Dwarf Galaxies and Dark Matter

Eva K. Grebel

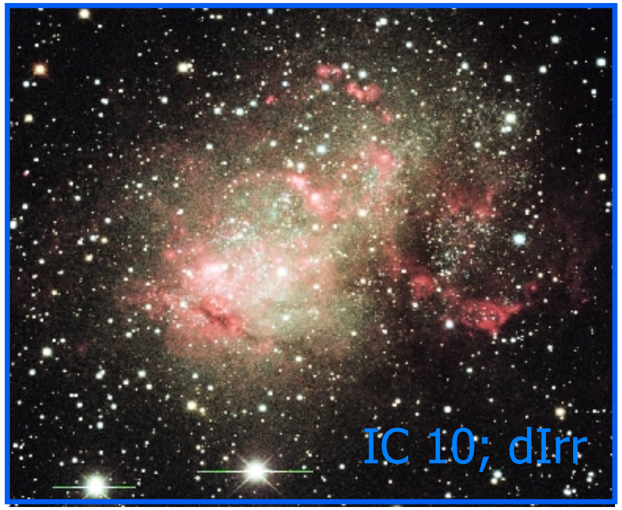
Astronomisches Rechen-Institut

Zentrum für Astronomie

der Universität Heidelberg

Why should you care about dwarf galaxies?

- Most numerous type of galaxy in the Universe
- Probably most dark-matter-dominated type of galaxy
- Possibly counterparts of cosmologically predicted small dark matter halos
  - ➡ Leftovers of cosmological building blocks
- Test objects for cosmological & galaxy evolution theories



Dwarf Galaxy Types $(\leq 1/100\ L_{\star};\ M_V \geq -18)$

- Dwarf elliptical galaxies
- Dwarf spheroidal galaxies
- Dwarf irregular galaxies
- Dwarf spiral galaxies / dwarf lenticulars
- Blue compact dwarf galaxies
- Ultra-compact dwarf galaxies
- Tidal dwarf galaxies (without dark matter)

Local Group

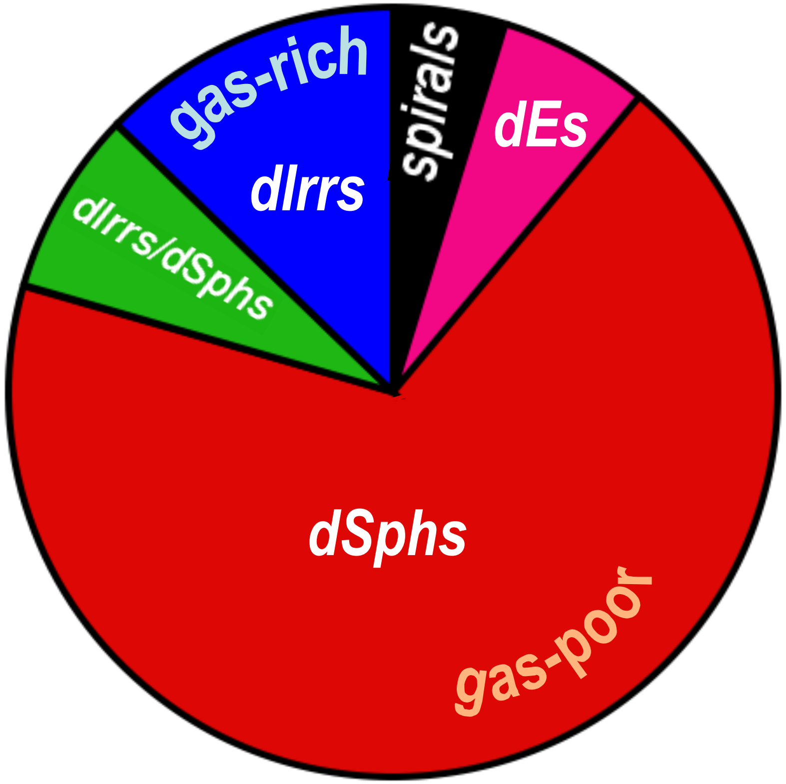
Milky Way

The evolving Local Group galaxy census

Certain or probable members:

≥ 71 galaxies within R_0 ~ 1 Mpc.

- 3 spiral galaxies (~ 95% mass).
- ≥ 68 dwarf and satellite galaxies (typically, $M_V \geq -18$).



Gas-deficient, late-type dwarf galaxies:

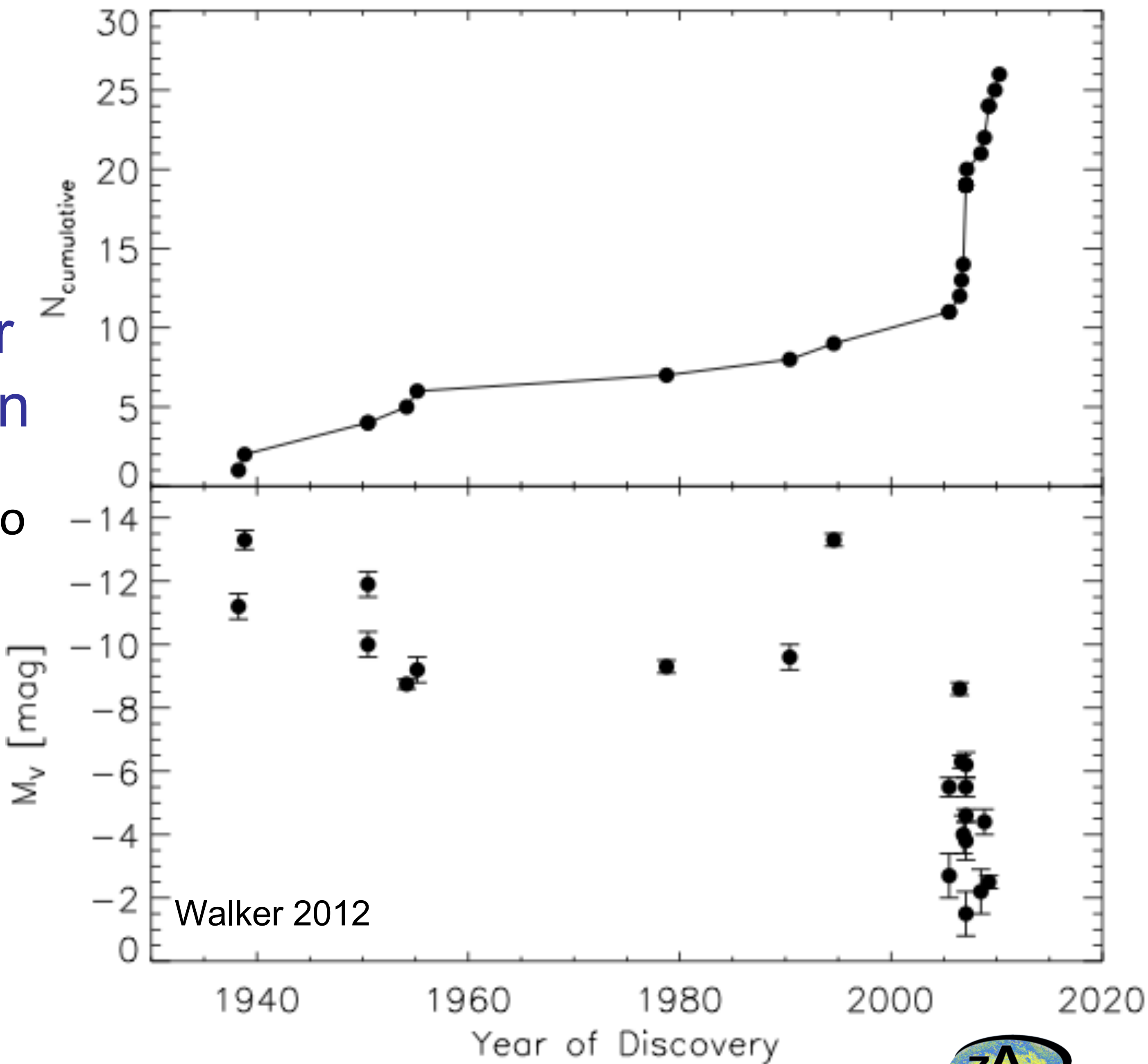
dwarf elliptical (**dEs: 3; 1 cE**) & dwarf spheroidal galaxies (**dSphs: 51**)

Gas-rich, early-type dwarf galaxies:

dwarf irregular galaxies (**dIrrs: 8**), transition types (**dIrrs/dSphs: 5**)

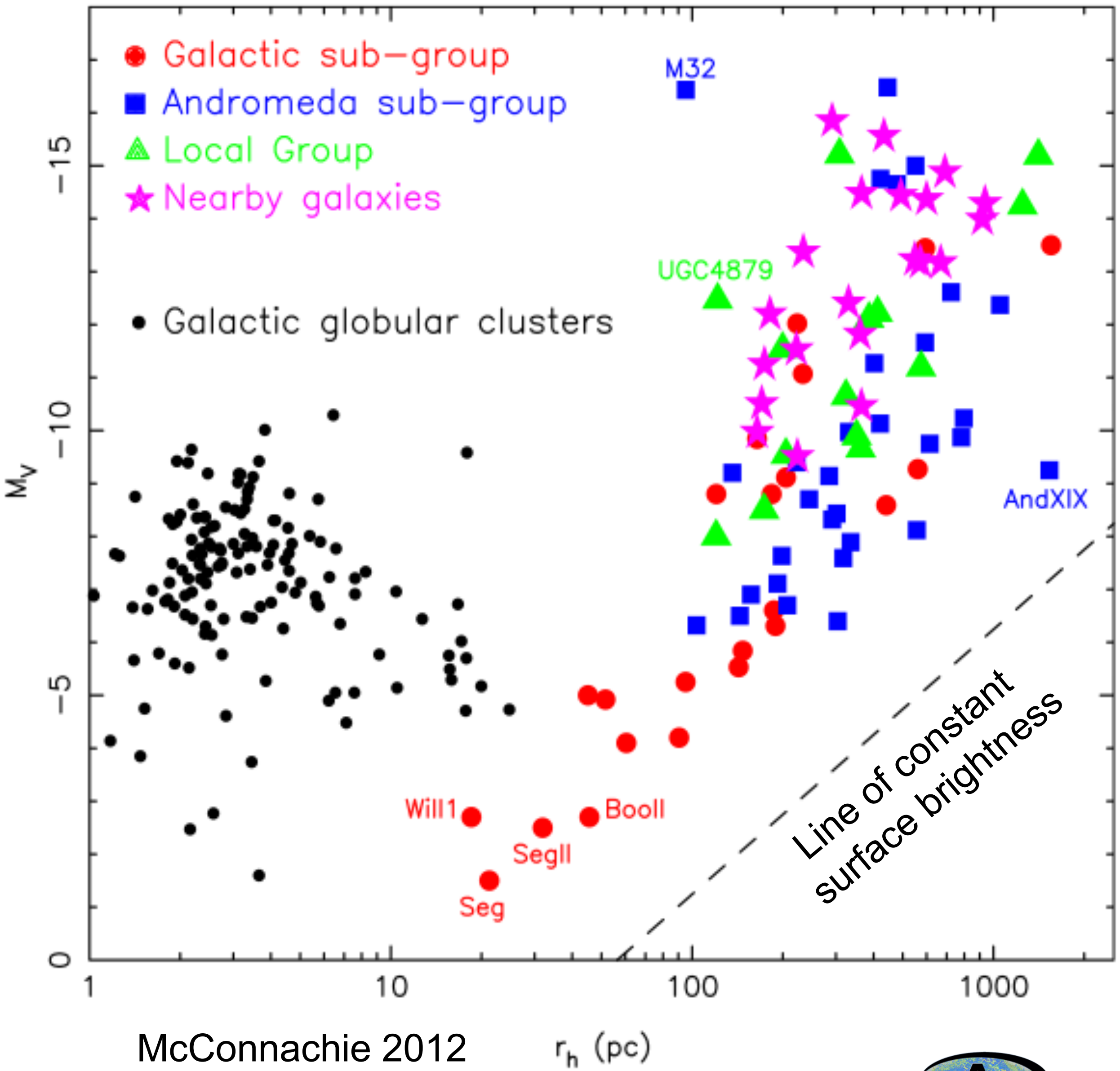
Discoveries of dSph Satellites of the Milky Way by Year of Publication

Largely thanks to large imaging surveys in the northern hemisphere (esp. SDSS, PAndAS).



Half-light radii and luminosities

- Luminosity distributions of dSphs and GCs overlap.
- DSphs typically have half-light radii ≥ 100 pc, while most GCs have $r_h \leq 10$ pc.
- Region between $10 \leq r_h$ [pc] ≤ 100 populated only by GCs with $M_V \leq -4$ and by dSphs with $M_V \geq -5$.



McConnachie 2012

THE ASTROPHYSICAL JOURNAL, 266:L17–L20, 1983 March 1

IS THERE NONLUMINOUS MATTER IN DWARF SPHEROIDAL GALAXIES?[1]

S. M. FABER AND D. N. C. LIN
Lick Observatory and Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz
Received 1982 August 23; accepted 1982 November 4

ABSTRACT

Evidence from tidal masses indicates that mass-to-light ratios of dwarf spheroidal galaxies are roughly one order of magnitude larger than those of globular clusters. We tentatively infer that dwarf spheroidal galaxies contain large amounts of nonluminous matter and in this regard resemble bigger galaxies. The luminosity profiles of dwarf spheroidal galaxies are also shown to be consistent with exponential laws, possibly indicating a closer evolutionary link to spiral-irregular galaxies than to elliptical galaxies.

$$r_t = d_p \left(\frac{M_{dSph}}{(3+\varepsilon) M_{MW}} \right)^{1/3}$$

M_{dSph}, M_{MW}: dSph and MW point masses.
d_p: pericentric distance (dSph)
ε: orbital eccentricity (dSph).

(King 1962, AJ, 67, 471)

DSphs assumed to be tidally truncated by Milky Way.

Galactic halo assumed to be isothermal sphere with v_{circ} = 225 km/s.

→ Mean $\langle M/L_V \rangle$ = 30.3 ± 19.3 (dSphs) and 1.34 ± 0.40 (GCs).

→ Non-luminous matter!

Internal motions estimated from virial theorem;

$$\Delta v = \sqrt{\frac{G M}{r_t}}$$

→ Predicted to be ≈ 10 km/s.

THE ASTROPHYSICAL JOURNAL, **266**:L11–L15, 1983 March 1

ACCURATE RADIAL VELOCITIES FOR CARBON STARS IN DRACO AND URSA MINOR: THE FIRST HINT OF A DWARF SPHEROIDAL MASS-TO-LIGHT RATIO[1]

MARC AARONSON
Steward Observatory, University of Arizona
Received 1982 August 6; accepted 1982 October 8

ABSTRACT

Velocities accurate to ~ 1 km s^{-1} have been obtained with the Multiple Mirror Telescope and echelle spectrograph for three carbon stars in the Draco dwarf galaxy and one carbon star in the Ursa Minor dwarf. These observations demonstrate that measurement of radial velocities having such high precision is quite feasible for stars as faint as $V \sim 18$ mag. The data presented here are of importance for understanding the dynamical history of the dwarf systems. In addition, they provide a first and tantalizing hint of the velocity dispersion in a dwarf spheroidal and suggest that Draco may have a mass-to-light ratio an order of magnitude greater than that found for galactic globulars. If confirmed, this result would support the existence of a massive halo about the Galaxy. It would furthermore rule out the possibility that neutrinos could provide a solution to the missing mass problem, if the dark matter on small and large scales is similar.

$$M = 167\, r_c\, \mu \left\langle v_r^2 \right\rangle$$

r_c: core radius [pc]
μ: dimensionless mass parameter (King)
$\langle v_r^2 \rangle$: radial velocity dispersion^2 [(km/s)^2]

(Illingworth 1976, ApJ, 204, 73)

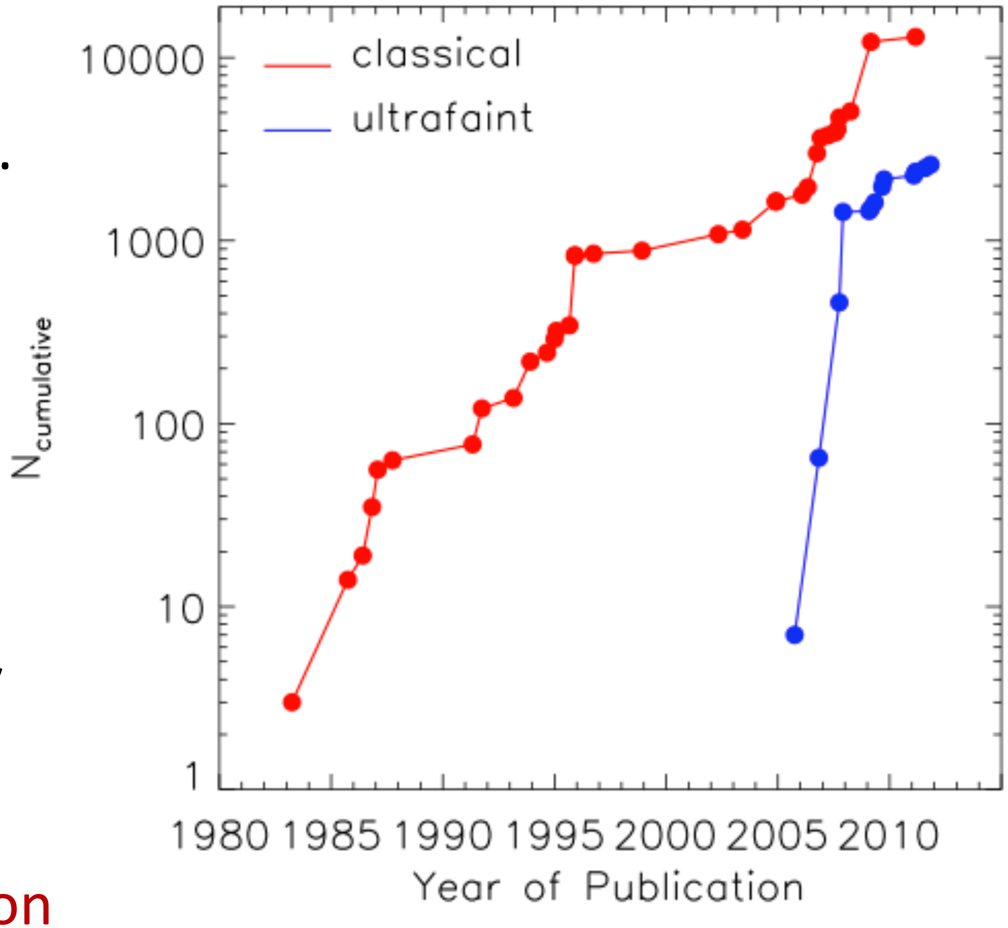
First measurement of a dSph's internal velocity dispersion based on *three* stars.

→ $\sigma \geq$ 6.5 km/s. Virial theorem: → mass → $M/L_V \approx 30\ [M/L_V]_\odot$.

→ Non-luminous matter!

Stellar Velocities

- Subsequent measurements of other dSphs all confirmed high velocity dispersions.
- Typically $\sigma \sim 6 - 12$ km/s.
- Initially very small samples.
- Advent of efficient multi-object spectrographs at 4 – 10 m telescopes led to vast samples of stars and coverage of entire angular extent of the dSphs.
- Influence of stellar binarity quantified/removed.
- Not only radial velocities, but radial velocity dispersion profiles along entire extent of the dwarfs.



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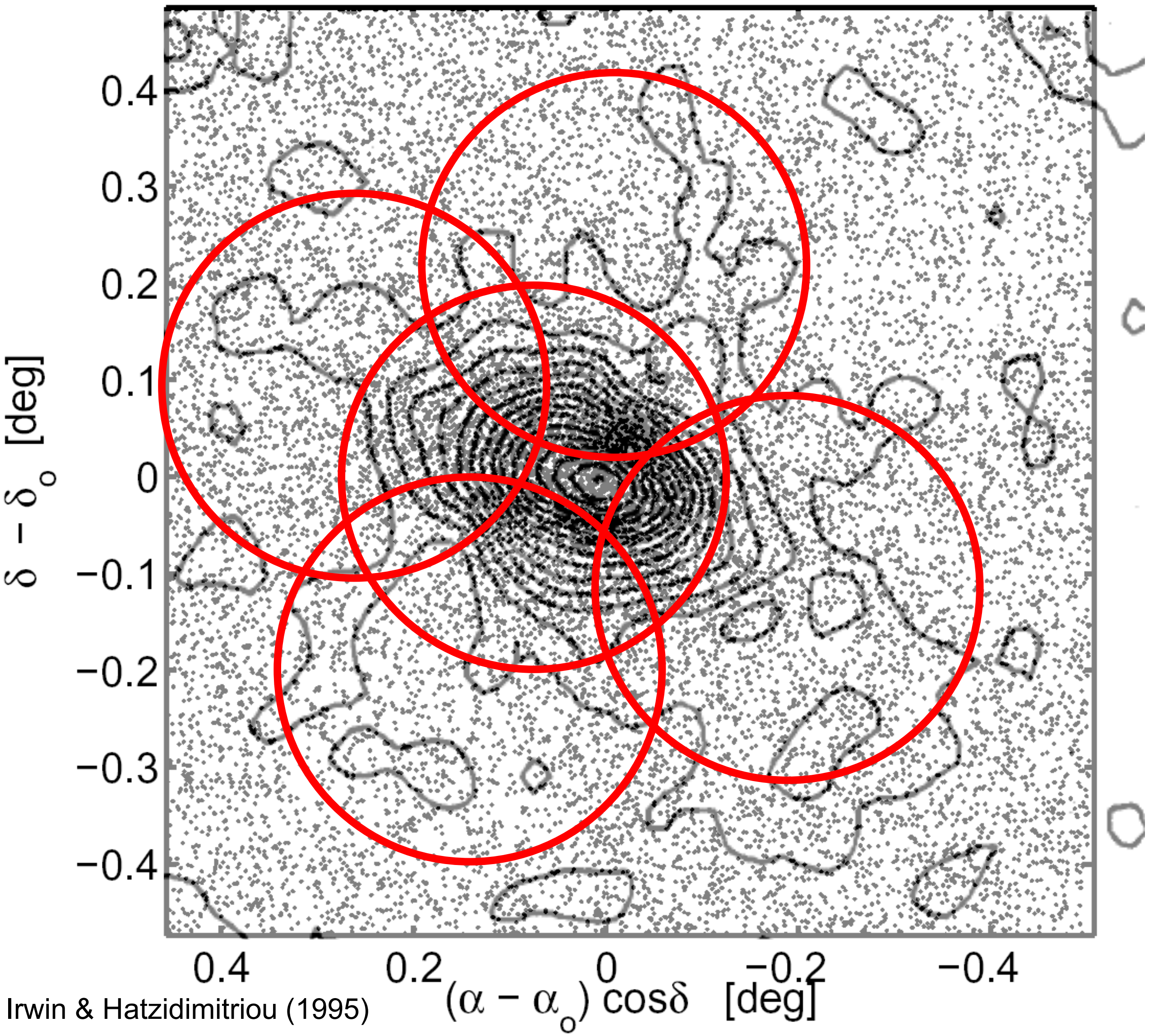
Stellar Velocities: Example Carina



Irwin & Hatzidimitriou (1995)

- 23 nights with VLT
- 108 h
- 5 Fields (Ø 25') [red]

FLAMES GIRAFFE:
132 fibres, 2 plates

1257 stars targeted

Low res., NIR spectra
(λ = 820 – 940nm (CaT),
R = 6500)

Koch, Grebel, et al.
2006, AJ, 131, 385

Radial Velocity Dispersion Profiles

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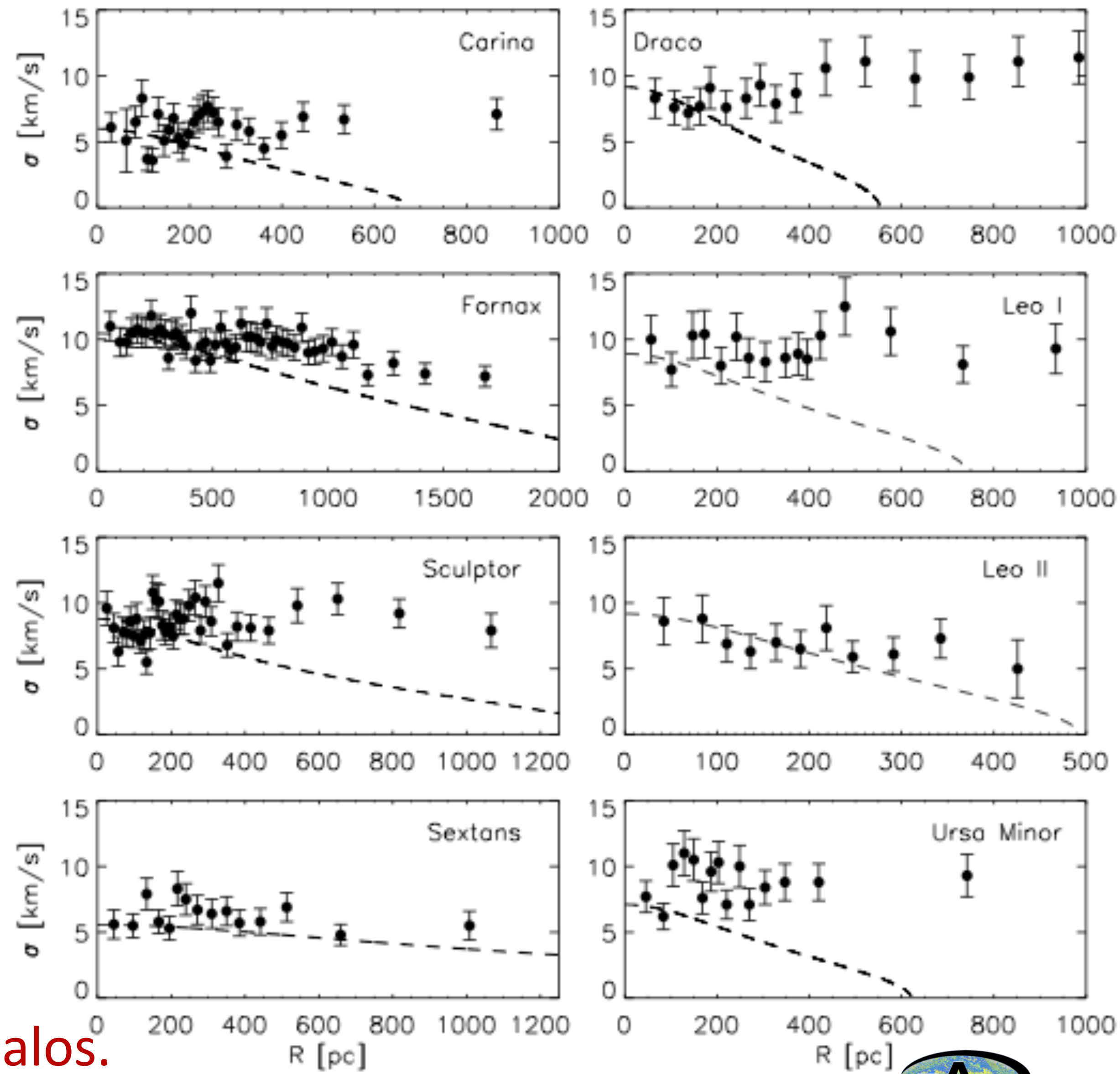
- Radial velocity dispersion profiles as function of galactocentric radius: ~ *flat.*
- Dashed line: Slope expected if mass follows light (King 1966 models); normalized to central dispersions.
- Large dispersions at large radii (in contrast to King models): dominant and extended DM halos.

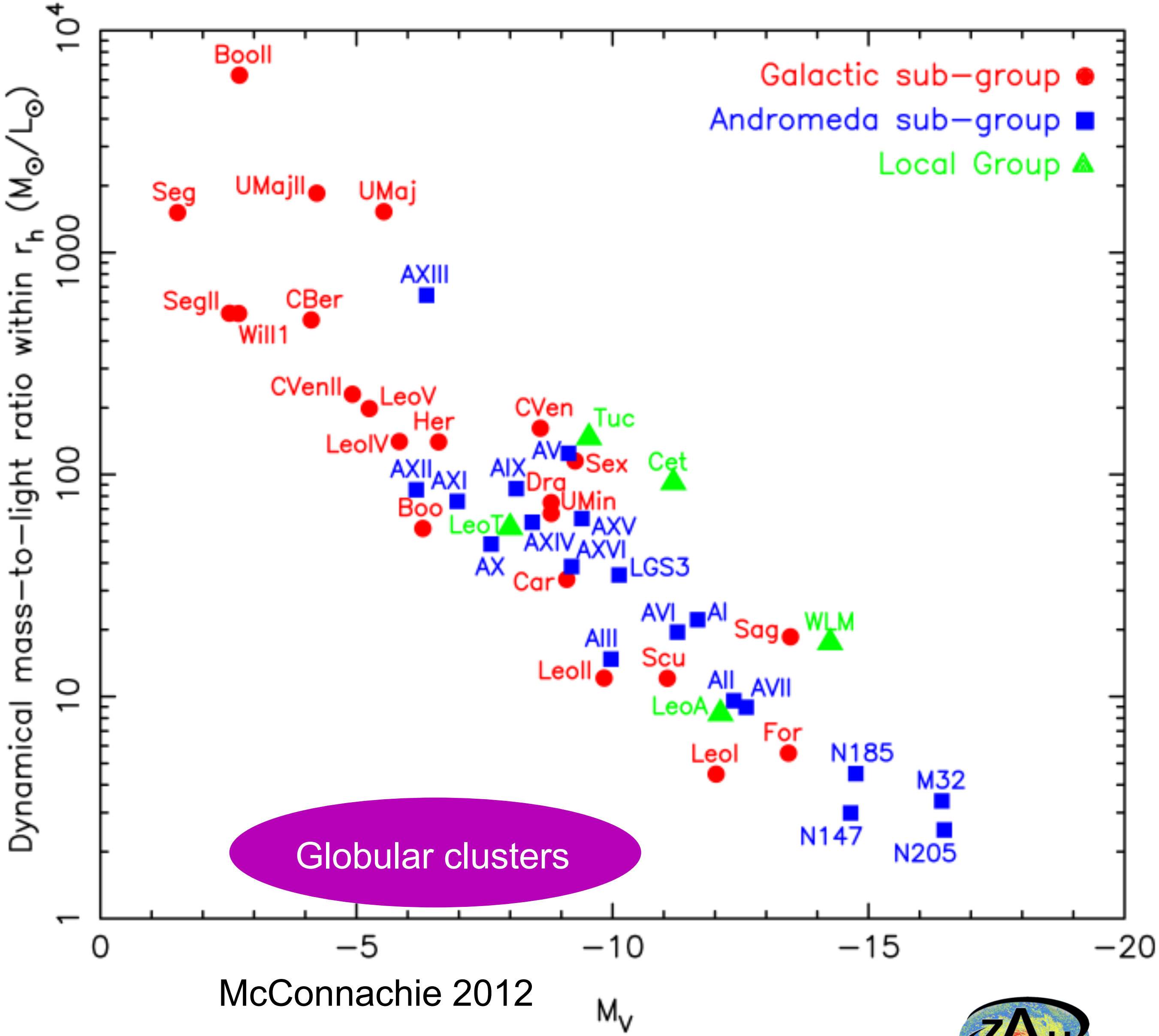


Dynamical Mass-to-Light Ratios vs. Luminosities

Dynamical mass-to-light ratios increase with decreasing luminosity.

Faintest dSphs are the most dark-matter-dominated ones.

Discontinuity in dynamical M/L_V between dSphs and globular clusters seems to mark a boundary between objects with dark matter and without.



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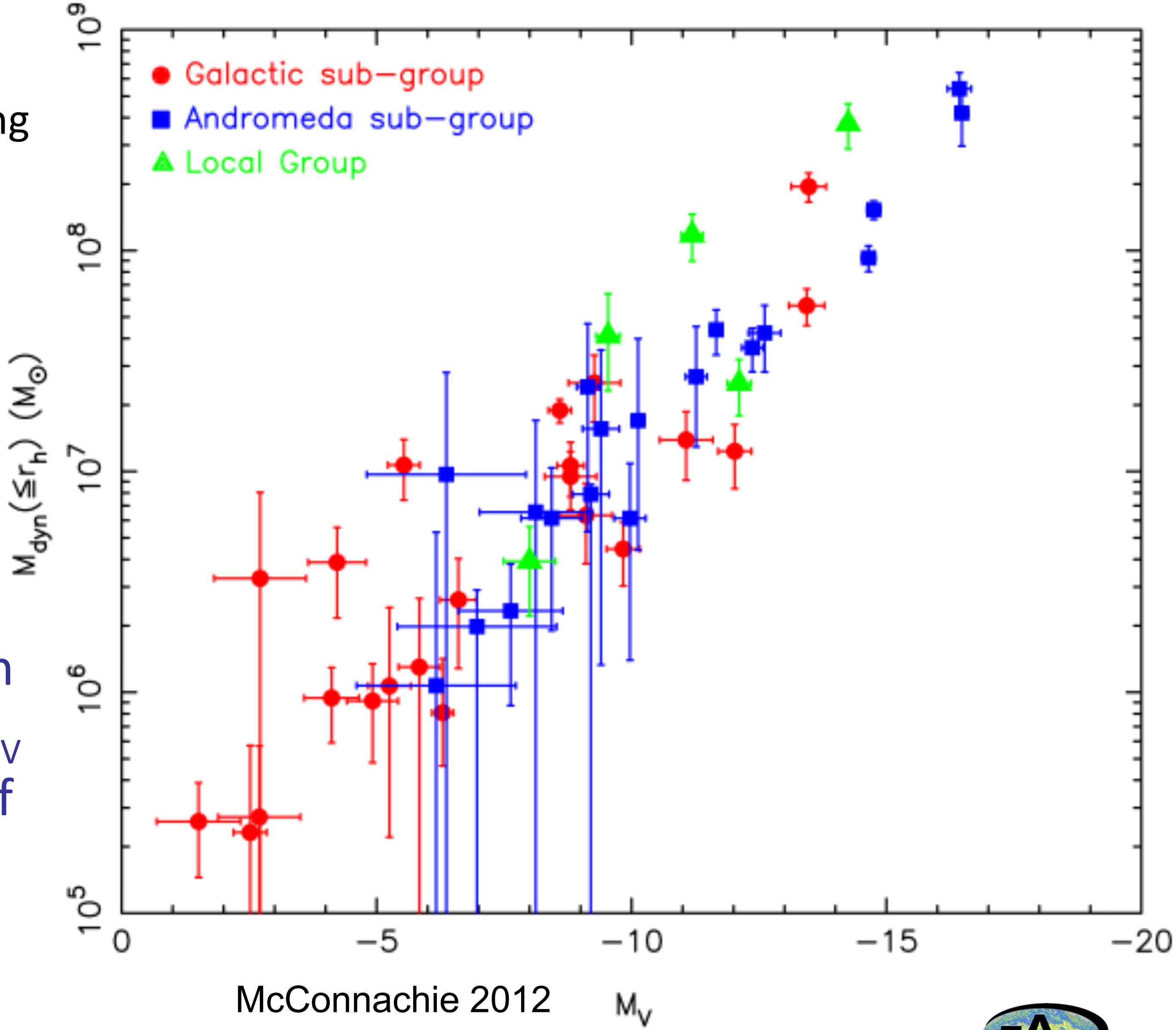
Dynamical Mass Estimates vs. Luminosities

Assumption: All Galaxies non-rotating (not true for the more massive dIrrs and for dEs).

Assumption also that all galaxies are in dynamical equilibrium.

Power-law relation between $M_{dyn}(\leq r_h)$ and M_V across a factor of almost 1 million in luminosity.



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Masses from Stellar Rotation and Velocity Dispersion

- Rotating spiral galaxies: circular velocity at radius r relates directly to enclosed mass via

$$v_{circ}^2 = \frac{G\,M(r)}{r}$$

- DSphs: Negligible ordered rotation.
- Support against gravity mainly from random stellar motions.

→ Velocity dispersion along line of sight, σ, characterizes stellar dynamics of a dSph.

- Relaxed system of characteristic size R: Virial theorem yields

$$\sigma^2 \propto \frac{G\,M}{R}$$

- While *in principle* even just measurement of a dSph's size and σ provide simple estimate of its mass, *in practice* several effects may inflate measured σ values above equilibrium values.

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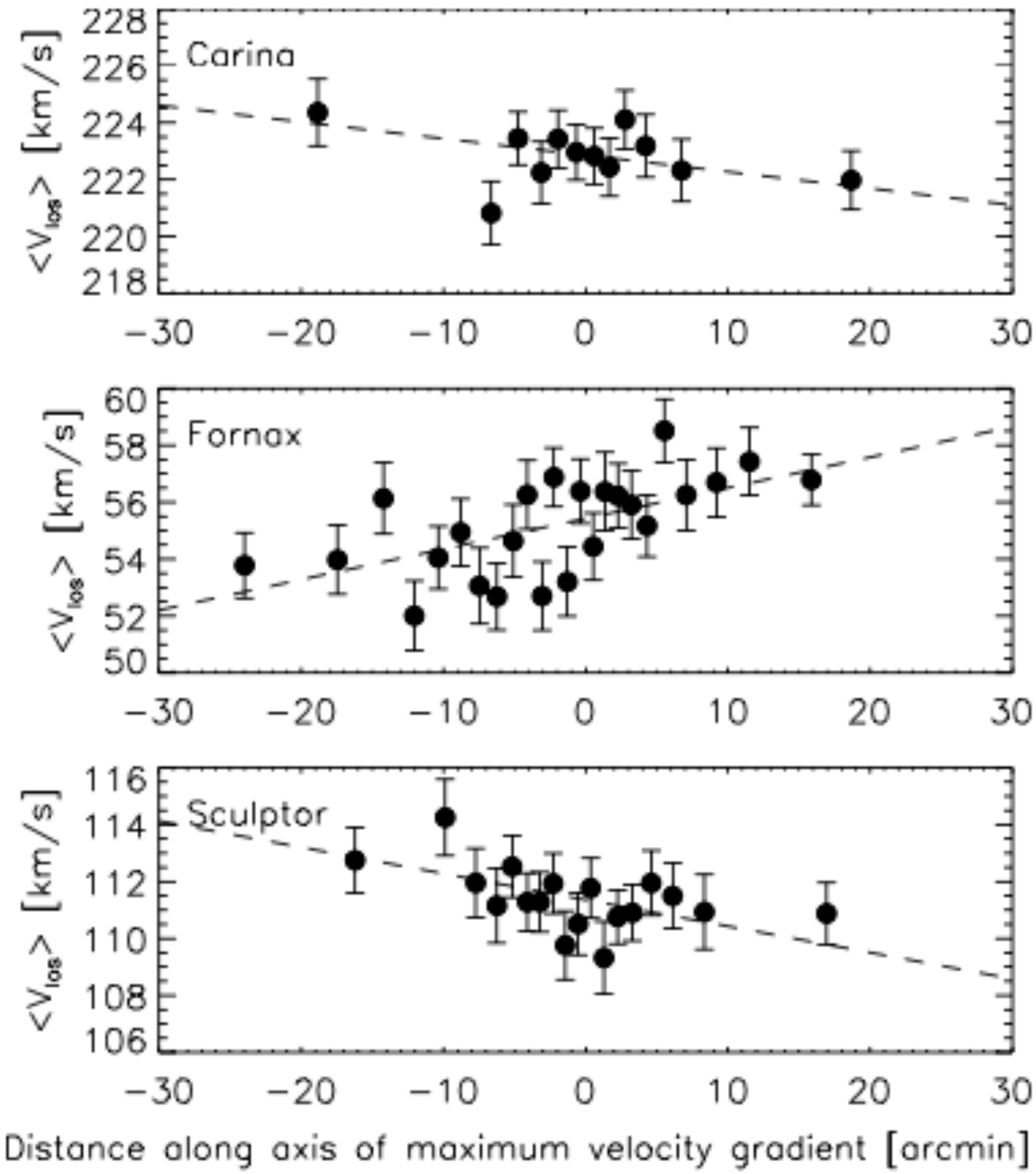
Rotation?

Rotation in dSphs:

Look for velocity gradients.

If/where present, then *less* than σ.

Even at outermost radii: $R_{max}\, dV/dR \leq 3$ km/s, while σ typically ~ 10 km/s.



Line-of-sight velocity gradients; Walker et al. 2009

External tides

External tides (due to motion within gravitational potential of the Milky Way):

- Can affect structure and kinematics of a satellite through, e.g., stripping, shocking, "stirring", and various orbital resonances.

→ Tides may inflate observed σ and resulting mass estimates.

  - Stripping: mass transfer from satellite to parent, preferentially from satellite's outer regions.
  - Shocking: Impulsive injection of energy as it plunges through the disk and/or near center of parent system (decreases satellite's central density; Read et al. 2006).

- Even strong tidal interactions do not significantly inflate a satellite's central σ (Piatek & Pryor 1995; Oh et al. 1995).

→ *Remains a reliable indicator of dynamical mass.*

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Unbound Tidal Remnants Without Dark Matter

The other extreme: Scenario where high velocity dispersions are purely due to tides and dSphs contain no dark matter (e.g., Kuhn & Miller 1989, Kroupa 1997).

→ DSphs considered to be unbound tidal remnants.

If so, should primarily affect dSphs closest to the Milky Way and should show the signature of elongated stellar structures (there are some candidates especially among the ultra-faint dSphs).

But can that hold for the entire, wide range of dSph distances (~ 30 ≤ D [kpc] ≤ ~ 250), especially when considering that these dSphs all follow a well-defined metallicity-luminosity relation?

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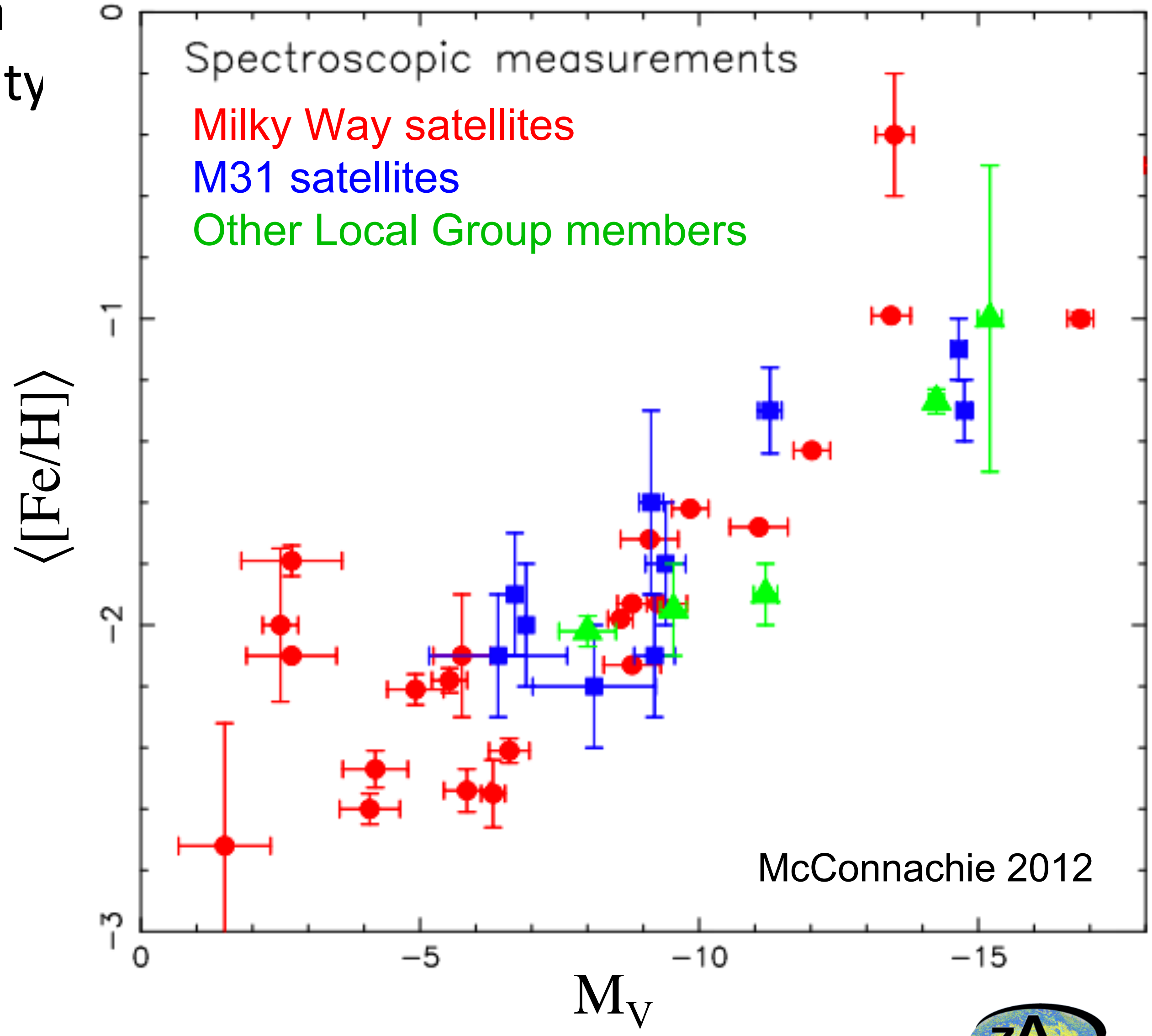
Unbound Tidal Remnants Without Dark Matter

Is the existence of a metallicity-luminosity relation consistent with dSphs being unbound tidal remnants without dark matter?

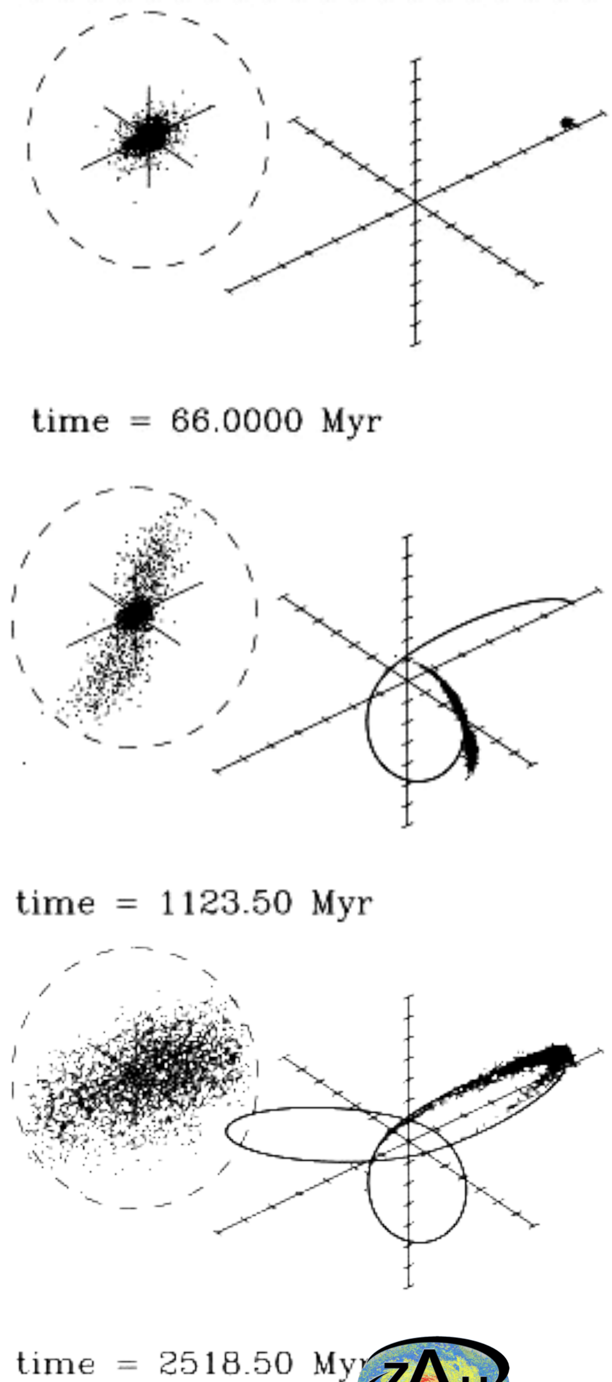


Unbound Tidal Remnants

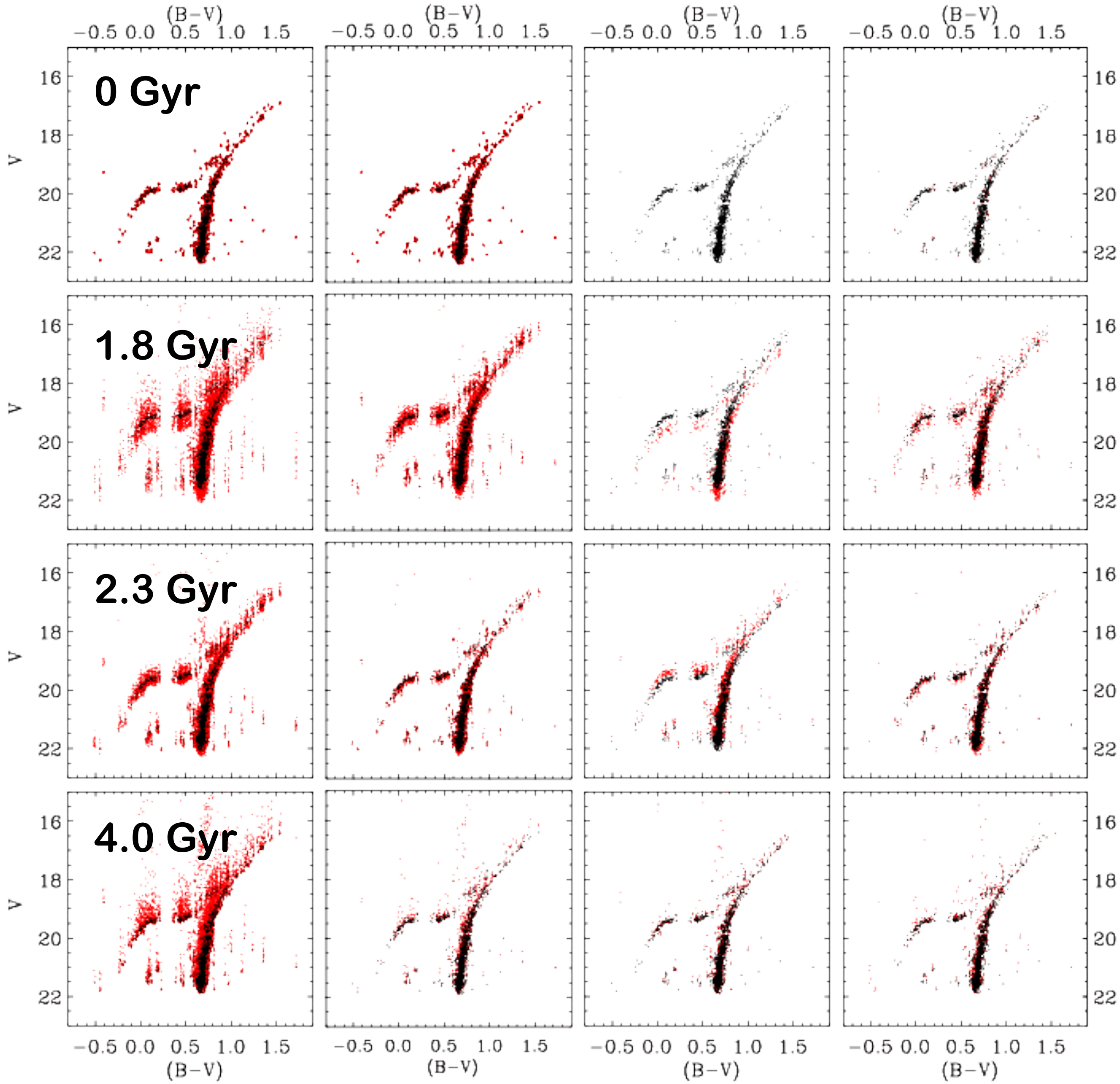
What if low-mass satellites are disrupted galaxies without dark matter?
Disrupted satellites would be long-lived, non-spherical, not in dynamical equilibrium, and have non-isotropic velocity dispersions. They could easily mimic the observed dSphs.
Their disruption would be hidden in contour plots if they were extended in depth along the line of sight.

(But: Then this should be visible for dSphs around M31 – not the case!)

Klessen & Kroupa 1998



5°x5° | 0.5°x0.5° center | 0.5°x0.5° W | 0.5°x0.5° N



Initial condition

Immediately after 2nd apo-galacticon

Shortly before 3rd apo-galacticon

Before the 5th apo-galacticon

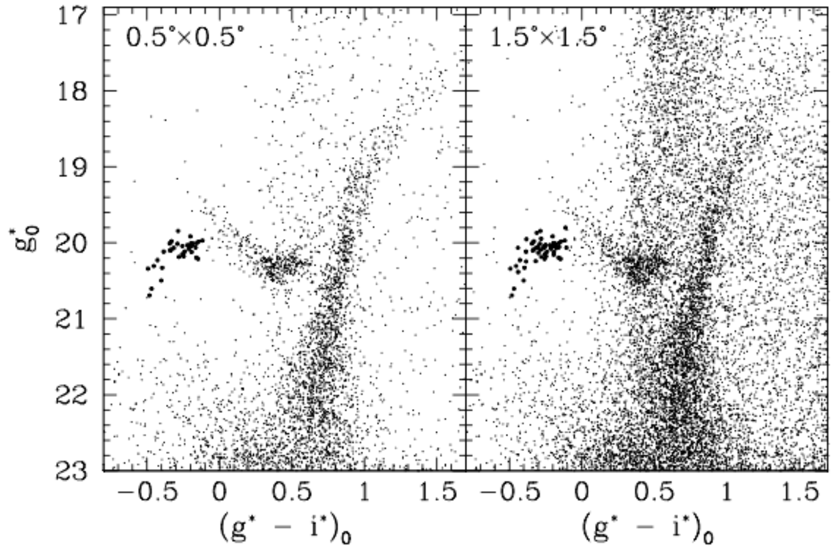
Klessen & Zhao 2001

Unbound Tidal Remnants Without Dark Matter

Draco Depth Extent:

Horizontal branch width remains small and constant regardless of the area sampled

→ Depth extent negligible



BLUE HORIZONTAL BRANCH WIDTH OF DRACO

Area (deg) (1)	$\langle \Delta g_0^* \rangle_{HB}$ (mag) (2)	Predicted $\langle \Delta V \rangle_{HB}$[a] (mag) (5)
0.25×0.25	0.12	0.125 ± 0.023
0.50×0.50	0.13	0.138 ± 0.023
1.00×1.00	0.13	0.162 ± 0.020
1.50×1.50	0.14	0.185 ± 0.018
2.00×2.00	0.13	0.207 ± 0.017
2.50×2.50	0.14	0.225 ± 0.016

Klessen, Grebel, & Harbeck 2003

Binary Stars

- In principle, binary star component orbital motions could contribute significantly to observed velocity dispersions.
- Simulations (Olszewski et al. 1996; Hargreaves et al. 1996) show: Scatter introduced by binaries is small compared to the measured dispersions of σ ~ 10 km/s.

→ Binaries do not significantly inflate dynamical masses of *classical* dSphs.

- Some *ultrafaint* dSphs: σ ~ 3 km/s.

→ Here, binaries *can* have an effect.

- For systems with intrinsic σ near 0 (as expected for ultra-faint dSphs without dark matter), binaries can inflate measured σ to as much as 4 km/s (McConnachie & Côté 2010).

→ Multi-epoch spectroscopic studies required.

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Assumptions Made in Mass Analyses

A common set of assumptions:

1. Dynamical equilibrium
2. Spherical symmetry
3. Isotropy of the velocity distribution $(\langle v_r^2 \rangle = \langle v_\theta^2 \rangle = \langle v_\phi^2 \rangle)$.
4. A single stellar component.
5. Mass density profile, $\rho(r)$, $\propto$ to the luminous density profile, $\nu(r)$
   → M/L = constant, or “mass follows light”.

But: We already know from velocity dispersion profiles that mass does *not* normally follow light in dSphs.

Moreover, deviations from spherical symmetry as well as two components are often observed (the latter can be addressed by superimposing two profiles).

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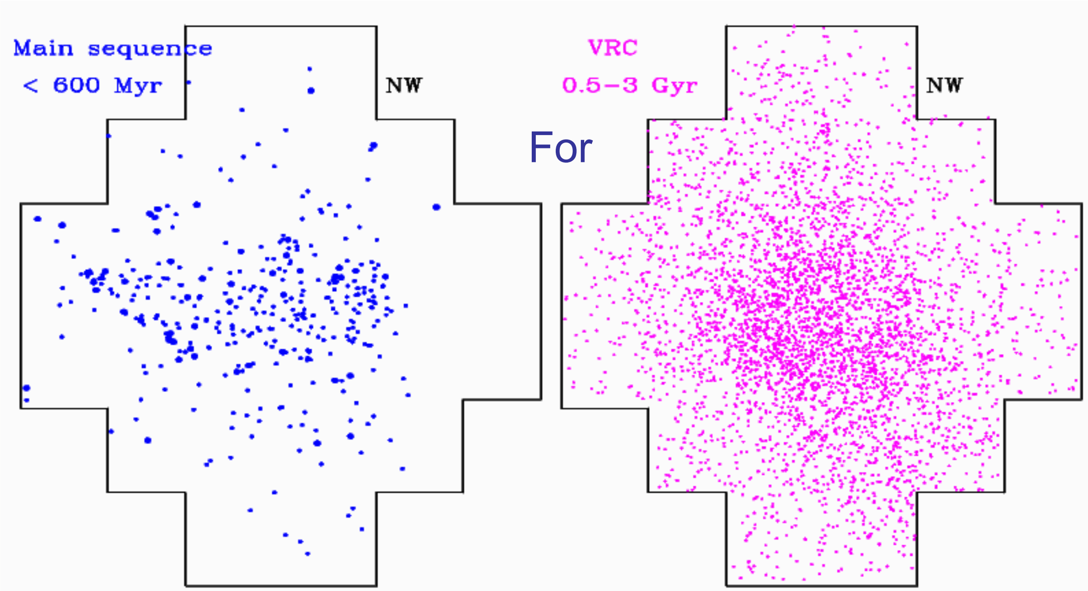
Structural Properties

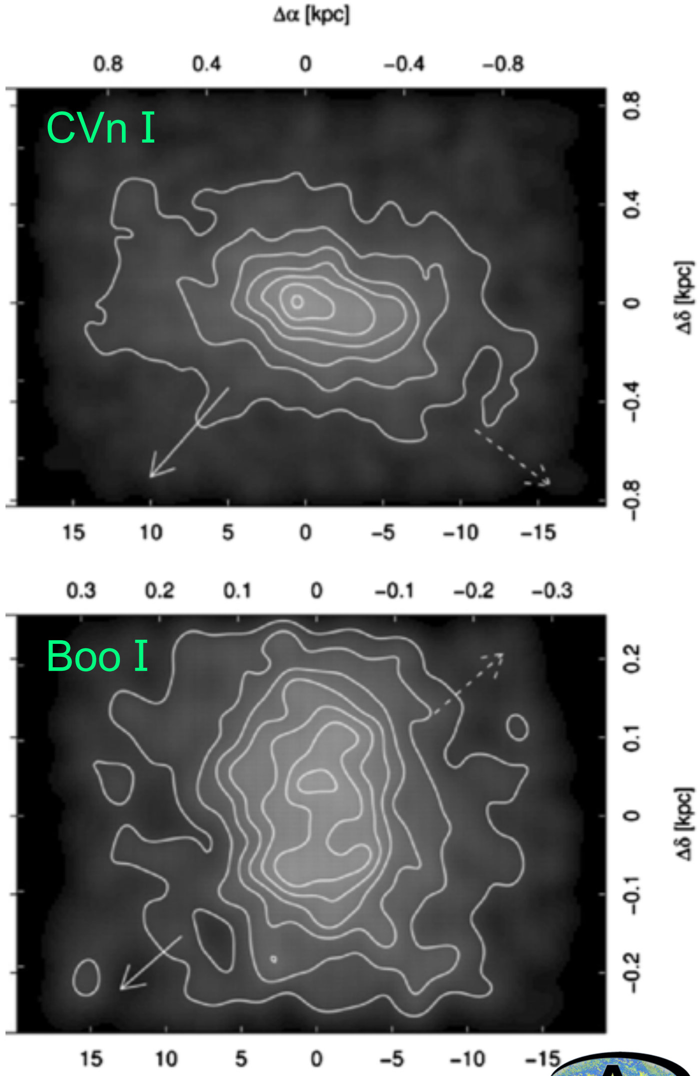
- Dwarf spheroidal galaxies show flattened profiles:

$$0.1 \leq \varepsilon \equiv 1 - \frac{b}{a} \leq 0.7$$

- DSphs may contain kinematically, chemically and spatially distinct stellar subpopulations.



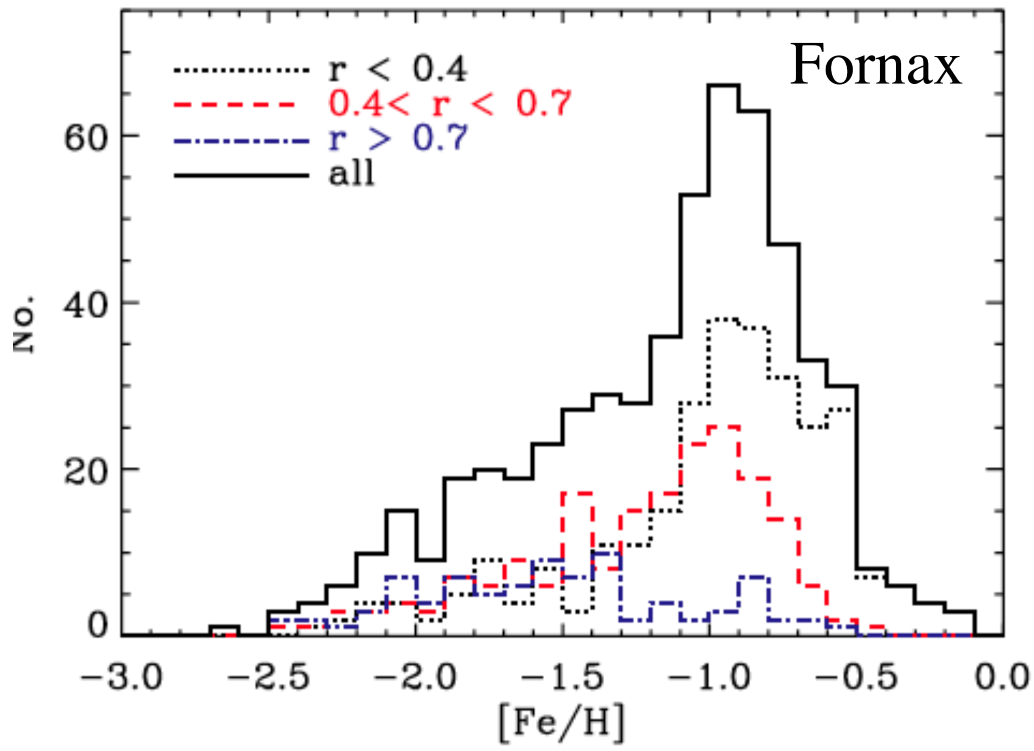
Grebel & Stetson 1999



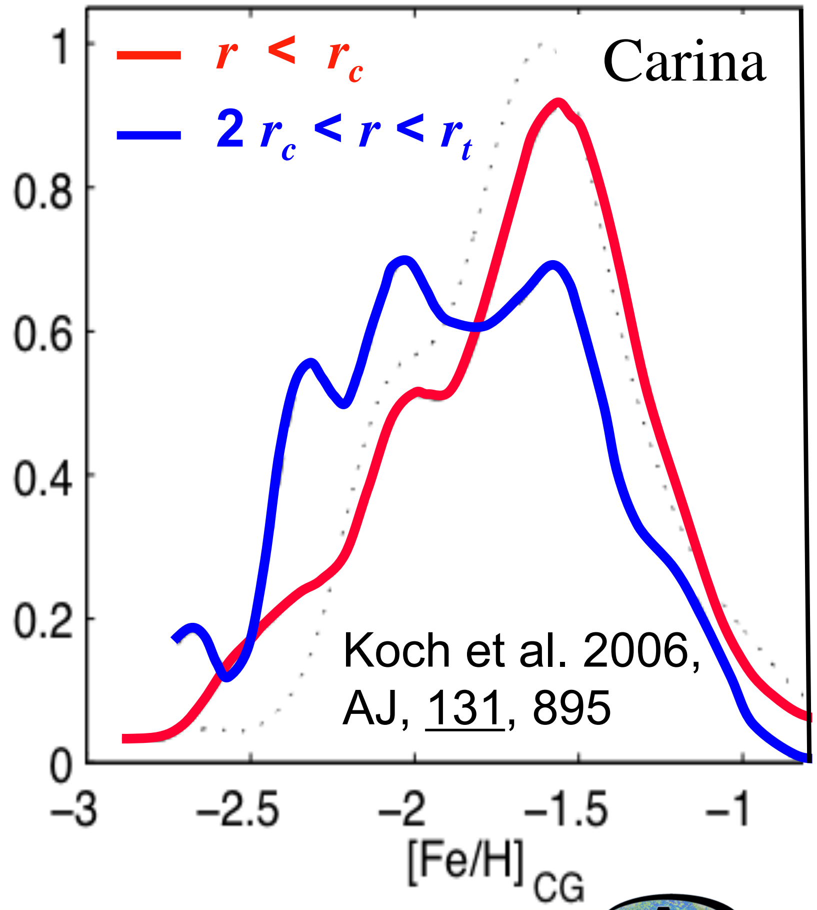
Okamoto et al. 2012, ApJ, 744, 96

Population Gradients

Younger and/or more metal-rich stars:
More centrally concentrated (e.g., Harbeck et al. 2001, AJ, 122, 3092)
and kinematically colder.



Battaglia et al. 2006, A&A, 459, 423



Assumptions Made in Mass Analyses

- Mass estimators based on the virial theorem implicitly assume than mass follows light.
- Standard kinematic analyses that include stars at large radii implicitly assume they are bound by a sufficiently extended dark matter halo.
- Conclusions about extended structure of dSph dark matter halos generally sensitive to the assumptions employed when determining which stars to include in kinematic analyses.
- But even mass-follows-light models require central mass-to-light ratios > 10 in order to fit the central σ of dSphs.
- Commonly employed Jeans mass modelling:
  No assumptions about mass following light, but degeneracy between mass and (unknown) orbital anisotropy profile.

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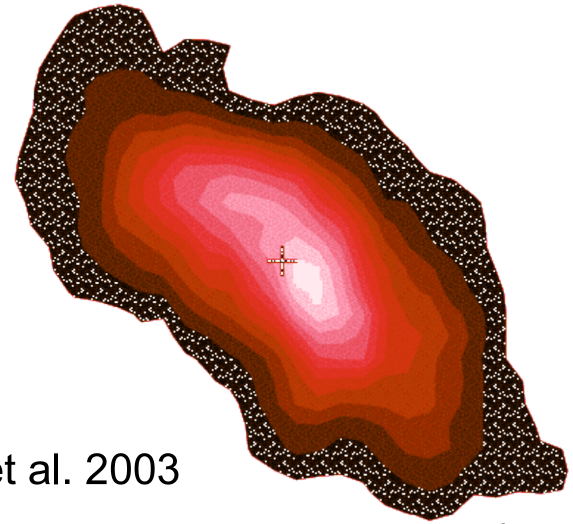
Shape of Dark Matter Profiles

Substructure in dSphs imposes constraints on shape of DM profile.

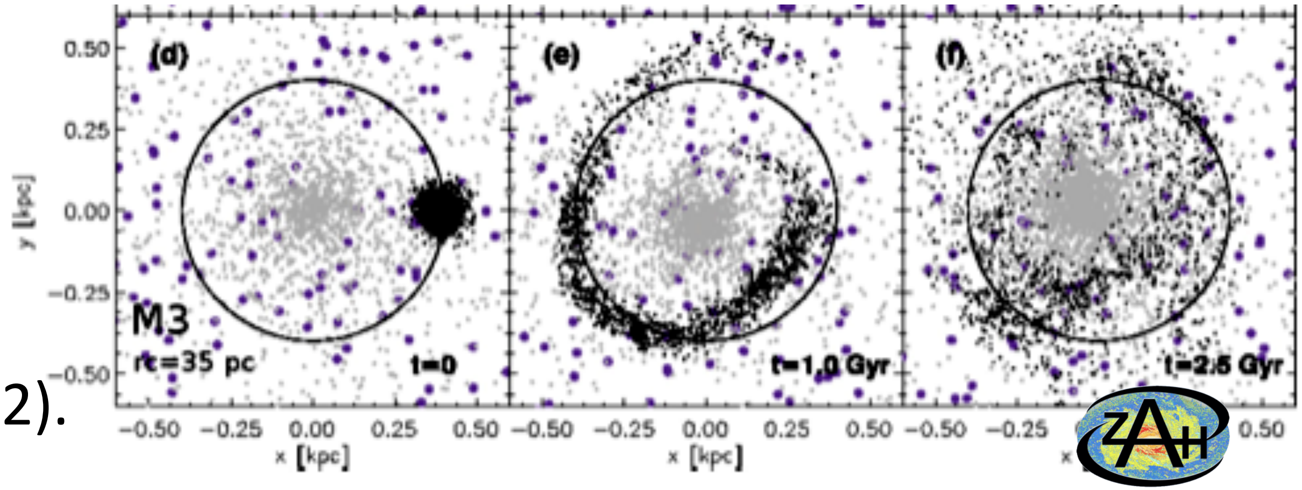
- Off-centered density clump in UMi (possibly remnant of dissolving star cluster) only long-lived when there is a central core.
- For cuspy profiles: Rapid dissolution (Kleyna et al. 2003).



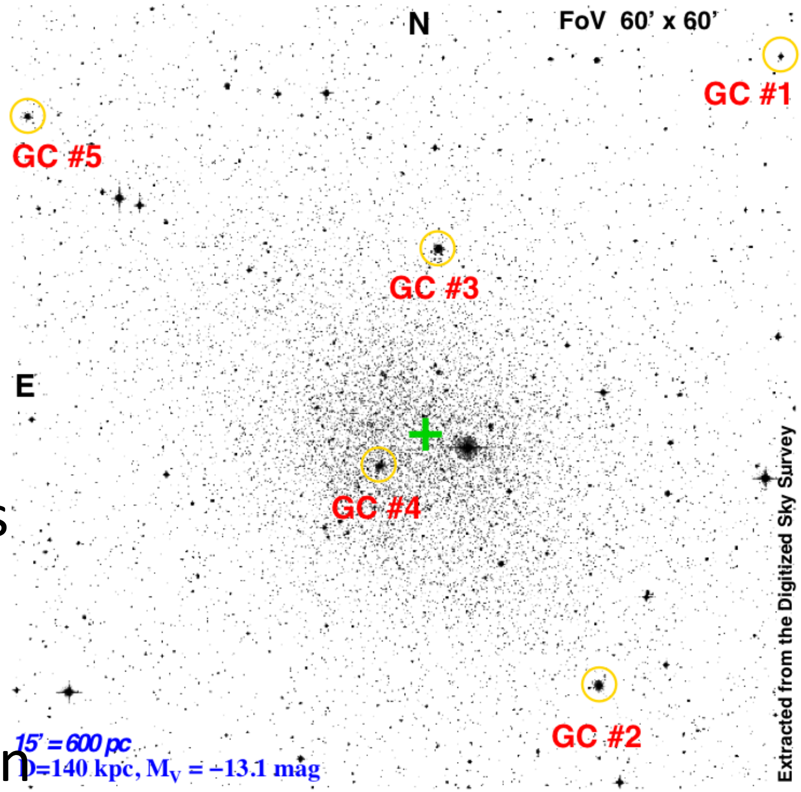
Palma et al. 2003

- If DM profile is not smooth, but clumpy (made up of subhalos): clump would survive for at most 1.5 Gyr.
- Small core: again rapid dissolution.

→ Smooth halo with large core (Lora et al. 2012).



Shape of Dark Matter Profiles



Substructure in dSphs constrains shape of DM profile.

- Fornax: Five globular clusters.
- Rate at which orbits of such clusters decay depends on underlying dSph potential (Hernandez & Gilmore 1998).
- Cusped potential: Dynamical friction would bring clusters to center within a few Gyr (Oh et al. 2000; Salcedo et al. 2006; Goerdt et al. 2006).
- Cored potential: only as close as core radius.

→ Core of constant density over the central few 100 pc in Fornax.

- Transfer of angular momentum to central DM can transform an originally cusped into a cored potential (Goerdt et al. 2010; Cole et al. 2011).

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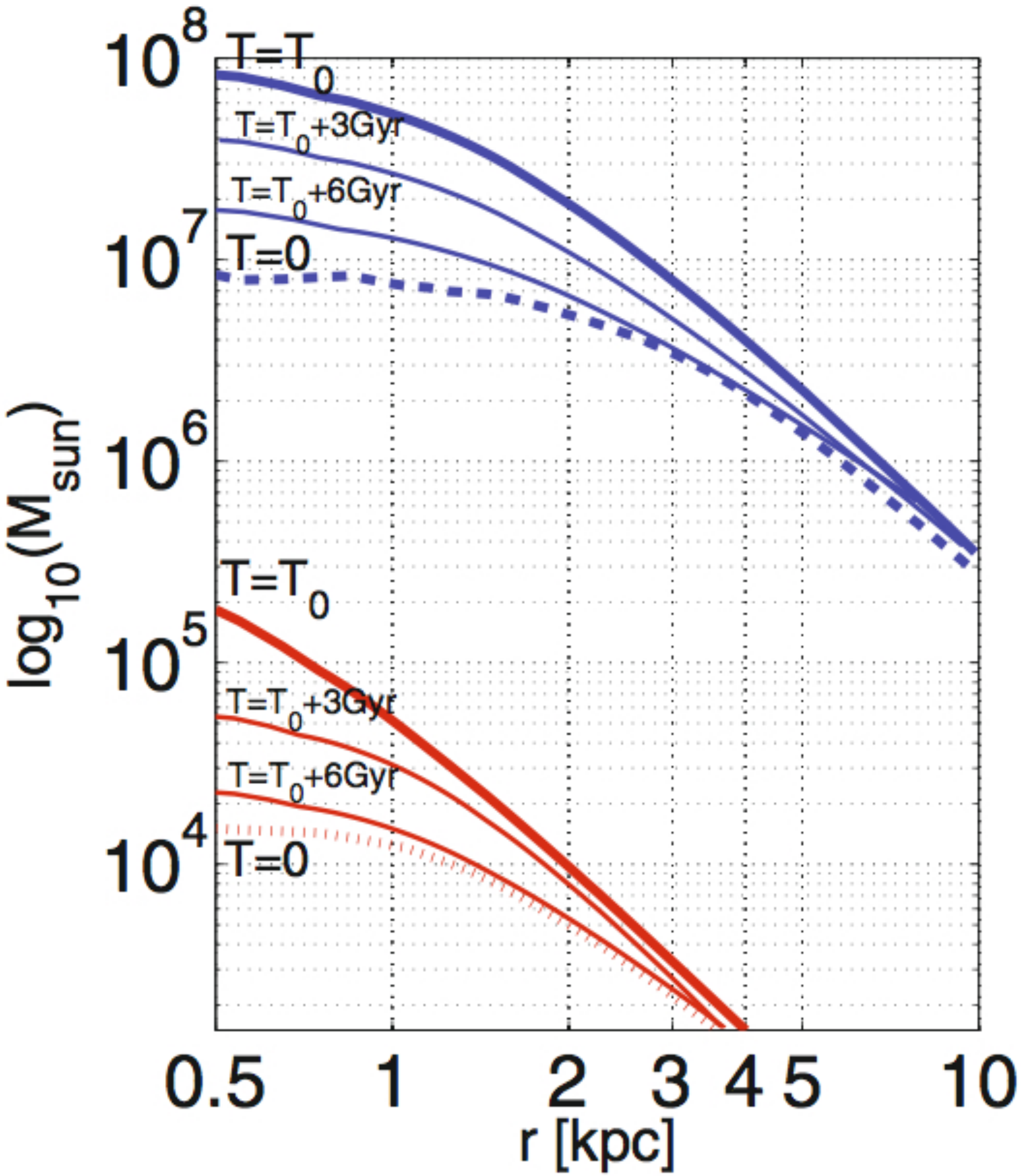
Halo Shape

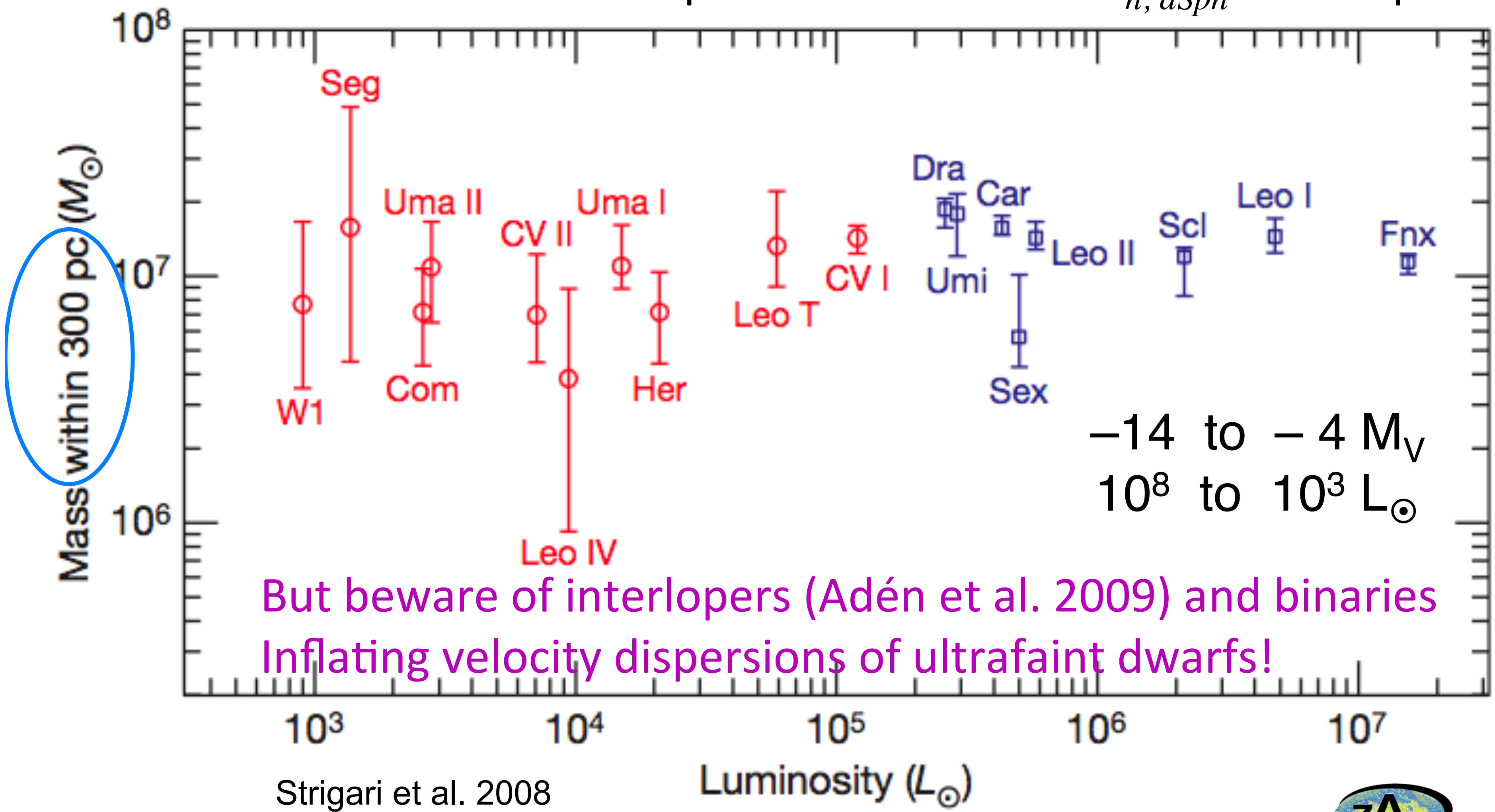
- Mass modelling also seems to prefer cored, not cuspy profiles.
- ΛCDM expecation: cusps (e.g., NFW).
- Flattening of cuspy to cored profiles also possible due to redistribution of mass due to star formation, feedback, relaxation.



Pasetto et al. 2010

A Common dSph Mass?

- Is each dSph embedded in DM halo of a few times $10^7\ M_\odot$?
- Is there a common mass profile? Note: $20 \leq r_{h,\,dSph} \leq 2000$ pc!



Strigari et al. 2008

Dark Matter in Dwarf Galaxies

- Plenty of evidence for non-luminous mass in dwarf galaxies.
- Despite uncertainties and assumptions made in various approaches of mass modeling:

→ Flat velocity dispersion profiles are strong evidence of dominant, extended dark matter halos.

- Particularly interesting: Ultra-faint dSphs.
- As for nature of dark matter: A major open question…
- One promising approach: Search for annihilation signals.