Nature of dark matter

Fornax: cusp or core

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IAP

Nature of dark matter

- **Cold Dark Matter**
- **Warm Dark Matter**
- **Fuzzy Dark Matter**
  (Hu et al. 2000, Hui et al. 2016)
- **Self-Interacting Dark Matter**
  (Spergel & Steinhardt 2000)

Nature of dark matter: Constraints from astrophysics

- **Large-scale constraints**

e.g. CMB,Lya

- **Small-scale constraints**

e.g.
-Number of satellite galaxies
-Dark matter density profiles of galaxies: cusp-core

Nature of dark matter:
Constraints from astrophysics

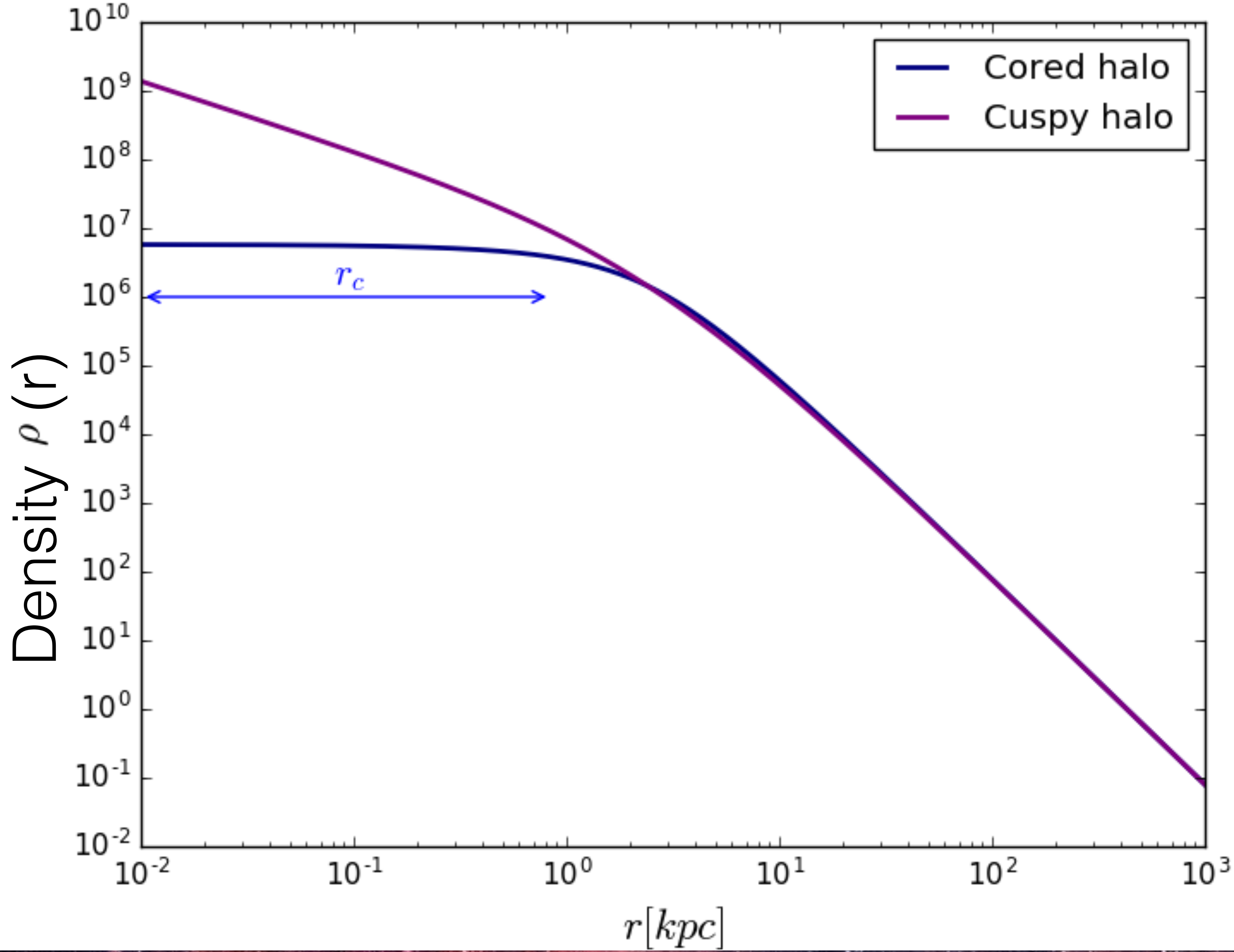
- **Large-scale constraints**

  e.g. CMB

- **Small-scale constraints**

e.g. Number of satellite galaxies,
dark matter density profiles of galaxies: cusp or core

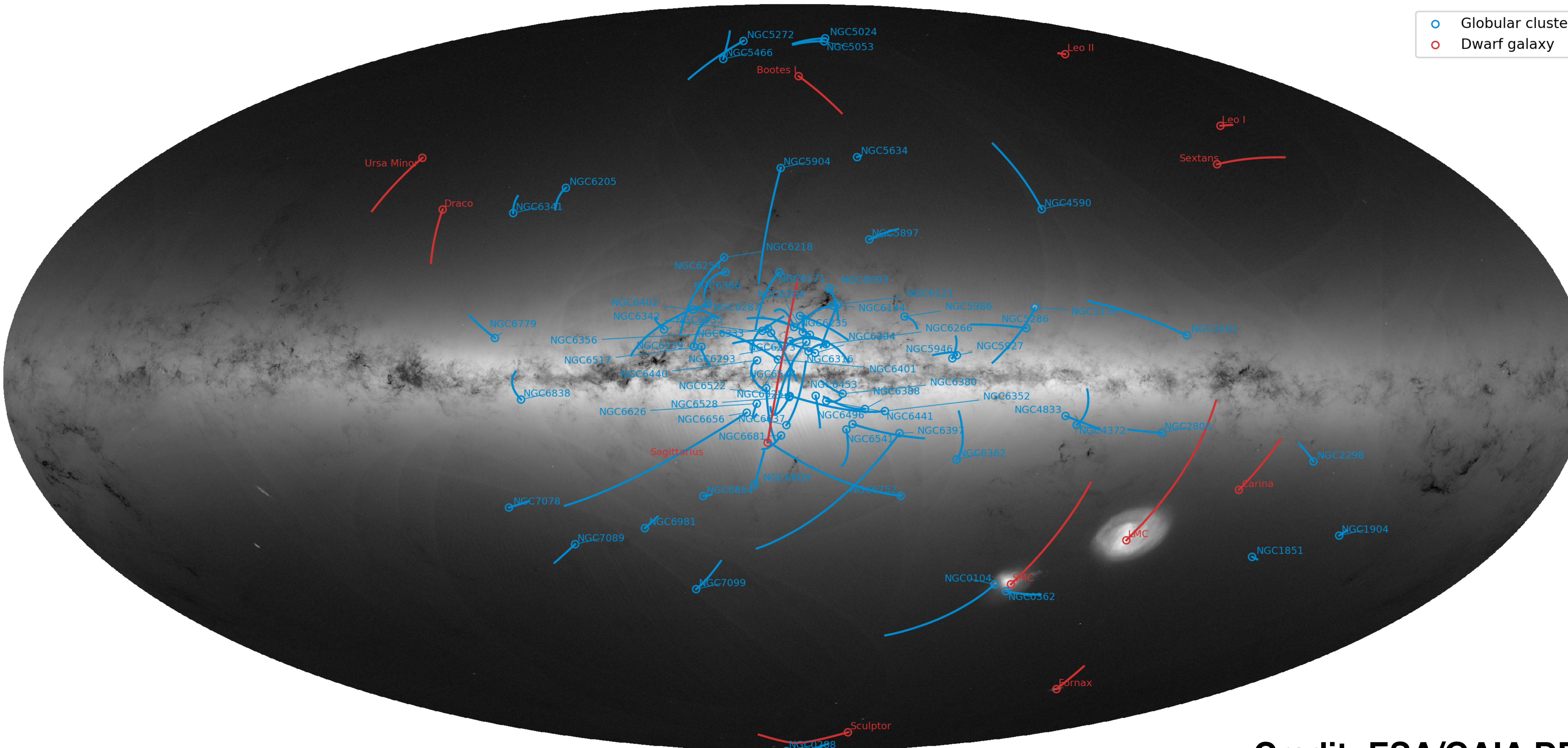
Cusp or core ?


Cored halo
Cuspy halo
r_c
Density ρ (r)
$r[kpc]$
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Nature of dark matter: cusp or core

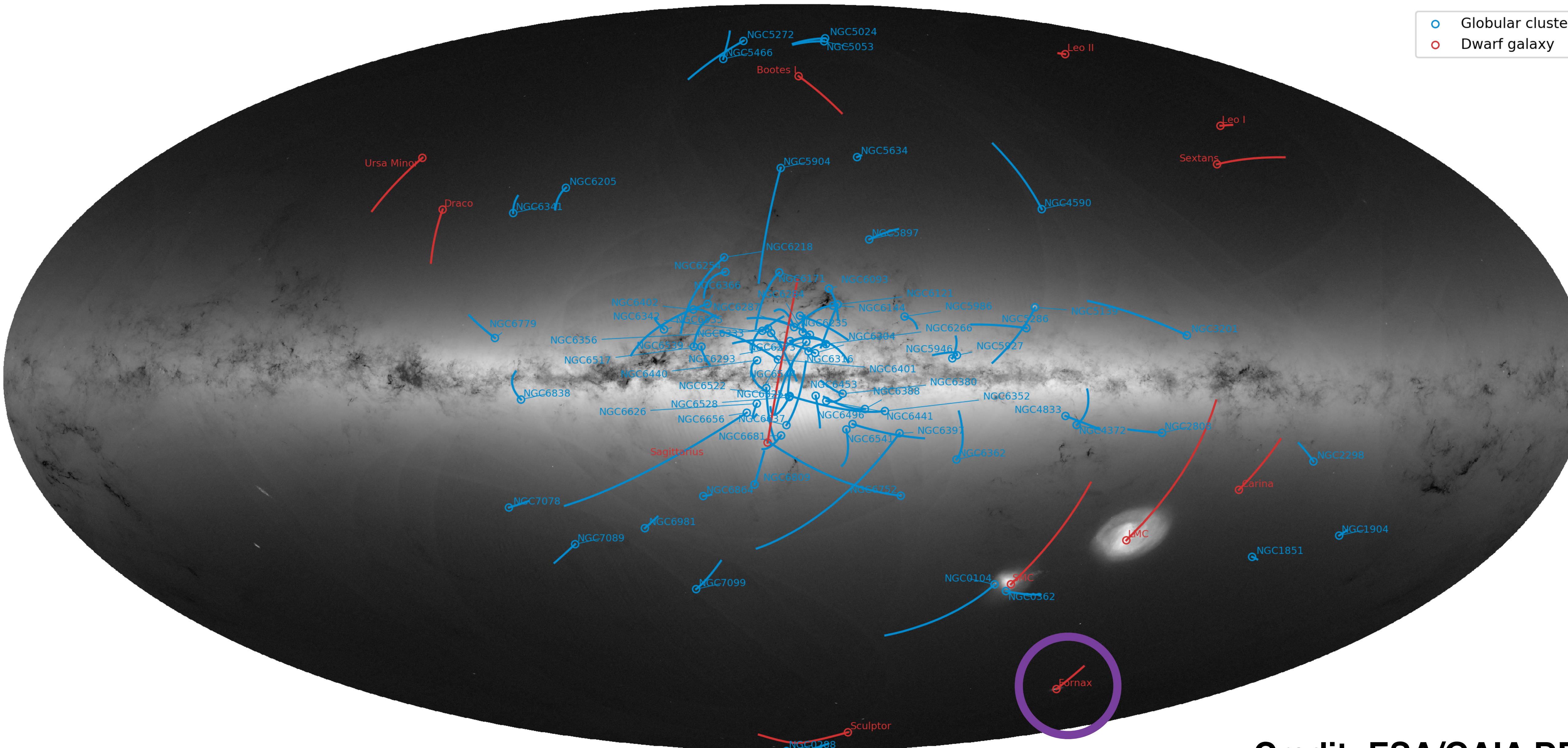
- **Cold Dark Matter** — **Cusp**
- **Warm Dark Matter** — **Core**
  (Colin et al. 2000; Bode et al. 2001)
- **Fuzzy Dark Matter** — **Core**
  (Hu et al. 2000; Hui et al. 2017)
- **Self-Interacting Dark Matter** — **Core**
  (Vogelsberger et al. 2012)

Cusp or core:
Observations of dark matter rich dwarf galaxies



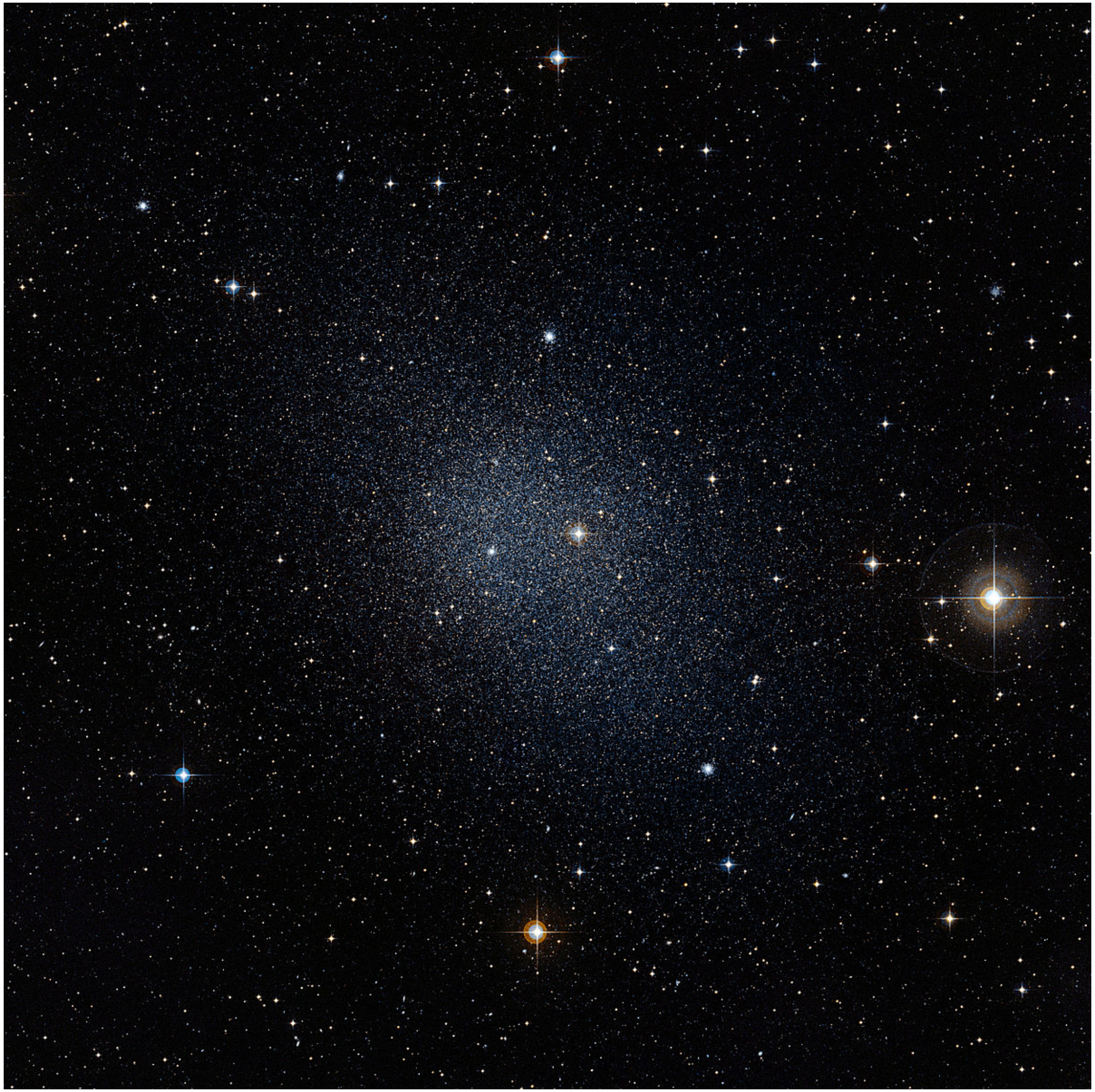
Credit: ESA/GAIA DR2

Cusp or core:
Observations of dark matter rich dwarf galaxies



Credit: ESA/GAIA DR2

Fornax dwarf galaxy

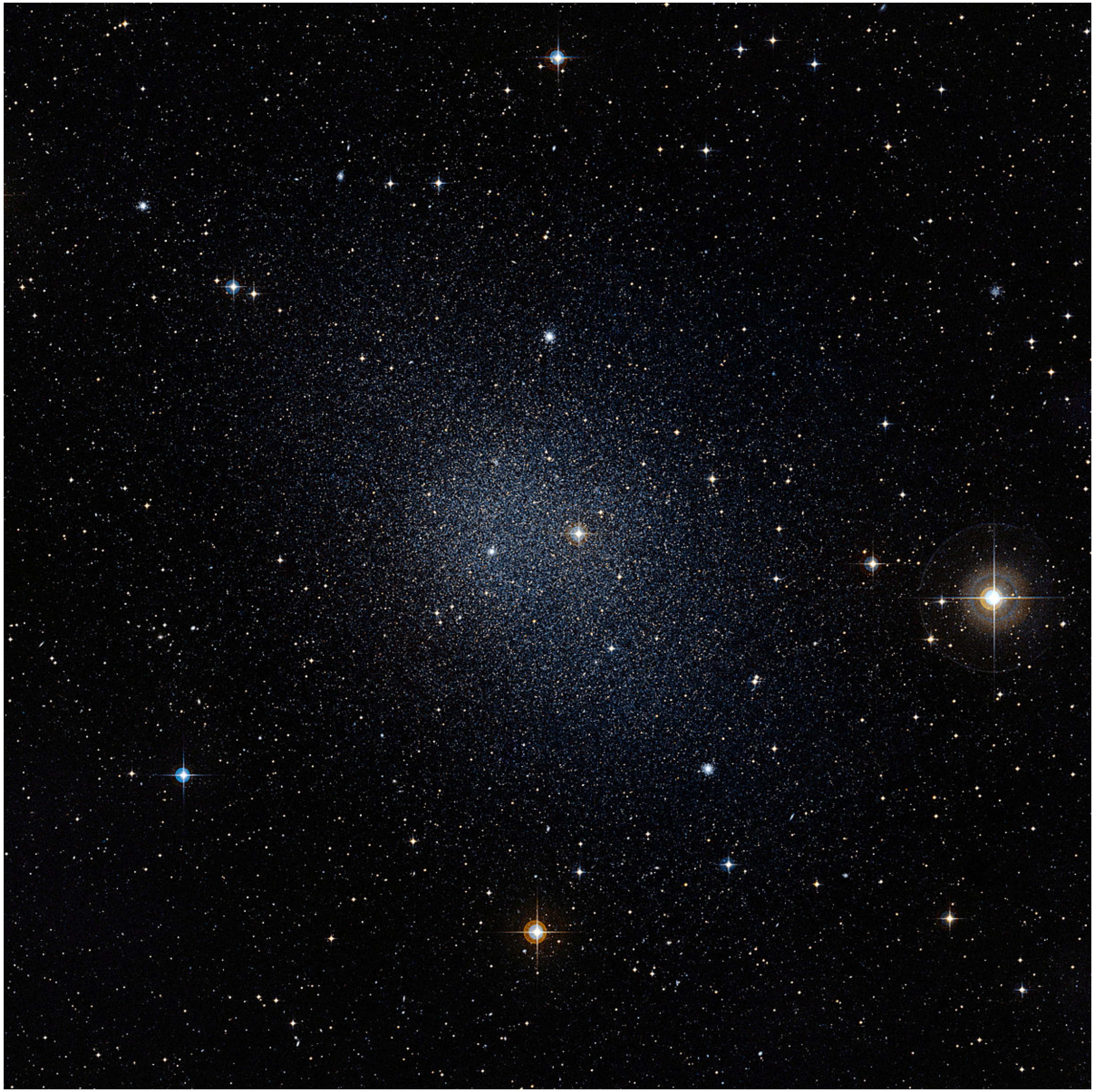


Cusp or core ?

- Kinematic data (Jeans modeling, simulations, …)
- Globular cluster data (positions, masses)

Credit: ESO/Digitized Sky Survey 2

Fornax dwarf galaxy



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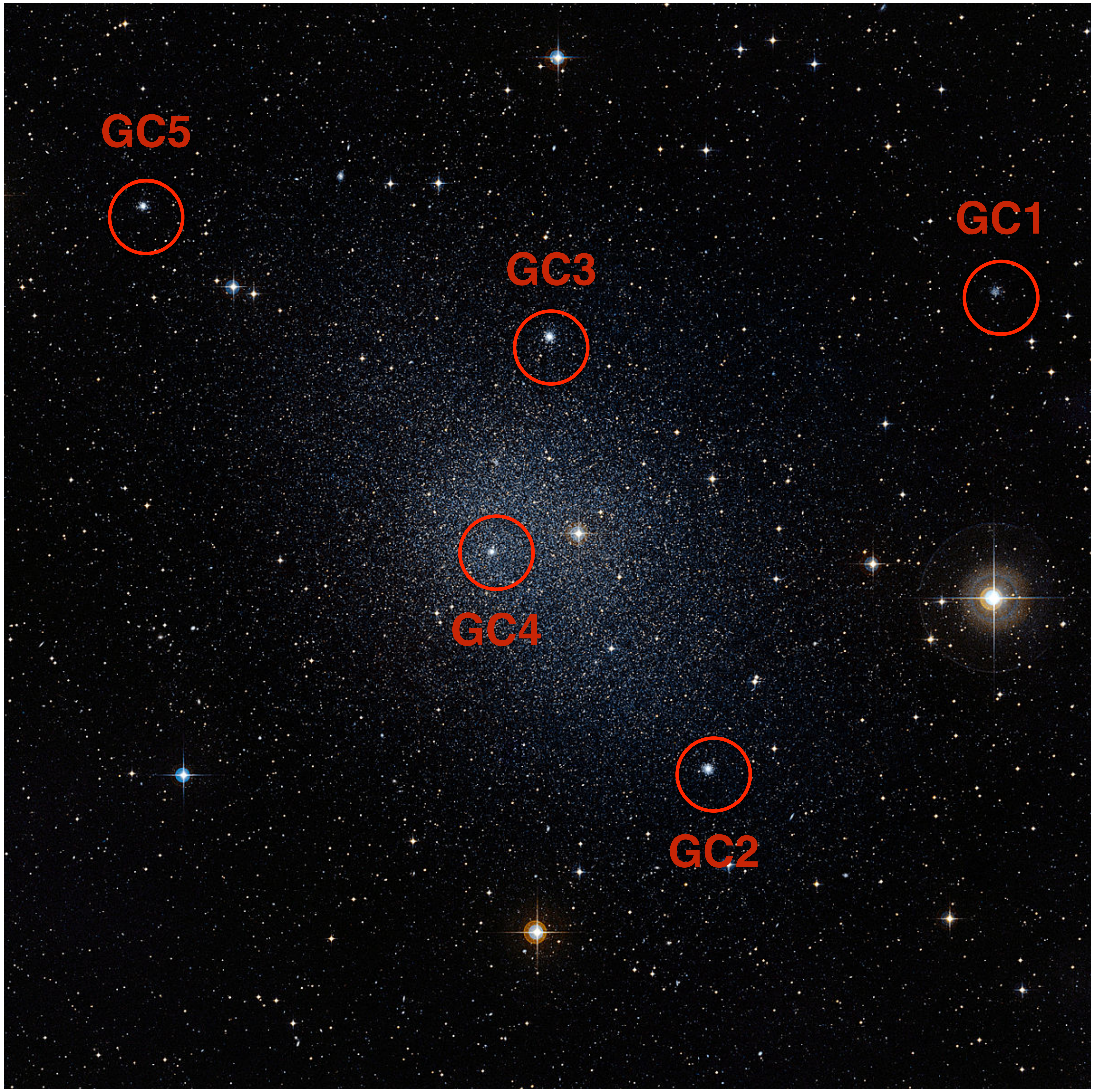

Cusp or core ?

- Kinematic data (Jeans modeling, simulations, …)
- spatial distribution and masses of Fornax globular clusters

Credit: ESO/Digitized Sky Survey 2

Sinking of globular clusters: Dynamical friction

$$F_{dyn} \propto \frac{\rho(r) M_{GC}^2}{V_c^2}$$

(Chandrasekhar 1943)

Dynamical friction

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The timing problem

(Chandrasekhar 1943)

Dynamical friction

$$F_{dyn} \propto \frac{\rho(r) M_{GC}^2}{V_c^2}$$

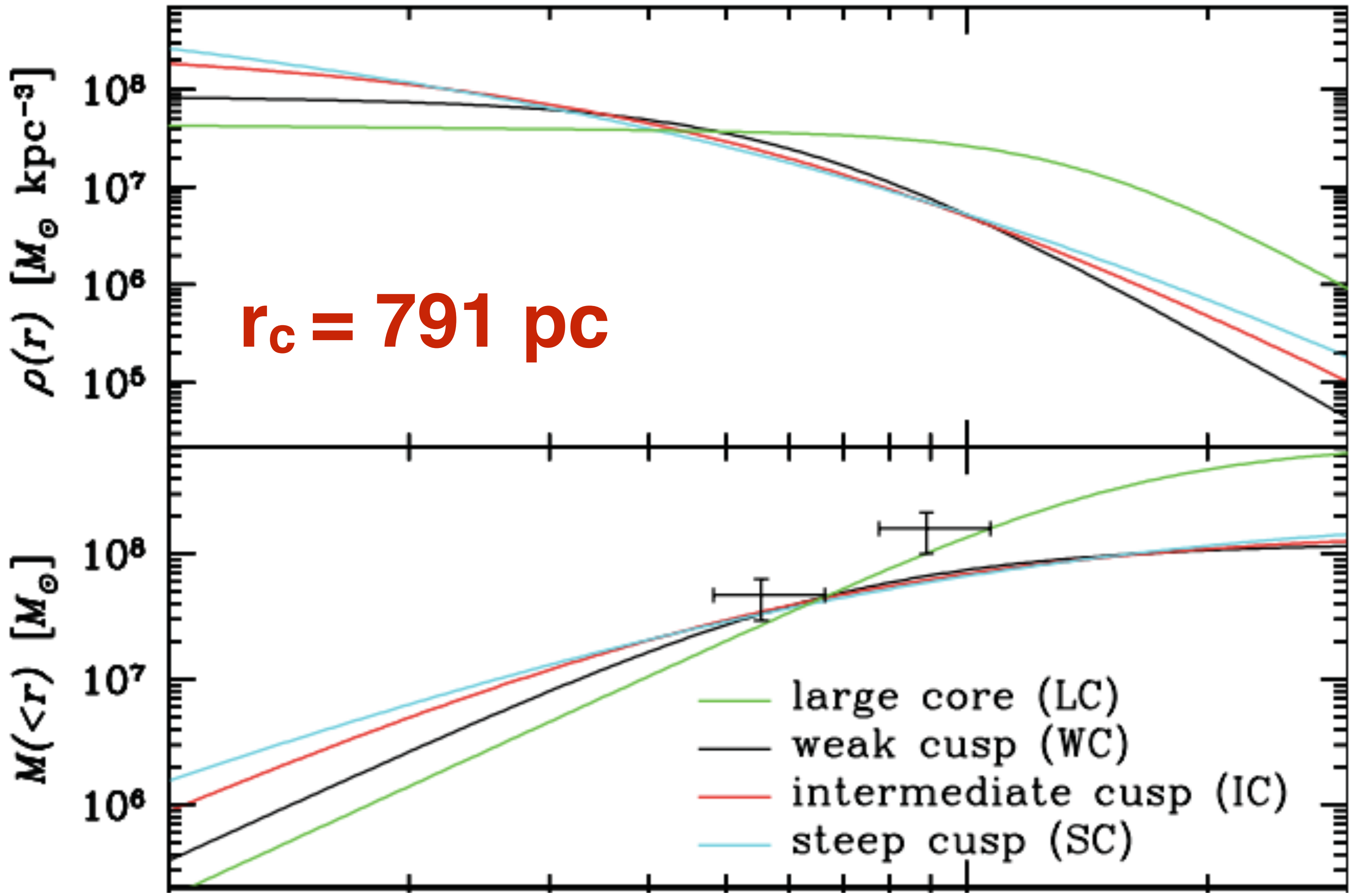
~~The timing problem~~

Cusp or Core ?

(Chandrasekhar 1943)

Timing problem: Cusp-core
Previous works

Previous works



Halo composed of particles
+
GC (single particle)

Cusp

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{r(r_s + r)^2}$$

Core

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

Previous works

Two solutions to the timing problem

Previous works

Two solutions to the timing problem

Large Core

Previous works

Two solutions to the timing problem

Large Core

↓

A steady-state solution

Previous works

Cole et al. 2012

Two solutions to the timing problem

Large Core | **Weak Cusp**

↓

A steady-state solution

Previous works

Two solutions to the timing problem

Large Core → A steady-state solution

Weak Cusp → An evolving solution

How to improve simulations ?

- Globular cluster point mass

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- Globular cluster point mass → **No mass loss**

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- No stellar component

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How to improve simulations ?

- Globular cluster point mass → **No mass loss**
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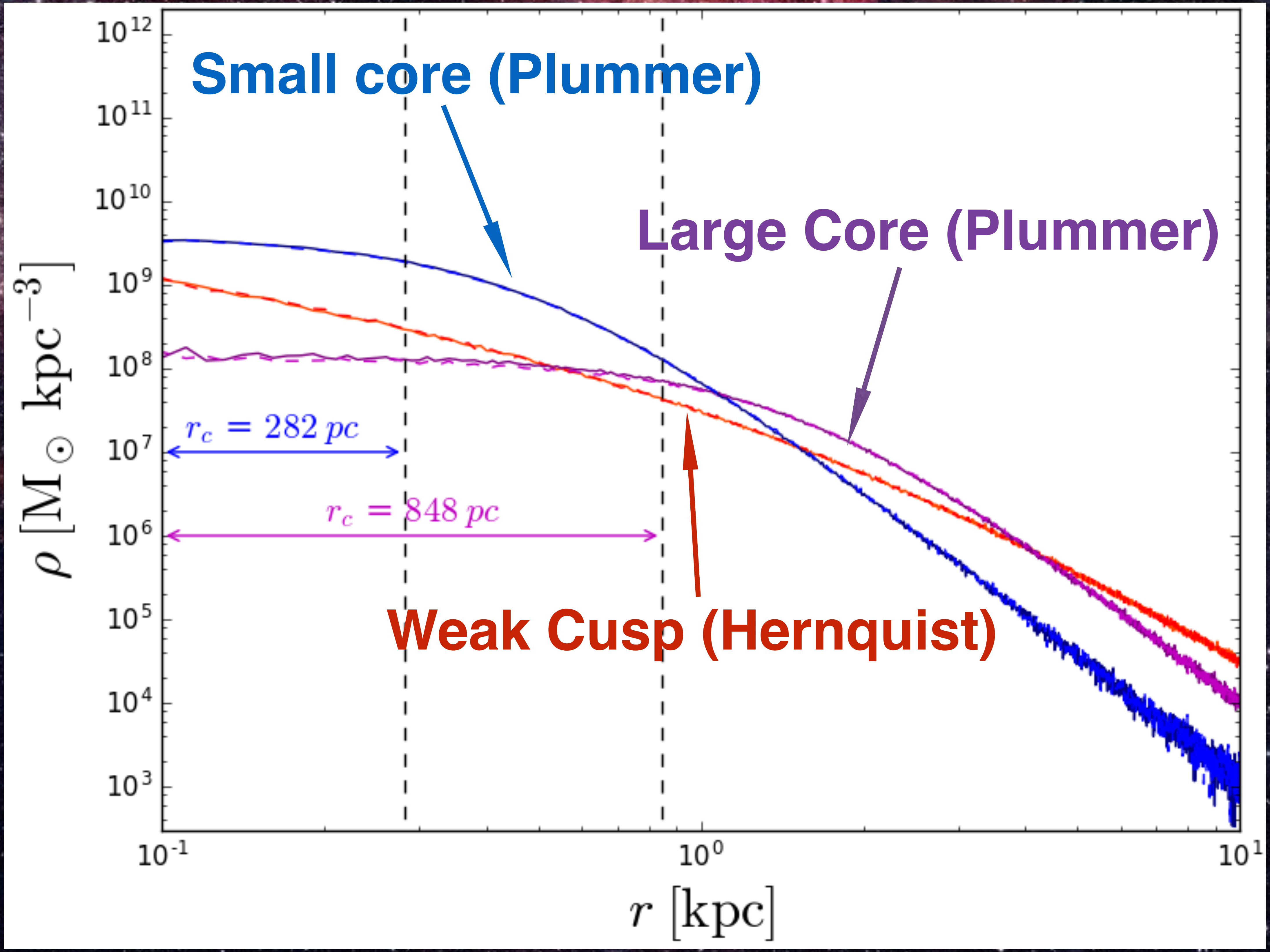
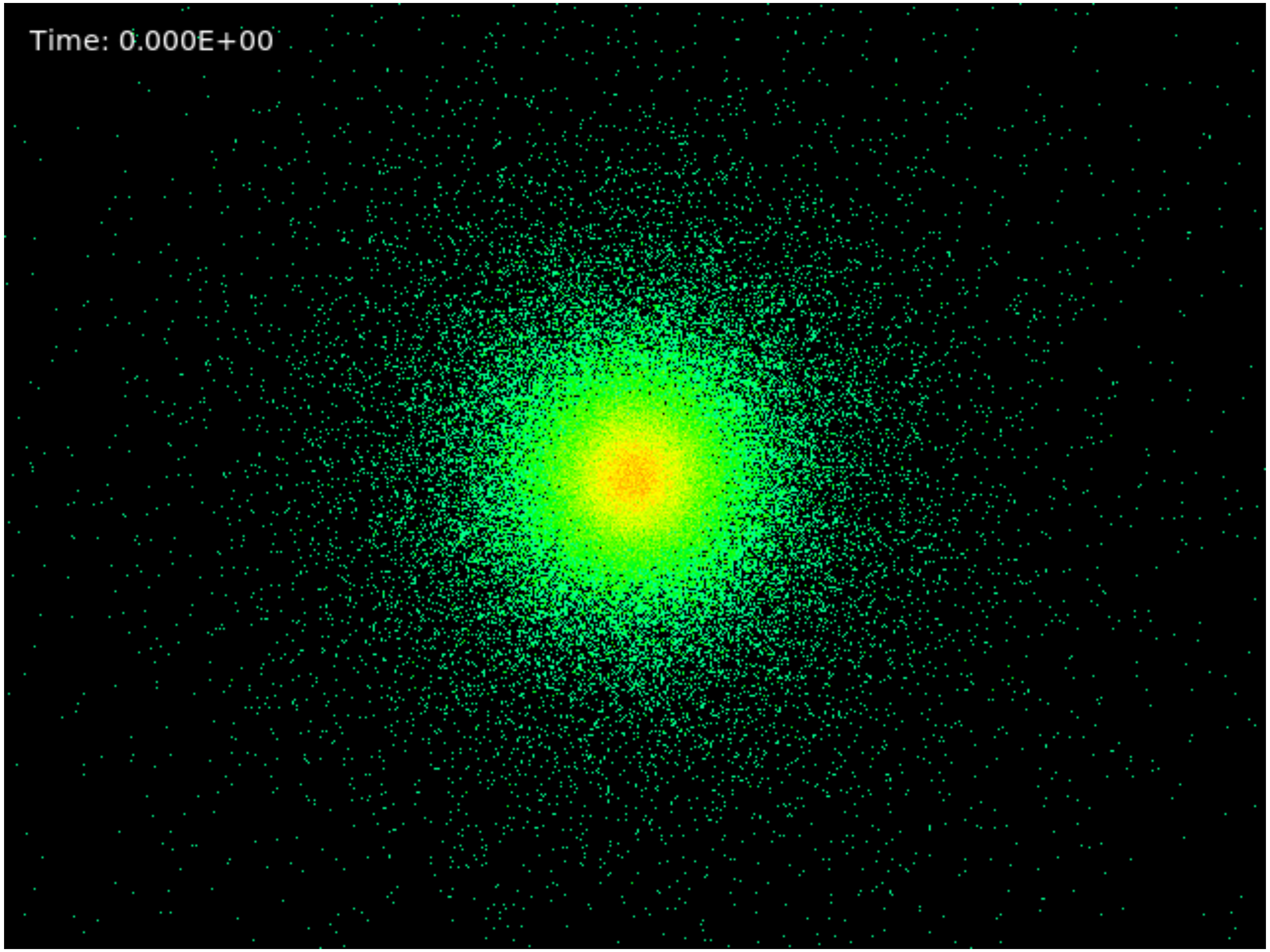
Dynamical friction
&
Tidal effects
are not properly taken into account !

Our work

DM density profiles of Fornax

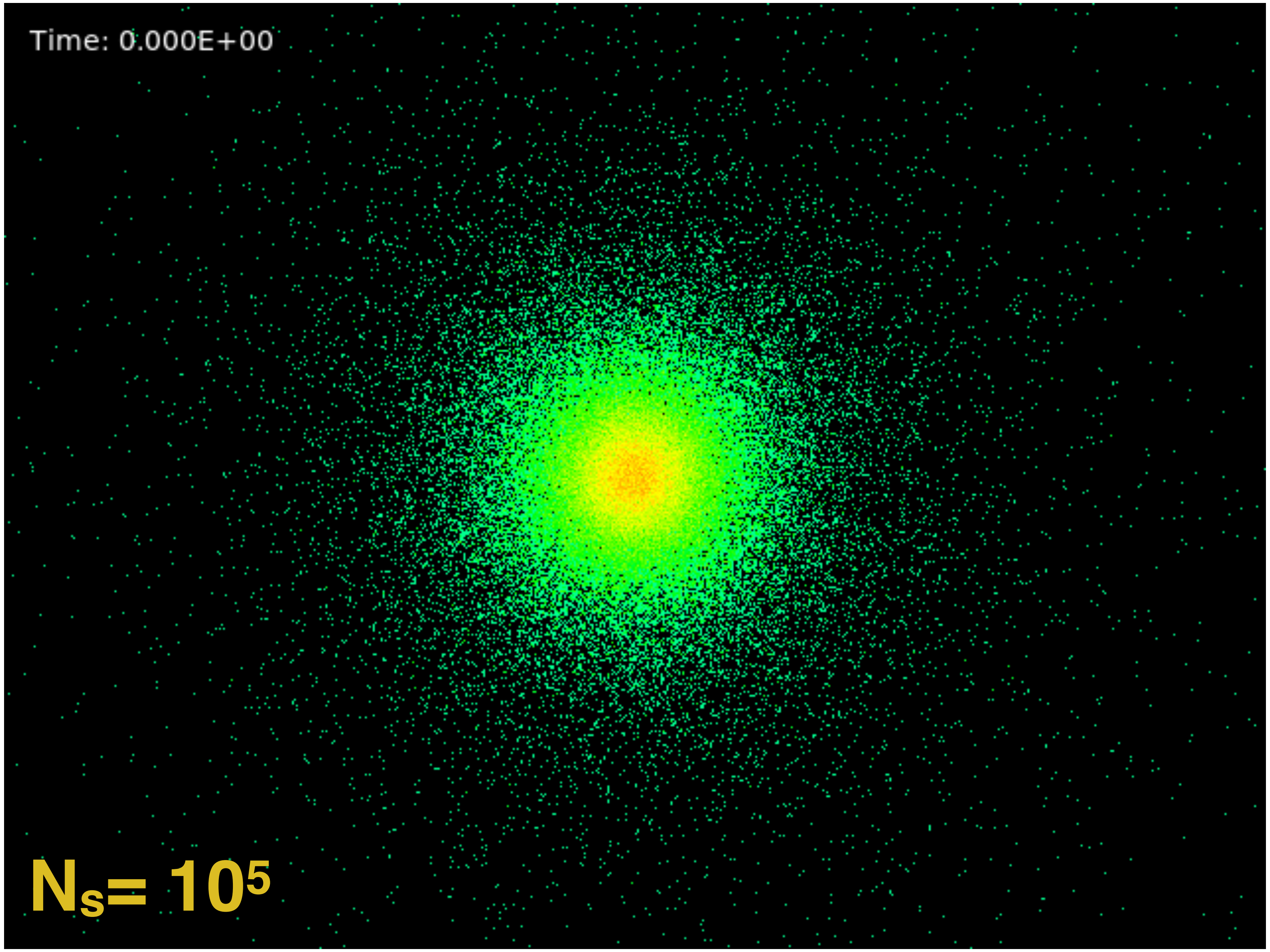


Initial conditions

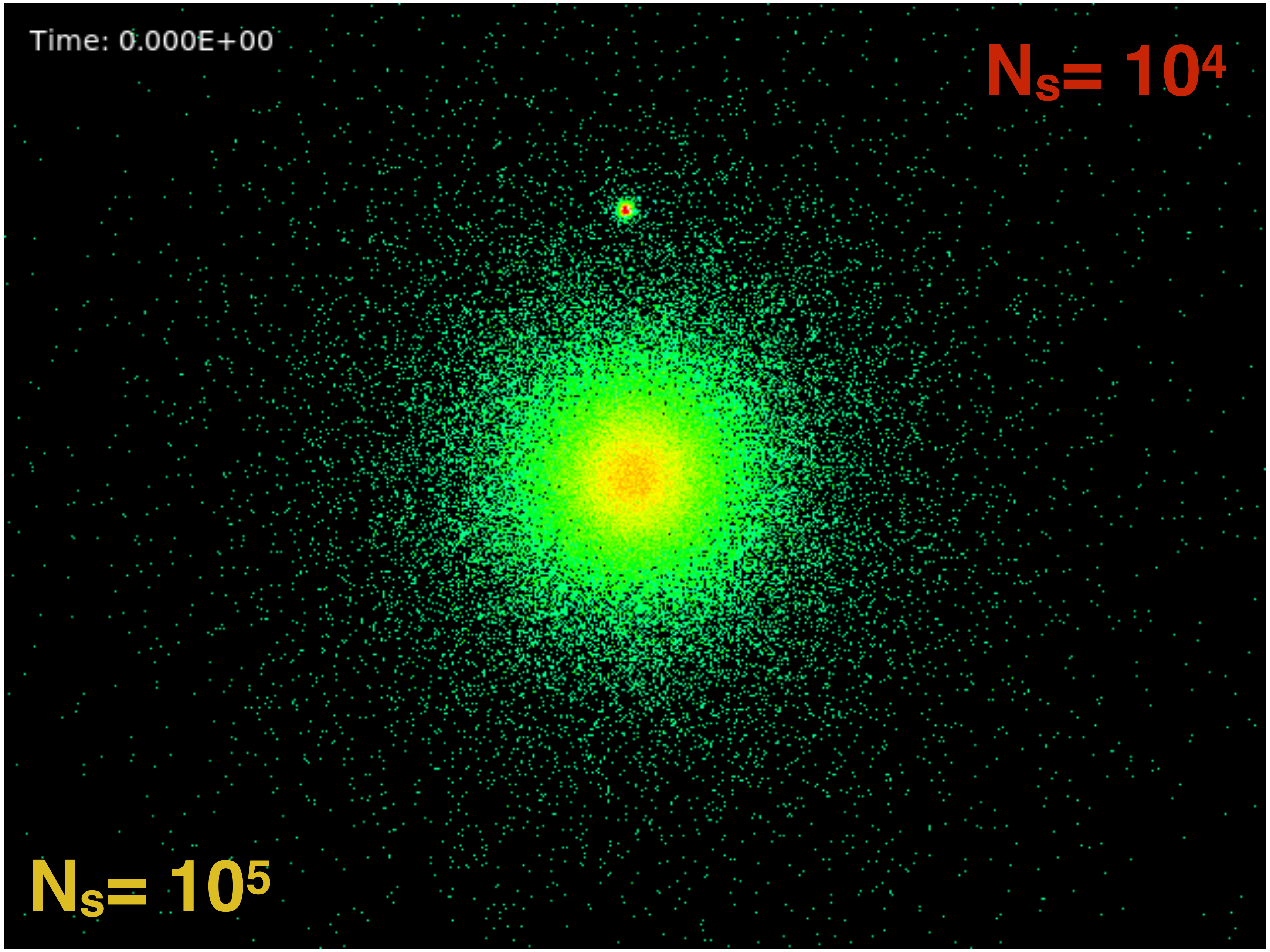


NBODYGEN (Sadoun et al. 2014)

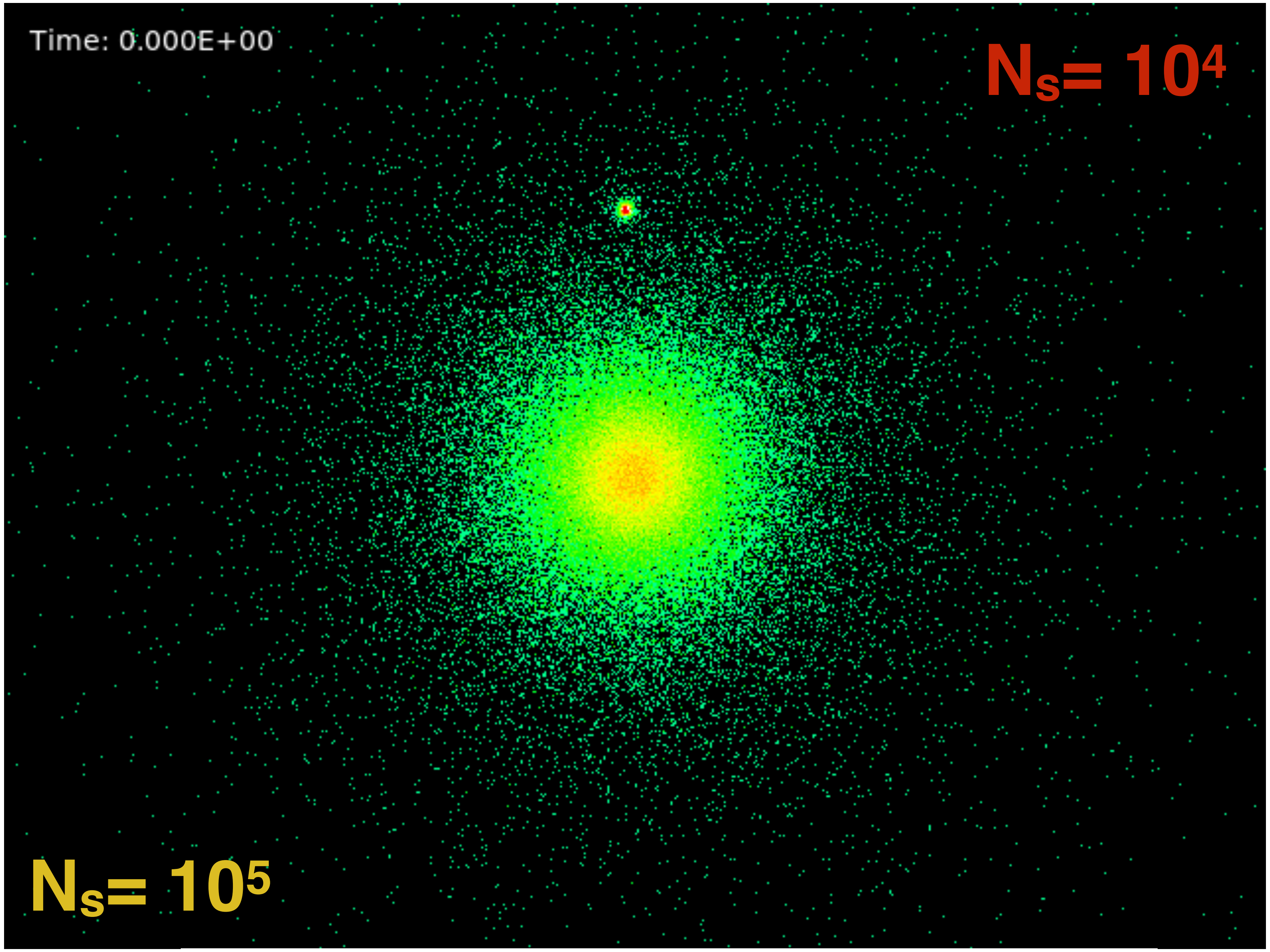
Initial conditions



Initial conditions

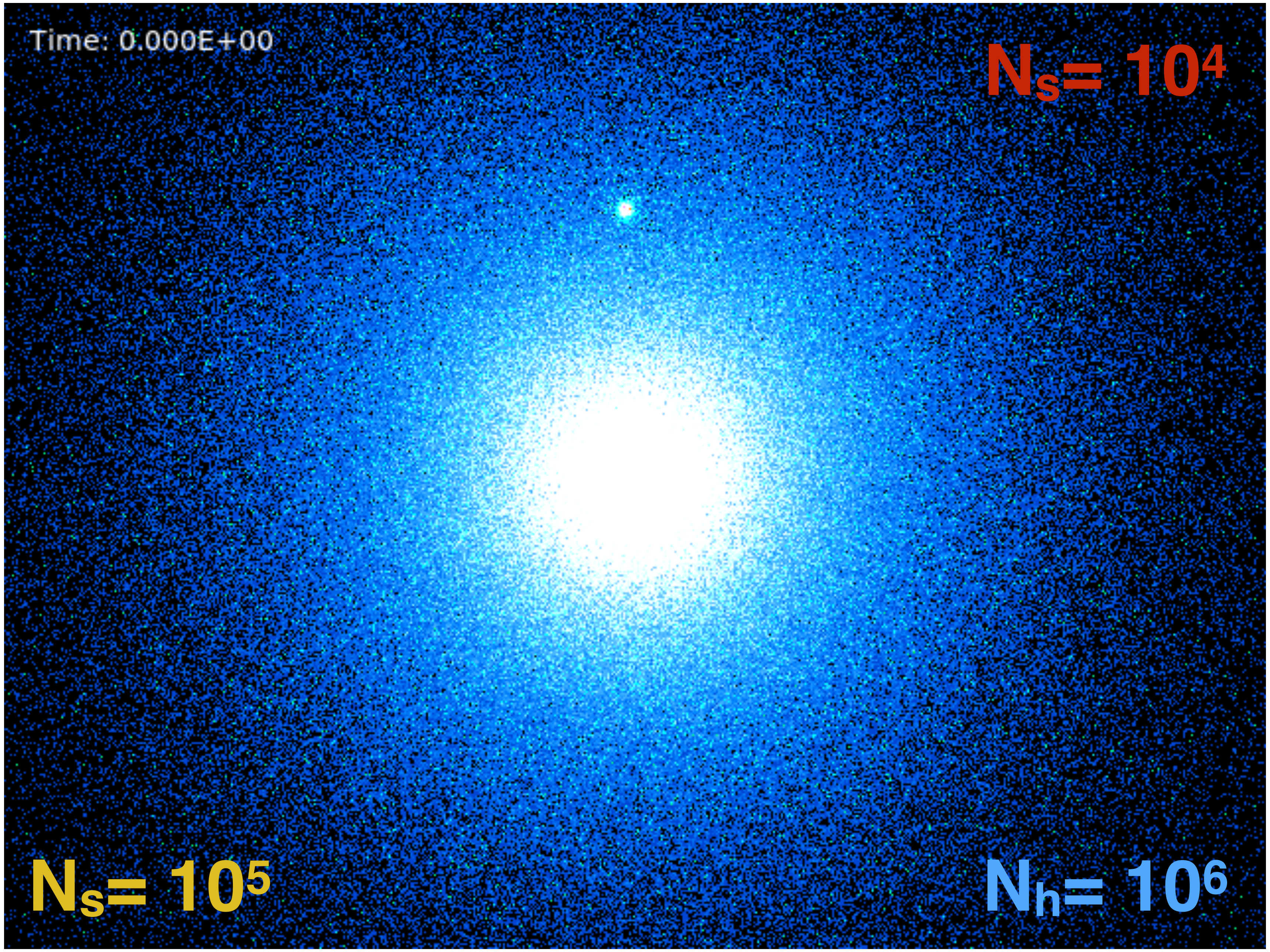


Initial conditions



$$V_c^2(r) = \frac{4\pi G}{r} \int_0^r \rho(u) u^2 du$$

Initial conditions



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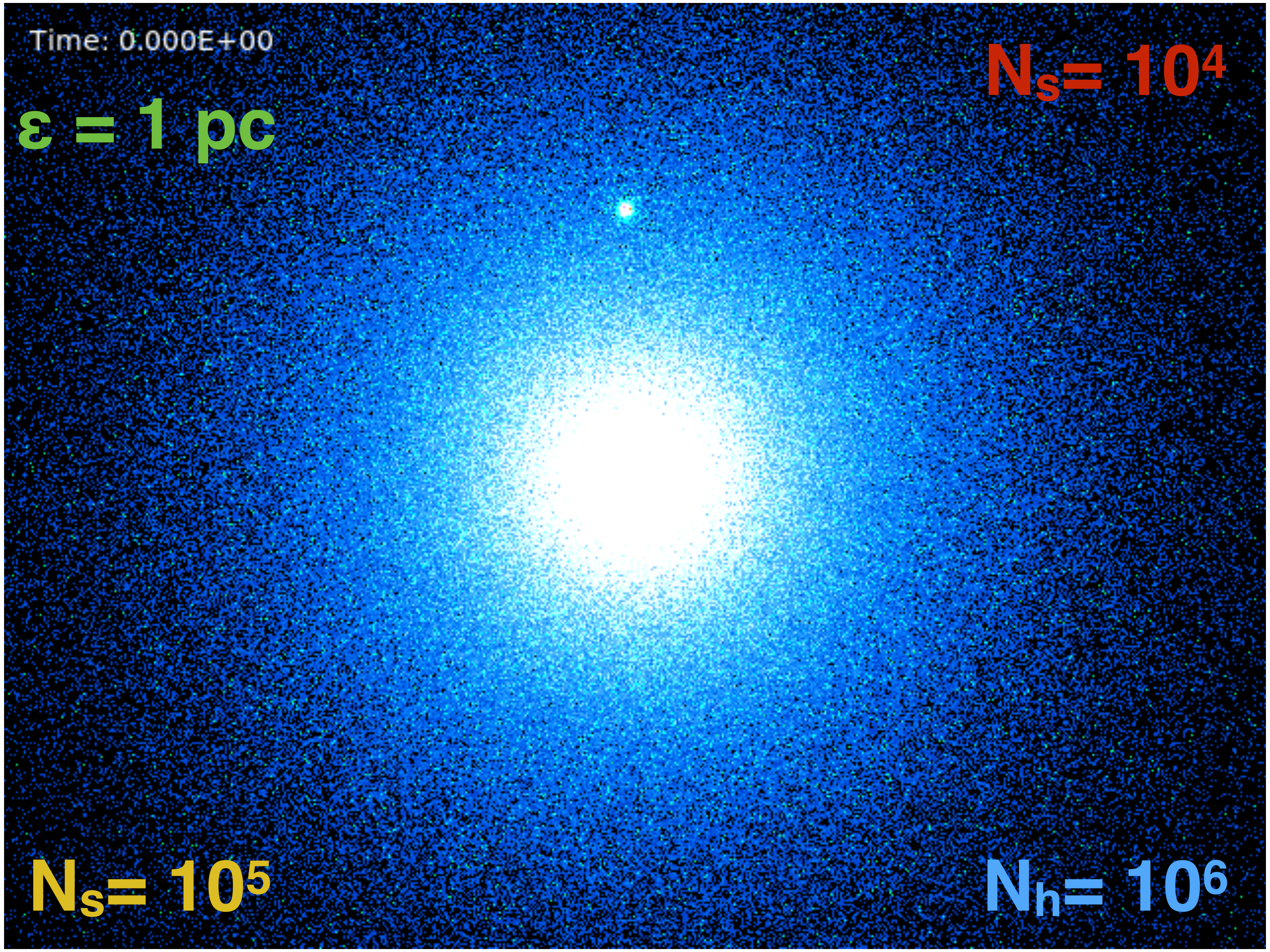
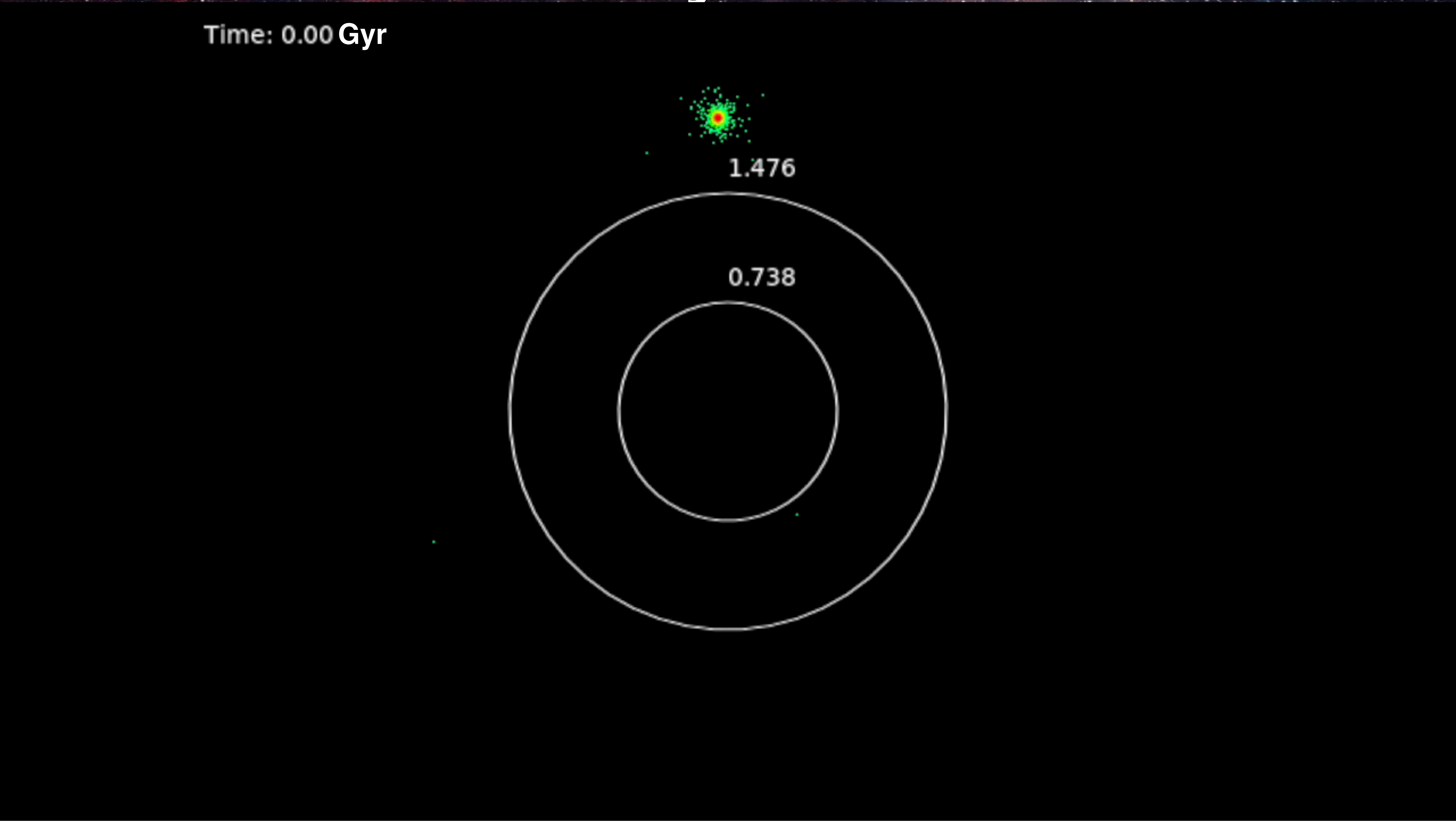
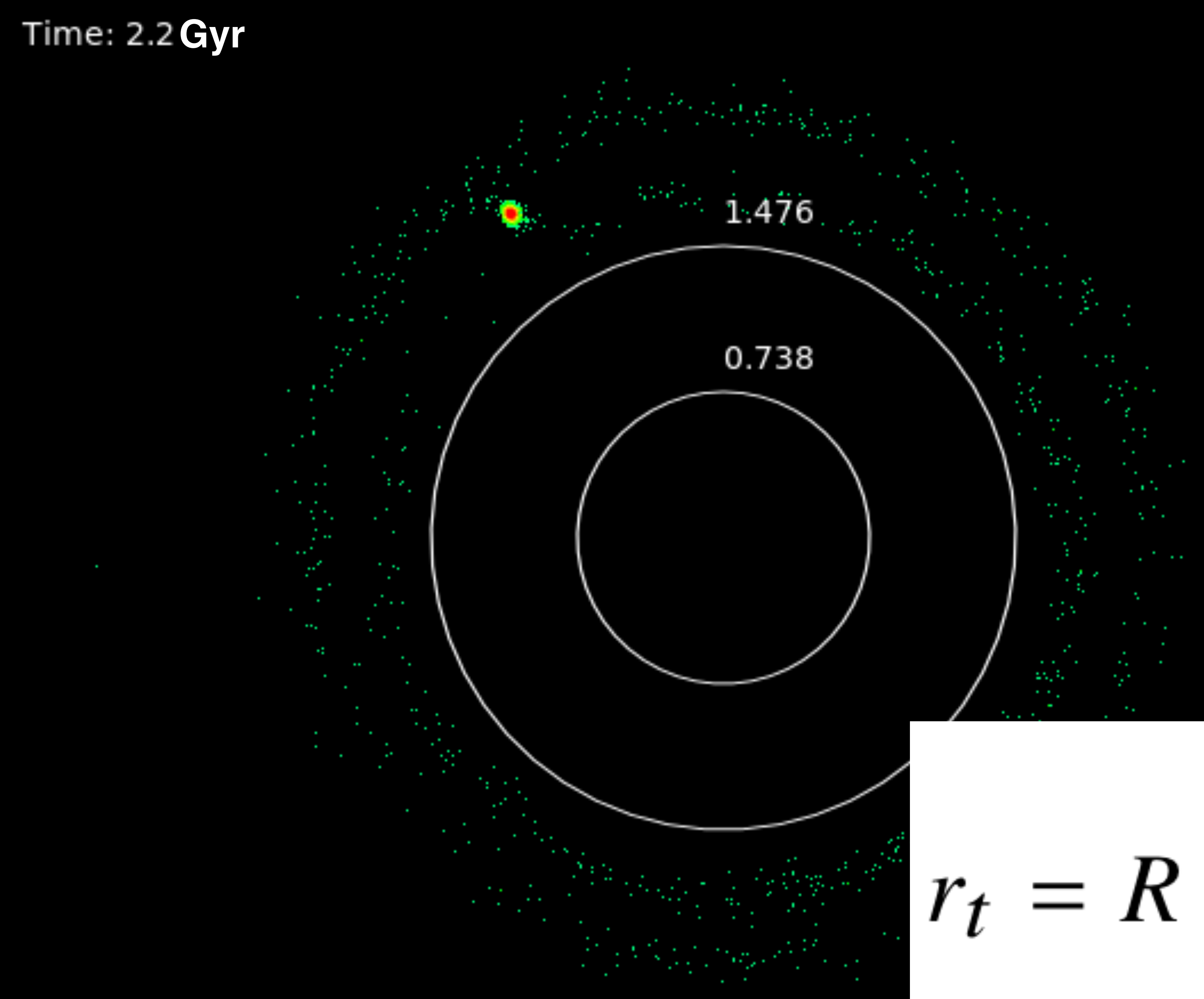


Live N-body simulations



(Gadget Viewer)

Live N-body simulations: Tidal forces



$$r_t = R\left(\frac{M_{GC}}{3M_F}\right)^{1/3}$$

(Gadget Viewer)

Free parameters for globular clusters: initial radius

- Initial radial distance of globular clusters

- Initial globular cluster mass

Free parameters for globular clusters: initial radius

- Initial radial distance of globular clusters
  - $0.24 < D_p < 1.6$ kpc
  - $R_t \sim 2$ kpc **(Walker & Penarrubia 2011)**
- Initial globular cluster mass

Free parameters for globular clusters: initial mass

(Larsen et al. 2012)	**Stellar mass**	**Metal-poor stars**
Fornax field	**3.82 x10⁷ M☉**	**44.9 x10⁵ M☉**
5 Globular clusters	**9.57 x10⁵ M☉**	**8.81 x10⁵ M☉**
Fraction		

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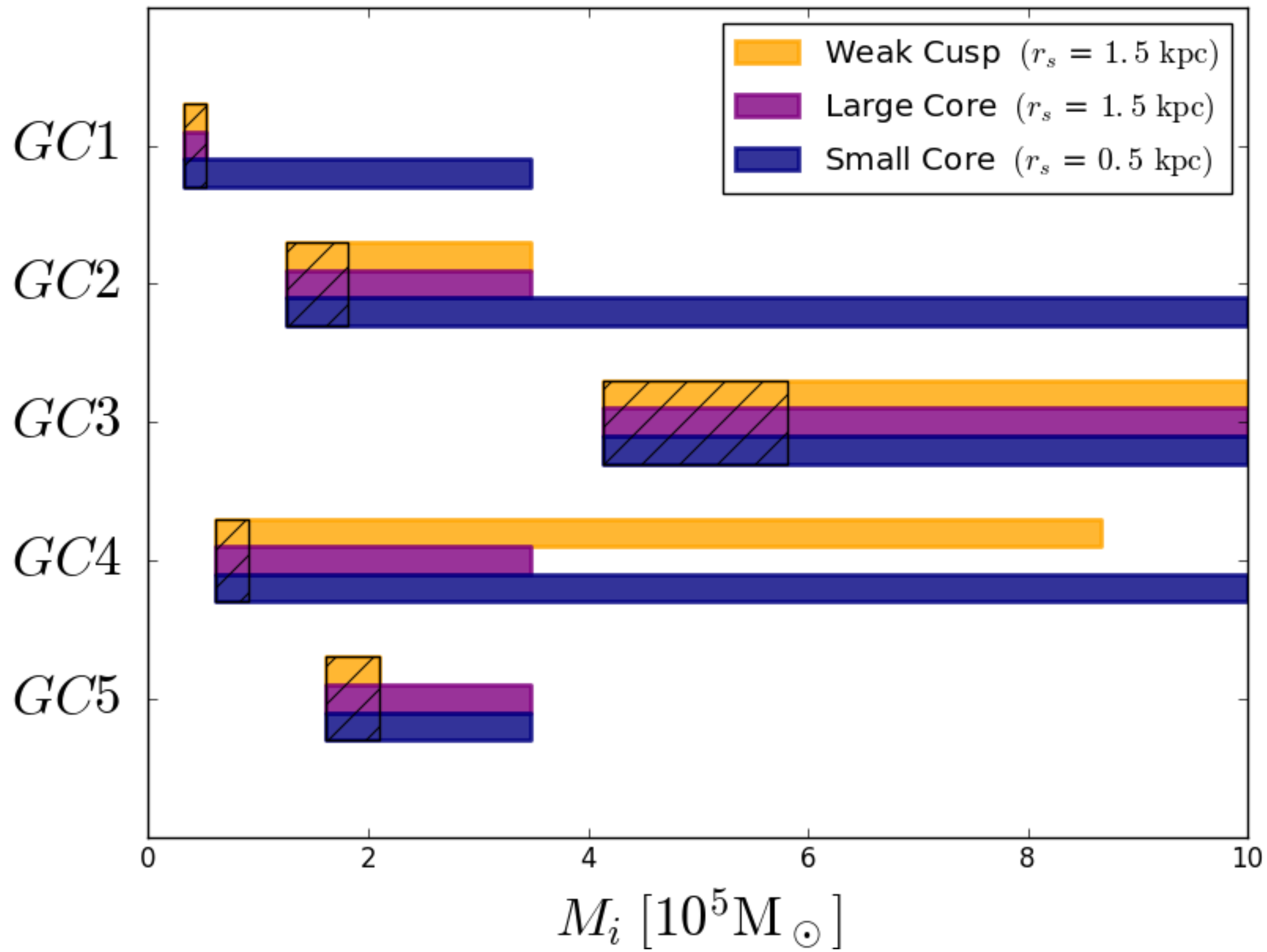
Fraction	2.5 %	19.6 %

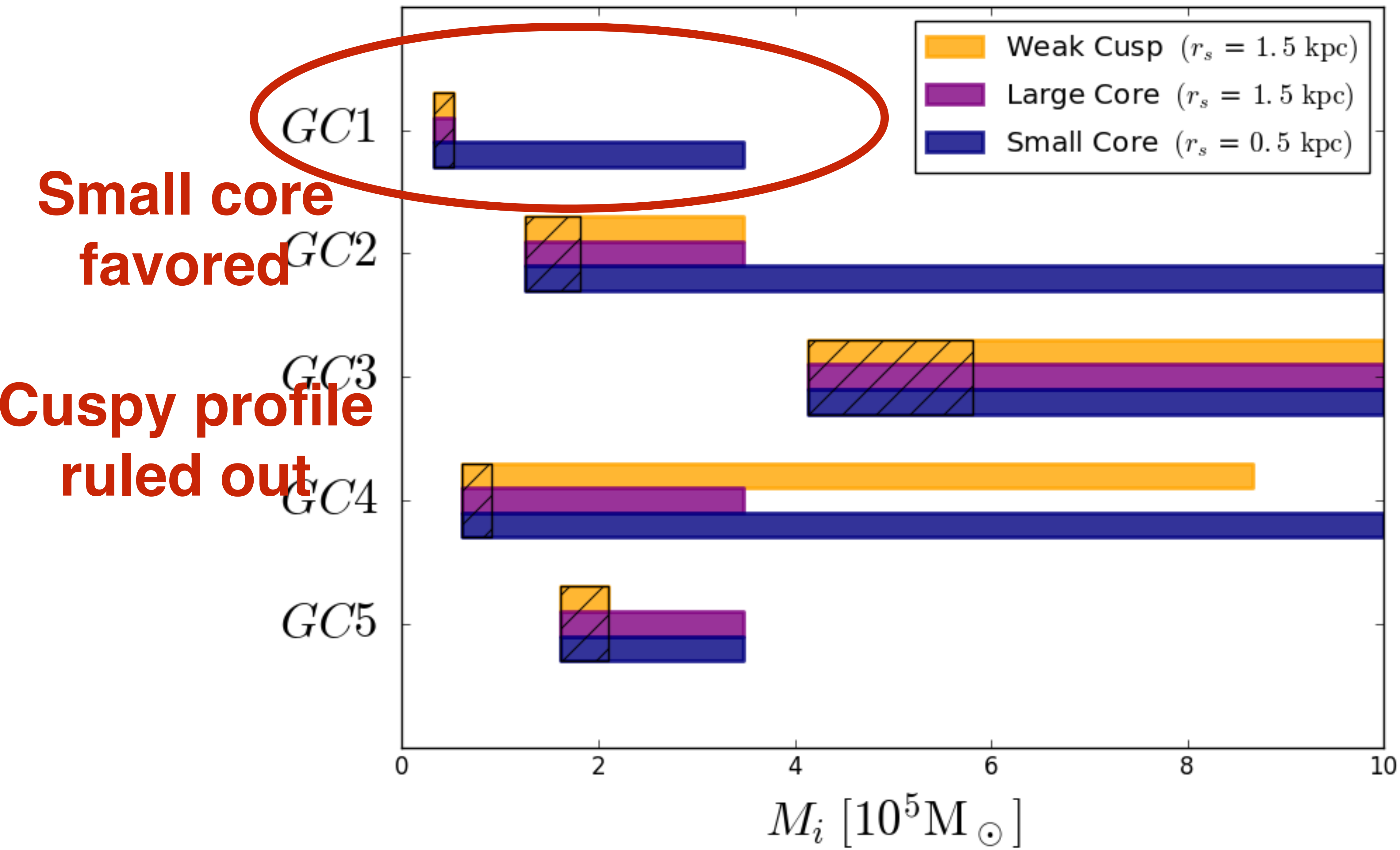
Globular clusters were initially more massive !

Summary



(Boldrini, Mohayaee & Silk 2018, in prep)

Summary



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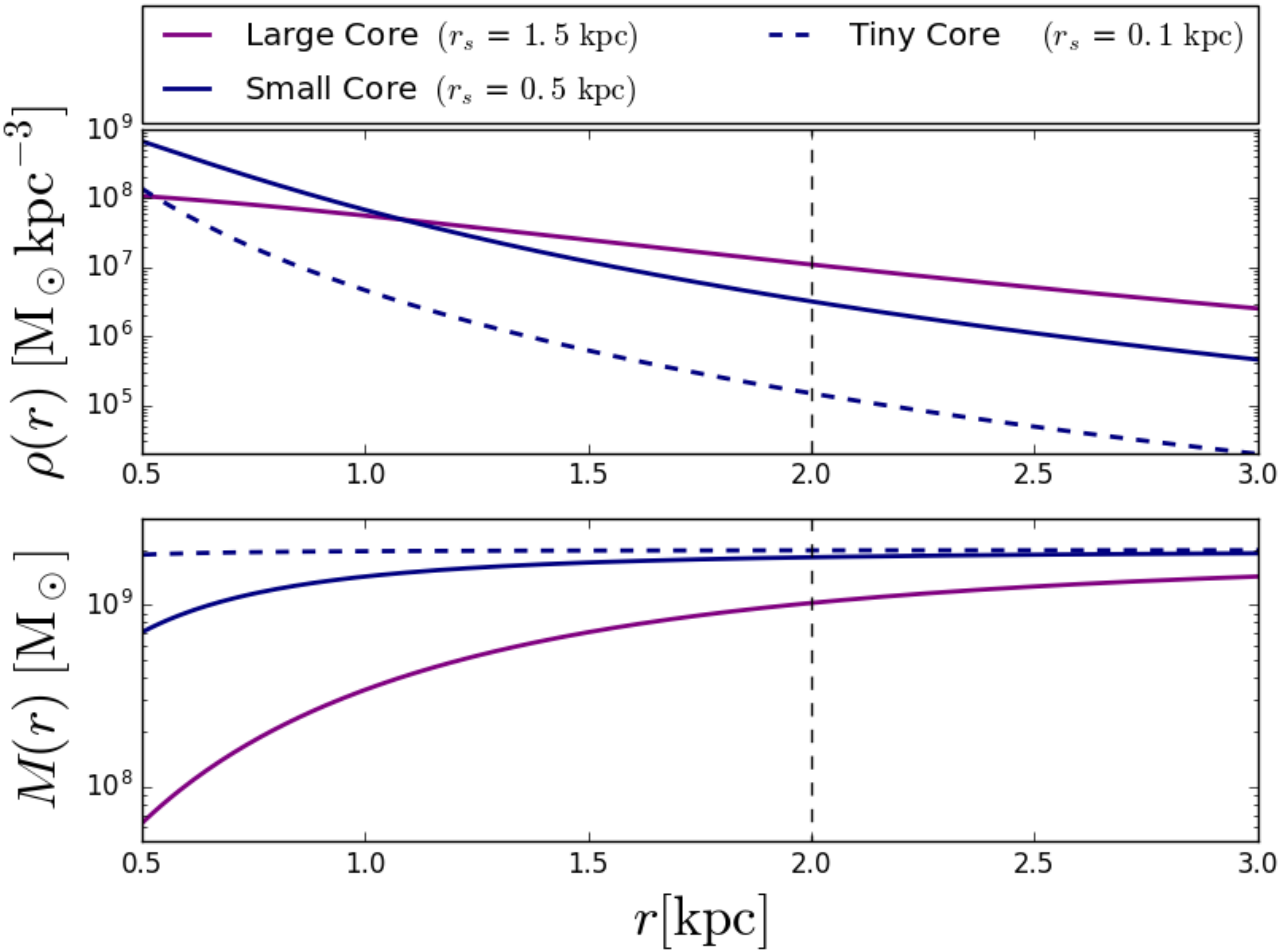
A constraint on the core radius



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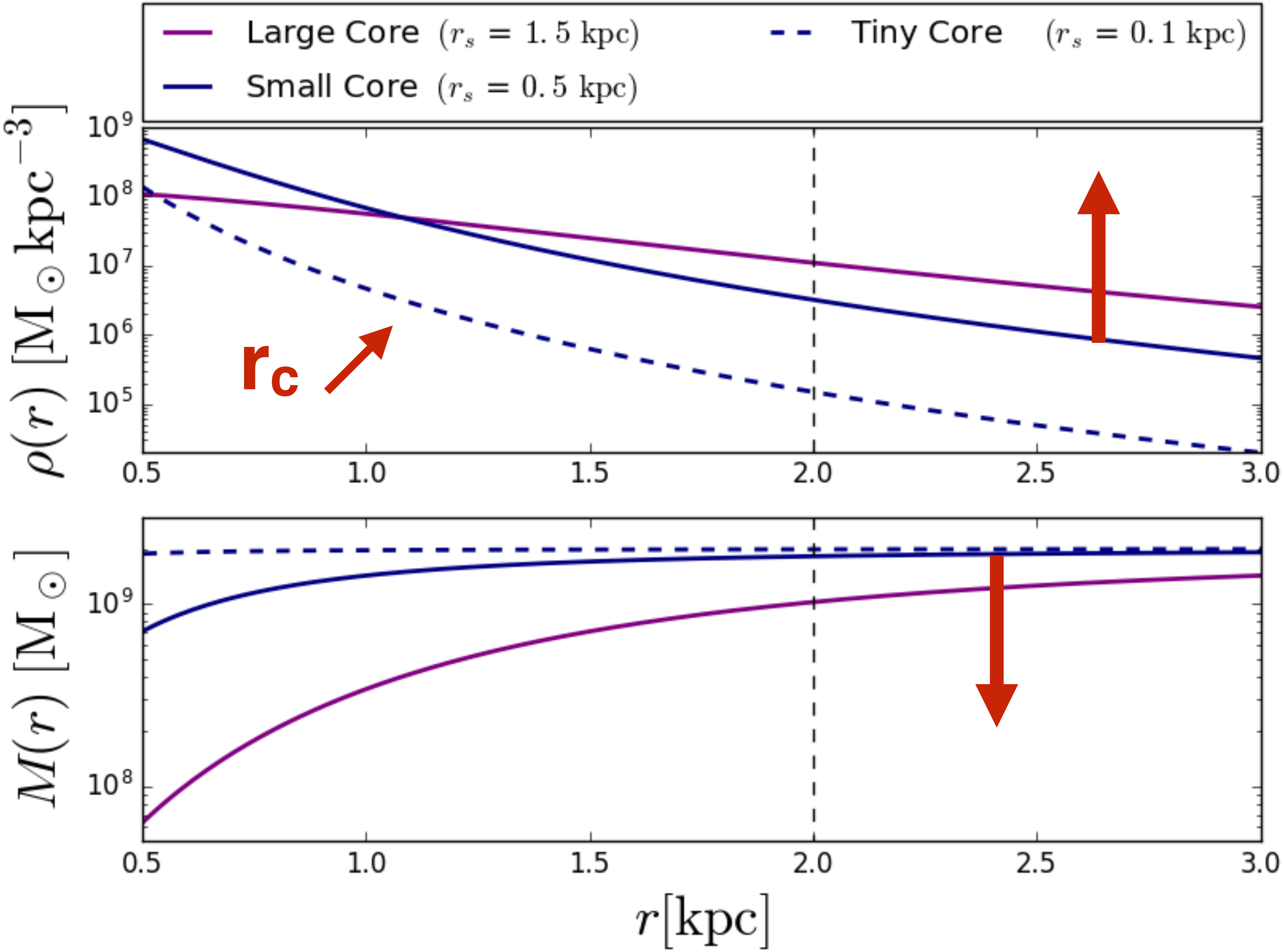

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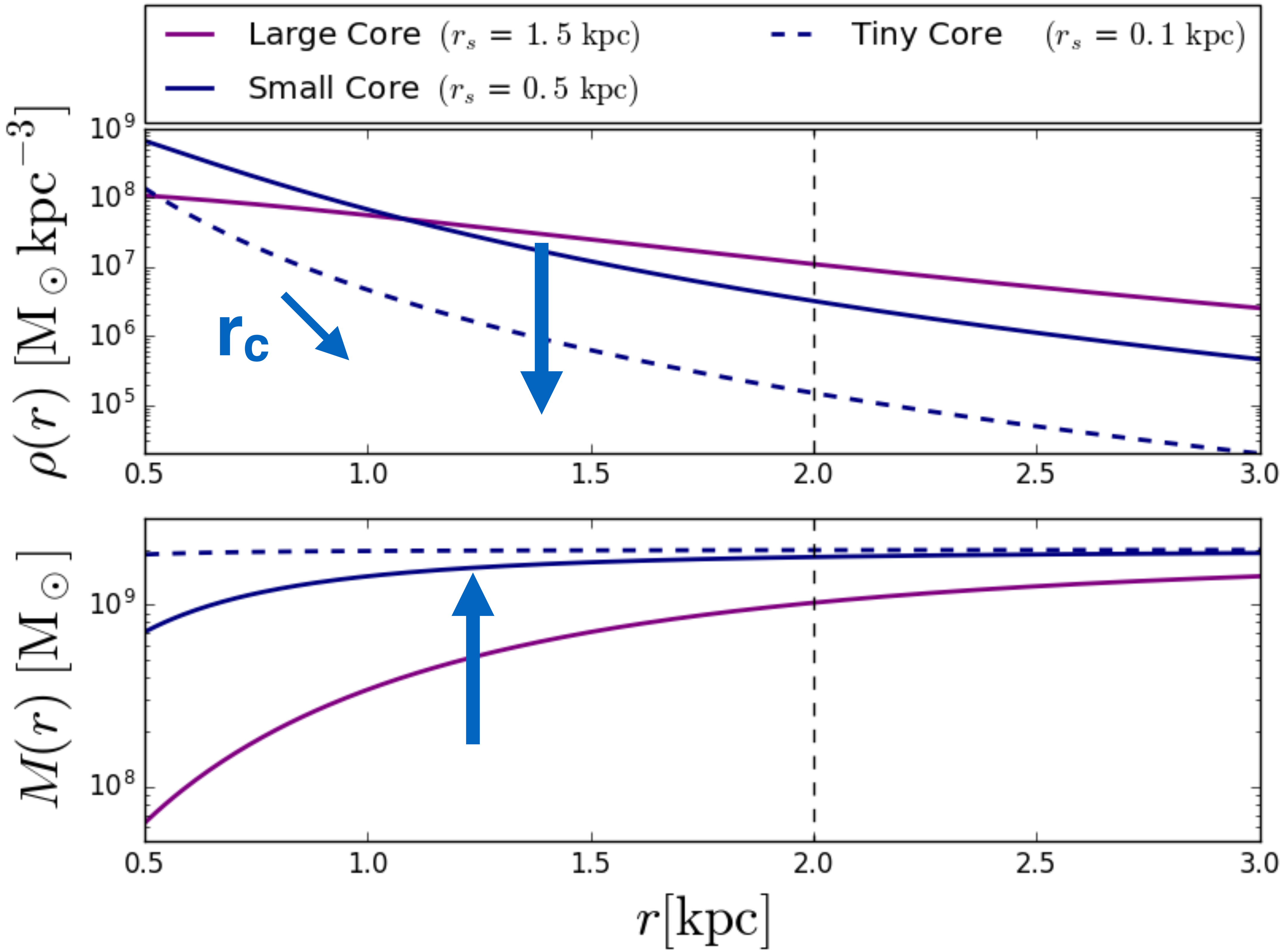

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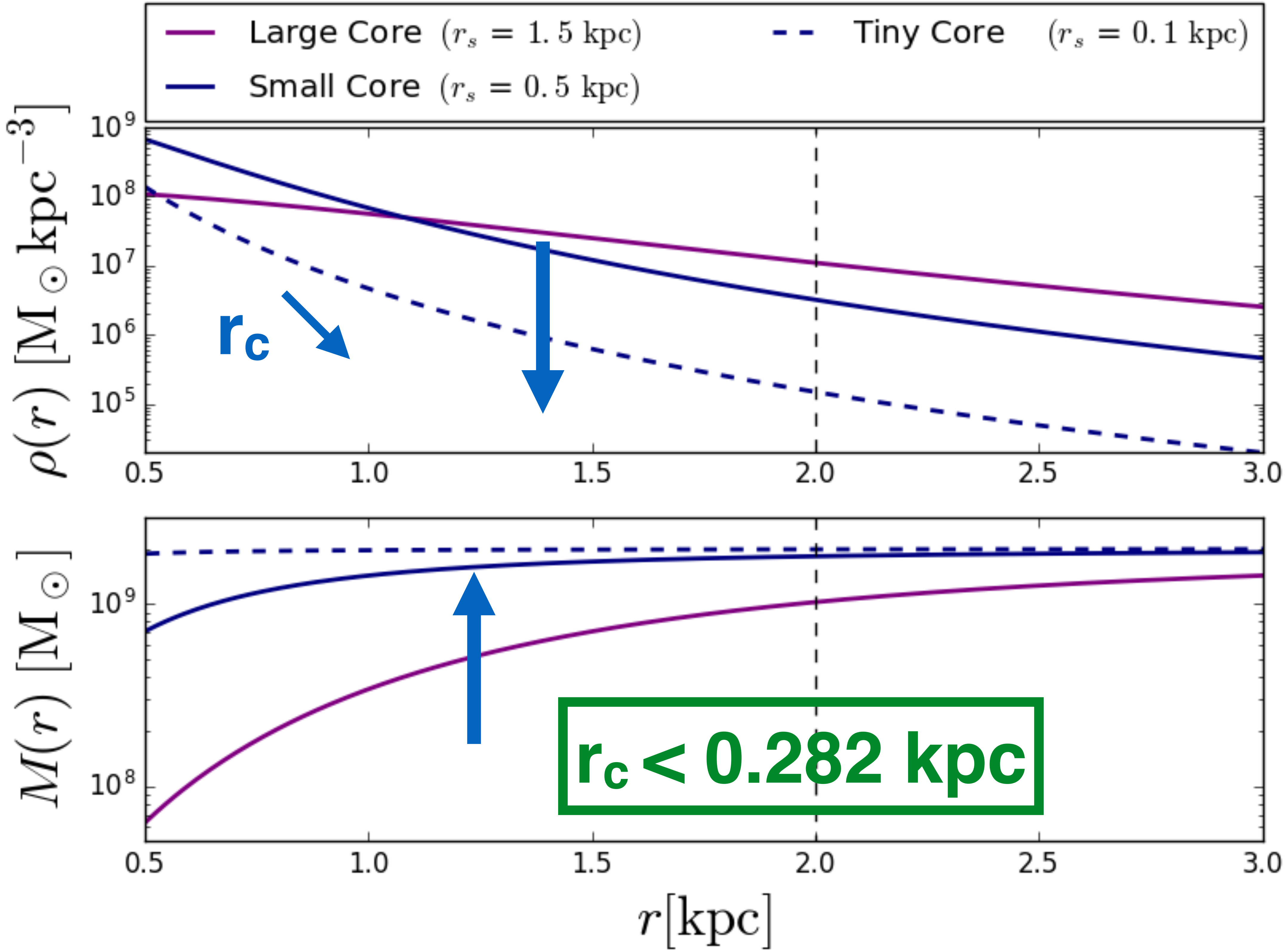

Implications of the nature of DM

Our result — $r_c < 0.282$ kpc

WDM (Strigari et al. 2006) — $r_c < 85$ pc for Fornax

FDM (Zhang et al. 2018) — $r_c \sim 3$ kpc

SIDM (Zavala et al. 2013) — $r_c > 500$ pc for Fornax

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SIDM (Zavala et al. 2013)	$r_c > 500$ pc for Fornax
CDM	Cusp +Gas heating (?) $100 < r_c < 300$ pc

Future works

- **Increasing simulation resolution (GPU)**

Future works

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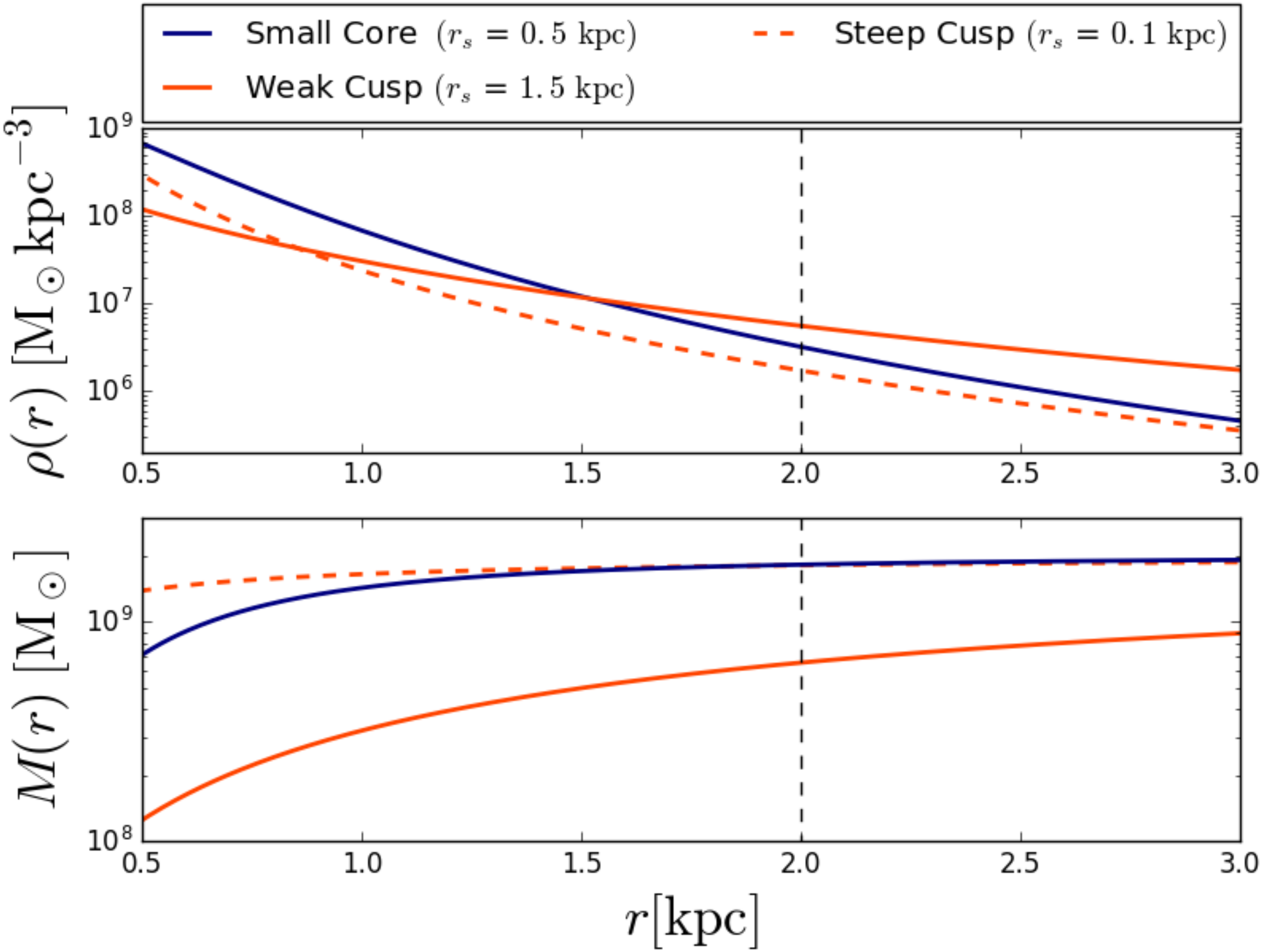
- **Testing Steep cusp or Tiny core**

Future works

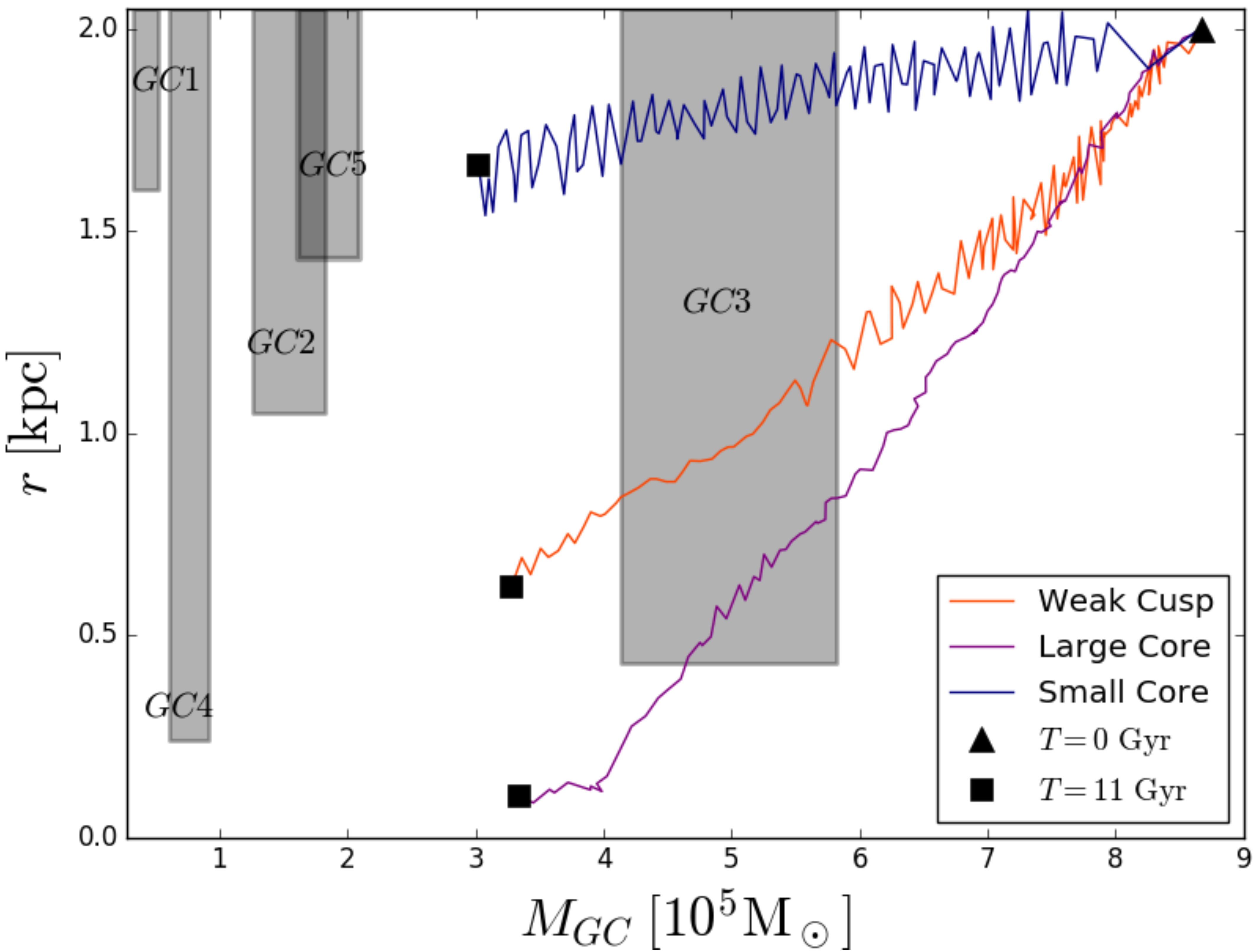
- **Increasing simulation resolution (GPU)**
- **Testing Steep cusp or Tiny core**
- **Running simulations for all the 5 globular clusters**

Thank you for your attention !

Return of the Cusp



Results



GC1
GC5
GC2
GC3
GC4
Weak Cusp
Large Core
Small Core
T = 0 Gyr
T = 11 Gyr
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5
6
7
8
9
r [kpc]
M_{GC} [10^5M$_\odot$]

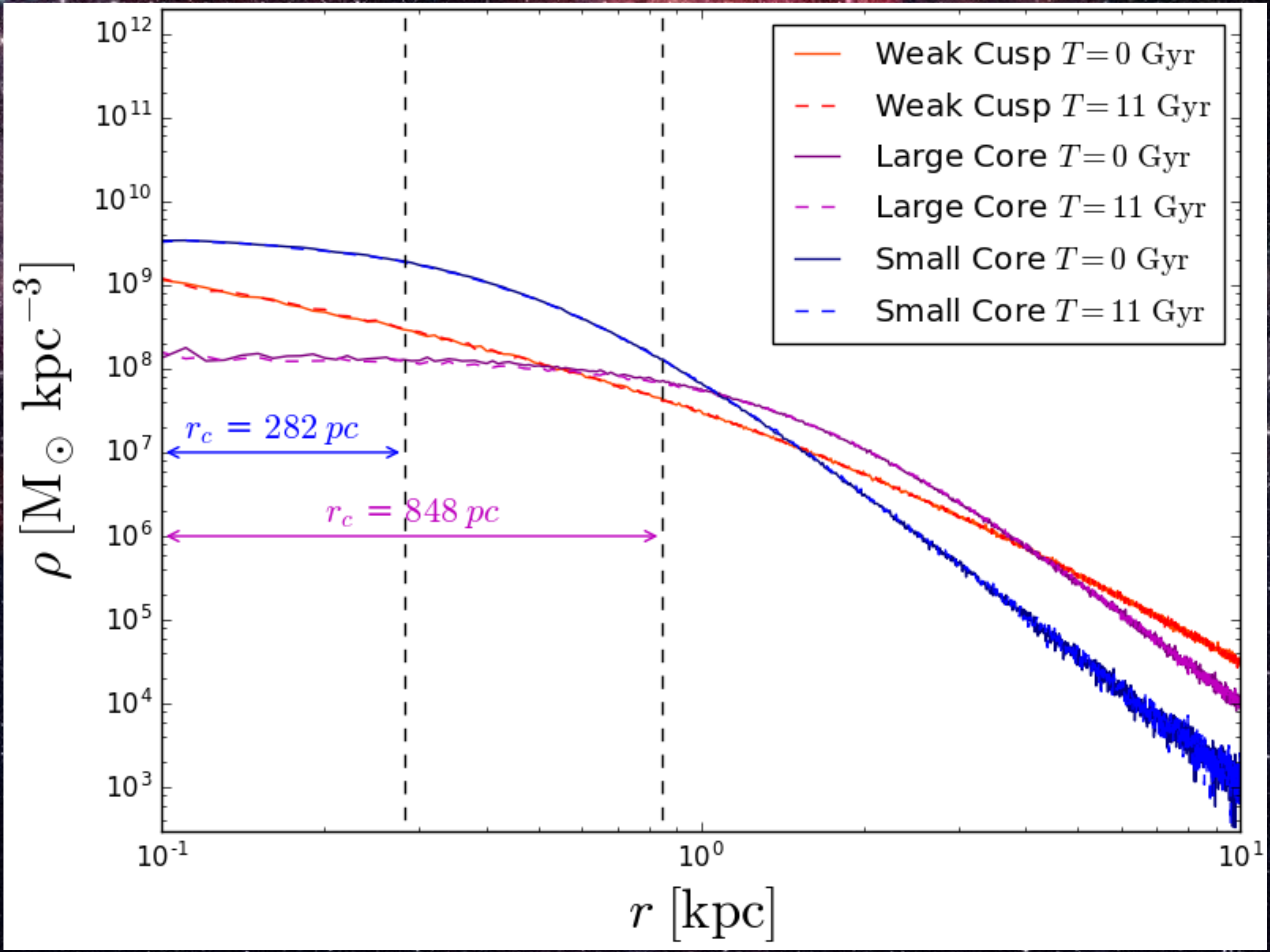
Questions?

Questions?

Questions?

Questions?

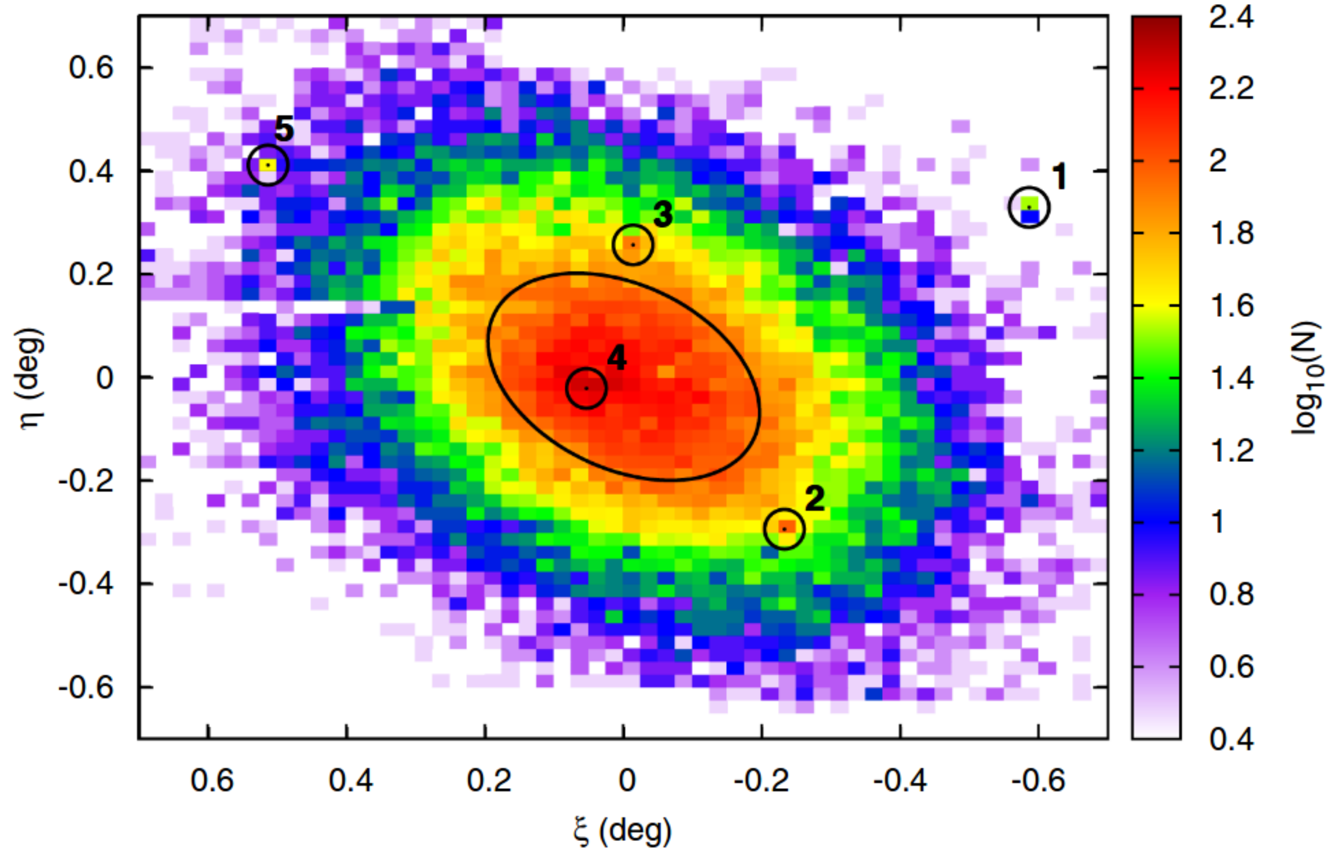
DM density profiles of Fornax

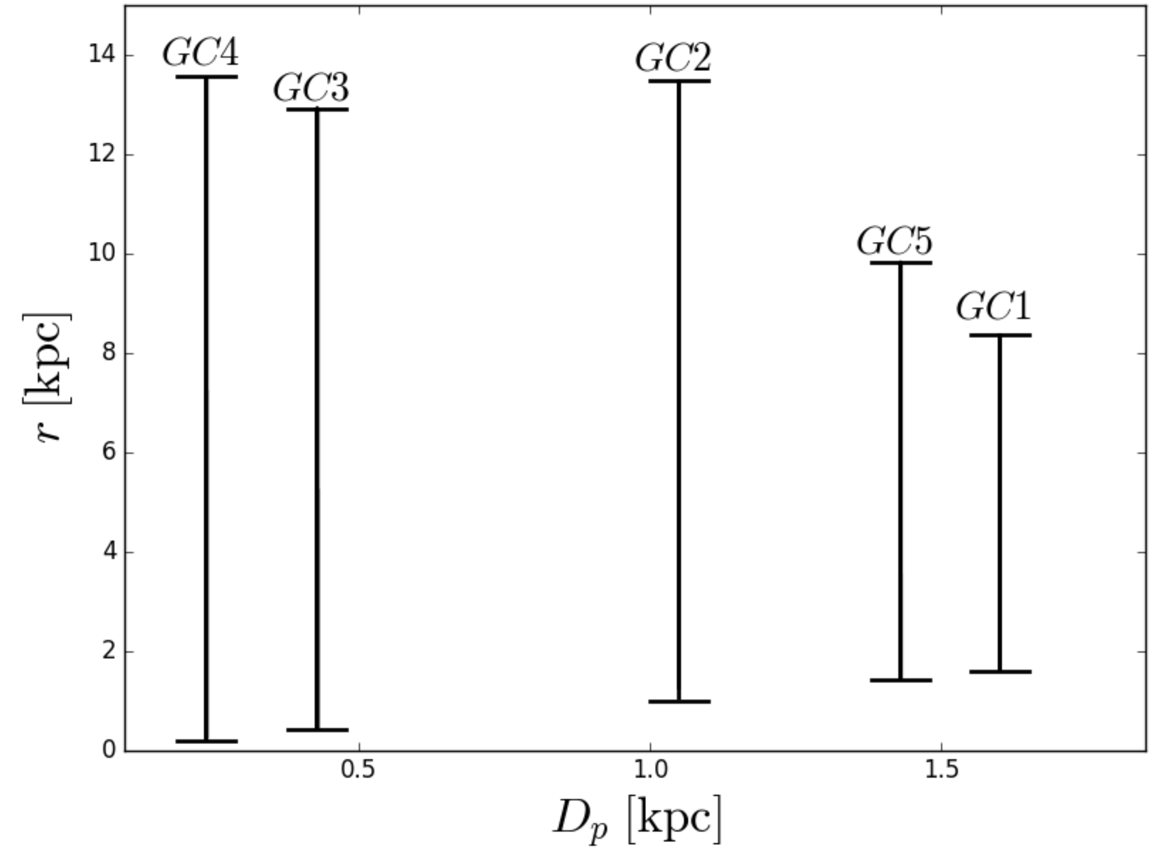


Fornax: the cusp-core problem

Globular cluster observations

Credit: de Boer & Fraser 2016





Object	Mass $[10^5\ M_\odot]$	r_k [pc]	R_p [kpc]	Distance [kpc]
dSph	1420	668	-	147 ± 4
GC1	0.42 ± 0.10	10.03	1.6	147.2 ± 4.1
GC2	1.54 ± 0.28	5.81	1.05	143.2 ± 3.3
GC3	4.98 ± 0.84	3.54	0.43	141.9 ± 3.9
GC4	0.76 ± 0.15	2.41	0.24	140.6 ± 3.2
GC5	1.86 ± 0.24	4.18	1.43	144.5 ± 3.3

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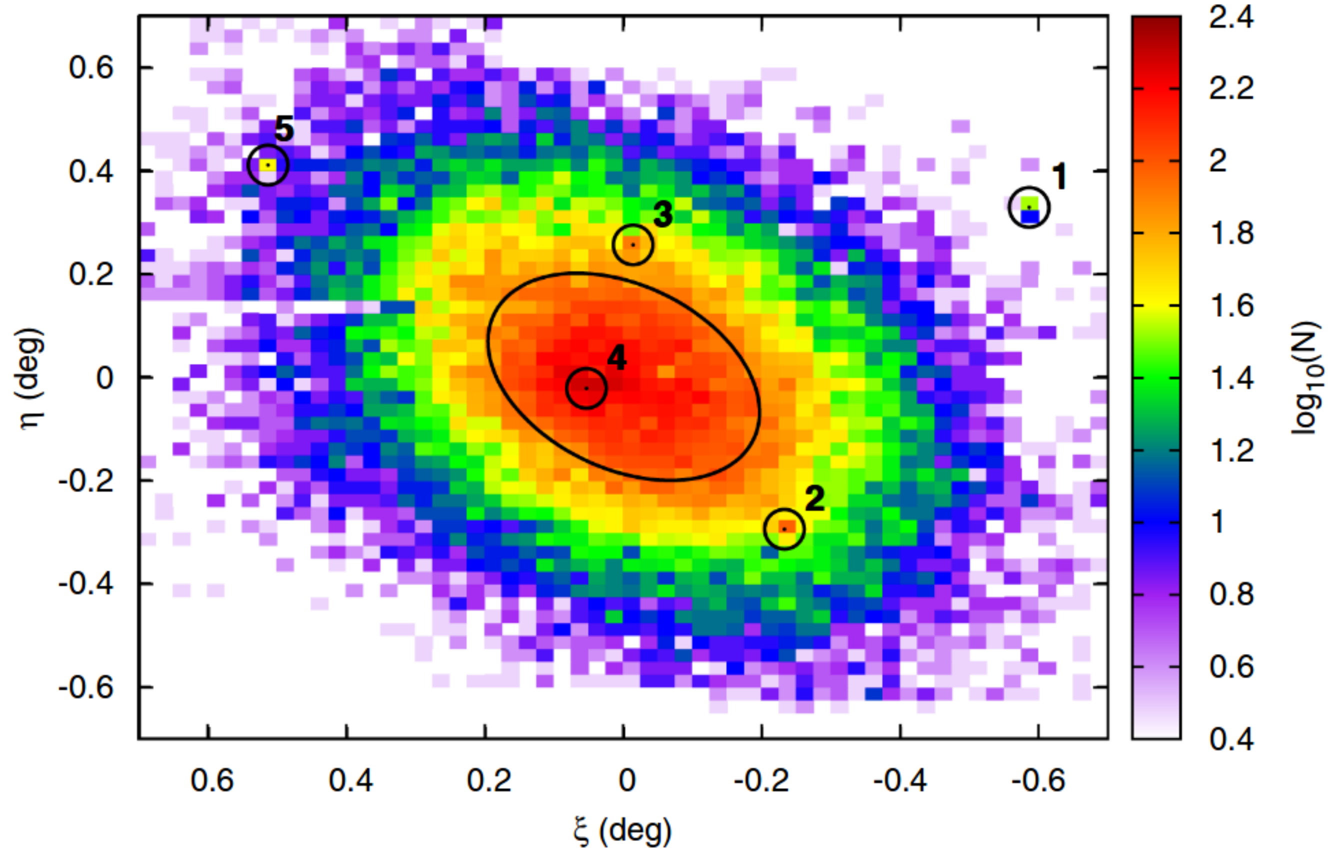

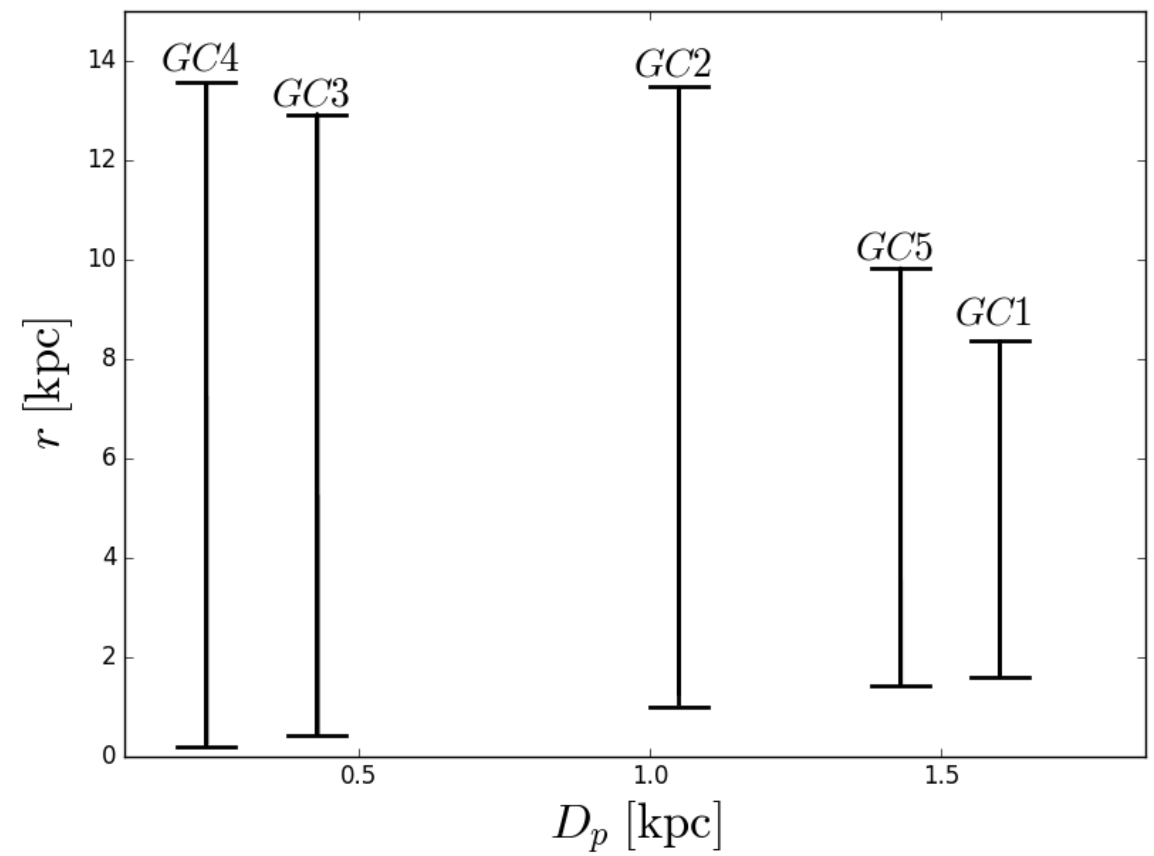

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$M_s = 44.9 \pm 5.3\ \times 10^5\ M_\odot$

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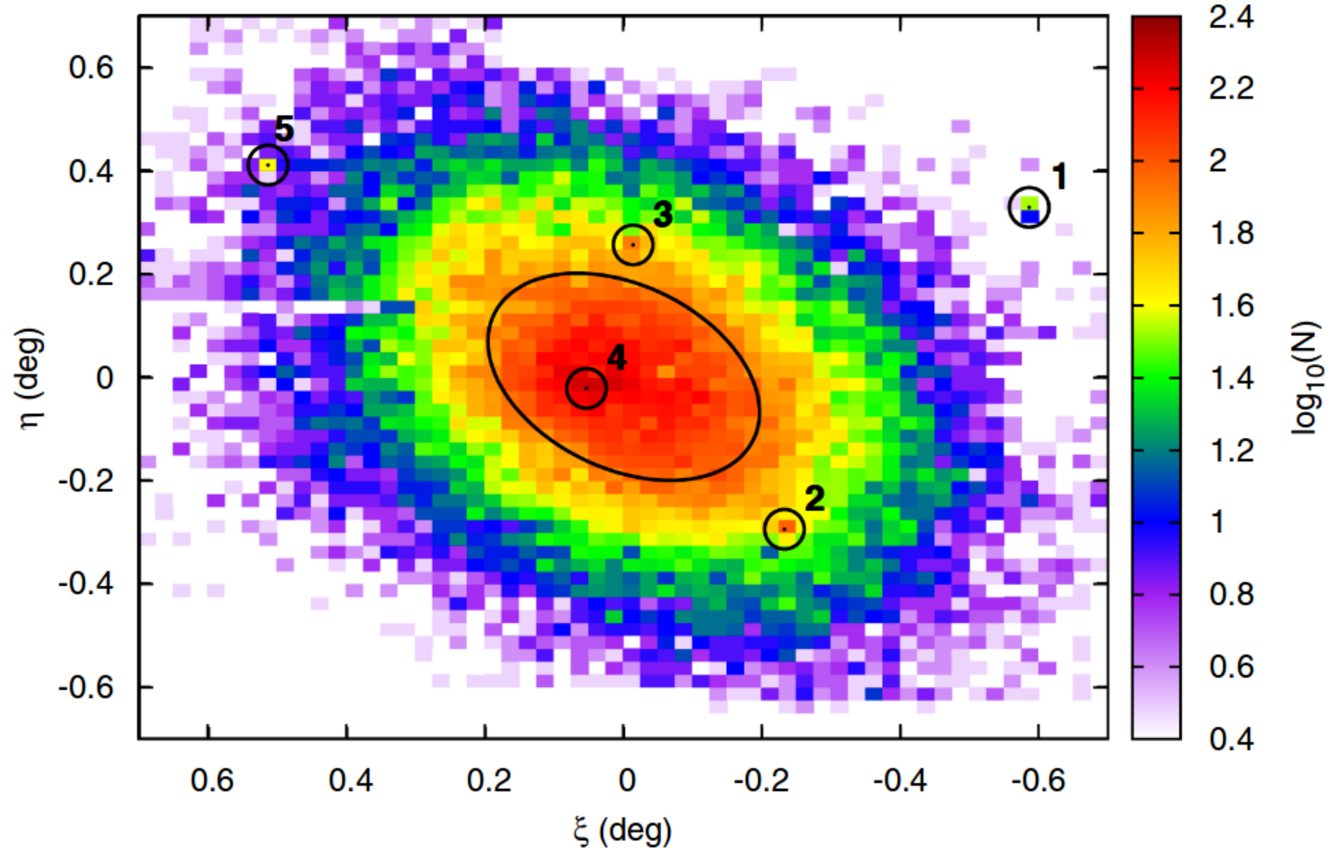

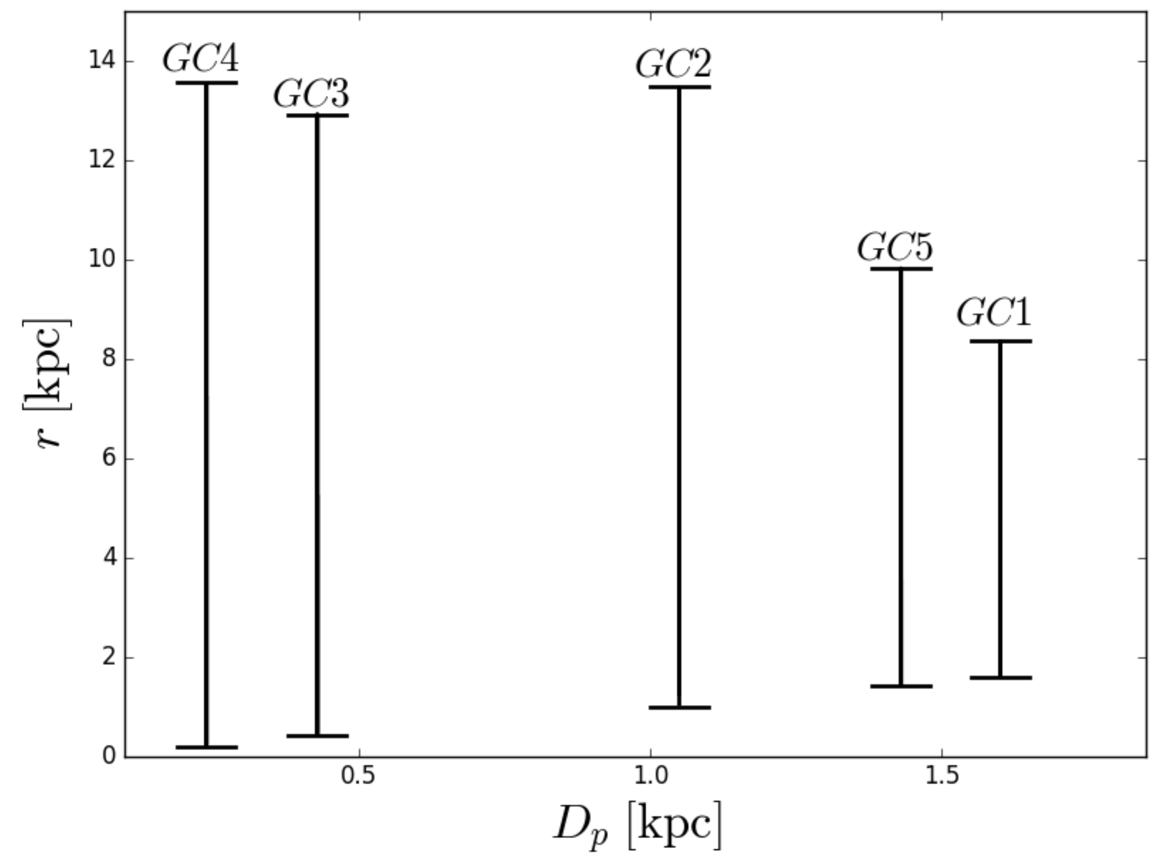

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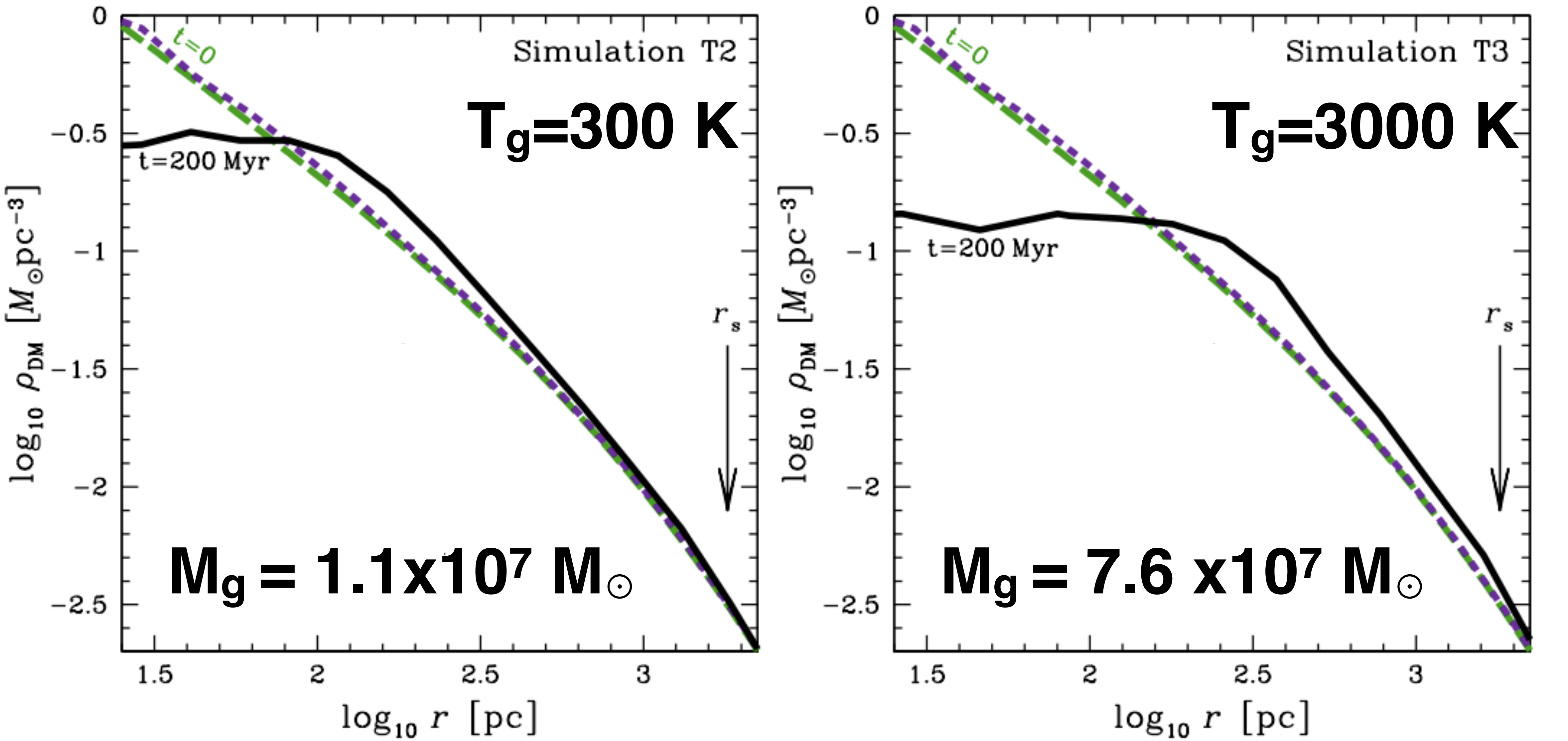
Age > 10 Gyr

Cold Dark Matter



r_c = 0.1 kpc

r_c = 0.3 kpc

(Nipoti & Binney 2013)

r_c < 0.282 kpc

Live N-body simulations

- Initial globular cluster mass

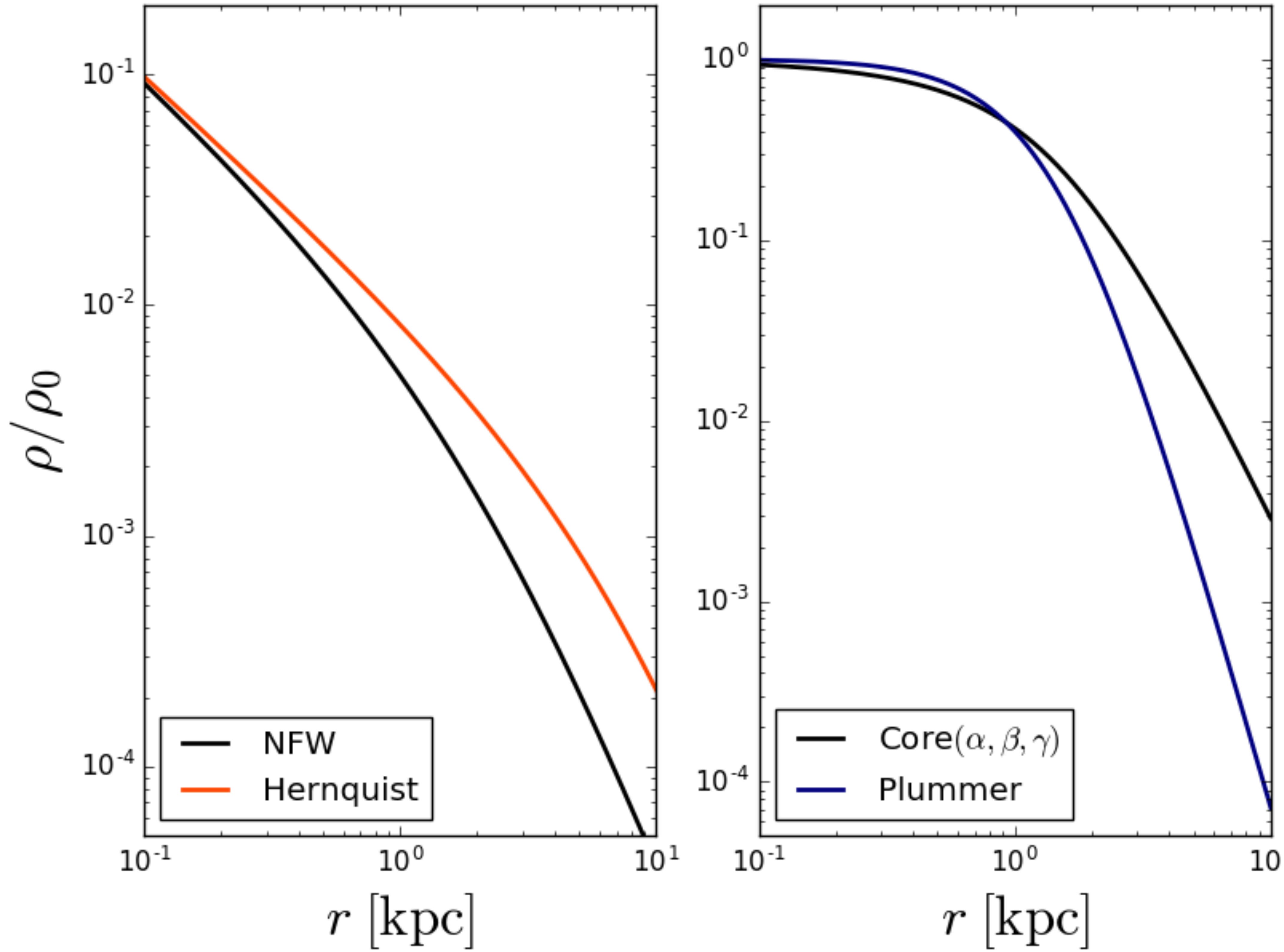
Low mass	**Medium mass**	**High mass**
$M_i = 1.71 \times 10^5 M_\odot$	**$M_i = 3.47 \times 10^5 M_\odot$**	**$M_i = 8.67 \times 10^5 M_\odot$**

- Initial globular radius

$r_i = 1.6$ kpc | **$r_i = 2$ kpc**

- $0.24 < D_p < 1.6$ kpc
- $R_t \sim 2$ kpc **(Walker & Penarrubia 2011)**

Profiles



10^{-1}
10^{-2}
10^{-3}
10^{-4}
ρ/ρ_0
NFW
Hernquist
10^{-1}
10^{0}
10^{1}
r [kpc]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Core(α, β, γ)
Plummer
10^{-1}
10^{0}
10
r [kpc]