

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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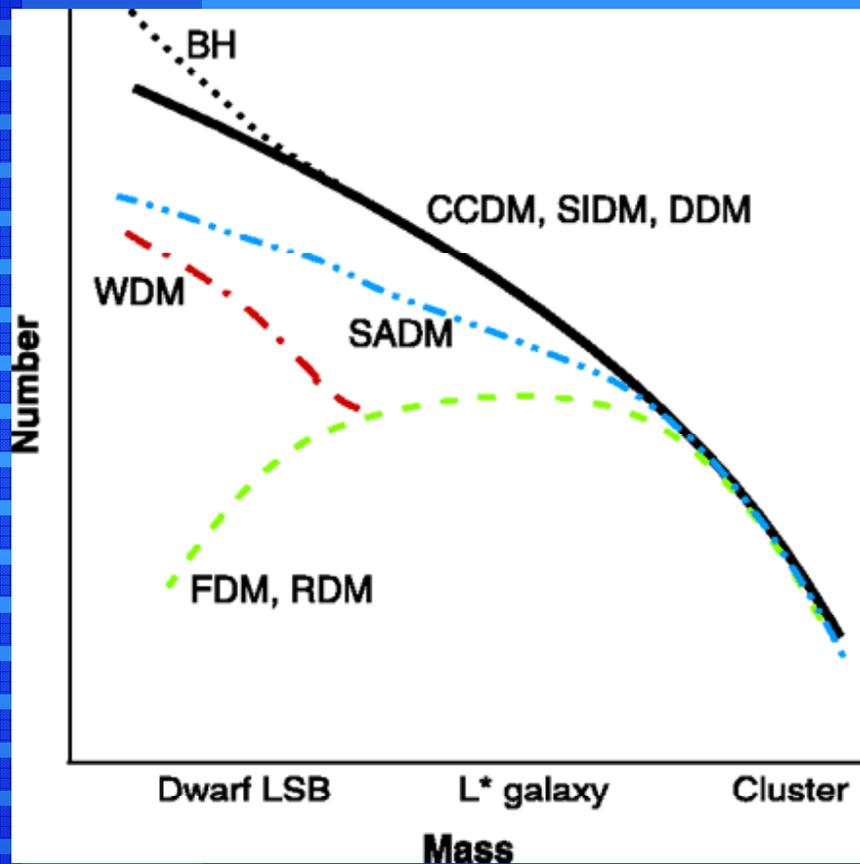
Mark Wilkinson, Rosie Wyse, Jan Kleyna,

Andreas Koch, Wyn Evans, Eva Grebel

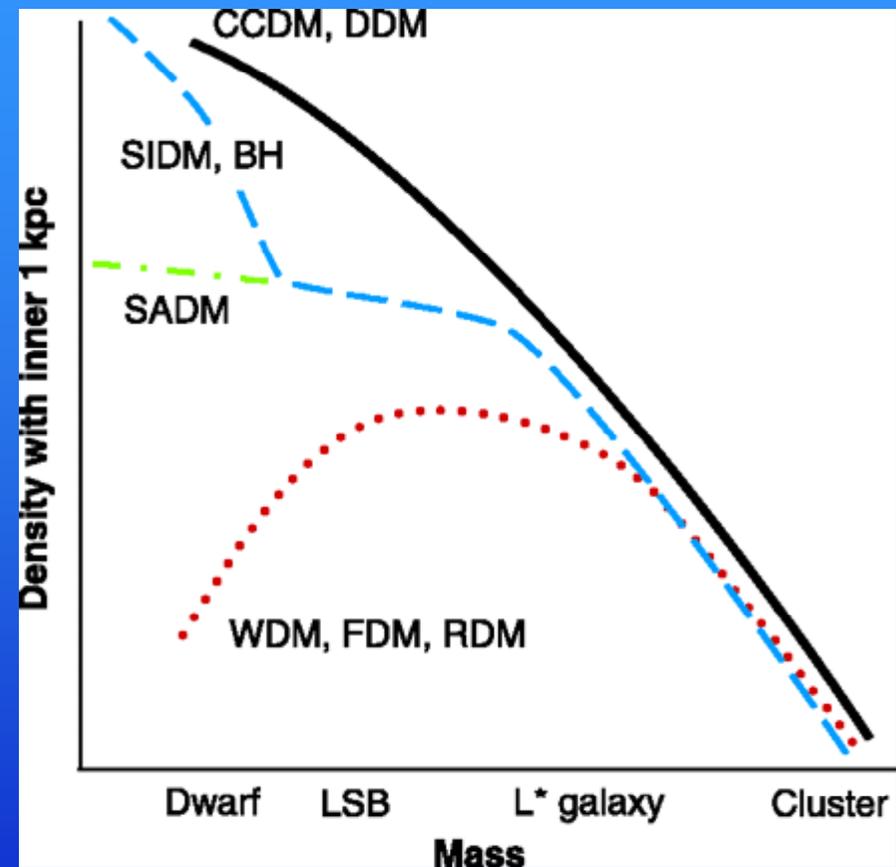
**Discovery work with Vasily Belokurov, Dan Zucker, Sergey
Koposov, et al**

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
 $\sigma \sim 10$ 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

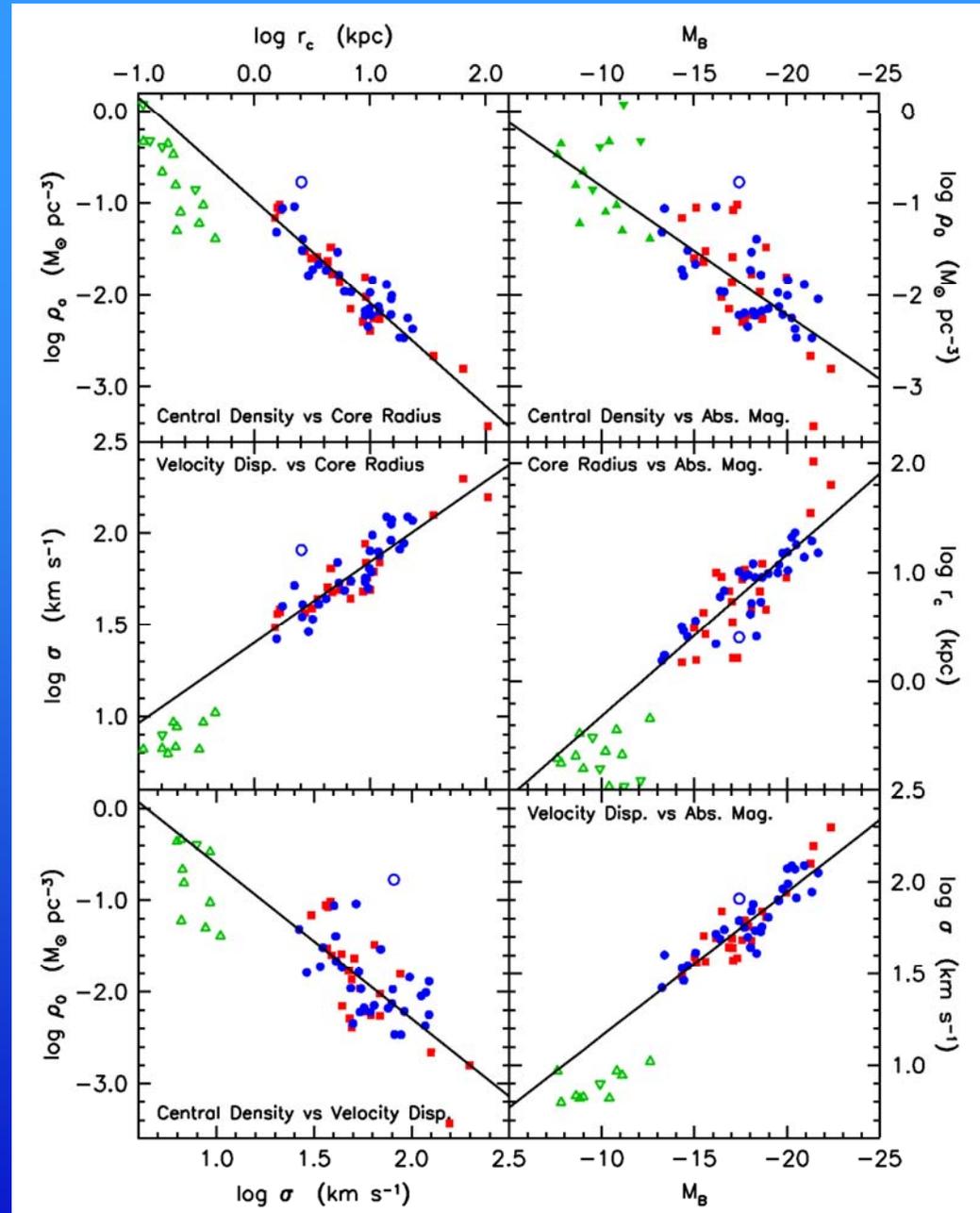
- Among the first systems to collapse, form stars
 - ◆ Star formation history and chemical enrichment are sensitive probes of stellar ‘feedback’, galactic winds, ram pressure stripping, re-ionization effects..
 - ◆ Accessible through current observations
- Most extreme (apparently) dark-matter dominated 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

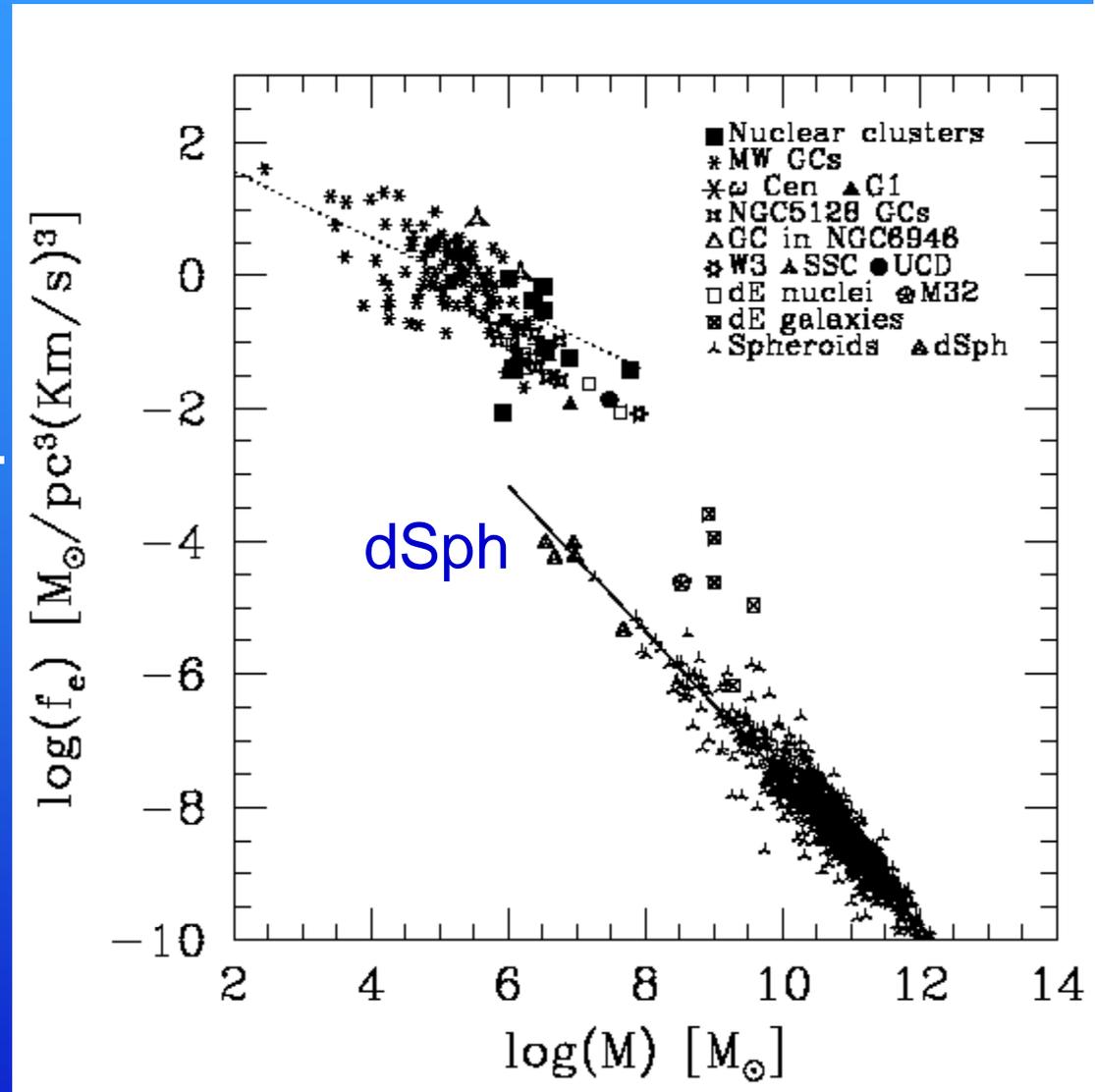


Dotted line is virial theorem
for stars, no DM

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

Why?

→ Dark Matter?



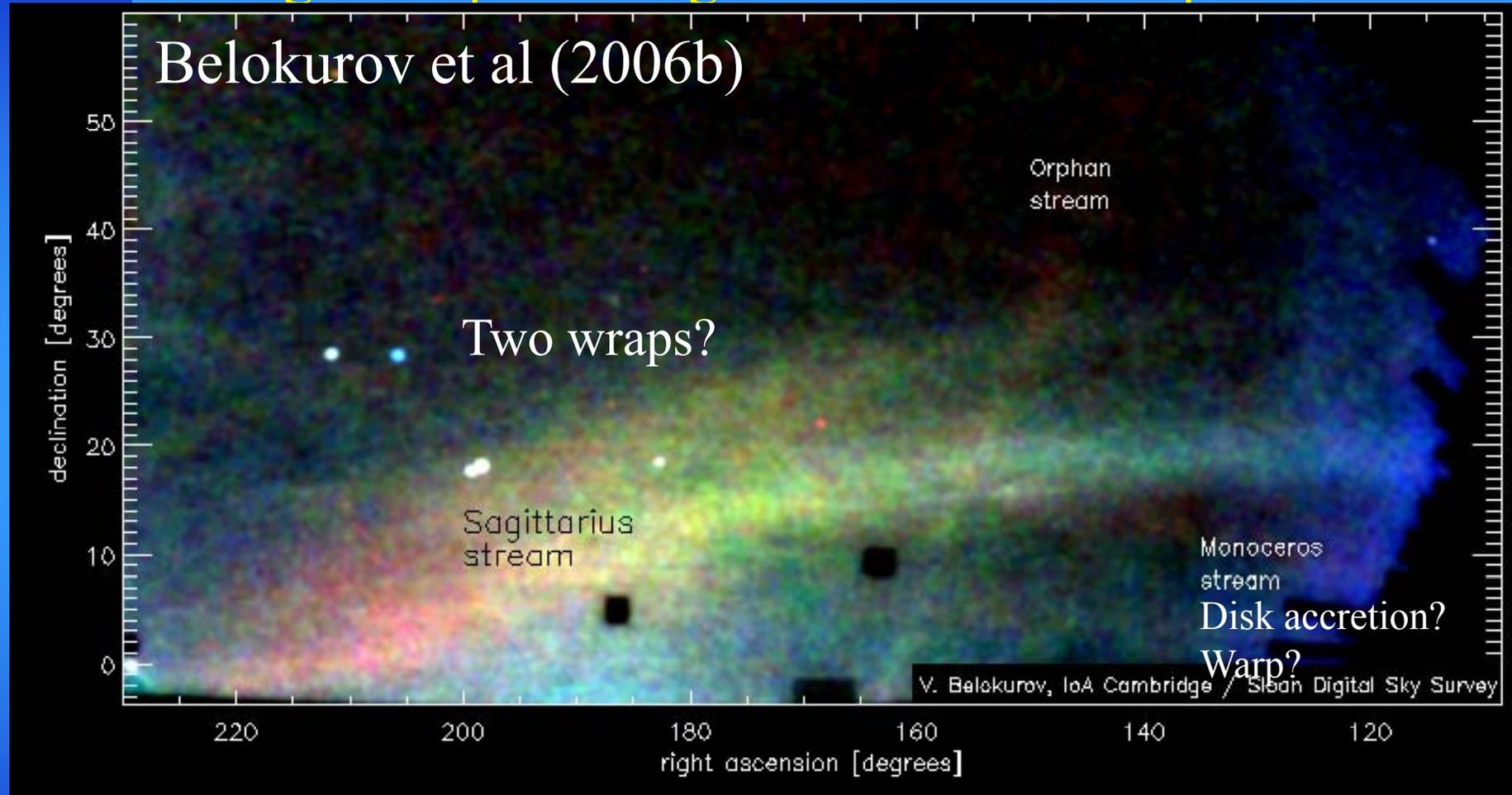
Phase space density ($\sim \rho/\sigma^3$) $\sim 1/(\sigma^2 r_h)$

- 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

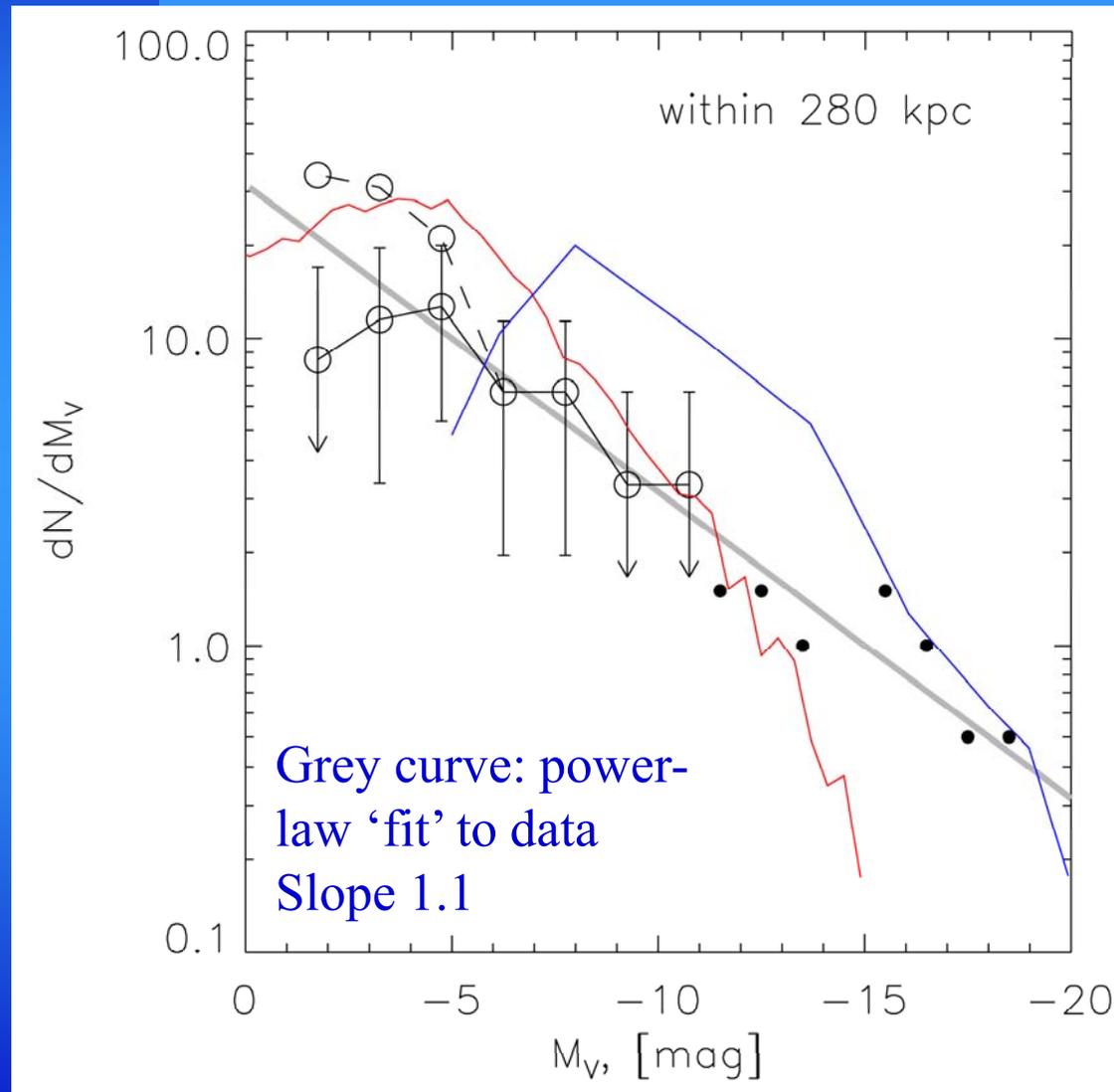


SDSS data, $19 < r < 22$, $g-r < 0.4$ colour-coded by mag (distance), blue (~ 10 kpc), green, red (~ 30 kpc)

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

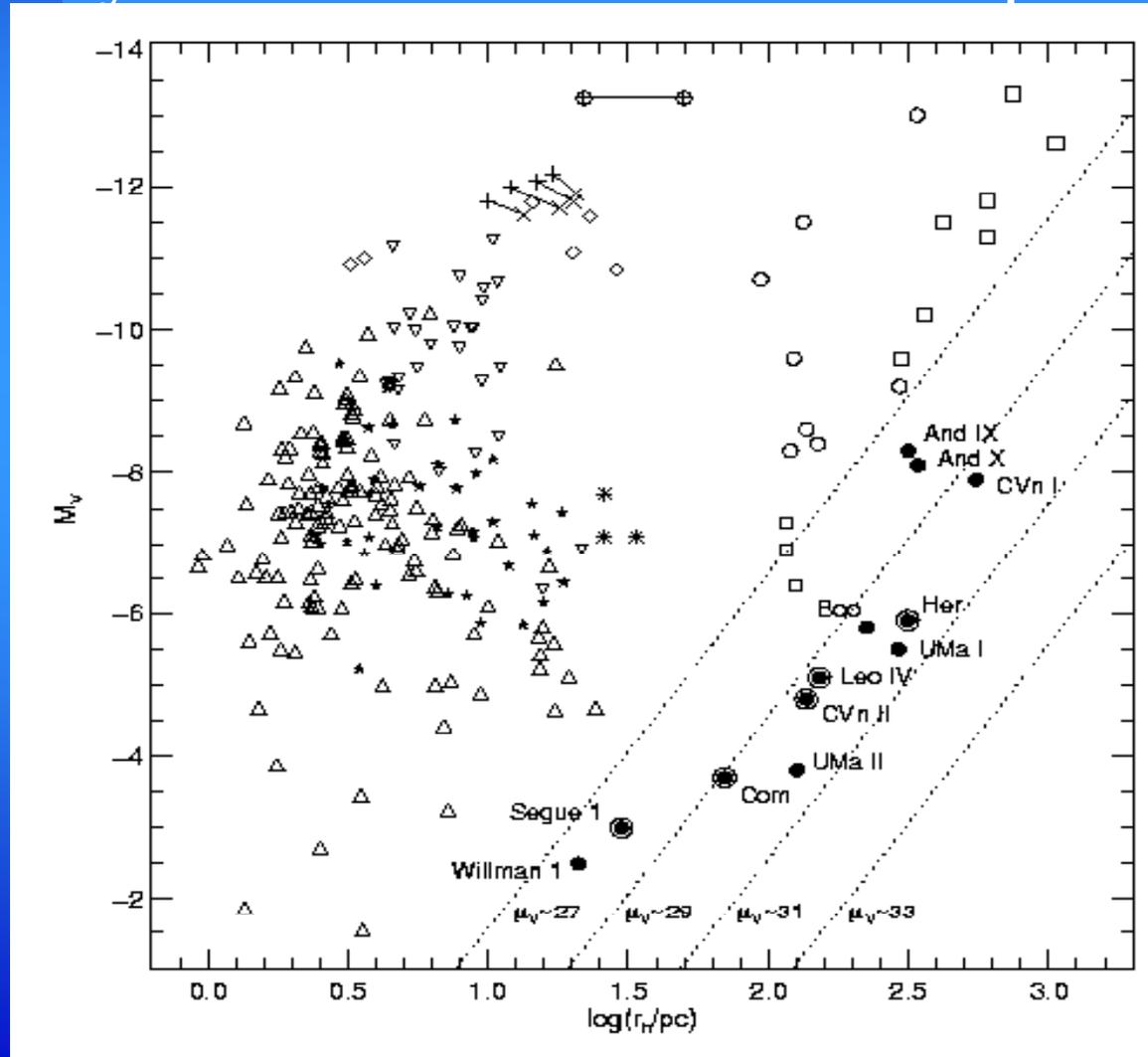
Filled symbols:
'all Local Group dSph'

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



← $\sim 10^3 L_{\odot}$

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

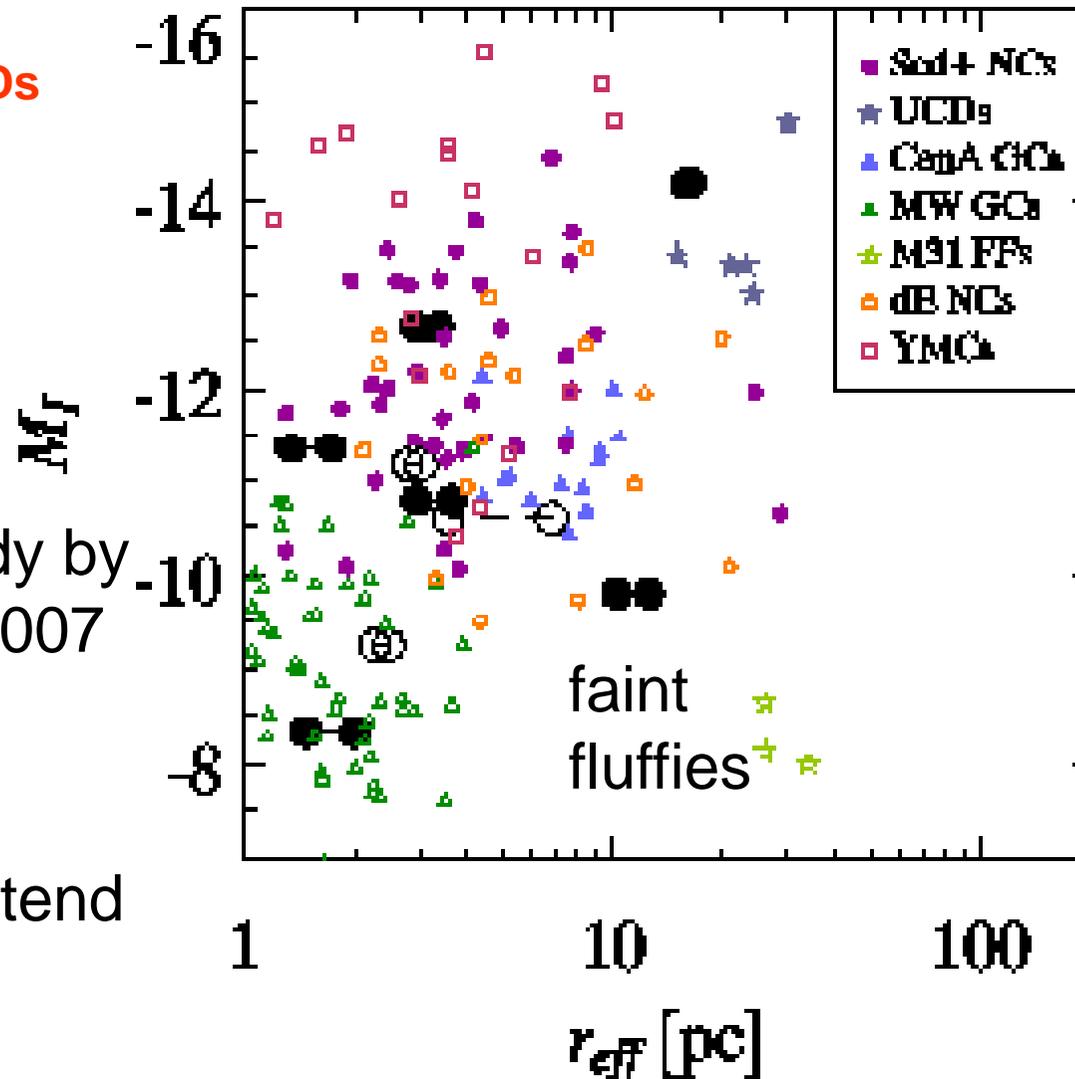
Seth et al astro-ph 0609302

Virgo & Fornax UCDs have stellar M/L –

Hilker et al, A&A 463 119 2007

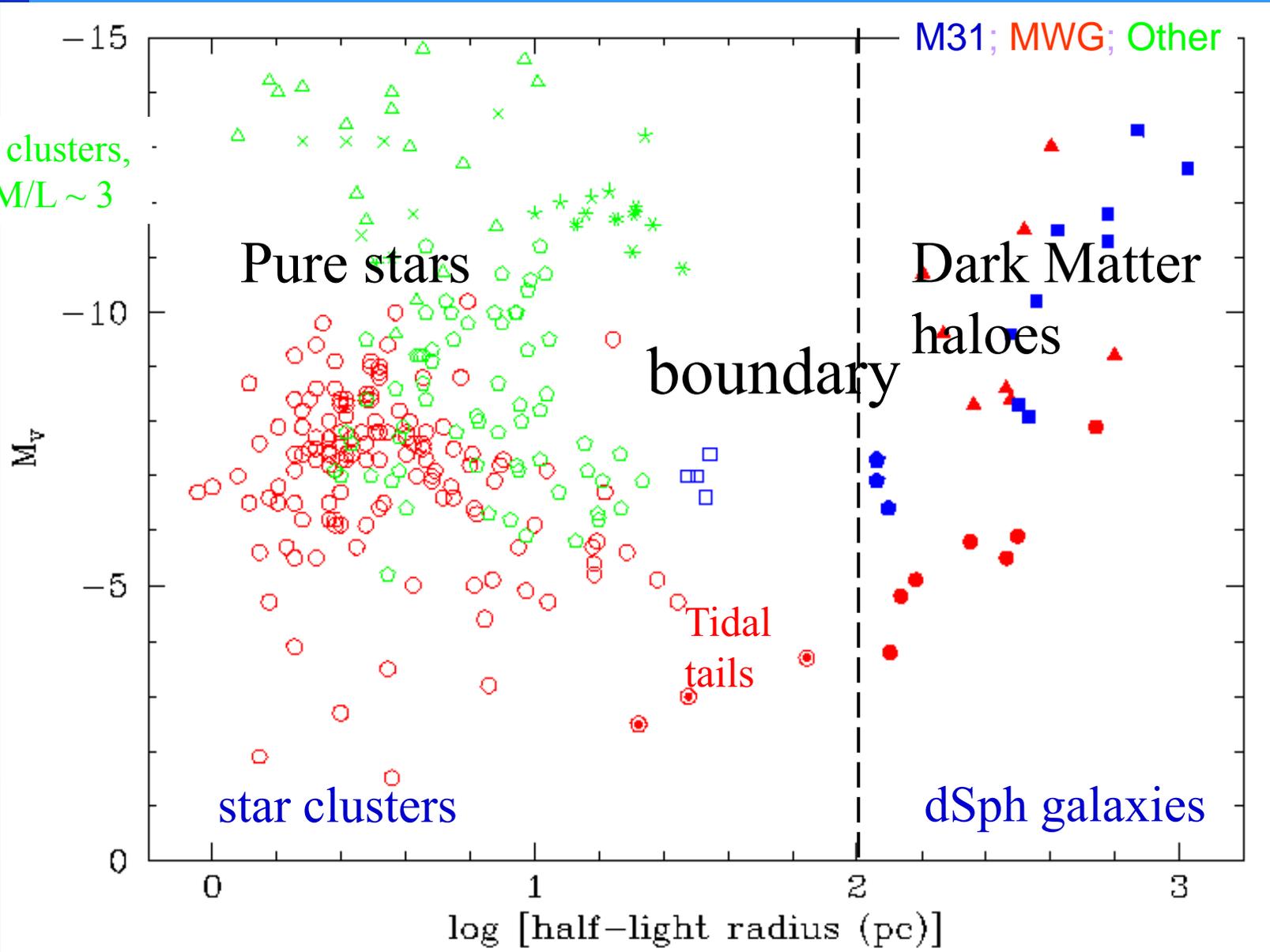
N5128 GC study by Rejkuba et al 2007

MWG GCs extend down to M_{-2}



Slightly different perspective... (updated data)

Nuclear clusters,
UCDs, $M/L \sim 3$



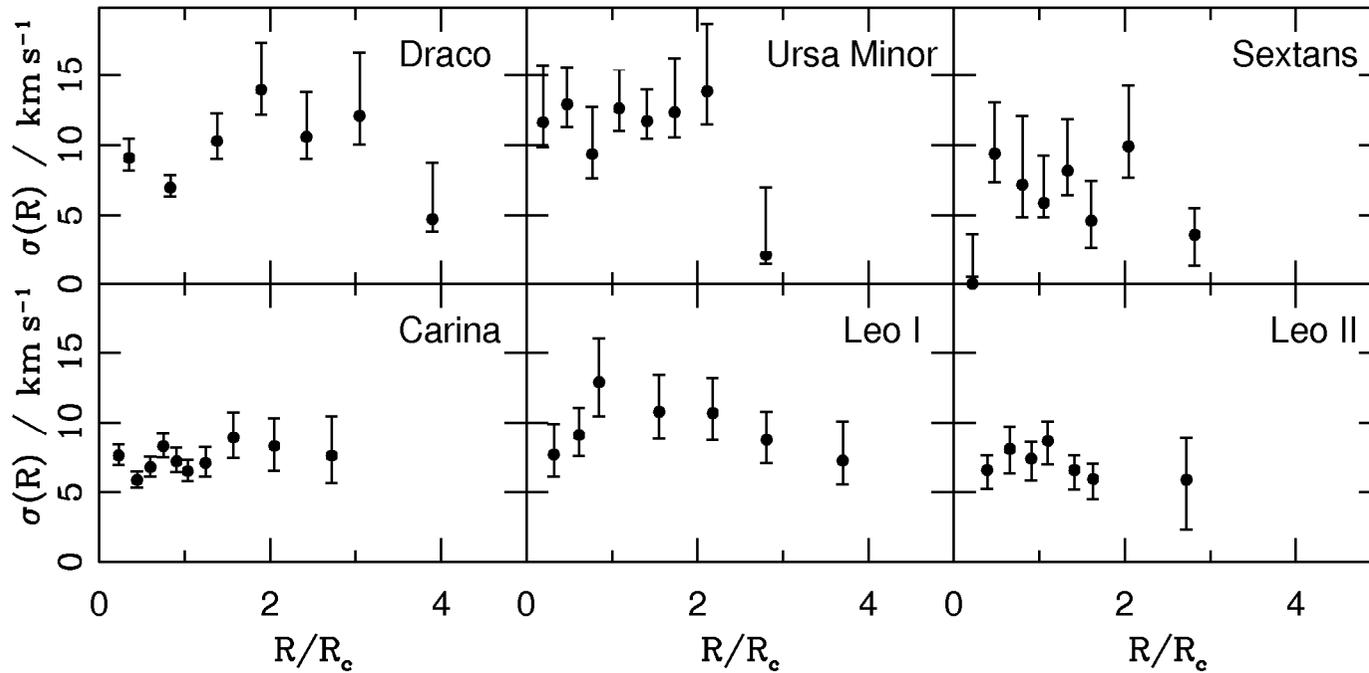
Gilmore, Wilkinson, RW et al 2007

Conclusion one:

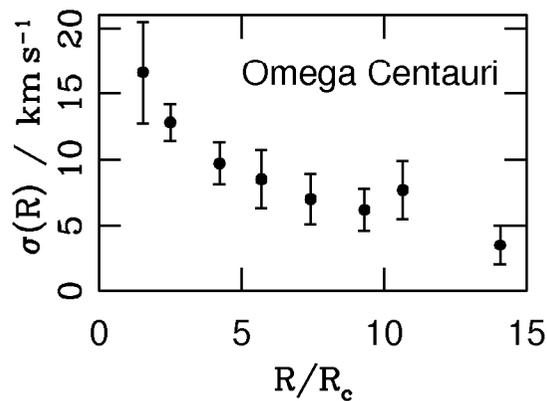
- Galaxy scaling relations work well, and indicate a systematic star-cluster *vs* small galaxy distinction in phase-space density
- There is a well-established size bi-modality
 - all systems with size $\lesssim 30\text{pc}$ are purely stellar
 $-16 < M_v < 0$ (!!) $M/L \sim 3$; e.g. UCDs, Hilker et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

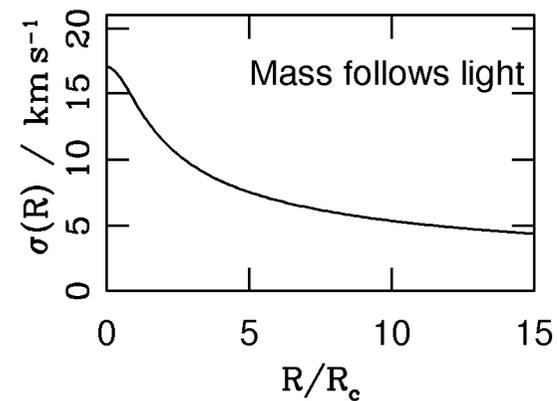
dSph



Seitzer 1983;
van de Ven
et al 06

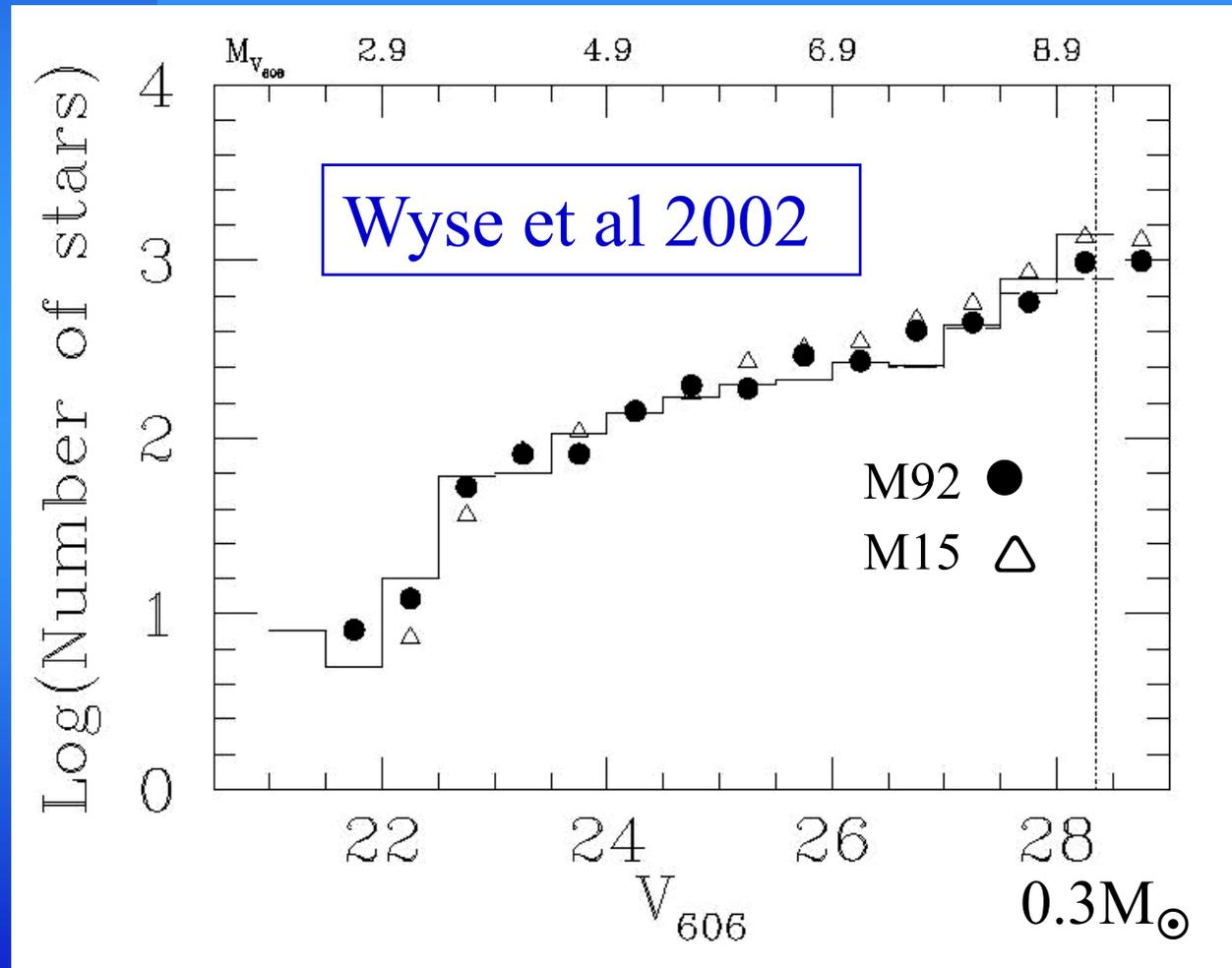


Globular
cluster
 $M/L_V \sim 2.5$



Main sequence luminosity functions of UMi dSph and of globular clusters are indistinguishable.

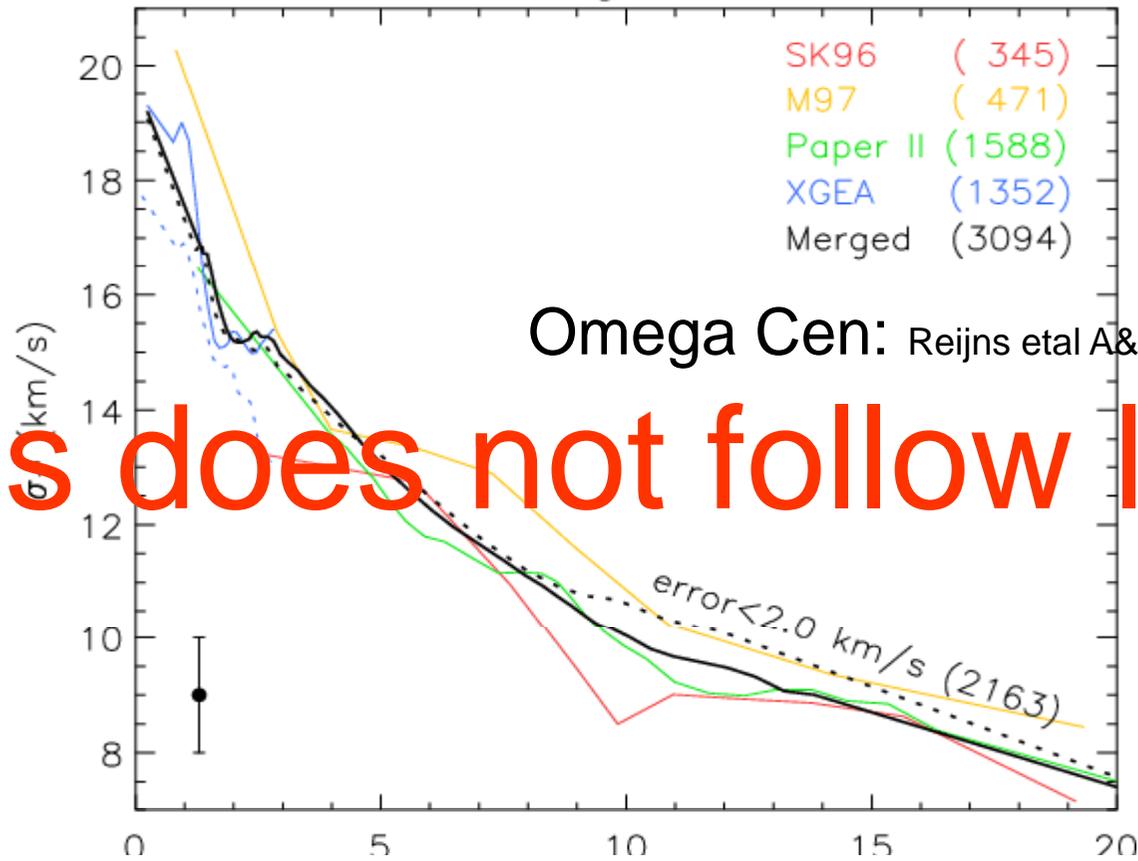
→ normal stellar M/L



HST star counts

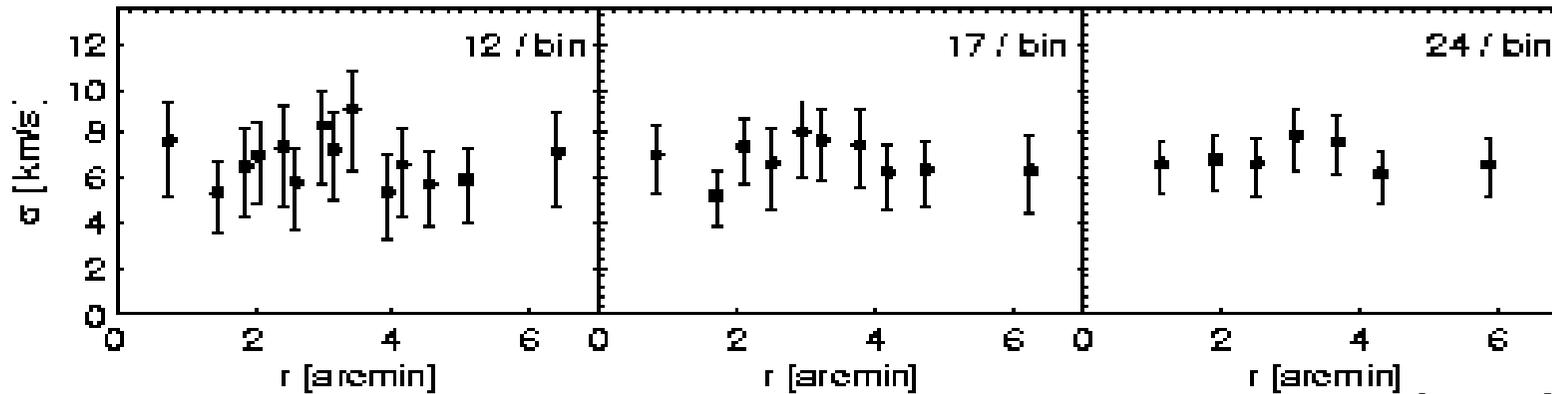
Massive-star
IMF constrained
by elemental
abundances –
also normal

line-of-sight velocities



Omega Cen: Reijns etal A&A 445 503

Mass does not follow light



Leo II: Koch etal

Mass measurements: the early context

- The “standard” value for local DM at the Sun is $0.3\text{GeV}/c^2/\text{cm}^3$, 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

$$M(r) = -\frac{r^2}{G} \left(\frac{1}{v} \frac{dv\sigma_r^2}{dr} + 2 \frac{\beta\sigma_r^2}{r} \right)$$

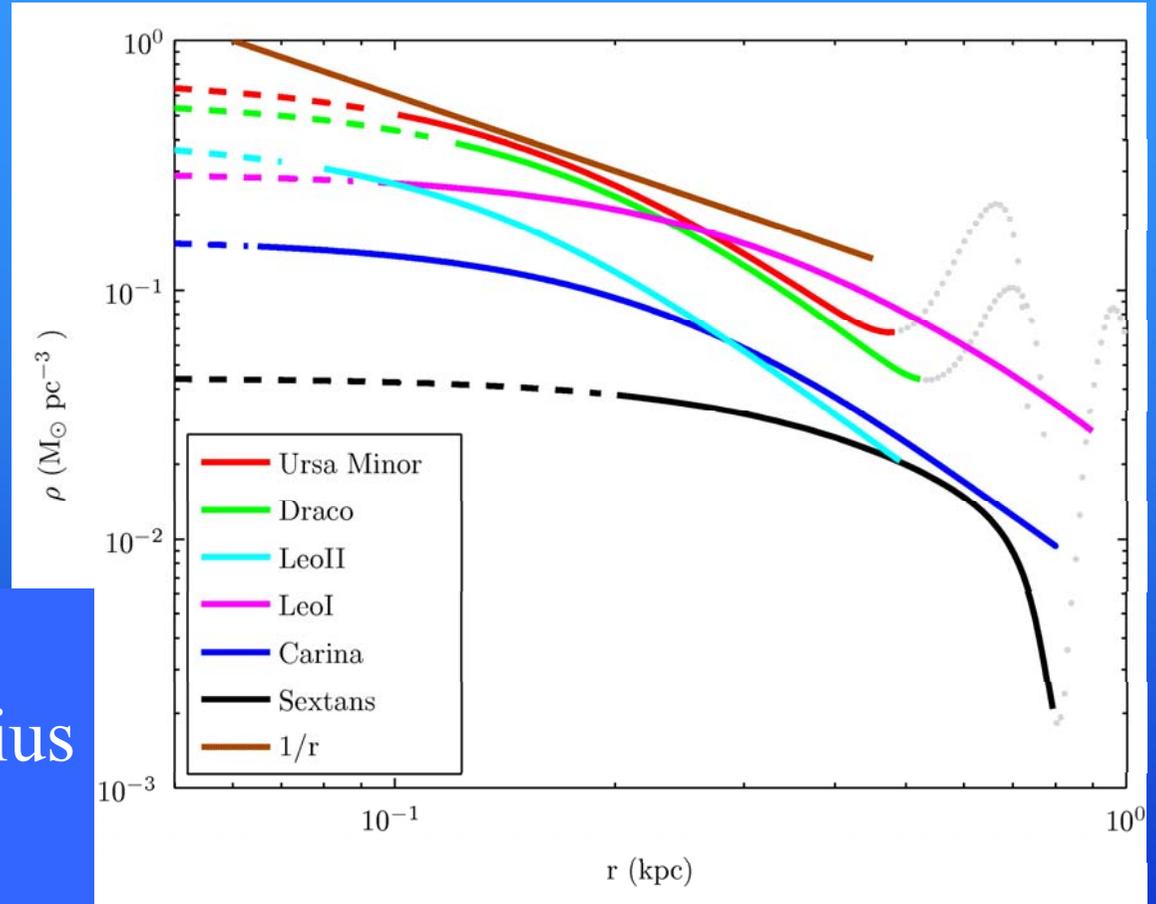
- ◆ Either (i) determine mass profile from projected dispersion profile, with assumed isotropy, and smooth functional fit to the light profile
- ◆ Or (ii) assume a parameterised mass model $M(r)$ and velocity dispersion anisotropy $\beta(r)$ and fit dispersion profile to find best forms of these (for 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 not 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

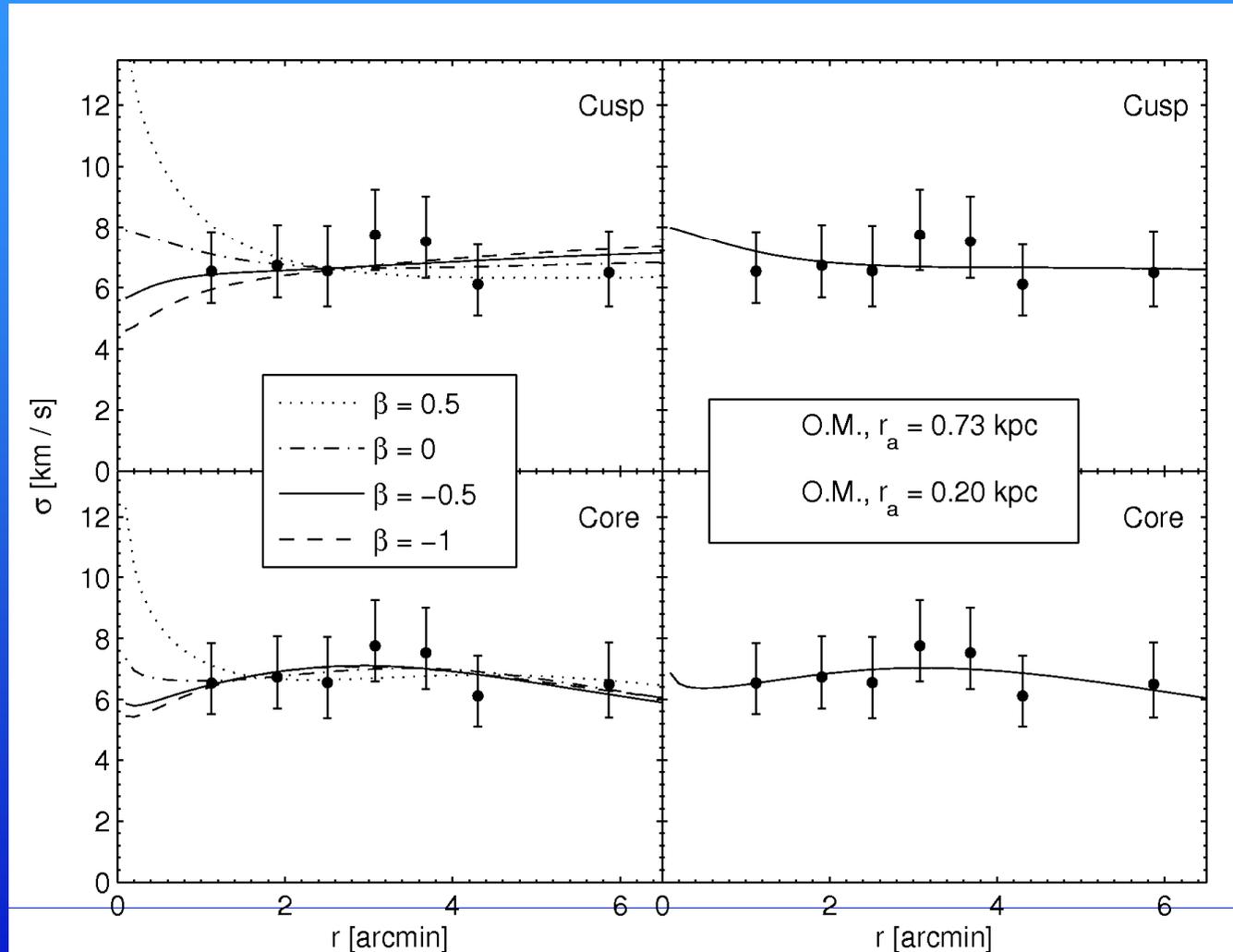
Koch et al 07
AJ 134 566 '07

Leo II

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

Fixed β

Radially varying β



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 et al, VLT high-resolution core/cusp project)

Conclusion two:

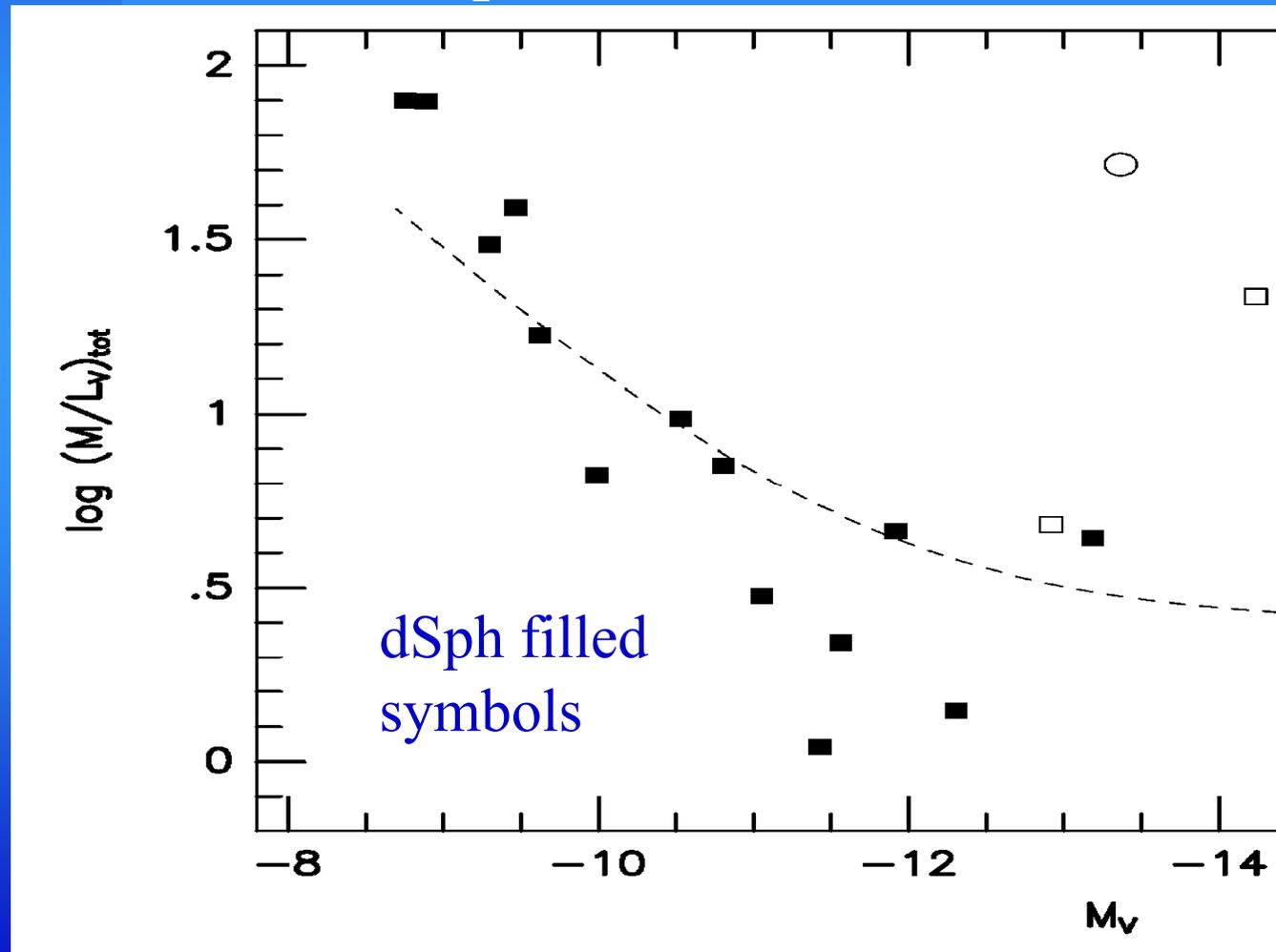
- High-quality kinematic data exist
- Jeans' analyses → prefers cored mass profiles
- Mass-anisotropy degeneracy *allows* cusps
- Substructure, dynamical friction → prefers cores
- Equilibrium assumption is valid inside optical radius
- More sophisticated DF analyses underway

- **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?

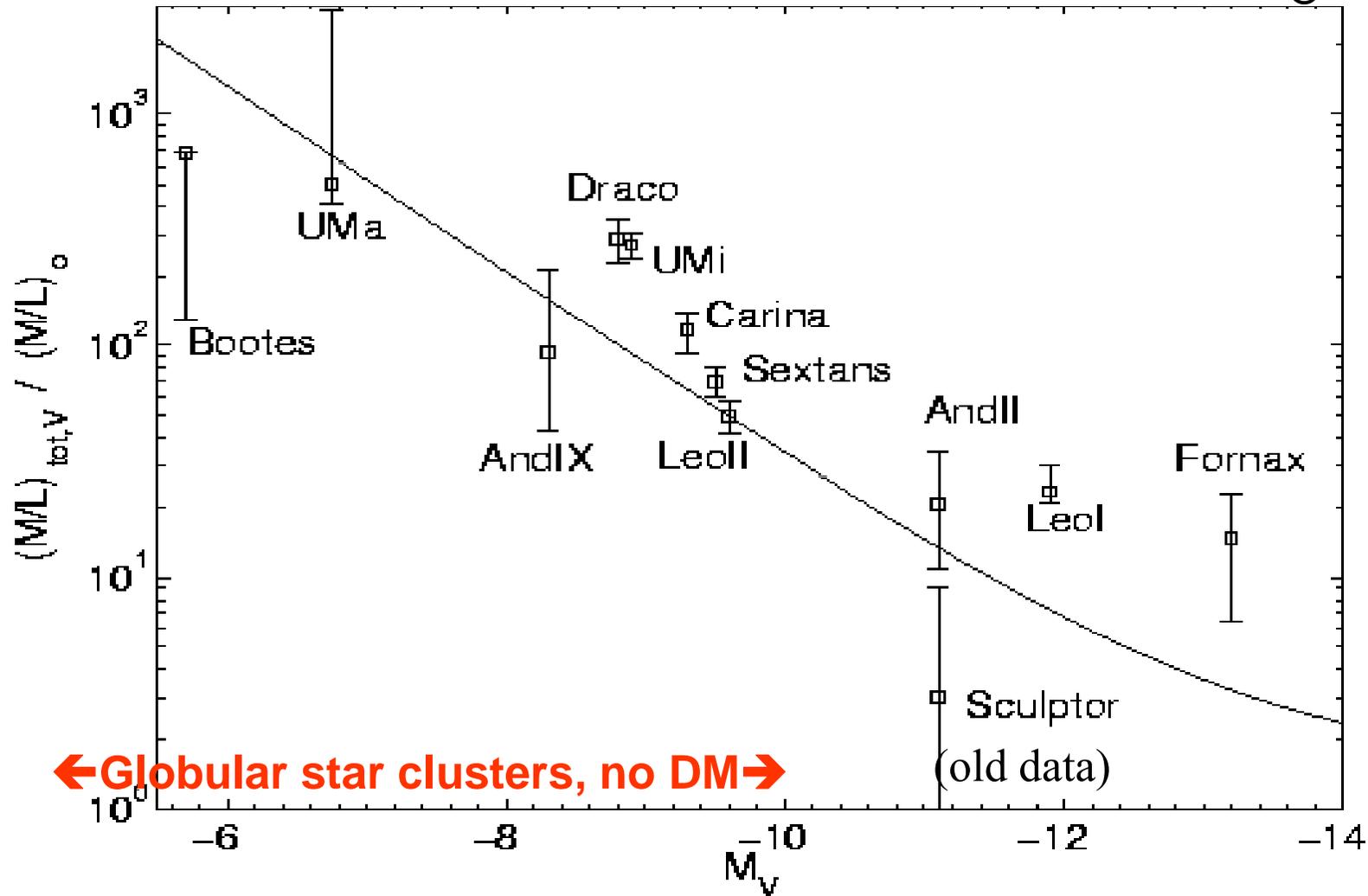
Based on central velocity dispersions only;
line corresponds to dark halo mass of $10^7 M_{\odot}$



Mateo 98
ARAA

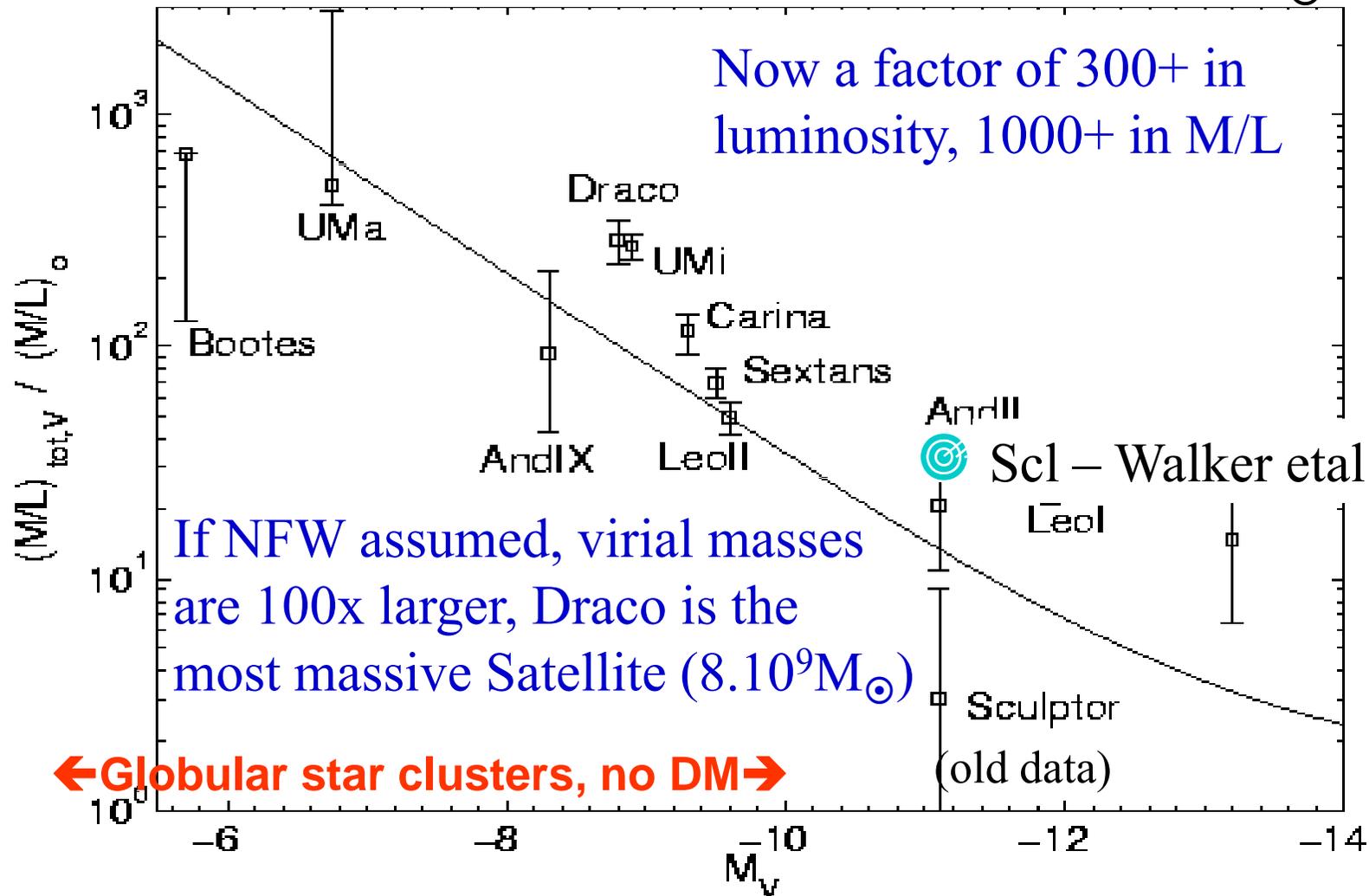
2007: extension of dynamic range [UMa, Boo, AndIX],
new kinematic studies: **Mateo plot improves.**

Mass enclosed within stellar extent $\sim 4 \times 10^7 M_{\odot}$

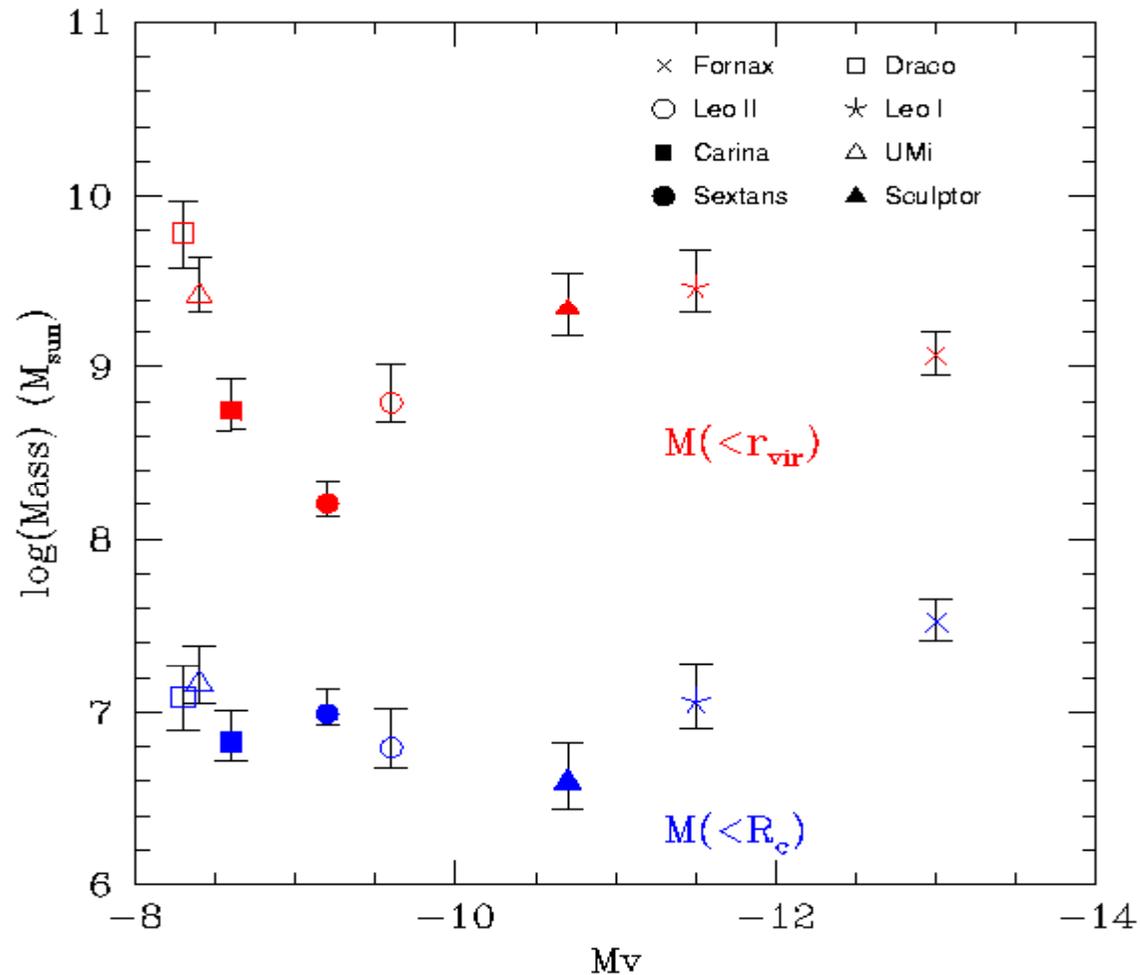


2007: extension of dynamic range [UMa, Boo, AndIX],
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Mass enclosed within stellar extent $\sim 4 \times 10^7 M_{\odot}$



NFW fits require very high mass, and a very wide range of mass
 Draco = $8.10^9 M_{\text{sun}}$ and $M/L=100,000$ MWG vs M31 offset
 no simple mass-luminosity link [astro-ph/0701780](https://arxiv.org/abs/astro-ph/0701780)
 Strigari et al (in prep) central mass fits – no simple rank



Consistency?

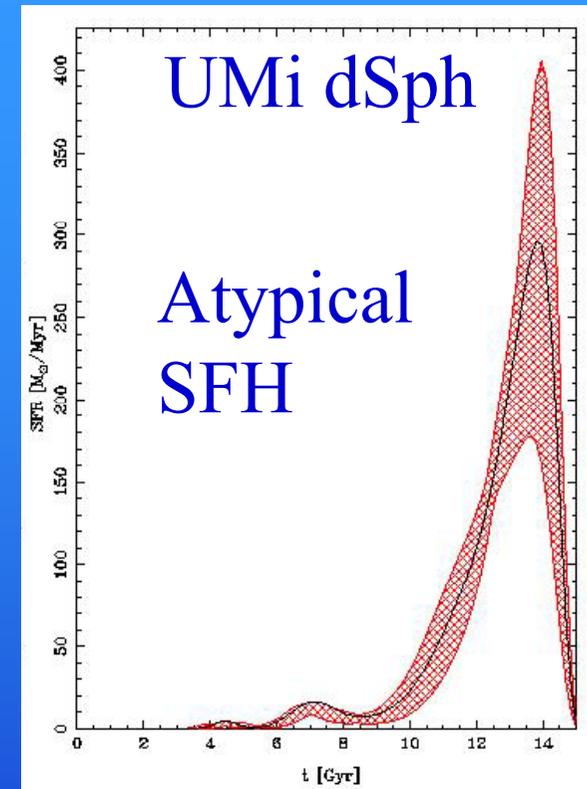
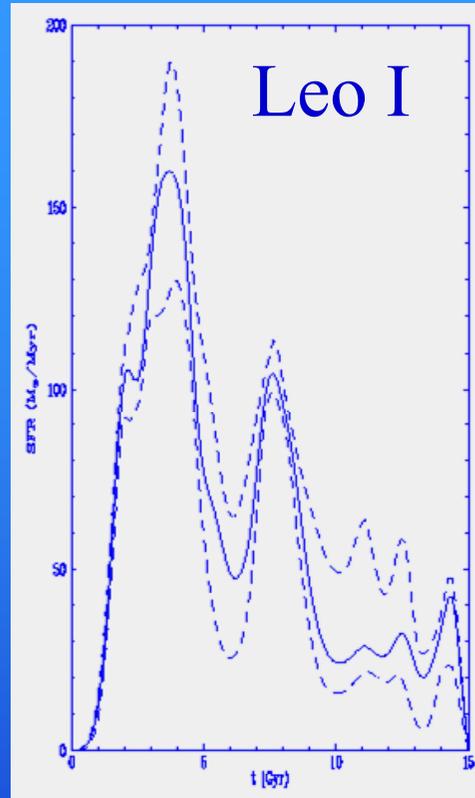
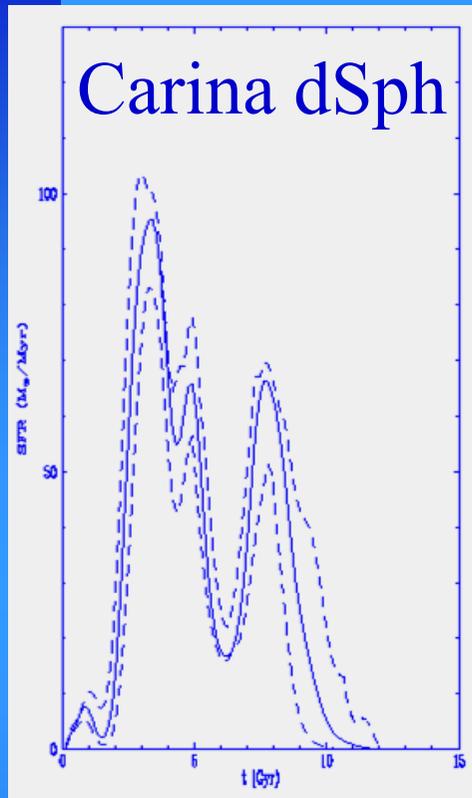
- A minimum half-light size for galaxies, $\sim 100\text{pc}$
- Cored mass profiles, with similar mean mass densities $\sim 0.1 M_{\odot}/\text{pc}^3$, $\sim 5\text{GeV}/\text{cc}$
- An apparent characteristic (minimum) mass dark halo in all dSph, mass $\sim 4 \times 10^7 M_{\odot}$

characteristic mass profile convolved with
characteristic normalisation must imply
characteristic mass \rightarrow 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

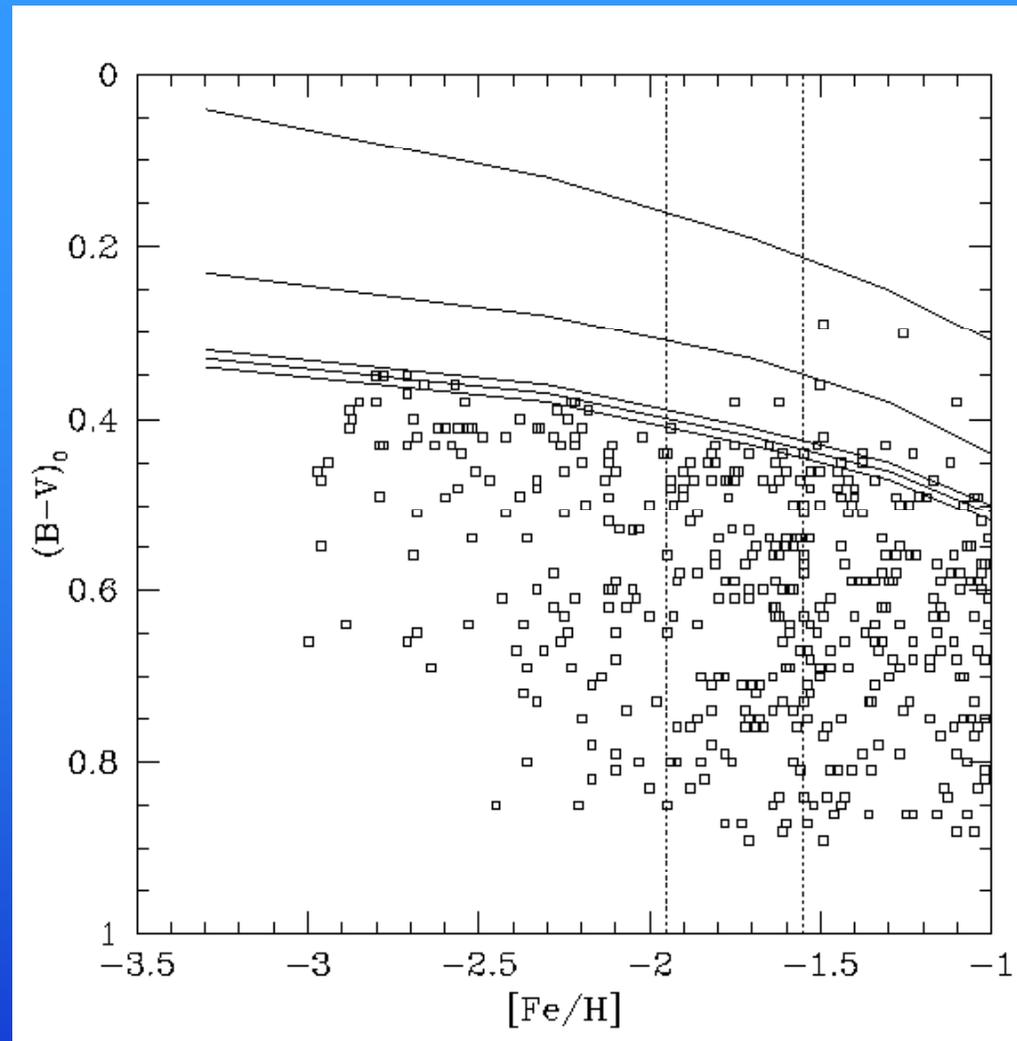


Intermediate-age population dominates in typical dSph satellite galaxies – with very low average SFR over long periods ($\sim 5M_{\odot}/10^5\text{yr}$), until recently

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 $[\text{Fe}/\text{H}]$ vs $B-V$ for local high-velocity
halo stars (Carney): few stars bluer (younger)
than old turnoffs (5Gyr, 10Gyr, 15Gyr Yale)

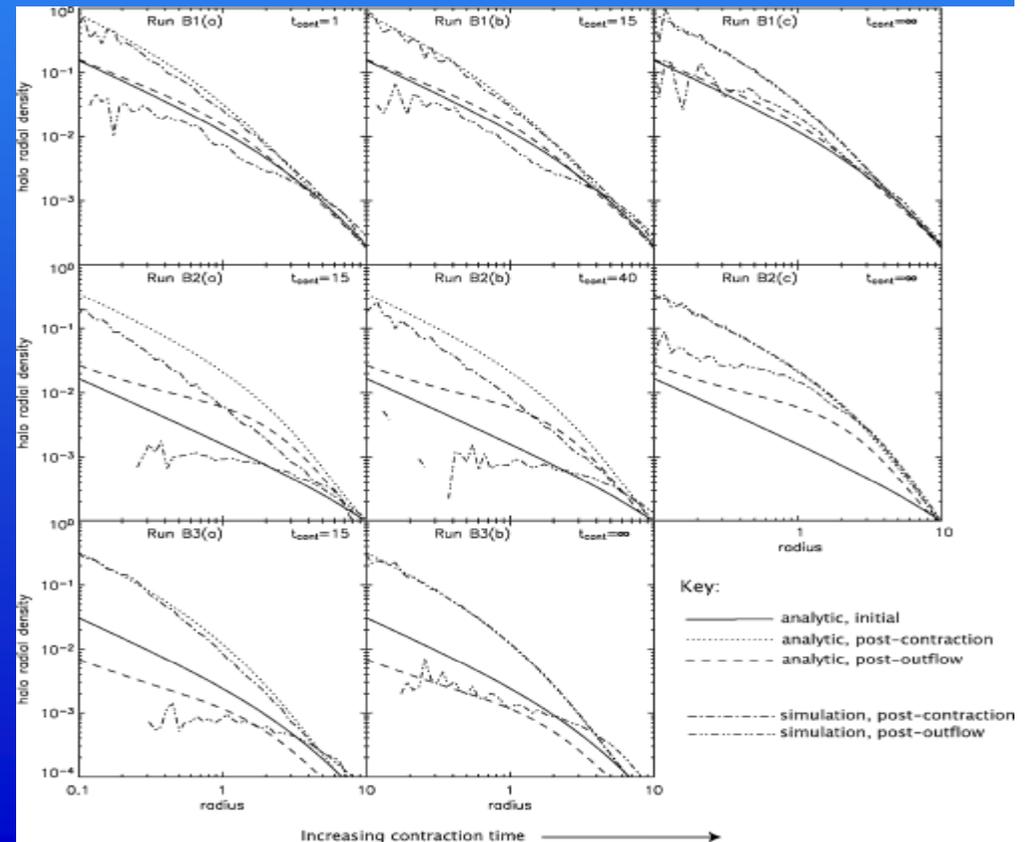


Very many attempts to model feedback on CDM structure....

- Some of our simple examples:
 - Read et al 2006 MN 367 387, MN 366 429, 2005 MN 356 107...; Fellhauer et al 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



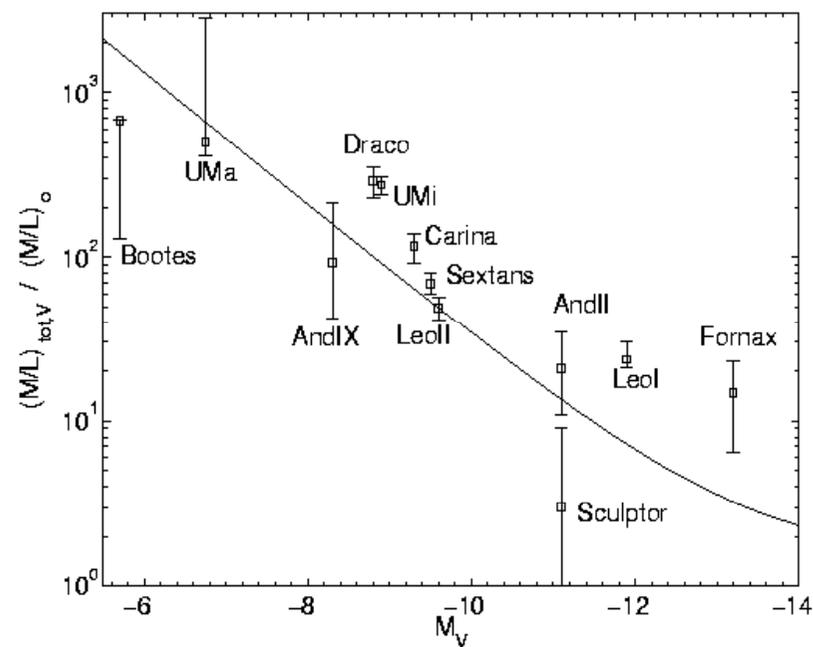
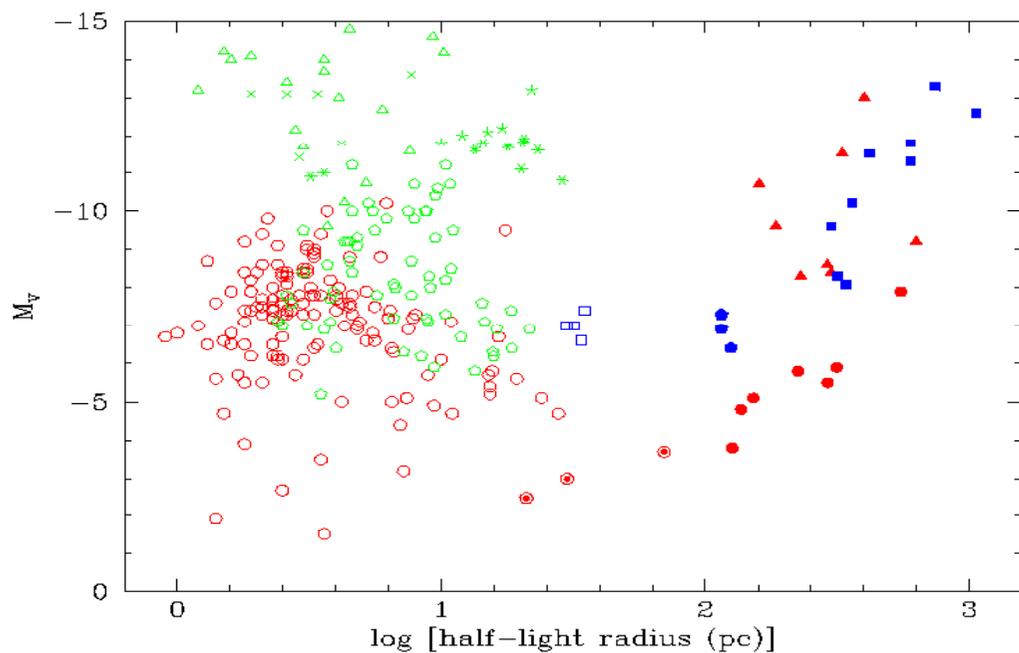
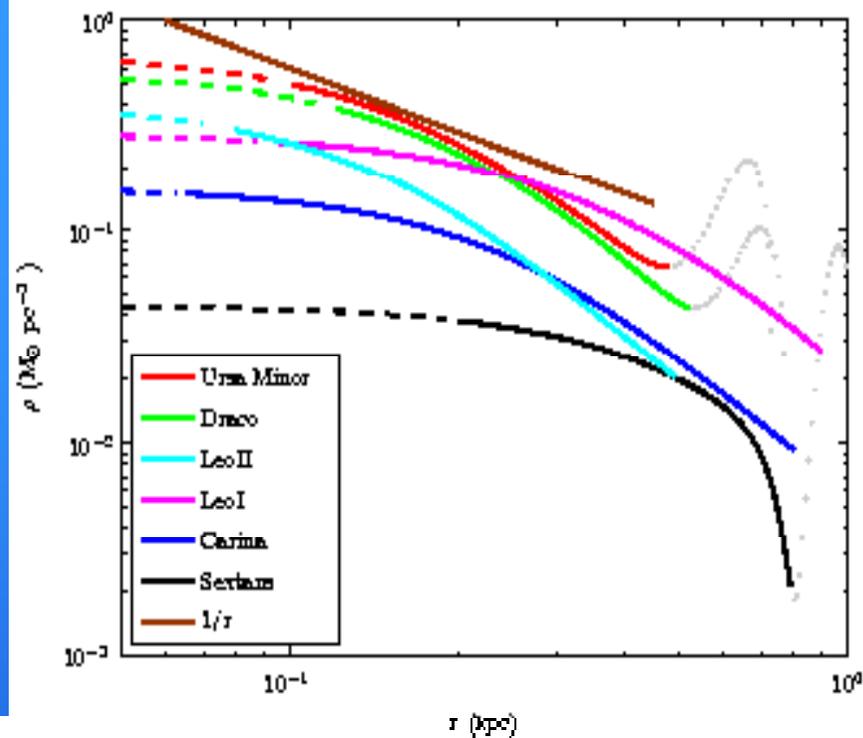
Summary:

- A minimum size for galaxies, $\sim 100\text{pc}$
 - ◆ Mass size scale somewhat larger (?), expected since baryons dissipate energy?
- Velocity dispersions of $\sim 10\text{km/s}$, \sim flat profile
- Cored mass profiles, with similar mean mass densities $\sim 0.1M_{\odot}/\text{pc}^3$, $\sim 5\text{GeV/cc}$
 - ◆ Phase space densities fairly constant, maximum for galaxies (cf Walcher et al 2005)
- An apparent characteristic (minimum) mass dark halo in all dSph, mass $\sim 4 \times 10^7 M_{\odot}$
 - ◆ 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:

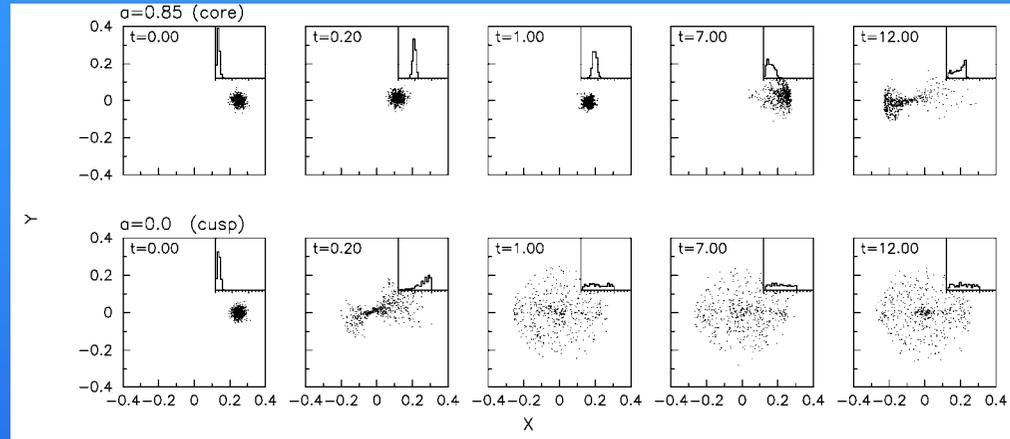
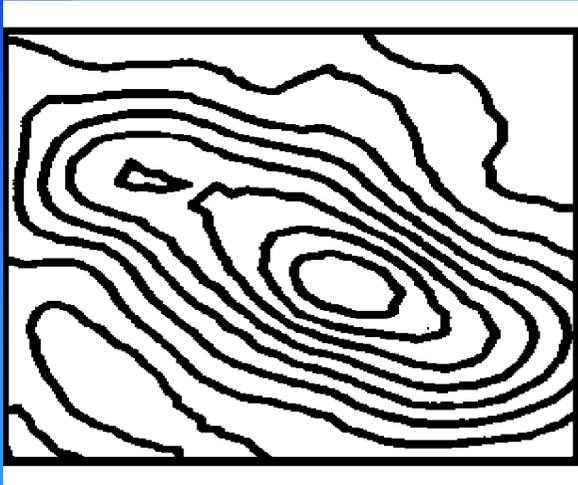
- Characteristic Density $\sim 10\text{GeV}/c^2/\text{cm}^3$
 - If DM is very massive particles, they must be extremely dilute (Higgs $\sim 100\text{GeV}$)
- Characteristic Scale above 100pc, several $10^7 M_{\odot}$
 - power-spectrum scale break?
 - This would (perhaps!) naturally solve the substructure 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 et al 2006