

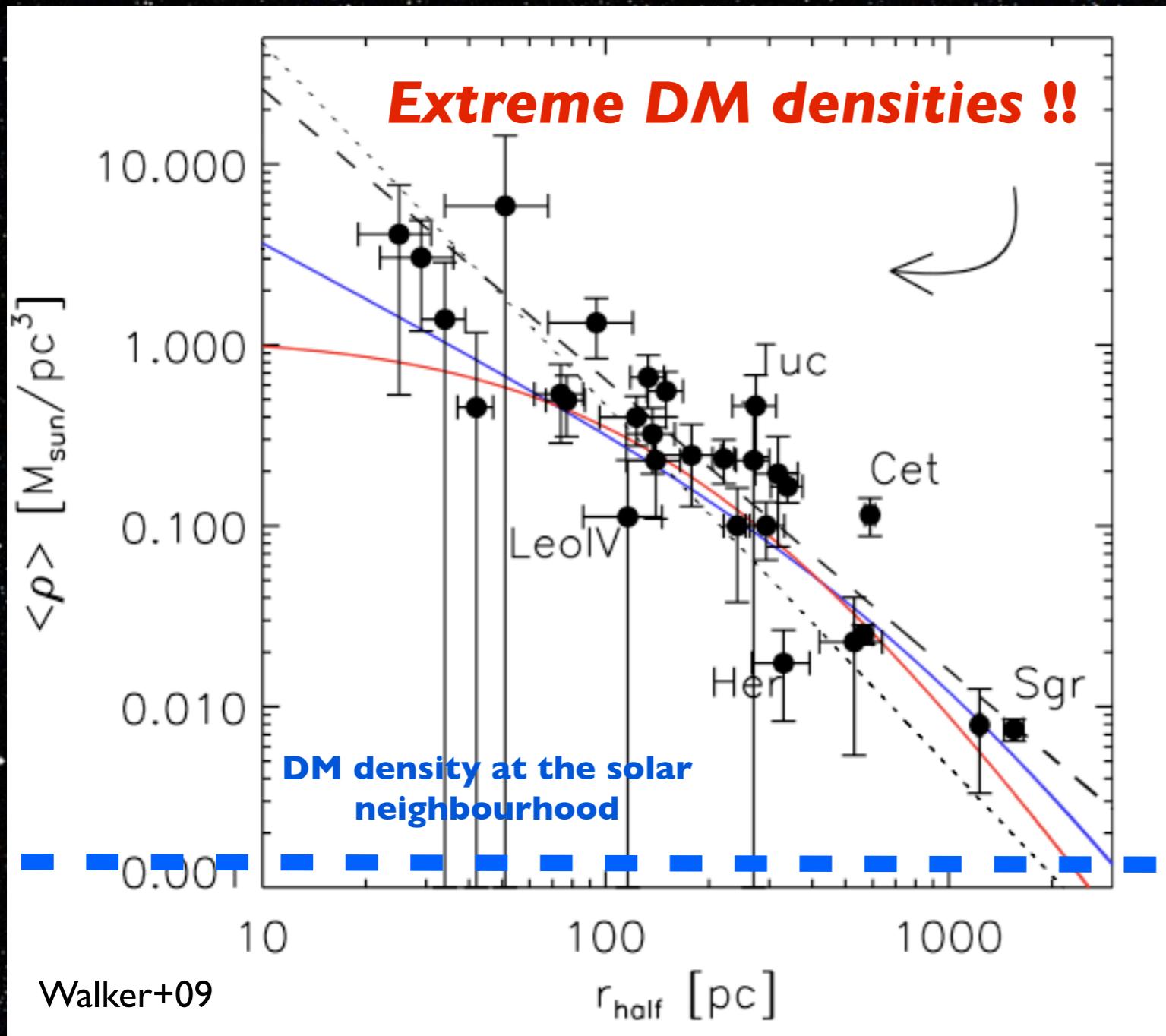
# Dark Matter particle constraints from Dwarf Spheroidals



Jorge Peñarrubia

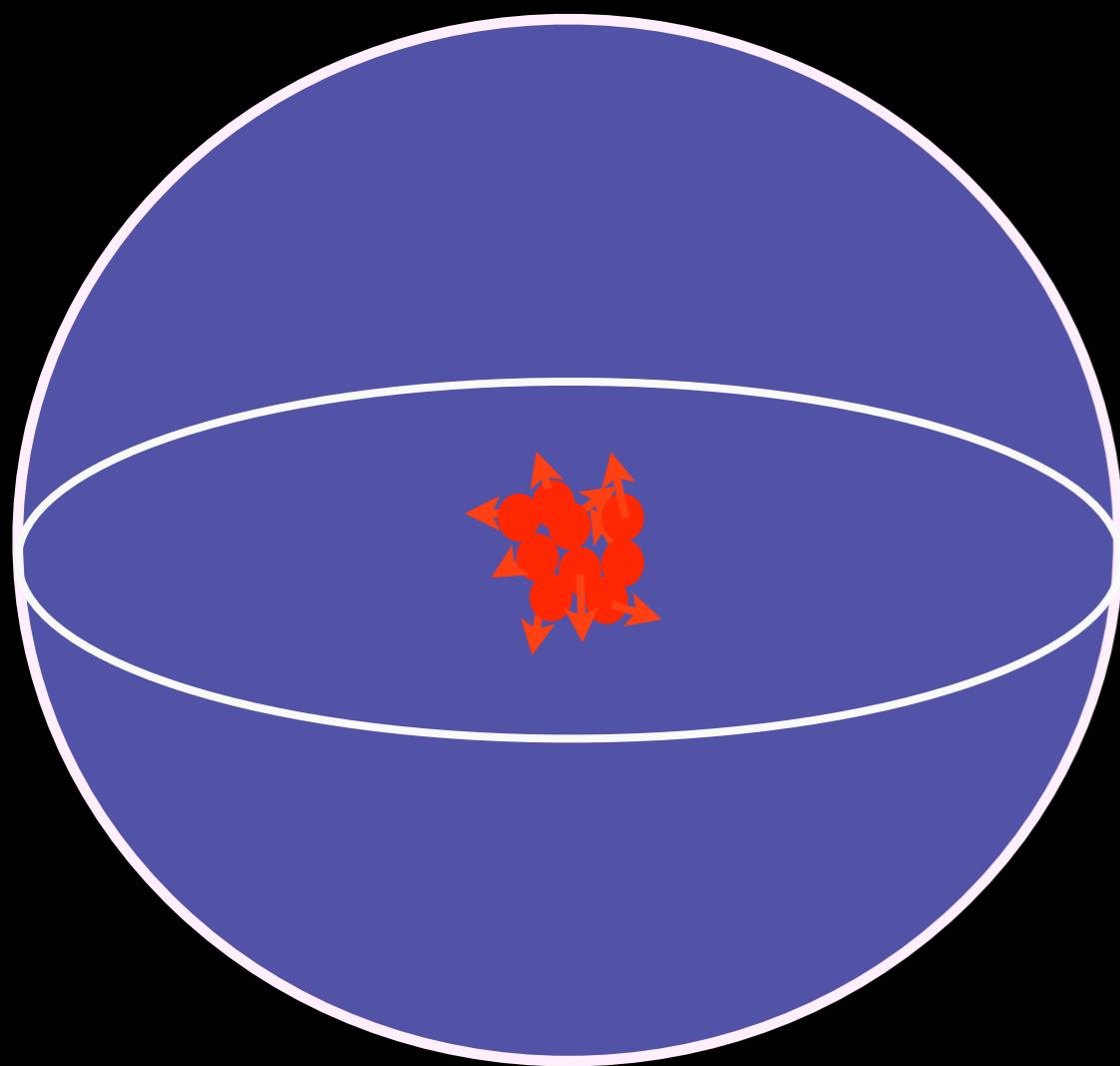
Amsterdam 25 June 2014

# Dwarf Spheroidal (satellite) galaxies



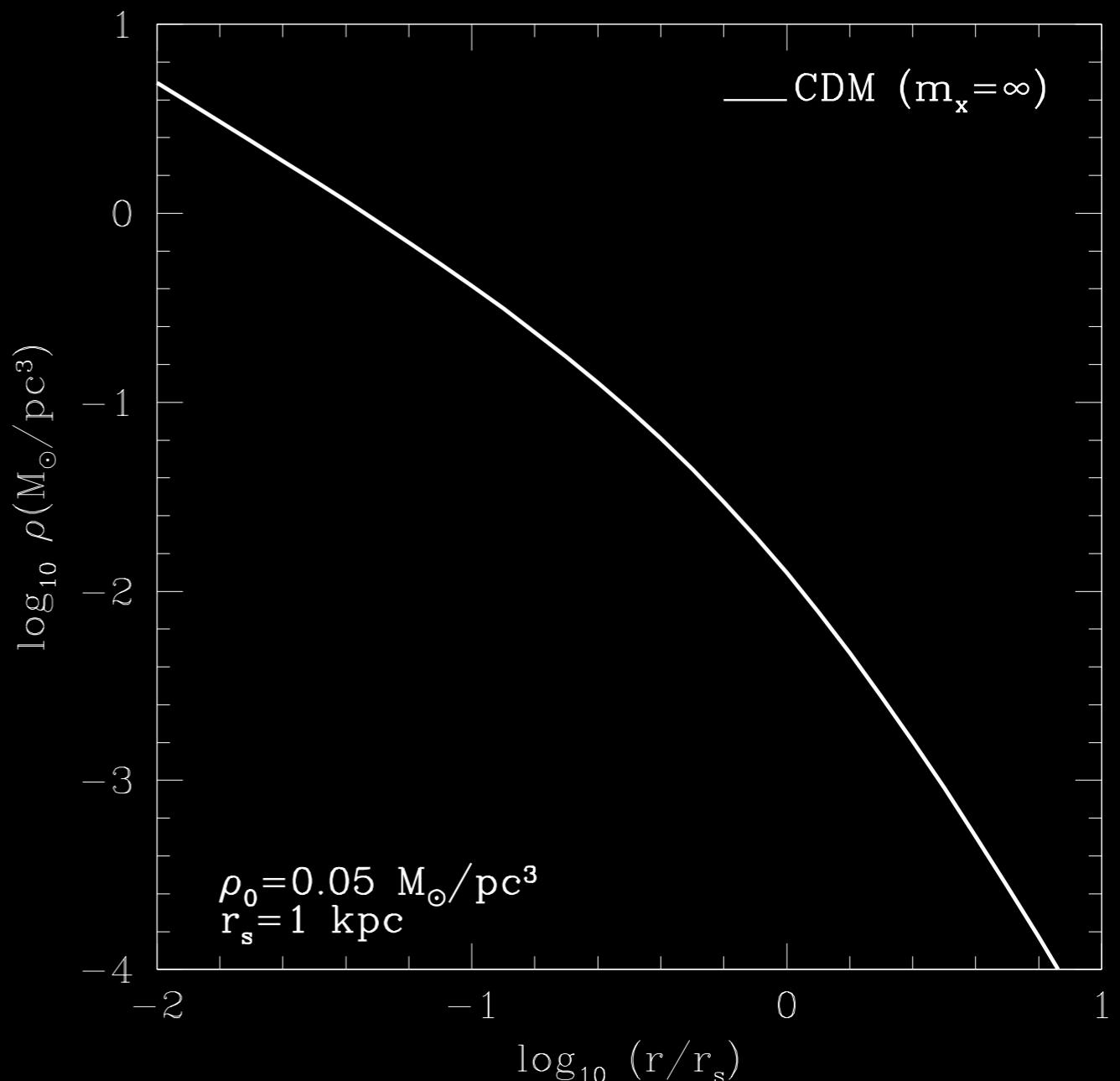
- ★ Faintest galaxies in the known Universe:  
 $10^3 < L/L_{\text{sol}} < 10^7$
- ★ Old, metal poor stellar populations  
 $0.1 < \text{age/Gyr} < 12$
- ★ High mass-to-light ratios:  
 $10 < M/L < 1000$   
(Potential dominated by DM)
- ★ No gas
- ★ No rotation (pressure-supported)

# The inner structure of DM haloes



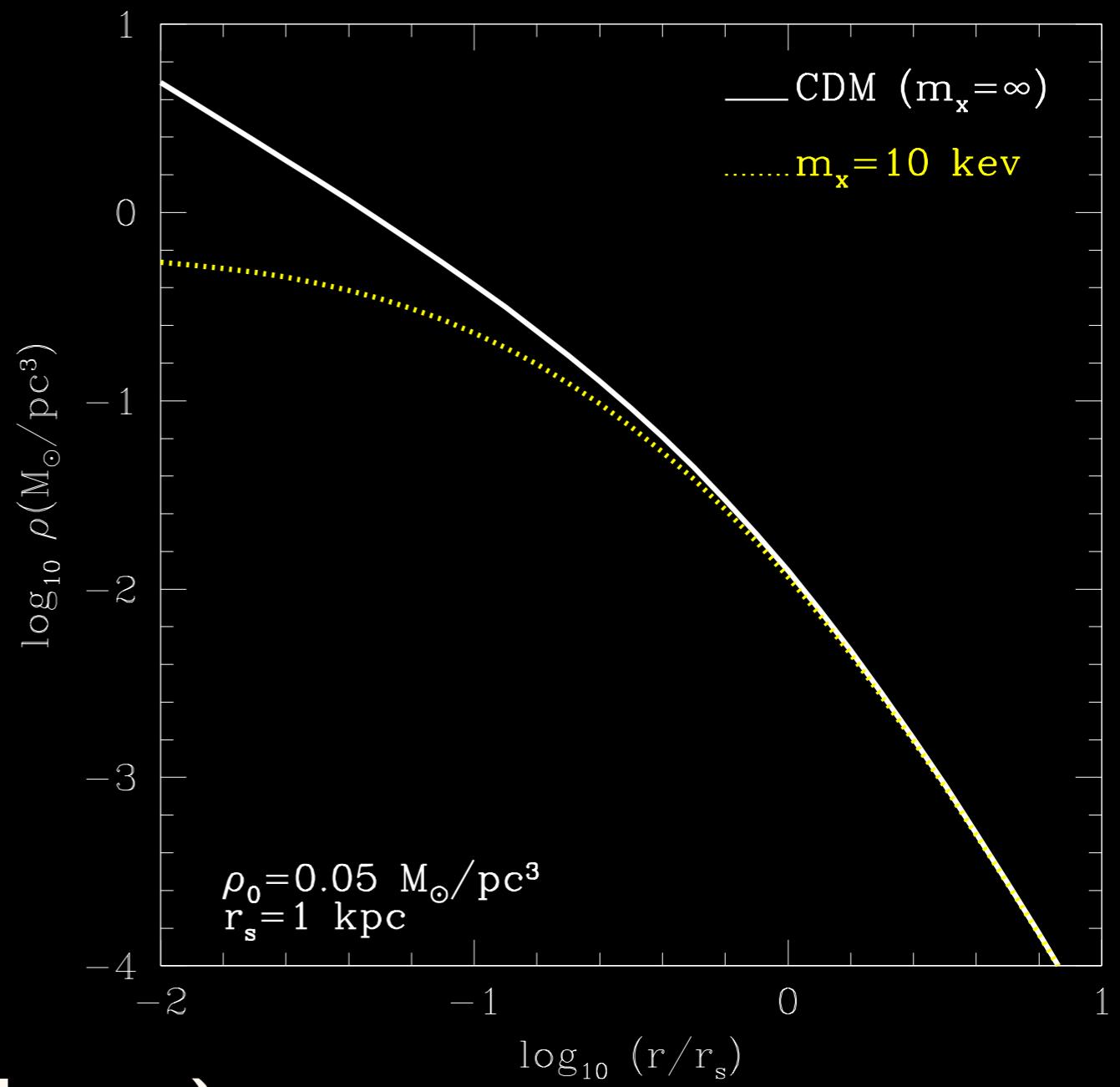
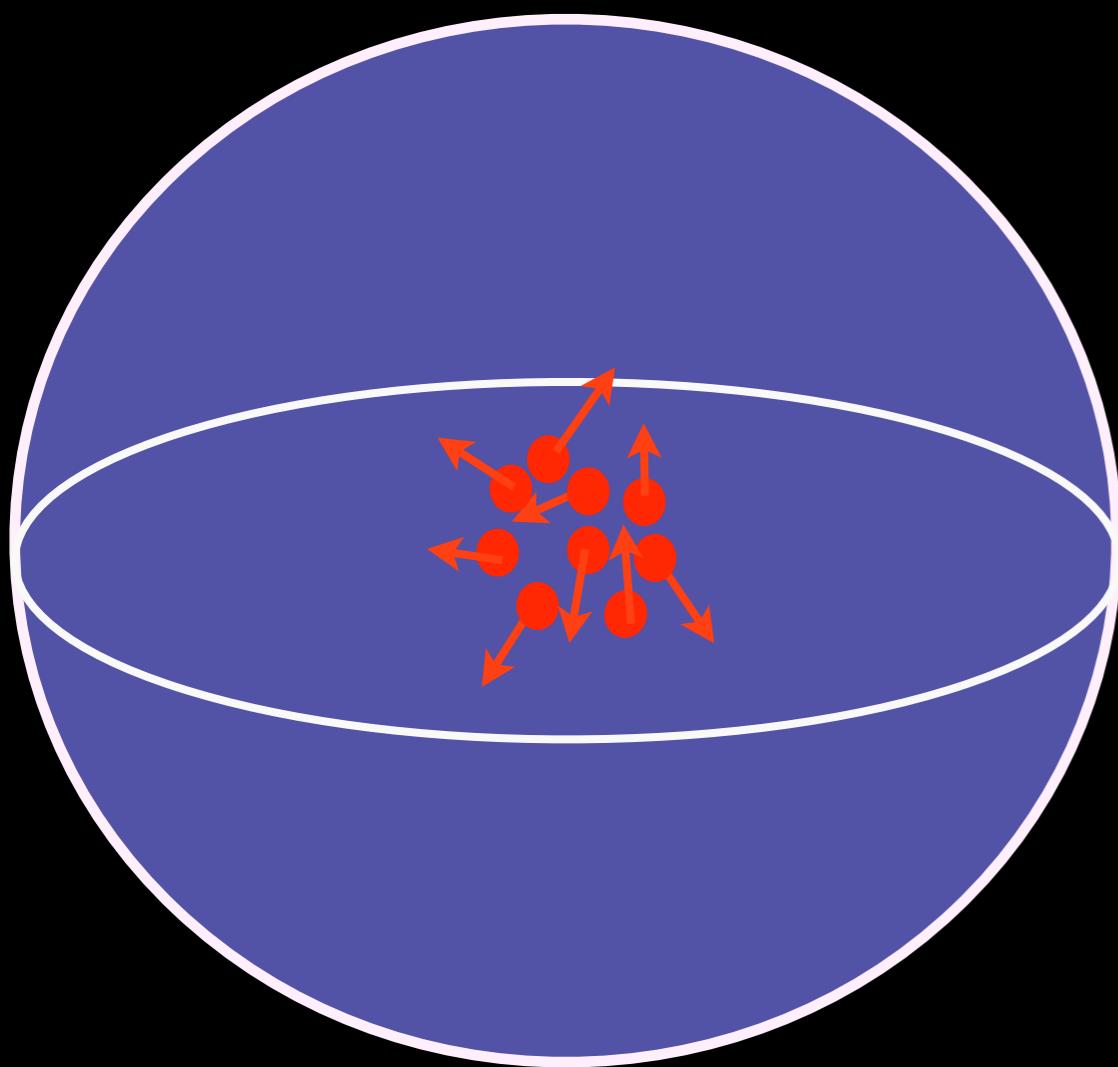
**CDM haloes follow a centrally-divergent density profile**

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



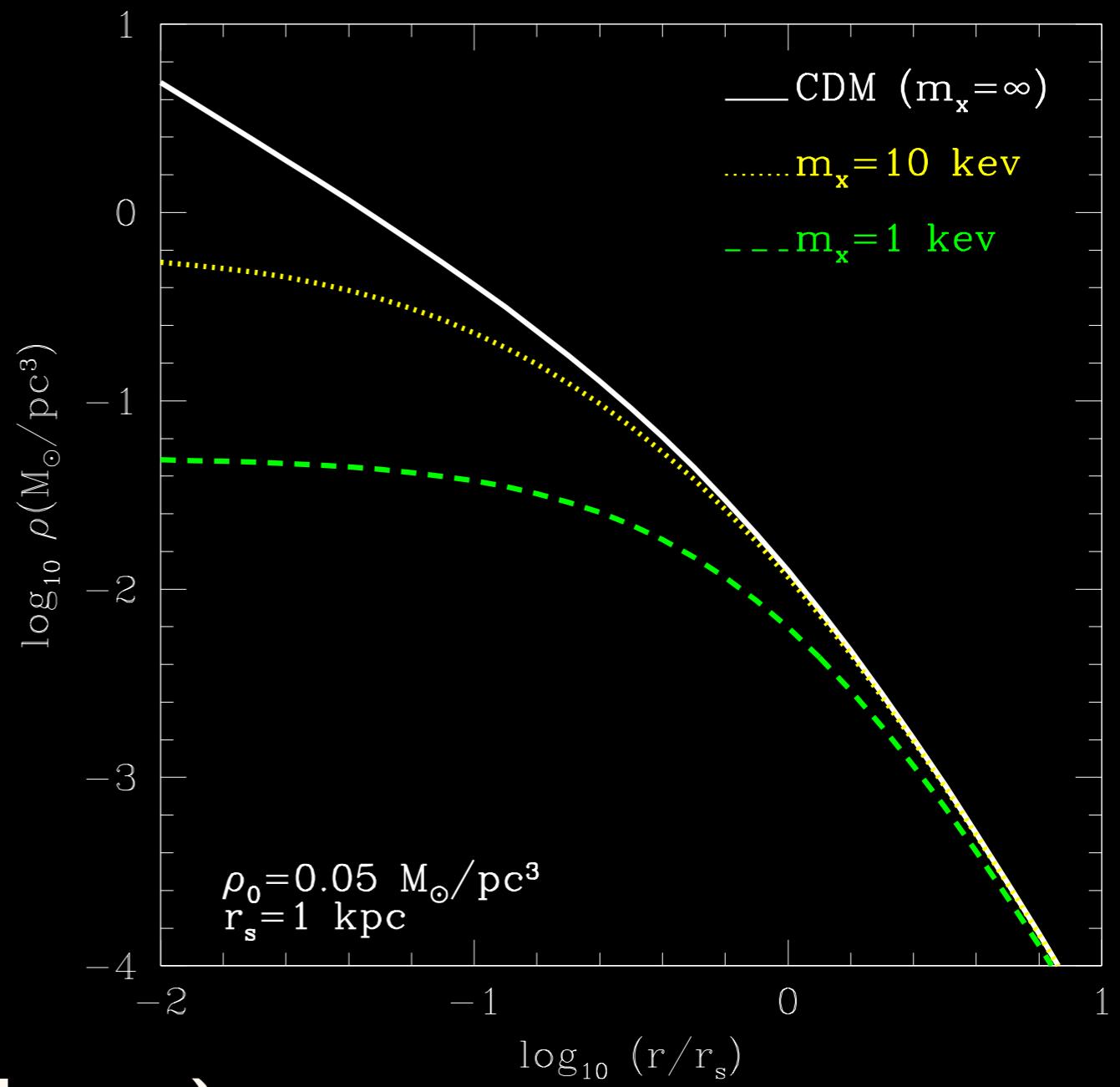
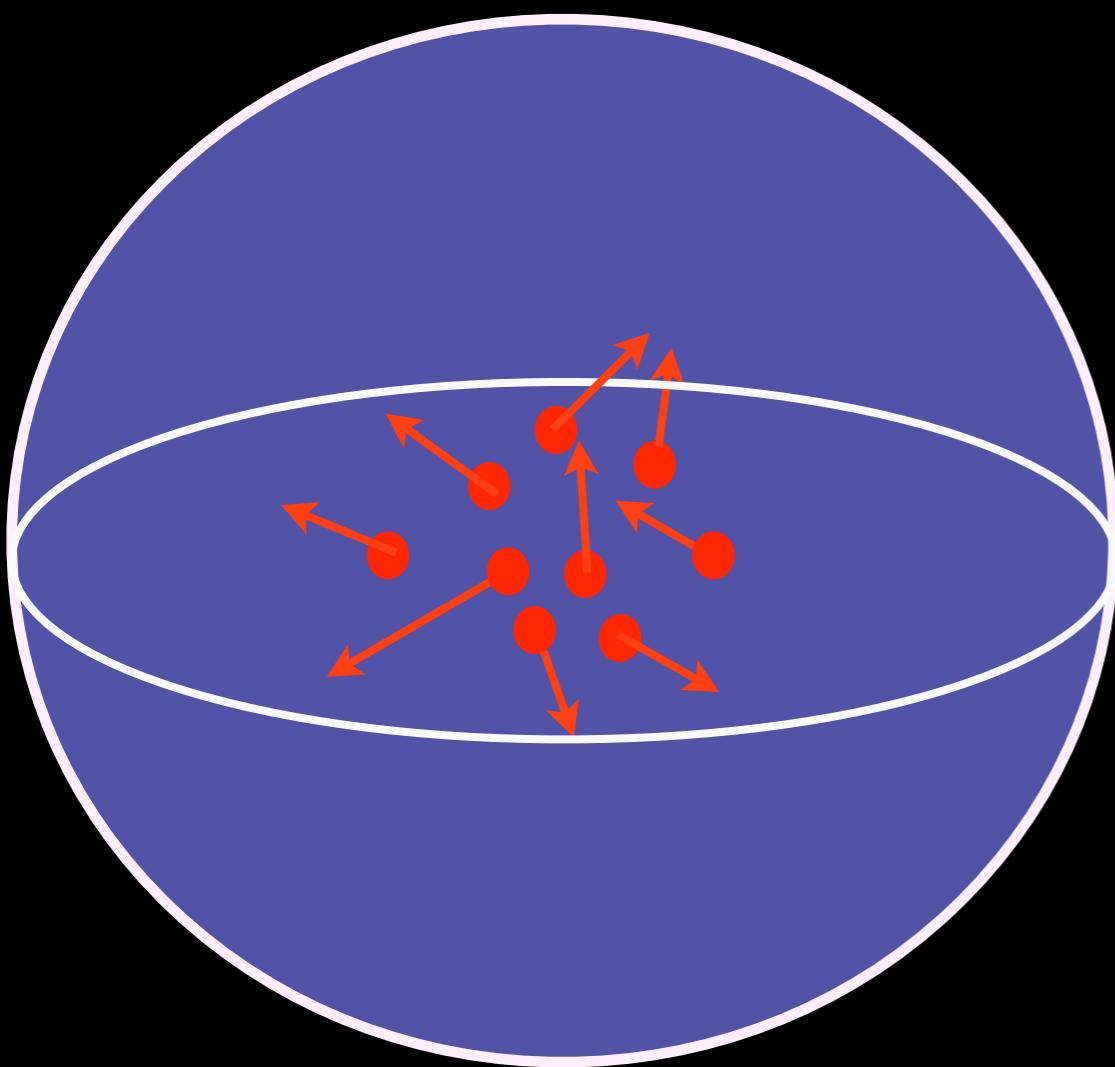
→ “cusp”

# The inner structure of DM haloes



- Relic thermal energy (low particle mass)
  - Quantum effects (e.g Fermionic pressure)
  - Scattering (large cross section)
- “cores”

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# Microscopic DM properties or baryonic feedback?

**Baryons may change  
the inner DM profile:**

\*SNe-driven gas outflows  
(Navarro+1996; Gnedin & Zhao 1992; Read & Gilmore 2005; Governato+2008, 2010, 2012; Pontzen & Governato 2012; Zolotov+12,13 ; Brooks & Zolotov 2014)

\*Orbital decay of dense clusters

(El-Zant+2001; Goerdt+2008; Cole+12)

$$M_* \sim 10^9 L_{\text{sol}}$$

THE FORMATION OF A BULGELESS GALAXY  
WITH A SHALLOW DARK MATTER CORE

Fabio Governato (University of Washington)  
Chris Brook (University of Central Lancashire)  
Lucio Mayer (ETH and University of Zurich)  
and the N-Body Shop

KEY: Blue: gas density map. The brighter regions represent gas that is actively forming stars. The clock shows the time from the Big Bang. The frame is 50,000 light years across.

Simulations were run on Columbia (NASA Advanced Supercomputing Center) and at ARSC

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**Does feedback alter DM distribution on all galactic scales?**

# Feedback limits

**Collective demand (population of satellite galaxies): number, scaling relationships**

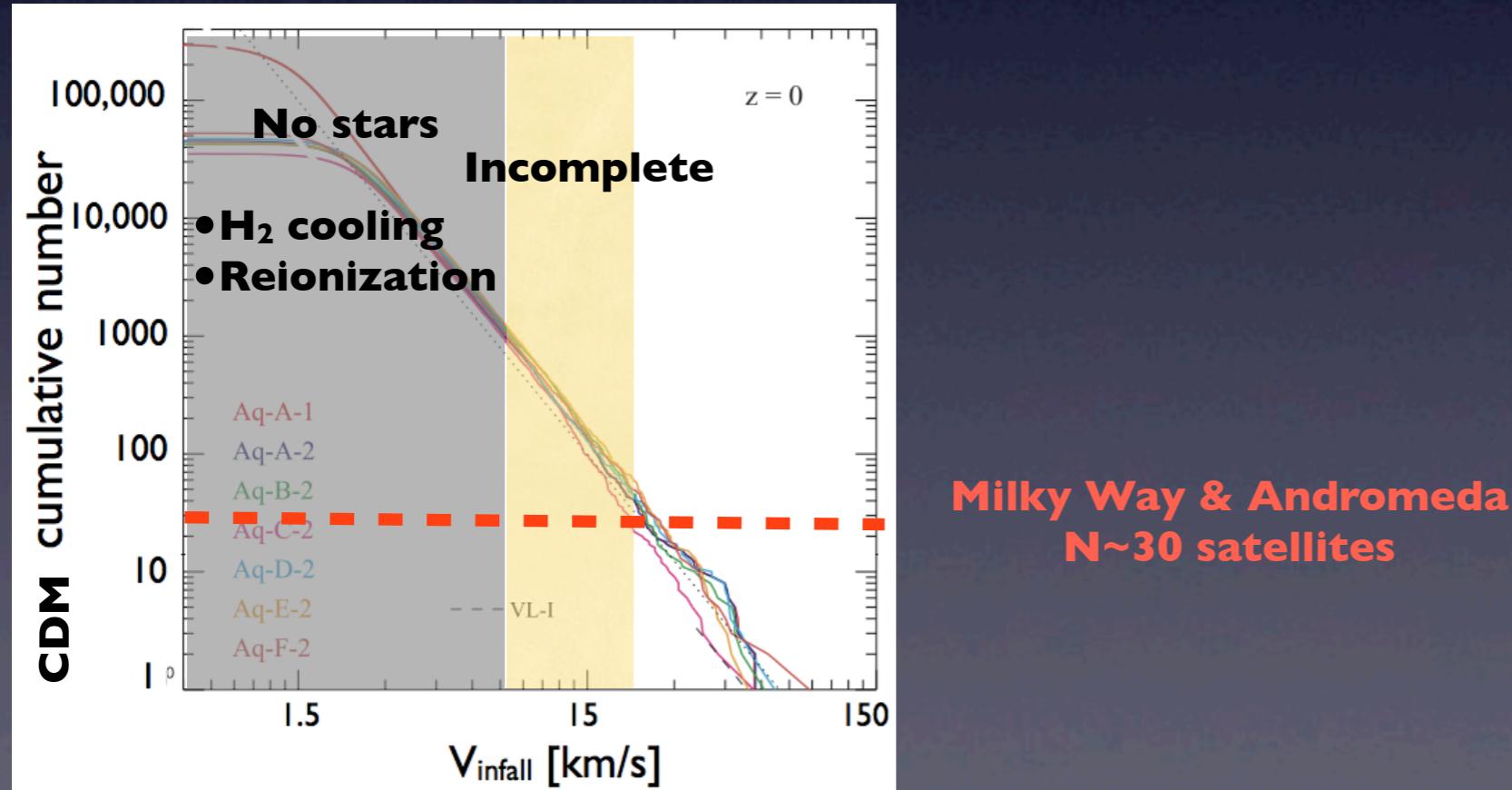


**Suppression star formation**

**Individual demand (cored density profiles): number, scaling relationships**

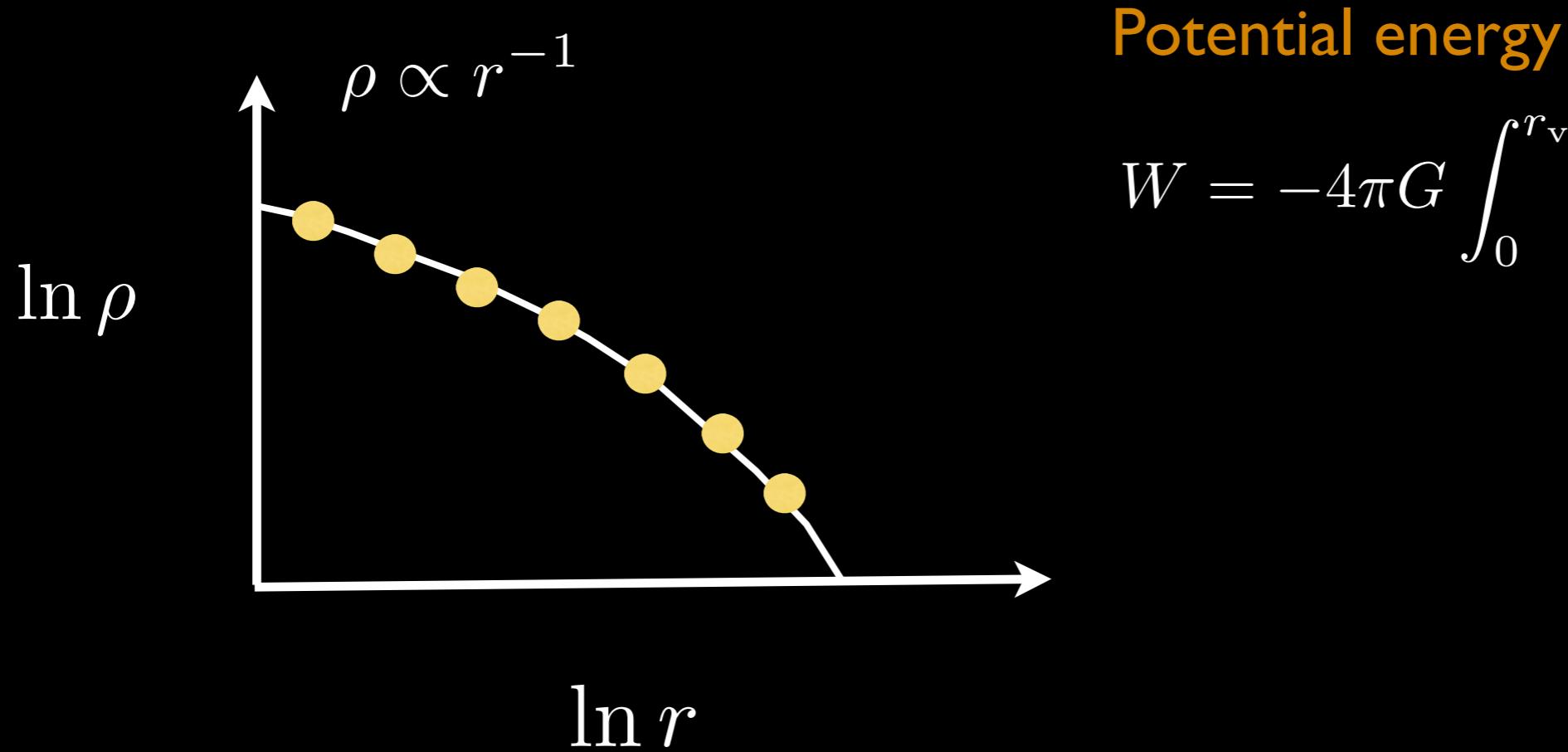


**Efficient star formation**



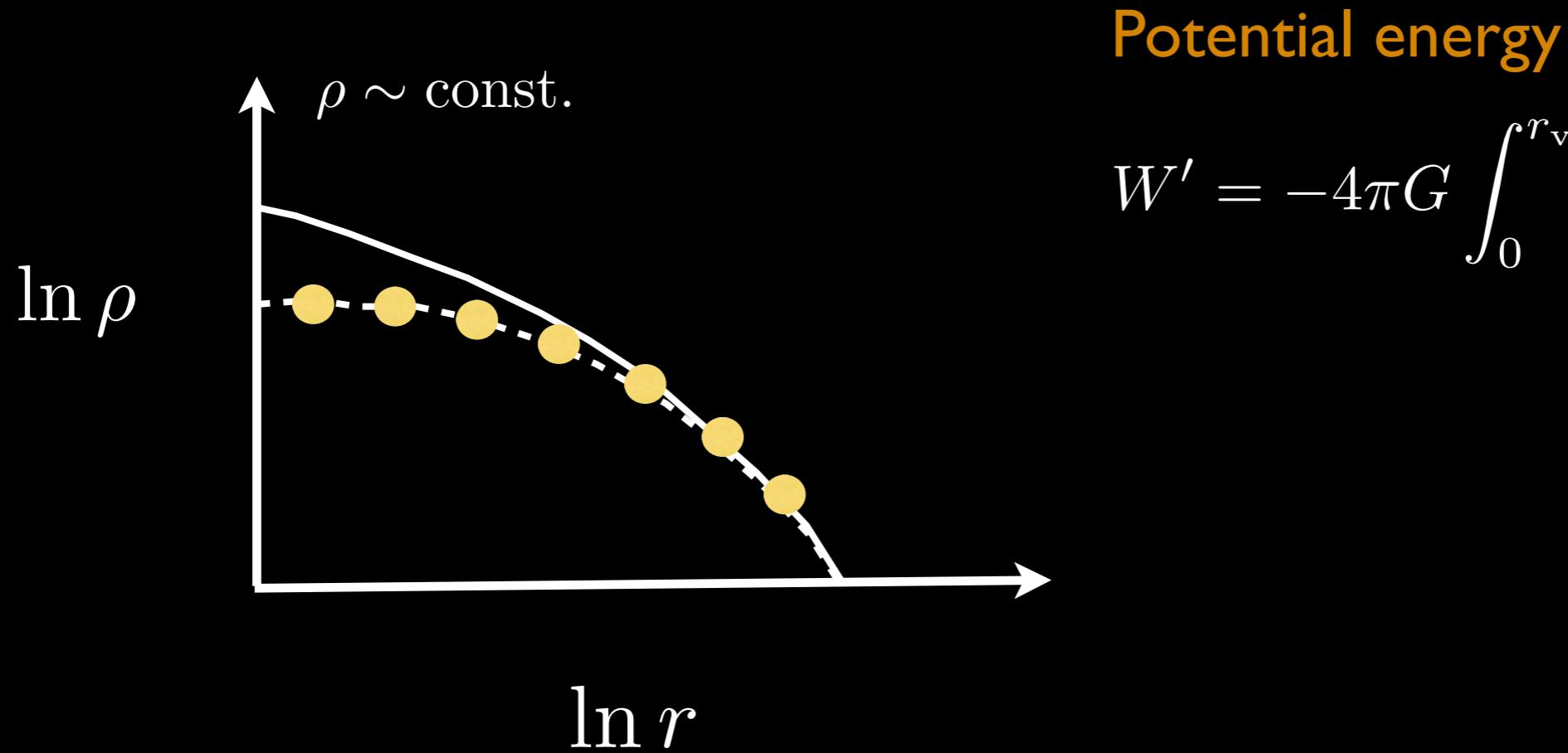
# Energy required to form cores

Peñarrubia, Pontzen, Walker & Koposov (2012)



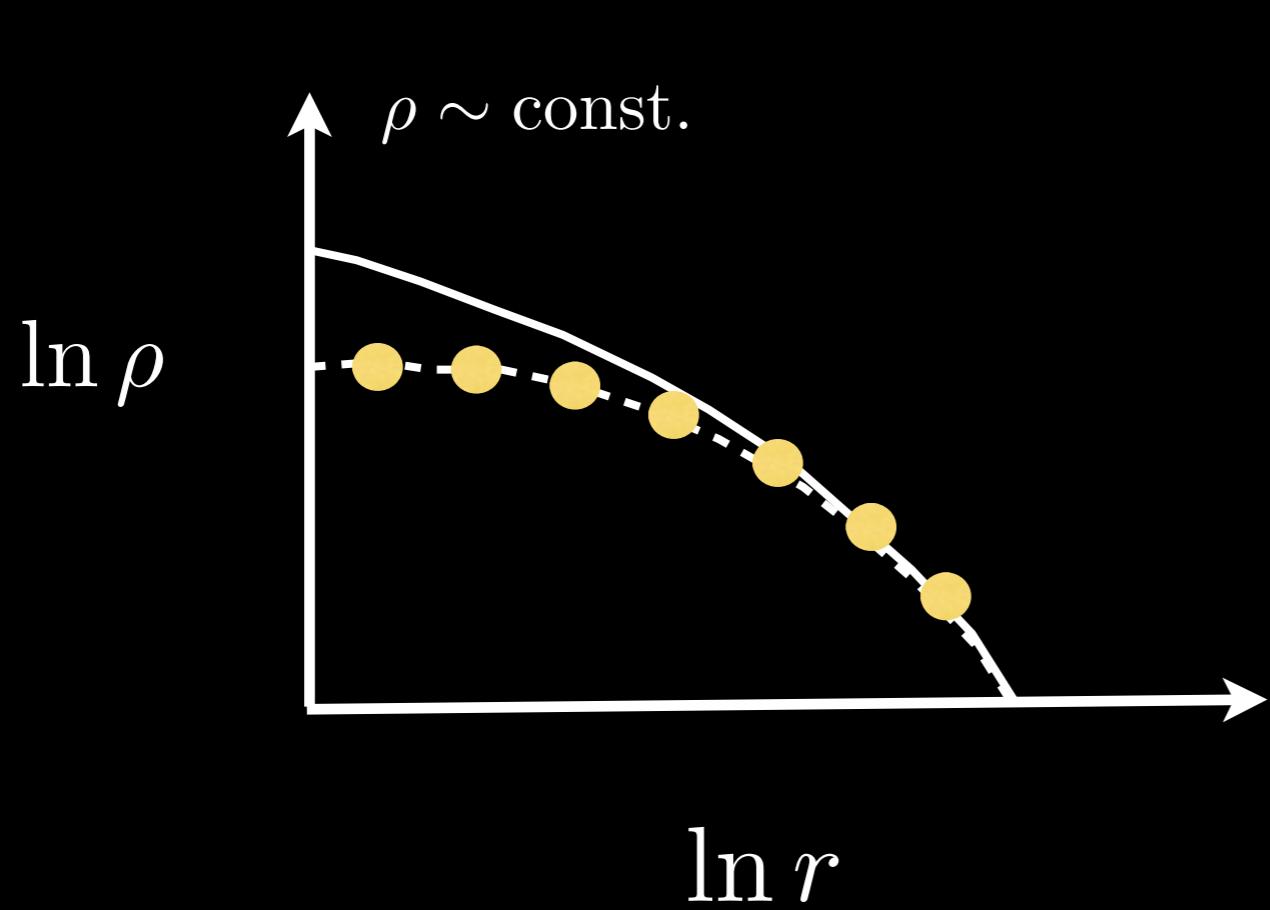
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Potential energy

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

Virial theorem

$$\Delta E = (W' - W)/2$$

how much energy can baryons produce?

# Feedback energy

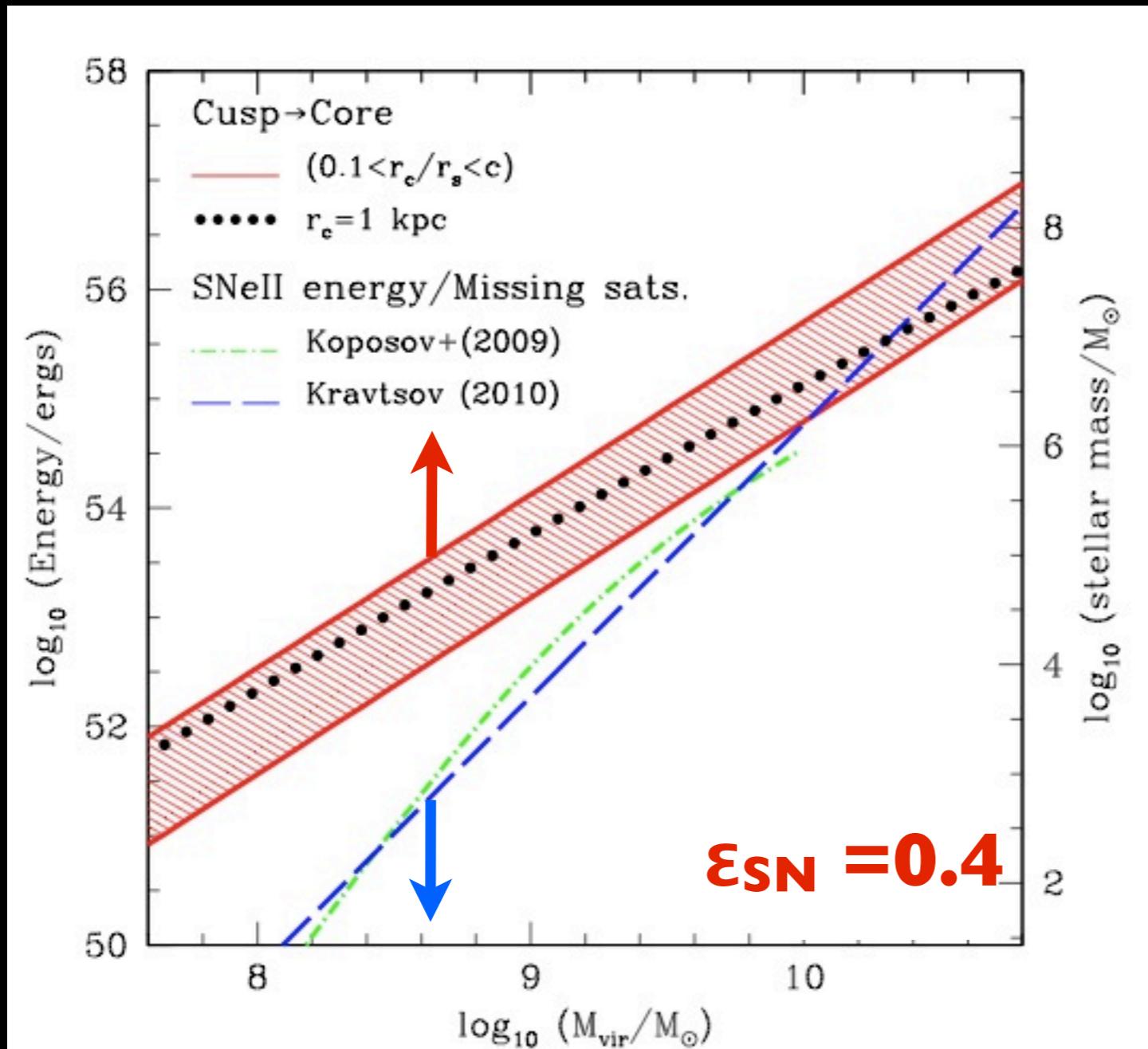
Peñarrubia, Pontzen, Walker & Koposov (2012)

$$E_{\text{fb}} \sim \frac{M_\star}{\langle m_\star \rangle} \xi(m_\star > 8M_\odot) E_{\text{SN}} \epsilon_{\text{SN}};$$

- $\xi = 0.0037$ ,  $\langle m_* \rangle = 0.4 M_{\text{sol}}$  (Kroupa IMF)
- $E_{\text{SN}} = 10^{51}$  erg
  - $\epsilon_{\text{SN}} = 0.01$  (Kellermann 1989)
  - $\epsilon_{\text{SN}} = 0.05$  (Revaz & Jablonka 2012)
  - $\epsilon_{\text{SN}} = 0.40$  (Governato et al. 2010)
  - $\epsilon_{\text{SN}} = 1.00$  (Governato et al. 2012; Zolotov et al. 2012)
- $\epsilon_{\text{SN}}$  ??? 

# Collective vs. individual demands

Peñarrubia, Pontzen, Walker & Koposov (2012)



## Star formation efficiency

$$F_\star \equiv \left( \frac{M_\star}{M_{\text{vir}}} \right) \left( \frac{\Omega_b}{\Omega_m} \right)^{-1}$$

### I - Missing satellites:

$$F_{\star, \text{missing}} \lesssim 10^{-3} \left( \frac{M_{\text{vir}}}{10^{10} M_\odot} \right)^{1/3}$$

(Kravtsov 2010; Tollerud et al. 2008; Koposov et al. 2009)

### 2- Core formation:

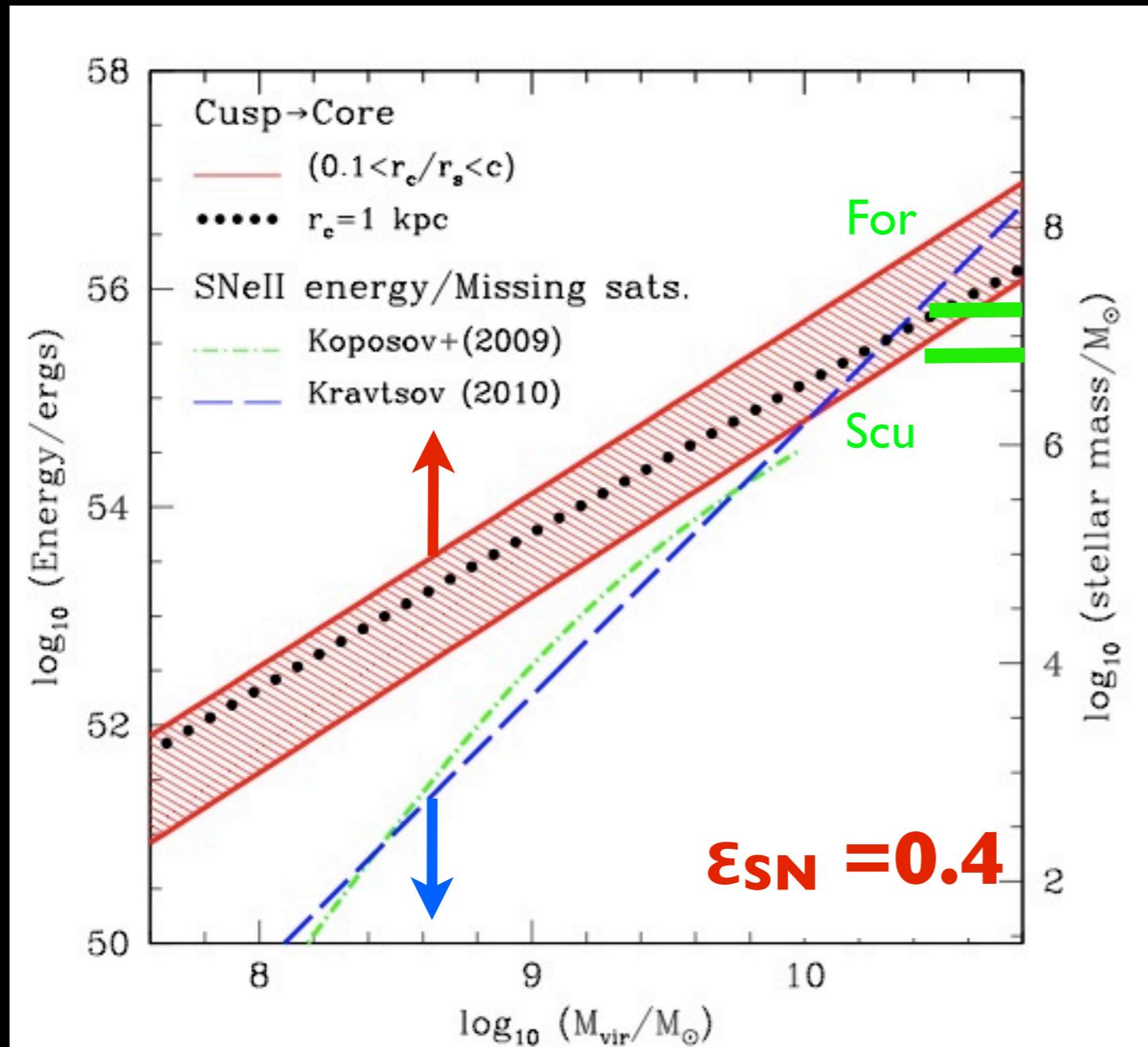
$$F_{\star, \text{core}}(z=0) \gtrsim 10^{-3} \left( \frac{M_{\text{vir}}}{10^{10} M_\odot} \right)^{2/3} \left( \frac{\epsilon_{SN}}{0.4} \right)$$



$$F_{\star, \text{core}}/F_{\star, \text{sat}} \sim (M_{\text{vir}}/10^{10} M_\odot)^{1/3} \lesssim 1$$

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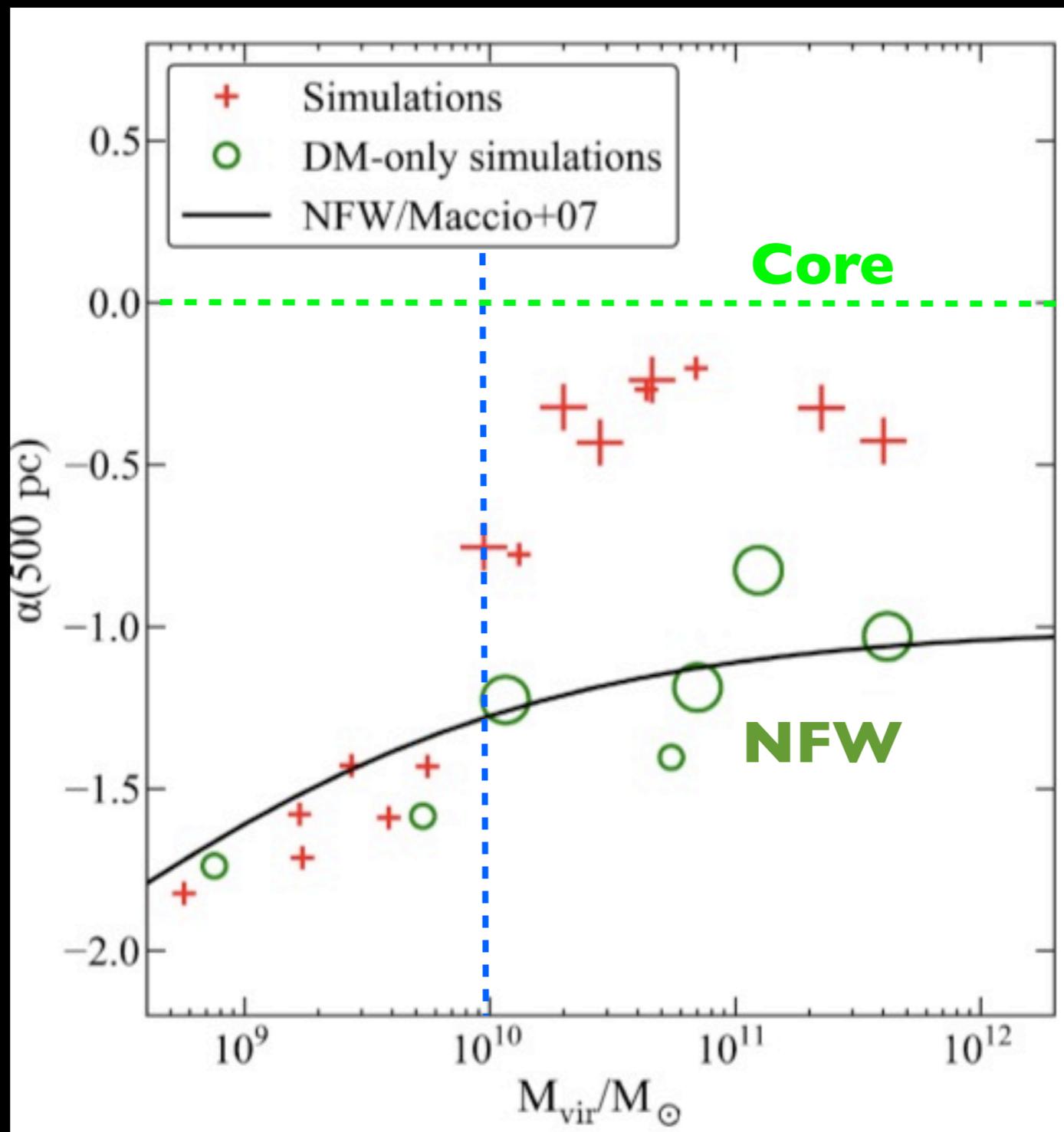
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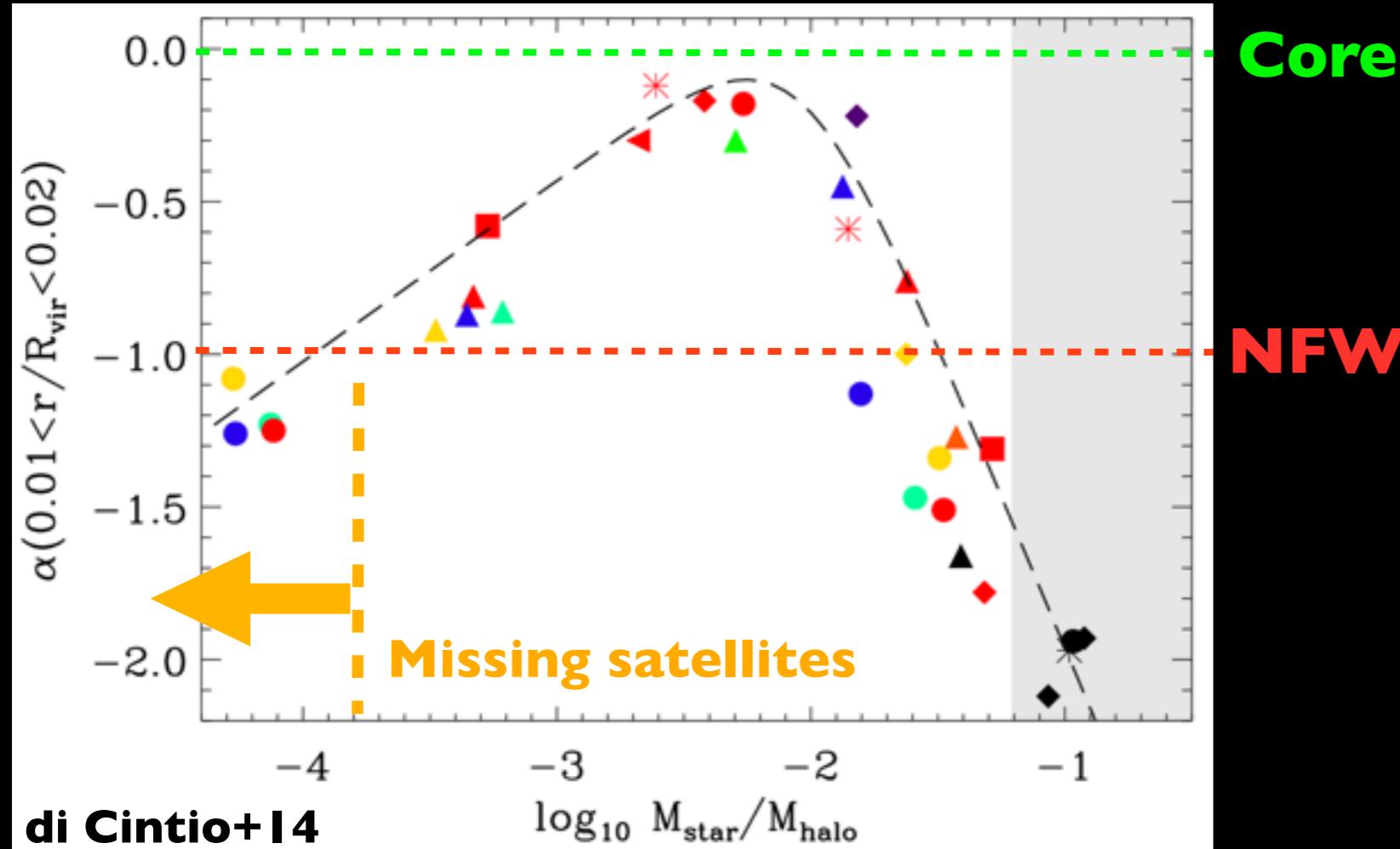
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# Results from hydro-cosmological simulations



Governato+12

# Results from hydro-cosmological simulations



Result independent of  
feedback recipe (symbols)

Satellite number:

$$\frac{M_{\text{star}}}{M_{\text{halo}}} < 10^{-3} \left( \frac{M_{\text{vir}}}{10^{10} M_{\odot}} \right)^{1/3} \left( \frac{\Omega_b}{\Omega_m} \right)$$

Kravtsov 2010; Tollerud et al. 2008;  
Koposov et al. 2009

**DM cusps in dSphs or else  
satellite over-abundance**

# WDM particle mass

## Maximum Phase-space density

Tremaine & Gunn 79; Hogan & Dalcanton 00; Bode+01;  
Boyarsky+09; Maccio+12; Shao+14; Horiuchi+14

$$mc^2 \left( \frac{g}{2} \right)^{1/4} \geq \langle f(\mathbf{r}, \mathbf{v}) \rangle$$

### 1- coarse density

$$Q = \frac{\bar{\rho}(r_h)}{(3\sigma^2)^{3/2}} = \frac{M(r_h)}{3^{1/2} 4\pi r_h^3 \nu_\star^3 \sigma_\star^3}$$

(**No assumptions on DM profile**)

$$M(r_h) \approx \frac{5}{2G} r_h \sigma_\star^2 \quad \text{robust mass estimator} \\ (\text{Walker+09; Wolf+10})$$

$$\nu_\star = \frac{\sigma}{\sigma_\star} \quad \text{unknown!}$$

### 2- isothermal core

$$\rho = \frac{\rho_0}{1 + (r/r_c)^2}$$

$$f_{\text{iso}}^{\max} = \frac{\rho_0}{(2\pi)^{3/2} \sigma^3} = \frac{1}{(2\pi)^{5/2} r_c^2 \nu_\star \sigma_\star}$$

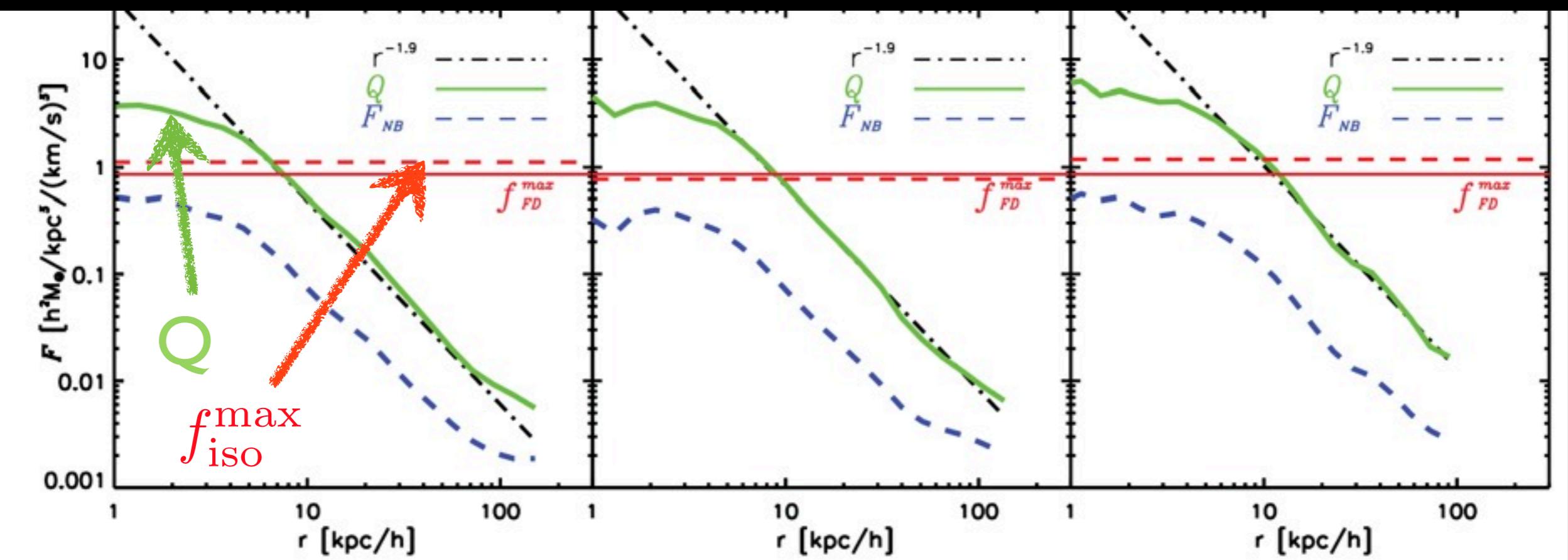
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Shao+14

# Fits

$$f_{\text{iso}}^{\max} = \frac{\rho_0}{(2\pi)^{3/2}\sigma^3} = \frac{1}{(2\pi)^{5/2}r_c^2\nu_\star\sigma_\star}$$

- core size  $r_c$  ?
- halo velocity dispersion ?

## Method:

1. Adopt a **stellar** density profile: (e.g. Plummer)
2. Generate Distribution Function for stars (equilibrium)
3. Fit the observed velocity dispersion and  $r_h$

$$f_\star(E) = \frac{1}{\sqrt{8}\pi^2} \frac{d}{dE} \int \frac{d\rho_\star}{d\Phi} \frac{d\Phi}{\sqrt{\Phi - E}}$$

Isotropic distrib. in spherical potential

# Fits

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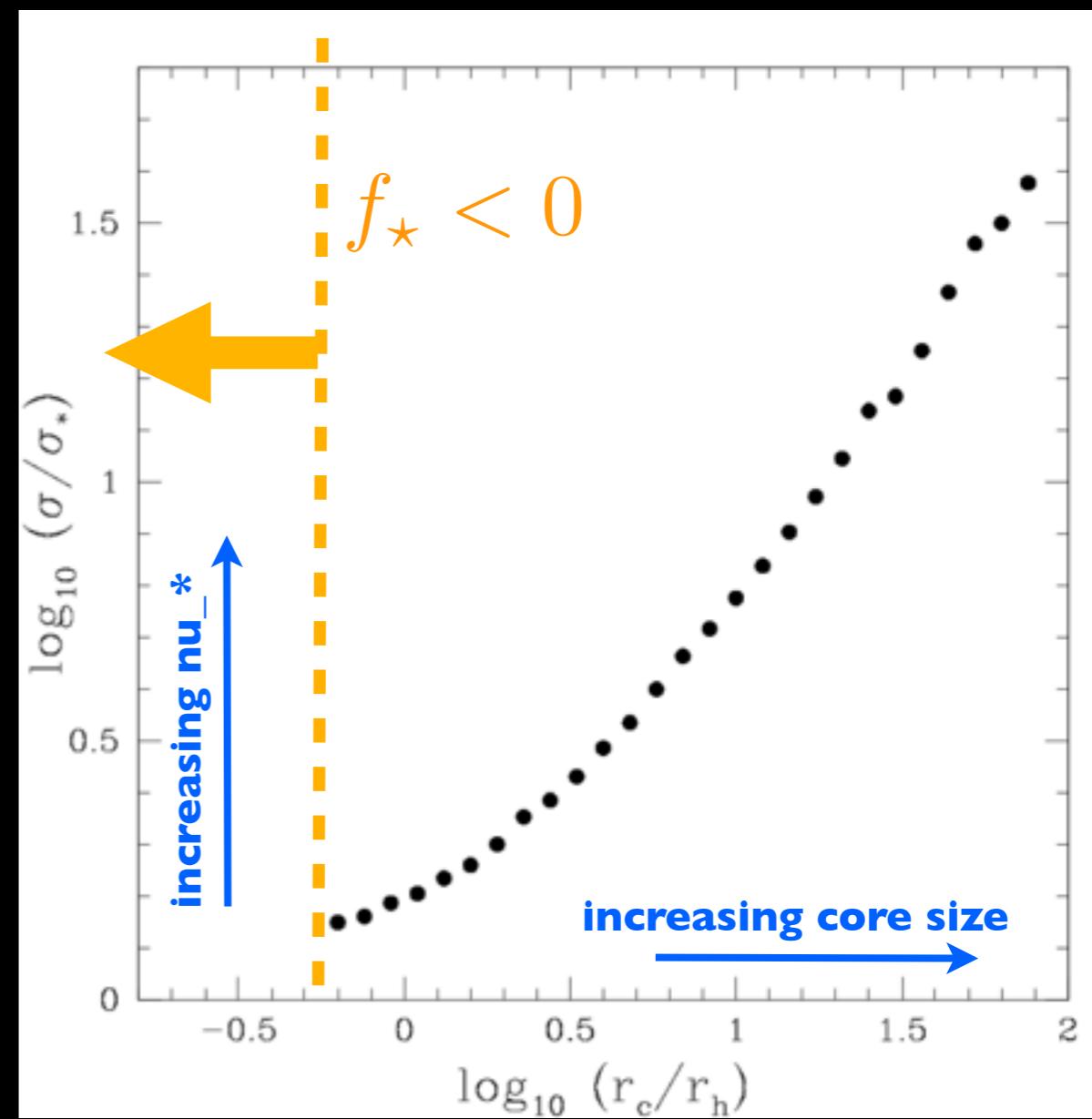
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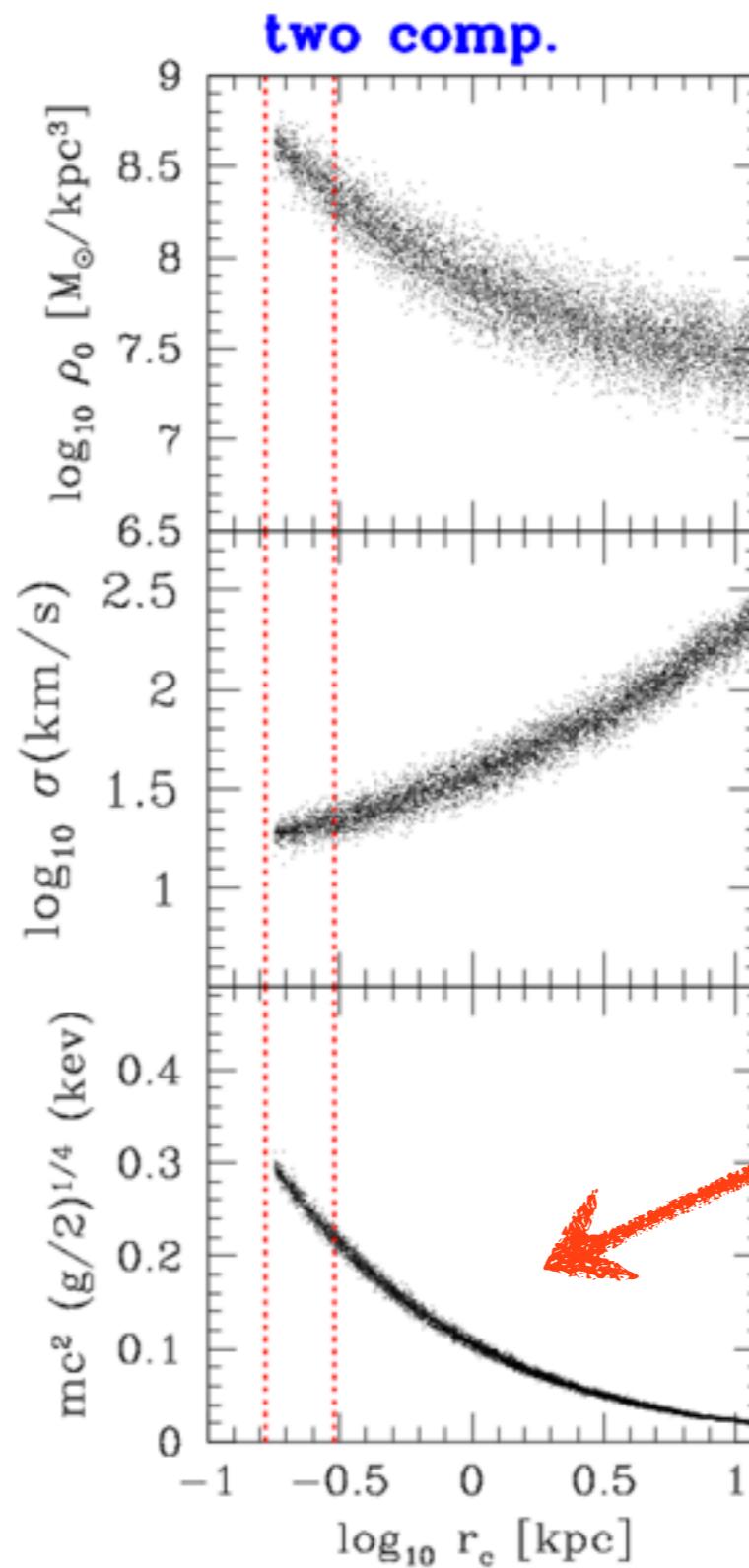
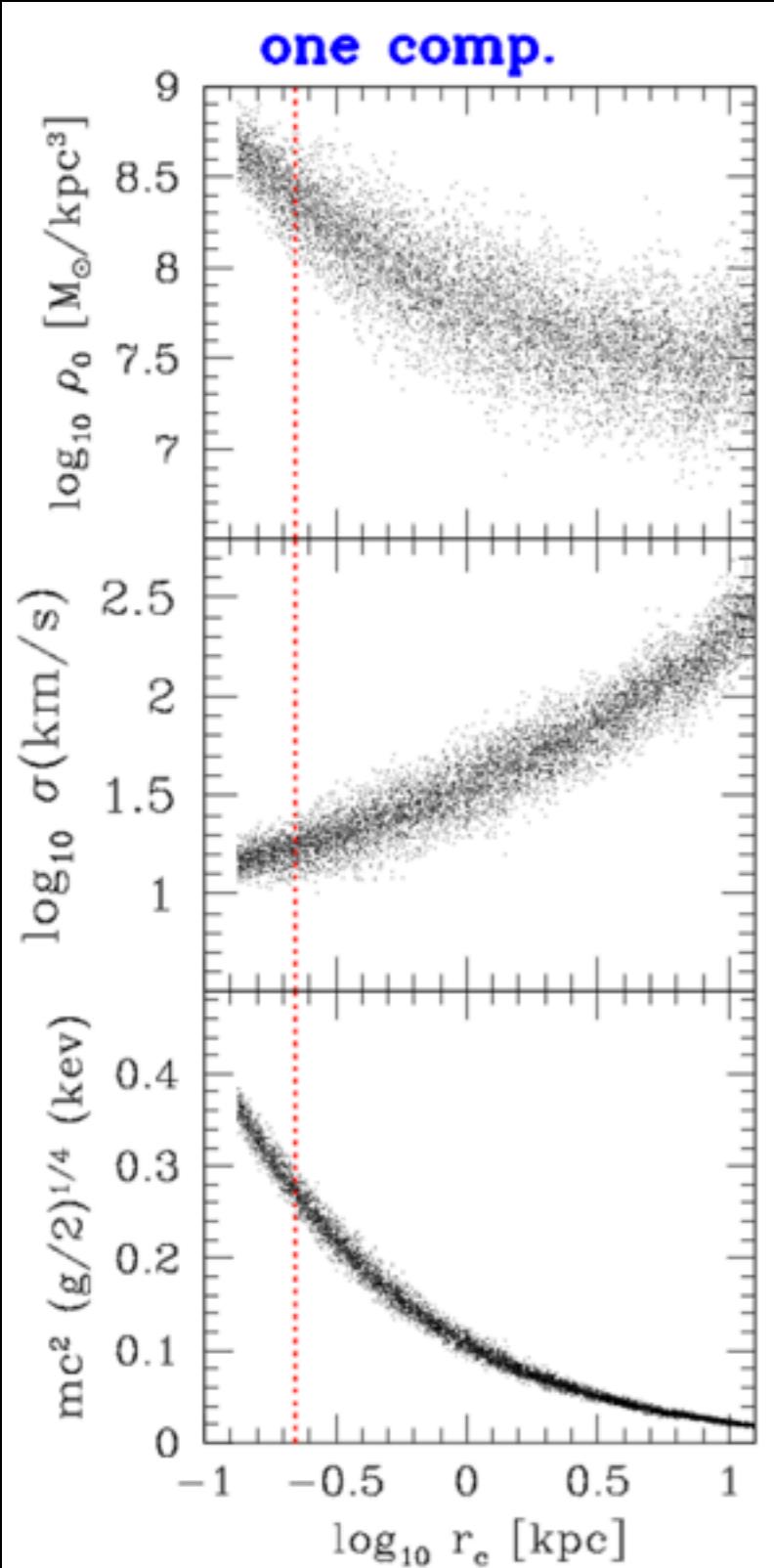
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Isotropic distrib. in spherical potential

dSph mass profile:  
core size arbitrary large



# Results: Sculptor dSph



**Two stellar components**  
(Walker & Peñarrubia 2011)

$$\log_{10}[r_{h,2}/\text{kpc}] = -0.52^{+0.04(+0.09)}_{-0.03(0.06)}$$

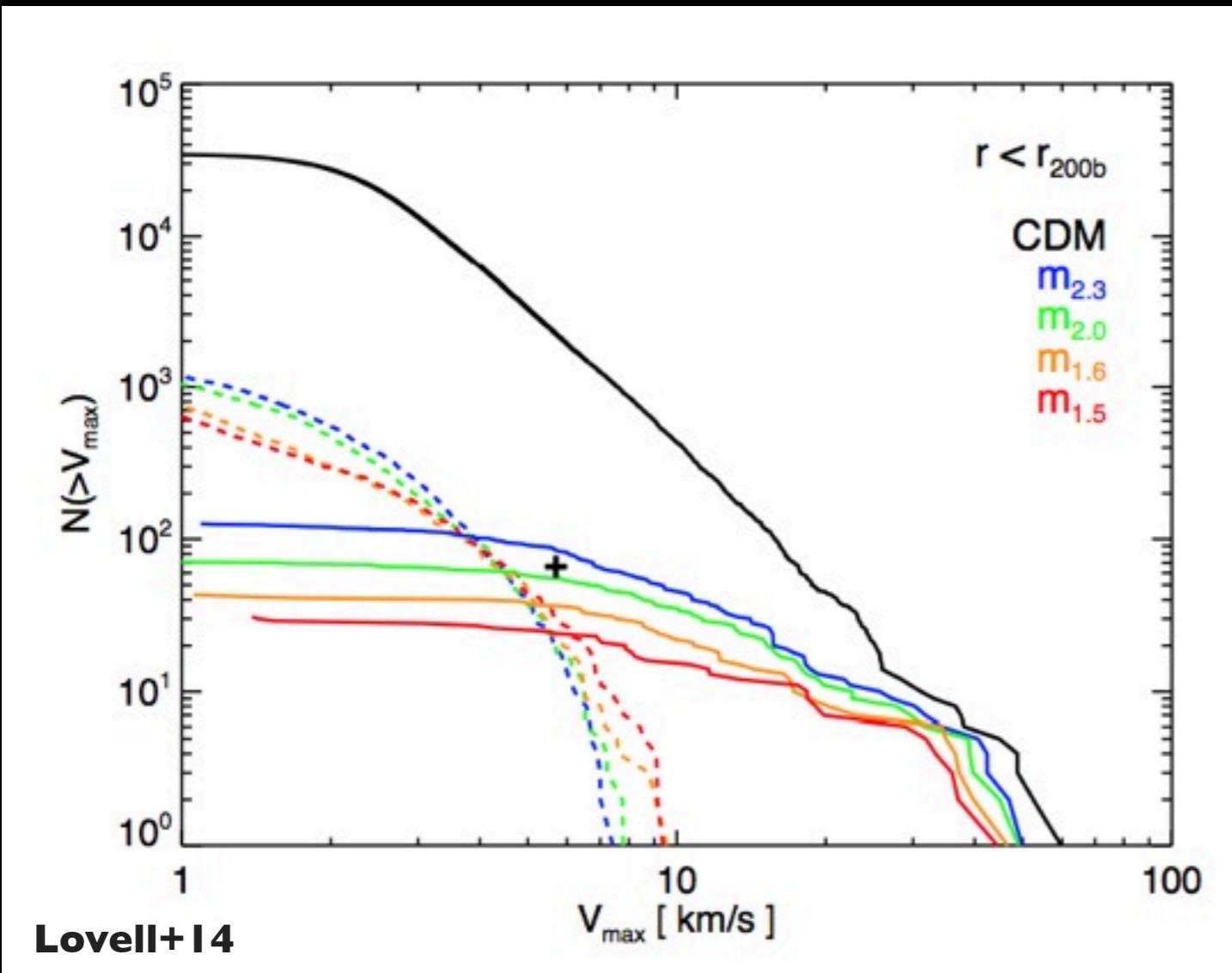
$$\log_{10}[r_{h,2}/r_{h,1}] = 0.55^{+0.06(+0.12)}_{-0.05(+0.10)}$$

$$\log_{10}[\sigma_1/\text{km/s}] = 1.62^{+0.06(+0.11)}_{-0.06(0.13)}$$

$$\log_{10}[\sigma_2/\text{km/s}] = 2.13^{+0.05(+0.10)}_{-0.04(0.08)}$$

**uncertain lower limit on  
particle mass**

# Number of visible structures



Truncation power-spectrum (Viel+05)

$$T^2(k) = \frac{P^{\text{WDM}}}{P^{\text{CDM}}} = [1 + (\alpha k)^{2\nu}]^{-5/\nu}$$

$$\alpha \sim 0.05 \left( \frac{m_\chi}{1\text{kev}} \right)^{-1.11}$$

$$\nu = 1$$

Milky Way ~23 satellites  
Andromeda ~28 satellites



particle mass above 1.5 kev

# Summary

- **CDM:** Effects of feedback limited at dSphs scales by number of visible satellites. DM cusps predicted at  $L \lesssim 10^6 M_{sol}$
- **WDM:** inferred size of DM cores and the number of dSphs cannot be explained simultaneously.  
Lyman-alpha constraints ( $m > 6$  kev; see M. Viel's talk) in tension with phase-space densities ( $m < 0.5$  kev)

# Open questions

## Theory: beyond null hypothesis

Incorporate macroscopic Quantum effects in the interactions between DM particles and baryons

- Relic thermal energy (thermal equilibrium at decoupling?)
- Macroscopic Quantum effects (e.g Fermionic pressure)
- Scattering (elastic/inelastic? solid ball models? Yukawa interactions?)

$$\frac{\text{N-body particle mass}}{\text{DM particle mass}} > 10^4 M_{\text{sol}}/\text{kev} \sim 10^{66} !!$$

## Observations:

Current constraints: Fornax & Sculptor  $M_* \sim 10^7 M_{\text{sol}}$

Signatures multiple components: Draco, UMi, Sextans & Leo II  $M_* \sim 10^5 M_{\text{sol}}$