A Universal Mass Profile for (Dwarf Spheroidal) Galaxies?

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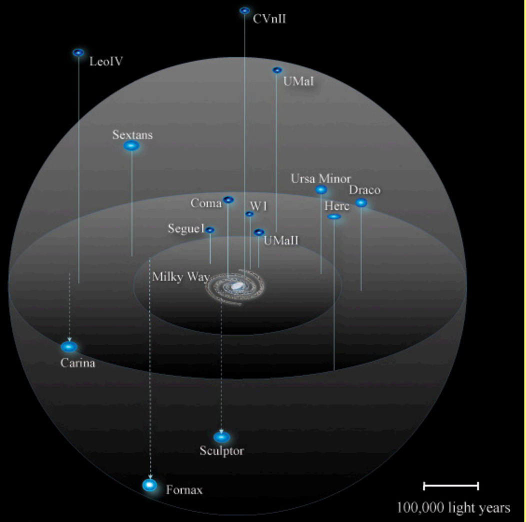


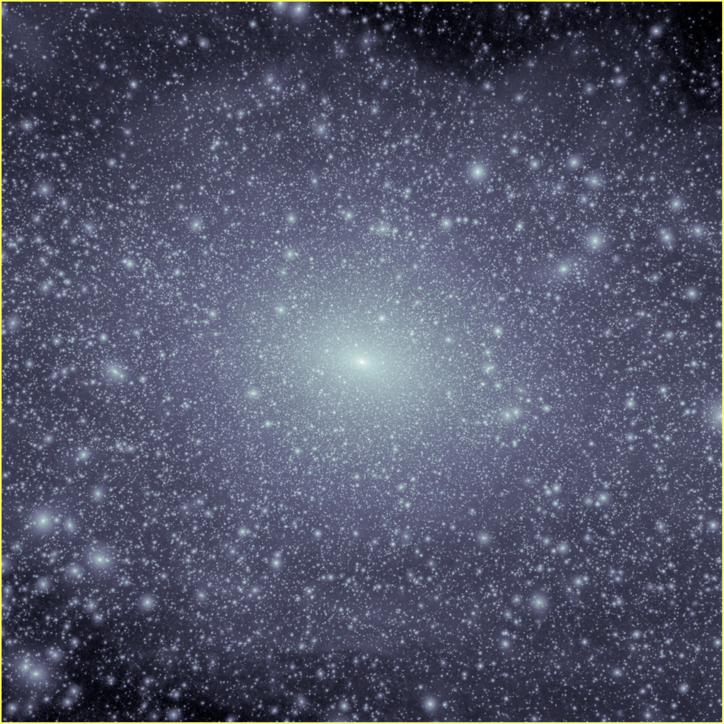
Image: J. Bullock/M. Geha/R. Powell

Aquarius simulation (Springel et al.)

Meudon, 9 June 2010

1. Milky Way Satellites

Dark Matter



Via Lactea II (Diemand, Kuhlen, Madau et al.)

Stars

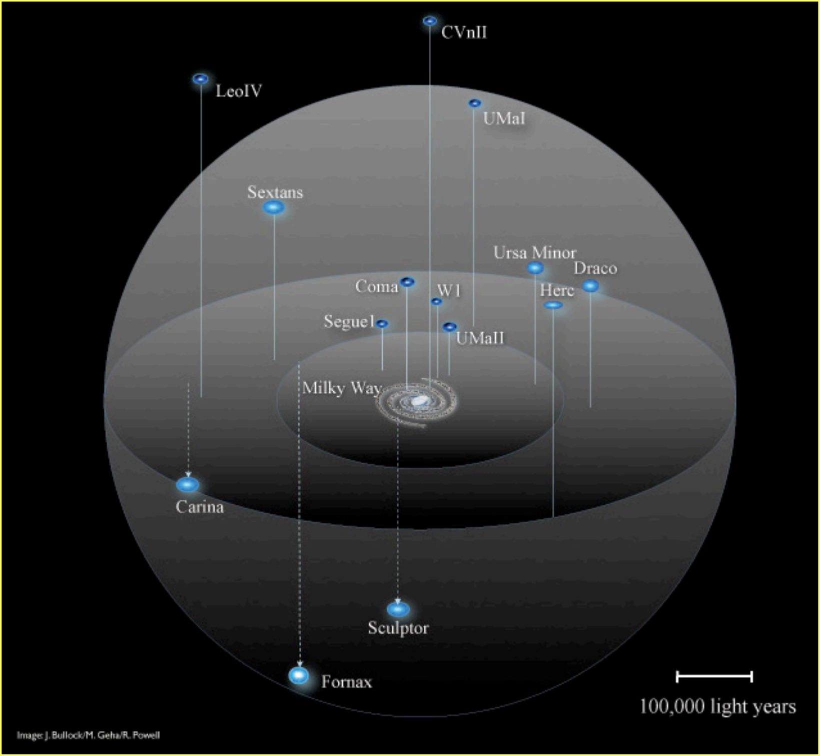
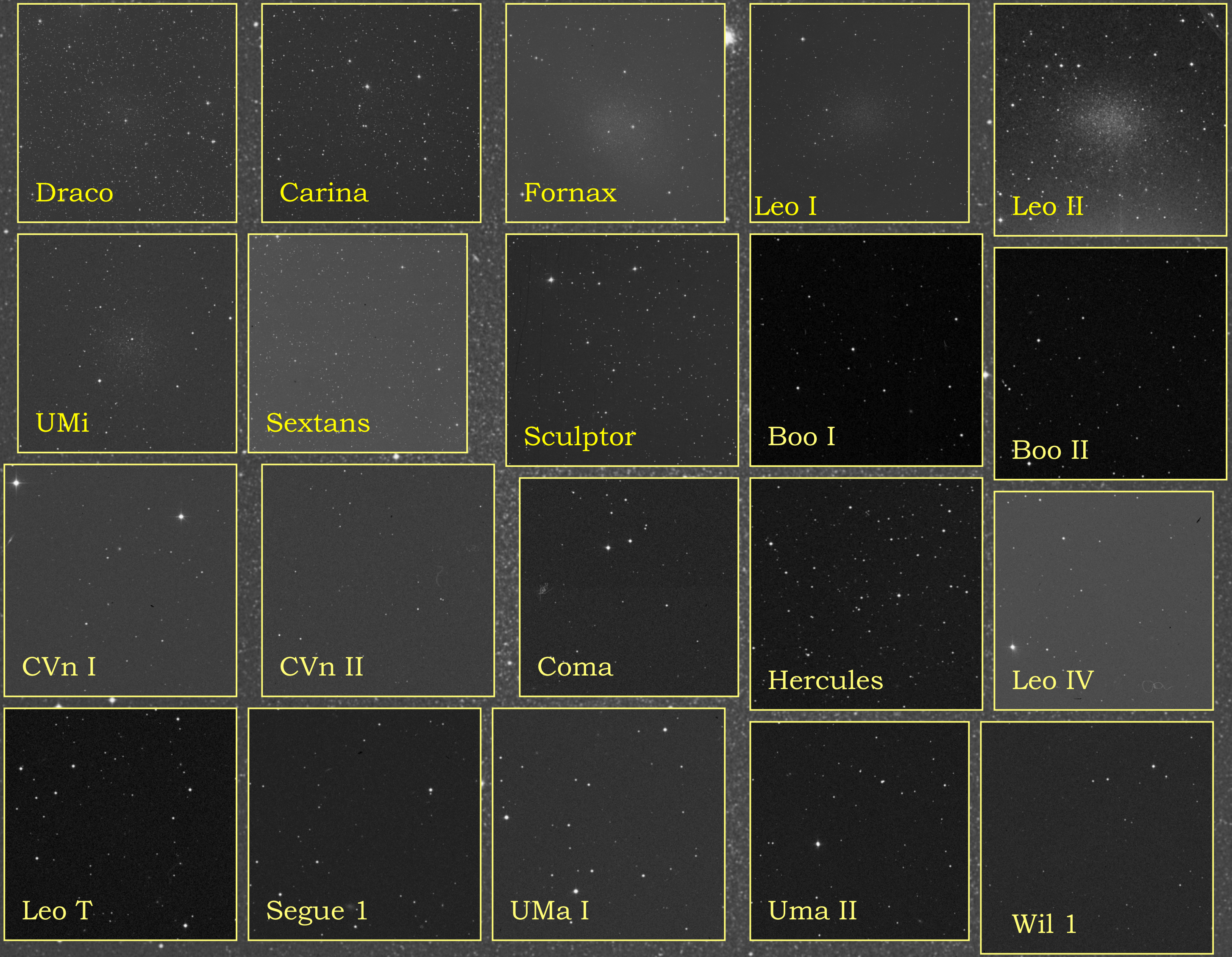


Image: J. Bullock/M. Geha/R. Powell

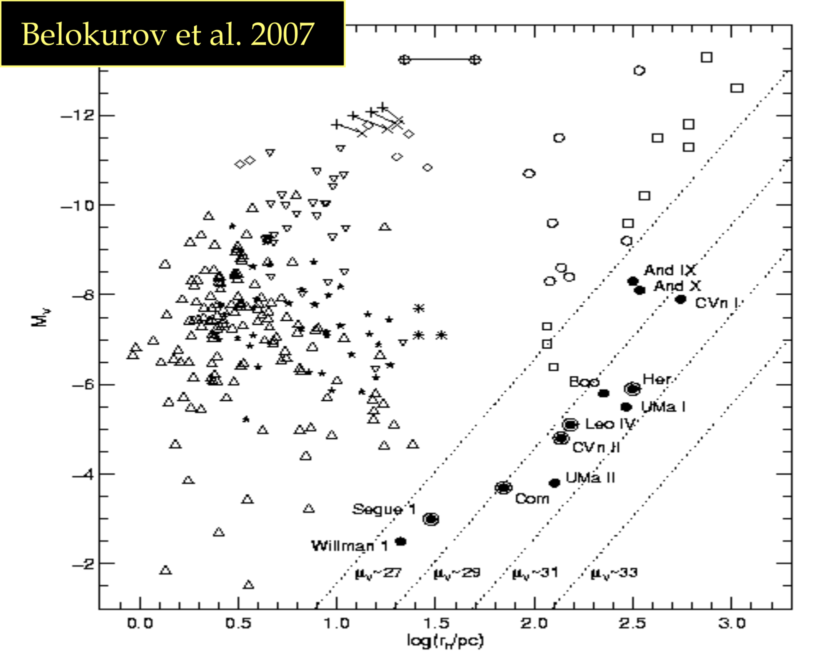
Milky Way Satellites



Milky Way Satellites: Star Clusters vs. Galaxies

- Globular Clusters
  - Pressure supported
  - 10^{3-6} L_sun
  - No gas
  - <v> ~ 5-15 km/s
  - ~Single age
  - R_{half} ~ 10 pc
  - No Dark Matter
- dSph galaxies
  - Pressure supported
  - 10^{3-7} L_sun
  - No gas
  - <v> ~ 5-15 km/s
  - Extended Star formation
  - R_{half} ~ 100 pc
  - Dark Matter

$$M \sim \frac{\bar{v}^2 R}{G}$$

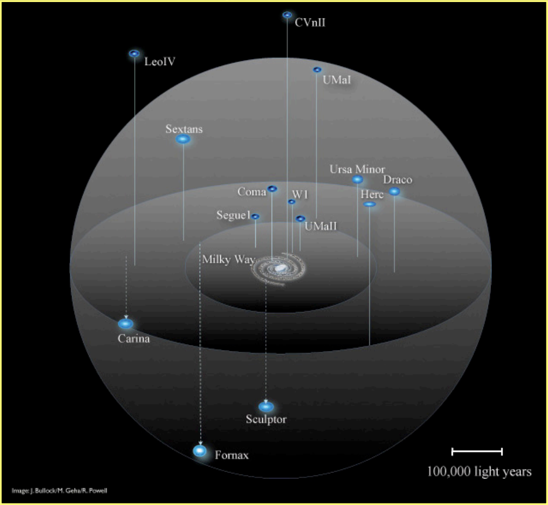

Belokurov et al. 2007

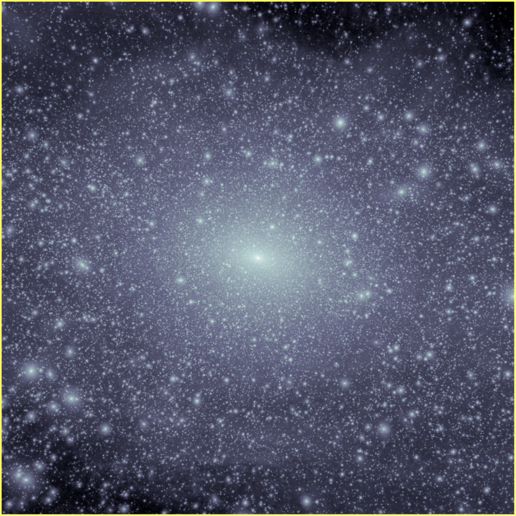
Milky Way Satellites:
Dwarf Spheroidal (dSph) Galaxies

- Lower limit of galaxy formation
  - Smallest: $r \sim 10^{1\text{-}3}$pc
  - Faintest: $L \sim 10^{3\text{-}7}\ L_{sun}$
  - Darkest: $M/L \sim 10^{1\text{-}3}$ solar
  - Most(?) Metal-Poor
- Tests of Cold Dark Matter
  - Mass Profiles

    ie., core vs cusp
  - Halo Mass Function

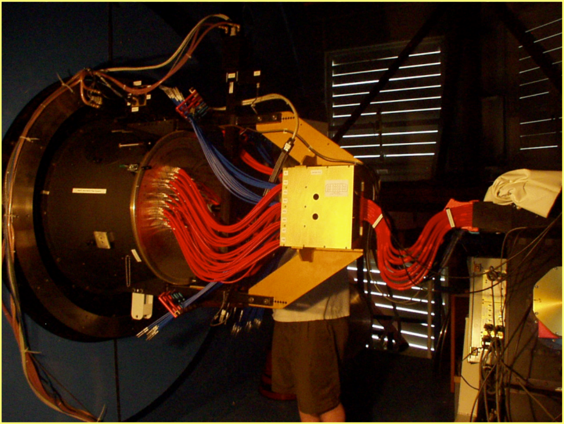
    Pick any two and solve for the third:
    - Dark matter
    - Baryon physics
    - dSph data

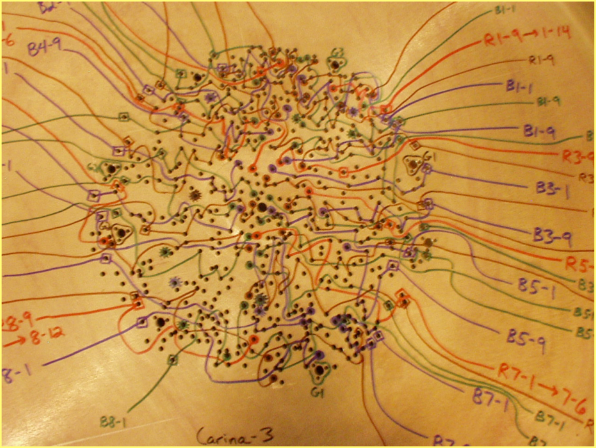


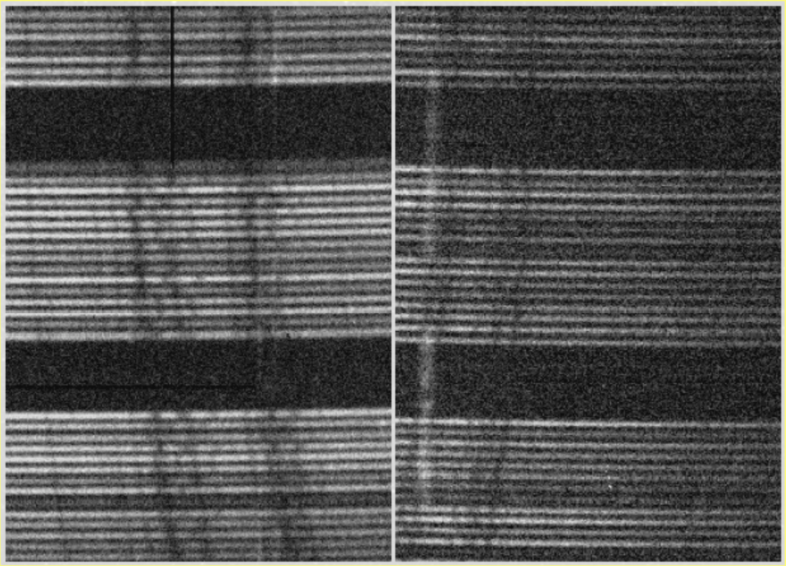


Diemand etal (2008); see also Springel etal (2008)

2. Data: Magellan, MMT, VLT



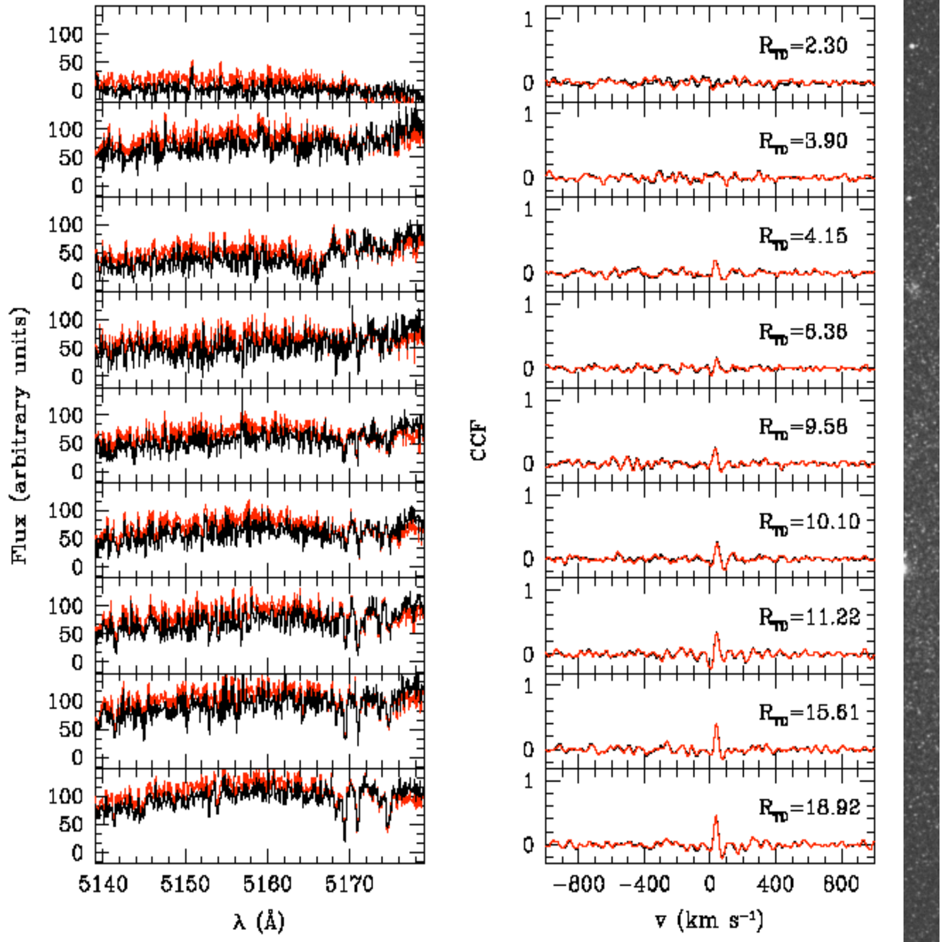


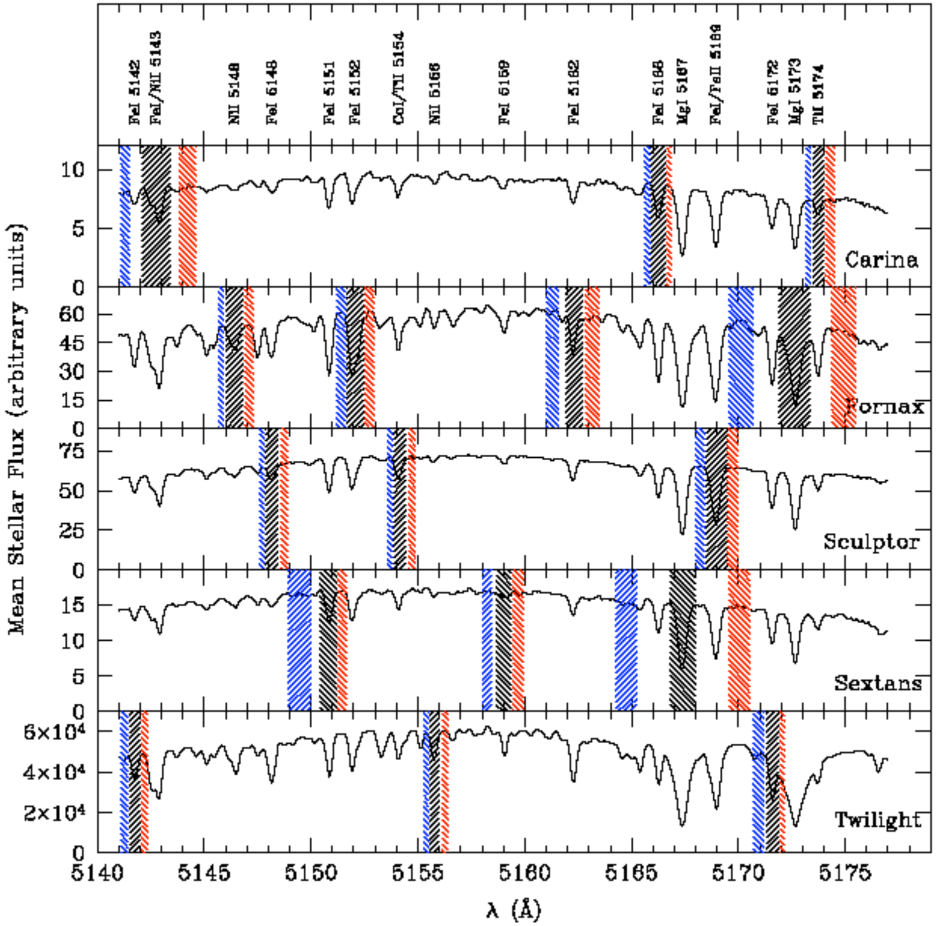


Observations: Spectroscopy of “Classical” dSphs

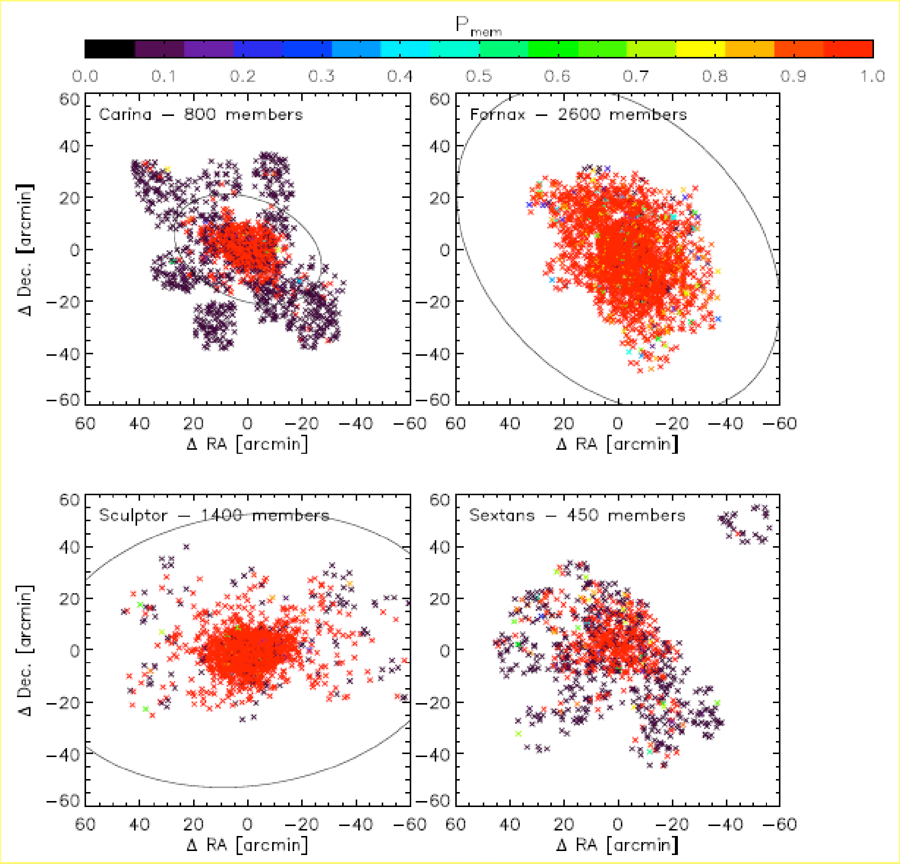
$$CCF(v) = \int S(v)[T(v) - v]\, dv$$

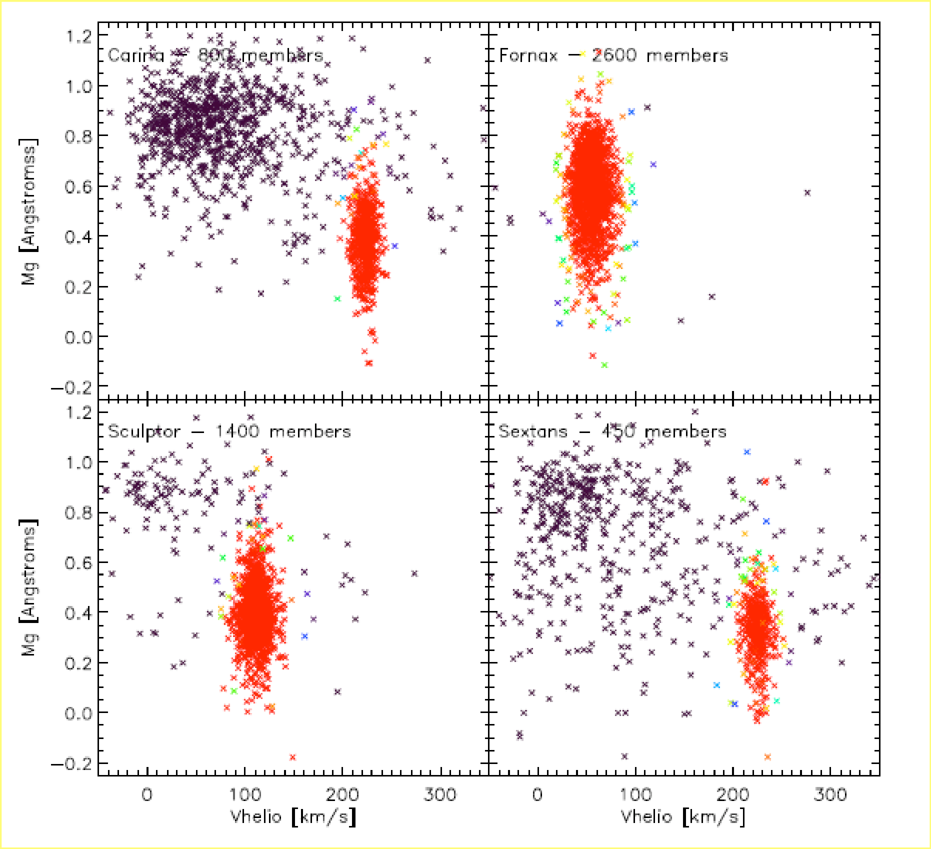
$$W = \int_{\lambda 1}^{\lambda_2} [1 - {}^{S(\lambda)}/_{C(\lambda)}]\, d\lambda$$





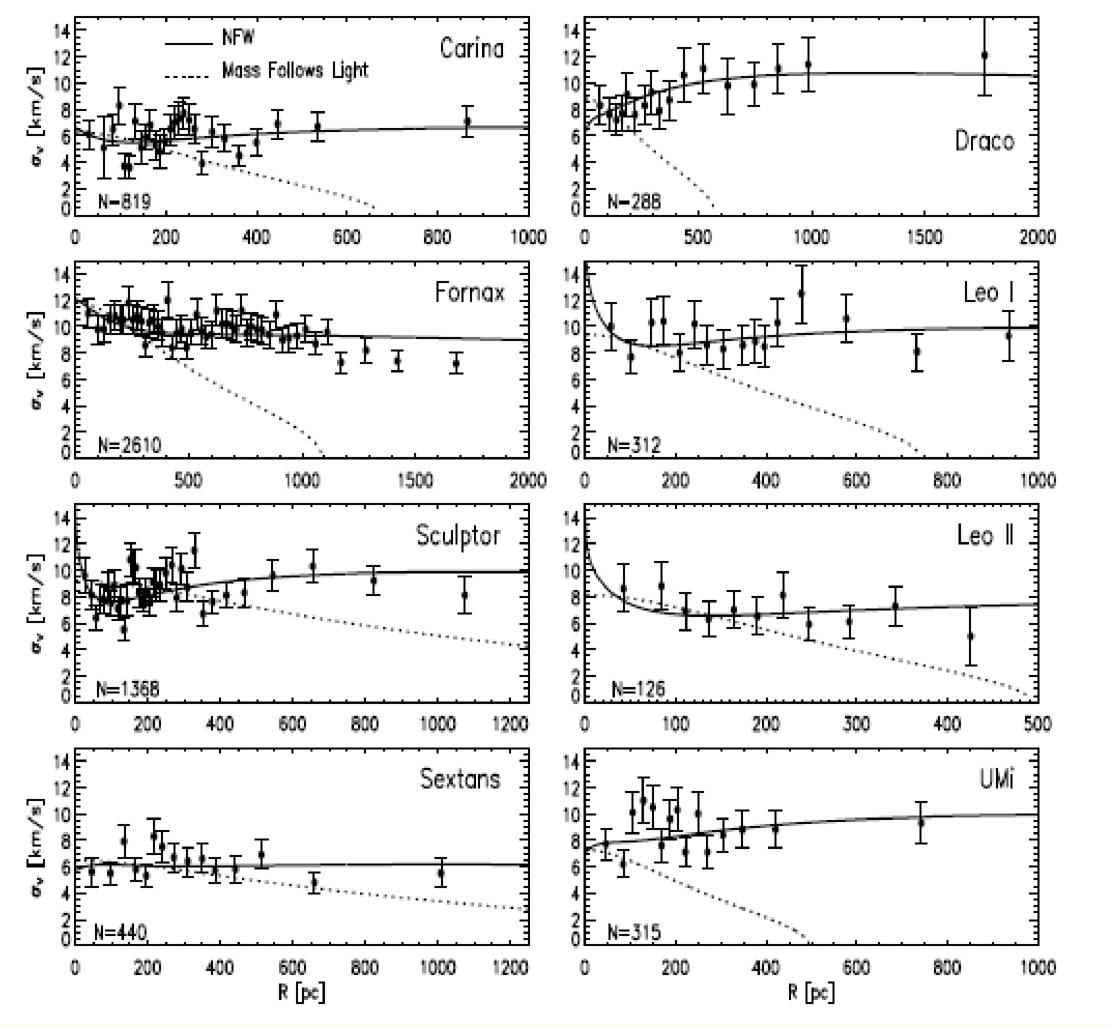
Data: Magellan Samples

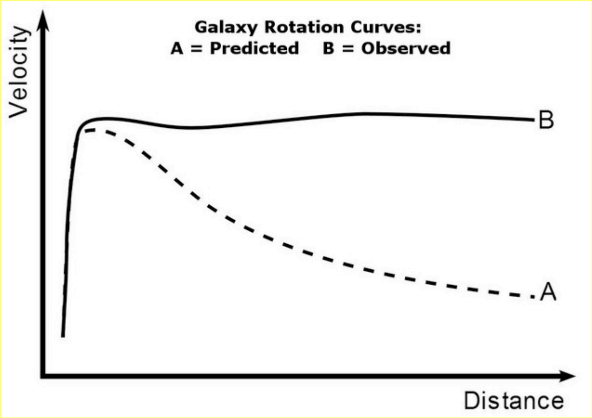




Walker etal (2009)

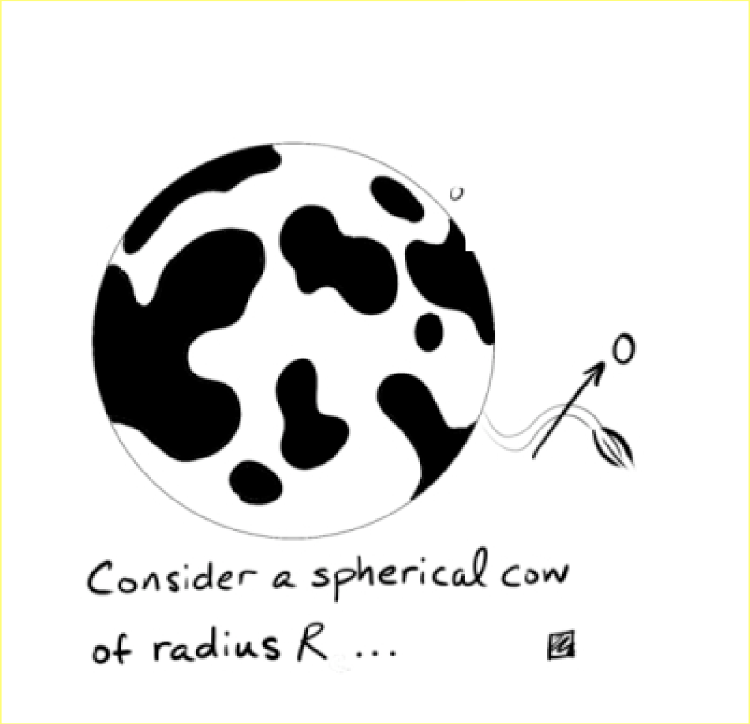
Data: Velocity Dispersion Profiles for ‘Classical’ dSphs





Walker etal. 2009

3. dSph Masses



dSph Masses: Kinematics with the Jeans Equation

Assumptions: Spherical symmetry, Dynamical equilibrium, Single (massless) stellar component, negligible binary motions

1) Collisionless Boltzmann Eq.

$$\frac{\partial f}{\partial t} + \mathbf{v}.\frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi.\frac{\partial f}{\partial \mathbf{v}} = 0$$

2) Jeans Eq. (spherical)

$$\frac{1}{\nu}\frac{d}{dr}(\nu\bar{v_r^2}) + 2\frac{\beta\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

3) Solution in terms of observables

$$\sigma_p^2(R) = \frac{2}{I(R)}\int_R^\infty\left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu(r)\bar{v_r^2}r}{\sqrt{r^2-R^2}}dr$$

4) Adopt Halo Model

$$\rho(r) = \rho_0\left(\frac{r}{r_s}\right)^{-\gamma}\left[1+\left(\frac{r}{r_s}\right)^\alpha\right]^{\frac{\gamma-3}{\alpha}}$$

Free Parameters: normalization, r_scale, alpha, gamma, beta=constant

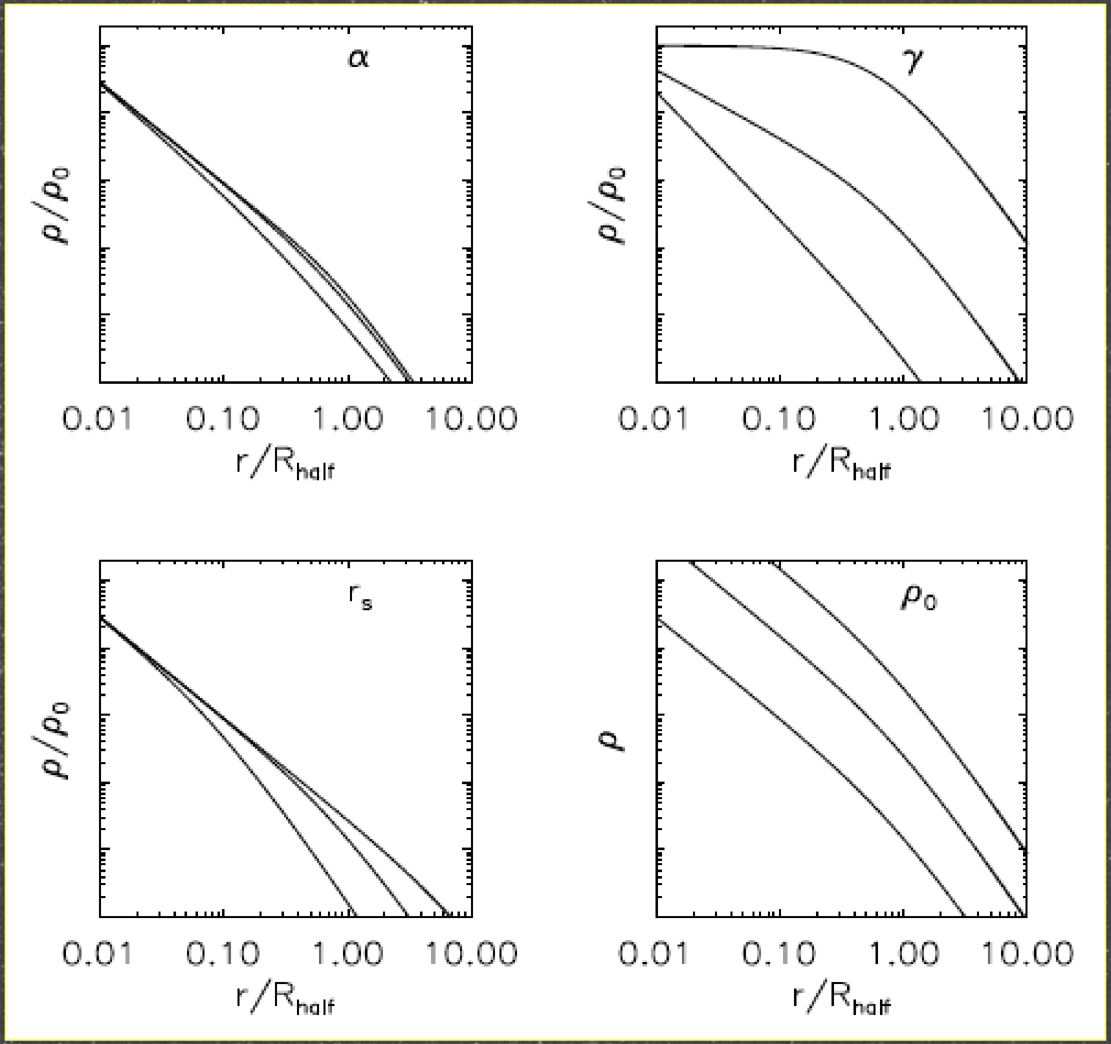
$\gamma = 0$ --> Core

$\gamma = \alpha = 1$ --> NFW Cusp

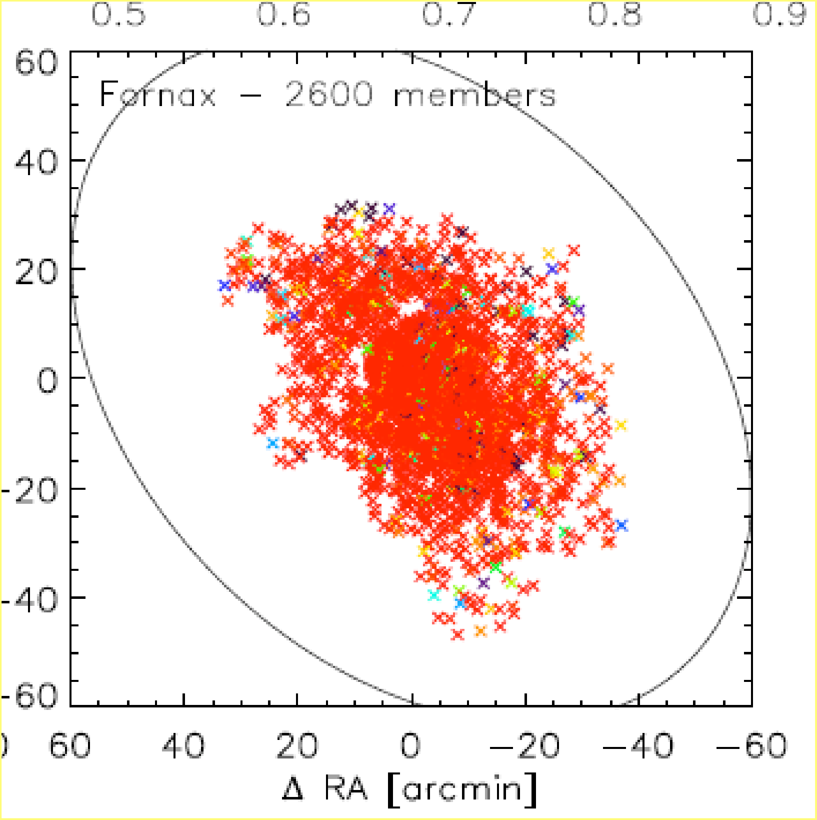
dSph Masses: Free Parameters

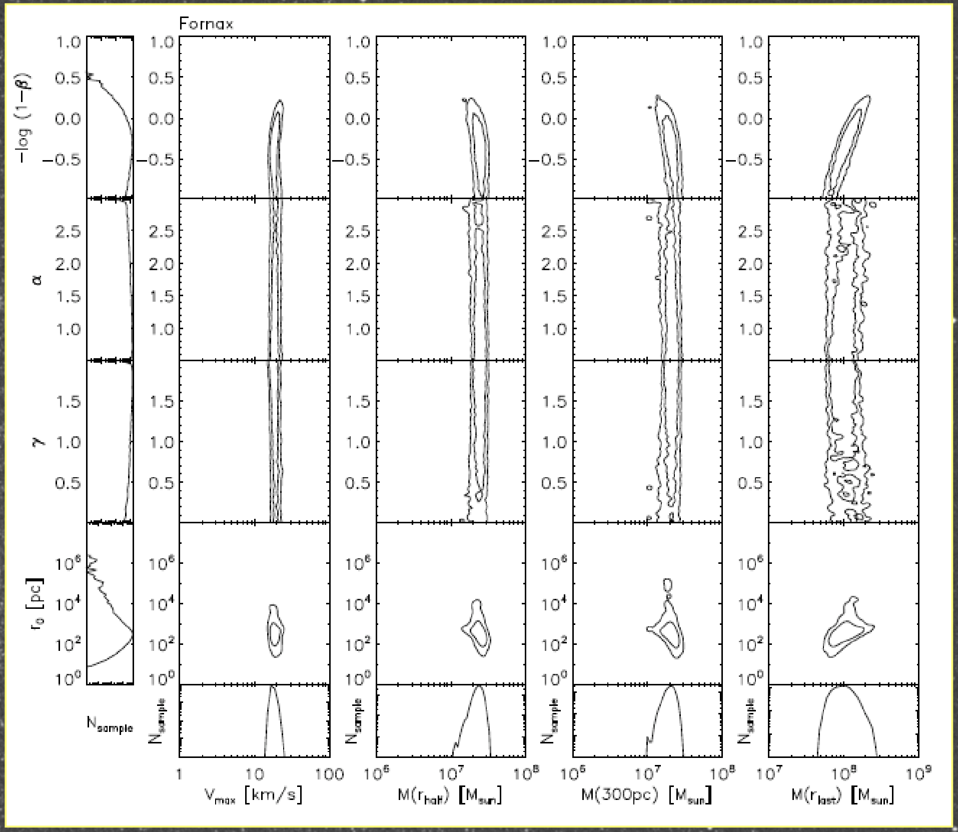
$$\rho(r) = \rho_0 \left(\frac{r}{r_s}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{\frac{\gamma-3}{\alpha}}$$

$$\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - \beta\frac{R^2}{r^2}\right) \frac{\nu(r)\bar{v}_r^2 r}{\sqrt{r^2 - R^2}} dr$$



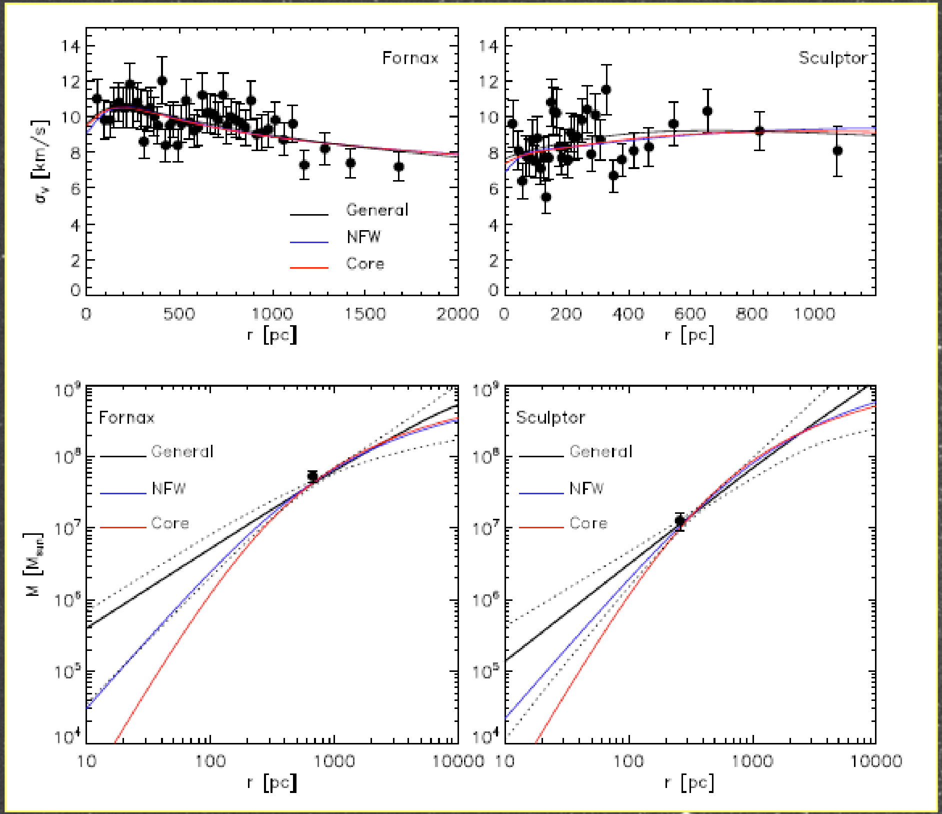
dSph Masses: Fornax

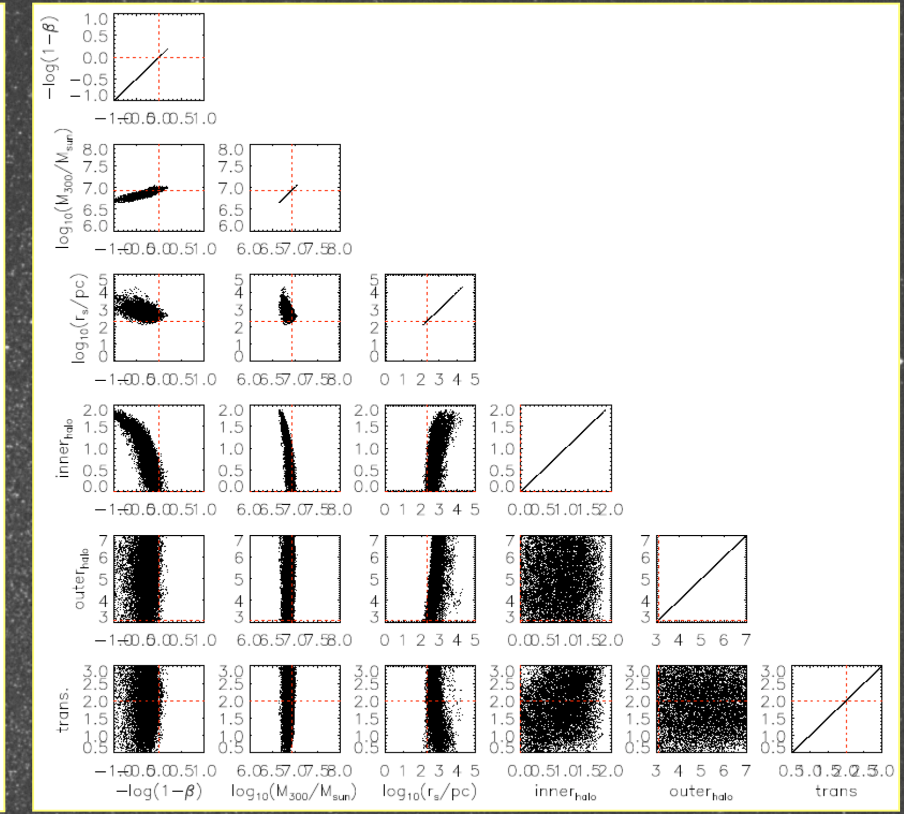




A “model-independent” constraint on V_{max} ~ 20 (-3/+4) km/s

dSph Masses: M(rhalf) is well-constrained





See also Peñarrubia etal 2007, Wolf etal 2009

dSph Masses: Simple Mass Estimator

Walker et al. (2009), see also Peñarrubia et al. (2008), Wolf et al. (2010)

$$\frac{1}{\nu}\frac{d}{dr}(\nu\bar{v_r^2}) + 2\frac{\beta\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

Jeans Eq.

Isotropy, flat vdisp profile -->

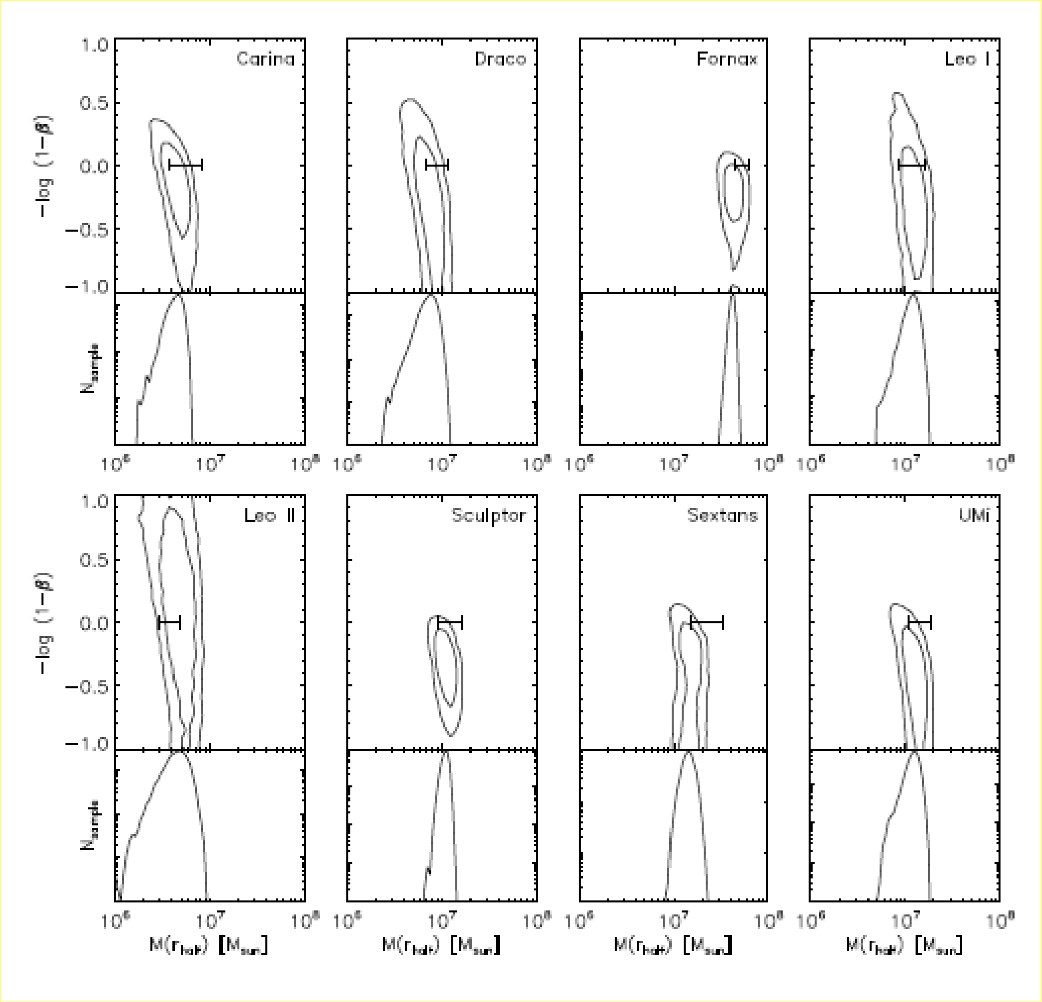
$$M(r) = -\frac{r^2\bar{v_r^2}}{G\nu}\frac{d\nu}{dr} = \frac{5r_{half}\sigma^2(\frac{r}{r_{half}})^3}{G[1+r^2/r_{half}^2]}$$

$$M(r_{half}) = \mu r_{half}\sigma^2$$

$$\mu \equiv 580\ M_\odot \mathrm{pc}^{-1}\mathrm{km}^{-2}\mathrm{s}^2$$

dSph Masses: Simple Mass Estimator vs. MCMC

$$M(r_{half}) = \mu r_{half} \sigma^2$$



Walker etal (2009)

dSph Masses: Data for 28 MW Satellites

$$M(r_{half}) = \mu r_{half} \sigma^2$$

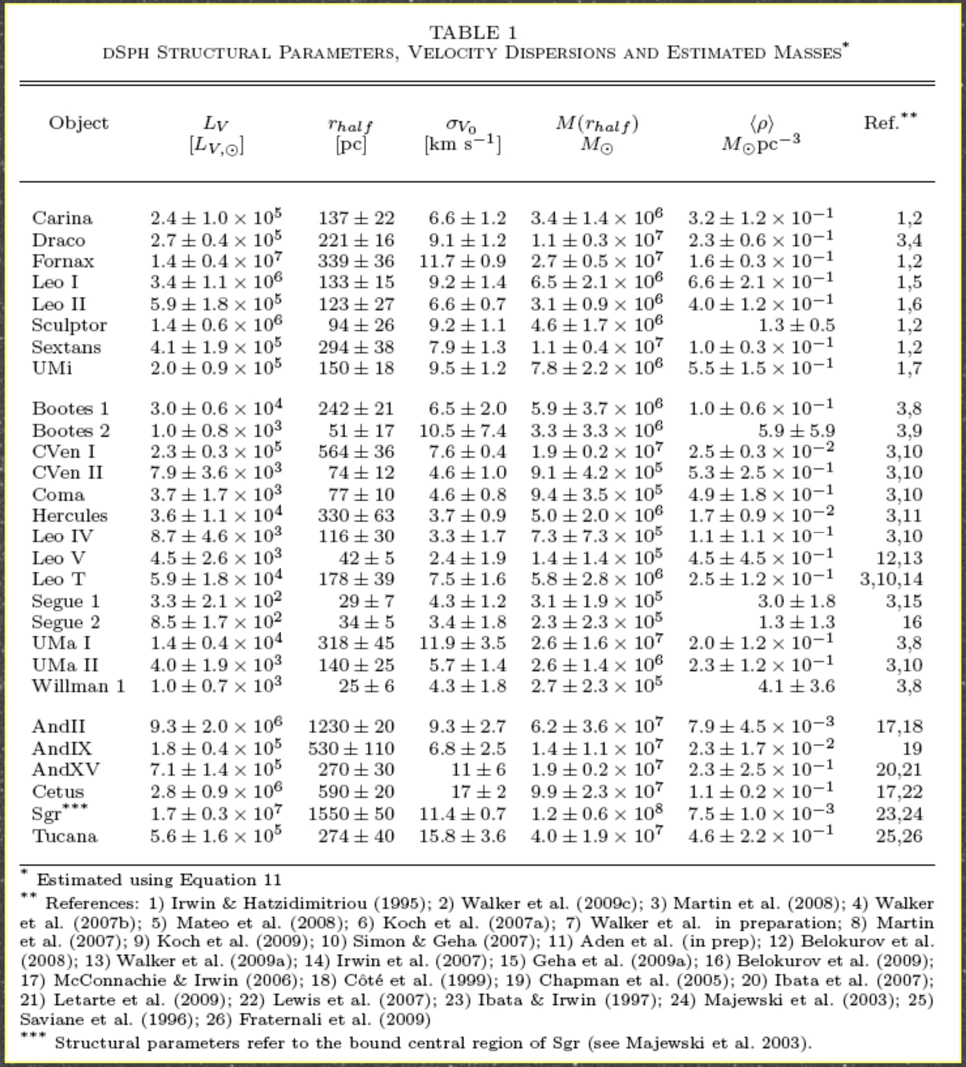


TABLE 1
DSPH STRUCTURAL PARAMETERS, VELOCITY DISPERSIONS AND ESTIMATED MASSES*

Object	L_V $[L_{V,\odot}]$	r_{half} [pc]	σ_{V_0} [km s^{-1}]	$M(r_{half})$ $M_\odot$	$\langle\rho\rangle$ $M_\odot pc^{-3}$	Ref.**
Carina	$2.4 \pm 1.0 \times 10^5$	137 ± 22	6.6 ± 1.2	$3.4 \pm 1.4 \times 10^6$	$3.2 \pm 1.2 \times 10^{-1}$	1,2
Draco	$2.7 \pm 0.4 \times 10^5$	221 ± 16	9.1 ± 1.2	$1.1 \pm 0.3 \times 10^7$	$2.3 \pm 0.6 \times 10^{-1}$	3,4
Fornax	$1.4 \pm 0.4 \times 10^7$	339 ± 36	11.7 ± 0.9	$2.7 \pm 0.5 \times 10^7$	$1.6 \pm 0.3 \times 10^{-1}$	1,2
Leo I	$3.4 \pm 1.1 \times 10^6$	133 ± 15	9.2 ± 1.4	$6.5 \pm 2.1 \times 10^6$	$6.6 \pm 2.1 \times 10^{-1}$	1,5
Leo II	$5.9 \pm 1.8 \times 10^5$	123 ± 27	6.6 ± 0.7	$3.1 \pm 0.9 \times 10^6$	$4.0 \pm 1.2 \times 10^{-1}$	1,6
Sculptor	$1.4 \pm 0.6 \times 10^6$	94 ± 26	9.2 ± 1.1	$4.6 \pm 1.7 \times 10^6$	1.3 ± 0.5	1,2
Sextans	$4.1 \pm 1.9 \times 10^5$	294 ± 38	7.9 ± 1.3	$1.1 \pm 0.4 \times 10^7$	$1.0 \pm 0.3 \times 10^{-1}$	1,2
UMi	$2.0 \pm 0.9 \times 10^5$	150 ± 18	9.5 ± 1.2	$7.8 \pm 2.2 \times 10^6$	$5.5 \pm 1.5 \times 10^{-1}$	1,7
Bootes 1	$3.0 \pm 0.6 \times 10^4$	242 ± 21	6.5 ± 2.0	$5.9 \pm 3.7 \times 10^6$	$1.0 \pm 0.6 \times 10^{-1}$	3,8
Bootes 2	$1.0 \pm 0.8 \times 10^3$	51 ± 17	10.5 ± 7.4	$3.3 \pm 3.3 \times 10^6$	5.9 ± 5.9	3,9
CVen I	$2.3 \pm 0.3 \times 10^5$	564 ± 36	7.6 ± 0.4	$1.9 \pm 0.2 \times 10^7$	$2.5 \pm 0.3 \times 10^{-2}$	3,10
CVen II	$7.9 \pm 3.6 \times 10^3$	74 ± 12	4.6 ± 1.0	$9.1 \pm 4.2 \times 10^5$	$5.3 \pm 2.5 \times 10^{-1}$	3,10
Coma	$3.7 \pm 1.7 \times 10^3$	77 ± 10	4.6 ± 0.8	$9.4 \pm 3.5 \times 10^5$	$4.9 \pm 1.8 \times 10^{-1}$	3,10
Hercules	$3.6 \pm 1.1 \times 10^4$	330 ± 63	3.7 ± 0.9	$5.0 \pm 2.0 \times 10^6$	$1.7 \pm 0.9 \times 10^{-2}$	3,11
Leo IV	$8.7 \pm 4.6 \times 10^3$	116 ± 30	3.3 ± 1.7	$7.3 \pm 7.3 \times 10^5$	$1.1 \pm 1.1 \times 10^{-1}$	3,10
Leo V	$4.5 \pm 2.6 \times 10^3$	42 ± 5	2.4 ± 1.9	$1.4 \pm 1.4 \times 10^5$	$4.5 \pm 4.5 \times 10^{-1}$	12,13
Leo T	$5.9 \pm 1.8 \times 10^4$	178 ± 39	7.5 ± 1.6	$5.8 \pm 2.8 \times 10^6$	$2.5 \pm 1.2 \times 10^{-1}$	3,10,14
Segue 1	$3.3 \pm 2.1 \times 10^2$	29 ± 7	4.3 ± 1.2	$3.1 \pm 1.9 \times 10^5$	3.0 ± 1.8	3,15
Segue 2	$8.5 \pm 1.7 \times 10^2$	34 ± 5	3.4 ± 1.8	$2.3 \pm 2.3 \times 10^5$	1.3 ± 1.3	16
UMa I	$1.4 \pm 0.4 \times 10^4$	318 ± 45	11.9 ± 3.5	$2.6 \pm 1.6 \times 10^7$	$2.0 \pm 1.2 \times 10^{-1}$	3,8
UMa II	$4.0 \pm 1.9 \times 10^3$	140 ± 25	5.7 ± 1.4	$2.6 \pm 1.4 \times 10^6$	$2.3 \pm 1.2 \times 10^{-1}$	3,10
Willman 1	$1.0 \pm 0.7 \times 10^3$	25 ± 6	4.3 ± 1.8	$2.7 \pm 2.3 \times 10^5$	4.1 ± 3.6	3,8
AndII	$9.3 \pm 2.0 \times 10^6$	1230 ± 20	9.3 ± 2.7	$6.2 \pm 3.6 \times 10^7$	$7.9 \pm 4.5 \times 10^{-3}$	17,18
AndIX	$1.8 \pm 0.4 \times 10^5$	530 ± 110	6.8 ± 2.5	$1.4 \pm 1.1 \times 10^7$	$2.3 \pm 1.7 \times 10^{-2}$	19
AndXV	$7.1 \pm 1.4 \times 10^5$	270 ± 30	11 ± 6	$1.9 \pm 0.2 \times 10^7$	$2.3 \pm 2.5 \times 10^{-1}$	20,21
Cetus	$2.8 \pm 0.9 \times 10^6$	590 ± 20	17 ± 2	$9.9 \pm 2.3 \times 10^7$	$1.1 \pm 0.2 \times 10^{-1}$	17,22
Sgr***	$1.7 \pm 0.3 \times 10^7$	1550 ± 50	11.4 ± 0.7	$1.2 \pm 0.6 \times 10^8$	$7.5 \pm 1.0 \times 10^{-3}$	23,24
Tucana	$5.6 \pm 1.6 \times 10^5$	274 ± 40	15.8 ± 3.6	$4.0 \pm 1.9 \times 10^7$	$4.6 \pm 2.2 \times 10^{-1}$	25,26

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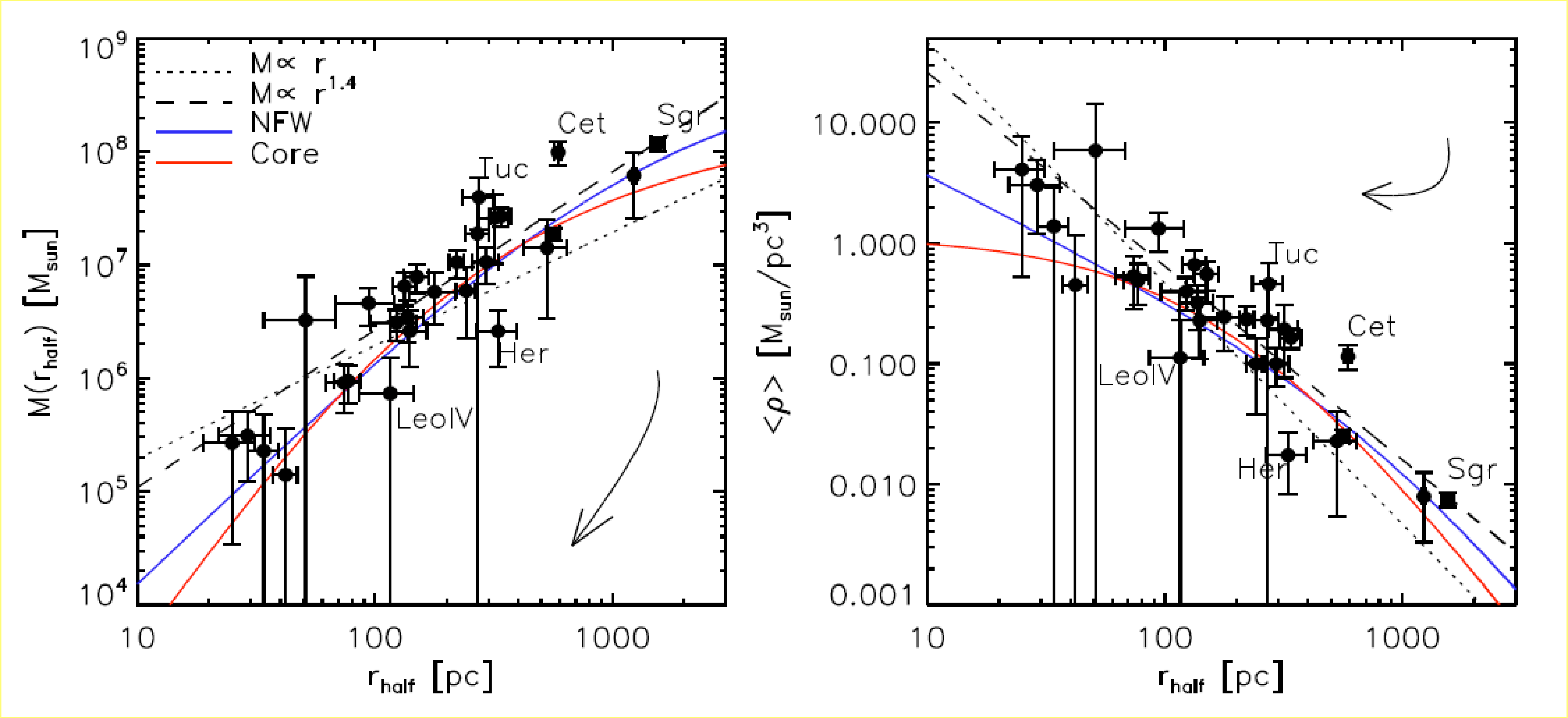
* Estimated using Equation 11

** References: 1) Irwin & Hatzidimitriou (1995); 2) Walker et al. (2009c); 3) Martin et al. (2008); 4) Walker et al. (2007b); 5) Mateo et al. (2008); 6) Koch et al. (2007a); 7) Walker et al. in preparation; 8) Martin et al. (2007); 9) Koch et al. (2009); 10) Simon & Geha (2007); 11) Aden et al. (in prep); 12) Belokurov et al. (2008); 13) Walker et al. (2009a); 14) Irwin et al. (2007); 15) Geha et al. (2009a); 16) Belokurov et al. (2009); 17) McConnachie & Irwin (2006); 18) Côté et al. (1999); 19) Chapman et al. (2005); 20) Ibata et al. (2007); 21) Letarte et al. (2009); 22) Lewis et al. (2007); 23) Ibata & Irwin (1997); 24) Majewski et al. (2003); 25) Saviane et al. (1996); 26) Fraternali et al. (2009)

*** Structural parameters refer to the bound central region of Sgr (see Majewski et al. 2003).

Walker etal (2009)

dSph Masses: M(rhalf) vs. rhalf

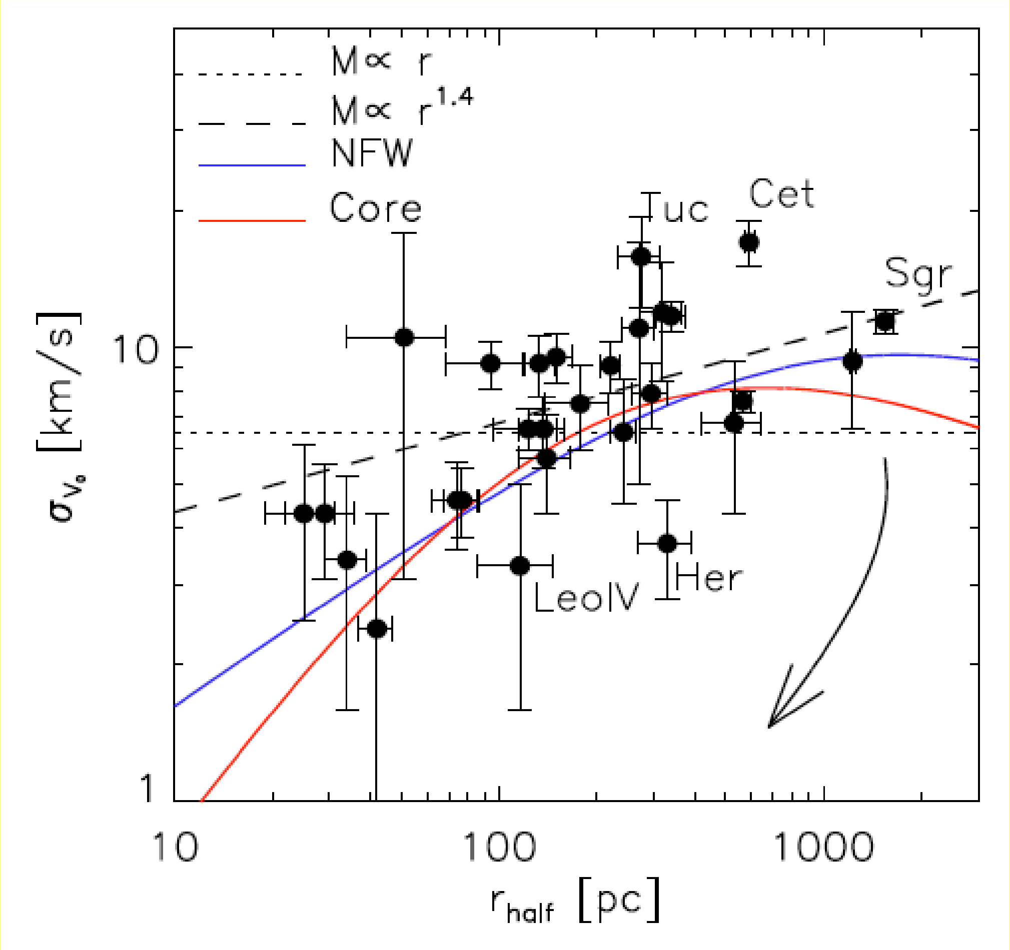


$$M(r_{half}) = \mu r_{half} \sigma^2$$

Walker etal 2009

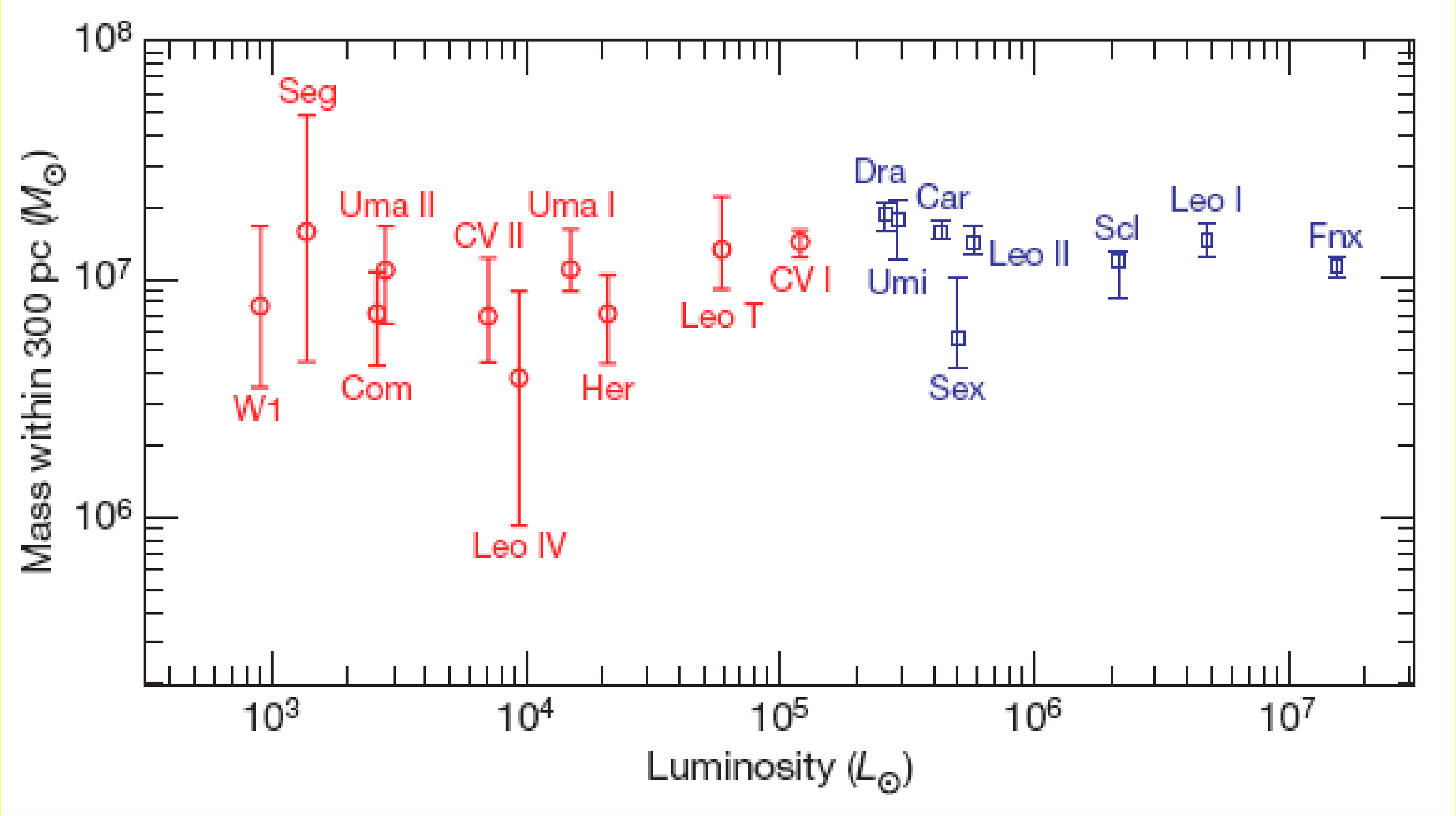
dSph Masses: Velocity Dispersion vs. Size
A new scaling relation for dSphs

$$M(r_{half}) = \mu r_{half} \sigma^2$$



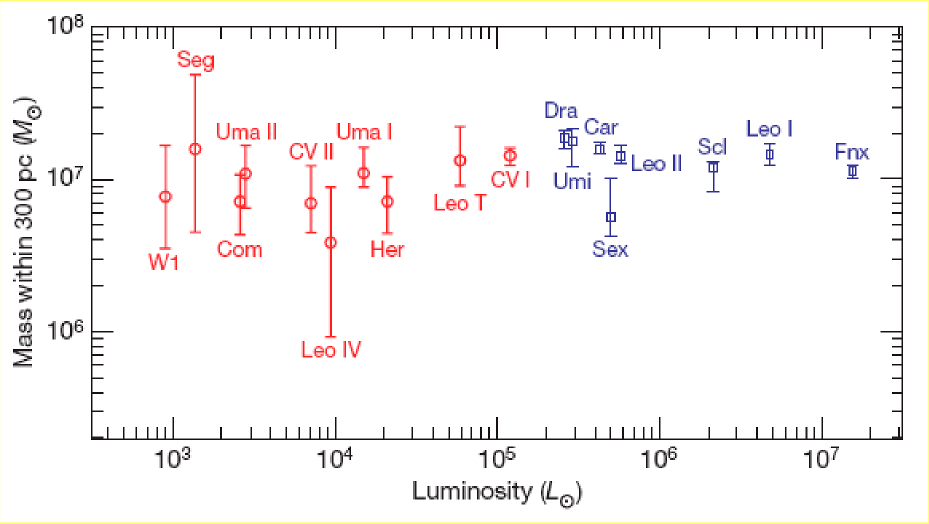
Walker etal (2009)

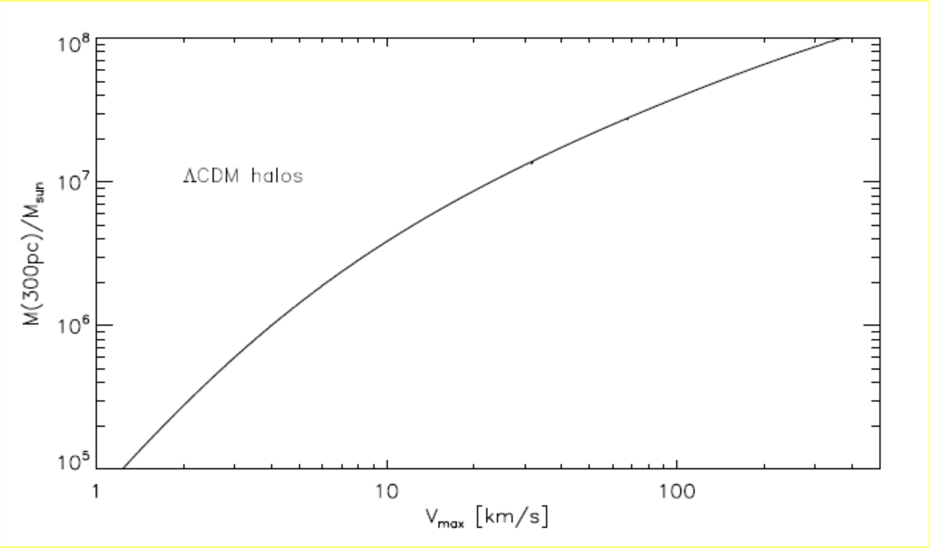
dSph Masses: A Minimum Mass for Galaxy Formation?



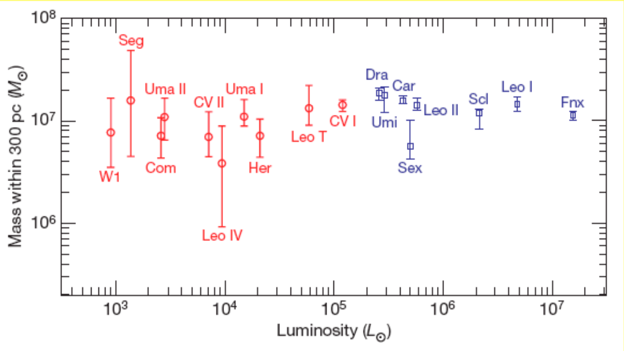
"M(300pc)~10^7 M_{sun}" (Strigari etal 2008, *Nature*)

dSph Masses: A Minimum Mass for Galaxy Formation?

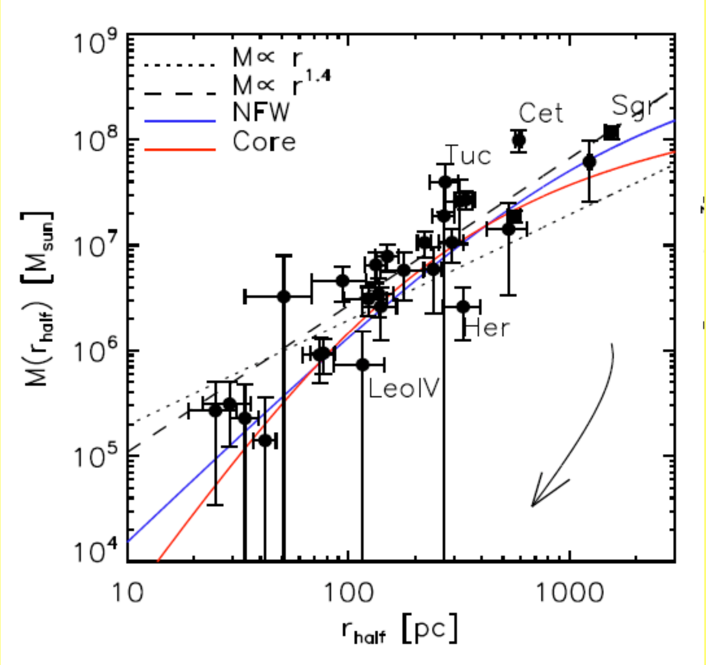




dSph Masses: M300 vs. M(rhalf)

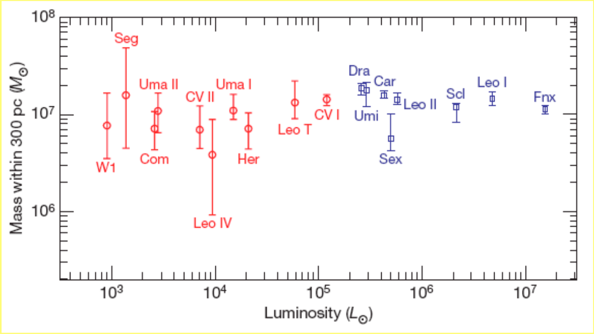


“M(300pc)~10^7 M_{sun}” (Strigari etal 2008)

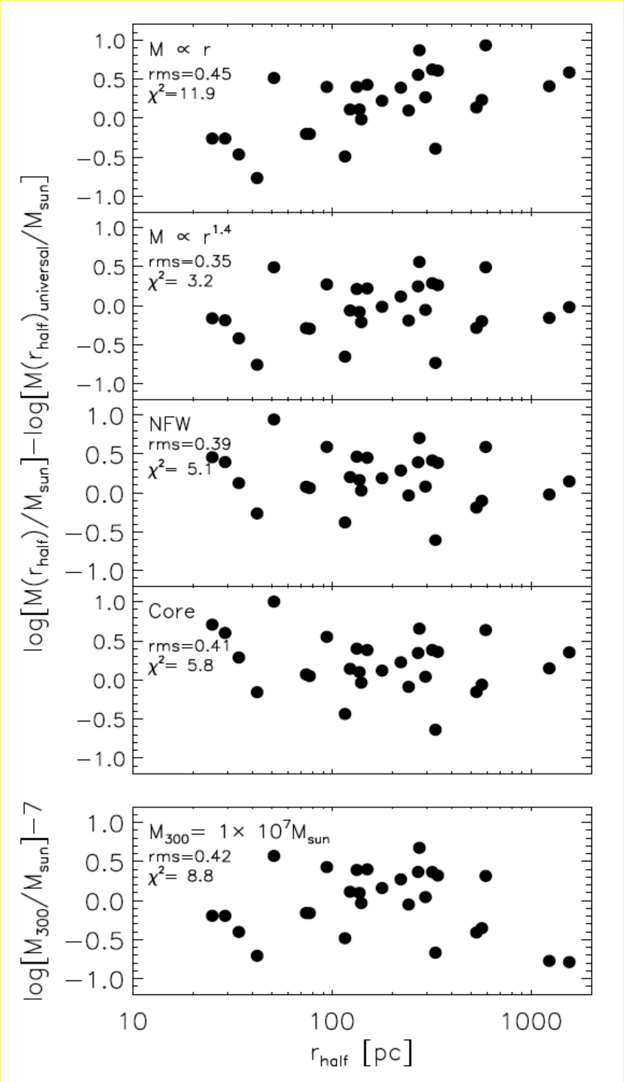


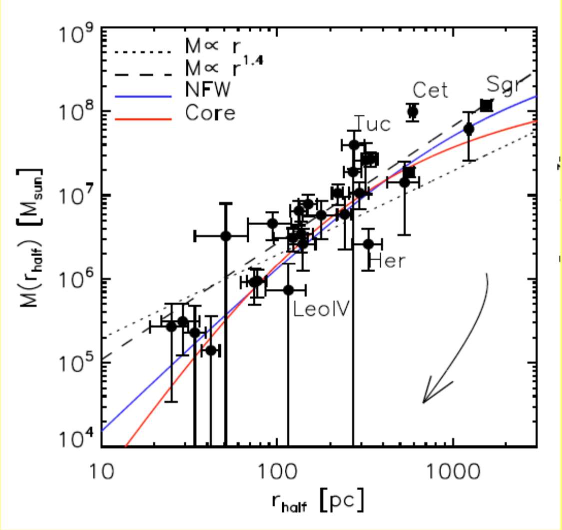
A “Universal” Mass Profile? (Walker etal 2009)

dSph Masses: Scatter



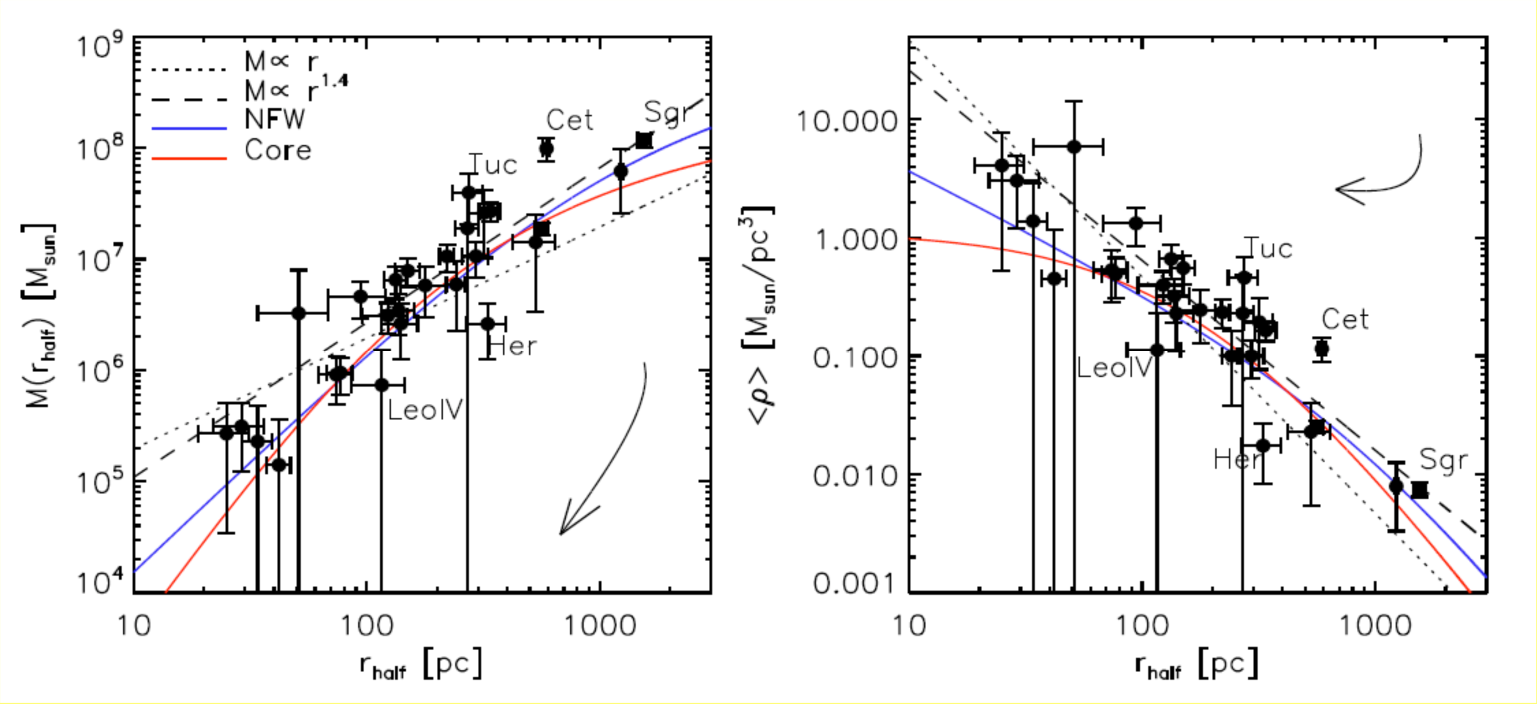
“M(300pc)~10^7 M_{sun}” (Strigari etal 2008)





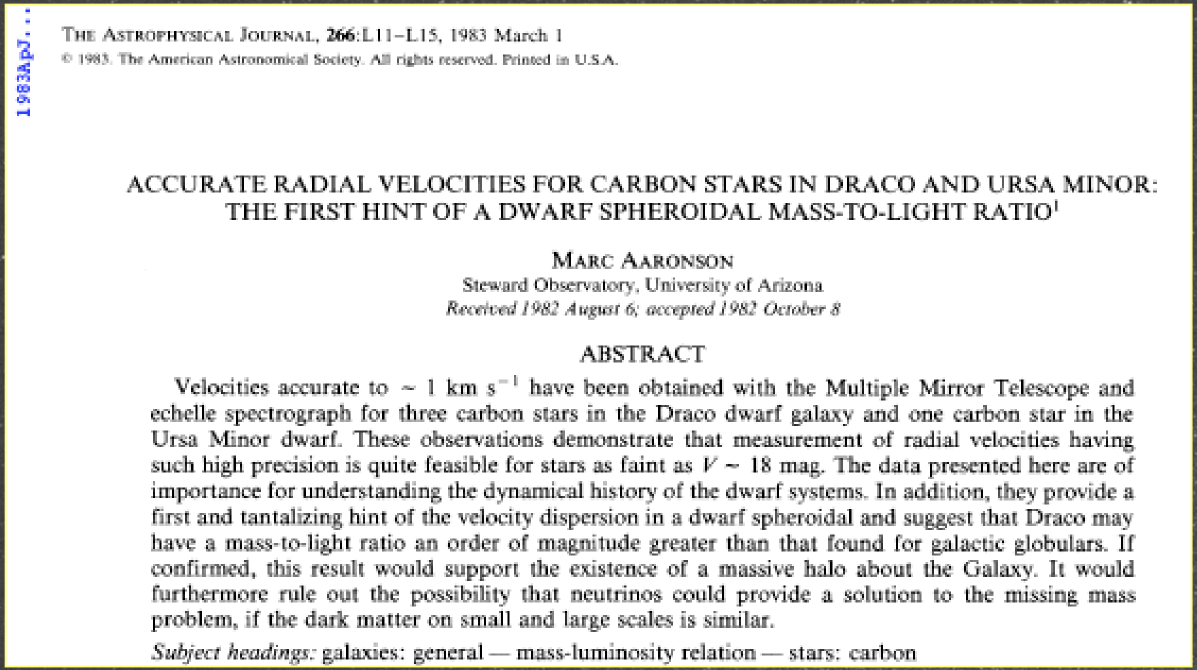
A “Universal” Mass Profile? (Walker etal 2009)

dSph Masses: Implications



- No empirically-determined minimum mass for galaxy formation -- mass profiles line up as far as each goes, but some may have r<<300pc, and therefore M << 10^7 Msun
- Large central densities for *all* dSphs?

4. A Brief History of dSph ‘Universality’



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

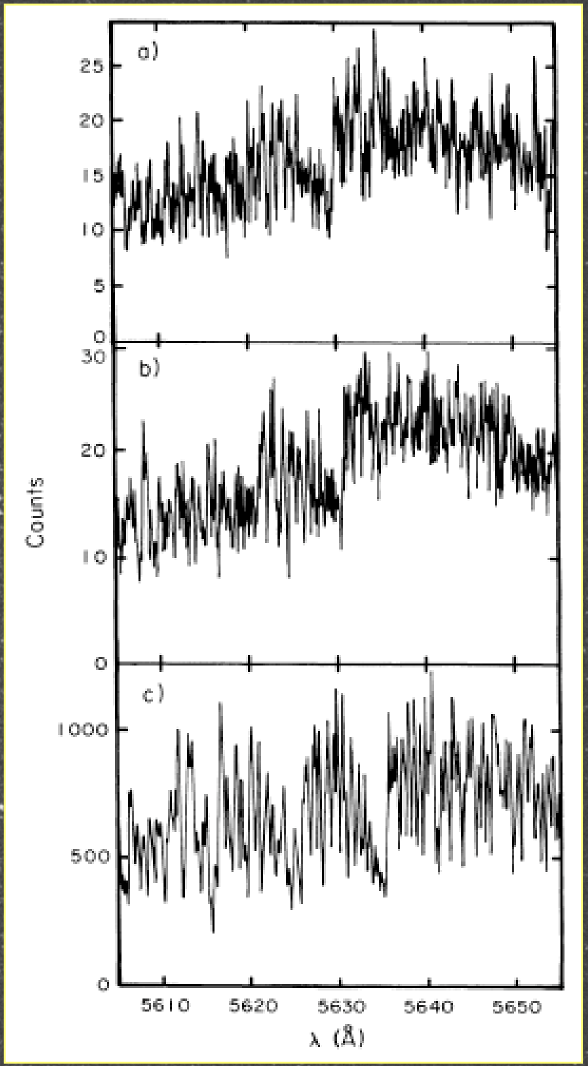
Received 1982 August 6; accepted 1982 October 8

ABSTRACT

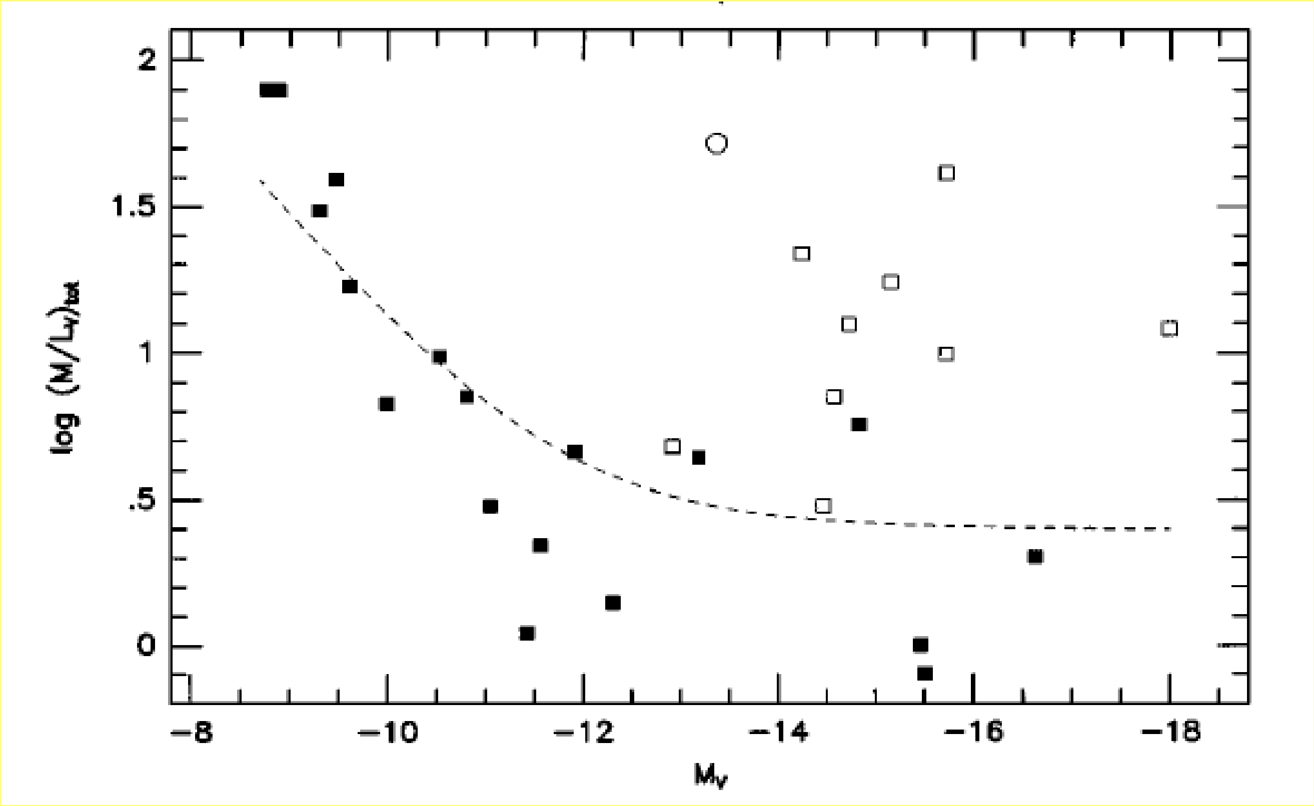
Velocities accurate to ~ 1 km s^{-1} have been obtained with the Multiple Mirror Telescope and echelle spectrograph for three carbon stars in the Draco dwarf galaxy and one carbon star in the Ursa Minor dwarf. These observations demonstrate that measurement of radial velocities having such high precision 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.

Subject headings: galaxies: general — mass-luminosity relation — stars: carbon

$$\sigma_V^2 \sim \frac{GM}{R}$$



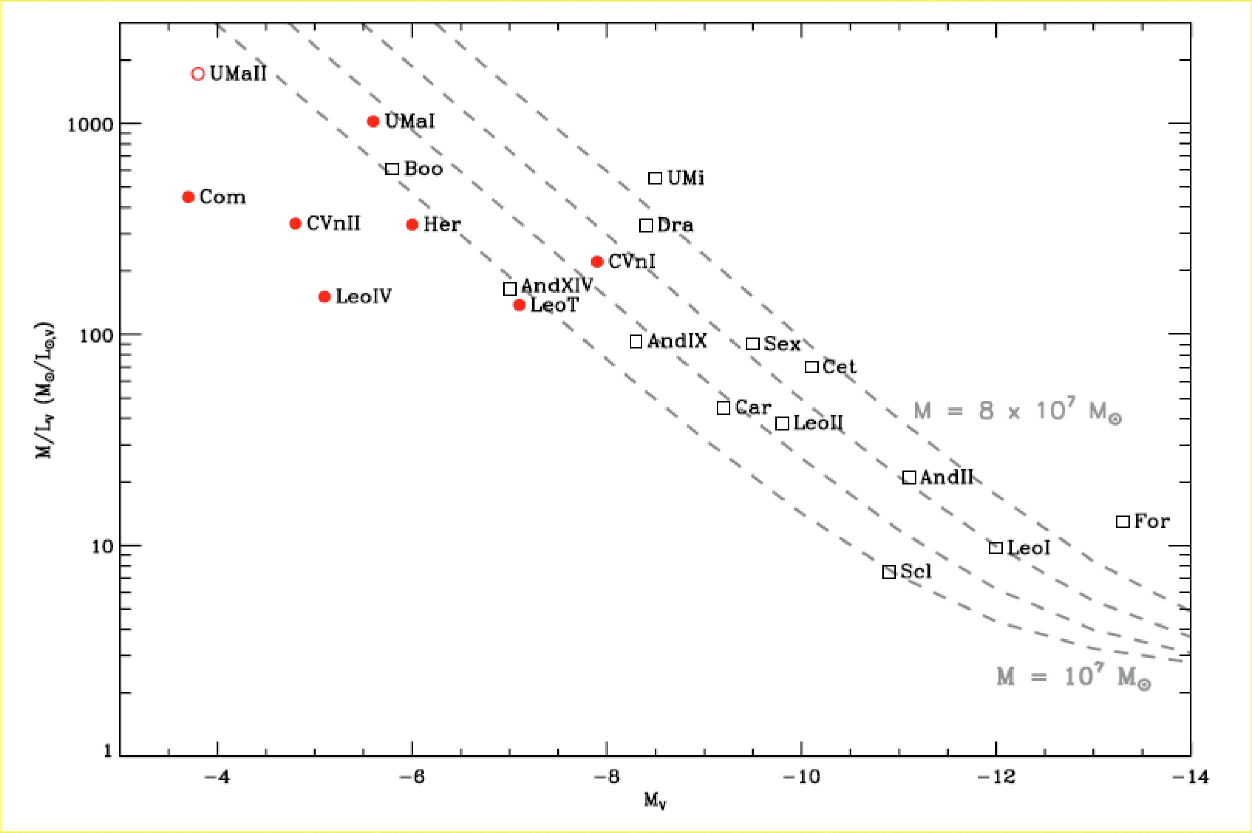
A Brief History of dSph ‘Universality’



$$\sigma_V^2 \sim \frac{GM}{R}$$

A Common dSph mass? (Mateo 1993, 1998)

A Brief History of dSph 'Universality'



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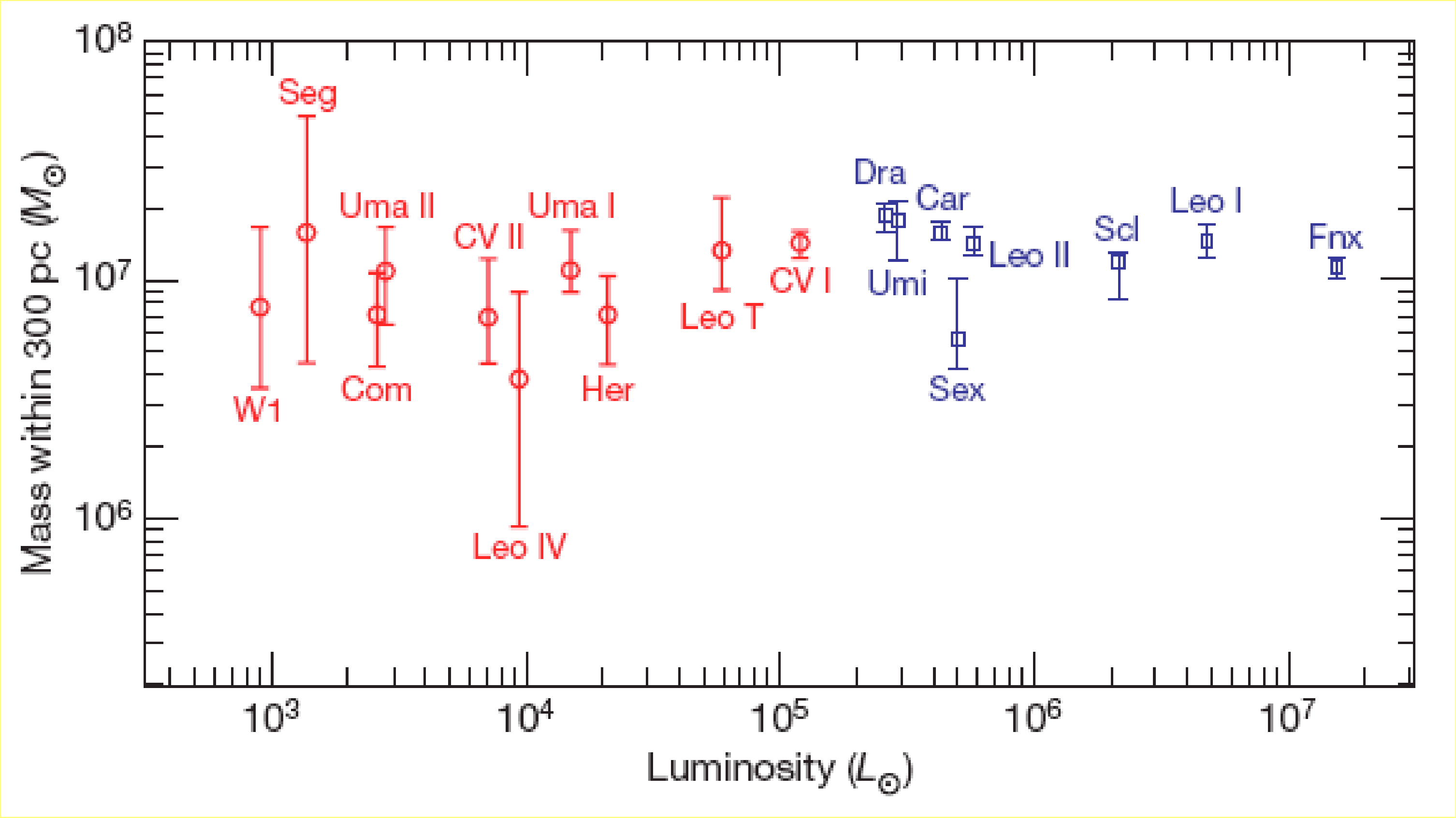
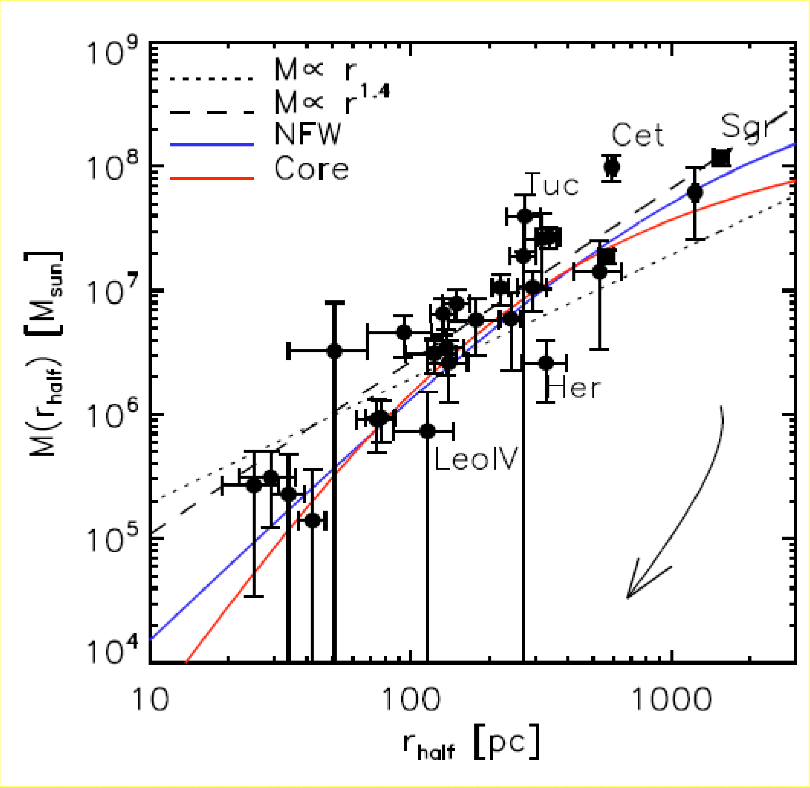
Ultrafaints deviate from a Common dSph mass? (Simon & Geha 2007)

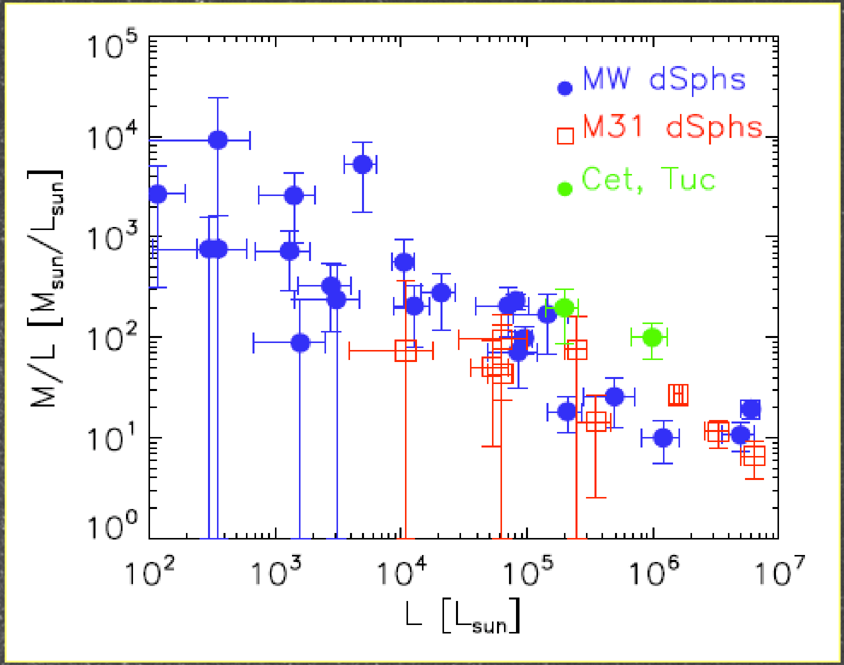
A Brief History of dSph 'Universality'



A Common dSph mass at r=300pc? (Strigari et al. 2008)

A Brief History of dSph ‘Universality’





$$M(r_{half}) = \mu r_{half} \sigma^2$$

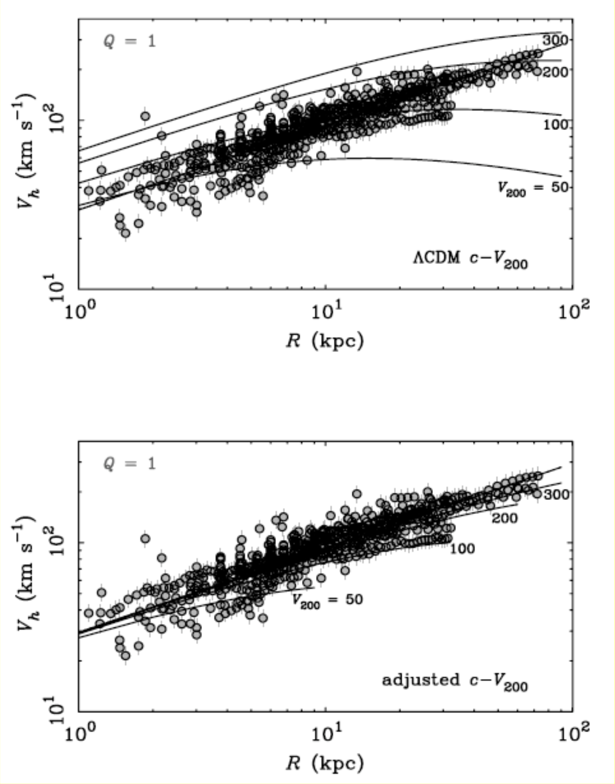
A Common dSph mass *profile*? (Walker et al. 2009)

A Brief History of dSph ‘Universality’

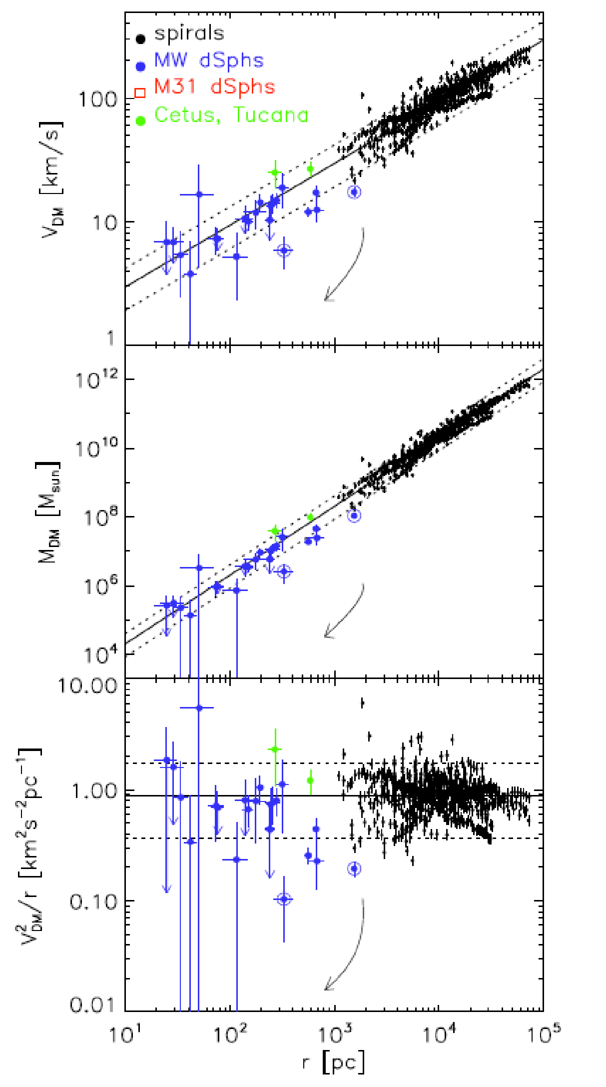
$$\log_{10}[V_{c,\mathrm{DM}}/(\mathrm{kms}^{-1})] = 1.47^{+0.15}_{-0.19} + 0.5\log_{10}[r/\mathrm{kpc}]$$

$$\frac{M_{\mathrm{DM}}(r)}{M_{\odot}} = 200^{+200}_{-120}\left(\frac{r}{\mathrm{pc}}\right)^{2}$$

$$g_{\mathrm{DM}} = 0.9^{+0.9}_{-0.5}\mathrm{km}^{2}\mathrm{s}^{-2}\mathrm{pc}^{-1} = 3^{+3}_{-2}\times 10^{-9}\mathrm{cms}^{-2}$$



McGaugh etal. (2007)



Walker etal. (2010)

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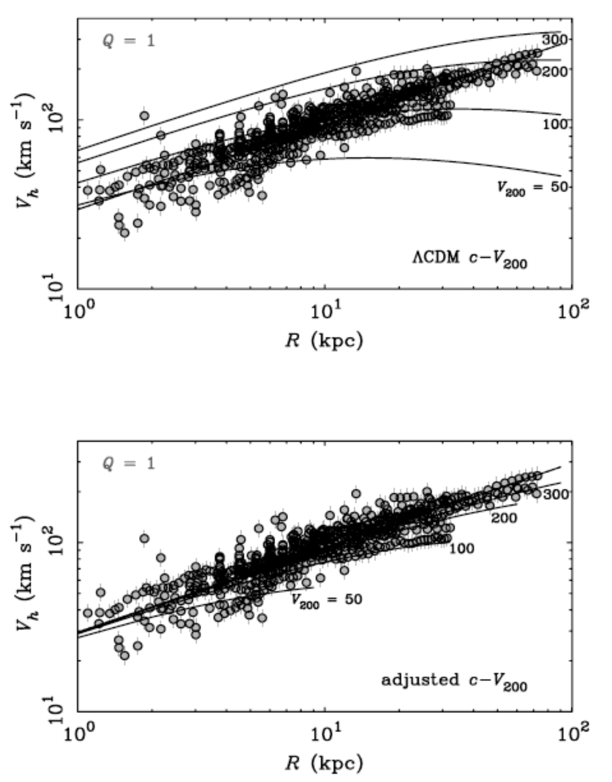

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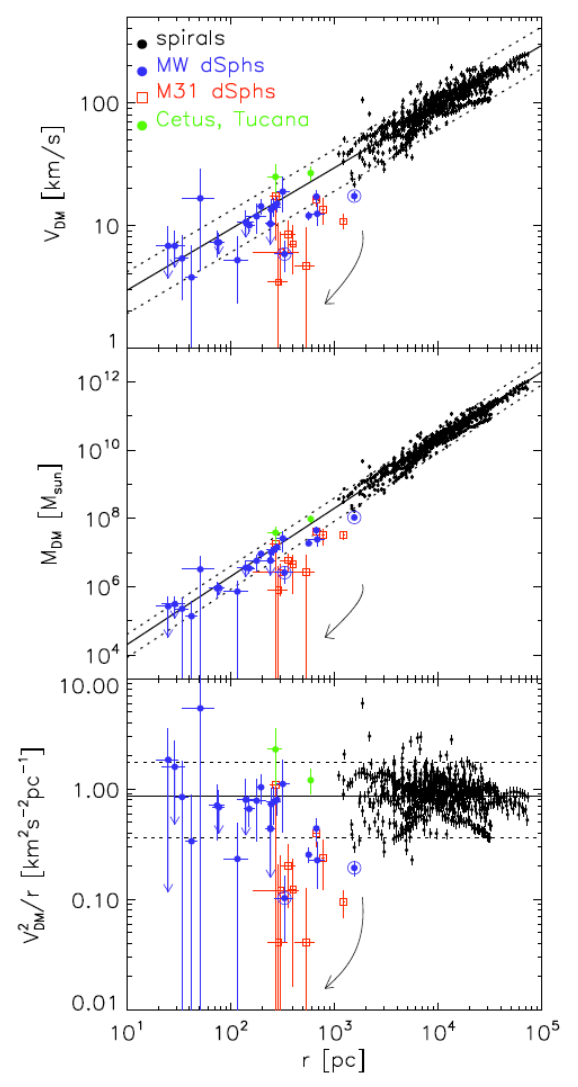
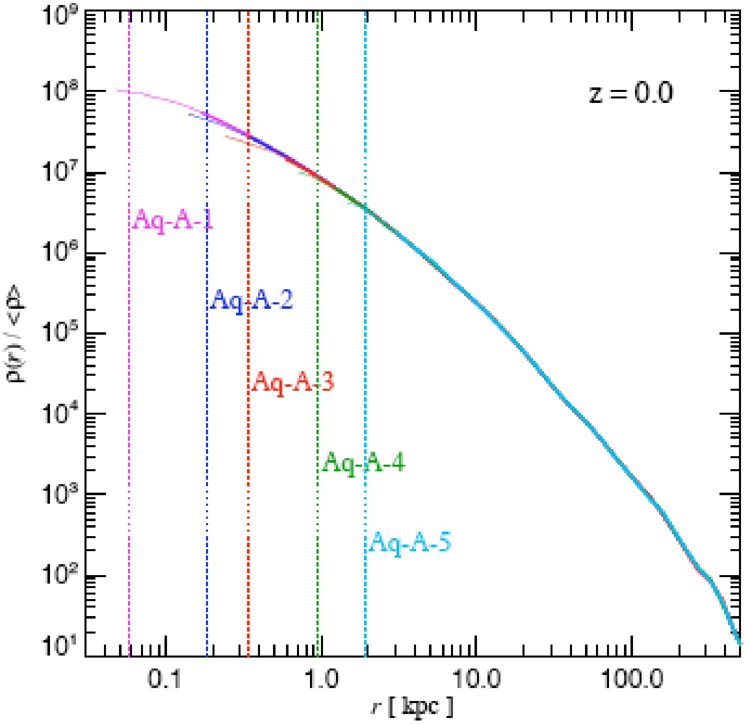
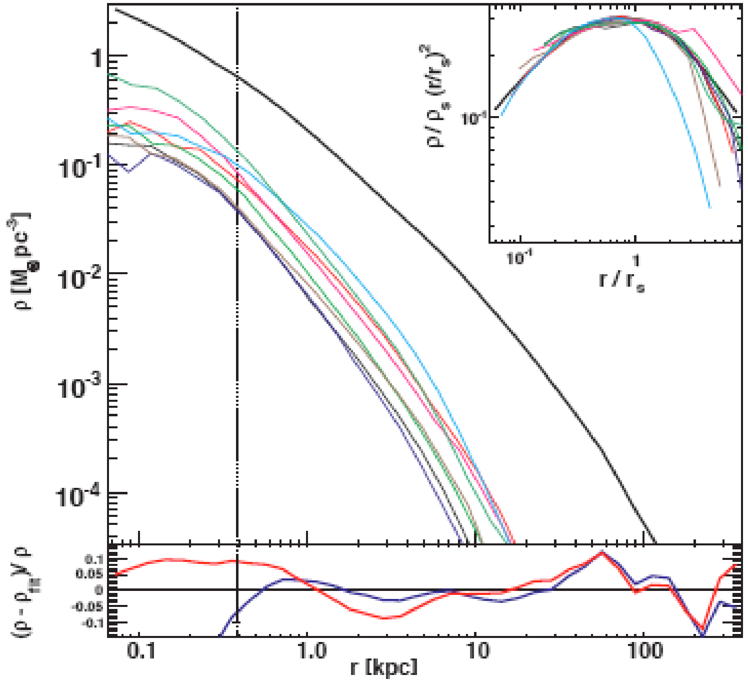


Walker etal. (2010)

END

4. Core vs. Cusp





Springel etal 2008

Diemand etal 2008

Core vs. Cusp: Stellar Dynamics

Collisionless Boltzmann Equation:

$$\frac{\partial f}{\partial t} + \mathbf{v}.\frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi.\frac{\partial f}{\partial \mathbf{v}} = 0$$

Distribution function

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

Gerhard (1991)

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

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

Free parameters: a, c, L_0

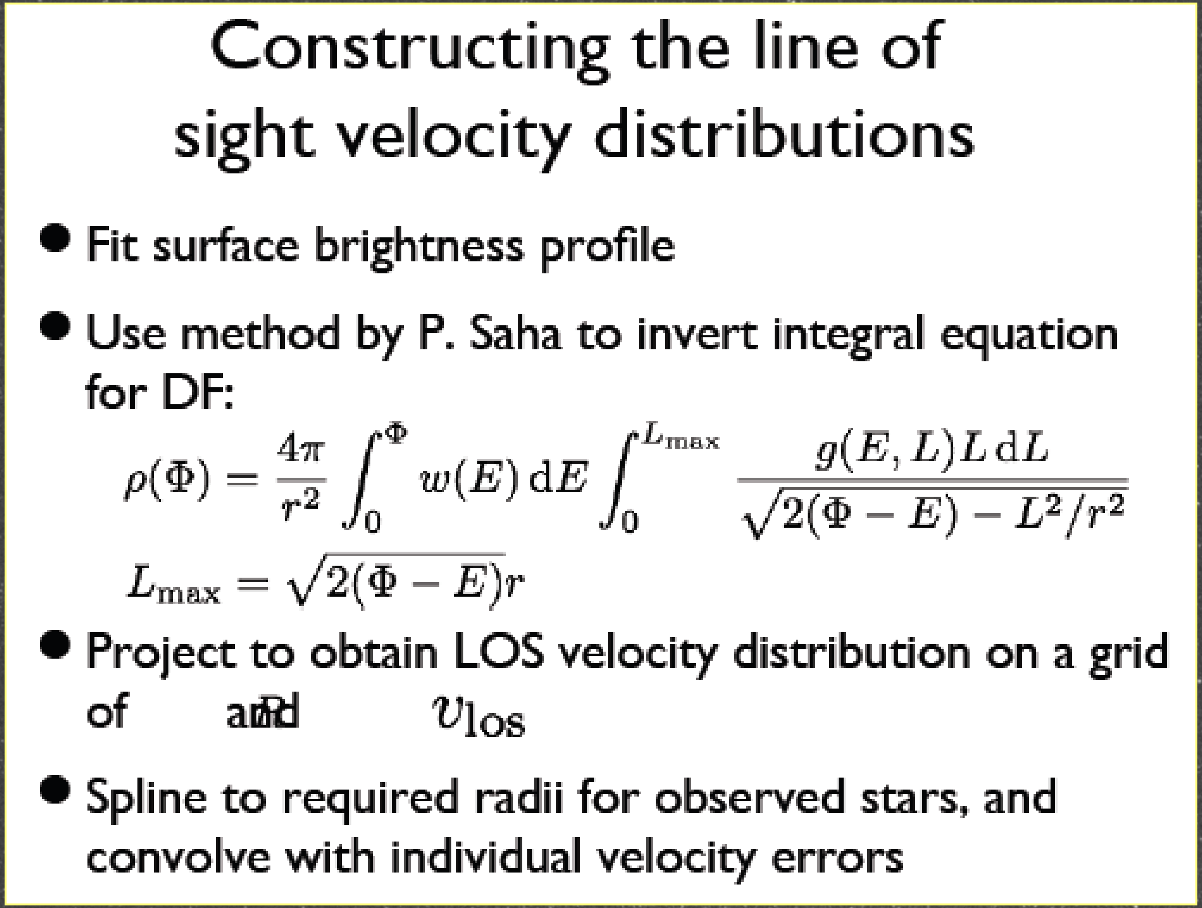
$$\rho_{\rm halo}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^\gamma \left(1 + \left(\frac{r}{r_s}\right)^{1/\alpha}\right)^{\alpha(\beta-\gamma)}}$$

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

Free parameters: rho_0, r_s, alpha, beta, gamma

M. Wilkinson etal (in prep)

Core vs. Cusp: Stellar Dynamics



Constructing the line of sight velocity distributions

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

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

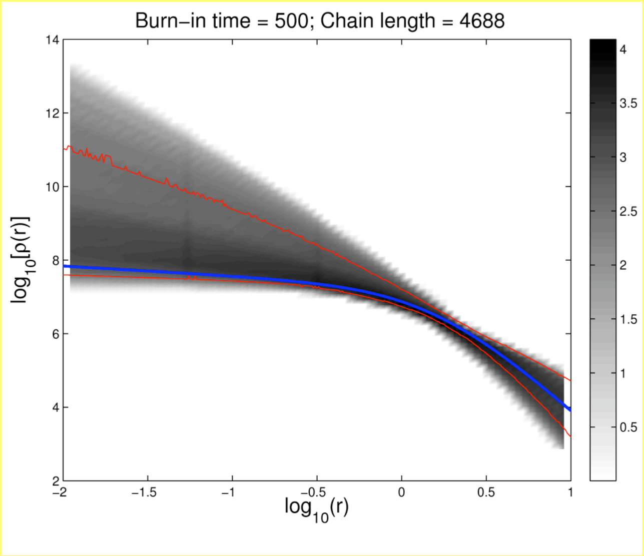
$$L_{\max} = \sqrt{2(\Phi-E)}r$$

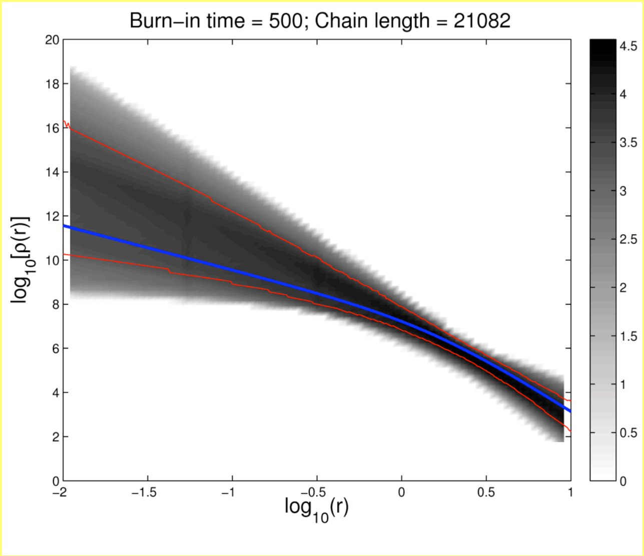
- Project to obtain LOS velocity distribution on a grid of and R v_{los}
- Spline to required radii for observed stars, and convolve with individual velocity errors

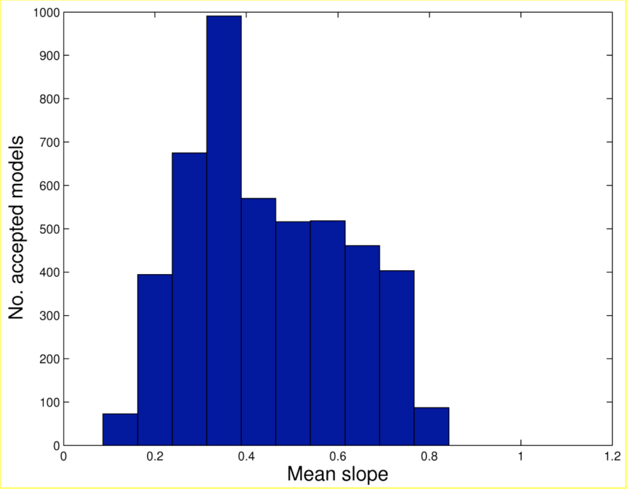
M. Wilkinson etal (in prep)

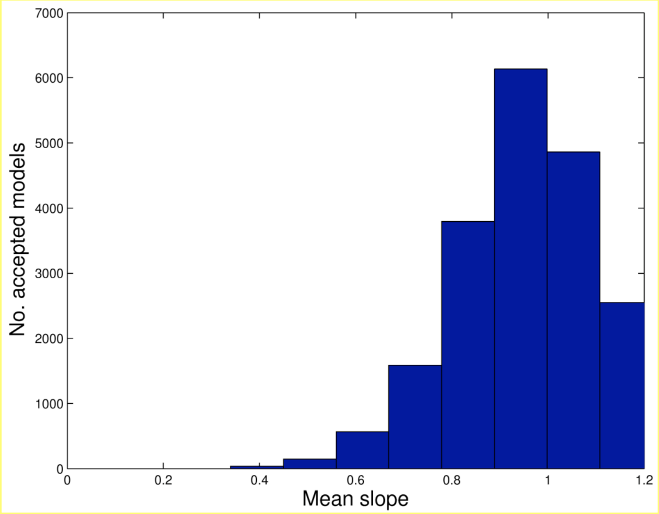
Core vs. Cusp: Tests on artificial data

M. Wilkinson etal. in prep



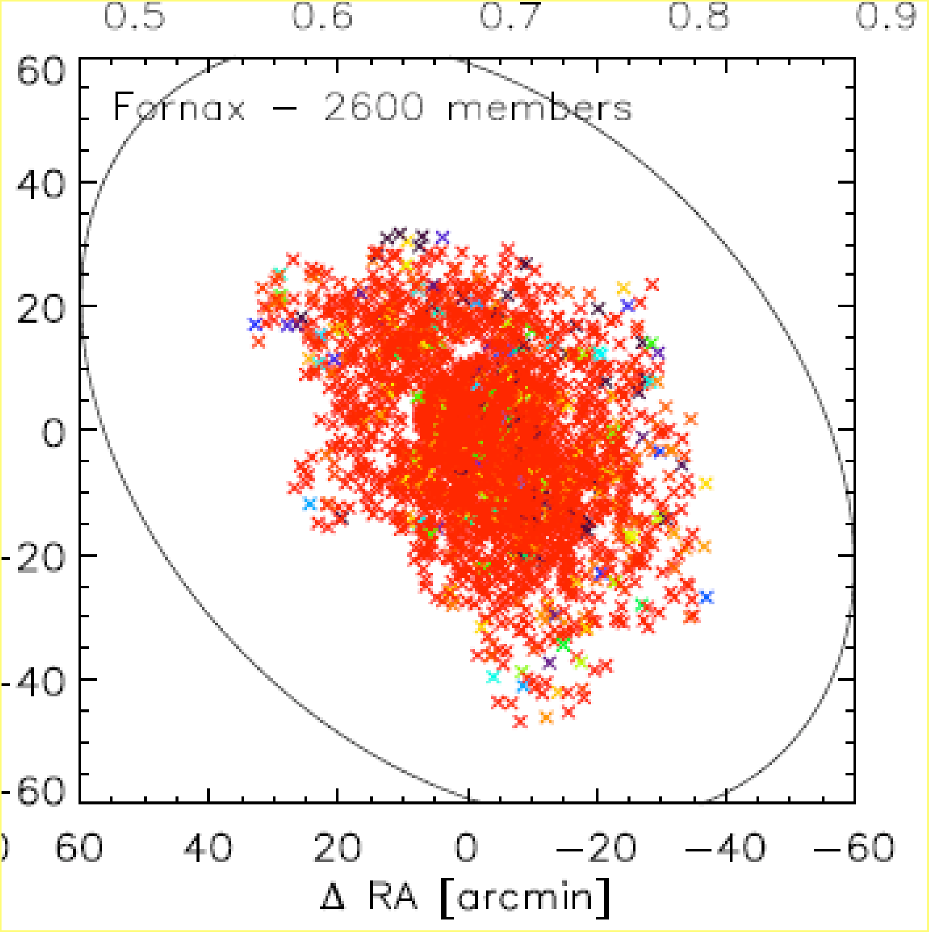






Requirement: ~ 2000 velocities at +/- 2 km/s

Core vs. Cusp: Stay Tuned for a Fornax result!

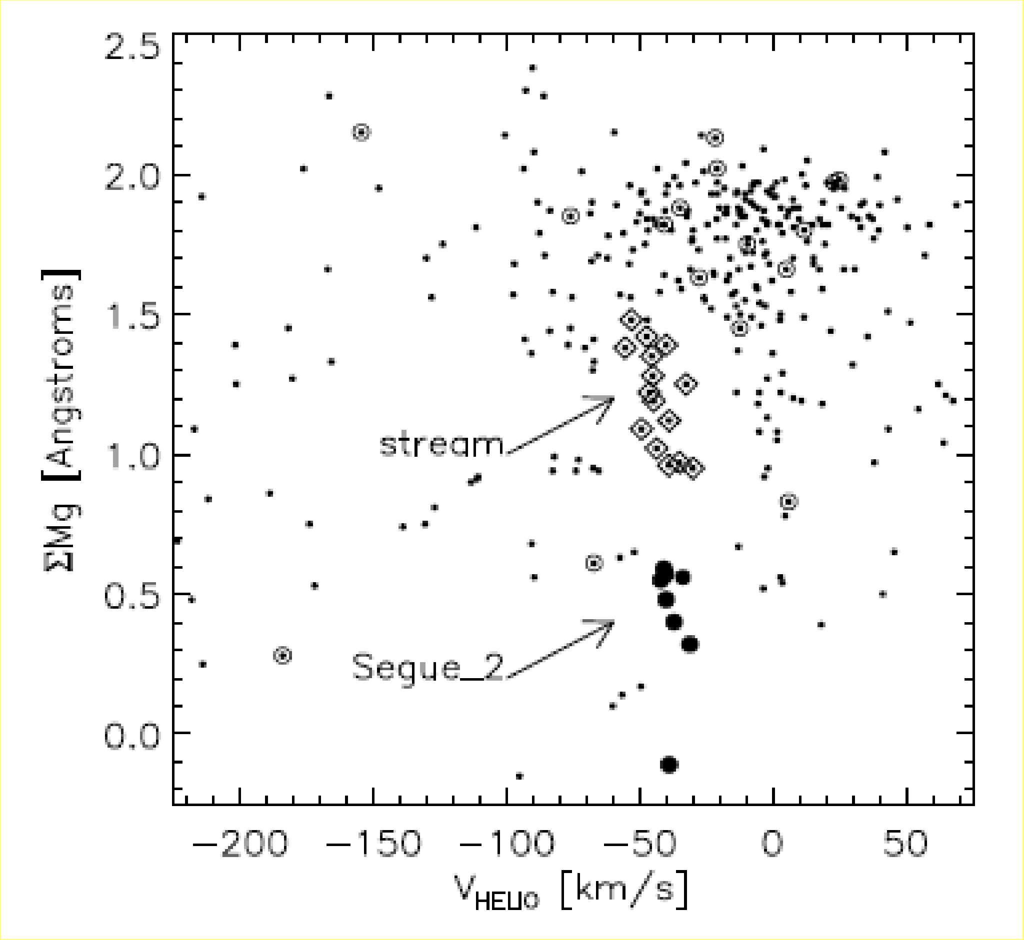


M. Wilkinson etal (in prep)

+ ~400 new members from Septemcer 2009 Magellan/MMFS run

End

Substructure of Substructure: Segue 2 in a stream?



Belokurov etal 2009