Some observed properties of Dark Matter:

a progress report on a dynamical and luminosity function study of the nearby dSph's

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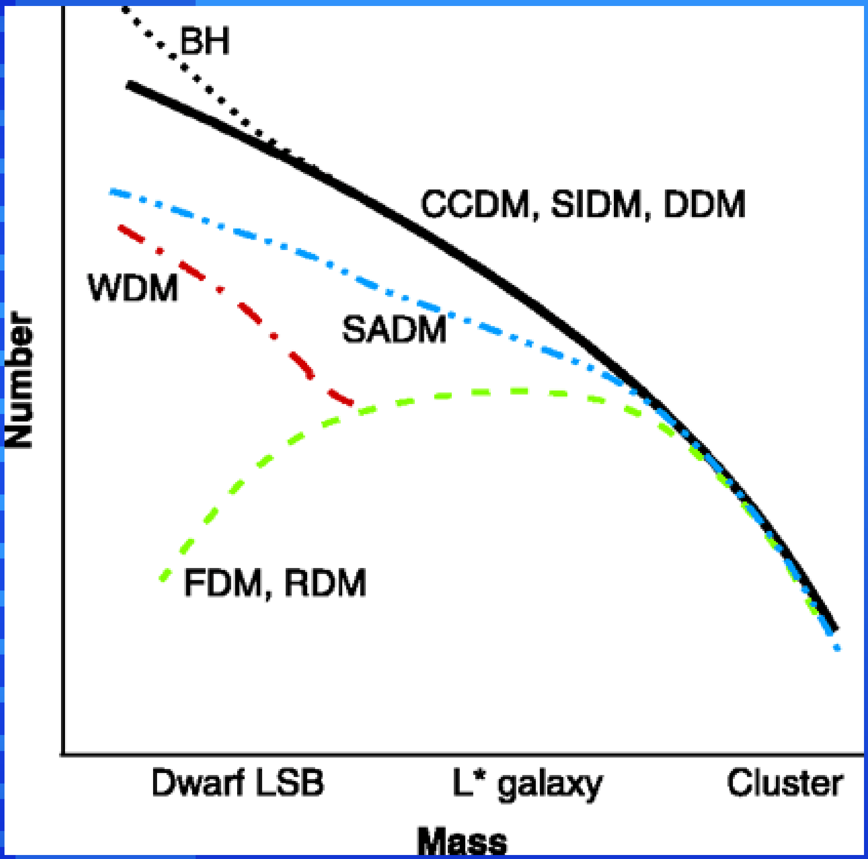
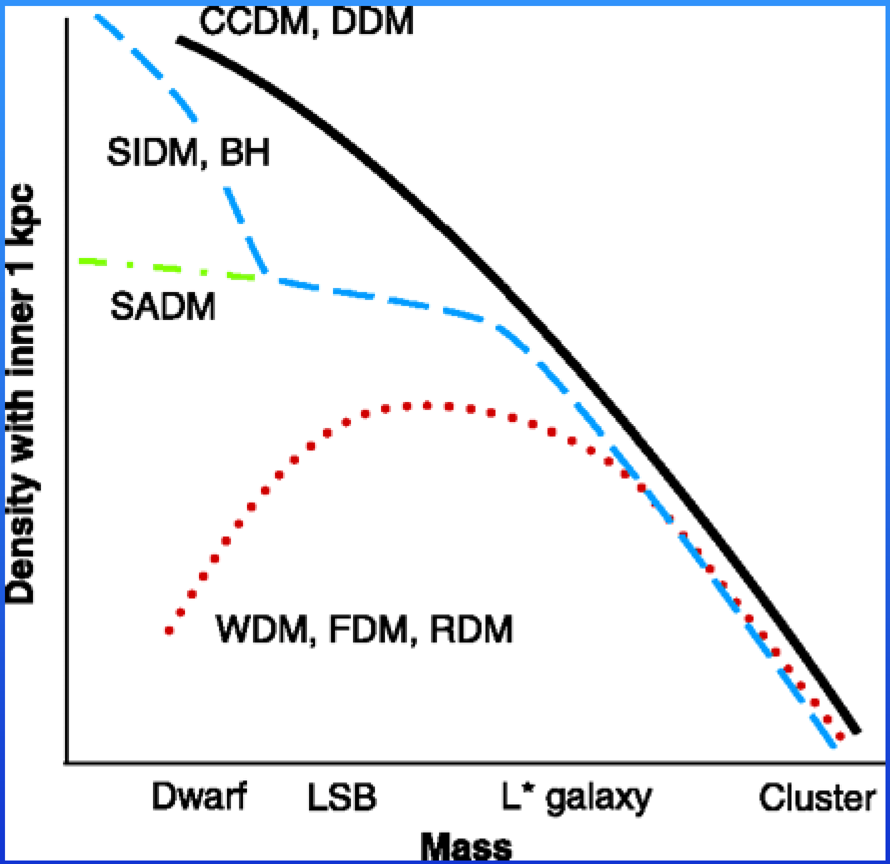
Discovery work with Vasily Belokurov, Dan Zucker,Sergey Koposov, et al

ApJ 663 948 2007 (july10), and arXiv 0706.2687

The smallest galaxies are the places one might see the nature of dark matter, & galaxy formation astrophysics





Dwarf galaxy mass function depends on DM type

Inner DM mass density depends on the type(s) of DM

Figs: Ostriker & Steinhardt 2003

Main Focus: Dwarf Spheroidals

- Low luminosity, low surface-brightness satellite galaxies, 'classical' $L \sim 10^6 L_\odot$, $\mu_V \sim 24$ mag/sq″
- Extremely gas-poor
- Apparently dark-matter dominated

$$\sigma \sim 10\text{km/s}, \;\; 10 \lesssim M/L \lesssim 100$$

- Metal-poor, mean stellar metallicity $\lesssim -1.5$ dex
- All contain old stars; extended star-formation histories typical, intermediate-age stars dominate
- Most common galaxy nearby
- Crucial tests for CDM and other models

- Among the first systems to collapse, form stars
  - Star formation history and chemical enrichment are sensitive probes of stellar ‘feedback’, galactic winds, ram pressure stripping, re-ionization effects..
  - Accessible through current observations
- Most extreme (apparently) dark-matter dominated systems: trends contain constraints on its nature (Dekel & Silk 1986; Kormendy & Freeman 04; Zaritsky et al 06)
- What are mass profiles within dSph? CDM predicts a cusp in central regions
  - Accessible through current observations
- Luminosity and mass functions critical tests

Kormendy & Freeman 04

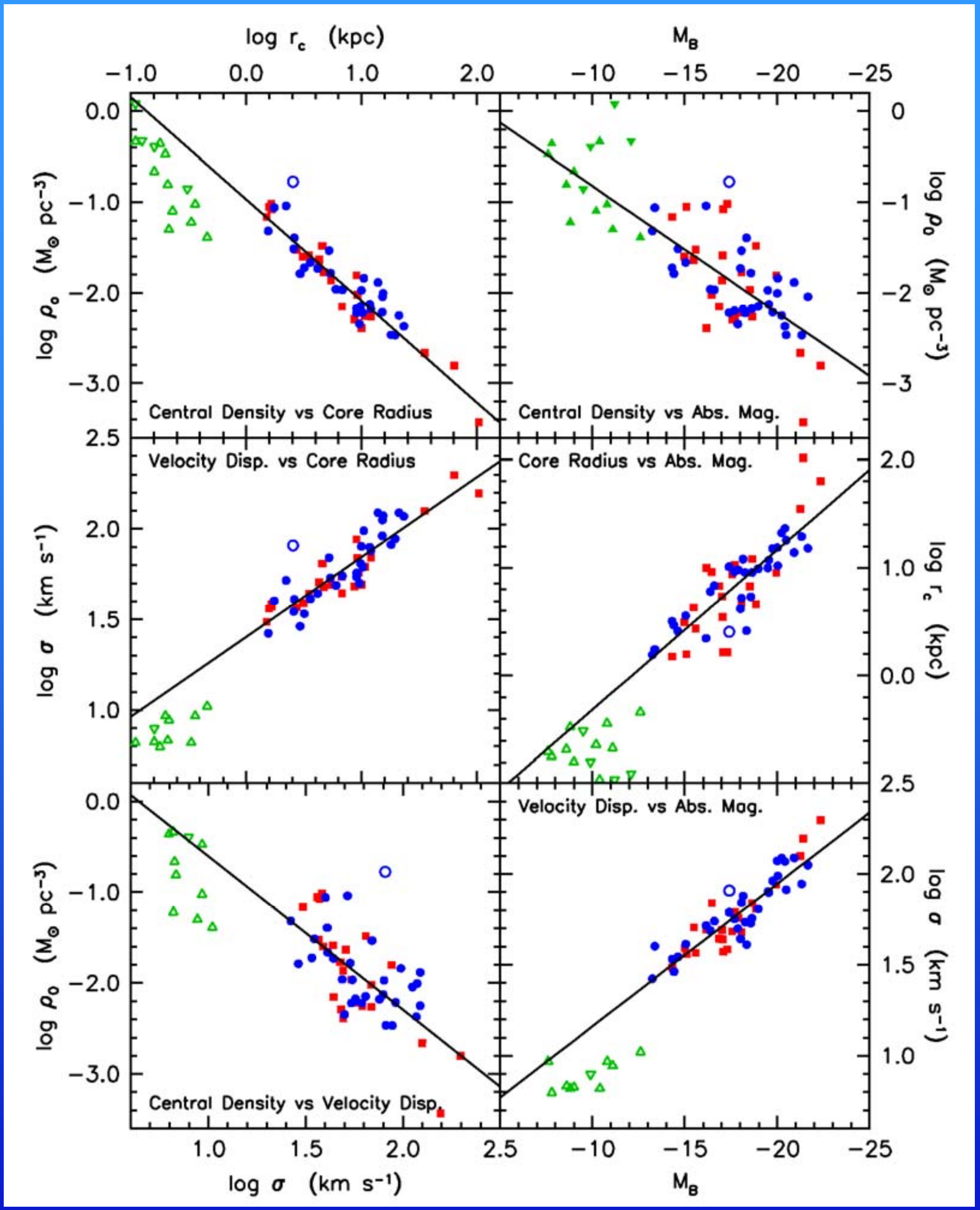
Disk galaxy scaling relations are well-established

Do the dSph (green) fit?

Yes, KF

No, they tend to lie BELOW the disk galaxy extrapolations..

Limits instead



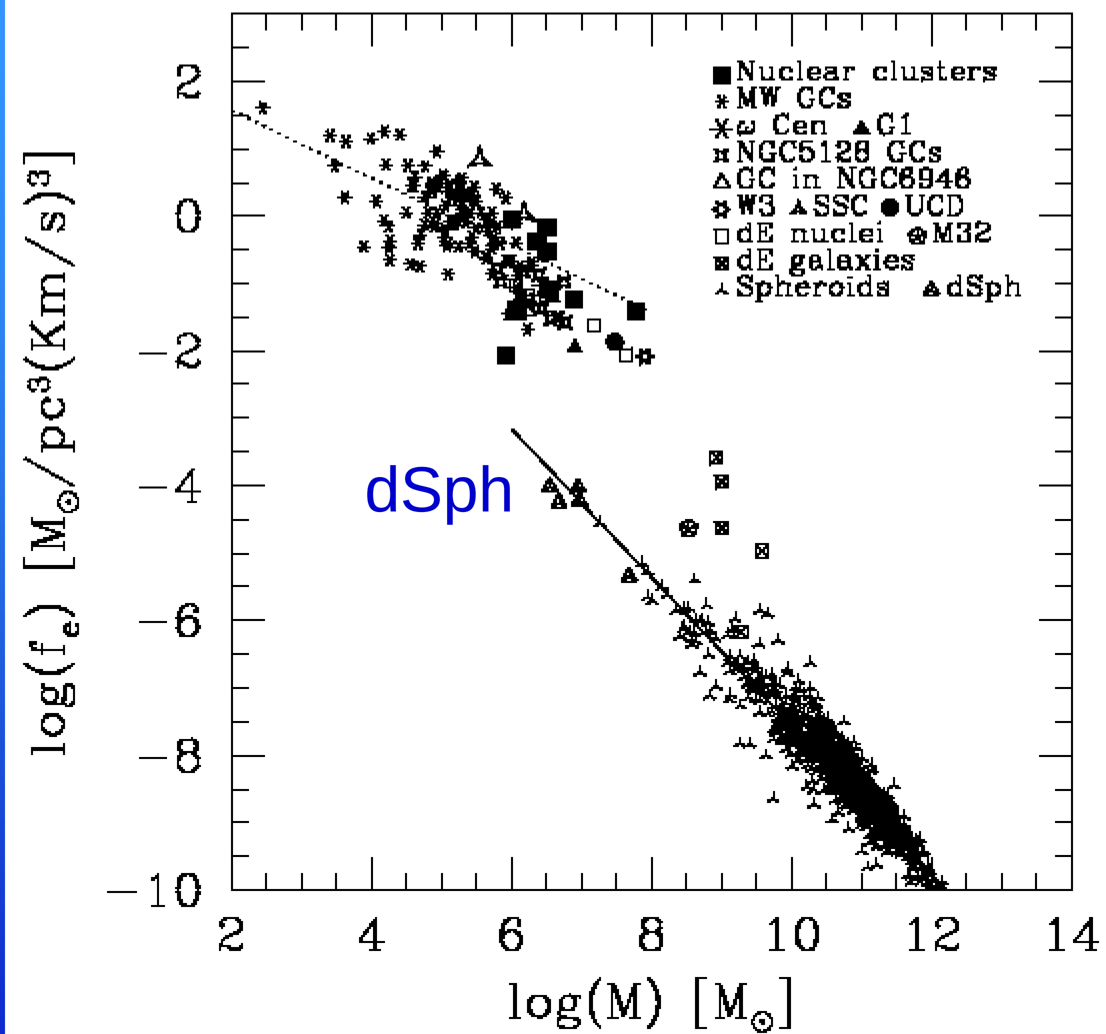
Dotted line is virial theorem for stars, no DM

Walcher et al 2005

There is a discontinuity in (stellar) phase-space density between small galaxies and star clusters.

Why?

→ Dark Matter?



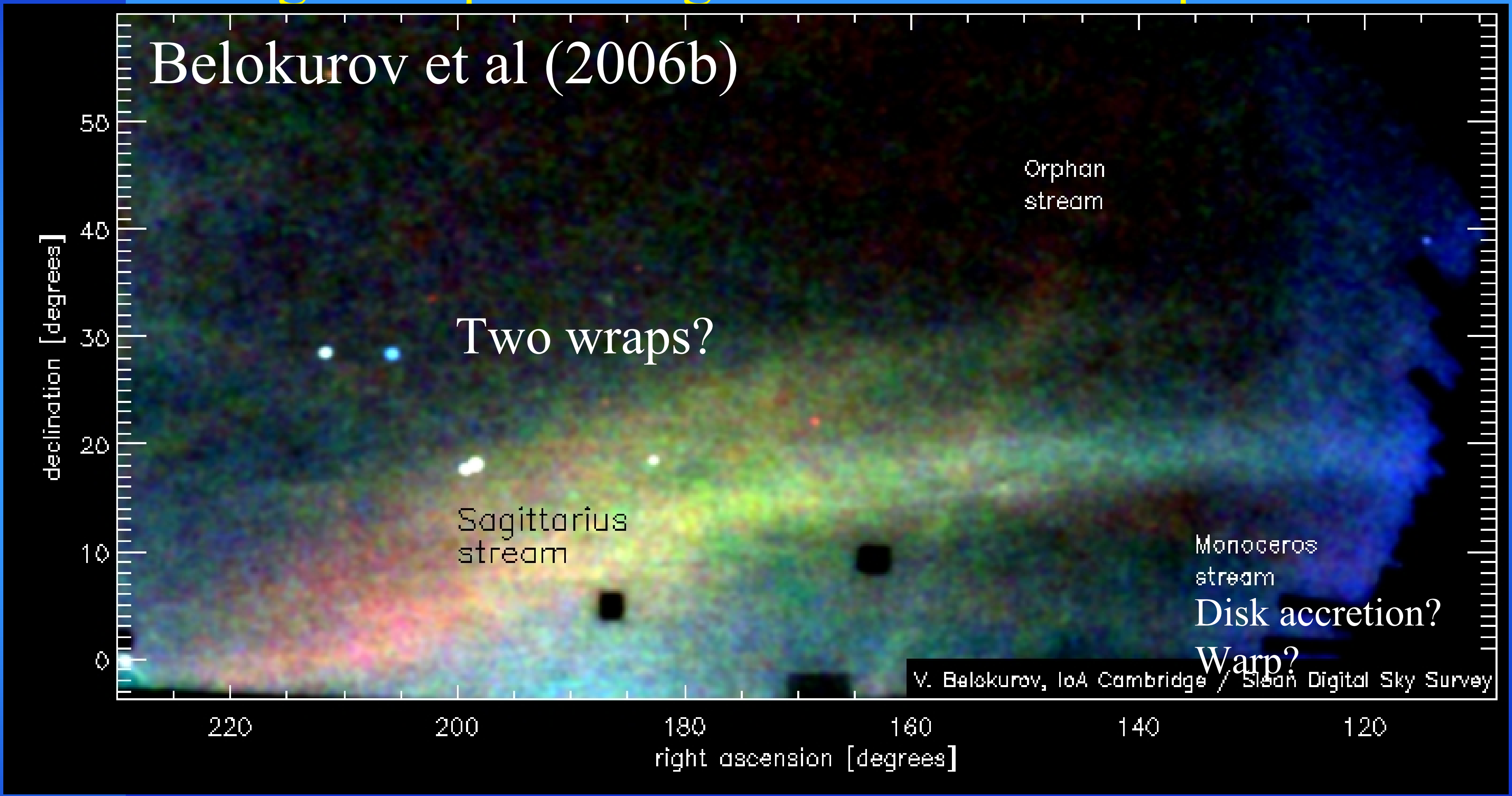
Phase space density ($\sim \rho/\sigma^3$) $\sim 1/(\sigma^2 r_h)$

- ➔ new large datasets of stellar line of sight kinematics, now covering spatial extent, & photometry for dSph satellite galaxies
- ➔ new discoveries; SDSS mostly – original key project (also Willman et al 05; Grillmair 06; Grillmair & Dionatos 06; Sakamoto & Hasegawa 06; Jerjen 07..)
- ➔ confirm and extend scaling relations
- ➔ Dark matter properties

G. Gilmore, M. Wilkinson, R.F.G.Wyse, J. Kleyna, A. Koch, N. Evans & E. Grebel 2007, ApJ v663 p948; astro-ph/0703308

Field of Streams (and dots)

Sgr tails probe large-scale DM halo: spherical

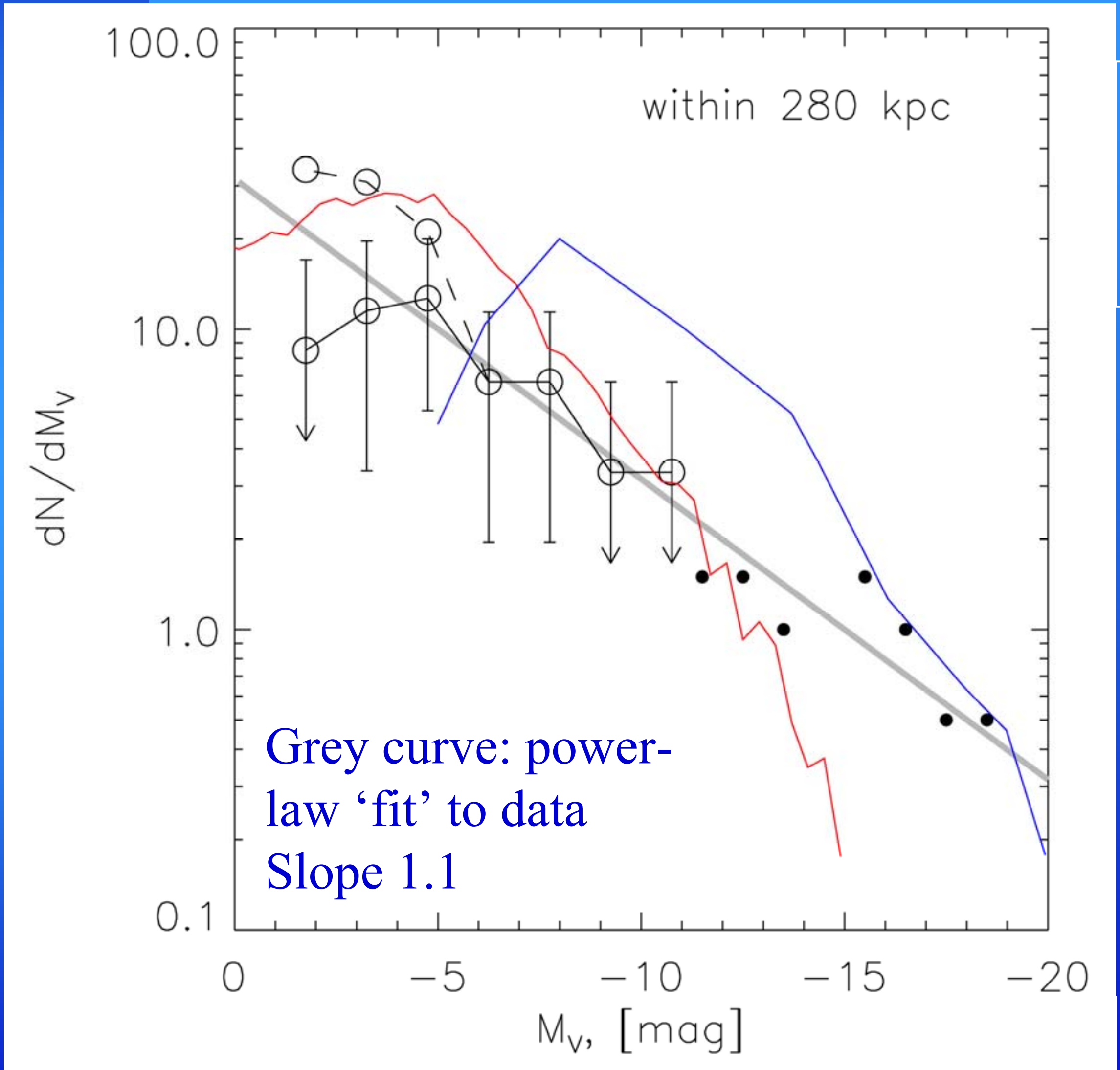


SDSS data, 19< r< 22, g-r < 0.4 colour-coded by mag (distance), blue (~10kpc), green, red (~30kpc)

Sgr discovered 1994 Ibata, Gilmore, Irwin Nat 370

Derived satellite luminosity function

Koposov et al 07 arXiv:0706.2687



Open symbols: Volume-corrected satellite LF from DR5

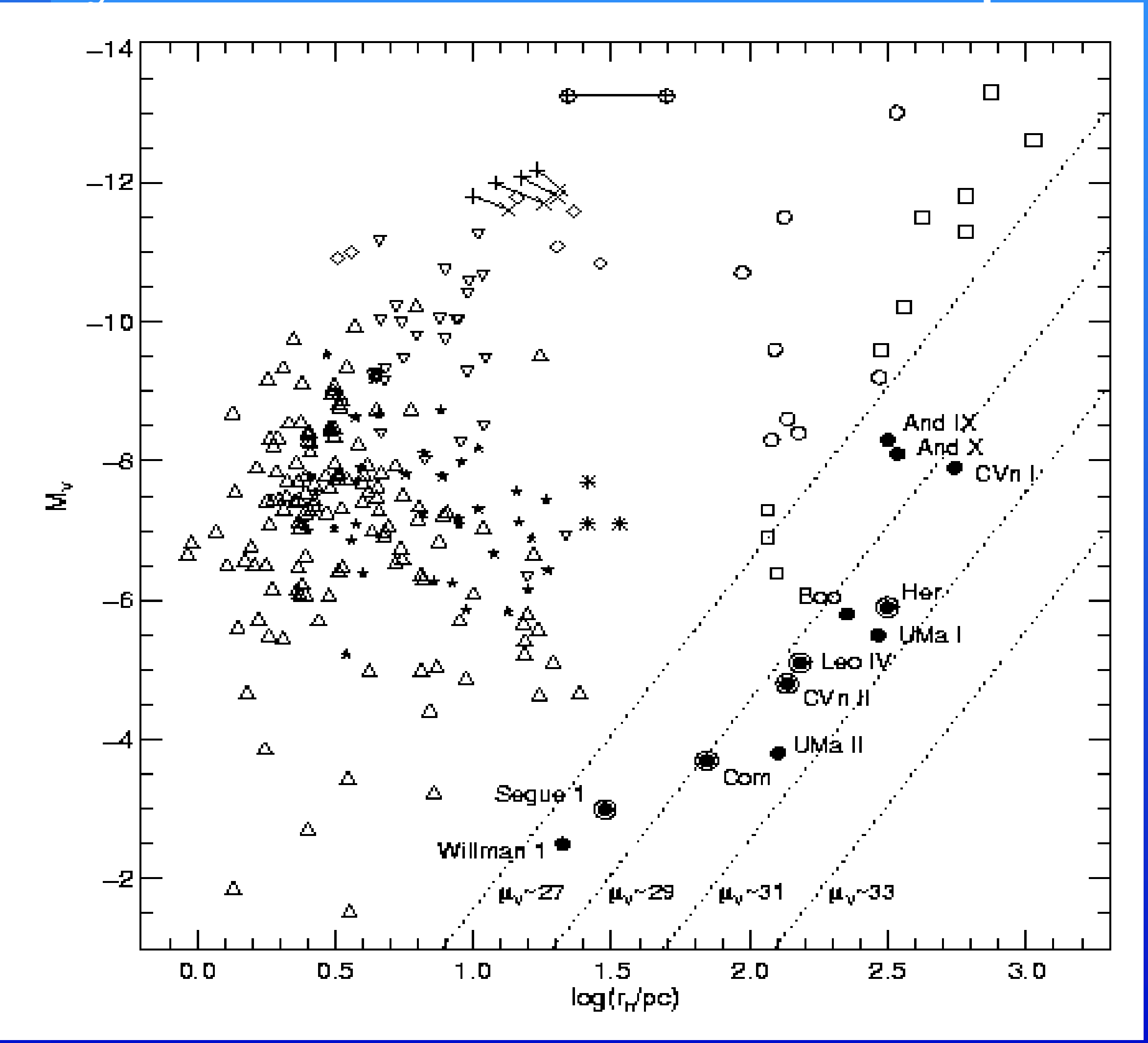
Filled symbols: 'all Local Group dSph'

Coloured curves: Semi-analytic theory (Benson et al 02, red Somerville 02, blue) Ignores surface-brightness discrepancies etc.

New systems extend overlap between galaxies and star clusters in luminosity

Belokurov et al. 2006

Analyses of kinematic follow-up underway



← ~10^3 $L_\odot$

New photometric and kinematic studies of UCDs, nuclear clusters, etc ➔ ALL the small things are purely stellar systems, M/L~1-4

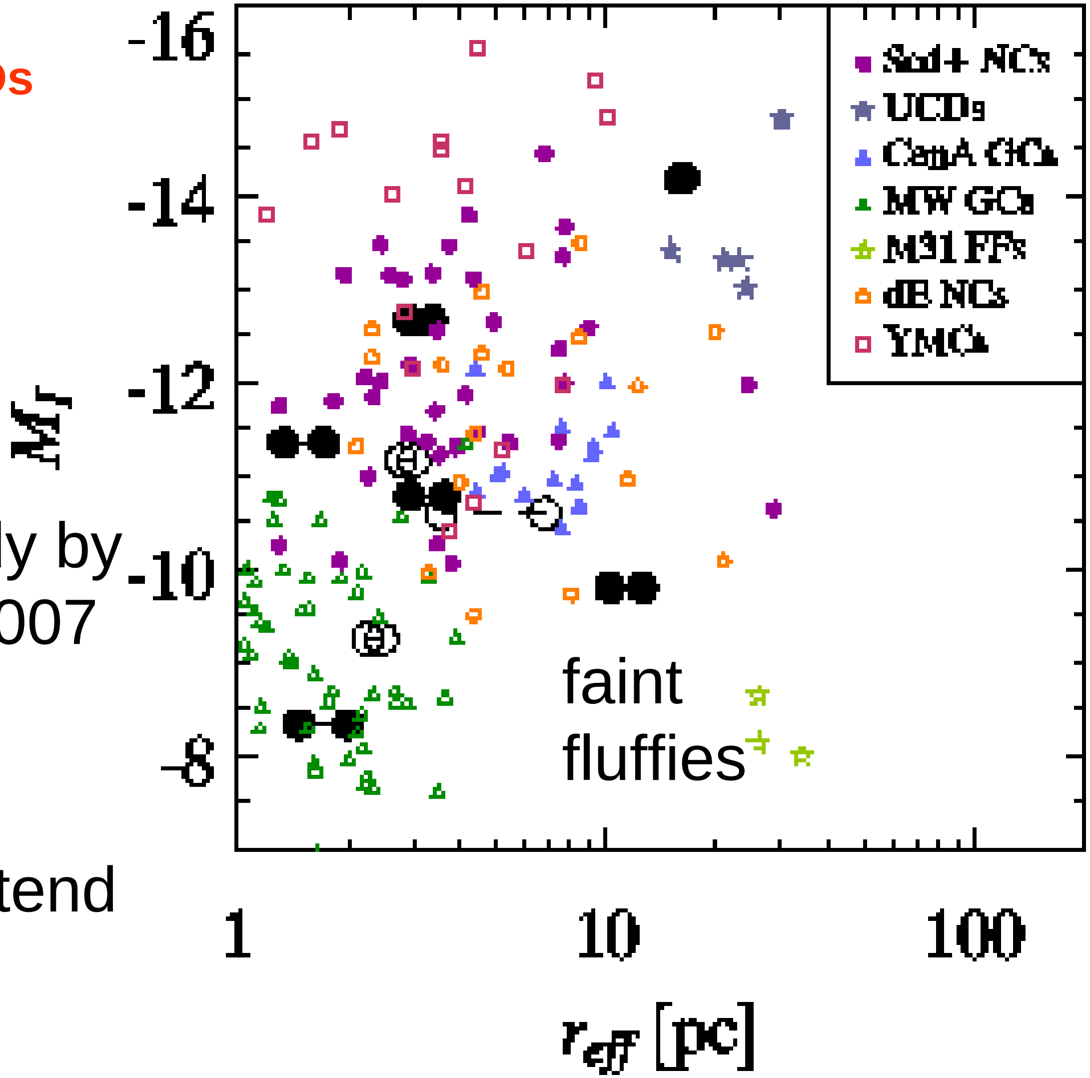
Seth etal astro-ph 0609302

Virgo & Fornax UCDs have stellar M/L –

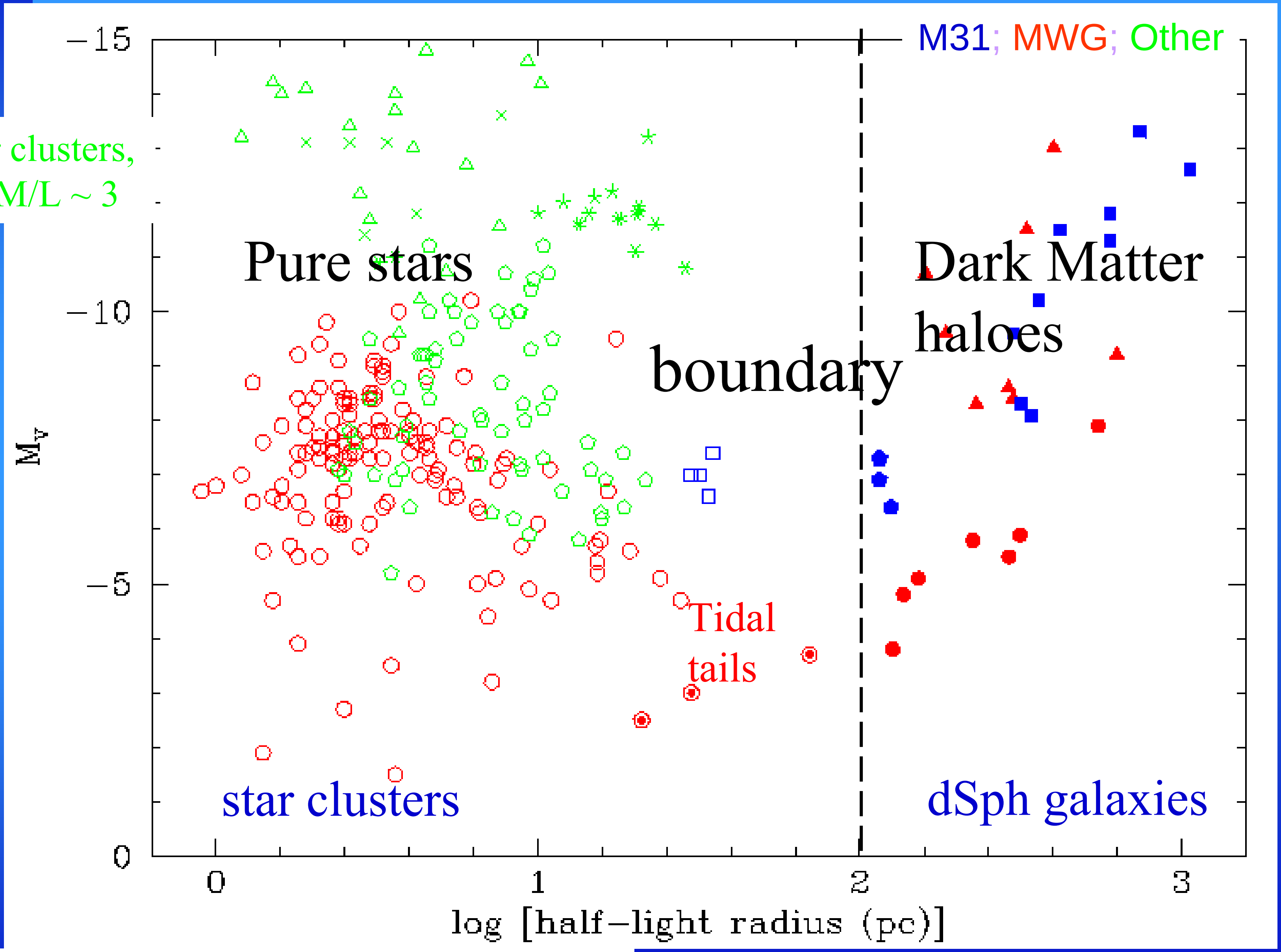
Hilker etal, A&A 463 119 2007

N5128 GC study by Rejkuba et al 2007

MWG GCs extend down to M~-2



Slightly different perspective… (updated data)



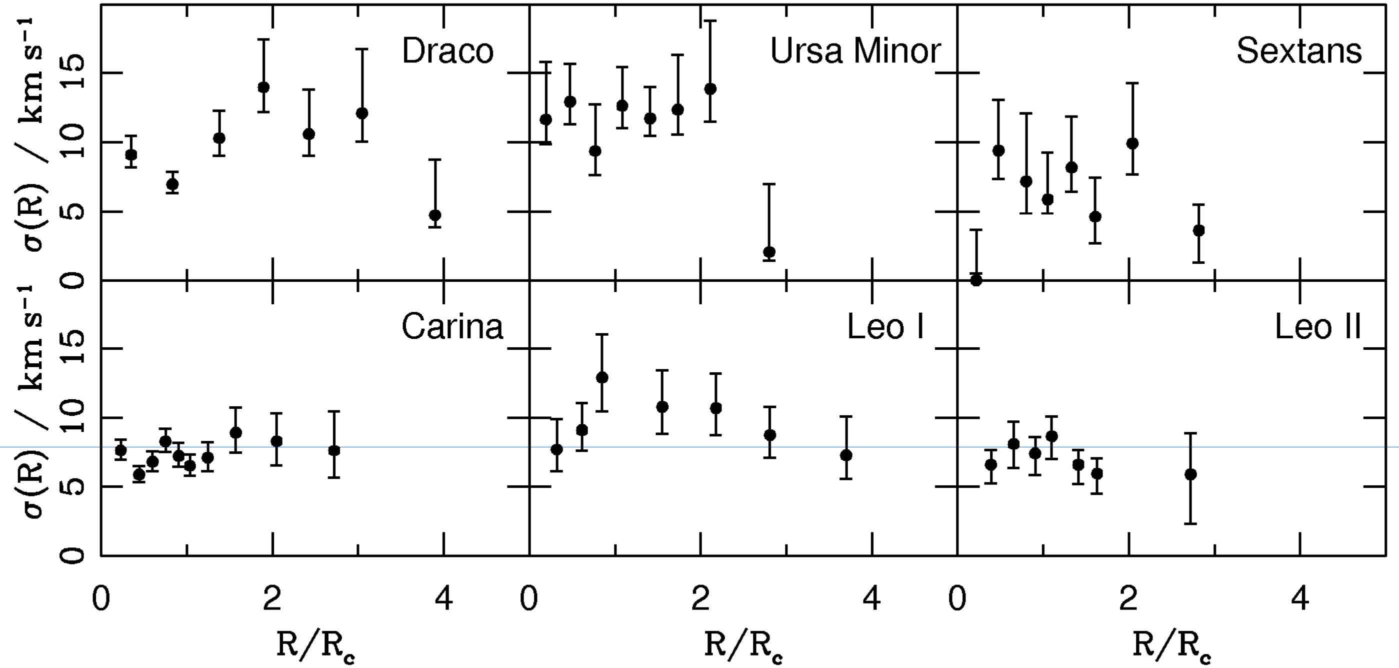
Gilmore, Wilkinson, RW et al 2007

Conclusion one:

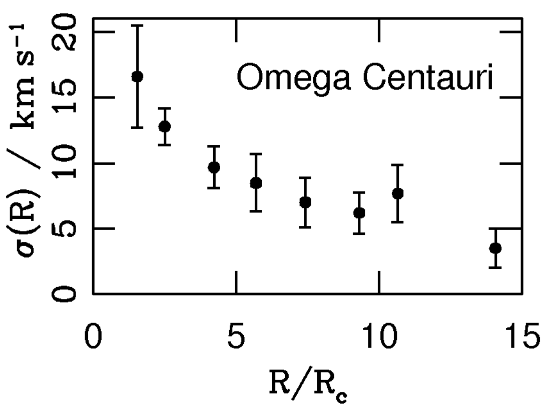
- Galaxy scaling relations work well, and indicate a systematic star-cluster *vs* small galaxy distinction in phase-space density
- There is a well-established size bi-modality
  - all systems with size $\lesssim$ 30pc are purely stellar
    $-16 < M_v < 0$ (!!) M/L ~ 3; e.g. UCDs, Hilker et al 07; Rejkuba et al 07
  - all systems with size greater than ~120pc have dark-matter halo
- There are no known (virial equilibrium) galaxies with half-light radius r < 120pc
- So now look at the dSph galaxies' masses

Stellar kinematic data across faces of dSph now quite extensive e.g. Gilmore et al 2007 MOND problem…

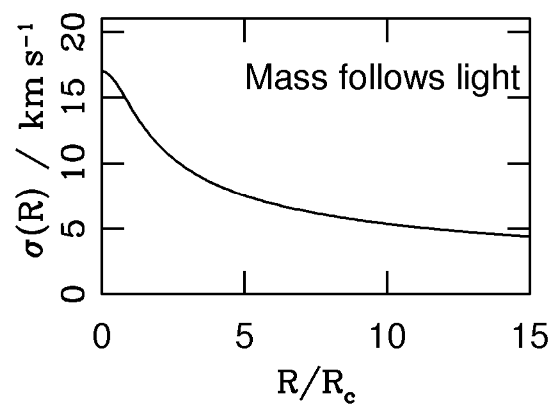
dSph



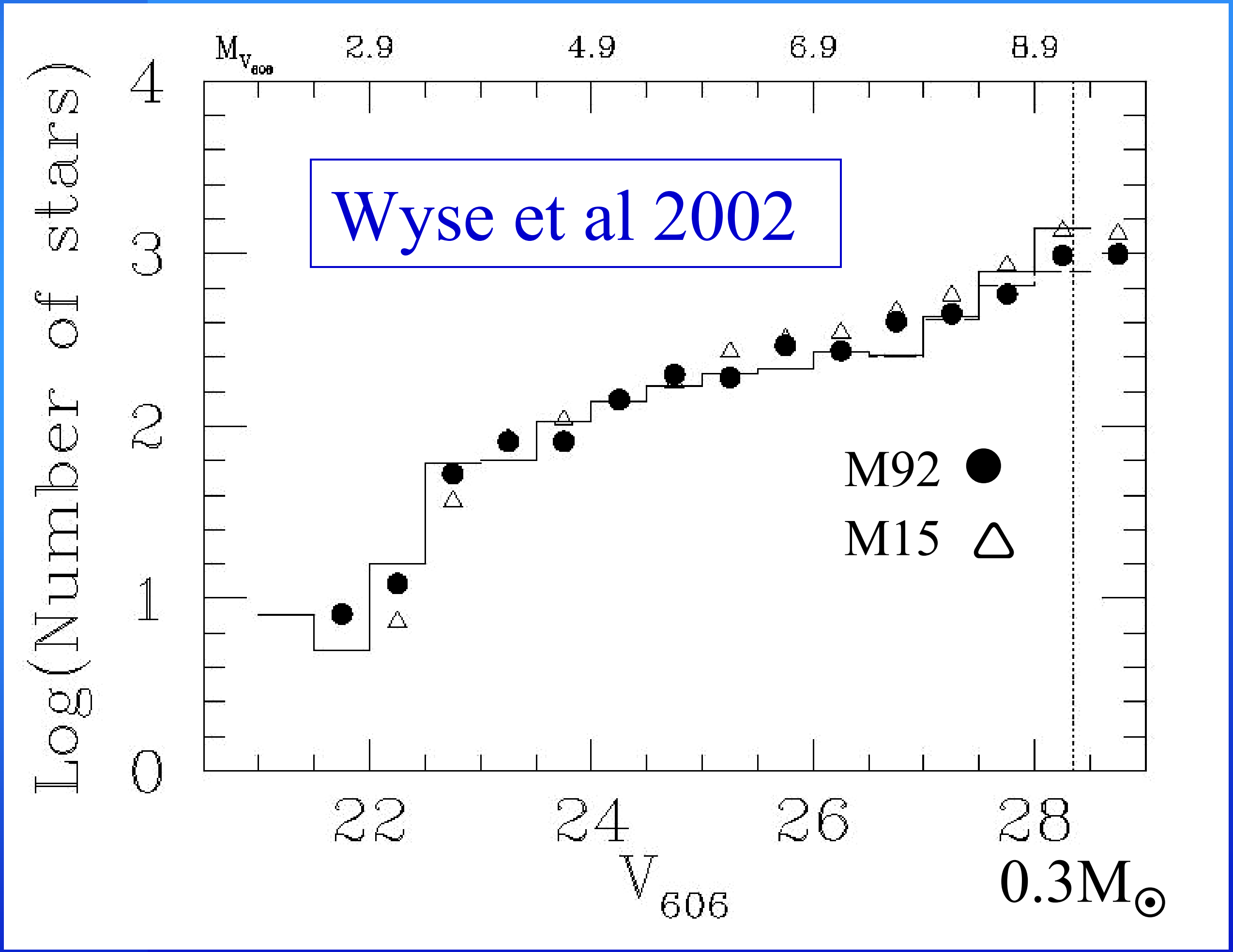
Seitzer 1983; van de Ven et al 06



Globular cluster $M/L_V \sim 2.5$



Main sequence luminosity functions of UMi dSph and of globular clusters are indistinguishable.
➔ normal stellar M/L

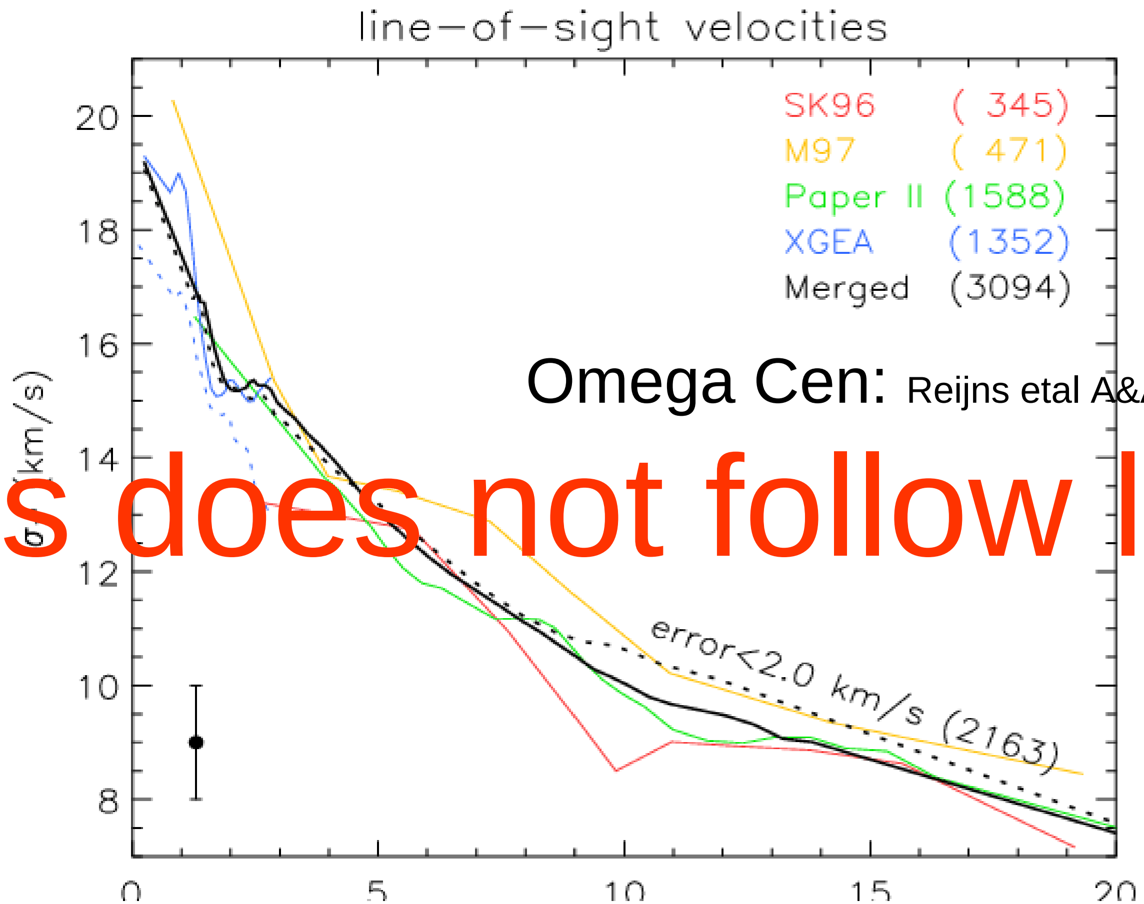


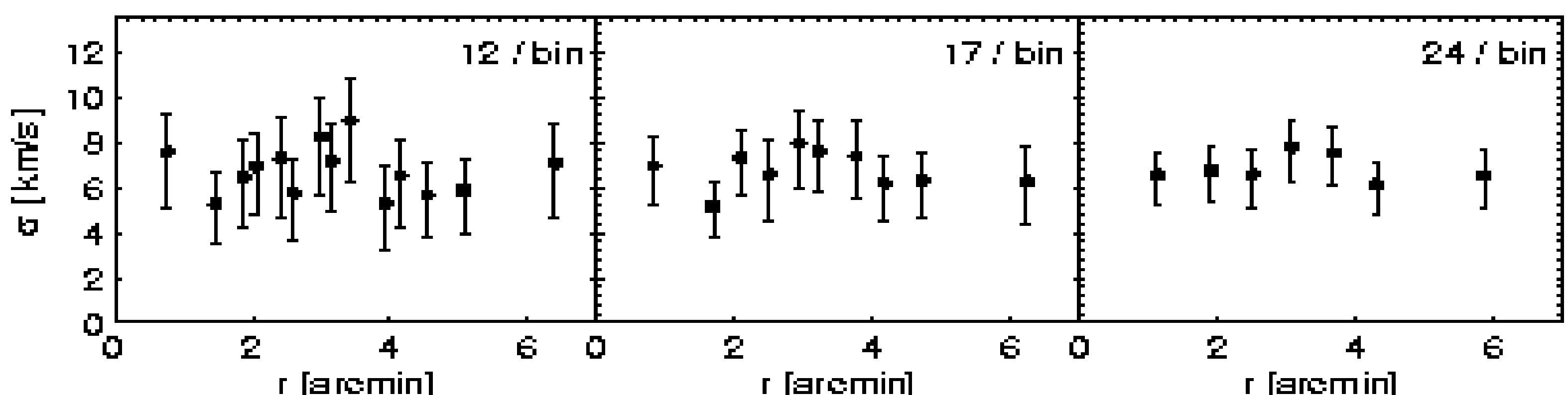
HST star counts

Massive-star IMF constrained by elemental abundances – also normal

Mass does not follow light

Omega Cen: Reijns etal A&A 445 503





Leo II: Koch etal

Mass measurements: the early context

- **The ``standard'' value for local DM at the Sun is 0.3GeV/c²/cm³, all in a `halo' component**
- (cf pdg.lbl.gov: Eidelman etal 2004)

- **the original work, and origin of this value, is the first analysis to include a full 3-D gravitational potential, parametric modelling, and a direct determination of both the relevant density scale length and kinematic (pressure) gradients from data, allowing full DF modelling for the first time:**

Kuijken & Gilmore 1989 (MN 239 571, 605, 651), 1991 (ApJ 367 L9);

Gilmore, Wyse & Kuijken (ARAA 27 555 1989):

cf Bienayme etal 2006 A&A 446 933 for a recent study

- **Dark halos are `predicted' down to sub-earth masses; but…**
- **Neither the local disk, nor star clusters, nor spiral arms, nor GMC, nor the solar system, have associated DM: Given the absence of a very local enhancement, what is the smallest scale on which DM is concentrated? How can sub-halos in dSph galaxies with star formation over 10Gyr avoid collecting any baryons?**

From kinematics to dynamics: Jeans equations, simple and robust method

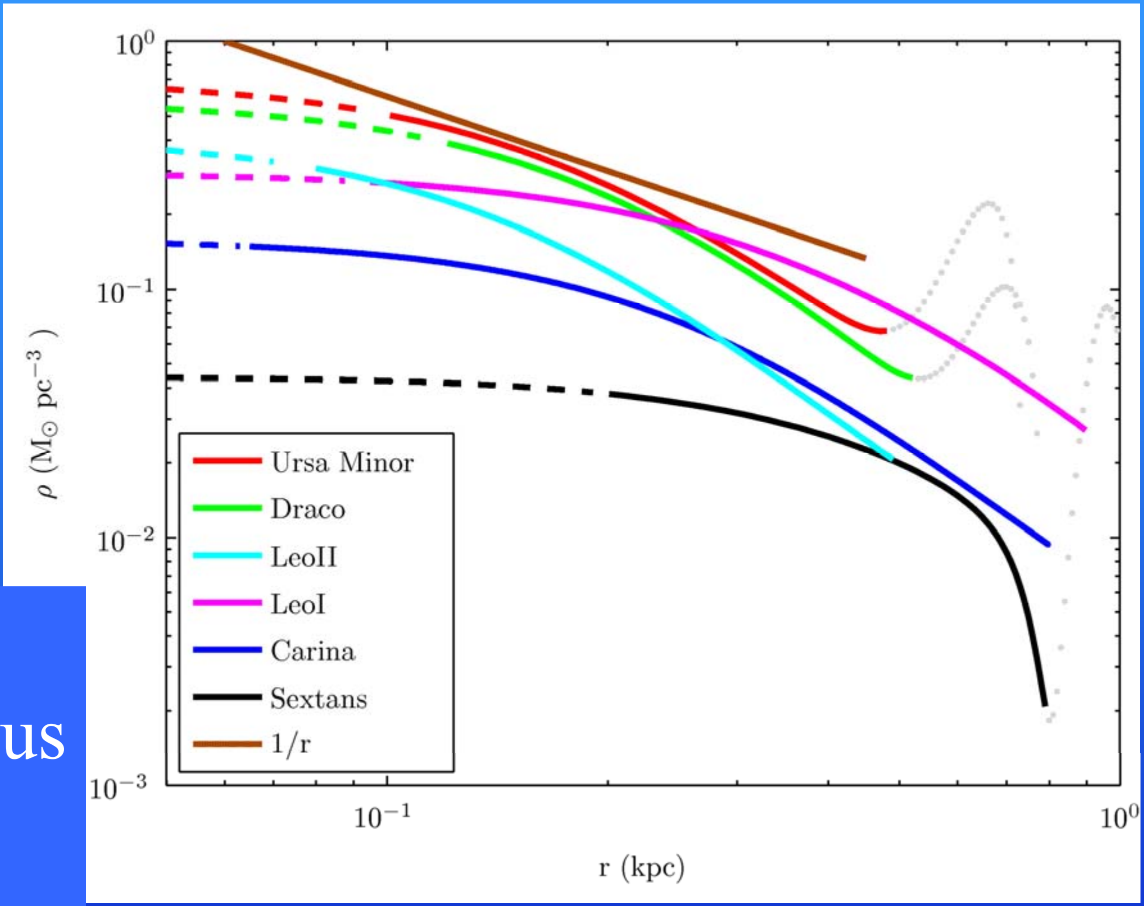
- Relates spatial distribution of stars and their velocity dispersion tensor to underlying mass profile

$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\nu\sigma_r^2}{\mathrm{d}r} + 2\frac{\beta\sigma_r^2}{r}\right)$$

  - Either (i) determine mass profile from projected dispersion profile, with assumed isotropy, and smooth functional fit to the light profile
  - Or (ii) assume a parameterised mass model M(r) and velocity dispersion anisotropy β(r) and fit dispersion profile to find best forms of these (for fixed light profile)
- Full distribution function modelling, as opposed to velocity moments, also underway: needs very large data sets. Where available, DF and Jeans’ models agree.
- King models are <u>not</u> appropriate for dSph → too few stars

Derived mass density profiles:

Jeans' equation with assumed isotropic velocity dispersion: All consistent with cores (similar results from other analyses)



CDM predicts slope of -1.3 at 1% of virial radius and asymptotes to -1 (Diemand et al. 04)

Need different technique at large radii, e.g. full velocity distribution function modelling.. And understand tides.

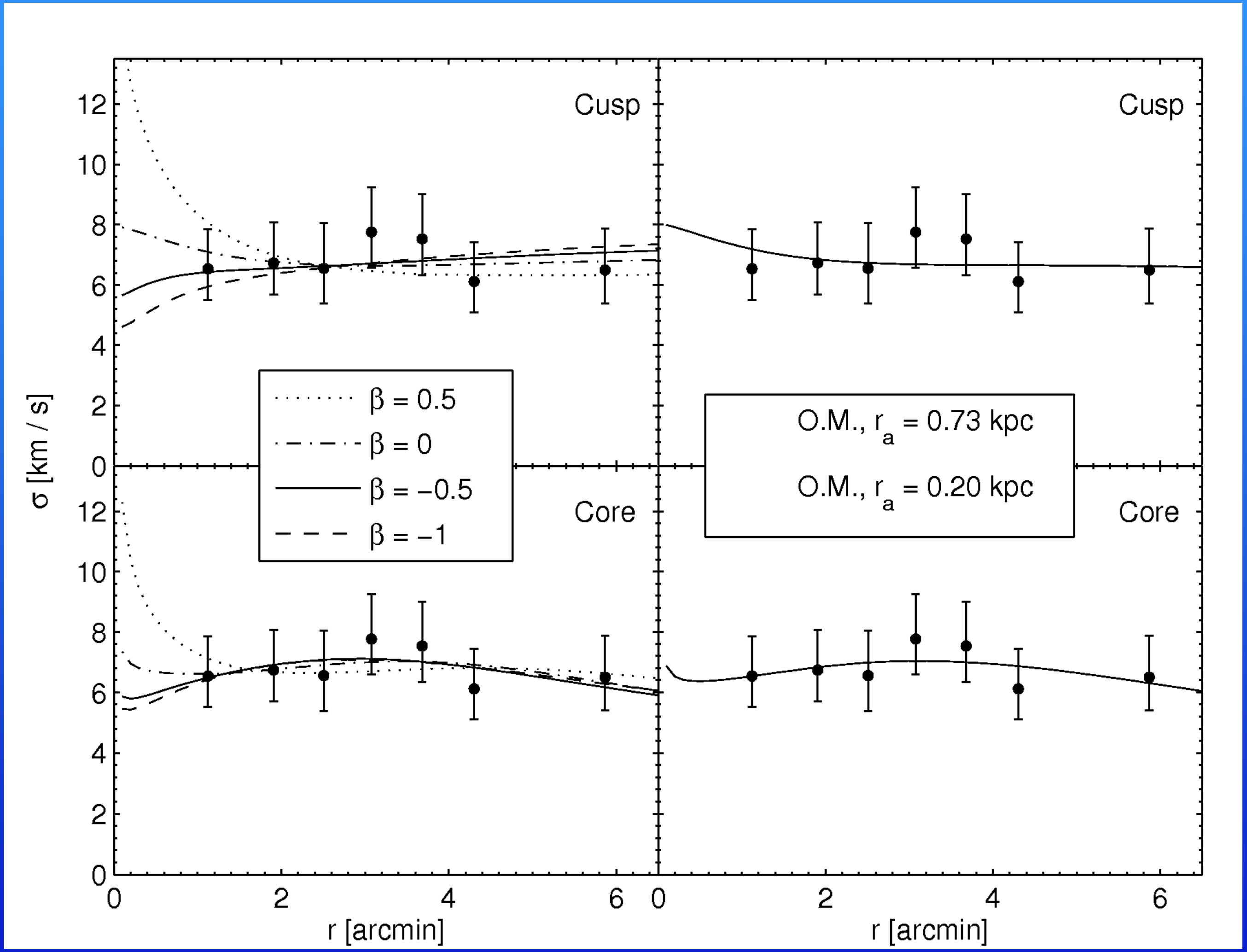
Core properties: adding anisotropy

Koch et al 07
AJ 134 566 ‘07

Fixed β — Radially varying β

Leo II

$$\beta = 1 - \frac{\langle v_\theta^2 \rangle}{\langle v_r^2 \rangle}$$



Core and/or mild tangential anisotropy slightly favoured

- Mass – anisotropy degeneracy prevents robust cusp/core distinction, but core provides better fit (see also Wu 2007 astro-ph/0702233)
- Break degeneracy by complementary information:
  - Ursa Minor has a cold subsystem, requiring shallow gradients for survival (Kleyna et al 2003 ApJL 588 L21)
  - Fornax globular clusters should have spiralled in through dynamical friction unless core (e.g. Goerdt et al 2006)
- Simplicity argues that cores favoured for all?
- New data and df-models underway to test (GG etal, VLT high-resolution core/cusp project)

Conclusion two:

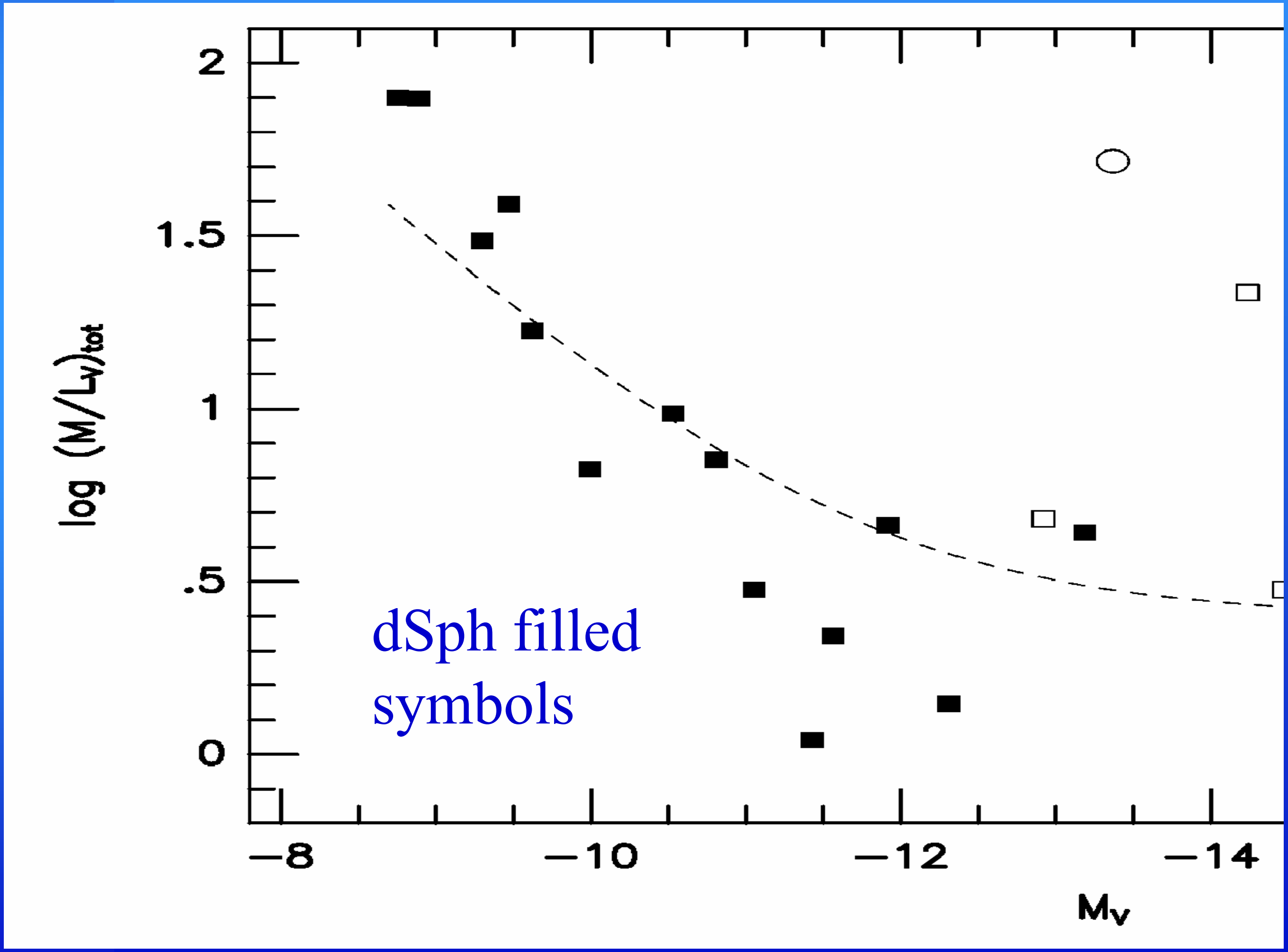
- High-quality kinematic data exist
- Jeans' analyses → prefers cored mass profiles
- Mass-anisotropy degeneracy *allows* cusps
- Substructure, dynamical friction → prefers cores
- Equilibrium assumption is valid inside optical radius
- More sophisticated DF analyses underway

- **Cores always preferred, but not always required**
- **Central densities always similar and low**
- **Consistent results from available DF analyses**

- Extending analysis to lower luminosity systems difficult due to small number of stars
- Integrate mass profile to enclosed mass:

Constant mass scale of dSph?

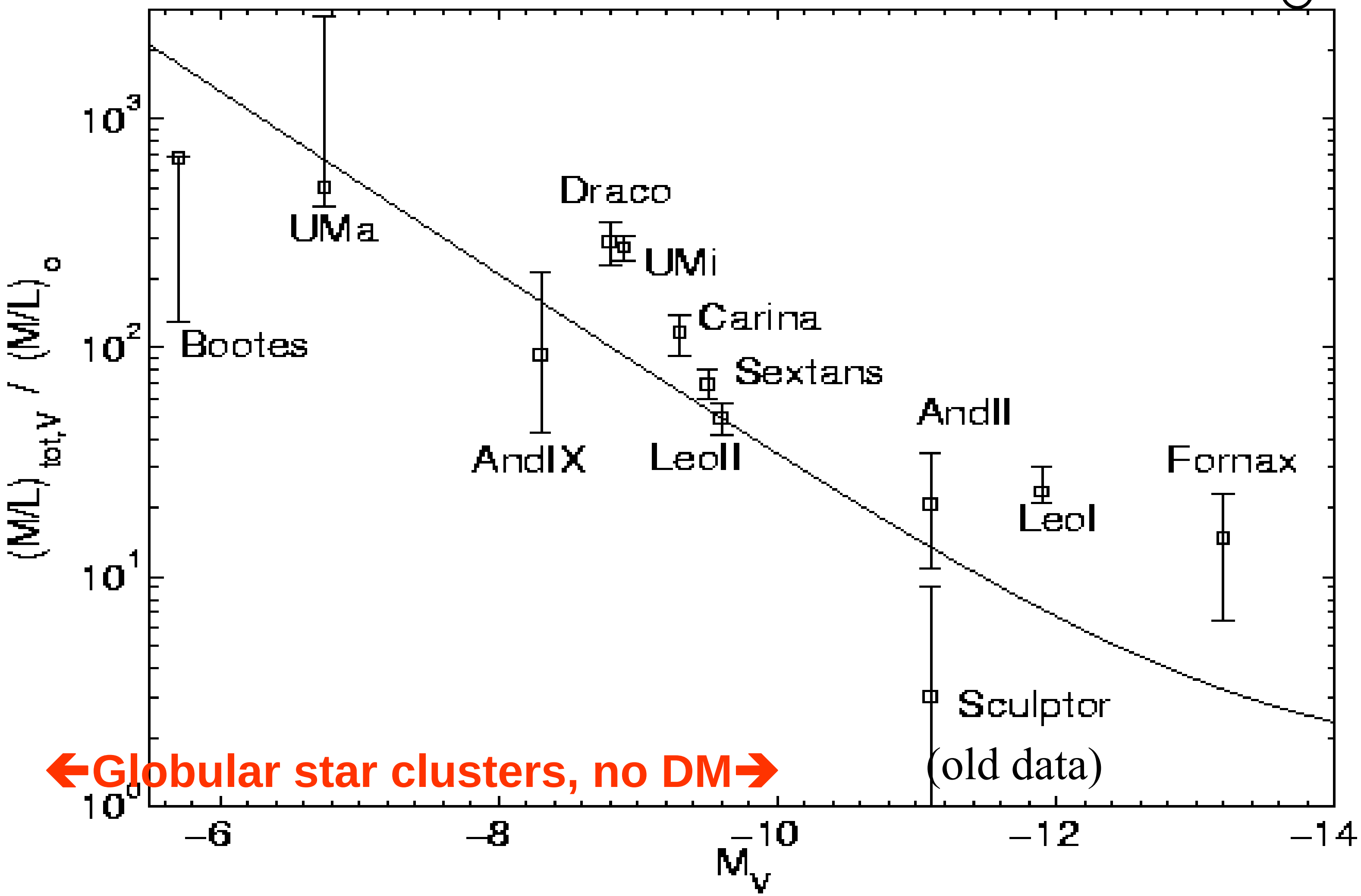
Based on central velocity dispersions only; line corresponds to dark halo mass of $10^7 M_\odot$



Mateo 98 ARAA

2007: extension of dynamic range [UMa, Boo, AndIX], new kinematic studies: Mateo plot improves.

Mass enclosed within stellar extent ~ 4 x $10^7 M_\odot$



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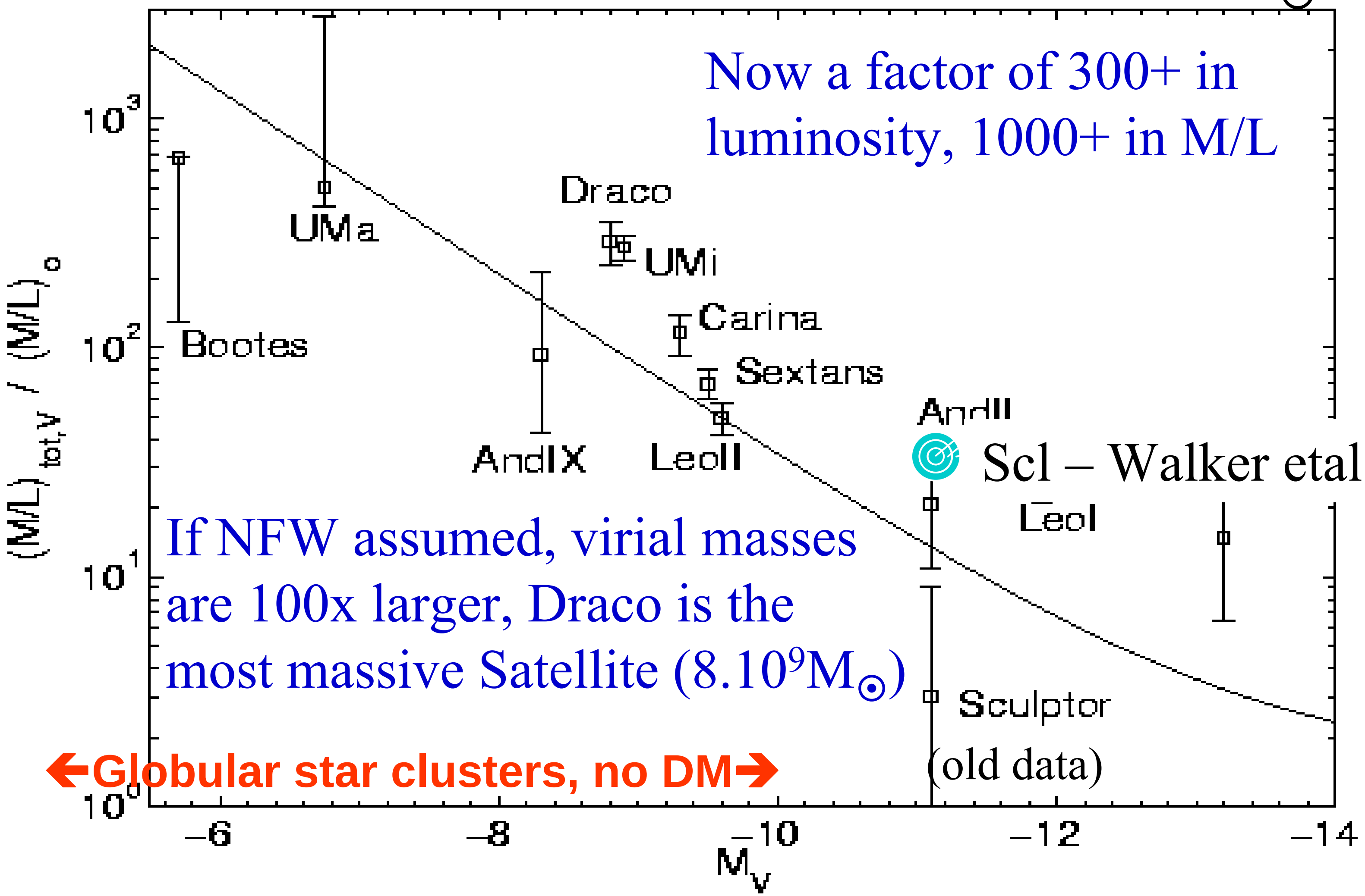
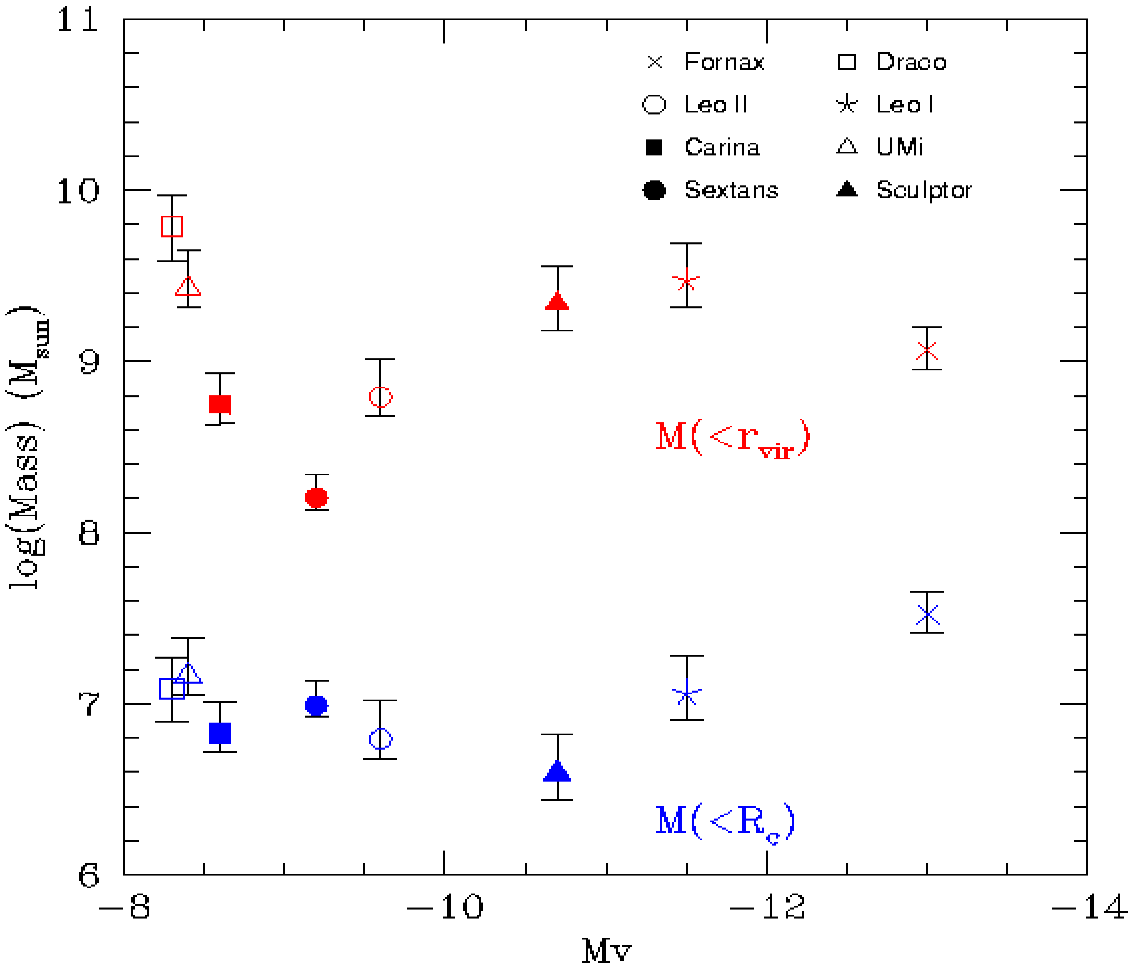


NFW fits require very high mass, and a very wide range of mass
Draco = 8.10^9Msun and M/L=100,000   MWG vs M31 offset
no simple mass-luminosity link   astro-ph/0701780
Strigari etal (in prep) central mass fits – no simple rank



Consistency?

- A minimum half-light size for galaxies, ~100pc
- Cored mass profiles, with similar mean mass densities ~0.1$M_\odot$/pc^3, ~5GeV/cc
- An apparent characteristic (minimum) mass dark halo in all dSph, mass ~4 x $10^7 M_\odot$

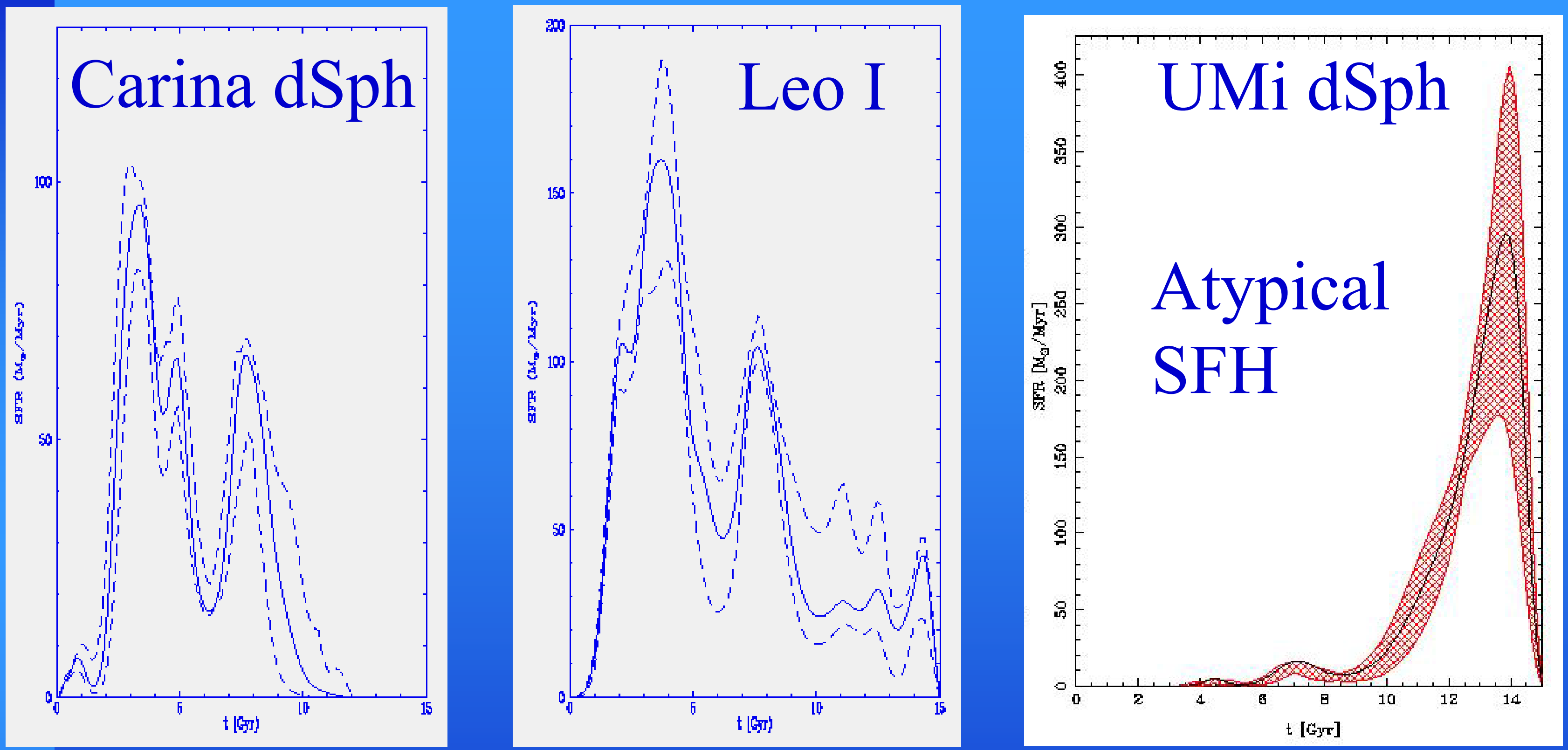
characteristic mass profile convolved with
characteristic normalisation must imply
characteristic mass → internal consistency

Implications from Astrophysics: Can one plausibly build a dSph as observed without disturbing the DM?

- Star formation histories and IMF are easily determined → survival history, energy input…
- Chemical element distributions define gas flows, accretion/wind rates,
- debris from destruction makes part of the field stellar halo: well-studied, must also be understood

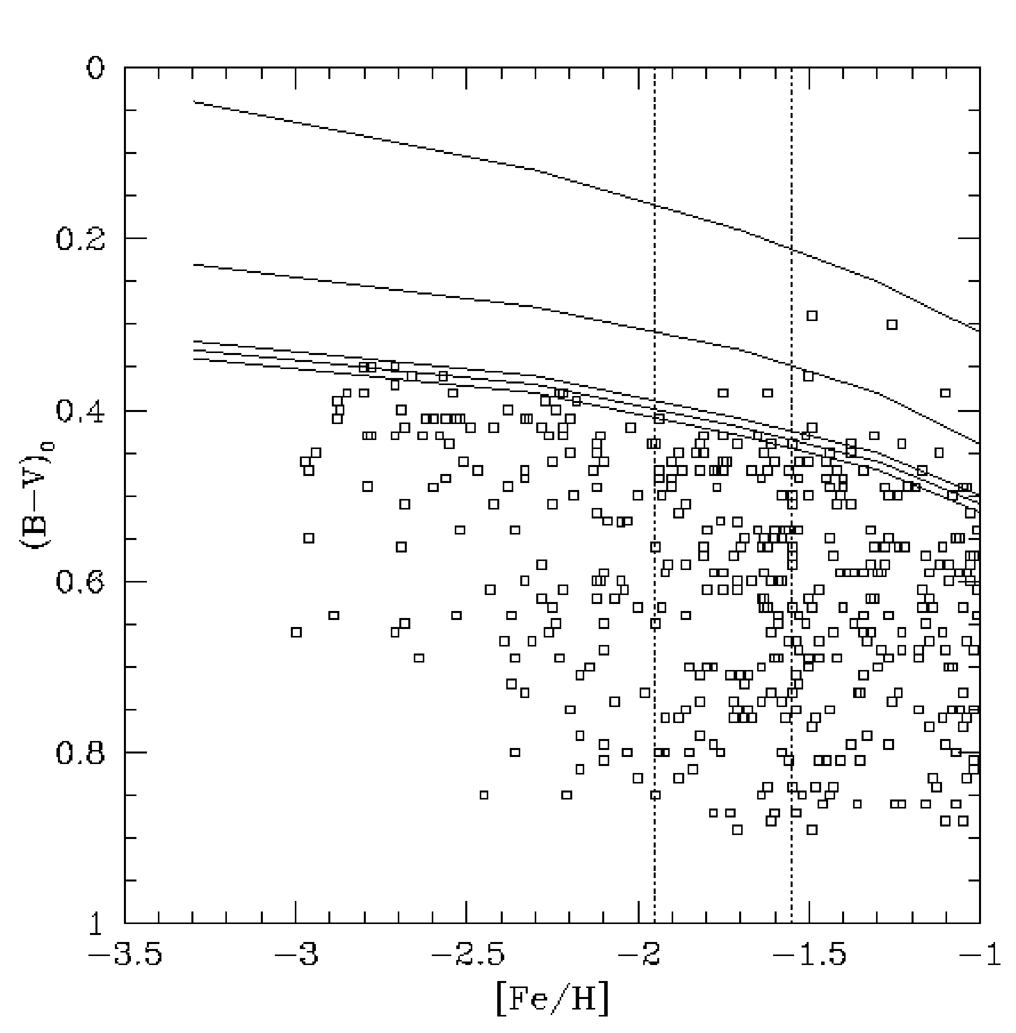
- Feedback processes are not free parameters

Hernandez, Gilmore & Valls-Gabaud 2000



Intermediate-age population dominates in typical dSph satellite galaxies – with very low average SFR over long periods (~$5M_\odot/10^5$yr), until recently

Bulk of stellar halo is OLD, as is bulge: Did not form from typical satellites disrupted later than a redshift of 2

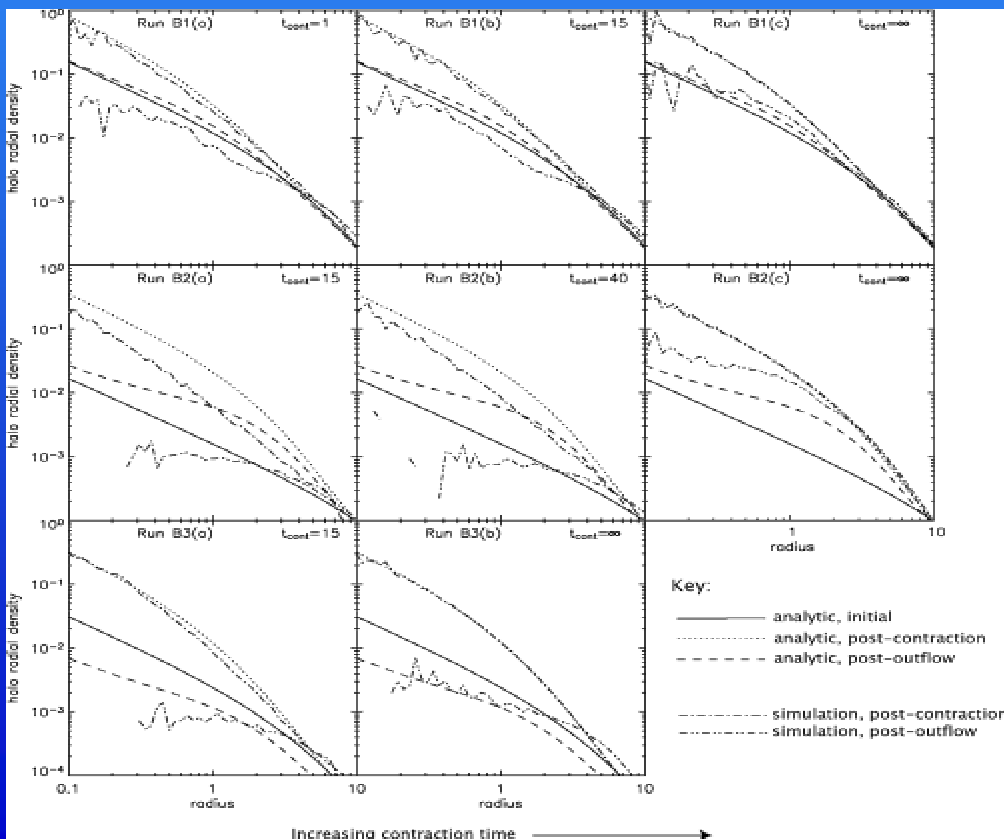


Unavane, Wyse & Gilmore 1996

Scatter plot of [Fe/H] vs B-V for local high-velocity halo stars (Carney): few stars bluer (younger) than old turnoffs (5Gyr, 10Gyr, 15Gyr Yale)

Very many attempts to model feedback on CDM structure….

- Some of our simple examples:
  - Read et al 2006 MN 367 387, MN 366 429, 2005 MN 356 107…; Fellhauer etal in prep
  - Conclusion:



DM halos certainly respond to tides and mass-loss, but secularly

If various histories leave similar mass profiles, history cannot be dominant

Summary:

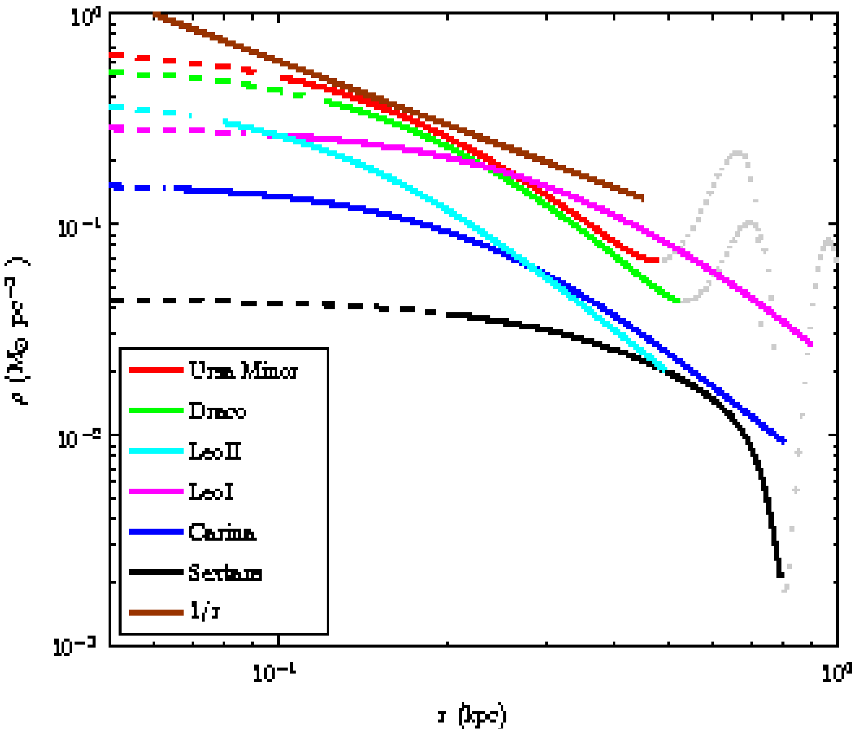
- A minimum size for galaxies, ~100pc
  - Mass size scale somewhat larger (?), expected since baryons dissipate energy?
- Velocity dispersions of ~10km/s, ~ flat profile
- Cored mass profiles, with similar mean mass densities ~0.1$M_{\odot}/pc^3$, ~5GeV/cc
  - Phase space densities fairly constant, maximum for galaxies (cf Walcher et al 2005)
- An apparent characteristic (minimum) mass dark halo in all dSph, mass ~4 x $10^7 M_{\odot}$
  - Extending analysis to lowest luminosity systems difficult – too few stars -- but suggestion from central dispersion of lower masses (Simons and Geha 07)

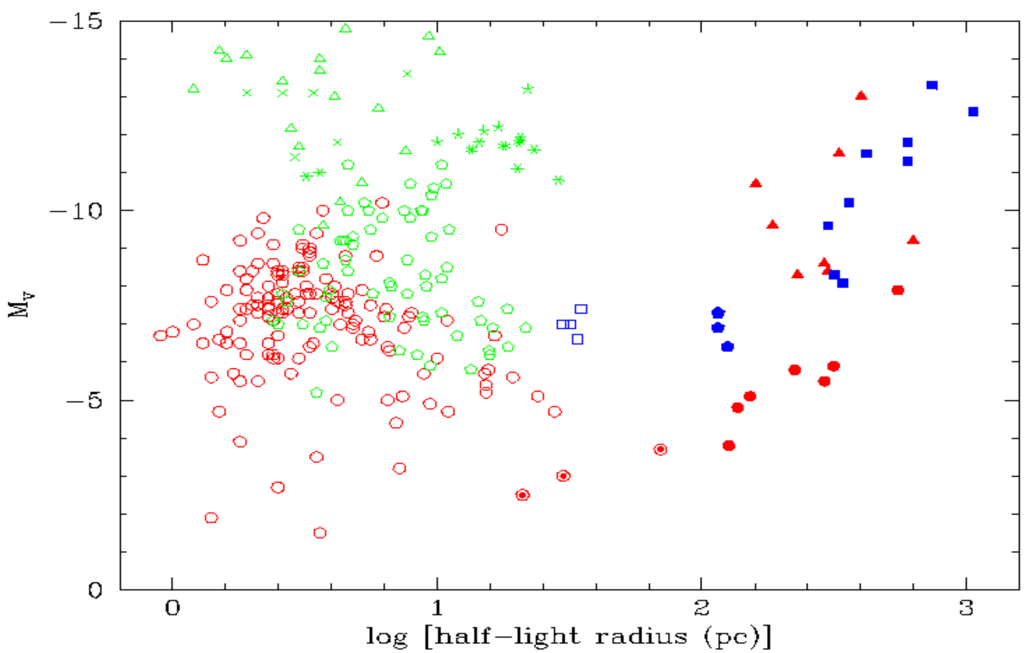
Implications for Dark Matter:

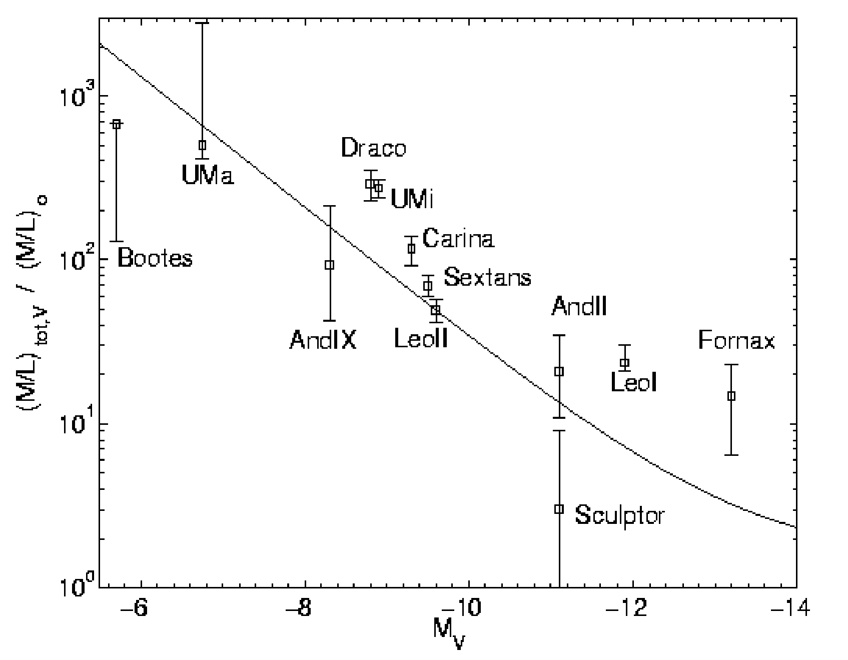
- Characteristic Density ~10GeV/c^2/cm^3
  - If DM is very massive particles, they must be extremely dilute (Higgs ~100GeV)
- Characteristic Scale above 100pc, several $10^7 M_\odot$
  - power-spectrum scale break?
  - This would (perhaps!) naturally solve the substructure and cusp problems
- Number counts low relative to CDM

- Need to consider seriously non-CDM candidates

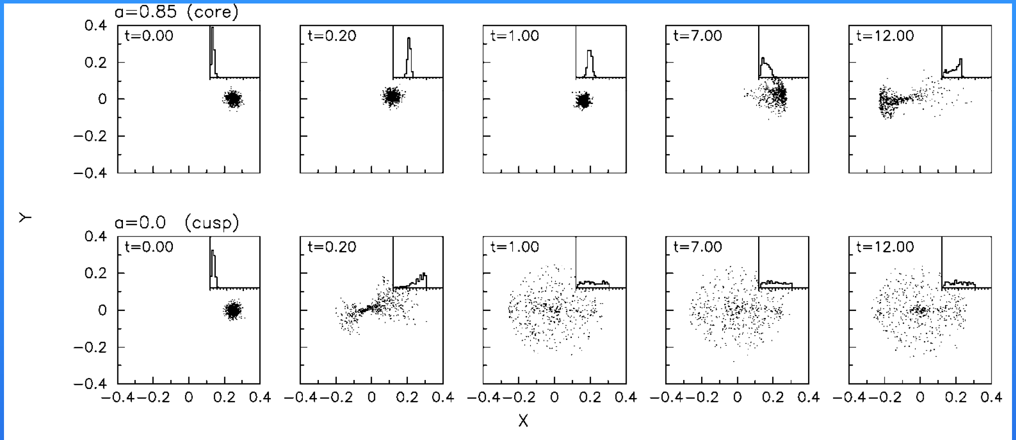
Properties of Dark-Matter Dominated dSph galaxies:







Breaking the degeneracy – first steps



- ➢Survival of cold subsystem in UMi dSph implies shallow mass density profile (Kleyna et al 03)
- ➢Dynamical friction limits on Fornax dSph Globular Clusters also favour cores to extend timescales Goerdt etal 2006