Dark Matter on small astrophysical scales

Gerry Gilmore
IoA Cambridge

Have we found the first galaxies?

Do we understand their histories well enough to probe their DM?

What are their DM properties?

Dynamics with Mark Wilkinson, Rosie Wyse, Jan Kleyna, Andreas Koch, Wyn Evans, Walter Dehnen, Eva Grebel,
Chemistry with Andreas Koch and John Norris
Discovery work with Vasily Belokurov, Dan Zucker, Sergey Koposov, et al

Simple extrapolation of the power-spectrum in CDM produces many astrophysics challenges

- Anti-hierachical problem
- Top-down, old red & dead..
- Satellite problem- too many small galaxies
- Void problem – model voids are not empty
- Angular momentum problem – real galaxies are too big
- Phase-space density problem – galaxy centres are lower density than models
- Large disks problem – late mergers should not allow large cold disks, which are common
- etc, etc, etc, etc, etc, etc, etc.....

- ➔ these allow a probe of both astrophysics and particle properties on kpc scales

Particle-astrophysics joint challenges

do very many puzzles imply very many particle types??

- MSSM has 120+ free parameters… and is just one of very many possible theories:
- neutrino masses and mixing
- baryogenesis
  - matter anti-matter asymmetry
- dark matter
- dark energy, gravity, CPT, Higgs/mass,…

Scale invariant power spectrum implies a UV divergence

➔ a physical cut-off at some scale:

Astrophysics ➔ `satellite problem`

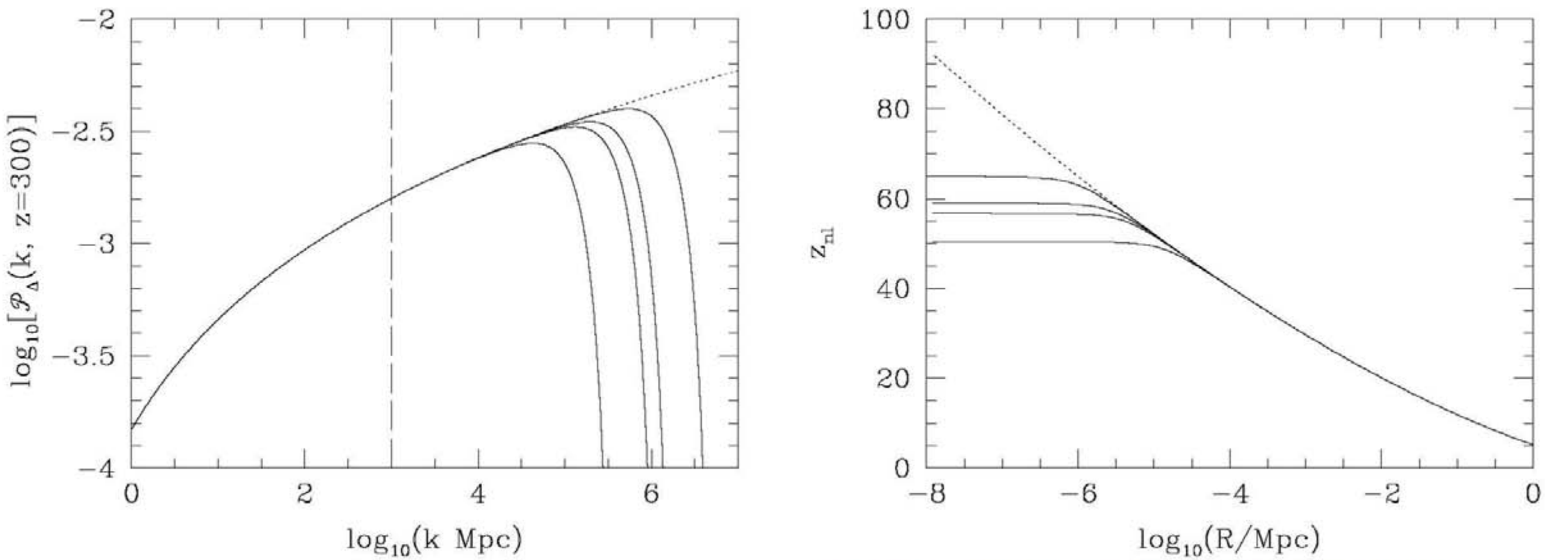
Is that scale astrophysically relevant?

Can it be deconvolved from feedback?

Anticipated DM effects on scales of pc up ➔first systems

Linear power spectrum at $z \sim 300$ and $z_{\rm nl}$

influence of WIMP microphysics



Green, Hofmann & Schwarz 2004; 2005

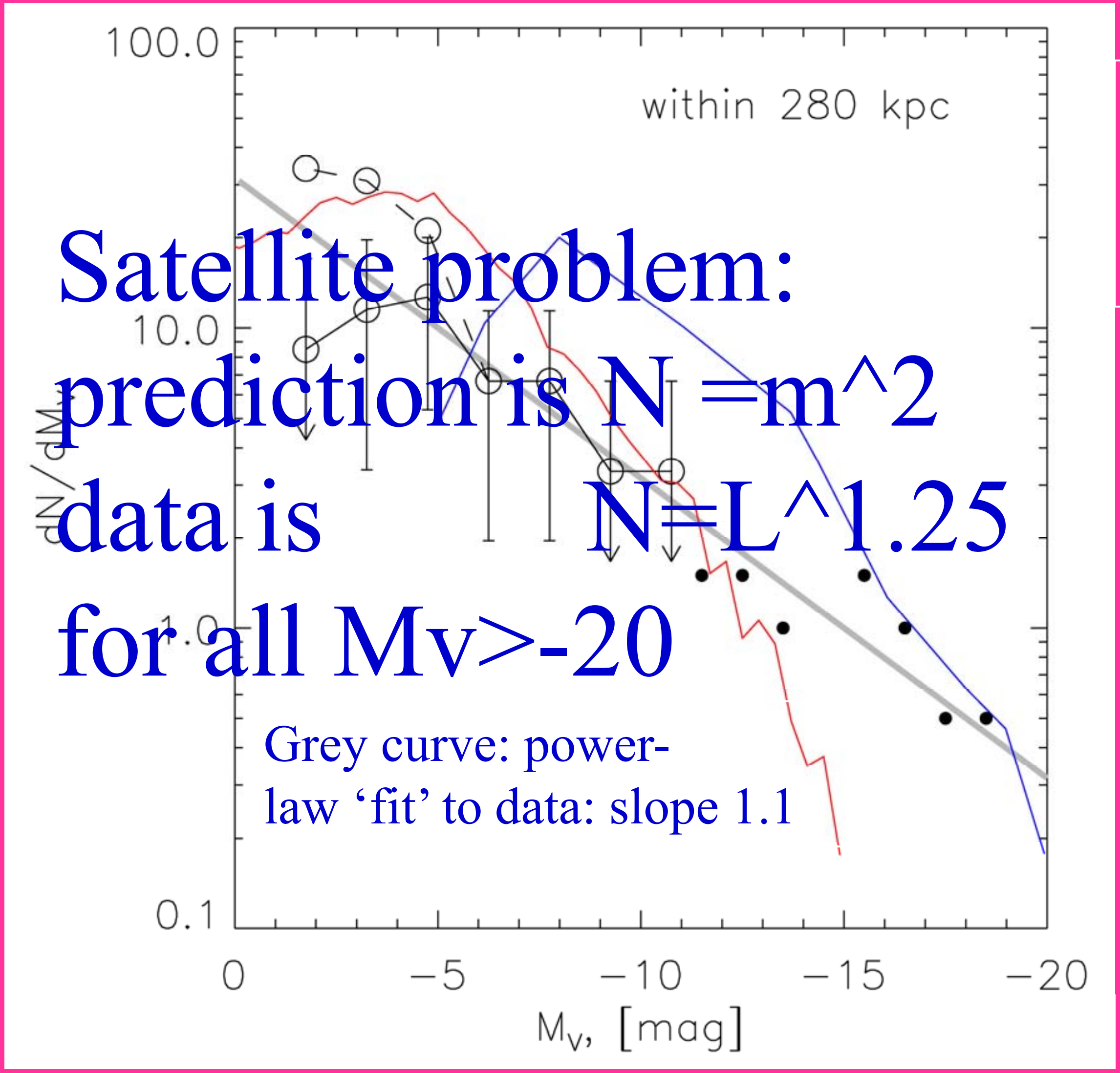
The smallest, oldest galaxies: dwarf Spheroidals

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

  $\sigma \sim 10$km/s, $10 < M/L < 100$
- Very metal-poor, all contain very old stars; but intermediate-age stars dominate
- They survive from a time before general pre-enrichment, and avoided extreme histories
- Their DM halos remain primordial
- Are they the first halos, as CDM requires?

Derived satellite *luminosity* function

Koposov et al 2008 ApJ 686 279



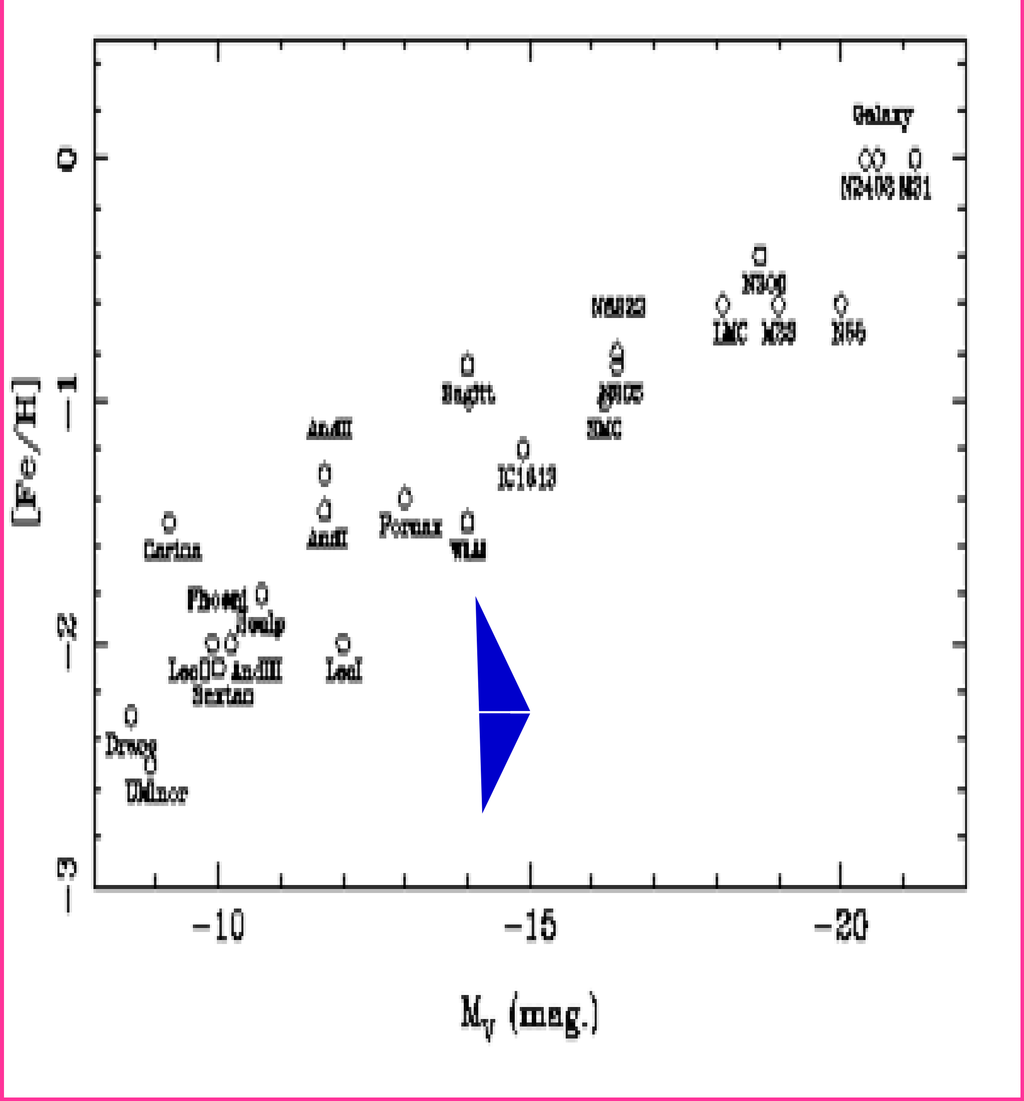
Open symbols: Volume-corrected satellite LF from DR5

Filled symbols: 'all Local Group dSph'

Coloured curves: Semi-analytic fit (Benson et al 02, red Somerville 02, blue)
We ignore BIG surface-brightness discrepancies
REALLY NEED MASS

Galaxies form tight sequences

- Tight mass-luminosity sequence
- Requires MOST stars to form **<u>during</u>** or after mergers, if mergers ubiquitous
- But dSph are gas-free
- Enrichment always final potential-depth limited?



All satellites have some old stars, but they are mostly young they have survived a Hubble time → no violent histories

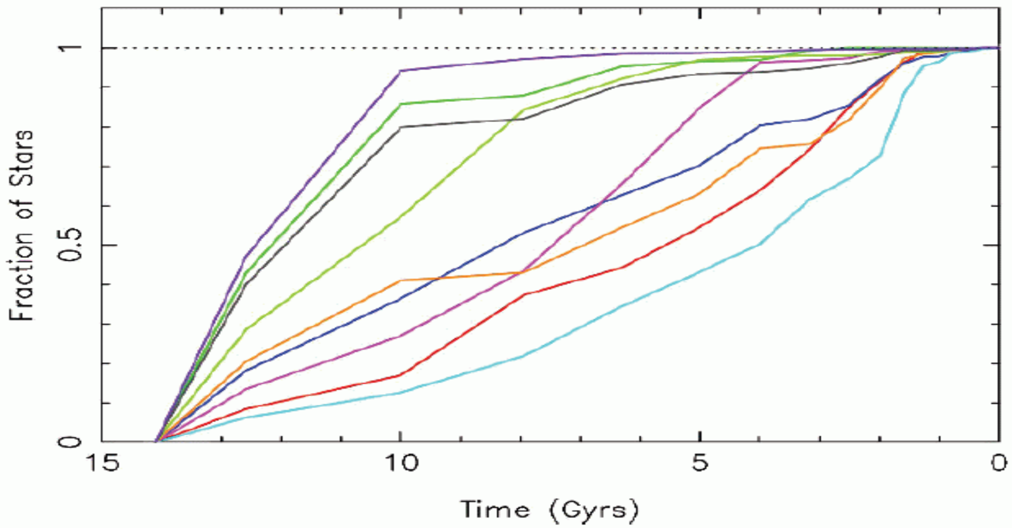


Fig. 1. Comparison of cumulative SFHs for several Local Group dSphs.

24 E.D. Skillman

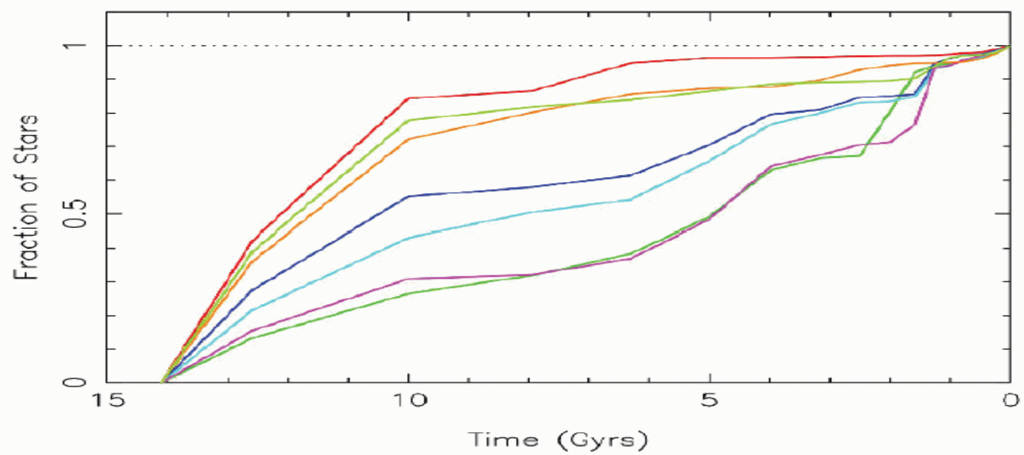
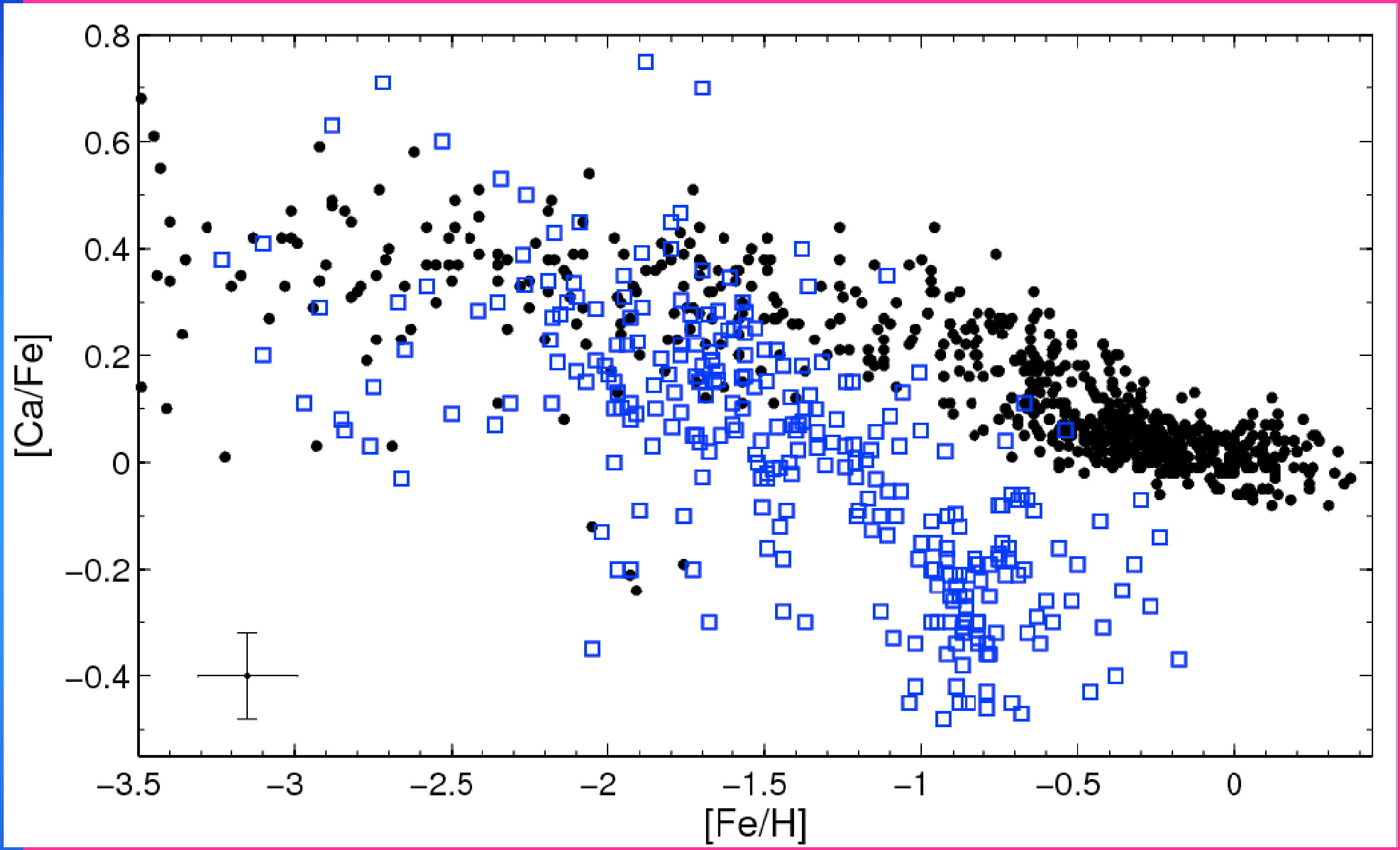


Fig. 2. Comparison of cumulative SFHs for several Local Group dIrrs.

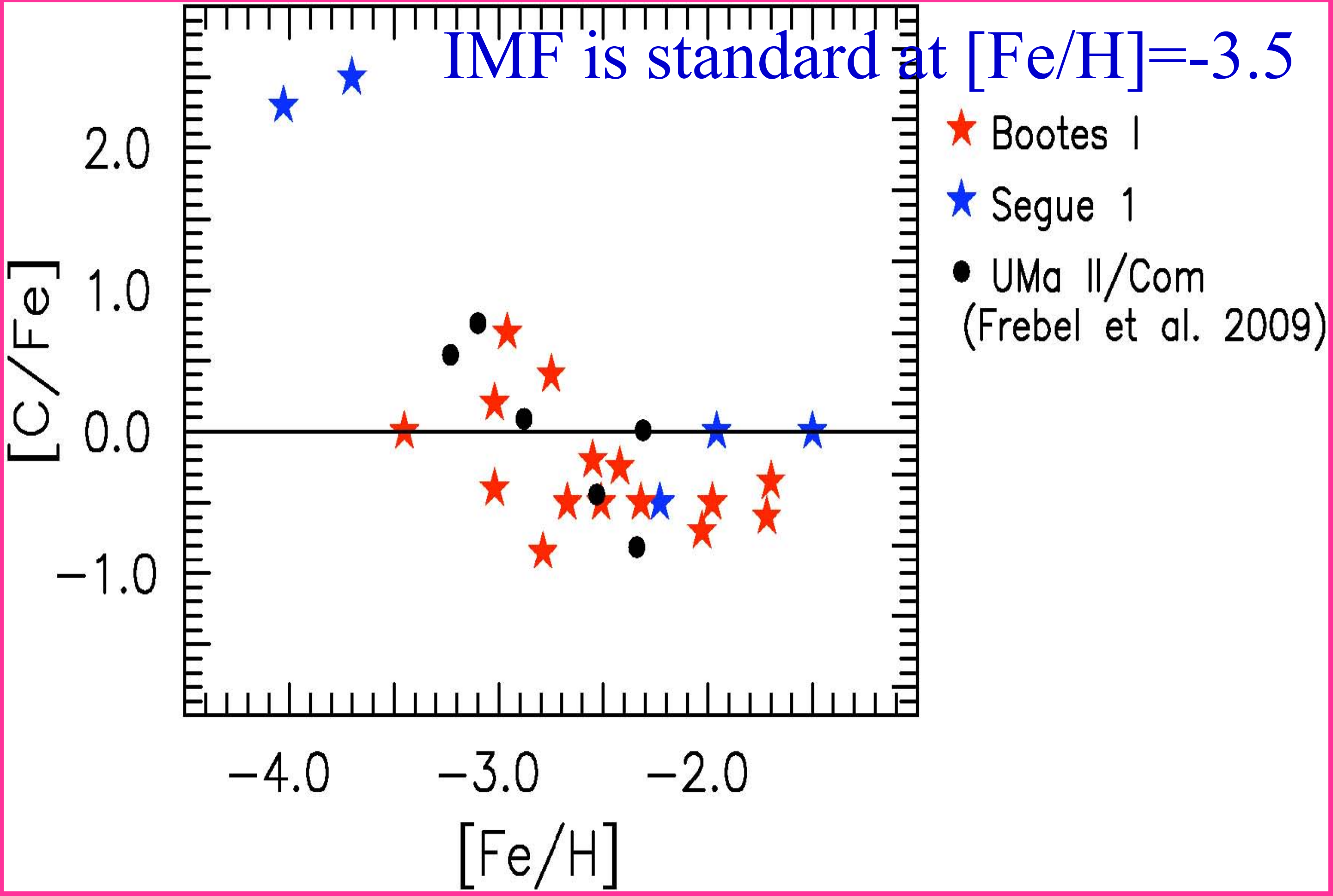
dSphs did not form the Galaxy



strong [α/Fe] discrepancy between dSph and halo stars, but note the overlap at the metal poor halo ➔ generic stellar IMF, not mergers

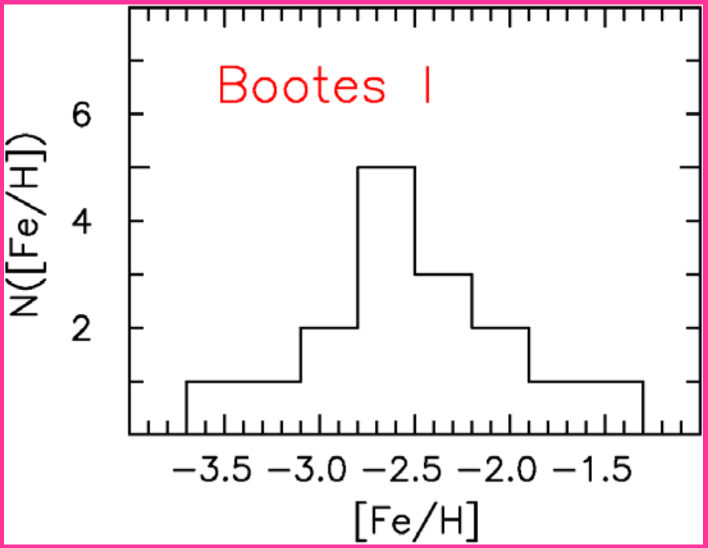
(Koch 2009, Rev. Mod. Ast., 21, 9)

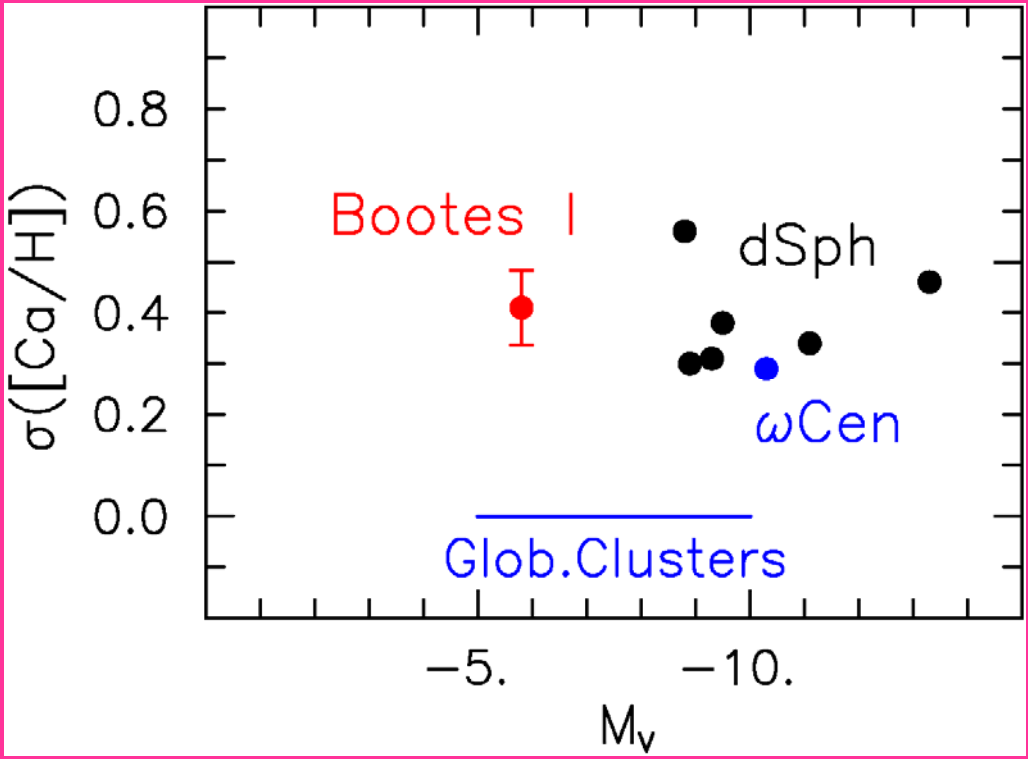
The faintest dSph contain the oldest most metal-poor stars
Are these the first stars? Why are they in the faintest dSph?
The first bound galaxies? Does PopIII underproduce Fe?



Norris, Wyse, GG etal in prepn

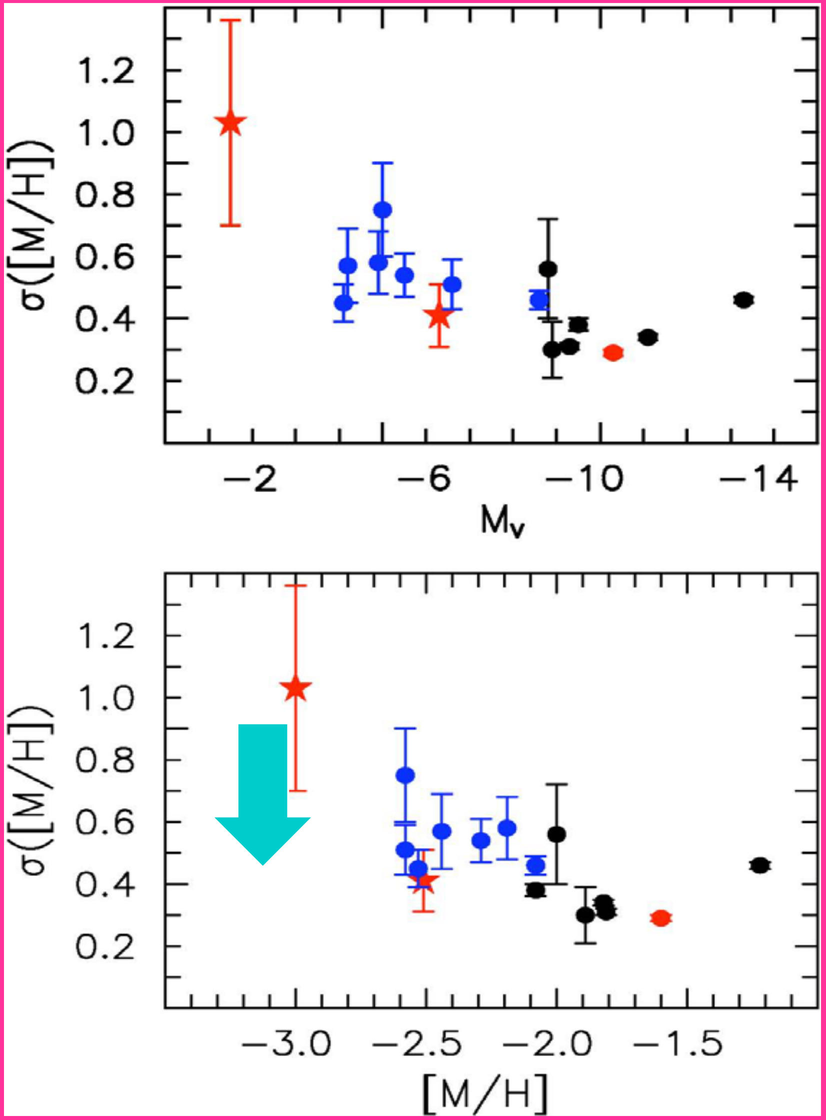
Abundance mean and dispersion is a mass proxy: even at extreme low luminosity, self-enrichment happened.
What is doing the pre-enrichment in more massive dSph?





Norris, GG, Wyse etal 2008 – apjl 689 L113
cf Kirby etal ApJ 685 L43
NB: self-enrichment on these scales requires low SFR, and weak feedback

Chemical enrichment dispersion is a mass proxy for smallest systems



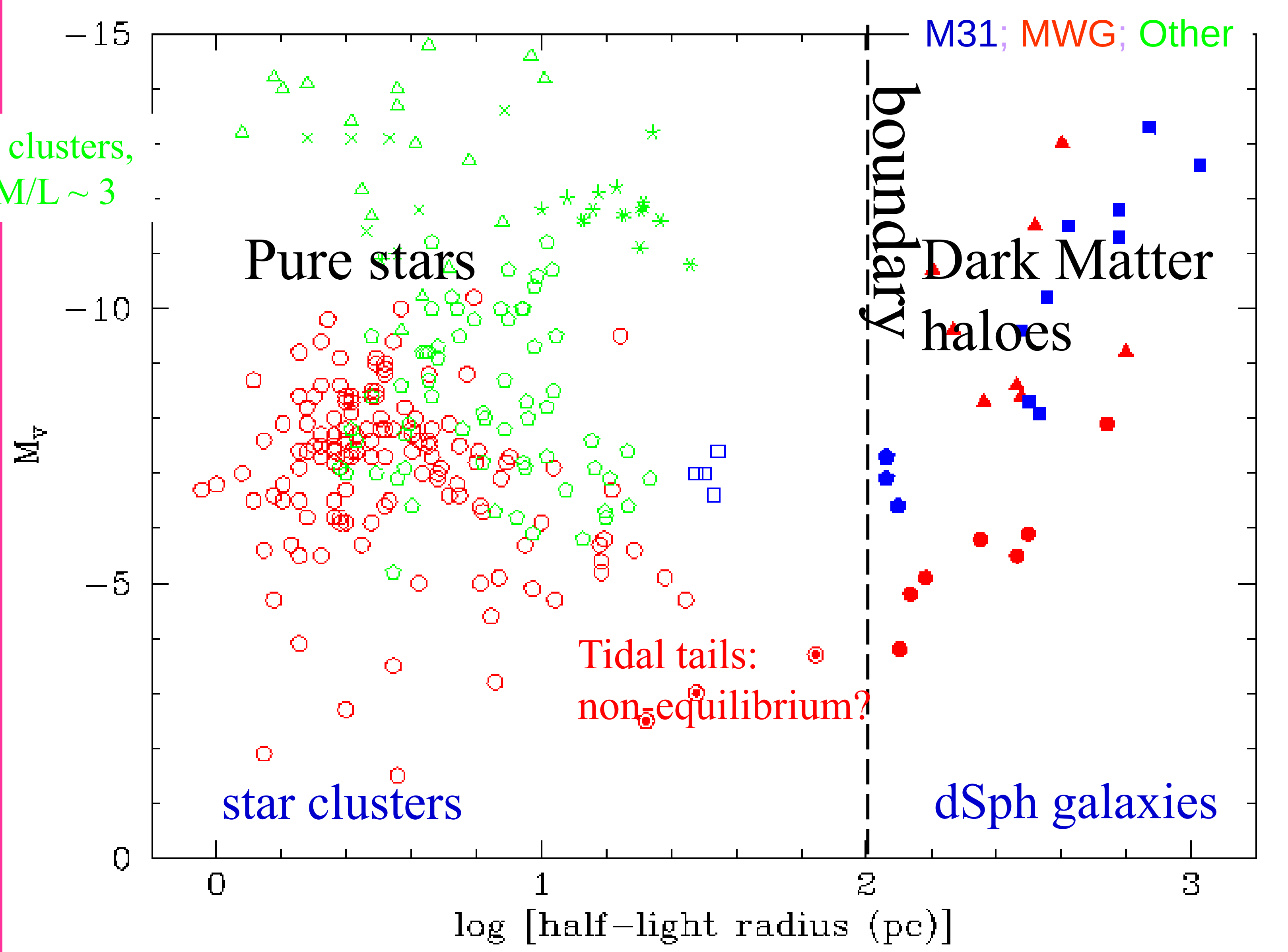
The lowest luminosity dSph are the most primordial, -more so than the most extreme Galactic stars and more massive dSph ➔ preenrichment happened: effect on Lyalpha??.

Now look at dark matter content

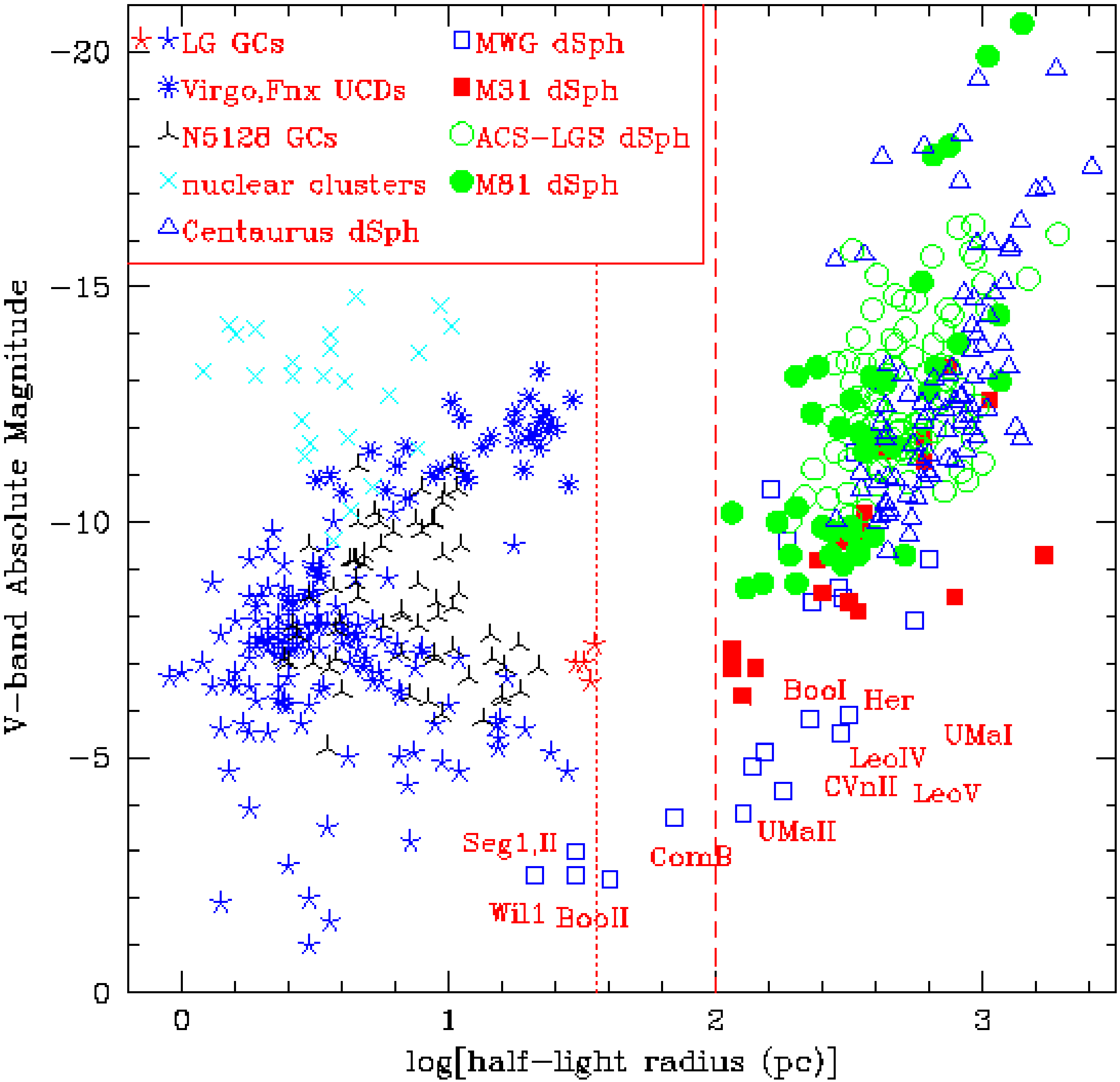
Norris, Wyse, GG etal ApJL 2008

Faint galaxies are not star clusters…

Nuclear clusters, UCDs, M/L ~ 3

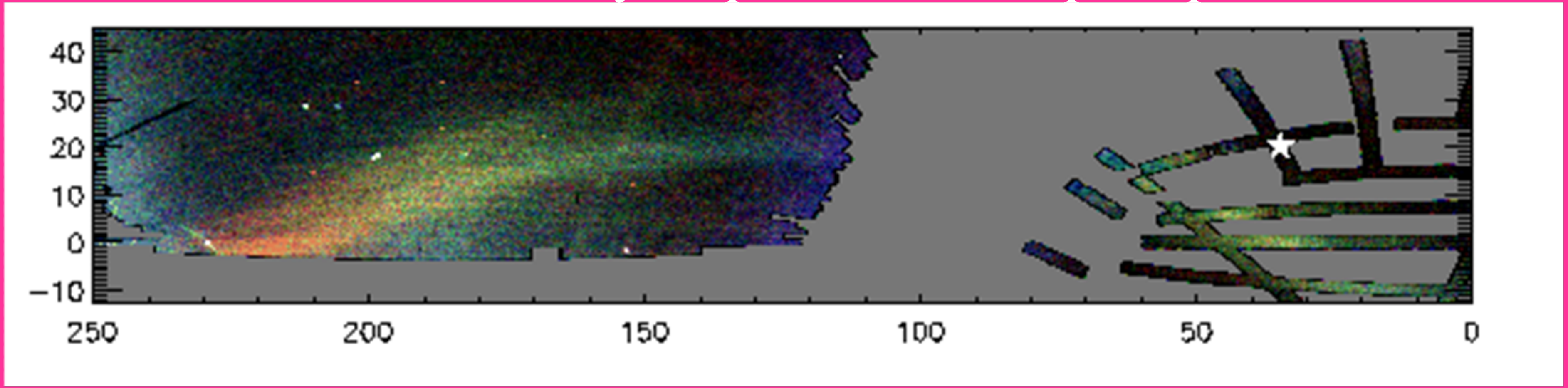


GG, Wilkinson, Wyse et al 2007



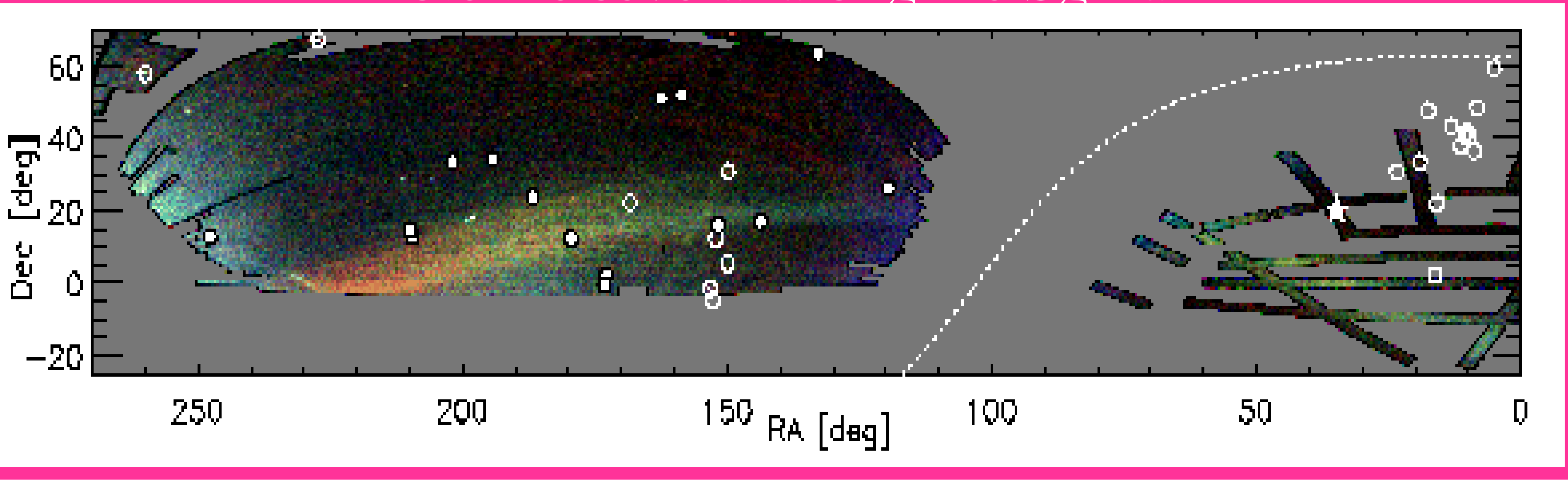
LG GCs
Virgo,Fnx UCDs
N5128 GCs
nuclear clusters
Centaurus dSph
MWG dSph
M31 dSph
ACS-LGS dSph
M81 dSph
BooI
Her
UMaI
LeoIV
CVnII
LeoV
UMaII
ComB
Seg1,II
Wil1
BooII
-20
-15
-10
-5
0
1
2
3
V-band Absolute Magnitude
log[half-light radius (pc)]

BEWARE: many dSph are in complex places!!



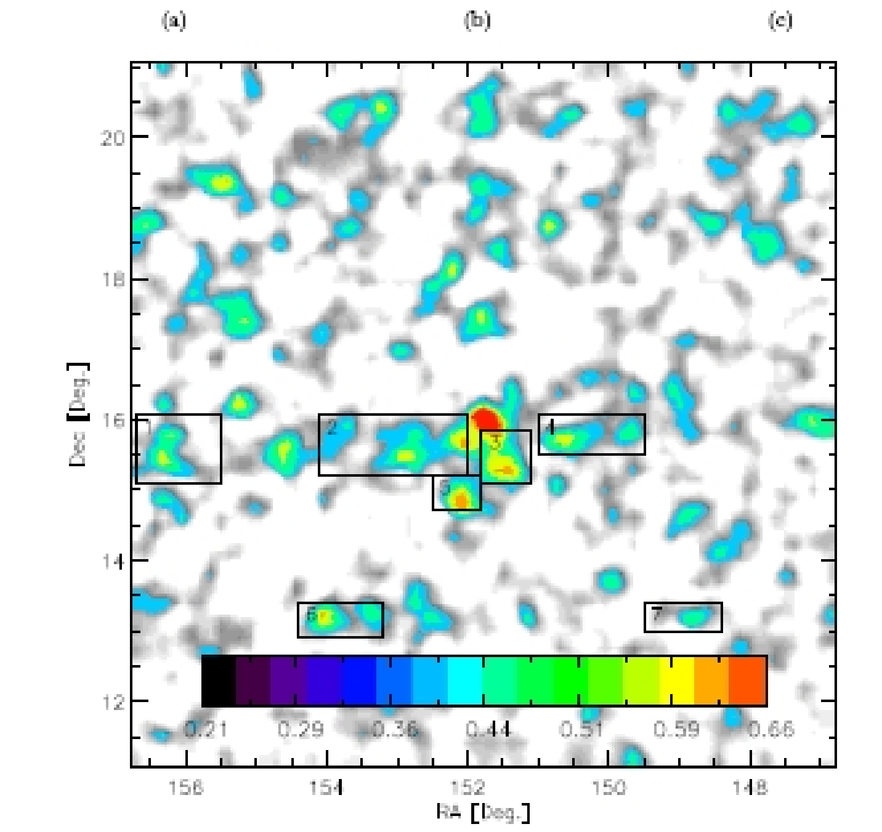
Segue-2 discovery paper : Belokurov etal arXiv: 0903.0818

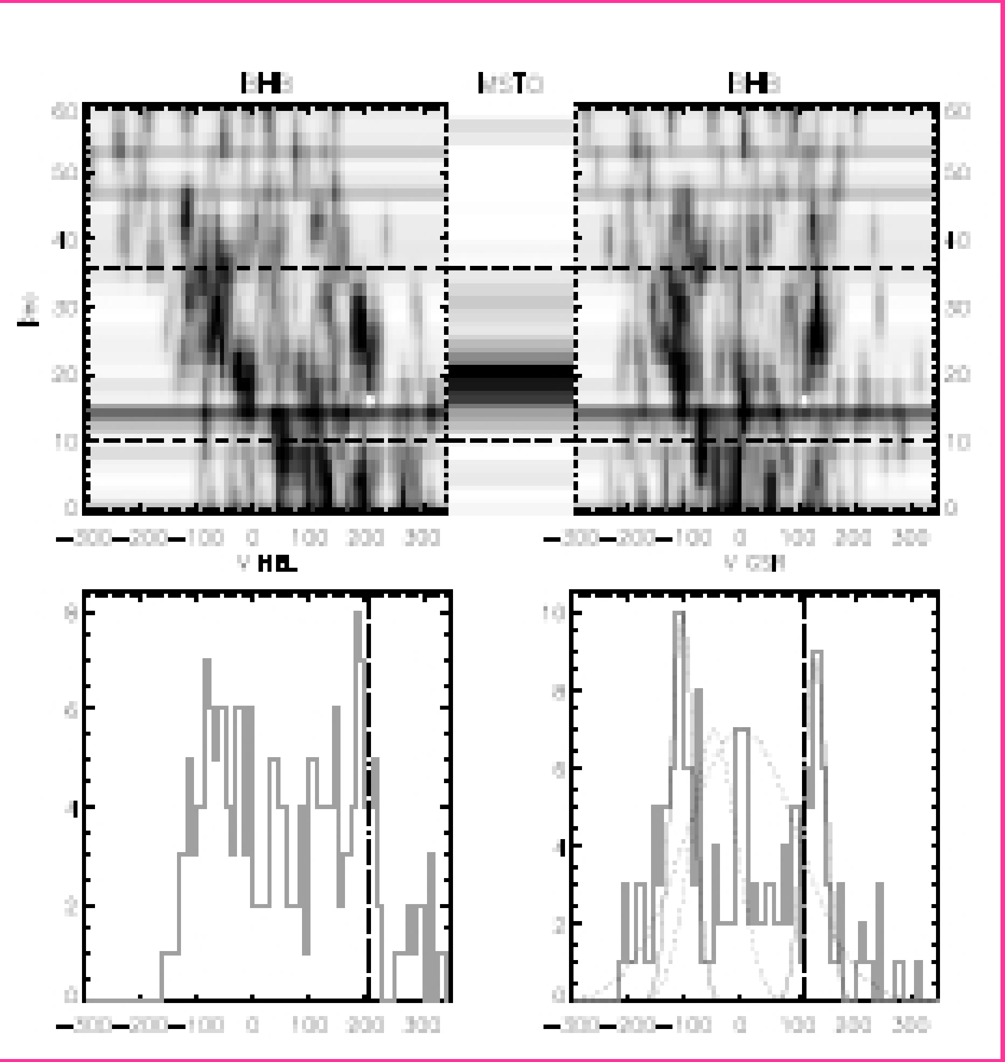
Classical dSph – open circles; ultra-faint – closed
note the several along the Sgr tail



Segue-1 is embedded in Sgr tails, in a complex velocity field

note confusion with Leo I...

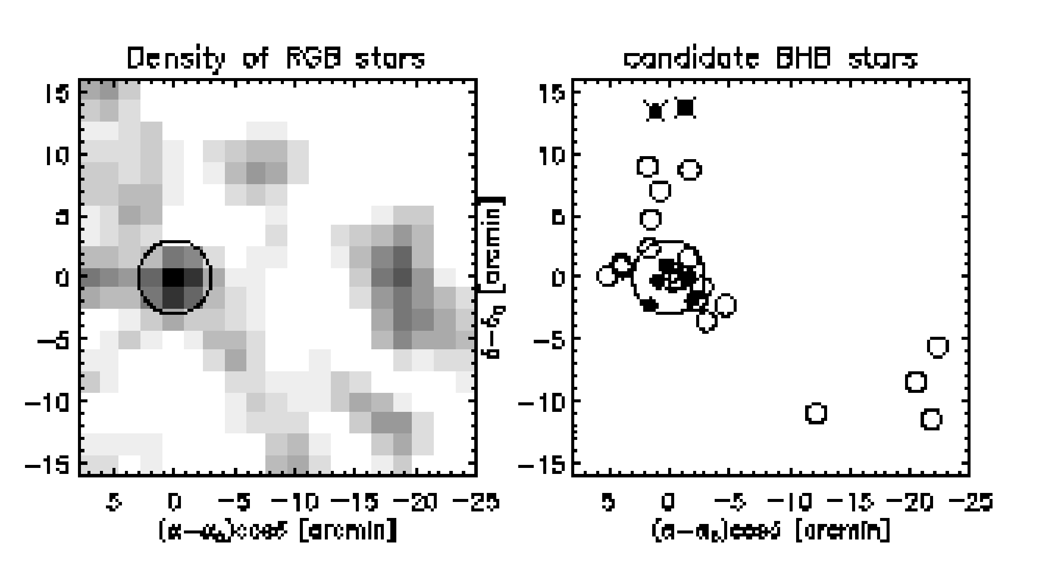


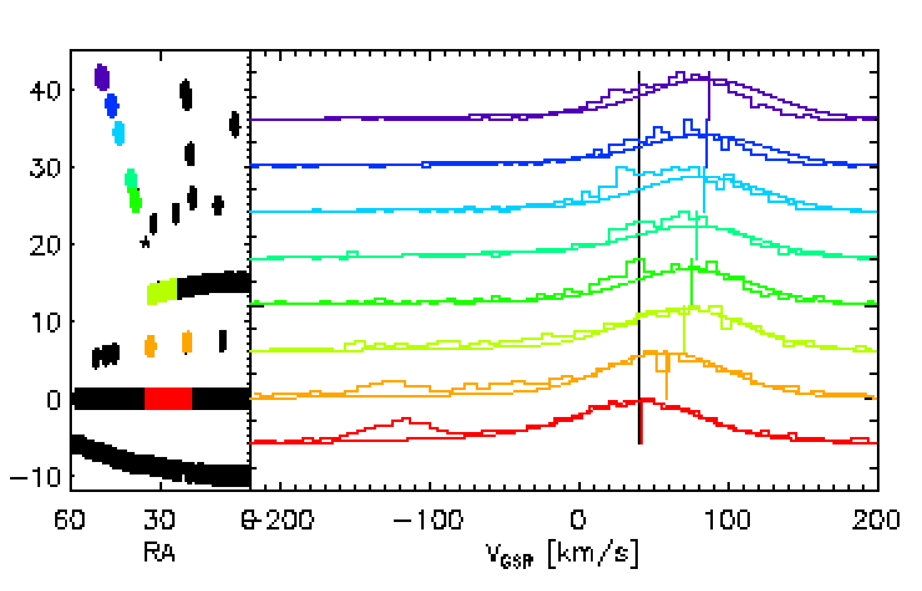


Niederste, Evans, Belokurov, Gilmore, Wyse, Norris - 2009

Some more complexity

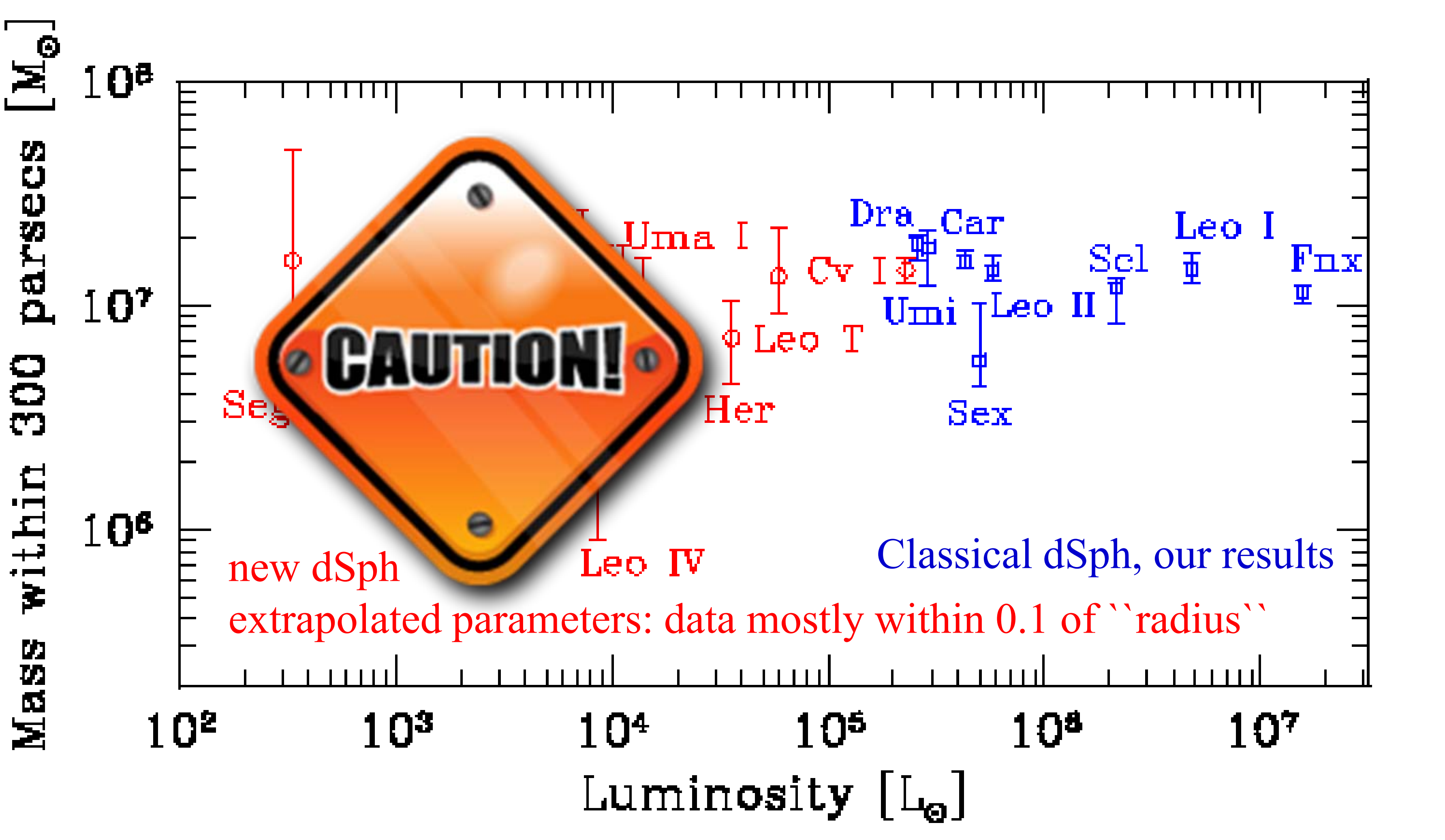
Leo V – complex density profile
Outermost BHBs are velocity members





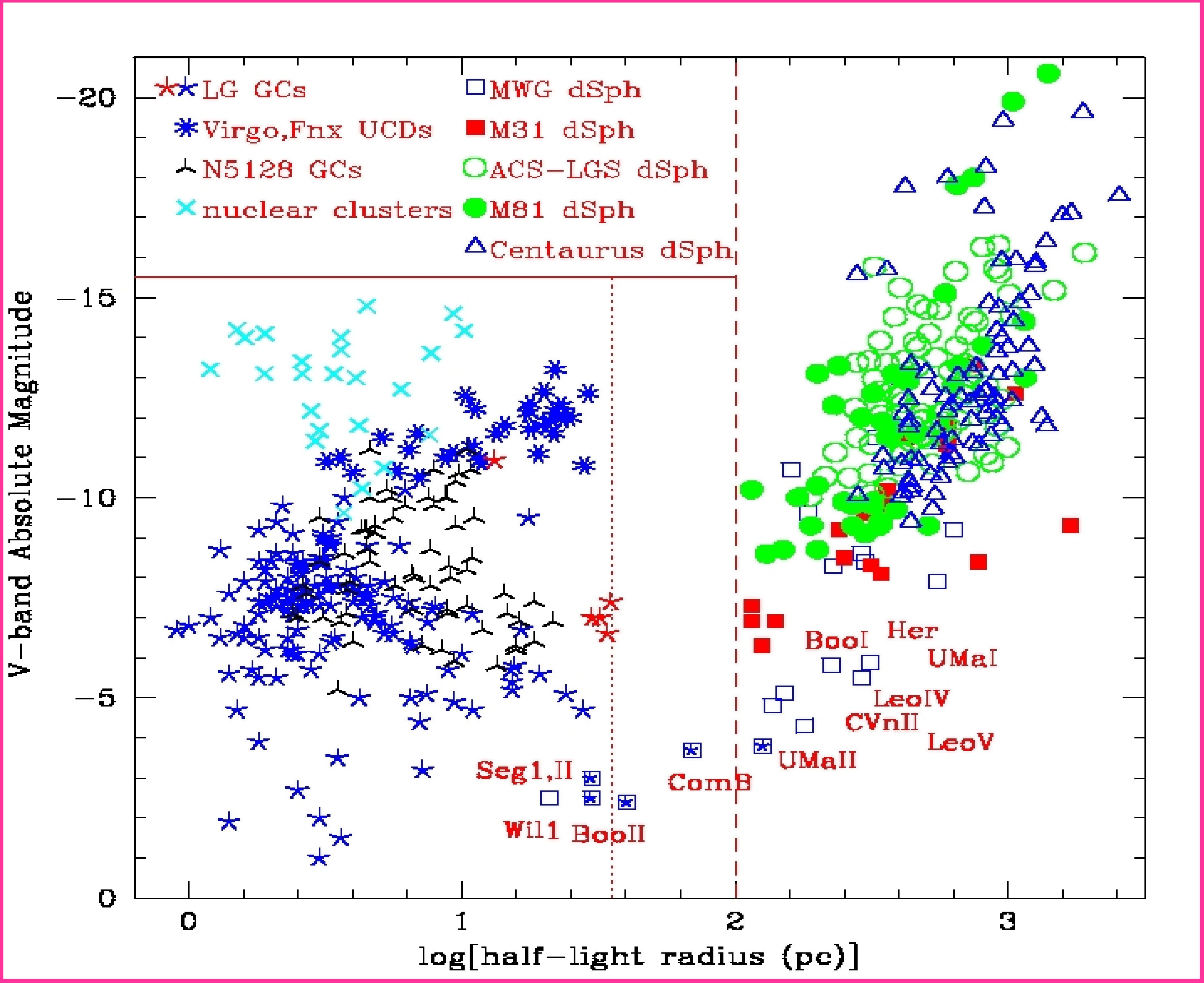
Seg-II– another halo stream connection

Claims of correlations are overdone:
the ultra-faints have limited data, many are in complex environs



Strigari etal Nature 454 1096 2008

Some systematic results seem robust – dSph are big at least when safe from galactic tides



Conclusion one: structures

There is a well-established size bi-modality:

- all systems with size < 30pc are purely stellar
- all systems with size greater than ~100pc have a dark-matter halo

- There are no known (virial equilibrium) galaxies with half-light radius r < 100pc
- The smallest systems are nearby, and messy
- Distant dSph are the oldest things, and have led gentle lives: they are the place to measure DM profiles

What can we say about the distribution of dark matter on small scales from dSph internal kinematics?

- 1) classical Jeans' models
- 2) sophisticated Jeans' models
- 3) full distribution function MCMC models

- Discount central velocity dispersion models

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

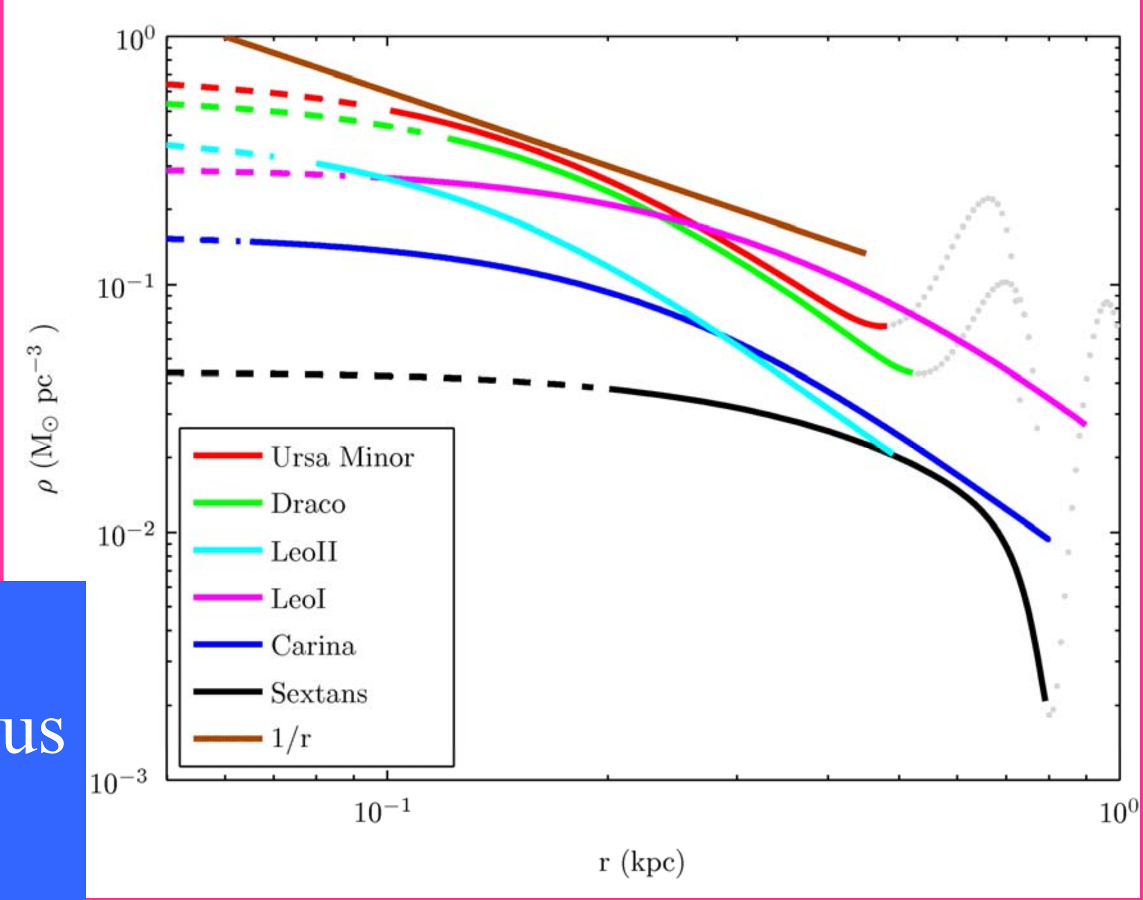
- Relates spatial distribution of stars and their velocity dispersion tensor to underlying mass profile

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

  - 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 use distribution function modelling, as opposed to velocity moments: need large data sets. DF and Jeans' models agree
- Show Jeans' results here first.
- [King models are <u>not</u> appropriate for dSph]

Derived mass density profiles:

Jeans' equation with ***assumed isotropic*** velocity dispersion: all consistent with cores.



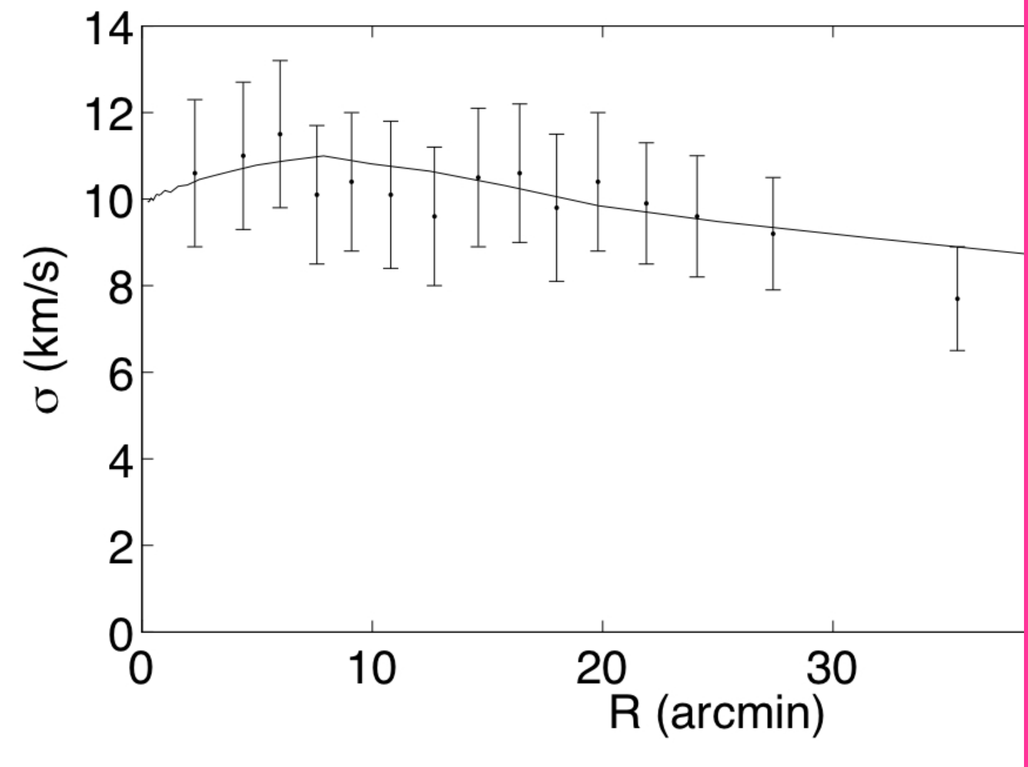
CDM predicts slope of -1.3 at 1% of virial radius and asymptotes to -1 (Diemand et al. 04)

NB these Jeans' models are to provide the most objective sample comparison – DF fitted models next.

What are we really measuring with non-DF, analyses?

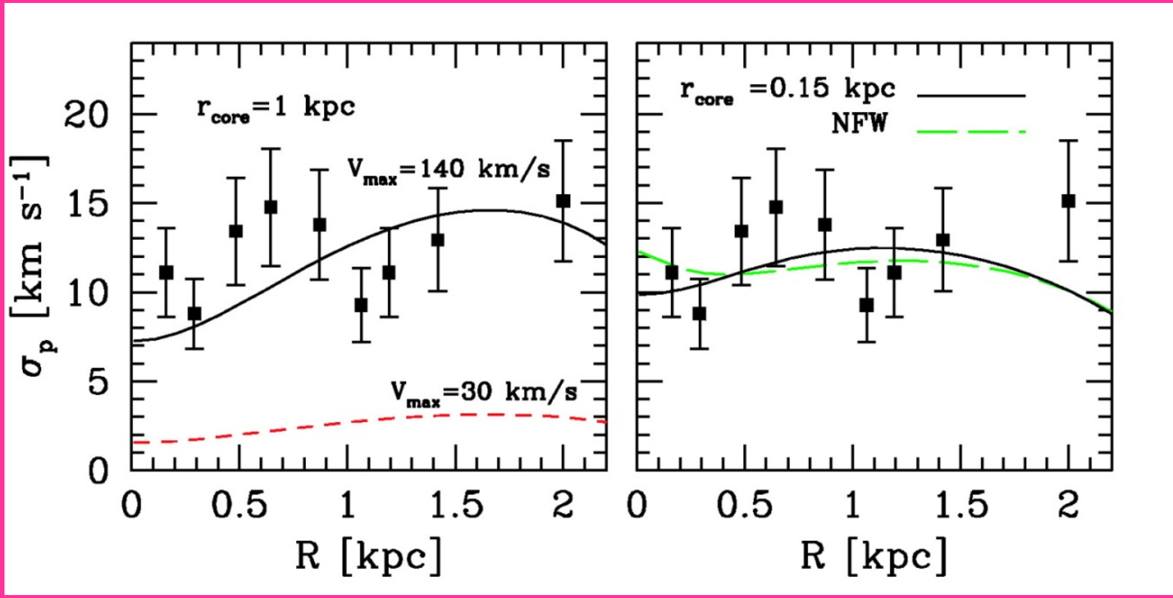
$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\nu\sigma_r^2}{\mathrm{d}r} + 2\frac{\beta\sigma_r^2}{r}\right)$$

- Dispersion profile close to flat, so sigma ~ cst, and range of sigma is small (data <2)
- derivative term is (log) luminosity profile : light, NOT mass, and this is similar in scale for all the dSph (factor of few)
- So the derived `mass` in a standard analysis is a measure of the radial extent of the data, and only a weak function of anything else
- .→ but one can do better

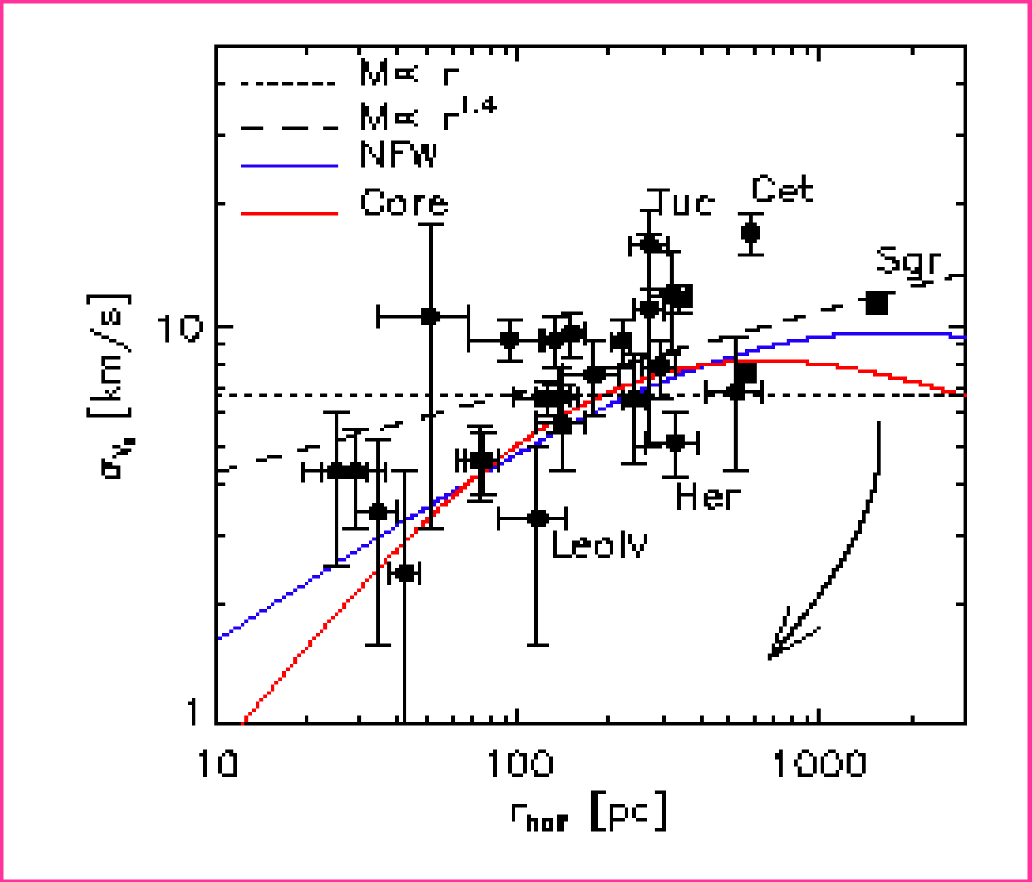


Note the data quality improvement:
First declining dispersion profile
➔Robust V_max=20+/-4 km/s

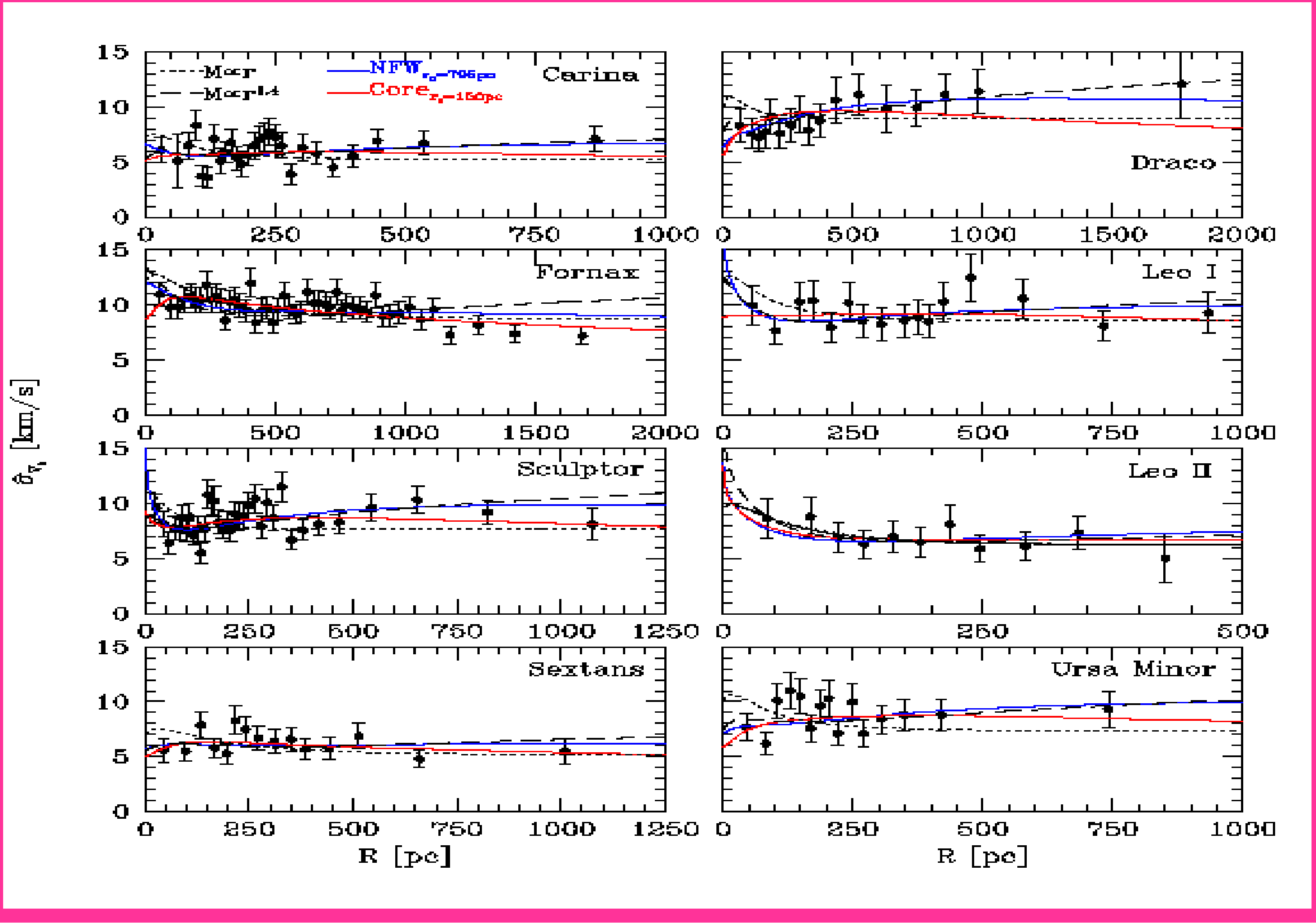
Top Walker etal 2009
Lower Strigari etal 2006 fit to
Walker etal 2006



One can use MCMC for optimal Jeans' analyses
[robust mass within the observed radius]
and there is new information: [Walker etal 0906.0341]
there is a velocity dispersion *vs* size relation!
albeit poor data for smallest and nearest systems, and real scatter
➔ mass vs radius statistical relation



MCMC Jeans' models – Walker etal 0906.0341– fit for anisotropy/stress: core-cusp degenerate
But require V_max<20km/s. These are low-mass.
➔ the higher mass halos really are missing.

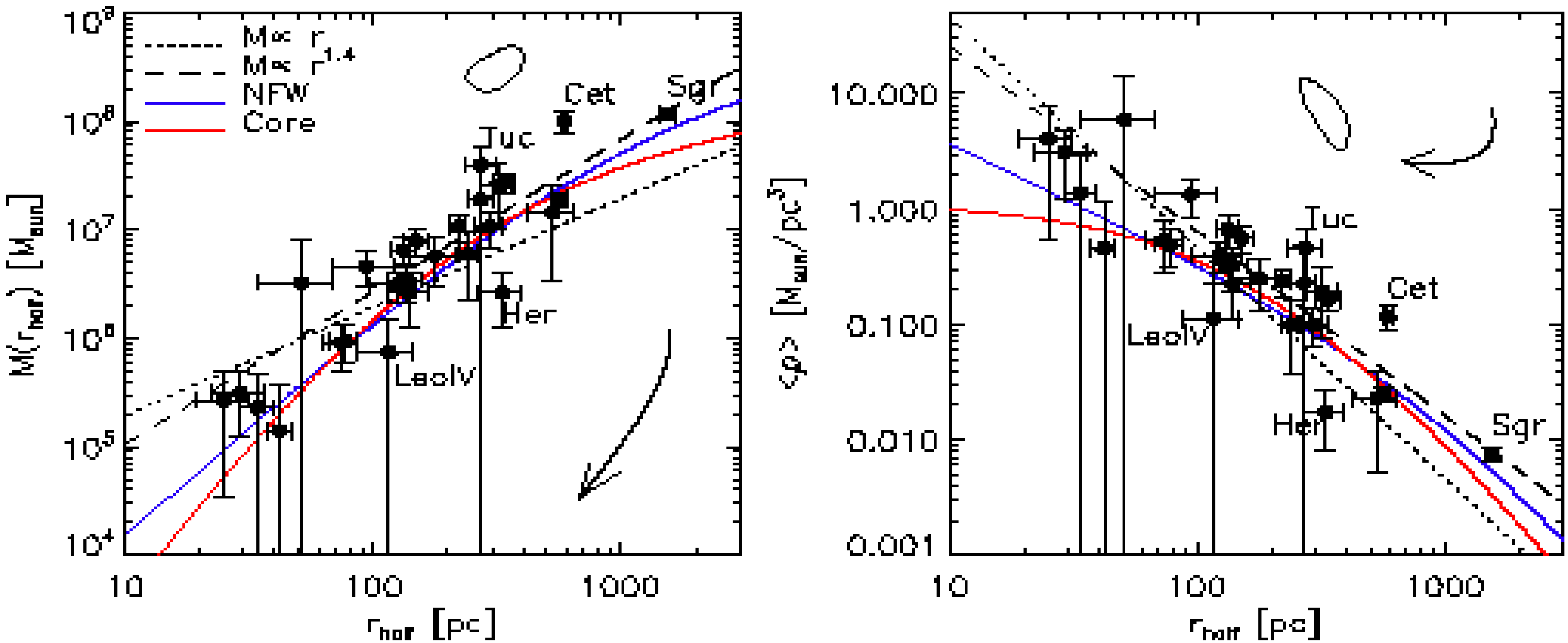


Scaling relations based on kinematic data:
➔ universal mass profile? NFW, r0=1kpc, core r=200pc

Beware smallest galaxies – complex!

Beware largest – tidal damage!

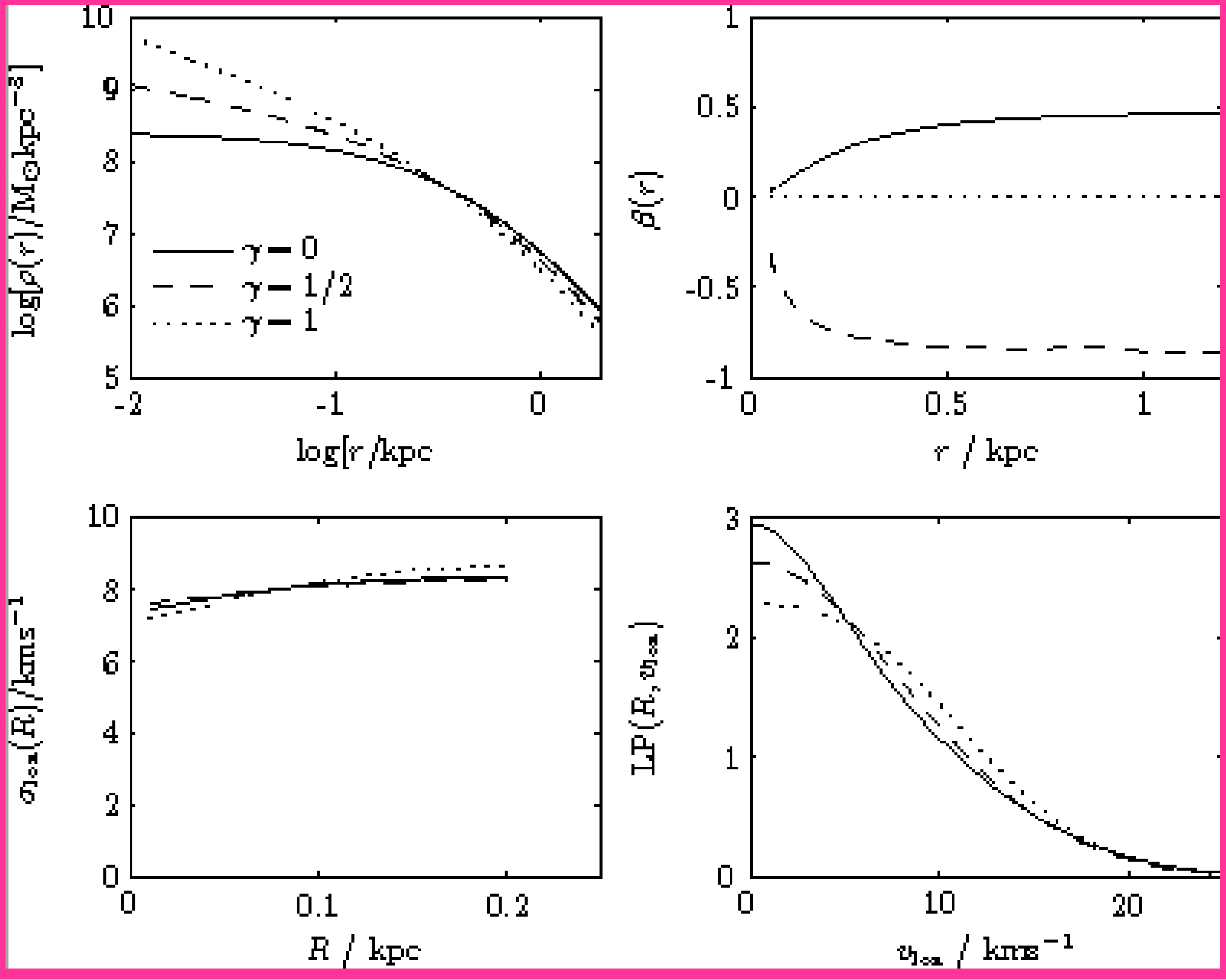
This is the best one can do without real modelling



- Mass – anisotropy degeneracy prevents robust cusp/core distinction, but core + small radial bias always provides slightly better fit than cusp + tangential bias (cf 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
- (GG etal, VLT/Magellan core/cusp project)

From kinematics to dynamics:
radial velocities have the information to measure gravitational potentials:
anisotropy vs mass profile

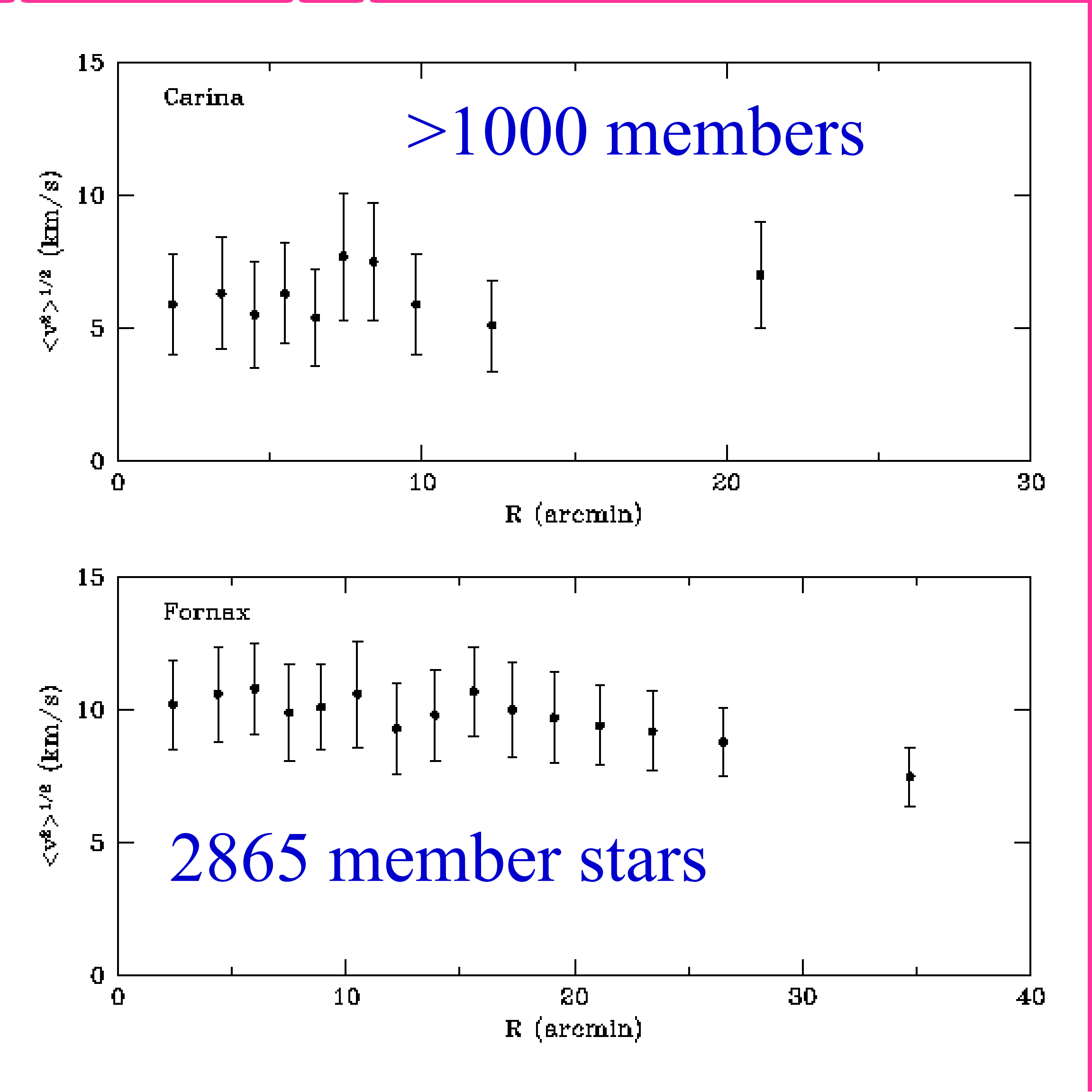
$$M(r) = -\frac{r^2}{G}\left(\frac{1}{\nu}\frac{\mathrm{d}\nu\sigma_r^2}{\mathrm{d}r} + 2\frac{\beta\sigma_r^2}{r}\right)$$



Very large precision kinematics now exist: Magellan+VLT

– vastly superior to the best rotation curves

-large samples after population selection



New models

Assumptions:

- Spherical symmetry
- Currently extending to tri-axial
- Equilibrium
- Tracer surface density from star counts

Models

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

$$\Sigma_*(R) = 2\int_R^{\infty} \frac{\rho_*(r) r {\rm d}r}{\sqrt{r^2 - R^2}}$$

Same form used for both halo and stars, but stellar parameters held fixed

Zhao model = generalised Hernquist/NFW/...

Distribution function

$$F(E,L) = w(E)g(E,L)$$

Gerhard (1991)

$$g(E,L) = \begin{cases} c + (1-c)(1-(1-x^2))^a & \text{tangential} \\ c + (1-c)(1-x^2)^a & \text{radial} \end{cases}$$

$$x(E,L) = \frac{L}{L_0 + L_{\rm circ}(E)}$$

Constructing the line of sight velocity distributions

- Fit surface brightness profile
- Use method by P. Saha to invert integral equation for DF:

$$\rho(\Phi) = \frac{4\pi}{r^2} \int_0^{\Phi} w(E)\, \mathrm{d}E \int_0^{L_{\max}} \frac{g(E, L) L\, \mathrm{d}L}{\sqrt{2(\Phi - E) - L^2/r^2}}$$

$$L_{\max} = \sqrt{2(\Phi - E)}r$$

- Project to obtain LOS velocity distribution on a grid of R and $v_{\rm los}$
- Spline to required radii for observed stars, and convolve with individual velocity errors

Fitting the kinematic data

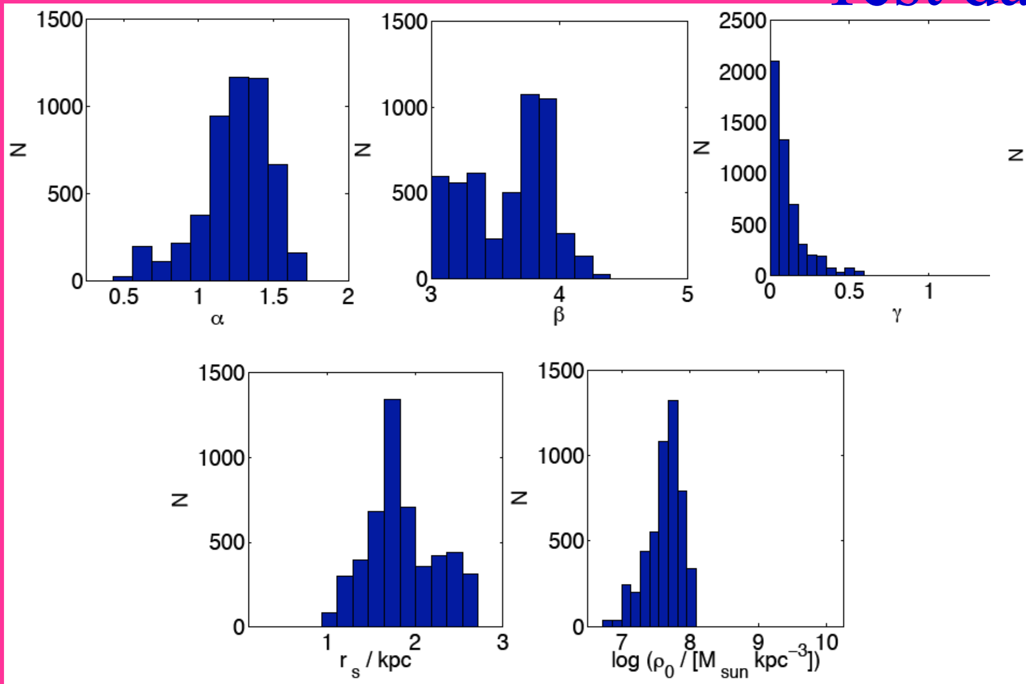
- Surface brightness profile determined from metal-poor data (v. similar to overall profile of Fornax)
- Markov-Chain-Monte-Carlo used to scan parameter space
- Parameters: 3 velocity distribution parameters

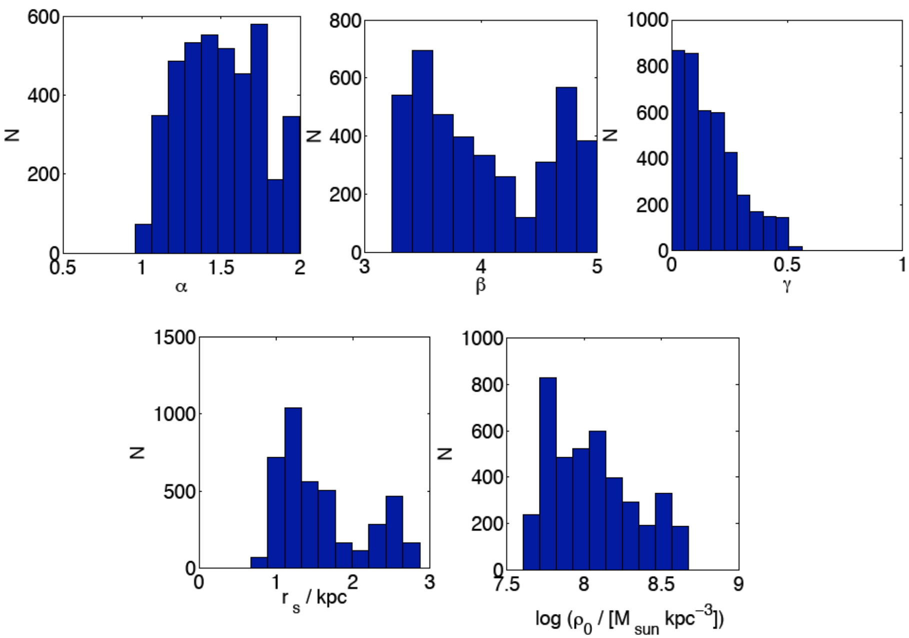
(a, c, L_0); 4 halo parameters ($\alpha, \beta, \gamma, \rho_0$)

- Multiple starting points for MCMC used - chains run in parallel and combined once “converged”
- Error convolution included - using only data with

$$\Delta v_{\rm los} < 2\,{\rm km\,s^{-1}}$$

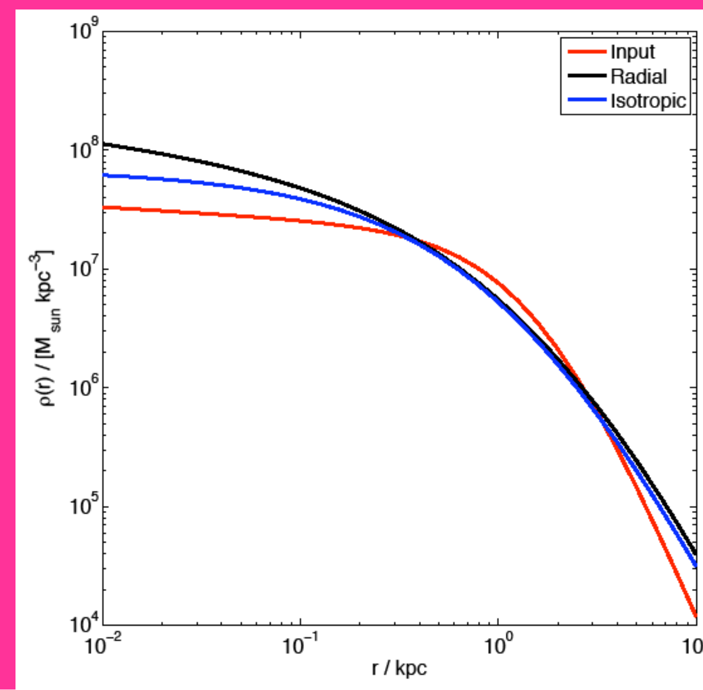
Test data





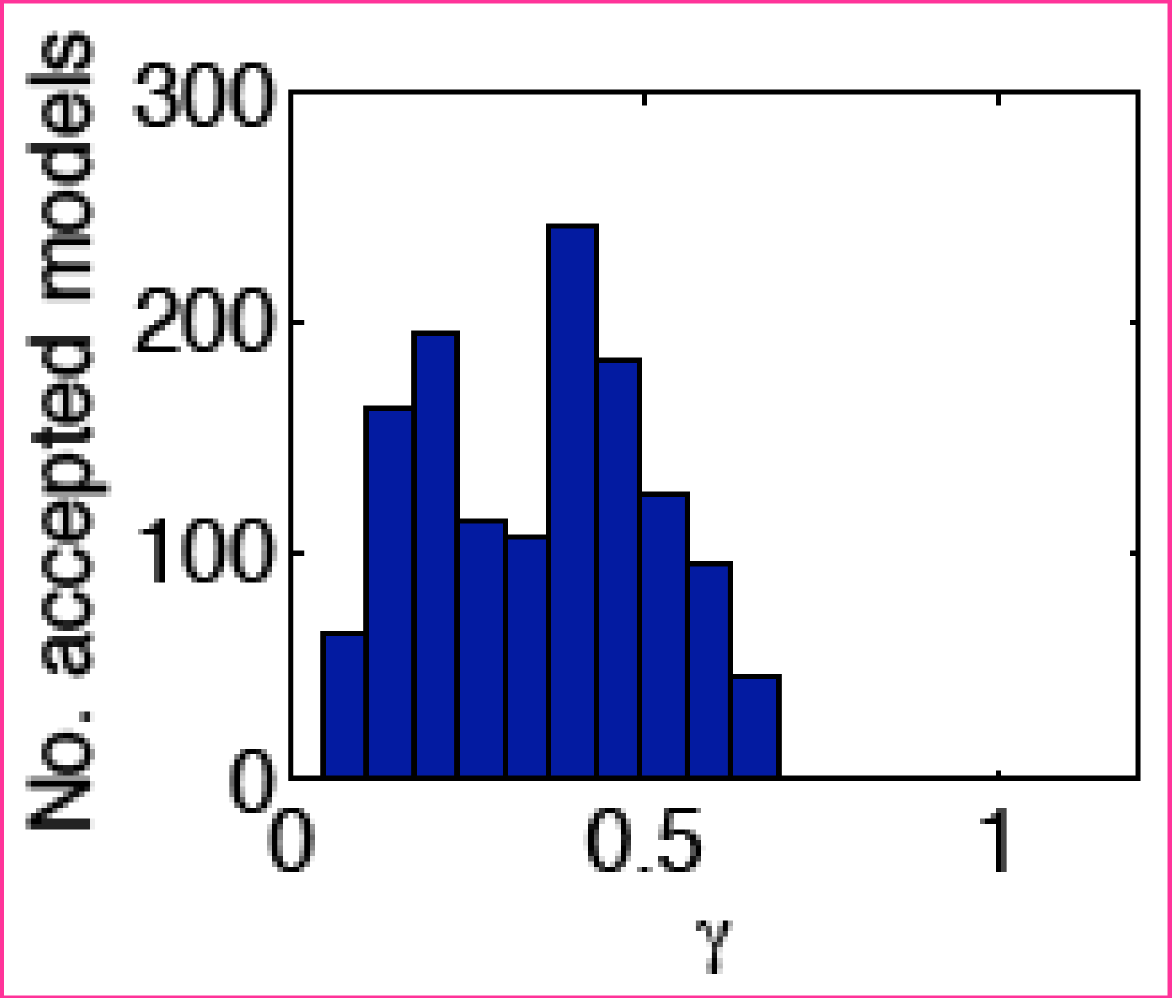
testing distribution function general models, and match data by Markov Chain MC –Wilkinson etal

-they reproduce test models with a conservative inner slope

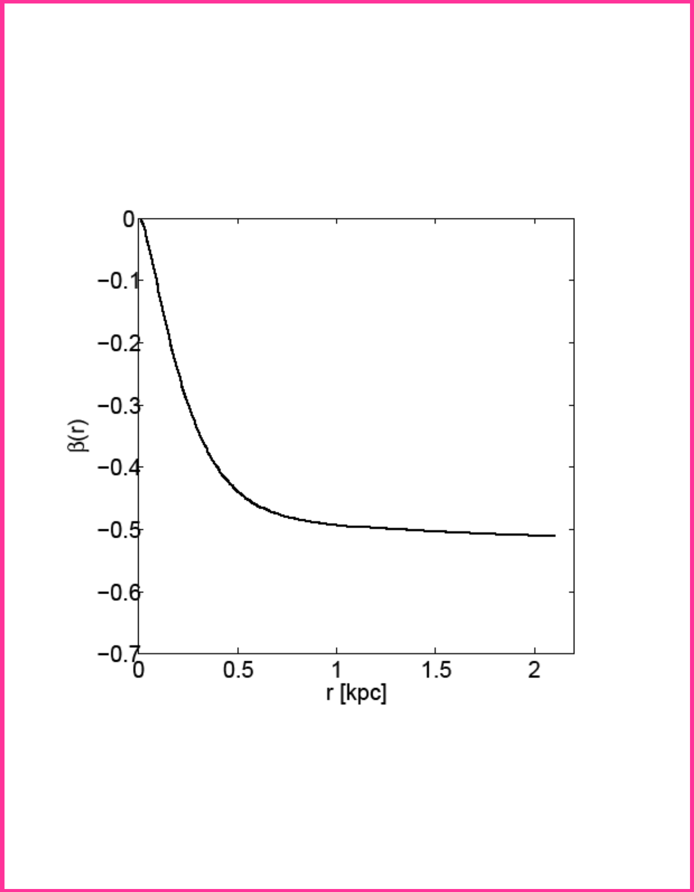


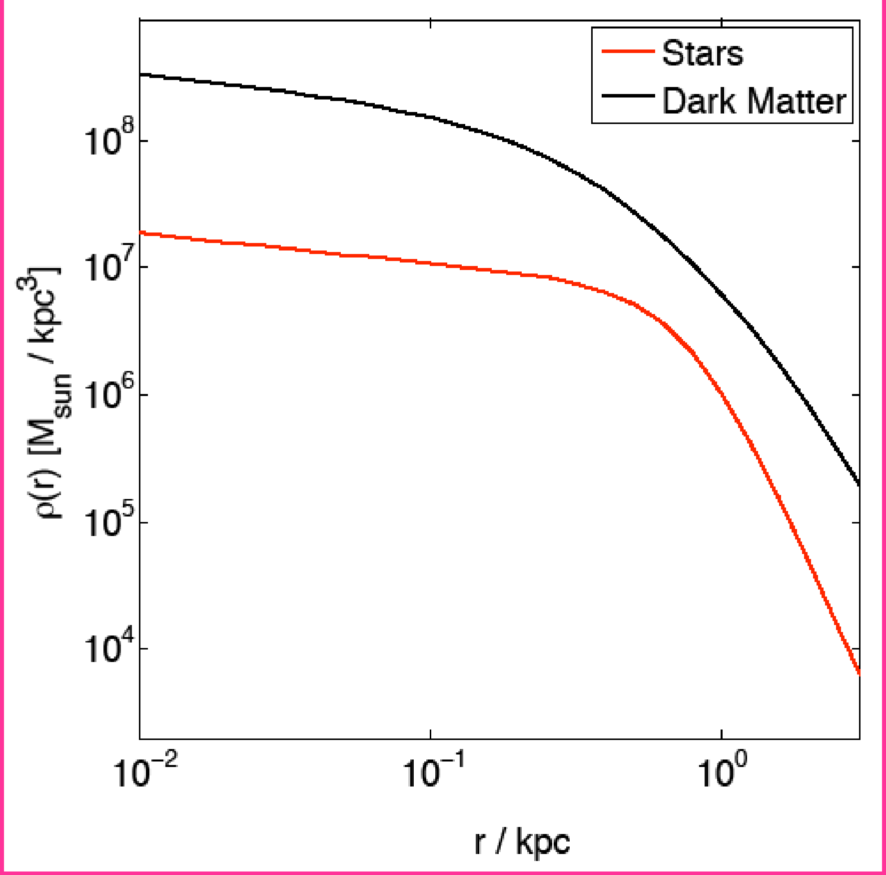
Fornax data analysis – 1600 stars

the answer – the DM inner density distribution in the Fornax dSph has slope ~0.3 – core-like, not cusped



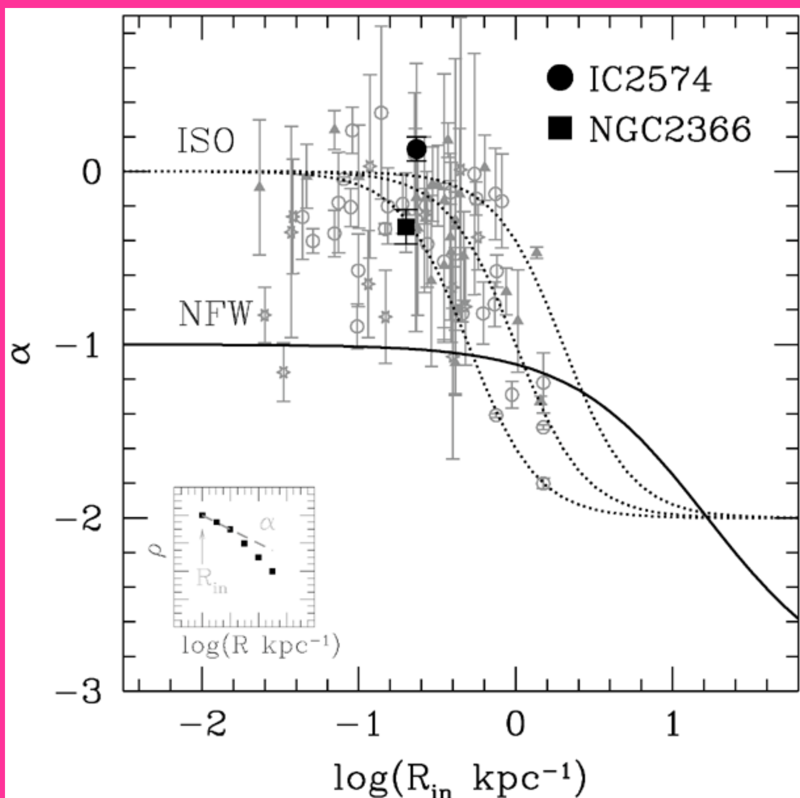
Kinematic profile is centrally isotropic, becoming tangentially biassed; half-mass radius ~1kpc, M_1/2=2.10^7M_sun inside 300pc

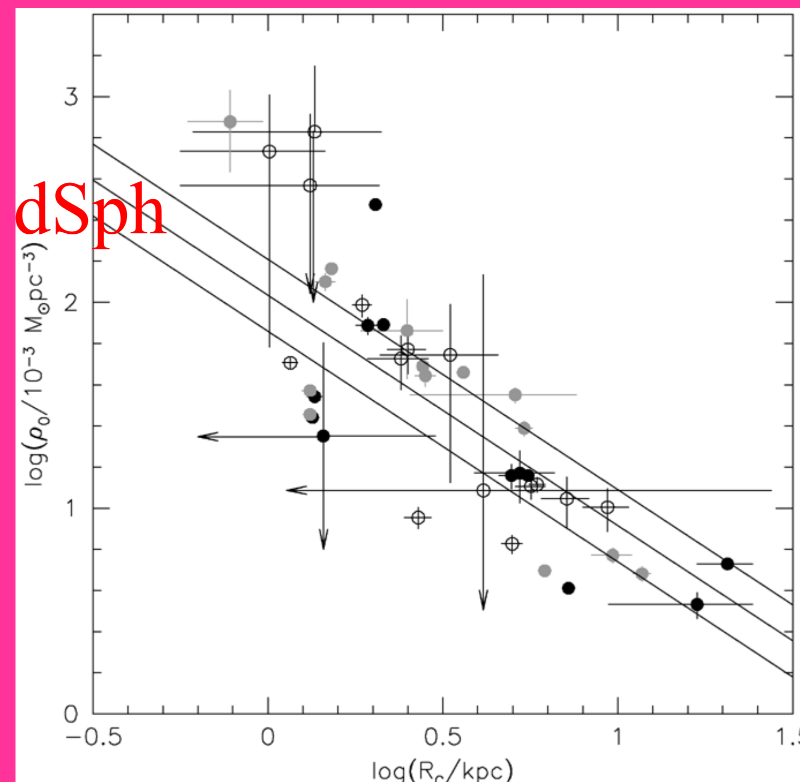




Are the dSph results consistent with other DM measures?

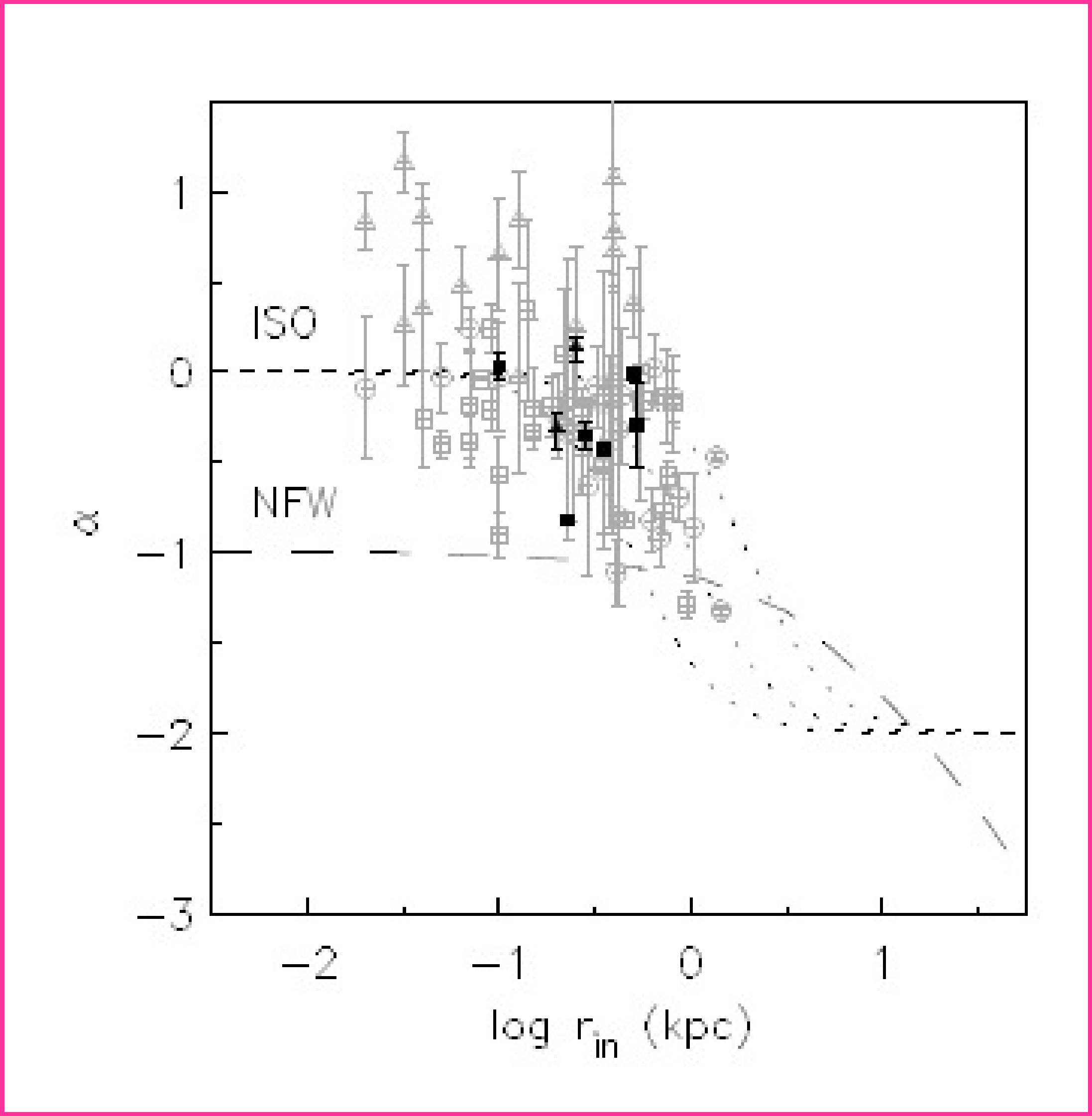
`Things` HI/Spitzer/Galex survey -- low-mass spirals consistent





Oh etal; de Blok etal AJ 2008 v136 2761; 2648

Central mass density profiles in DM-dominated systems are, in every measured case, core-like. The dSph are consistent.

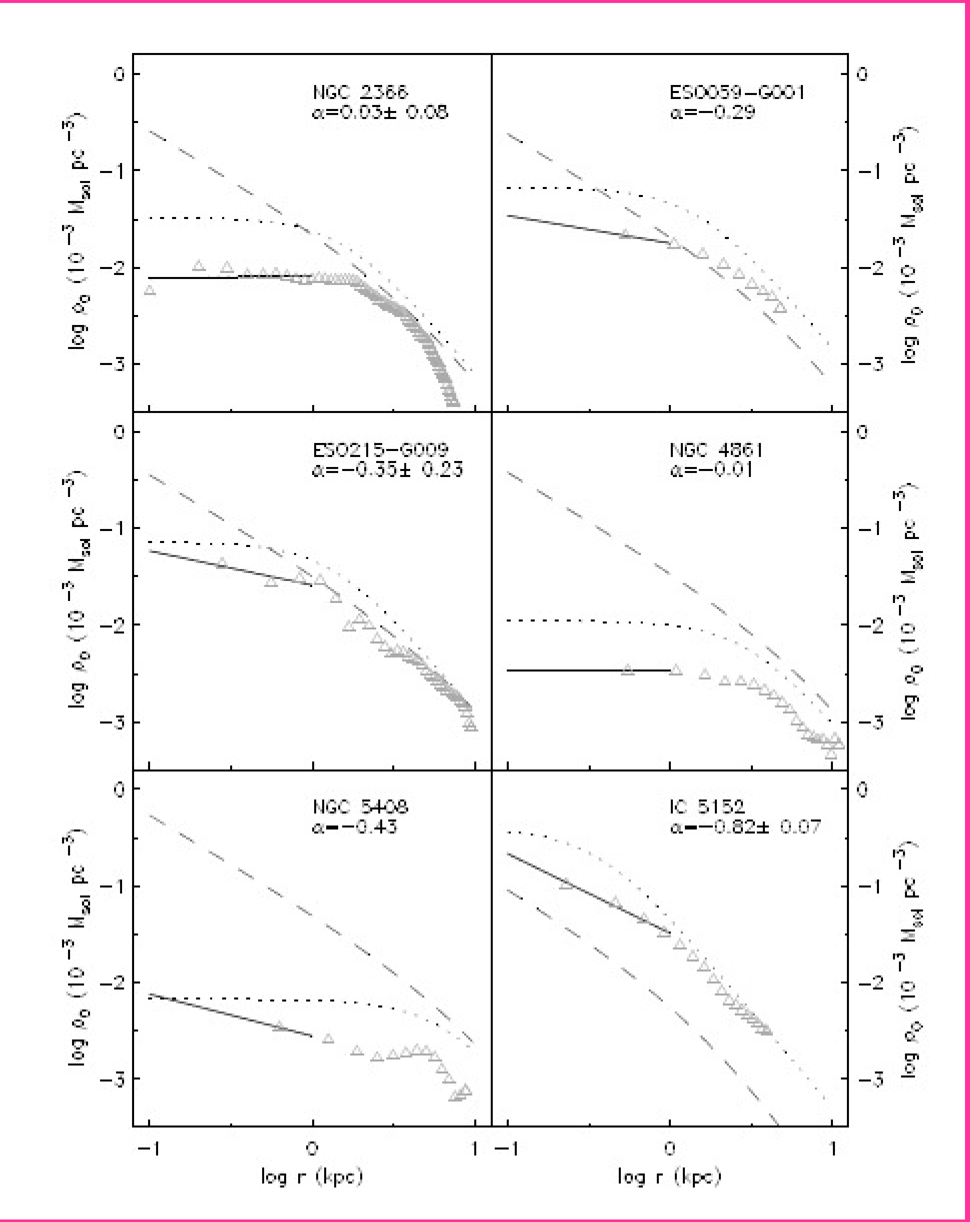


LSB spiral analysis by Van Eymeren etal 0906.4654

Other data from
deBlok 2001
deBlok&Bosma 2002
Swaters 2003

Dark Matter mass distributions on sub-kpc scales are in every measured case core-like.

Recent LSB disk studies, and dSph analyses agree – DM has a shallow density profile in systems where we understand the astrophysics well-enough to be sure we are measuring initial conditions.



Dynamical analyses

- High-quality kinematic data exist
- mass analyses → prefers cored mass profiles
- Substructure, dynamical friction → prefers cores
- Equilibrium assumption is valid inside optical radius
- More sophisticated DF analyses agree well

- Mass-anisotropy degeneracy broken by DF analysis
- **Central densities always similar and low**
- **Central mass profiles are shallow**
- **Characteristic scale of few x100pc**

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
- lots of similar challenges on galaxy scales
- Need to consider a variety of DM candidates?

Summary-1:

- The Galaxy is not built from dSph
- --ages are inconsistent
- -- chemical enrichment history inconsistent

-- Merging happens, and continues today – but is creating a galactic halo which is very different than the extant Pop-II halo we have today. The outer galaxy is becoming young and metal-rich...

Pre-Galactic abundances in lowest-luminosity dSph are resolving very early stars [and re-ionisation?]

The dSph are ancient, have led gentle lives, and continued star formation for a Hubble time

➔ no major perturbations to their dark matter

Summary-2:

- 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

  - phase space densities fairly constant, maximum for galaxies – are they the first halos?

  - We have the first real V_max – Fornax, V_m=20+/-4km/s
  - We do not know masses for the lowest luminosity systems
  - But some interesting scaling relations are developing

available analyses always suggest flat inner profiles

– more dSph galaxies under study