Dark Matter in Local Group Dwarf spheroidal galaxies

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Outline

- What are dSphs and why are they interesting?
- Kinematic evidence for dark matter in dSphs
- Cores vs cusps in dSphs
- Dynamical modelling of the Fornax dSph
- Conclusions

Collaborators

Gerry Gilmore (Cambridge)
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Justin Read (Zurich)
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Fiorenza Donato (Torino)
Vasily Belokurov (Cambridge)
Melvyn Davies (Lund)
Wyn Evans (Cambridge)
Sofia Feltzing (Lund)
Eva Grebel (Heidelberg)
Rosemary Wyse (JHU)
Dan Zucker (Sydney)

The Aquarius simulation

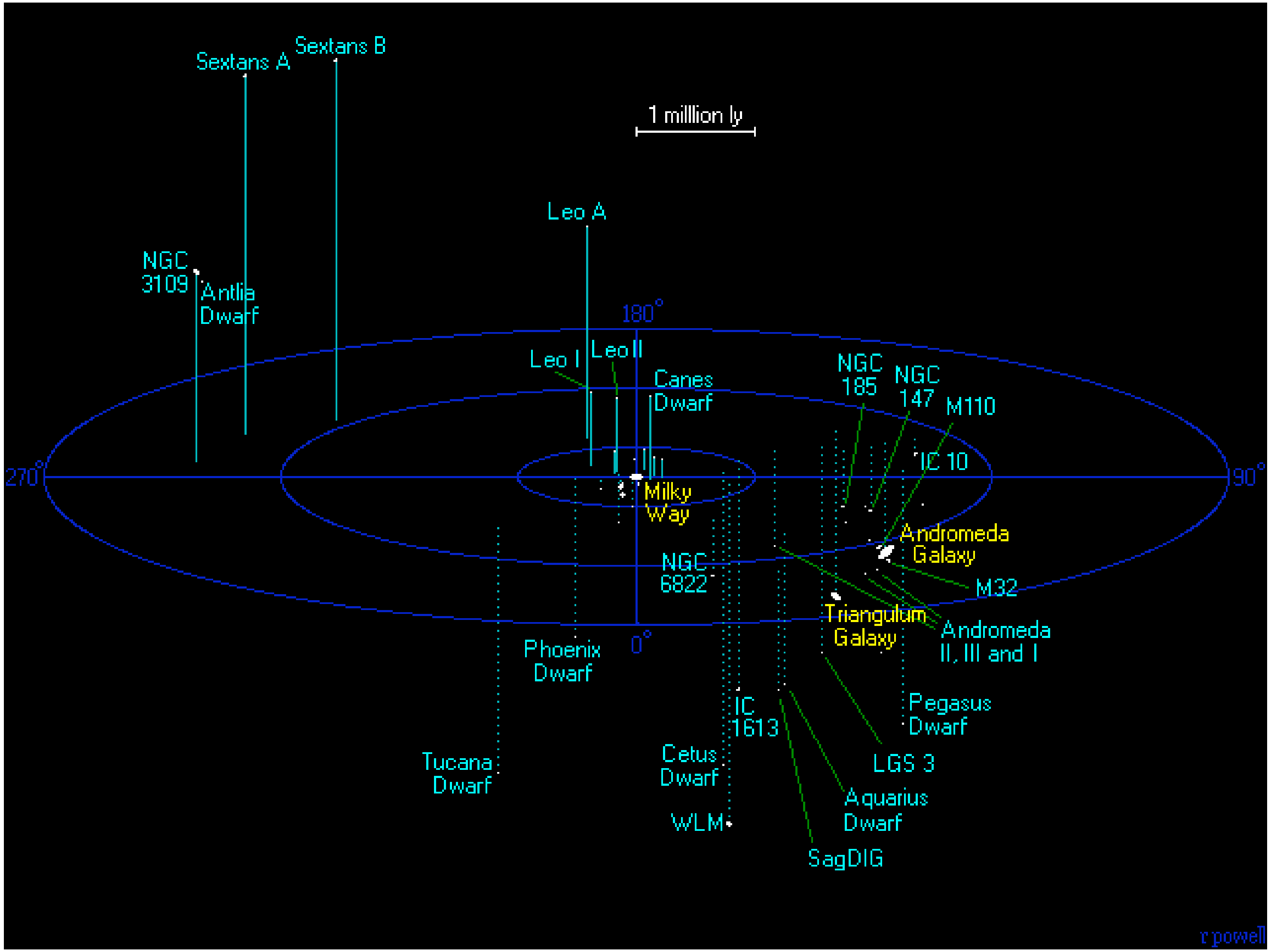
Springel et al. (2008)

Dark Matter: open questions

- What is dark matter?

  (CDM, WDM, cold gas, black holes....)
- How is dark matter distributed?
  - Mpc scales: Λ-CDM performs well
  - kpc scales: possible problems
    - satellite crisis
    - cusps/cores
- Does dark matter exist? MOND?

Local Group Satellites



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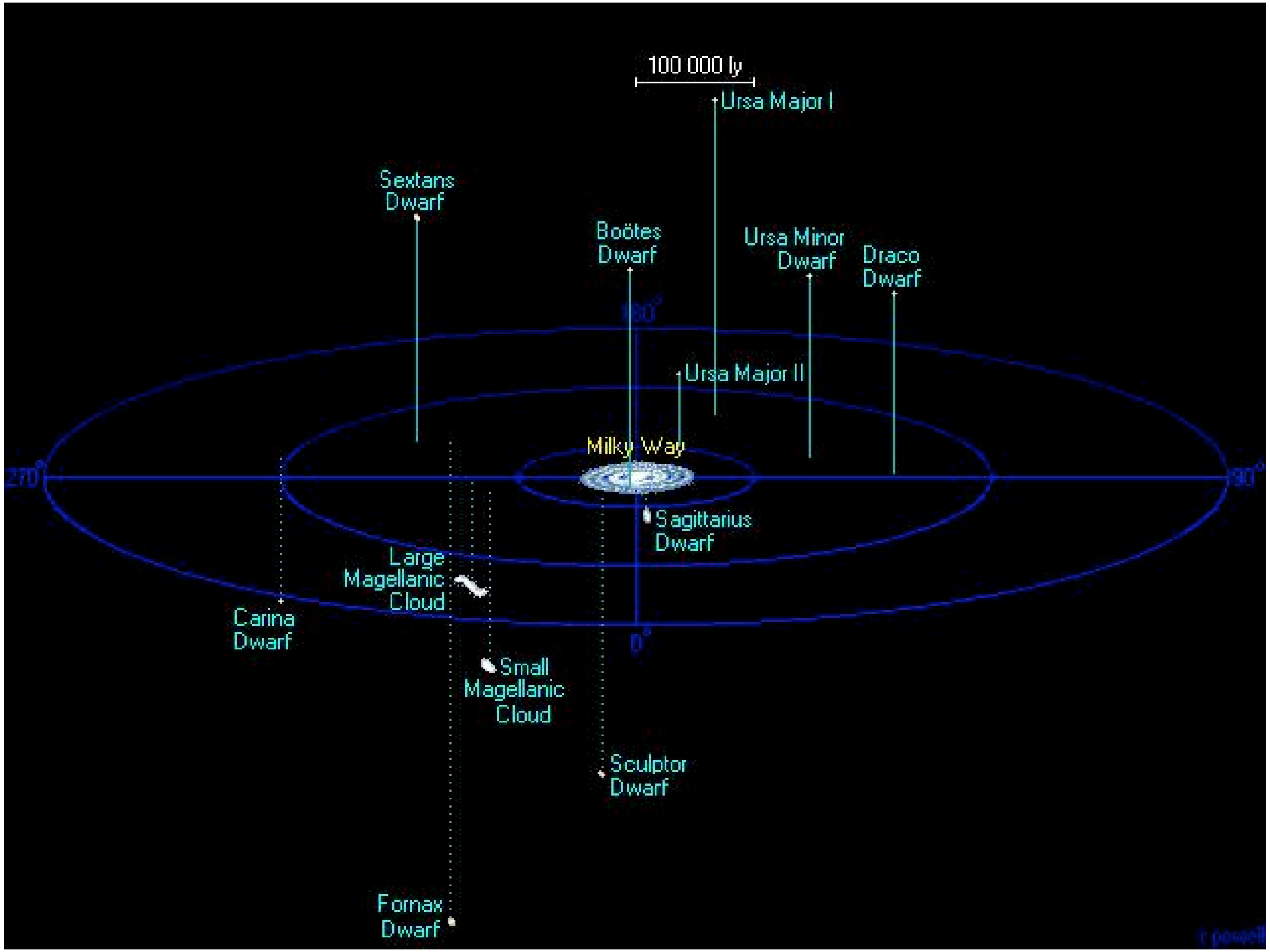

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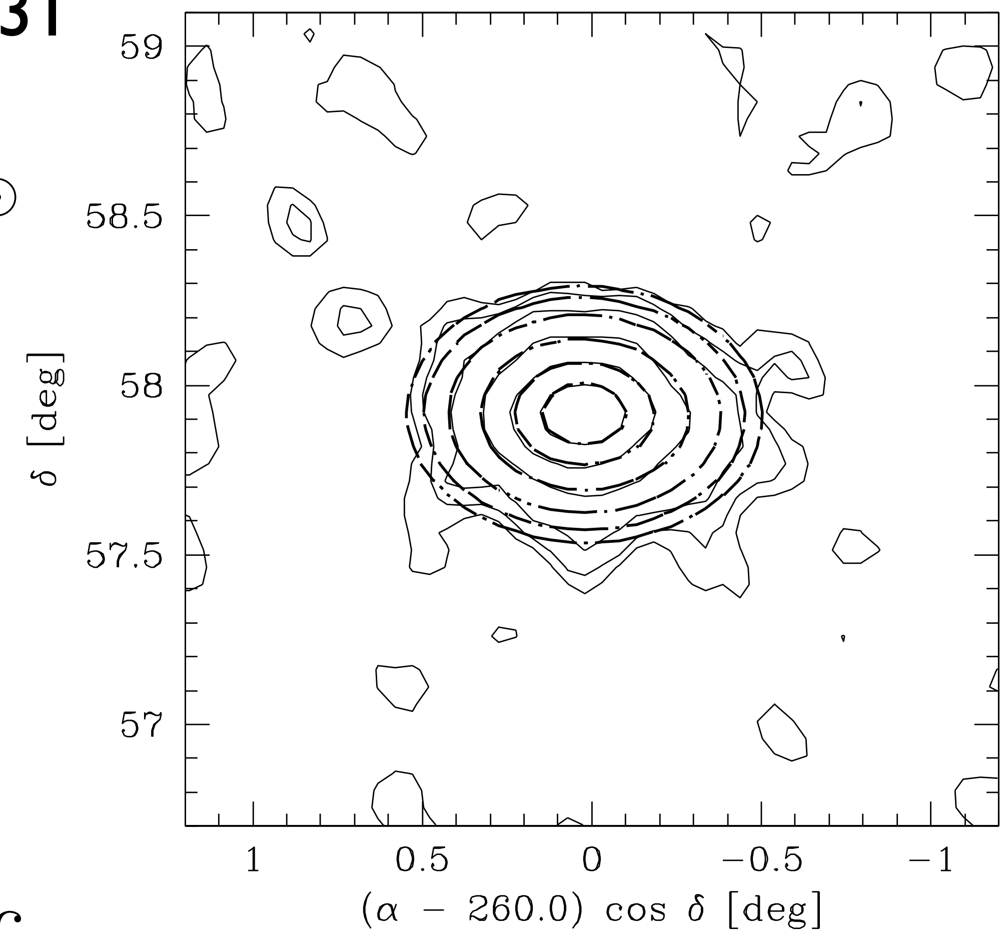
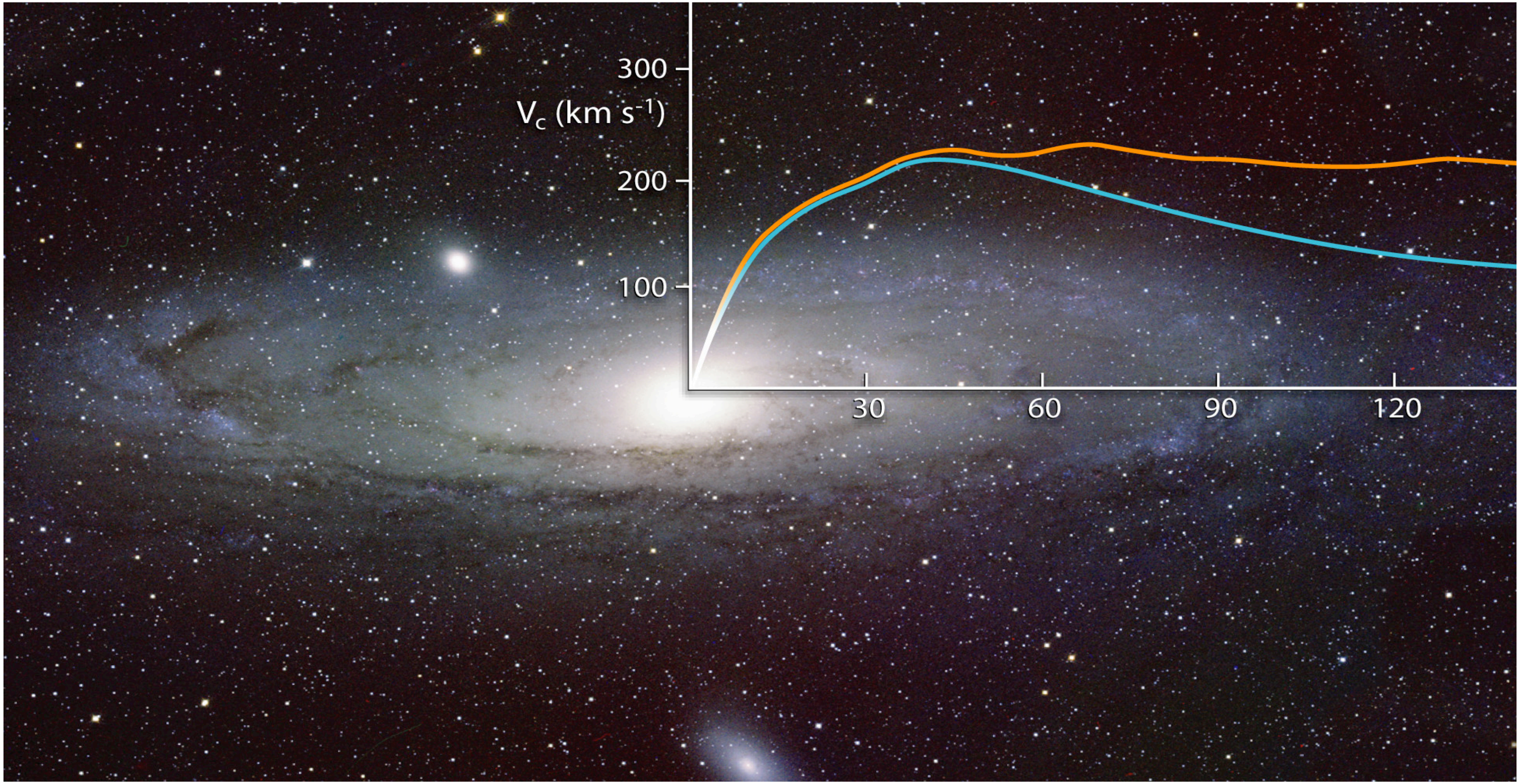
Dwarf spheroidal galaxies: basic properties

- Low luminosity, gas-poor satellites of Milky Way and M31
- $L = 2 \times 10^3 L_\odot - 2 \times 10^7 L_\odot$
- Range of stellar populations and star formation histories
- No well-defined tidal radii
- $\sigma_0 \sim 7 - 12\,\mathrm{km\,s^{-1}}$
- Core radii $r_0 \approx 130 - 500\,\mathrm{pc}$
- Large inferred mass-to-light ratios (10s to 100s)



Odenkirchen et al. (2001)

Rotation curves of disk systems



Gas moving on circular orbits can be used to measure enclosed mass via

$$v_{\rm c}^2 = \frac{GM(r)}{r}$$

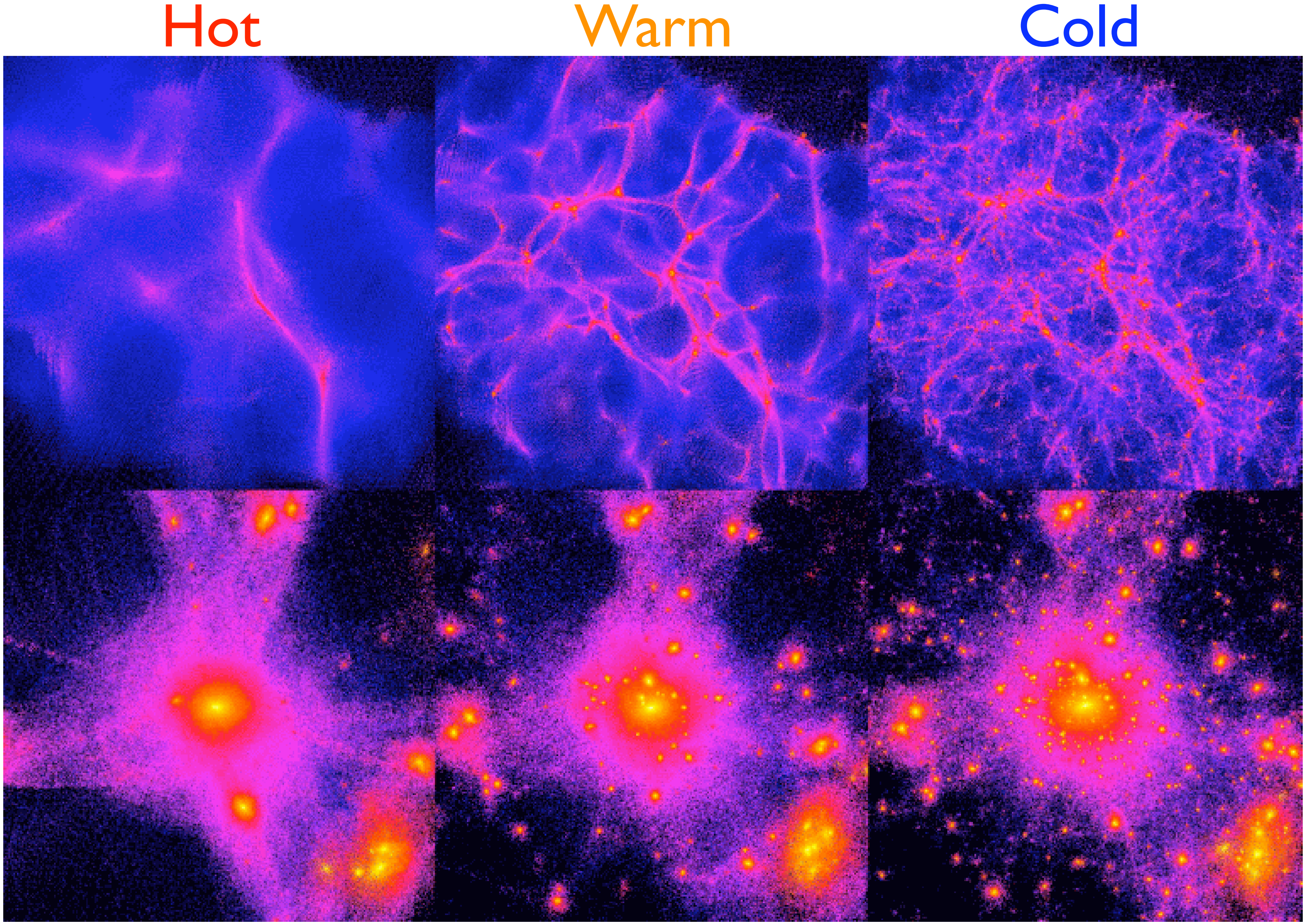
Masses of spheroidal systems

- For a system in virial equillibrium

$$\sigma^2 = \frac{GM}{r_{\rm g}}$$

- Complications:
  - distribution of orbital shapes (anisotropy)
  - we only observe one component of velocity

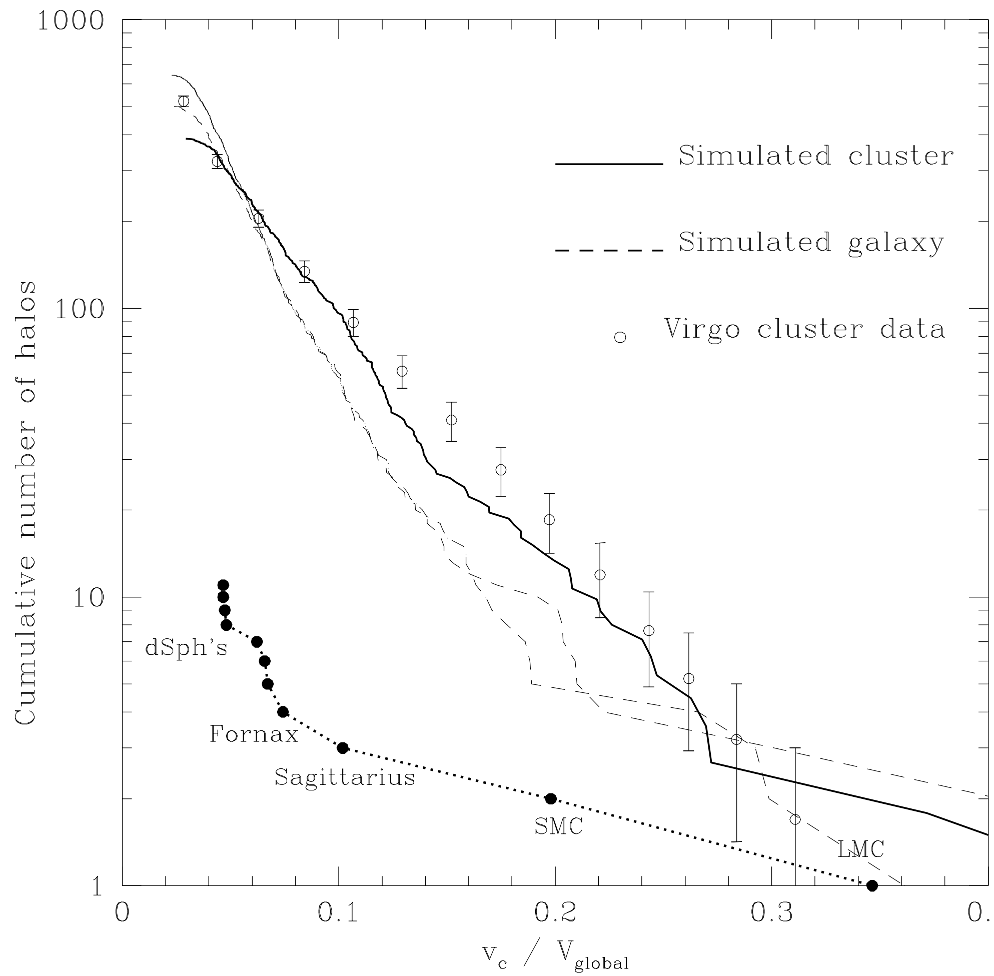
Satellites and dark matter



Moore

The "satellite crisis" of cold dark matter

- Cosmological simulations over-predict the numbers of low mass satellites around a galaxy like the Milky Way
- Is the census of Local Group galaxies complete? What are the total masses of dSphs?
- Several possibilities have been suggested to explain low numbers, including "feedback", re-ionisation, tidal disruption, biased star formation



Moore et al. (1999)

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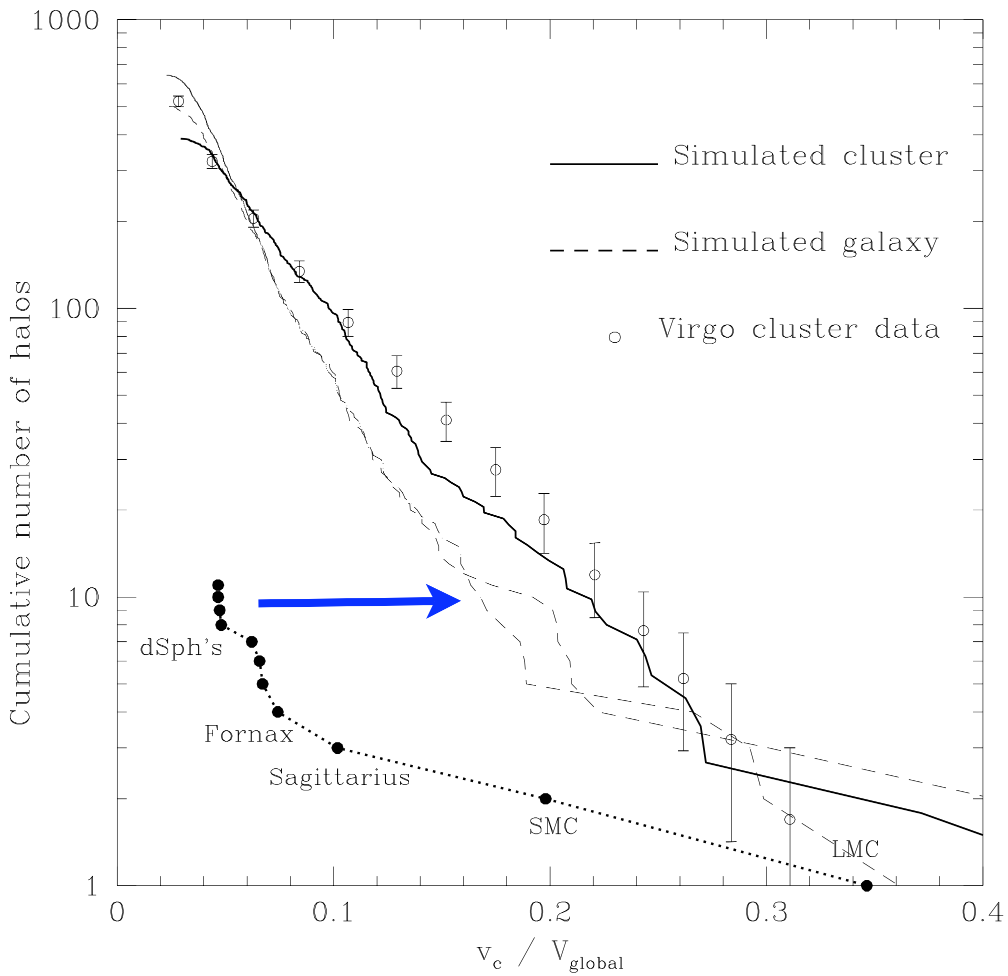

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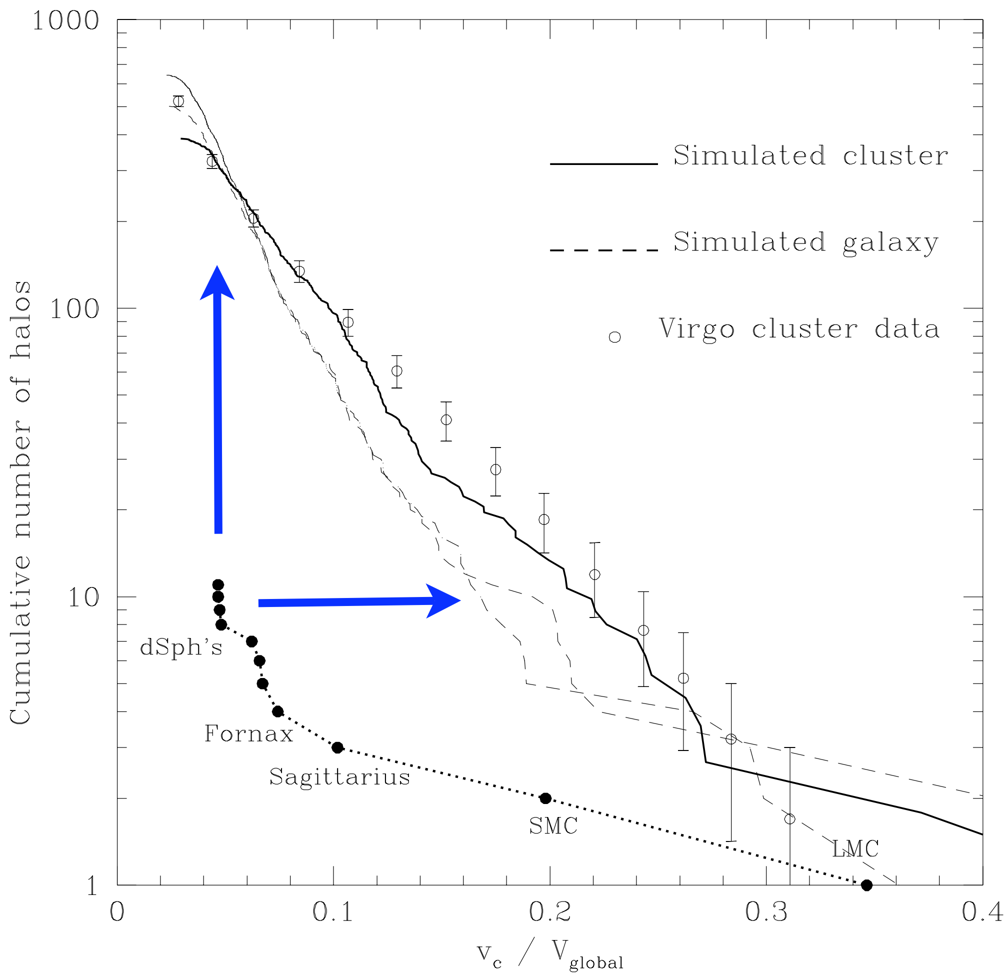
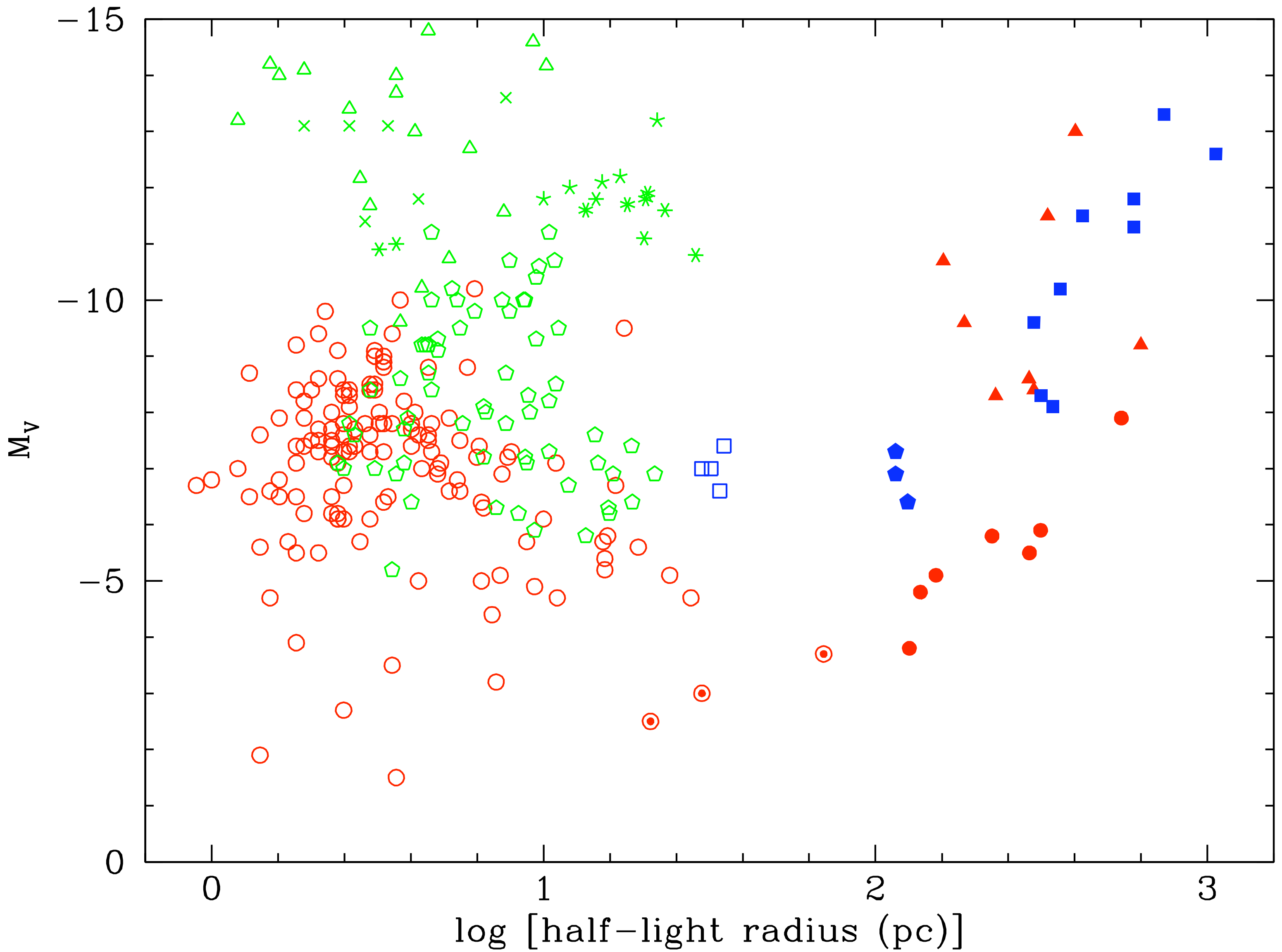


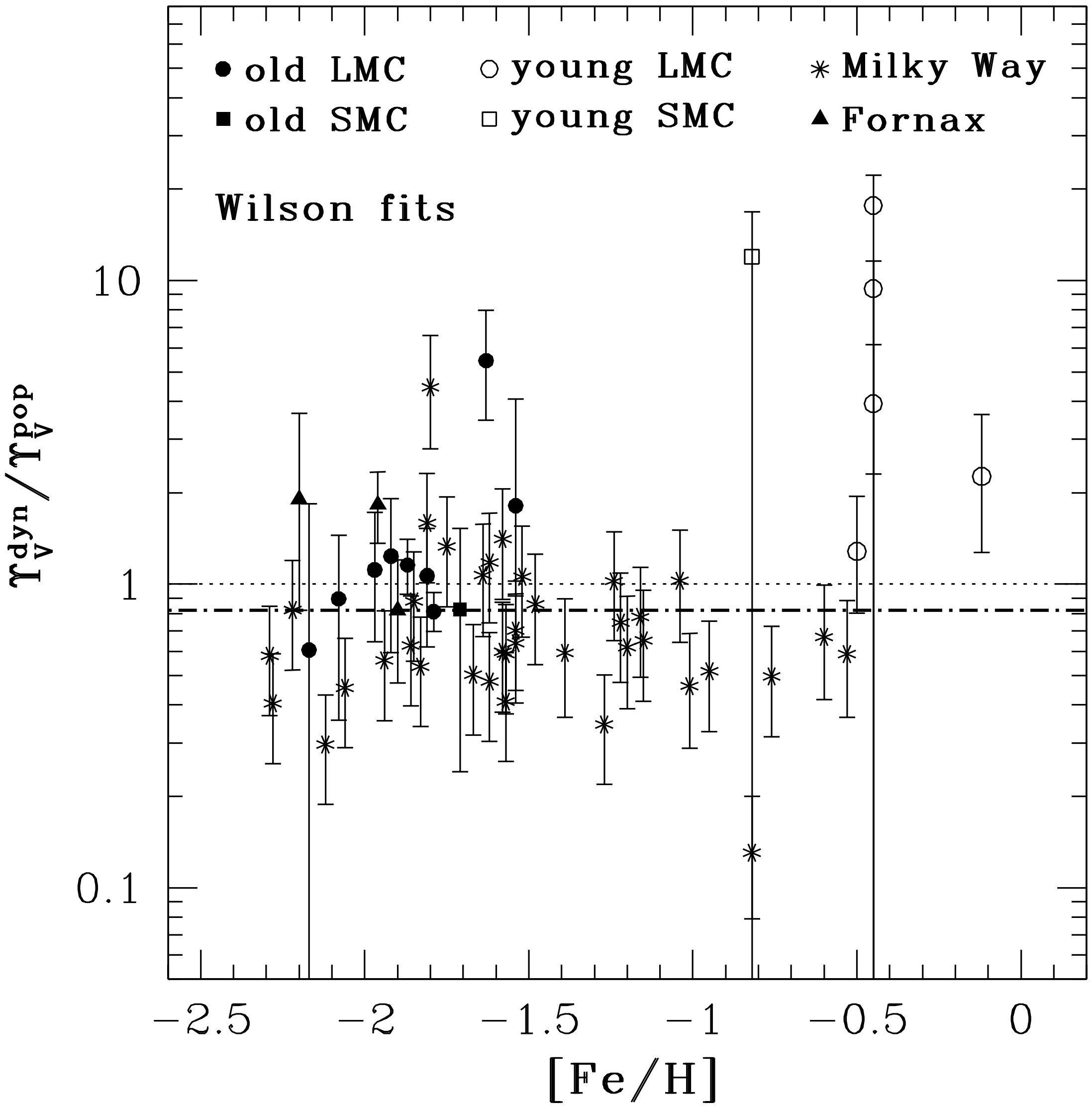
Moore et al. (1999)

Size distribution of stellar systems



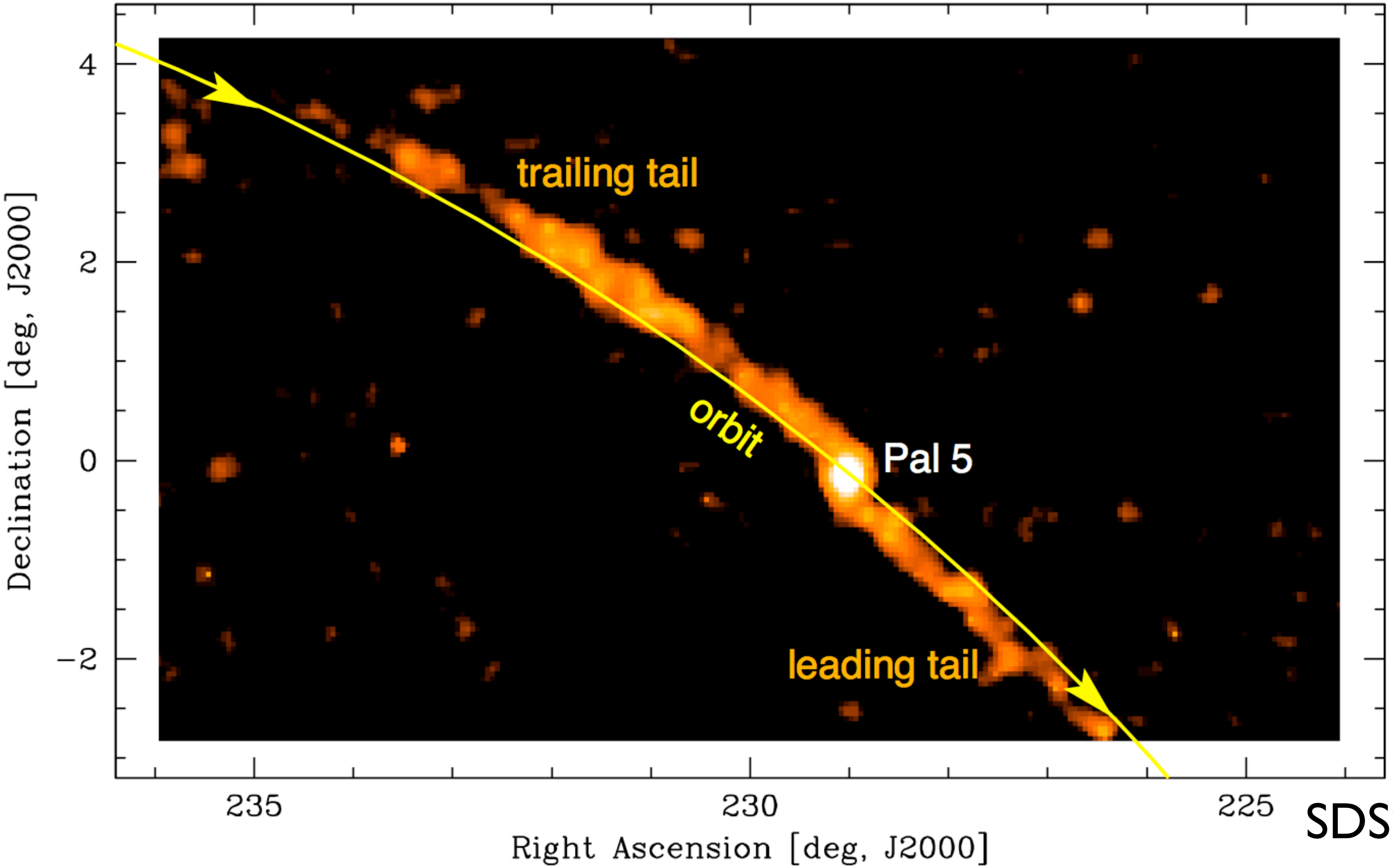
Gilmore et al. (2007)

Mass-to-light ratios of star clusters



- Global M/L of clusters consistent with stellar population estimates (McLaughlin & van der Marel, 2005)

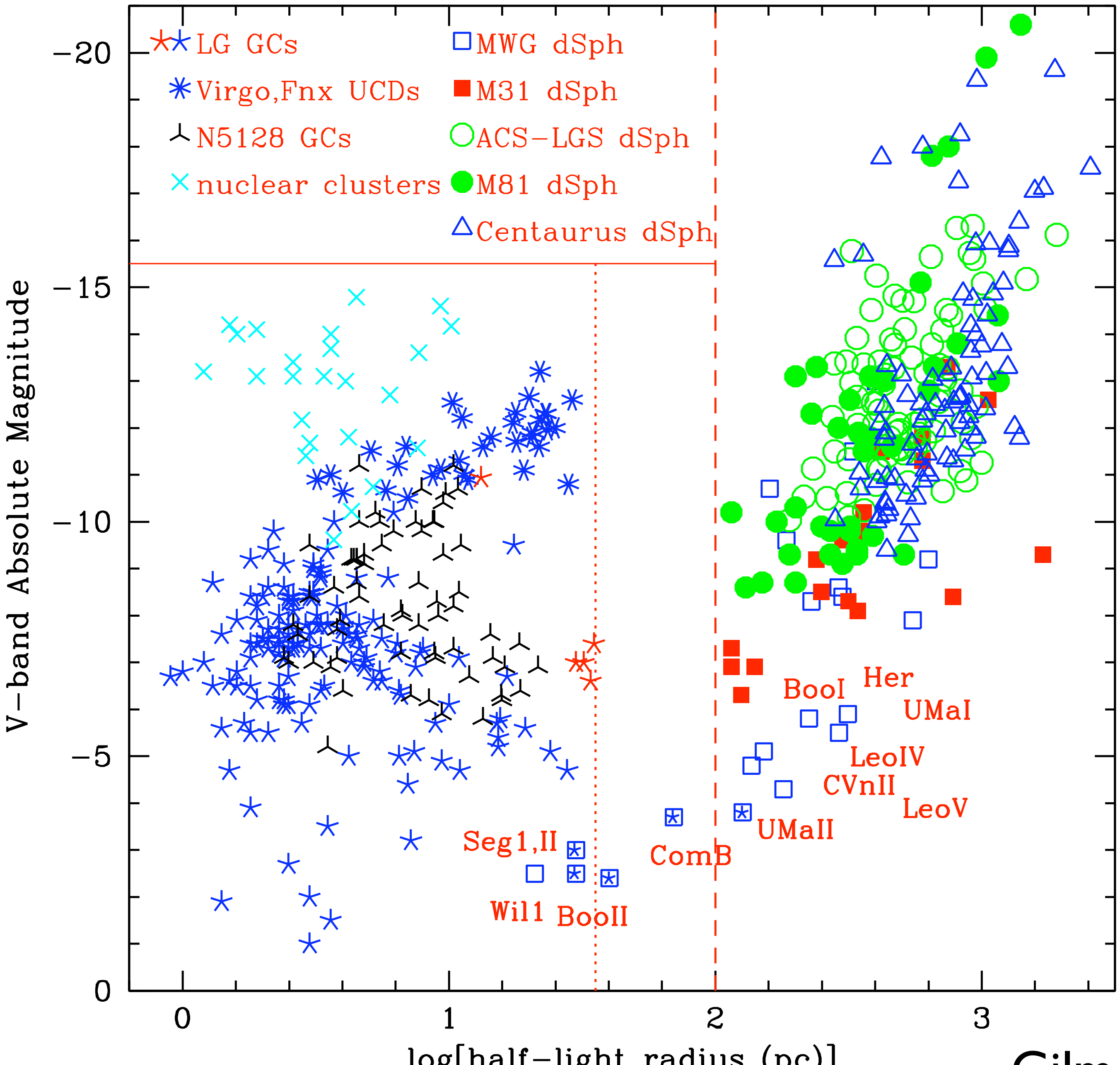
Mass-to-light ratios of star clusters



SDSS, 2002

- Presence of luminous tidal tails around star clusters shows that they are strongly affected by the Milky Way tidal field

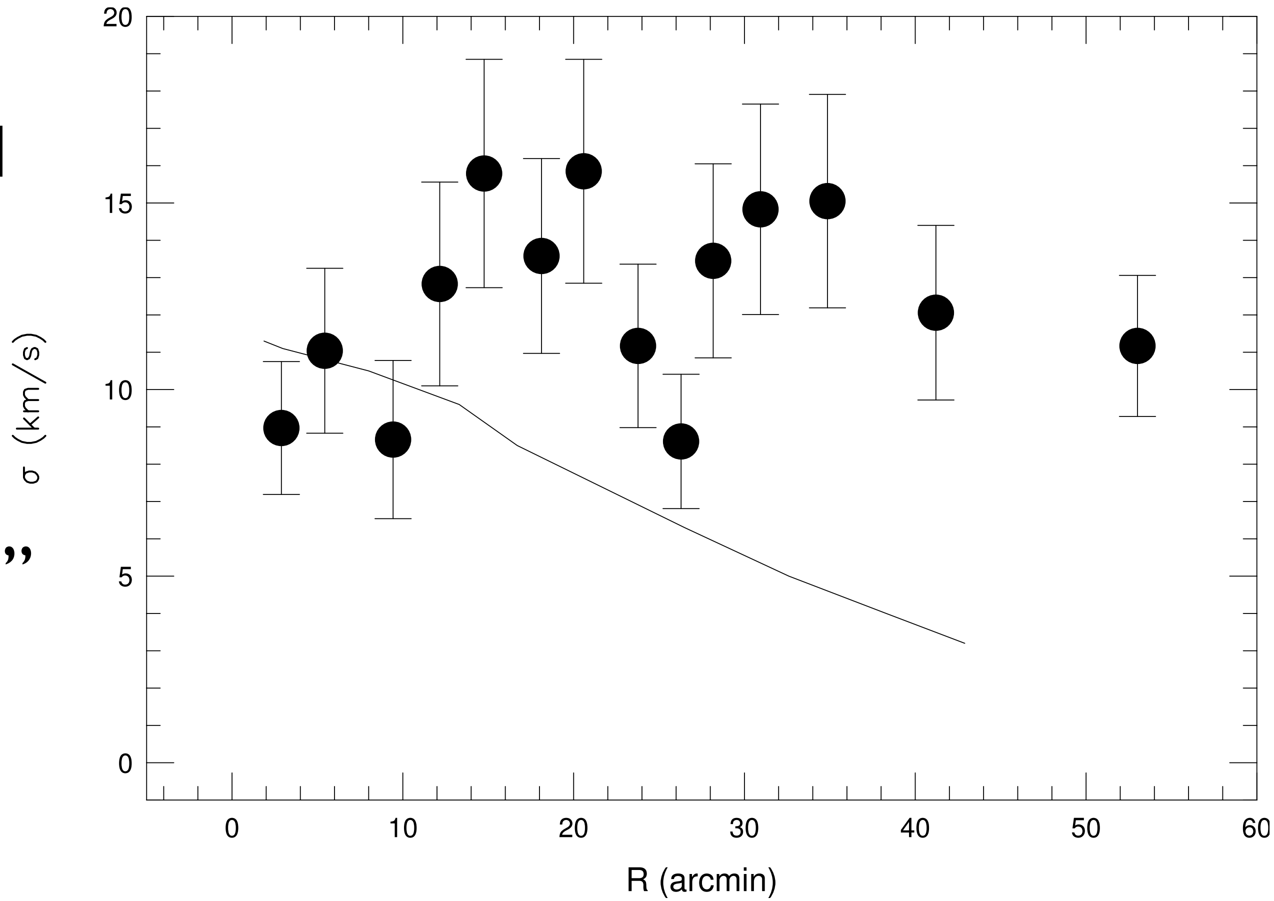
Size distribution of stellar systems



Gilmore et al. (2009)

Kinematic observations in dSphs

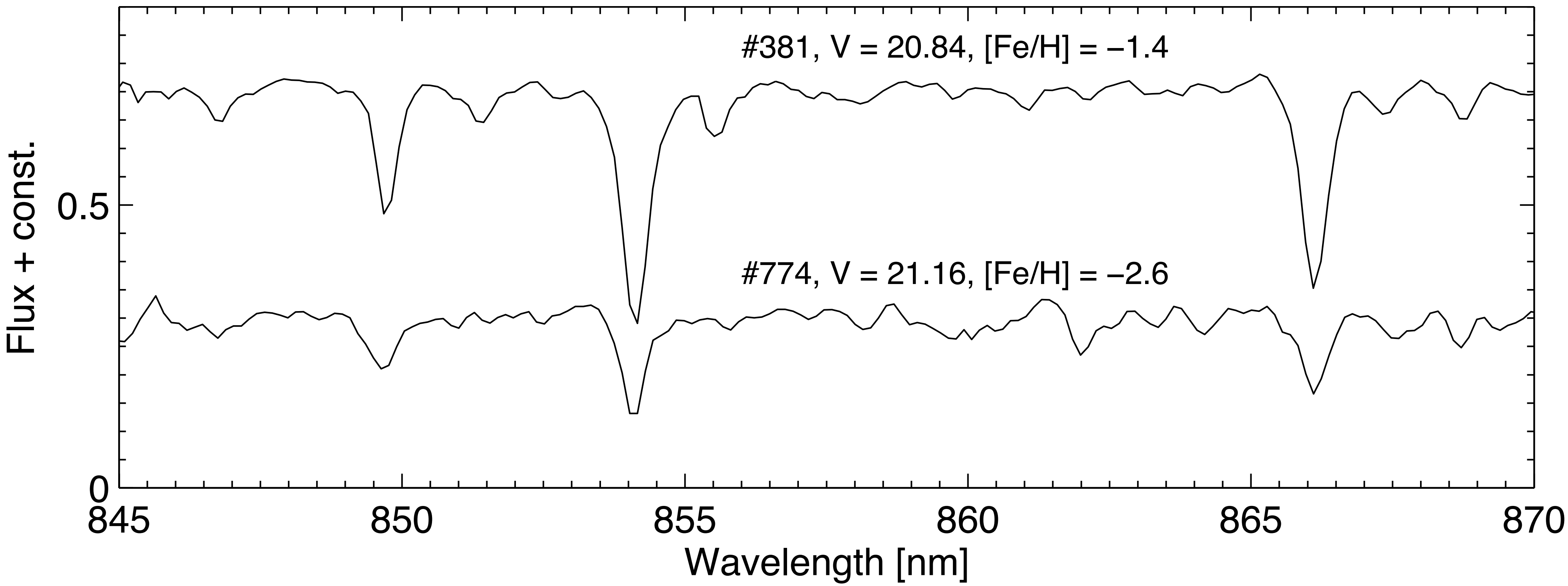
- 1983: Aaronson measured velocity dispersion of Draco based on observations of 3 carbon stars - inferred M/L ~ 30
- 1990: Pryor & Kormendy showed that extended haloes are compatible with observations of dispersions and light profiles
- 1997: Mateo published first dispersion profile of Fornax
- 2000+: Dispersion profiles of all "classical" dSphs now measured using multi-object spectrographs



Recent kinematic observations

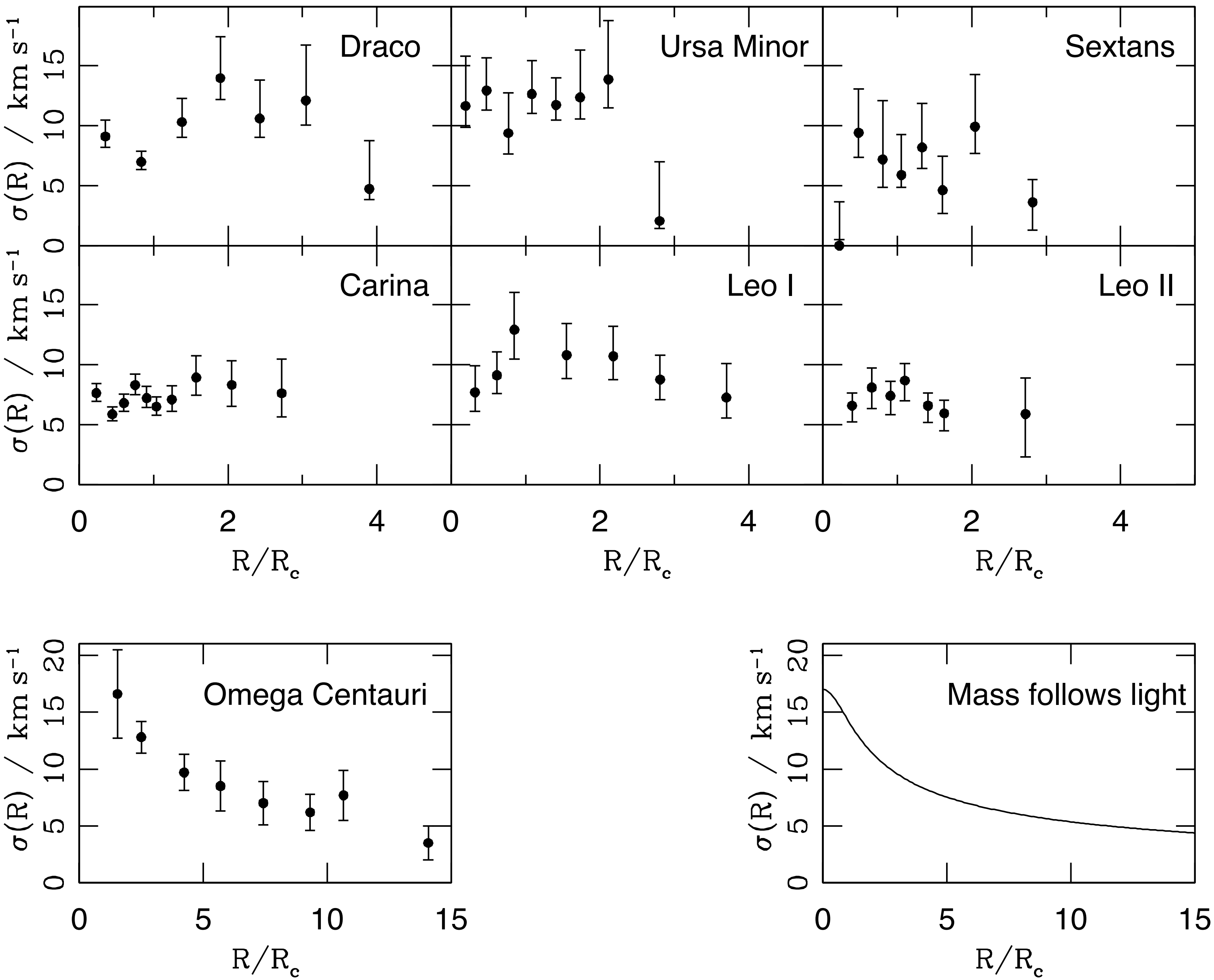
- Instruments: AF2/WYFFOS (WHT, La Palma); FLAMES (VLT); GMOS (Gemini); DEIMOS (Keck); MIKE (Magellan)
- Ca triplet velocities for (mostly) RGB stars with V $< 20.5 - 21$
- $\Delta v \sim 1 - 5\,\mathrm{km\,s^{-1}}$
- Full radial coverage in each dSph, now with ~ 1000 stars per galaxy
- Ca/Mg triplet abundance estimates also possible (e.g. Battaglia et al. 2006; Tolstoy et al. 2004; Koch et al. 2005; Walker et al. 2008)

Sample spectra



Koch et al. (2007)

dSph velocity dispersion profiles

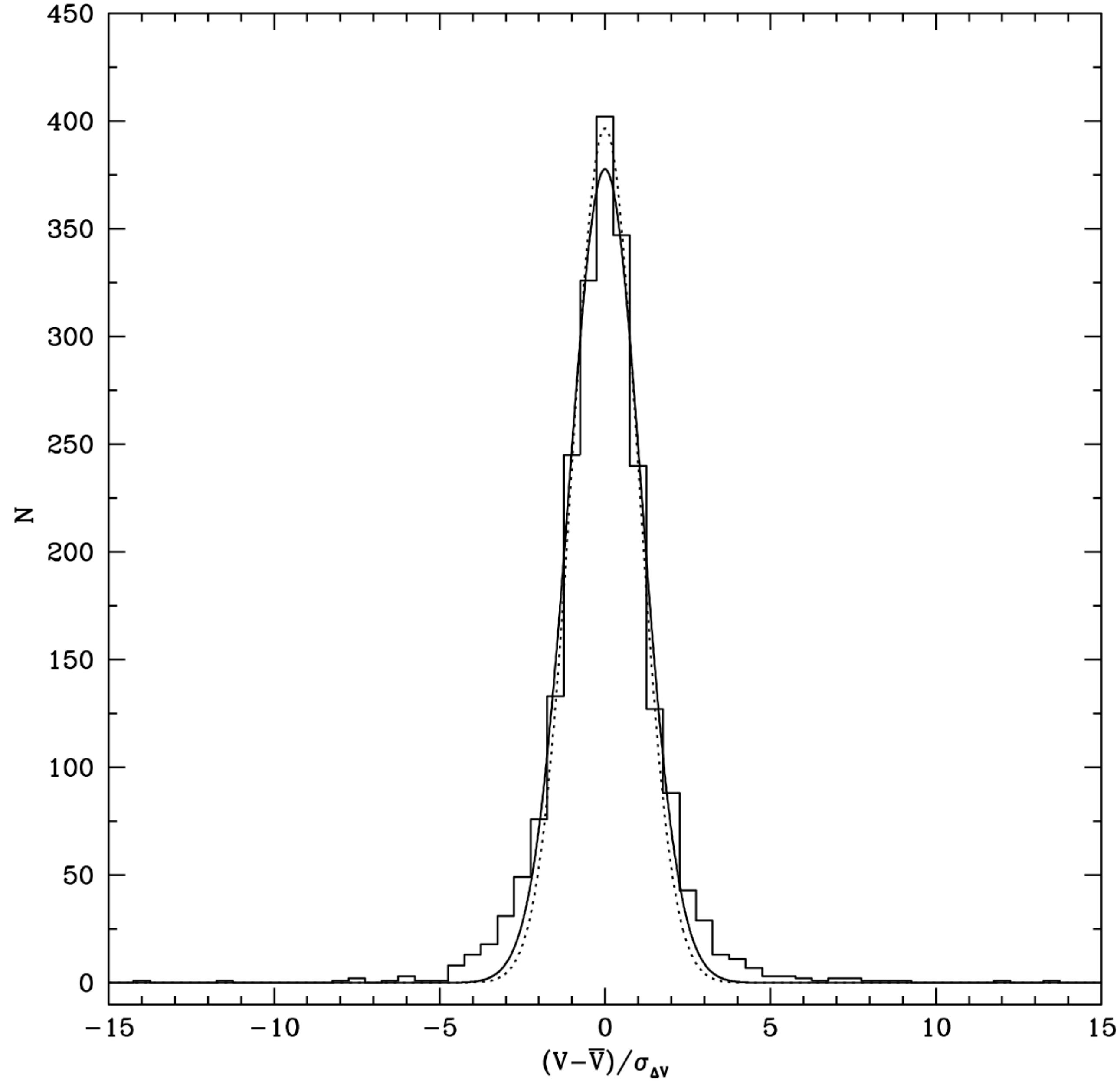


Gilmore et al. (2007)

Possible explanations for large velocity dispersions

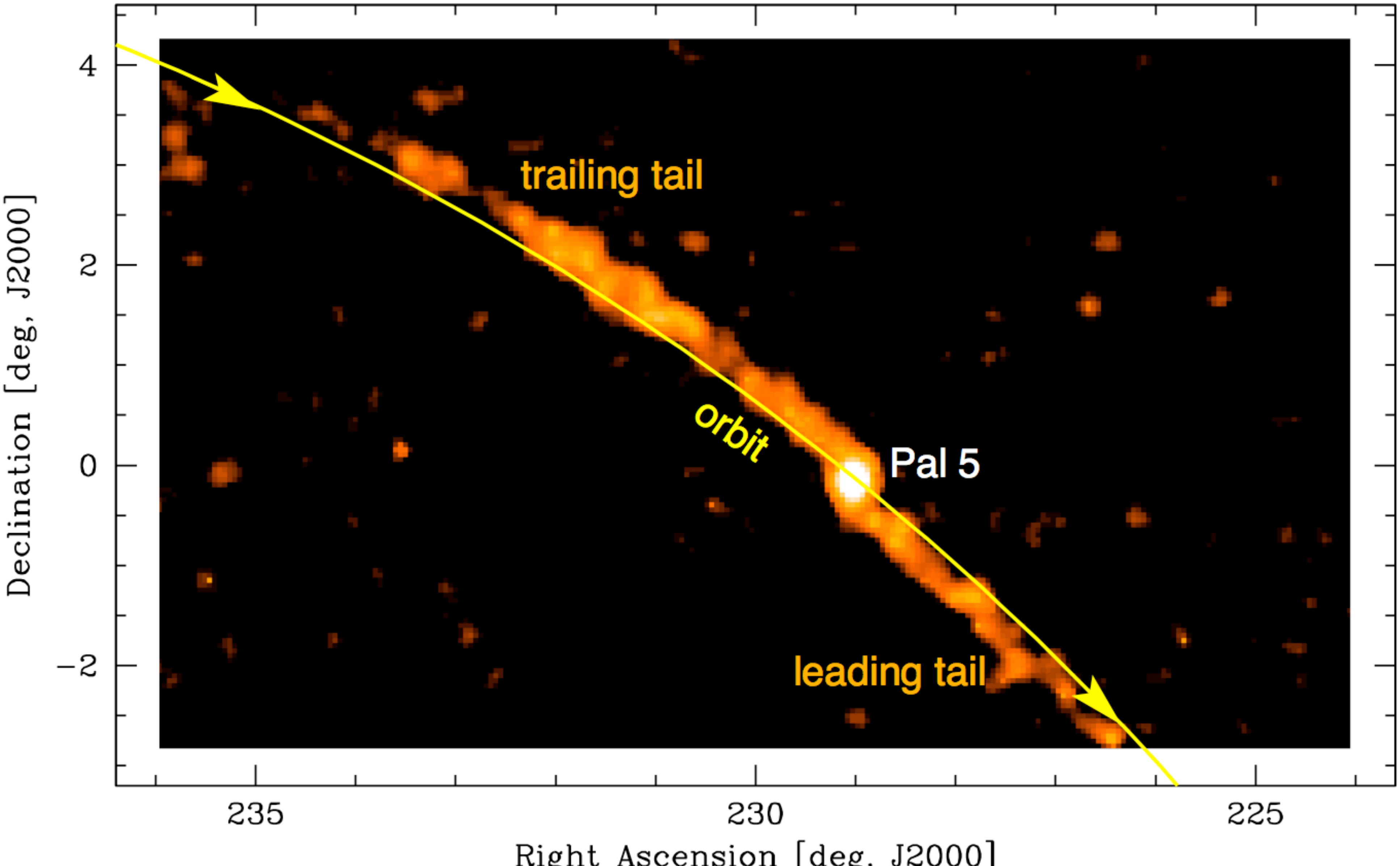
- Stellar atmospheric effects
  - **not** significant (Walker et al.,2005, 2006)
- Binary stars
  - **not** significant (Kleyna et al. 2002; Walker et al., 2006)
- Tidal interaction with the Milky Way
- Anisotropic velocity distribution
- Dark matter halo
- MOdified Newtonian Dynamics (MOND)?

Binary fractions in dSphs



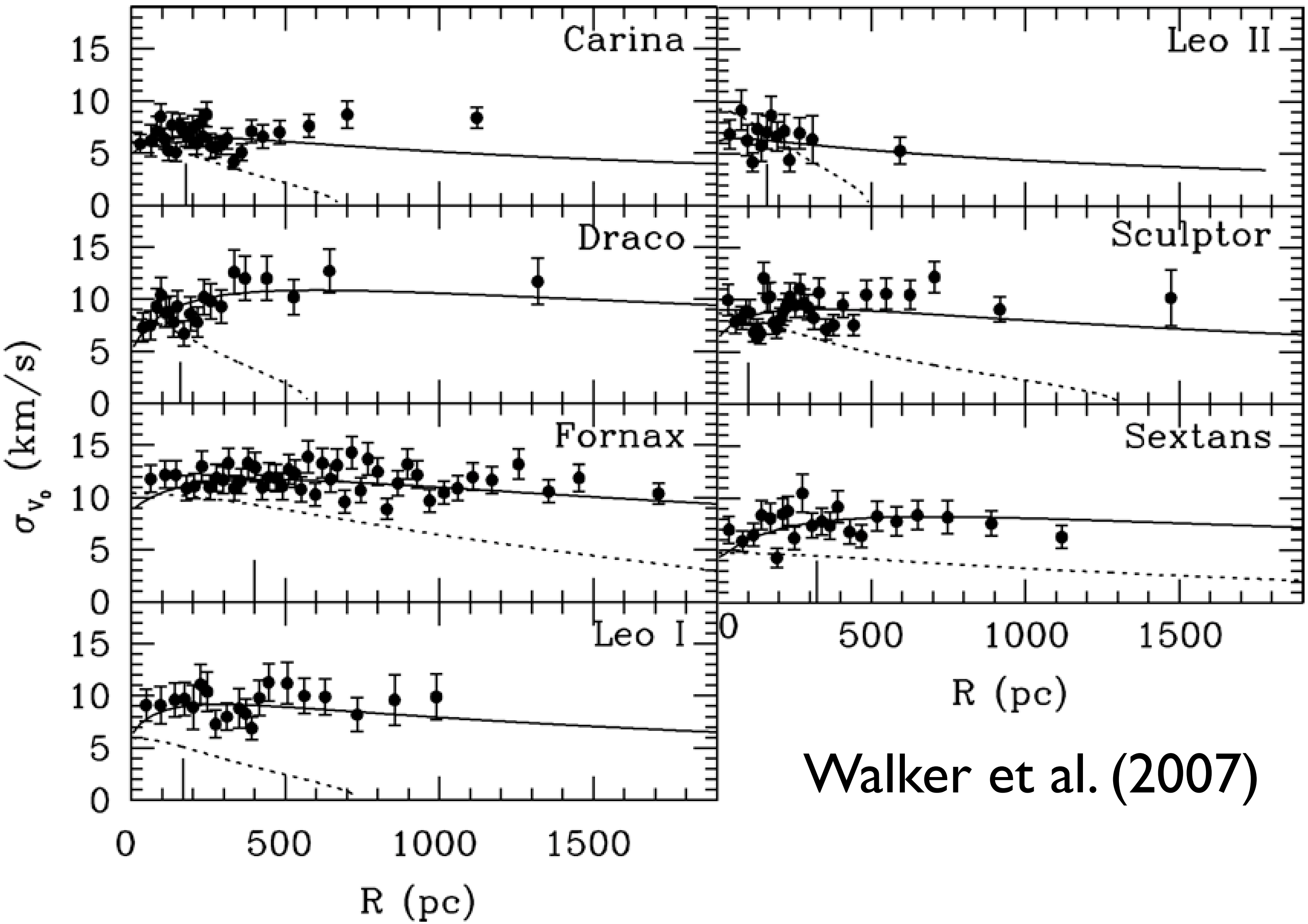
Walker et al., 2006

Tidal tails and dSph dispersions



SDSS, 2002

Velocity dispersion profiles II



Walker et al. (2007)

dSph dispersion profiles generally remain flat to large radii

Mass profiles of dSphs

Jeans equations give simple relation between kinematics, the light distribution and the underlying mass distribution

$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\,\nu\sigma_r^2}{\mathrm{d}\,r} + 2\,\frac{\beta\sigma_r^2}{r}\right) \qquad \beta(r) = 1 - \frac{\langle v_{\mathrm{t}}^2\rangle}{2\langle v_{\mathrm{r}}^2\rangle}$$

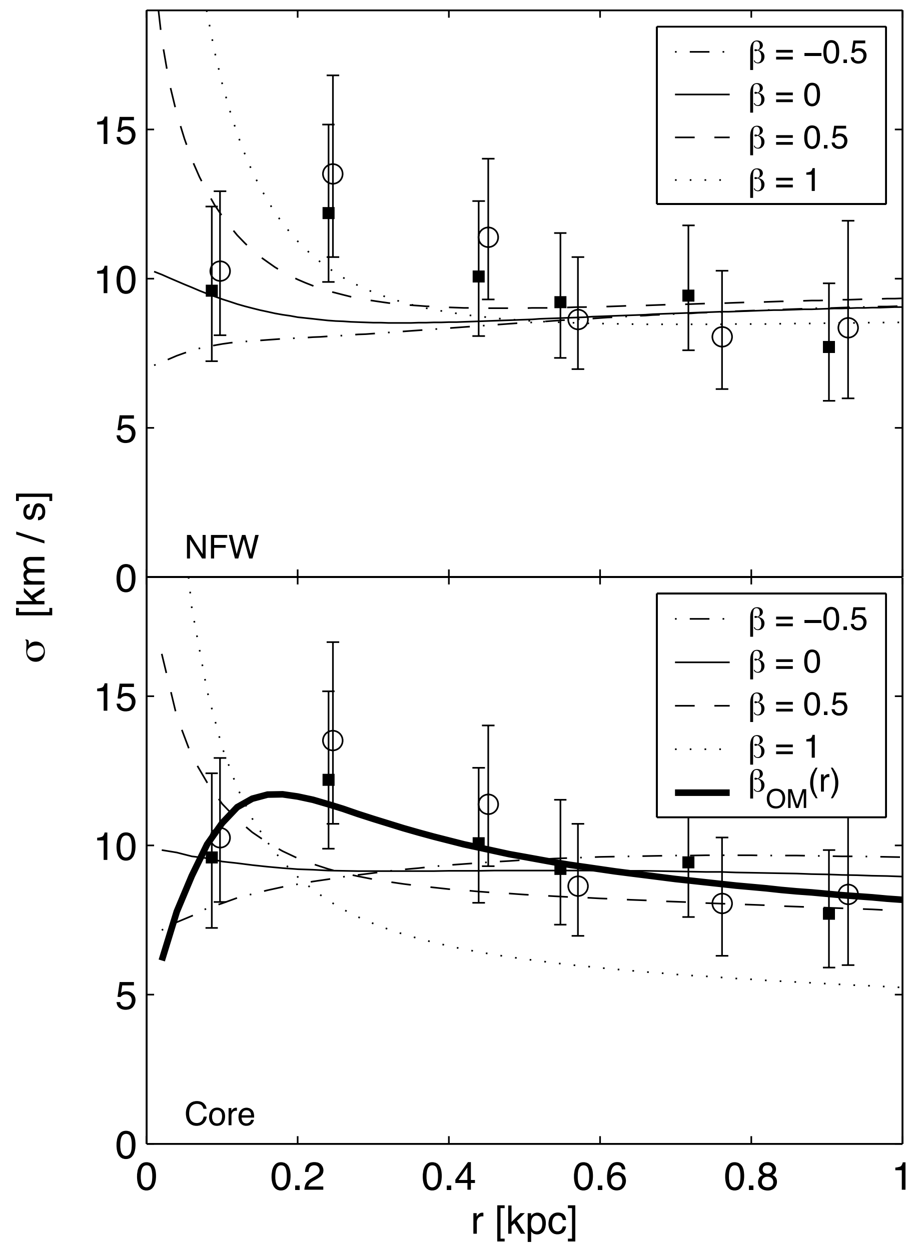
We can either:

1. Assume a parameterised mass model $M(r)$ and velocity anisotropy $\beta(r)$ and fit dispersion profile

    or

2. Use Jeans equations to determine mass profile from projected velocity dispersion profile and a fit to the light distribution

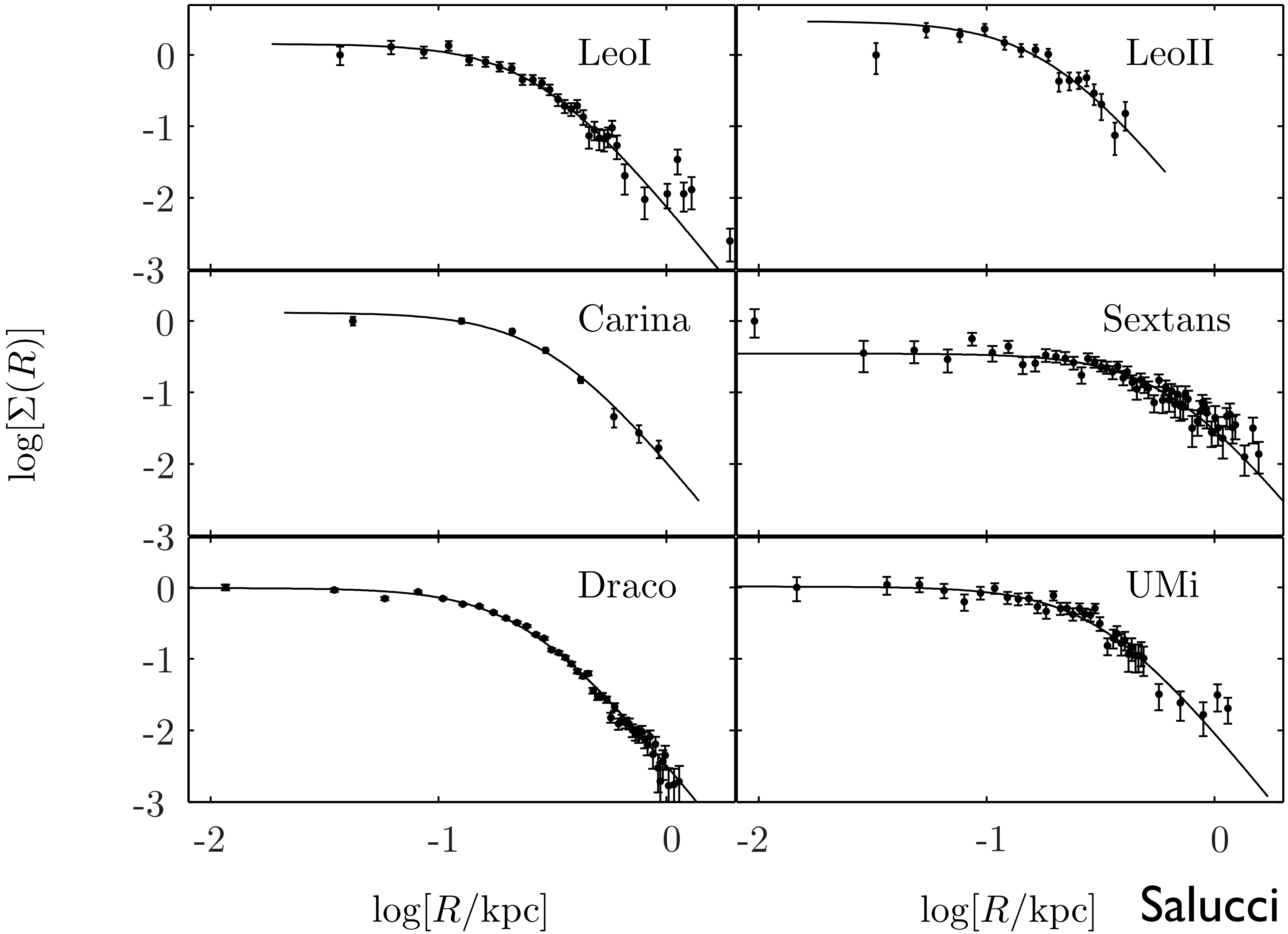
Fitting dSph dispersion profiles: Leo I



Koch et al. (2007)

- Assume either NFW halo (1 free halo parameter) or generalised Hernquist profile (4 free halo parameters)
- Best-fit dispersion obtained for cored profiles with roughly isotropic velocity dispersions
- Significant velocity anisotropy not favoured (but not excluded)
- Enclosed mass $\sim 8 \times 10^7 M_\odot$ in both cored and cusped haloes

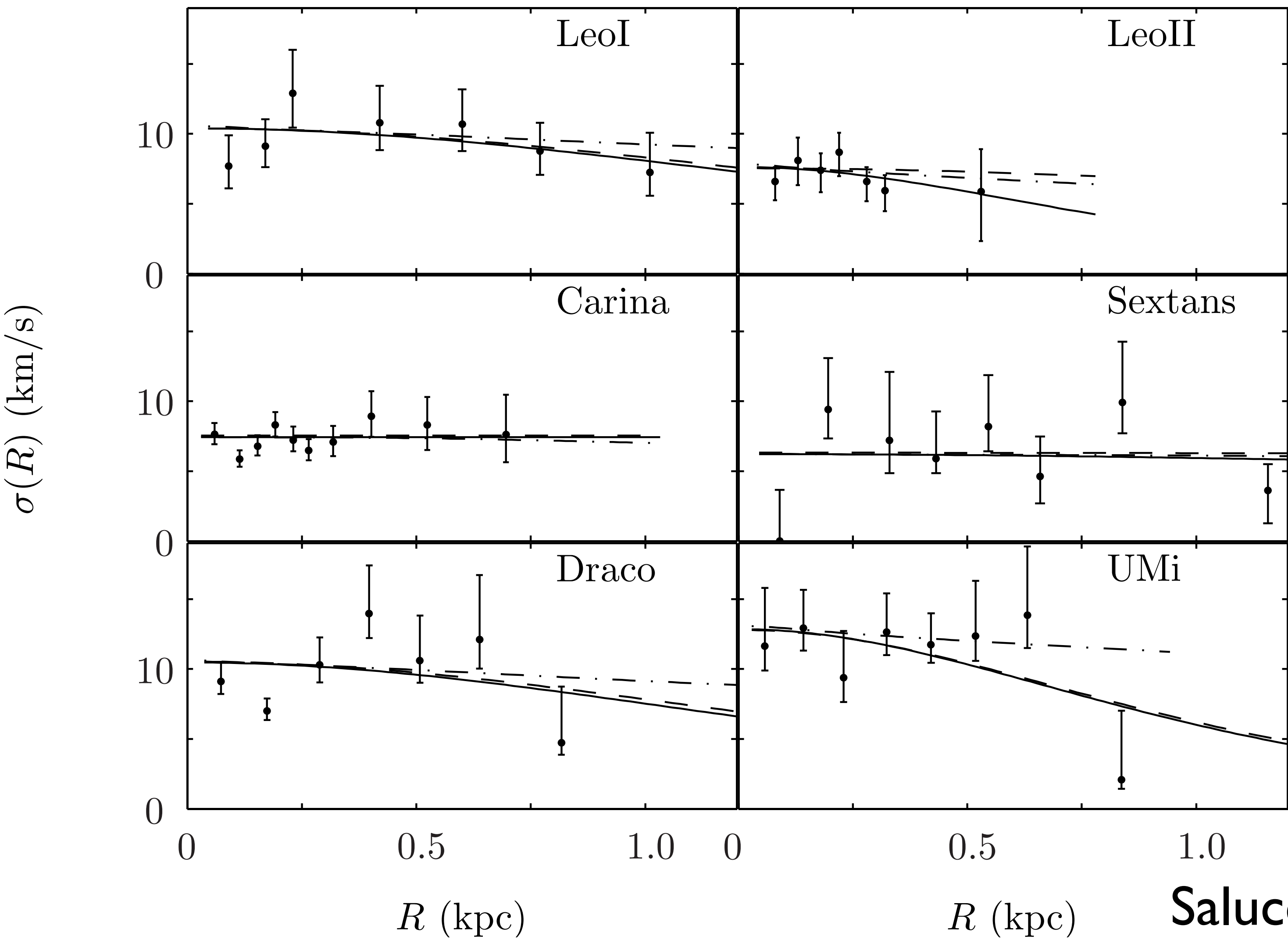
Jeans equation models of dSph haloes



Salucci et al., (2009)

- Stellar density profiles fitted with Plummer models

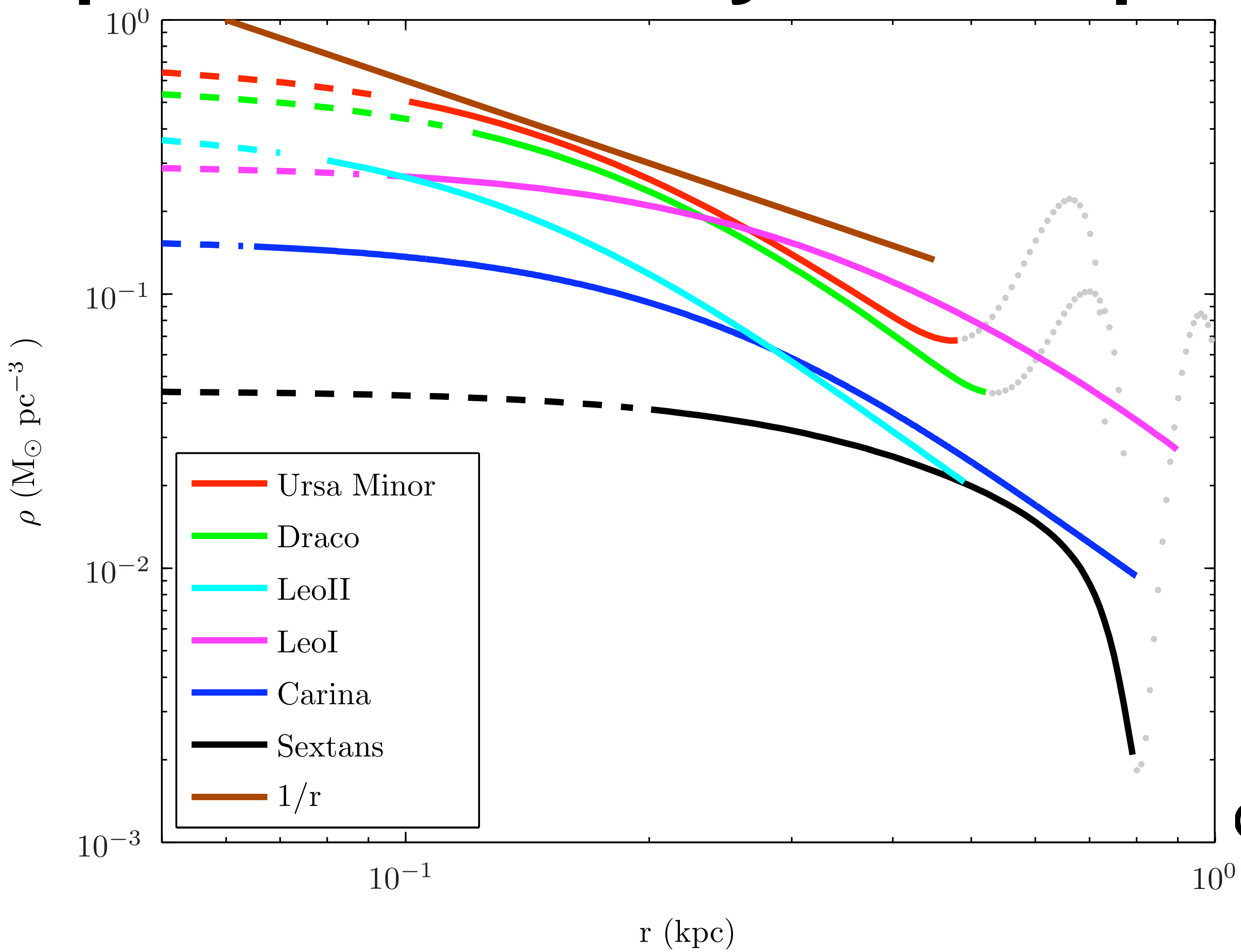
Jeans equation models of dSph haloes



Salucci et al., (2009)

- Velocity dispersion profiles: $\sigma(R) = \dfrac{\sigma_0}{\left(1 + \left(\frac{R}{R_s}\right)^2\right)^2}$

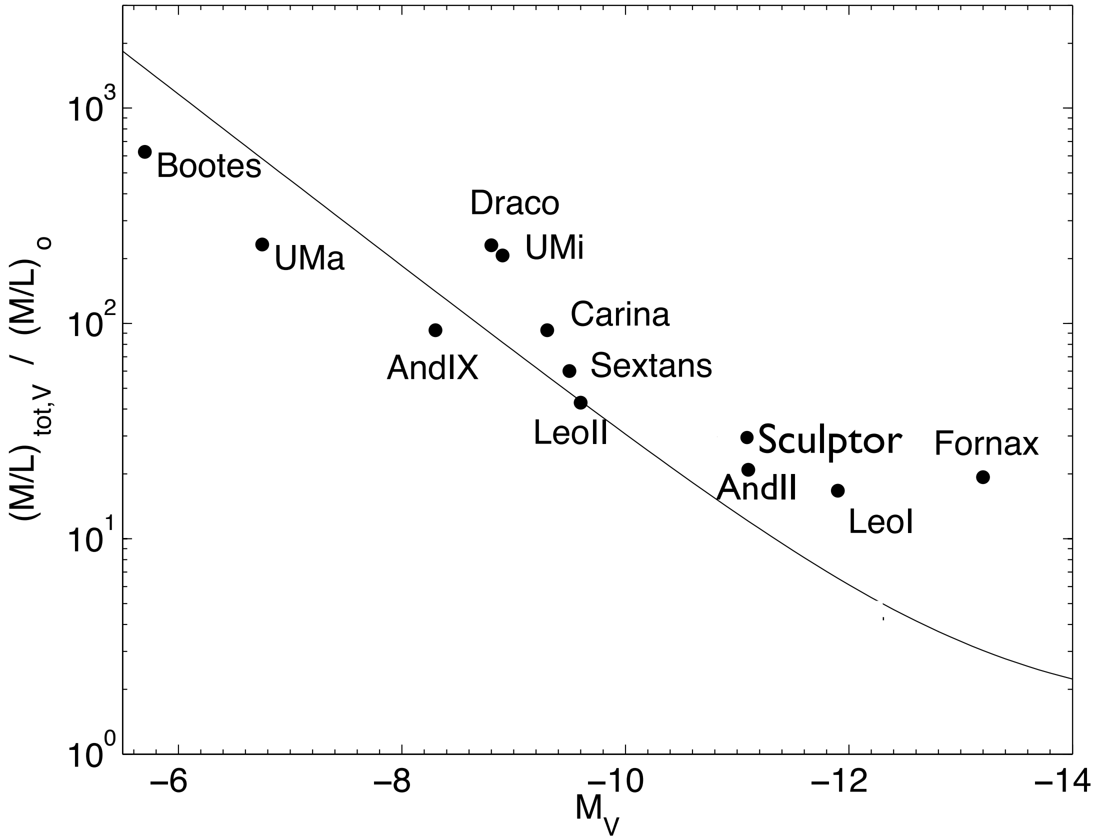
Halo profiles from Jeans equations



Gilmore et al., (2007)

- Assumptions: spherical symmetry, velocity isotropy, equilibrium
- Kinematics consistent with cored haloes

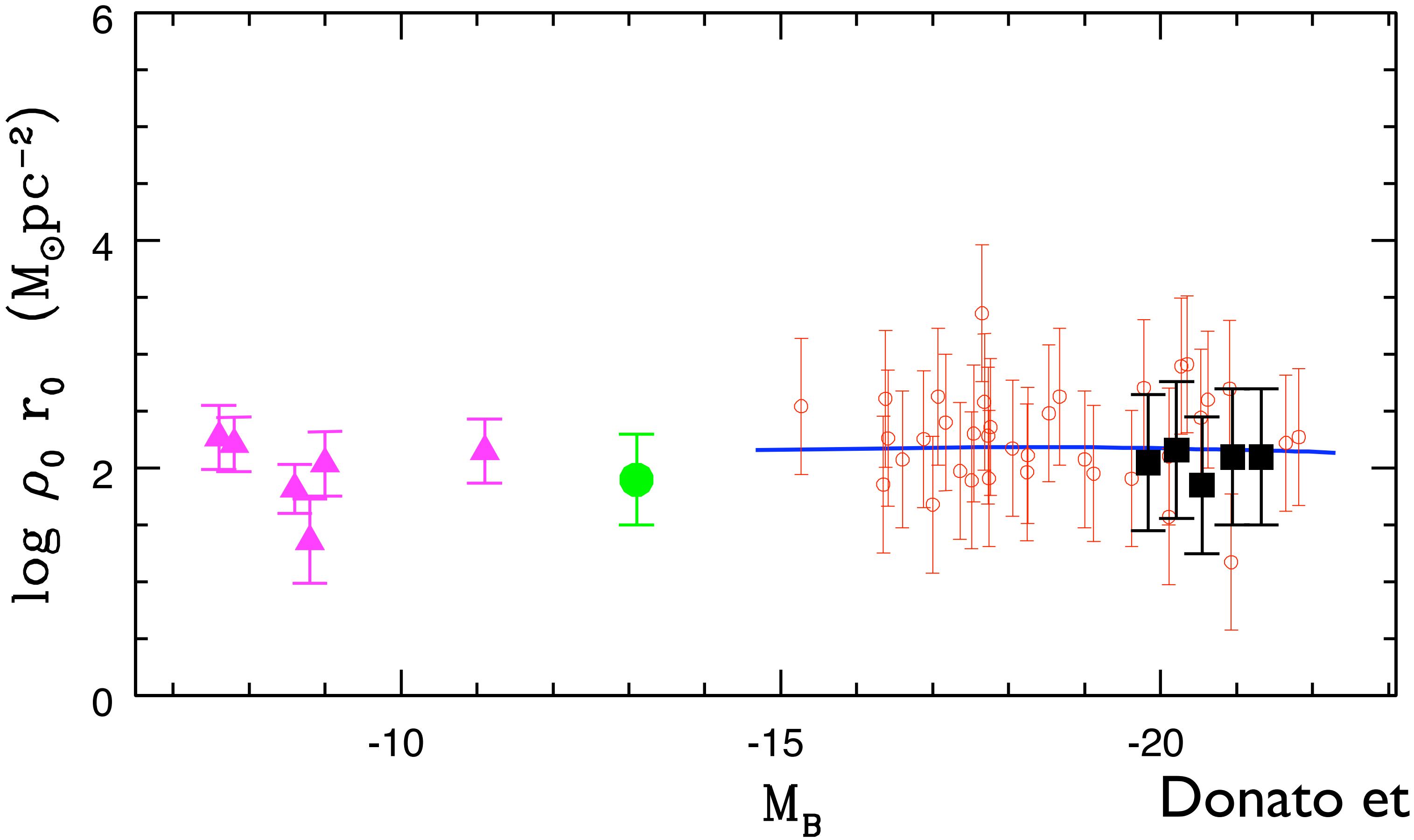
Global trends of dSph haloes



Mateo et al. (1998)
Gilmore et al. (2007)

- Majority of current data consistent with cored dark matter distributions and a mass scale (interior to light) of $\sim 4 \times 10^7 \mathrm{M}_\odot$
- Mean dark matter density $\lesssim 0.1\, \mathrm{M}_\odot\, \mathrm{pc}^{-3} (5 \mathrm{GeV/c^2\, cm^{-3}})$
- NFW halo: $\overline{\rho}(r < 10\, \mathrm{pc}) \approx 60\, \mathrm{M}_\odot\, \mathrm{pc}^{-3} (2\, \mathrm{TeV/c^2 cm^{-3}})$

A constant projected halo density?



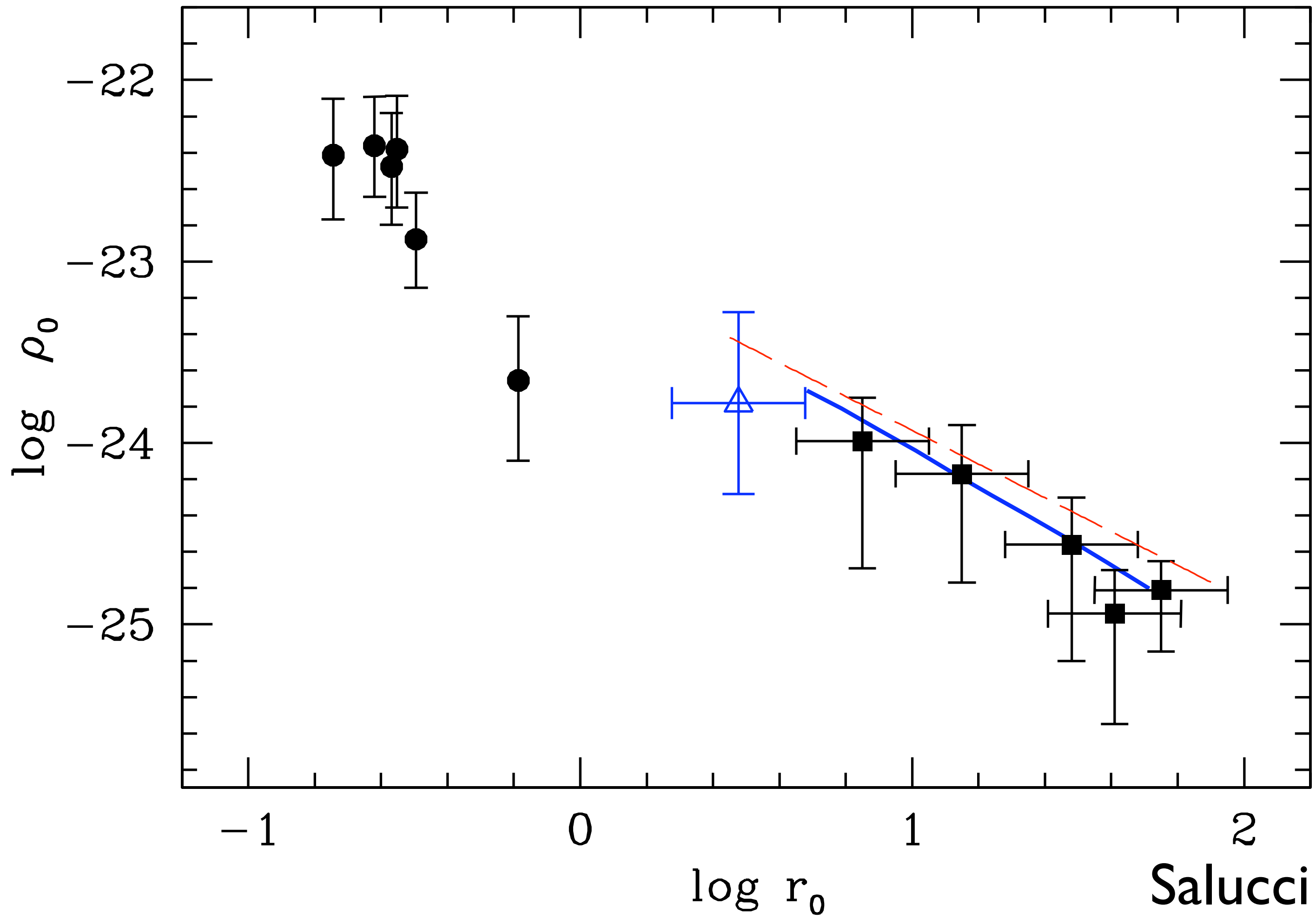
Donato et al., subm.

- Spiral and LSB galaxy data are consistent with constant value of $\rho_0 r_0 = 110^{+50}_{-30}\,\mathrm{M_\odot pc^{-2}}$

  (c.f. Kormendy & Freeman, 2004; Spano et al. 2008)

- dSph data consistent with the extrapolation of this relation

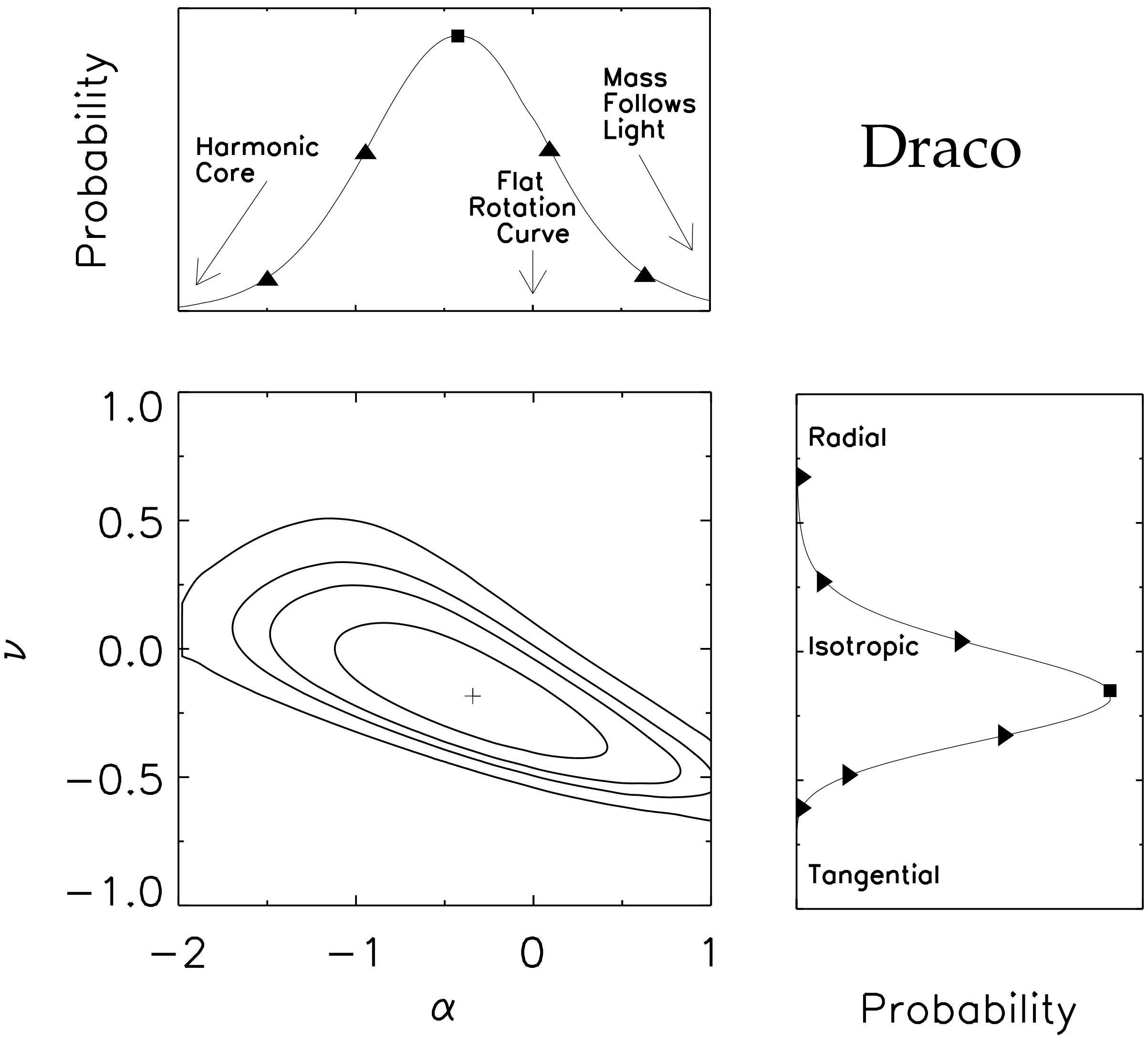
dSph/spiral scaling relations?



Salucci et al., in prep.

- Without knowledge of velocity anisotropy, halo core radii r_0 are *not constrained* by the dispersion profiles alone
- However, dSph data are consistent with *extrapolations* from spiral scaling relations (the "Universal Rotation Curve")

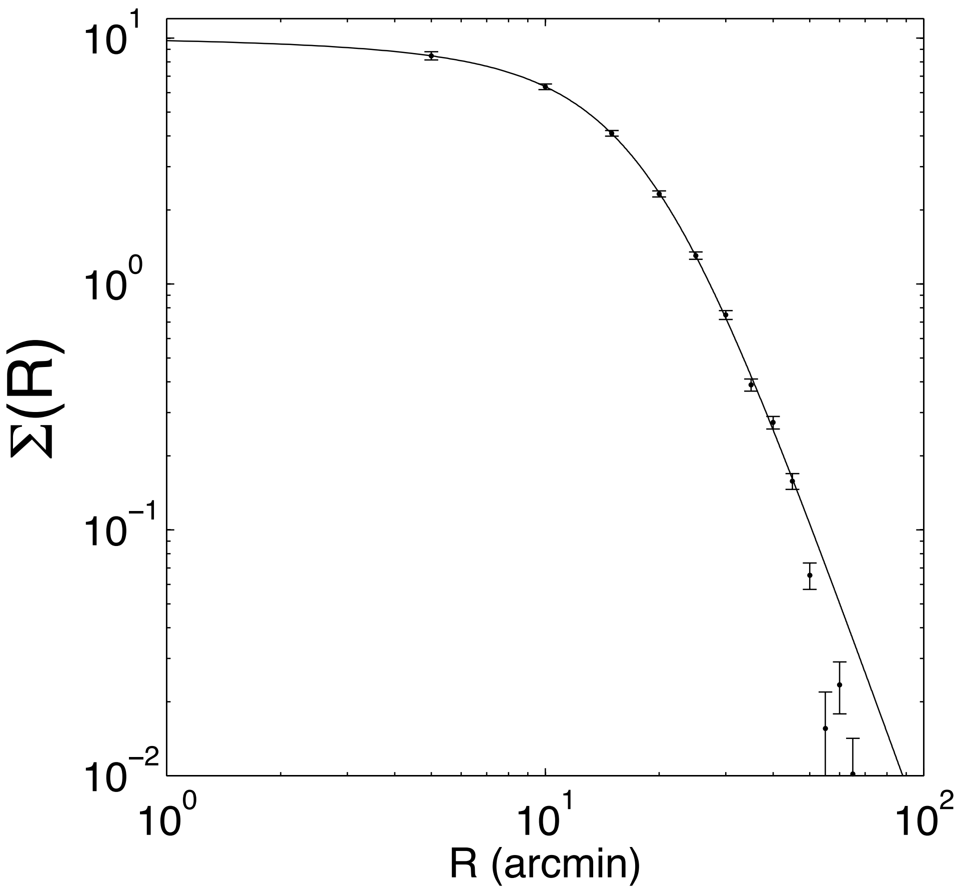
Distribution function modelling:
breaking the mass-anisotropy degeneracy



Kleyna et al. (2002); Wilkinson et al. (2002)

- 2-parameter models (halo profile extent, velocity anisotropy)
- Use un-binned spatial and velocity distribution of the stars
- Model convolved with observational errors and binary velocities
- Mass-follows-light models excluded at $> 2.5\sigma$

Can we measure dSph halo profiles?

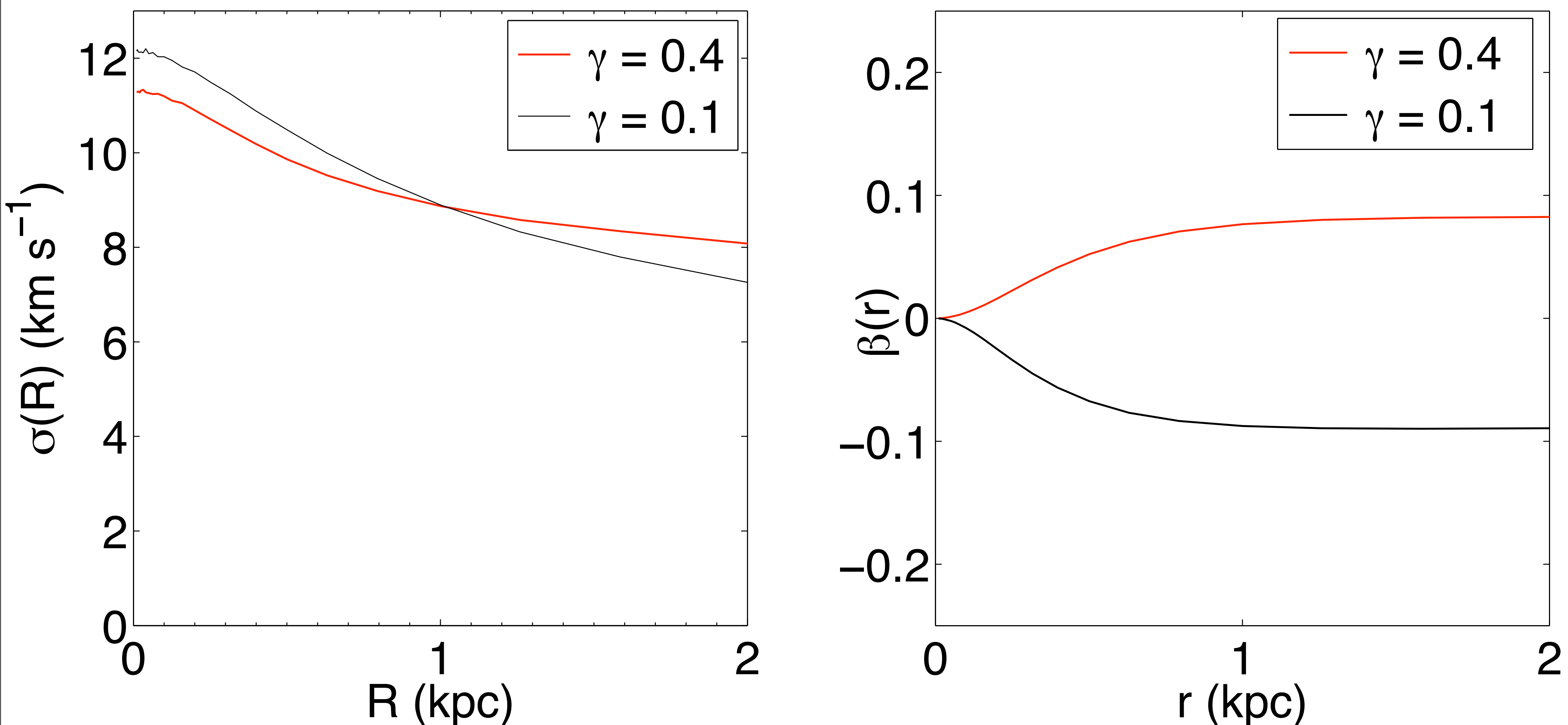


- Dispersion profiles alone cannot break degeneracy between mass profile and velocity anisotropy
- New family of distribution functions of form (Gerhard et al. 1991)
  $F(E, L) = g(E)h(E, L^2)$
- Halo profile with 5 parameters

Wilkinson et al., in prep.

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_\mathrm{s}}\right)^{\gamma} \left(1 + \left(\frac{r}{r_\mathrm{s}}\right)^{1/\alpha}\right)^{\alpha(\beta-\gamma)}}$$

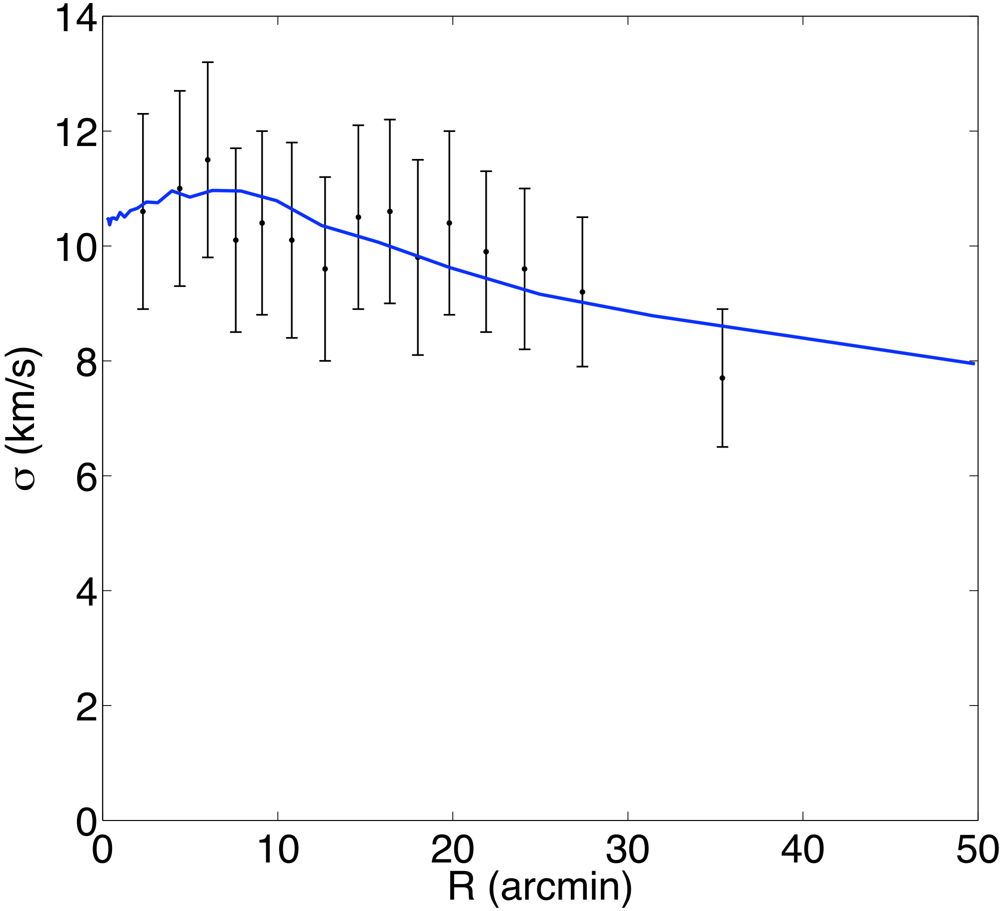
Breaking the mass-anisotropy degeneracy

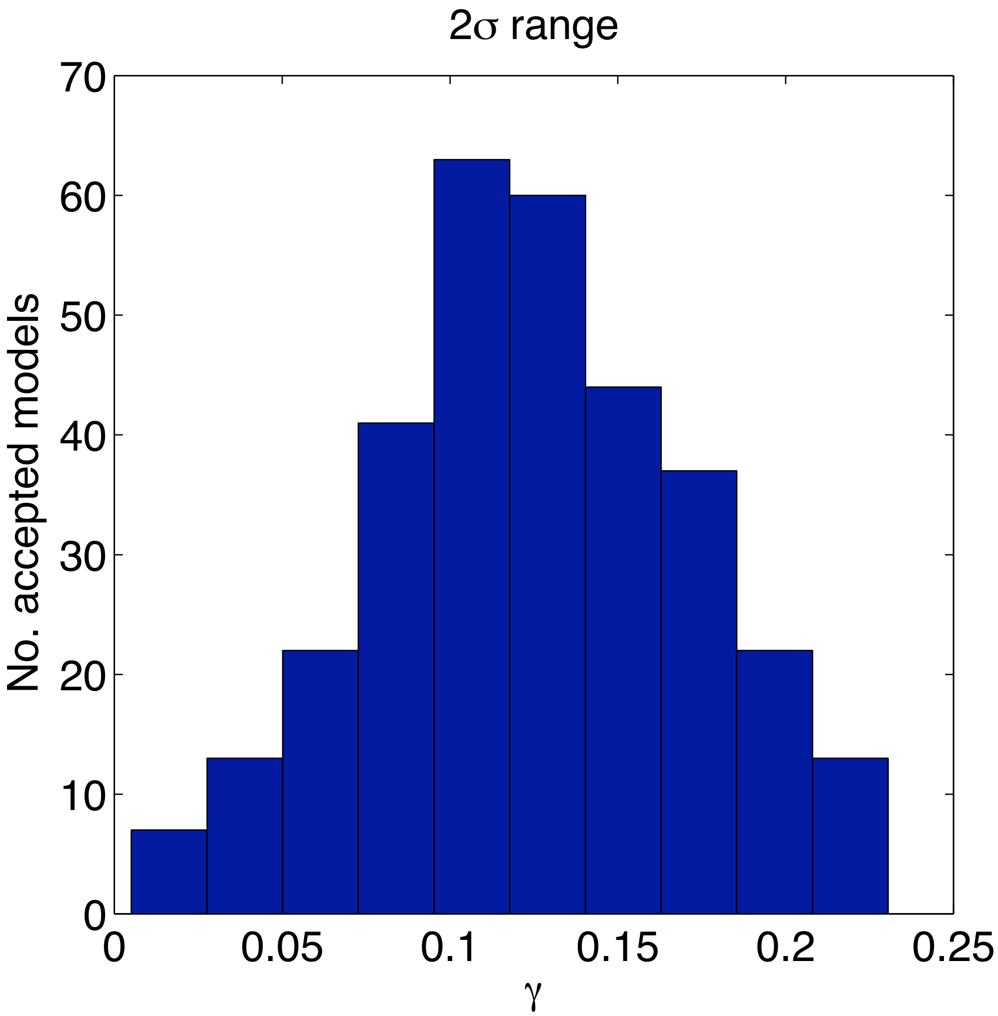


Wilkinson et al., (in prep.)

- Data-sets of ~1000s of stars required to break degeneracy and constrain log-slope of inner density profile

Fornax kinematics: first hint of a core





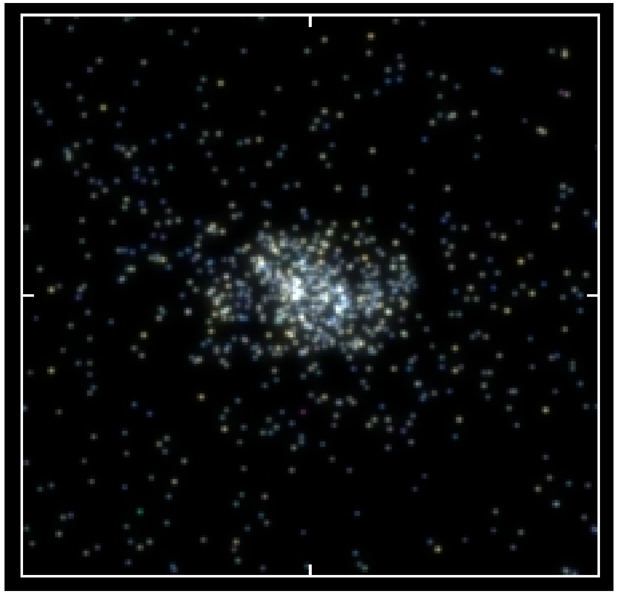
- Markov-Chain-Monte-Carlo used to scan parameter space
- Shallow inner profiles marginally preferred by data

Conclusions

- Dwarf spheroidal galaxies are valuable laboratories for investigating the small-scale distribution of dark matter
- Current kinematic data are consistent with high mass-to-light ratios and cored dark matter distributions
- Distribution-function models of individual stellar velocities can constrain halo density profiles
- (Preliminary) Dynamical models suggest shallow inner halo slope in Fornax

New dSphs in the SDSS

CVnI



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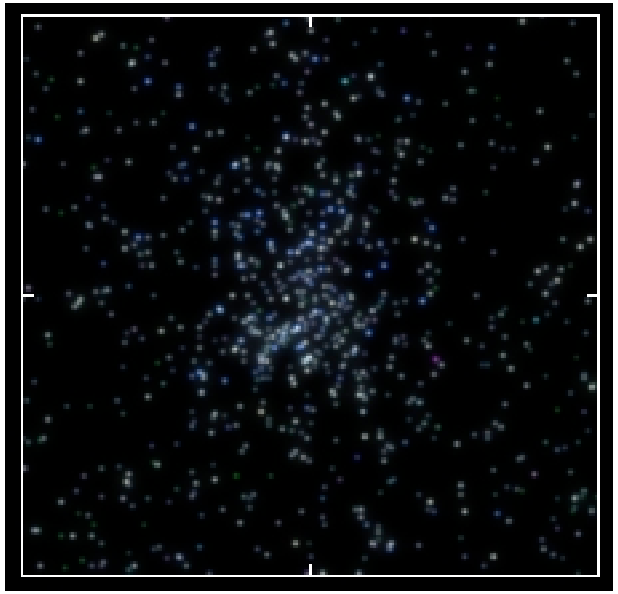
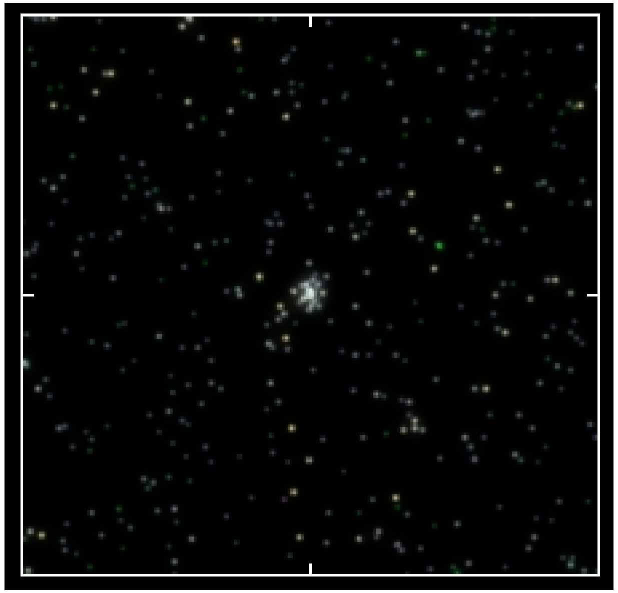


- Ultra-faint companions to Milky Way
- Some likely to be in process of tidal disruption

CVnII



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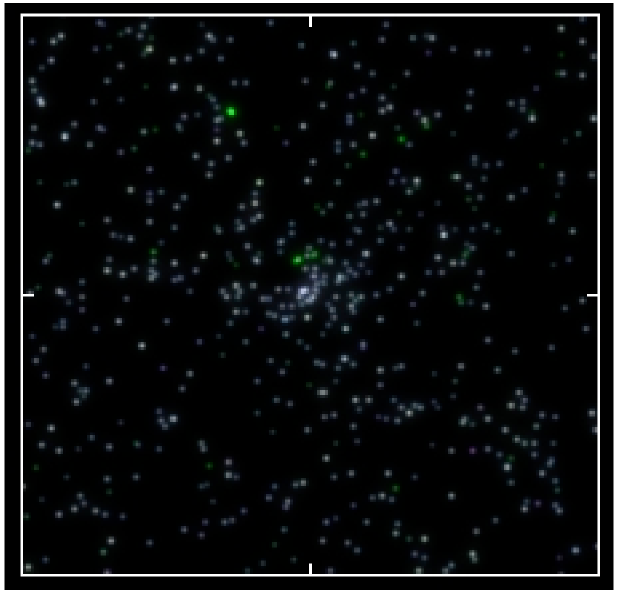
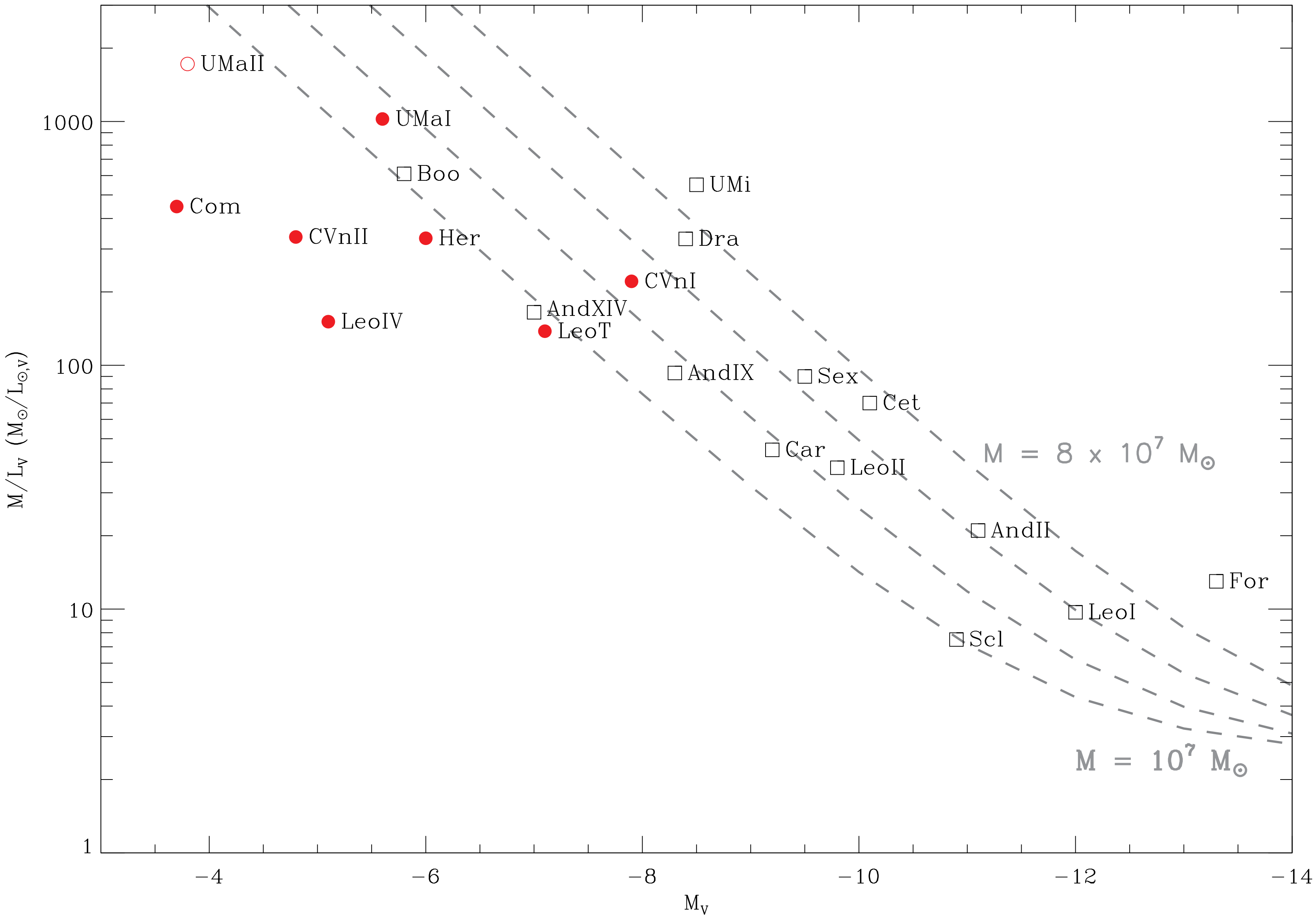


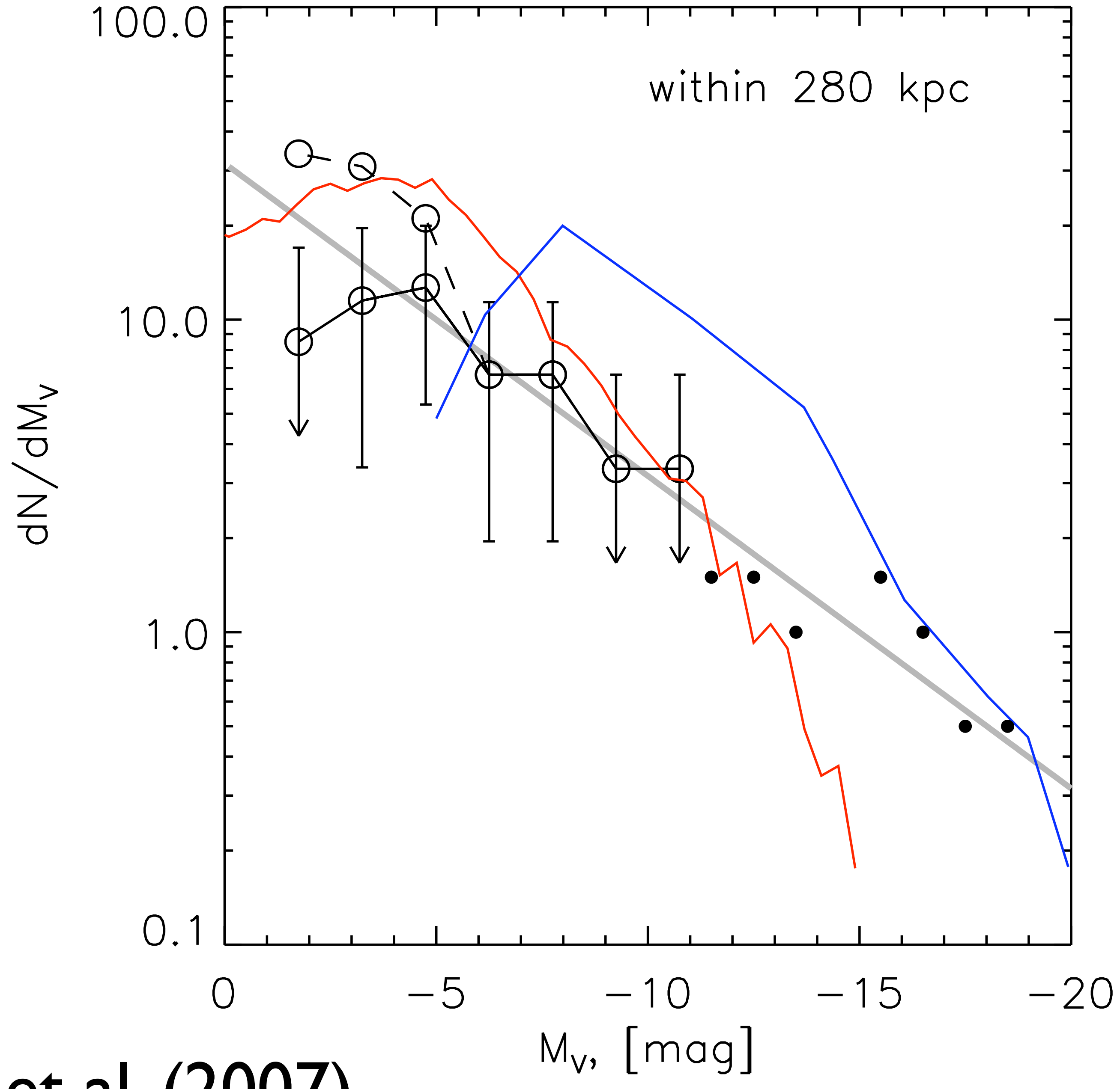
Belokurov et al.
Zucker et al.

Including the new dSphs...



Simon & Geha (2007)

The dSph luminosity function



Koposov et al. (2007)