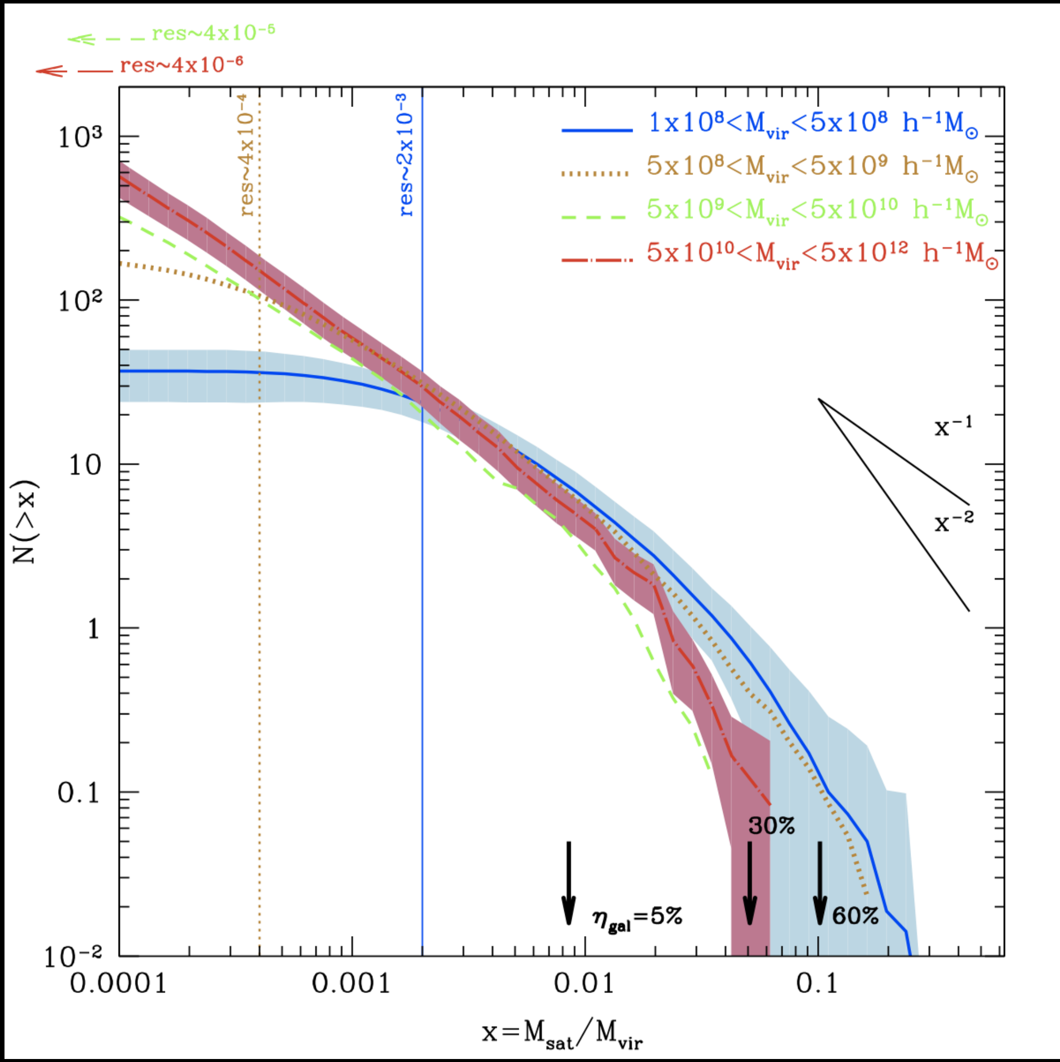


Helmi et al. 2012

Factors affecting changes. II

- Mass spectrum of perturbers:
  - # of encounters with an object of a given mass-ratio (at pericentre): dN/dx
  - This function is within uncertainties scale-independent
    - Like mass-function (Springel et al. 2008)

- Example:
  - A dwarf galaxy with η_{gal} ~ 5% experiences many more encounters with Msat = Mdisk
  - MW-like galaxies has a 10x smaller probability



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Change in scale-height

- Since spectrum of perturbers is scale-free, changes depend mostly on f_{gas} and η_{gal}

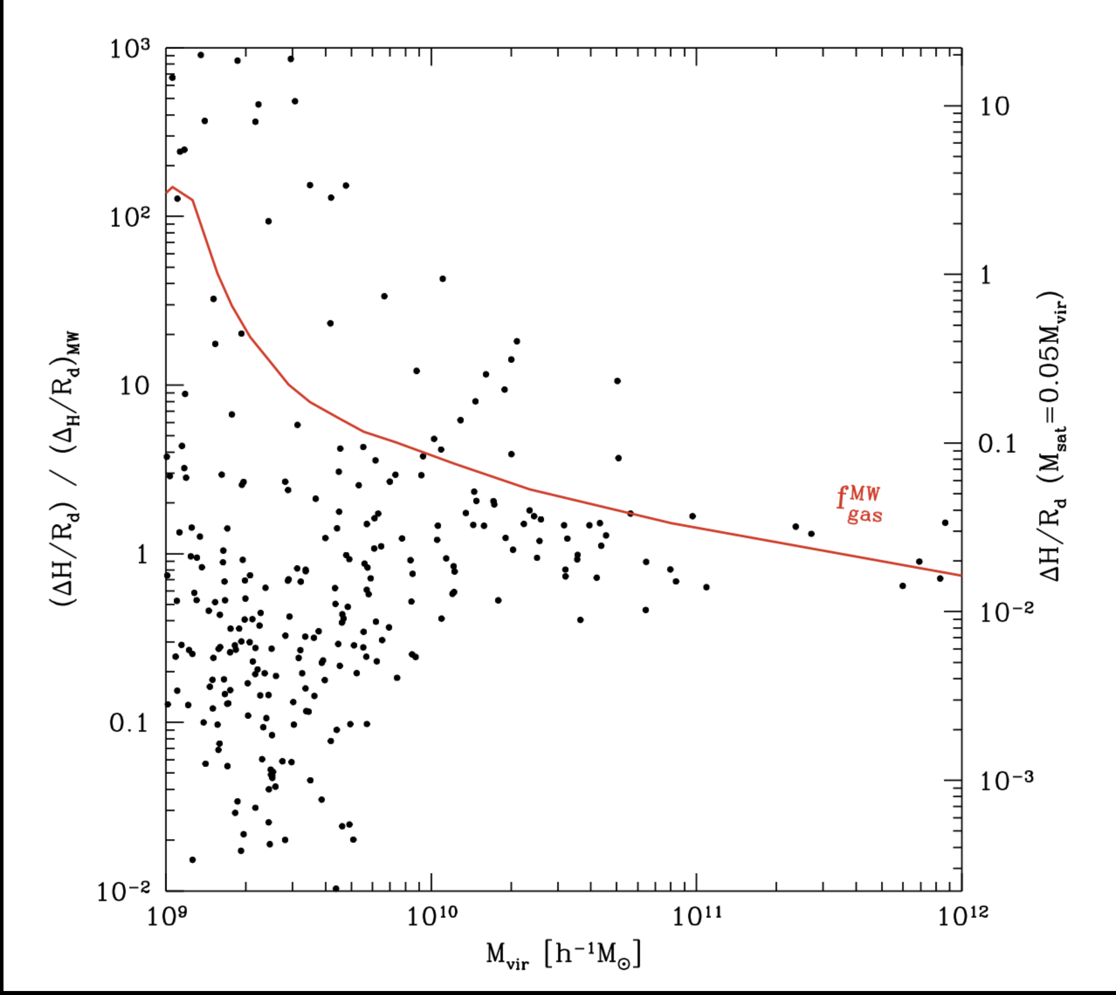
- For dwarf ($M_{vir} \sim 10^{10}$ Msun) with f_{gas}^{MW}, same Msat/Mvir encounter is 100x more damaging

  Msat/Mvir = 0.05, $\Delta H/R_d \sim 2.7$

  negligible for MW

- When gas fraction is high, perturbations will not lead to significant heating
  - But they can lead to starbursts

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



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Observations

Apparent axis ratios for isolated late-type galaxies

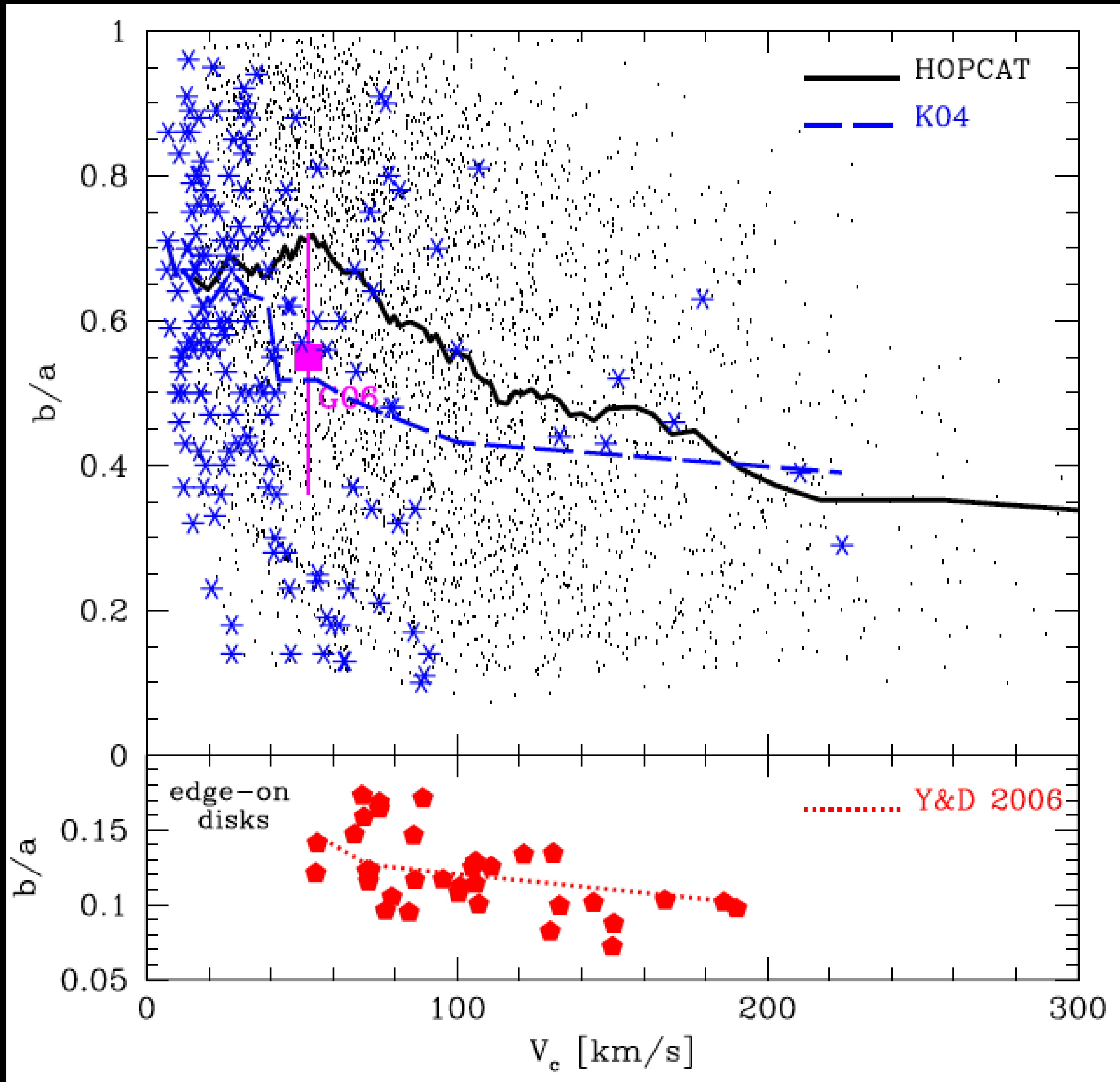
Doyle et al (2005), Karachentsev et al. (2004) Geha et al. (2006)

There are no "thin" disky dwarfs: spheroidal/irregular morphologies

b/a increases towards fainter luminosities

True axis ratios for edge-on disks (Yoachim & Dalcanton 2006)

Thick disks are more prominent/common for lower mass systems



Helmi et al. 2012

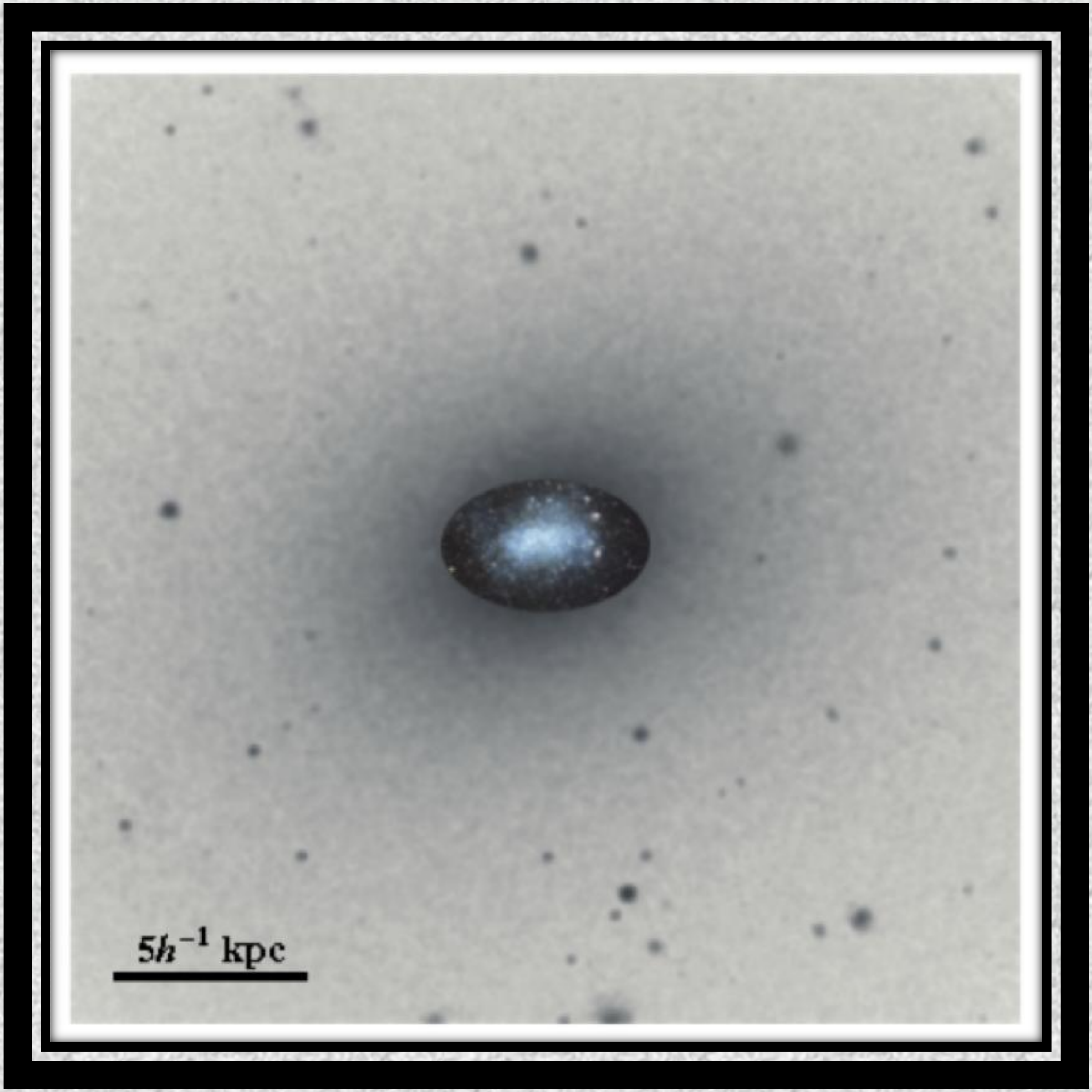
Implications/Summary

- Other mechanisms can explain increase in thickness for fainter galaxies
  temperature floor, random vs rotation comparable…Kauffman et al. 2007; Robertson & Kravtsov 2008

- The satellites of dwarf galaxies will be mostly dark and mergers lead to drastic morphological changes
  - Inefficient SF in dwarf implies lower Md, more often comparable to Msat

- Could explain
  - Isolated dwarf spheroidals: merger(s) of a disky dwarf with a dark satellite
  - Isolated starbursting dwarf galaxies: merger of a gas rich dwarf with a dark satellite
    Depending on orbital parameters, mass-ratio, the increase in SFR can be very significant (see poster by Starkenburg); could explain BCDs (even with several nuclei)

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



Thank you!