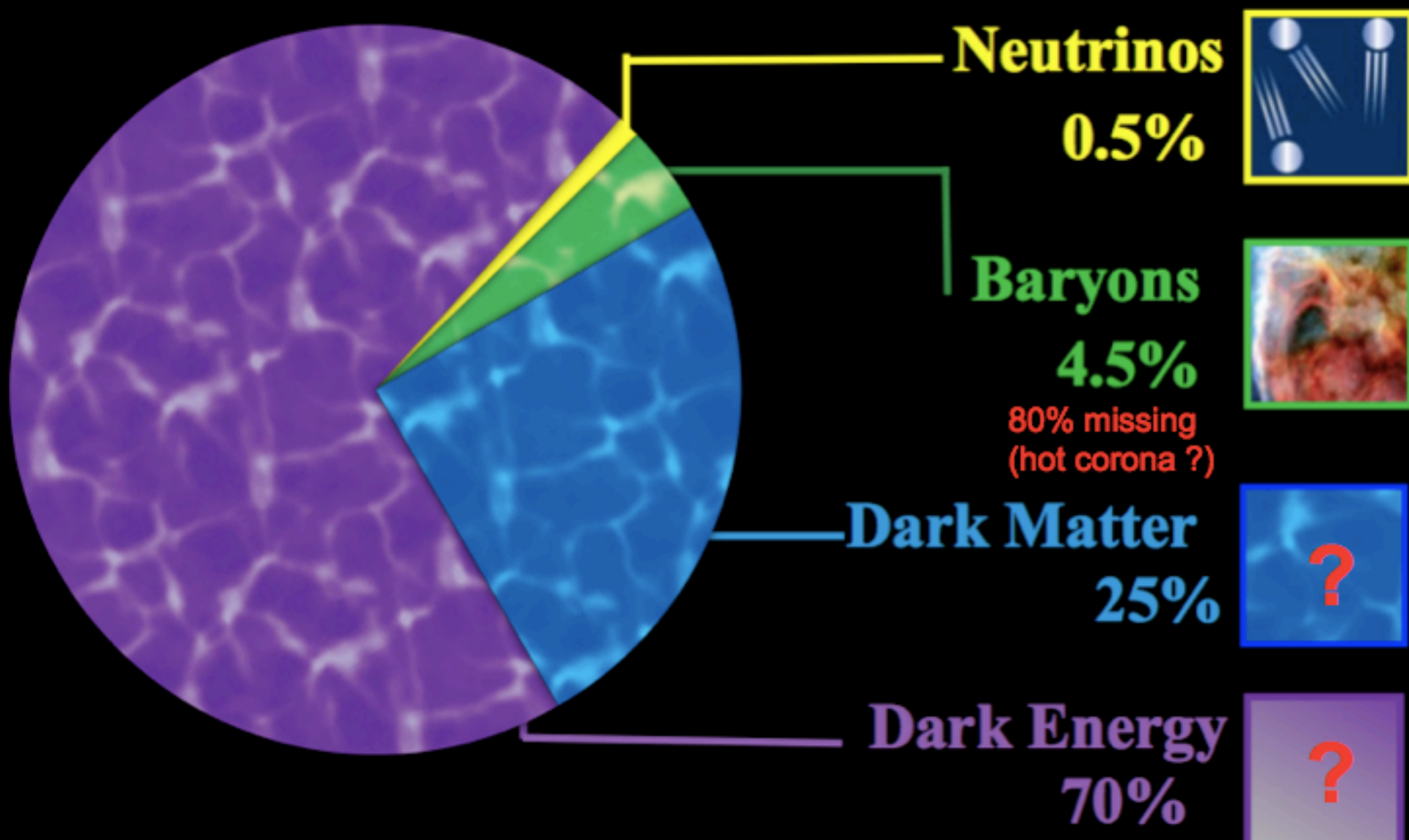
Testing cosmological models with dwarf spheroidals

Jorge Peñarrubia

Paris
7th of June 2012

Universe Composition



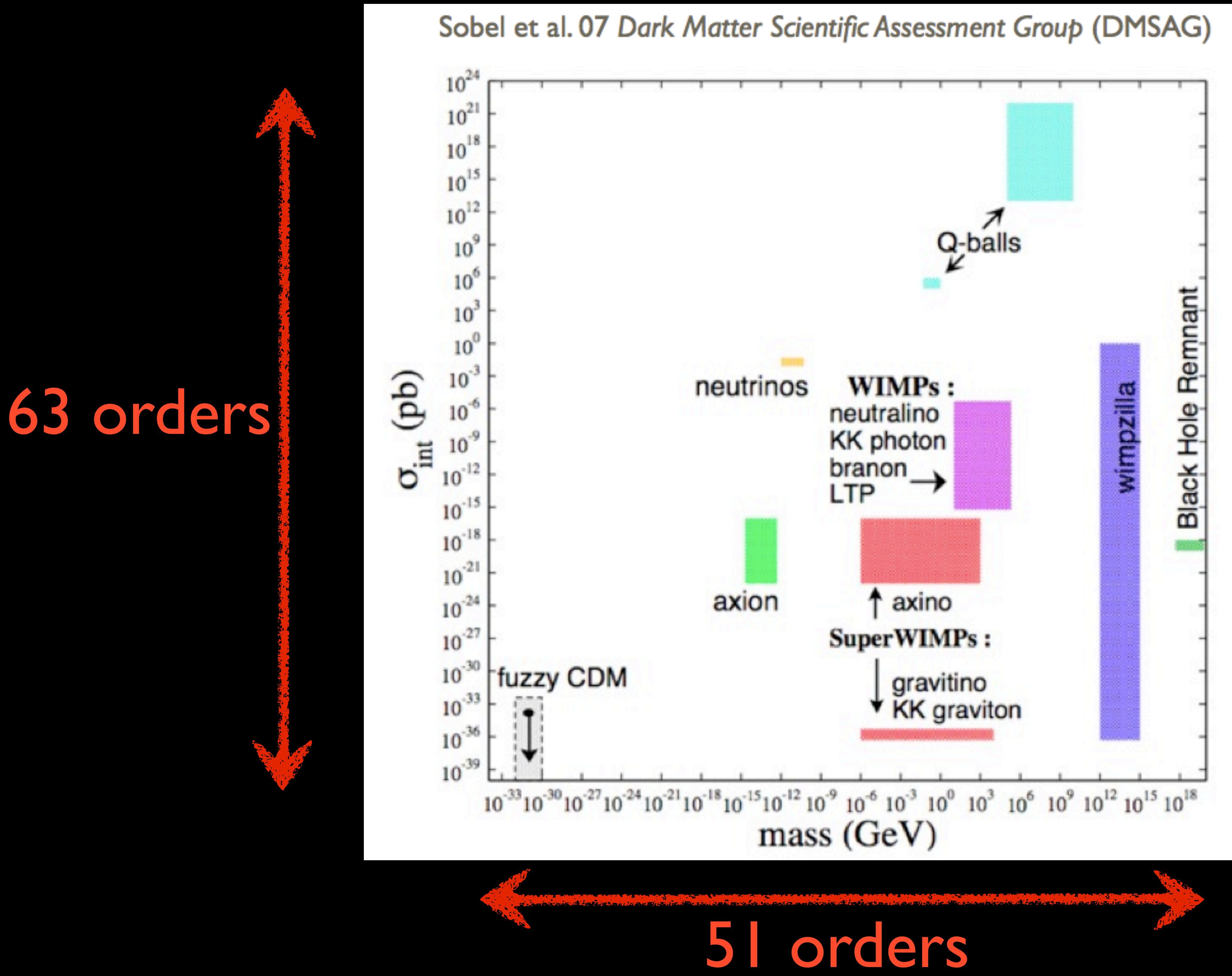
WMAP7

DM particle models: Constraints

Assumption: dark matter is composed of "*exotic*" particles (i.e. beyond the current standard model of particle physics) that were created after the Big Bang

1. Relic density (CMB)
2. Electrically Neutral
3. Consistent with the Big Bang Nucleosintesis
4. Leave stellar evolution unchanged
5. Compatible with constraints on self-interactions
6. Compatible with direct-searches constraints
7. It can be manufactured in the laboratory

DM particle models: Constraints



DM particle models: Classification

HOT
$<10^2$ ev

WARM
$10^3 - 10^5$ ev

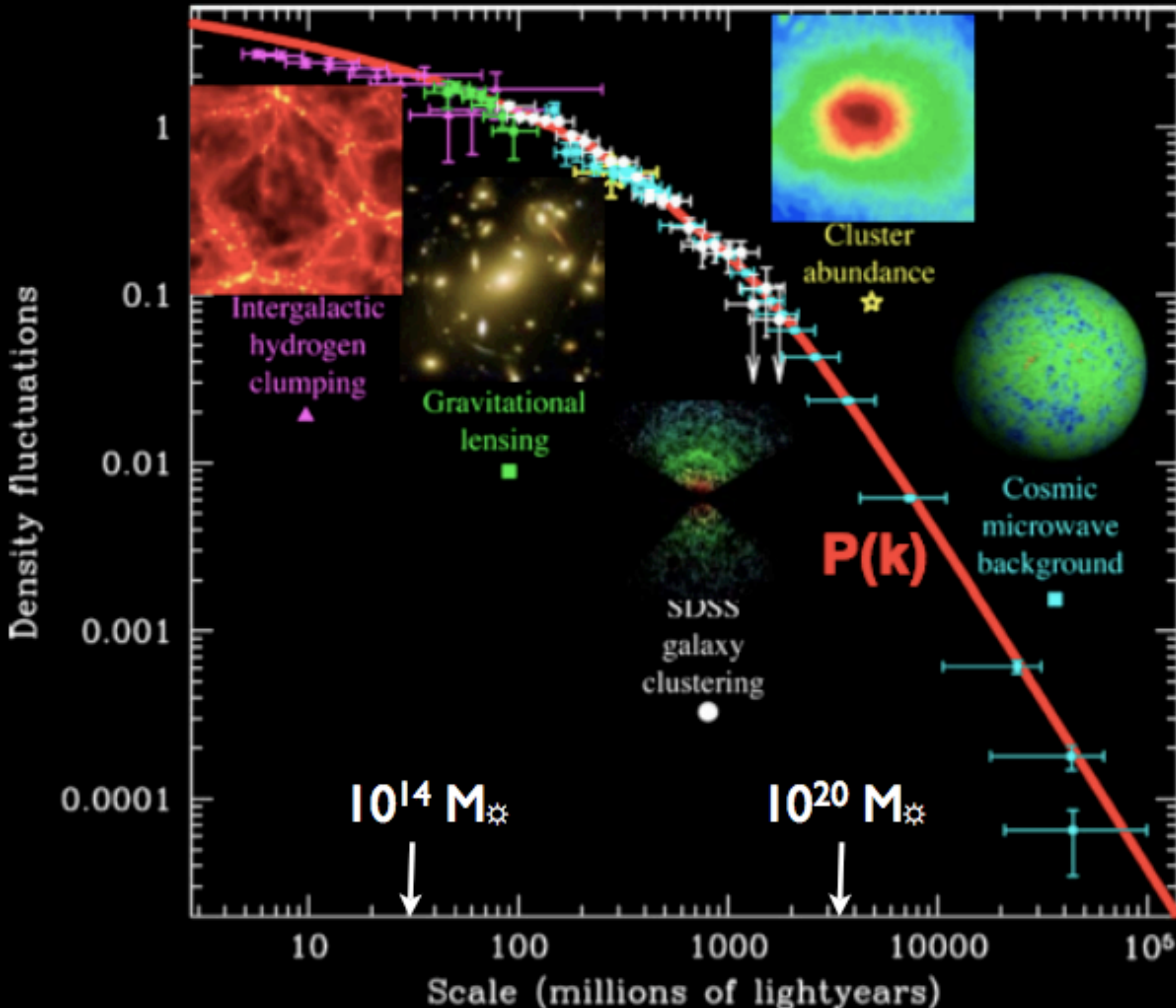
COLD
$10^9 - 10^{12}$ ev

$\lambda_{FS} \equiv$ *"average distance travelled by a DM particle before it falls in a potential well"*

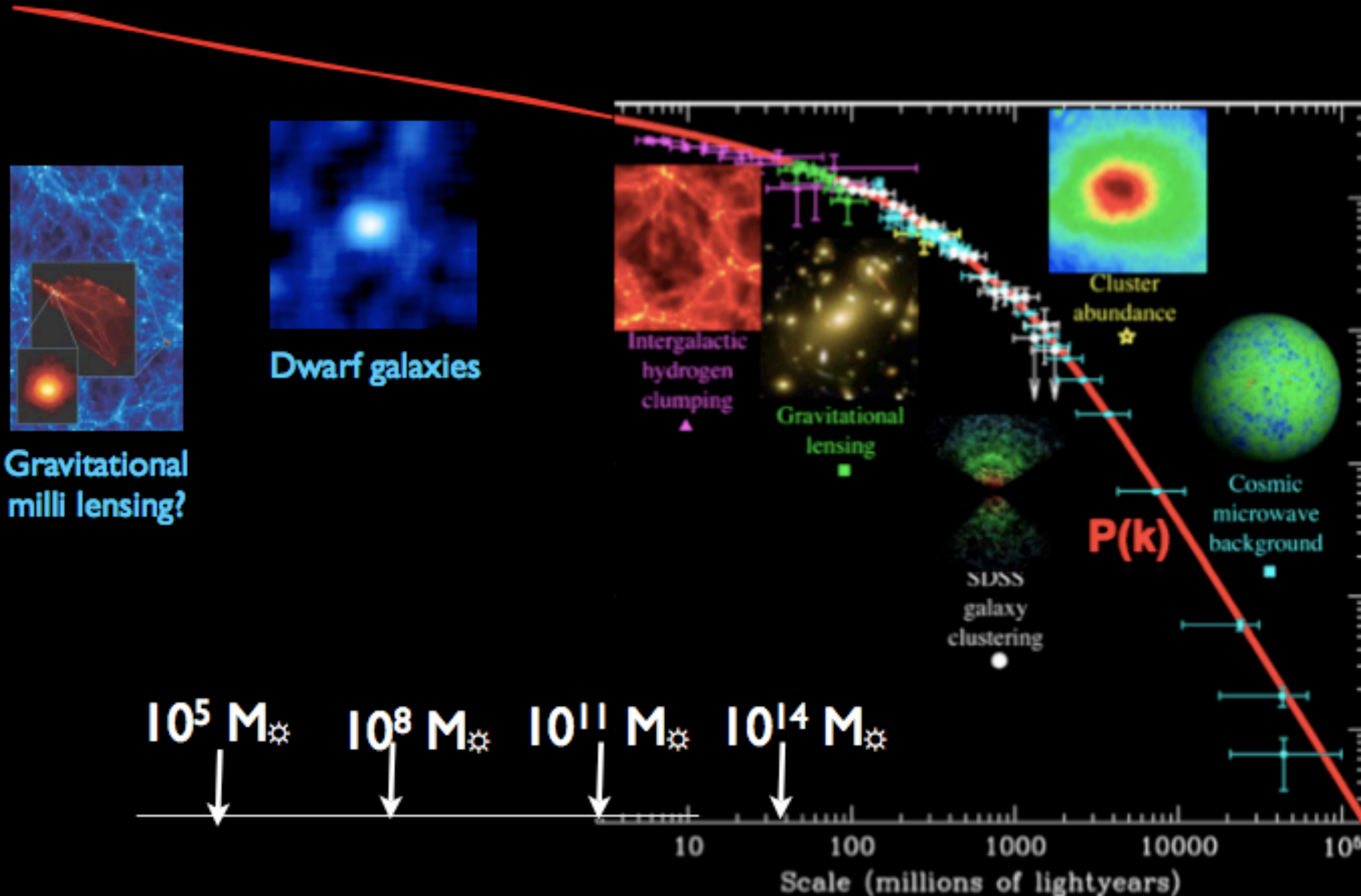
$\lambda_{FS} \sim 20$ Mpc (30 ev / m_ν)

$\lambda_{FS} \sim 1$ Mpc (1 kev / m_ν)

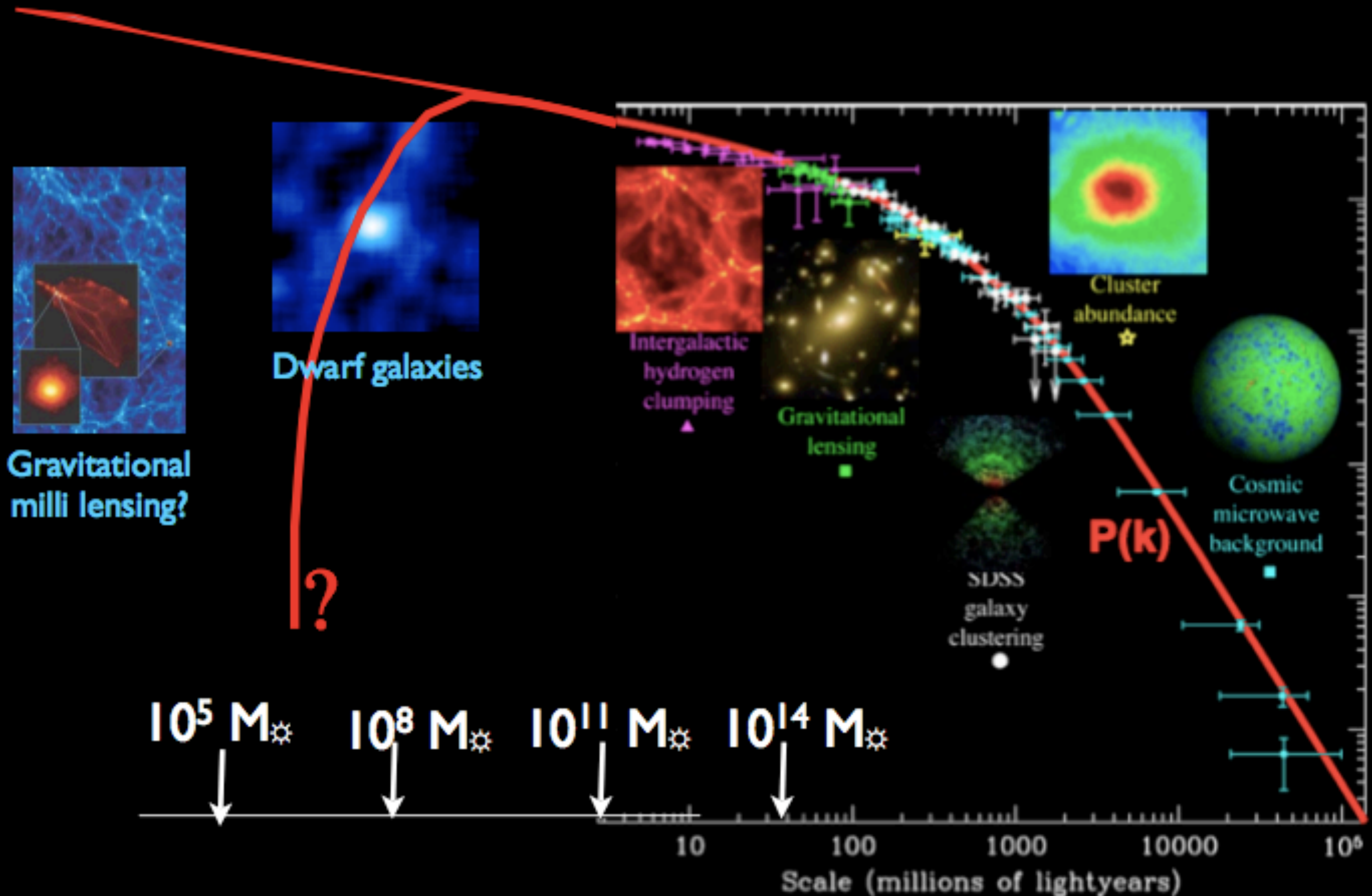
$\lambda_{FS} \sim 3.7$ pc (100 Gev / m_ν)$^{1/2}$



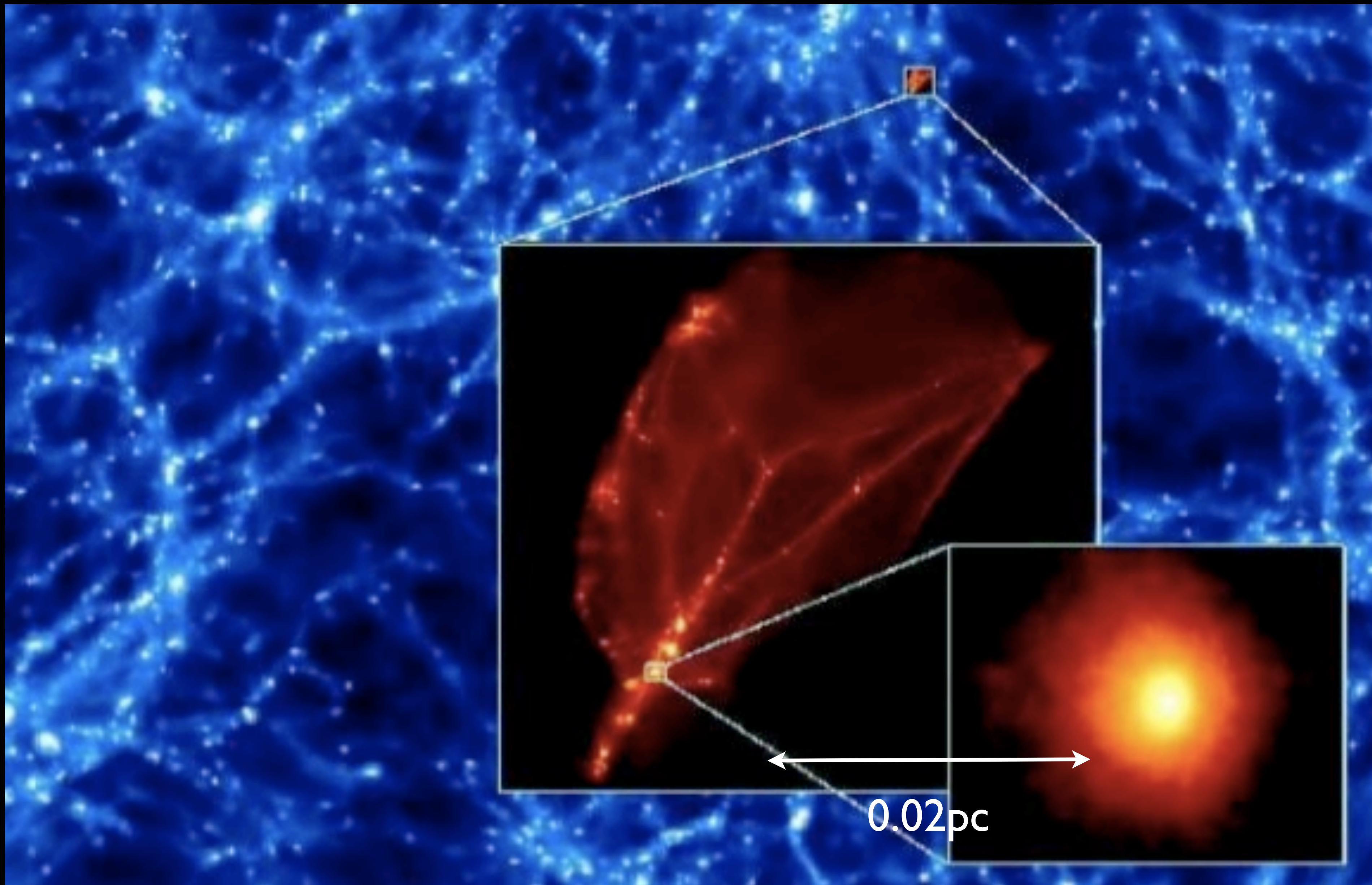
CDM prediction



Gravitational milli lensing?
Dwarf galaxies
Intergalactic hydrogen clumping
Gravitational lensing
Cluster abundance
SDSS galaxy clustering
P(k)
Cosmic microwave background
10⁵ M☼
10⁸ M☼
10¹¹ M☼
10¹⁴ M☼
10
100
1000
10000
10⁵
Scale (millions of lightyears)



Clues on the nature of DM must be searched on small scales

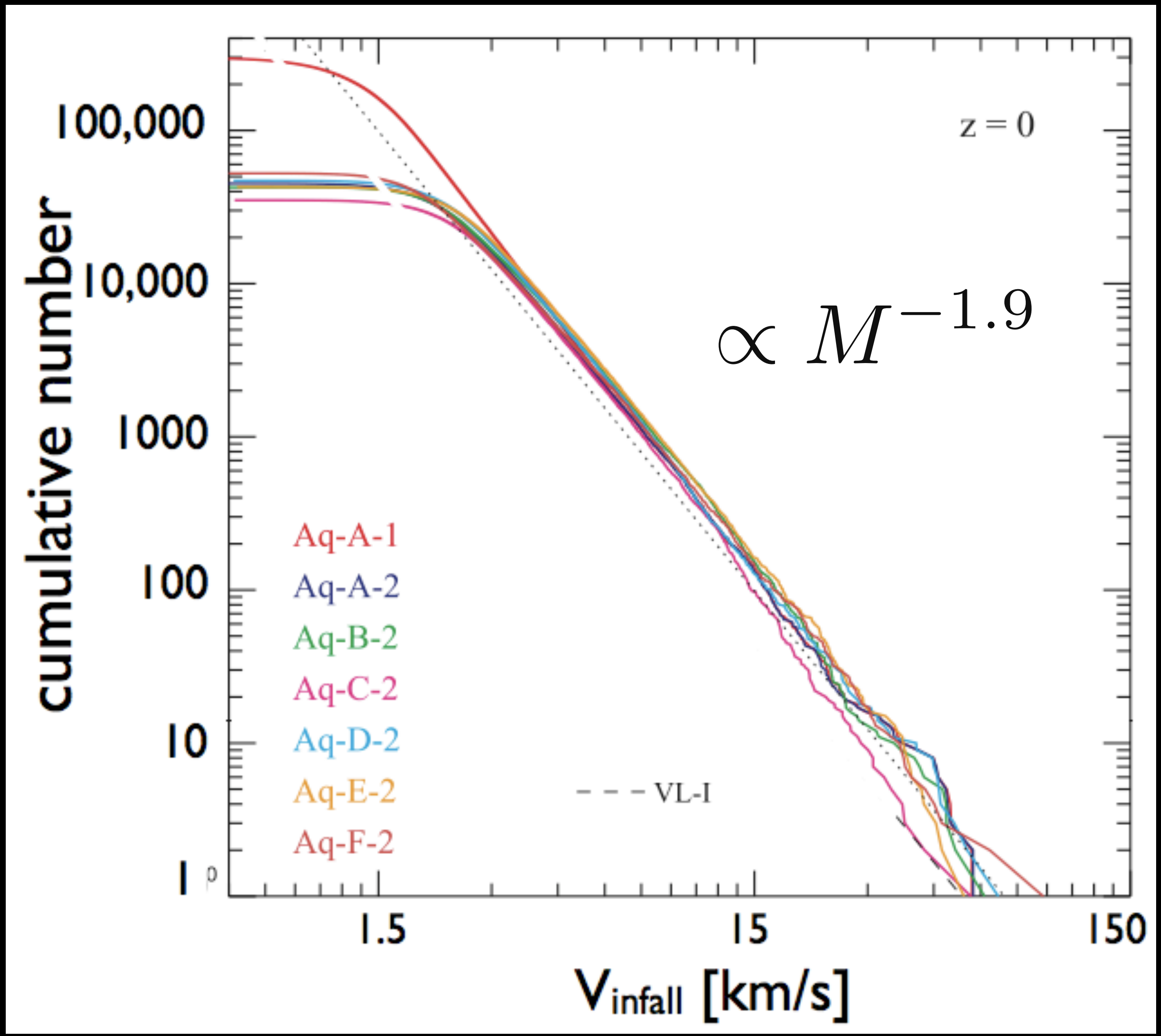


Diemand+05

DM particle mass ~ 100 Gev

- $M_{subhalo,MW} > 10^{-5}\ M_{sol}$
- $N_{subhalo,MW} > 10^{14}$ (!) → all of them galaxies?

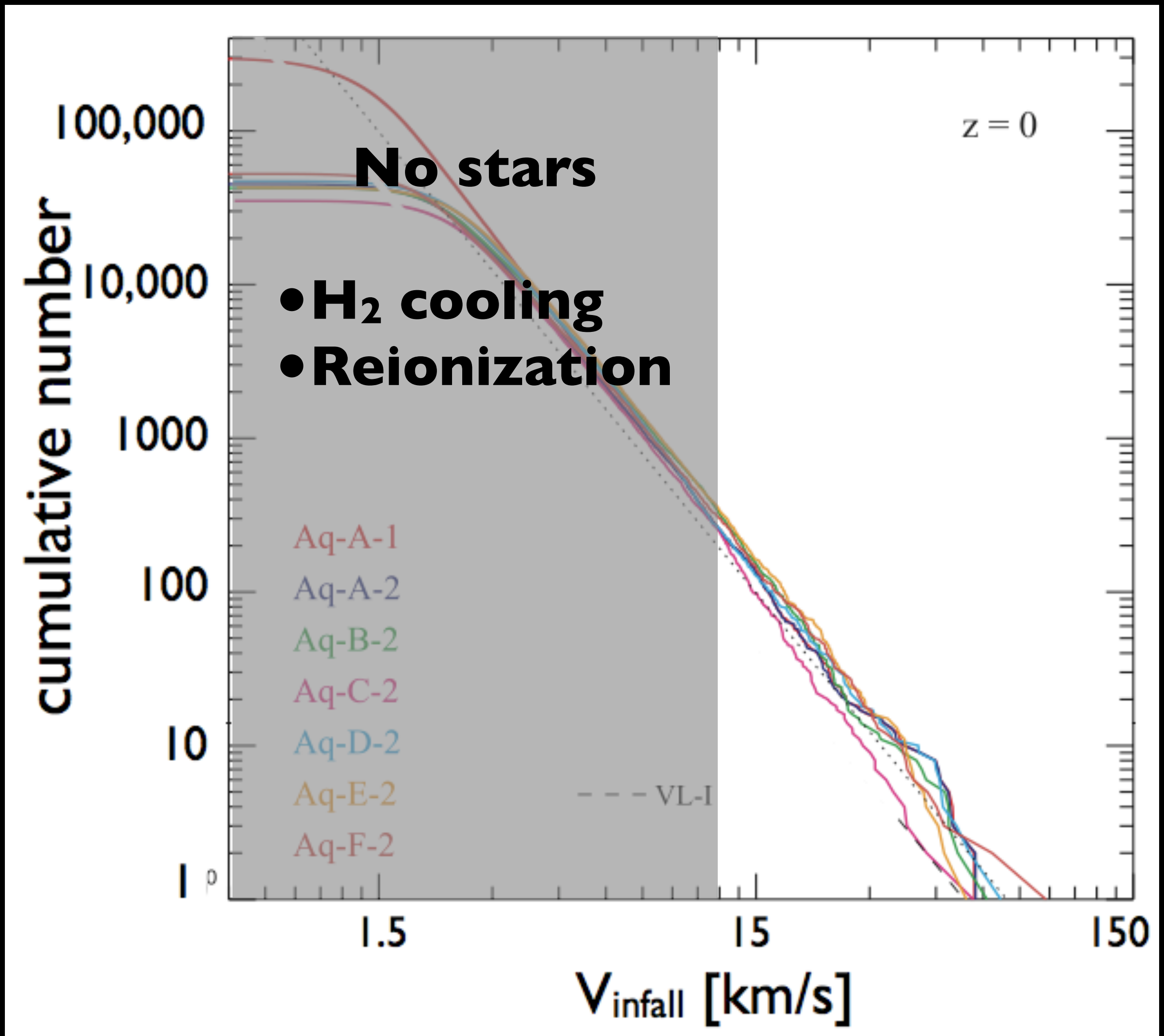
The "*missing satellite*" problem



MW: ~25 dSph satellites

M31: ~23 dSph sats.

The “*missing satellite*” problem



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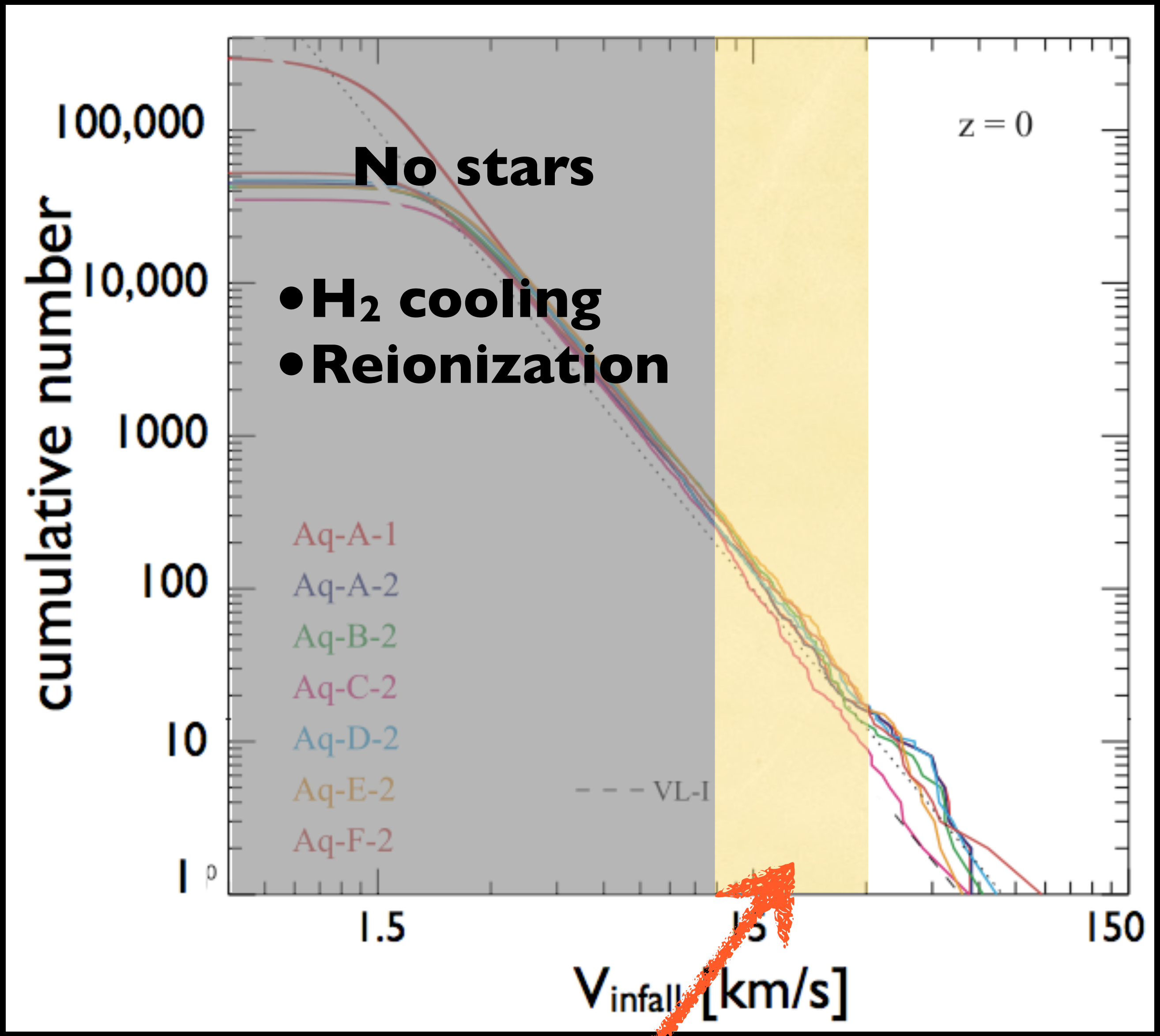


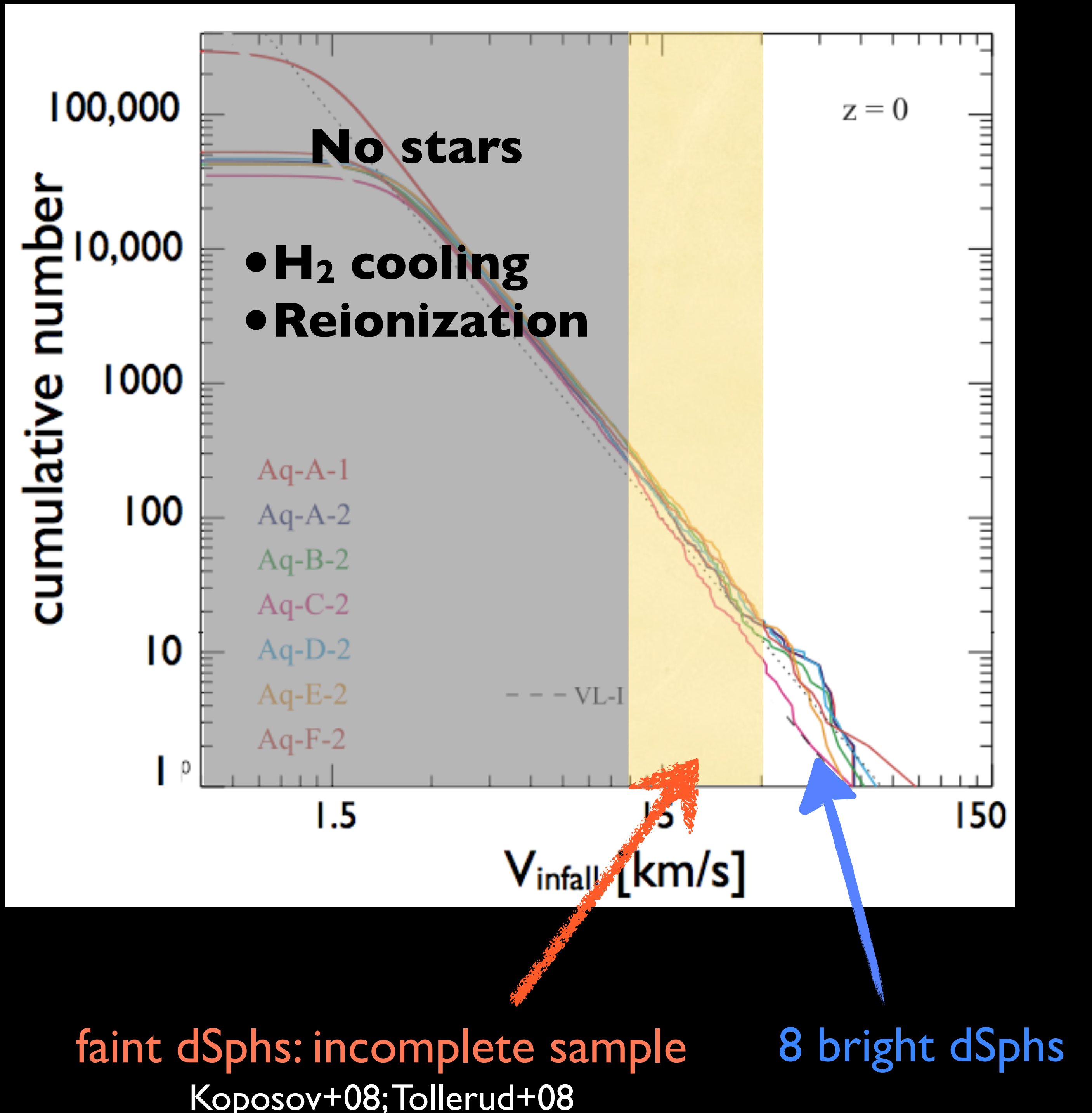
MW: ~25 dSph satellites

M31: ~23 dSph sats.

faint dSphs: incomplete sample

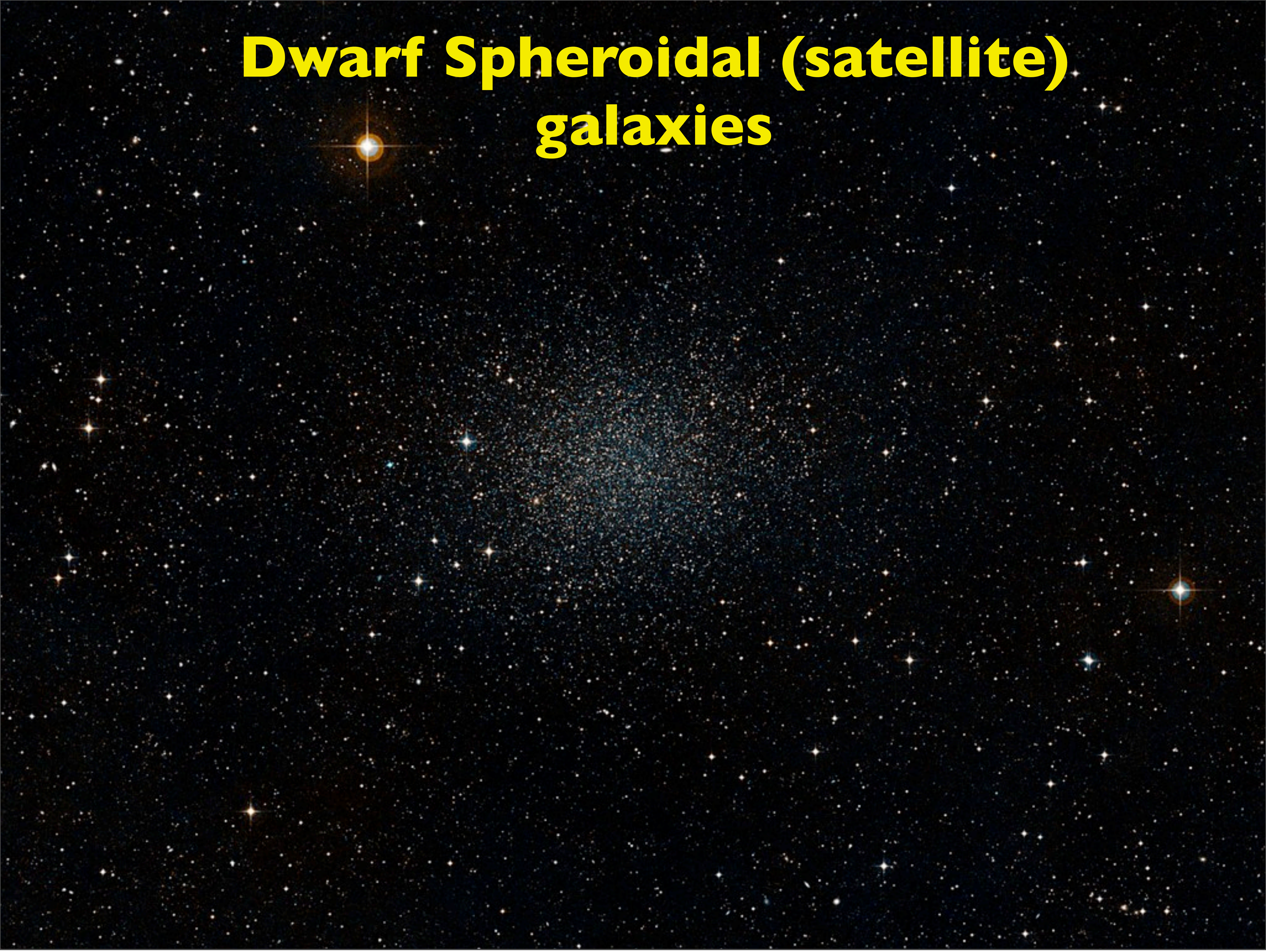
Koposov+08; Tollerud+08

The "*missing satellite*" problem



Inconclusive results ...

Dwarf Spheroidal (satellite) galaxies



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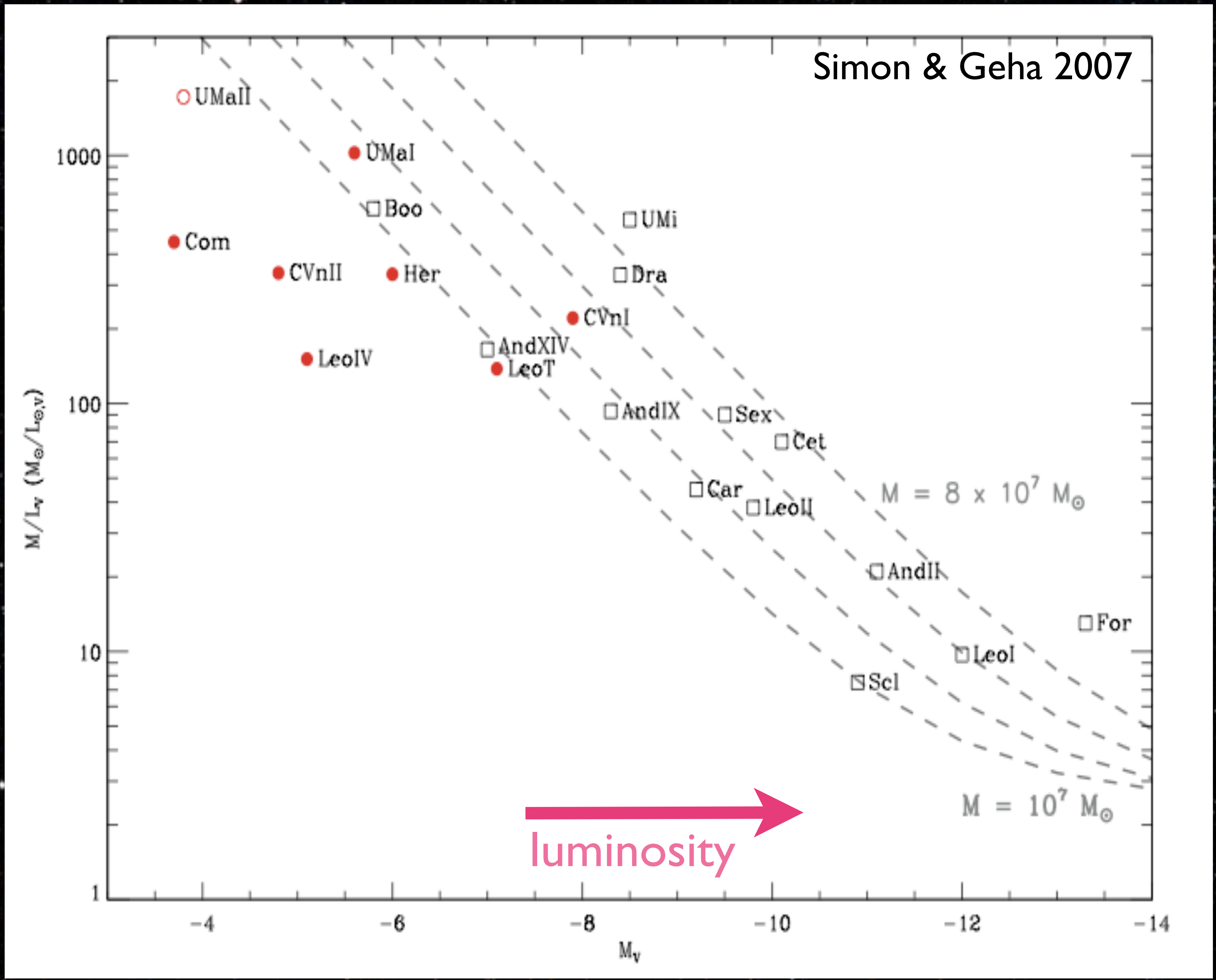

★ **Faintest galaxies in the known Universe:**
$10^3 < L/L_{sol} < 10^7$

★**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)**

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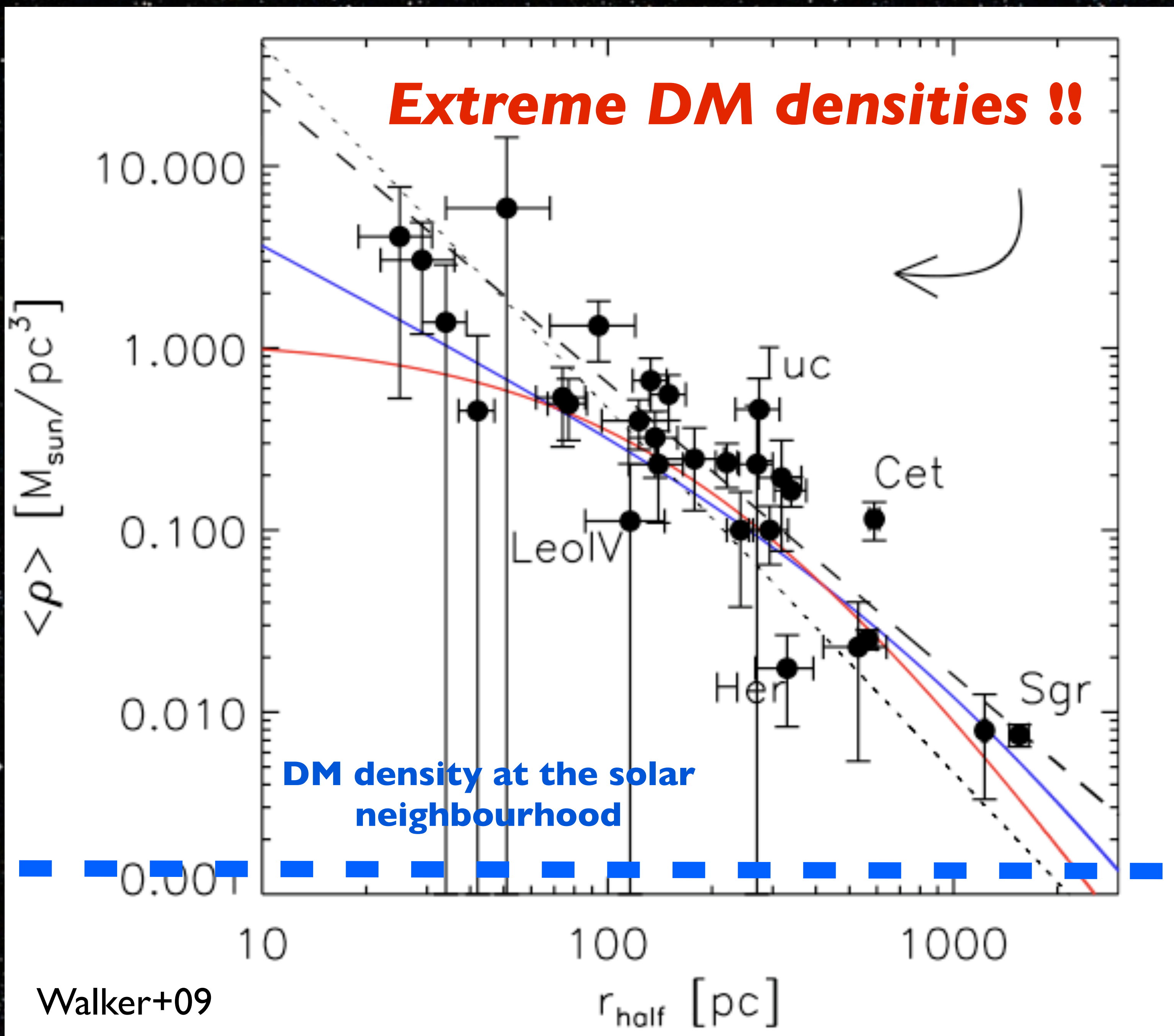

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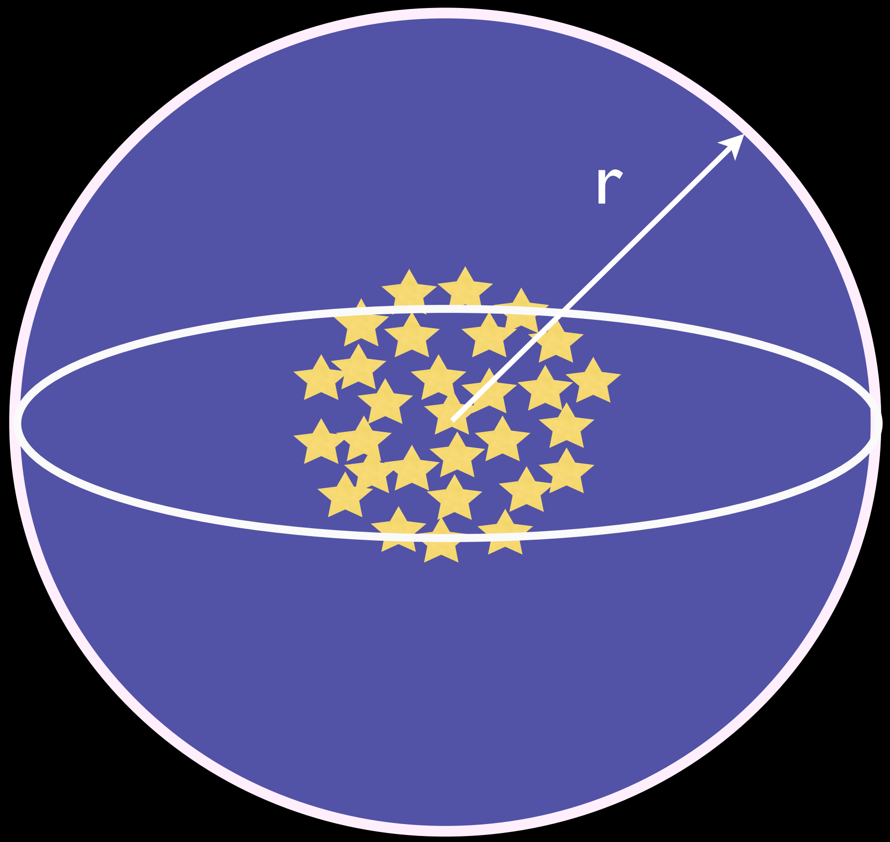
Talk overview



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

dwarf spheroidal galaxies

1- Existence of "dark" substructures

→ ***missing sat. problem***

2- DM distribution in galactic haloes

→ ***core/cusp problem***

“dark” substructures in dSphs

* ✳ dSphs have virial masses
  $M_{vir} \lesssim 10^9 M_{sol}$

  Strigari+07; Peñarrubia+08; Walker+09; Wolf+09

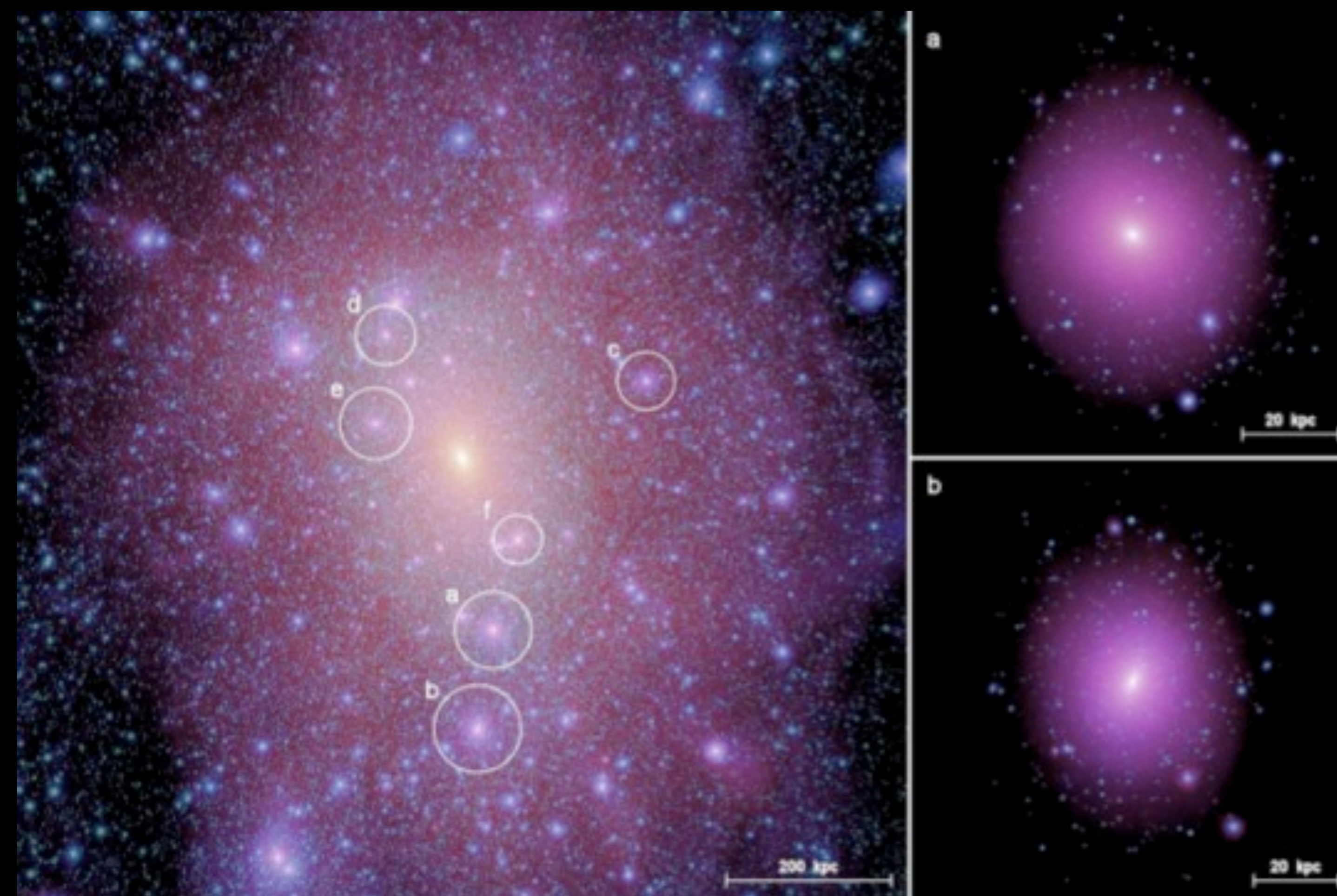
* ✳ CDM mass function:

  $dN/dm \propto m^{-1.9}$

  NFW97; Diemand+07; Springel+08

↓

DM **substructures** in dSphs
have $m \lesssim 0.01 M_{vir} \sim 10^7 M_{sol}$
i.e. they are “**dark**”



sub-sub haloes in CDM simulations (Springel+08)

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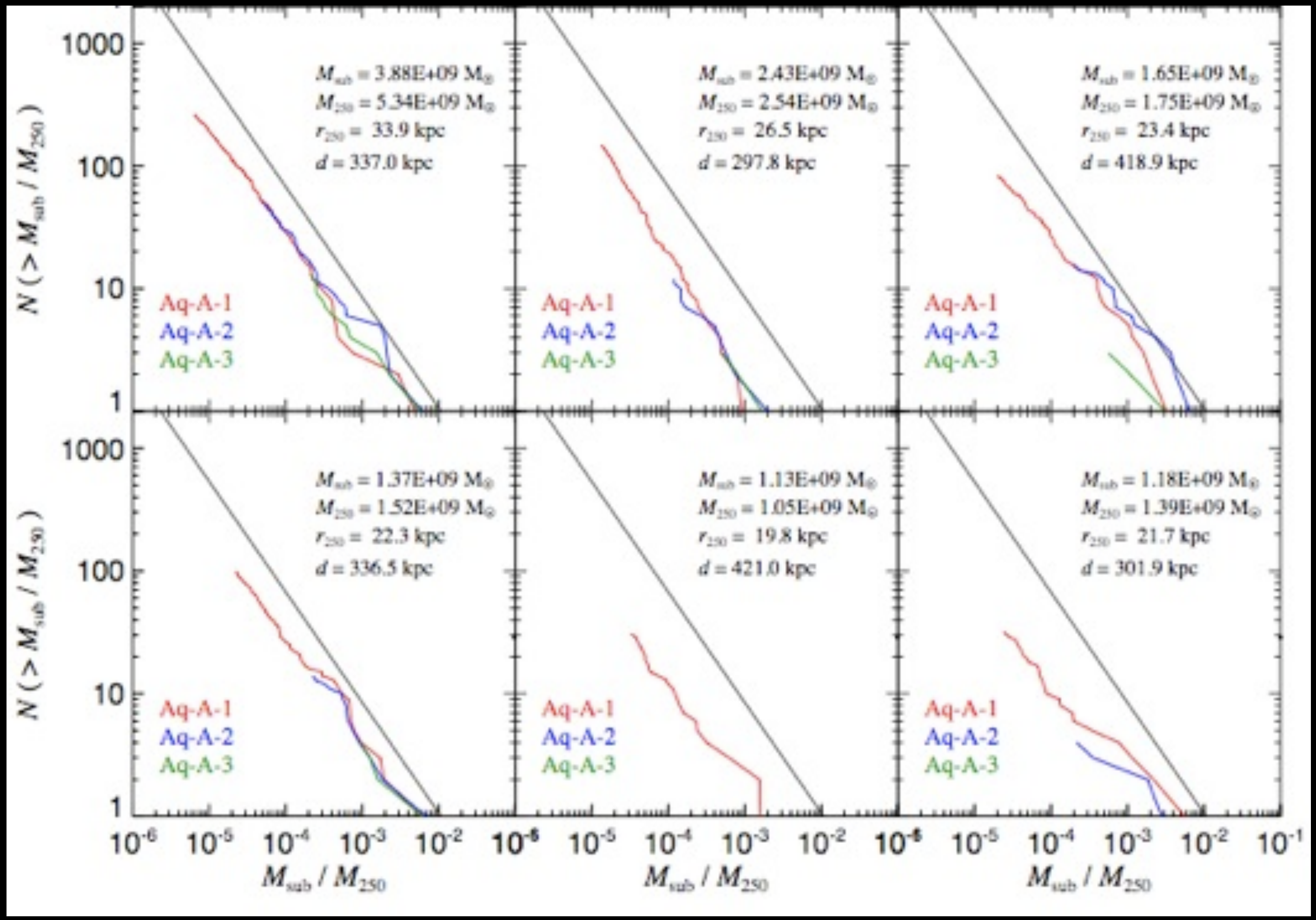
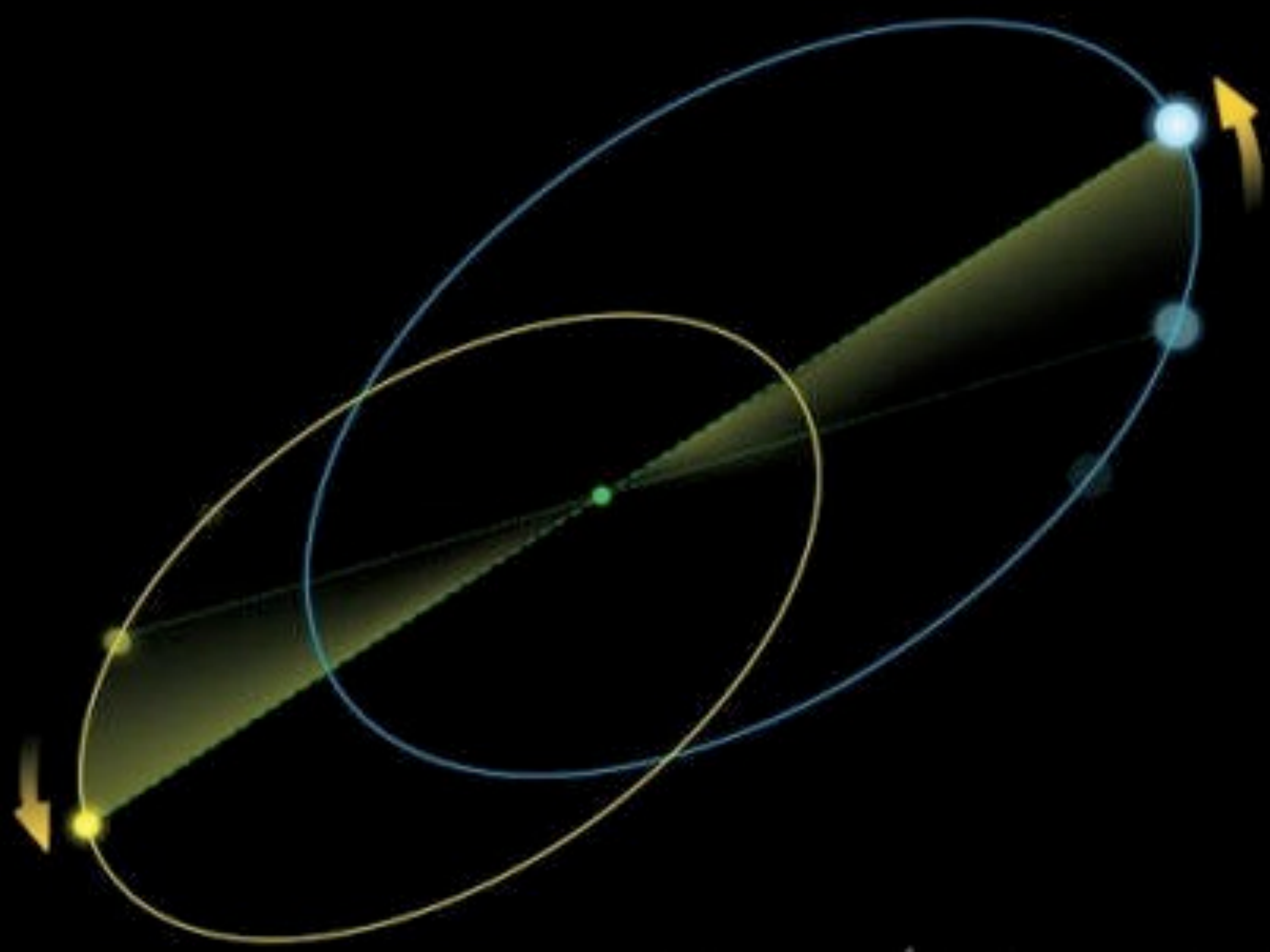


sub-sub haloes in CDM simulations (Springel+08)

Disruption of binary stars by "dark" substructures



Wide binaries have very low binding energies

$$E = -G M_b / 2a$$

small tidal perturbations can disrupt these systems

↓

Probes of **clumpiness** in the galaxy potential

e.g MACHOS in the MW halo: Carr & Sakellariadou (1999); Chaname & Gould (2004)

Disruption of binary stars by "dark" substructures

$$< \Delta E >= \frac{7G^2 M_p^2 a^2}{3V_{\rm rel}^2 b^4} U(b/r_h);$$

mean change of energy after encounter with DM sub-subhalo

$U(b/r_h) \approx 1$ non-penetrating encounters

stellar halo of the MW: $V_{rel} \sim \sqrt{2} \times 160$ km/s
dSphs $V_{rel} \sim \sqrt{2} \times 10$ km/s

"Catastrophic" encounters: $\frac{< \Delta E >}{E_b} > 1 \longrightarrow M_p > M_{\rm p,crit}$

$$M_{\rm p,crit} \approx 2M_\odot \frac{V_{\rm rel}}{\sqrt{2} \cdot 10{\rm kms}^{-1}} \left(\frac{M_b}{1M_\odot} \frac{a}{0.1{\rm pc}} \right)^{1/2};$$

Disruption of binary stars by "dark" substructures

Analytically we expect binaries with $a > a_{max}$ to be disrupted

$$a_{\rm max} \equiv \left(\frac{k_{\rm cat}}{G\rho_p\Delta t}\right)^{2/3}(GM_b)^{1/3};$$

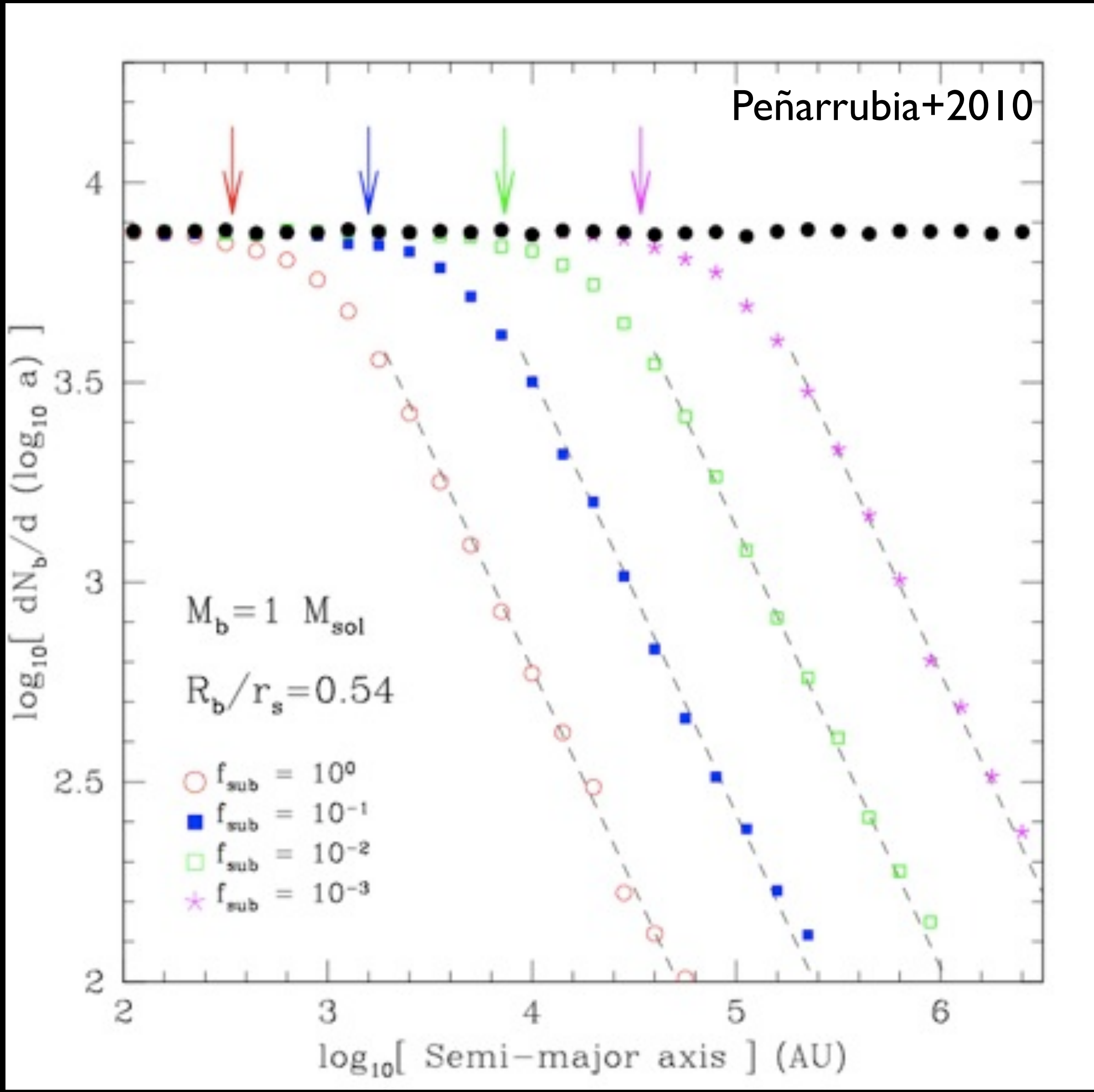
$$\begin{cases} k_{\rm cat} \simeq 0.07 & \text{(Bahcall+85)} \\ \Delta t \equiv t_{\rm now} - t_{\rm form} \\ \rho_p = \dfrac{f_{\rm sub} M_{\rm vir}}{4\pi/3 R_b^3} & \text{Density of sub-sub haloes} \end{cases}$$

CDM field haloes: $f_{sub} \sim 10^{-2}$

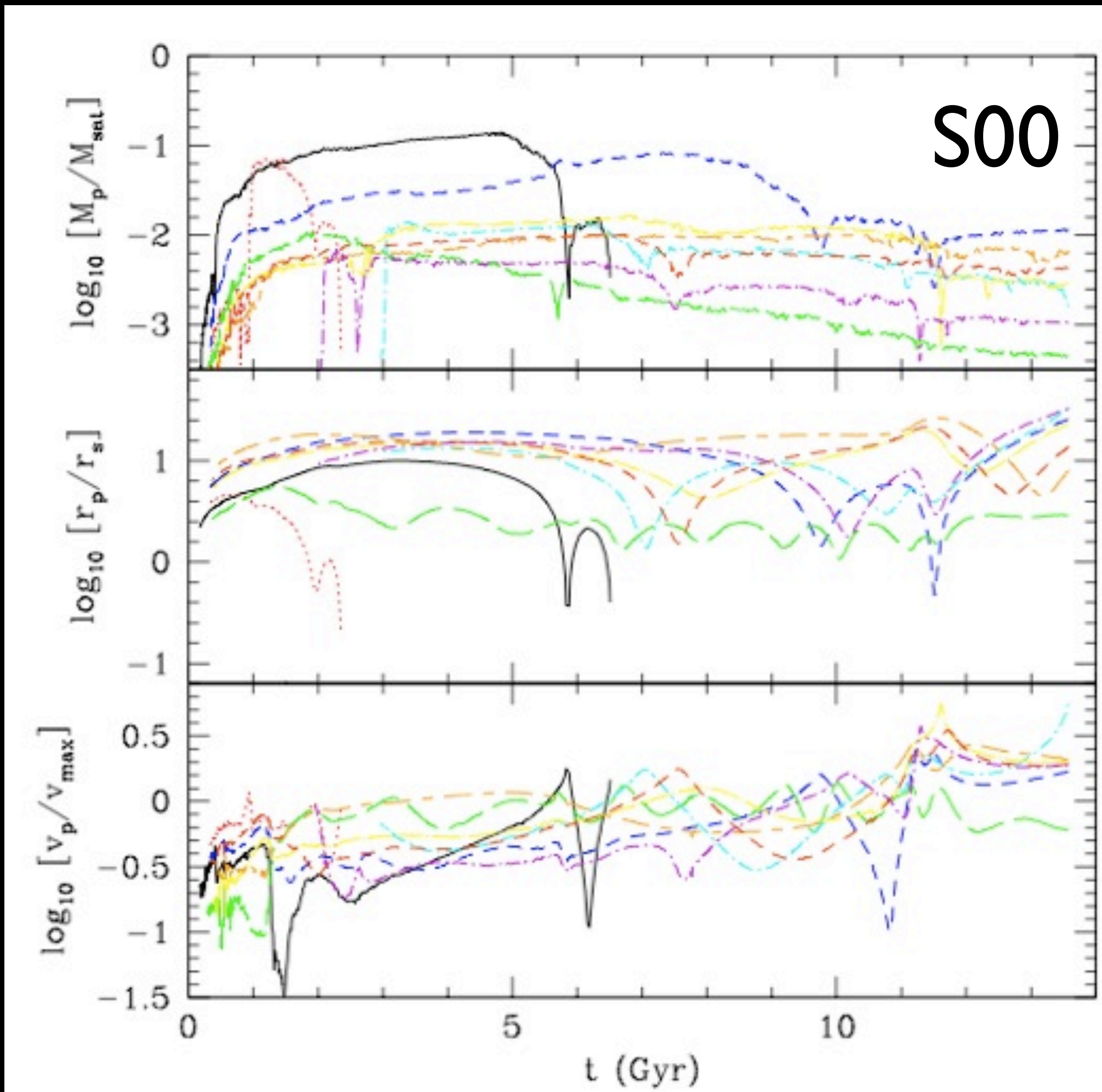
✳**We expect a truncation in the binary separation function at**
$a_{max} \sim 10^4$ AU $\simeq$ 0.05 pc
✳**The *perturbed* separation function scales as**

$dN_b/da \propto a^{-2.1}$ for $a \gtrsim a_{max}$

Monte-Carlo/N-body simulations



The Aquarius satellites



Aquarius sims: Assembly of a MW-like galaxy halo with 5×10^9 particles (particle mass $=10^4$ M_{sol})

Springel et al. (2008)

↓

Position, velocity & mass of sub-subhaloes in satellite haloes

↓

Generate samples of binary stars in the host satellites

Substructures: $$< \Delta E > = \frac{7G^2 M_p^2 a^2}{3V_{\rm rel}^2 b^4} U(b/r_h);$$

Smooth field: $$r_J(r) = \left[\frac{M_b}{3M_{\rm sat}(< r)}\right]^{1/3} r$$

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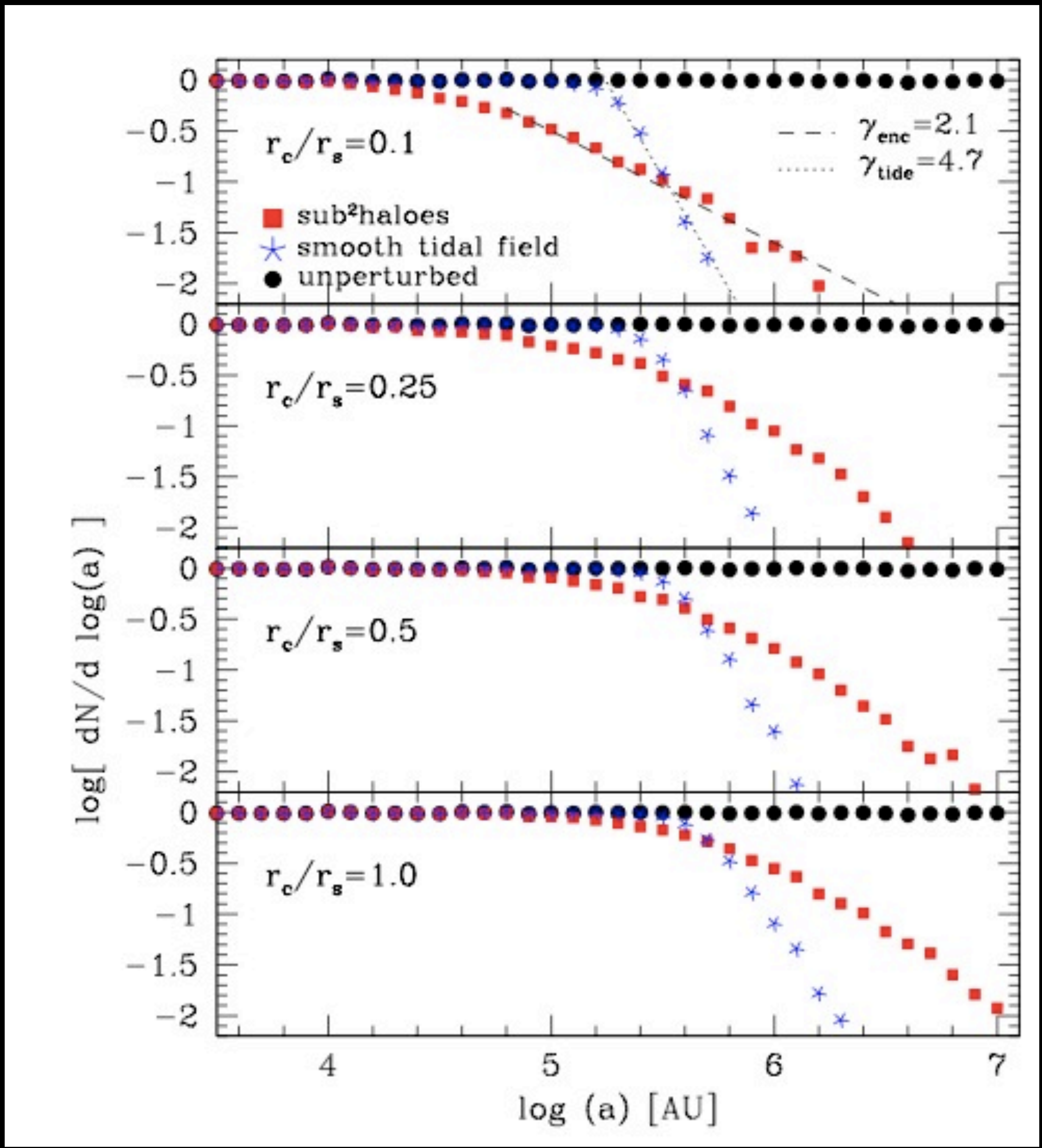

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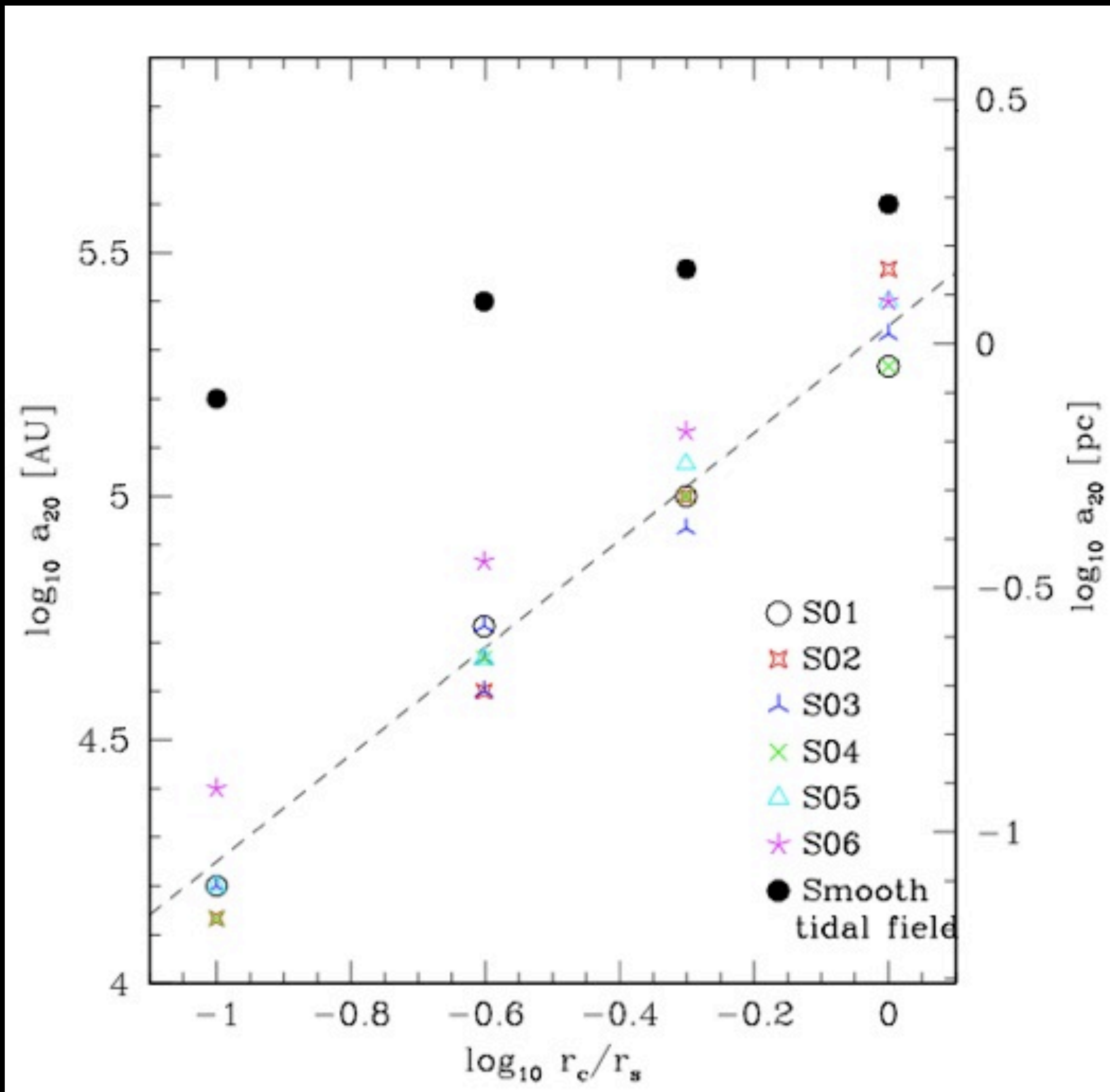

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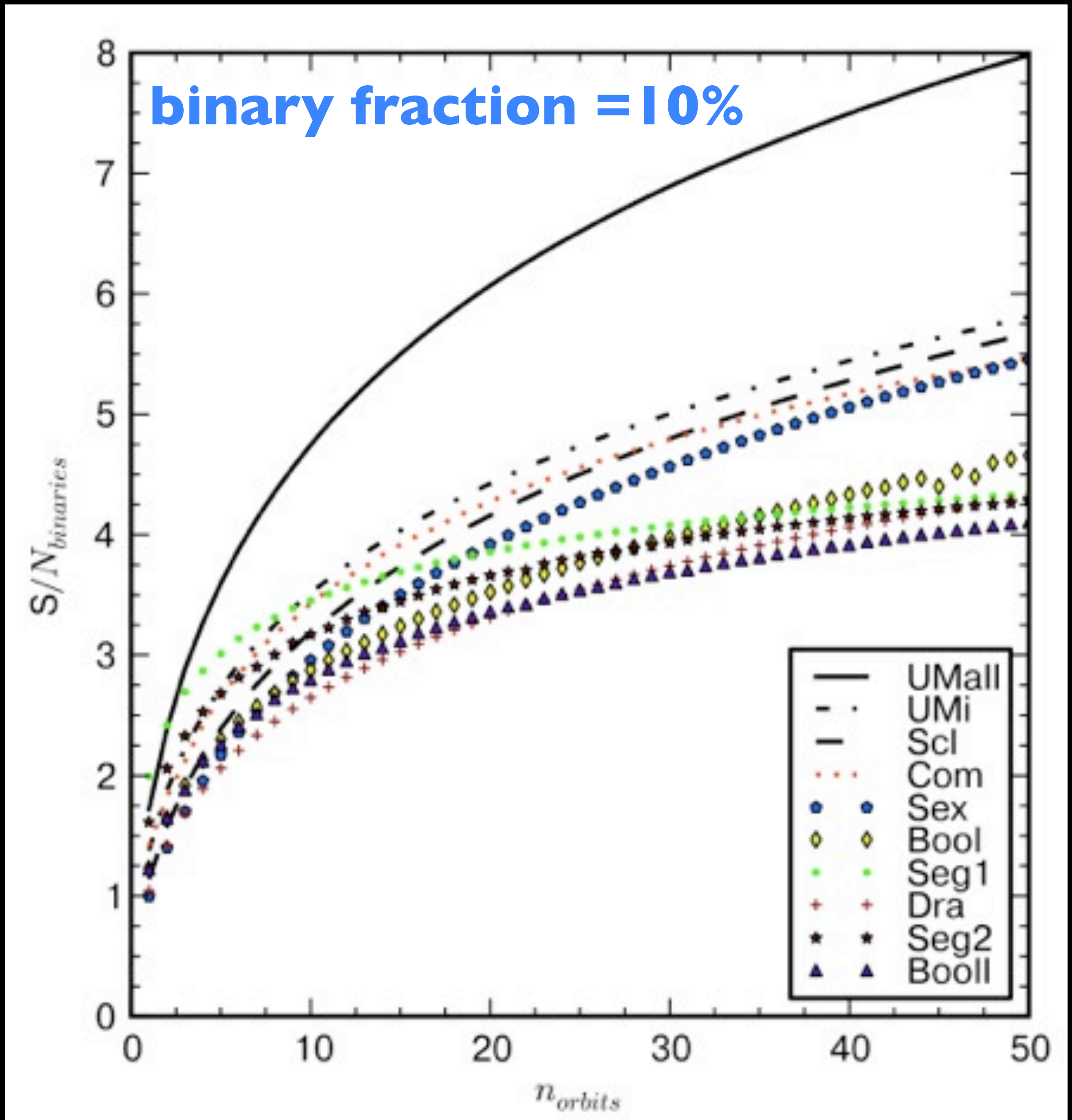
Detection of binary stars in dSphs

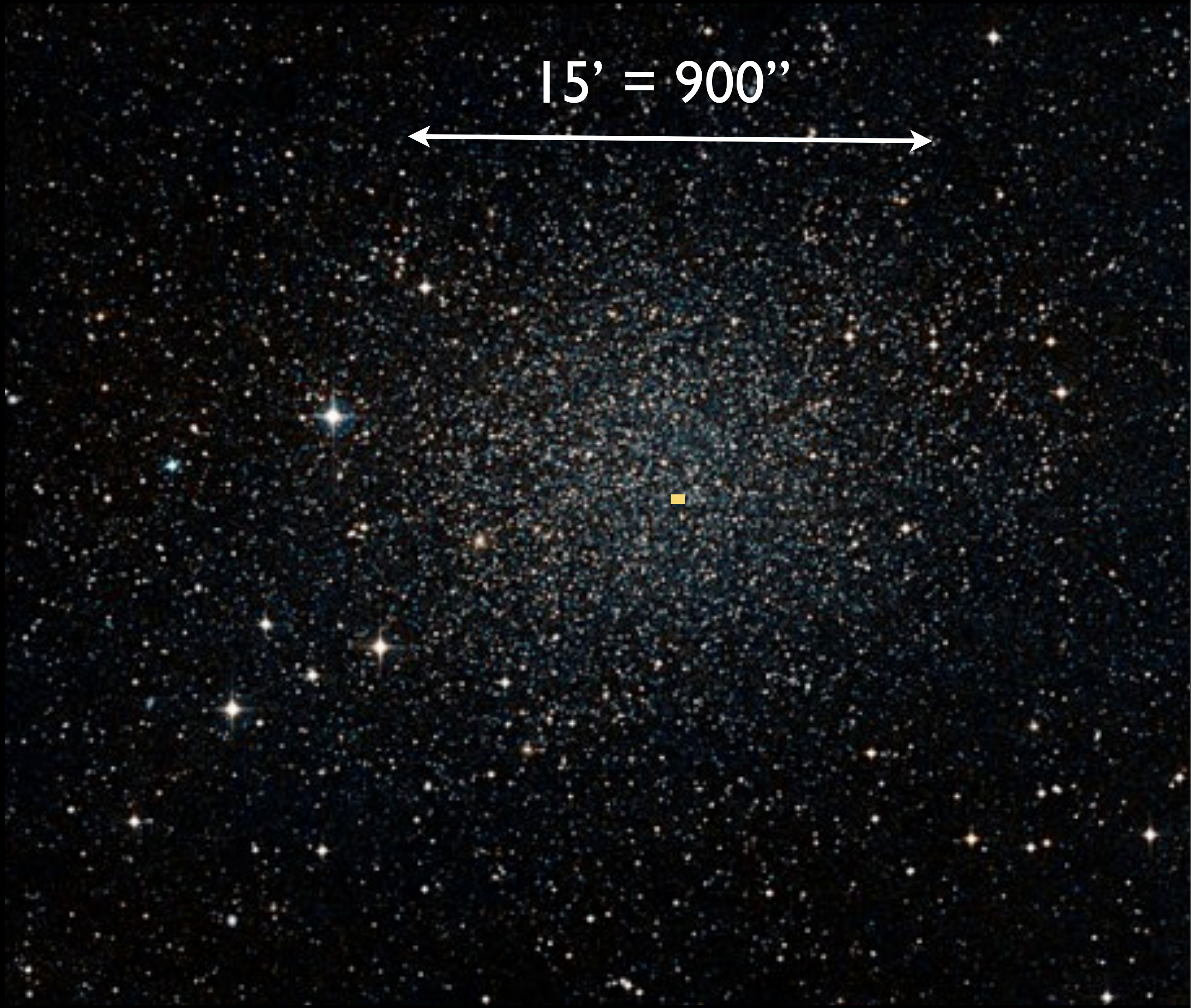
challenging owing to their large heliocentric distance



Peñarrubia+2010

ACS camera on Hubble:

- resolution = 4x 0.05” pixels
- f.o.v = 25”x25”
- limiting magnitude = 29^{mag}



The inner structure of Cold (?) DM haloes

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Collision-less N-body sims. of structure formation

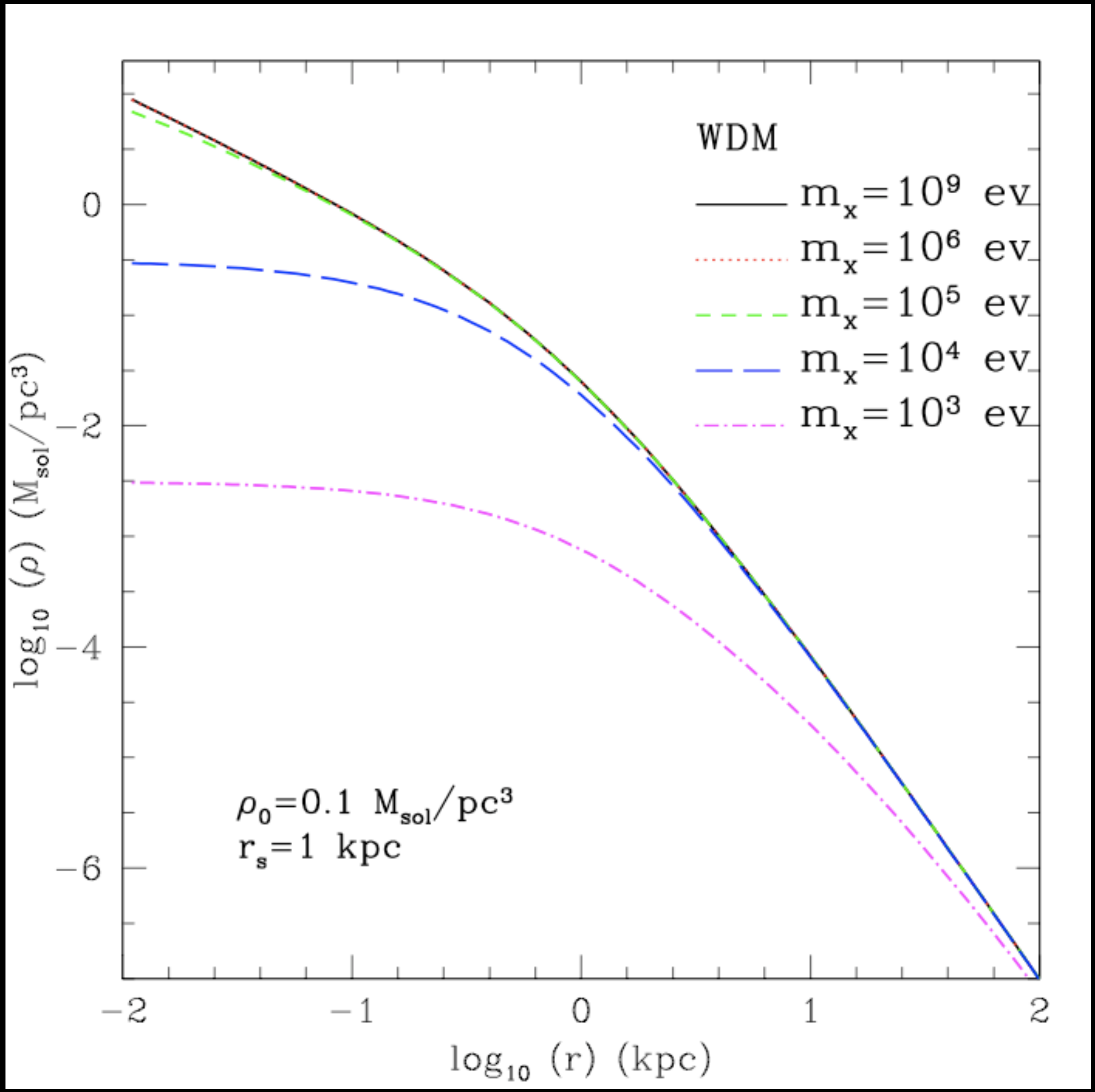
↓

CDM haloes follow a universal density profile that **diverges** at r=0 (**cusp**)

Dubinsky & Carlberg 91, NFW97, Moore+98, Diemand+ 05)

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

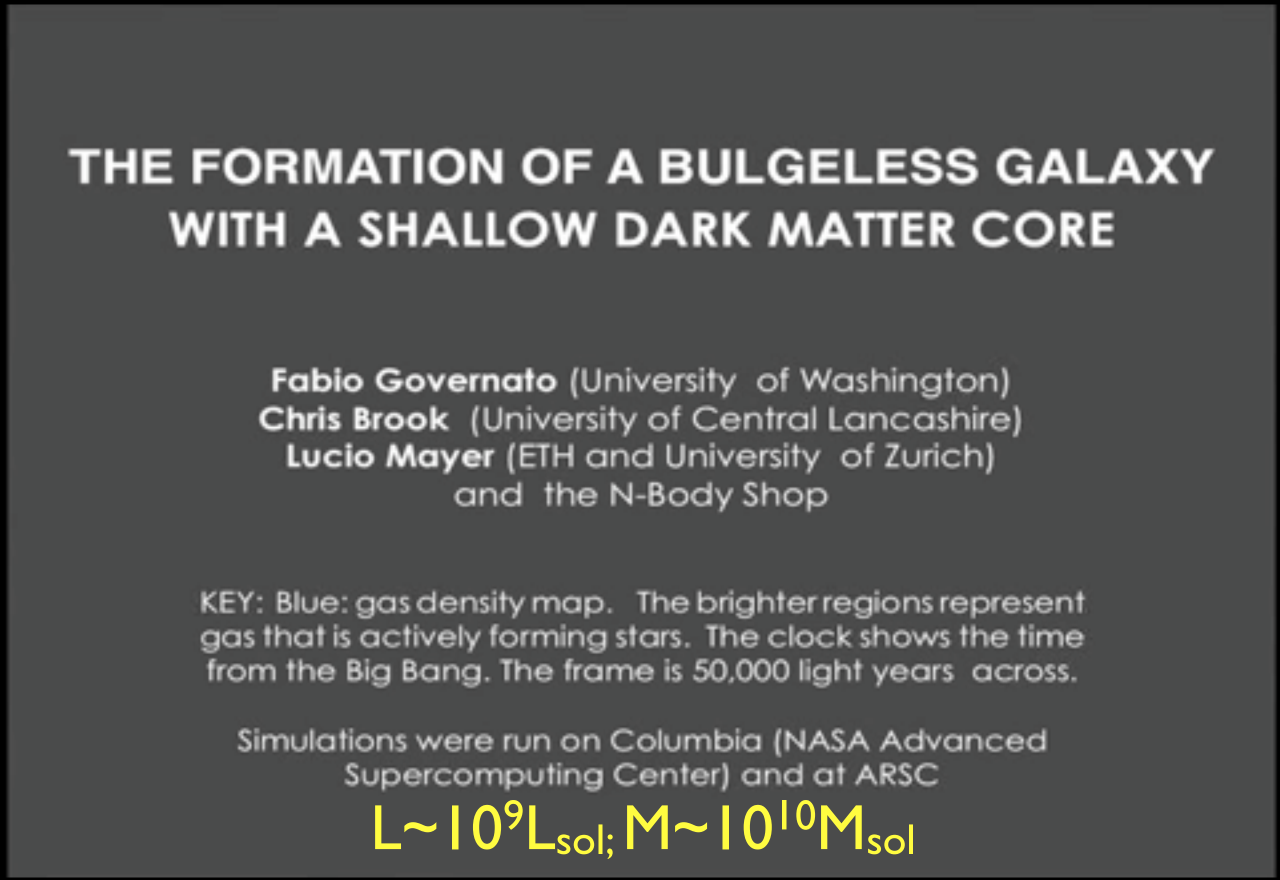
Bode+01



Baryonic feedback

Baryons may alter the inner DM profile:

- ✳SNe-driven gas outflows
  (Navarro+1996; Gnedin & Zhao1992; Read & Gilmore2005; Governato+2008, 2010)
- ✳SNe-induced resonant motion of bulk gas
  (Mashchenko+2006, 2008)
- ✳Orbital decay of dense clusters
  (El-Zant+2001; Goerdt+2008



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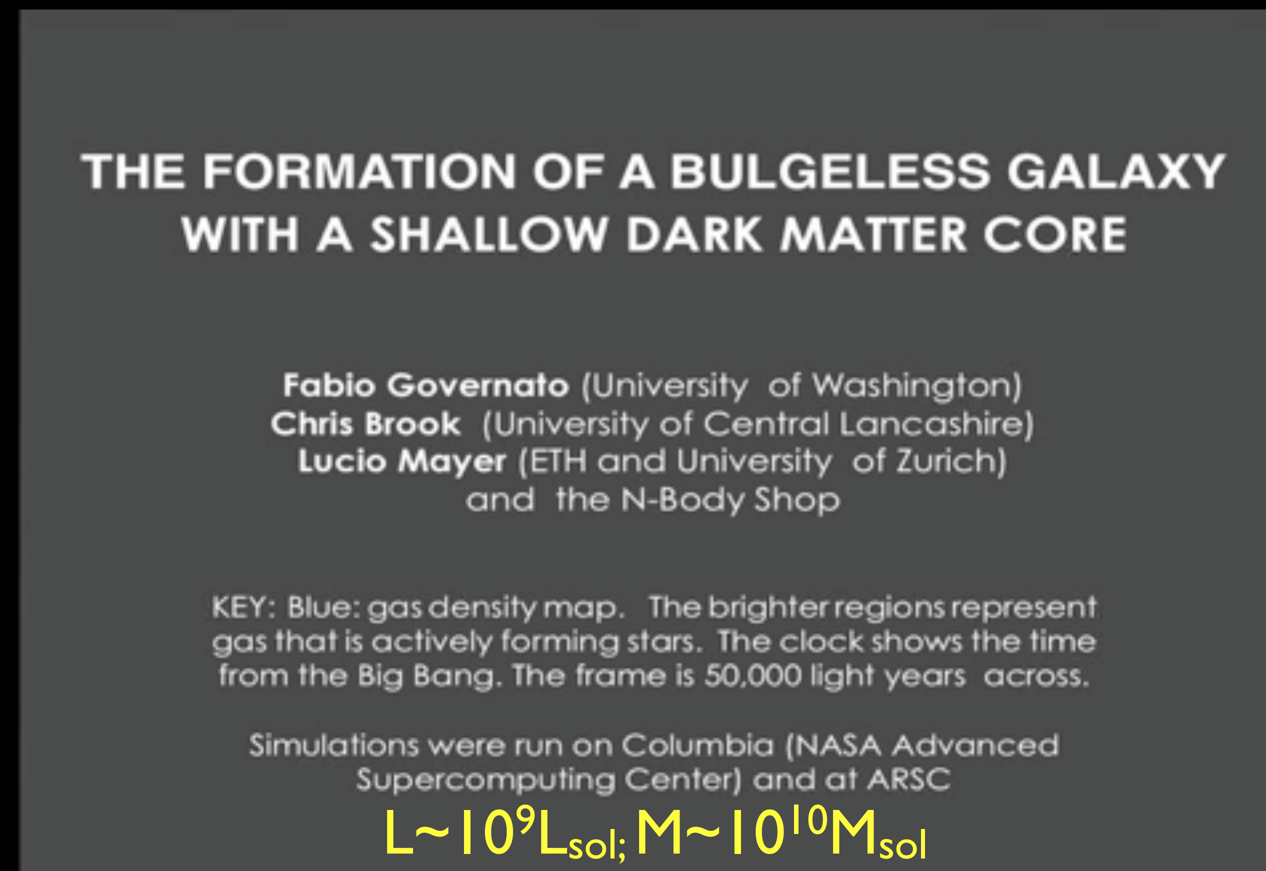

$L \sim 10^9 L_{sol}$; $M \sim 10^{10} M_{sol}$

Do those process affect dSphs? (100-1000 less luminous)

Baryonic feedback in CDM dSphs

The baryons in the Milky Way satellites

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Accepted 2011 October 9. Received 2011 September 29; in original form 2011 May 18

ABSTRACT

We investigate the formation and evolution of satellite galaxies using smoothed particle hydrodynamics (SPH) simulations of a Milky Way (MW) like system, focusing on the best resolved examples, analogous to the classical MW satellites. Comparing with a pure dark matter simulation, we find that the condensation of baryons has had a relatively minor effect on the structure of the satellites' dark matter haloes. The stellar mass that forms in each satellite agrees relatively well over three levels of resolution (a factor of ~64 in particle mass) and scales with (sub)halo mass in a similar way in an independent semi-analytical model. Our model provides a relatively good match to the average luminosity function of the MW and M31. To establish whether the potential wells of our satellites are realistic, we measure their masses within observationally determined half-light radii, finding that they have somewhat higher mass-to-light ratios than those derived for the MW dSphs from stellar kinematic data; the most massive examples are most discrepant. A statistical test yields an ~6 per cent probability that the simulated and observationally derived distributions of masses are consistent. If the satellite population of the MW is typical, our results could imply that feedback processes not properly captured by our simulations have reduced the central densities of subhaloes, or that they initially formed with lower concentrations, as would be the case, for example, if the dark matter were made of warm, rather than cold particles.

Same results found independently by
Sawala, Scannapieco, Maio & White (2010)

The inner structure of Cold (?) DM haloes

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

Jeans equations

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

- ✳ Halo mass profile
- ✳ stellar density profile

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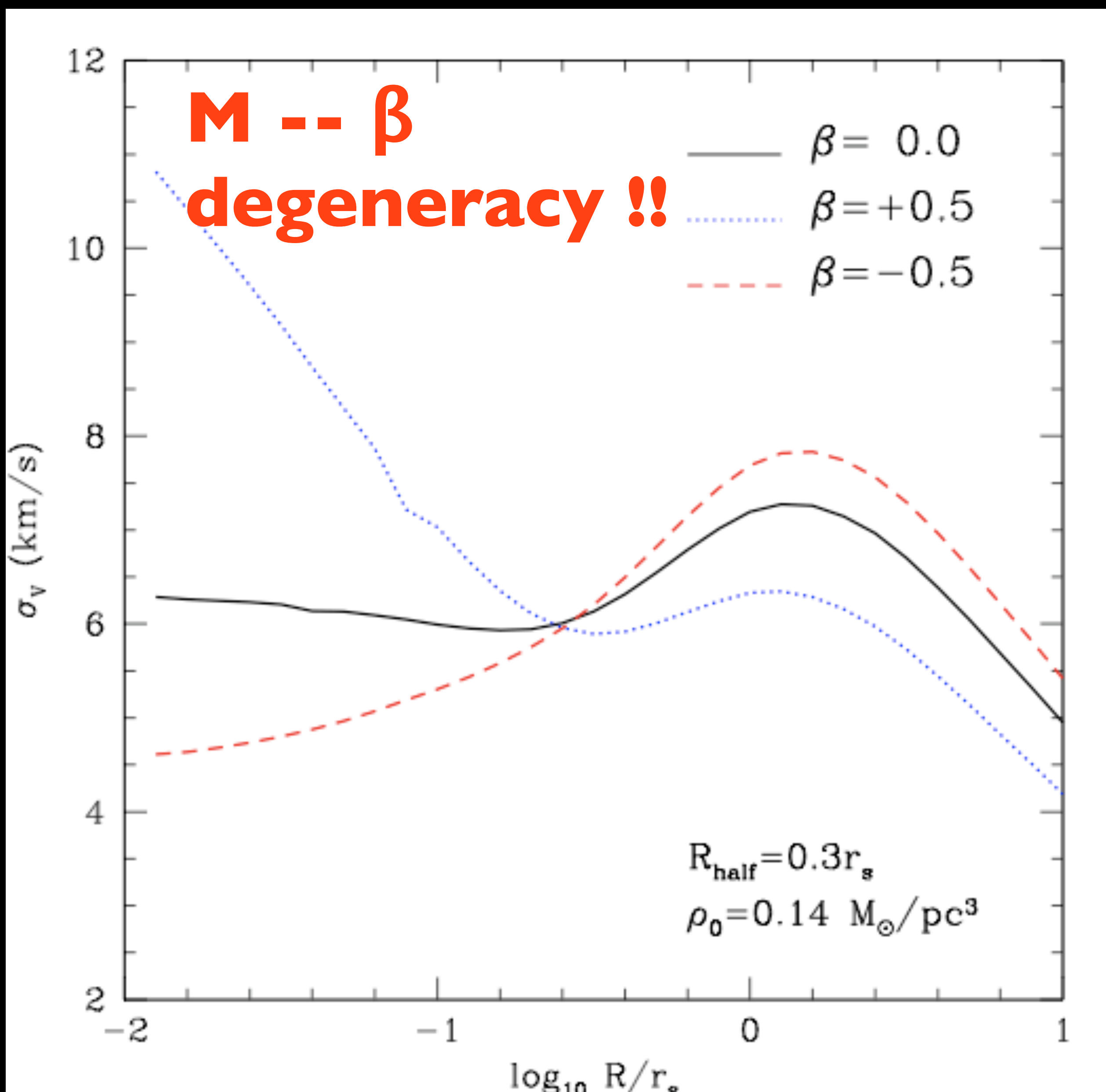

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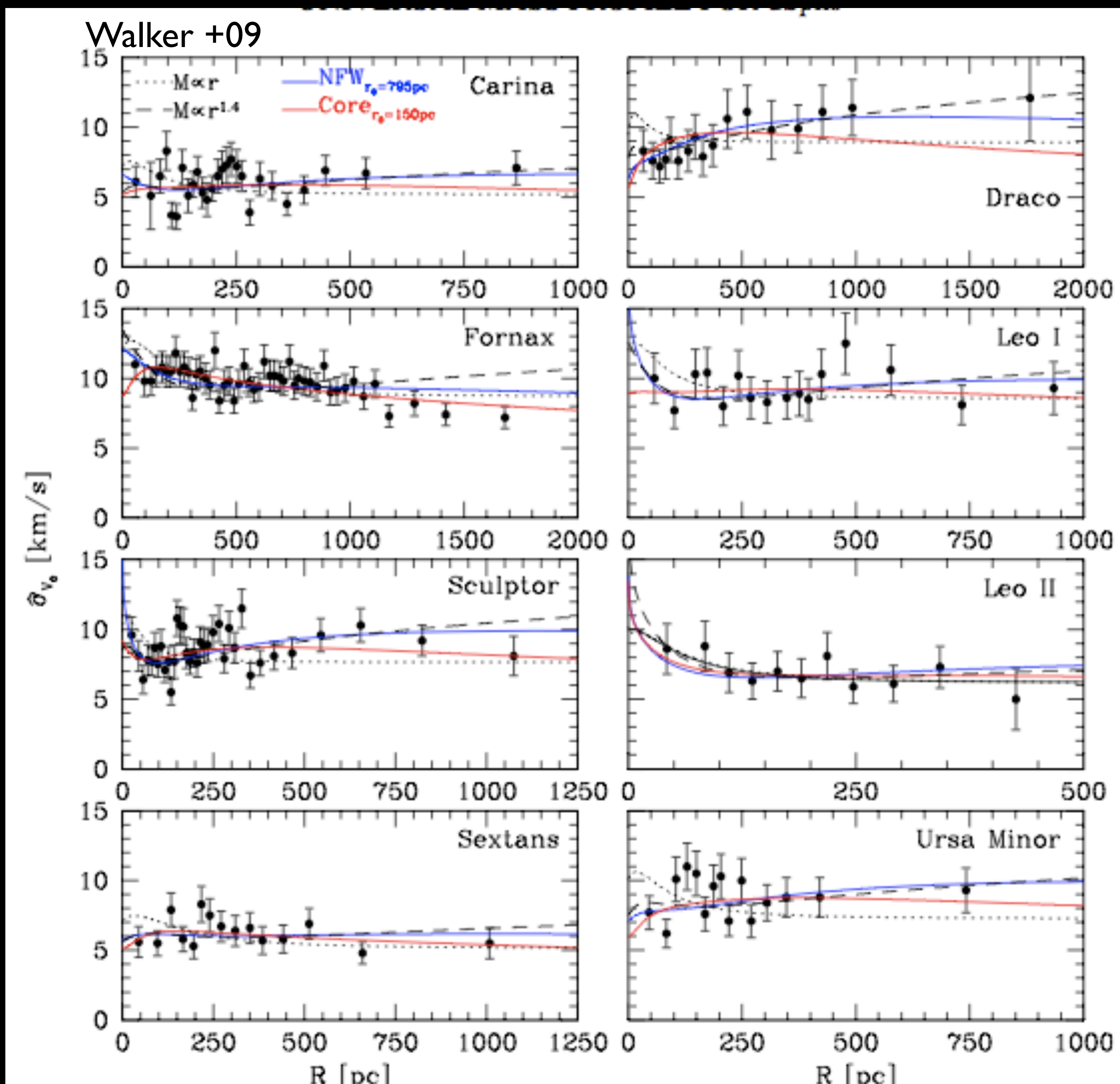
Projected velocity dispersion

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

DM cusps?

NFW profile
cored profile



Unknown β(r)

Unknown M(r)

e.g. Battaglia+08; Walker+09

Can we break the degeneracy?

THE IDEA

Walker & Peñarrubia (2011)

THE IDEA

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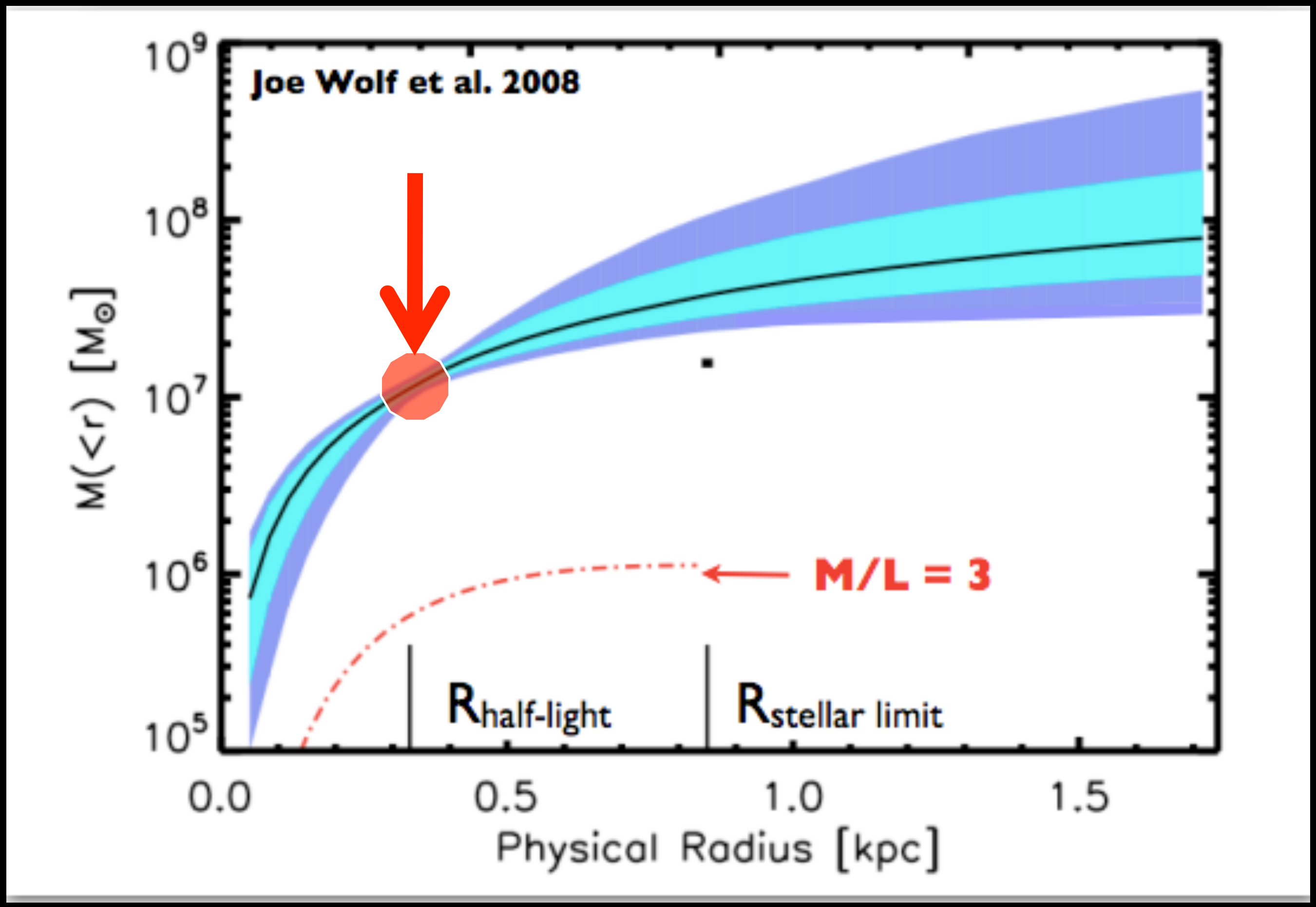
M -- β degeneracy breaks at $R \approx R_{half}$

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



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

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

THE IDEA

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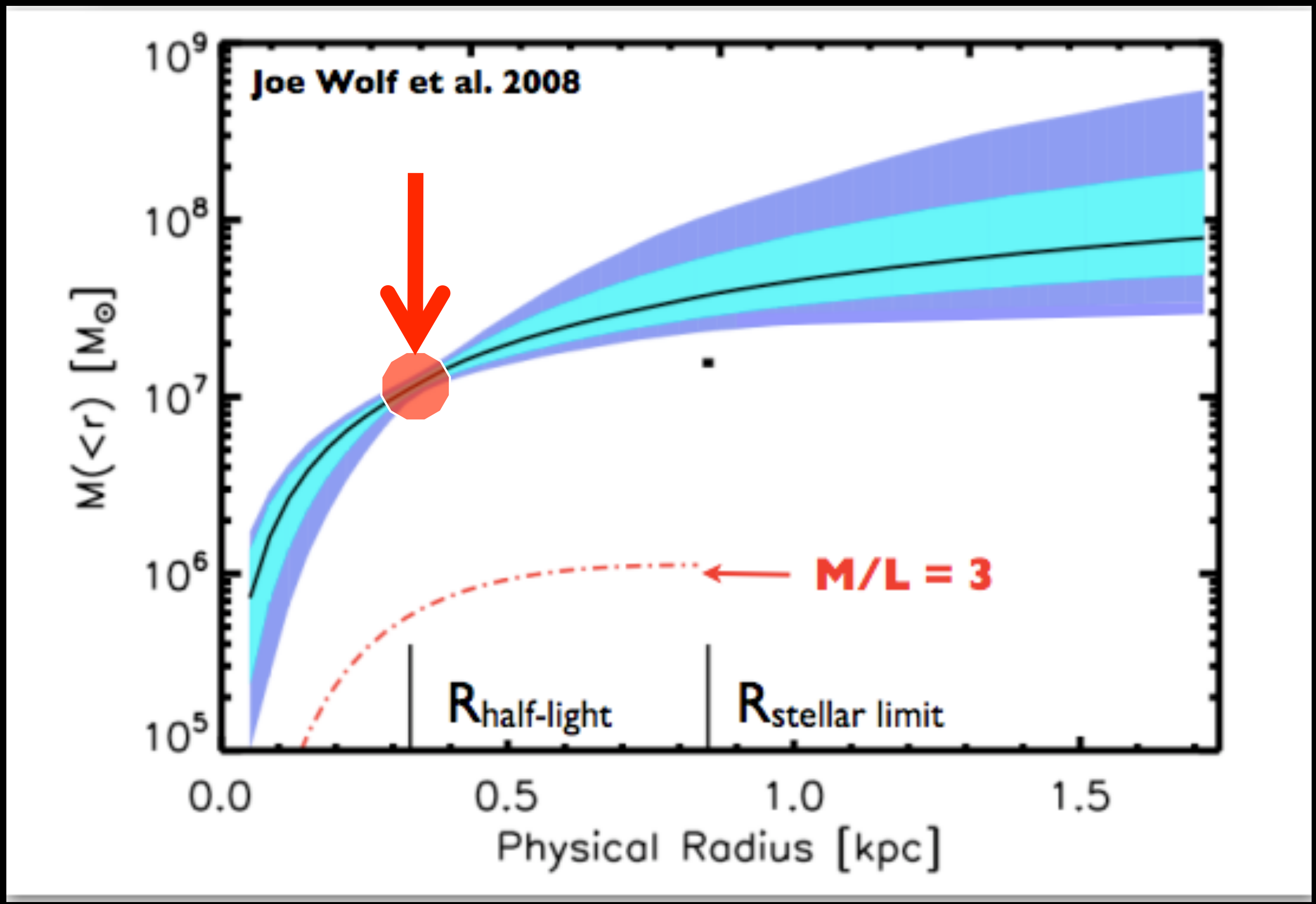
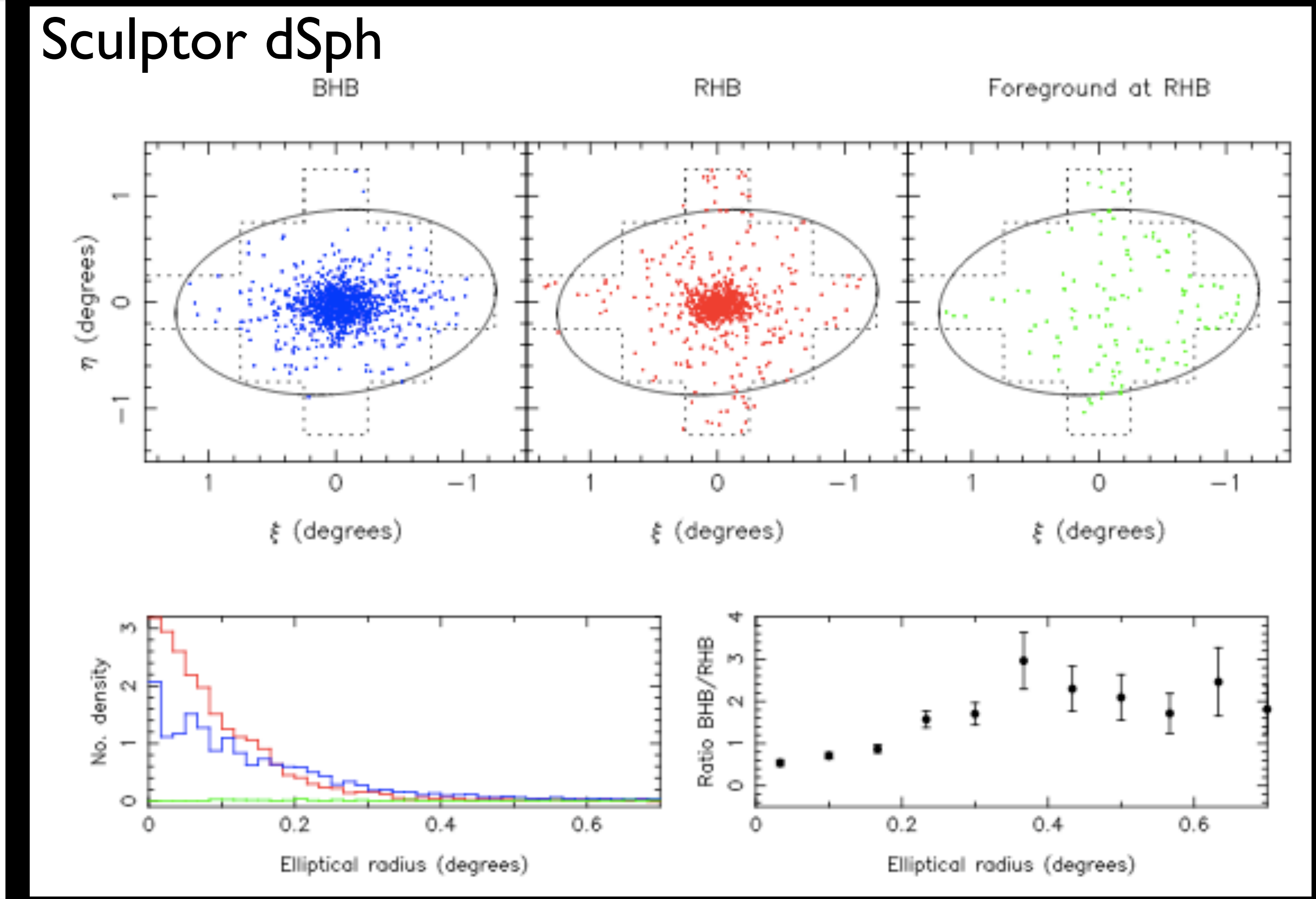
Some dSphs show spatially + kinematically distinct stellar components





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Tolstoy + 04 (see also Battaglia+08)

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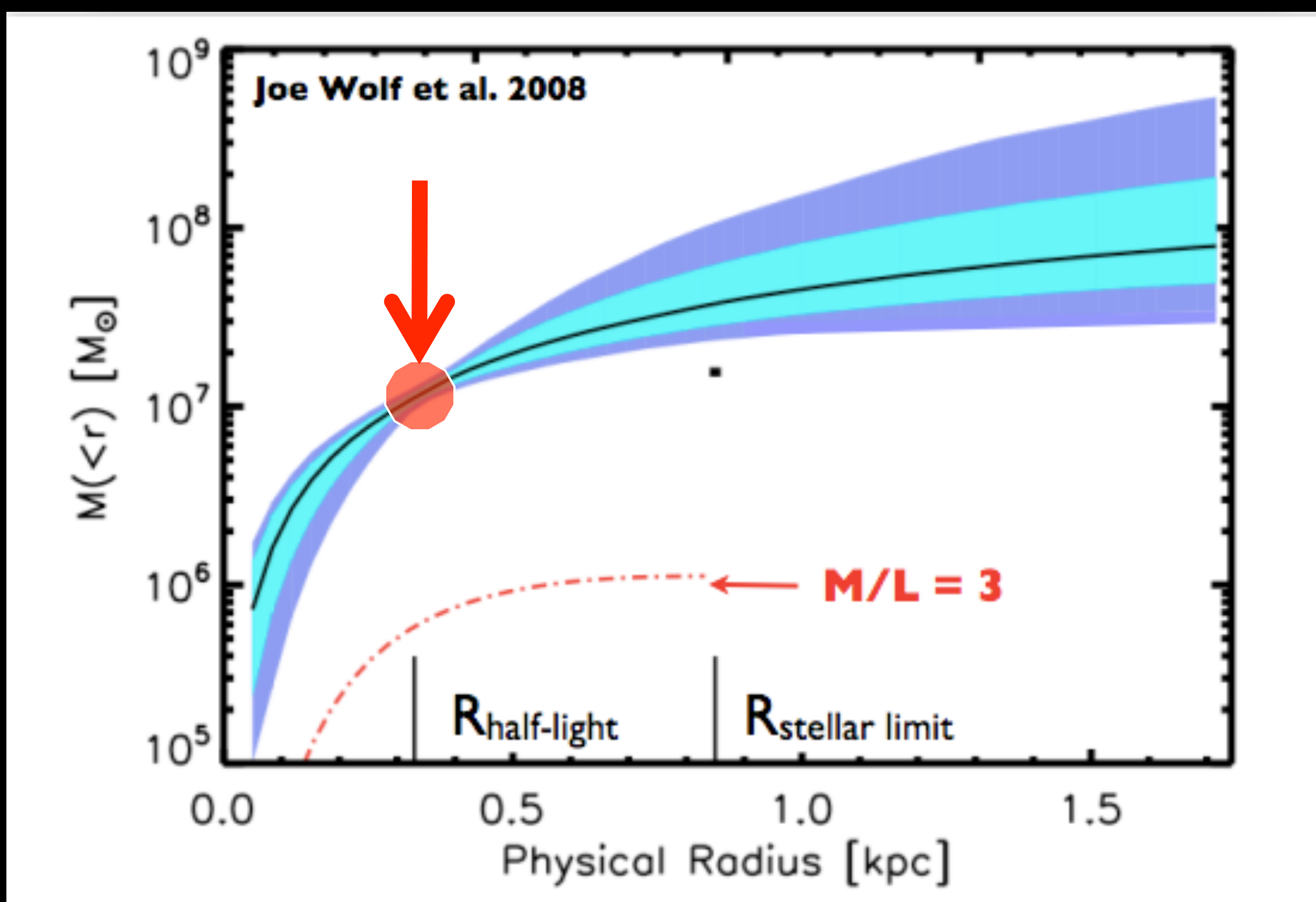

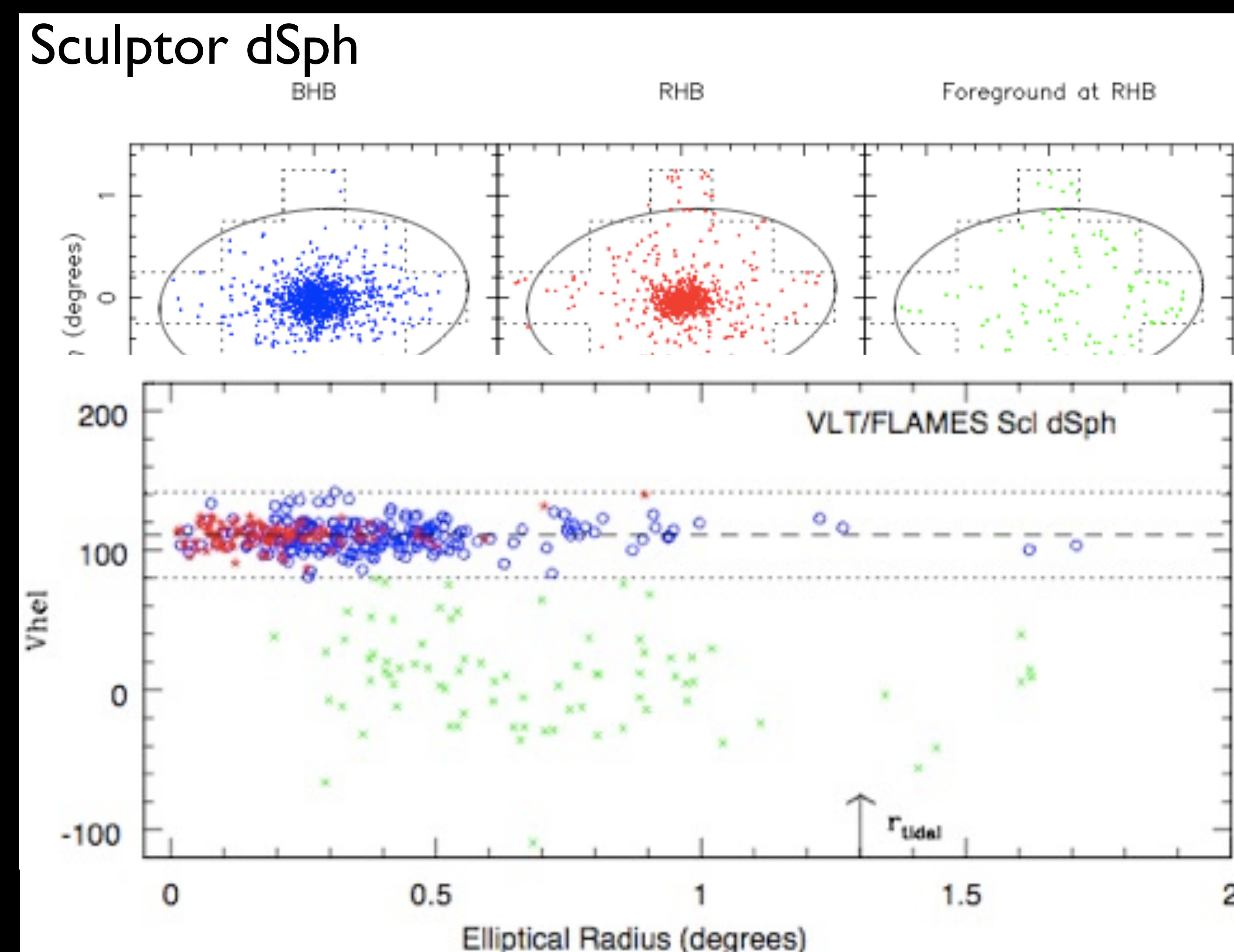

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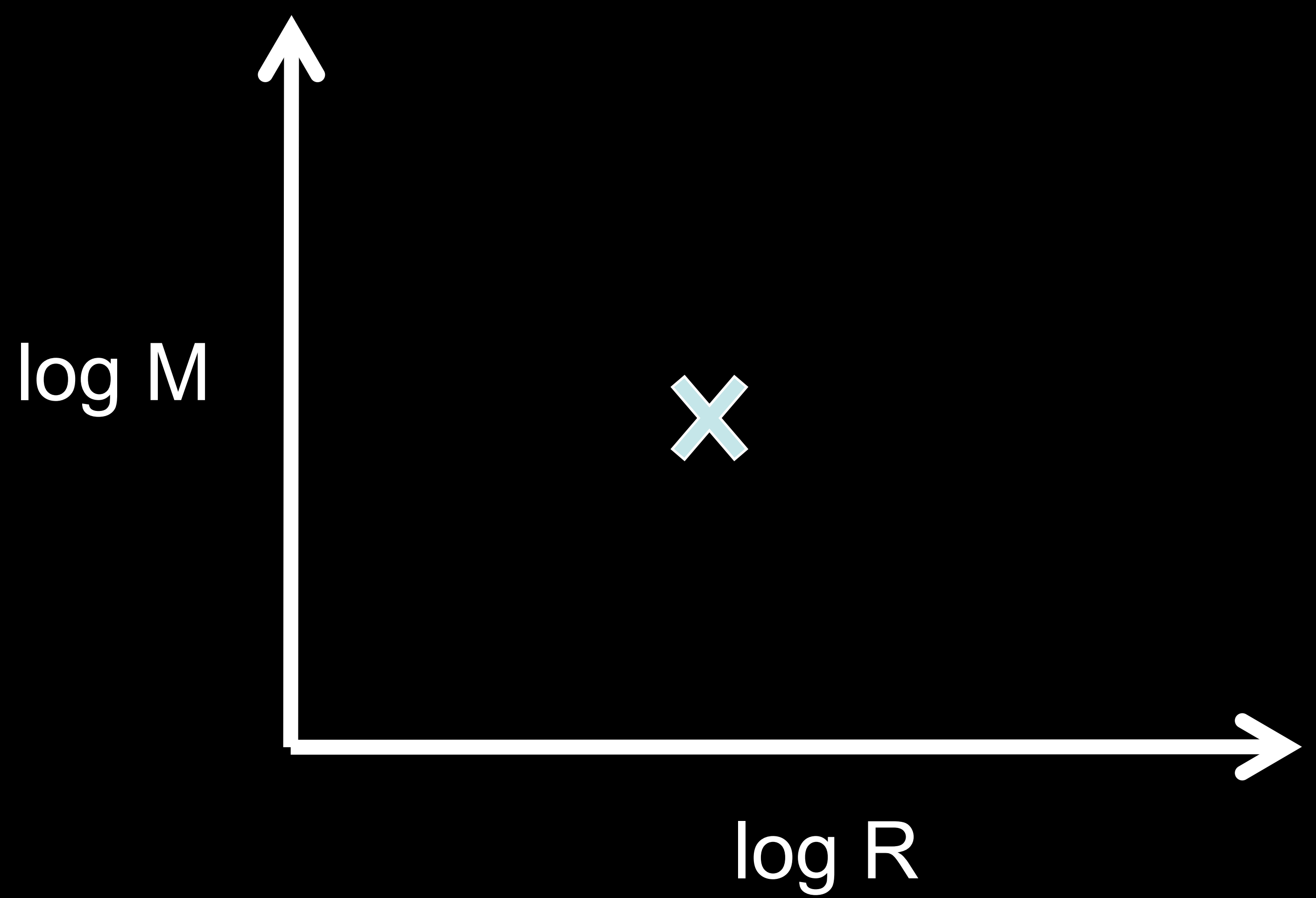

THE IDEA

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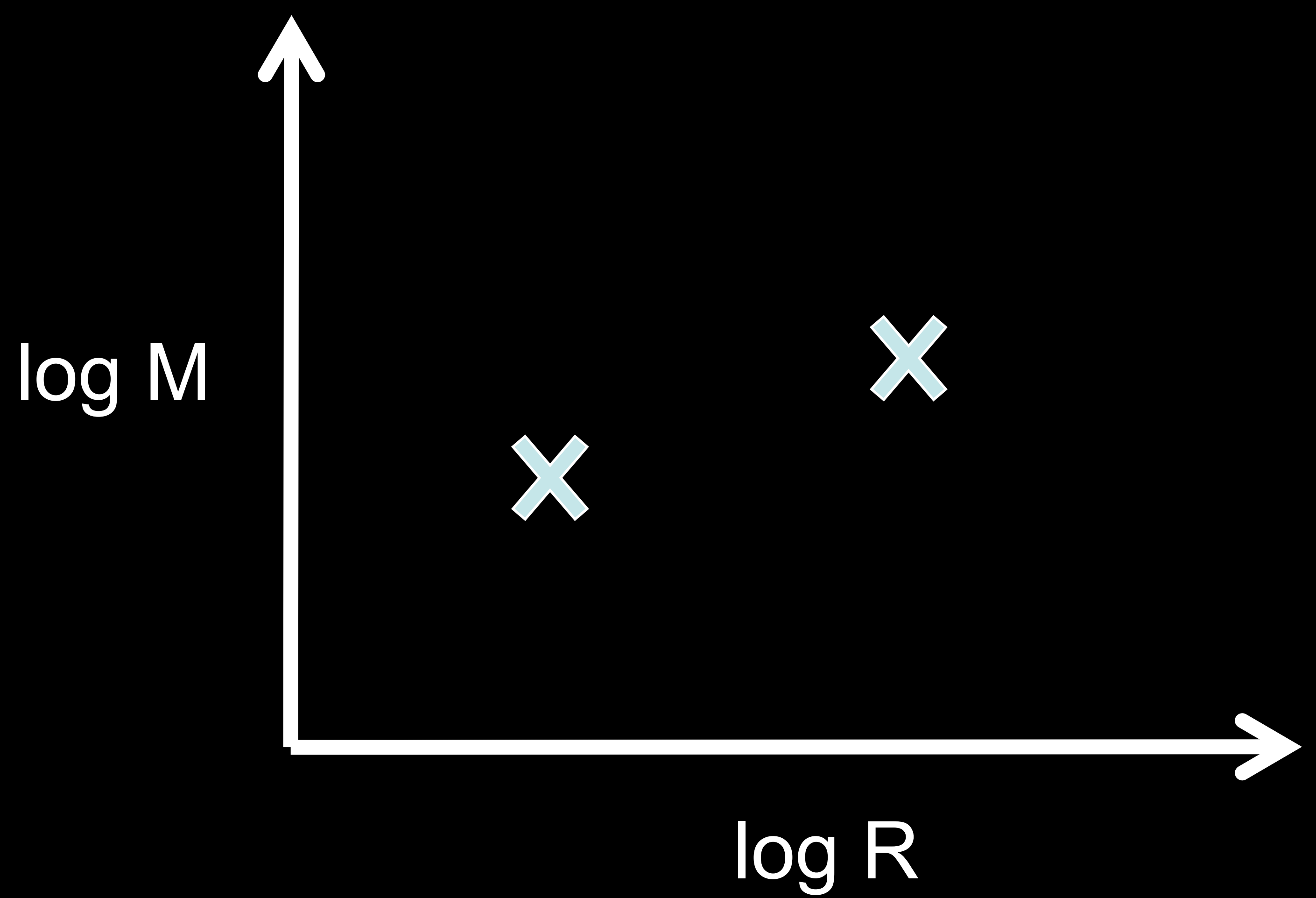
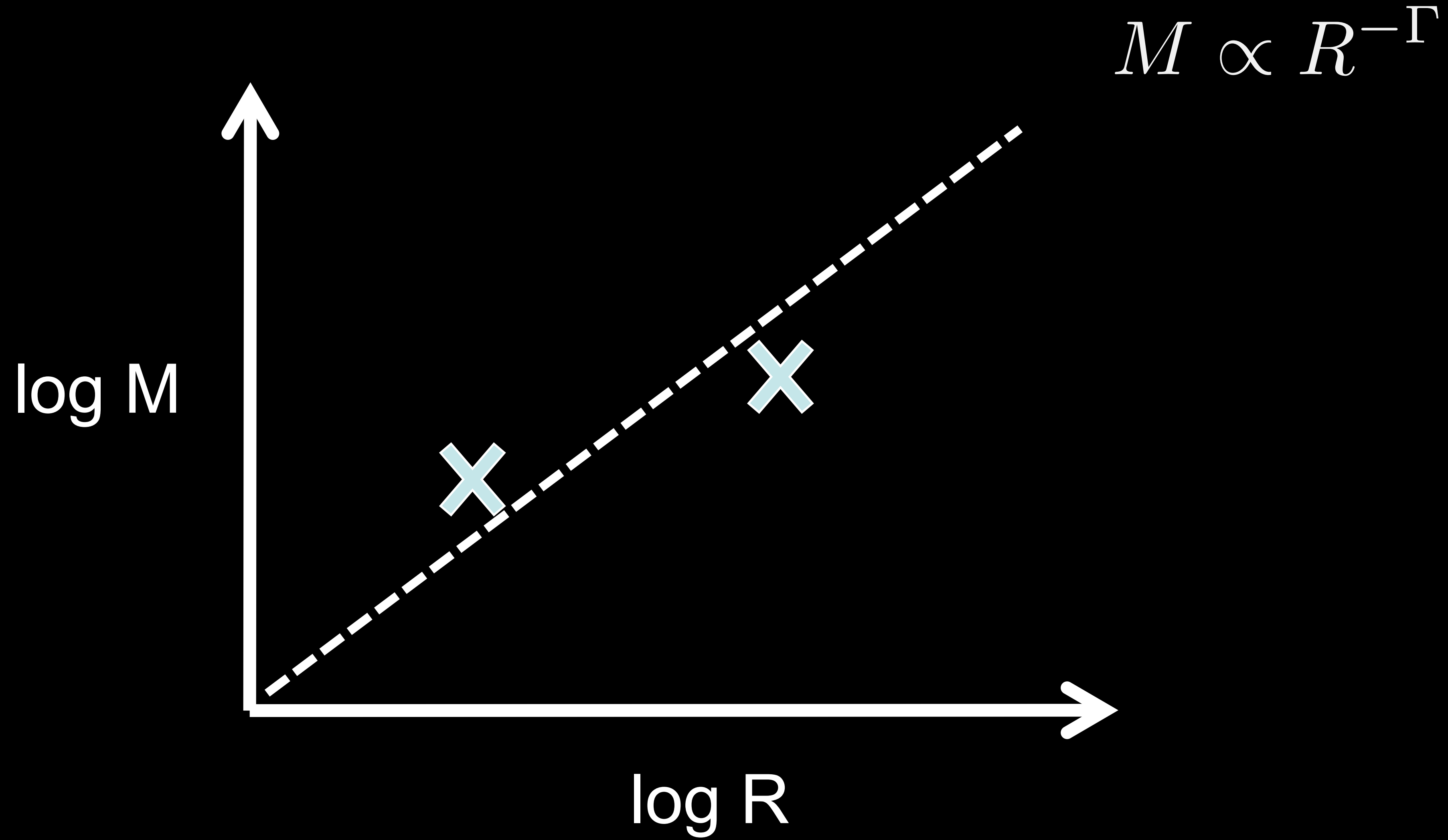


THE IDEA

Walker & Peñarrubia (2011)



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

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

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

Method

Walker & Peñarrubia (2011)

MCMC algorithm:
2 stellar components + MW foreground contamination

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

Method

Walker & Peñarrubia (2011)

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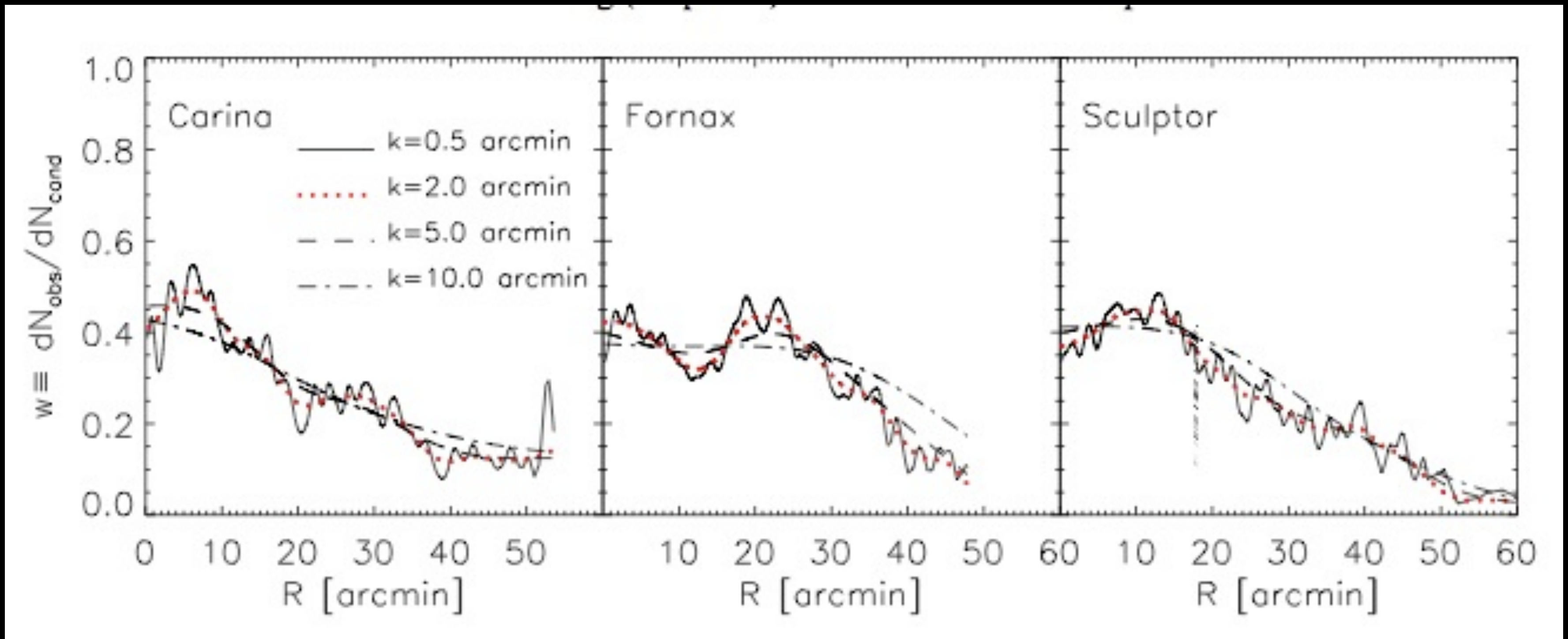
MCMC algorithm:

2 stellar components + MW foreground contamination



Method

Walker & Peñarrubia (2011)

$$L(\{R_i, V_i, W_i'\}_{i=1}^{N_{\rm sample}} | \vec{S}) =$$

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

MCMC algorithm:

2 stellar components + MW foreground contamination

Priors (14 free parameters)

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

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

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

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

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

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

DM potential

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)

Thursday, 7 June 2012

Tests

Walker & Peñarrubia (2011)

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

Stellar Profile (Equation 15)				Dark Matter Profile (Equation 16)				
r_* [pc]	α_*	β_*	γ_*	ρ_0 [$M_\odot$pc^{-3}]	r_{DM} [pc]	α_{DM}	β_{DM}	γ_{DM}
Cored Halos								
Isotropic ($r_a = \infty$)								
100	2	5	0.1	0.064	1000	1	3	0
250	2	5	0.1	0.064	1000	1	3	0
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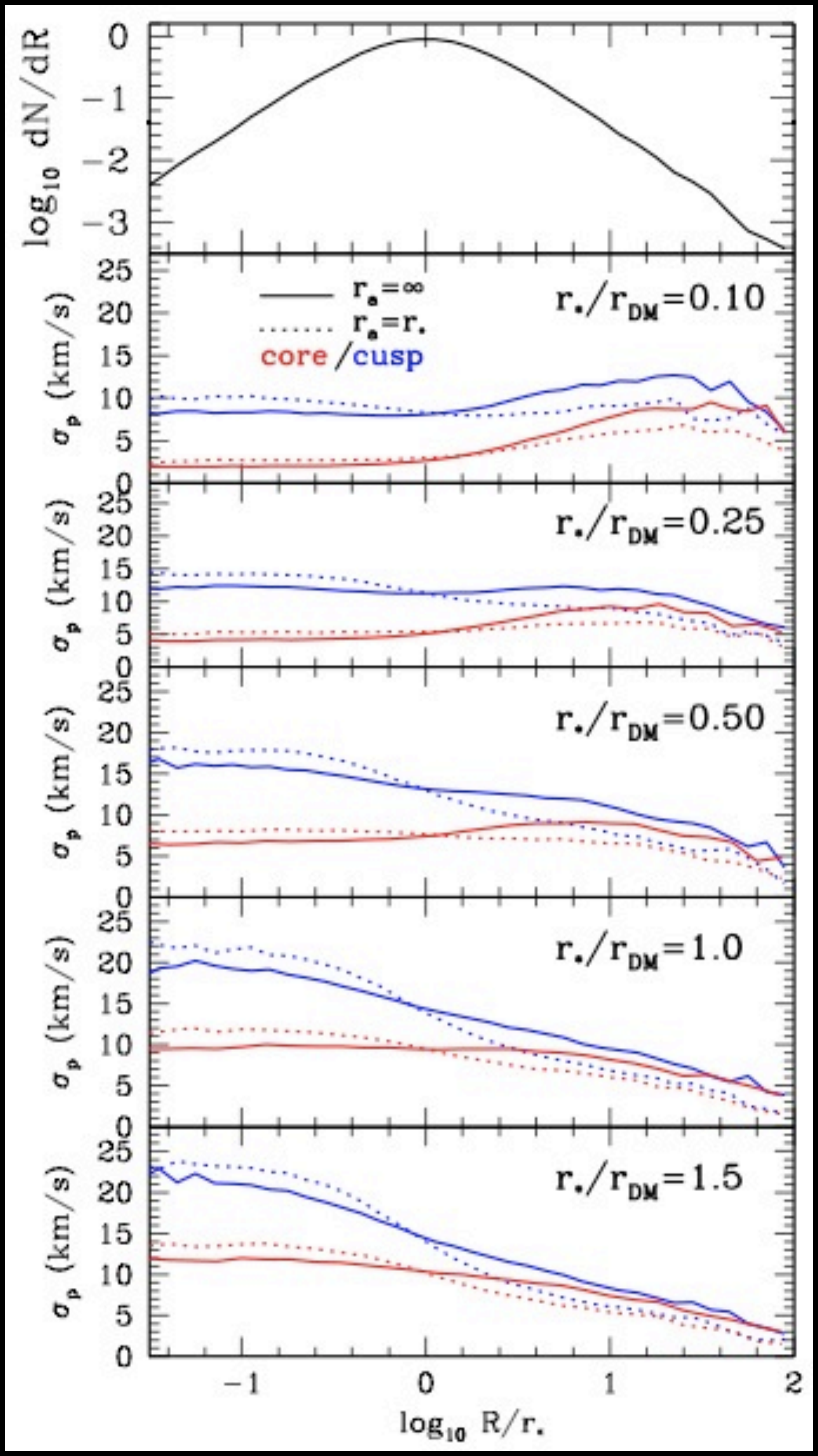

Tests

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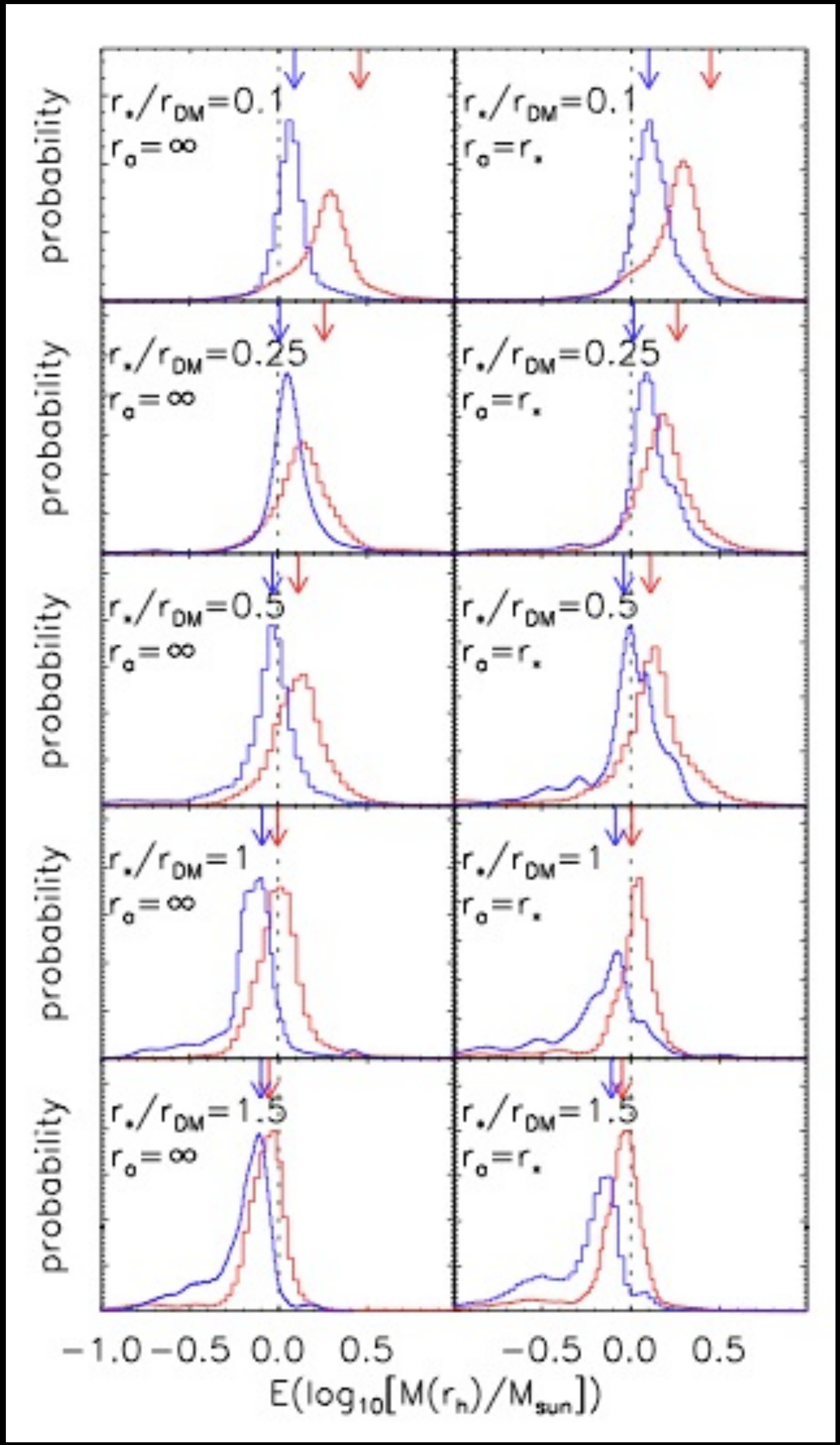
isotropic **anisotropic**



Tests

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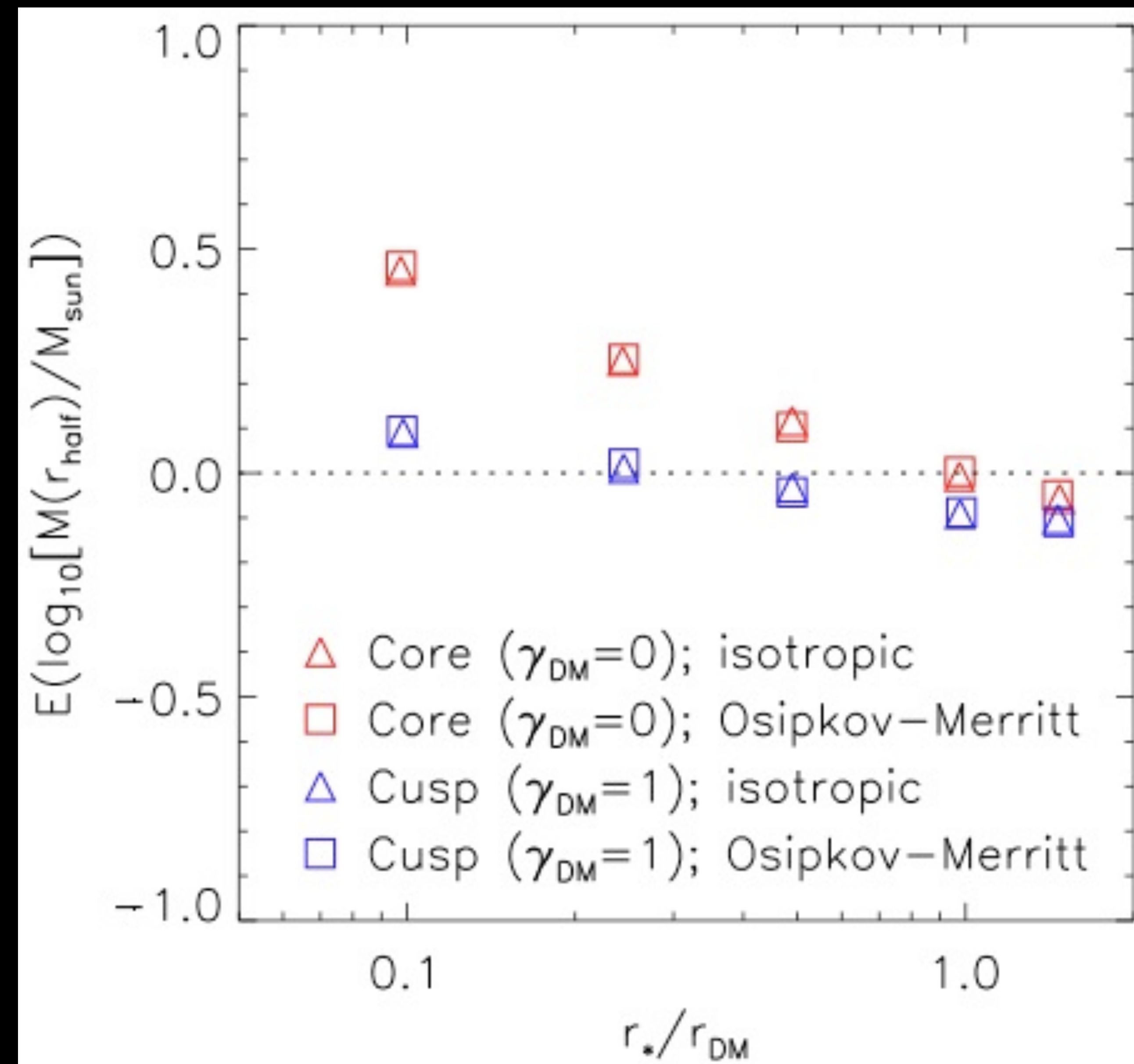

$$M(R_{\rm half}) \approx \mu R_{\rm half} \langle \sigma_V \rangle^2$$

Tests

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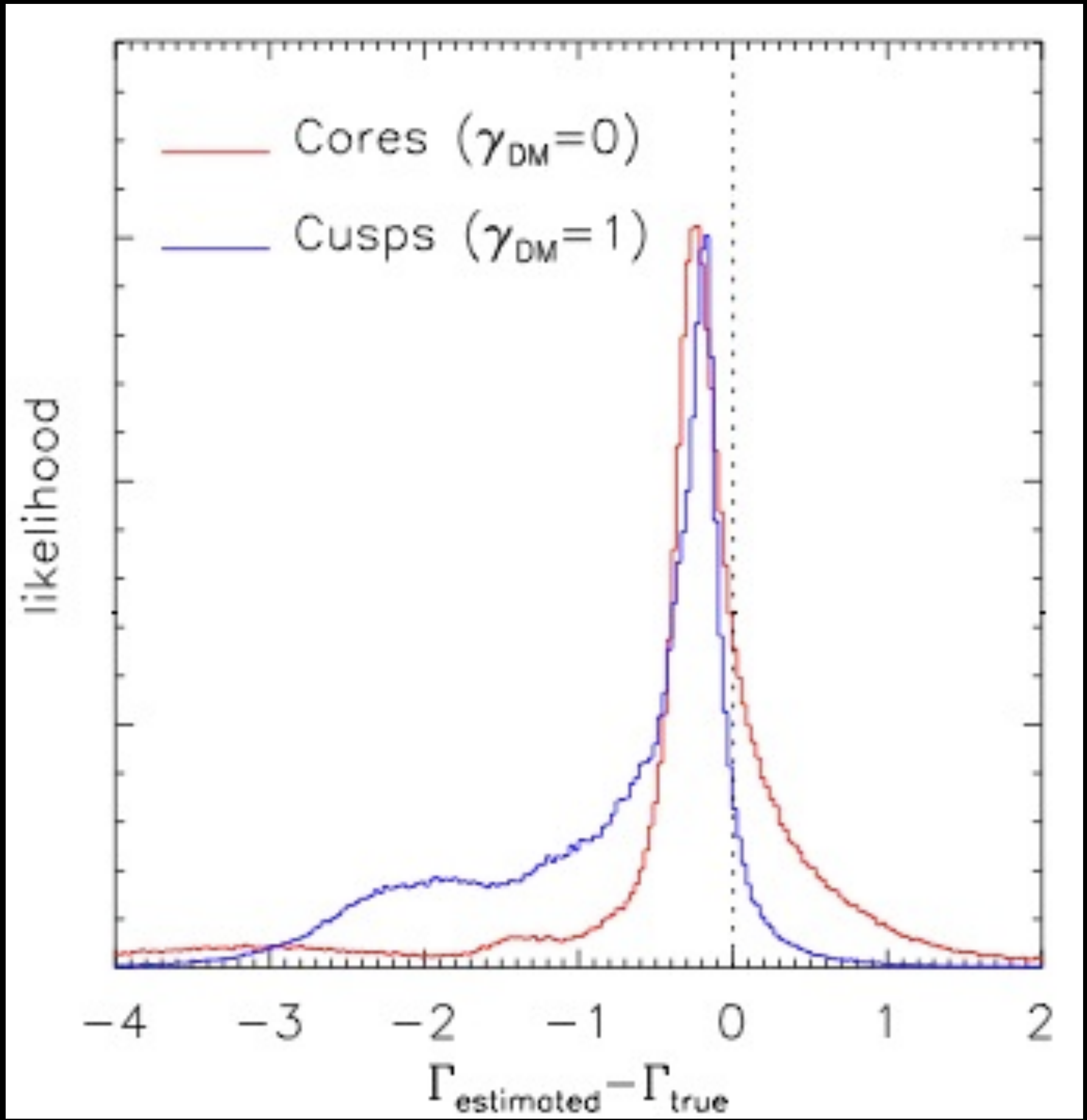
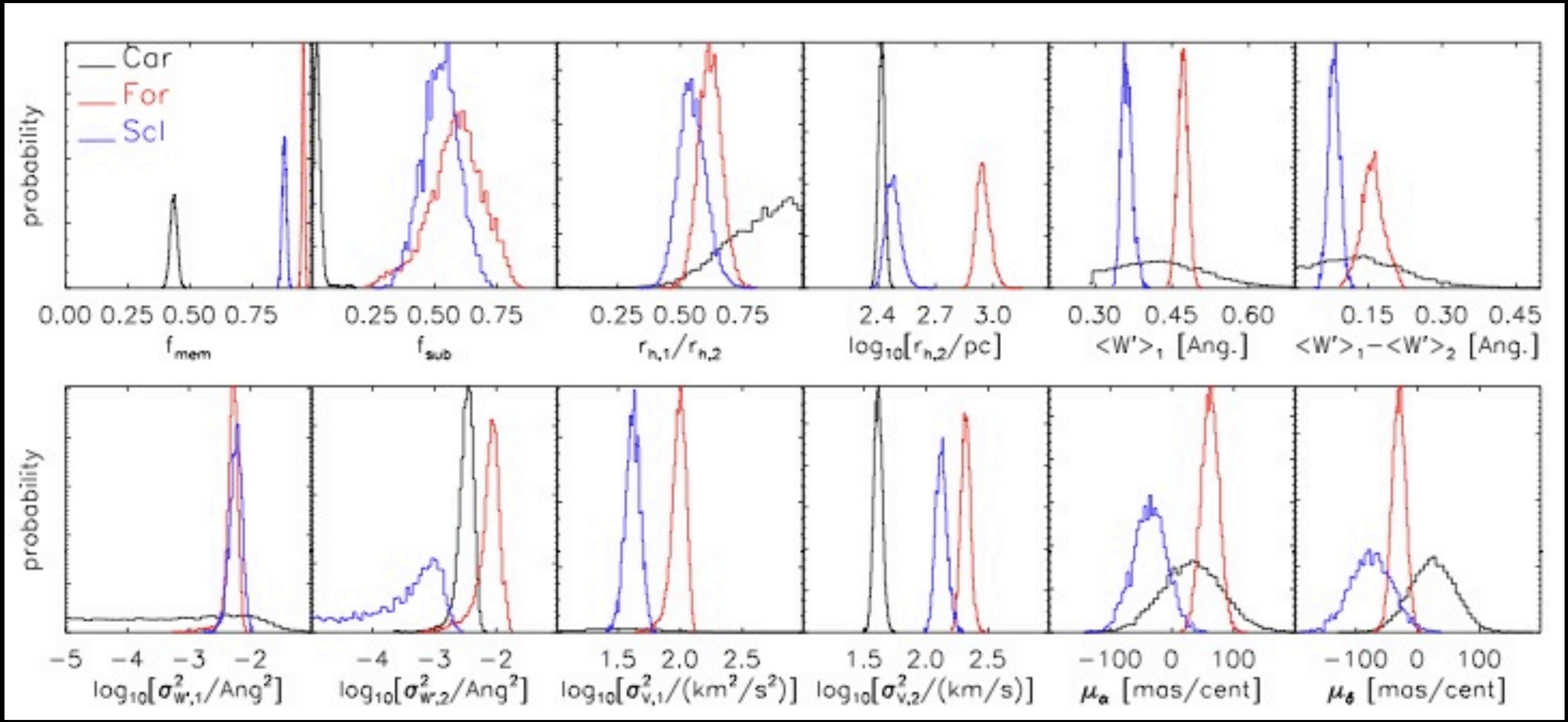


Results

Walker & Peñarrubia (2011)



MCMC posteriors

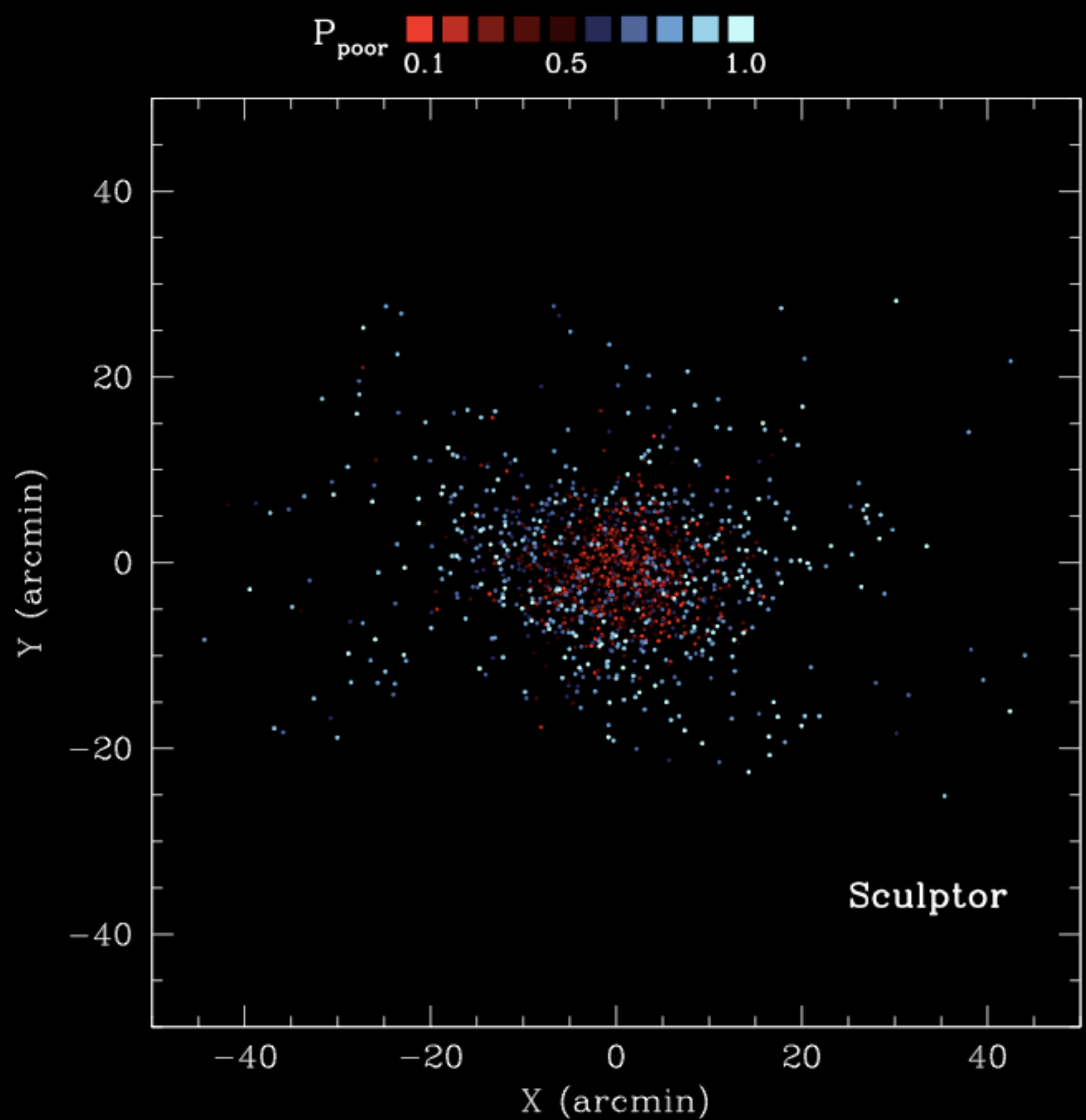
Two components detected in **Sculptor** and **Fornax**

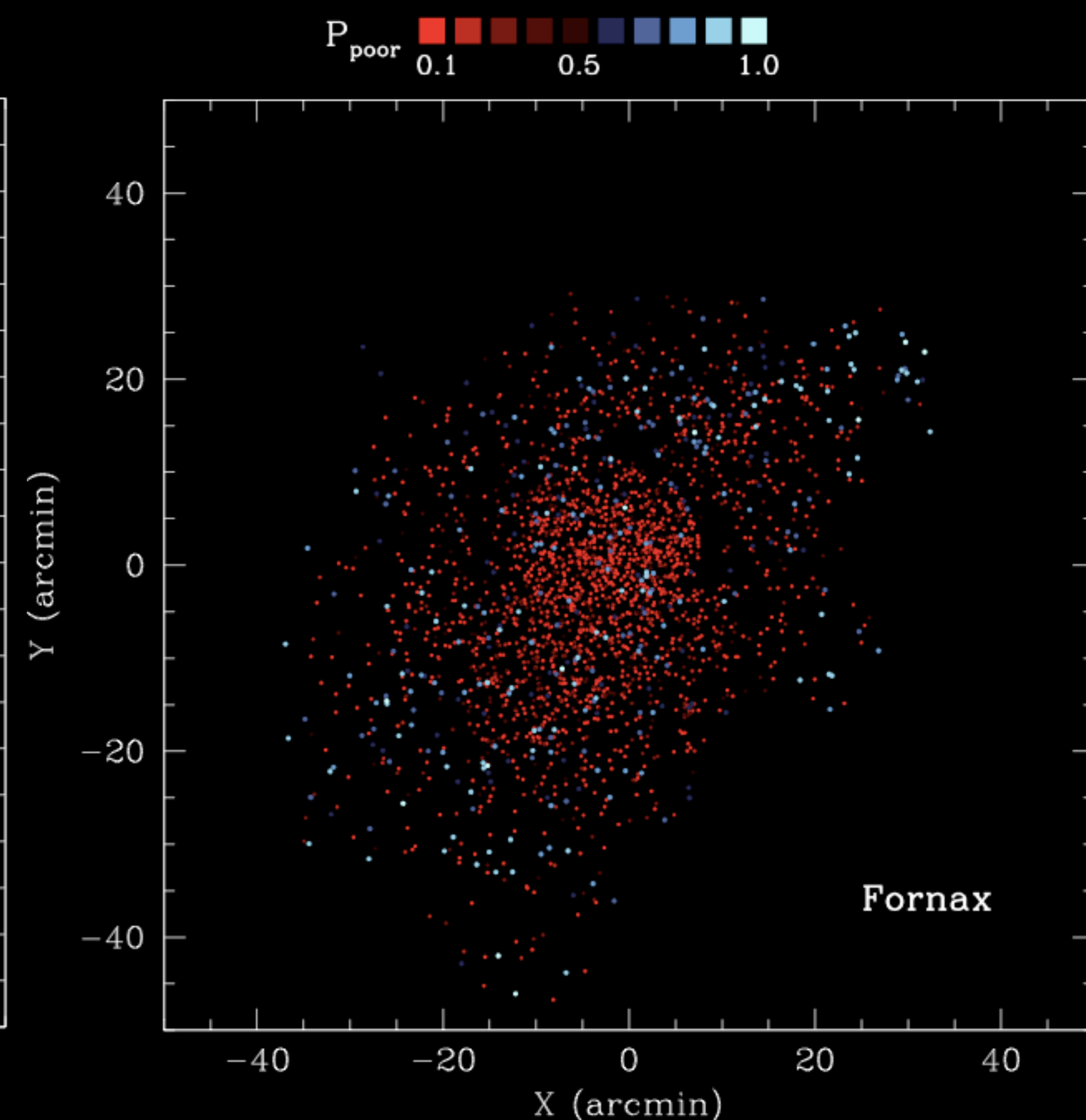
We recover published data on:

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

Results

Walker & Peñarrubia (2011)



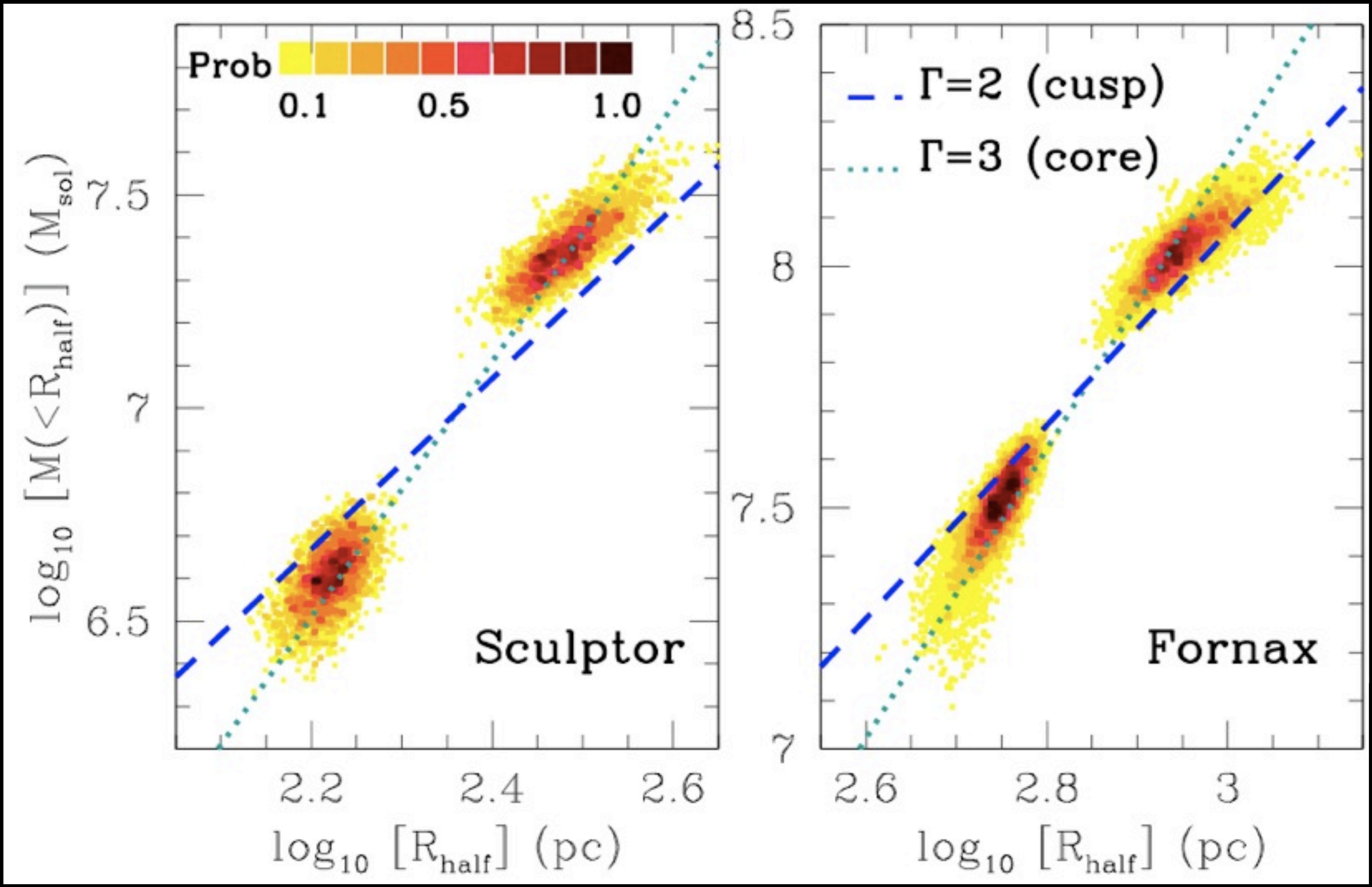


N_{sample}= 1497 spectra

N_{sample}= 2603 spectra

Results

Walker & Peñarrubia (2011)



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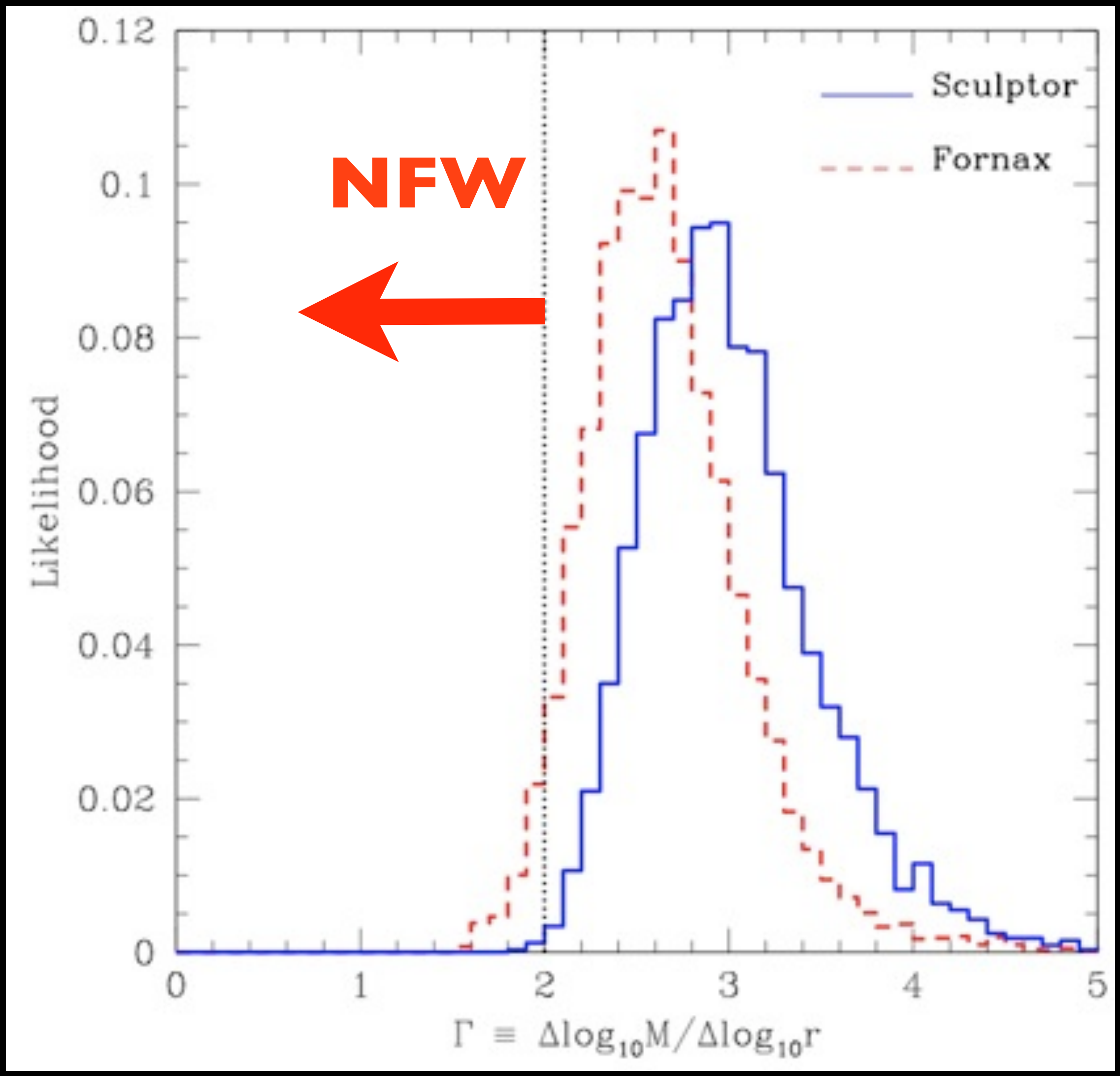
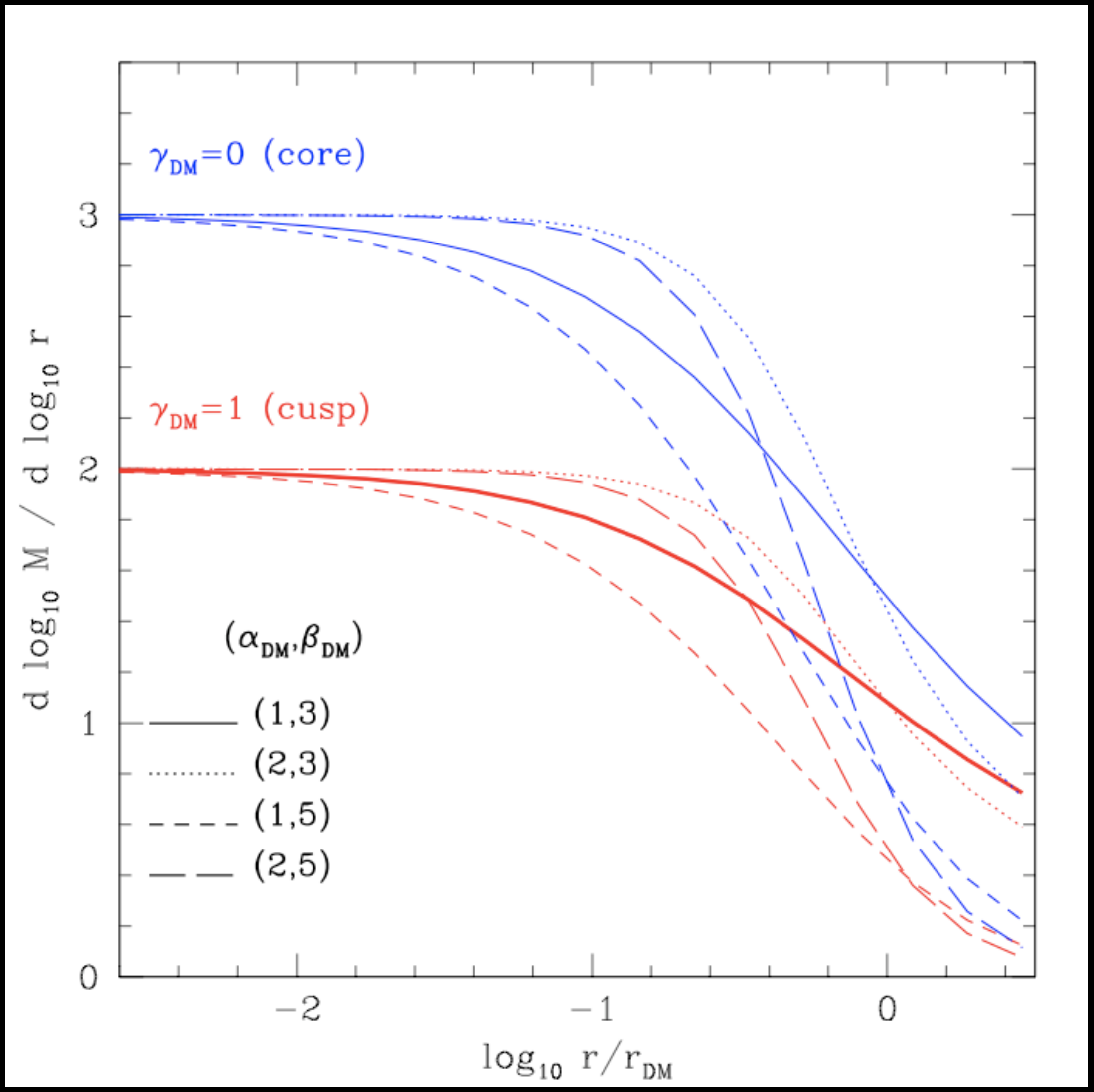


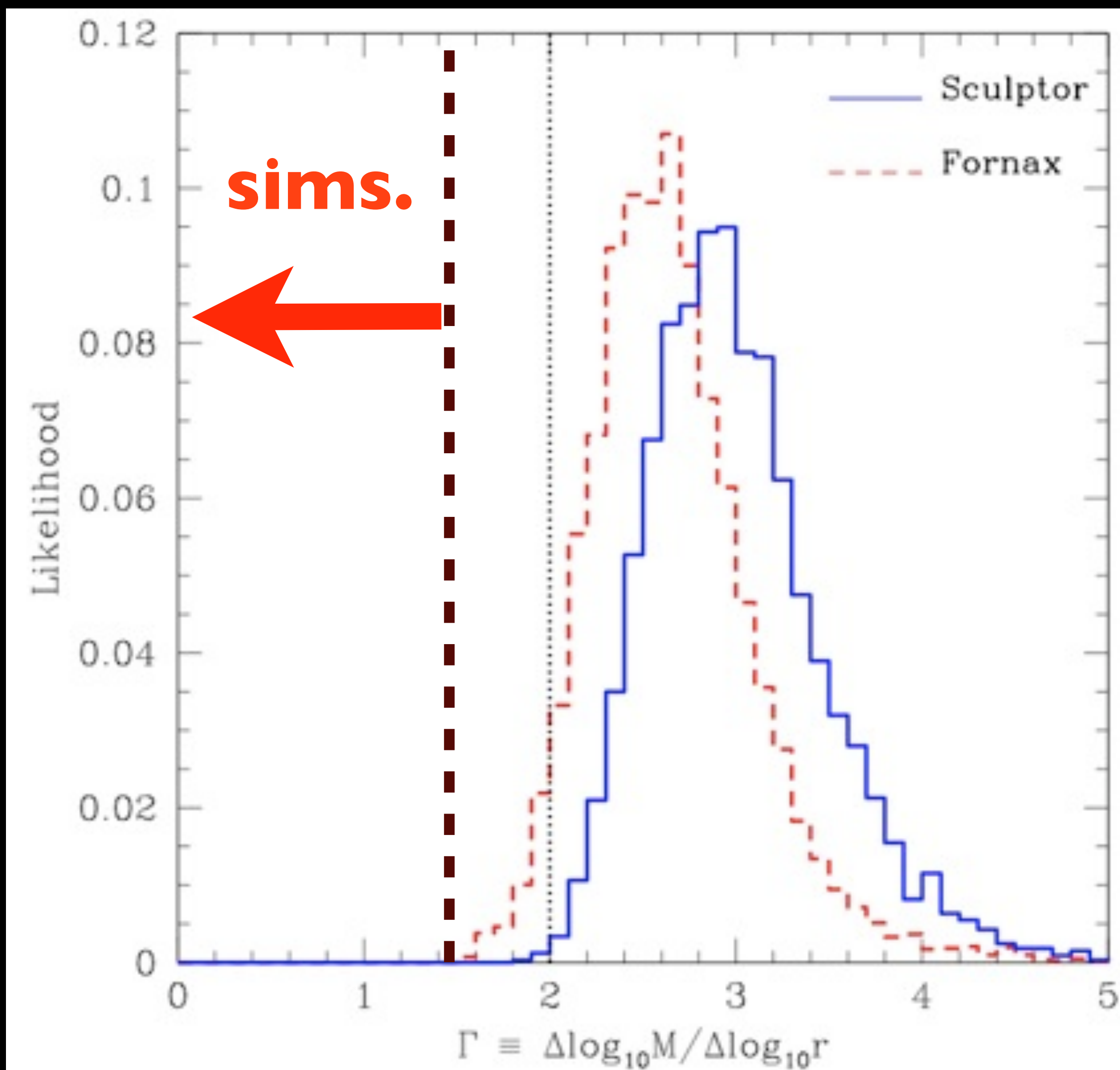


$$\rho_{\rm DM} = \frac{\rho_0}{\left(r/r_{\rm DM}\right)^{\gamma_{\rm DM}}\left[1+(r/r_{\rm DM})^{\alpha_{\rm DM}}\right]^{(\beta_{\rm DM}-\gamma_{\rm DM})/\alpha_{\rm DM})}}$$

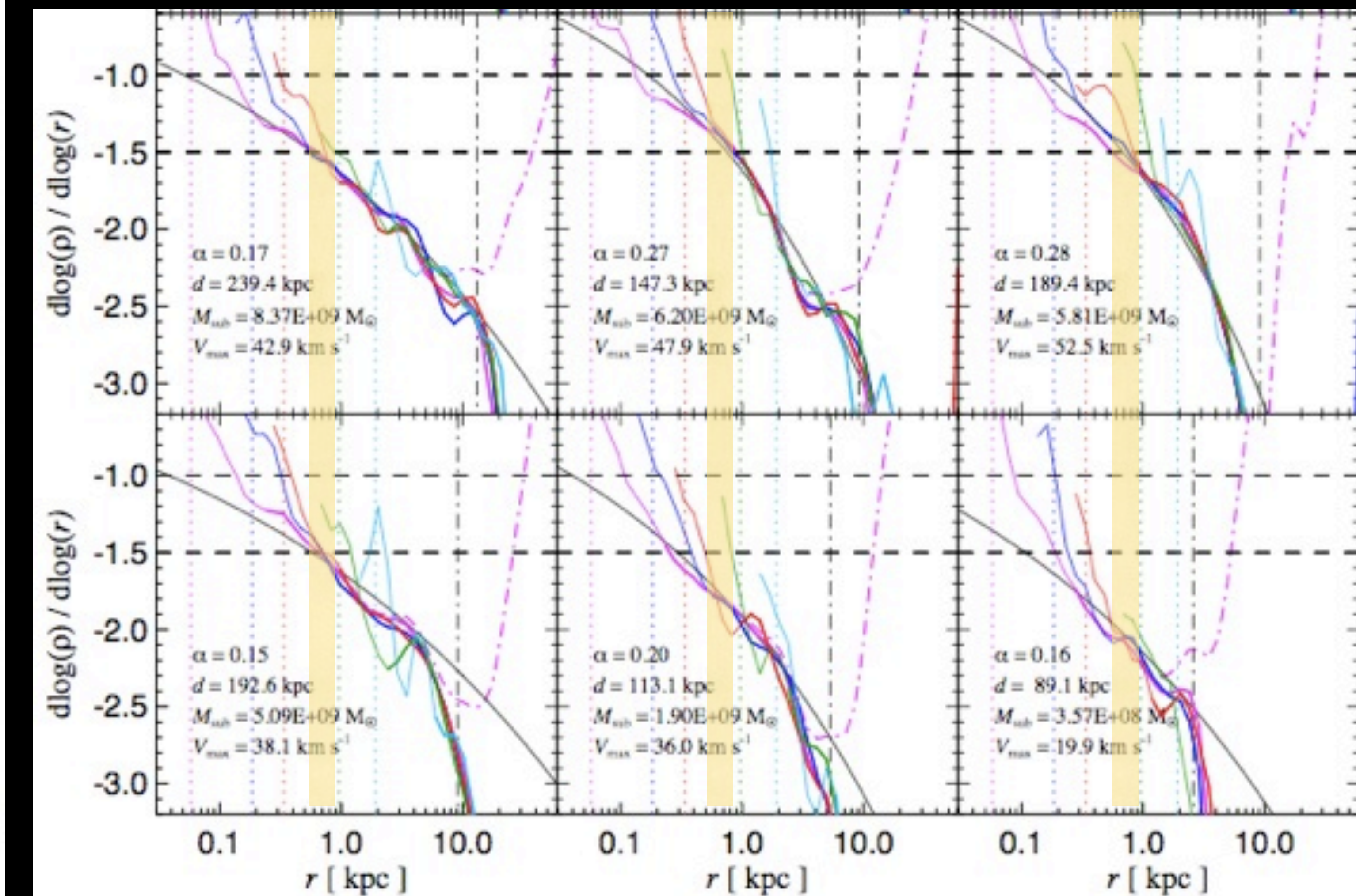
NFW ruled out in Fornax and Sculptor at a 96% and 99% confidence level

Results

Walker & Peñarrubia (2011)



Springel+08



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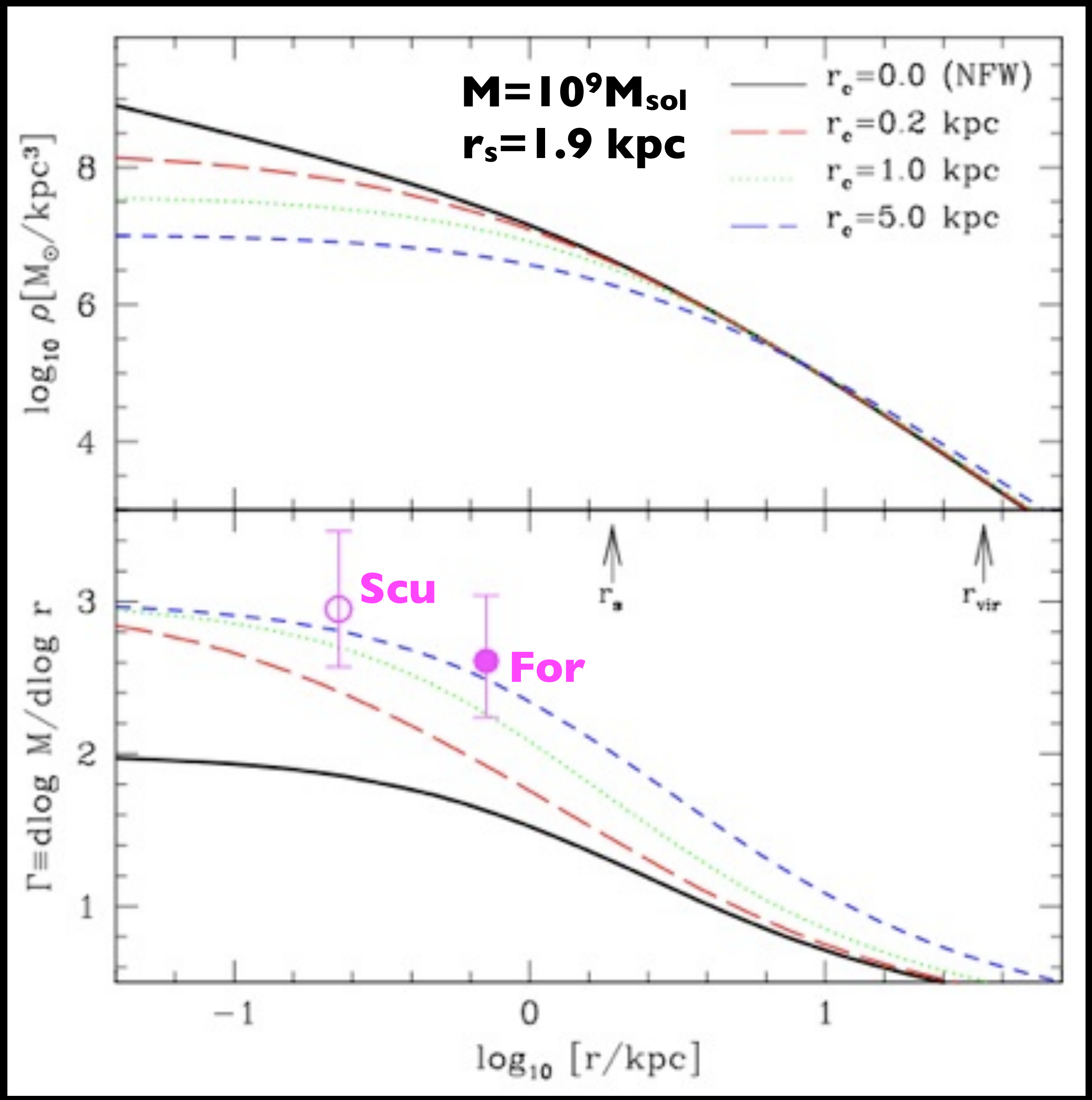
Profiles from collision-less cosmological simulations of satellites ruled out in Fornax and Sculptor at a 99.98% and 99.999% confidence level

Core size

Only slope mass profile is known

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



for $r_h \ll r_s$

$$\Gamma(r_h) \approx 3 - \frac{3+2x}{4x}\left(\frac{r_h}{r_s}\right); \quad x \equiv r_c/r_s$$

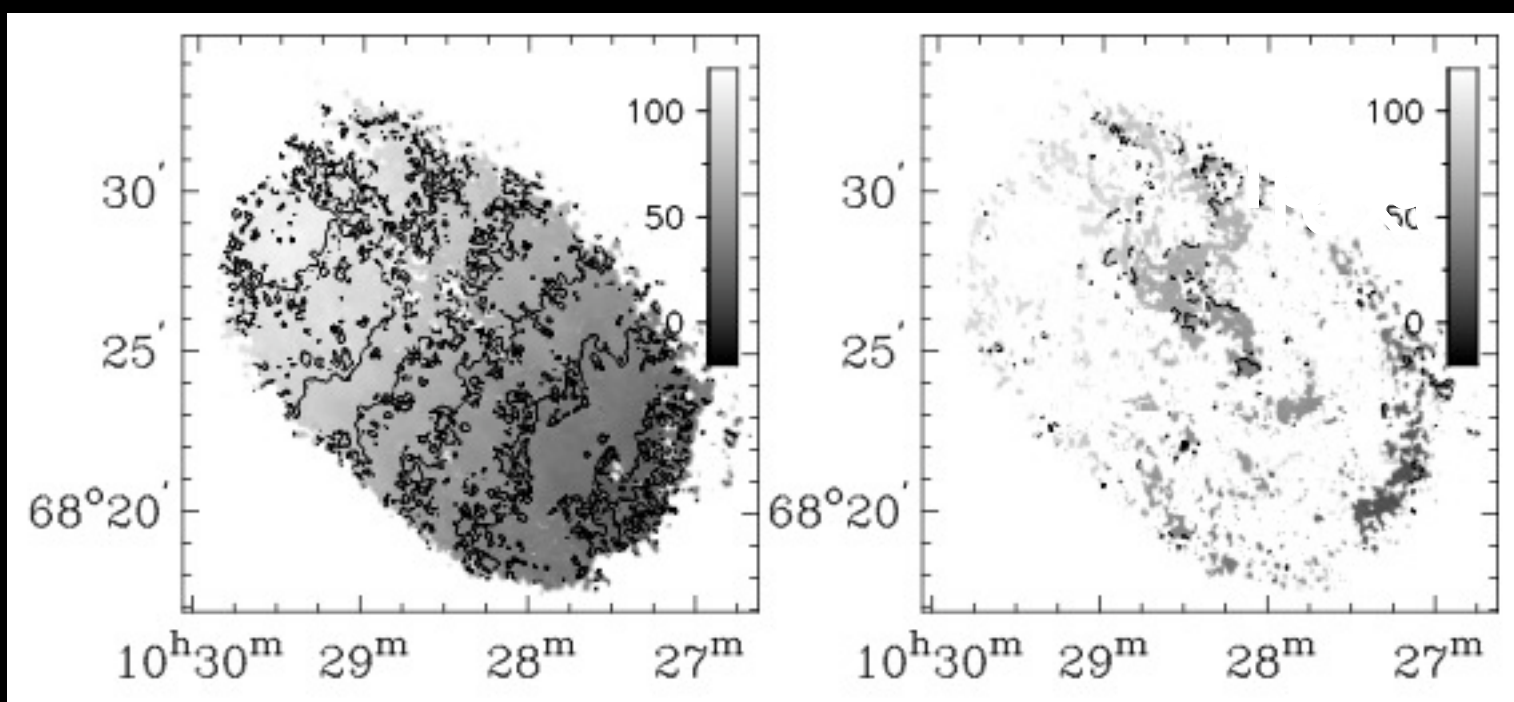
Only lower limits on r_c can be derived

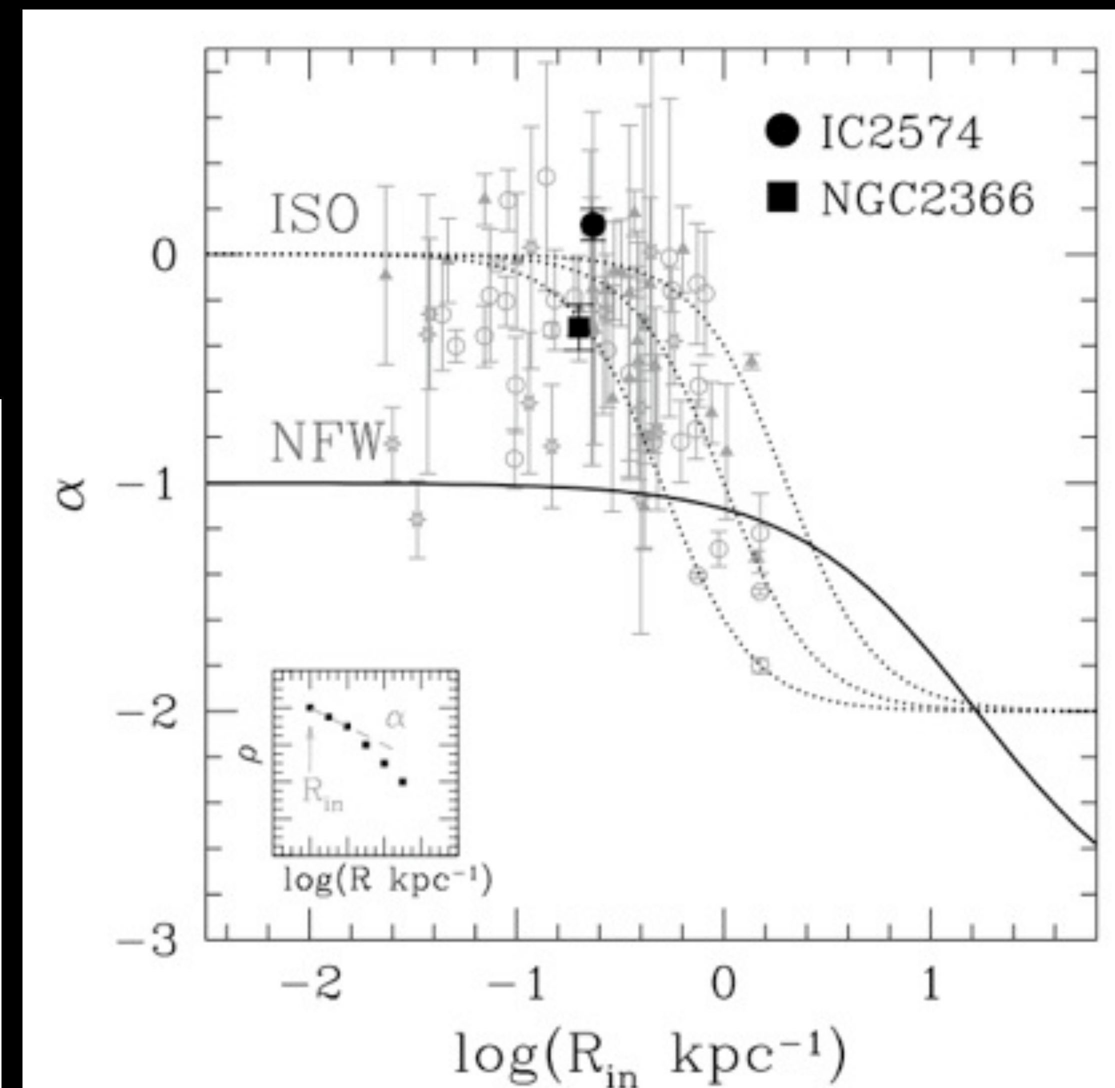
$rc \gg r_h \sim 0.5\text{-}1.0$ kpc

The core/cusp problem

Most **LSB** and **late-type** galaxies (10^{10}--10^{11} M_{sol}) show rotation curves indicative of ***cored*** DM profiles

de Blok+ 2001; de Blok & Bosma 2002; Swaters+2003



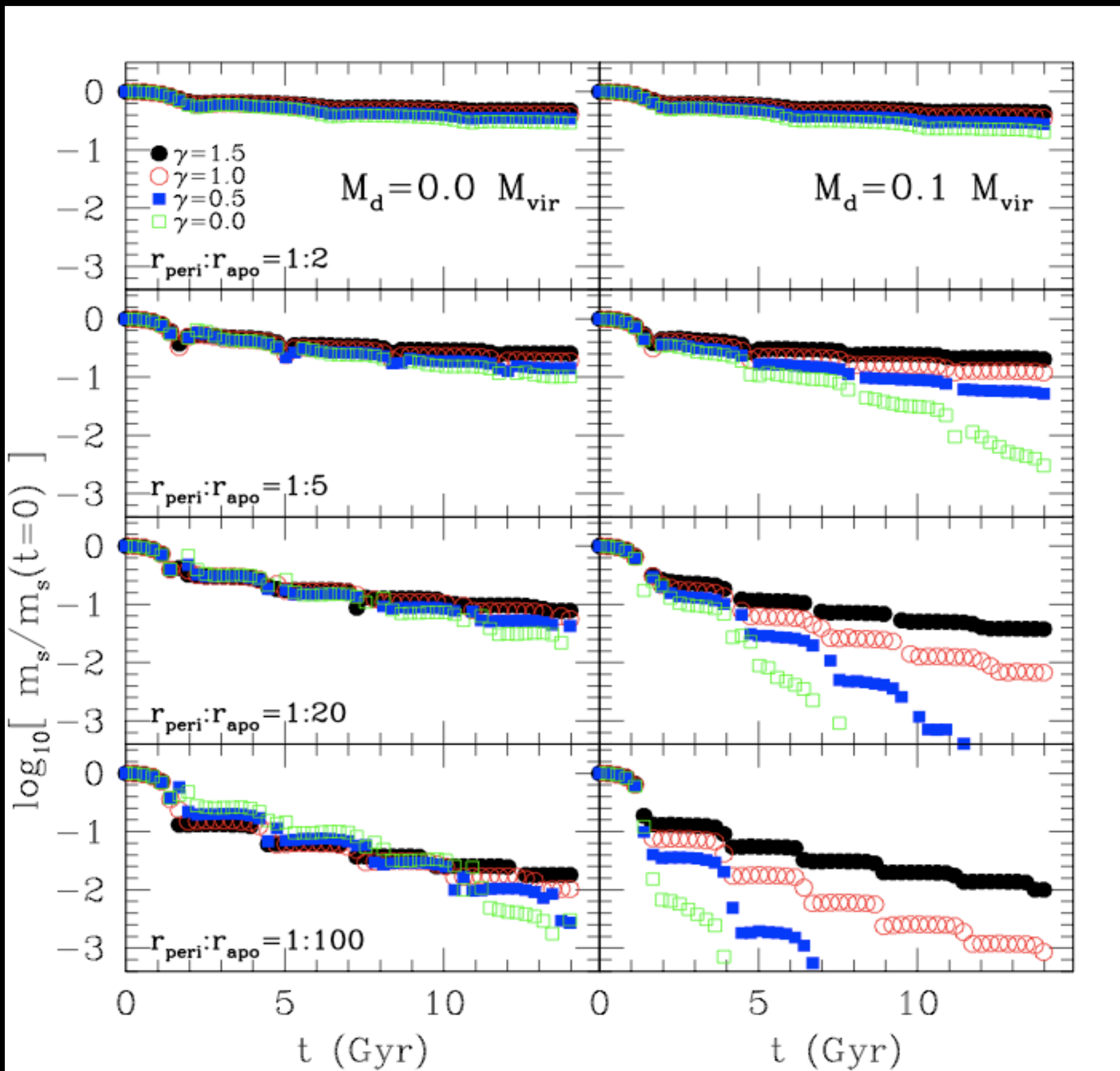


Oh+08

2D velocities from the THINGS survey confirm the result

Oh+2008; Kuzio de Naray 2008, 2009; de Blok+2010

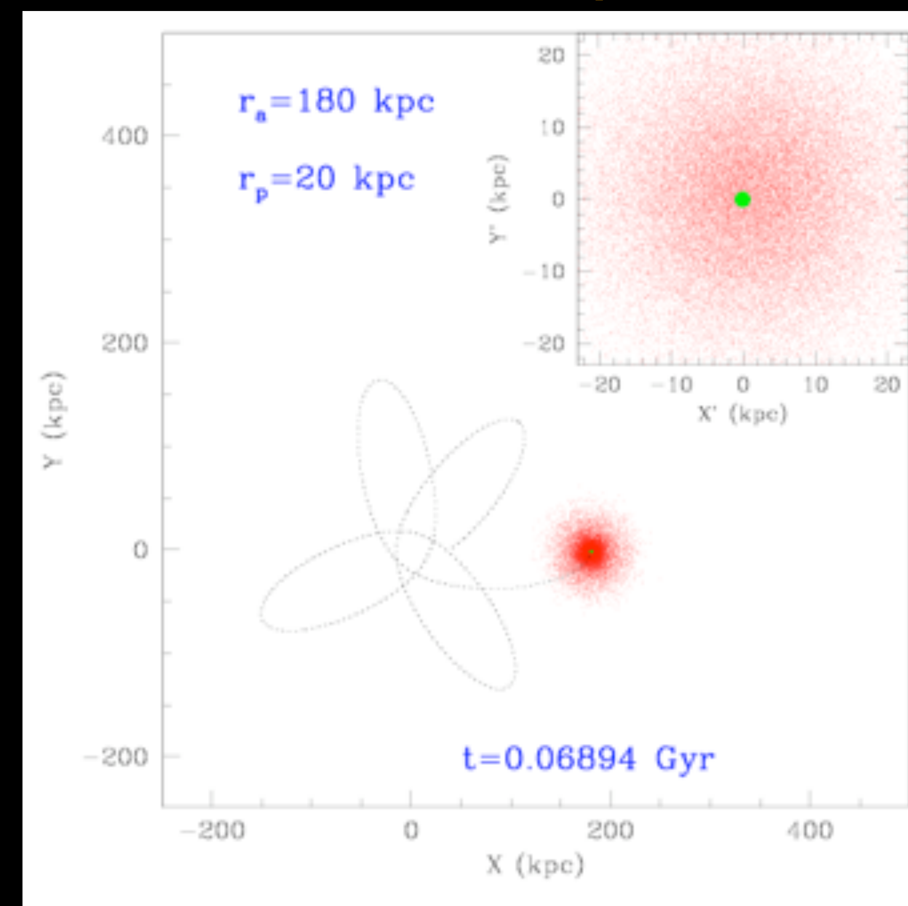
Impact of cored DM profiles on Galaxy formation



Peñarrubia+2010

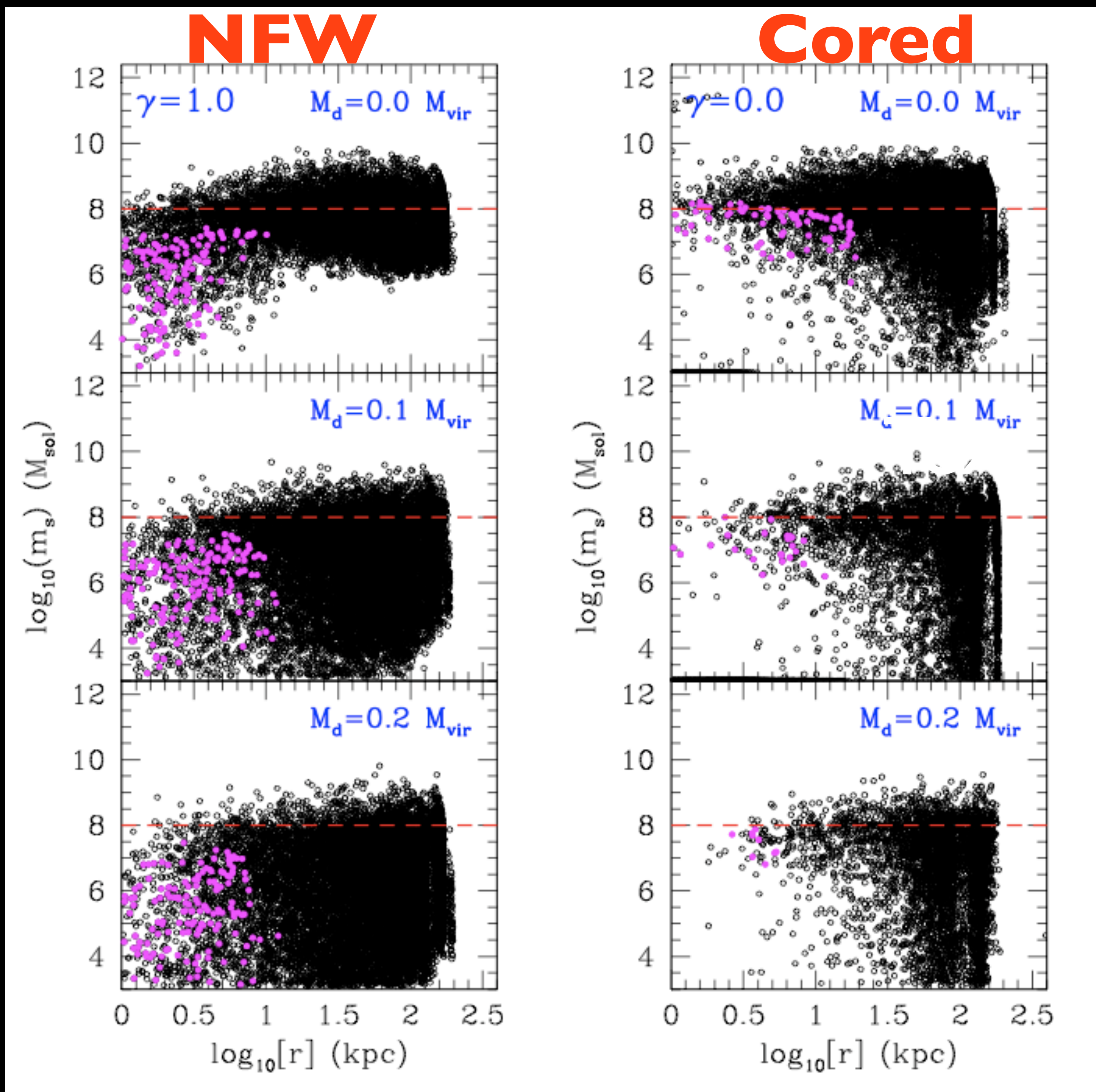
N-body simulations:

- 6x10^5 particles,
- resolution=10 pc



Cuspy haloes (γ≥1) cannot be disrupted by the host tidal field

Impact of cored DM profiles on Galaxy formation



Peñarrubia+2010

$M_{sat}(t_{acc}) \geq 10^8\ M_{sol}$

(possibly luminous)

Galactic discs deplete inner regions from satellites

↓

- ✳number of tidal streams?
- ✳stellar halo profile?

Summary

1) Wide binaries in dSphs probe the existence of **dark** substructures
2) We have introduced a robust method to measure the mass profiles of pressure-supported galaxies with multiple stellar components
3) Applied to dSphs it rules out NFW profiles (Fornax~96%; Sculptor~99%)
4) This is in tension with CDM hydrodynamical simulations that follow the formation of (field) dSphs (Sawala+10; Parry+12)
5) The presence of DM cores in satellite galaxies has a strong impact on their mass evolution in the MW tidal field, as well as on the formation of stellar halo

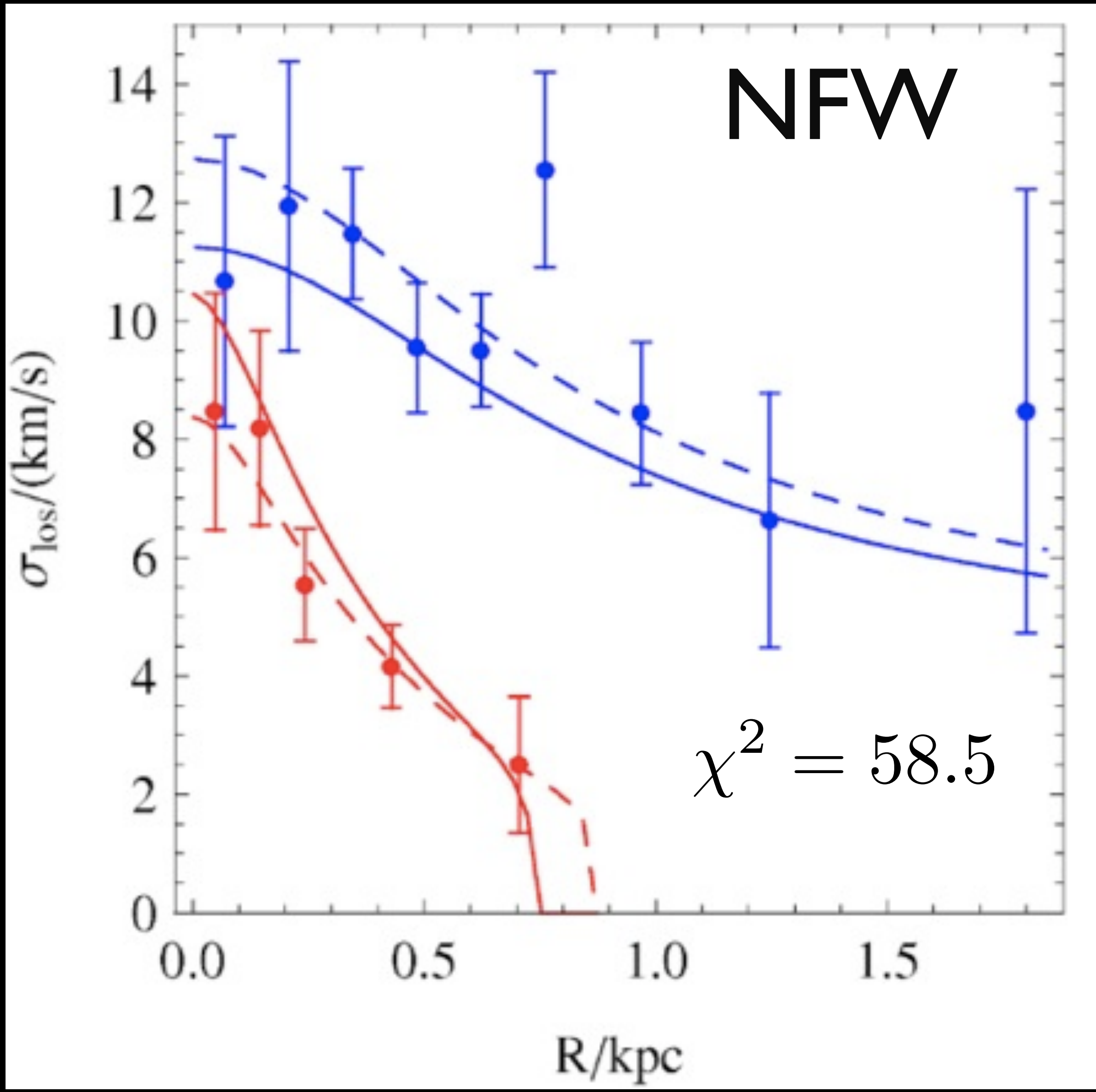
Future work

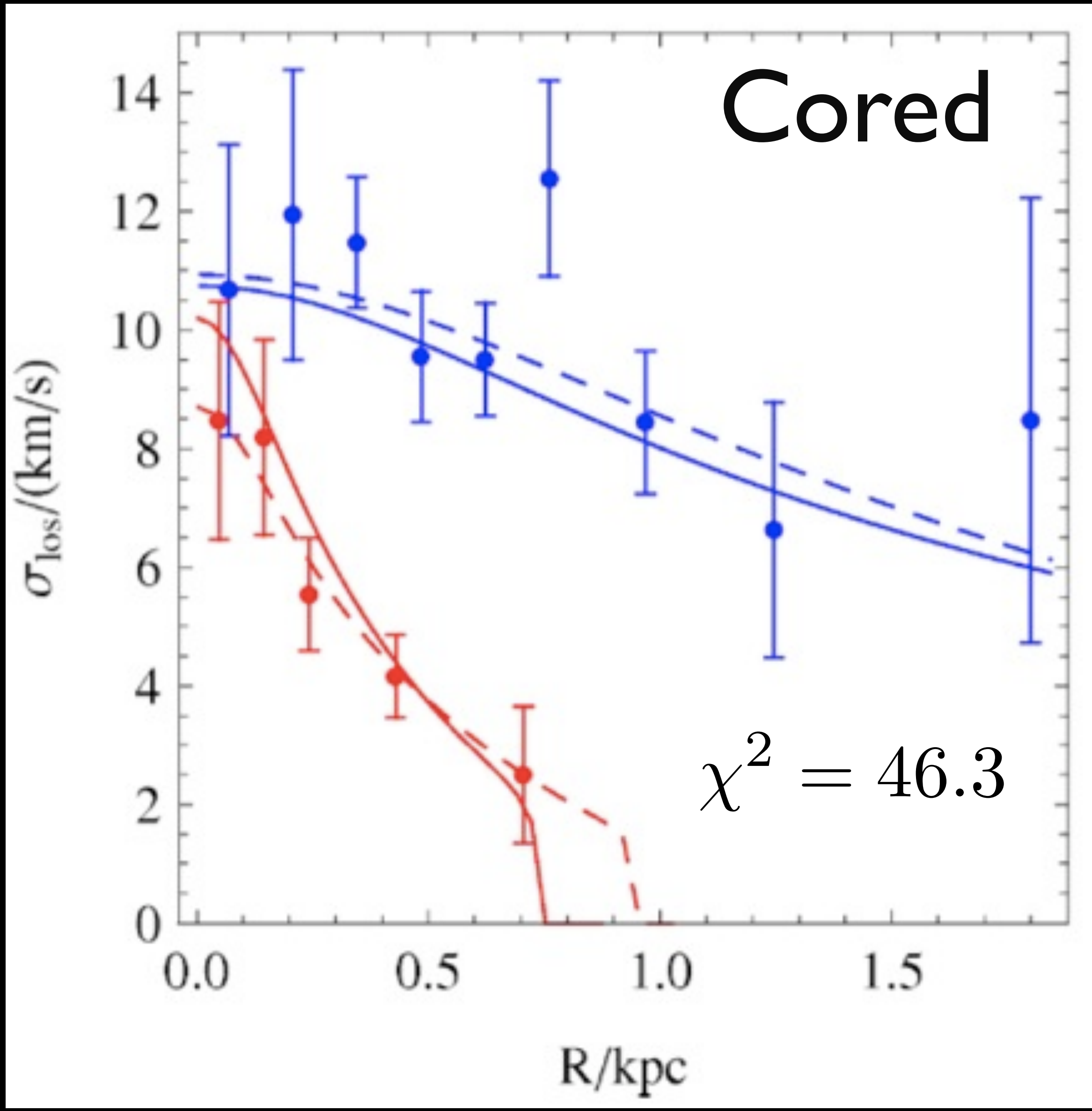
1) Increase the sample of stars with measured radial velocities in MW dSphs
2) N-body simulations of the Milky Way formation where satellites are embedded in a cored DM profile

Dynamical models

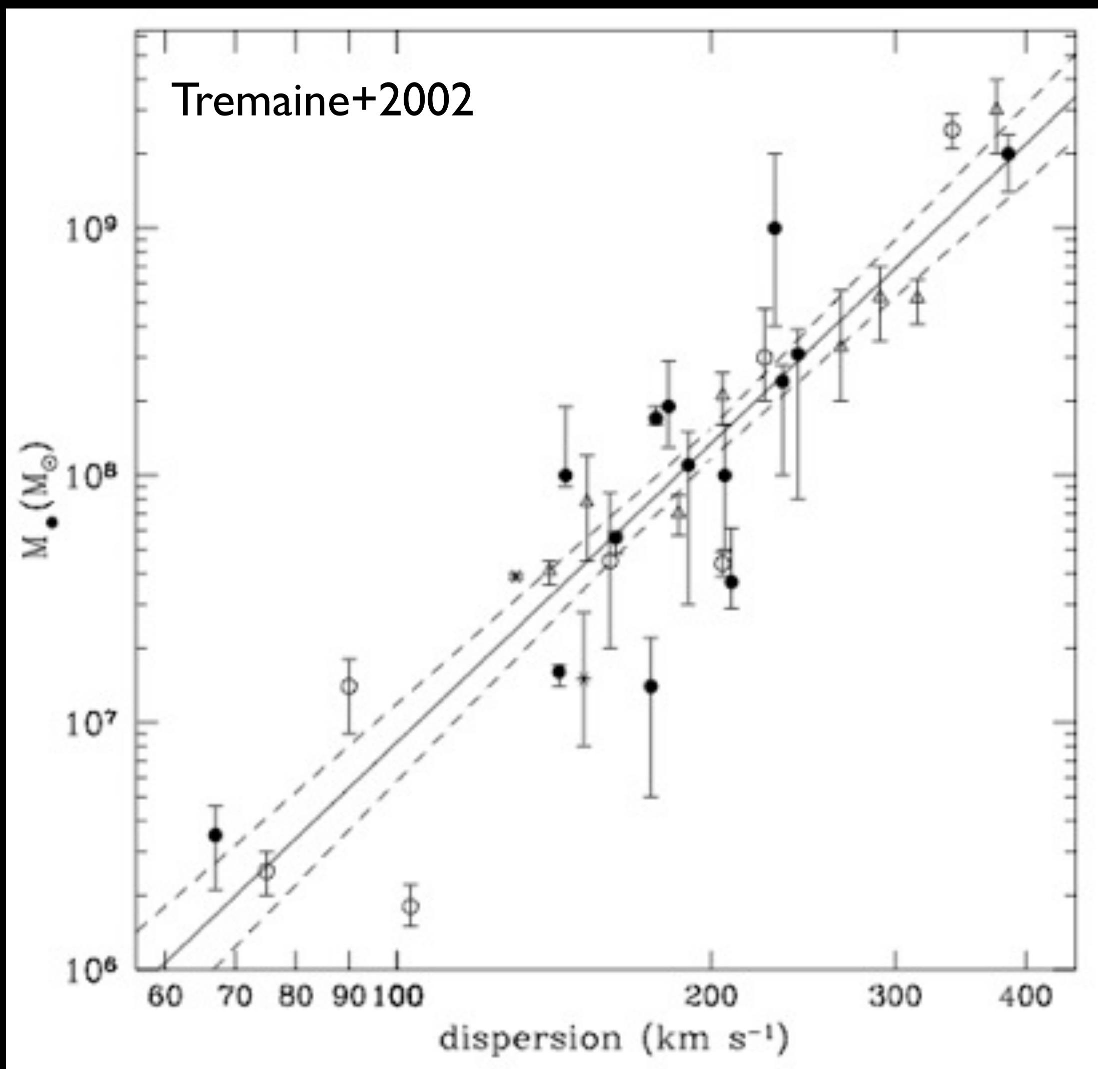
Amorisco & Evans (2012) bin projected velocities
and fit Michie-King DFs to **Sculptor***

*_**metallicity cut**_
***model dependent** → uncertainties?





Black Holes in dSphs?



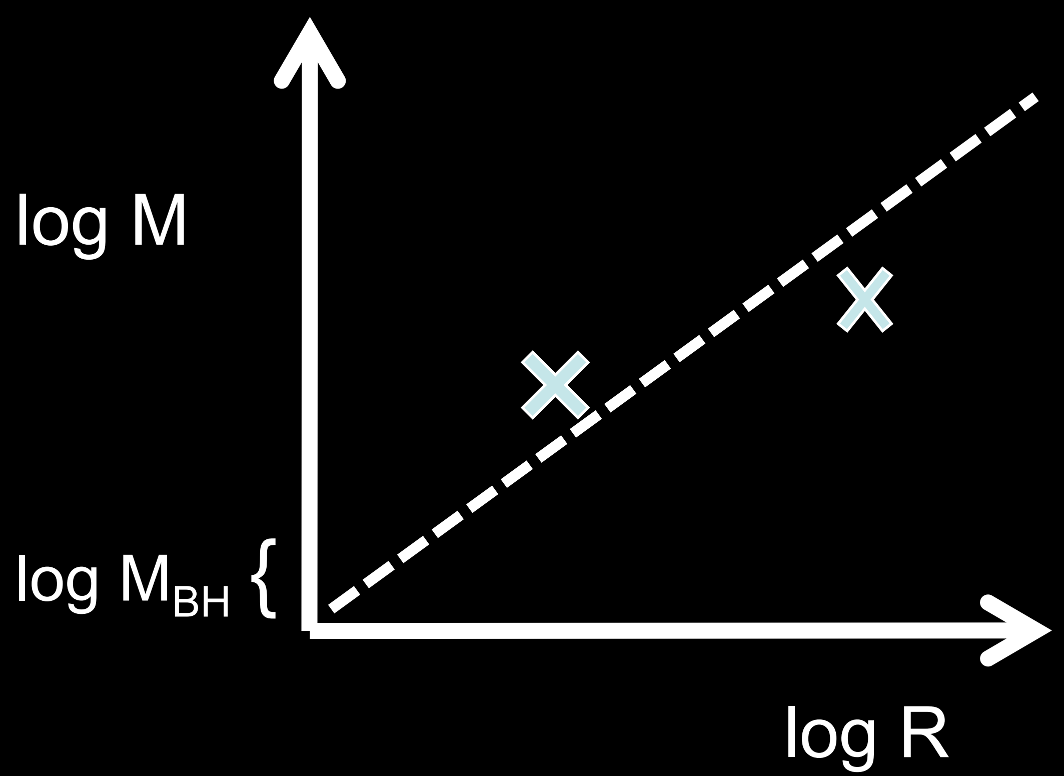
tight correlation between the mass of the central BH and the galaxy luminosity in pressure-supported galaxies

Gebhardt+ 2000; Tremaine+2002; Ferrarese & Ford 2005; Hu 2008; Gadotti & Kauffmann 2009

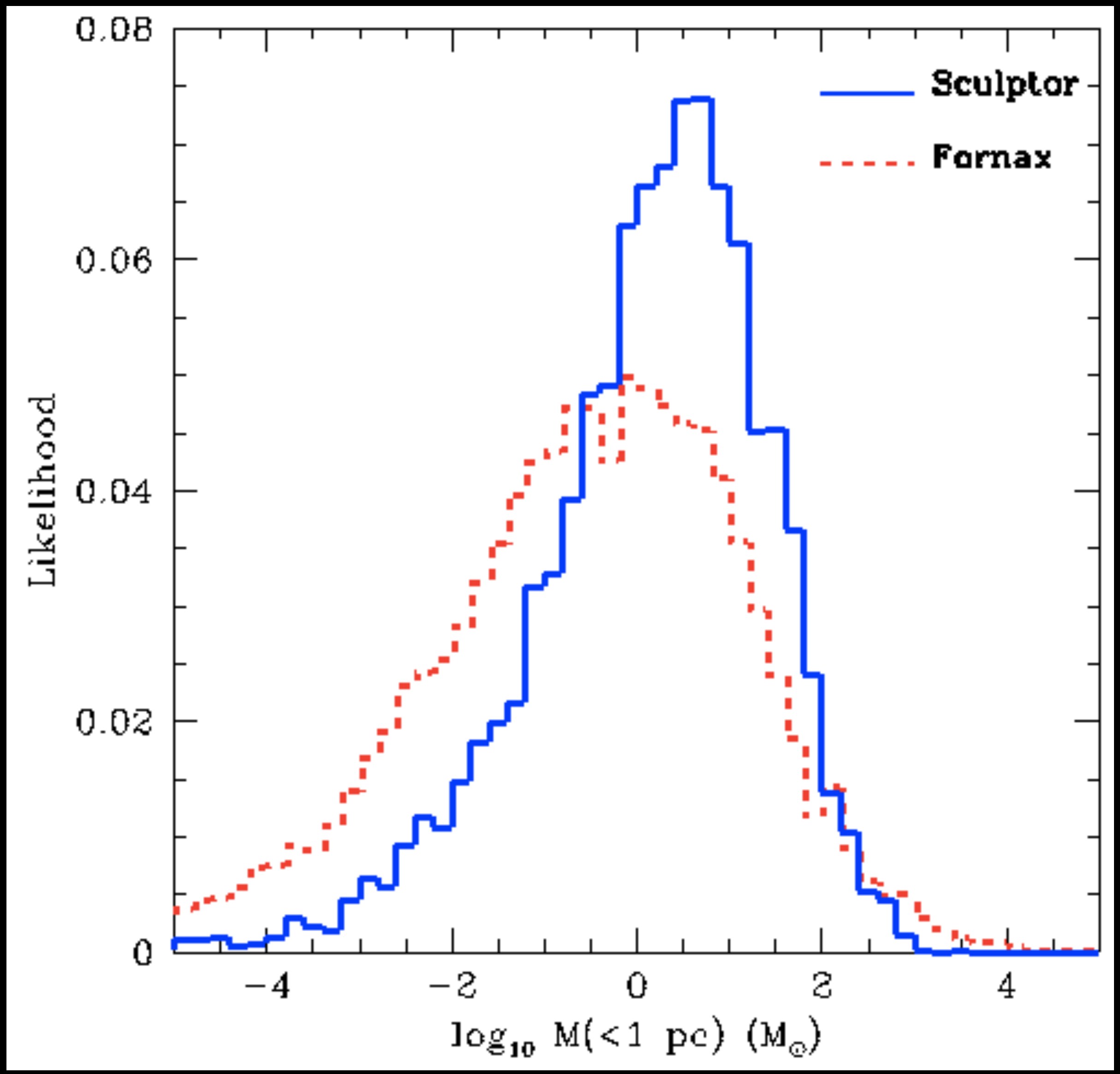
$$M_{\rm BH} \sim 10^8 M_\odot \left(\frac{\sigma_\star}{200{\rm kms}^{-1}} \right)^{3.75}$$

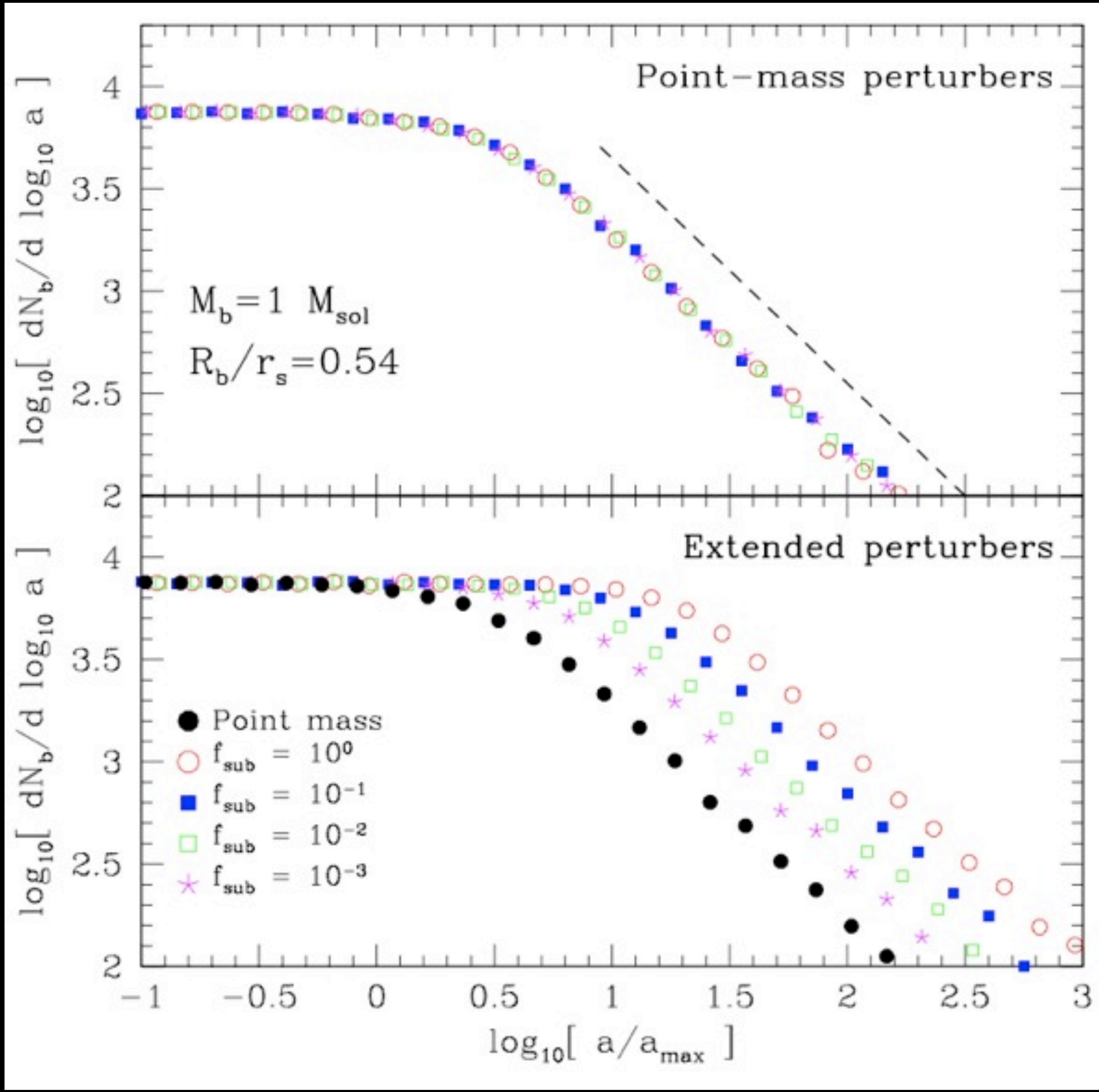
$M_{\rm BH,dSph} \sim 10^3\ M_{\rm sol}$

Black Holes in dSphs?

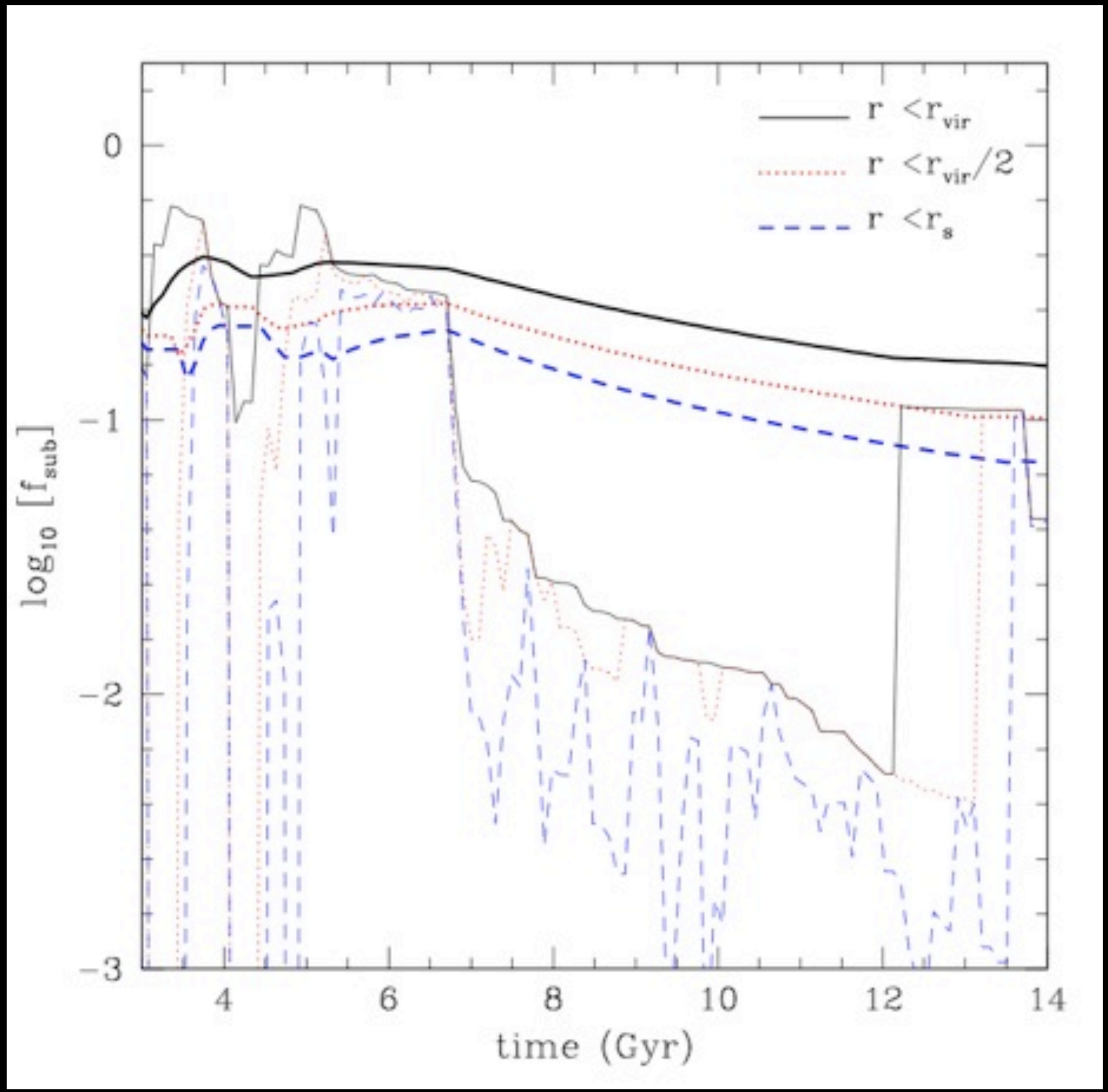


No clear evidence for BHs




Point−mass perturbers
$M_b = 1\ M_{sol}$
$R_b/r_s = 0.54$
Extended perturbers
Point mass
$f_{sub} = 10^0$
$f_{sub} = 10^{-1}$
$f_{sub} = 10^{-2}$
$f_{sub} = 10^{-3}$
$\log_{10}[\ dN_b/d\ \log_{10} a\ ]$
$\log_{10}[\ a/a_{max}\ ]$
−1
−0.5
0
0.5
1
1.5
2
2.5
3
4
3.5
3
2.5
2

z = 48.4
T = 0.05 Gyr
500 kpc



r < r_{vir}
r < $r_{vir}/2$
r < r_s
$\log_{10}[f_{sub}]$
time (Gyr)

TESTS

Synthetic data sets

(self-consistently calculated *by M. Wilkinson* from distribution functions)

1- stellar distribution

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

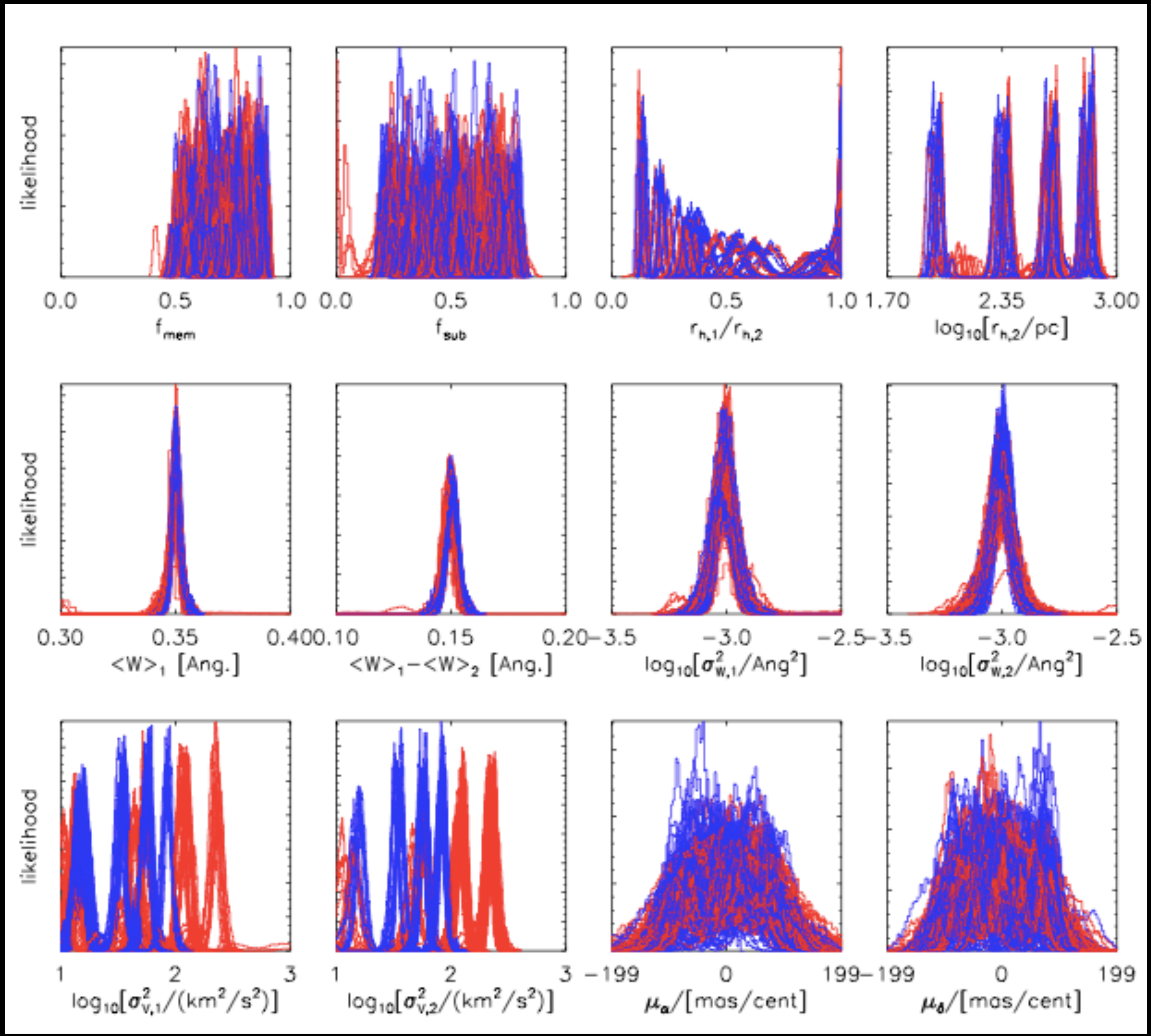
2- stellar kinematics

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

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

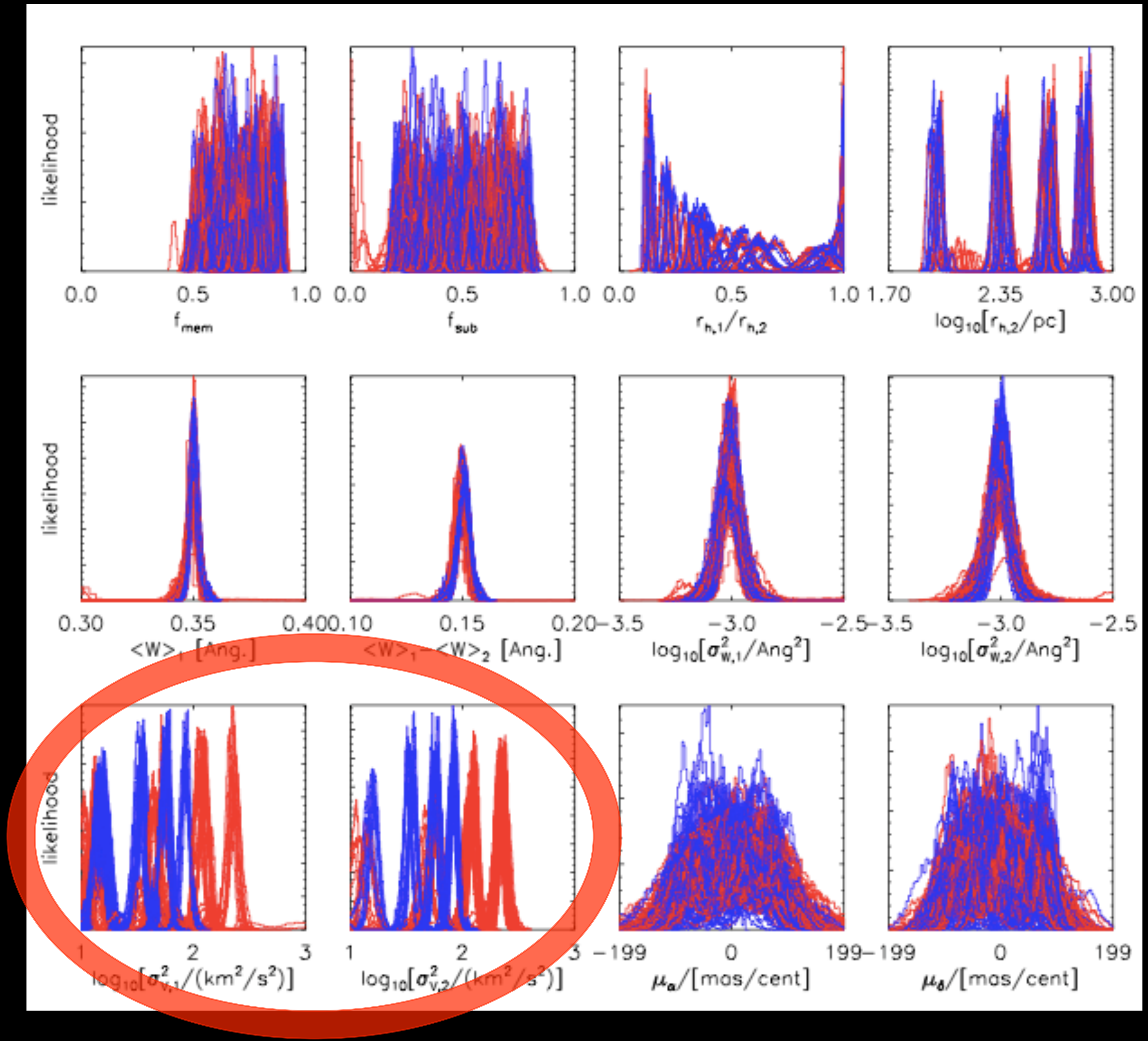
	Stellar Profile (Equation 14)				Dark Matter Profile (Equation 15)				
β_{ani}	r_* [pc]	α_*	β_*	γ_*	ρ_0 [$M_\odot$ pc^{-3}]	r_{DM} [pc]	α_{DM}	β_{DM}	γ_{DM}
Cored Halos									
Isotropic									
0.00	100	2	5	0.0	0.064	1000	2	3.1	0.0
0.00	250	2	5	0.0	0.064	1000	2	3.1	0.0
0.00	500	2	5	0.0	0.064	1000	2	3.1	0.0
0.00	1000	2	5	0.0	0.064	1000	2	3.1	0.0
Radially Anisotropic									
+0.25	100	2	5	0.6	0.064	1000	2	3.1	0.0
+0.25	250	2	5	0.6	0.064	1000	2	3.1	0.0
+0.25	500	2	5	0.6	0.064	1000	2	3.1	0.0
+0.25	1000	2	5	0.6	0.064	1000	2	3.1	0.0
Tangentially Anisotropic									
−0.45	100	2	5	0.0	0.064	1000	2	3.1	0.0
−0.45	250	2	5	0.0	0.064	1000	2	3.1	0.0
−0.45	500	2	5	0.0	0.064	1000	2	3.1	0.0
−0.45	1000	2	5	0.0	0.064	1000	2	3.1	0.0
Cusped Halos									
Isotropic									
0.00	100	2	5	0.1	0.014	1000	2	3.1	0.9
0.00	250	2	5	0.1	0.014	1000	2	3.1	0.9
0.00	500	2	5	0.1	0.014	1000	2	3.1	0.9
0.00	1000	2	5	0.1	0.014	1000	2	3.1	0.9
Radially Anisotropic									
+0.25	100	2	5	0.6	0.014	1000	2	3.1	0.9
+0.25	250	2	5	0.6	0.014	1000	2	3.1	0.9
+0.25	500	2	5	0.6	0.014	1000	2	3.1	0.9
+0.25	1000	2	5	0.6	0.014	1000	2	3.1	0.9
Tangentially Anisotropic									
−0.45	100	2	5	0.1	0.014	1000	2	3.1	0.9
−0.45	250	2	5	0.1	0.014	1000	2	3.1	0.9
−0.45	500	2	5	0.1	0.014	1000	2	3.1	0.9
−0.45	1000	2	5	0.1	0.014	1000	2	3.1	0.9

TESTS



CUSP
CORE

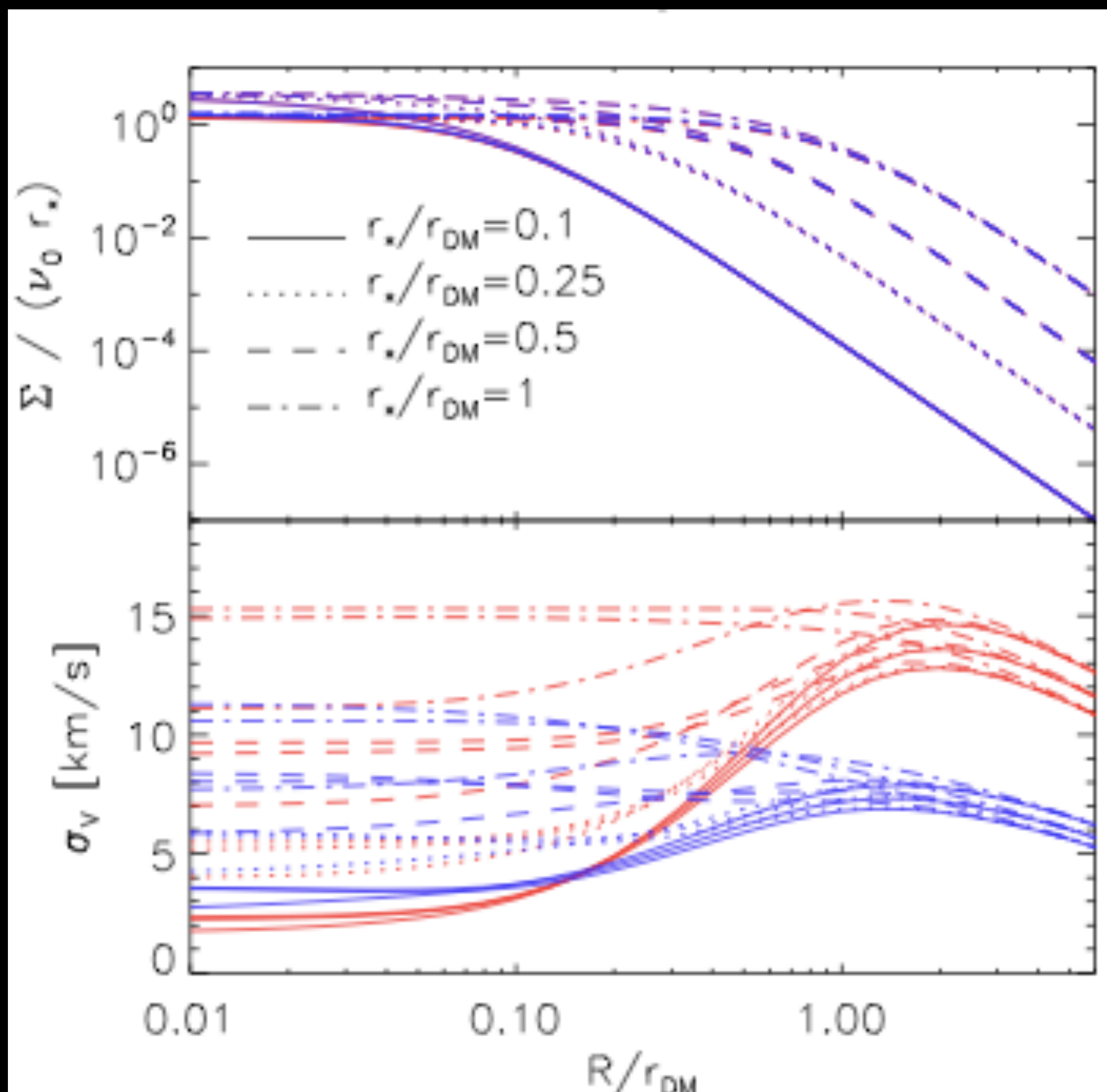
TESTS

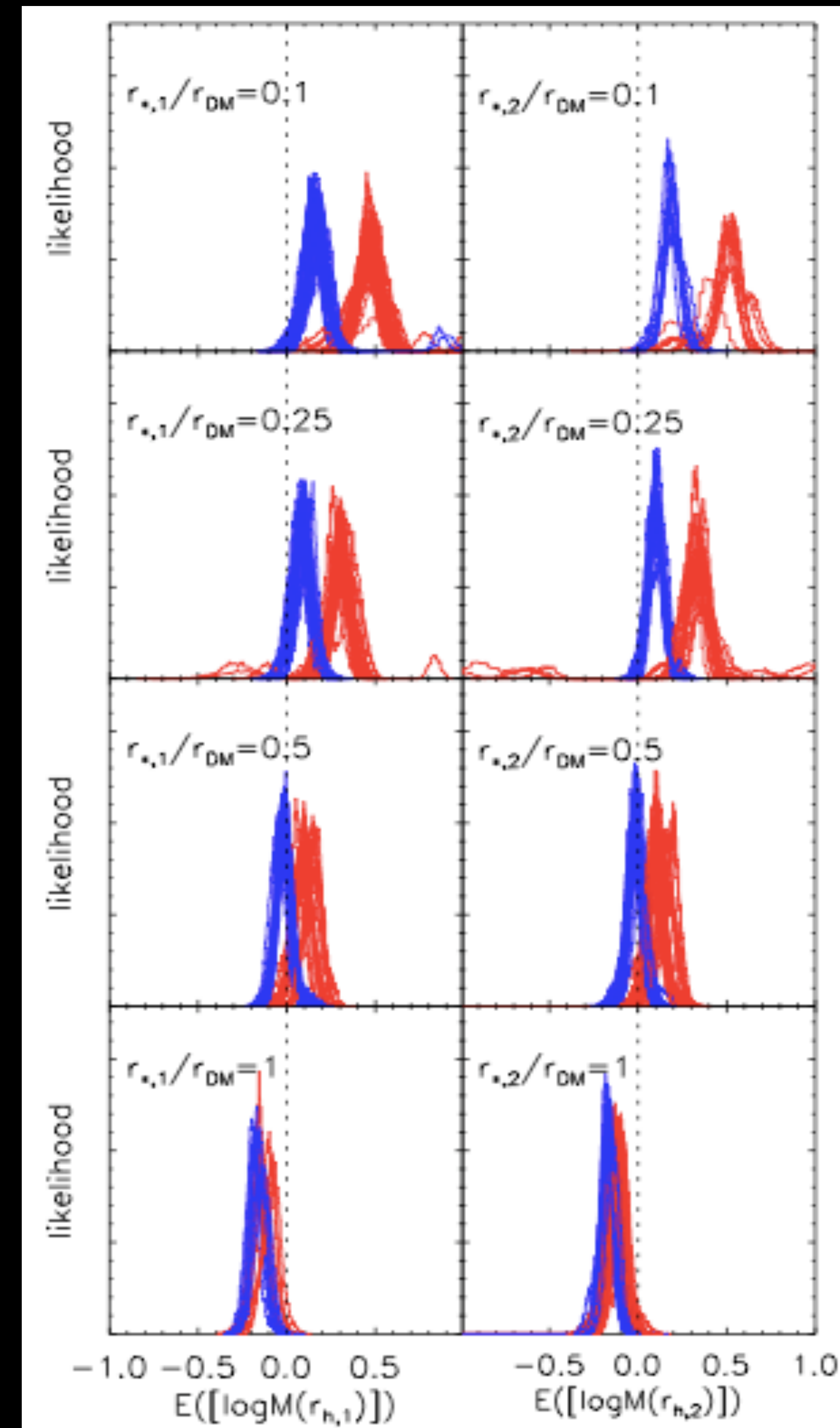


CUSP

CORE

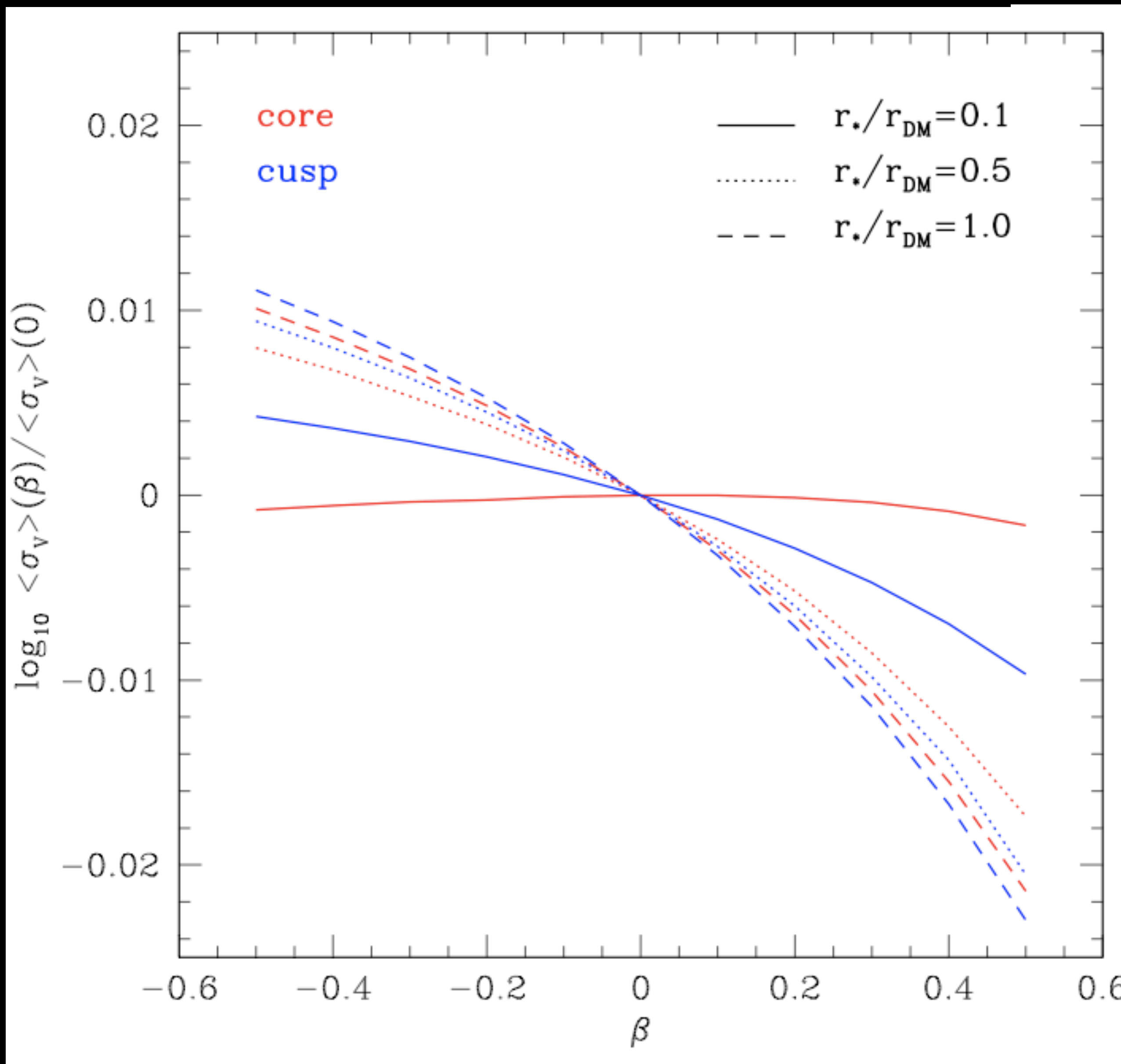
TESTS

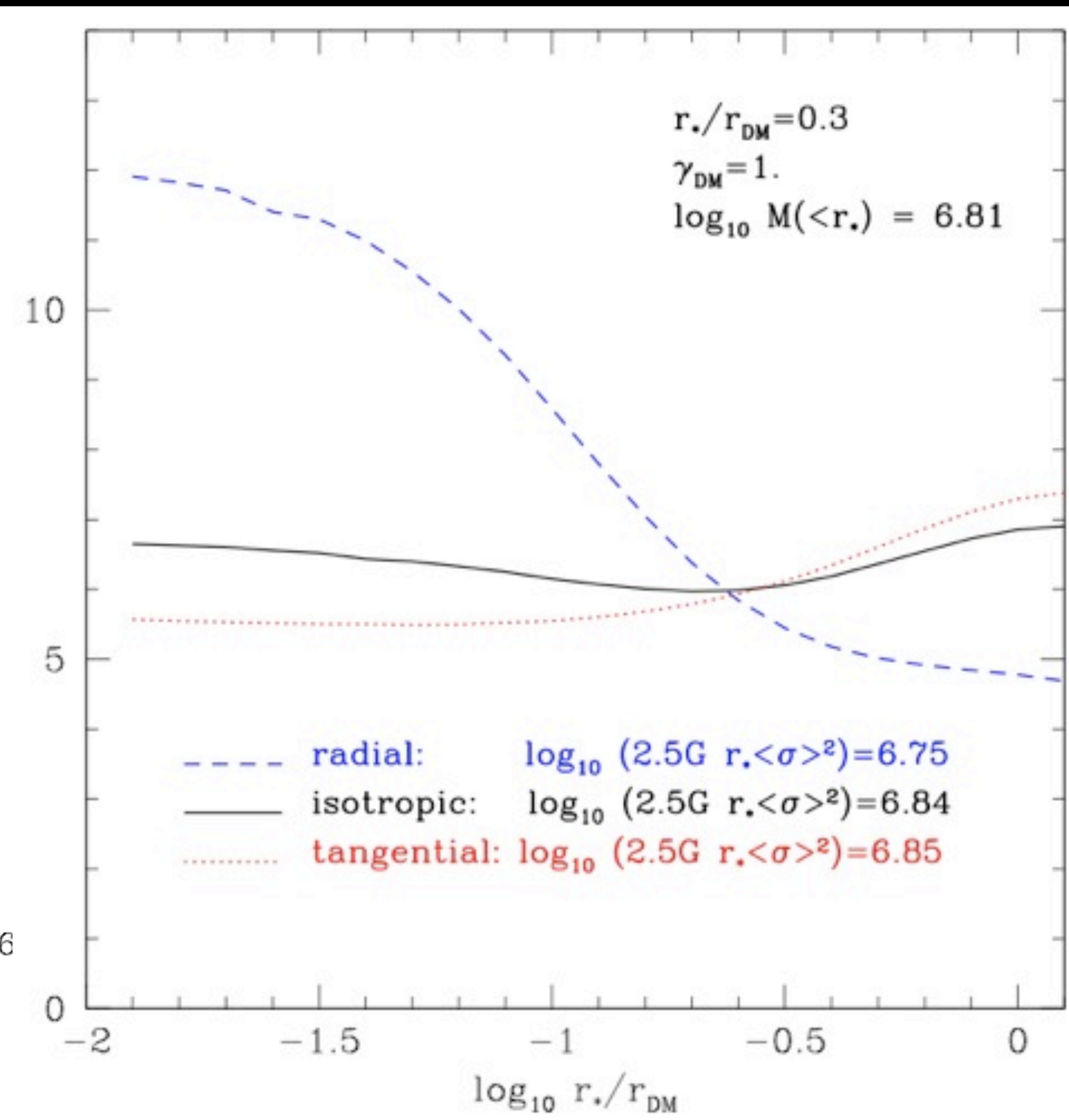




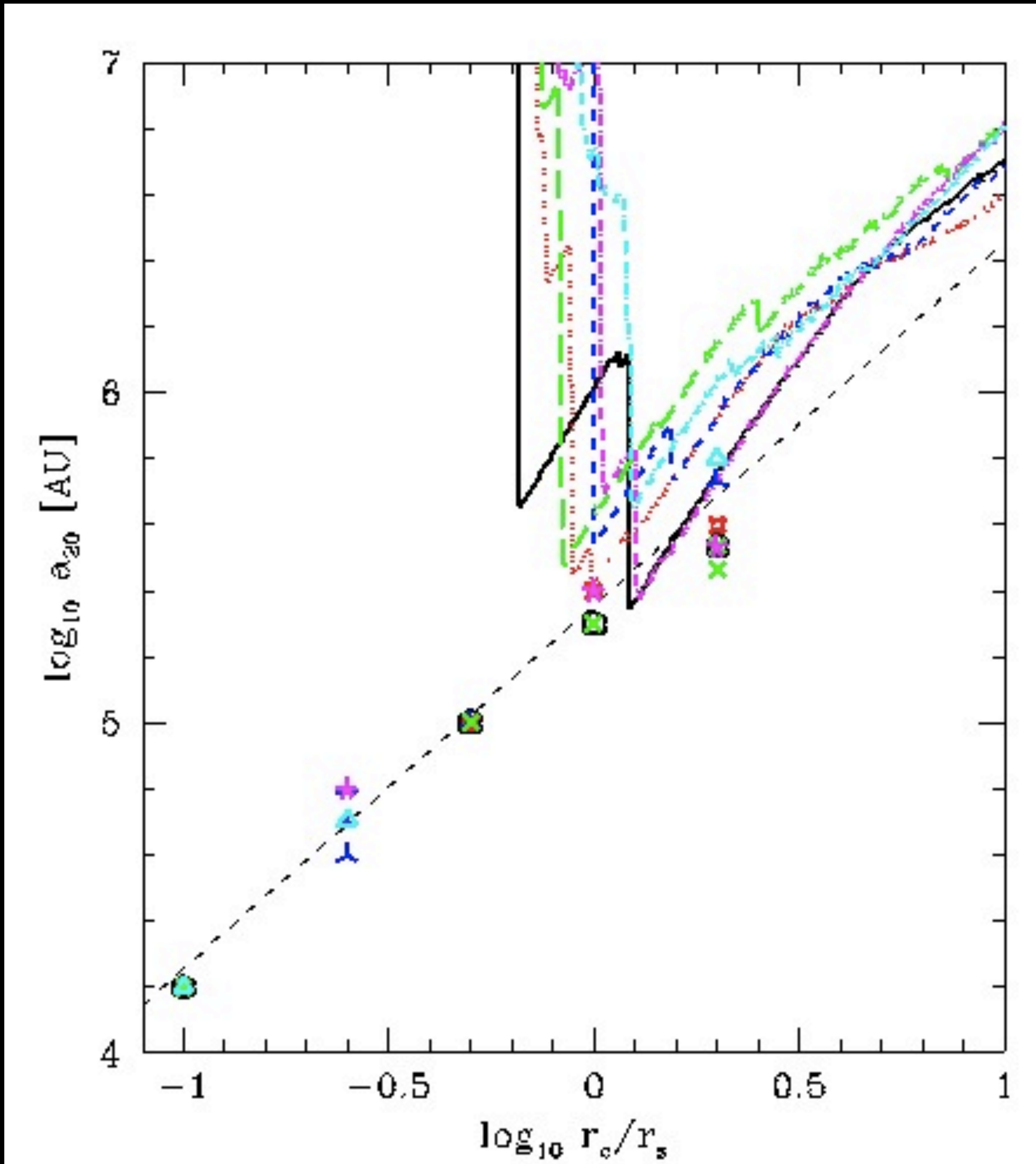
DM halo mass slope **underestimated**

$M(<R_{half})$ over-estimated as $R_{half}/r_{DM} \rightarrow 0$


core
cusp
r*/rDM=0.1
r*/rDM=0.5
r*/rDM=1.0
0.02
0.01
0
−0.01
−0.02
log10 <σv>(β)/<σv>(0)
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
β


r*/rDM=0.3
γDM=1.
log10 M(<r*) = 6.81
radial: log10 (2.5G r*<σ>²)=6.75
isotropic: log10 (2.5G r*<σ>²)=6.84
tangential: log10 (2.5G r*<σ>²)=6.85
10
5
0
−2
−1.5
−1
−0.5
0
log10 r*/rDM

dSph	Distance [kpc]	$r_{\rm half}$ [pc]	$\sigma_\star$ [km s^{-1}]
Segue I	28 ± 2	29 ± 7	4.3 ± 1.2
Ursa Major II	36 ± 5	140 ± 25	6.7 ± 1.4
Bootes II	40 ± 8	51 ± 17	10.5 ± 7.4
Segue II	41 ± 5	34 ± 5	3.4 ± 1.8
Wilman I	43 ± 7	25 ± 6	4.3 ± 1.8
Coma	45 ± 4	77 ± 10	4.6 ± 0.8
Bootes I	64 ± 3	242 ± 21	6.5 ± 2.0
Ursa Minor	67 ± 3	280 ± 15	9.5 ± 1.2
Sculptor	79 ± 4	260 ± 39	9.2 ± 1.1
Draco	81 ± 6	196 ± 12	9.1 ± 1.2
Sextans	88 ± 4	682 ± 117	7.9 ± 1.3
Ursa Major I	100 ± 8	318 ± 45	11.9 ± 3.5
Carina	102 ± 5	241 ± 23	6.6 ± 1.2
Hercules	126 ± 12	330 ± 63	3.7 ± 0.9
Fornax	140 ± 8	668 ± 34	11.7 ± 0.9
Leo IV	160 ± 15	116 ± 30	3.3 ± 1.7
Canis Venatici II	160 ± 5	74 ± 12	4.6 ± 1.0
Leo V	180 ± 15	42 ± 5	2.4 ± 1.9
Leo II	207 ± 12	151 ± 17	6.6 ± 0.7
Canis Venatici I	217 ± 10	564 ± 36	7.6 ± 0.4
Leo I	253 ± 30	246 ± 19	9.2 ± 1.4
Leo T	411 ± 38	178 ± 39	7.5 ± 1.6



7
6
5
4
$\log_{10} a_{20}$ [AU]
−1
−0.5
0
0.5
1
$\log_{10} r_c/r_s$