The Dwarf Galaxy Population and Density Profiles

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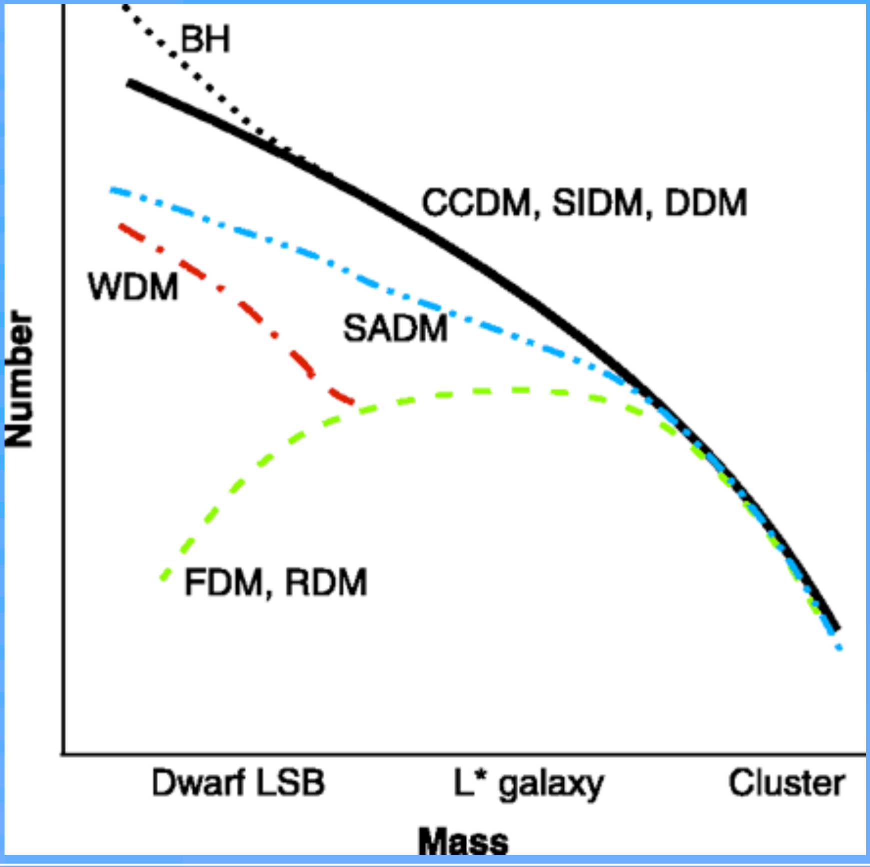
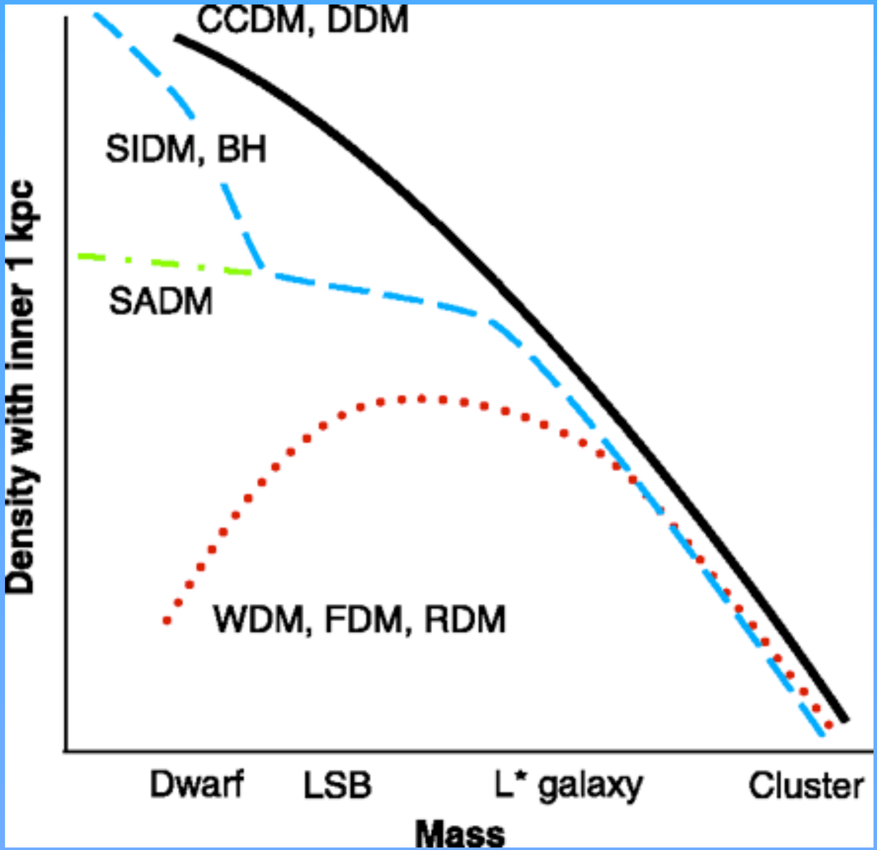
ΛCDM cosmology extremely successful on large scales. The smallest galaxies are the place one must see the nature of dark matter & galaxy formation astrophysics





Dwarf galaxy mass function depends on DM type

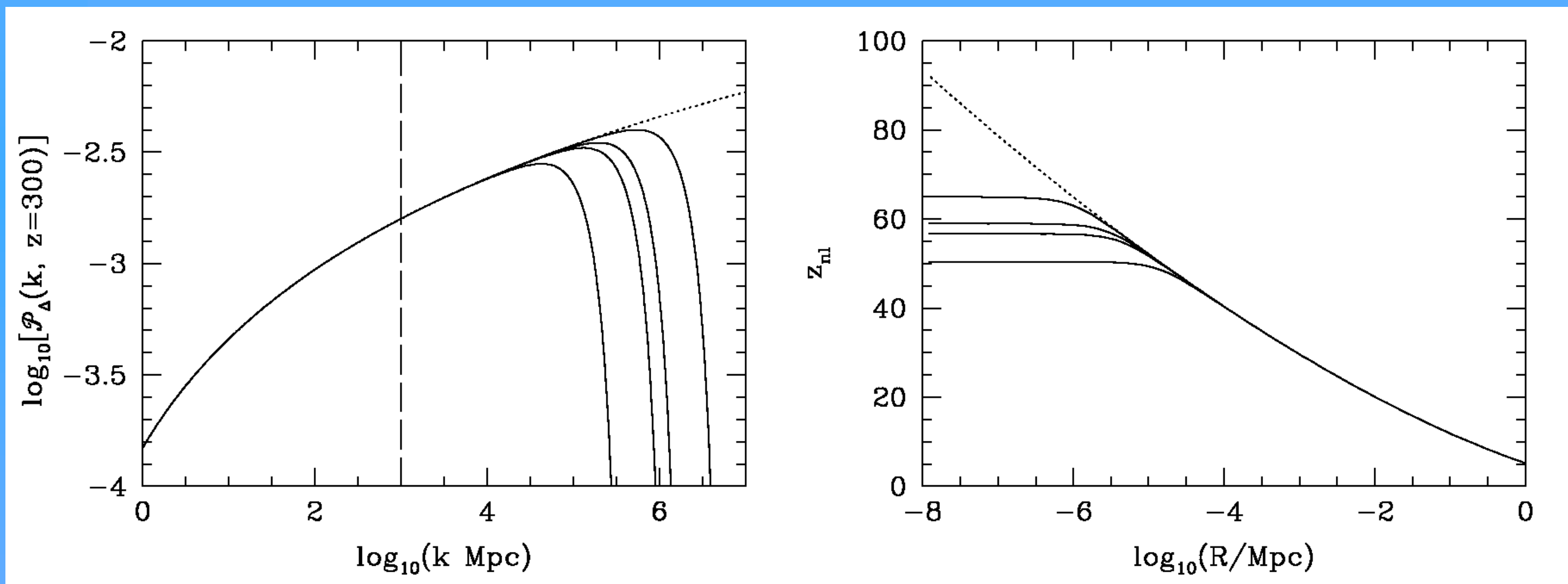
Inner DM mass density depends on the type(s) of DM

Figs: Ostriker & Steinhardt 2003

Linear power spectrum at z ~ 300, showing influence of WIMP microphysics:

Physical scales of interest correspond to smallest galaxies

Anticipated DM effects on scales of pc up ➔ first systems



Green, Hofmann & Schwarz 2005

Galaxy-scale Challenges for CDM

- On galaxy scales there is an opportunity to learn some (astro)physics:
  - Large galaxies of old stars, small galaxies of young stars →'downsizing'
  - Massive pure-thin-disk galaxies exist: None should since mergers heat and puff-up disks
  - The MWG has a thick disk, and these stars are old, as in the bulge. This seems common but implies little merging since early times, to build them up
  - Sgr dSph in the MWG proves late minor merging happens, but is clearly not dominant process in evolution of MWG except the outer halo, $R_{GC} \gtrsim 25$ kpc
  - The 'feedback' requirement: otherwise gas cools and stars form too efficiently, plus angular momentum transported away from gas in mergers
  - The substructure problem – how to hide them?

The smallest galaxies as probes of Dark Matter:

- ➔ new large datasets of stellar line-of-sight kinematics, now covering spatial extent, & photometry for dSph satellite galaxies. Our kinematic data are from VLT, Keck, Gemini, AAT, WHT, Magellan (other groups include Tolstoy et al, Walker et al, Geha et al)
- ➔ new discoveries; SDSS mostly – original key project (Belokurov et al 06,07,08; also Willman et al 05; Grillmair 06; Grillmair & Dionatos 06; Sakamoto & Hasegawa 06; Jerjen 07; Walsh et al. 07..)
  - ➔ Dark matter properties
- ➔ Spectra also allow derivation of stellar metallicity distribution, supplemented by smaller samples with high resolution for detailed elemental abundances
  - ➔ Chemical evolution, early star formation, stellar initial mass function and 'feedback' constraints

Dwarf Spheroidals

- Low luminosity, low surface-brightness satellite galaxies, 'classically' $L \sim 10^6 L_\odot$, $\mu_V \sim 24$ mag/″ ($\sim 10\ L_\odot/pc^2$)
  - plus ultra-faint galaxies discovered by SDSS
  - how faint and small do they go?
- Extremely gas-poor
- No net rotation, supported by stellar 'pressure', velocity dispersion
- Apparently dark-matter dominated
  - velocity dispersion ~ 10km/s, $10 \lesssim M/L \lesssim 1000$
- Metal-poor, mean stellar metallicity $\lesssim -1.5$ dex (1/30 solar value)
- Extended star-formation histories typical, from early epochs
- Most common galaxy in nearby Universe
- Crucial tests for models of structure formation and star formation

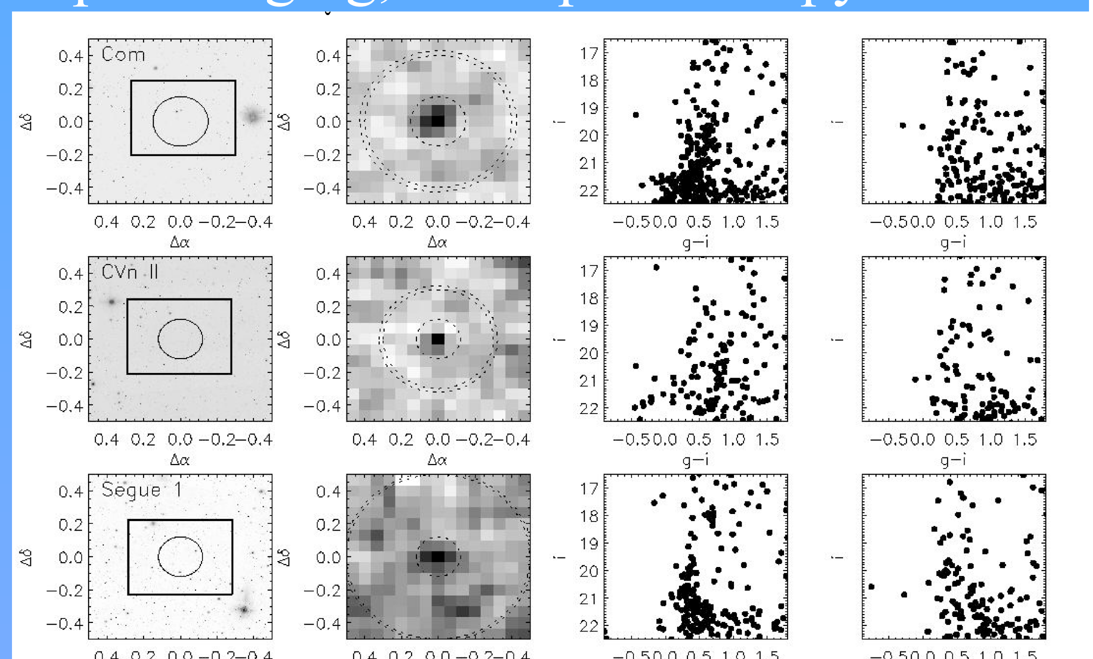
A Typical ‘Classical’ Dwarf Spheroidal Satellite Galaxy:

Three recent discoveries from SDSS (Belokurov et al, inc RW 06a) – all require confirmation with deeper imaging, then spectroscopy

dSph (?) d=45kpc

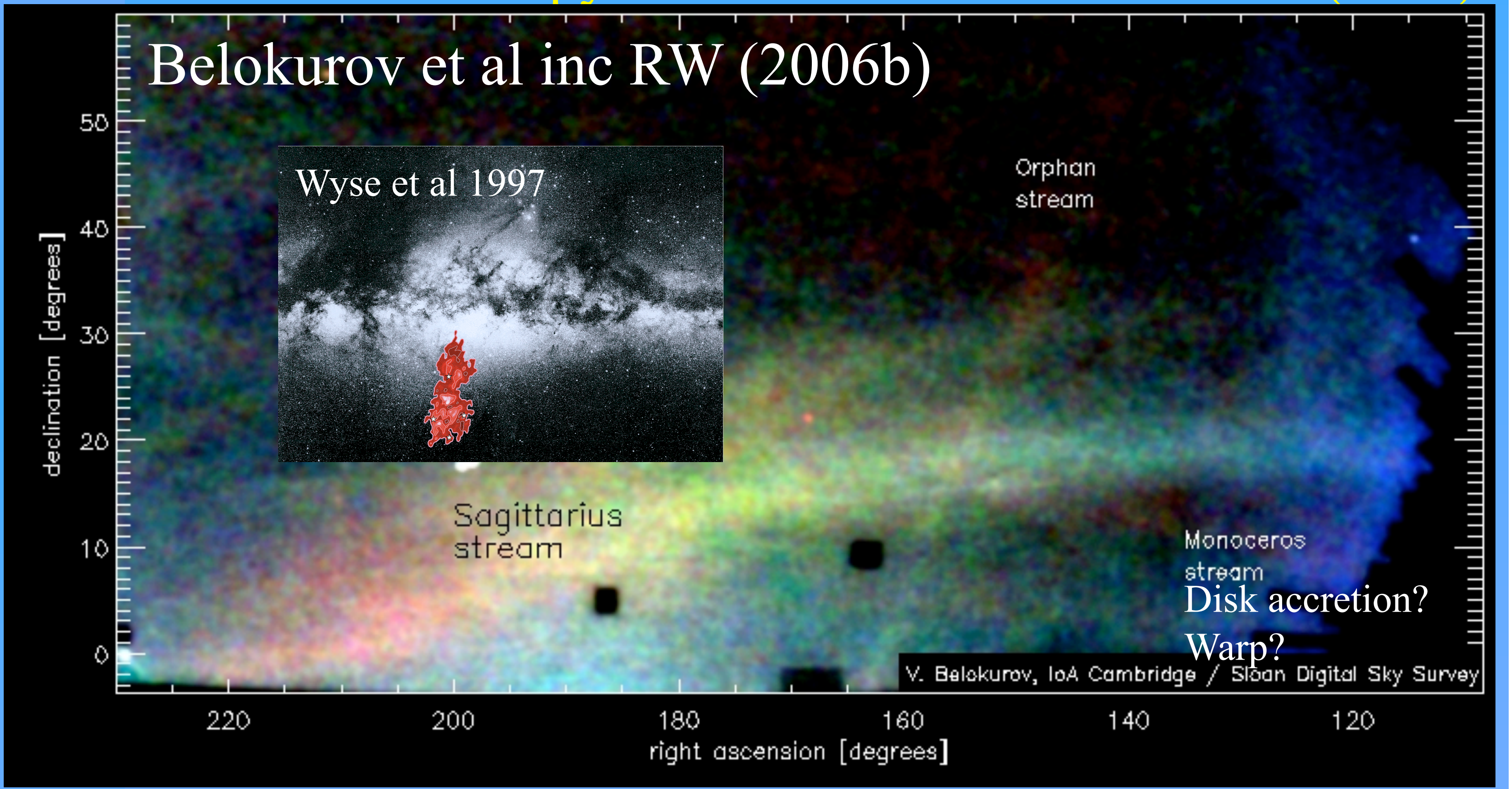
dSph d=150kpc

glob (?) d=25kpc



Field of Streams (and dots)

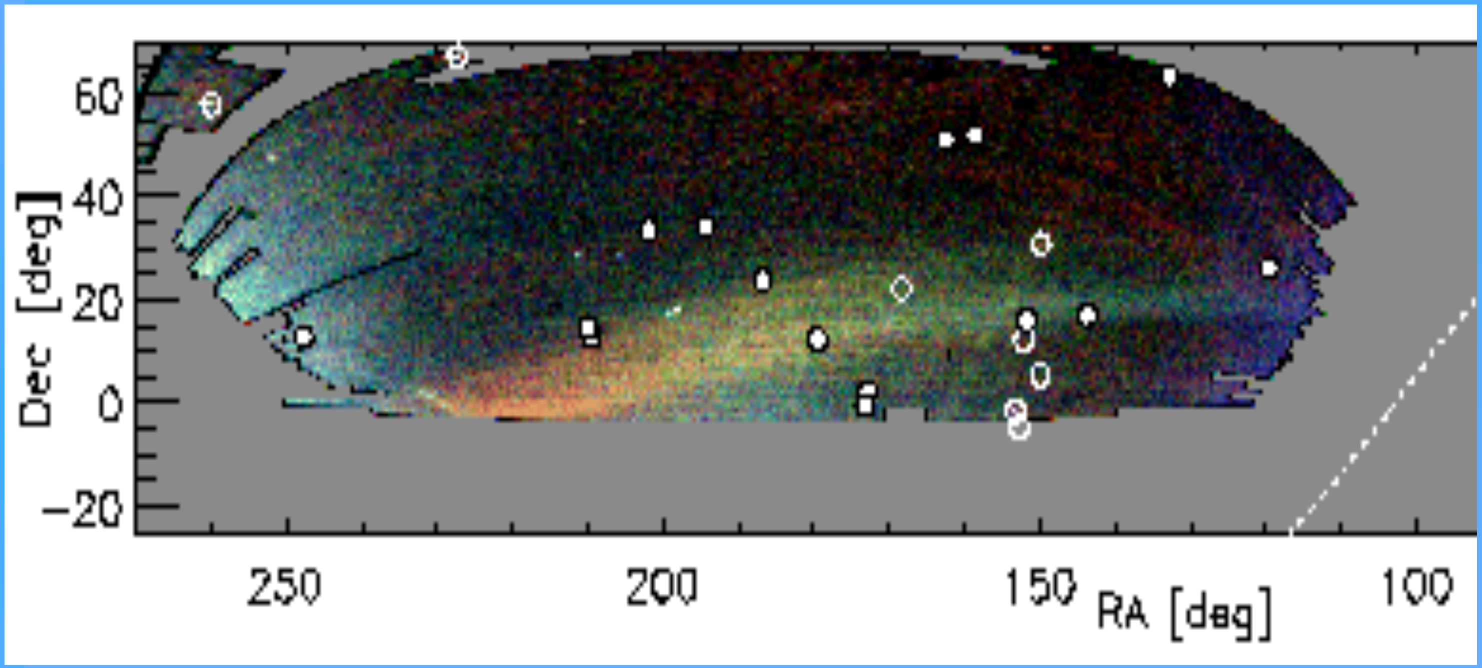
outer stellar halo is lumpy: but is a small mass fraction (15%)



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

Field of Streams - updated

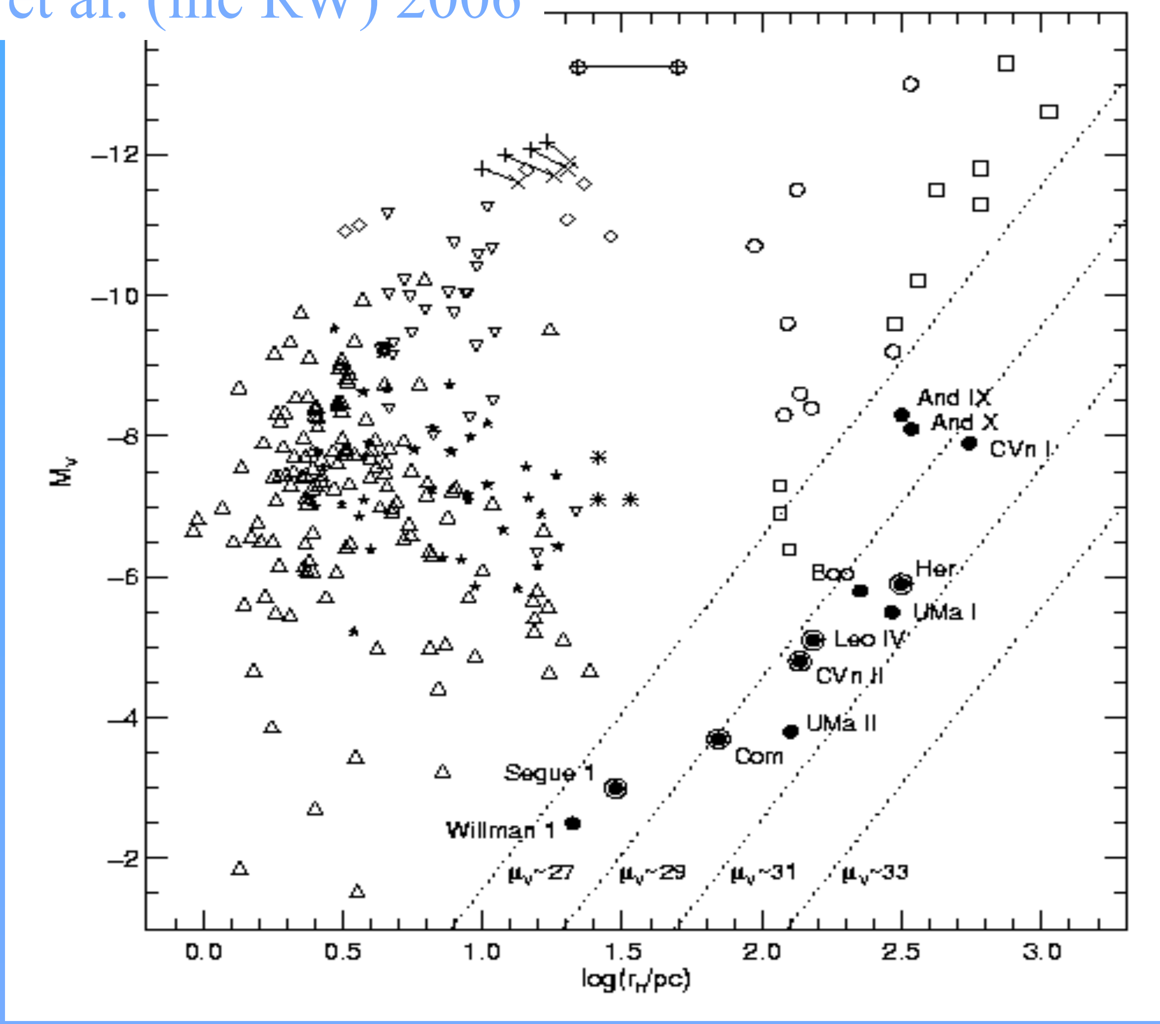
Gilmore et al; Belokurov et al 09



Classical dSph – open circles; ultra-faint – closed
Note several along the Sgr tail, some within same range of distances

New systems extend overlap between galaxies and star clusters in luminosity: Kinematic and metallicity follow-up data required to establish cluster/galaxy: dark halo or not?

Belokurov et al. (inc RW) 2006



Less faint

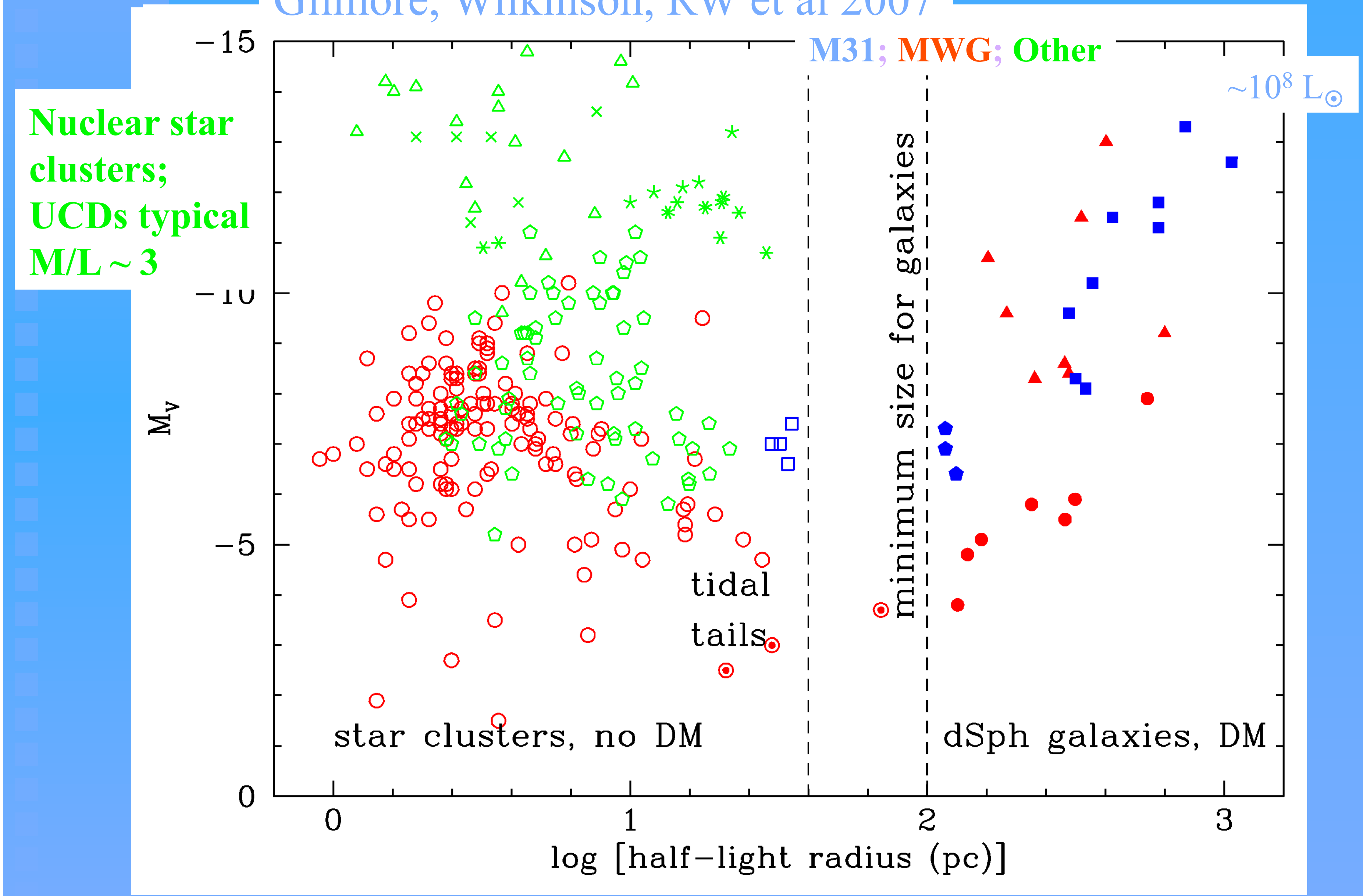
← ~10^7 $L_\odot$

← ~10^3 $L_\odot$

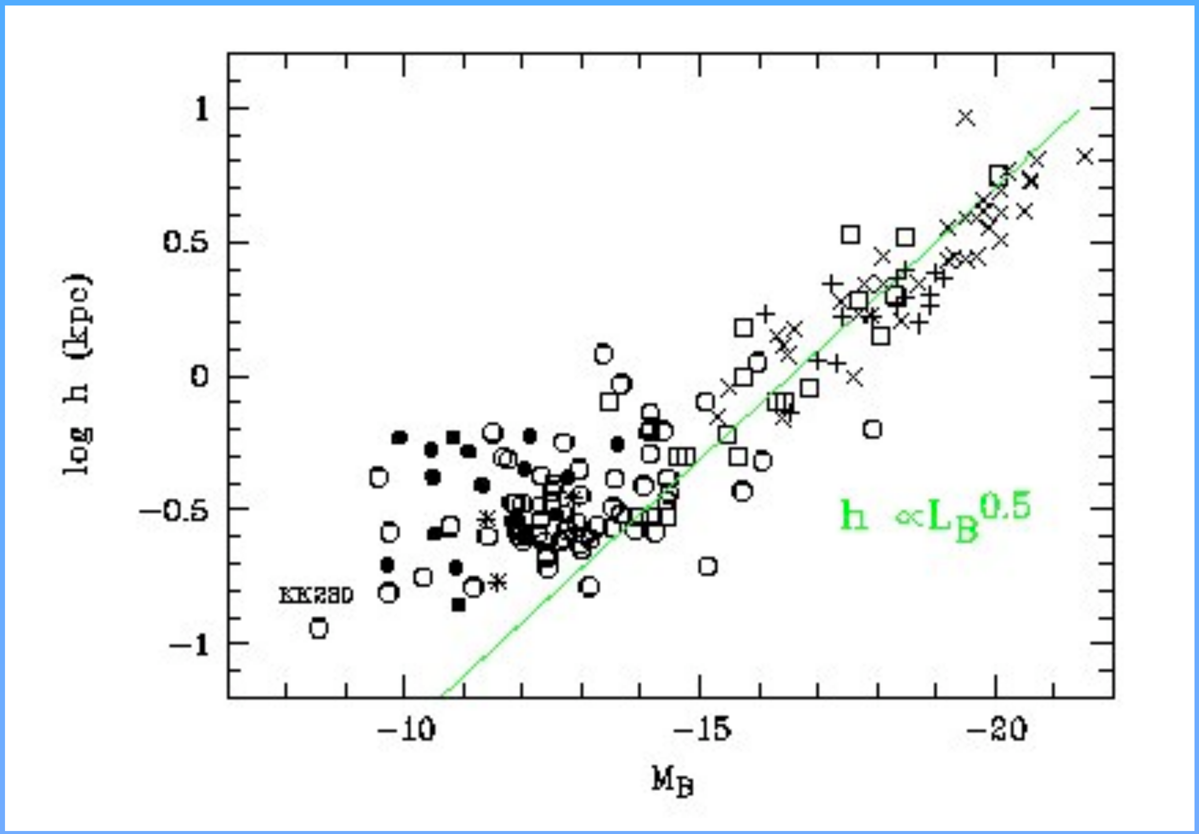
More faint

Slightly different perspective… (updated data)

Gilmore, Wilkinson, RW et al 2007

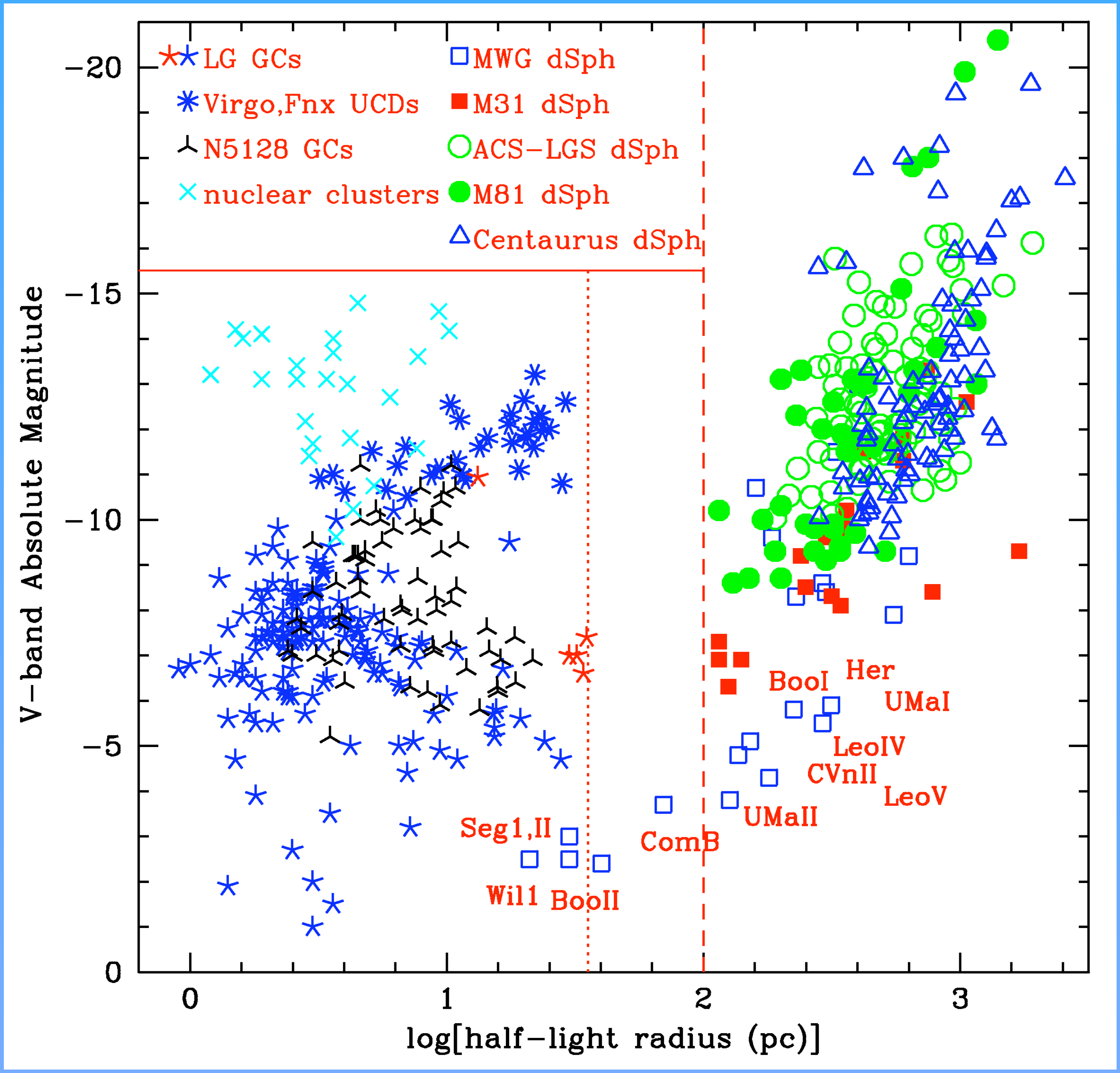


Sharina et al 08: local (<10Mpc) low-luminosity dwarfs do not lie on extrapolation of scale-length scaling of larger disks: scale-lengths are larger
-- same minimum scale?

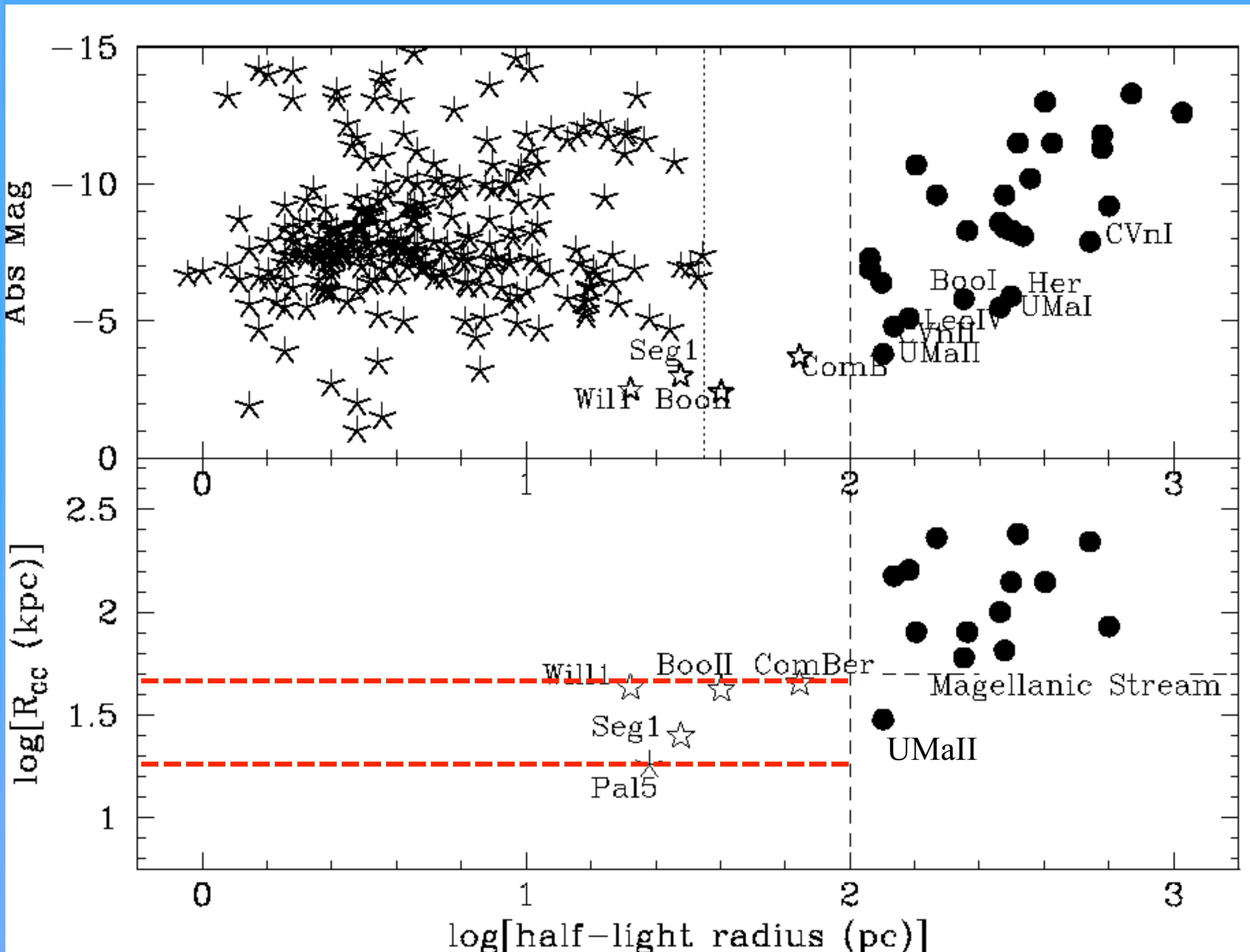


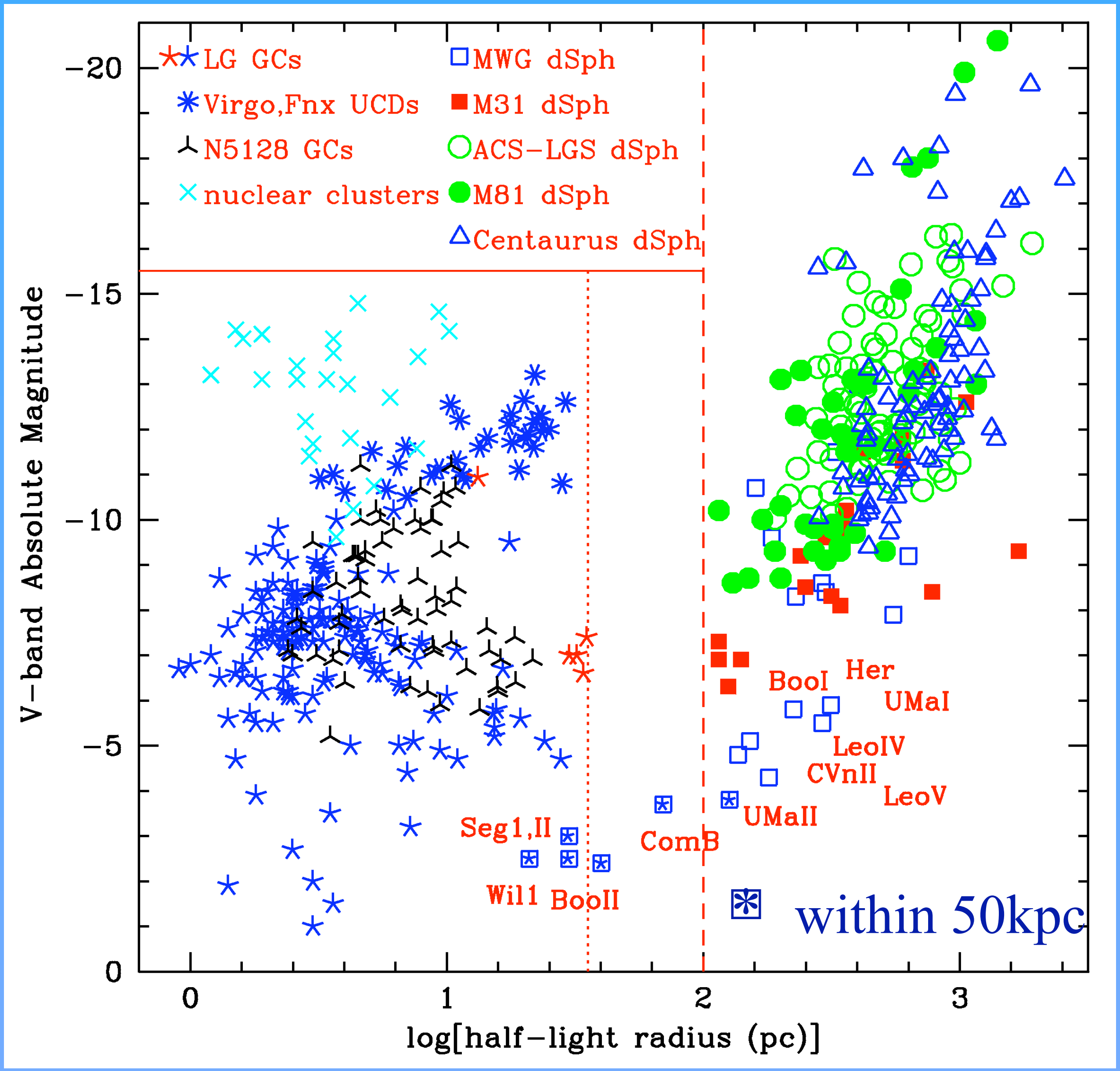
Exponential fits to surface photometry from HST

Add more data:



‘Compact dSph’ are very close….within distance range of debris from the Sagittarius dSph (red dashed lines)
(Sgr stream does not pass through solar neighbourhood, at least as traced by stars, Seabroke et al, inc RW, 2008)



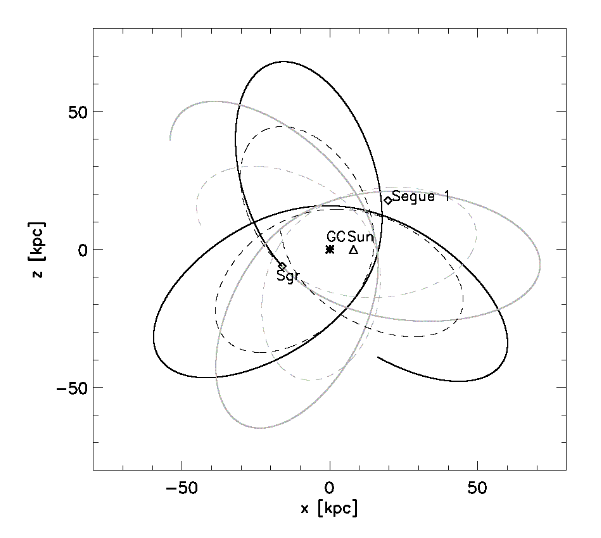


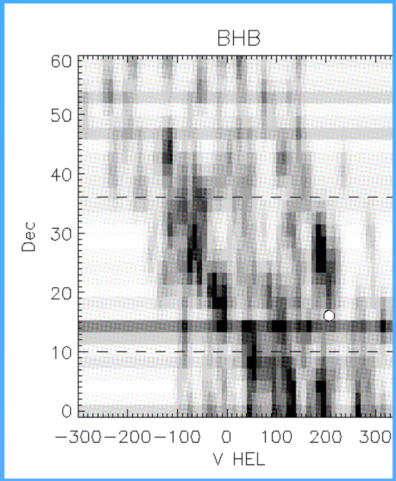
LG GCs
Virgo,Fnx UCDs
N5128 GCs
nuclear clusters
MWG dSph
M31 dSph
ACS−LGS dSph
M81 dSph
Centaurus dSph
V−band Absolute Magnitude
−20
−15
−10
−5
0
0
1
2
3
log[half−light radius (pc)]
Seg1,II
Wil1
BooII
ComB
UMaII
BooI
Her
UMaI
LeoIV
CVnII
LeoV
within 50kpc

Segue 1: Most dark-matter dominated, faintest galaxy -- and compact?

- Radial velocity data for stars in central region of Segue 1 → very dark-matter dominated system, faintest galaxy known (Geha et al 2008)
- However, system is at location of debris from the Sgr dSph -- line-of-sight, distance and velocity (Niederste-Ostholt et al inc RW, 2009), and ‘members’ are very extended on sky
- Cannot exclude contamination and spuriously high velocity dispersion – membership difficult
- Cannot ignore tidal effects in determining structure
- Chemical abundances critical in establishing star cluster/galaxy

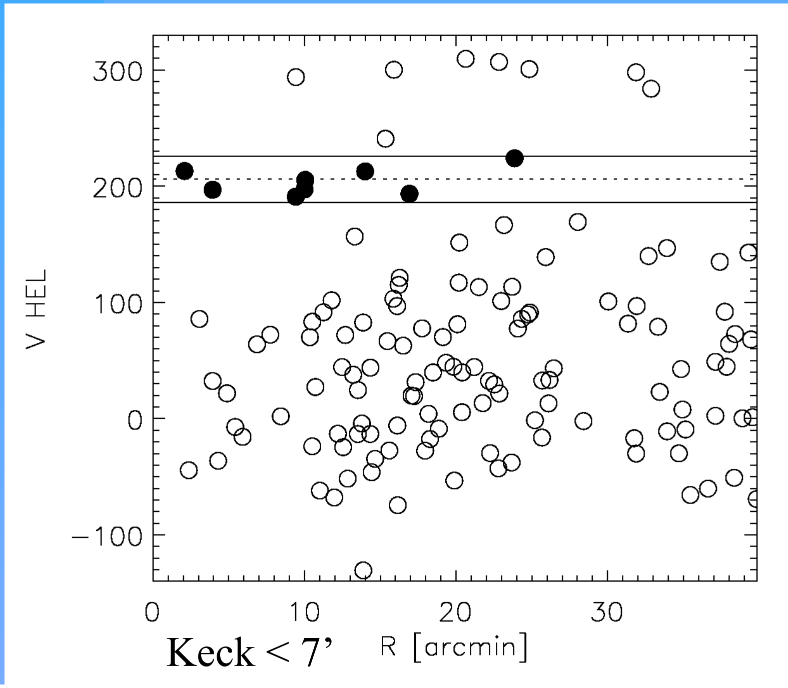
Plausible orbits of Sgr



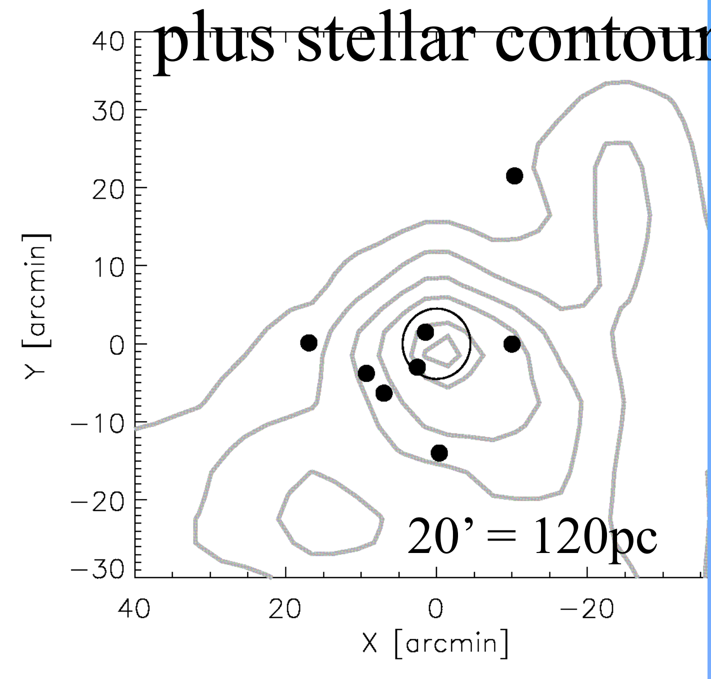


Radial velocities of Blue Horizontal Branch stars from SDSS show streams, match Segue 1 (dot)

Wide-area data from AAT/AAΩ (Gilmore, Wyse, Norris)

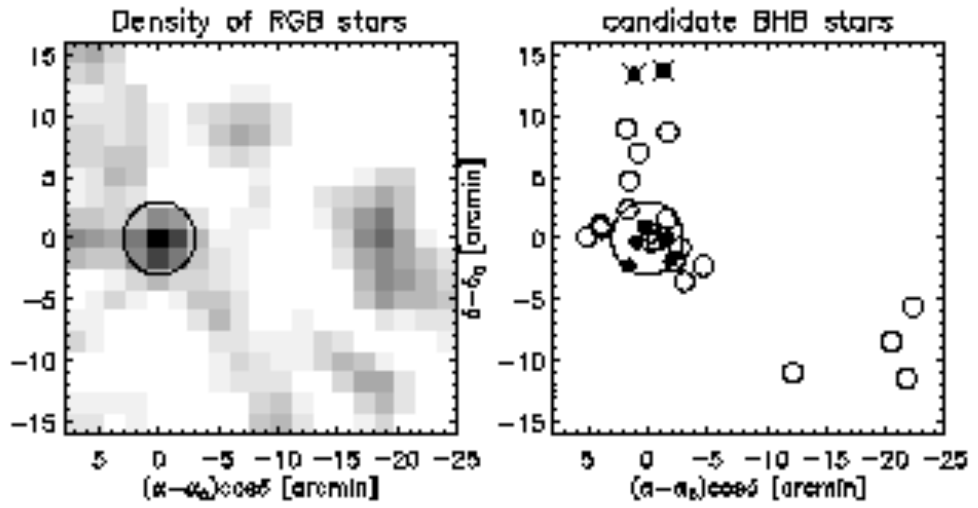


plus stellar contours

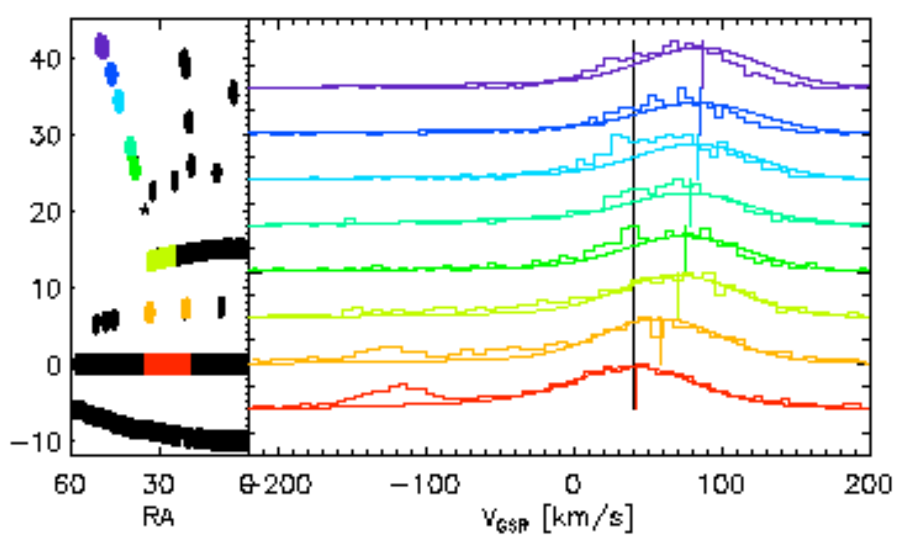


Some more complexity:

Belokurov et al 2008



Leo V (distance 180kpc) – complex density profile: outermost BHBs are velocity members (Walker et al 2009)



Segue-II– another halo stream connection Belokurov et al 2009

Dark Matter Length Scale

- There is a well-established size bi-modality
  - all systems with size < 30pc are purely stellar
    $-16 < M_v < -1$, $M/L \lesssim 4$; e.g. globular clusters, nuclear star clusters..
  - all systems with size greater than ~120pc have dark-matter halo : minimum scale of dark matter?
  - Expect dark matter scale length to be at least equal to stellar scale length (gas dissipates prior to star formation)
- There are no confirmed (equilibrium) galaxies with half-light radius r < 120pc
  - a few tidally disturbed systems, faint and closer than 50kpc to Galactic center –regime of Sgr tidal tails/streams

From kinematics to dynamics: Jeans equation, and full distribution function modelling

- Jeans equation relates spatial distribution of stars and their velocity dispersion tensor to underlying mass profile

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

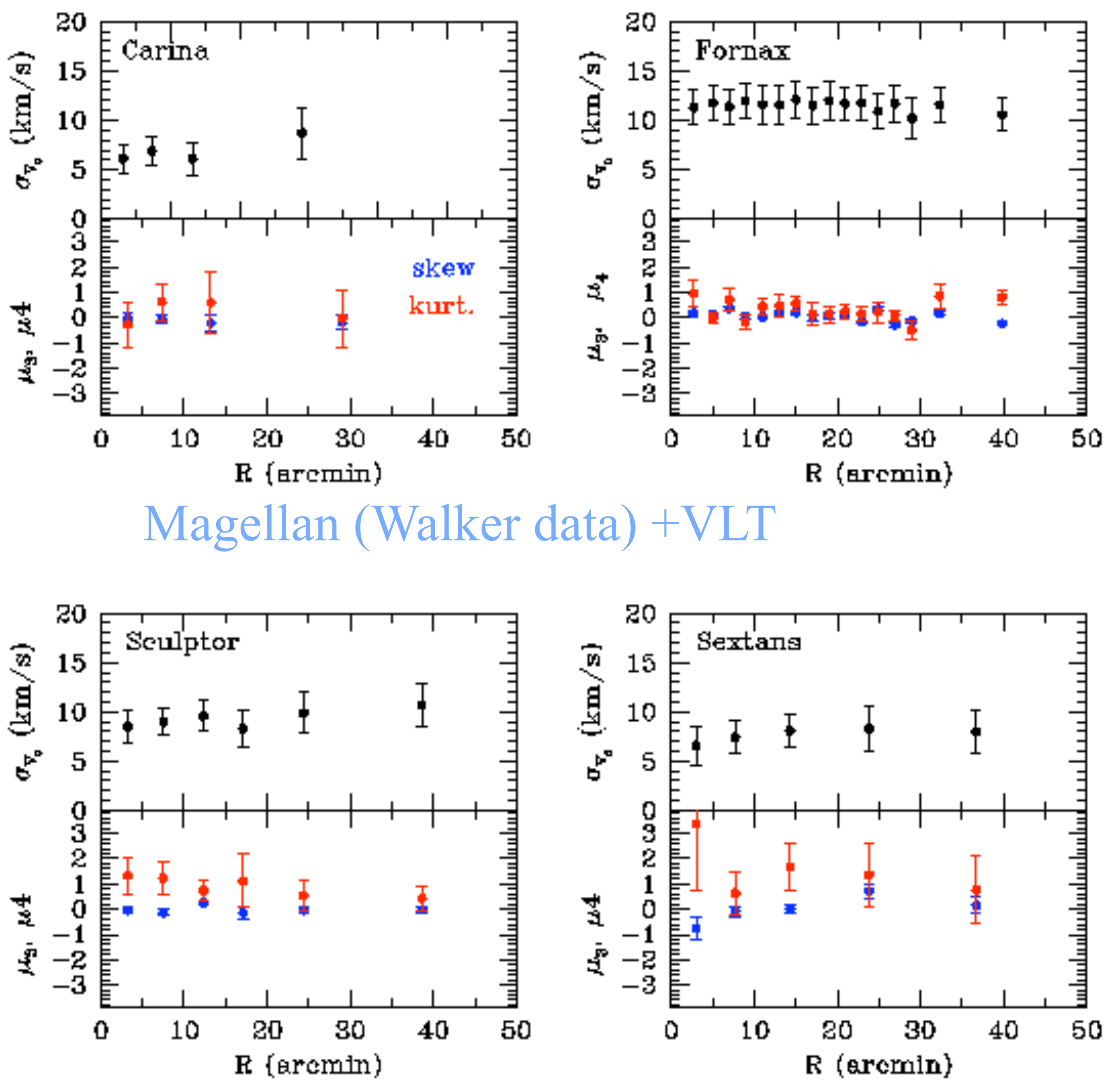
  - Either (i) determine mass profile from projected dispersion profile, with assumed isotropy, and smooth functional fit to the light profile
  - Or (ii) assume a parameterised mass model M(r) and velocity dispersion anisotropy β(r) and fit dispersion profile to find best forms of these (for fixed light profile)
- We also use distribution function modelling, as opposed to velocity moments: need large data sets. DF and Jeans' models agree
- Show Jeans' results here for most objective comparison
- King models are <u>not</u> appropriate for dSph, too few stars

Full distribution function modelling of these data underway

Members:
Fornax: 2610
Sculptor: 1365
Sextans: 441
Carina: 1150

Yield:
Car, Sext ~50%
For,Scl ~80%

Non-members:
Wyse et al 2006

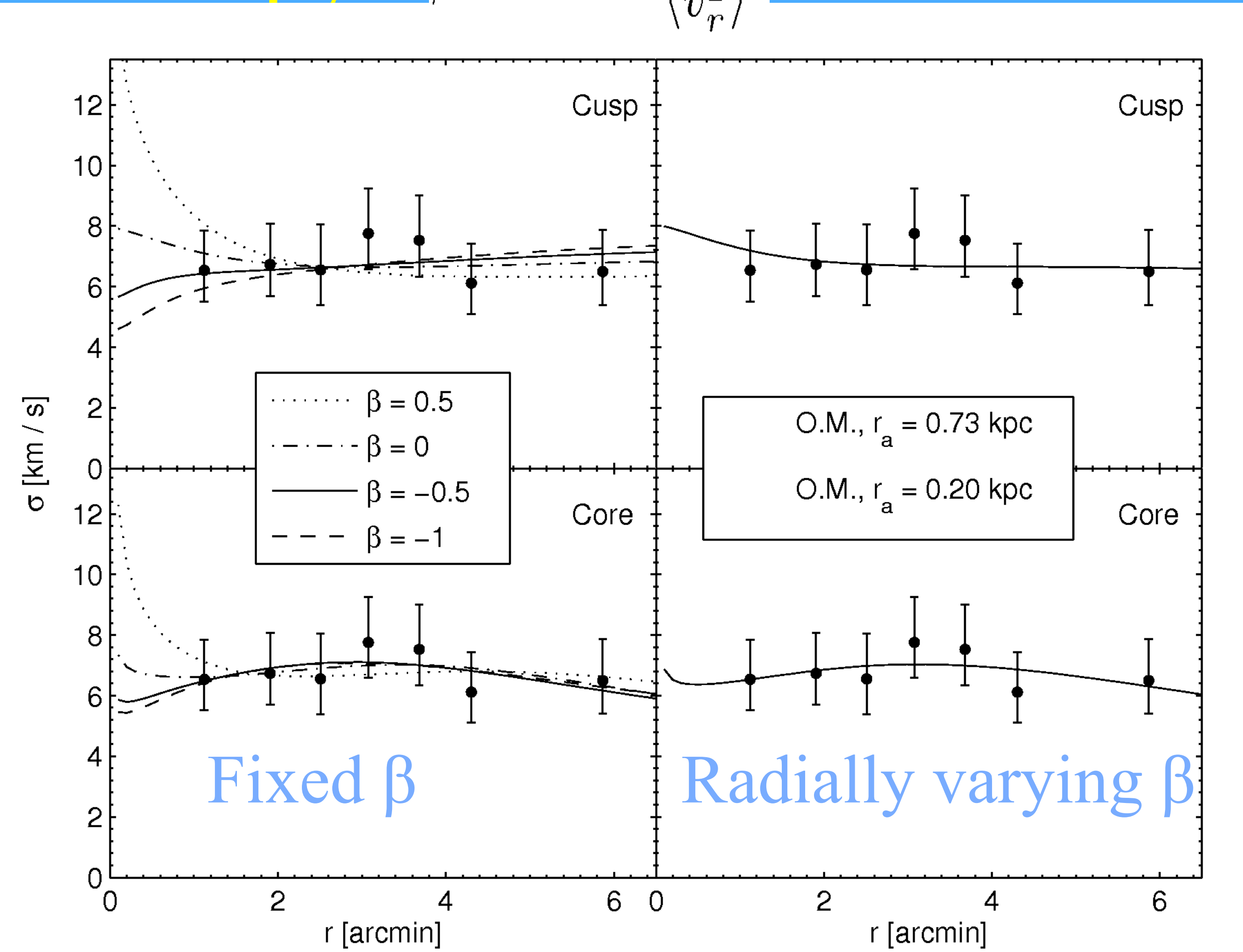


Magellan (Walker data) +VLT

Adding velocity dispersion anisotropy: $\beta = 1 - \frac{\langle v_\theta^2 \rangle}{\langle v_r^2 \rangle}$

Koch et al, inc RW 2007

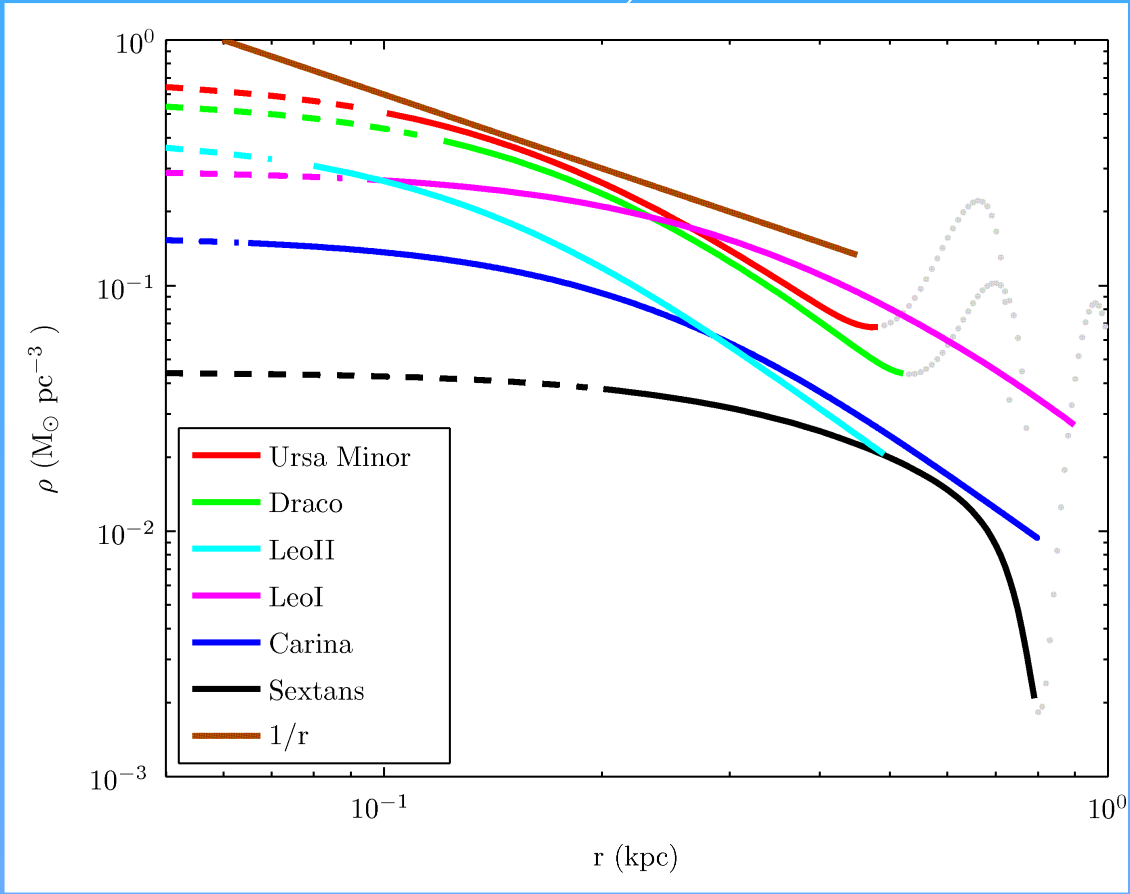
Leo II



Cores slightly favoured, but not conclusive

Gilmore et al, inc RW 2007

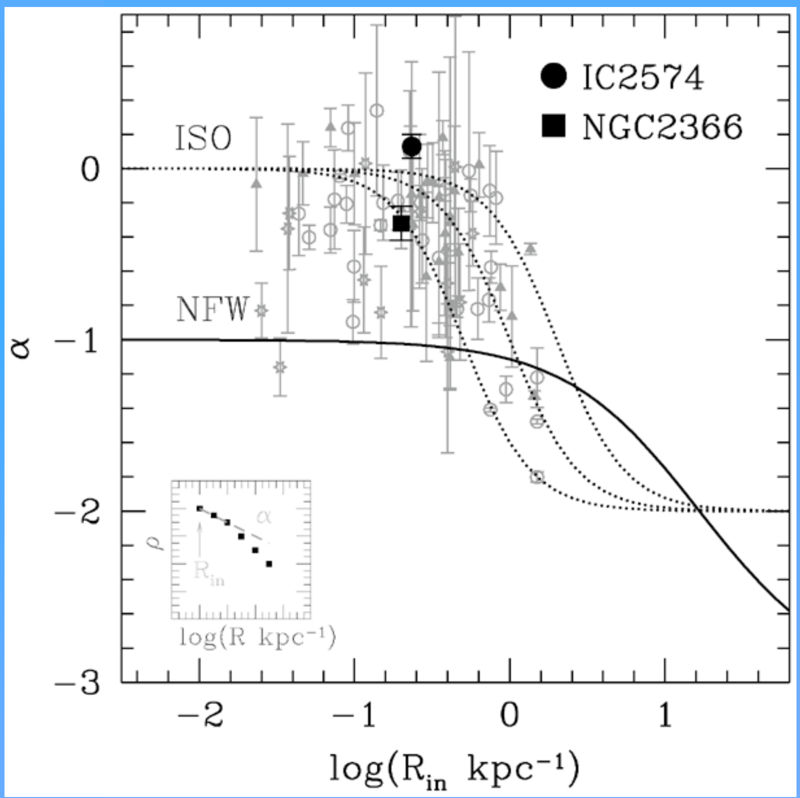
Mass density profiles: Jeans' equation with assumed isotropic velocity dispersion: All consistent with cores (similar results from other independent analyses e.g. Wu 2007) →CDM predicts slope of −1.3 at 1% of virial radius, asymptotes to −1 (Diemand et al. 04) as indicated in plot



- These Jeans' models are to provide the most objective comparison among galaxies, which all have different baryonic histories and hence different 'feedback'

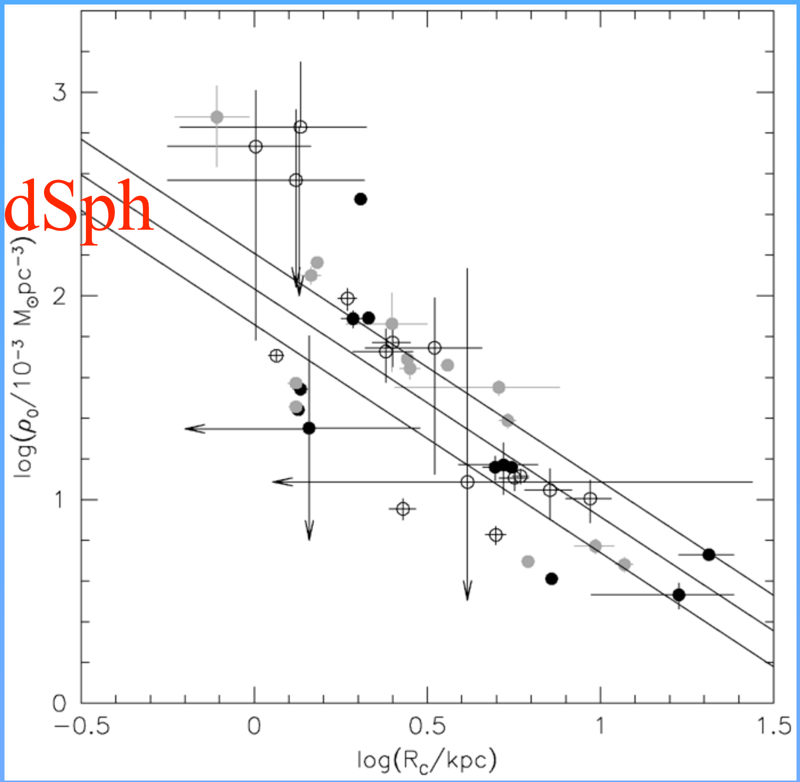
‘Things’ HI/Spitzer/Galex survey -- low-mass spirals consistent

Inner density slope



Core density

dSph



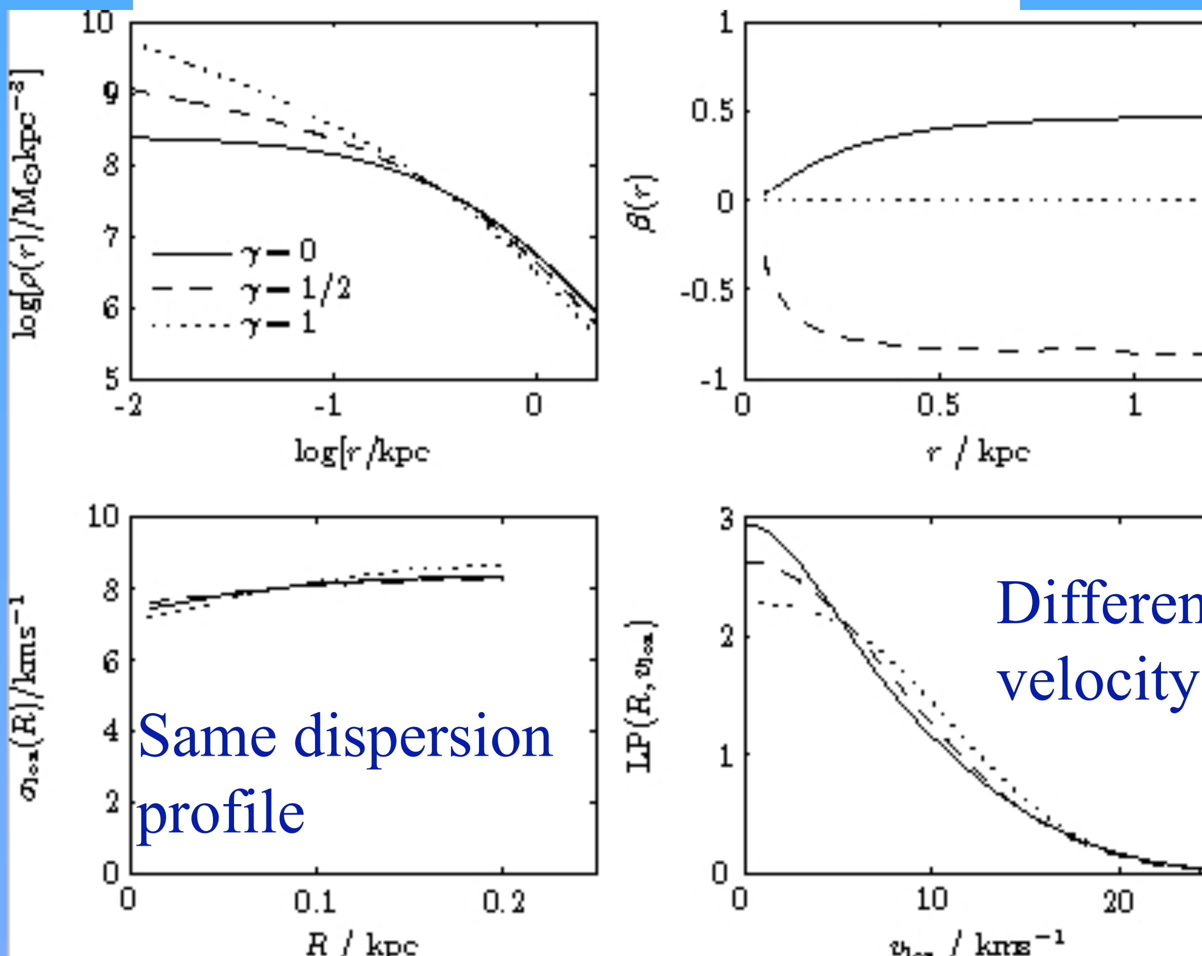
Oh et al 2008

de Blok et al 2008

- Central densities always similar and (relatively) low
- Mass – anisotropy degeneracy prevents robust cusp/core distinction, but core + small radial bias provides slightly better fit (see also Wu 2007)
- Break degeneracy by complementary information:
  - Ursa Minor has a cold subsystem, requiring shallow gradients for survival (Kleyna et al 2003)
  - Fornax globular clusters (age ~10Gyr) should have spiralled in through dynamical friction in ~few Gyr unless core (e.g. Goerdt et al 2006) – and many dwarf galaxies have globular clusters (e.g. Lotz et al 2001)
- Simplicity argues that cores favoured for all
- New data and DF-models underway to test (VLT cusp/core project, PI Gilmore)

From kinematics to dynamics: anisotropy vs mass profile degeneracy

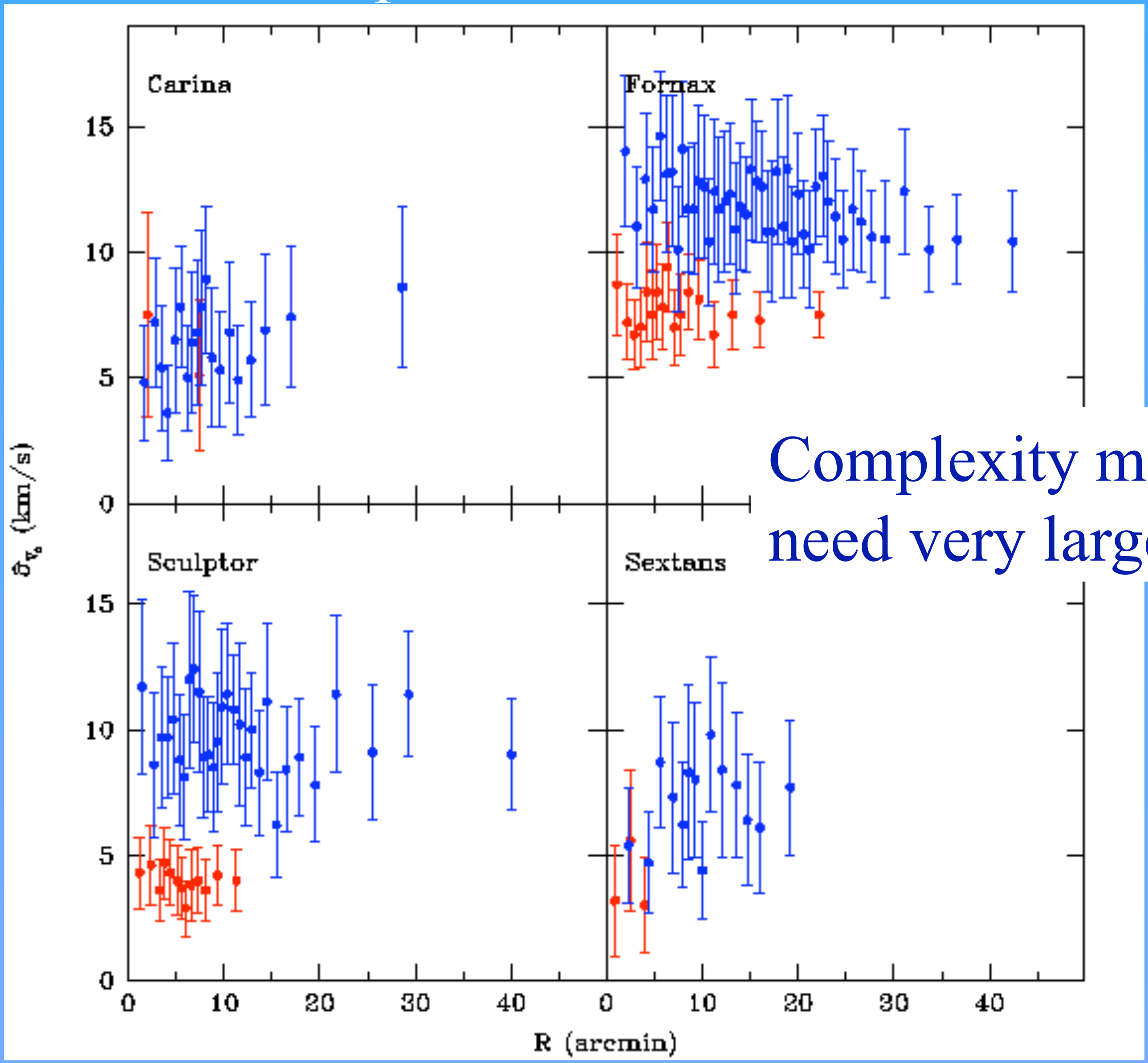
$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\,\nu\sigma_r^2}{\mathrm{d}\,r} + 2\frac{\beta\sigma_r^2}{r}\right)$$



Same dispersion profile

Different radial velocity distribution

Multi-component dispersions in dSph
Blue: metal-poor stars, red: metal-rich stars

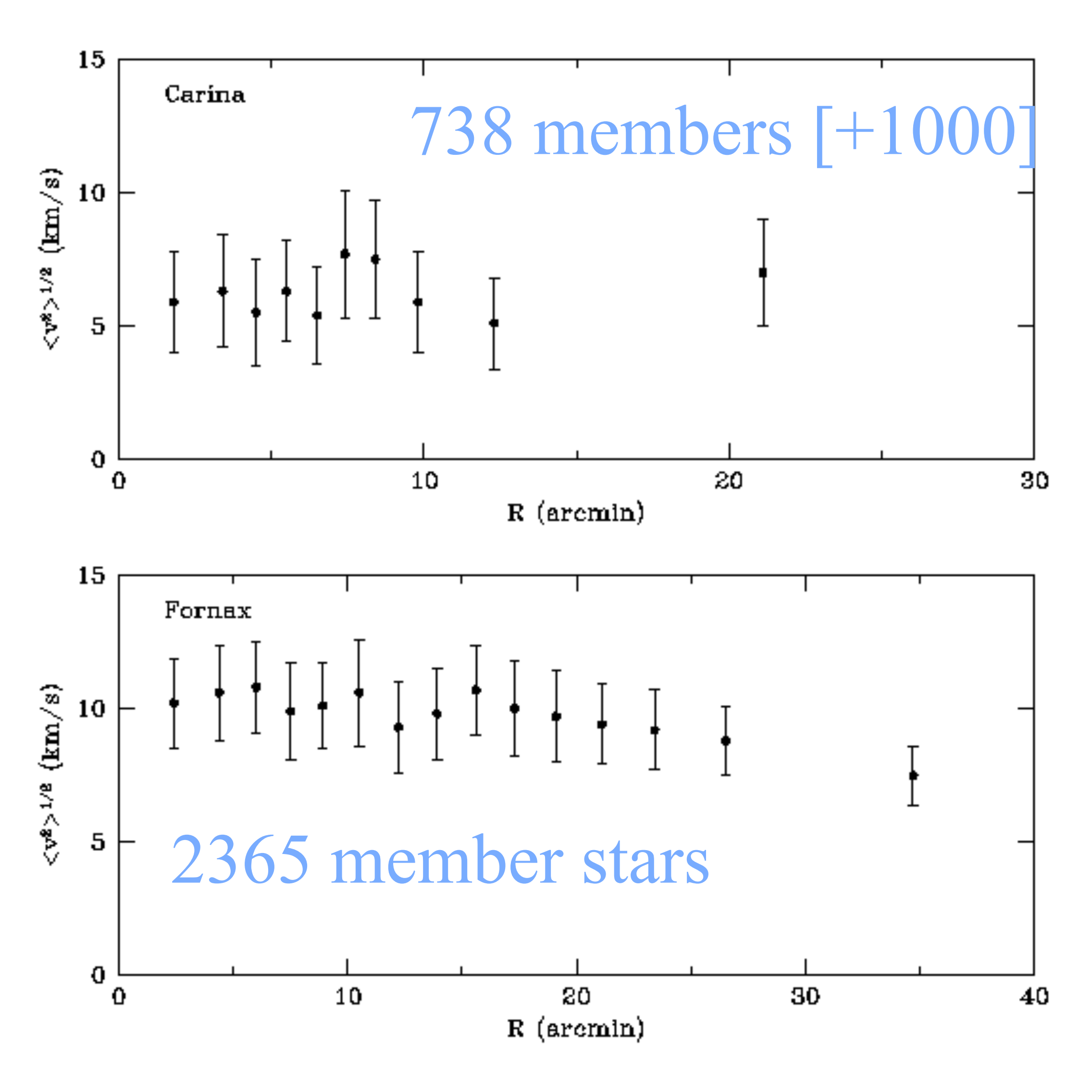


Complexity means
need very large samples

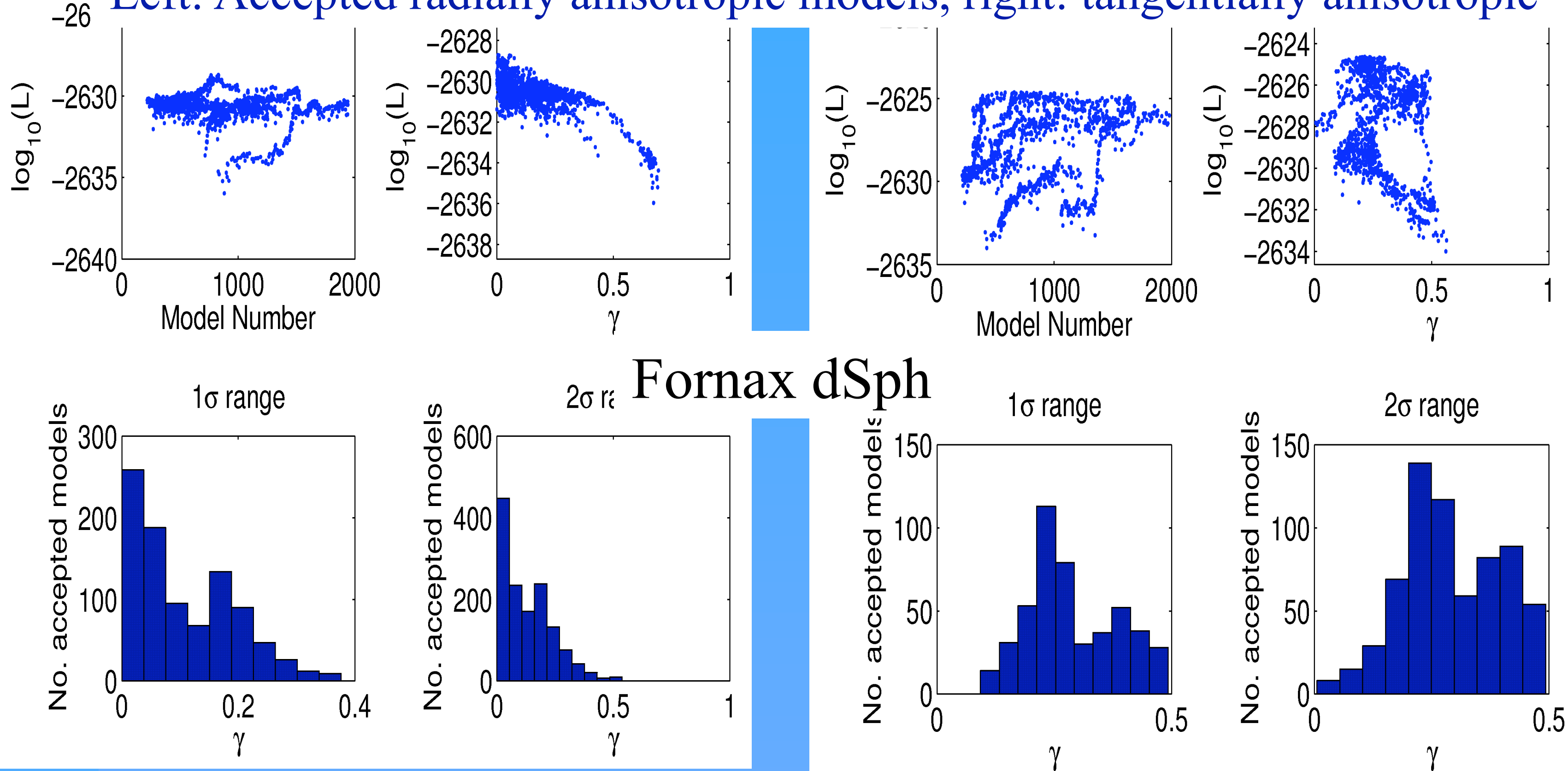
Very large precision kinematics now exist: Magellan+VLT

– vastly superior to the best rotation curves

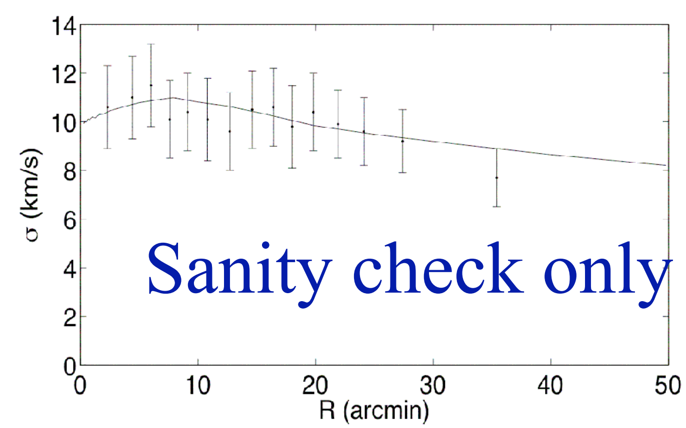
– large samples after population selection: metal-poor



Left: Accepted radially anisotropic models, right: tangentially anisotropic



Fornax dSph

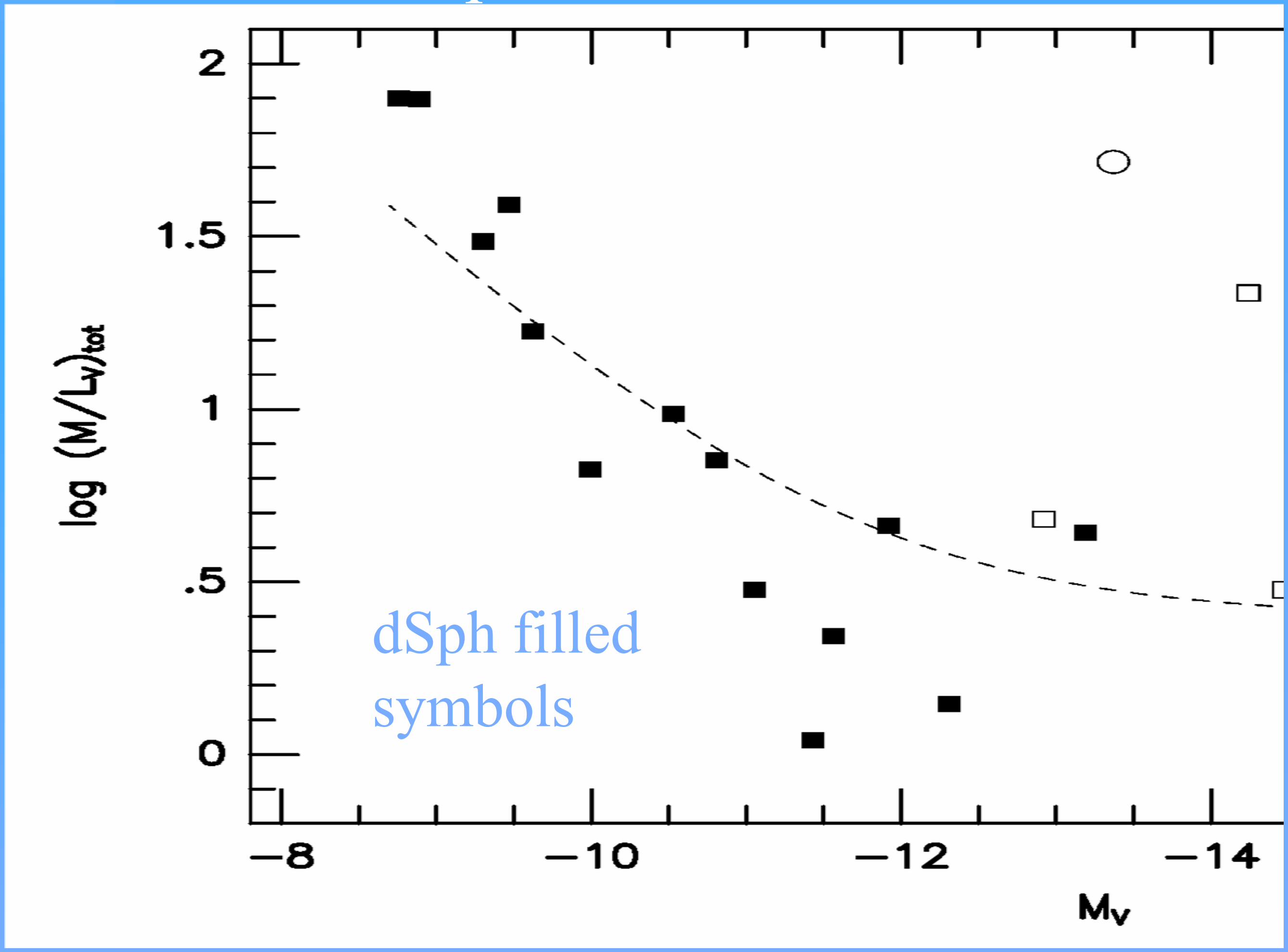


Sanity check only

We build 2-integral, anisotropic distribution function general models, and match data by Markov Chain Monte Carlo - half of the chains start with $\gamma > 0.5$, but converge to $\gamma < 0.5$ ➔ favour cores

Constant mass scale of dSph:

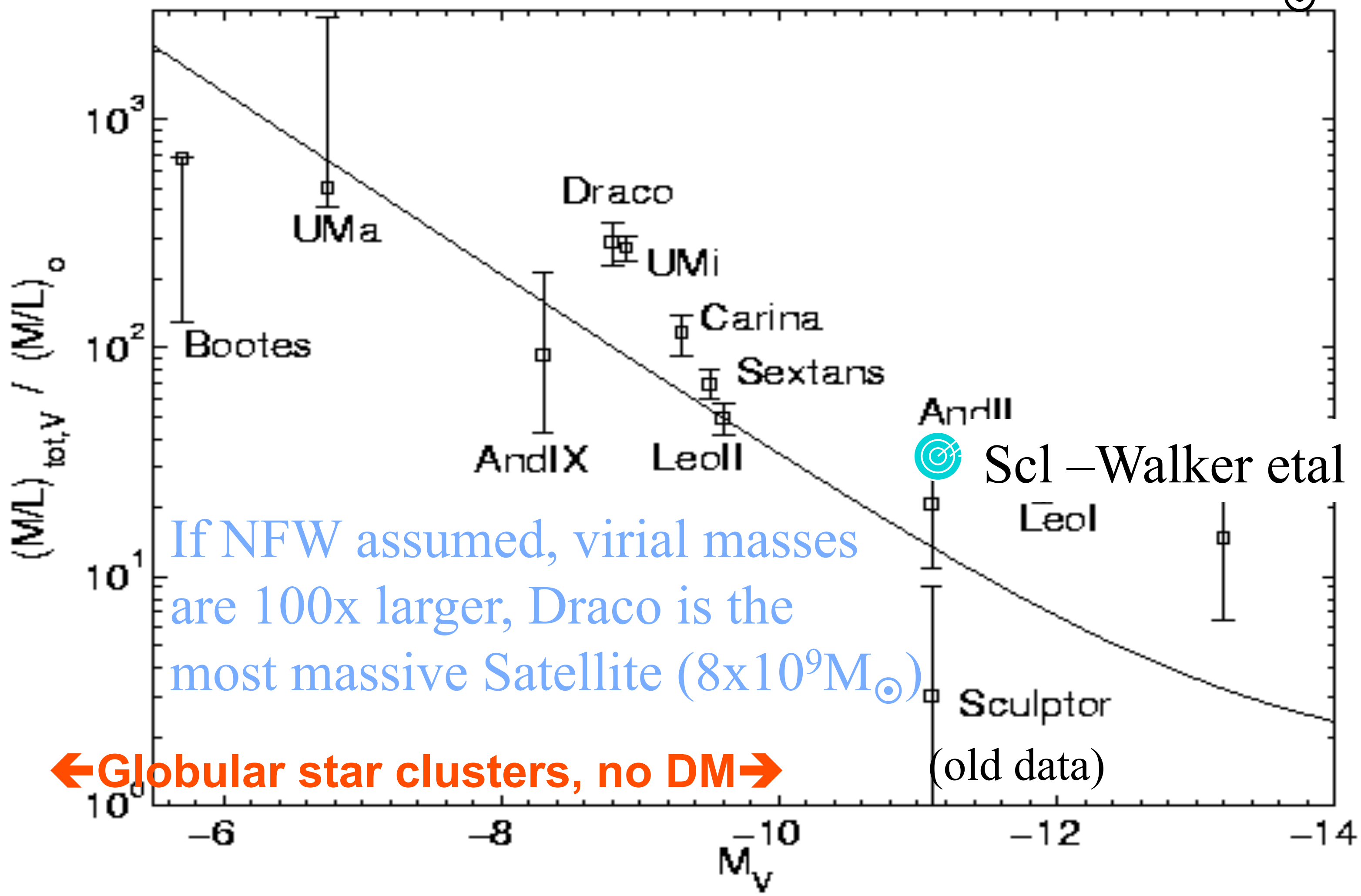
Based on central velocity dispersions only;
line corresponds to dark halo mass of $10^7 M_\odot$



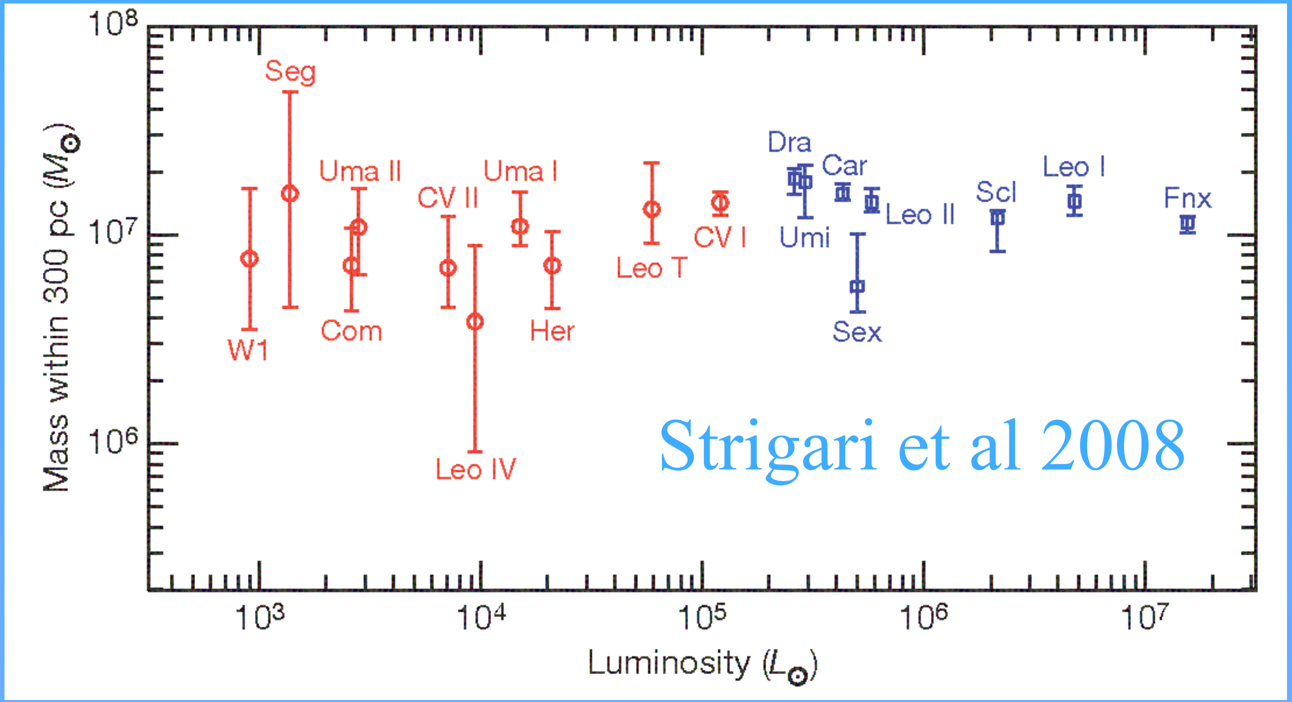
Mateo 98
ARAA

New kinematic studies with radial coverage (Gilmore et al 2007): confirms & greatly extends

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



Extending analysis to lowest luminosity systems difficult – few stars, and many are in complex environments. Limited data, only central velocity dispersion at present.



Blue symbols: 'classical' dSph, have velocity dispersion profiles to last modelled point, reproduces our results

Red symbols: Ultra-faint dSph, data only in central region, extrapolation in radius by factor of at least 100

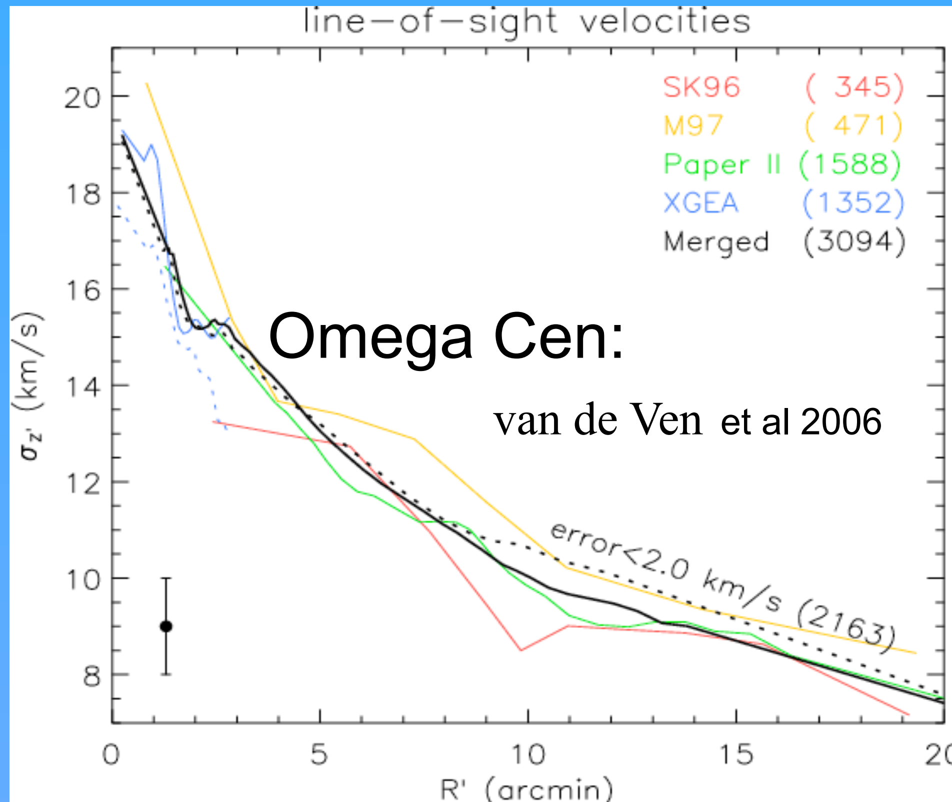
Summary:

- A minimum physical scale for galaxies:

  half-light radius >100pc

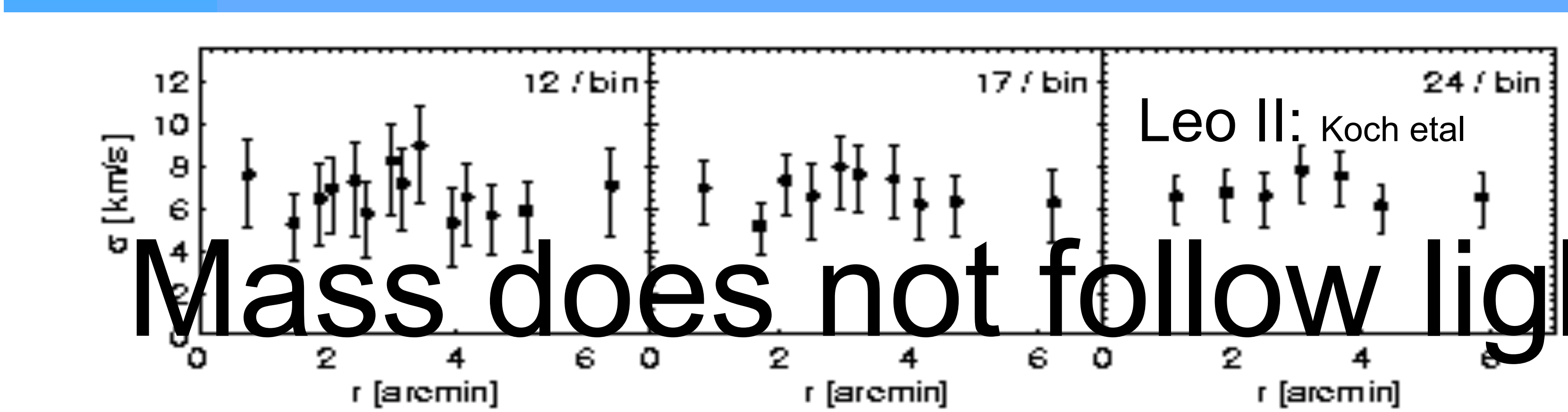
  - mass size scale somewhat larger (x2?)
- Cored mass profiles, with similar low mean mass densities

  $\sim 0.1 M_{\odot}/pc^3$, ~10GeV/cc
- An apparent characteristic (minimum) mass dark halo in all luminous dSph, mass $\sim 10^7 M_{\odot}$
  - this is a consistency check, constant density plus scale, not new info
  - masses for the lowest luminosity systems uncertain
- Wide range of stellar populations (age distributions, chemical evolution) despite similar dark matter haloes – constrains ‘feedback’
- Adds to challenges for CDM: need to consider a variety of DM candidates



Omega Cen:

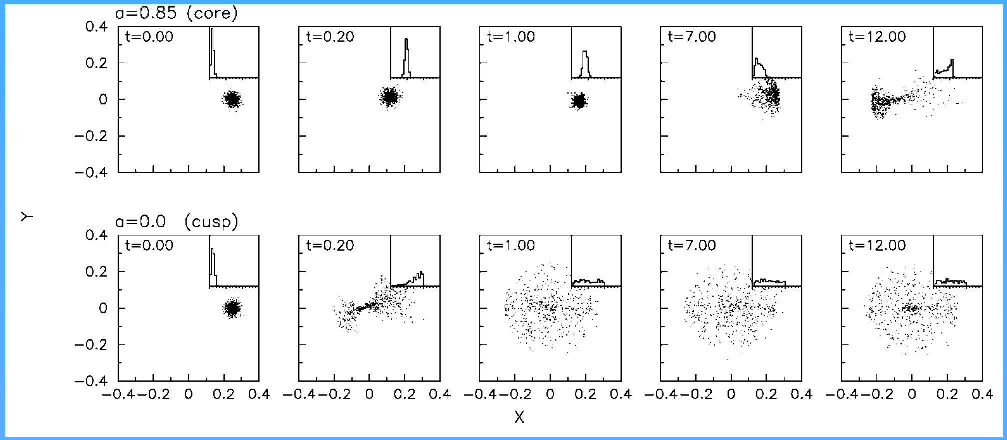
van de Ven et al 2006



Leo II: Koch etal

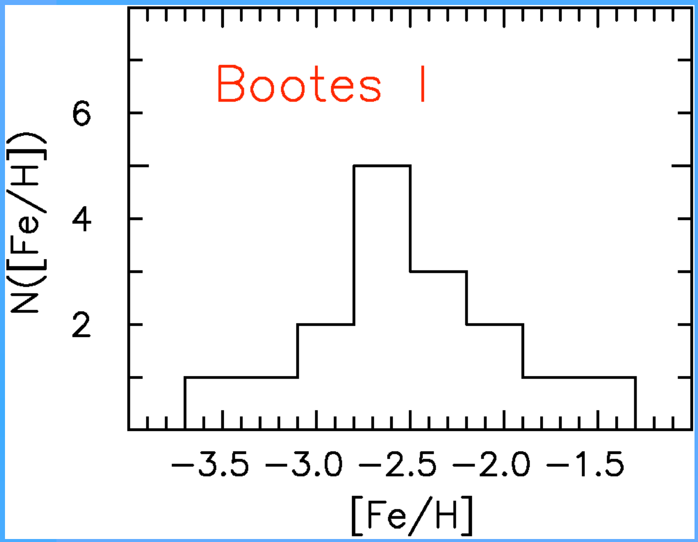
Mass does not follow light

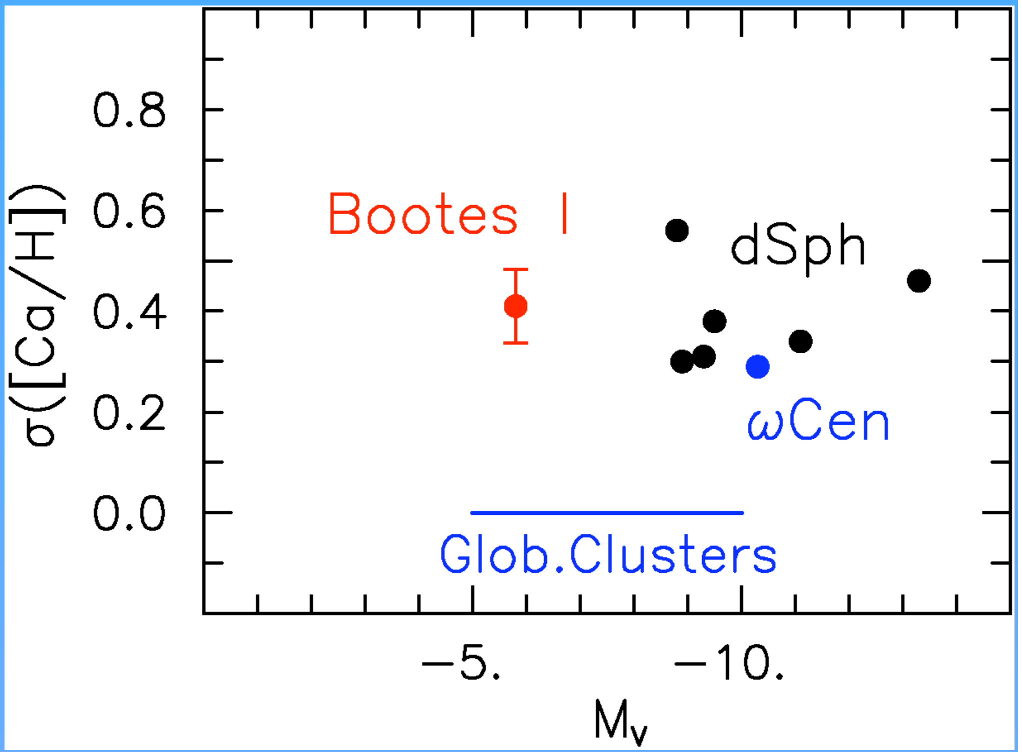
Breaking the degeneracy – indirect hints



- Survival of cold subsystem (former star cluster) in UMi dSph implies shallow mass density profile (Kleyna et al 03)
- Dynamical friction limits on Fornax dSph Globular Clusters (survivors) also favour cores to extend timescales (Hernandez & Gilmore 1998; Goerdt et al 2006;, Read et al 2006)

Abundance mean and dispersion is a mass proxy, and a direct test of the minimum length scale hypothesis



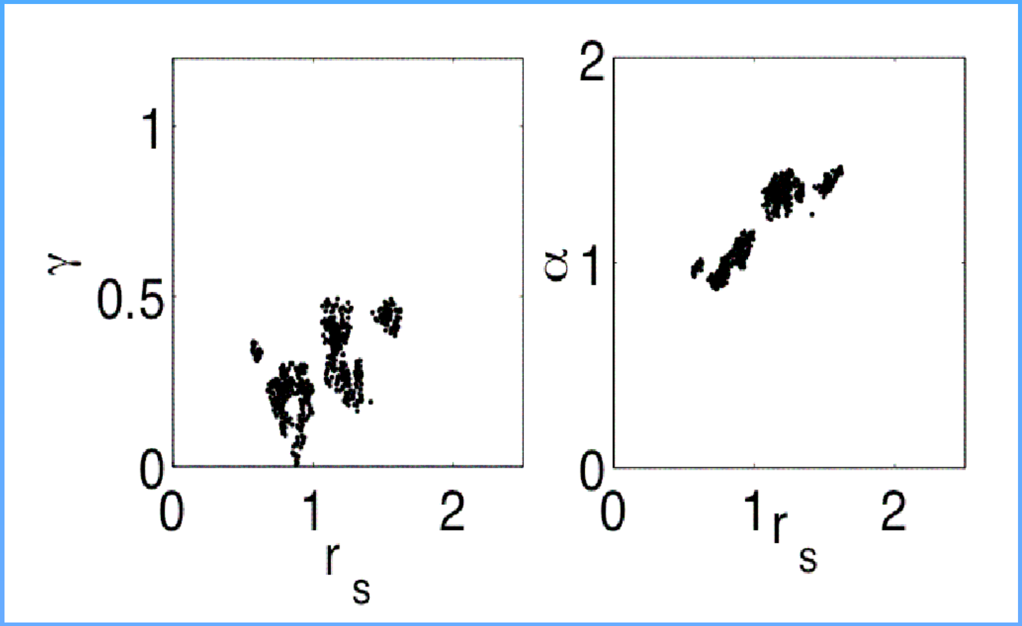


Norris, Gilmore, Wyse et al 2008;
Also Kirby et al 2008

NB: self-enrichment on these scales requires low SFR, and weak feedback

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

Zhao 1996



Main degeneracies in model fits are between halo scale length and slopes in density law; despite these, models within 2σ of the most-likely, constrain $\gamma < 0.5$

Sgr dSph discovered as a 'moving group':

Sgr stars have a distinct distribution in colour-velocity space: age and metallicity distributions are different from bulge → bulge not merged Sgr-like systems

Ibata, Gilmore & Irwin 1995