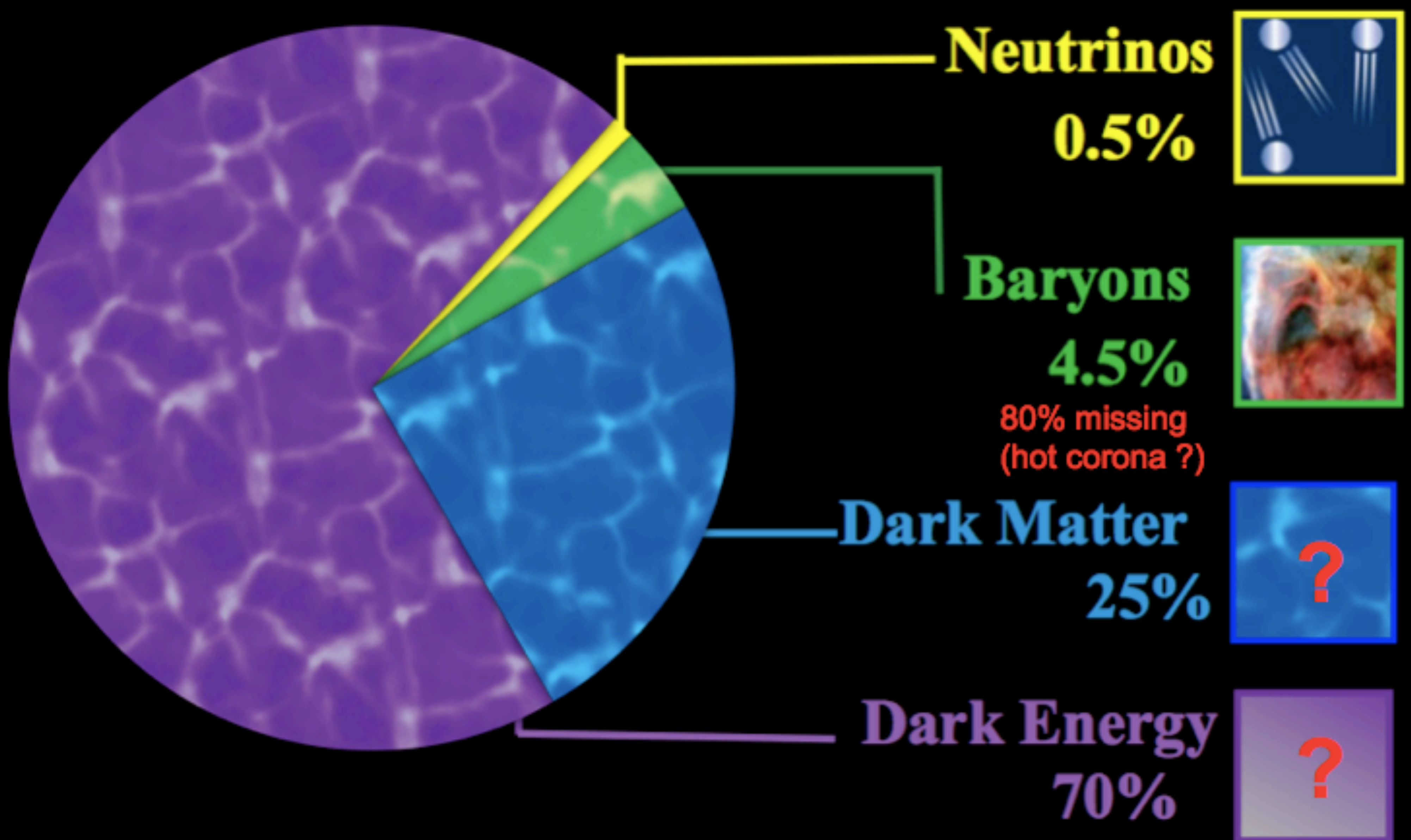
Mass modelling of dwarf spheroidals

Jorge Peñarrubia

Santiago de Chile 13
April 2015

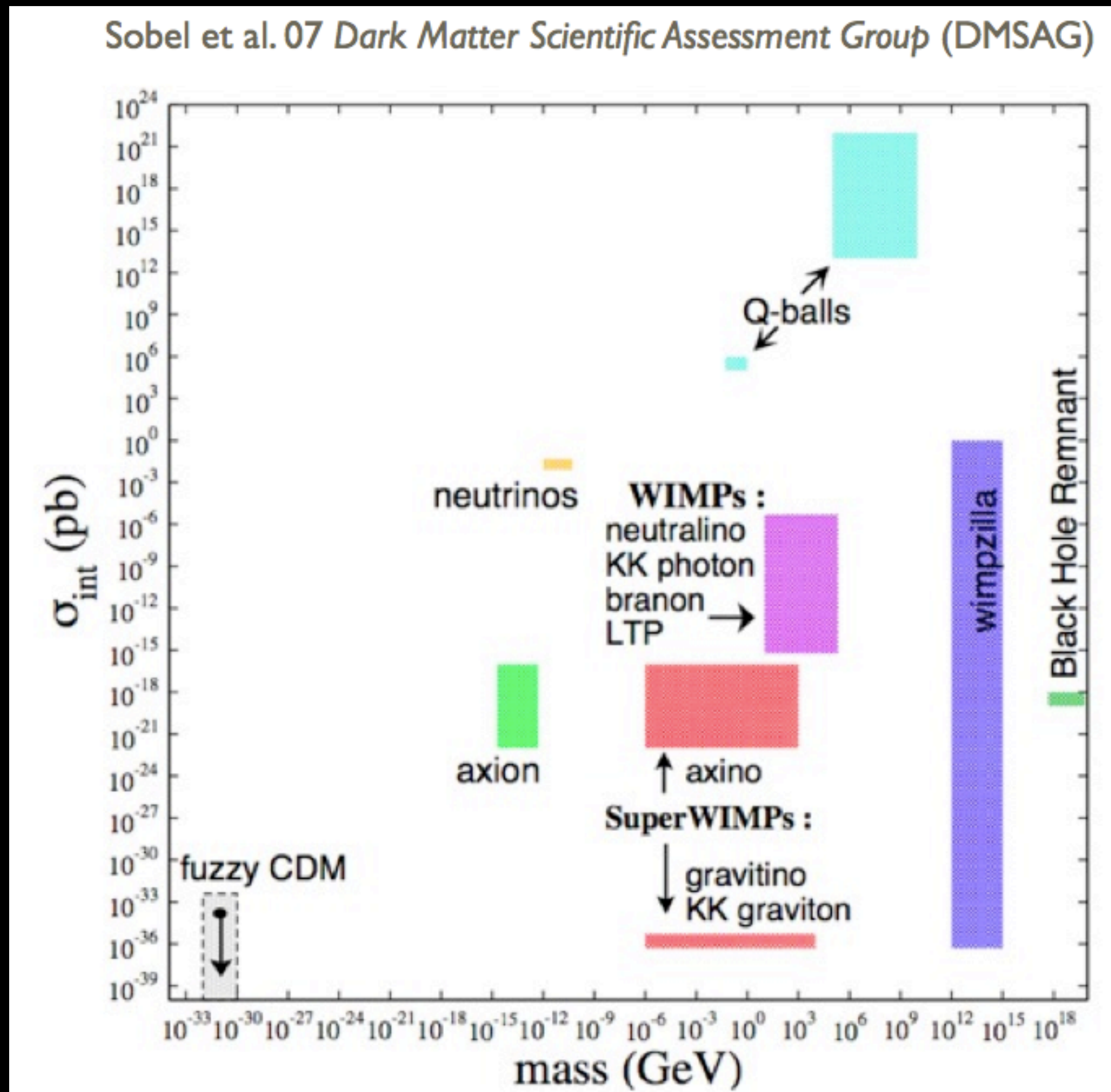
Universe Composition

Assumption: GR is correct



WMAP7

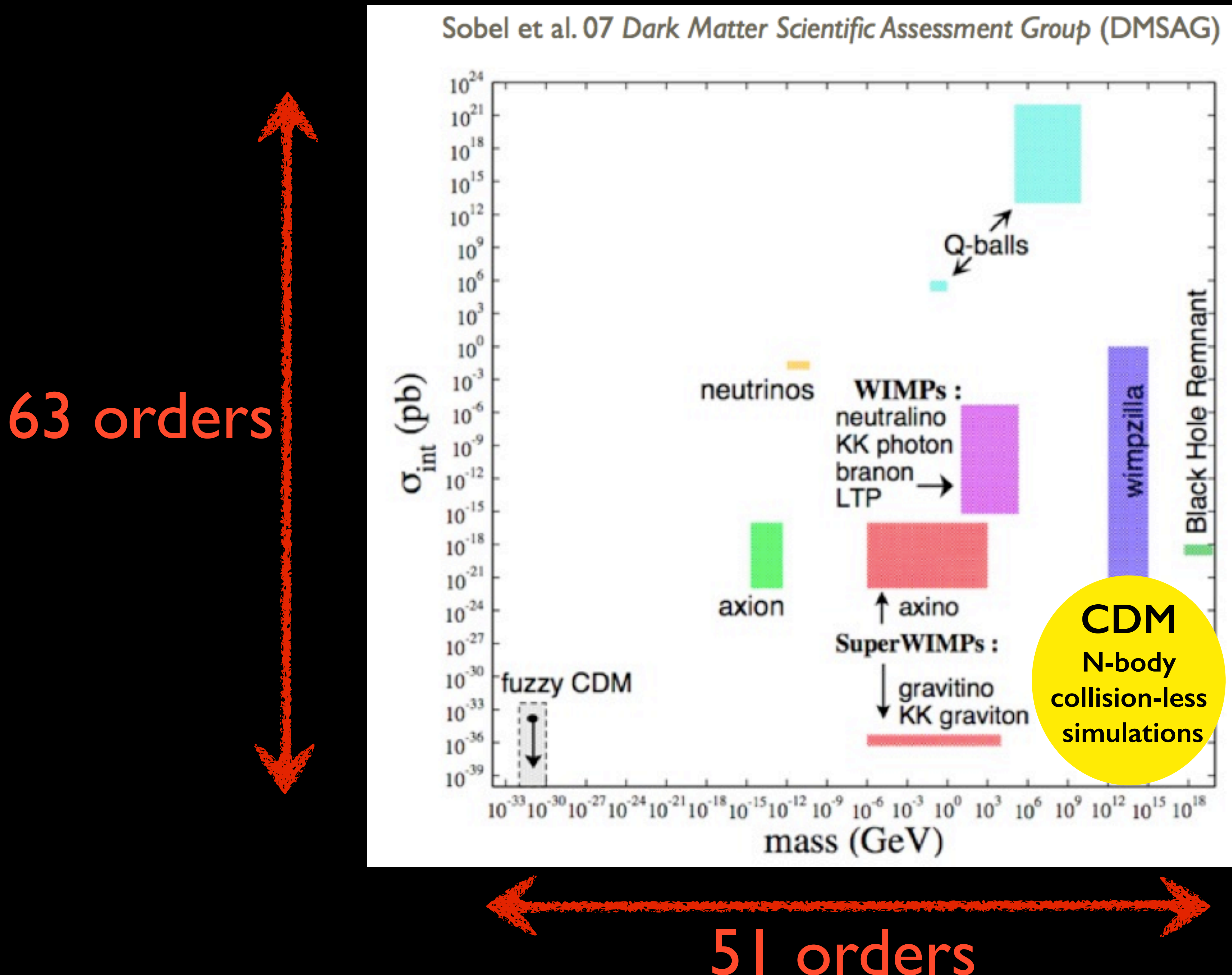
DM particle models: Constraints



63 orders

51 orders

DM particle models: Constraints



Constraints on
DM-particle *mass* & *cross-section*

1- Counting number of structures in the Universe

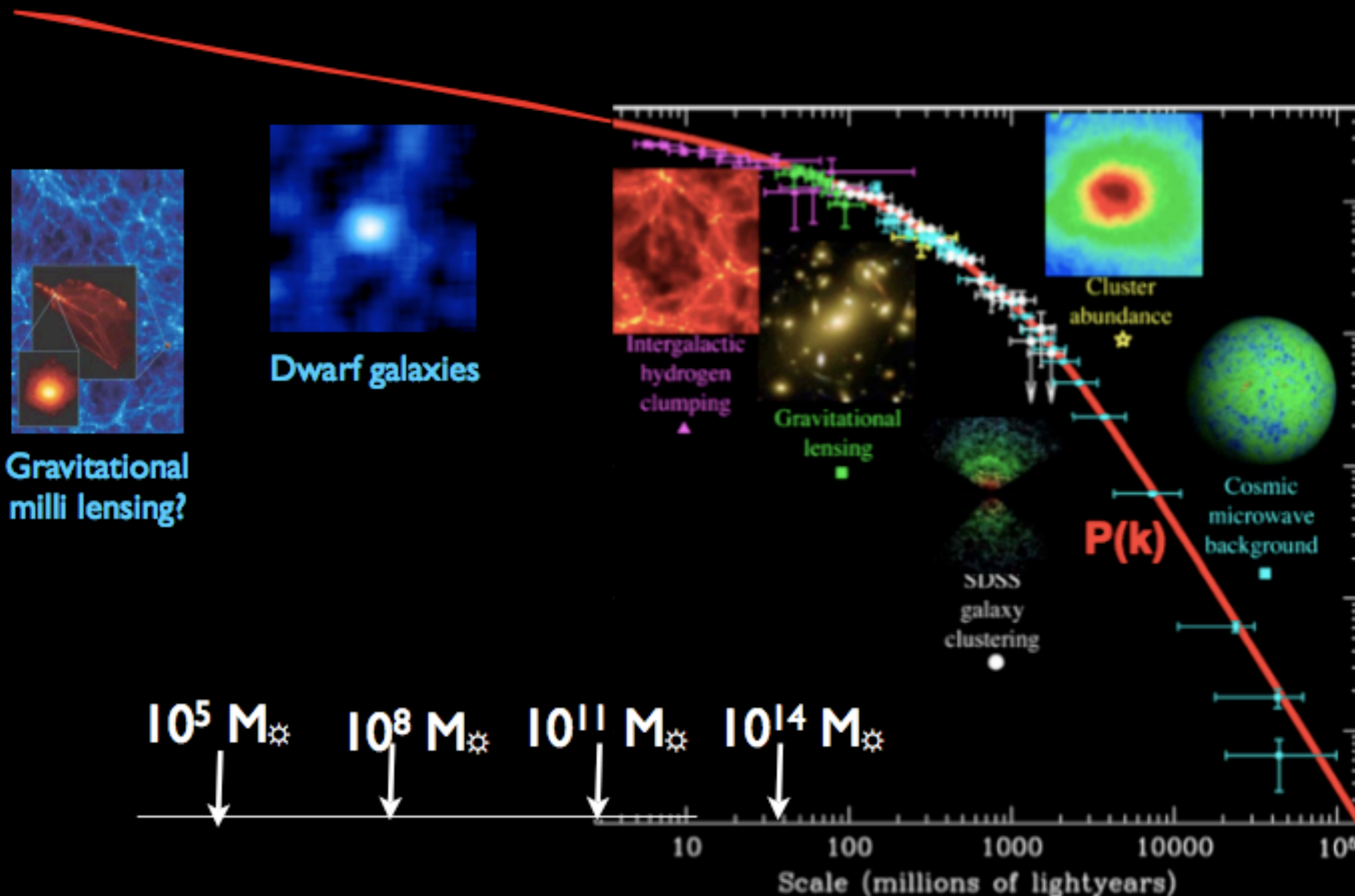
2- Measuring inner structure of DM haloes

3- Seeking DM-annihilation signals in galaxies

4- Detecting DM particles on Earth

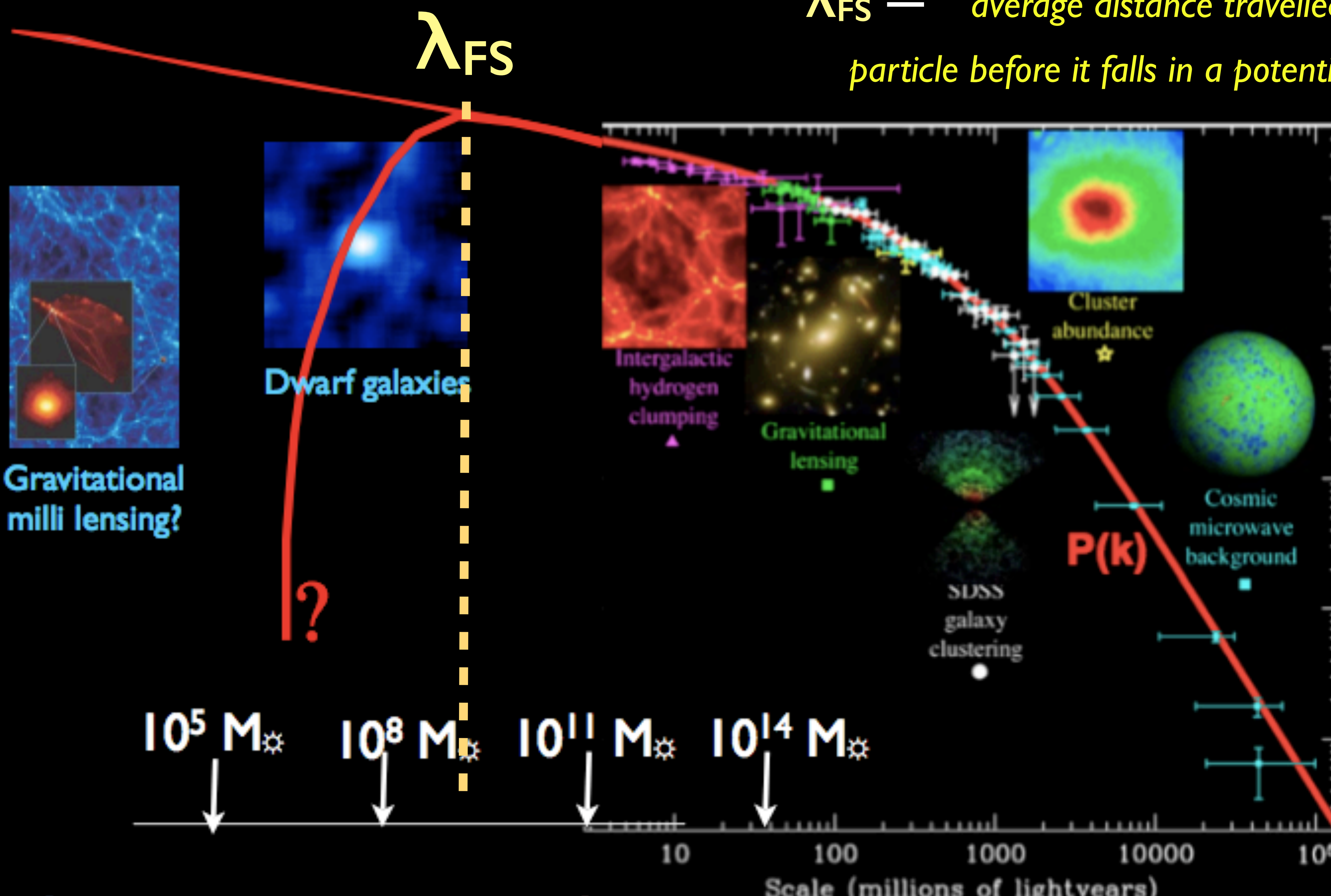
5- Manufacturing DM in particle accelerators

Substructure abundance



Substructure abundance

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



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

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

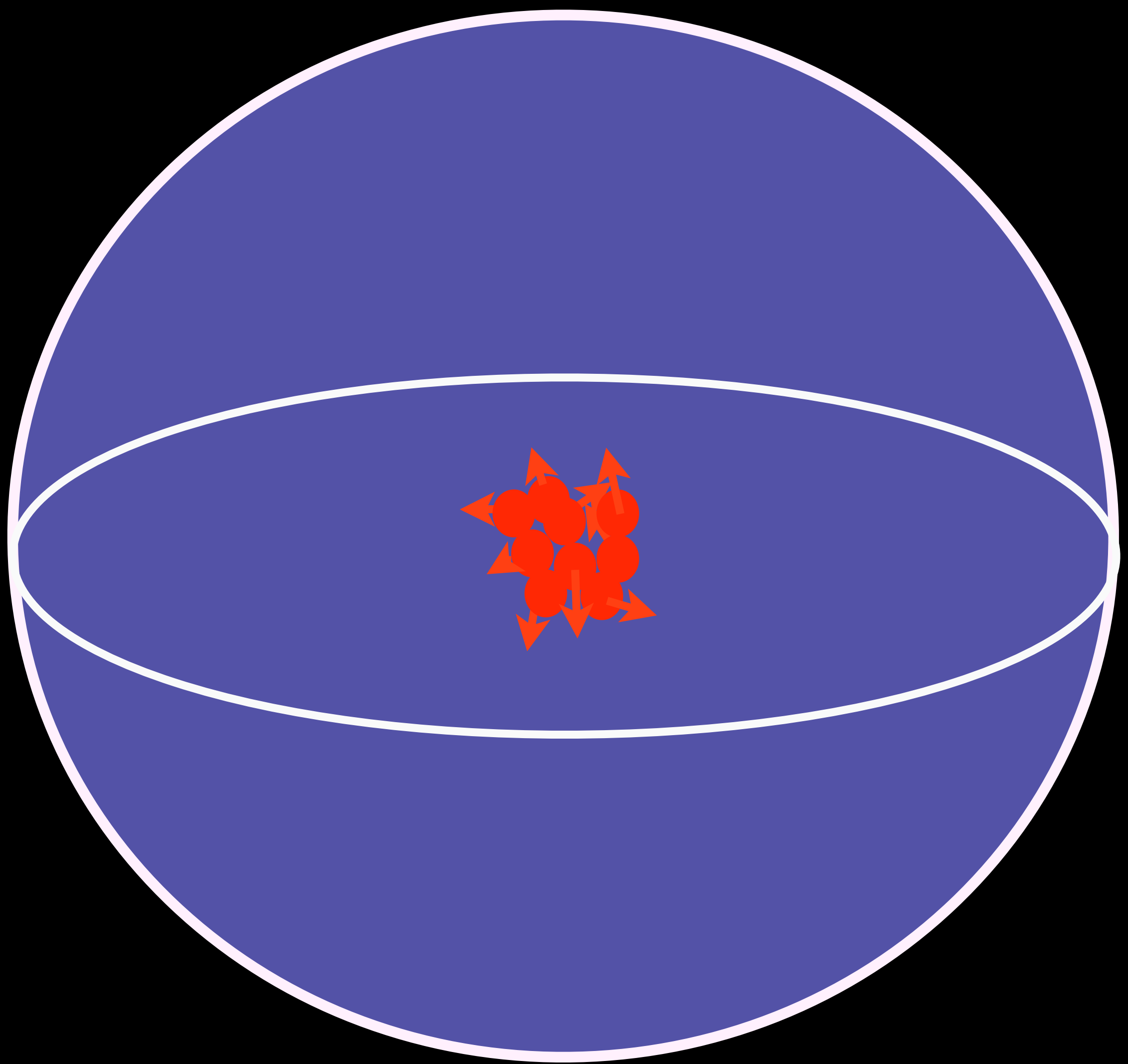
WARM
$10^3 - 10^5$ ev

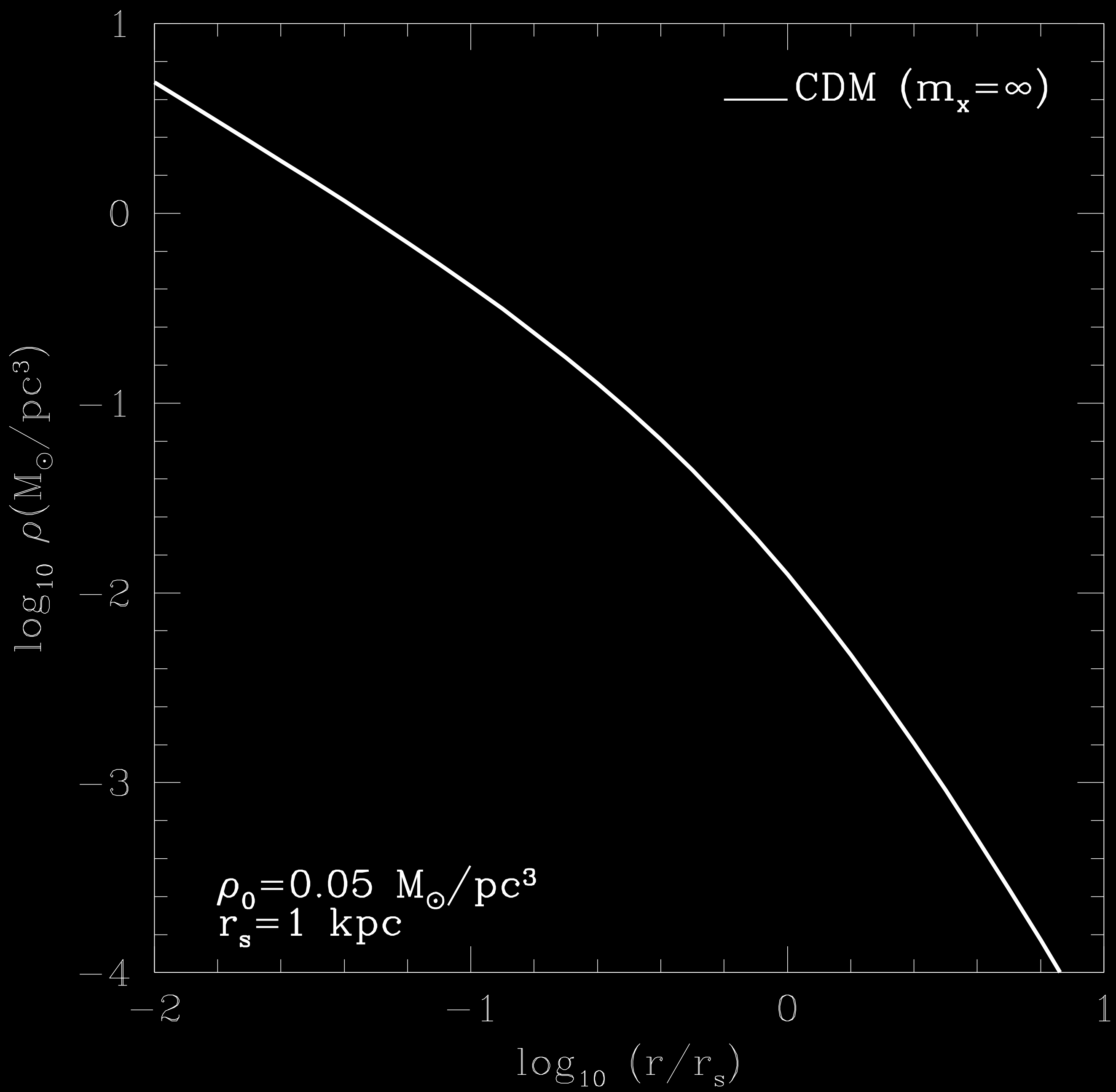
$\lambda_{FS} \sim 100$ kpc $(1 \text{ kev} / m_\nu)$

HOT
$<10^2$ ev

$\lambda_{FS} \sim 20$ Mpc $(30 \text{ ev} / m_\nu)$

The inner structure of DM haloes



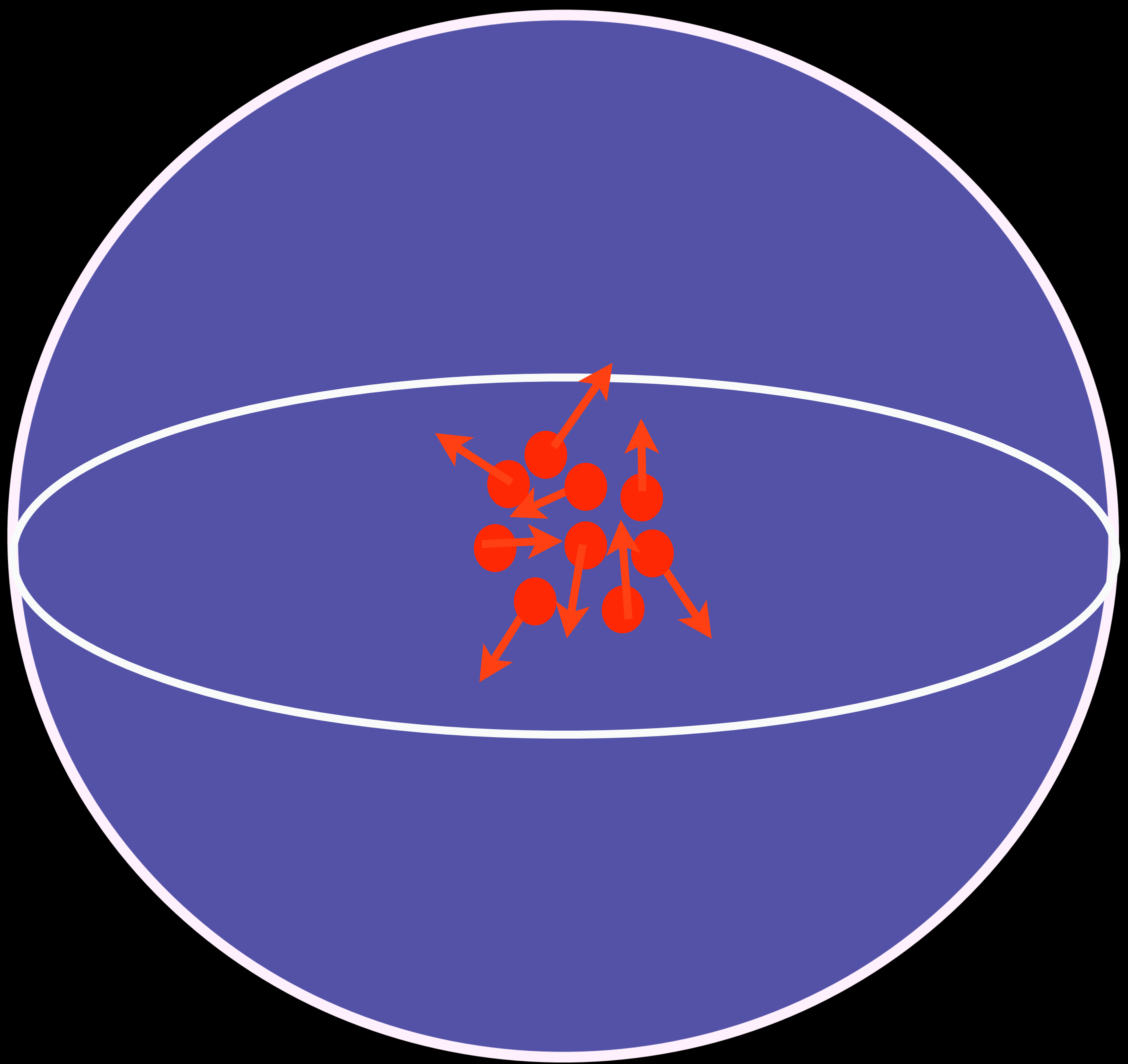


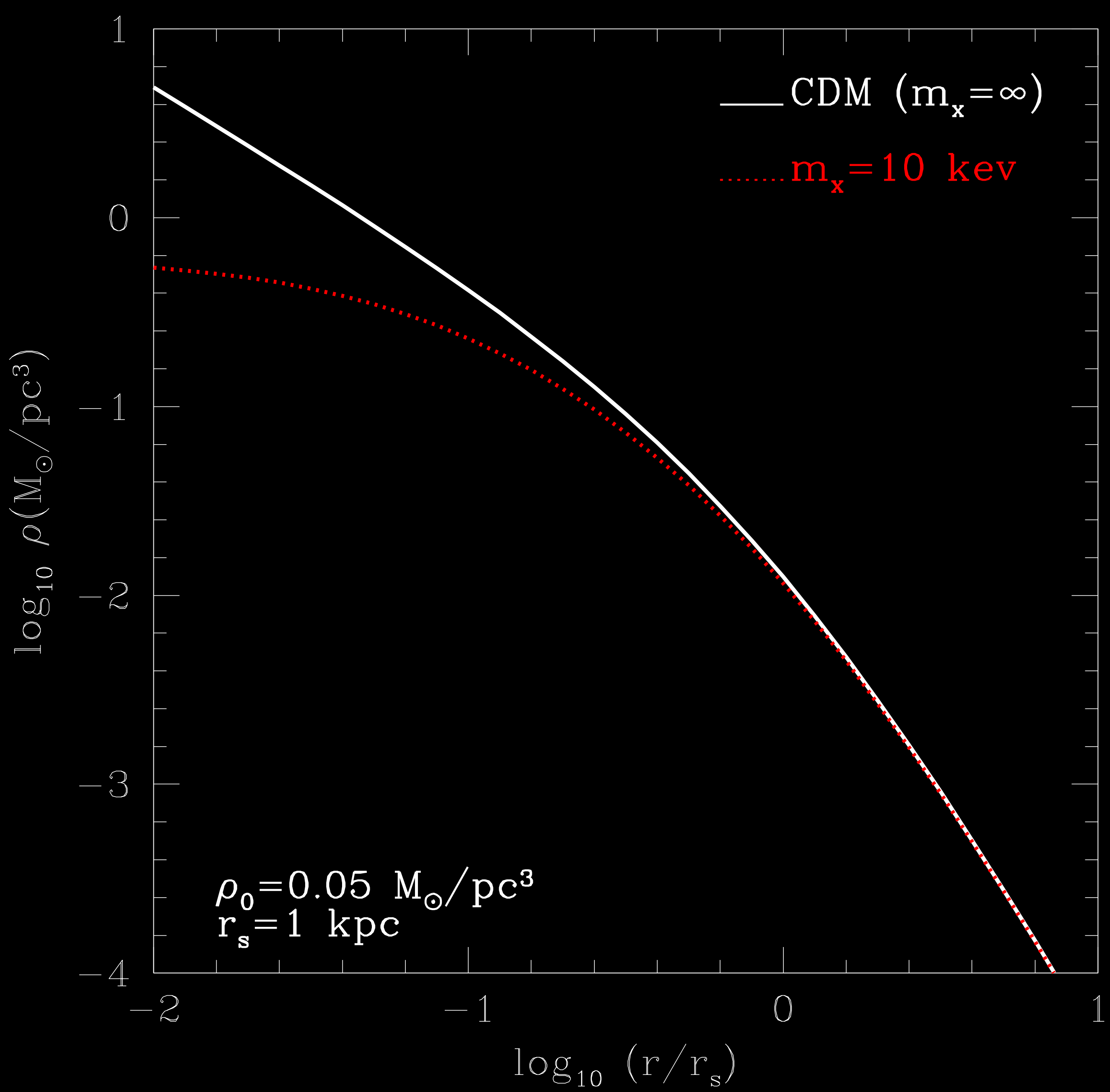
CDM haloes follow a *centrally-divergent* density profile

→ dark matter "cusp"

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

The inner structure of DM haloes

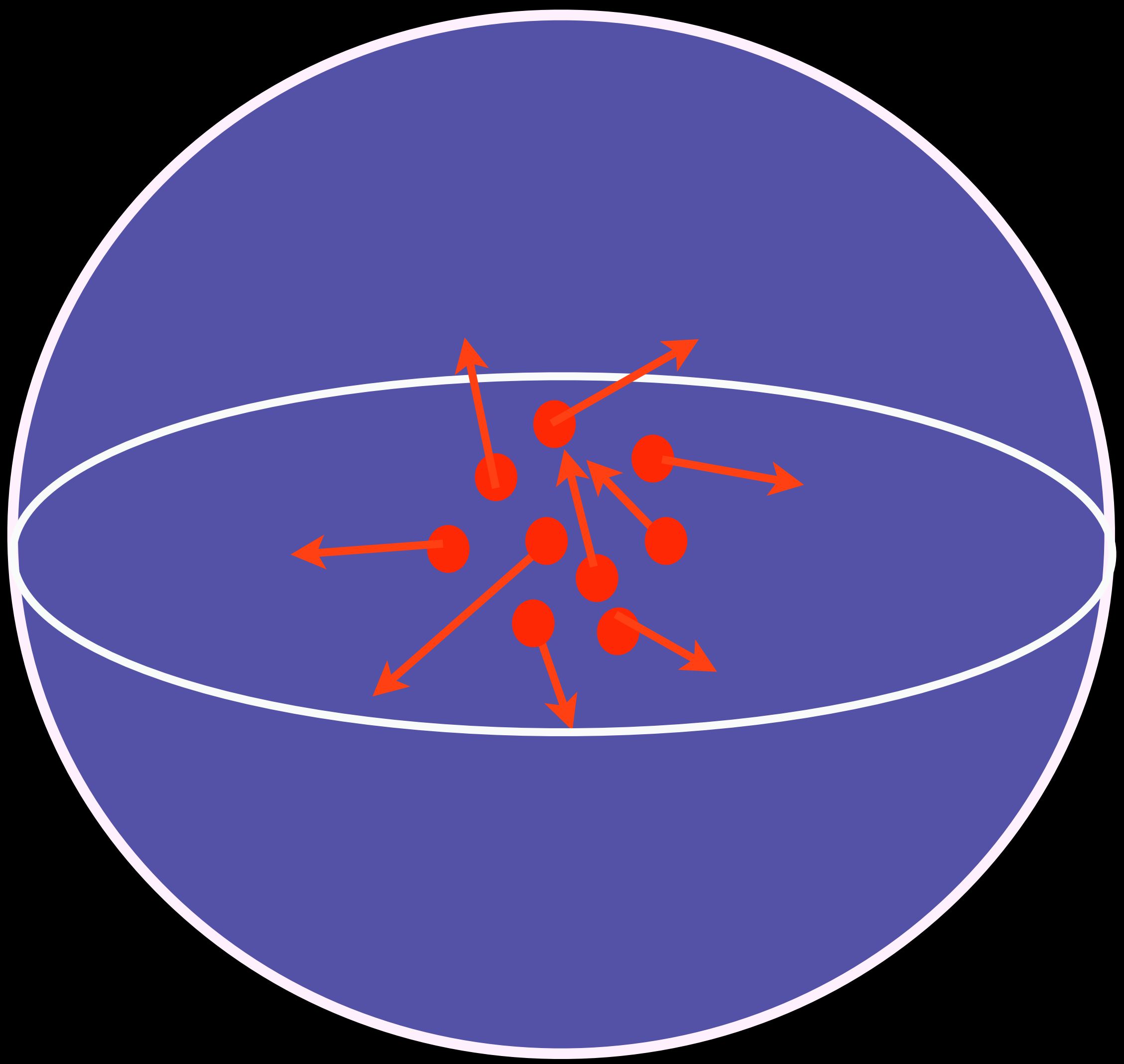


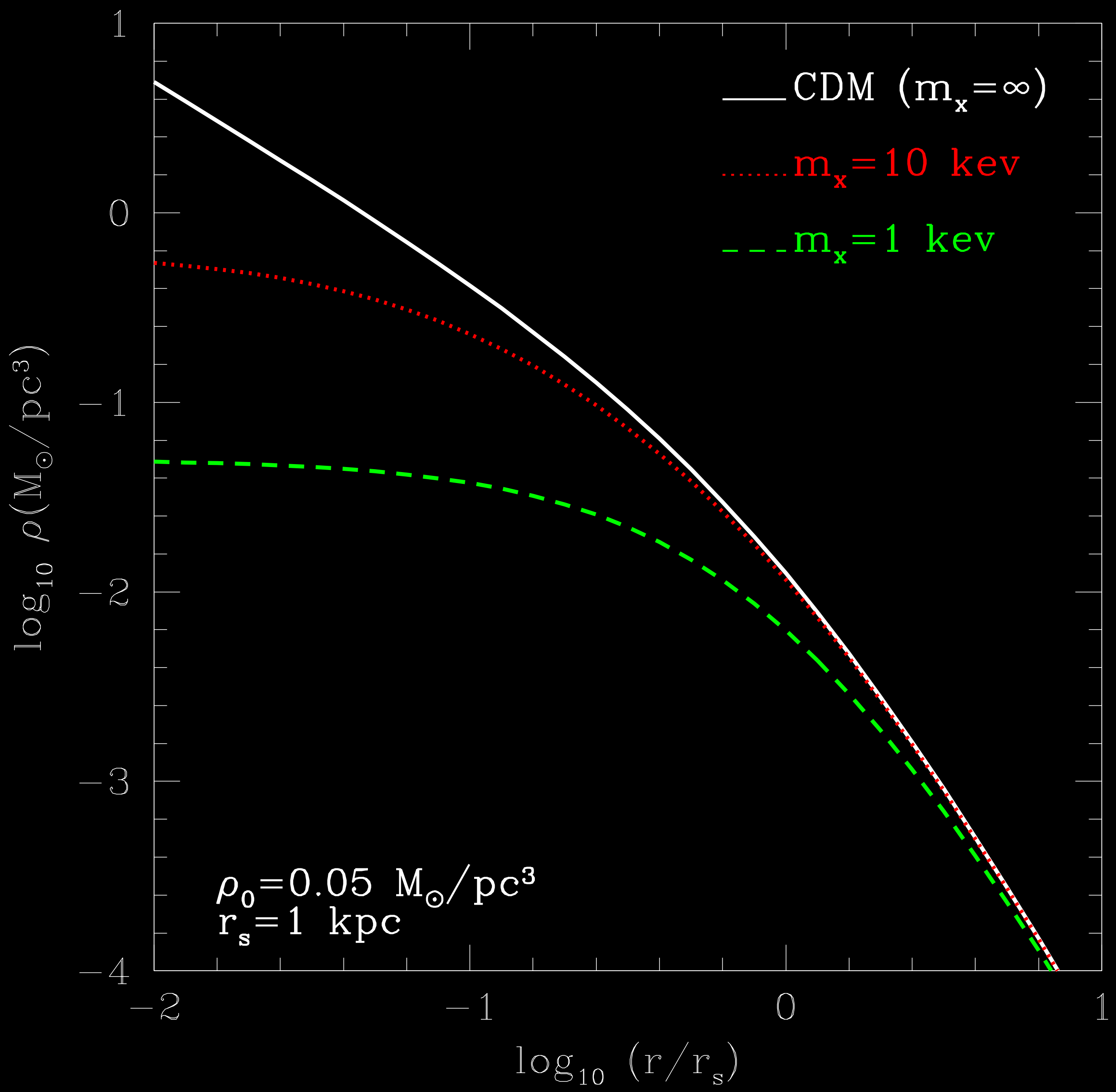


- **Relic thermal energy** (low particle mass)
- **Scattering** (large cross section)

→ dark matter "cores"

The inner structure of DM haloes





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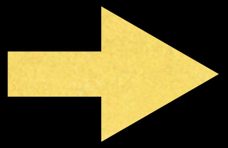
- **Scattering** **(large cross section)**



dark matter “cores”

The extreme properties of dSphs

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

★**Smallest**
$30 < r_{half}/pc < 2000$

★Most numerous satellites

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

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

★**No gas**

★**No rotation**

★**DM particle mass & cross section**

★**Gravity tests**

★**Star formation/feedback in low mass haloes**

★**Hierarchical galaxy formation**

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.

Illingworth (1976) mass estimate for Globular Clusters

$$M = 167 r_c \mu < v_r^2 > \quad (\mu \approx 4 \text{ King models})$$

from 3 carbon stars:

$$M/L = 0.72 < v_r^2/(\mathrm{km/s})^2 > \approx 31$$

Assumptions:

- Equilibrium
- mass follows light
- spherical shape
- **isotropic** velocity

The era of multi-fibre spectrographs

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- Equilibrium
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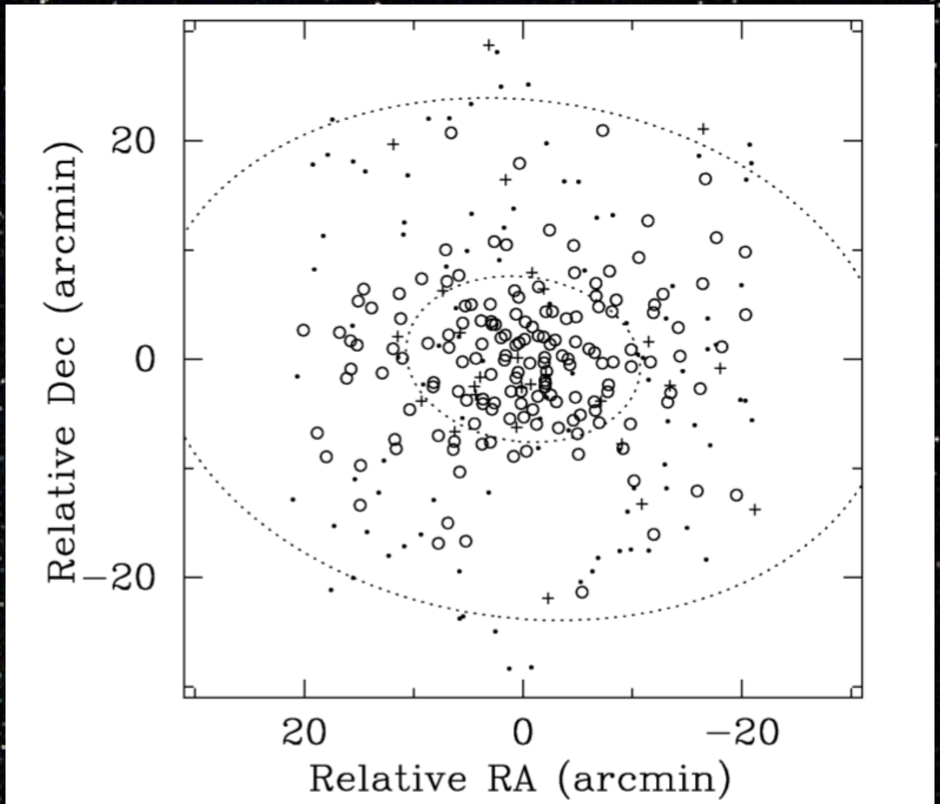
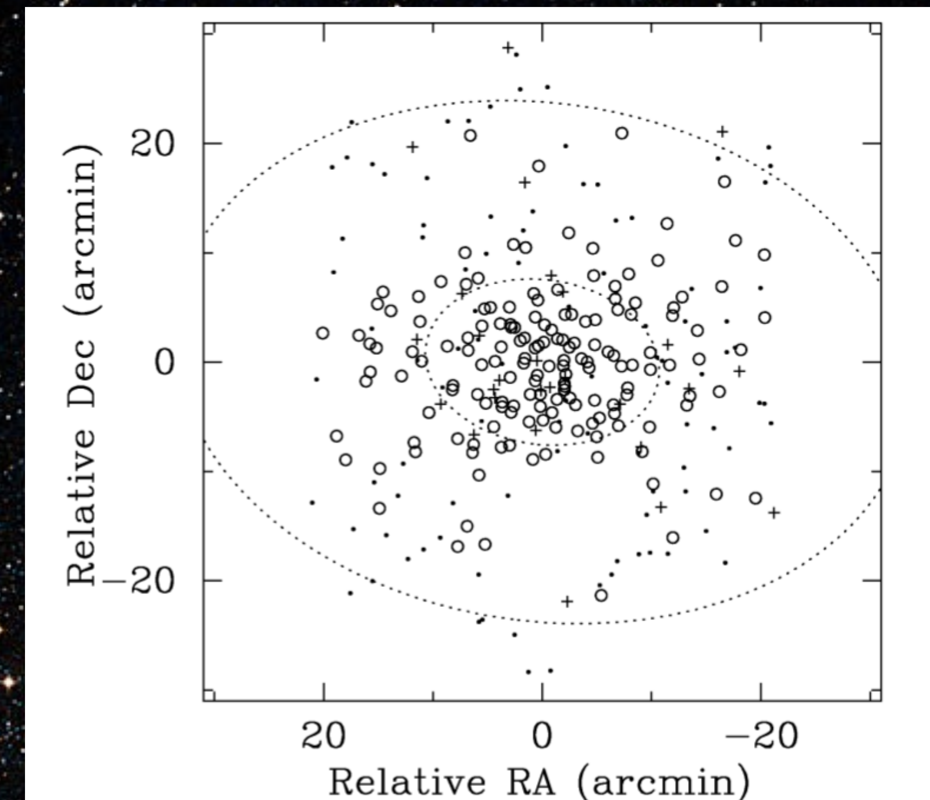


Kleyna+02: 165 members

The era of multi-fibre spectrographs

Assumptions:

- Equilibrium
- ~~mass follows light~~
- spherical shape
- ~~isotropic velocity~~
- known form of the (DM) potential
- constant anisotropy



Kleyna+02: 165 members

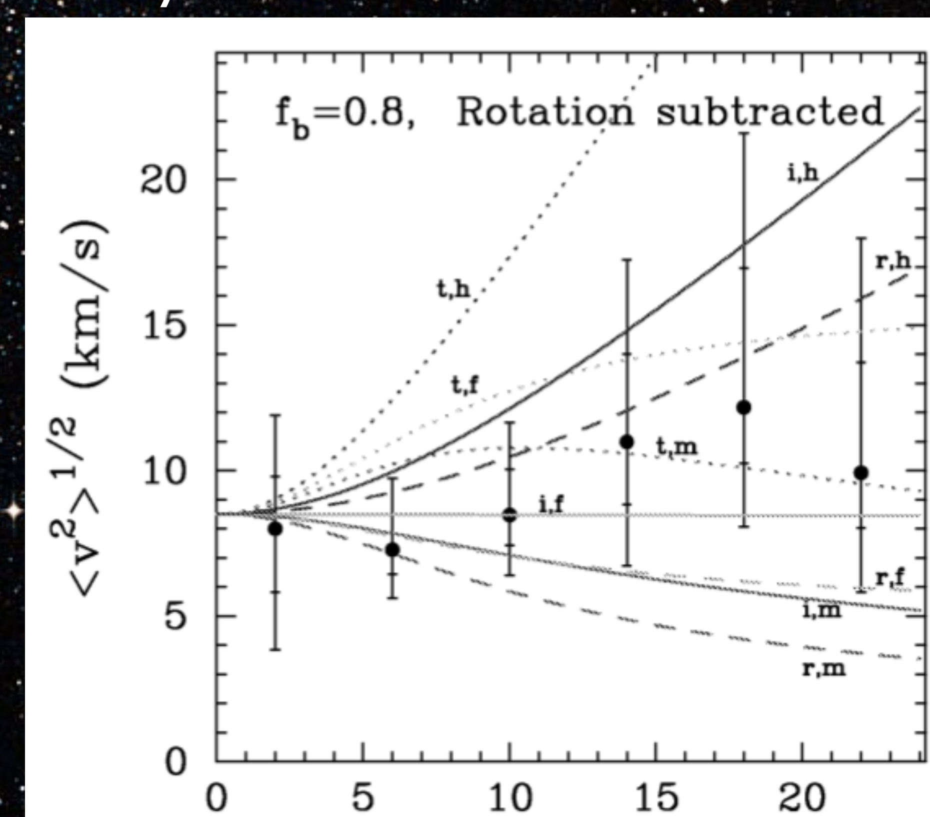
Wilkinson+02: stars mass-loss tracers of the underlying potential

$$\Phi = \frac{\Phi_0}{(1+r^2)^{\alpha/2}}$$

$$\rho_\star = \frac{\rho_0}{[1+(r/r_c)^2]^{5/2}}$$

} f(E,L)

Anisotropic DF



Wilkinson+02

Schwarzschild modelling: orbits

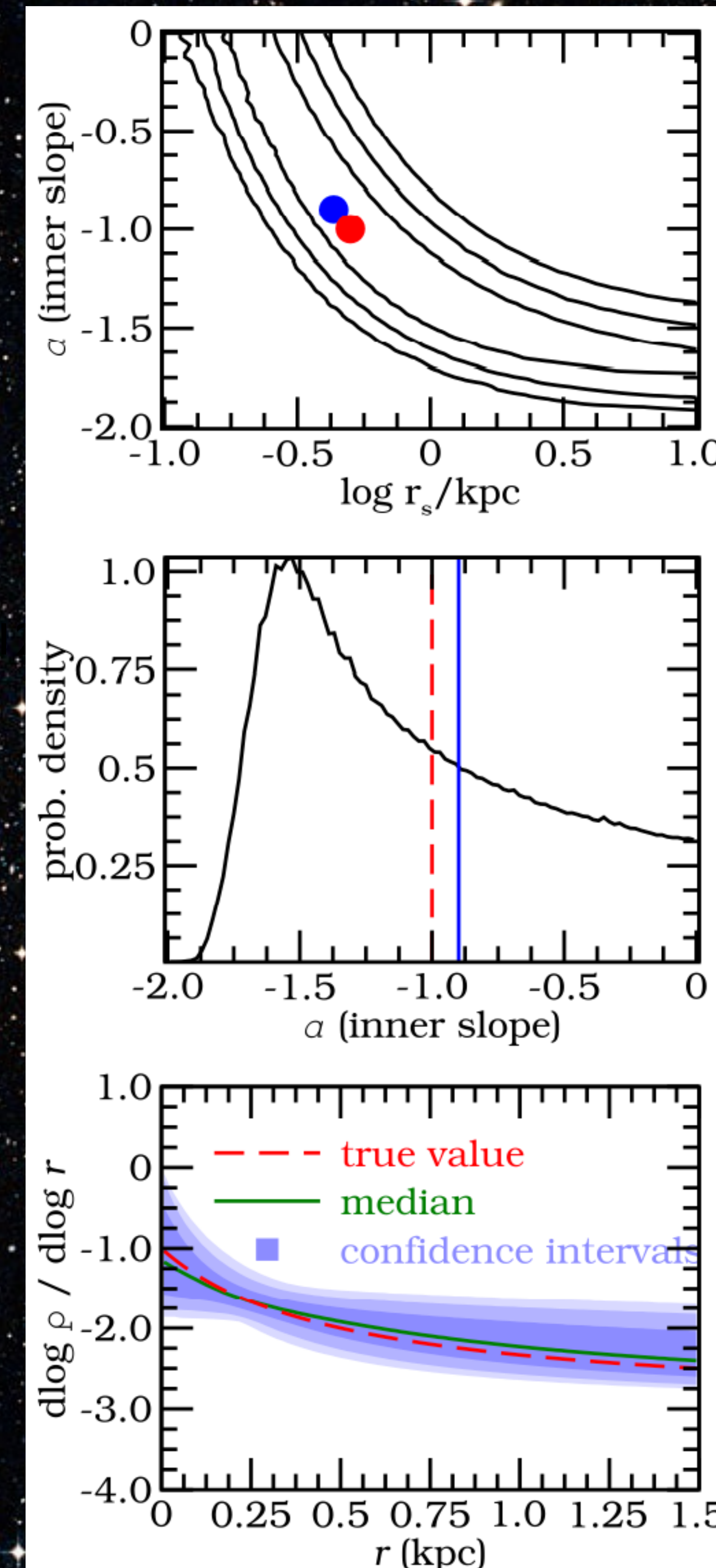
Assumptions:

- Equilibrium
- ~~mass follows light~~
- ~~spherical shape~~
- ~~isotropic velocity~~
- known form of the (DM) potential
- <u>arbitrary</u> anisotropy

Construction of orbital libraries in a given potential.
Subset chosen in order to match v_los(R)

$$\rho_{\rm DM} = \rho_0 (r/r_s)^{\alpha} (1 + r/r_s)^{-(3+\alpha)}$$

Using **mock** data Breddels+13 conclude that current **current kinematic samples are too small** to break degeneracies in the (spherical) halo profile



Breddles+13

Jeans modelling: fast and easy

Assumptions:

- Equilibrium
- ~~mass follows light~~
- spherical shape
- ~~isotropic velocity~~
- known form of the (DM) potential
- <u>arbitrary</u> anisotropy

Working with the moments of a DF is considerably simpler than constructing DF for a potential/luminous profile pair

$$\frac{\partial}{\partial r}(\rho\sigma_r^2) + \frac{\partial\Phi}{\partial r}\rho + \frac{2\beta}{r}(\rho\sigma_r^2) = 0.$$

spherical Jeans eqs.

$$\sigma_r^2(r) = \frac{1}{r^{2\beta}\rho(r)}\int_r^{\infty} dr' r'^{2\beta}\rho(r')\frac{\partial\Phi}{\partial r}.$$

$$\sigma_{\rm los}^2(R) = \frac{2}{\Sigma(R)}\int_R^{+\infty} dr\left(1 - \beta(r)\frac{R^2}{r^2}\right)\frac{\rho(r)\sigma_r^2 r}{\sqrt{r^2 - R^2}}.$$

Jeans modelling: fast and easy

Assumptions:

- Equilibrium
- ~~mass follows light~~
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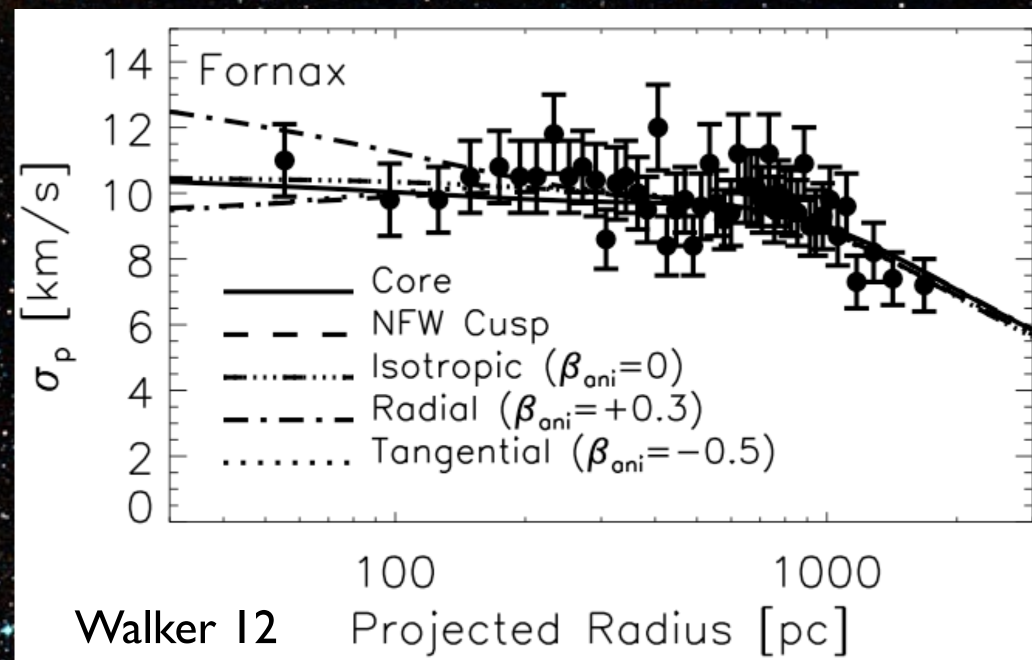

Unknown β(r)

↓

Unknown M(r)

(although fitting **kurtosis(R)** may help to break degeneracy, Richardson+Fairbairn 13,14)

Working with the moments of a DF is considerably simpler than constructing DF for a potential/luminous profile pair

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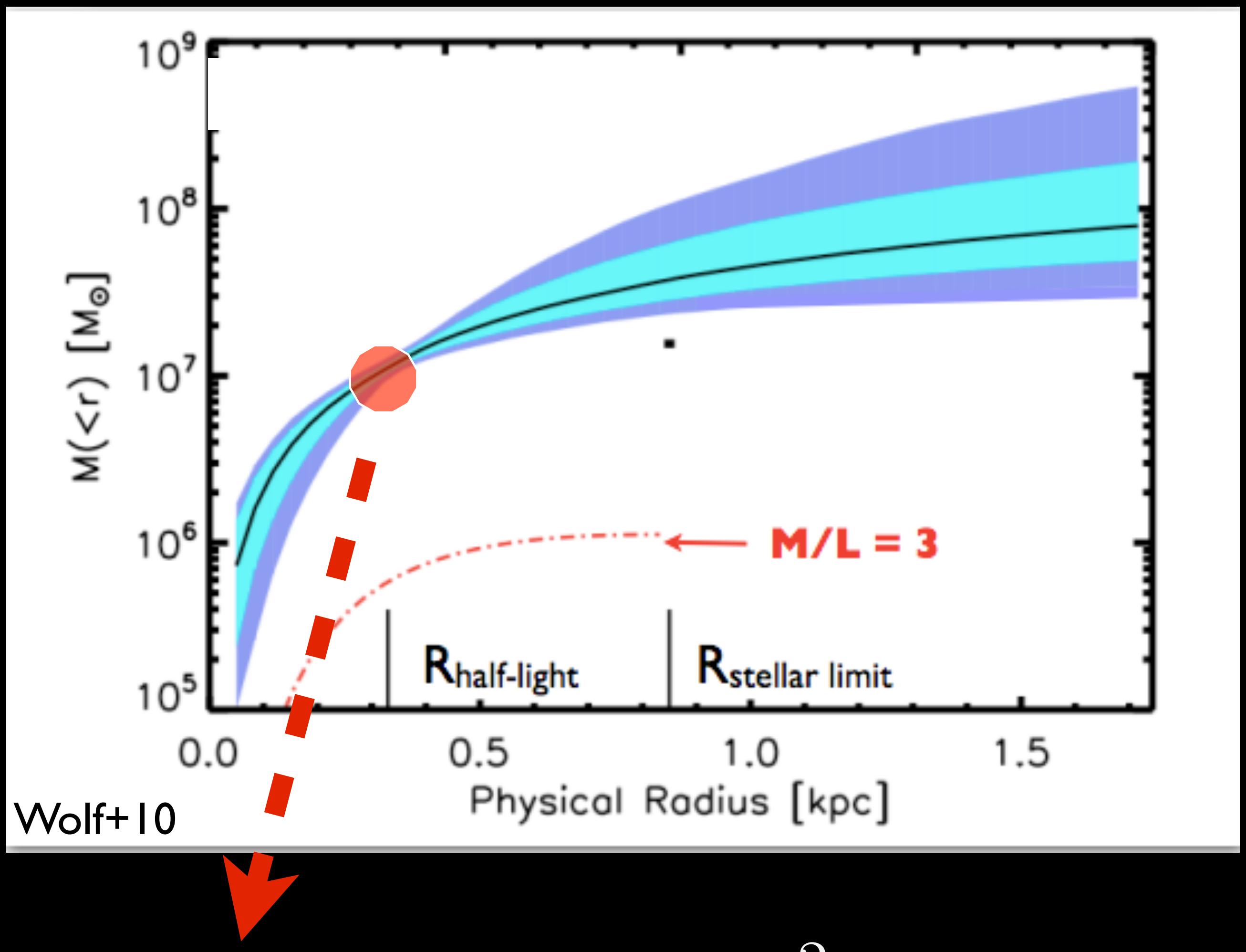
mass-anisotropy degeneracy

Breaking the degeneracy

Walker & Peñarrubia (2011)

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

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)

mass estimator
insensitive to β !!

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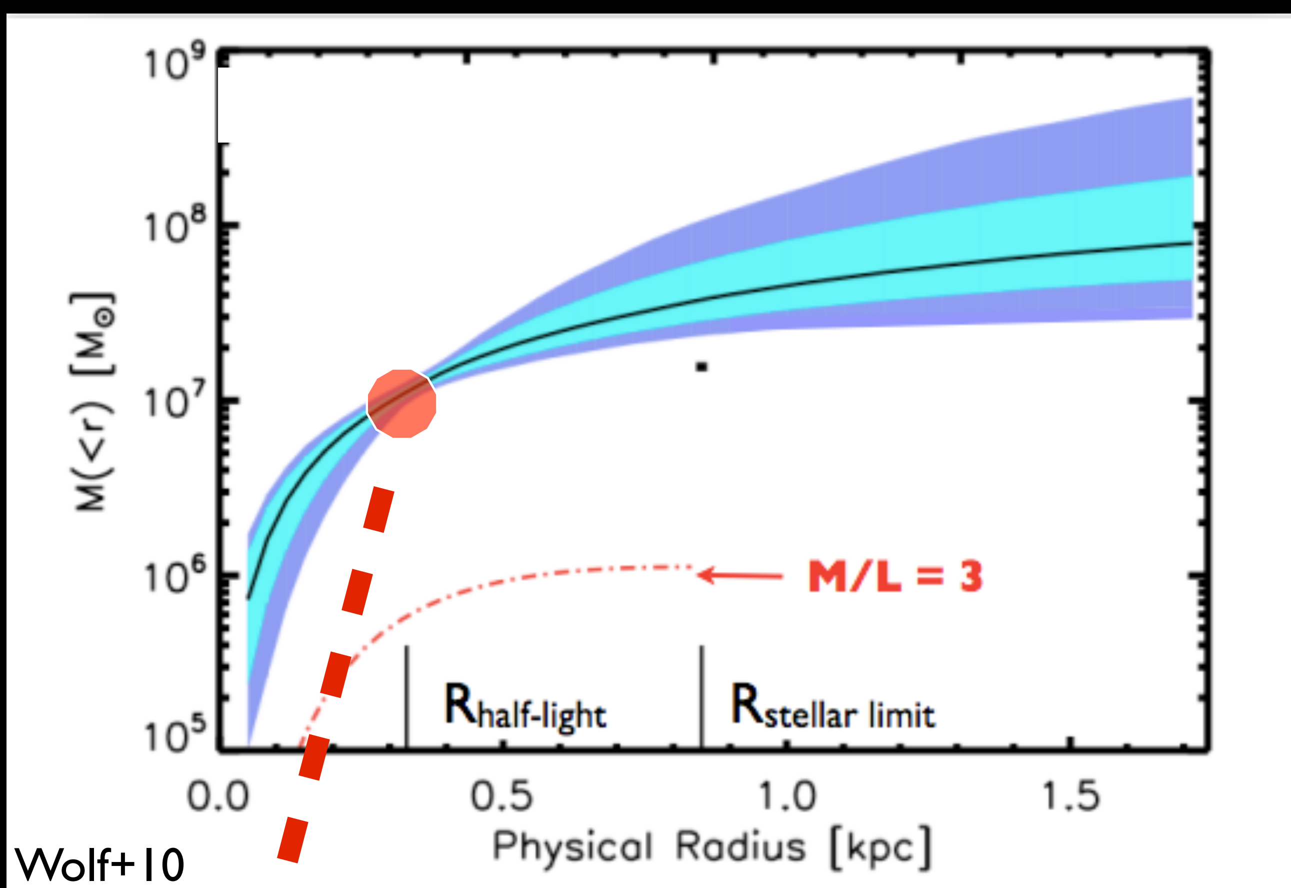
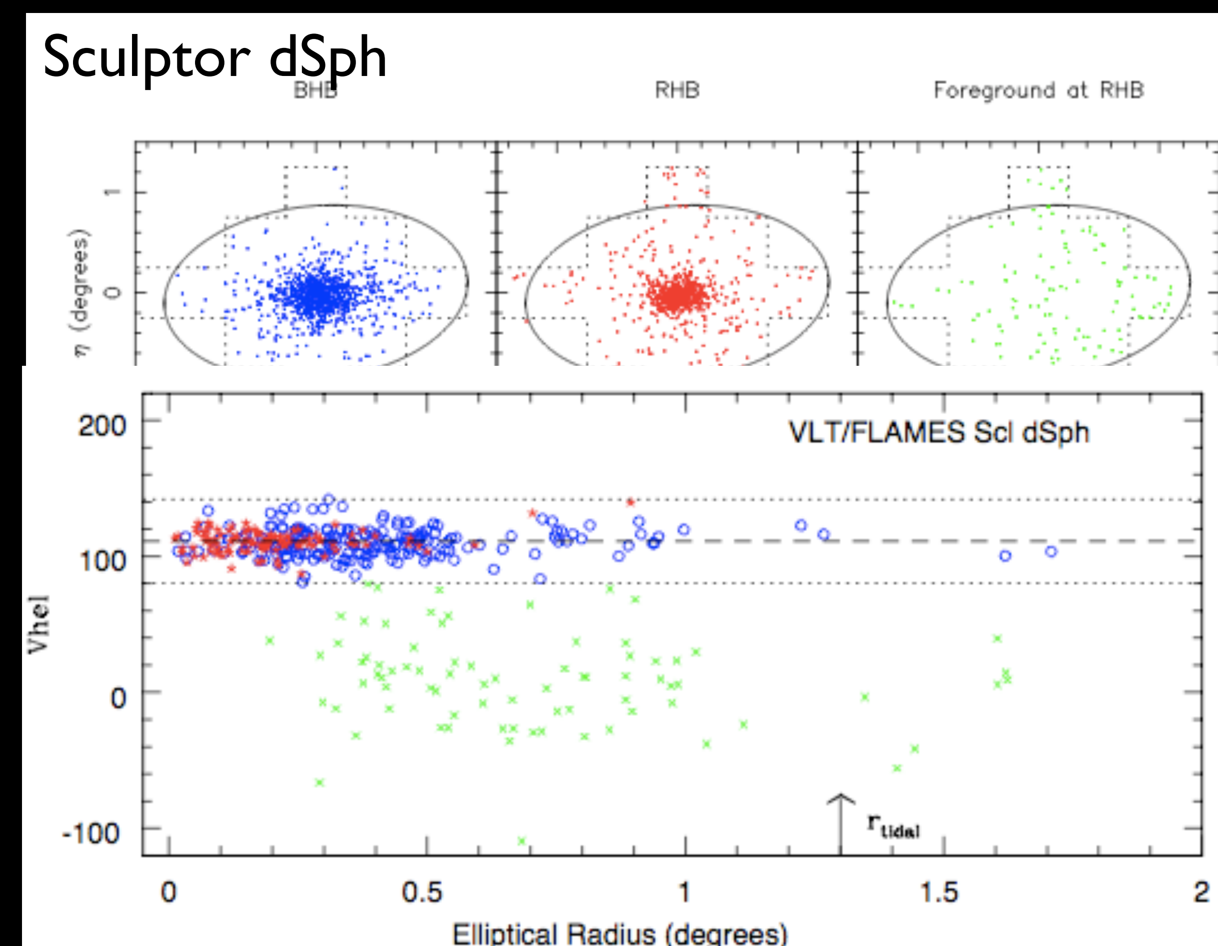


Some dSphs show spatially + kinematically distinct stellar components



Tolstoy + 04 (see also Battaglia+08)

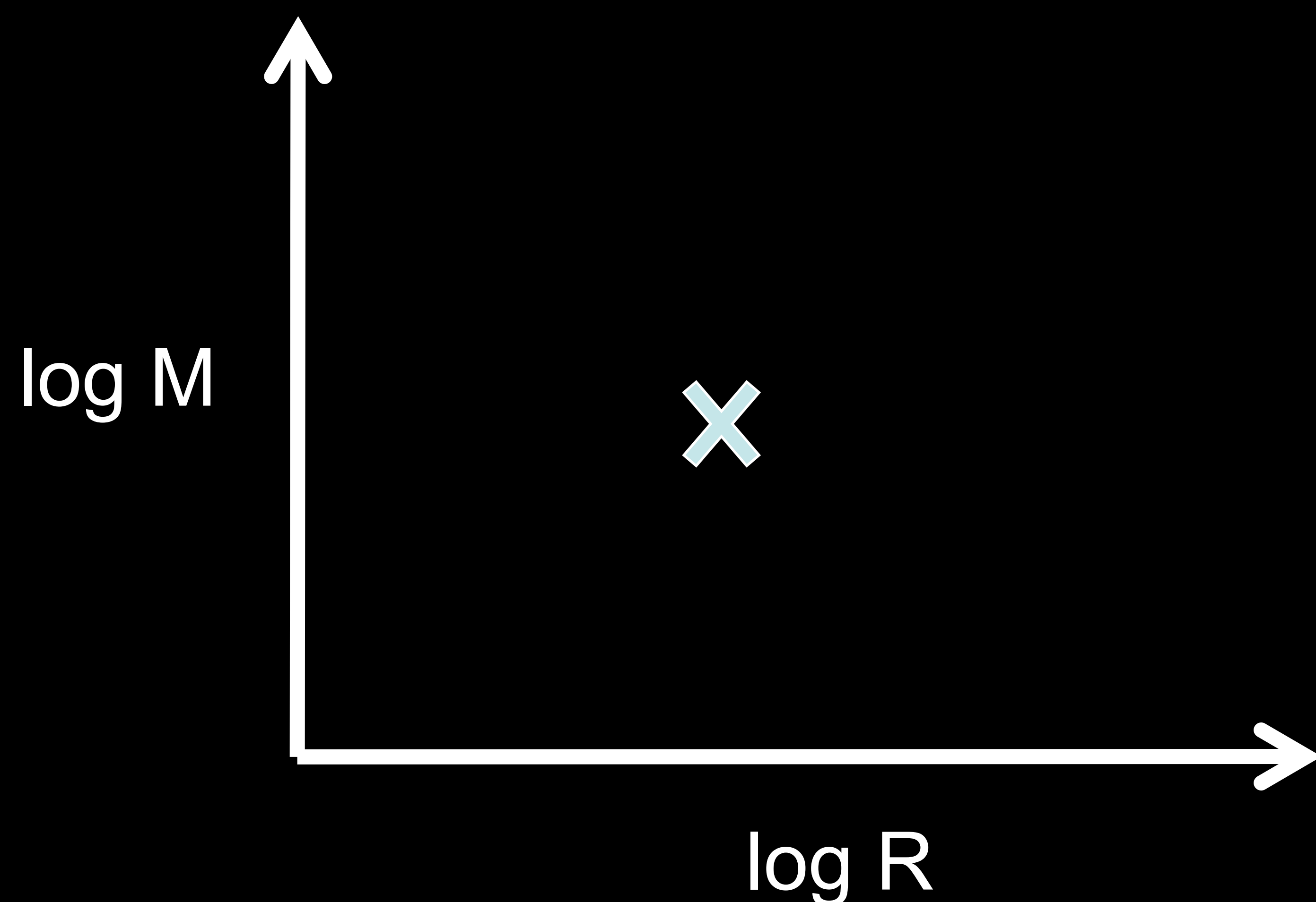
$$M(R_{\rm half}) \approx \mu R_{\rm half} \langle \sigma_V \rangle^2$$

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

mass estimator insensitive to β !!

Multi-component splitting

Walker & Peñarrubia (2011)



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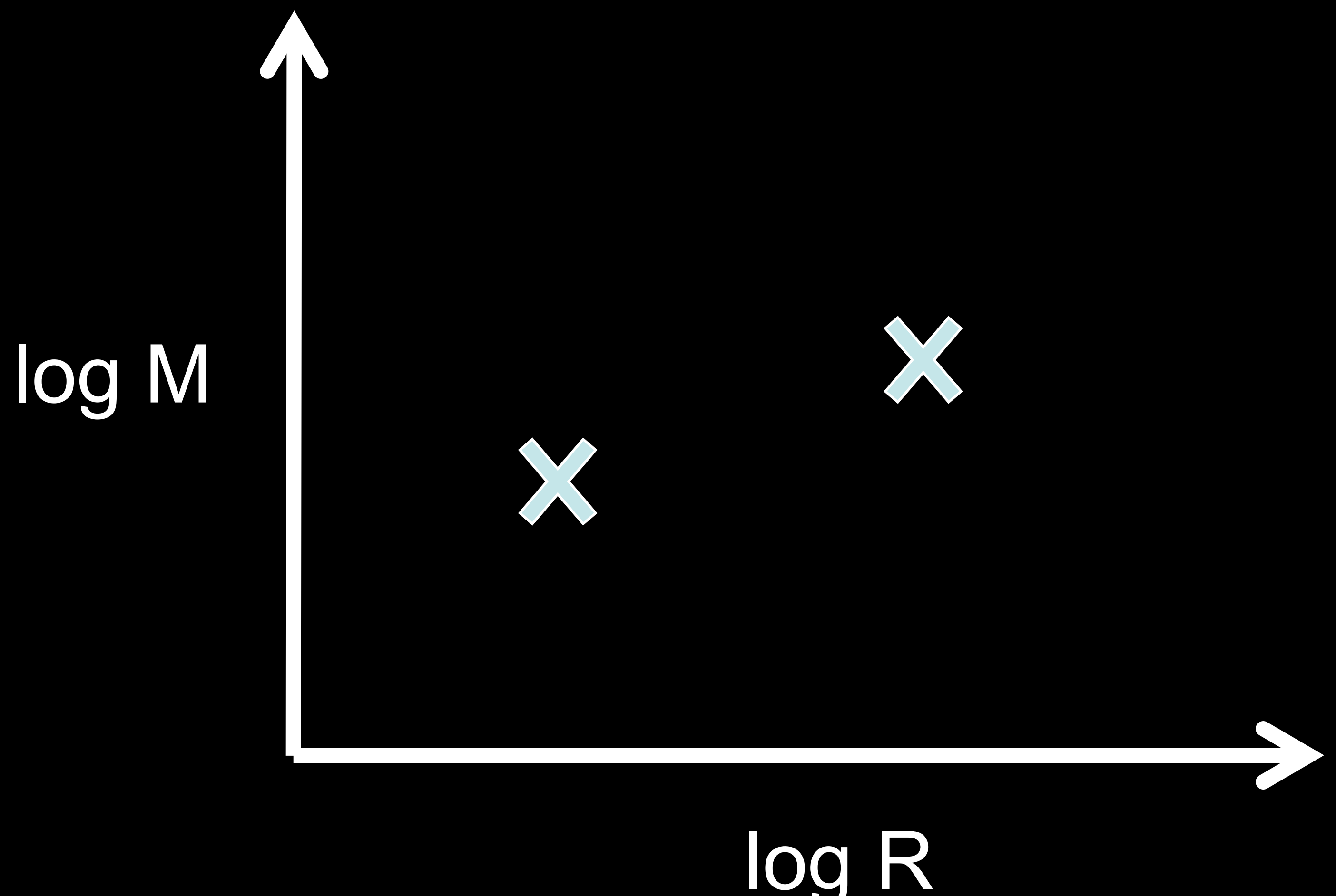
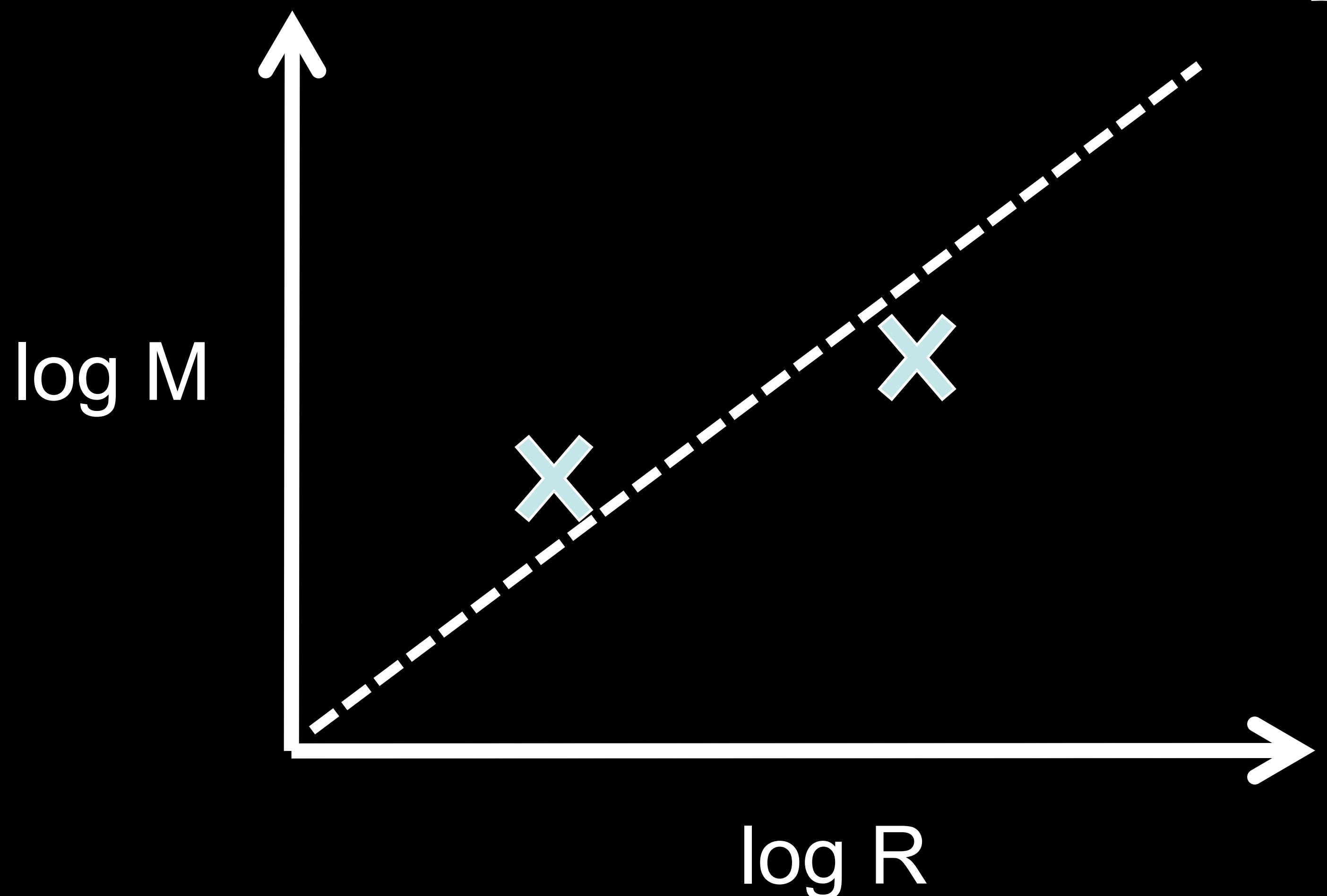


Multi-component splitting

Walker & Peñarrubia (2011)

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

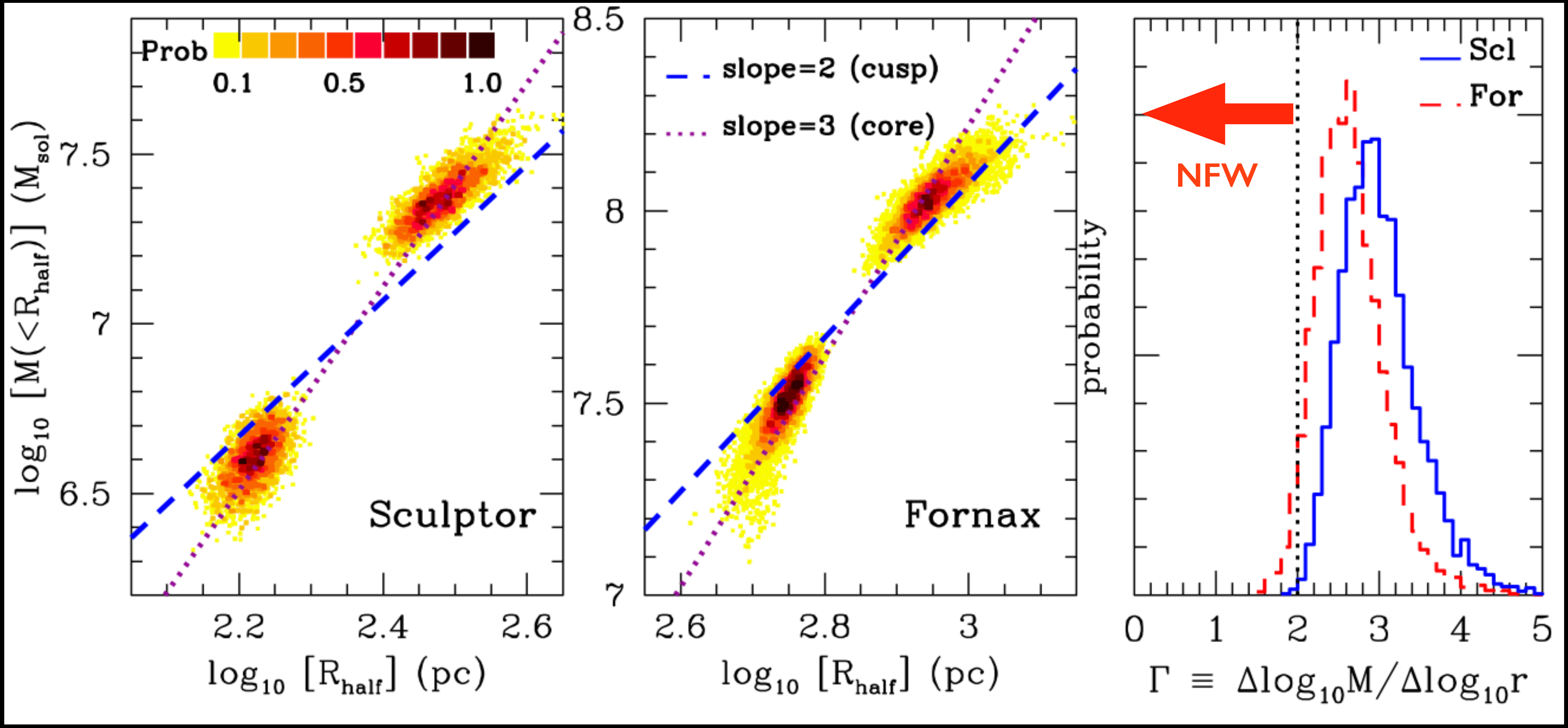


$$M(R_h) \approx \mu R_h \langle \sigma^2 \rangle \quad \Rightarrow \quad \Gamma = 1 + \frac{\log[\langle \sigma_2^2 \rangle / \langle \sigma_1^2 \rangle]}{\log[R_{h,2}/R_{h,1}]}$$

directly from observables w/o dynamical modelling!

Sculptor, Fornax

Walker & Peñarrubia (2011)



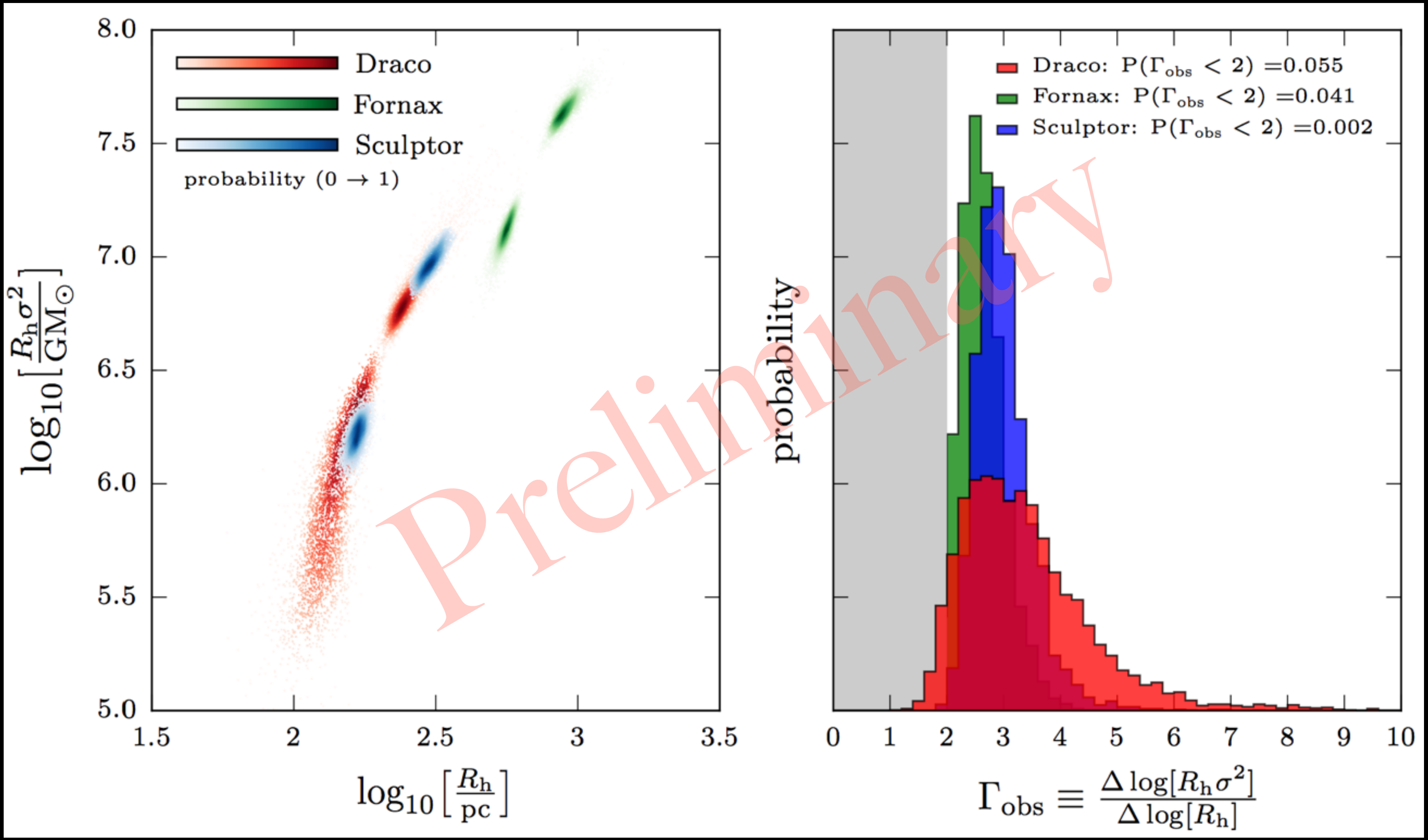
DM cusps ruled out in Sculptor and Fornax at a 93% and 97% confidence level

$$\Gamma \leq 3 - \gamma$$

see also Amorisco & Evans(2012); Agnello & Evans(2012); Jardel & Gebhardt (2012)

Sculptor, Fornax.... & Draco

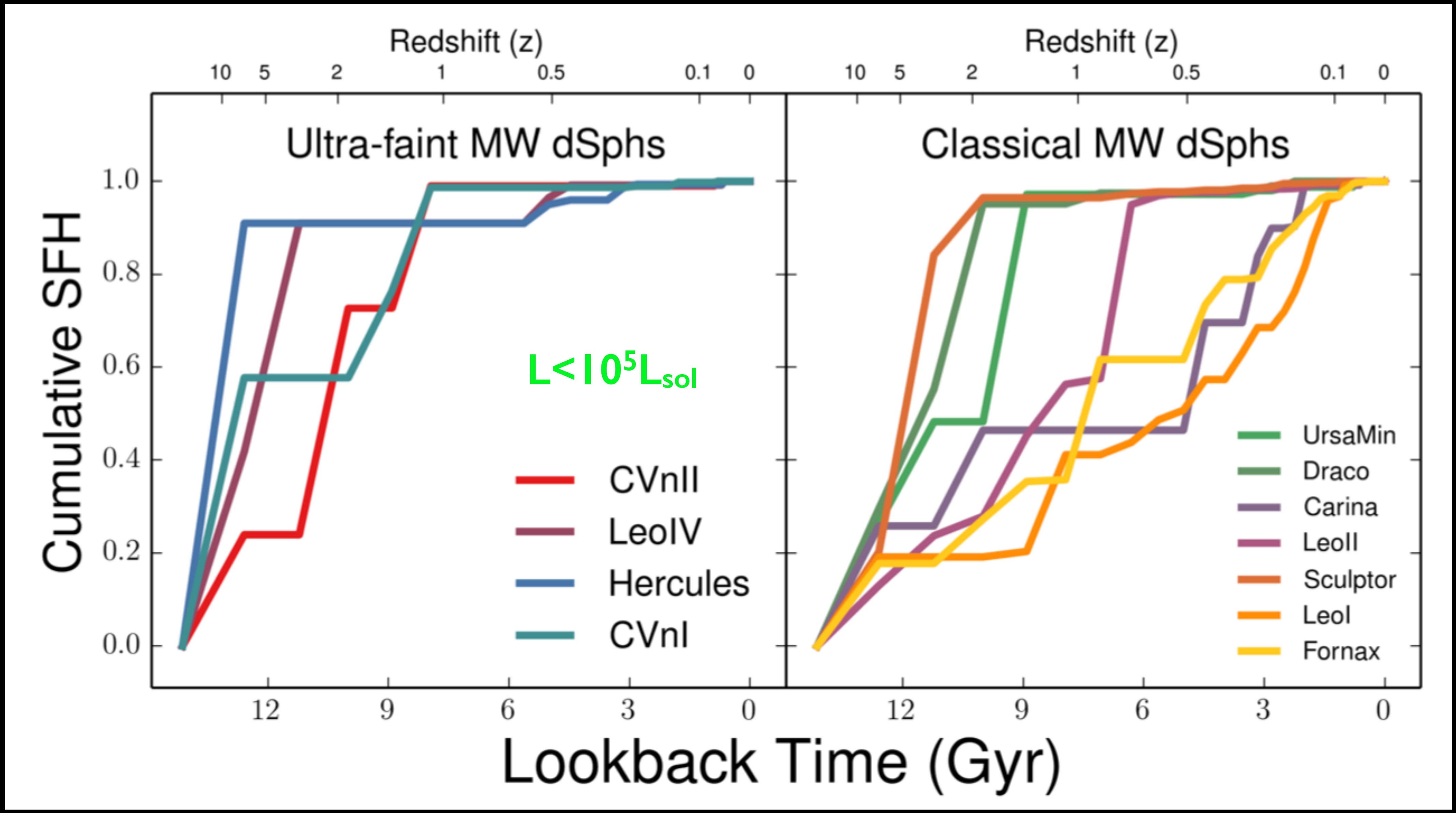
Walker, Peñarrubia, Mateo & Olzweski + 15

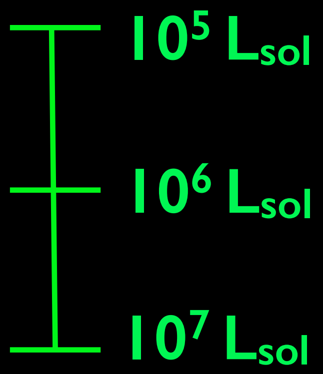


With $L \sim 10^5 L_{sol}$ Draco is ~300 times fainter than Fornax and 50 times fainter than Sculptor

DM profile in fainter dSphs?

Star formation histories (HST data)





Weisz+14

Faint dSphs only have one star formation episode → multiple chemo-dynamical components??

Tidal streams of dSphs

Errani, Peñarrubia & Tormen (2015)

*** Dark Matter**

$$\rho = \frac{\rho_0}{(r/a)^\gamma (1 + r/a)^{3-\gamma}}$$

$\gamma = 1$ cusp

$\gamma = 0$ core

- N = 2x10^6 particles
- grid size = 10 pc

*** Stars (particle tagging)**

$$\rho_\star = \frac{\rho_{0,\star}}{[1 + (r/r_c)^2]^{5/2}}$$

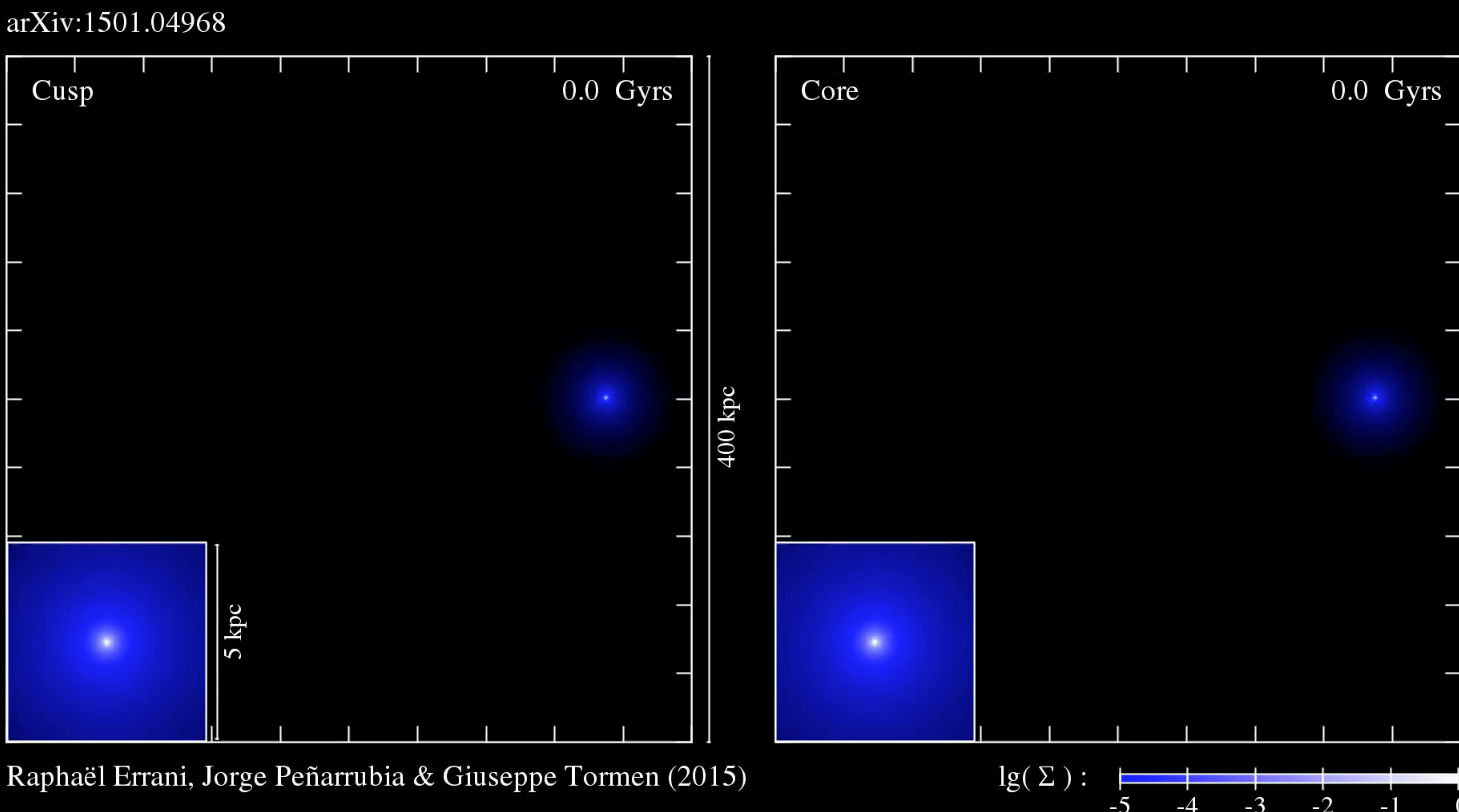
Initial conditions chosen such that observables independent of halo profile

$$M_{\rm core}(< r_h) = M_{\rm cusp}(< r_h)$$

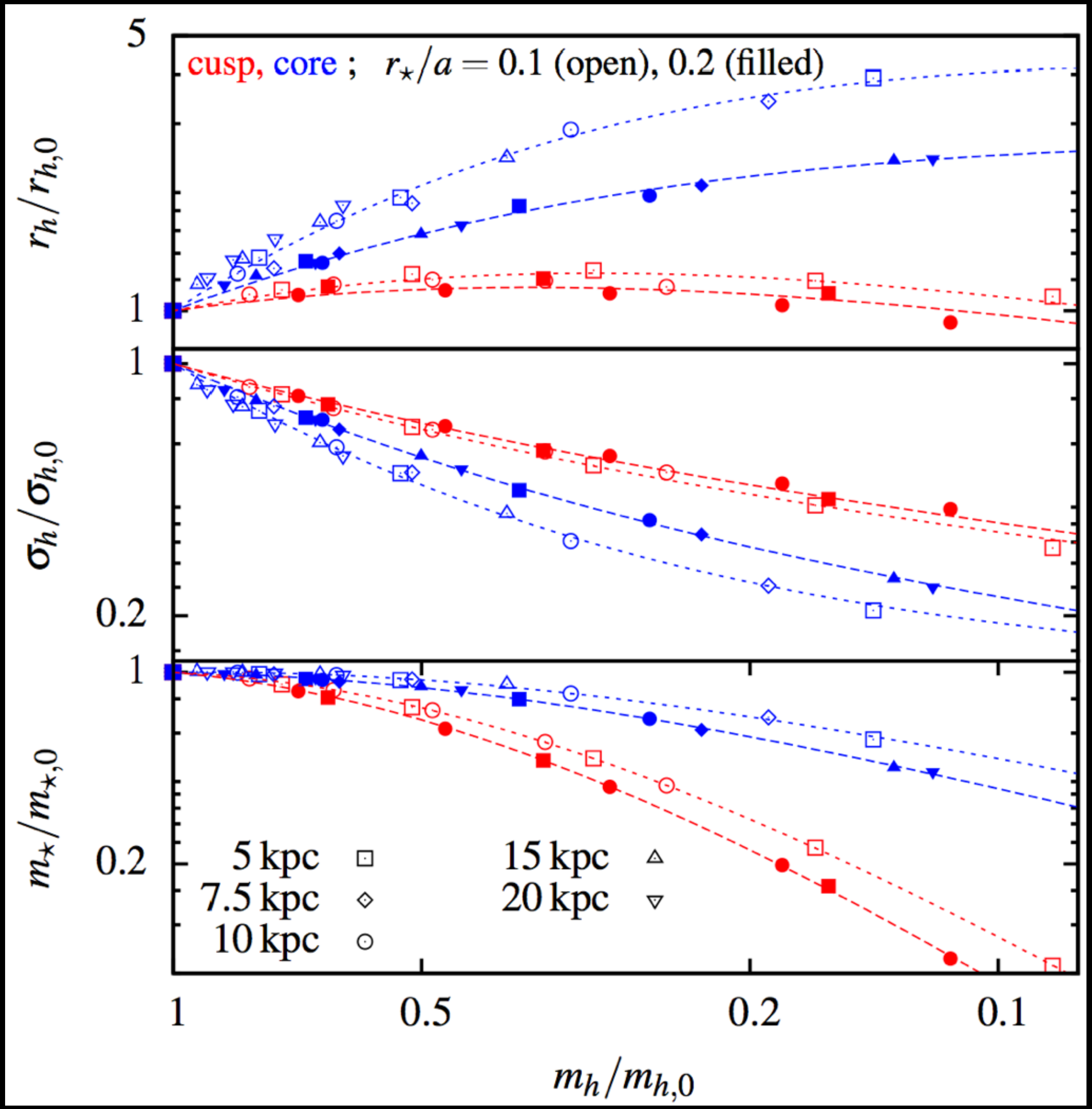
$$\frac{M_{\rm core}}{M_{\rm cusp}} = 1 + \frac{a}{r_h} > 1$$

Cored models more massive!

Stellar streams: surface density



Tidal evolution of dSphs



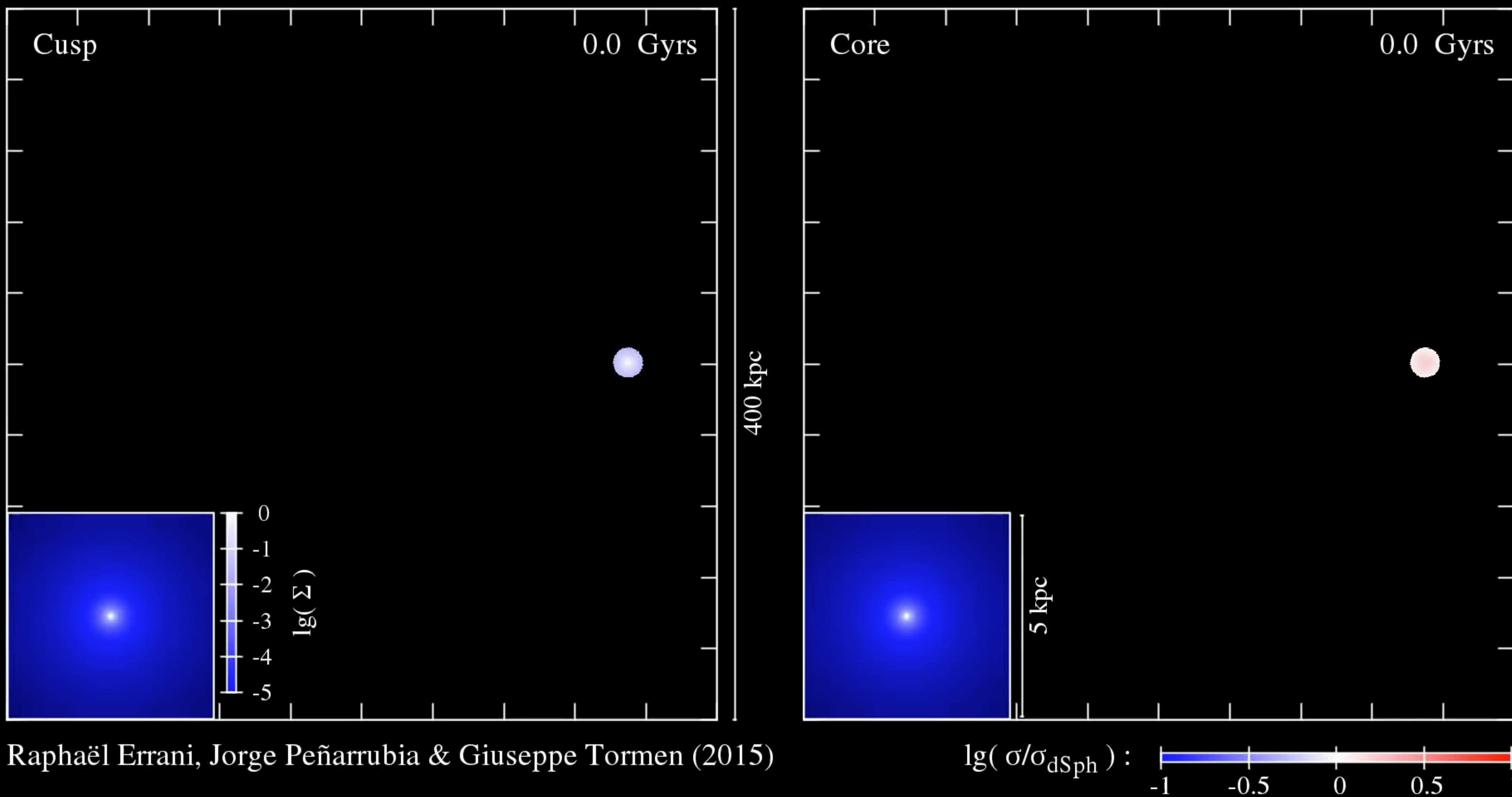
dSphs acted on by tides follow well-defined **tidal tracks**

For same amount of mass lost **cored** dSphs are **larger** and **colder** than **cuspy** dSphs

The sensitivity to core/cusp increases for *deeply segregated* stellar components ($r_* << a$)

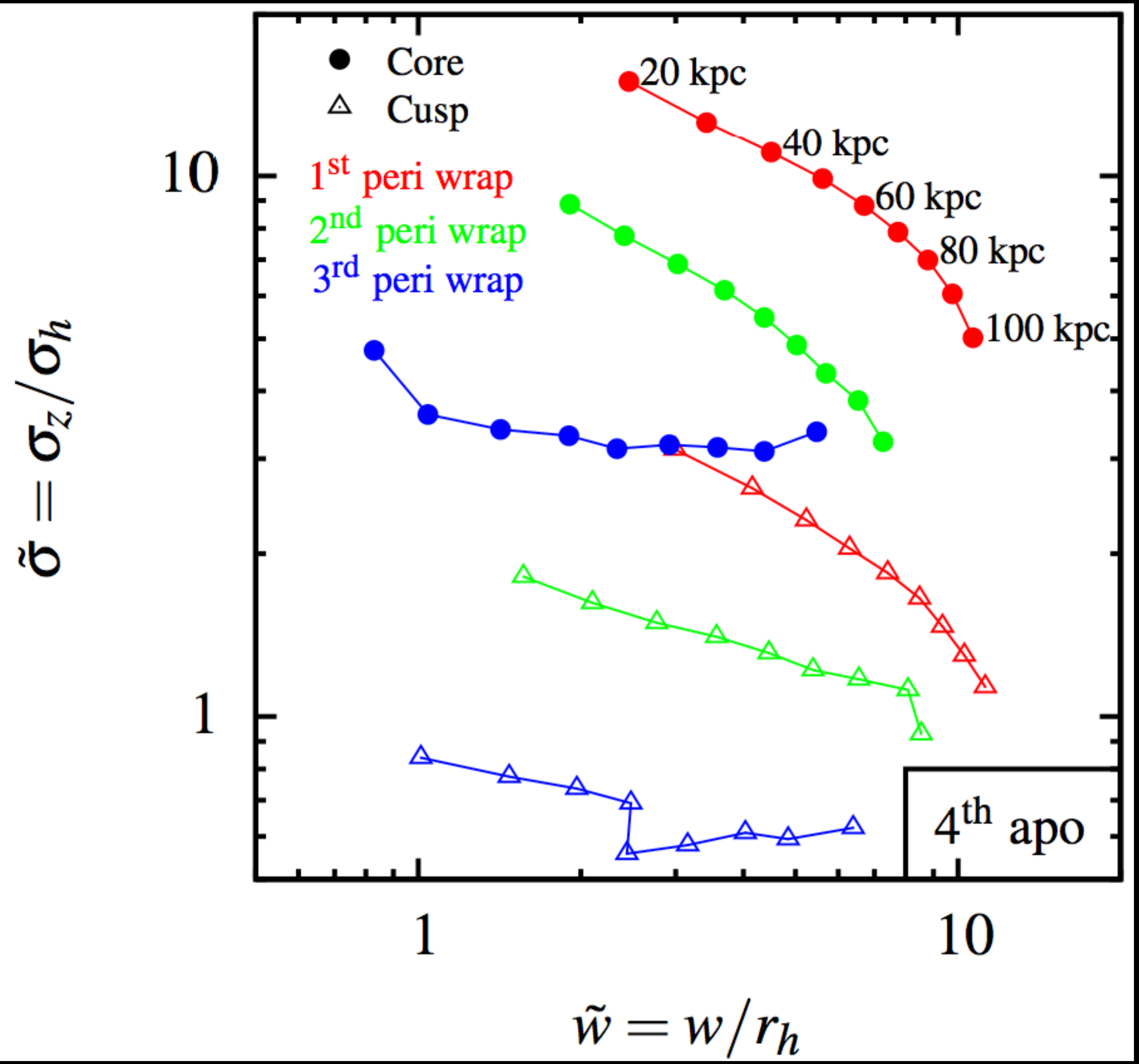
Stellar streams: kinematics

arXiv:1501.04968



Raphaël Errani, Jorge Peñarrubia & Giuseppe Tormen (2015)

Stellar streams: radial dependence

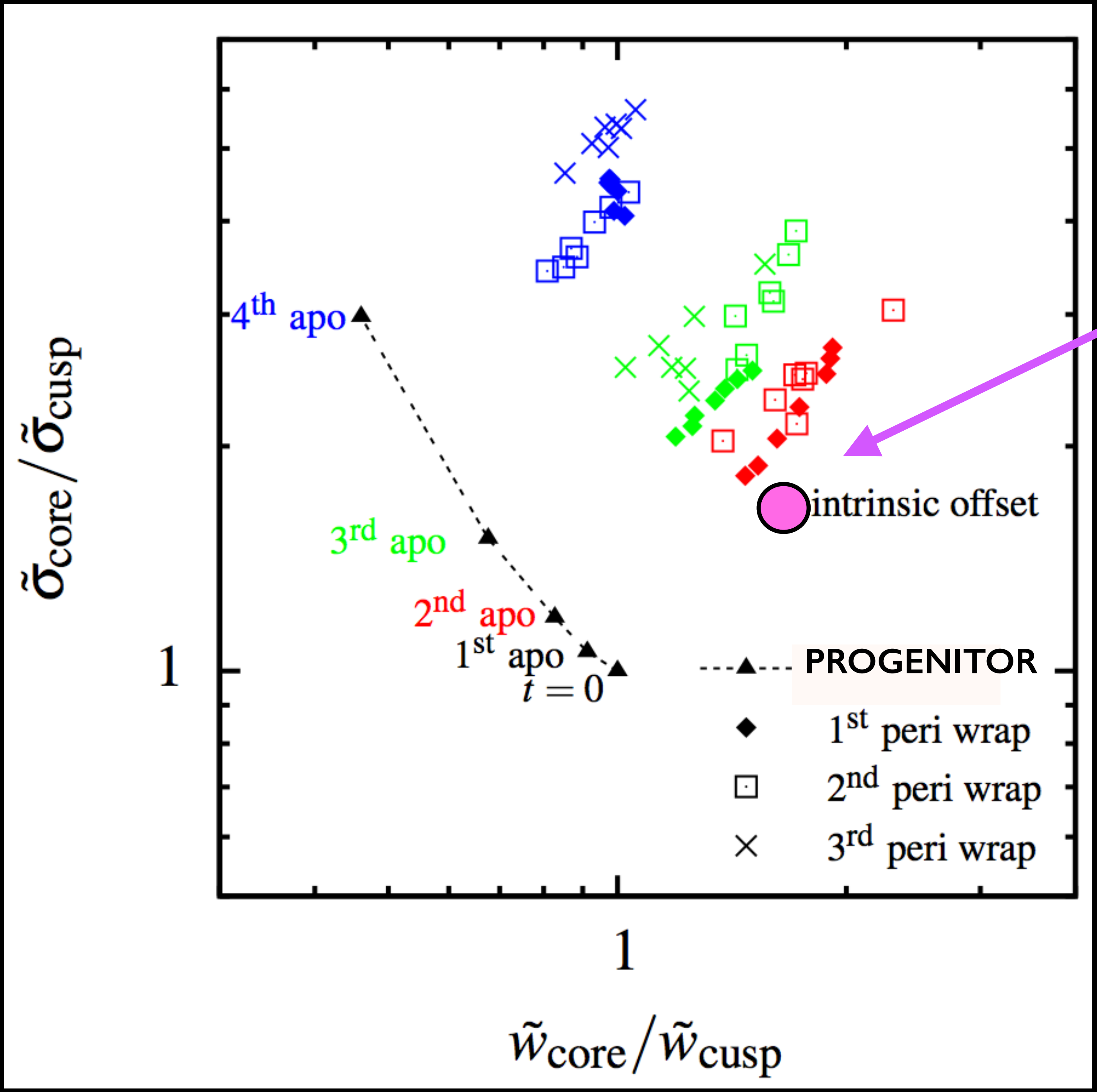


normalized **width** and **velocity dispersion** of the stream to the half-light radius and mean velocity dispersion of the progenitor:

↓

cored dSphs lead to systematically **hotter** streams

streams: core/cusp problem



Systematic offset in stream properties at t=0

$$\sigma_z \approx \left[\frac{GM(<r_t)}{r_t}\right]^{1/2}$$

$$r_t \sim M^{1/3}$$ (e.g. Amorisco 2015)

$r_{t,core}/r_{t,cusp} \simeq 1.7$

$\sigma_{z,core}/\sigma_{z,cusp} \simeq 1.7$

* fixing the progenitor's properties yields an offset in the associated stream!

* offset increases with stream age & stellar segregation

* offset evolves parallel to tidal tracks

Summary

- Equilibrium models suggest that presence of DM cores extends down to $L \sim 10^5\, L_{sol}$

- dSphs embedded in cored haloes have streams that are systematically hotter than those embedded in cuspy haloes

- Depending on the age of the stream, the velocity dispersion of cored models can be 2-4x higher than those of cuspy models

- Difference increases with stream age and stellar segregation within the progenitor's DM halo

- Sgr is the obvious target in the MW

- Such (large) kinematic differences can be straightforwardly measured in streams associated to dSphs in external galaxies

animations at:
http://www.roe.ac.uk/~raer/tidalstreams