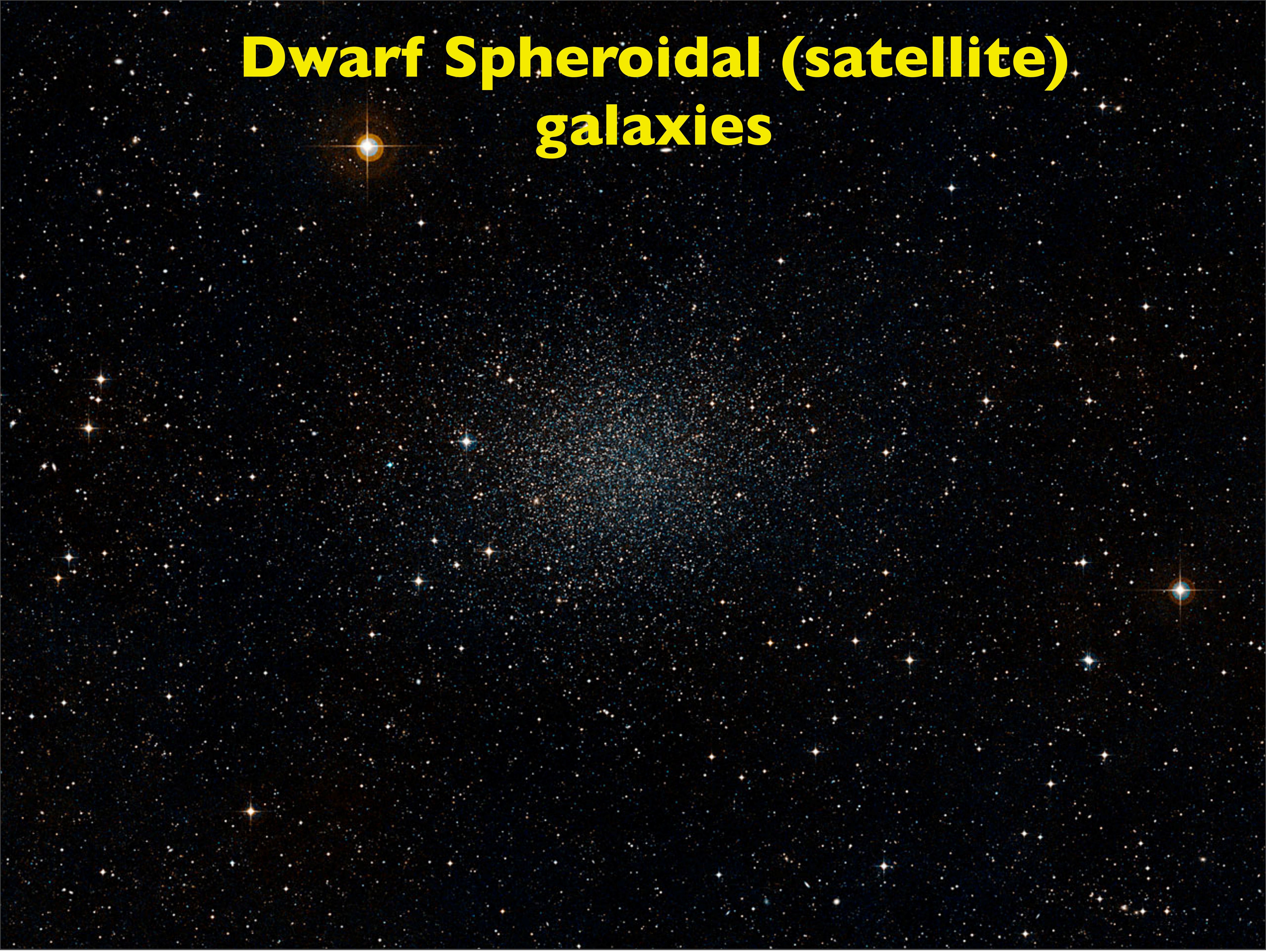
A method for measuring the mass profile of dwarf spheroidals

Jorge Peñarrubia
in collaboration with Matt Walker

UNIVERSITY OF CAMBRIDGE

Durham 2011

Dwarf Spheroidal (satellite) galaxies



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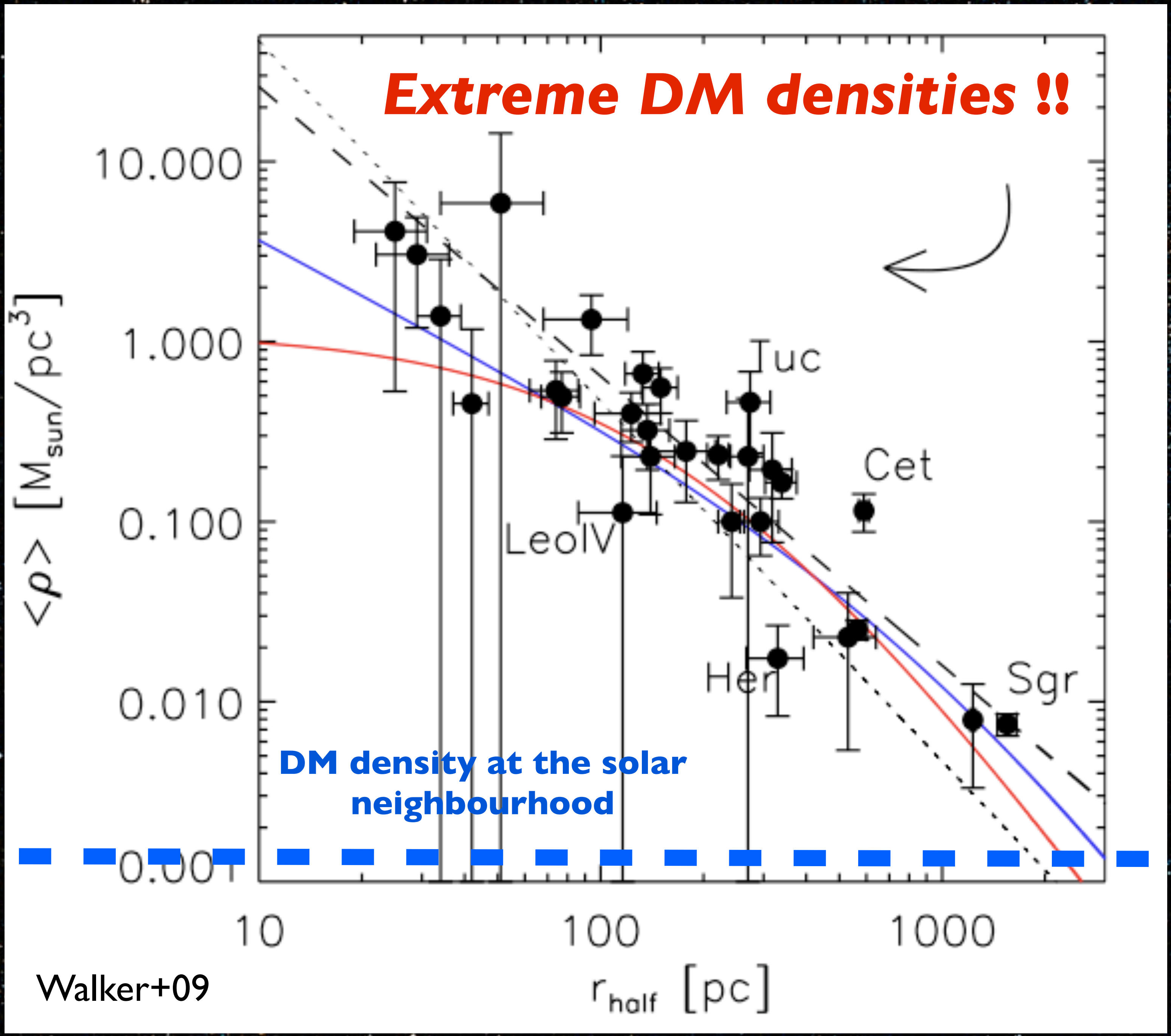


★ **Faintest galaxies in the known Universe:**
$10^3 < L/L_{sol} < 10^7$

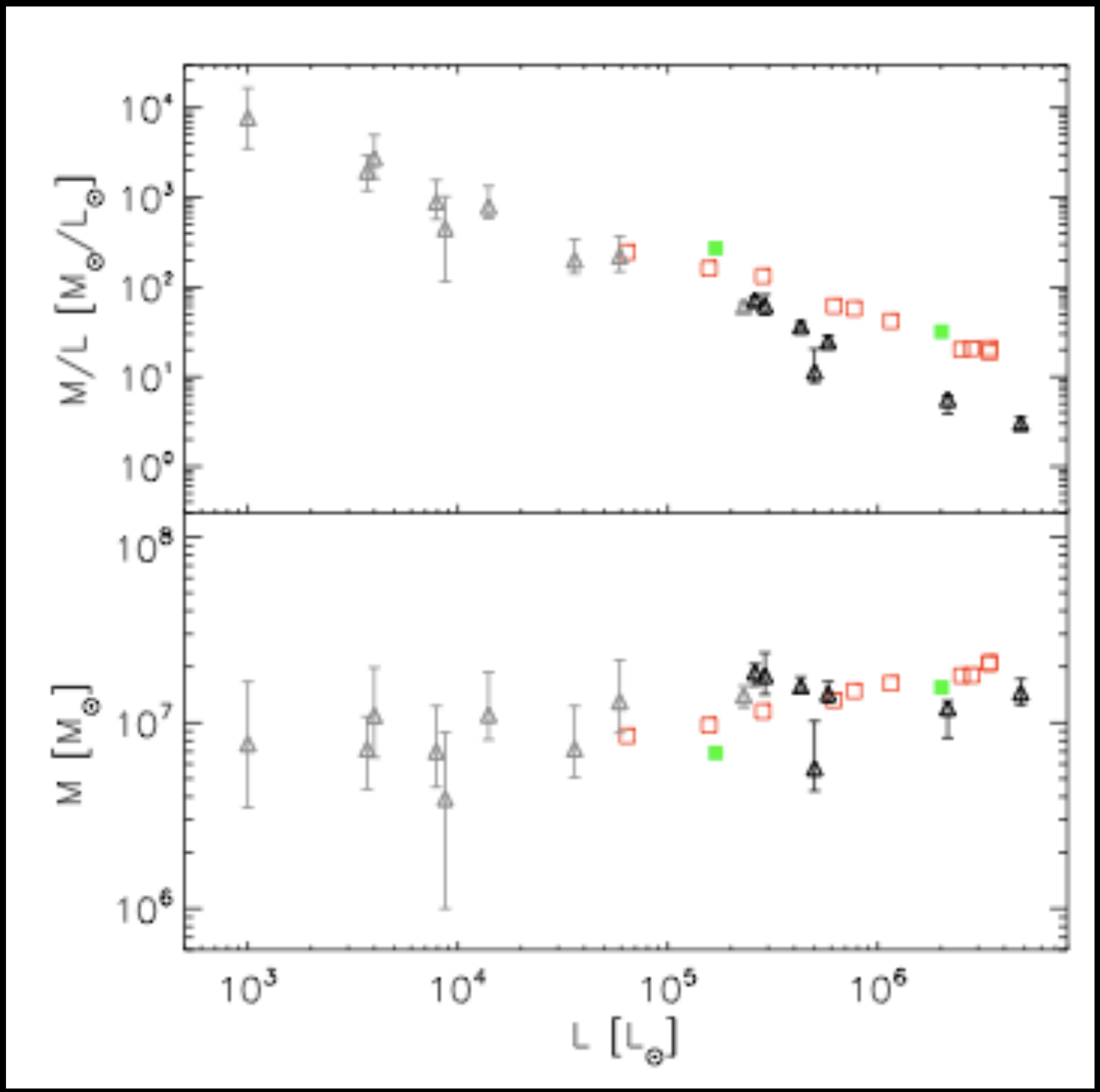
★ **High mass-to-light ratios:**
$10 < M/L < 1000$
(Potential dominated by DM)

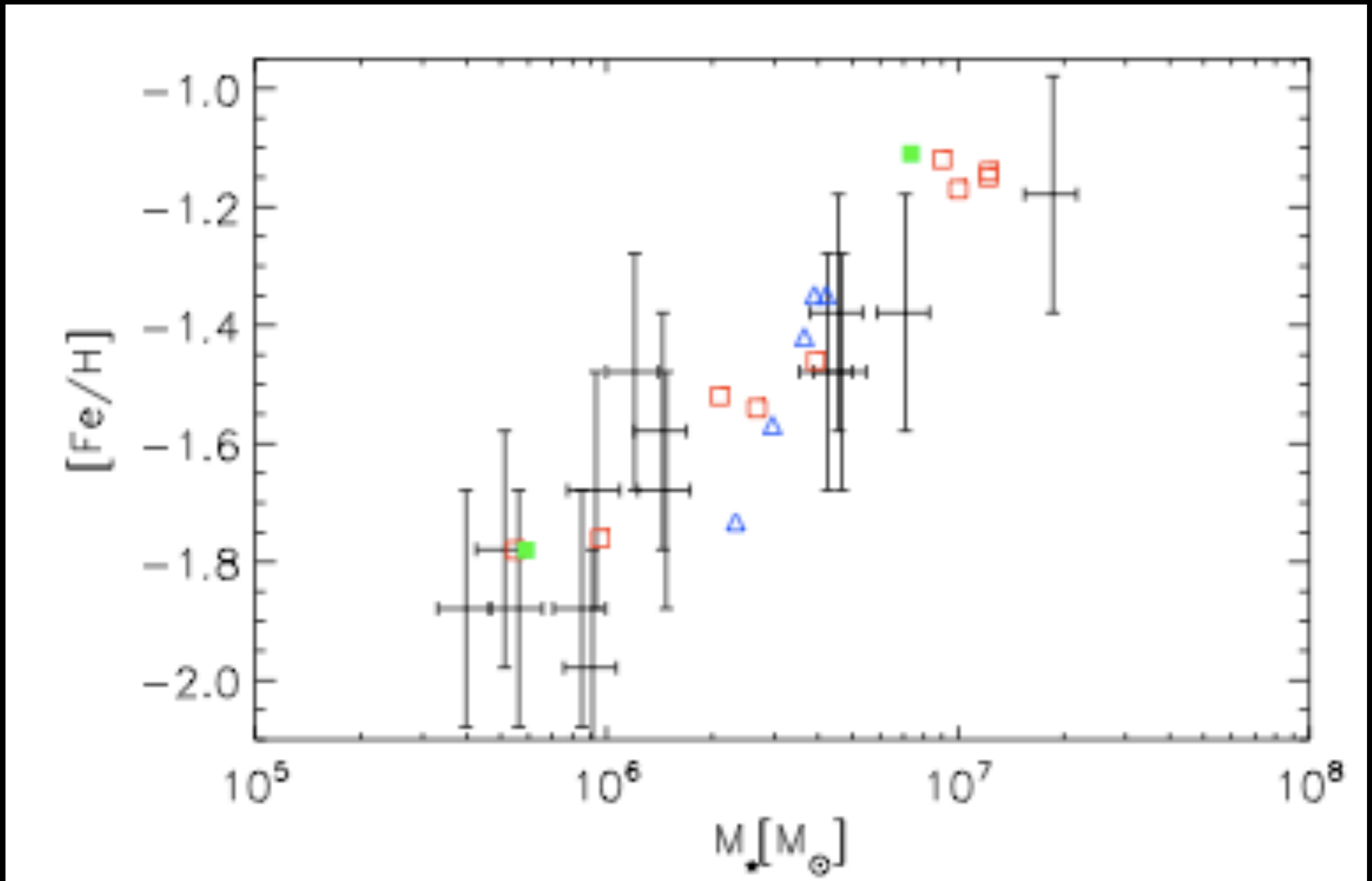
★ **Old, metal poor stellar populations**
$0.1 < age/Gyr < 12$

★ **No gas**

★ **No rotation (pressure-supported)**

The inner structure of dSphs





Sawala+10

Hydro N-body sims. of dSph formation

(SF/feedback tuned to reproduce scaling relationships)

→

DM halo profile of dSphs **unaffected** by baryons =**cusp**

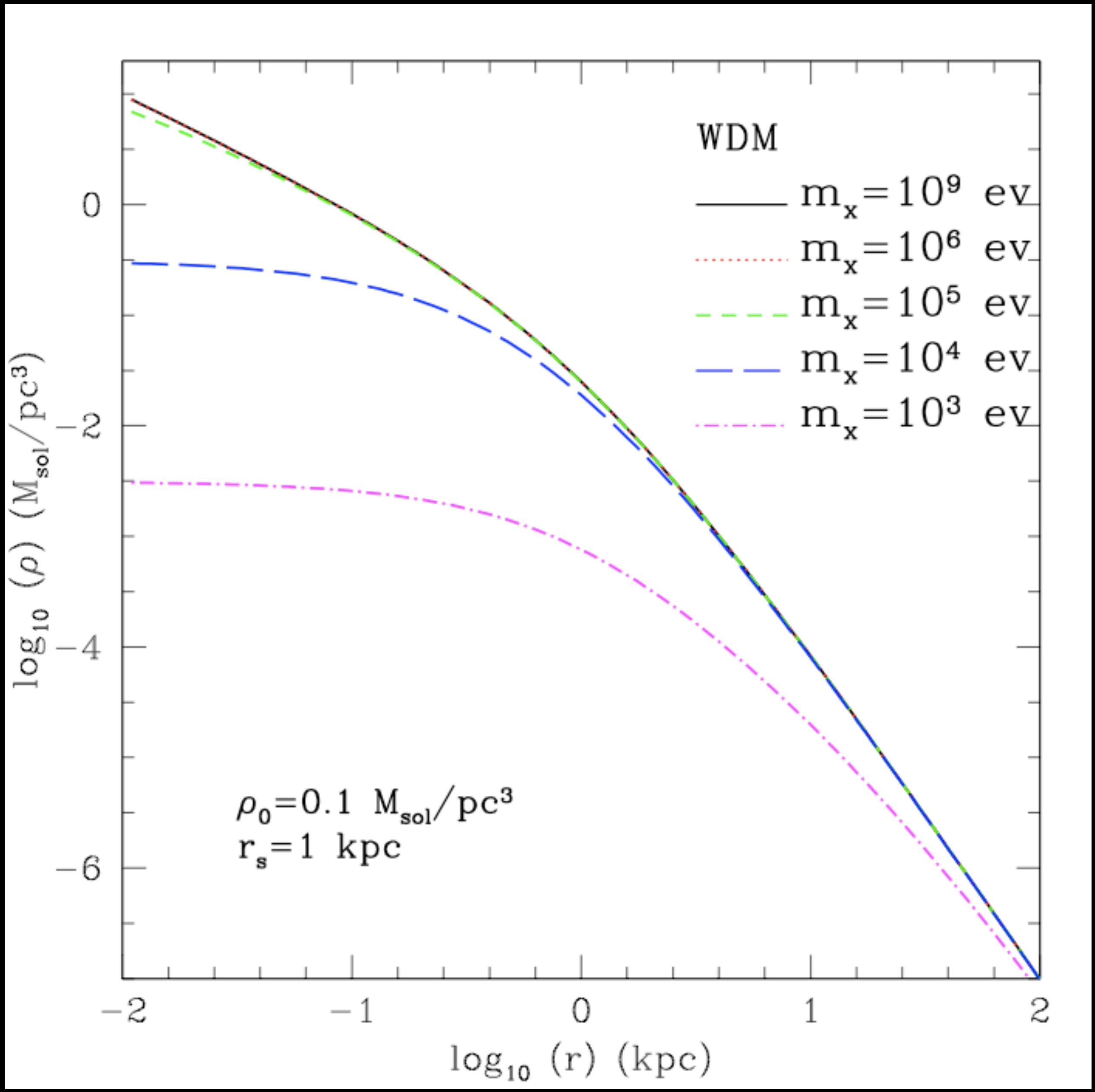
(Sawala+10; Parry+11)

(different codes + SF/feedback recipes)

The inner structure of dSphs

$$r_c > 32\left(\frac{10\mathrm{km/s}}{\sigma}\right)^{1/2}\left(\frac{\mathrm{keV}}{m_\chi}\right)^{2}\mathrm{pc}$$

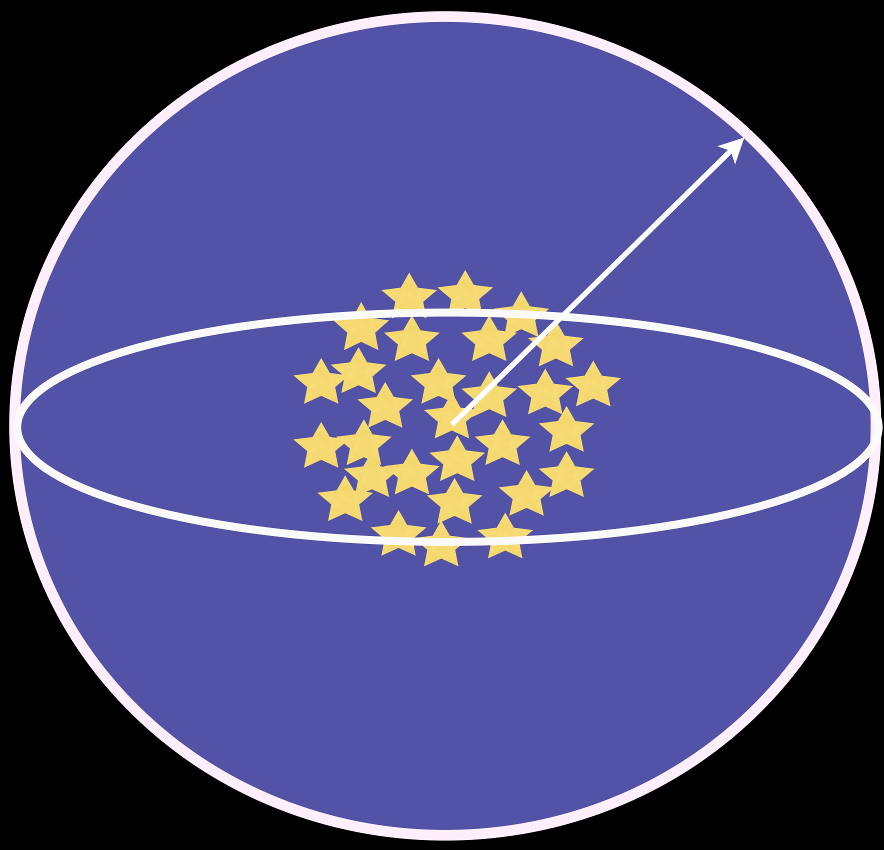
Bode+01



Constraints on **DM particle mass** comparable to those from **Lyα forest**

Can we measure $\rho_{DM}(r)$?

The inner structure of dSphs



stars ≡ mass-loss tracers of the **DM potential**

The inner structure of dSphs

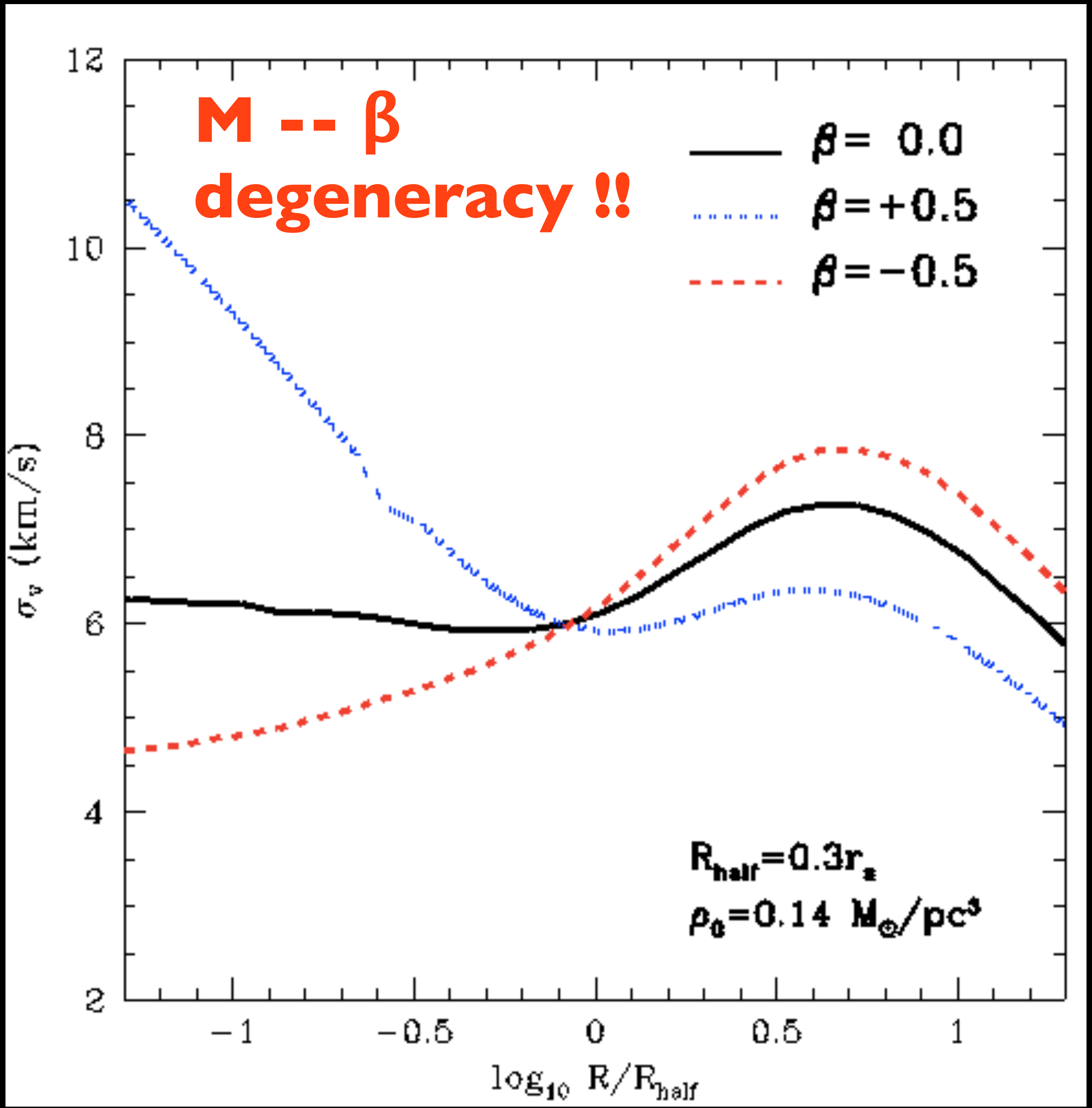
stars ≡ mass-loss tracers of the **DM potential**

Jeans equations

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

- ✳ Halo mass profile
- ✳ stellar density profile
- ✳ radial component of the velocity dispersion
- ✳ velocity anisotropy **$\beta \equiv 1 - \sigma_t^2 / \sigma_r^2$**

The inner structure of dSphs



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Projected velocity dispersion

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

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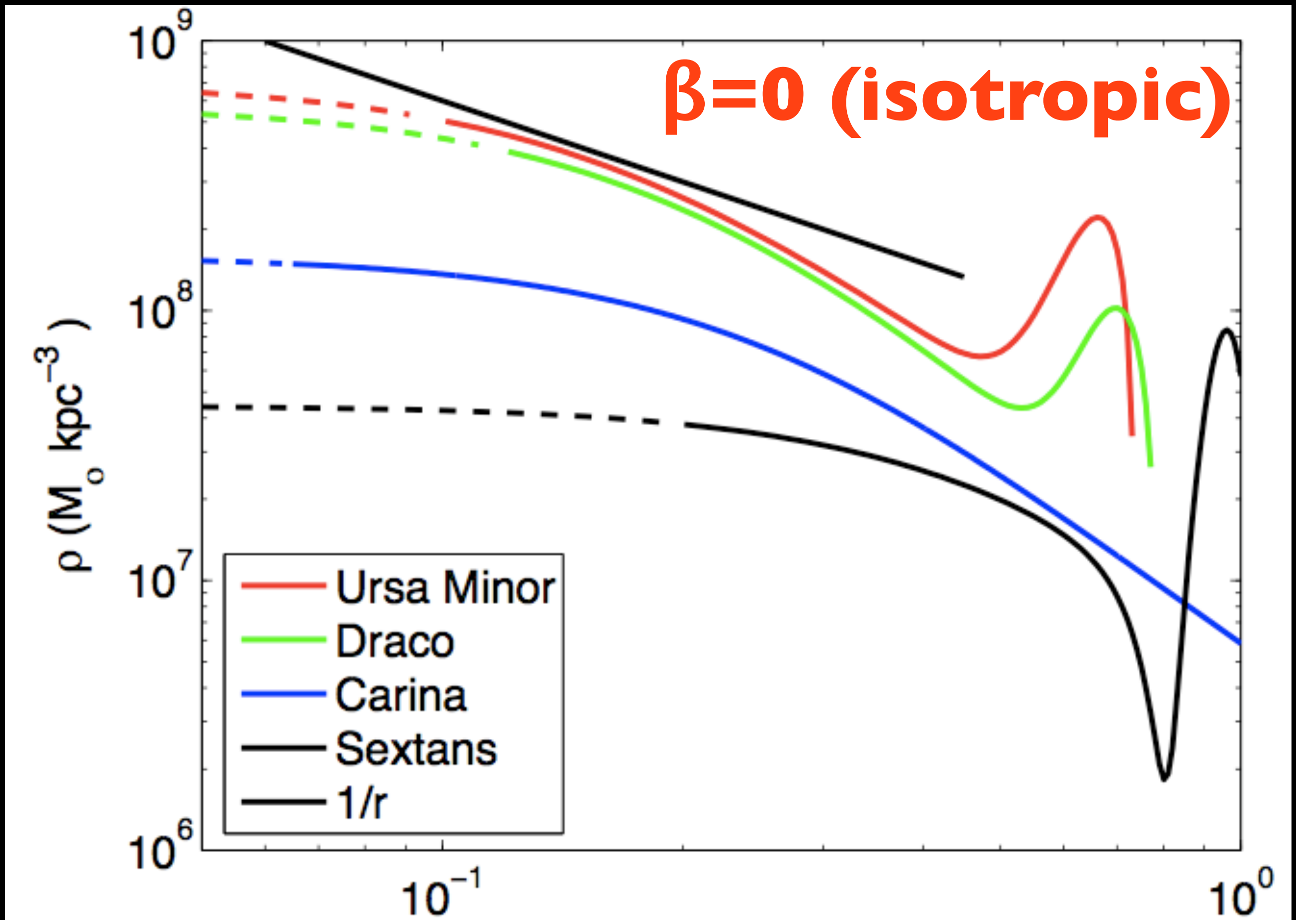

Gilmore+07

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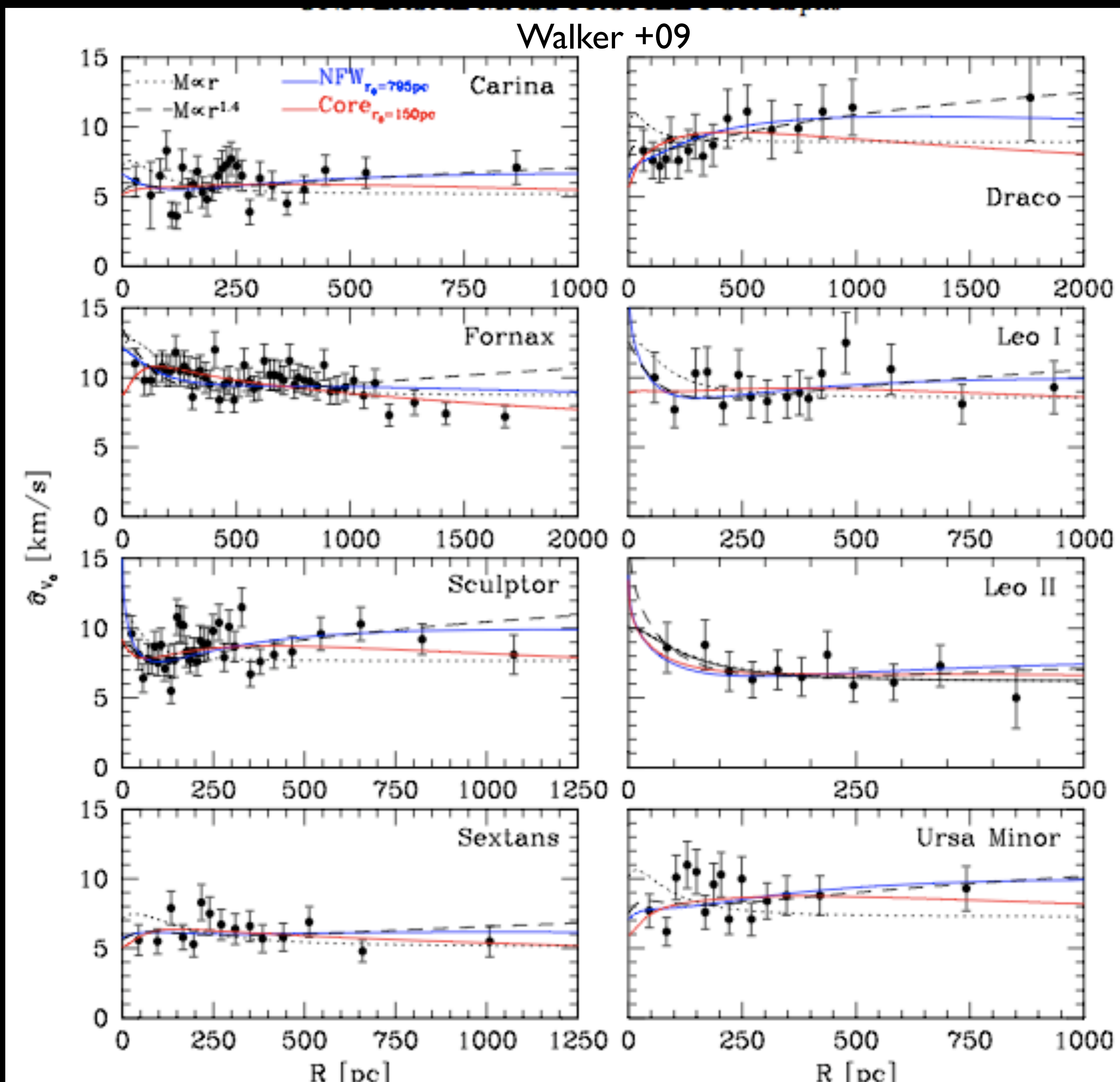
DM cusps or cores?

NFW profile
cored profile
β allowed to vary



Unknown β(r)

Unknown M(r)

e.g. Battaglia+08; Walker+09

Can we break the degeneracy?

THE IDEA

Walker & Peñarrubia (2011)

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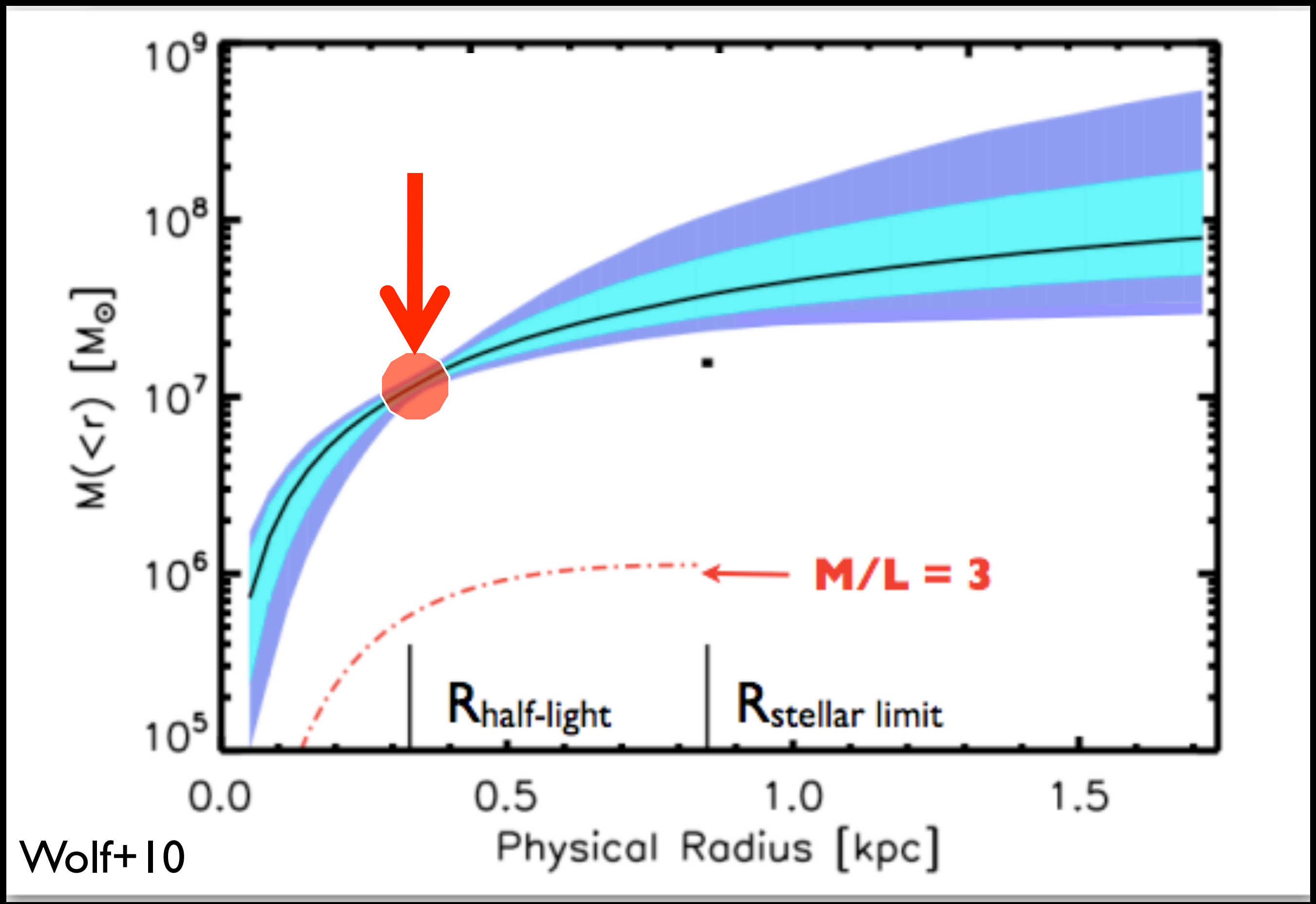
M -- β degeneracy breaks at $R \approx R_{half}$

Peñarrubia+08; Walker+09; Wolf+10; Amorisco & Evans 2010



$$M(R_{\rm half}) \approx \mu R_{\rm half} \langle \sigma_V \rangle^2$$

$\mu \approx 480 M_{\odot} \mathrm{pc}^{-1} \mathrm{km}^{-2} \mathrm{s}^{-2}$ (Walker+09)

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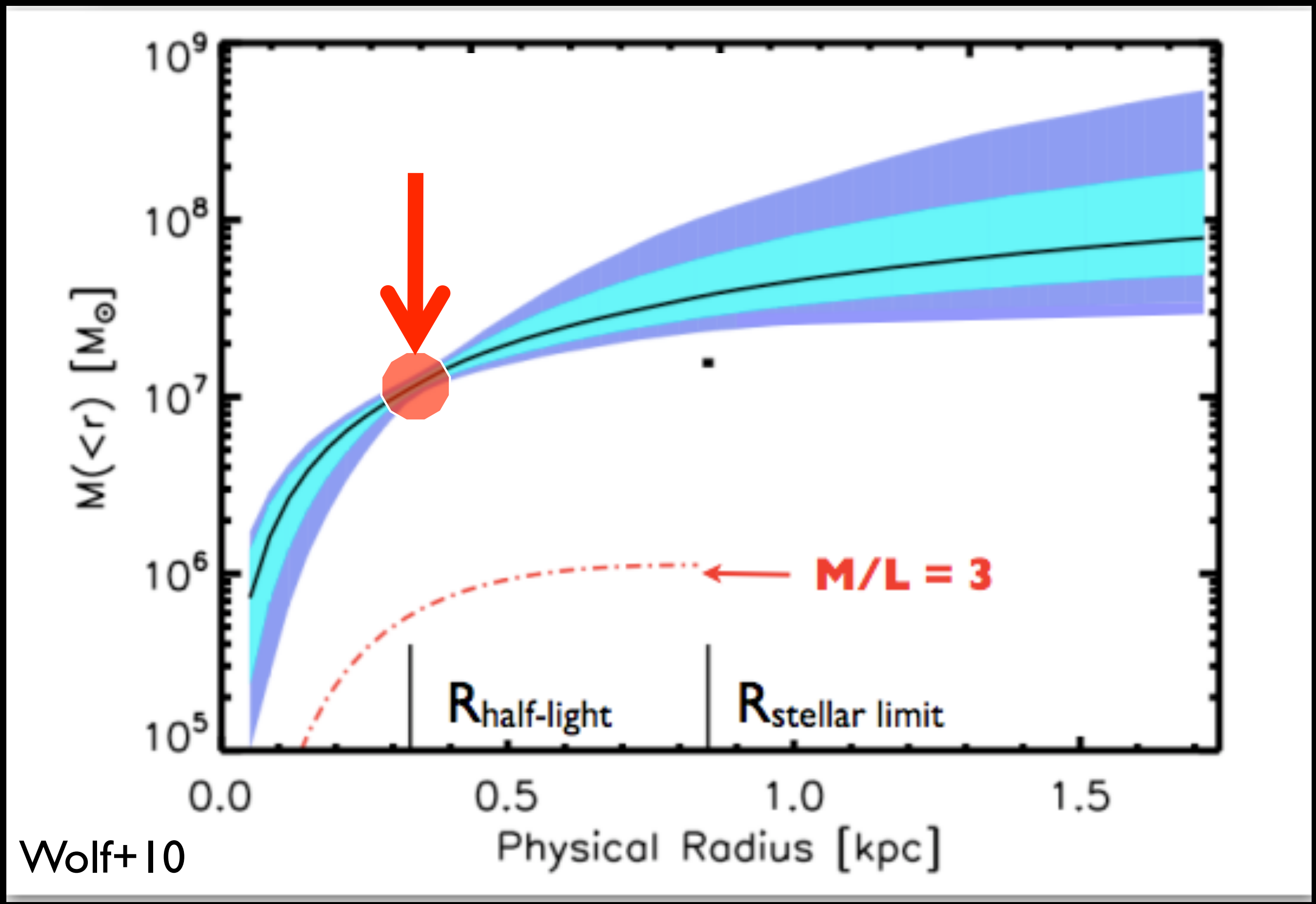
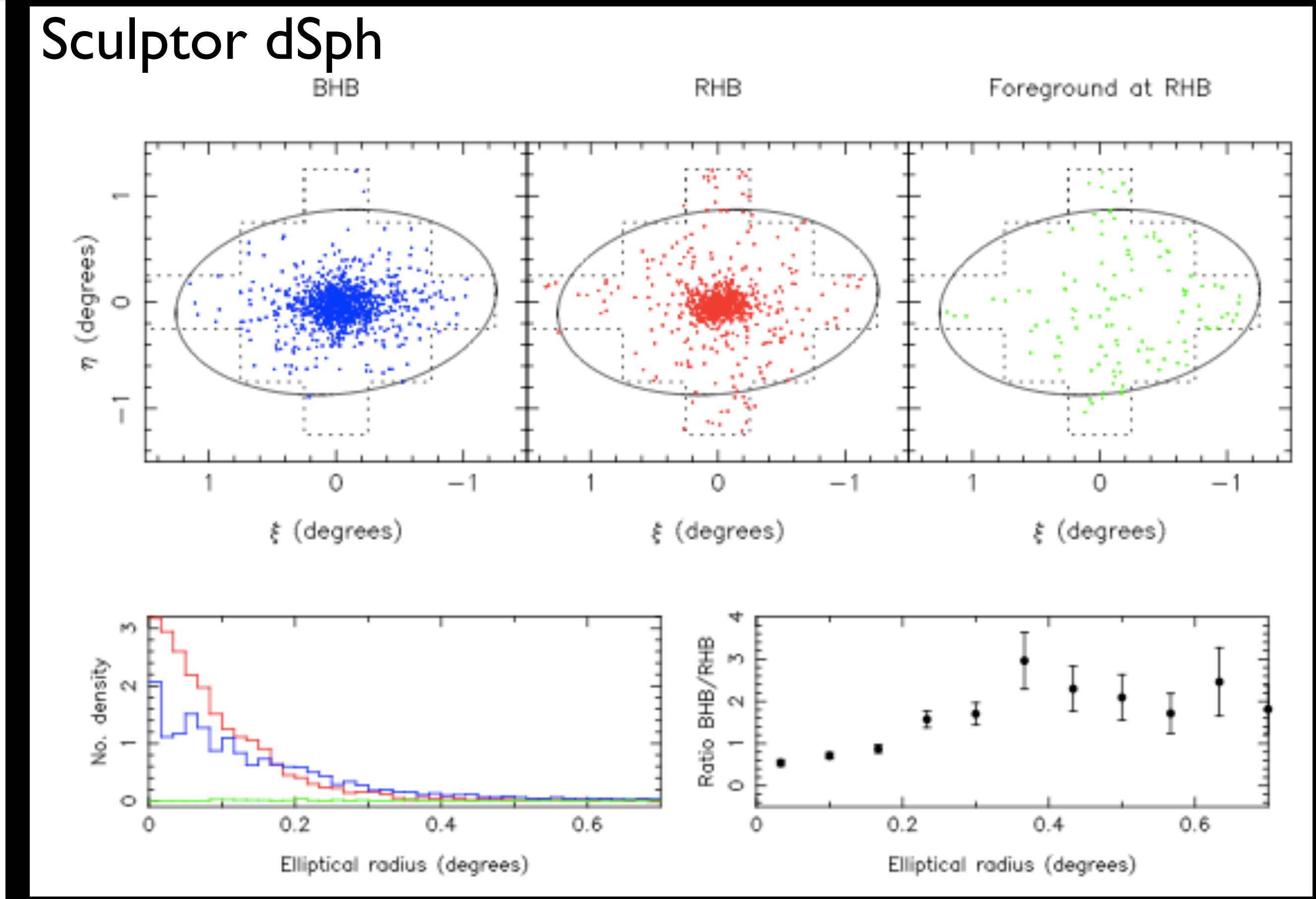
Some dSphs show spatially + kinematically distinct stellar components





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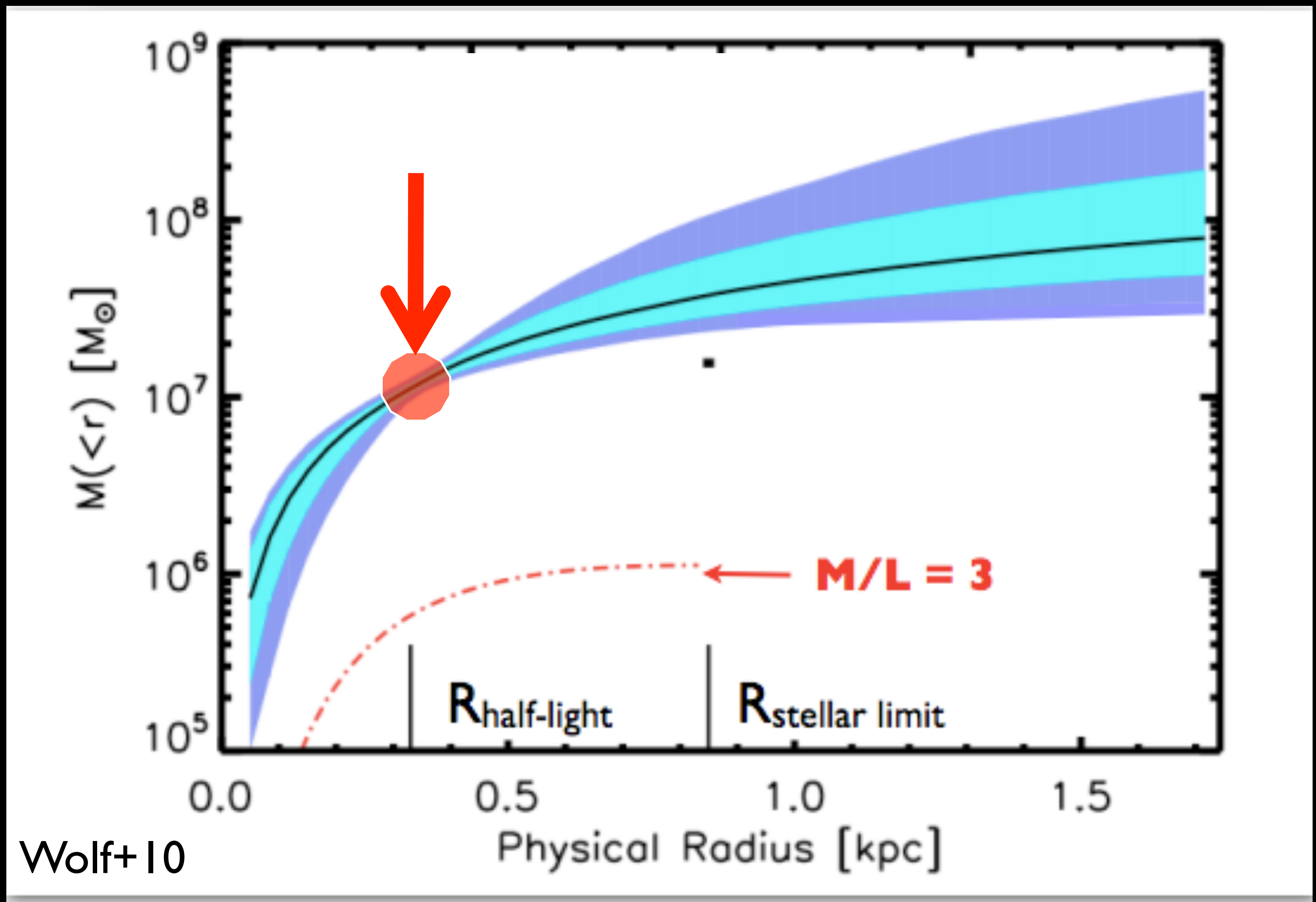

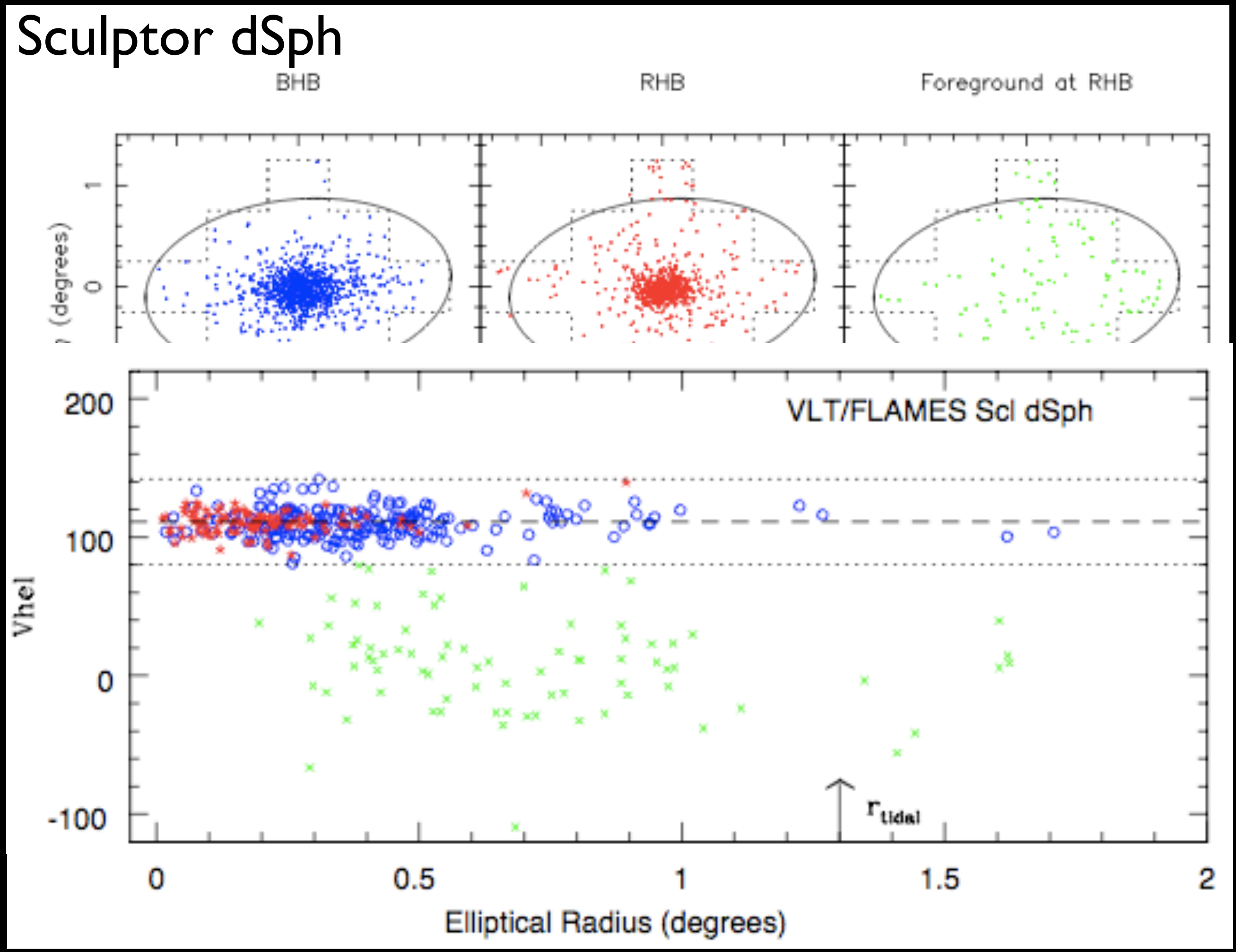

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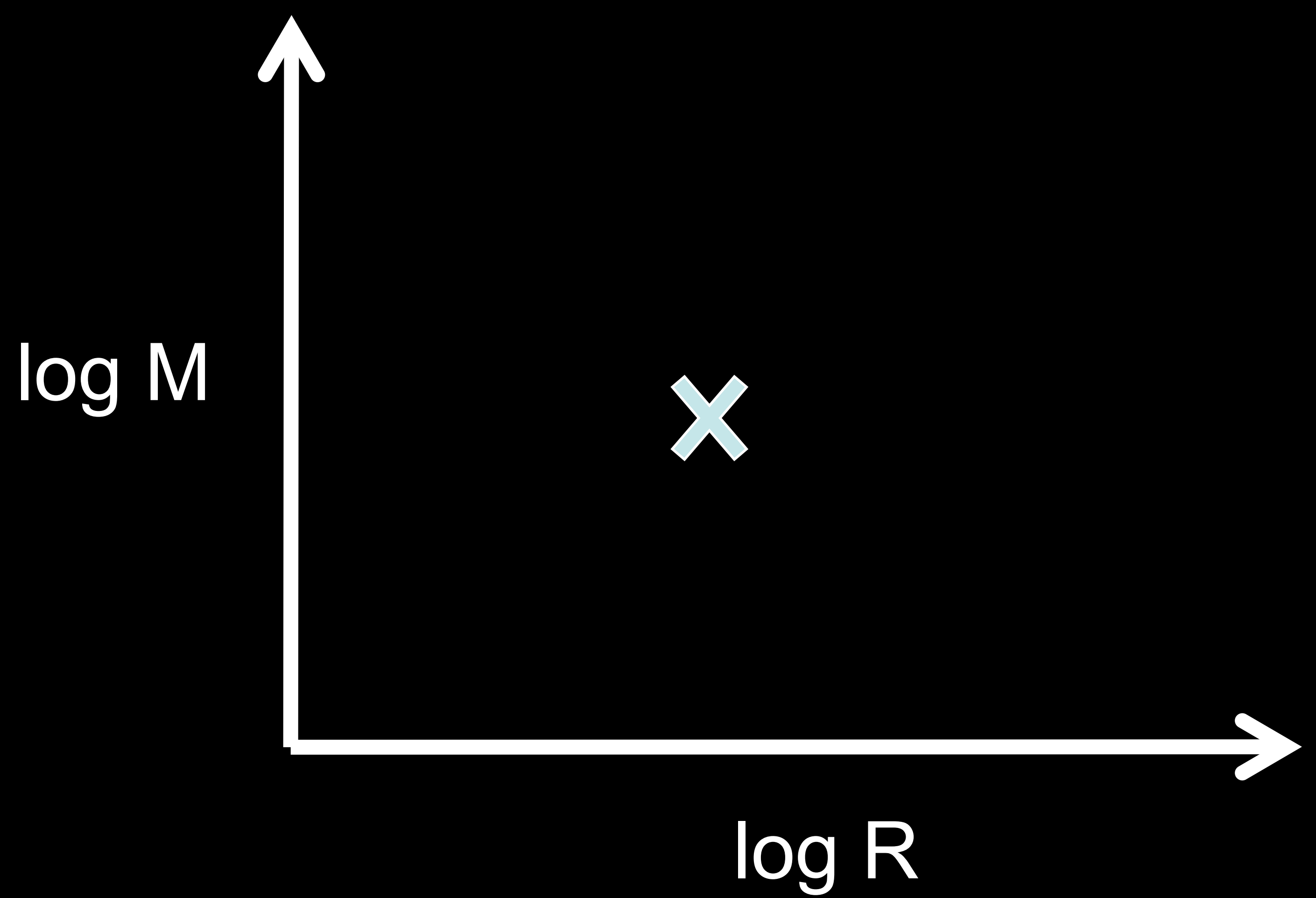

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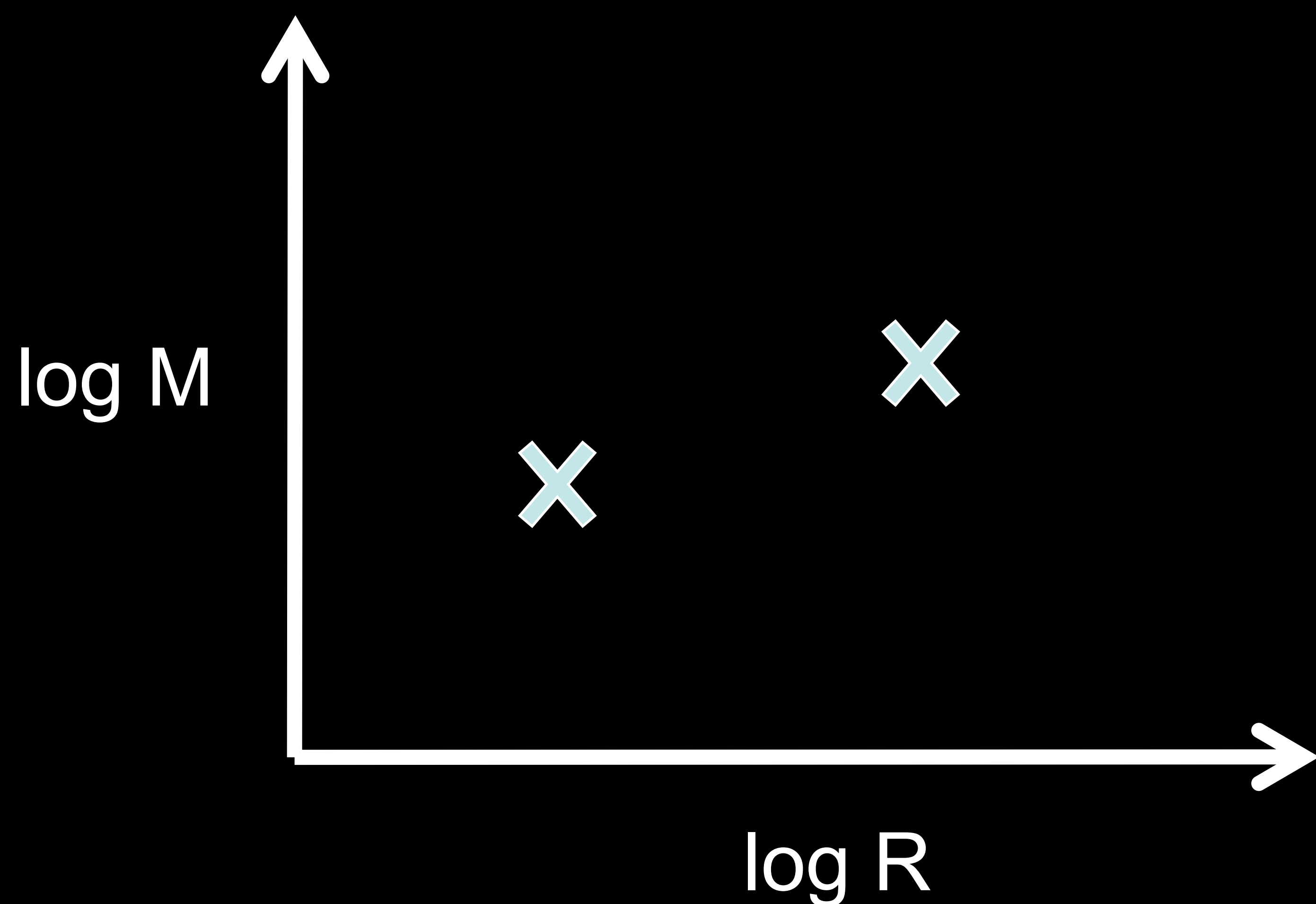
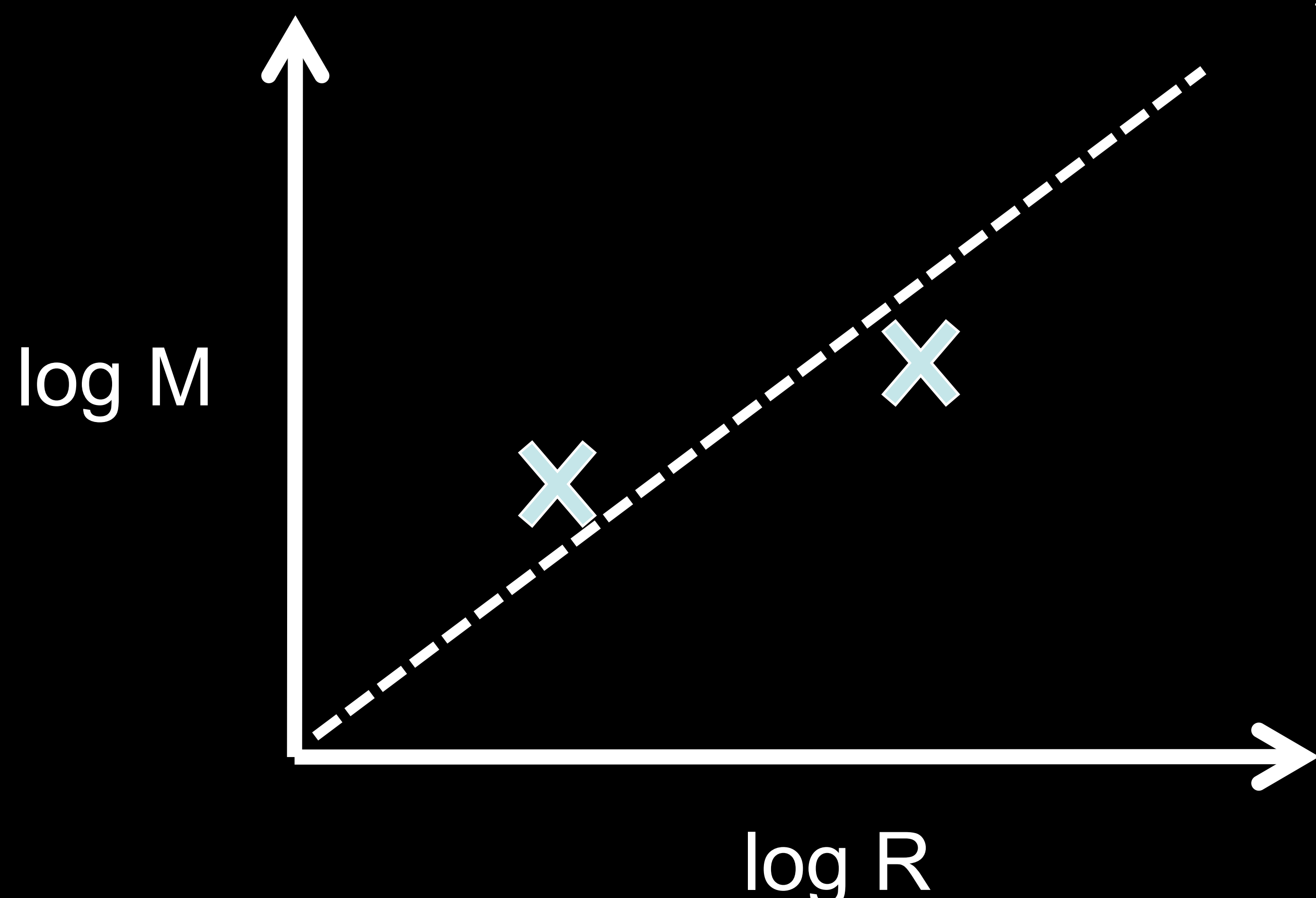


THE IDEA

Walker & Peñarrubia (2011)

$$M \propto R^{-\Gamma}$$



$$dM = 4\pi \rho_{\rm DM} r^2 dr$$

$$\rho_{\rm DM} \propto r^{-1} \longrightarrow \Gamma \approx 2$$

$$\rho_{\rm DM} \propto \text{const.} \longrightarrow \Gamma \approx 3$$

Method

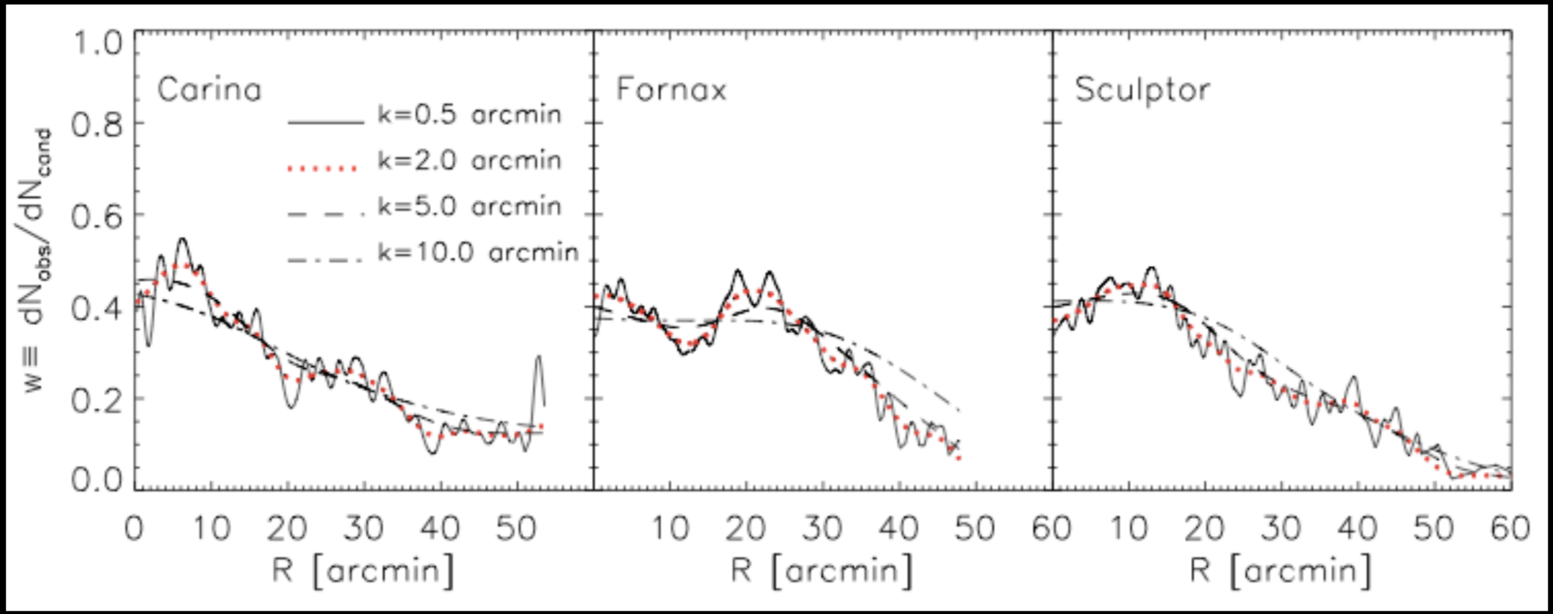
Walker & Peñarrubia (2011)

MCMC algorithm to separate 2 stellar components + MW foreground contamination

$$L(\{R_i, V_i, W_i'\}_{i=1}^{N_{\rm sample}}|\vec{S}) = \prod_{i=1}^{N_{\rm sample}} \Bigg[f_1 \frac{w(R_i) p_{R,1}(R_i) p_{V,1}(V_i) p_{W',1}(W_i')}{\int_0^\infty w(R) p_{R,1}(R) dR} + f_2 \frac{w(R_i) p_{R,2}(R_i) p_{V,2}(V_i) p_{W',2}(W_i')}{\int_0^\infty w(R) p_{R,2}(R) dR}$$
$$(1 - f_1 - f_2) \hat{p}_{{\rm MW},R}(R_i) \hat{p}_{{\rm MW},V}(V_i) \hat{p}_{{\rm MW},W'}(W_i') \Bigg]$$

Spatial sampling

correction: Gill+88



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Priors (14 free parameters)

$$p_i(R, V, W) = p_{R,i}(R) p_{V,i}(V) p_{W,i}(W);$$

Plummer prof: $p_{R,i}(R) = \frac{2R/r_i^2}{\left(1 + R^2/r_i^2\right)^2}$

Gaussian $p_{V,i}$ and $p_{W,i}$

- f_{mem} = $(N_1+N_2) / (N_1+N_2+N_{MW})$ — Fraction of dwarf members
- $f_{sub,2}$ = $N_2 / (N_1+N_2)$ — Fraction of stars in comp. 2
- $r_{half,2}$ — Half-light radius of comp. 2
- $r_{half,1} / r_{half,2}$ — Ratio of Half-light radii
- $\langle W_1 \rangle$ — Mean spectral index of comp. 1
- $\langle W_1 \rangle - \langle W_2 \rangle$ — Spectral index difference
- σ_{W1} — Spectral index dispersion of comp.1
- σ_{W2} — Spectral index dispersion of comp.2
- σ_{V1} — Velocity dispersion of comp.1
- σ_{V2} — Velocity dispersion of comp.2
- μ_α — Proper motion in R.A.
- μ_δ — Proper motion in Declination

Tests

Walker & Peñarrubia (2011)

Synthetic data sets:

$$\nu_*(r) = \nu_0 \left(\frac{r}{r_*}\right)^{-\gamma_*} \left[1 + \left(\frac{r}{r_*}\right)^{\alpha_*}\right]^{(\gamma_* - \beta_*)/\alpha_*}.$$

Plummer: $(\alpha,\beta,\gamma)_* = (2,5,0)$

$$\rho_{\rm DM}(r) = \rho_0 \left(\frac{r}{r_{\rm DM}}\right)^{-\gamma_{\rm DM}} \left[1 + \left(\frac{r}{r_{\rm DM}}\right)^{\alpha_{\rm DM}}\right]^{(\gamma_{\rm DM} - \beta_{\rm DM})/\alpha_{\rm DM}}.$$

NFW: $(\alpha,\beta,\gamma)_{DM} = (1,3,1)$

Opsikov-Merritt DFs

$$Q \equiv E + \frac{L^2}{2r_a^2} = \frac{1}{2}[v_r^2 + (1 + r^2/r_a^2)v_t^2] + U(r)$$

DM potential

$$f(Q) = \frac{1}{\sqrt{8}\pi^2} \int_Q^0 \frac{d^2\rho_Q}{dU^2} \frac{dU}{\sqrt{U - Q}}$$

where $\rho_Q(r) \equiv (1 + r^2/r_a^2)\rho(r)$

stellar density

$$\beta \equiv 1 - \frac{\sigma_t^2}{\sigma_r^2} = \frac{r^2}{r_a^2 + r^2}$$

$r << r_a$ $\beta=0$ (isotropic)

$r >> r_a$ $\beta=1$ (radially anisotropic)

Tests

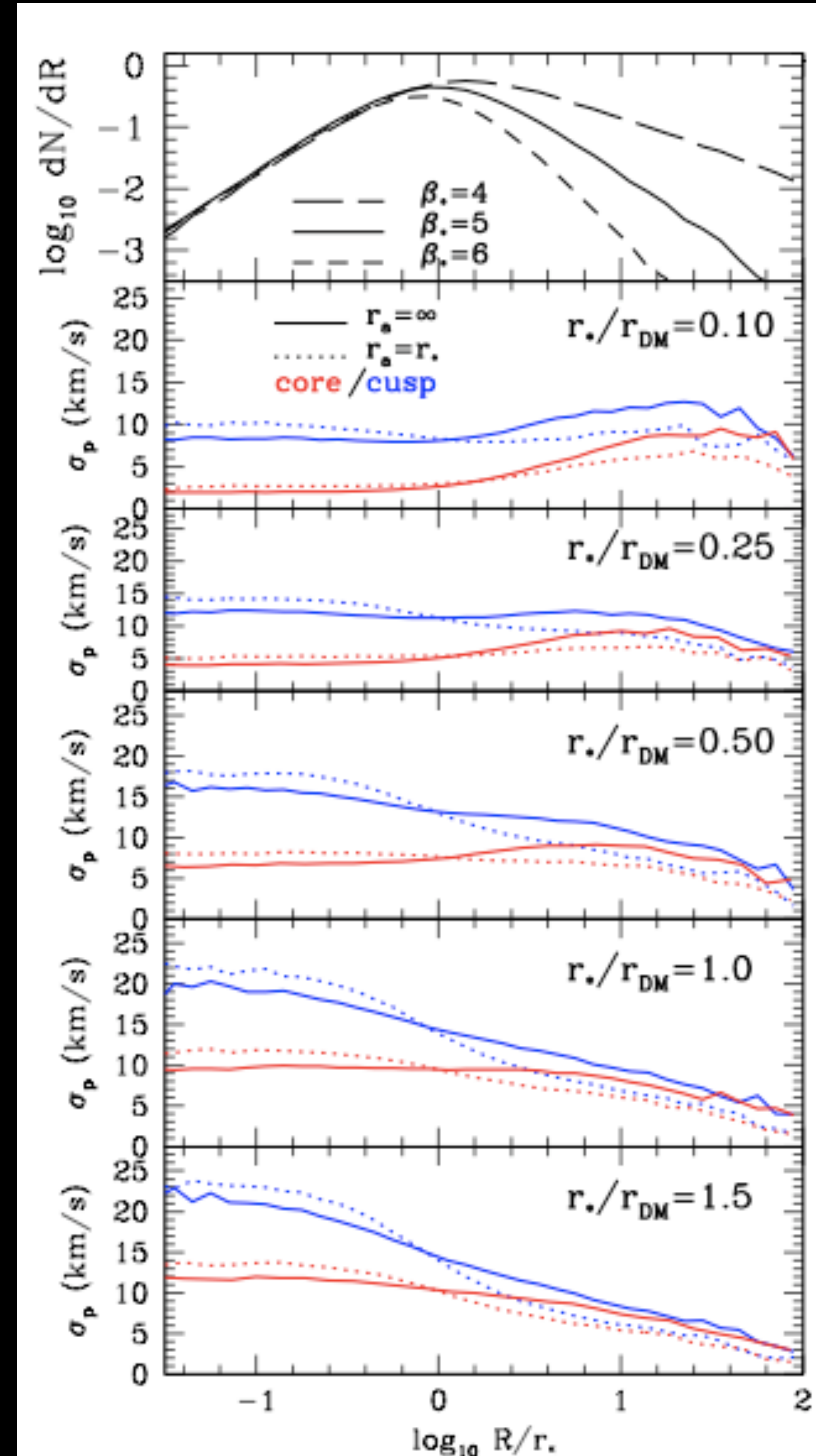
Walker & Peñarrubia (2011)

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)		
	$\rho_0/(M_\odot {\rm pc}^{-3})$	0.064
	$r_{\rm DM}/{\rm kpc}$	1
	$\alpha_{\rm DM}$	1
	$\beta_{\rm DM}$	3
	$\gamma_{\rm DM}$	0, 1

- Combination of parameters= 60 dynamical models.
- Combination of 2 comp.=3600 models

For each dynamical model 10 realizations with:
* $1000 < N_1+N_2+N_{MW} < 3000$
* $0.4 < (N_1+N_2)/(N_1+N_2+N_{MW}) < 0.9$
* $0.0 < (\langle W_2\rangle - \langle W_1\rangle)/A < 0.25$



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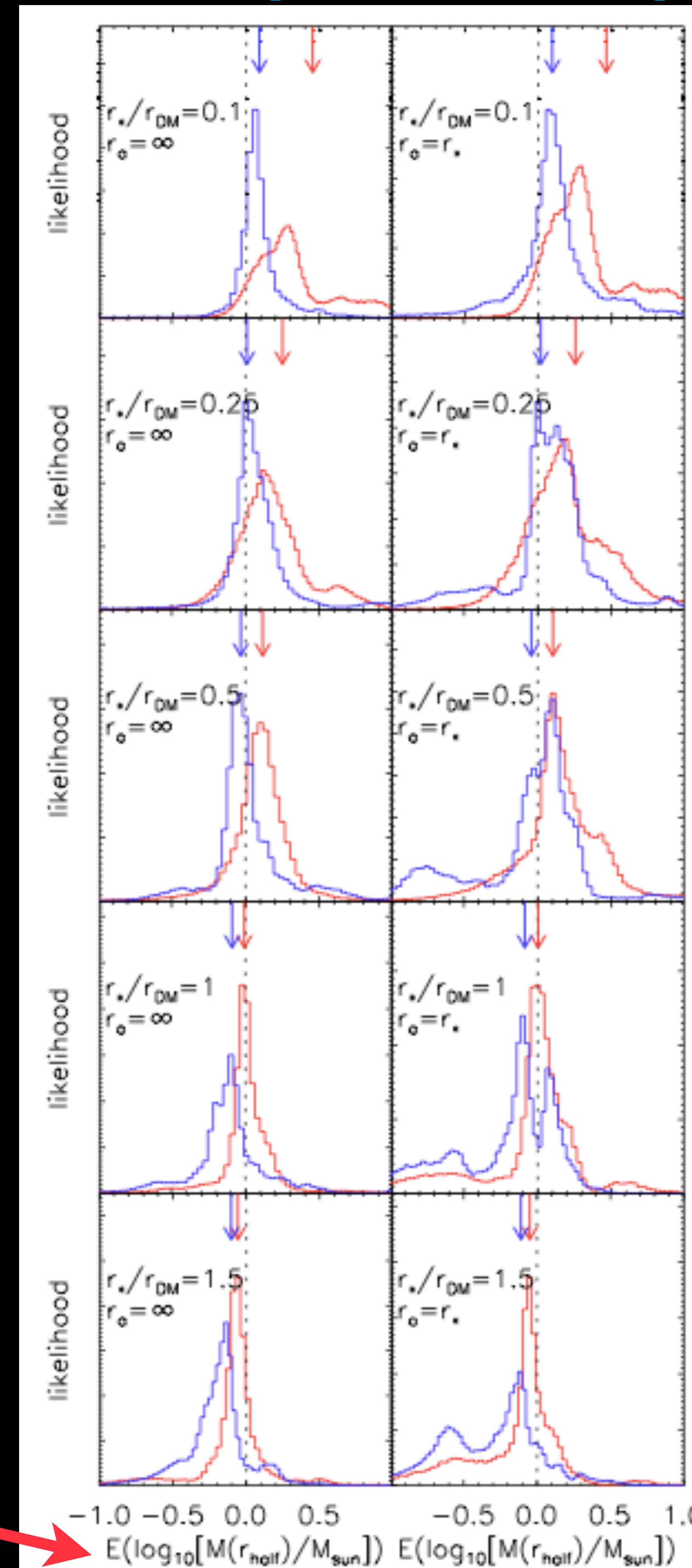
$$E(\log M) = \log M_{true} - \log M_{out}$$

Isotropic Anisotropic



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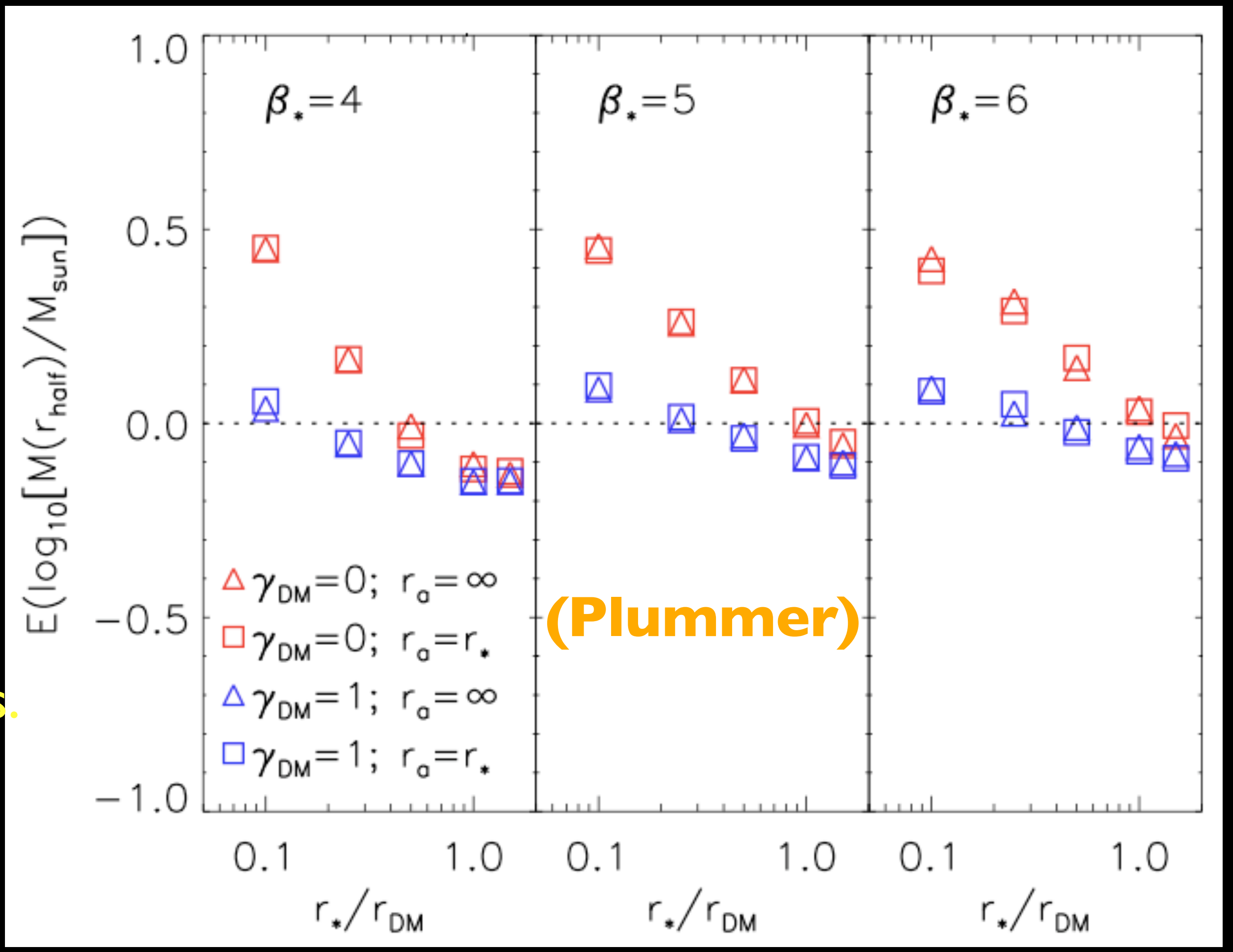

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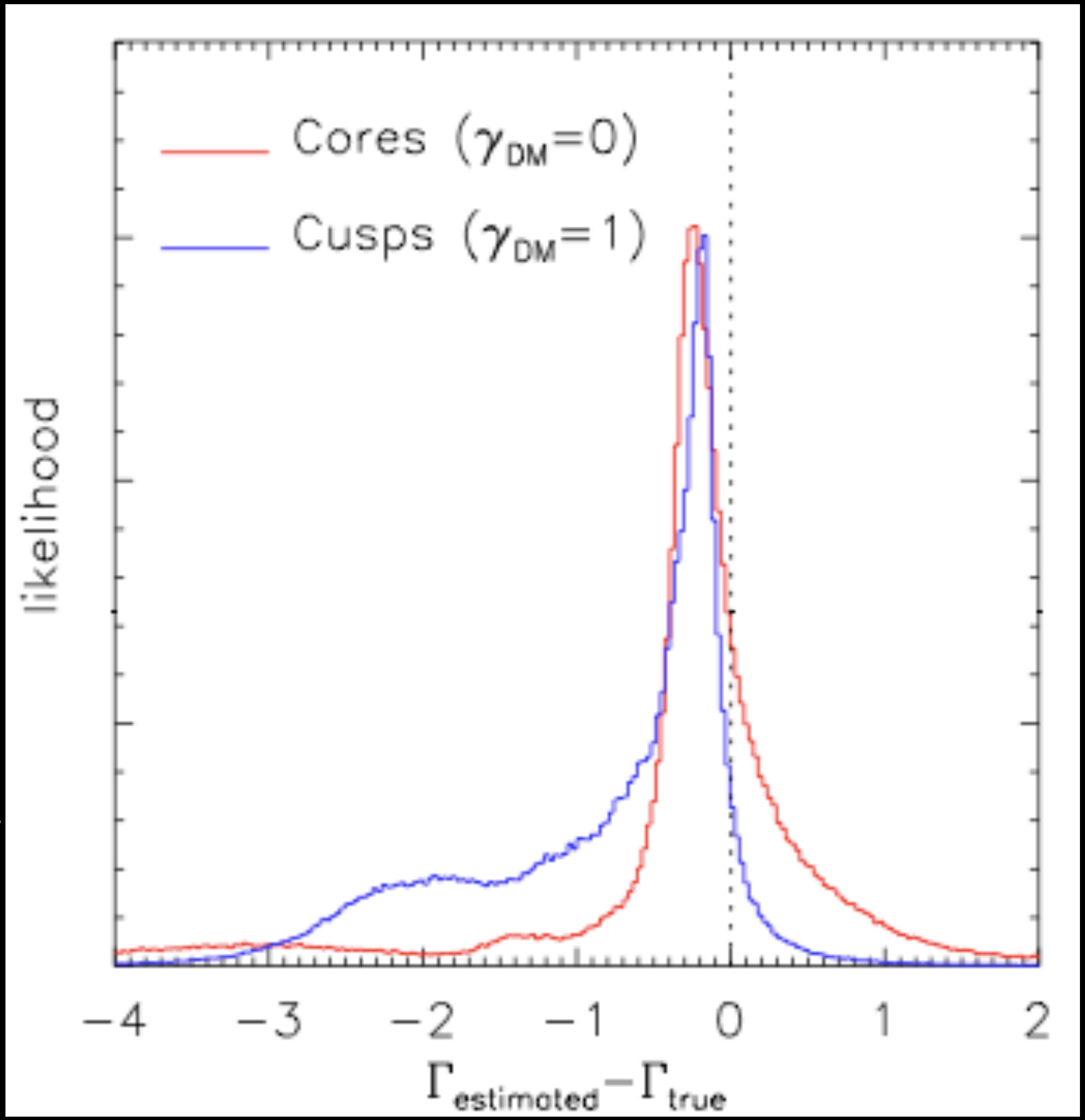

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Test results: Slope of mass profile tends to be slightly under-estimated

Results

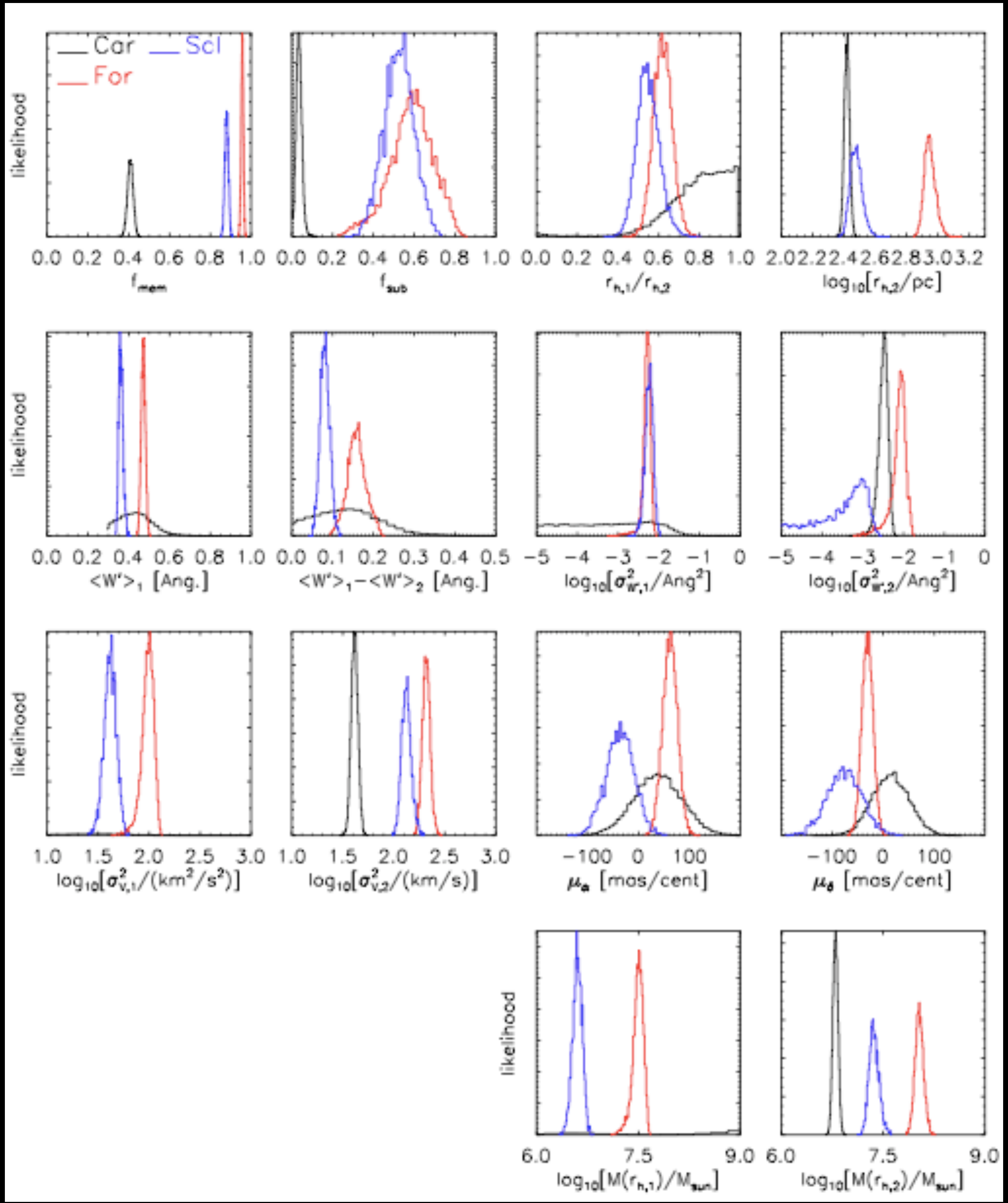
Walker & Peñarrubia (2011)

14-parameter MCMC fit

- Fornax, Scuptor: 2 comp. are clearly separated
- Carina: single component

We recover published data on:

1. proper motions
2. mean velocity dispersion
3. averaged R_{half}
4. mean metallicity



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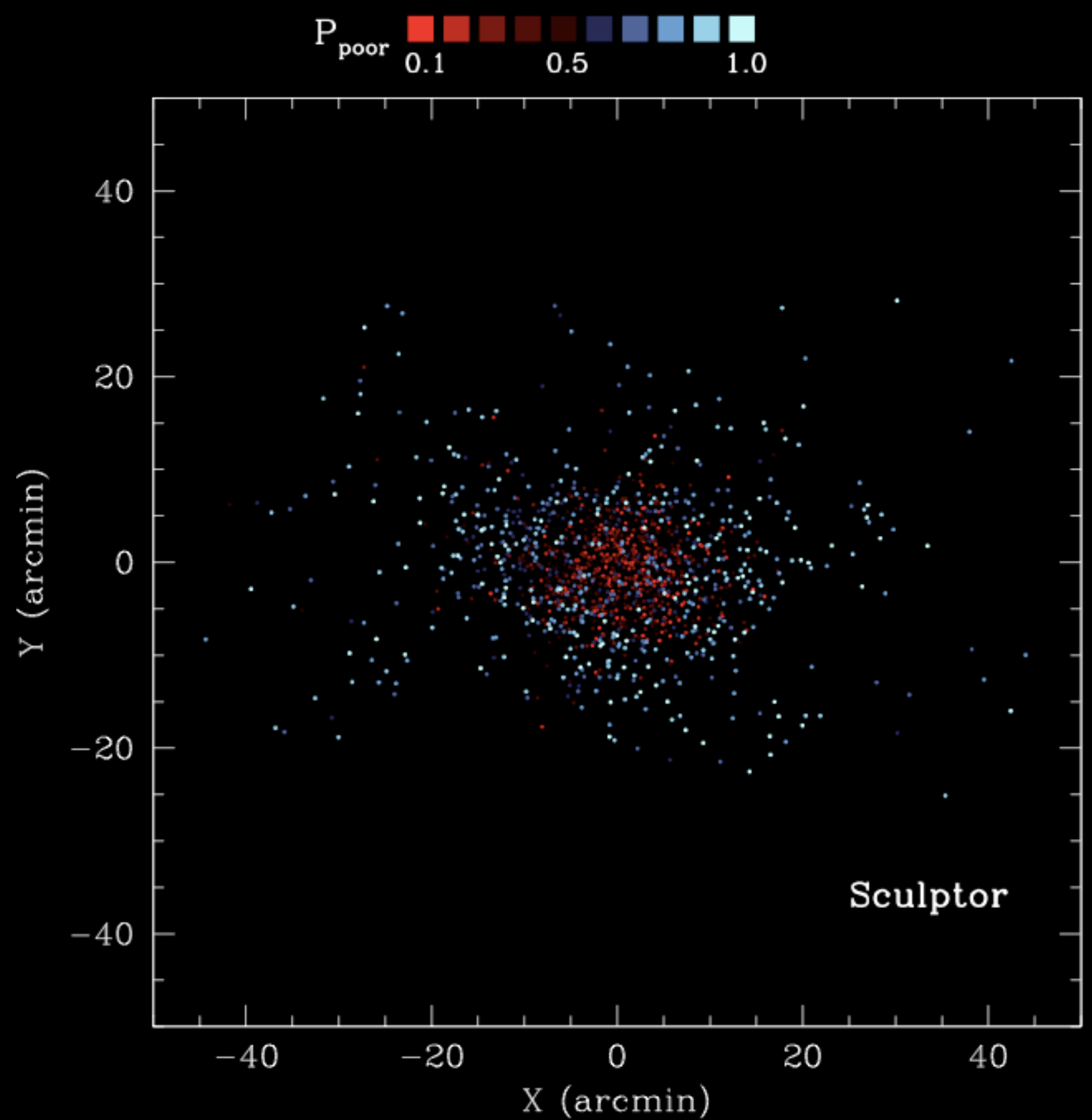

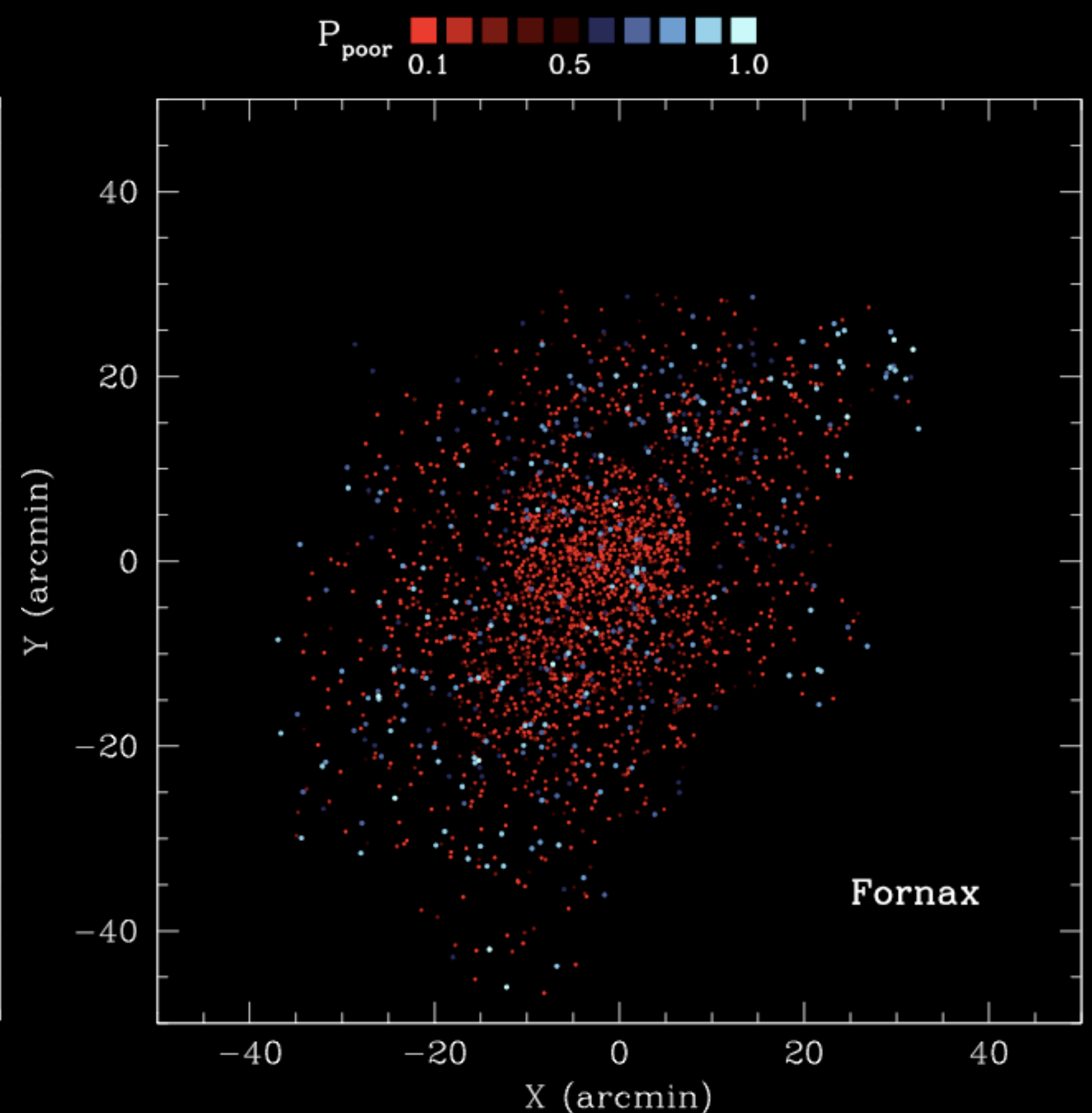

N_{sample}= 1497 spectra

N_{sample}= 2603 spectra

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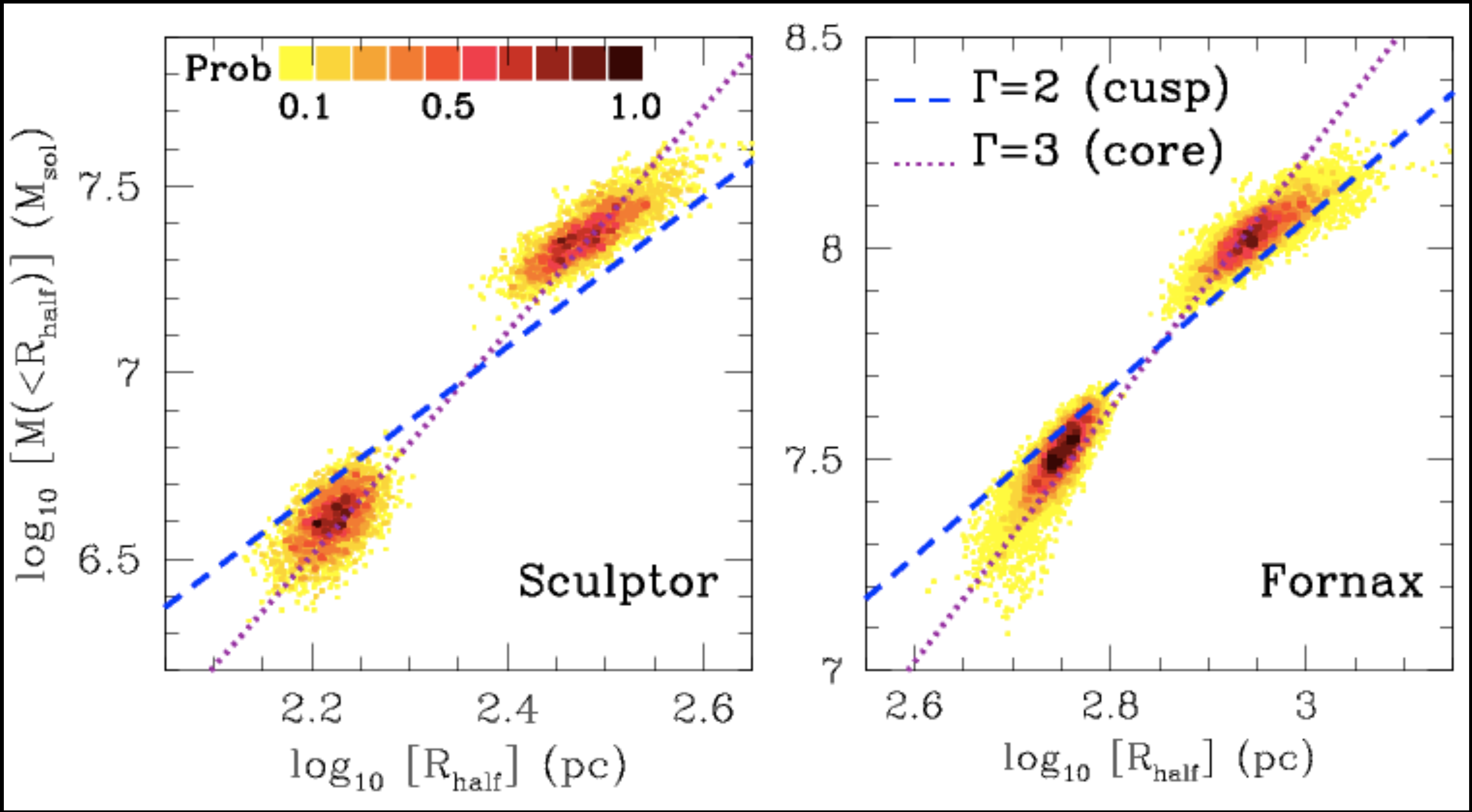

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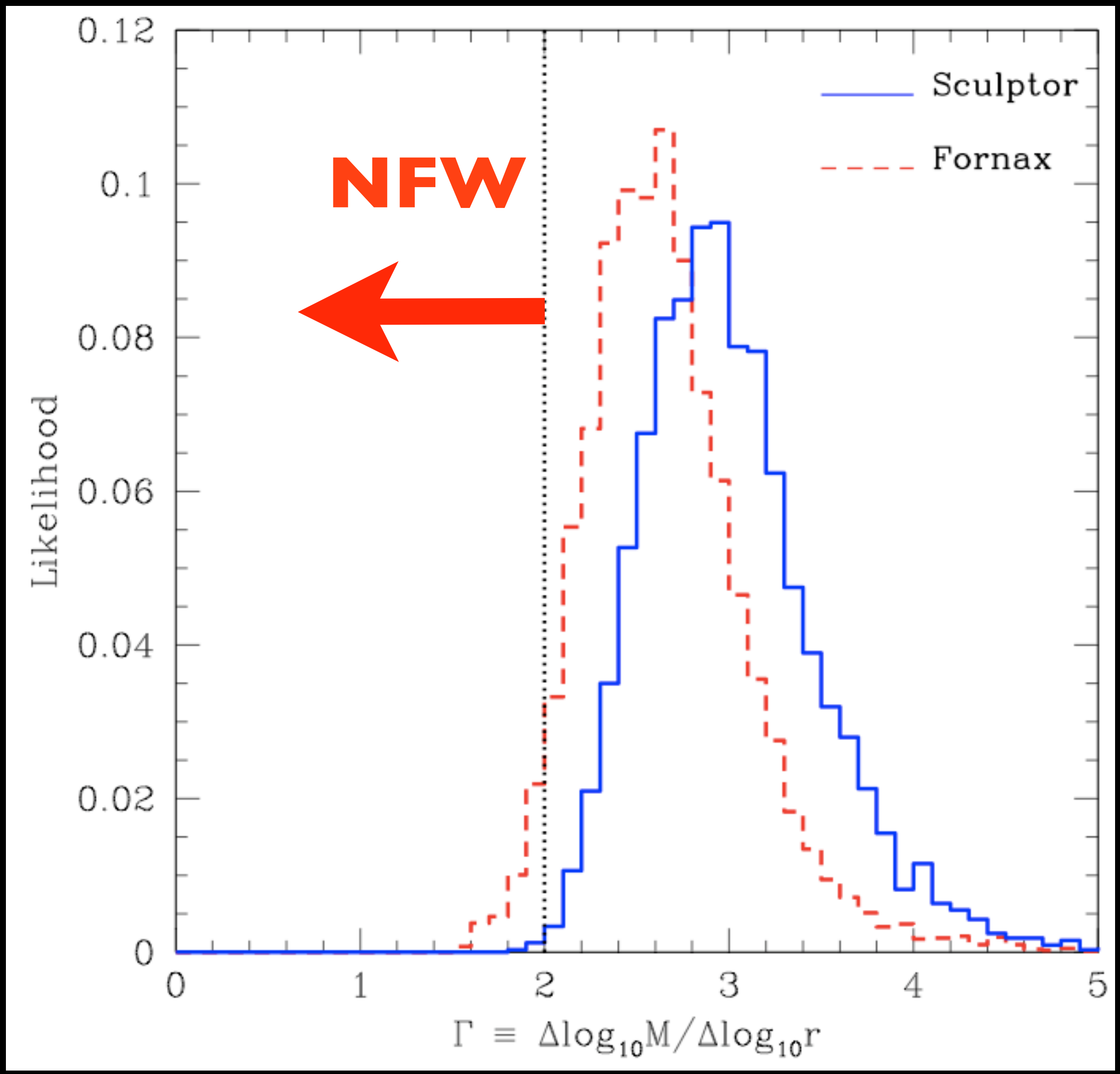

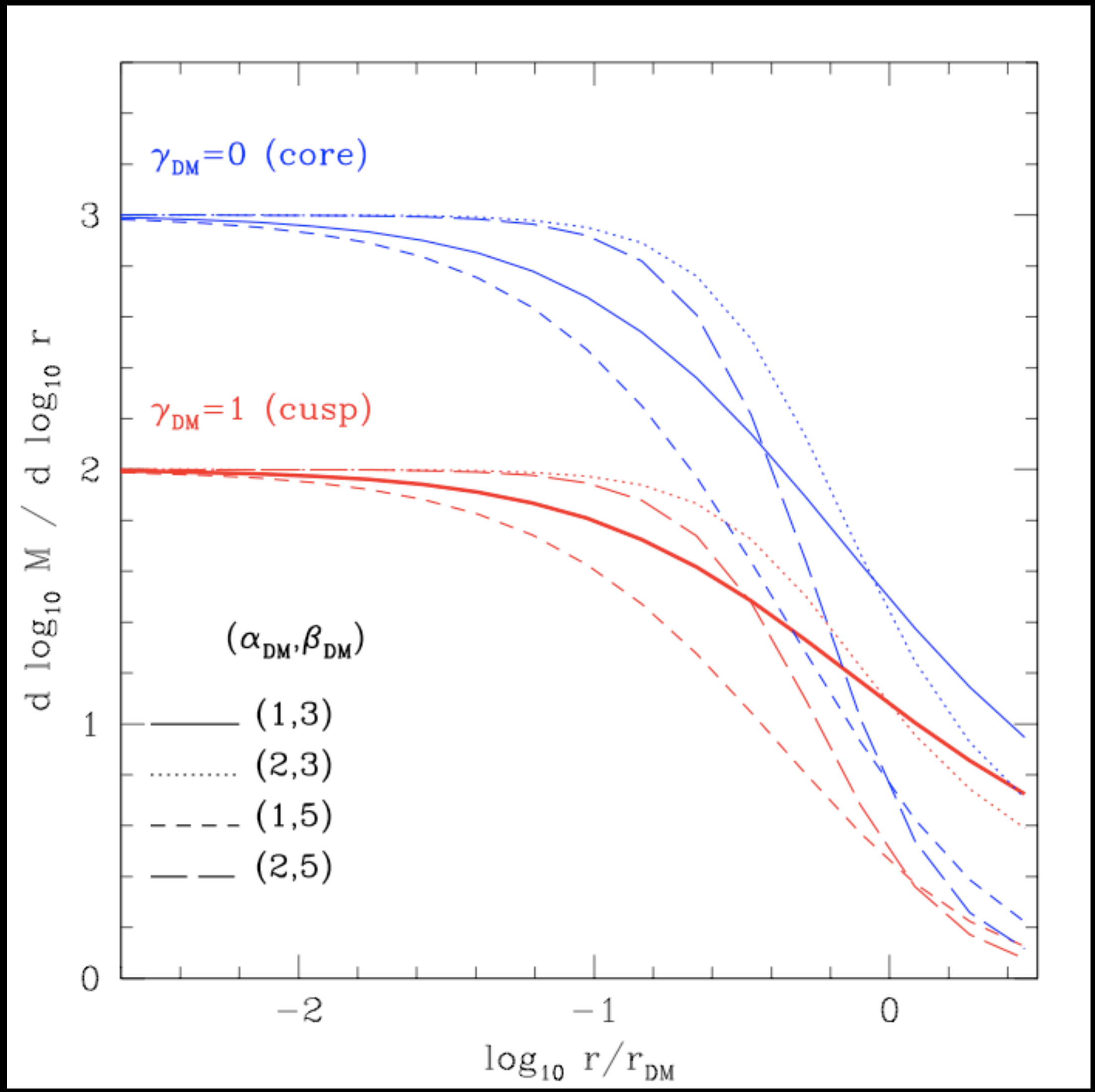

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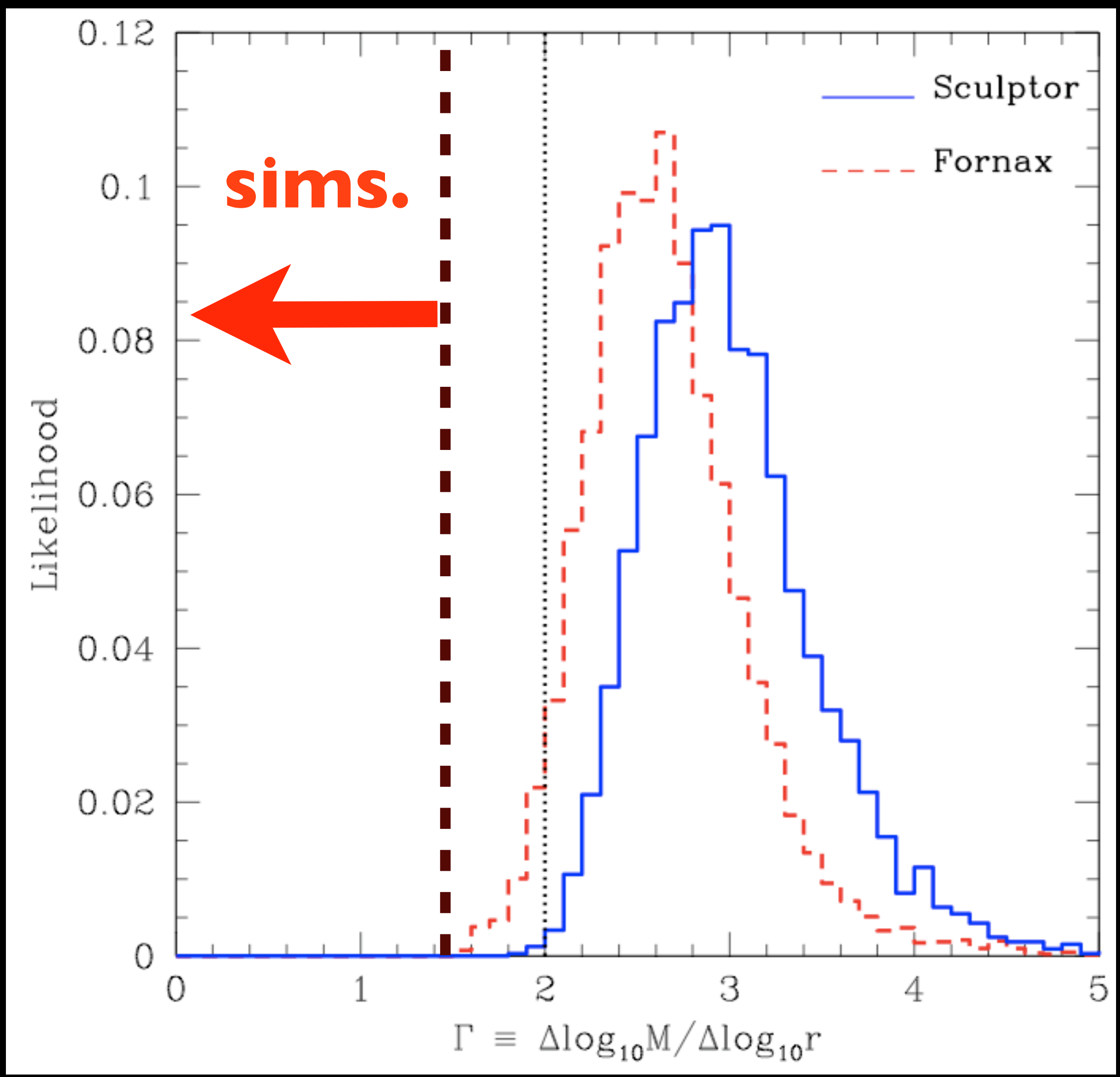
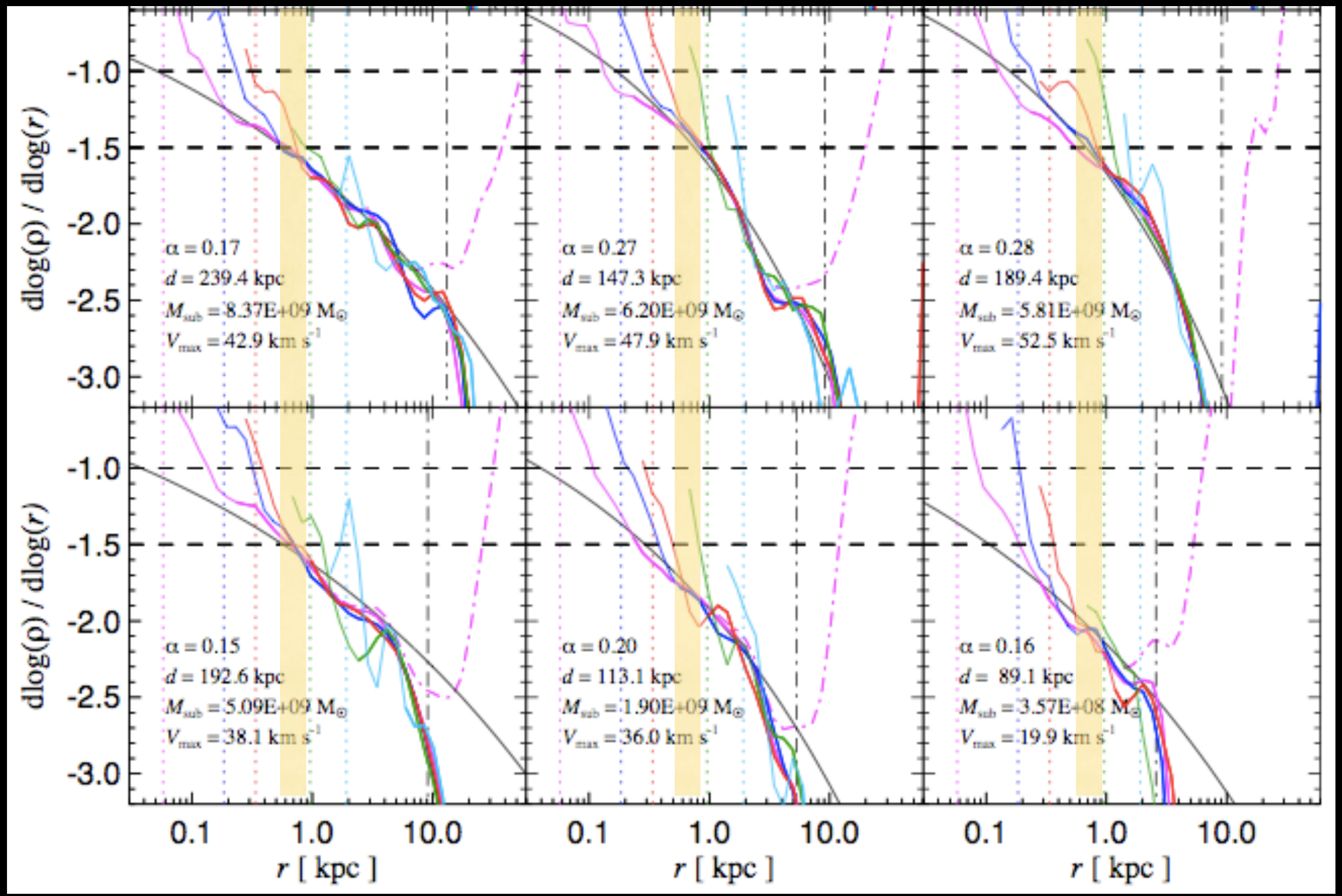
NFW ruled out in Fornax and Sculptor at a 96% and 99% confidence level

Results

Walker & Peñarrubia (2011)



Springel+08



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Profiles from collision-less cosmological simulations of satellites ruled out in Fornax and Sculptor at a 99.98% and 99.999% confidence level

Summary

- 2 out of 2 dSphs show DM cores
- This measurement appears not to be easily accommodated within CDM (Sawala+10; Parry+11)
- Tantalizing case for **WDM** (Bode+01: m_X~10 kev) ???

Future Work

1. Inspect model built-in assumptions (e.g. triaxial DM halo; N_{comp}>2)
2. Increase the sample of stars with measured radial velocities in Fornax (L/L_{sol} ~10^7) and Sculptor (L/L_{sol} ~10^6) dSphs
3. **Fainter** (L/L_{sol} ~10^5--10^6) candidates for holding multiple stellar populations:

Milky Way: Draco, Canis Venatici, Ursa Minor, Leo I and Leo II

Andromeda: And I, II and VI