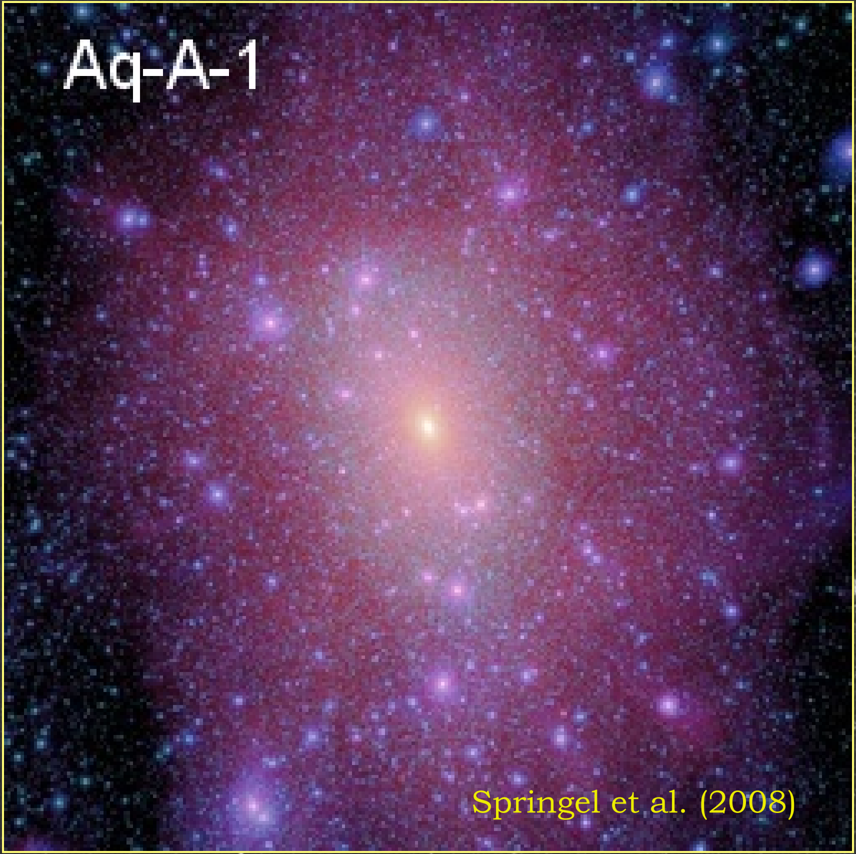
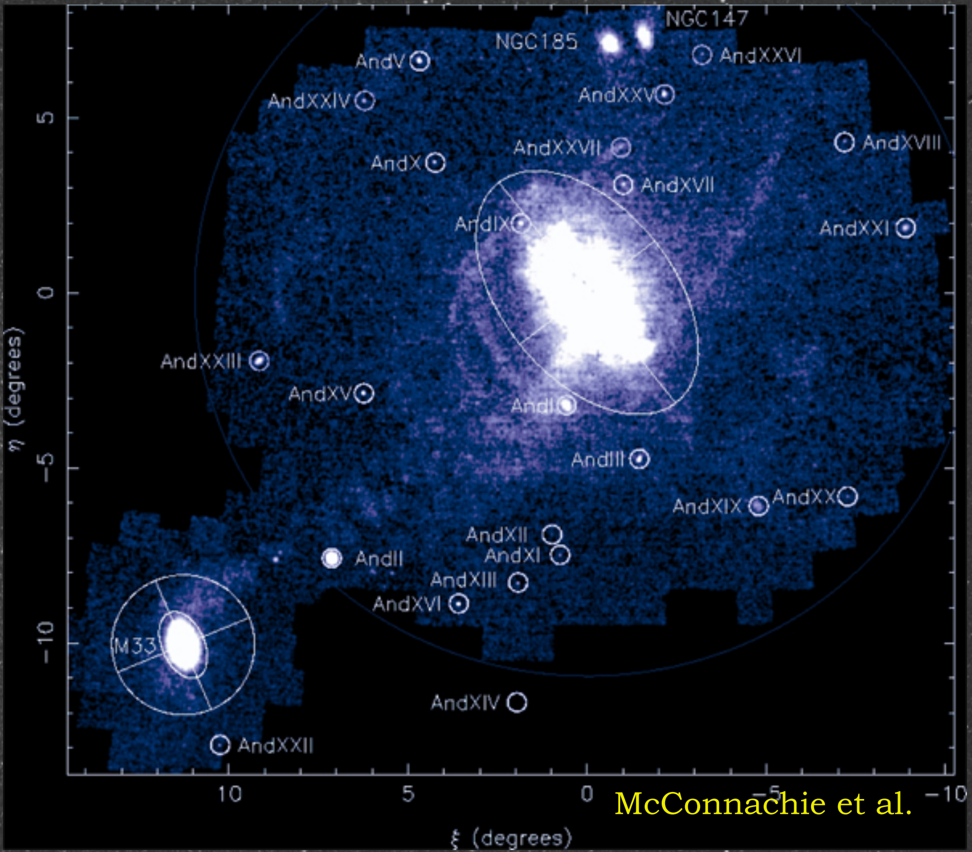
Dark Matter in the Smallest Galaxies

Matthew Walker – Harvard/CfA



Springel et al. (2008)



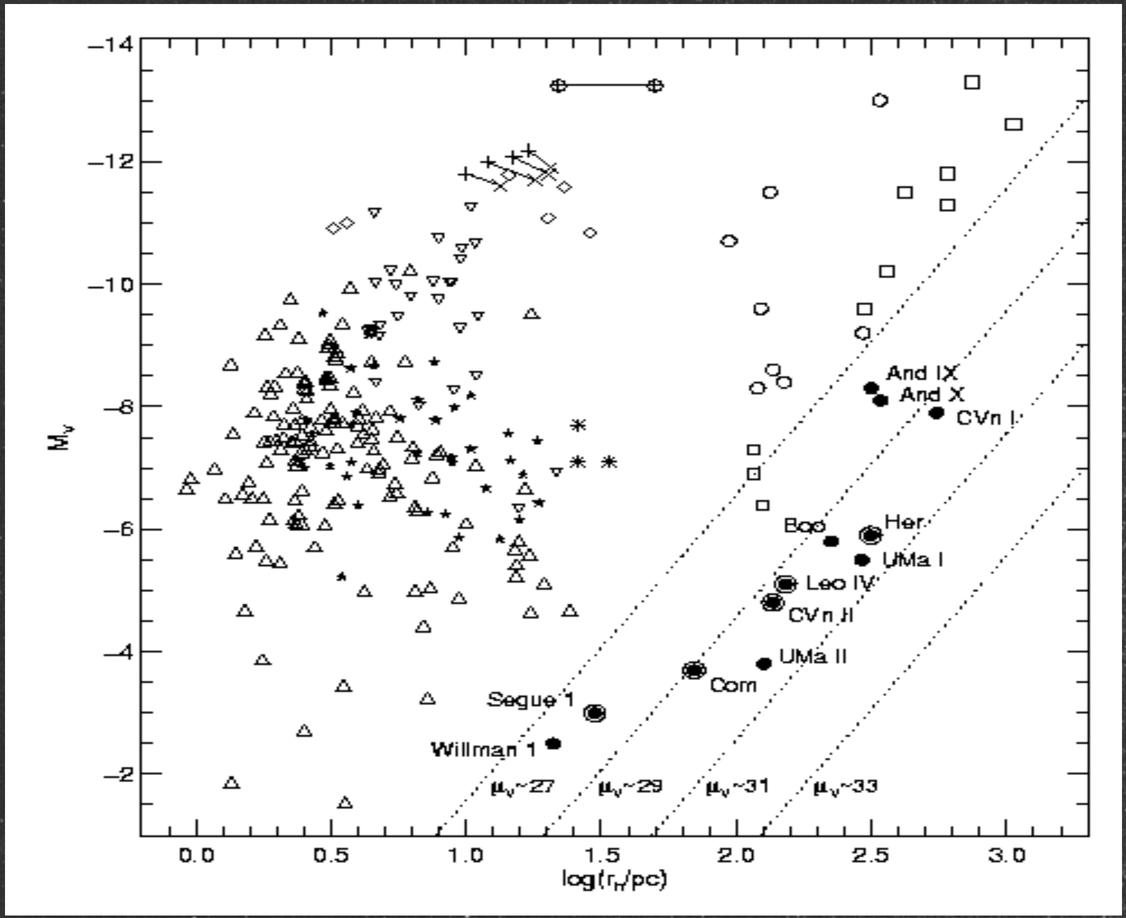
McConnachie et al.

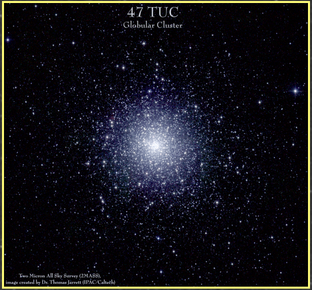
16th Paris Cosmology Colloquium

Observatoire de Paris

26 July 2012

Milky Way Satellites





Belokurov et al. 2007

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

Cold Dark Matter in N-body simulations

THE STRUCTURE OF COLD DARK MATTER HALOS

JOHN DUBINSKI AND R. G. CARLBERG
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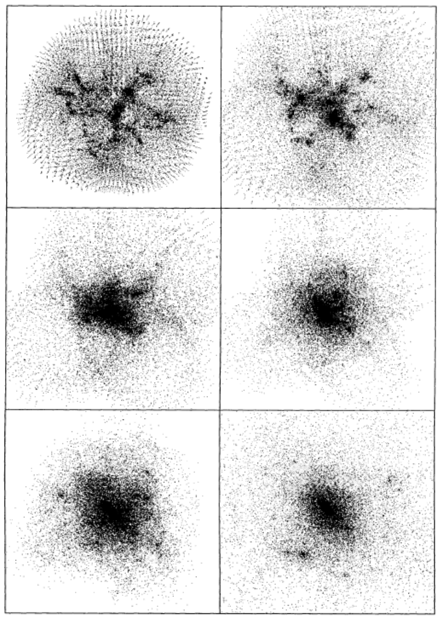
Received 1990 December 26; accepted 1991 March 22

ABSTRACT

The density profiles and shapes of dark halos are studied using the results of N-body simulations of the gravitational collapse of density peaks. The simulations use from 3×10^4 to 3×10^5 particles, which allow density profiles and shapes to be well resolved. The core radius of a typical dark halo is found to be no greater than the softening radius, $\epsilon = 1.4$ kpc. The density profiles can be fitted with an analytical model with an effective power law which varies between -1 in the center to -4 at large radii. The dark halos have circular velocity curves which behave like the circular velocity contribution of the dark component of spiral galaxies inferred from rotation curve decompositions. The halos are strongly triaxial and very flat, with $\langle c/a \rangle = 0.50$ and $\langle b/a \rangle = 0.71$. There are roughly equal numbers of dark halos with oblate and prolate forms. The distribution of ellipticities in projection for dark halos reaches a maximum at $\epsilon = 0.5$, in contrast to the ellipticity distribution of elliptical galaxies, which peaks at $\epsilon = 0.2$.

Subject headings: dark matter — galaxies: structure — numerical methods

Dubinski & Carlberg (1991)



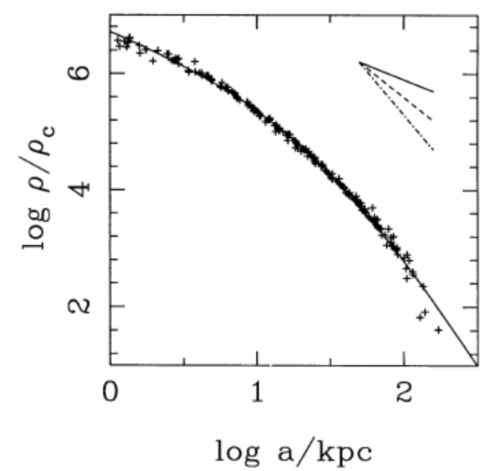


FIG. 2.—Density profiles of dark halos. Density is in units of the critical density ρ_c, and the elliptical radius a is in kpc. Thirteen points were used for the two-parameter fit of Hernquist's profile for each of the 14 halos. Each set of points has been renormalized to the fiducial Hernquist profile, with $r_s = 28$ kpc and $M_s = 2.1 \times 10^{12}\ M_\odot$ represented by the solid line. The lines in the upper right-hand corner present power-law slopes of -1, -2, and -3, respectively.

Cold Dark Matter in N-body simulations

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

Navarro, Frenk & White (NFW) 1997

THE ASTROPHYSICAL JOURNAL, 490: 493–508, 1997 December 1

A UNIVERSAL DENSITY PROFILE FROM HIERARCHICAL CLUSTERING

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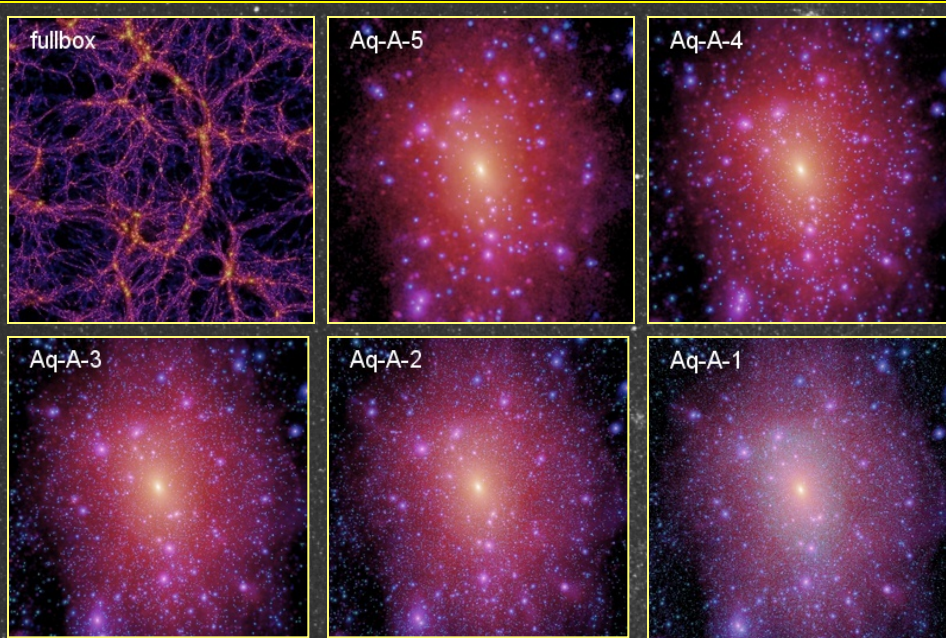
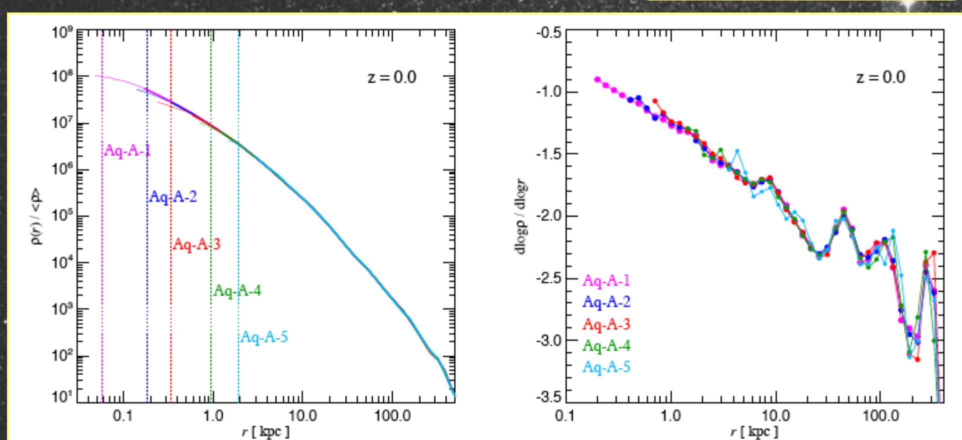
Received 1996 November 13; accepted 1997 July 15

ABSTRACT

We use high-resolution *N*-body simulations to study the equilibrium density profiles of dark matter halos in hierarchically clustering universes. We find that all such profiles have the same shape, independent of the halo mass, the initial density fluctuation spectrum, and the values of the cosmological parameters. Spherically averaged equilibrium profiles are well fitted over two decades in radius by a simple formula originally proposed to describe the structure of galaxy clusters in a cold dark matter universe. In any particular cosmology, the two scale parameters of the fit, the halo mass and its characteristic density, are strongly correlated. Low-mass halos are significantly denser than more massive systems, a correlation that reflects the higher collapse redshift of small halos. The characteristic density of an equilibrium halo is proportional to the density of the universe at the time it was assembled. A suitable definition of this assembly time allows the same proportionality constant to be used for all the cosmologies that we have tested. We compare our results with previous work on halo density profiles and show that there is good agreement. We also provide a step-by-step analytic procedure, based on the Press-Schechter formalism, that allows accurate equilibrium profiles to be calculated as a function of mass in any hierarchical model.
Subject headings: cosmology: theory — dark matter — galaxies: halos — methods: numerical

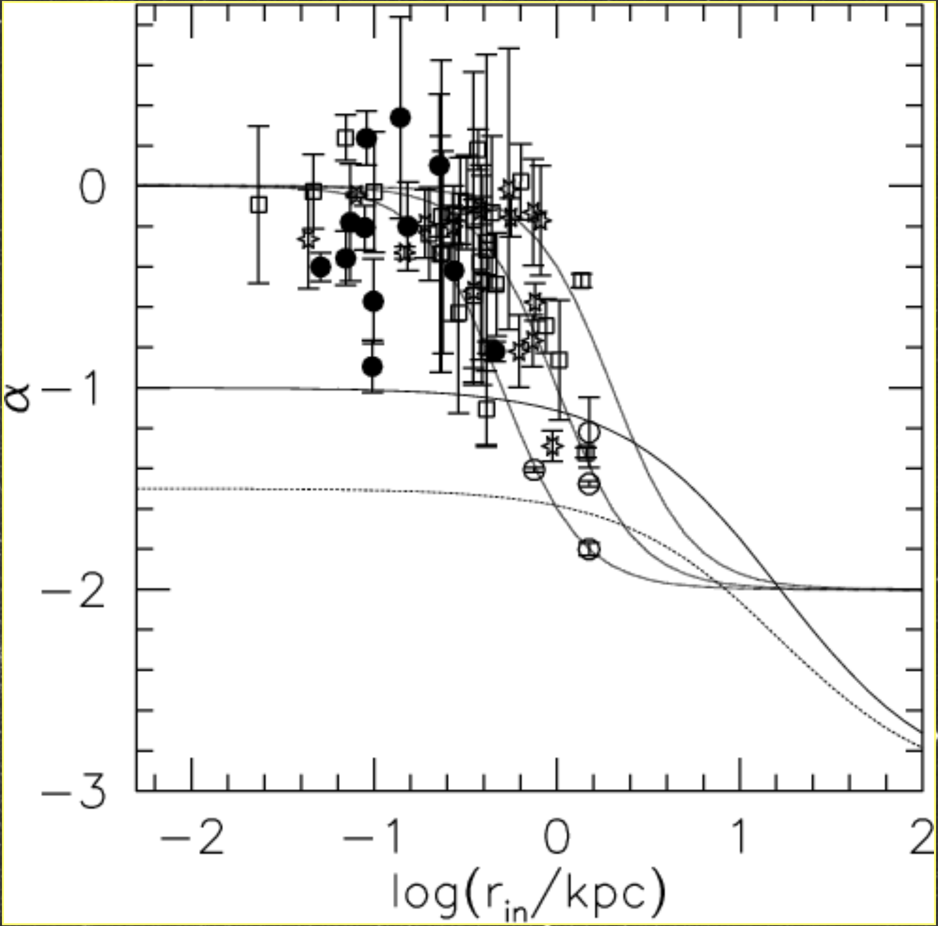
Cold Dark Matter in N-body simulations





Springel etal. 2008, also
Diemand et al., Kuhlen et al.

Data for spiral galaxies



de Blok & Bosma (2002)

BARYONS!

1996MNRAS.2

The cores of dwarf galaxy haloes

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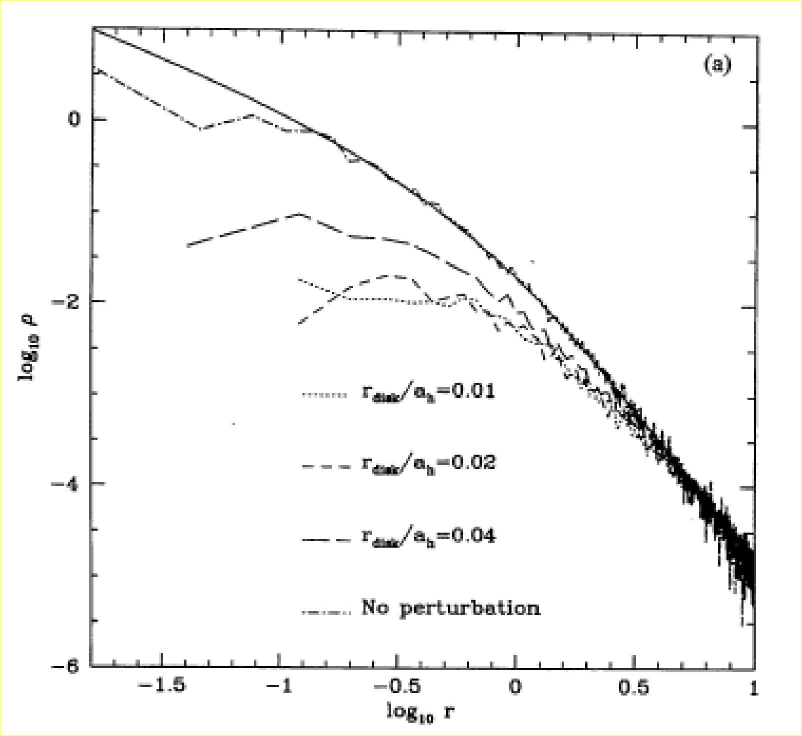
[2]Physics Department, University of Durham, South Road, Durham DH1 3LE

Accepted 1996 September 2. Received 1996 August 28; in original form 1996 June 26

ABSTRACT
We use *N*-body simulations to examine the effects of mass outflows on the density profiles of cold dark matter (CDM) haloes surrounding dwarf galaxies. In particular, we investigate the consequences of supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy disc after a vigorous episode of star formation. We show that this sudden loss of mass leads to the formation of a core in the dark matter density profile, although the original halo is modelled by a coreless (Hernquist) profile. The core radius thus created is a sensitive function of the mass and radius of the baryonic disc being blown up. The loss of a disc with mass and size consistent with primordial nucleosynthesis constraints and angular momentum considerations imprints a core radius that is only a small fraction of the original scalelength of the halo. These small perturbations are, however, enough to reconcile the rotation curves of dwarf irregulars with the density profiles of haloes formed in the standard CDM scenario.

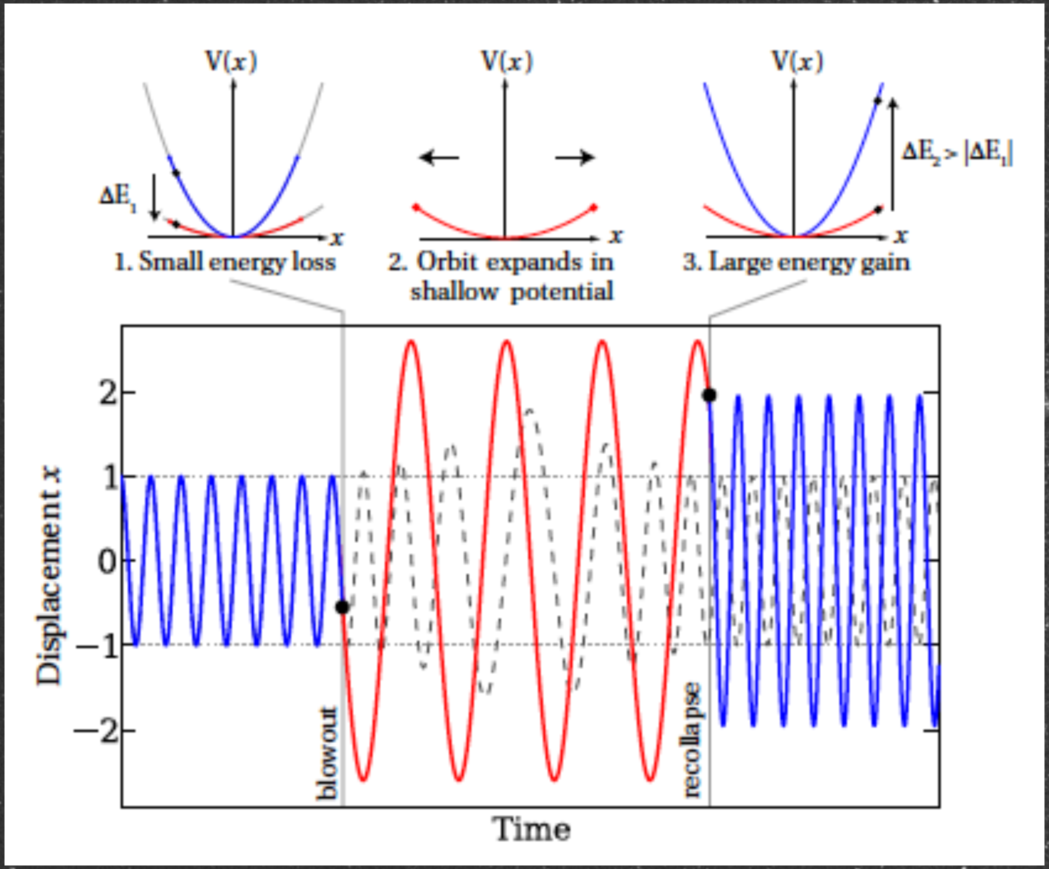
Navarro etal. (1996)

-Blowout of baryons can transform cusp into core as halo readjusts.



How supernova feedback turns dark matter cusps into cores

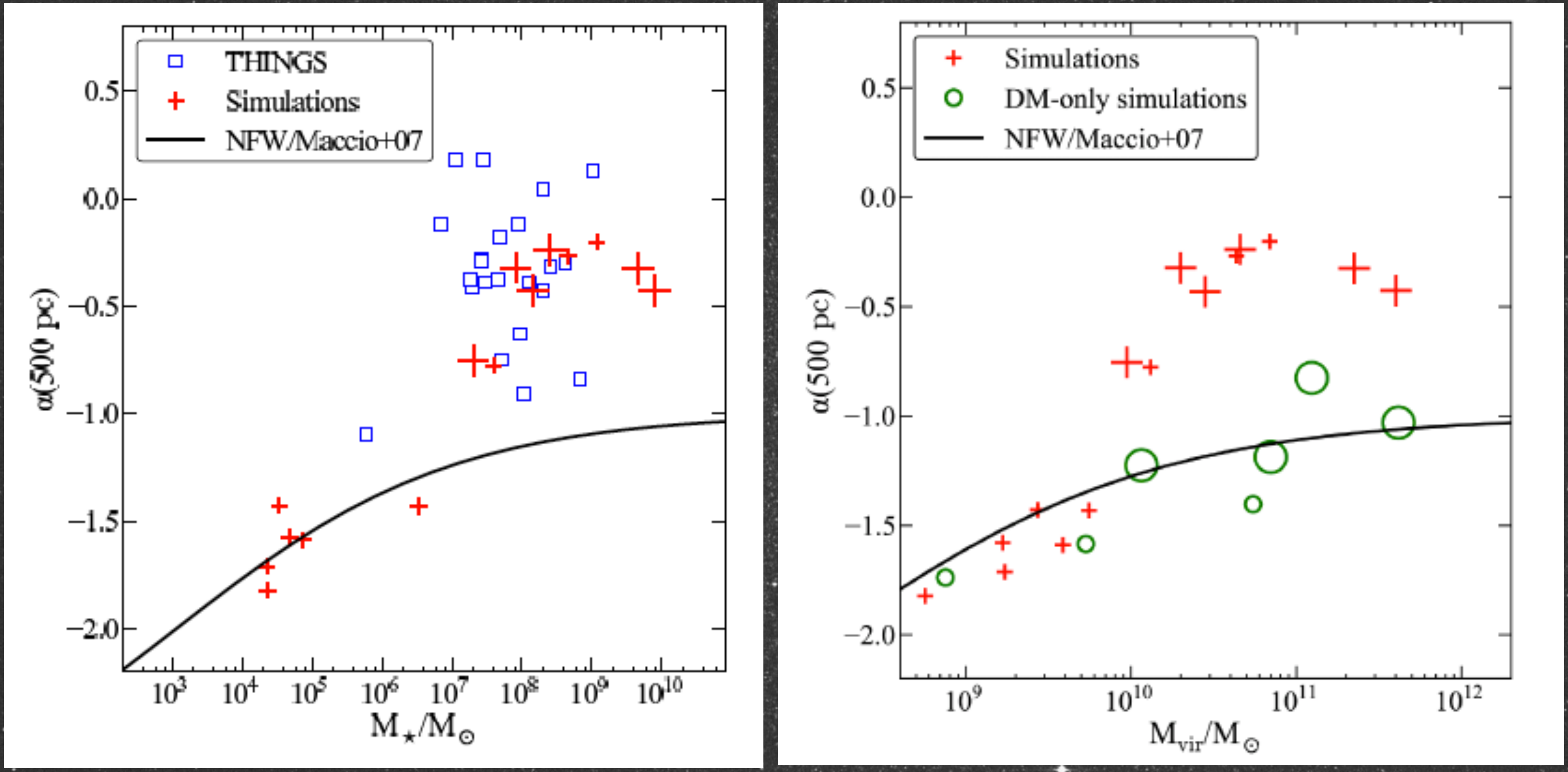
Andrew Pontzen[1,2,3★], Fabio Governato[4]
[1] Kavli Institute for Cosmology and Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
[2] Emmanuel College, St Andrew's Street, Cambridge, CB2 3AP UK
[3] Oxford Astrophysics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK
[4] Astronomy Department, University of Washington, Seattle, WA 98195, USA



Pontzen & Governato (2012)

Cuspy No More: How Outflows Affect the Central Dark Matter and Baryon Distribution in ΛCDM Galaxies.

F.Governato[1⋆] A.Zolotov[2], A.Pontzen[3], C.Christensen[4], S.H.Oh[5,6], A. M.Brooks[7], T.Quinn[1], S.Shen[8], J.Wadsley[9]



Governato etal. (2012)

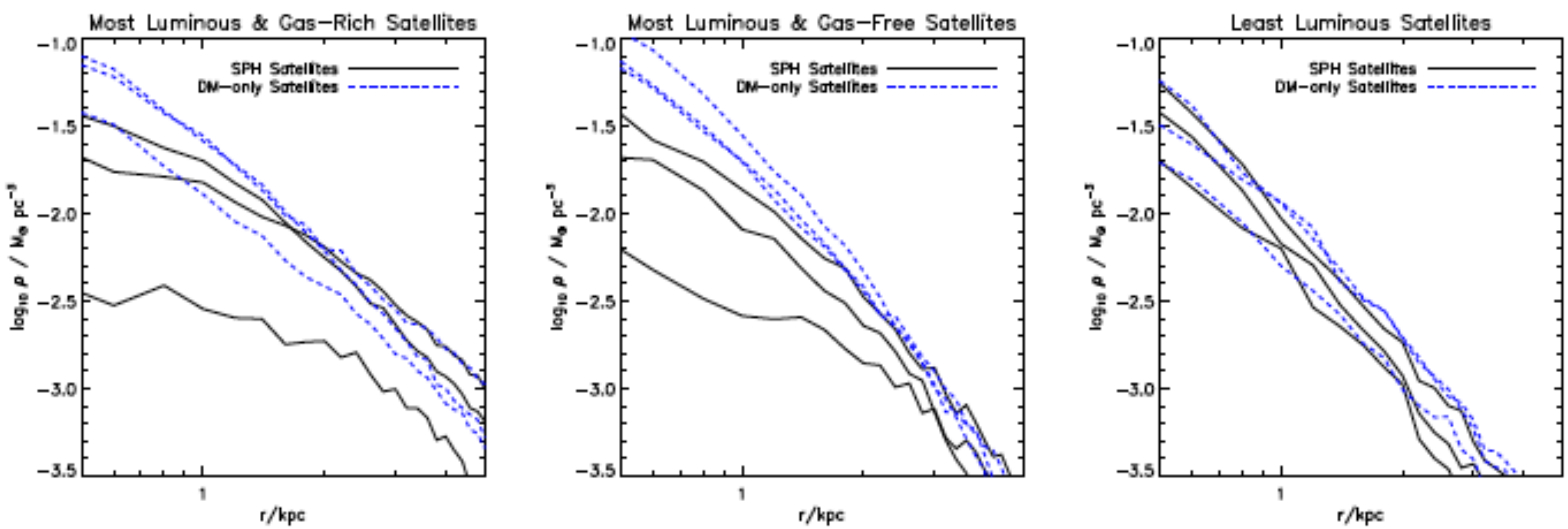
WHY BARYONS MATTER: THE KINEMATICS OF DWARF SPHEROIDAL SATELLITES

Alyson M. Brooks[1], Adi Zolotov[2]

(Dated: July 12, 2012)
Submitted for publication in ApJ Letters

ABSTRACT

We use some of the highest resolution cosmological simulations ever produced of Milky Way-mass galaxies that include both baryons and dark matter to show that baryonic physics (energetic feedback from supernovae and subsequent tidal stripping) significantly reduces the dark matter mass in the central regions of luminous satellite galaxies. The reduced central masses of the simulated satellites reproduce the observed internal dynamics of Milky Way and M31 satellites as a function of luminosity. Including baryonic physics in Cold Dark Matter models naturally explains the observed low dark matter densities in the Milky Way's dwarf spheroidal population. Our simulations therefore resolve the tension between kinematics predicted in Cold Dark Mater theory and observations of satellites, without invoking alternative forms of dark matter.



Zolotov etal. (arXiv:1207.0007), Brooks & Zolotov (arXiv:1207.2468

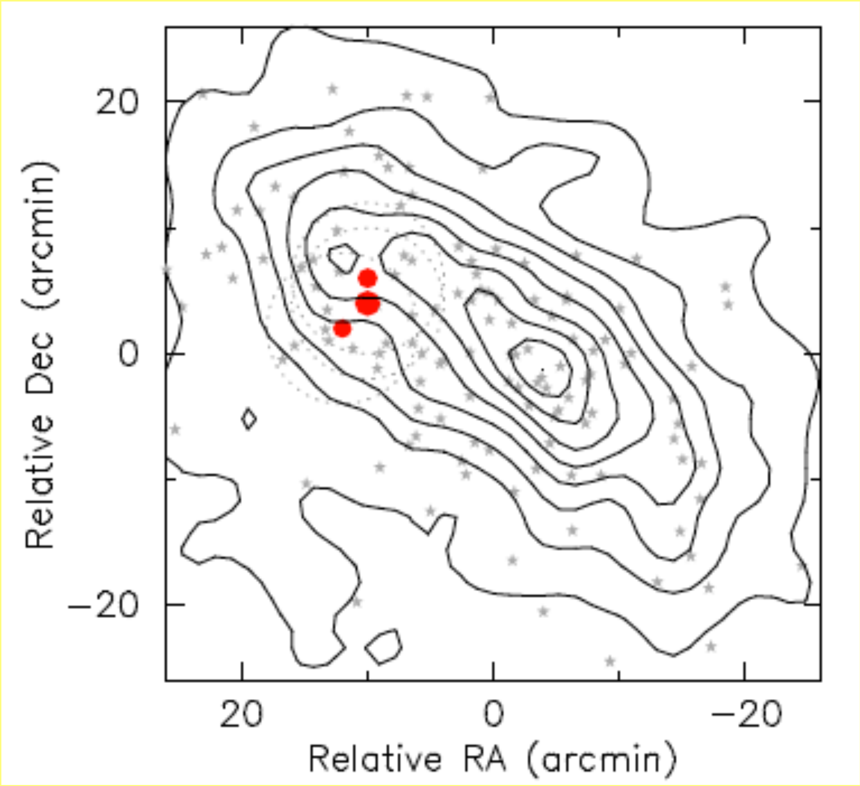
(Indirect) Evidence for Cores in dSphs

Fornax globular clusters

Goerdt et al. (2006);

Cole et al. (2012)

Ursa Minor substructure

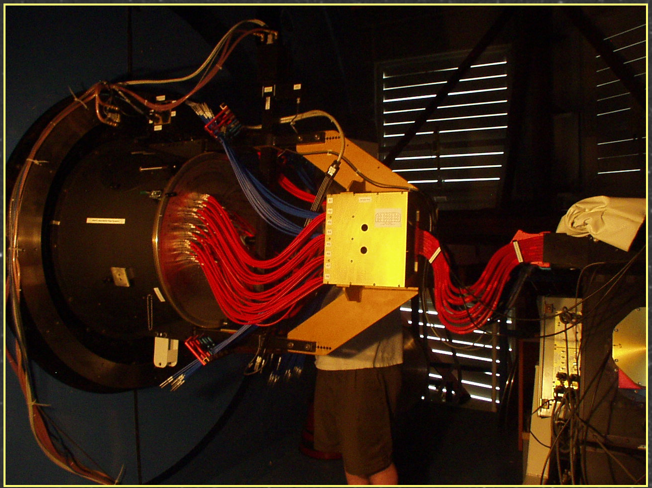


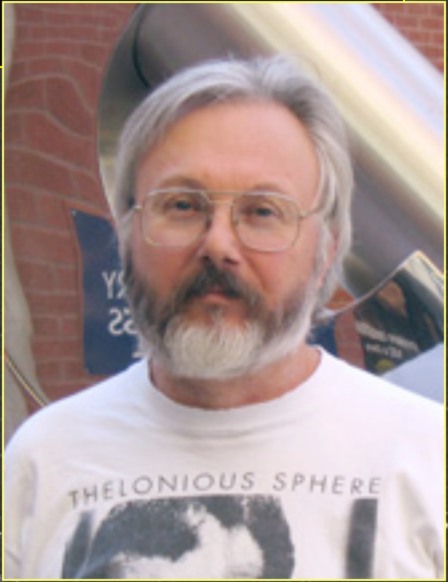
Kleyna et al. (2003)

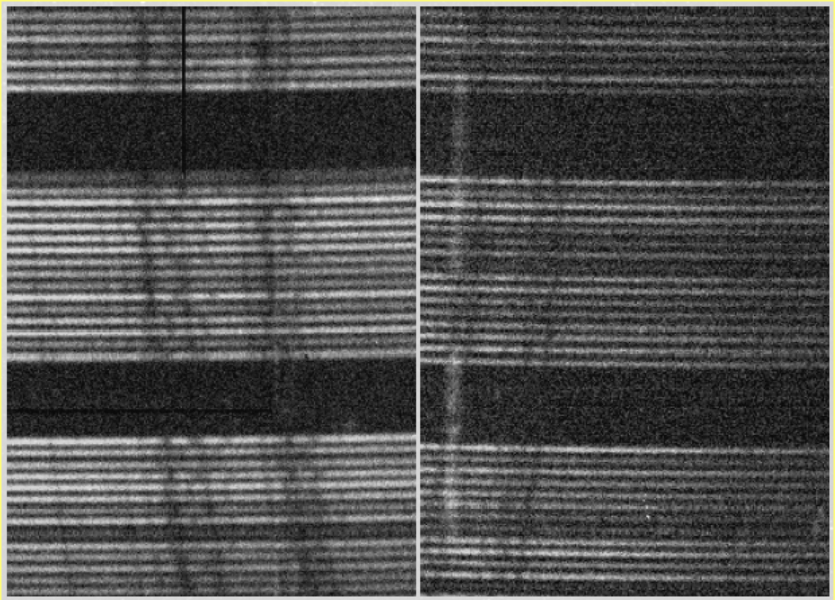
Lora et al (2012)

Magellan Spectroscopic Observations

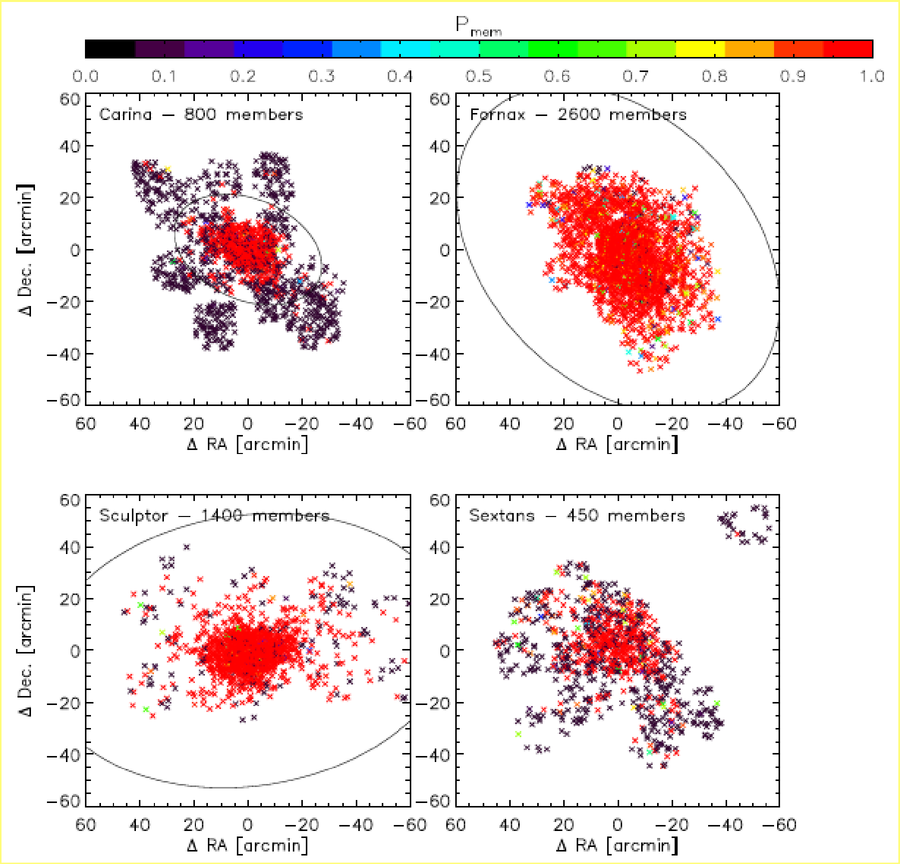
w/ Mario Mateo & Ed Olszewski

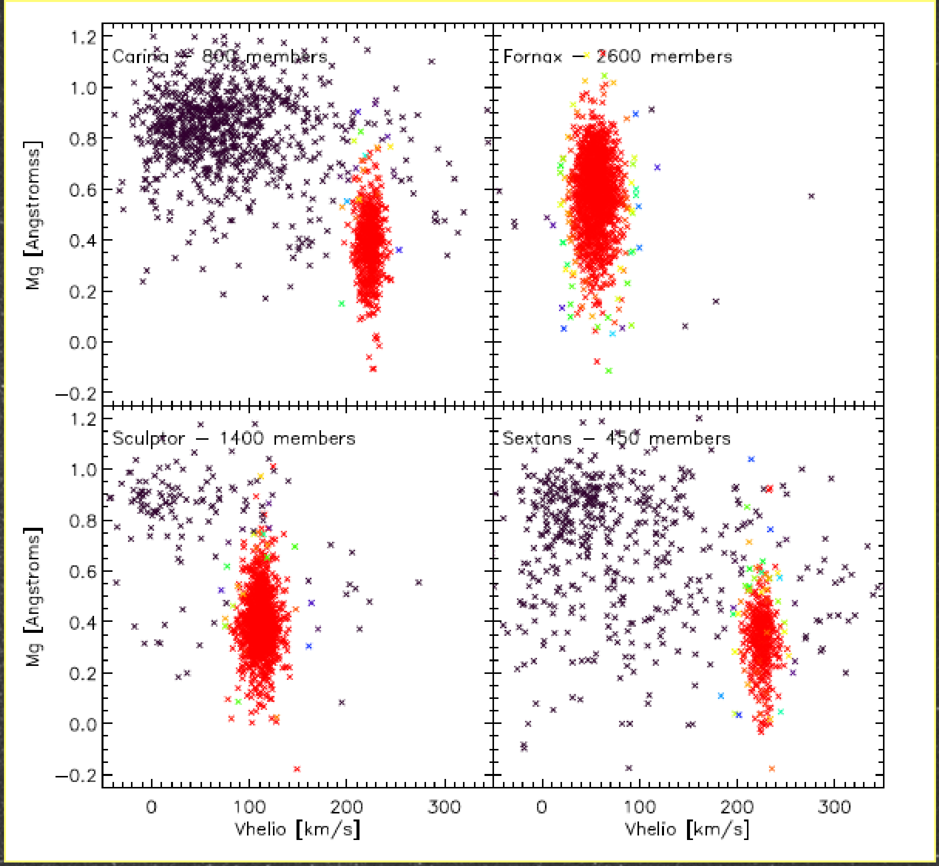






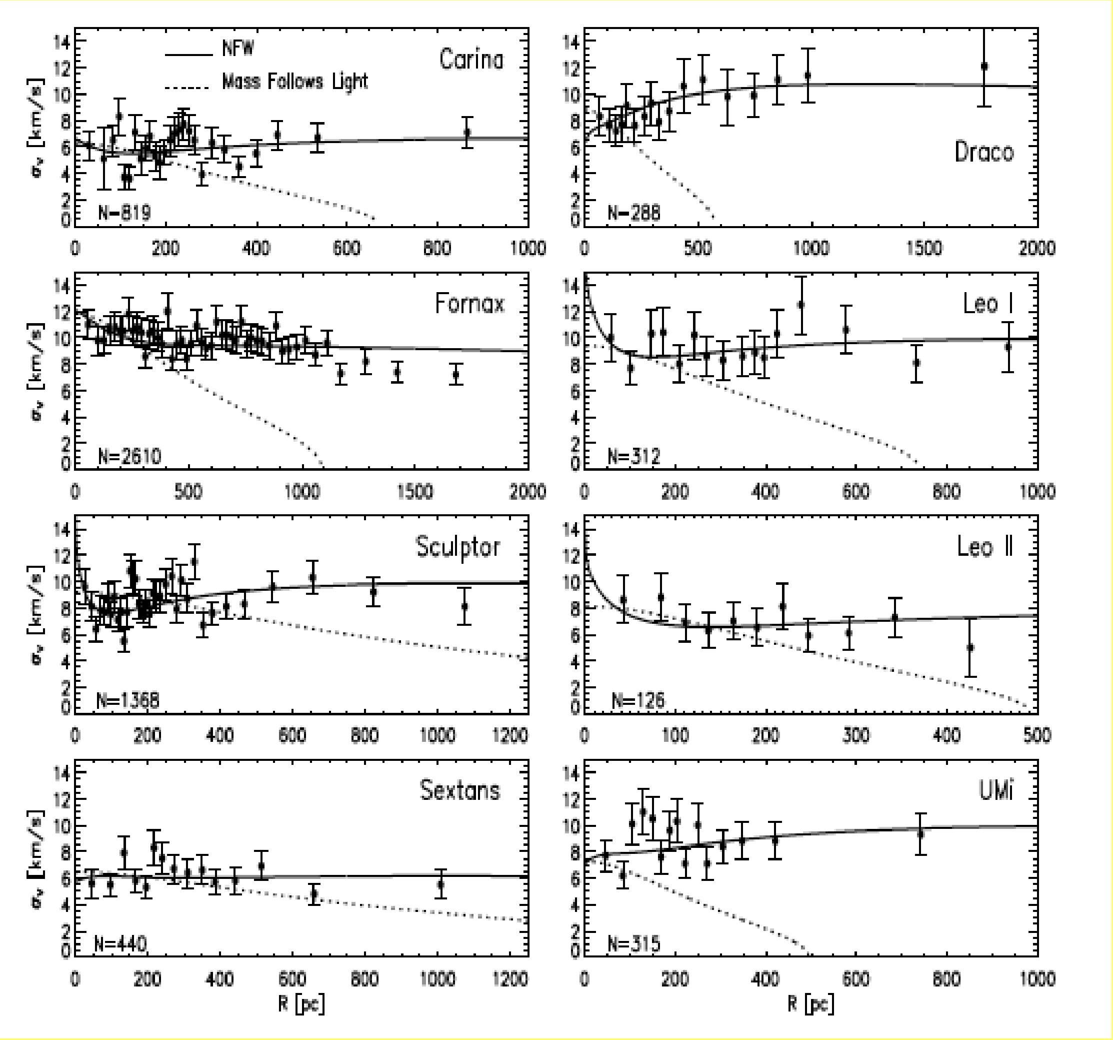
Data: Magellan Samples





Walker etal (2009)

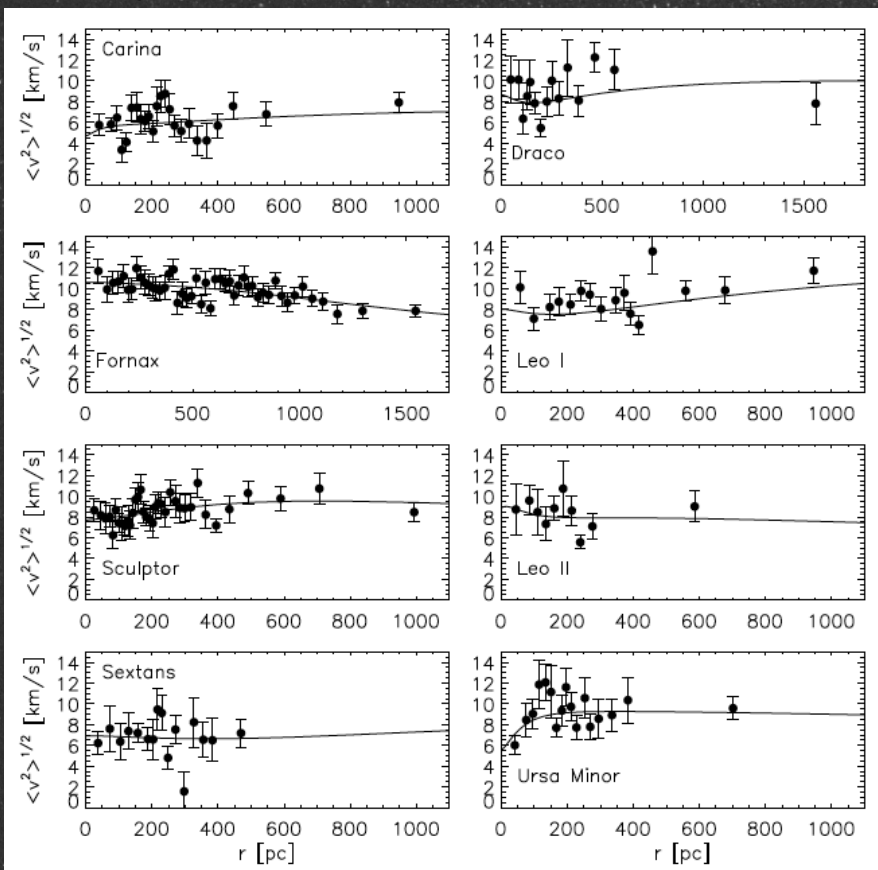
Velocity Dispersion Profiles for 'Classical' dSphs

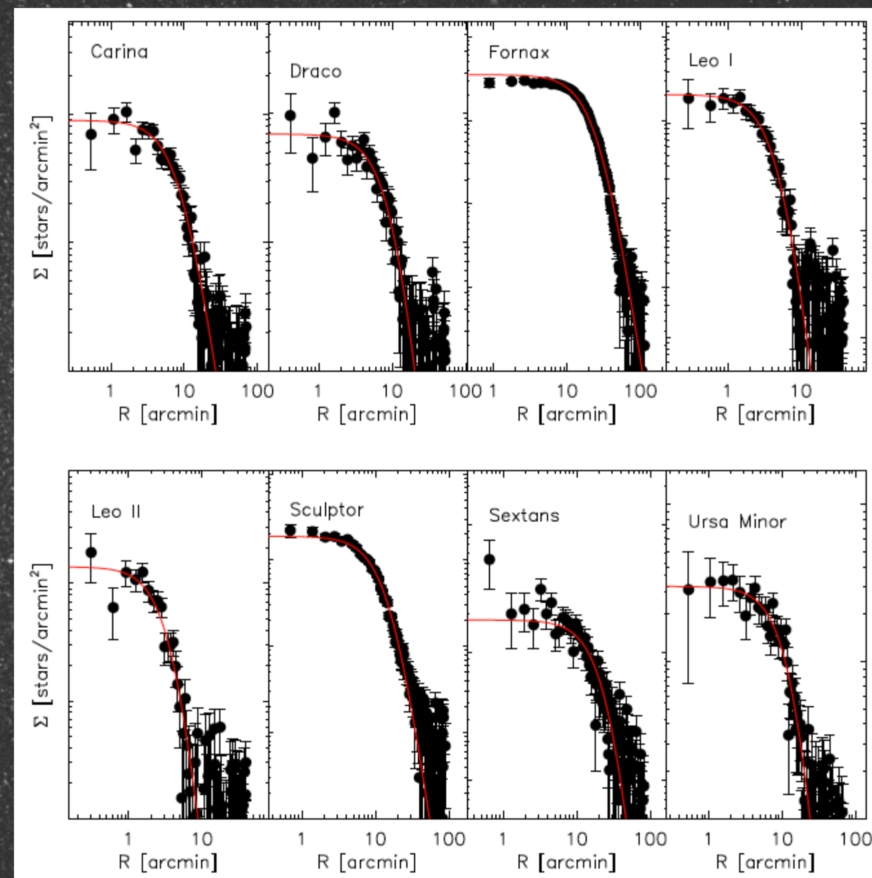


Walker etal. 2009

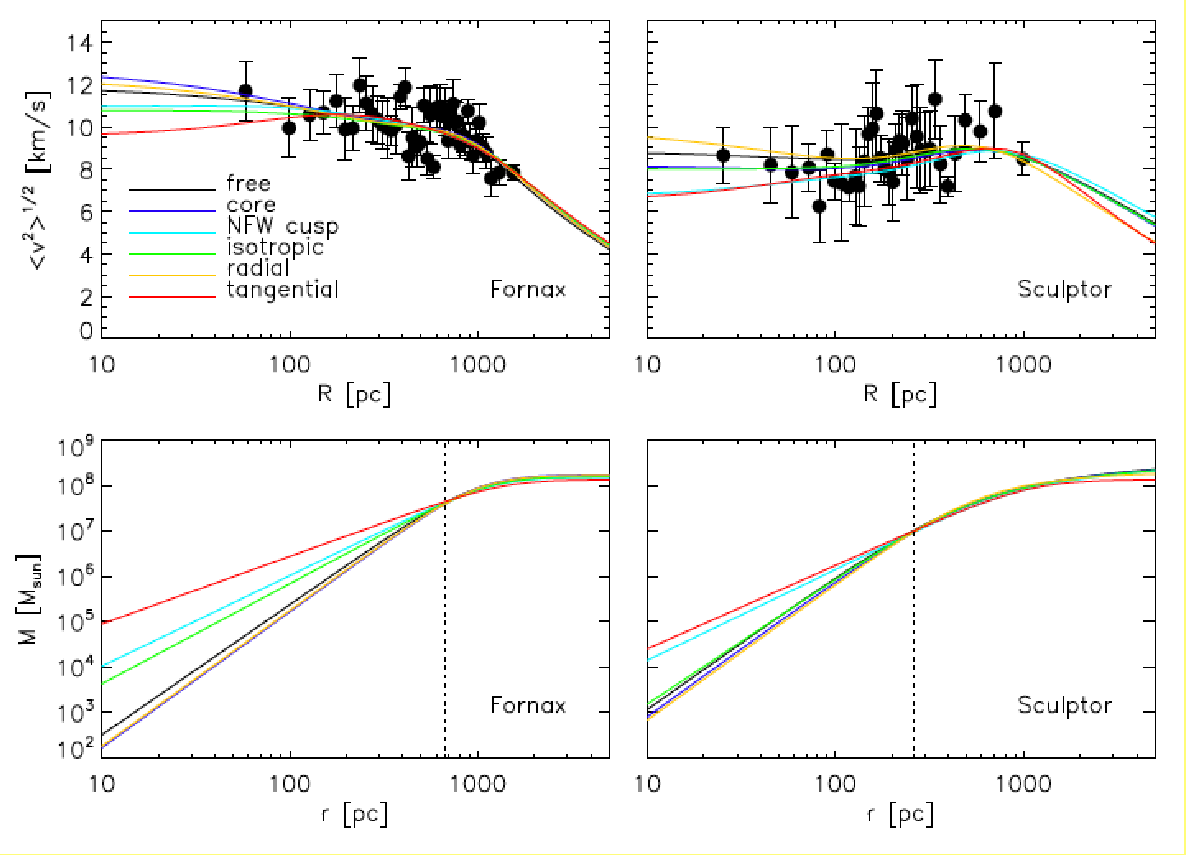
Kinematics with the Jeans Equation: Fits to Data

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





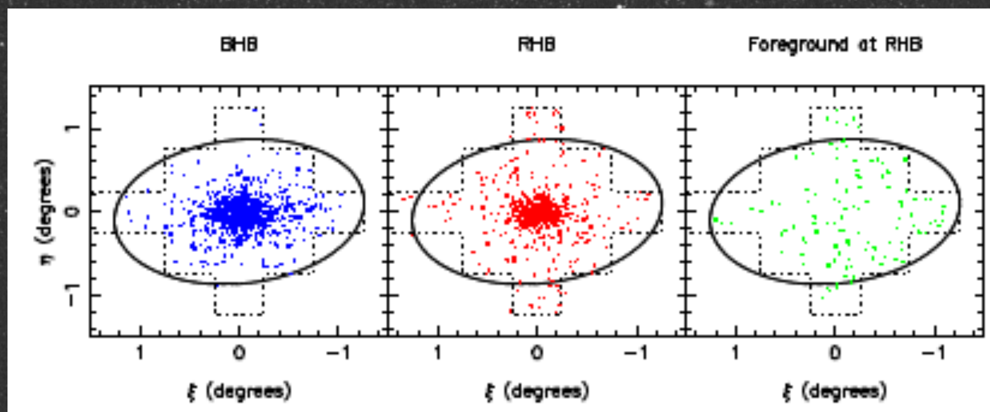
Kinematics with the Jeans Equation



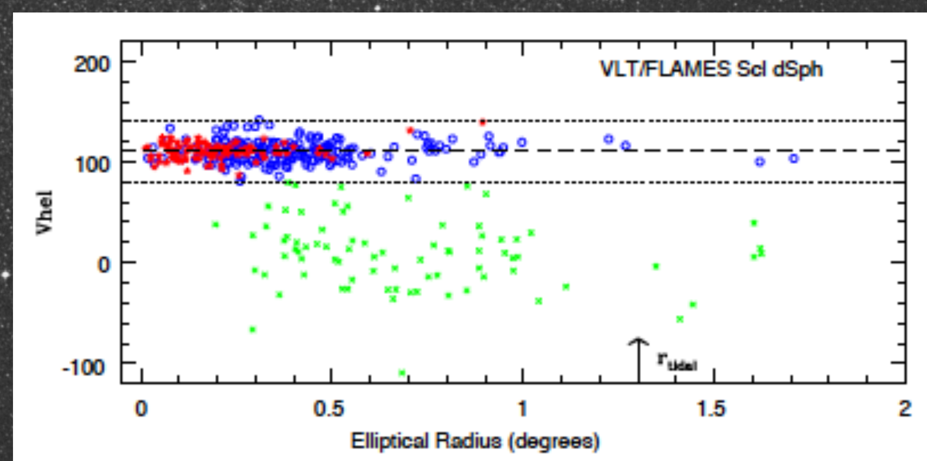
$$M(R_{half}) \sim 5\sigma_V^2 \frac{R_{half}}{2G}$$

Two distinct ancient components in the Sculptor Dwarf Spheroidal Galaxy: First Results from DART[1]

Eline Tolstoy[2], M.J. Irwin[3], A. Helmi[2], G. Battaglia[2], P. Jablonka[4], V. Hill[4], K.A. Venn[5], M.D. Shetrone[6], B. Letarte[2], A.A. Cole[2], F. Primas[7], P. Francois[4], N. Arimoto[8], K. Sadakane[8], A. Kaufer[9], T. Szeifert[9], T. Abel[10],

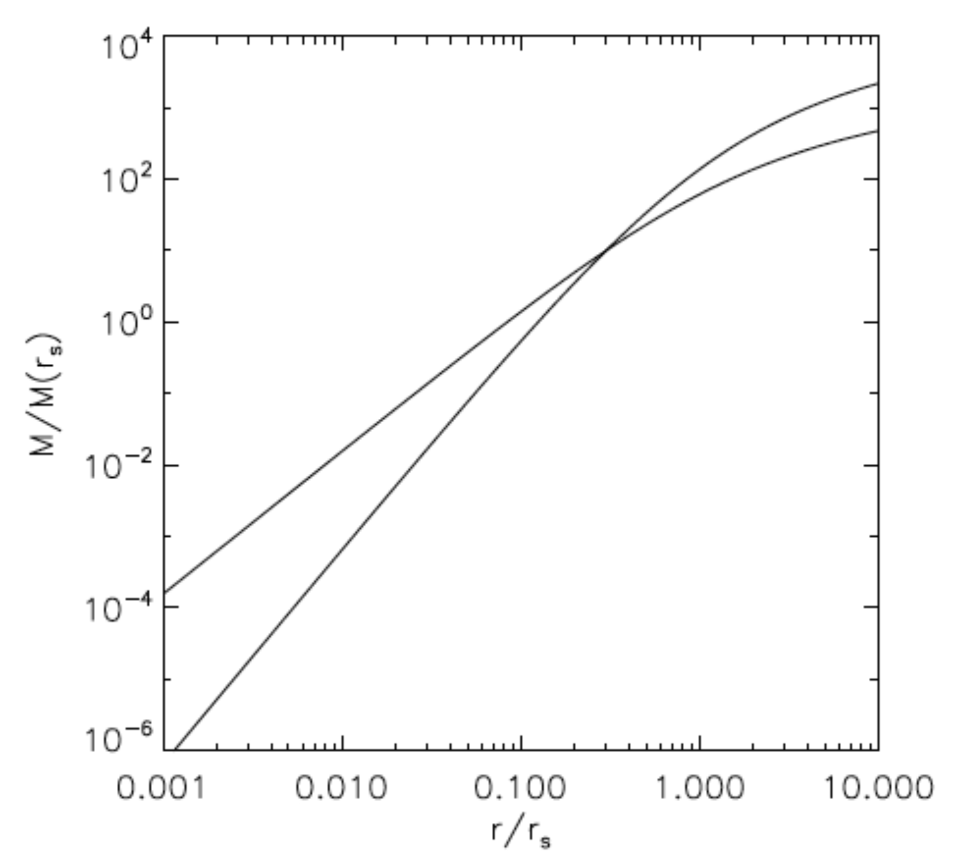


Tolstoy etal (2004)

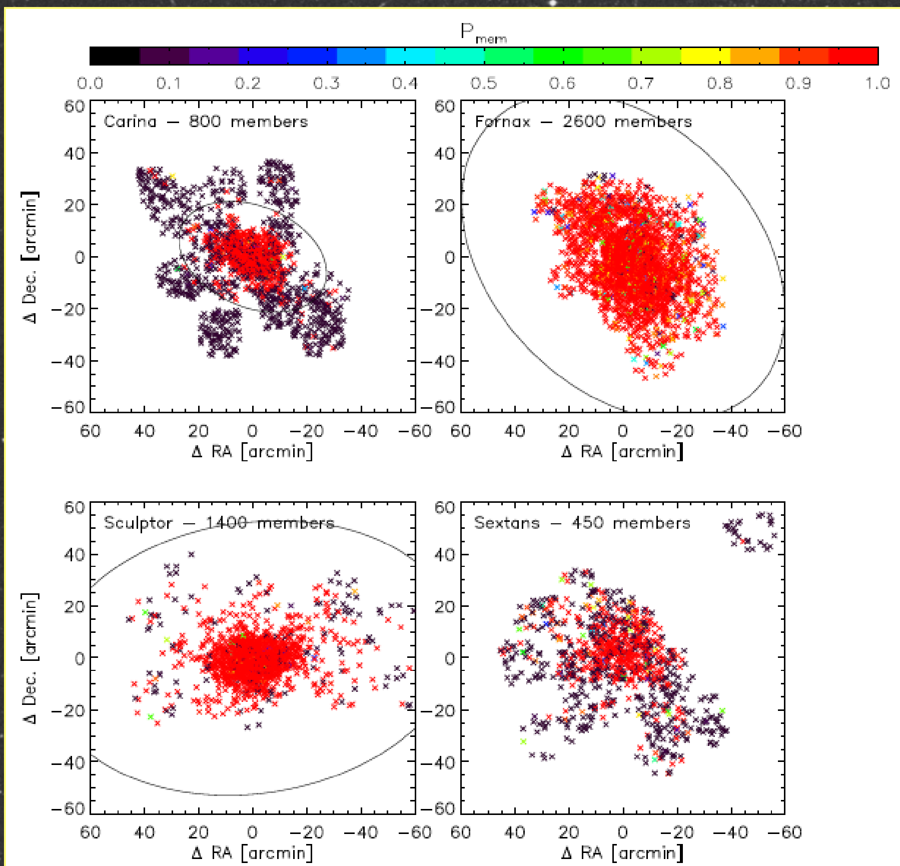


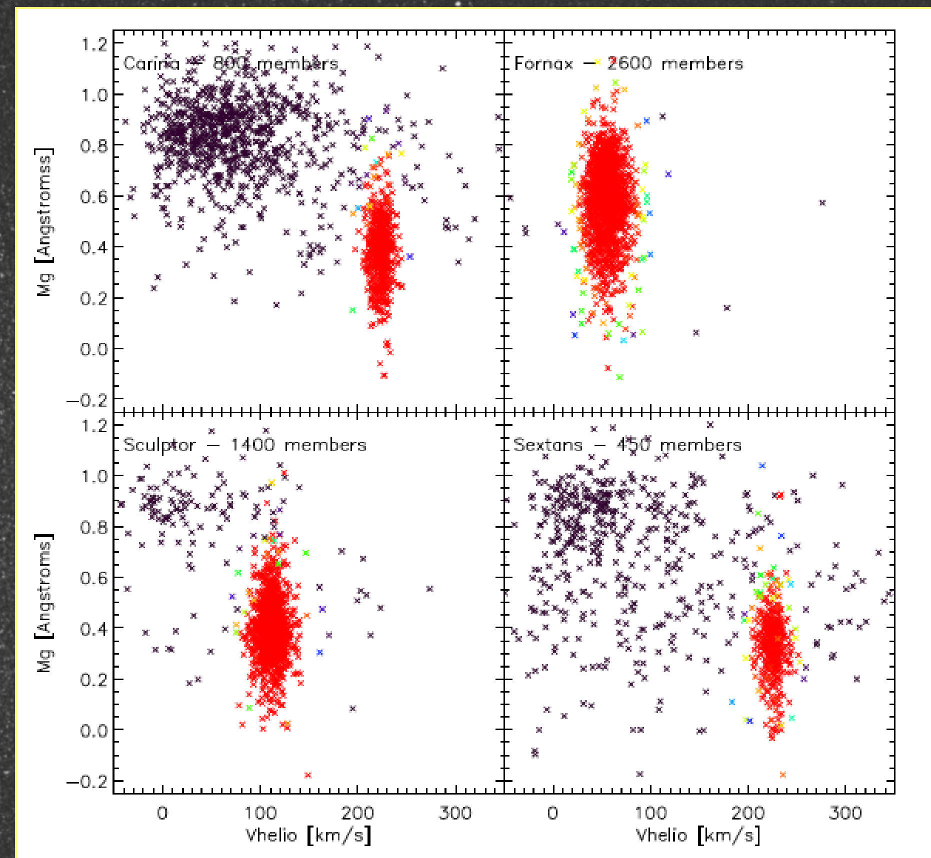
Also: Fornax (Battaglia et al. 2006)Sextans: (Battaglia et al. 2010)

$$M(r_h) \approx \frac{5 r_h \sigma_V^2}{2G}$$



$$\Gamma \equiv \frac{\Delta \log M}{\Delta \log r} = \frac{\log[M(r_{\mathrm{h},2})/M(r_{\mathrm{h},1})]}{\log[r_{\mathrm{h},2}/r_{\mathrm{h},1}]} \approx 1 + \frac{\log[\sigma_{V,2}^2/\sigma_{V,1}^2]}{\log[r_{\mathrm{h},2}/r_{\mathrm{h},1}]}$$





Walker etal (2009)

$$L(\{R_i, V_i, W_i'\}_{i=1}^{N_{\mathrm{sample}}} | \vec{S}) = \prod_{i=1}^{N_{\mathrm{sample}}} \left[f_1 \frac{w(R_i) p_1(R_i, V_i, W_i')}{\int\int\int w(R) p_1(R, V, W') dR dV dW'} + f_2 \frac{w(R_i) p_2(R_i, V_i, W_i')}{\int\int\int w(R) p_2(R, V, W') dR dV dW'} \right.$$
$$\left. + (1 - f_1 - f_2) \frac{w(R_i) p_{\mathrm{MW}}(R_i, V_i, W_i')}{\int\int\int w(R) p_{\mathrm{MW}}(R, V, W') dR dV dW'} \right]$$

$$p_{R,1}(R) = \frac{2R/r_{h,1}^2}{(1 + R^2/r_{h,1}^2)^2}$$

Plummer

$$p_{V,1}(V, \alpha_*, \delta_*) = \frac{1}{\sqrt{2\pi(\sigma_{V,1}^2 + \epsilon_V^2)}} \exp\left[-\frac{1}{2} \frac{(V - \langle V \rangle_{\alpha_*, \delta_*})^2}{\sigma_{V,1}^2 + \epsilon_V^2} \right]$$

Gaussian

$$p_{W,1}(W) = \frac{1}{\sqrt{2\pi(\sigma_{W,1}^2 + \epsilon_W^2)}} \exp\left[-\frac{1}{2} \frac{(W - \langle W \rangle_1)^2}{\sigma_{W,1}^2 + \epsilon_W^2} \right]$$

Gaussian

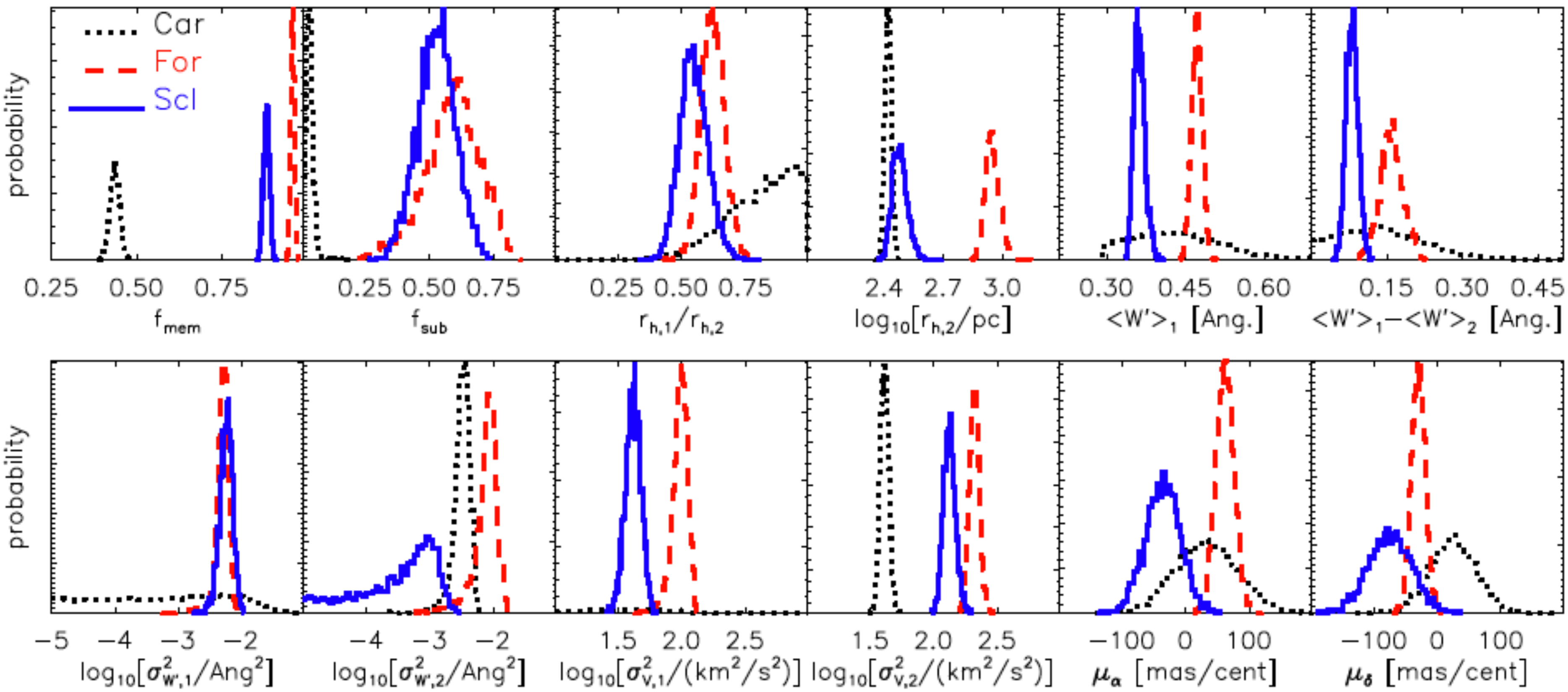
$$L(\{R_i, V_i, W_i'\}_{i=1}^{N_{\rm sample}} | \vec{S}) = \prod_{i=1}^{N_{\rm sample}} \left[f_1 \frac{w(R_i) p_1(R_i, V_i, W_i')}{\int\int\int w(R) p_1(R, V, W') dR dV dW'} + f_2 \frac{w(R_i) p_2(R_i, V_i, W_i')}{\int\int\int w(R) p_2(R, V, W') dR dV dW'} + (1 - f_1 - f_2) \frac{w(R_i) p_{\rm MW}(R_i, V_i, W_i')}{\int\int\int w(R) p_{\rm MW}(R, V, W') dR dV dW'} \right]$$

MCMC PARAMETERS AND TOP-HAT PRIORS FOR TWO-COMPONENT MODEL

Parameter	Minimum	Maxium	Description
$f_{\rm mem}$	0	1	$\equiv (N_1 + N_2)/(N_1 + N_2 + N_{\rm MW})$, fraction of stars belonging to dSph
$f_{\rm sub}$	0	1	$\equiv N_1/(N_1 + N_2)$, fraction of members belonging to MR component
$r_{h,1}/r_{h,2}$	0	1	ratio of half-light radii for metal-rich (MR) and metal-poor (MP) components
$\log_{10}[r_{h,2}/\rm pc]$	0	3	half-light radius of MP component
$\langle W \rangle_1/\rm Å$	−3	+3	mean reduced Mg index of MR component
$(\langle W \rangle_1 - \langle W \rangle_2)/\rm Å$	0	3	offset of mean Mg indices
$\log_{10}[\sigma^2_{W,1}/\rm Å^2]$	−5	+1	squared dispersion of reduced Mg index, MR component
$\log_{10}[\sigma^2_{W,2}/\rm Å^2]$	−5	+1	squared dispersion of reduced Mg index, MP component
$\log_{10}[\sigma^2_{V,1}/(\rm km^2 s^{-2})]$	−5	+5	squared velocity dispersion, MR component
$\log_{10}[\sigma^2_{V,2}/(\rm km^2 s^{-2})]$	−5	+5	squared velocity dispersion, MP component
$\mu_\alpha/(\rm mas/century)$	−1000	+1000	RA proper motion of dSph
$\mu_\delta/(\rm mas/century)$	−1000	+1000	Dec. proper motion of dSph

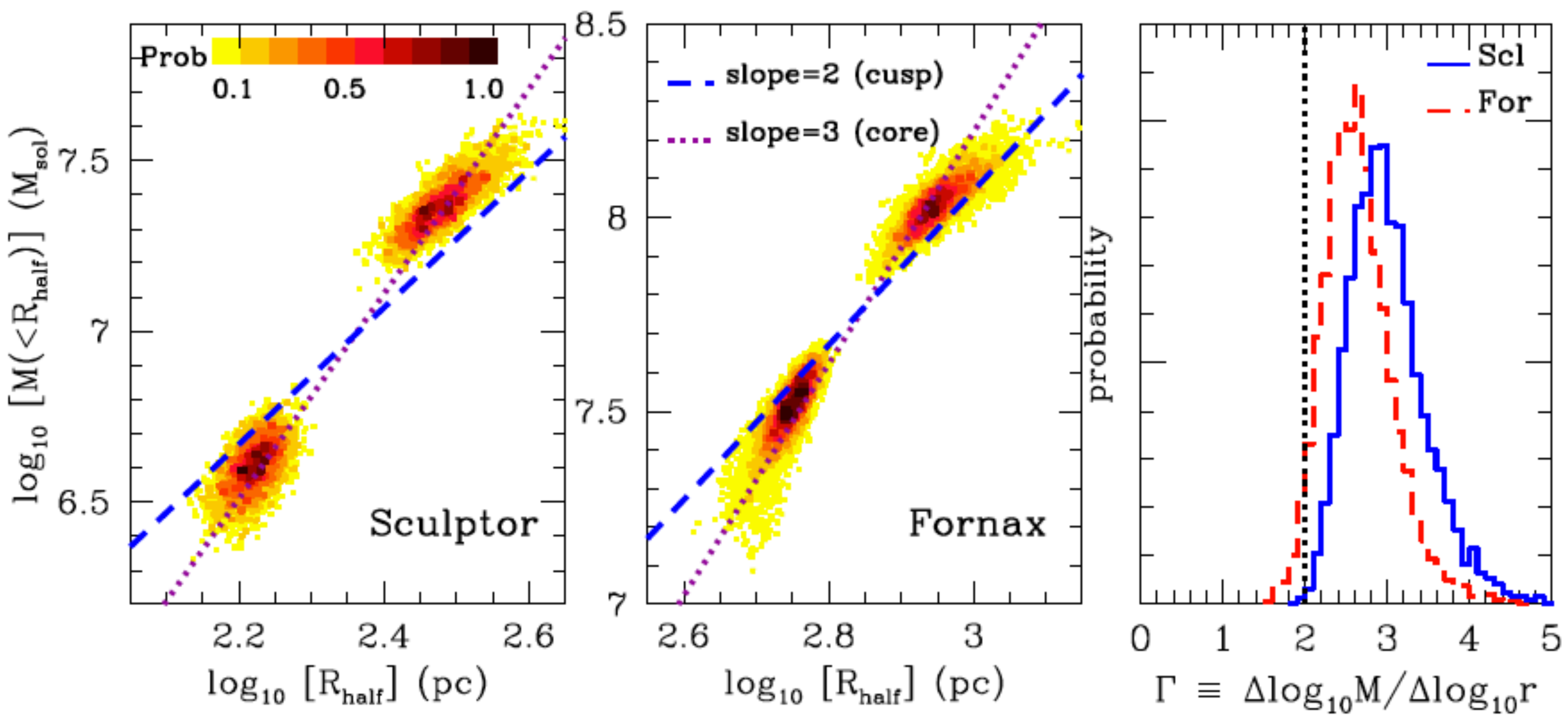
Walker & Peñarrubia (2012)

Results



Walker & Peñarrubia (2012)

Results



Walker & Peñarrubia (2012)

$$\Gamma \equiv \frac{\Delta \log M}{\Delta \log r} = \frac{\log[M(r_{\mathrm{h},2})/M(r_{\mathrm{h},1})]}{\log[r_{\mathrm{h},2}/r_{\mathrm{h},1}]} \approx 1 + \frac{\log[\sigma^2_{V,2}/\sigma^2_{V,1}]}{\log[r_{\mathrm{h},2}/r_{\mathrm{h},1}]}$$

Dark Matter Cores and Cusps: The Case of Multiple Stellar Populations in Dwarf Spheroidals

N. C. Amorisco[1*] and N. W. Evans[1]
[1]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

Amorisco & Evans (2012)

THE DARK MATTER DENSITY PROFILE OF THE FORNAX DWARF

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Department of Astronomy, University of Texas at Austin, 1 University Station C1400, Austin, TX 78712;
jardel:gebhardt@astro.as.utexas.edu
ACCEPTED TO APJ: *29 November 2011*

ABSTRACT

We construct axisymmetric Schwarzschild models to measure the mass profile of the local group dwarf galaxy Fornax. These models require no assumptions to be made about the orbital anisotropy of the stars, as is the case for commonly used Jeans models. We test a variety of parameterizations of dark matter density profiles and find cored models with uniform density $\rho_c = (1.6 \pm 0.1) \times 10^{-2} M_\odot$ pc^{-3} fit significantly better than the cuspy halos predicted by cold dark matter simulations. We also construct models with an intermediate-mass black hole, but are unable to make a detection. We place a 1-σ upper limit on the mass of a potential intermediate-mass black hole at $M_\bullet \leq 3.2 \times 10^4 M_\odot$.

Jardel & Gebhardt (2012)

A VIRIAL CORE IN THE SCULPTOR DWARF SPHEROIDAL GALAXY

A. AGNELLO AND N. W. EVANS
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
Draft version May 31, 2012

ABSTRACT

The projected virial theorem is applied to the case of multiple stellar populations in the nearby dwarf spheroidal galaxies. As each population must reside in the same gravitational potential, this provides strong constraints on the nature of the dark matter halo. We derive necessary conditions for two populations with Plummer or exponential surface brightnesses to reside in a cusped Navarro-Frenk-White (NFW) halo. We apply our methods to the Sculptor dwarf spheroidal, and show that there is no NFW halo compatible with the energetics of the two populations. The dark halo must possess a core radius of $\sim$ 120 pc for the virial solutions for the two populations to be consistent. This conclusion remains true, even if the effects of flattening or self-gravity of the stellar populations are included.

Agnello & Evans (2012)

Conclusion

At present, cold dark matter (CDM) hypothesis does not yield accurate predictions regarding the stellar dynamics of the most dark-matter-dominated galaxies.

Possible solutions:

-complexities of baryonic physics (predictions?)

-self-interacting CDM (epicycles?)

OR

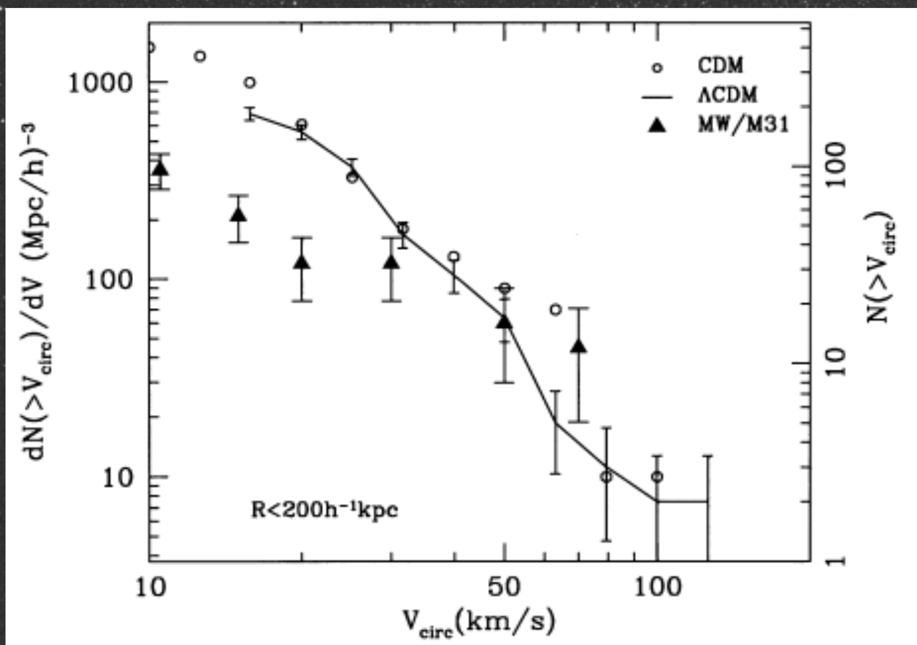
-warm(er) dark matter?

THE COUPLING BETWEEN THE CORE/CUSP AND MISSING SATELLITE PROBLEMS

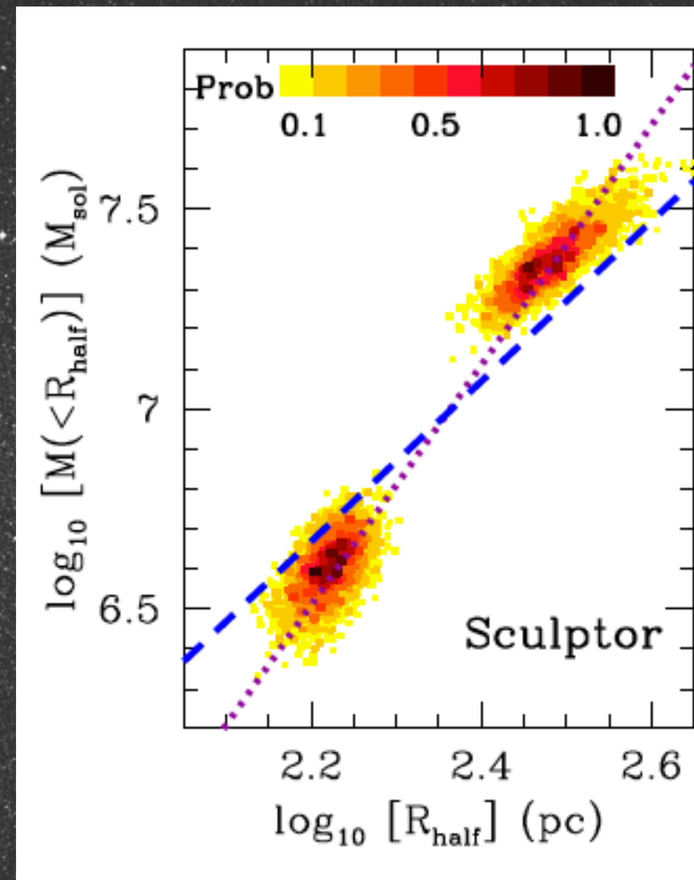
Jorge Peñarrubia[1,2], Andrew Pontzen[3], Matthew G. Walker[4] & Sergey E. Koposov[2,5]

Draft version July 13, 2012

Peñarrubia etal (arXiv:1207.2772)



Klypin et al.1999

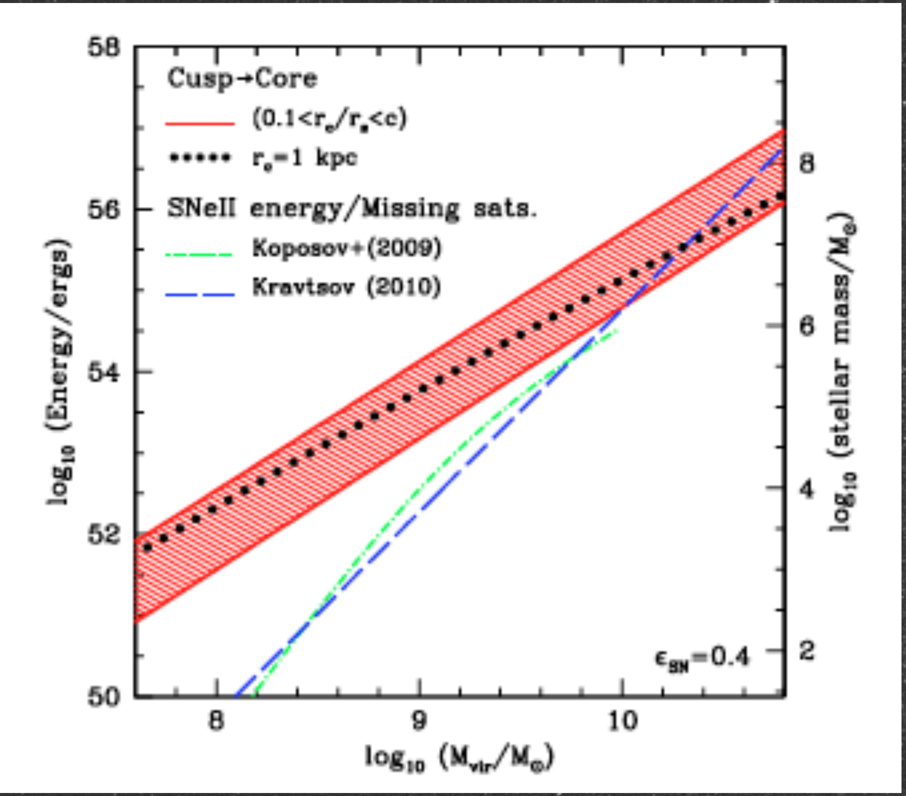


Walker & Peñarrubia (2012)

THE COUPLING BETWEEN THE CORE/CUSP AND MISSING SATELLITE PROBLEMS

Jorge Peñarrubia[1,2], Andrew Pontzen[3], Matthew G. Walker[4] & Sergey E. Koposov[2,5]

Draft version July 13, 2012



$$\rho(r) = \frac{\rho_0 r_s^3}{(r_c + r)(r_s + r)^2}$$

$$W = -4\pi G \int_0^{r_{\rm vir}} \rho(r) M(r) r dr$$

$$\Delta E \leq \frac{M_\star}{\langle m_\star \rangle} \xi(m_\star > 8 M_\odot) E_{\rm SN} \epsilon_{\rm SN}$$

$$F_{\star,\rm sat} \approx 10^{-3} \left(\frac{M_{\rm vir}}{10^{10} M_\odot} \right)^{1/3}$$

$$F_{\star,\rm core}(z=0) \gtrsim 10^{-3} \left(\frac{M_{\rm vir}}{10^{10} M_\odot} \right)^{2/3} \left(\frac{\epsilon_{\rm SN}}{0.4} \right)^{-1}$$

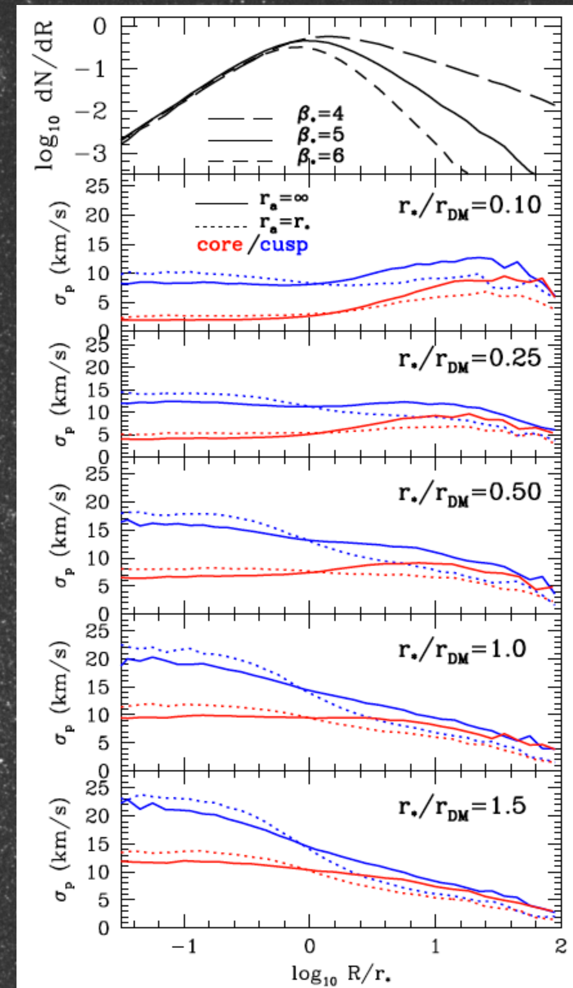
Peñarrubia etal (arXiv:1207.2772)


END

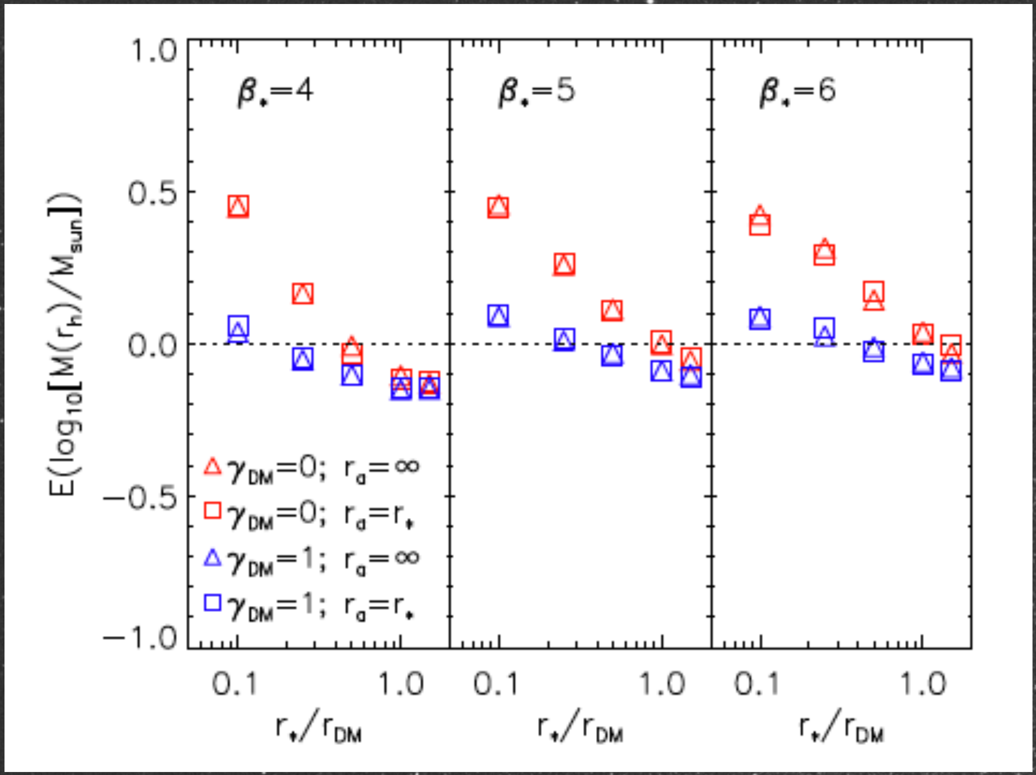
Tests

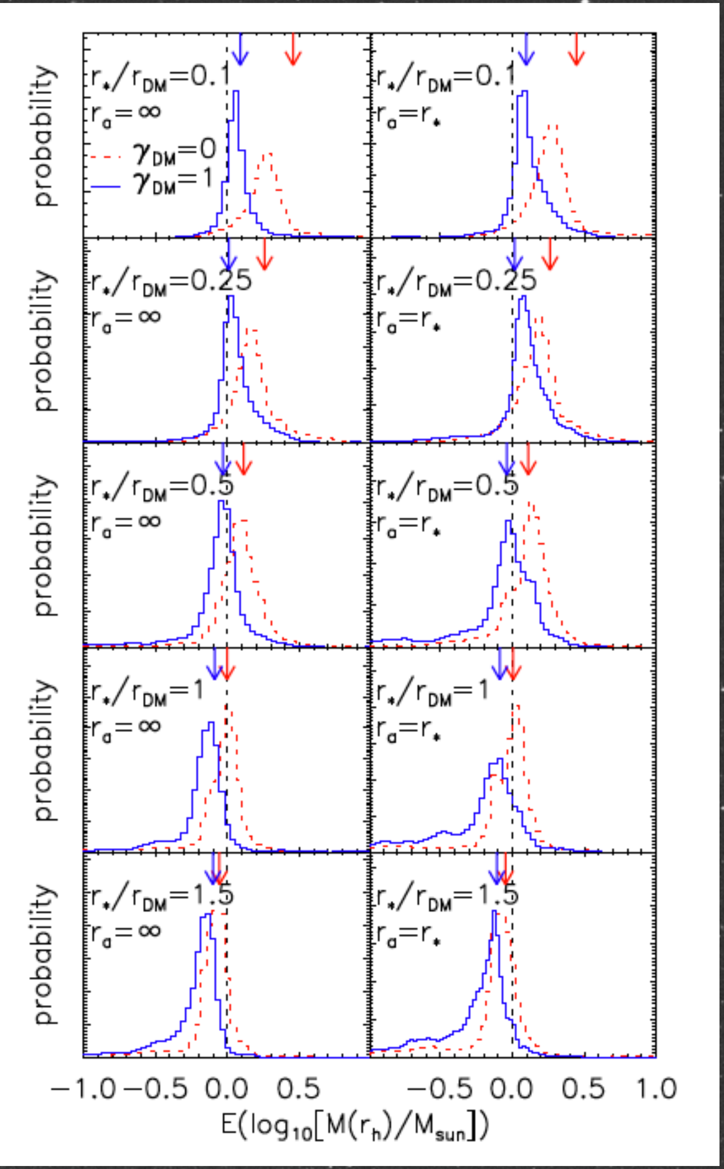
TABLE 3
TESTS ON SYNTHETIC DATA: GRID OF INPUT PARAMETERS FOR DYNAMICAL TEST MODELS

Profile	Parameter	values considered
Stellar Subcomponent (Eq. 15)		
	$r_*/r_{\rm DM}$	0.10, 0.25, 0.50, 1.0, 1.5
	α_*	2
	β_*	4, 5, 6
	γ_*	0.1
	r_a/r_*	$1, \infty$
Dark Matter Halo (Eq. 16)		
	$\rho_0/(M_\odot \mathrm{pc}^{-3})$	0.064
	$r_{\rm DM}/\mathrm{kpc}$	1
	$\alpha_{\rm DM}$	1
	$\beta_{\rm DM}$	3
	$\gamma_{\rm DM}$	0, 1

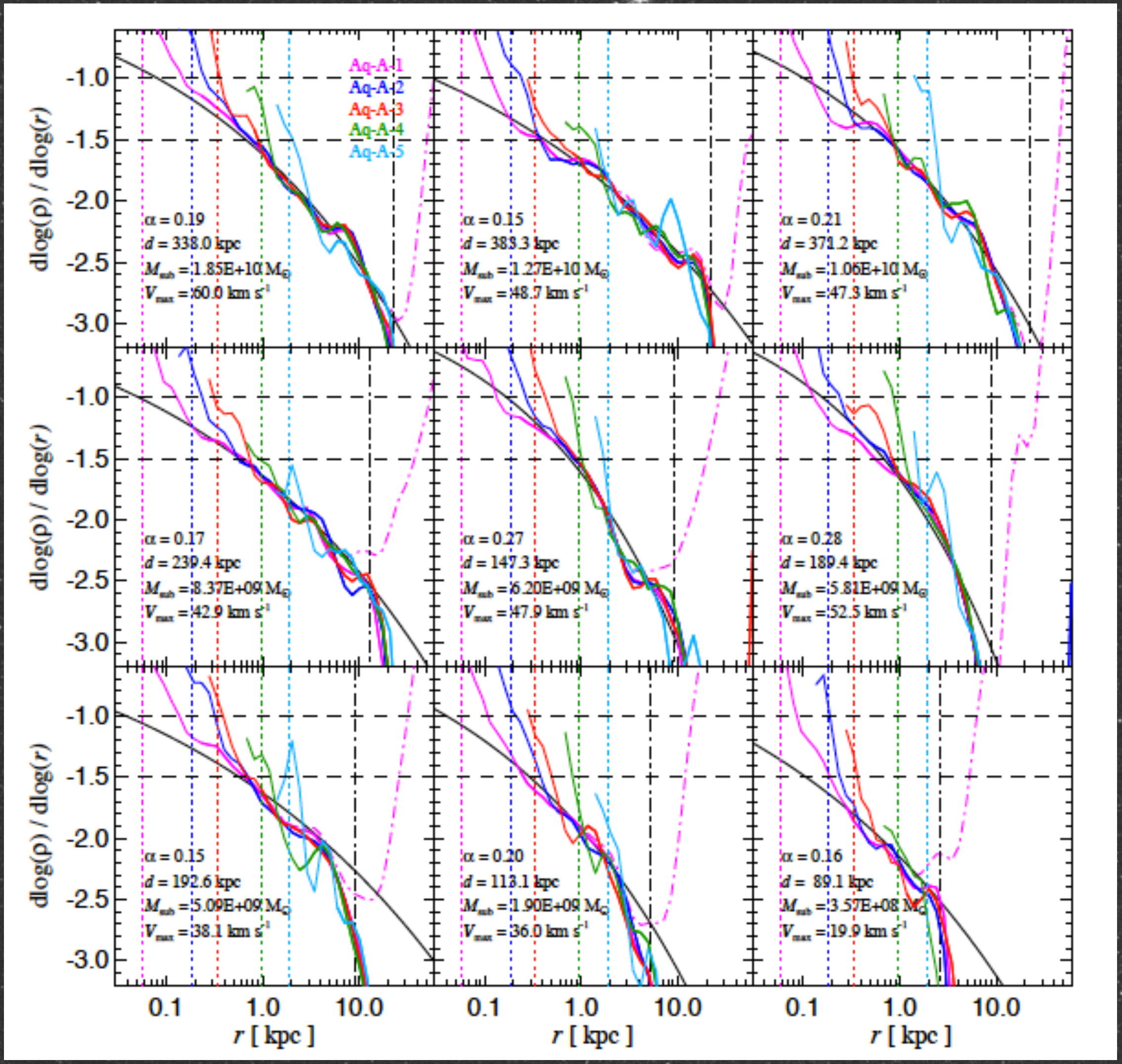


bias in mass estimator $M(\propto R_h) \propto R_h\sigma^2$



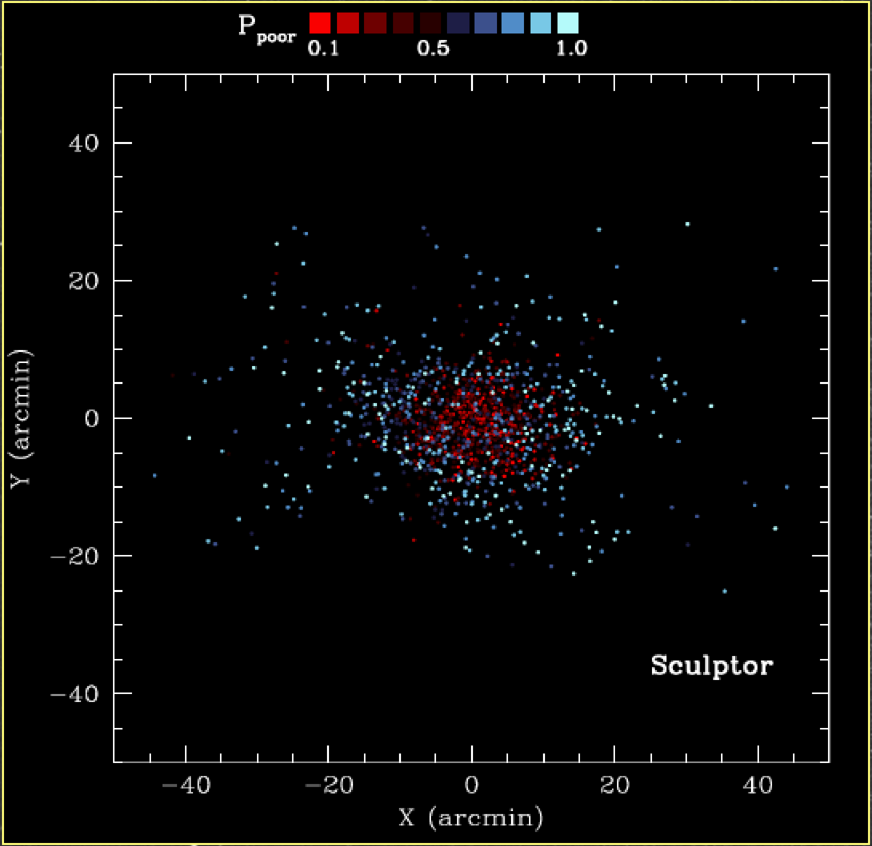


Aquarius subhalos

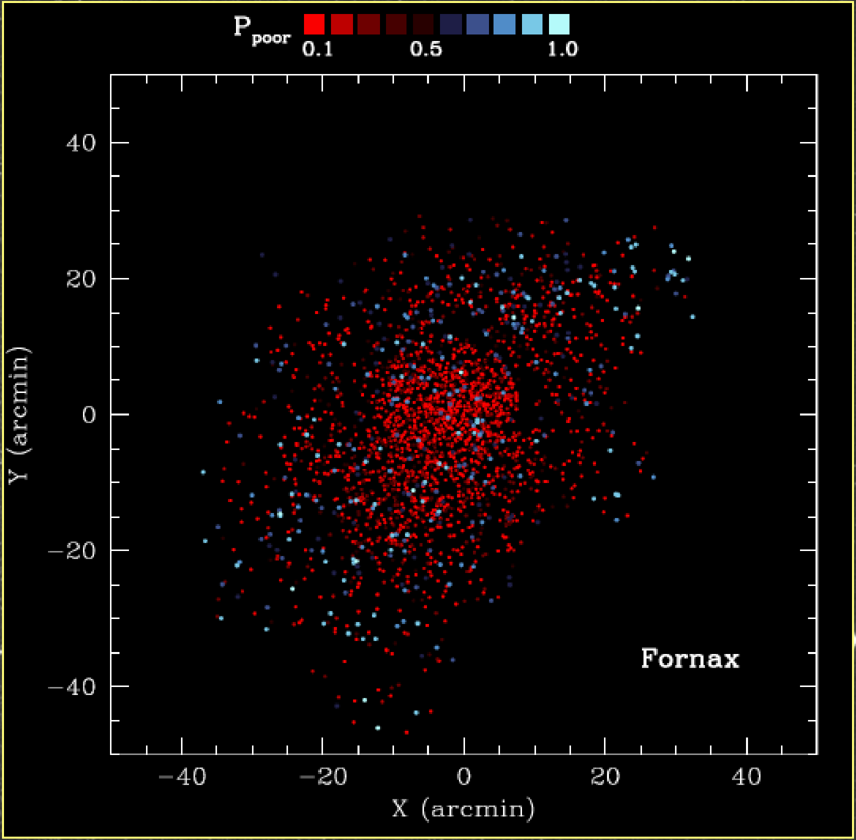


Springel et al (2008)

Results



P_{poor}
0.1
0.5
1.0
40
20
0
−20
−40
Y (arcmin)
−40
−20
0
20
40
X (arcmin)
Sculptor



P_{poor}
0.1
0.5
1.0
40
20
0
−20
−40
Y (arcmin)
−40
−20
0
20
40
X (arcmin)
Fornax