Cusp-core problems

Pierre BOLDRINI
Institut d'Astrophysique de Paris (IAP), Sorbonne University

Roya MOHAYAEE
Joe SILK

JHU, October 9th

- **Fornax globular cluster distributions: implications for the cusp-core problem,**
  Boldrini et al. 2019 **https://arxiv.org/abs/1903.00354**

- **Embedding globular clusters in dark matter minihalos solves the cusp-core and timing problems in the Fornax dwarf galaxy**
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- **Primordial black holes as dark matter: cusp-to-core transition in low-mass dwarf galaxies**
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- **Diversity of transient cores of dwarf galaxies in ΛCDM**
  Boldrini et al. in prep.

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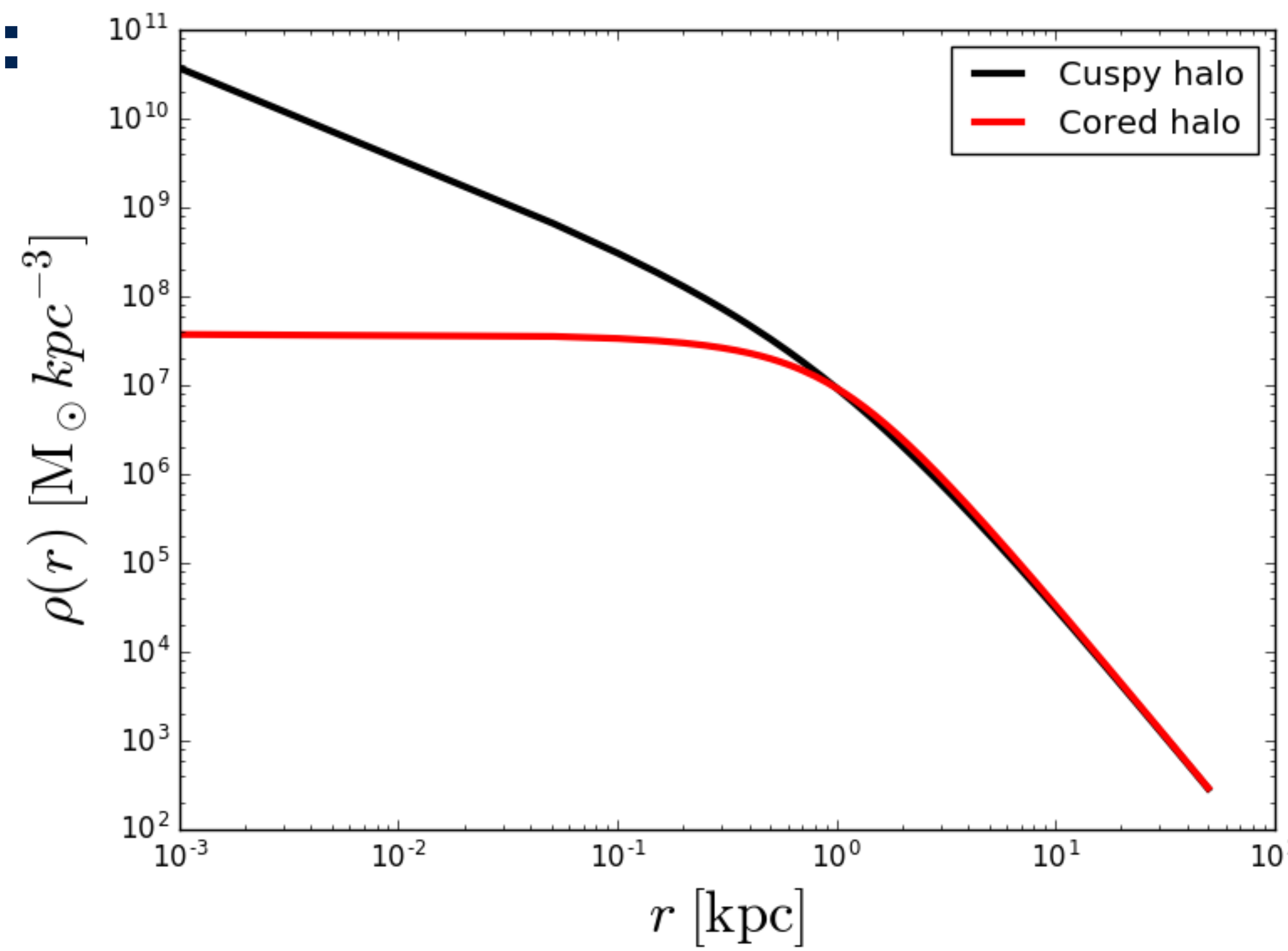
Today!!

Cusp-core problem

Astrophysical constraints:

- **Large-scale constraints**
  e.g. CMB

- **Small-scale constraints**
  e.g. Number of satellite galaxies, Dark matter density profile



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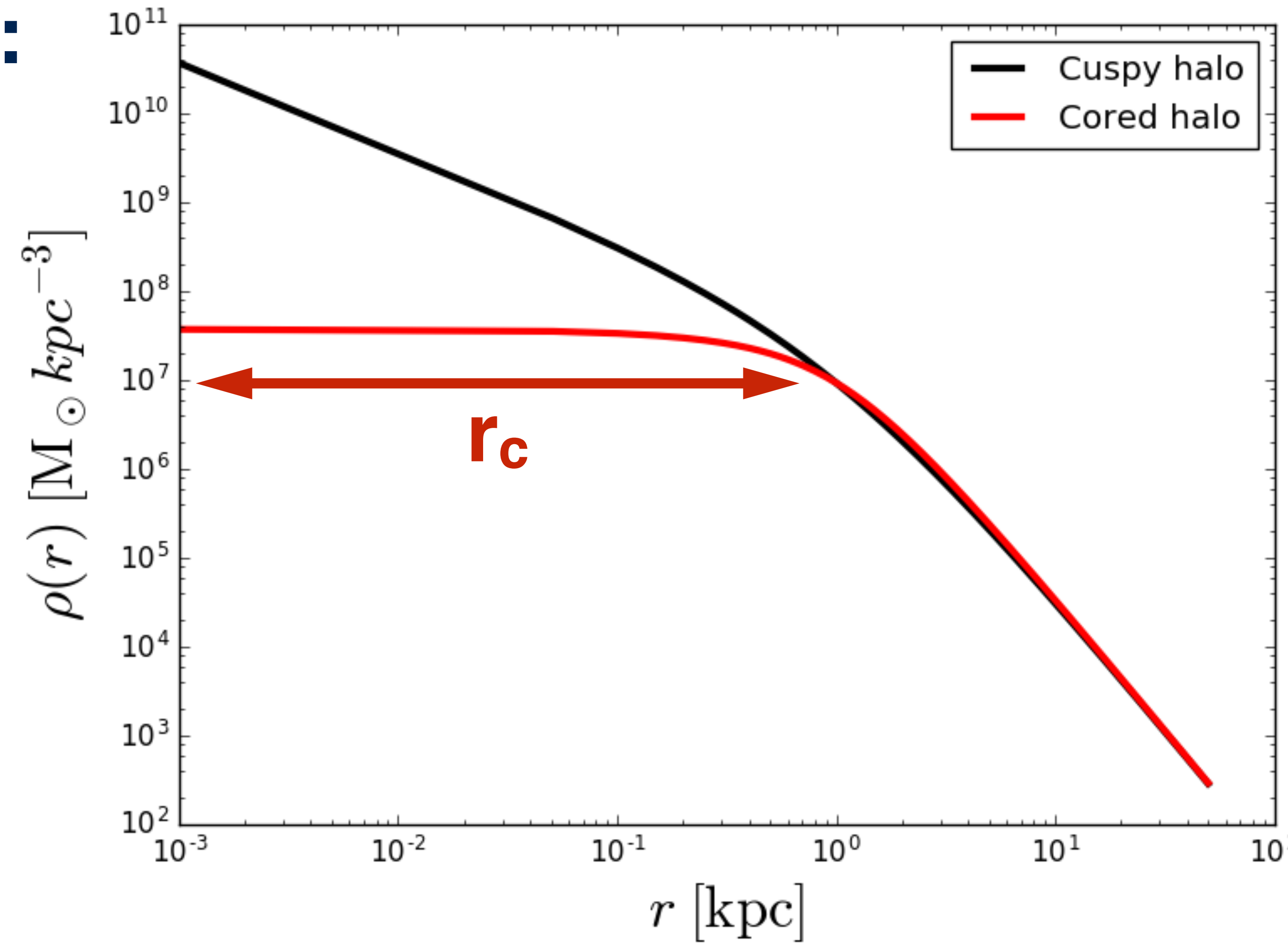

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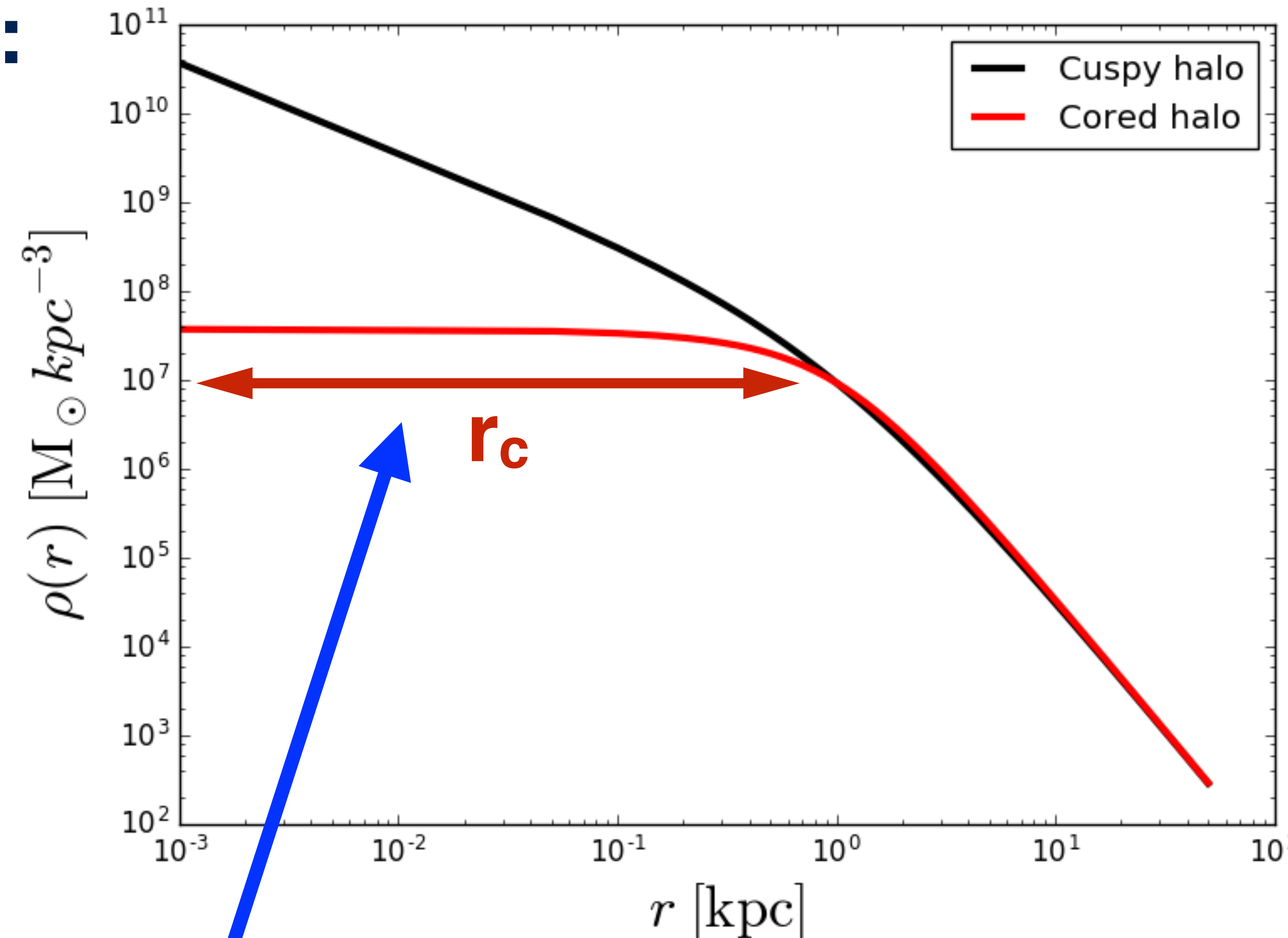

Observations

(Adams et al. 2014 and references therein)

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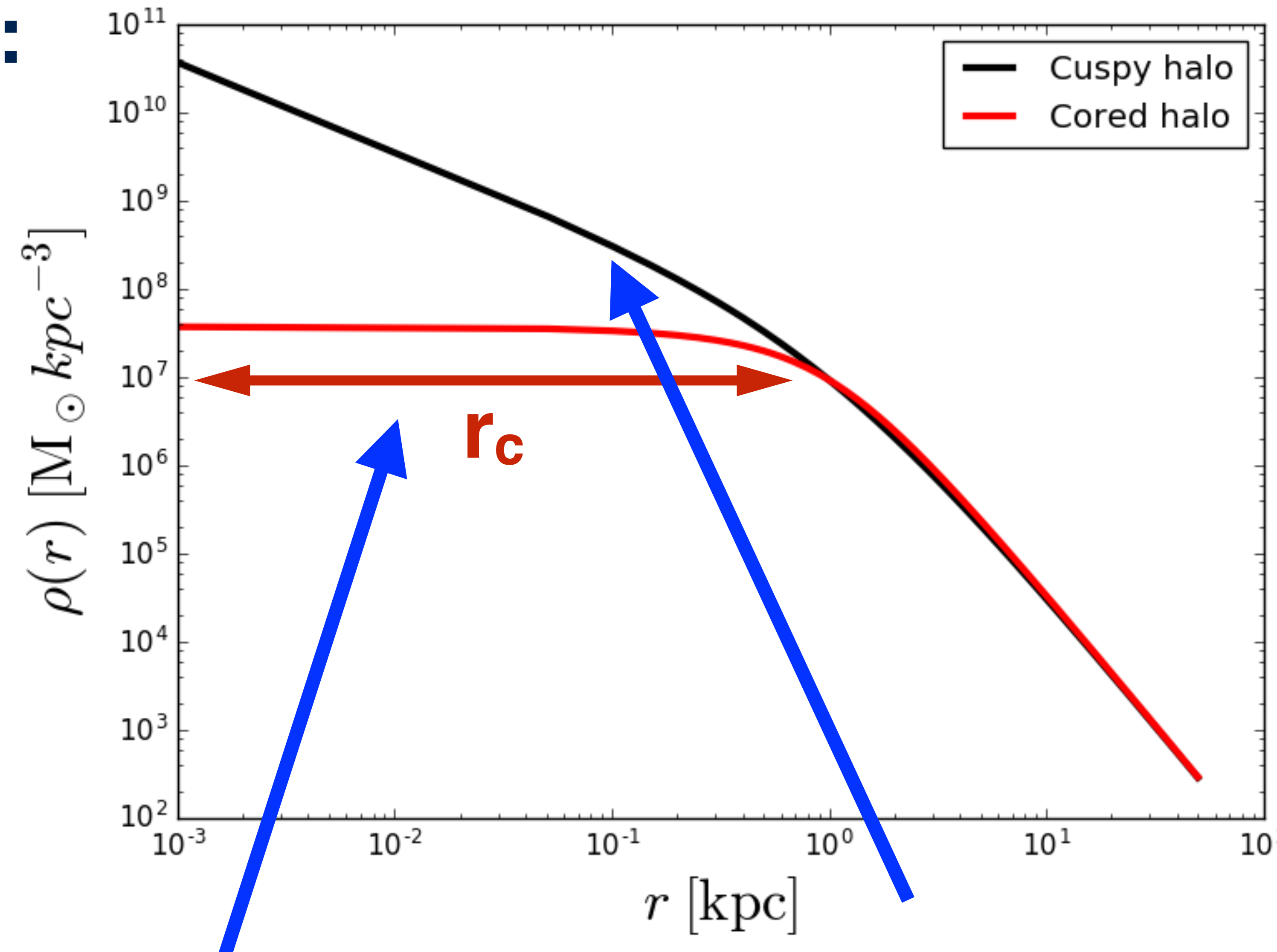


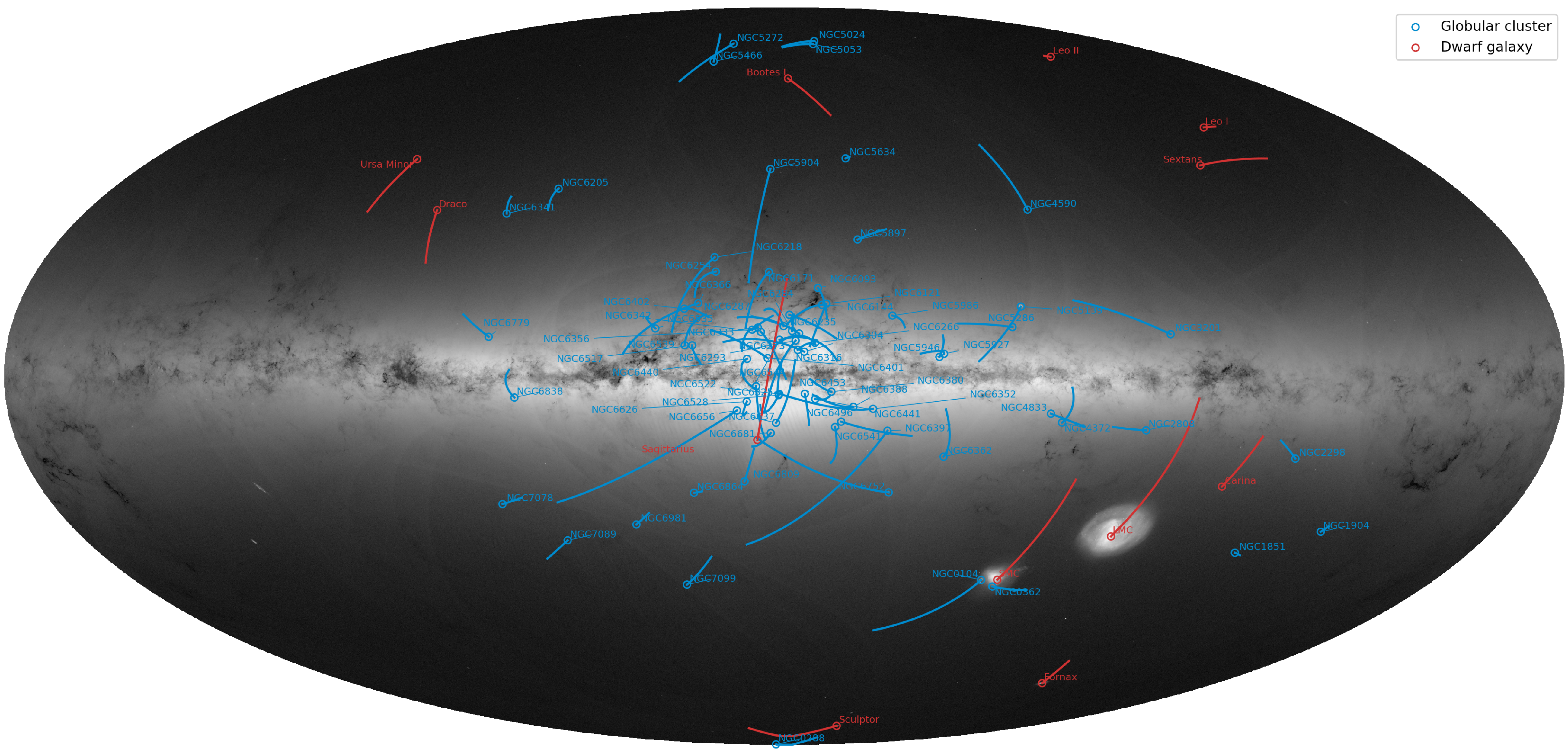
Observations

(Adams et al. 2014 and references therein)

Cosmological simulations

(Navarro et al. 1996, 1997)

Nature of dark matter:
Observations of dark matter rich dwarf galaxies



Credit: ESA/GAIA DR2

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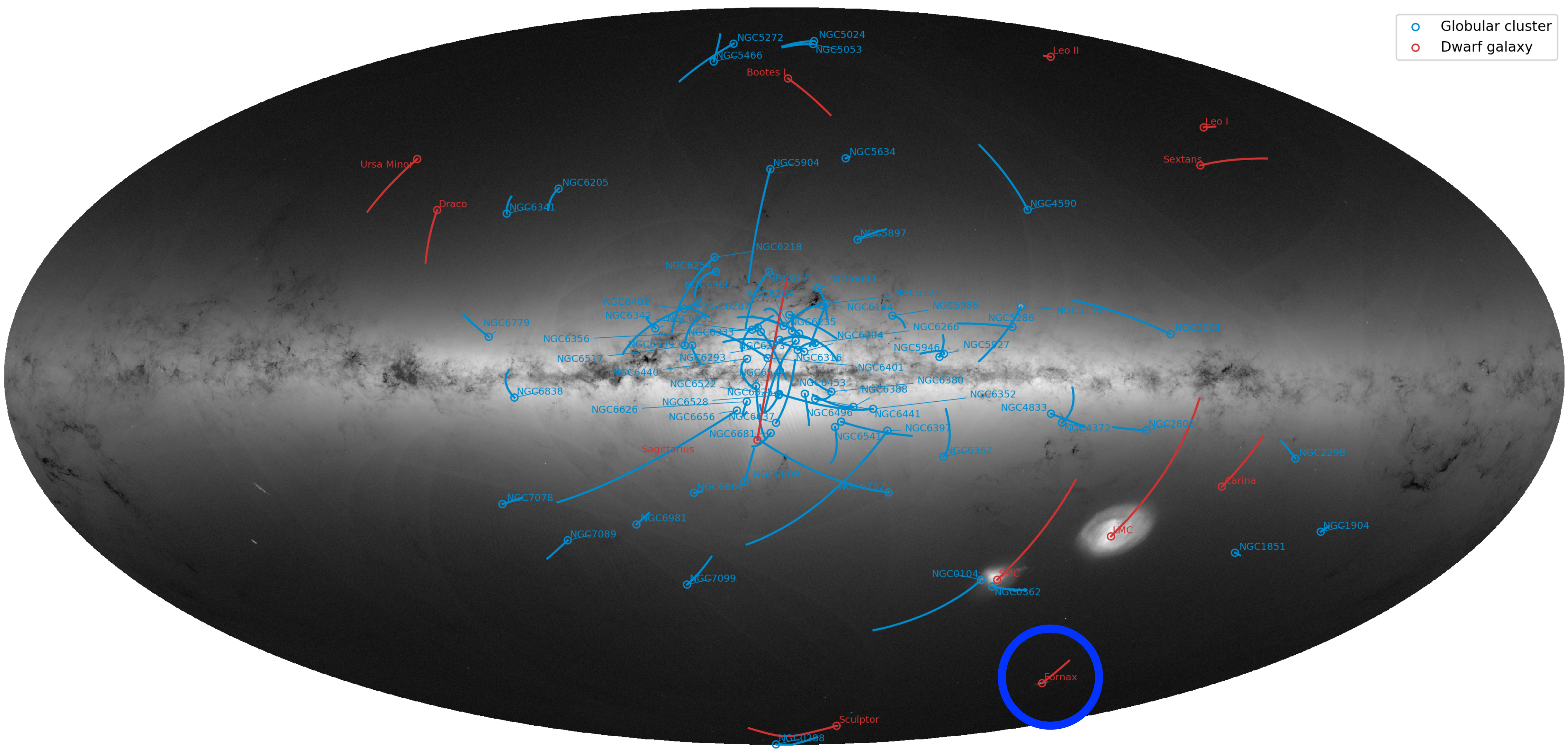

Credit: ESA/GAIA DR2

Fornax dwarf galaxy

Credit: ESO/Digitized Sky Survey 2

- DM core

Fornax dwarf galaxy

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Cusp-core problem

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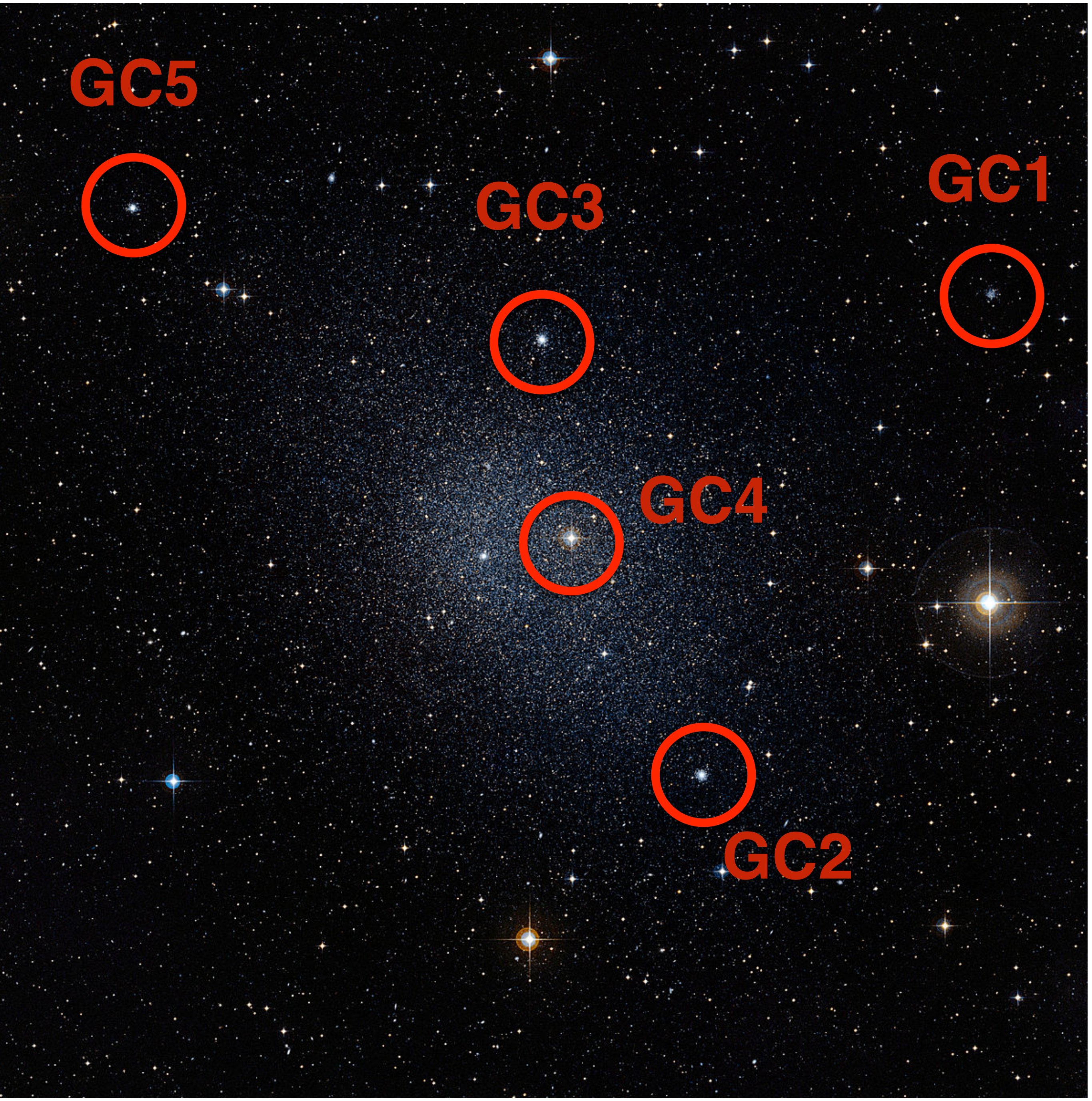

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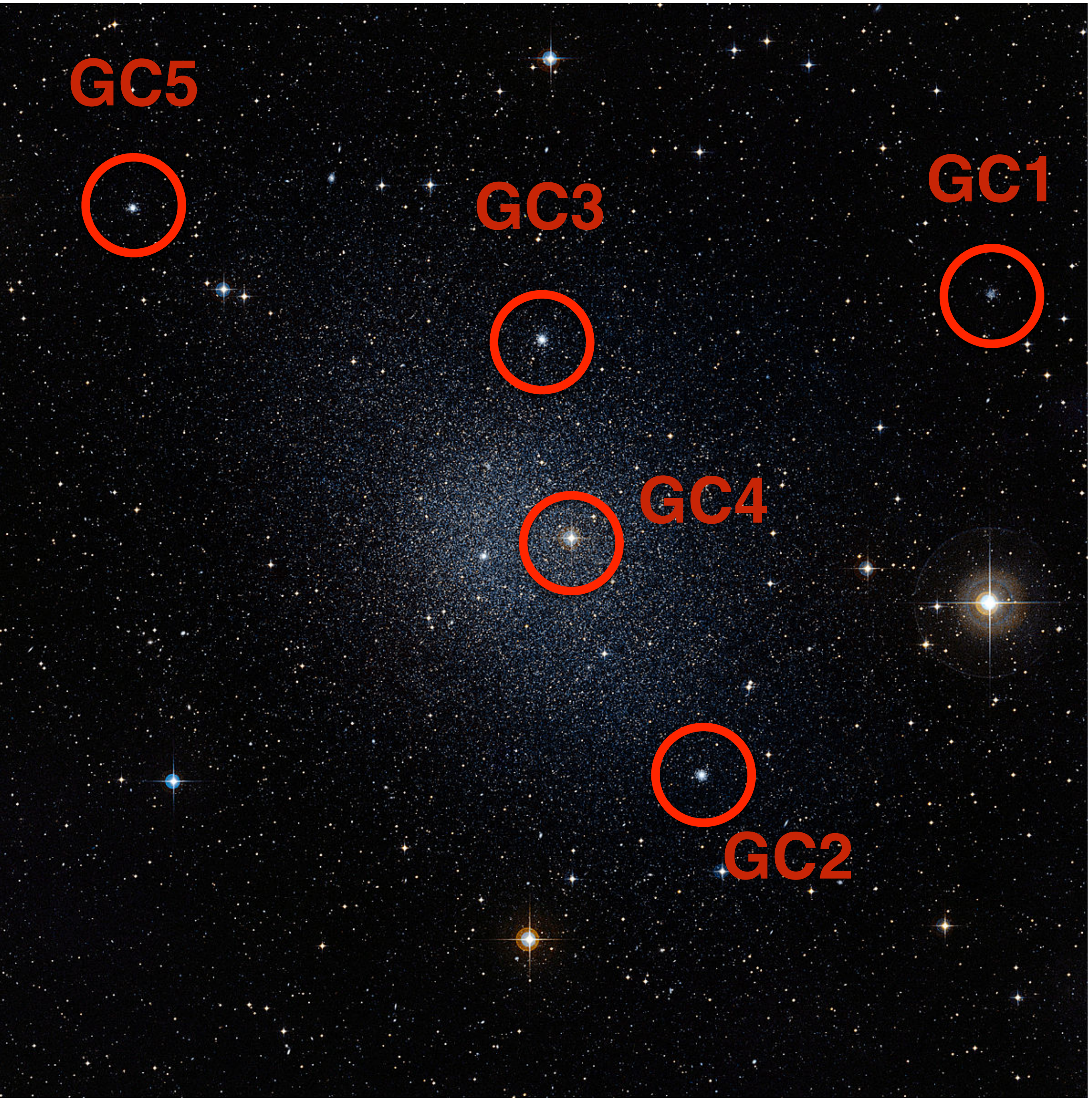
- DM core

Cusp-core problem

- 5-6 observed globular clusters (>10 Gyr)

Fornax dwarf galaxy



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Cusp-core problem

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Fornax timing problem

Formation of globular clusters: 2 scenarios

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- Gravitationally bound gas clouds in the early Universe and formed inside their present-day host galaxies **(Peebles et al. 2018, Kravtsov et al. 2005, Kruijssen 2015)**

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Not been **detected**, but:

- Maybe observational **signatures** **(Sollima et al. 2016, Olszewski et al. 2009; Kuzma et al. 2016; Peñarrubia et al. 2017)**
- **Lost a large** fraction of their DM halo **(Bromm et al. 2002)**

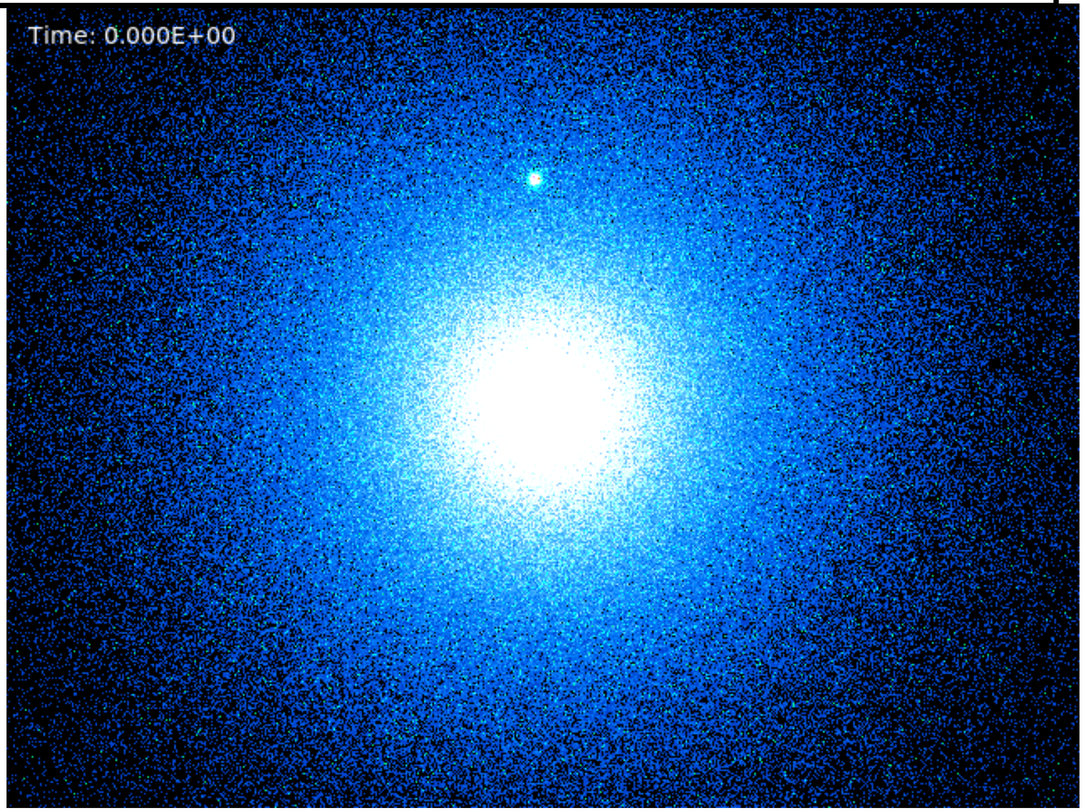
Fully GPU *N*-body simulations

Dynamical friction
&
Tidal stripping

Fully GPU *N*-body simulations

Dynamical friction
&
Tidal stripping

Self-gravitating system composed of DM particles



Fully GPU *N*-body simulations

Dynamical friction
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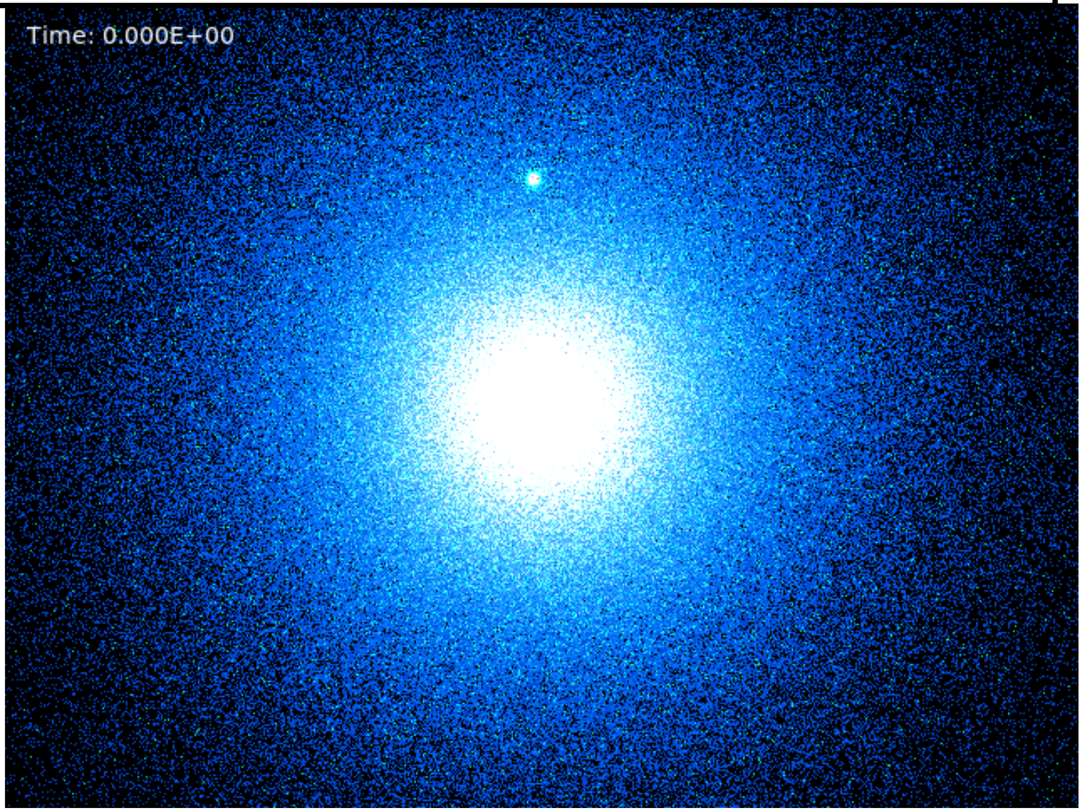
Fully GPU collisionless *N*-body code, GOTHIC

(Miki & Umemura 2017)

Self-gravitating system composed of DM particles



Modelling
Fornax ~ 10^7 particles
Minihalo+GCs ~ 10^5 particles

Resolution
~ 20 pc

Simulation time
12 & 4 Gyr

Initial conditions

Fornax

- 10^9 $M_\odot$ halo + NFW profile

- $\sim 10^7$ $M_\odot$ stars + Plummer profile

Initial conditions

Fornax

- 10^9 $M_\odot$ halo + NFW profile
- ~ 10^7 $M_\odot$ stars + Plummer profile

GCs + DM minihalo

- 10^6 $M_\odot$ stars + King profile
- 10^7 $M_\odot$ DM component + NFW profile

Initial conditions

Fornax

- 10^9 $M_\odot$ halo + NFW profile

- ~ 10^7 $M_\odot$ stars + Plummer profile

GCs + DM minihalo

- 10^6 $M_\odot$ stars + King profile

$\boxed{M_{mh}/M_{*}=20}$

- 10^7 $M_\odot$ DM component + NFW profile

Two scenarios

	Redshift	Object	r [kpc]	v_x [km/s]	v_y [km/s]	v_z [km/s]	$\|v\|$ [km/s]
GCs accreted 10-12 Gyr ago by Fornax	$z = 3$	E_1	2.11	20.22	1.6	8.1	21.8
		E_2	2.74	16.42	3.28	15.75	22.99
		E_3	1.1	38.62	15.44	18.94	39.97
		E_4	1.76	13.46	21.46	26.87	36.94
		E_5	1.14	32.81	6.93	7.89	34.37
GCs accreted 4 Gyr ago by Fornax	$z = 0.36$	O_1	5.32	13.9	1.31	14.38	20.04
		O_2	2.07	9.43	19.05	21.42	30.18
		O_3	1.95	37.49	4.55	6.21	38.28
		O_4	2.19	3.51	3.87	34.0	34.39
		O_5	2.05	19.62	29.8	15.1	38.75

(Boldrini et al. 2019)

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GCs accreted 10-12 Gyr ago by Fornax ($z = 3$ rows)

GCs accreted 4 Gyr ago by Fornax ($z = 0.36$ rows)

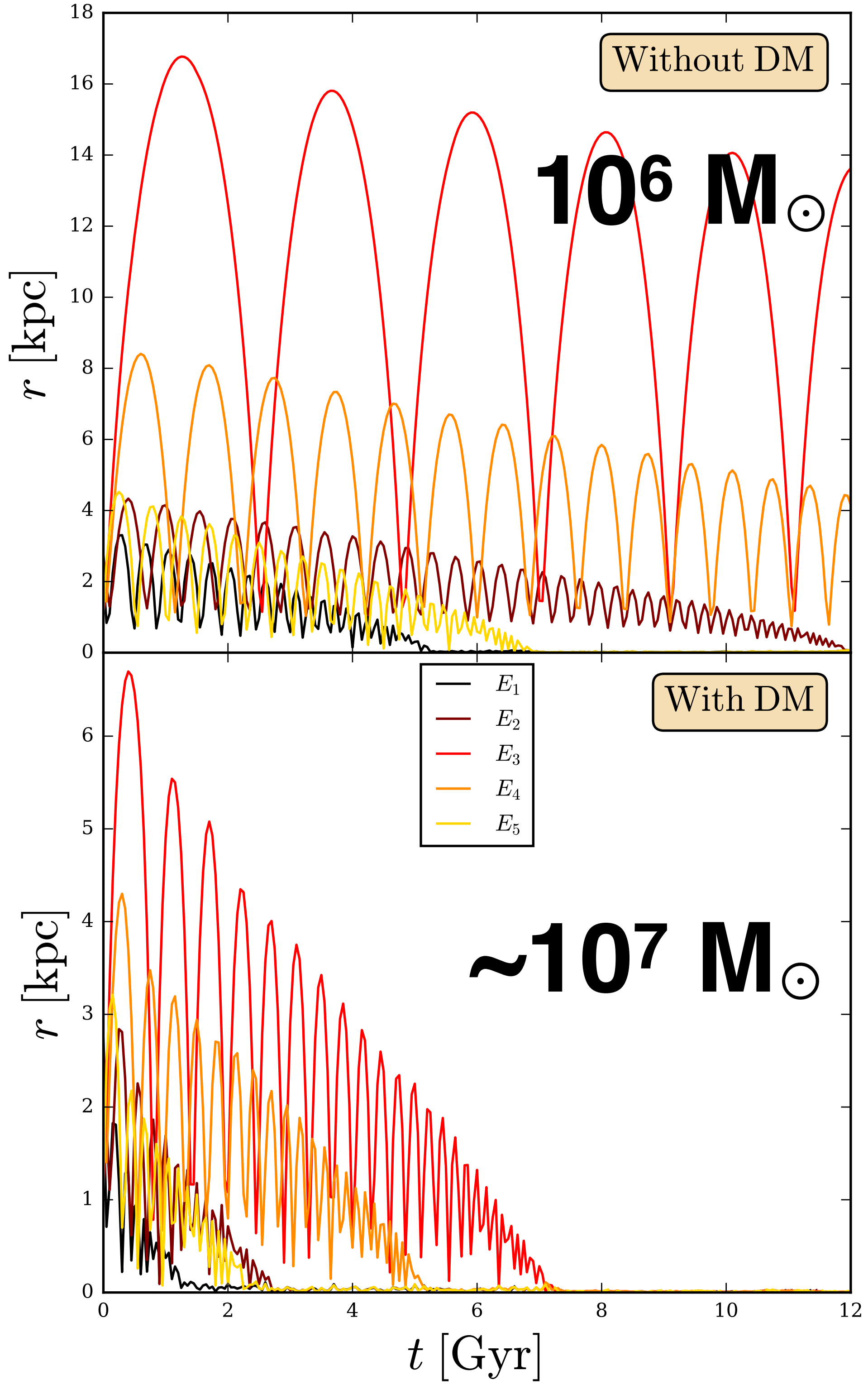
Most prevalent positions and velocities from Illustris TNG-100 cosmological simulations

(Boldrini et al. 2019)

Early accretion scenario: Timing problem

GCs accreted 10-12 Gyr ago by Fornax

Early accretion scenario: Timing problem



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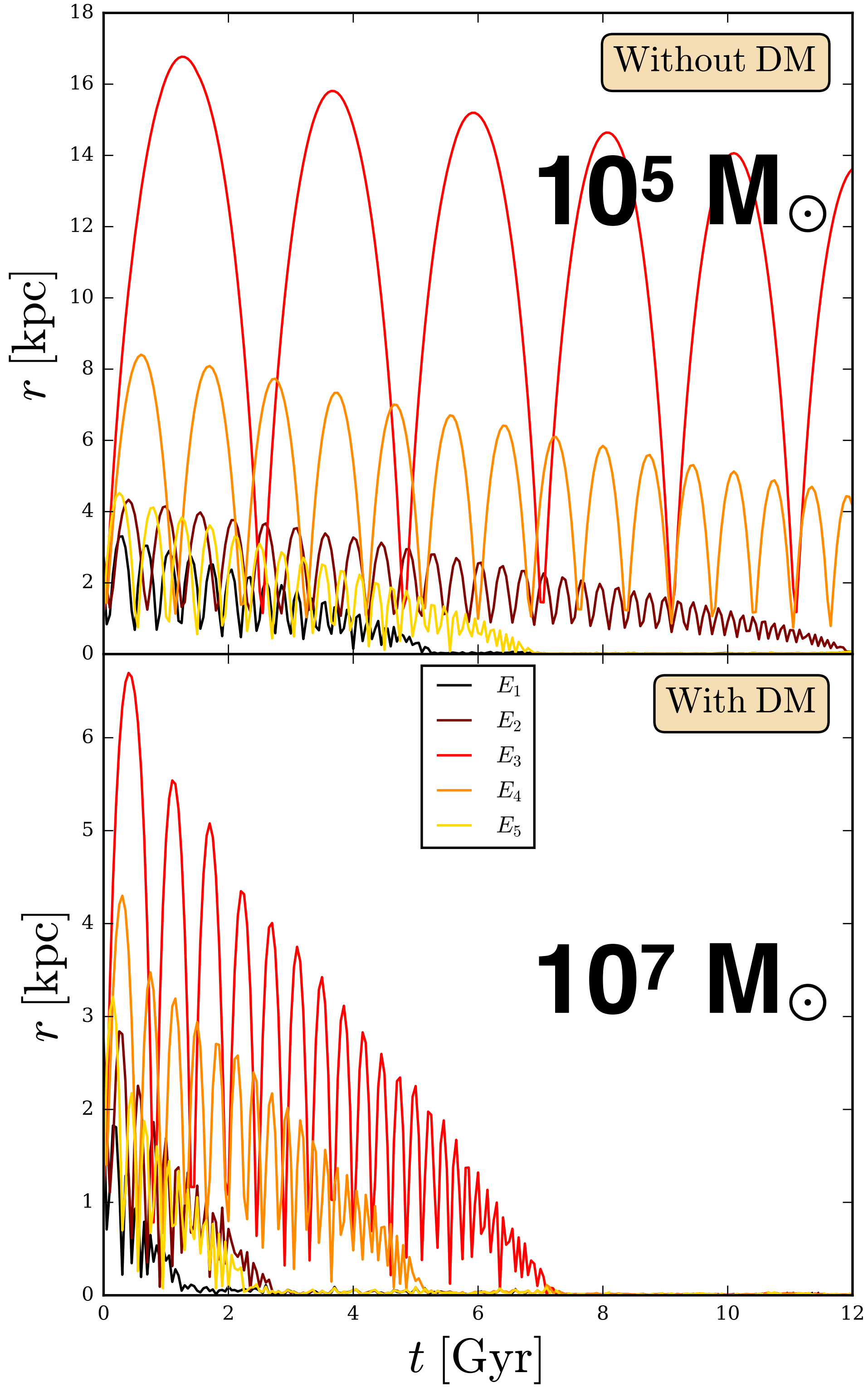

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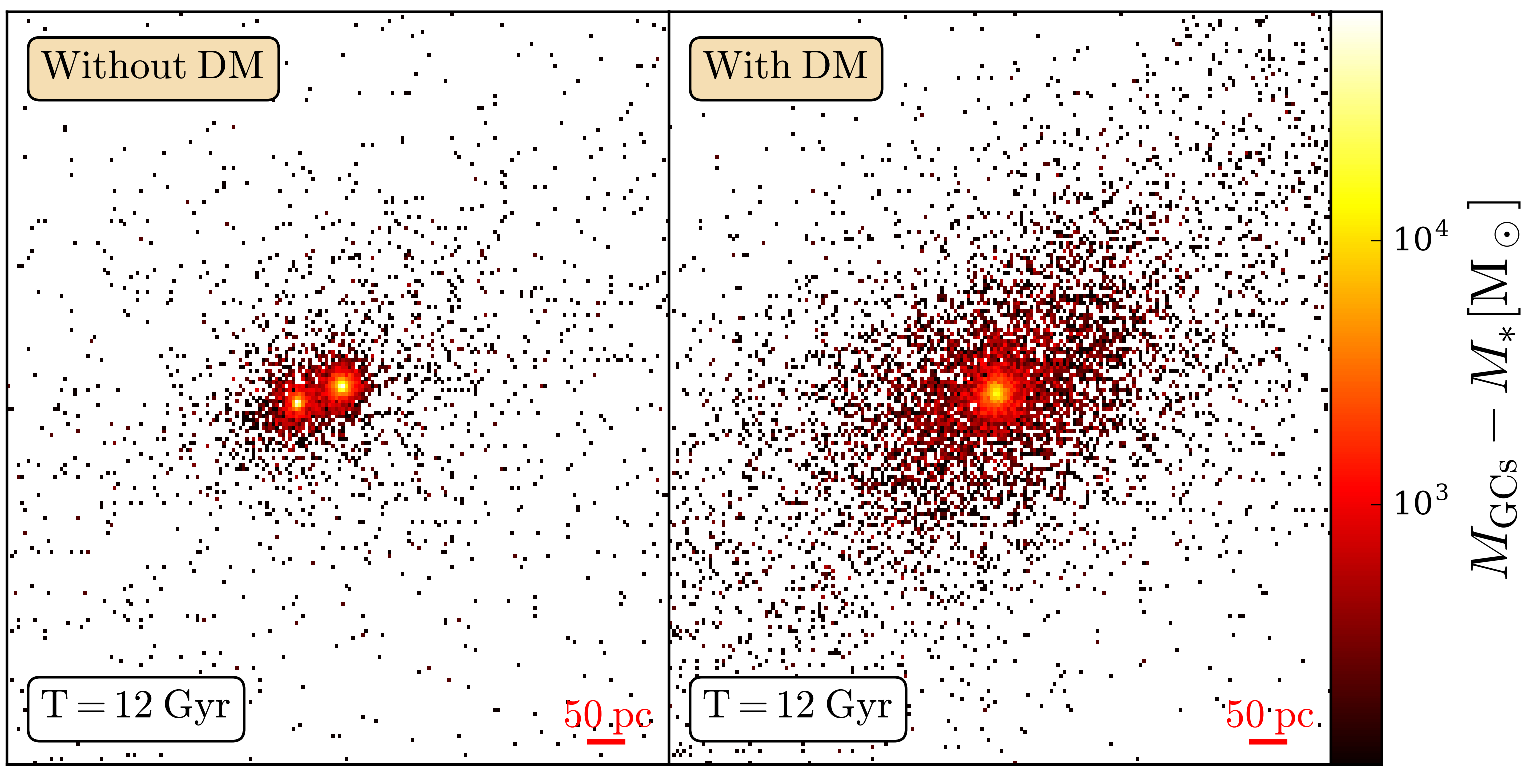

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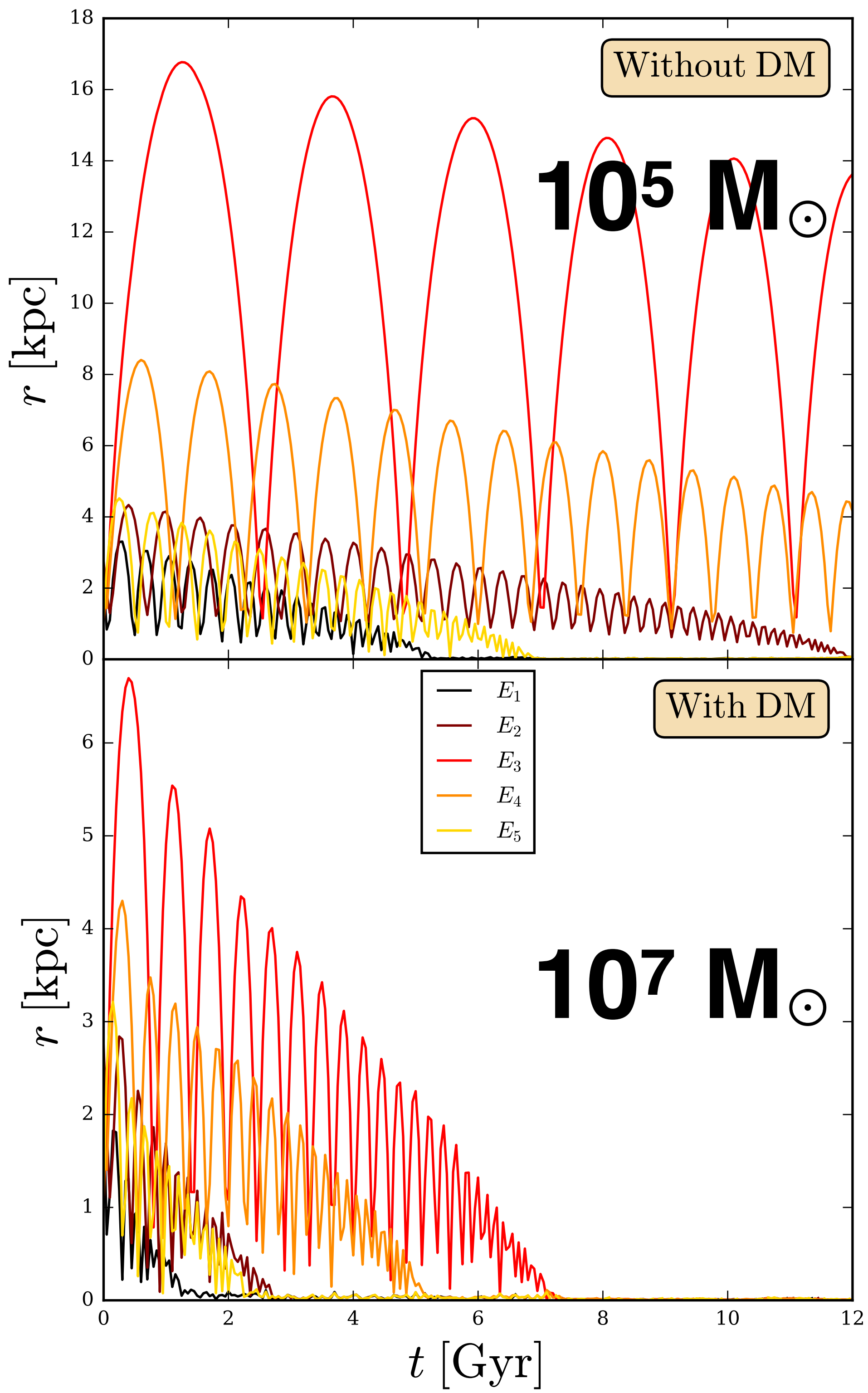

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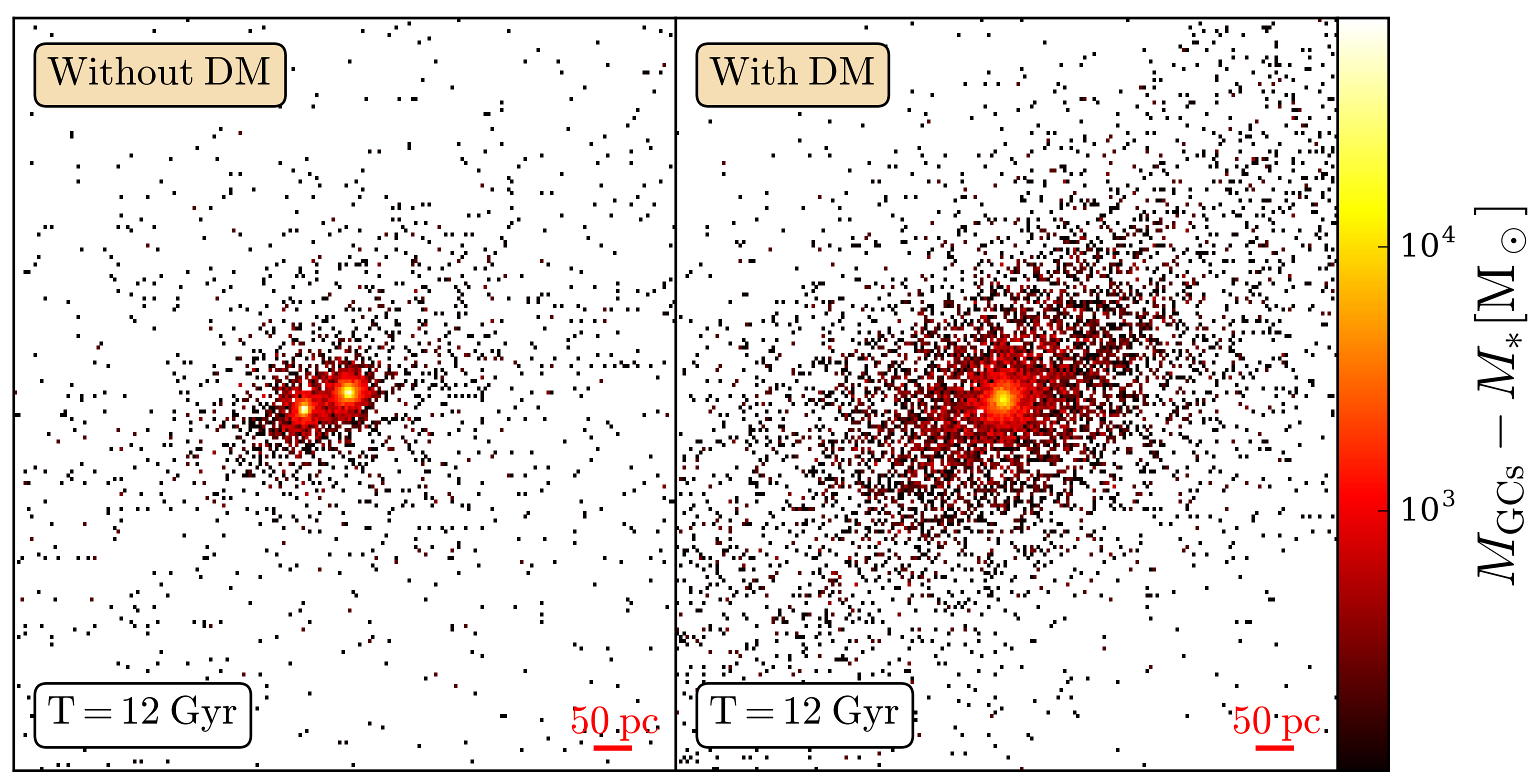

Timing problem

(Boldrini et al. 2019)

Early accretion scenario: cusp-core problem

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Early accretion scenario: cusp-core problem

- **Fit model for subhalo+host**

$$\rho(r) = \rho_c W(r) + [1 - W(r)]\rho_{\rm NFW}(r)$$

$$2W(r) = 1 - \mathrm{erf}\left(\frac{r - r_c}{2\delta}\right)$$

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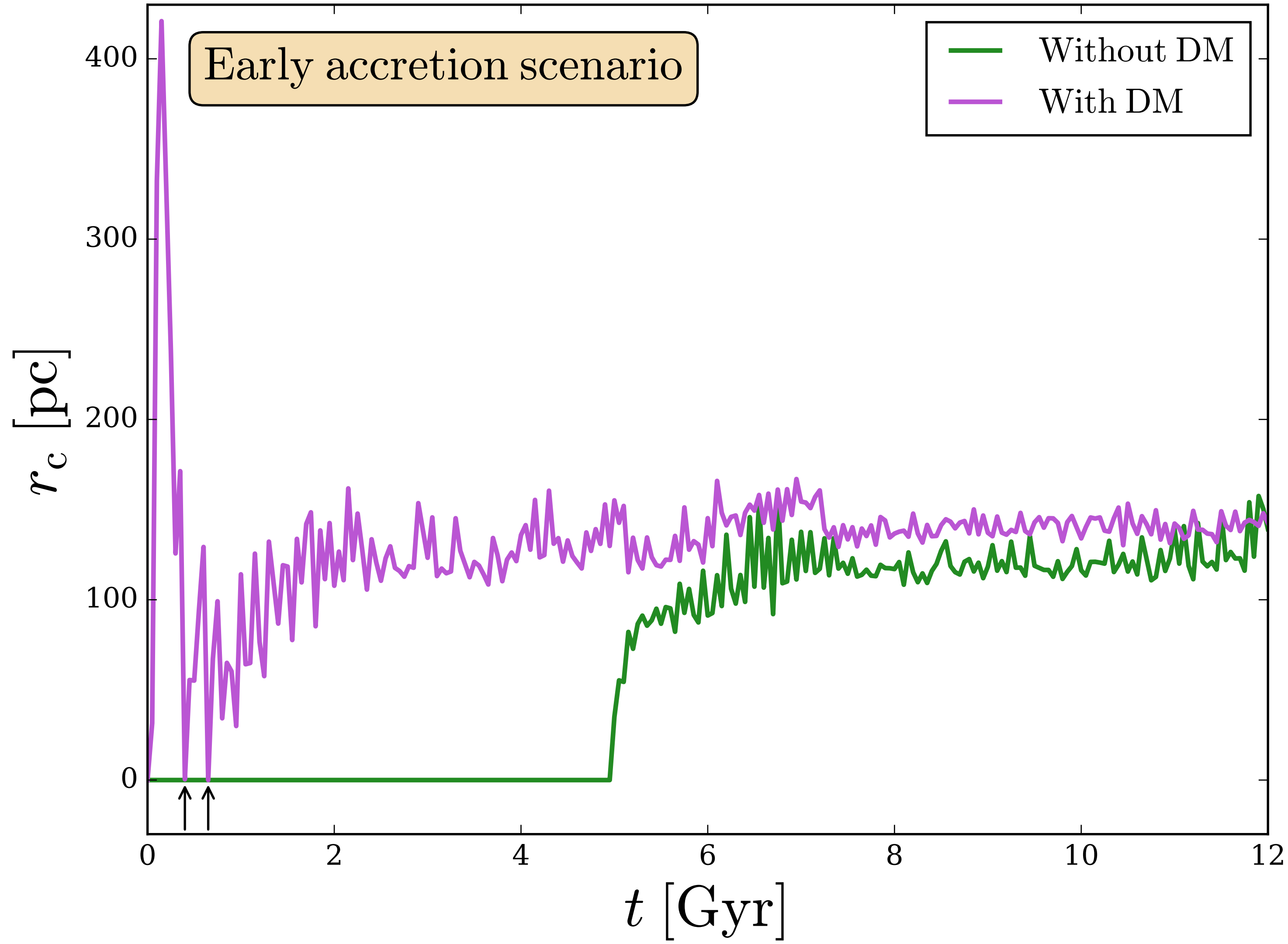

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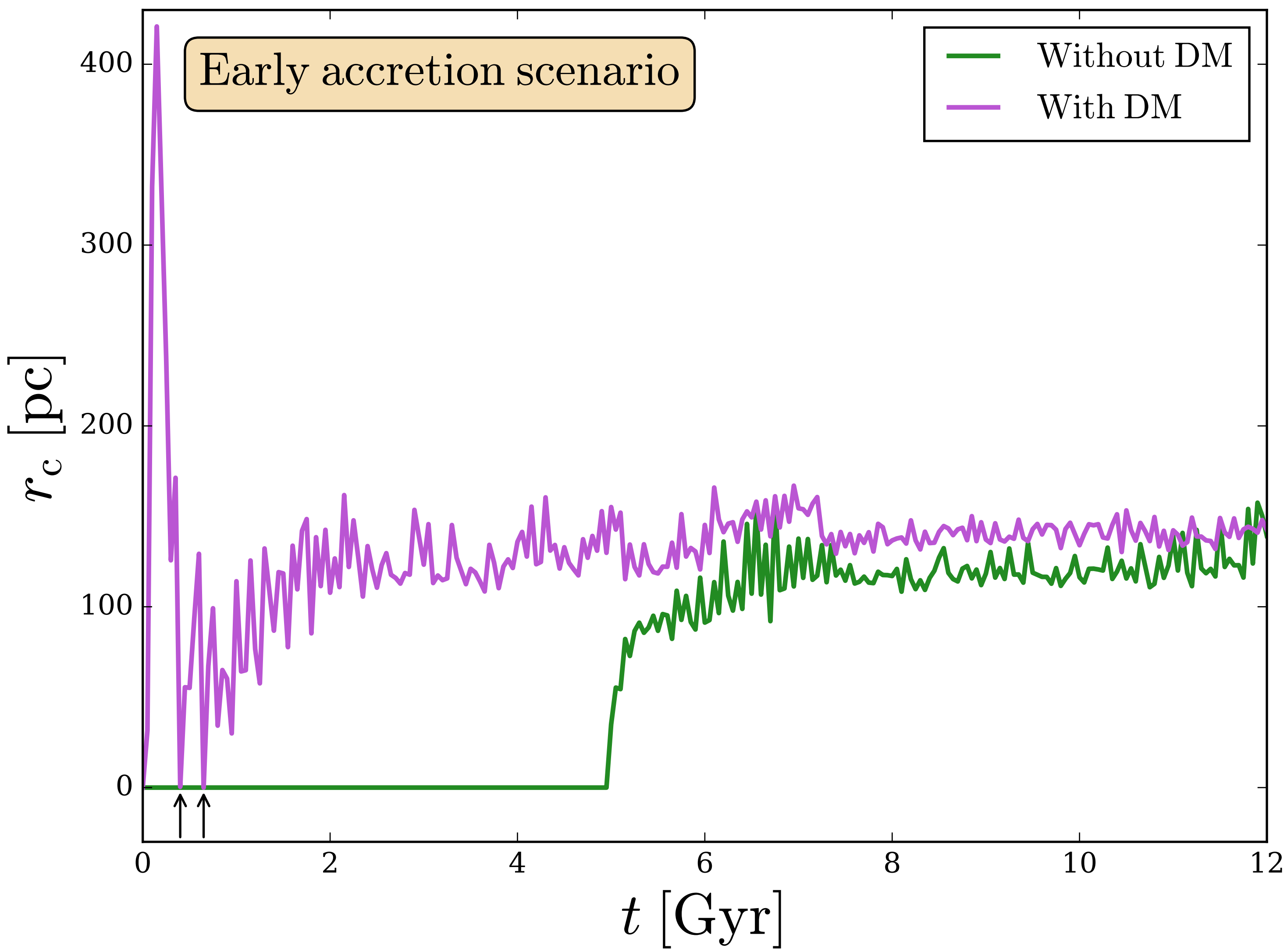

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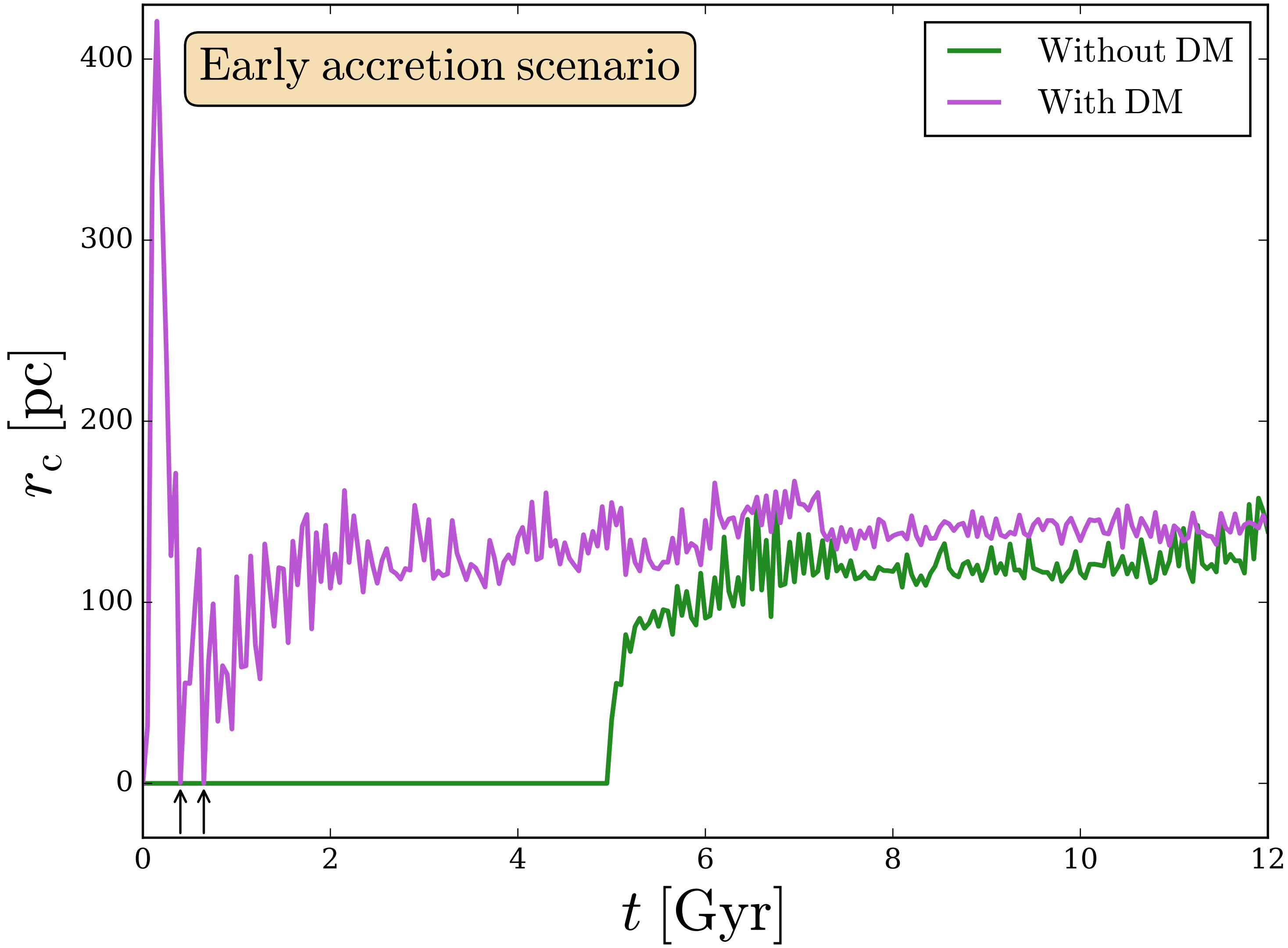


No cusp-core problem in ΛCDM

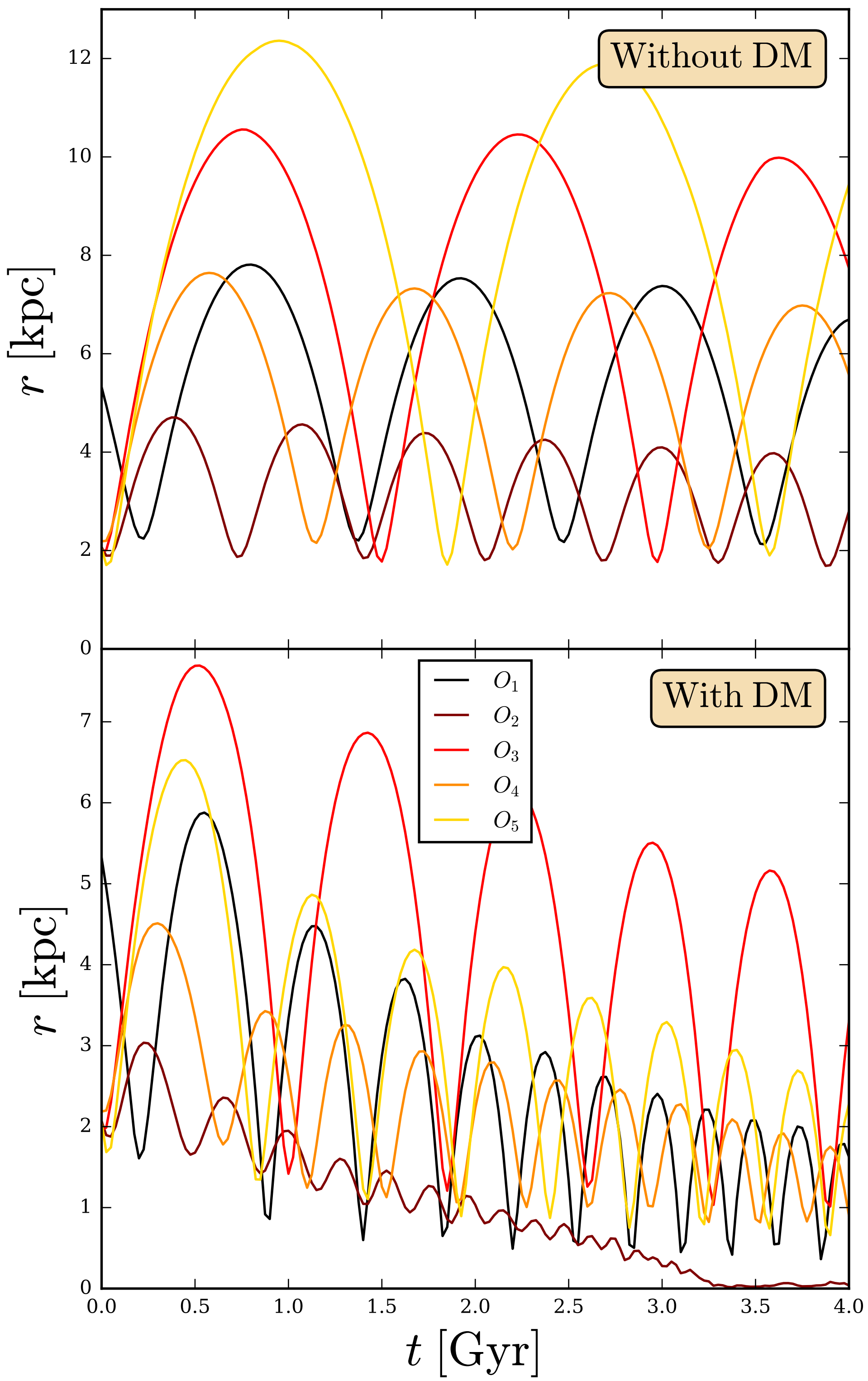
(Boldrini et al. 2019)

Recent accretion scenario: timing problem

GCs accreted 4 Gyr ago by Fornax

(Boldrini et al. 2019)

Recent accretion scenario: timing problem



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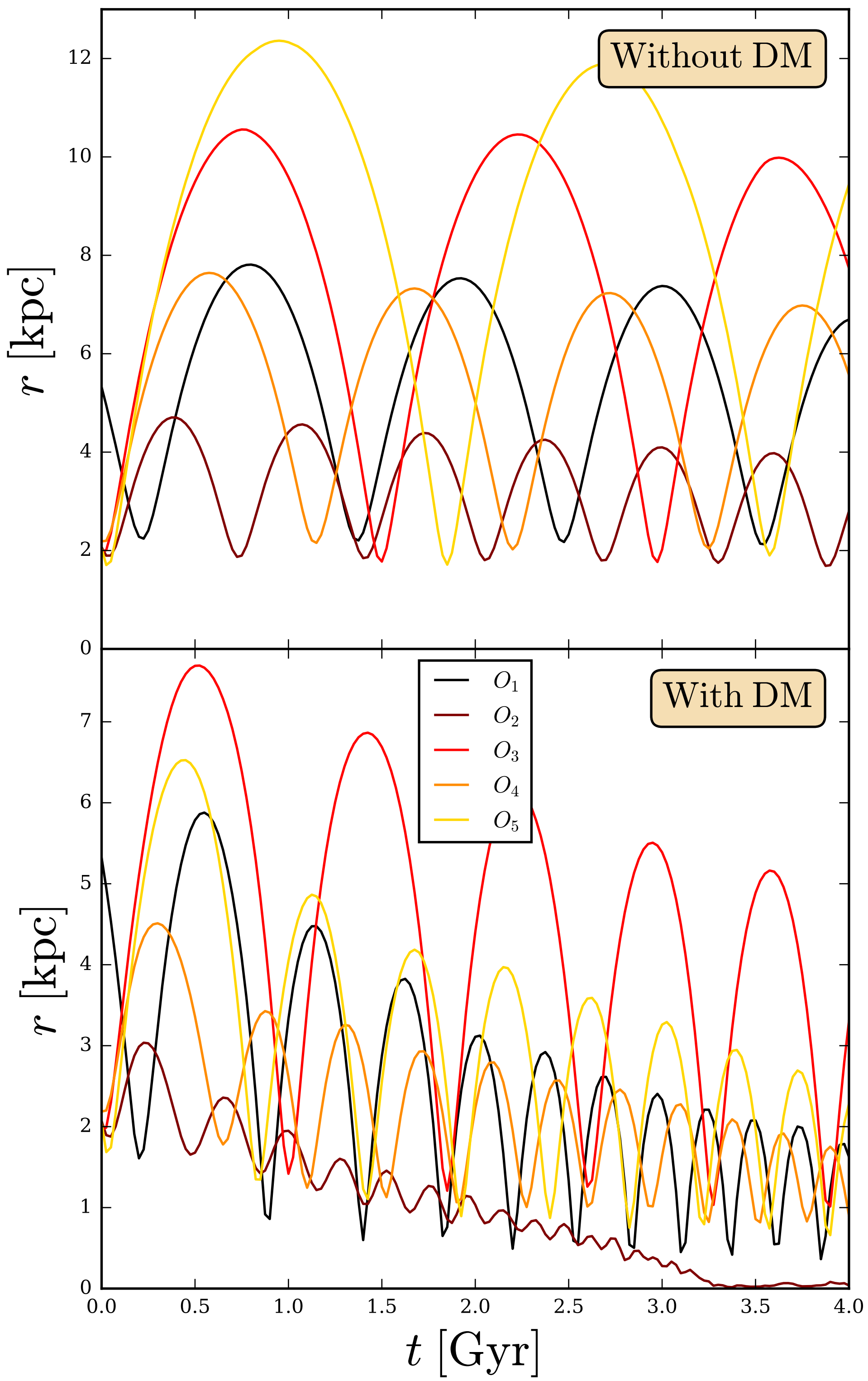

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GC1	0.42 ± 0.10	1.6	O_3	1.01	6.17	9.98 ± 0.1
GC2	1.54 ± 0.28	1.05	O_5	0.66	3.97	9.83 ± 0.15
GC3	4.98 ± 0.84	0.43	O_1	0.36	3.12	8.36 ± 1.34
GC4	0.76 ± 0.15	0.24	O_2	0.016	1.03	7.1 ± 1.74
GC5	1.86 ± 0.24	1.43	O_4	0.82	2.79	9.57 ± 0.37

Observations

Simulations

(Boldrini et al. 2019)

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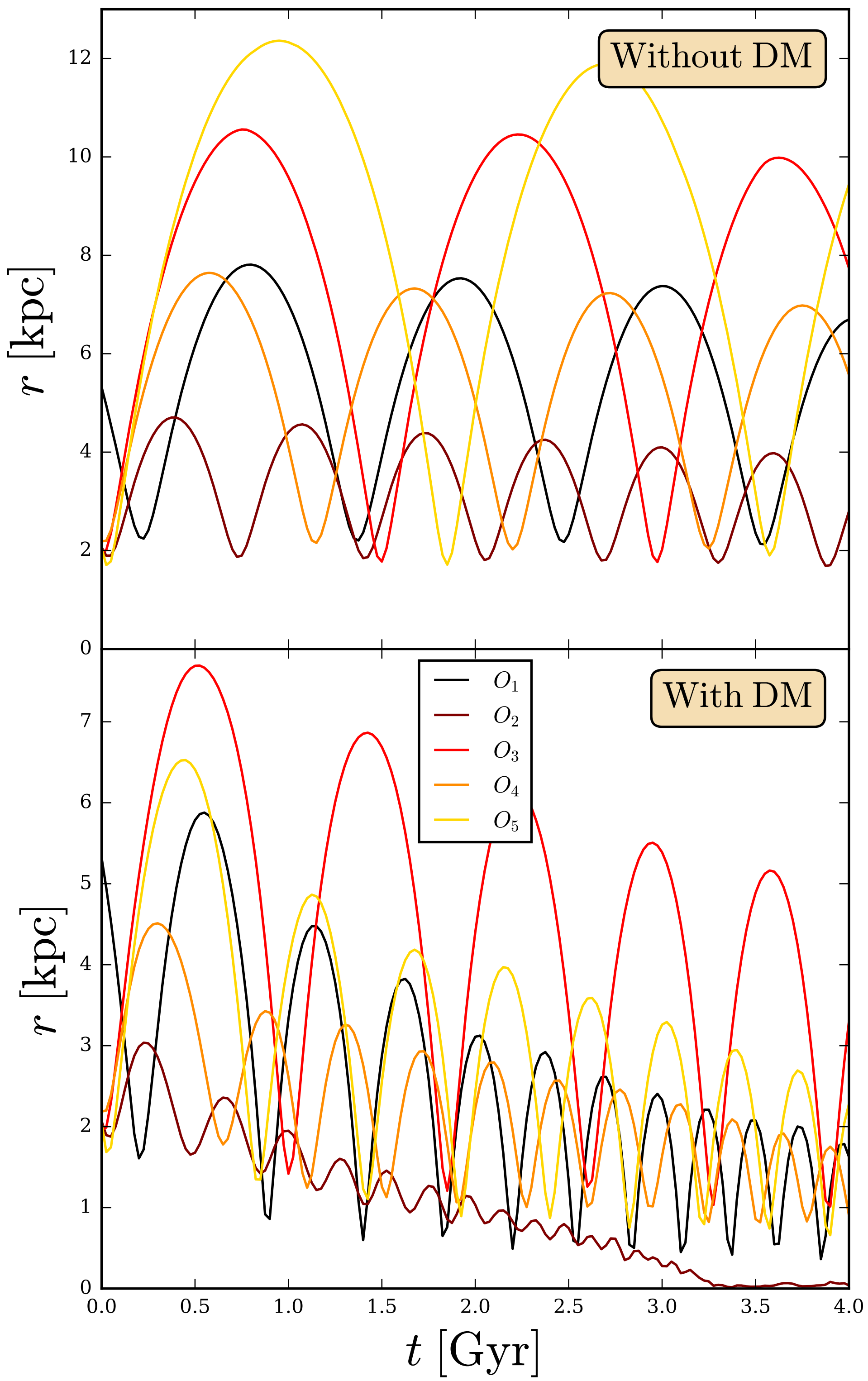

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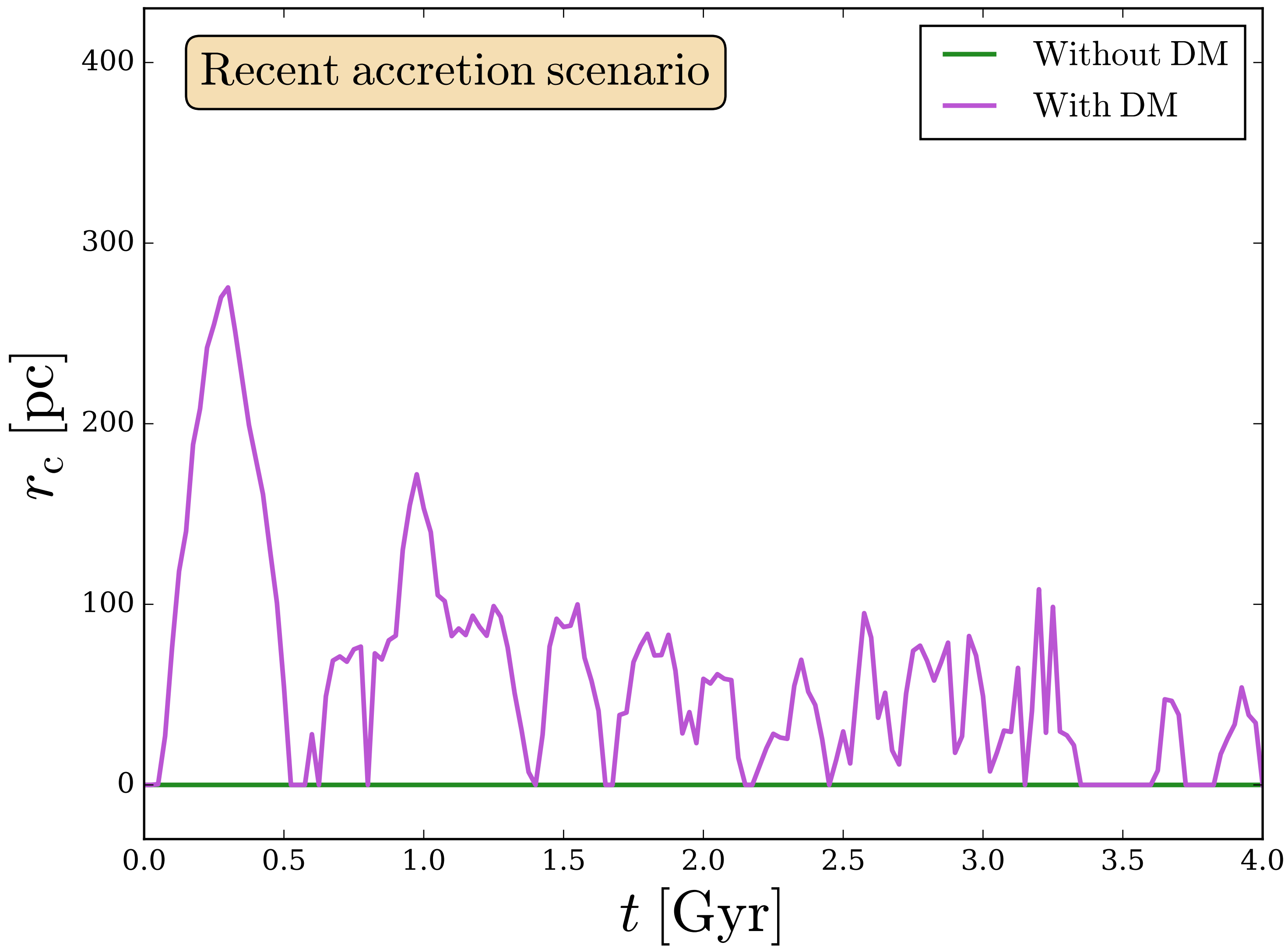

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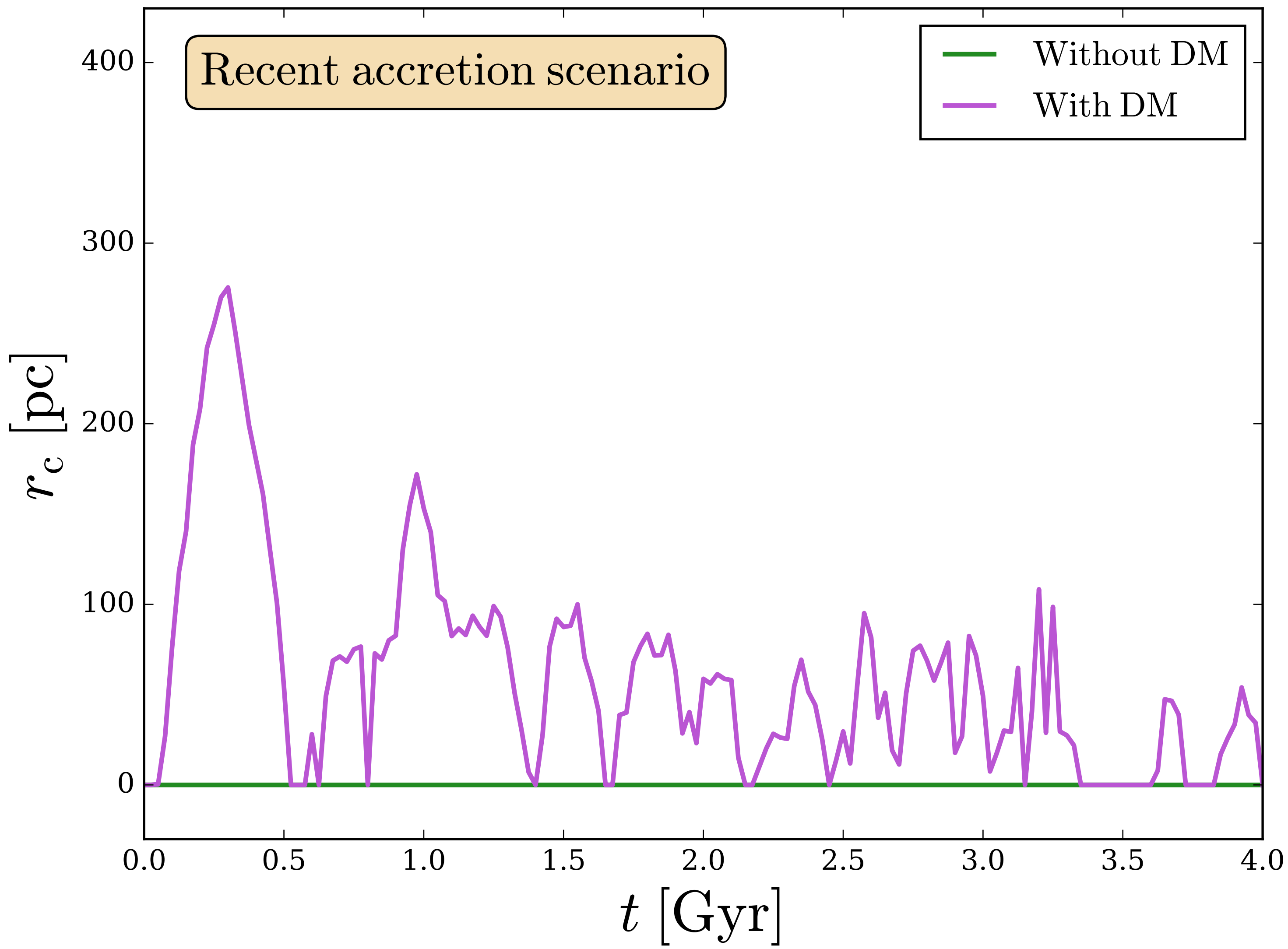

No cusp-core problem in ΛCDM

(Boldrini et al. 2019)

Implications

DM minihalo
as a new component of GCs

Implications

DM minihalo
as a new component of GCs

↓

- **create DM cores in ΛCDM**
- **DM cores of different sizes**

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DM minihalo
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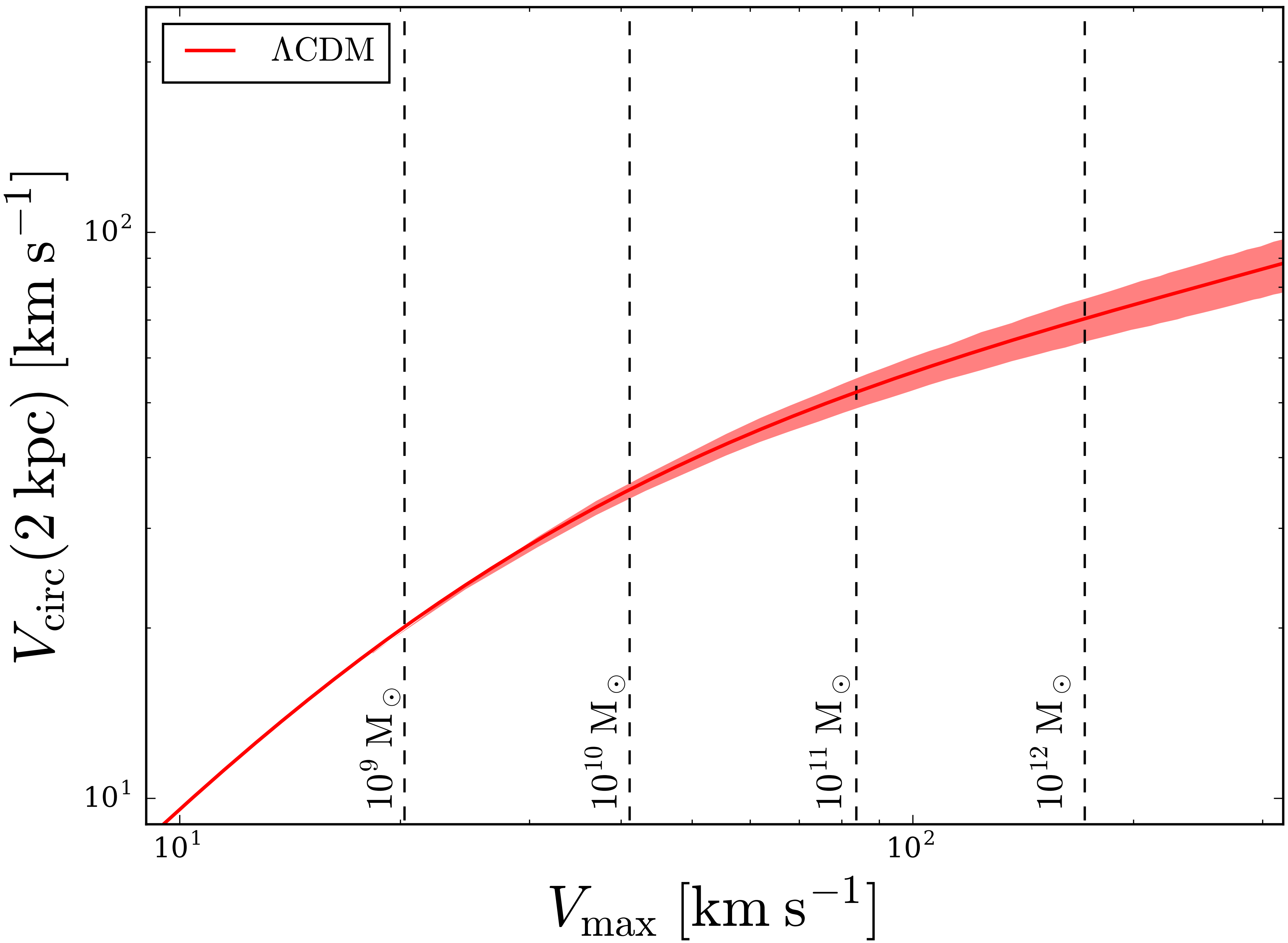
↓

Diversity problem

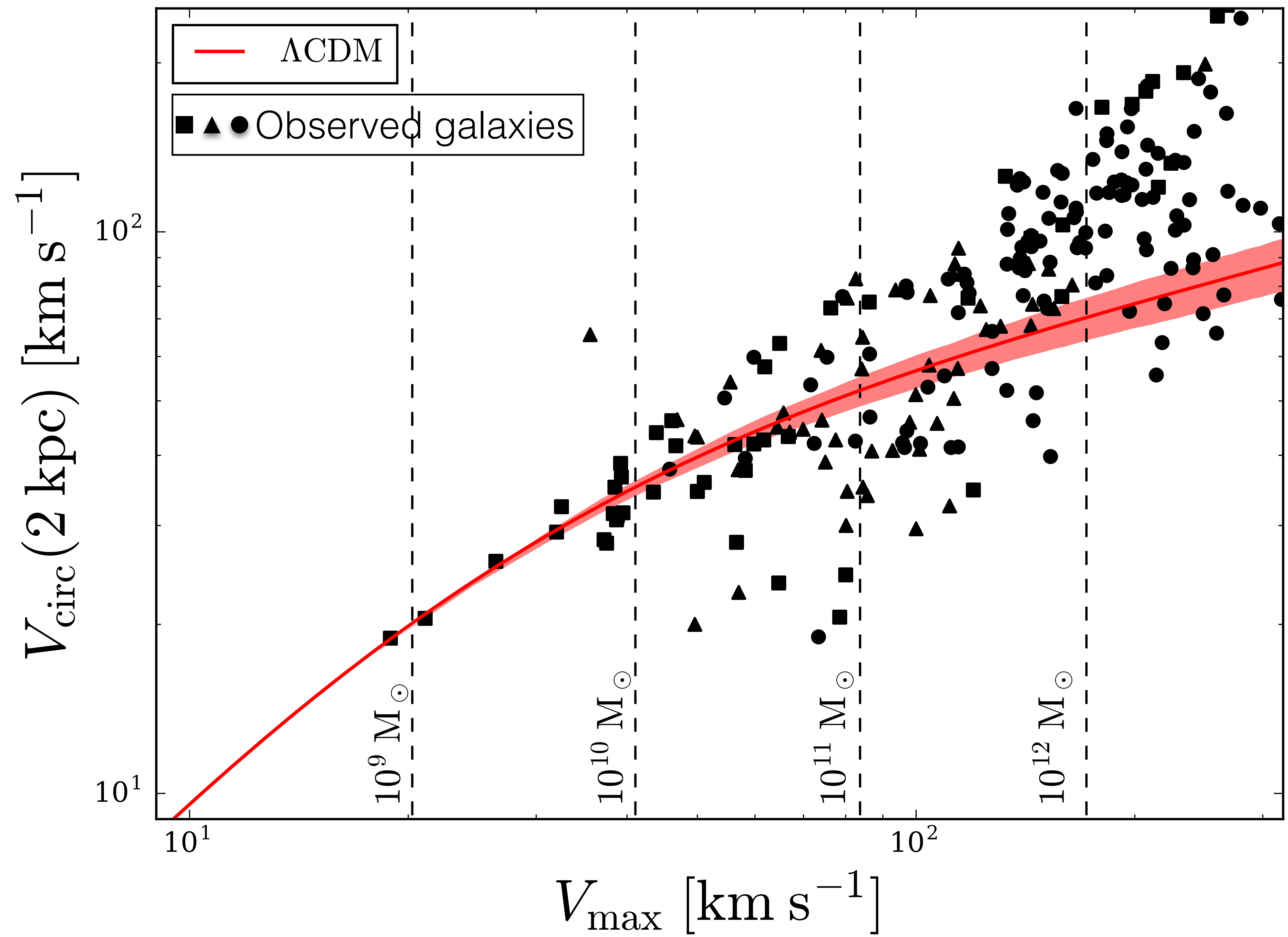
Diversity problem



$$\boxed{\log_{10}(c_{200}) = 0.905 - 0.101\log_{10}(M_{200}h - 12)}$$

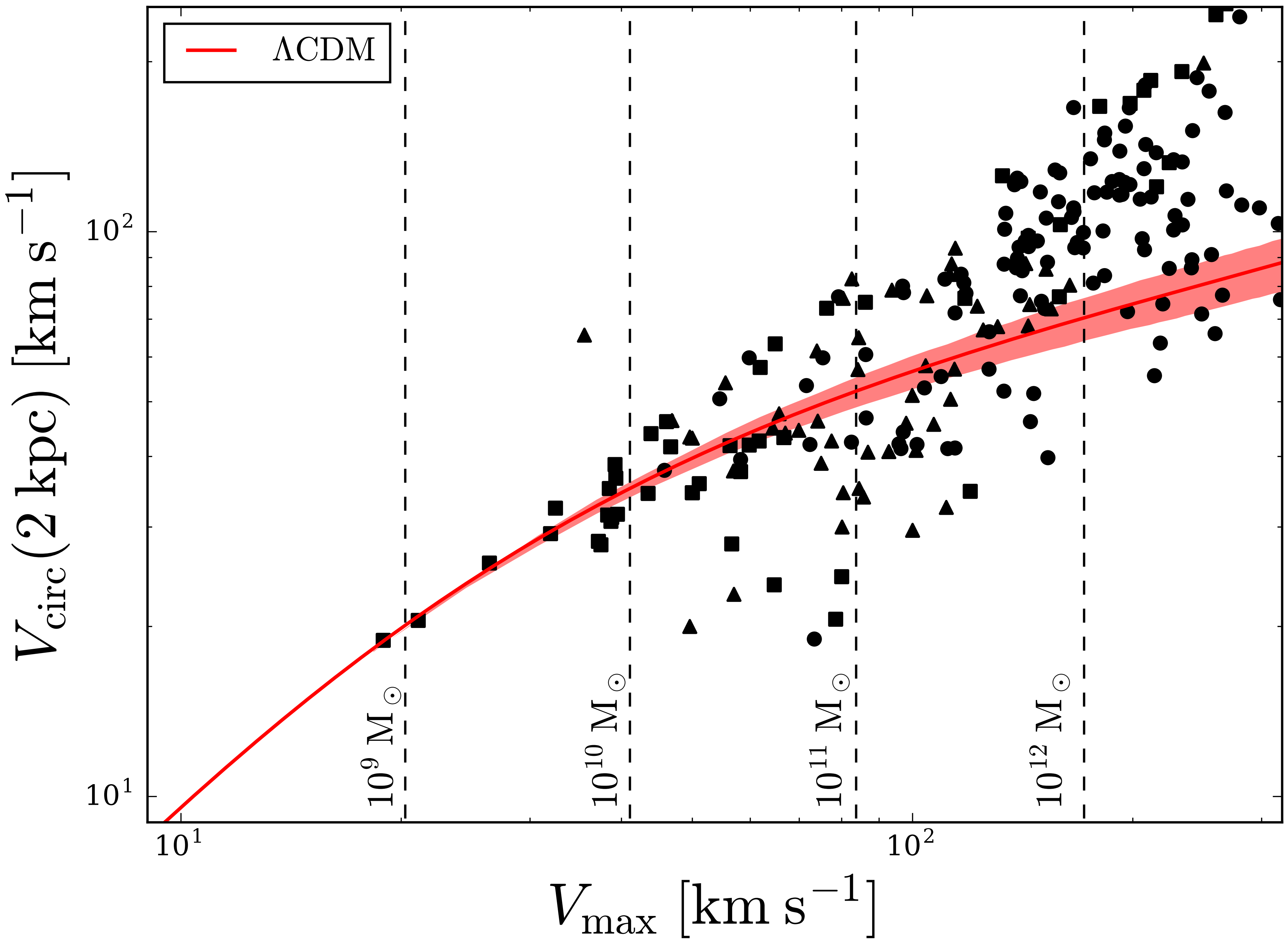
(Dutton et Maccio 2014)

Diversity problem



(Oman et al. 2015)

CDM + baryons?



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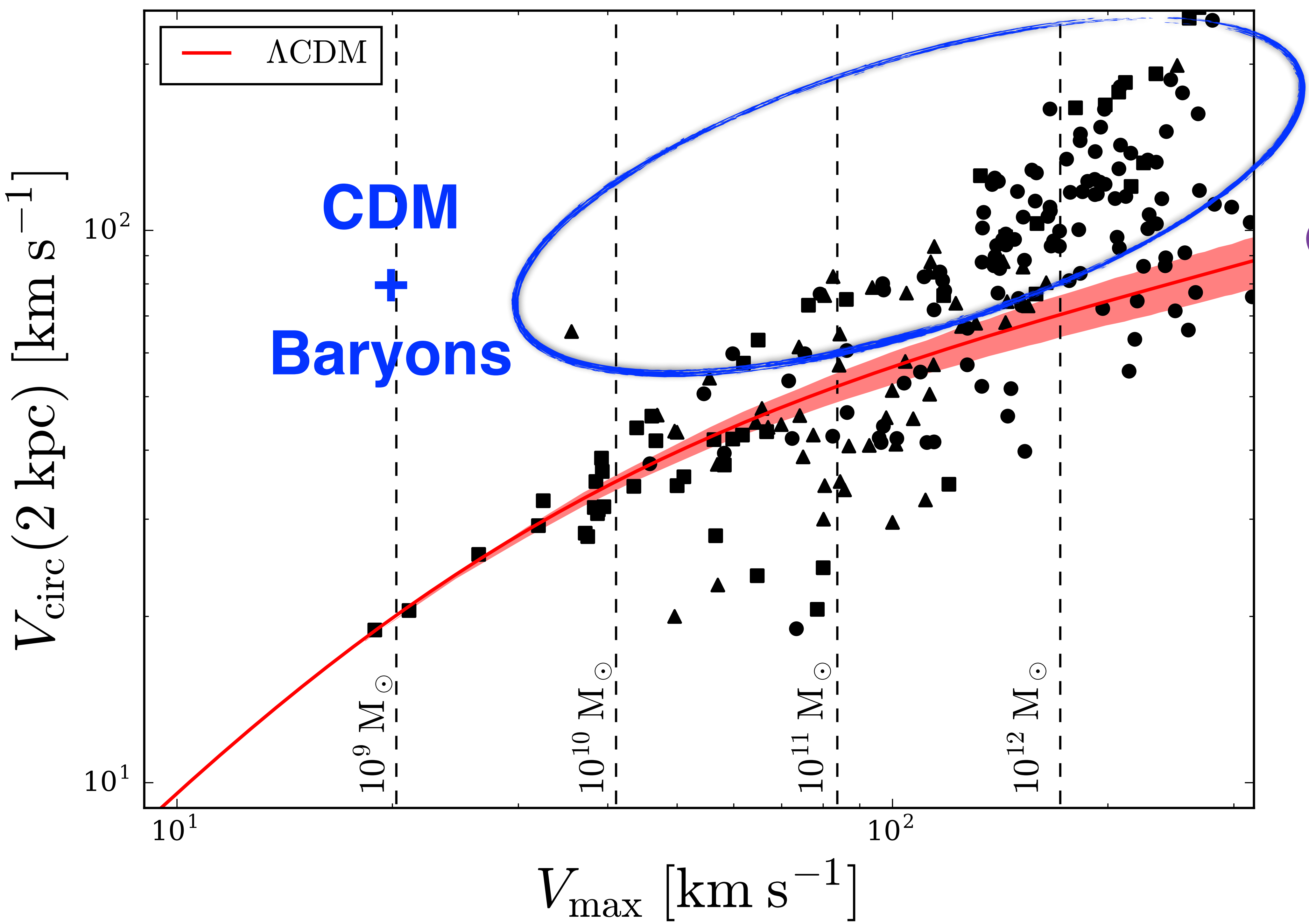
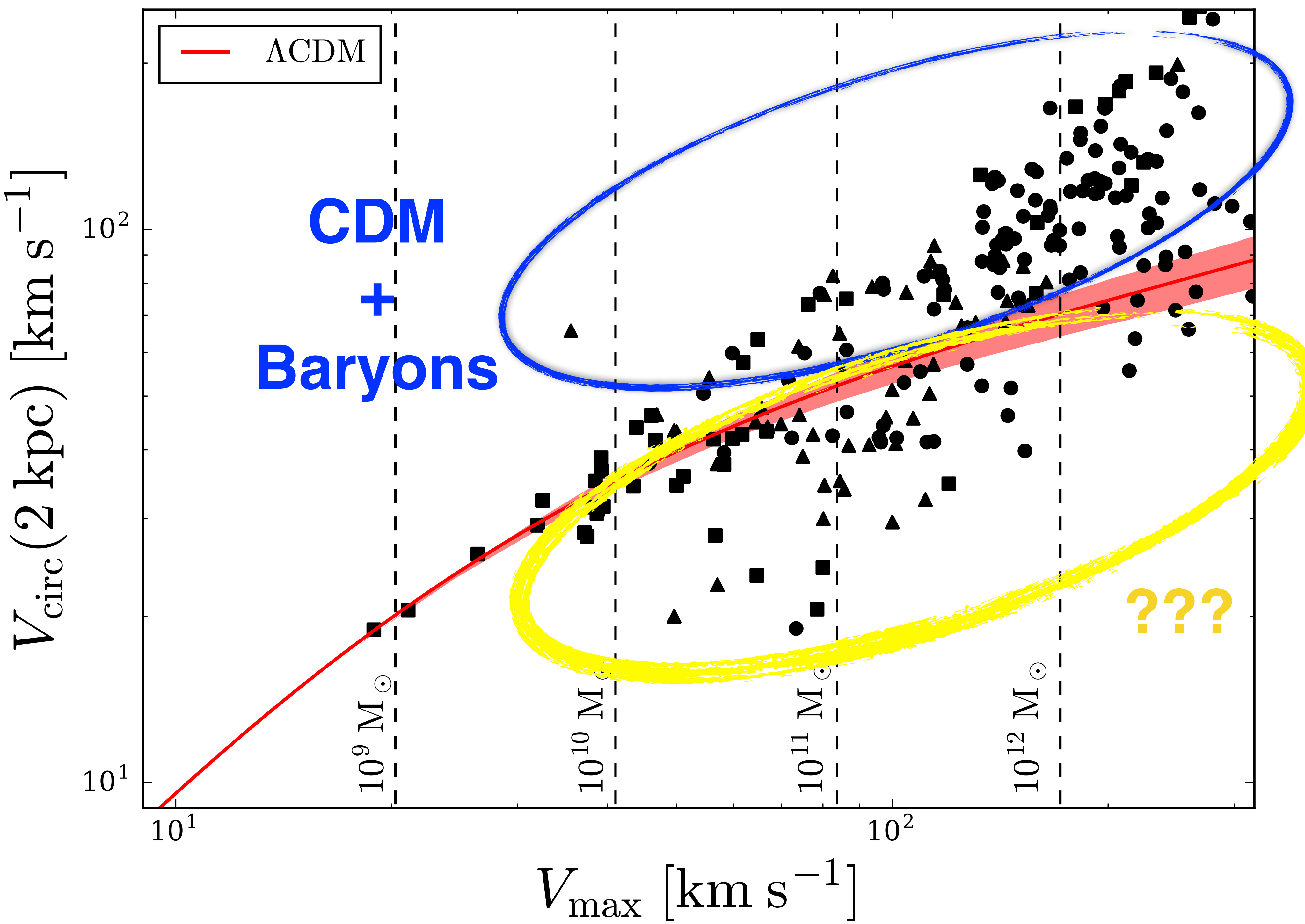


EAGLE and LOCAL GROUPS hydrodynamical simulations

(Schaye et al. 2015, Sawala et al. 2014)

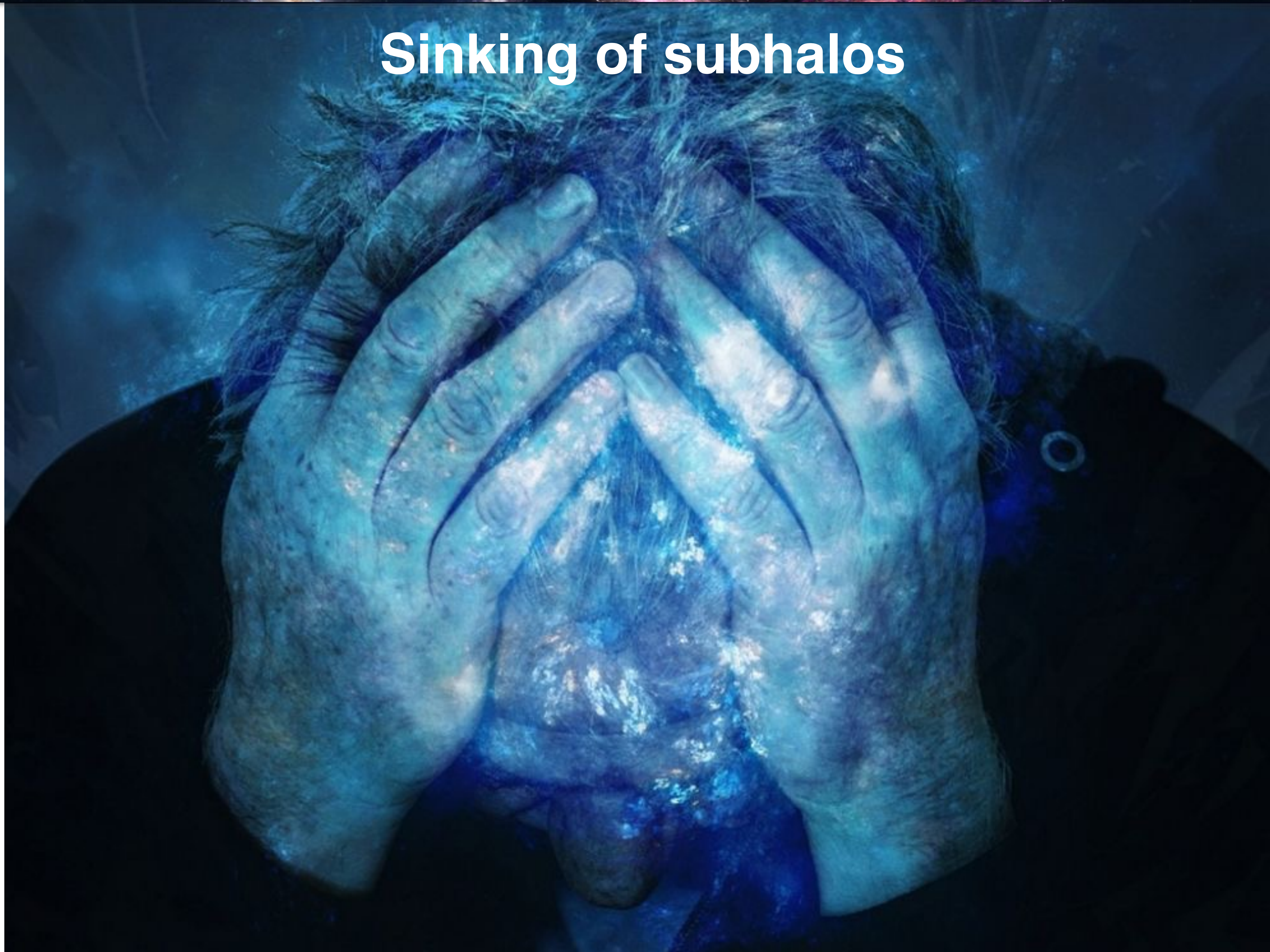
(Oman et al. 2015)

New solution?



ΛCDM mechanism

ΛCDM mechanism



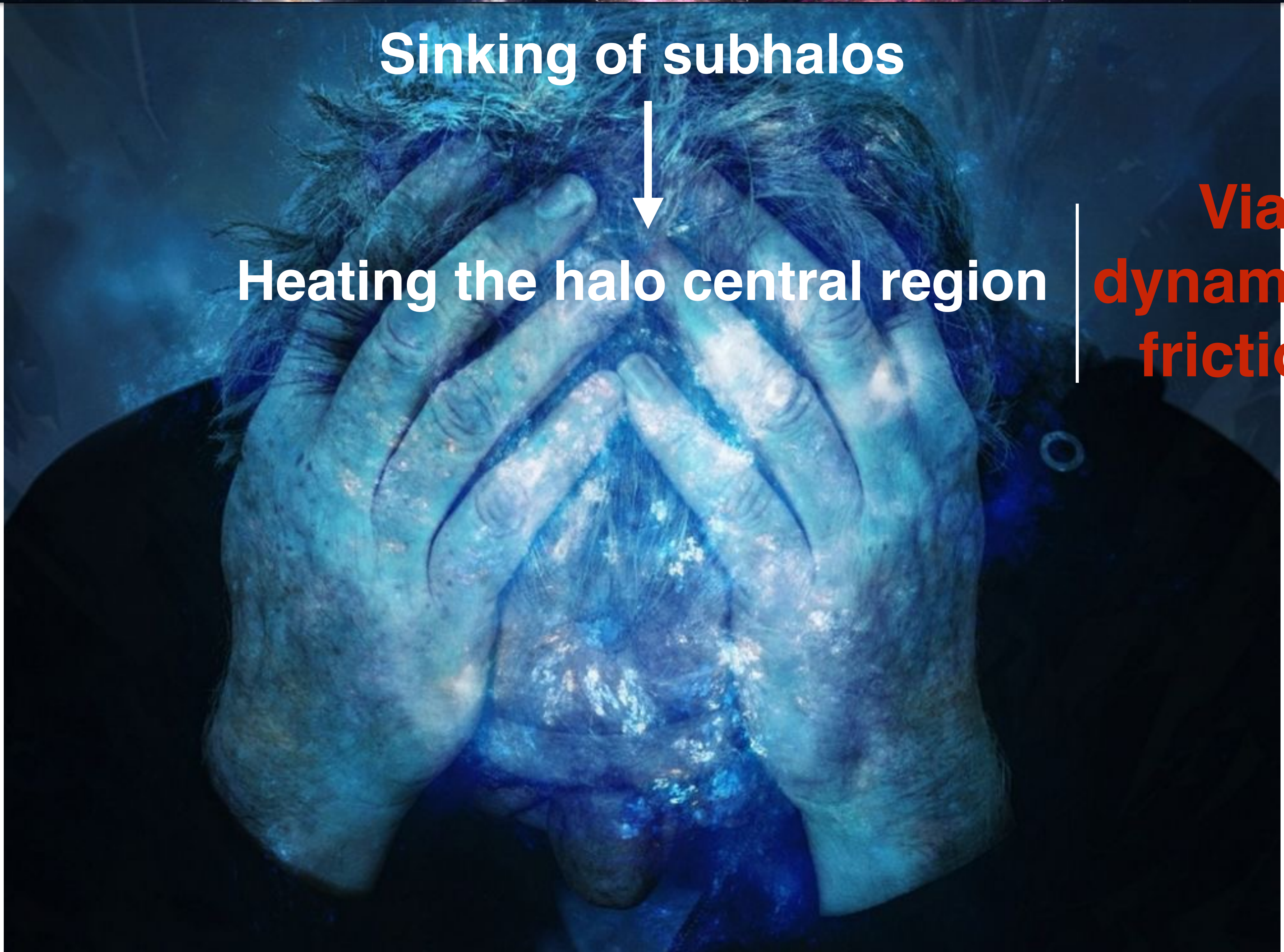
ΛCDM mechanism

Sinking of subhalos

↓

Heating the halo central region

ΛCDM mechanism



Sinking of subhalos

↓

Heating the halo central region

Via dynamical friction

ΛCDM mechanism

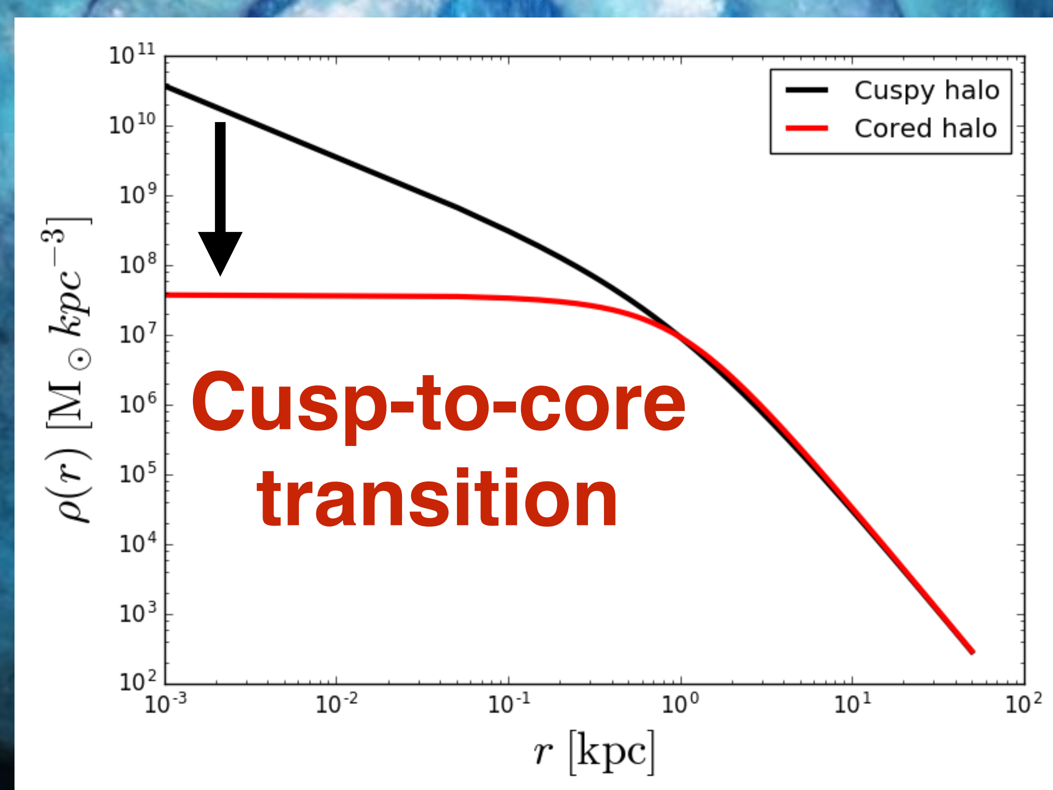
Sinking of subhalos

↓

Heating the halo central region

↓

Via dynamical friction



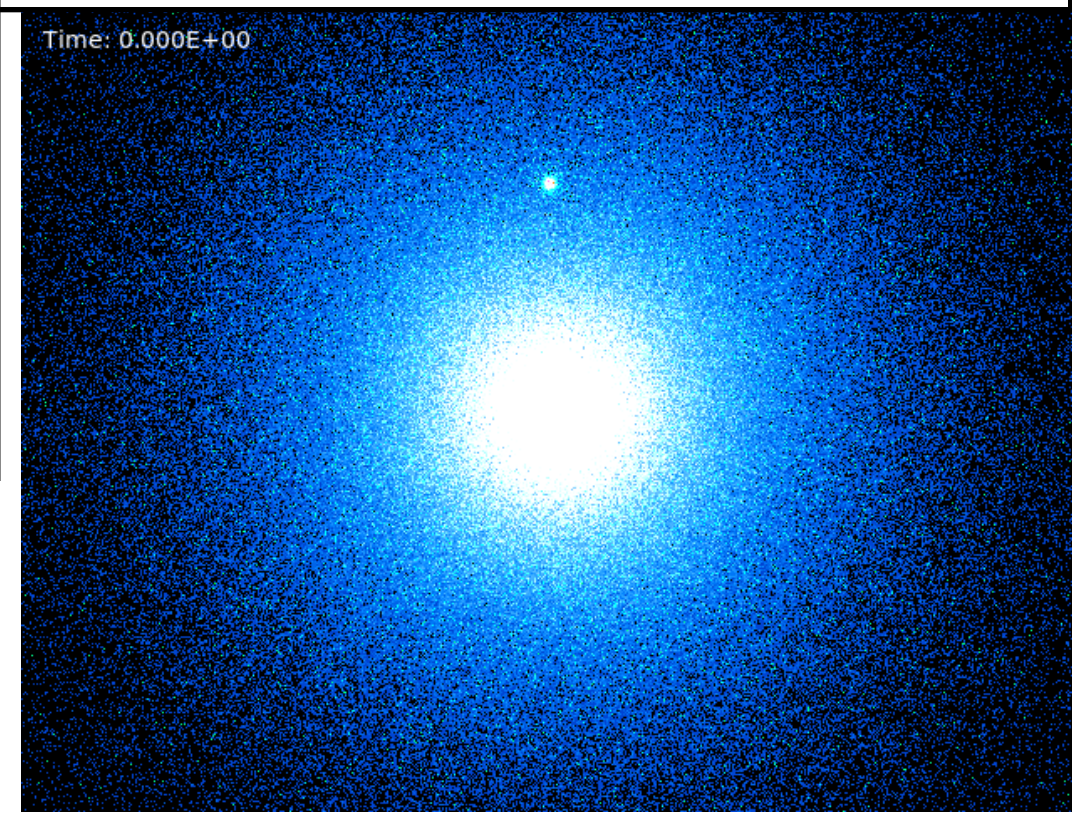
Fully GPU *N*-body simulations

Dynamical friction
&
Tidal stripping

Fully GPU collisionless *N*-body code, GOTHIC

(Miki & Umemura 2017)

Self-gravitating system composed of DM particles



Modelling
Host halo ~ 10^7 particles
Subhalos ~ 10^5 particles

Resolution
~ 20 - 30 pc

Simulation time
12 Gyr

Subhalo initial conditions

- **Average number of subhalo accretion per Gyr for $10 < M_{host} / M_{sub} < 100$**
  (Neinstein et Dekel 2008)

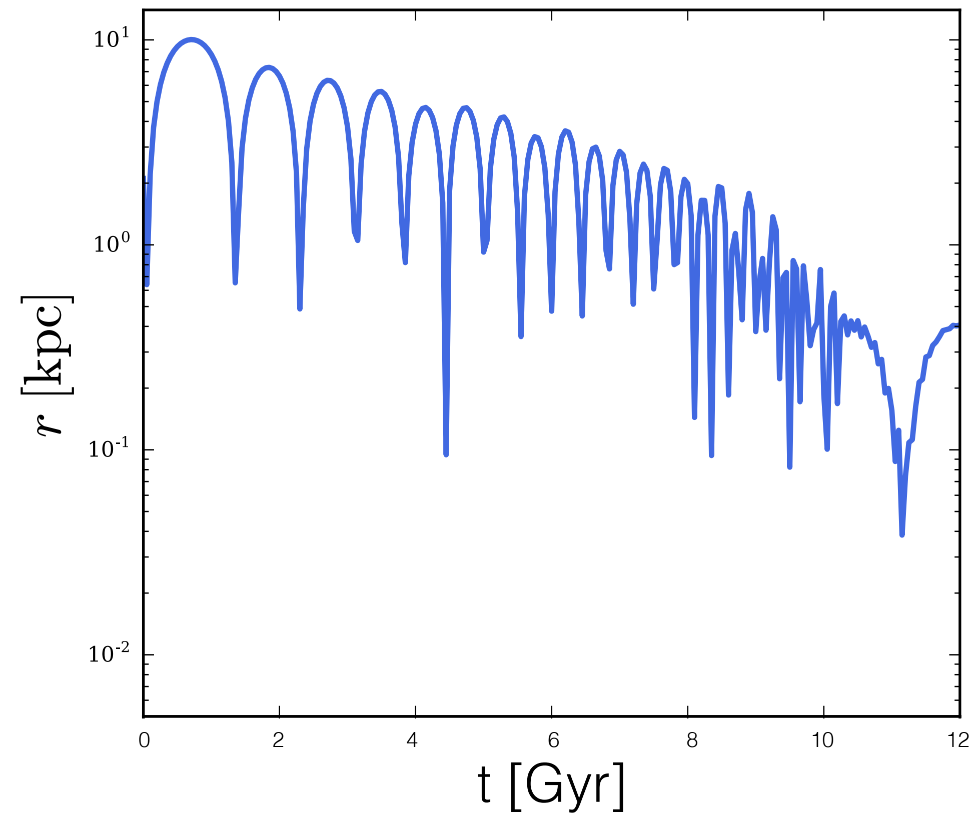
Halo mass $[M_{\odot}]$	$N_{\mathrm{m}}(z = 3)$
10^9	~3-4
10^{10}	~4-5
10^{12}	~6-7
10^{13}	~8-9

- **Average velocity of subhalos during the infall**
  (Wetzel 2011, Jiang et al. 2015)

radial orbit approach

Host halo + subhalo scenario

- 10^9 $M_\odot$ host halo (NFW at z=3)
- one 2×10^7 $M_\odot$ subhalo (NFW at z=3)

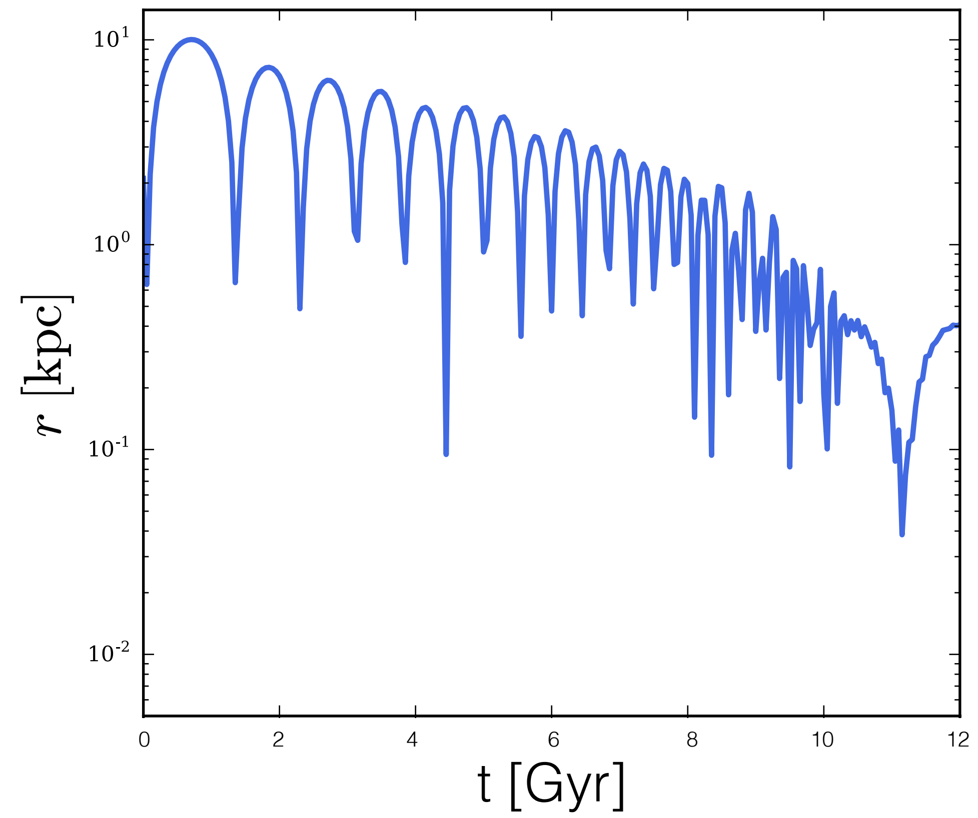


Host halo + subhalo scenario

- **$10^9\ M_\odot$ host halo (NFW at z=3)**
- **one $2 \times 10^7\ M_\odot$ subhalo (NFW at z=3)**
- **Fit model for subhalo+host**

$$\rho(r) = \rho_c W(r) + [1 - W(r)]\rho_{\rm NFW}(r)$$

$$2W(r) = 1 - \mathrm{erf}\left(\frac{r - r_c}{2\delta}\right)$$



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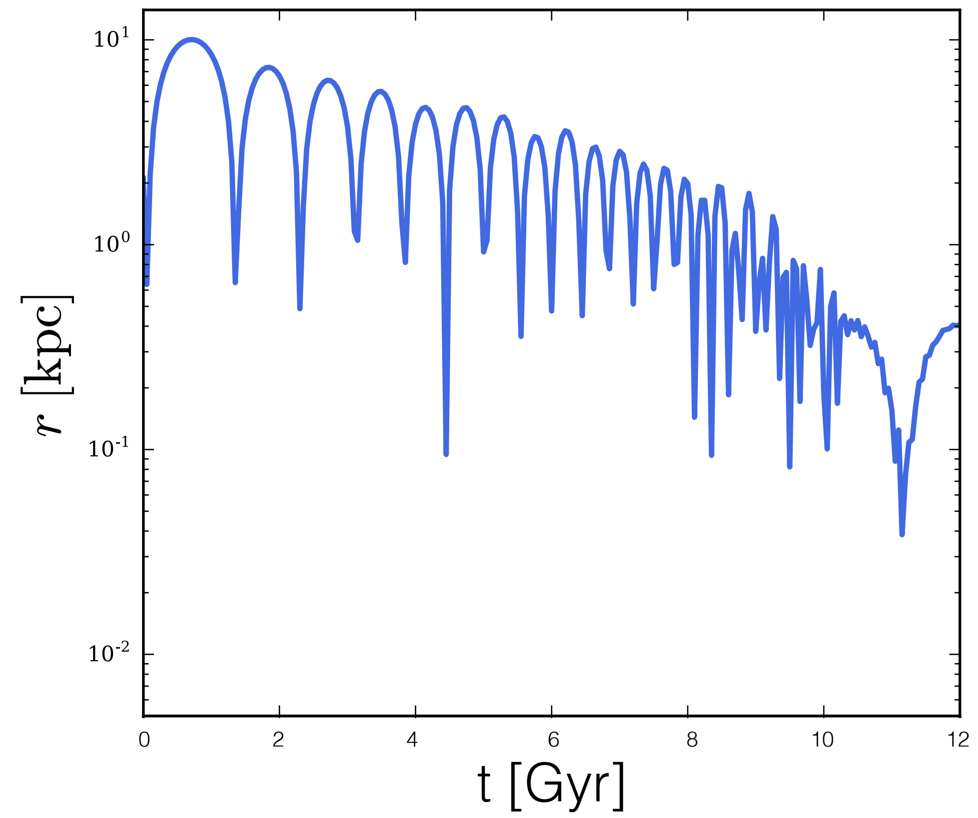

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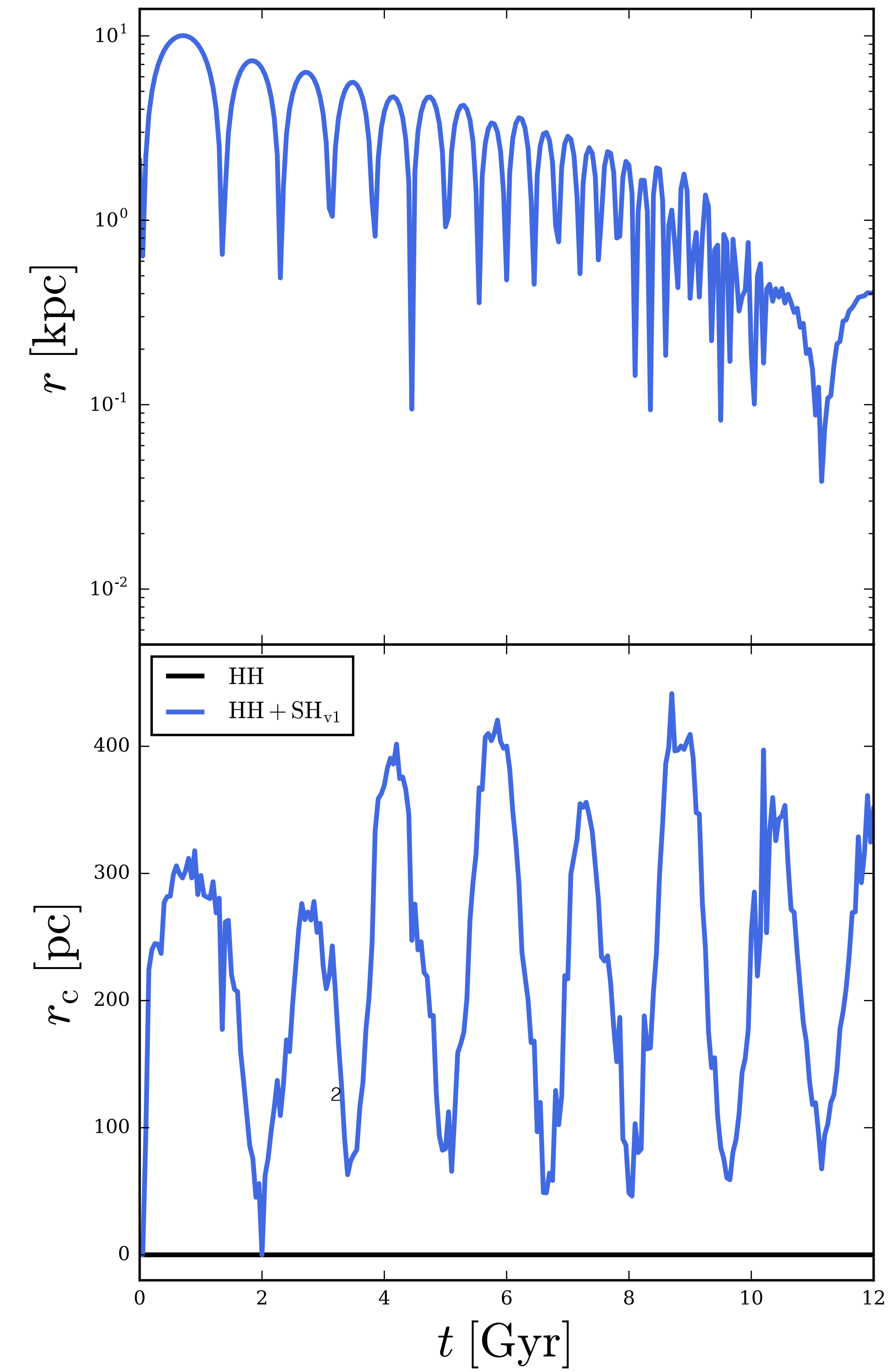

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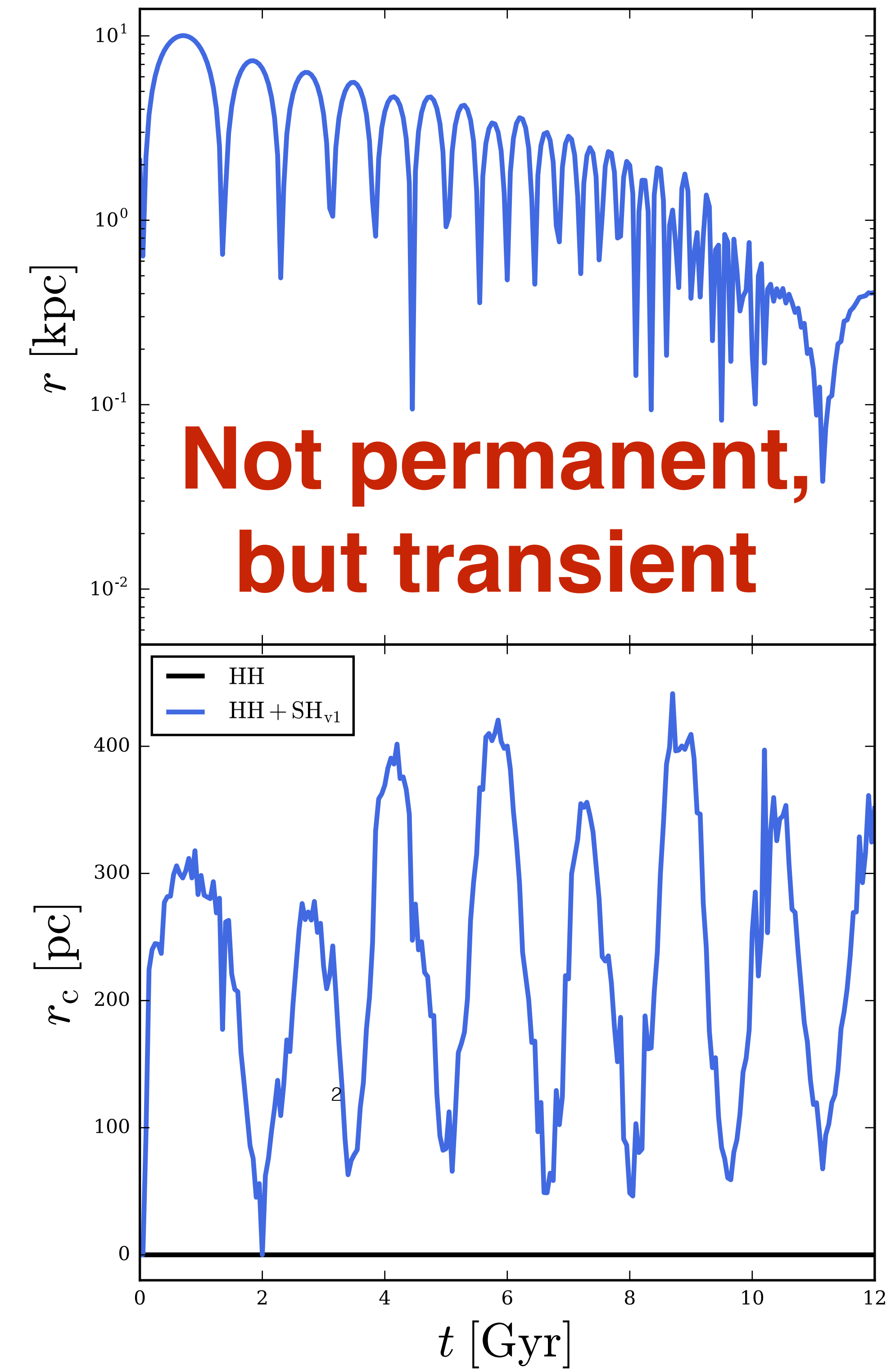

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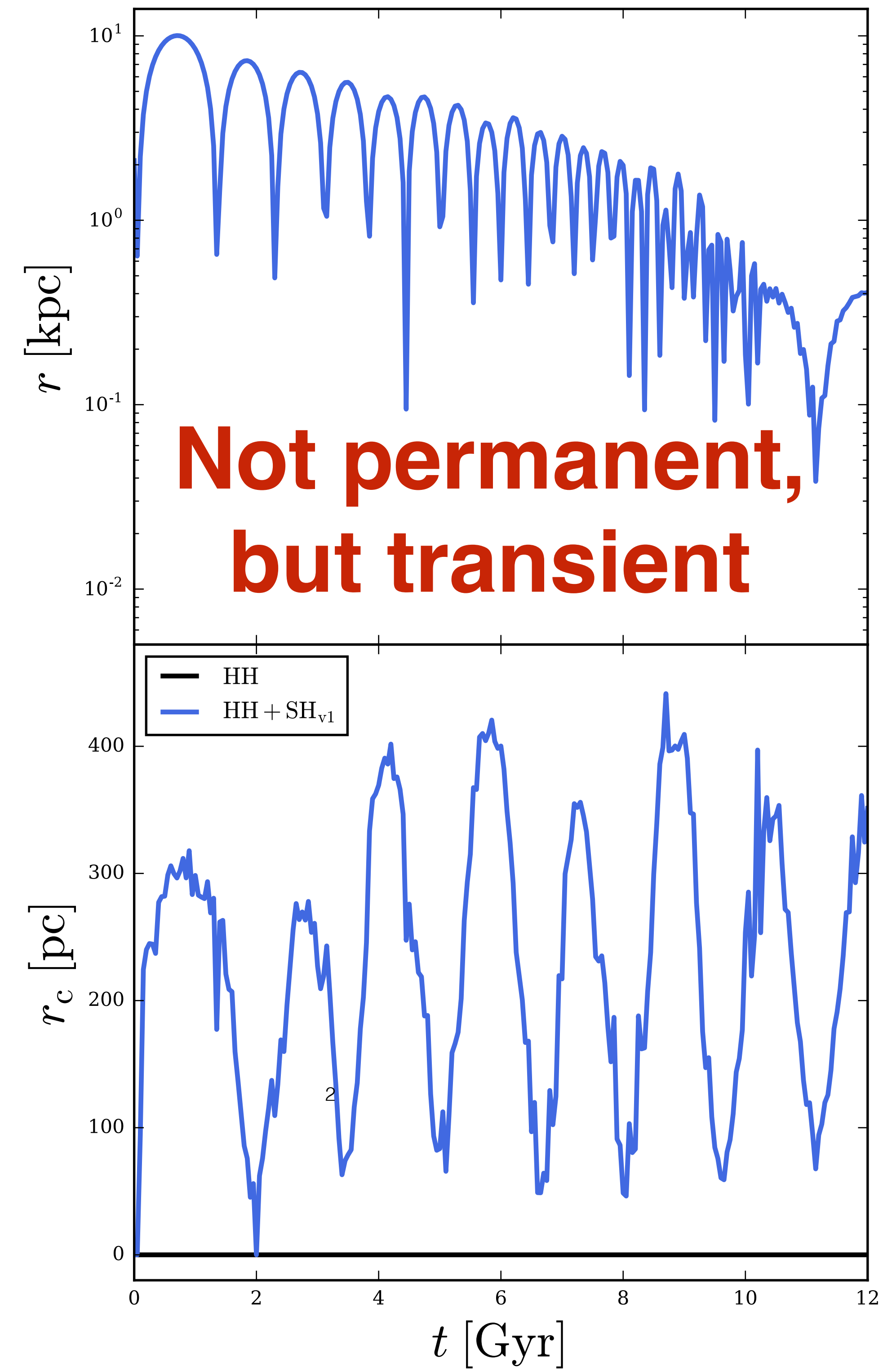
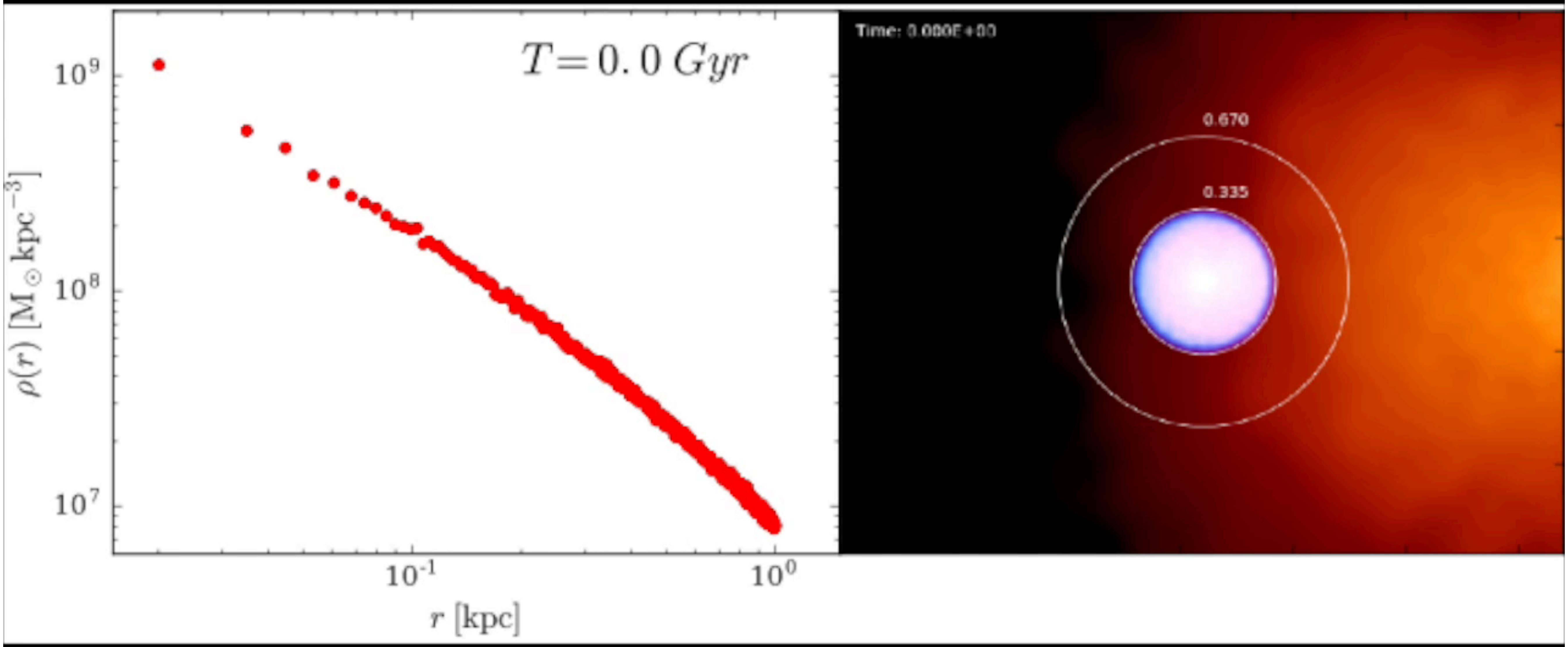


No cusp-core problem in ΛCDM

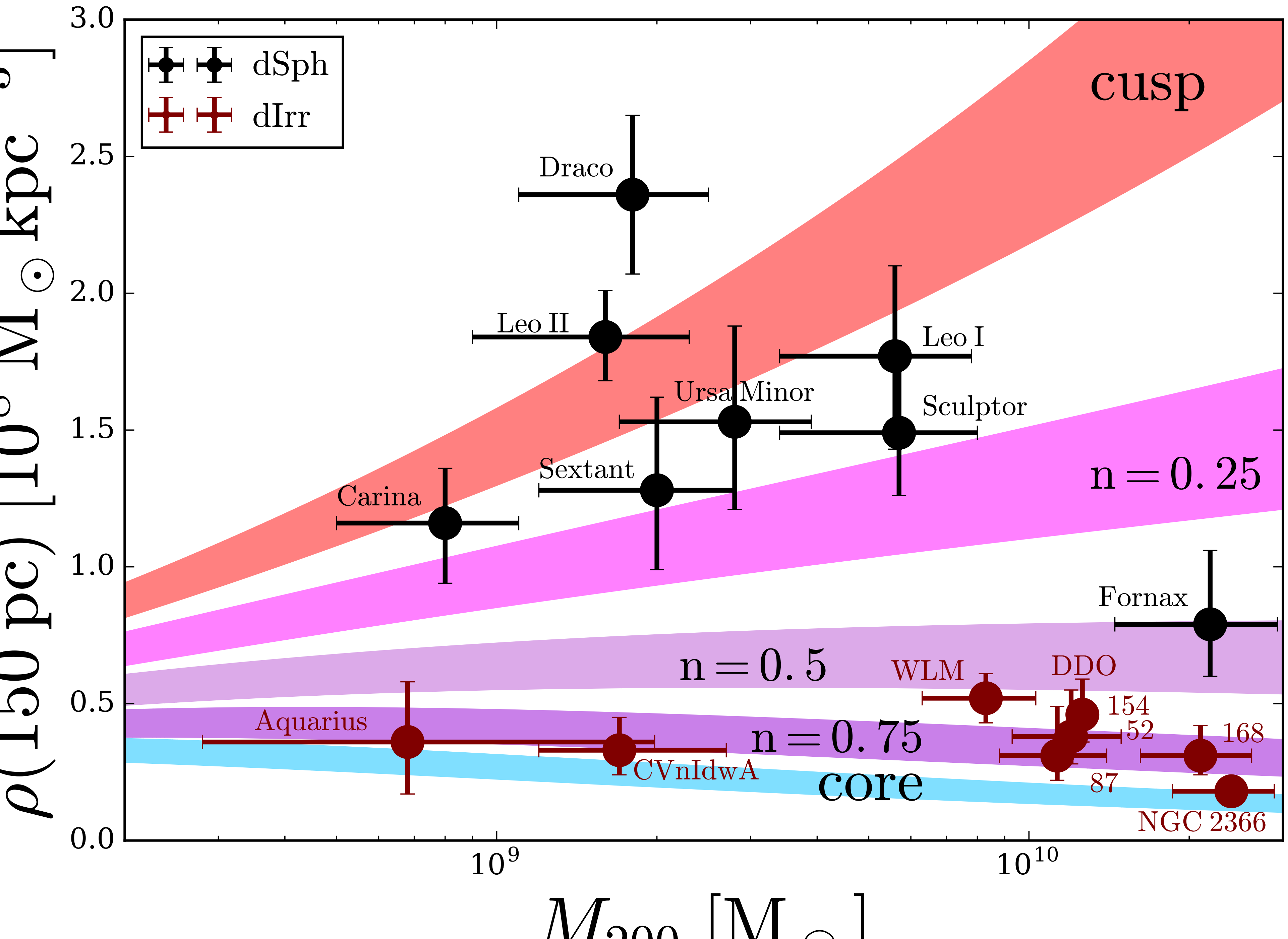
Subhalo heats the halo centre



(Boldrini et al. in prep)

Inner density of dSph galaxies

Fully cuspy $0 < n \leqslant 1$ **Fully core**



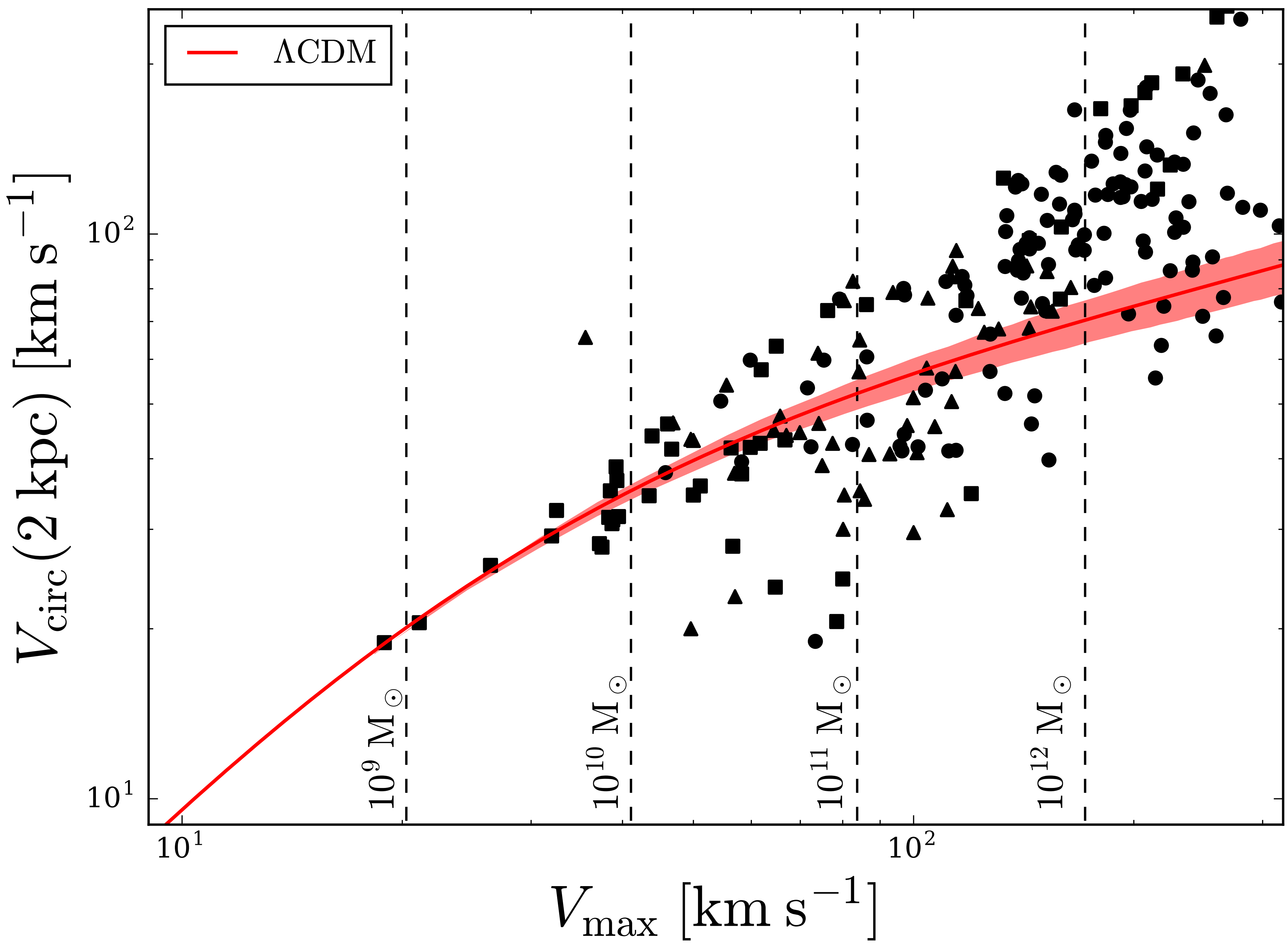
CoreNFW model

(Read et al. 2016)

(Read et al. 2019)

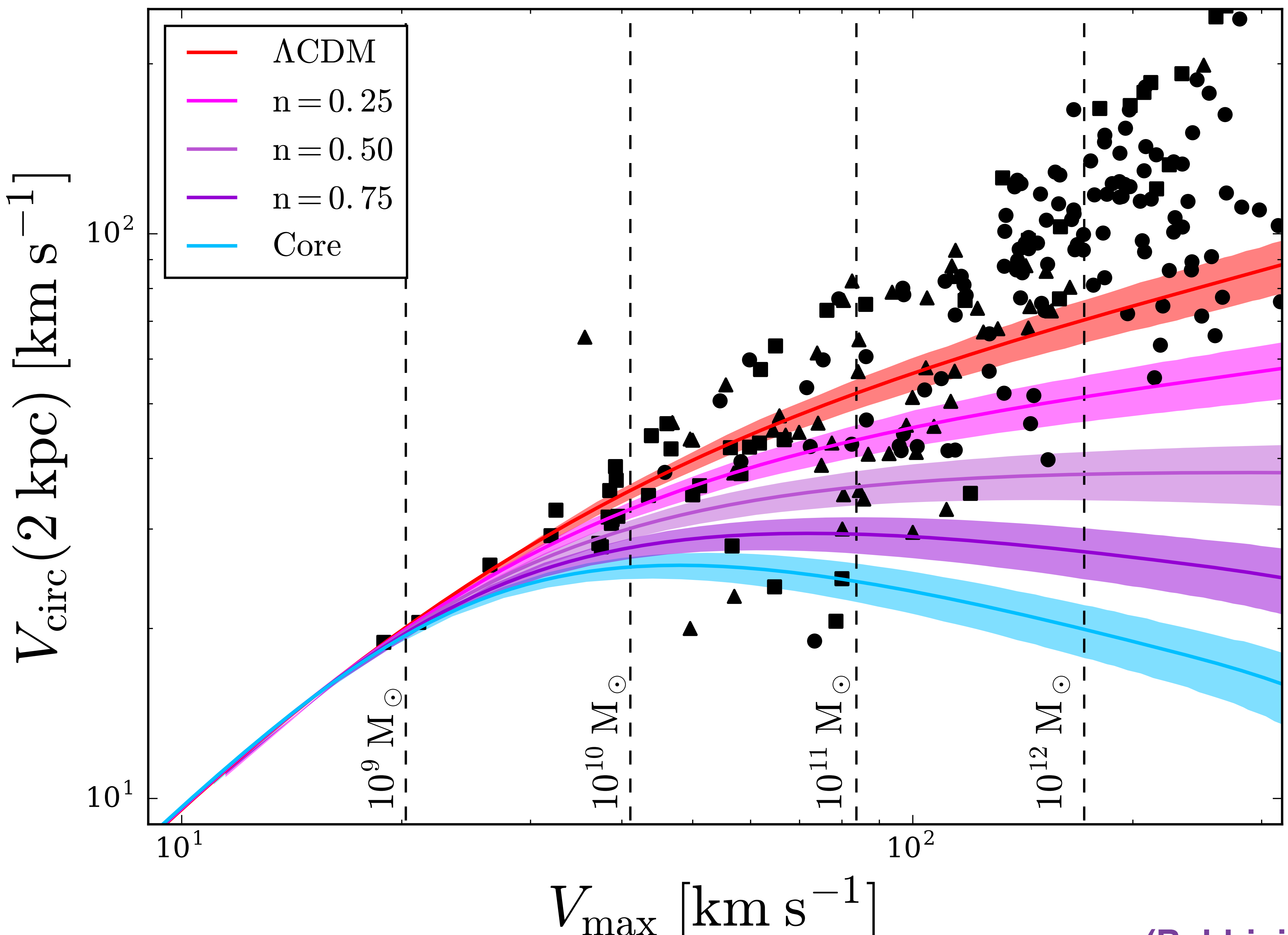
(Boldrini et al. in prep)

Diversity problem?



(Oman et al. 2015)

Diversity problem?



(Boldrini et al. in prep)

(Oman et al. 2015)

Cosmological simulations

Why cosmological simulations do not see this transition?

- **Not sufficient resolution for host halo $M < 10^{12}\ M_\odot$**

Cosmological simulations

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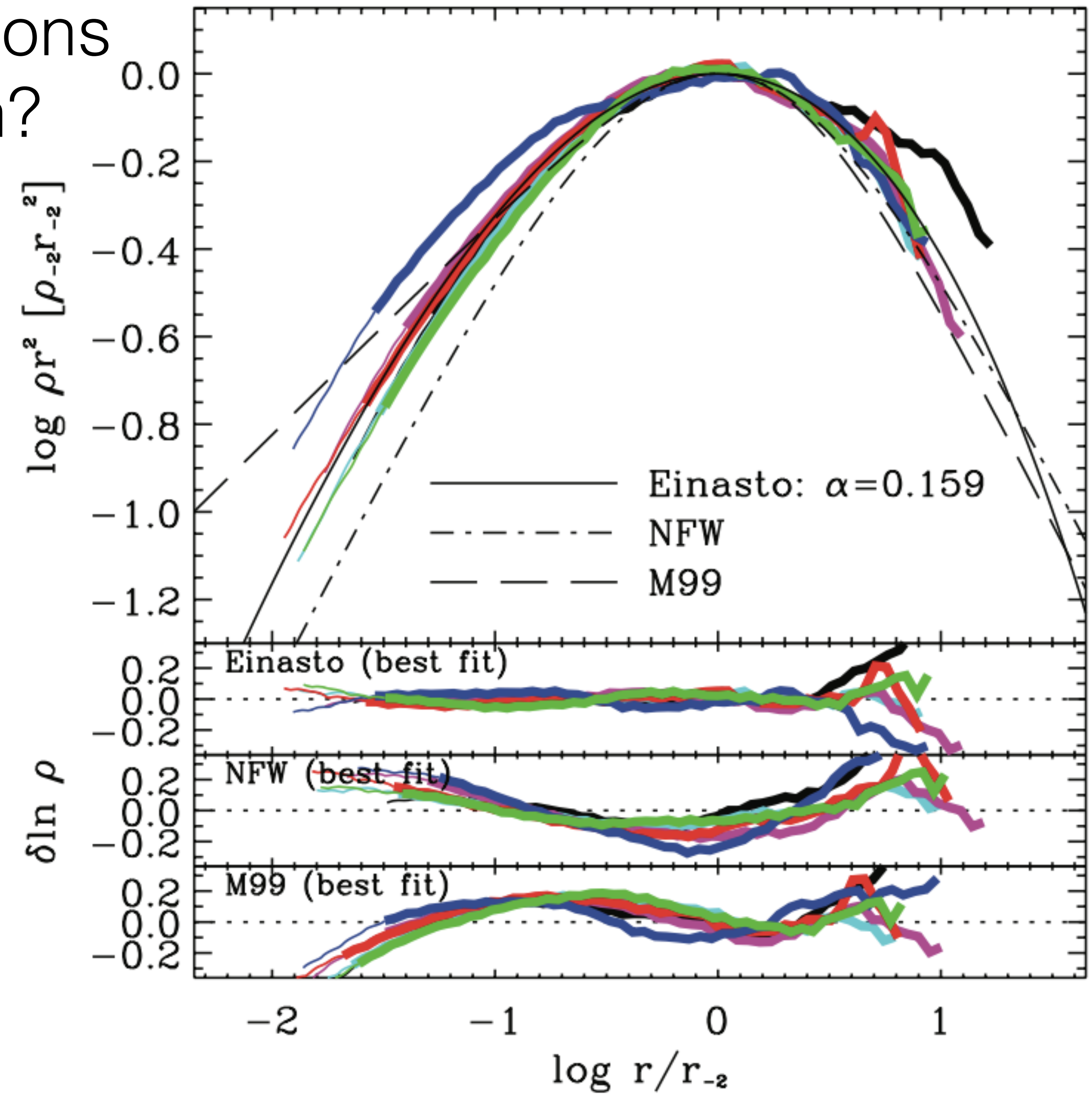

(Navarro et al. 2010)

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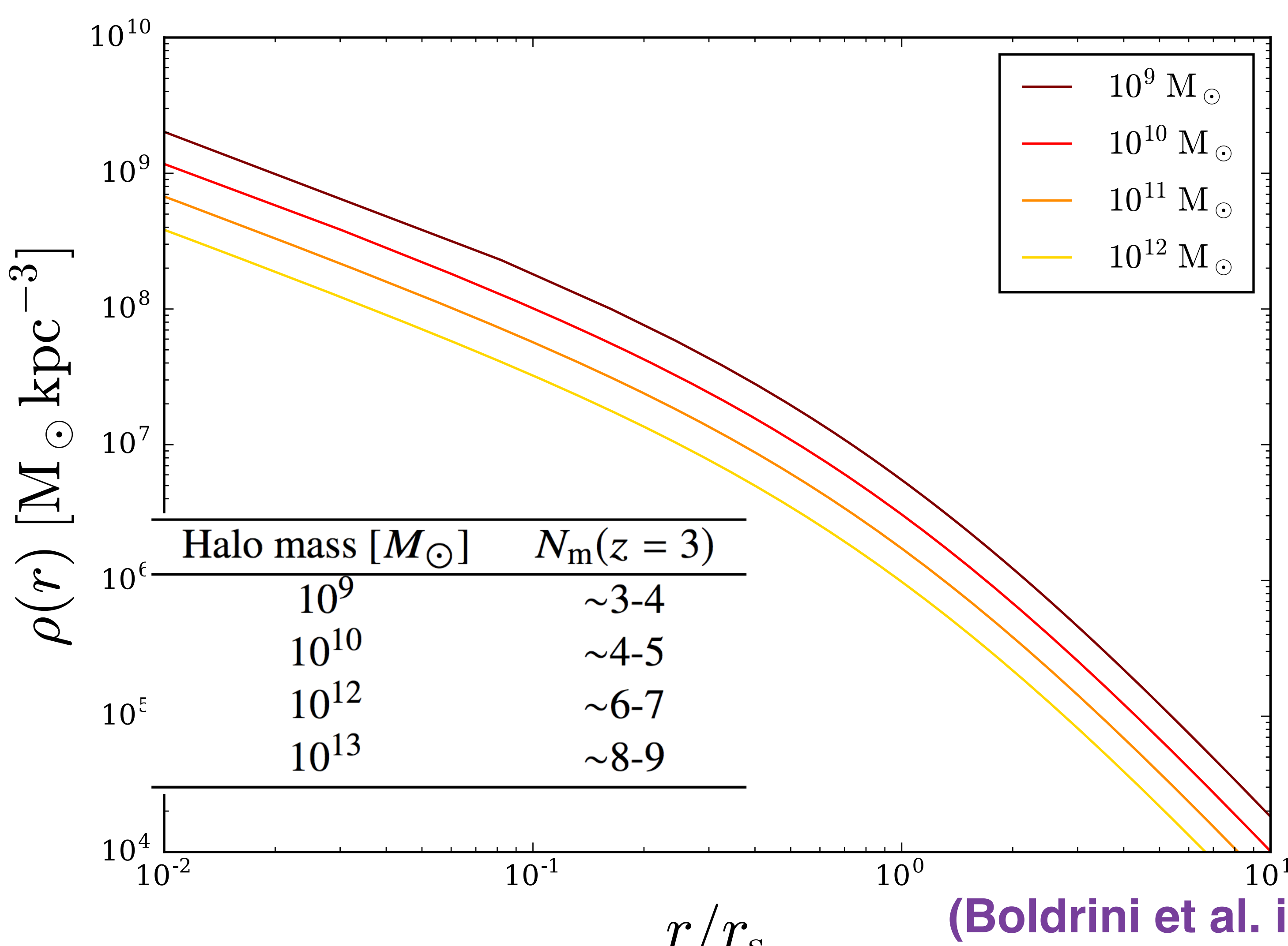

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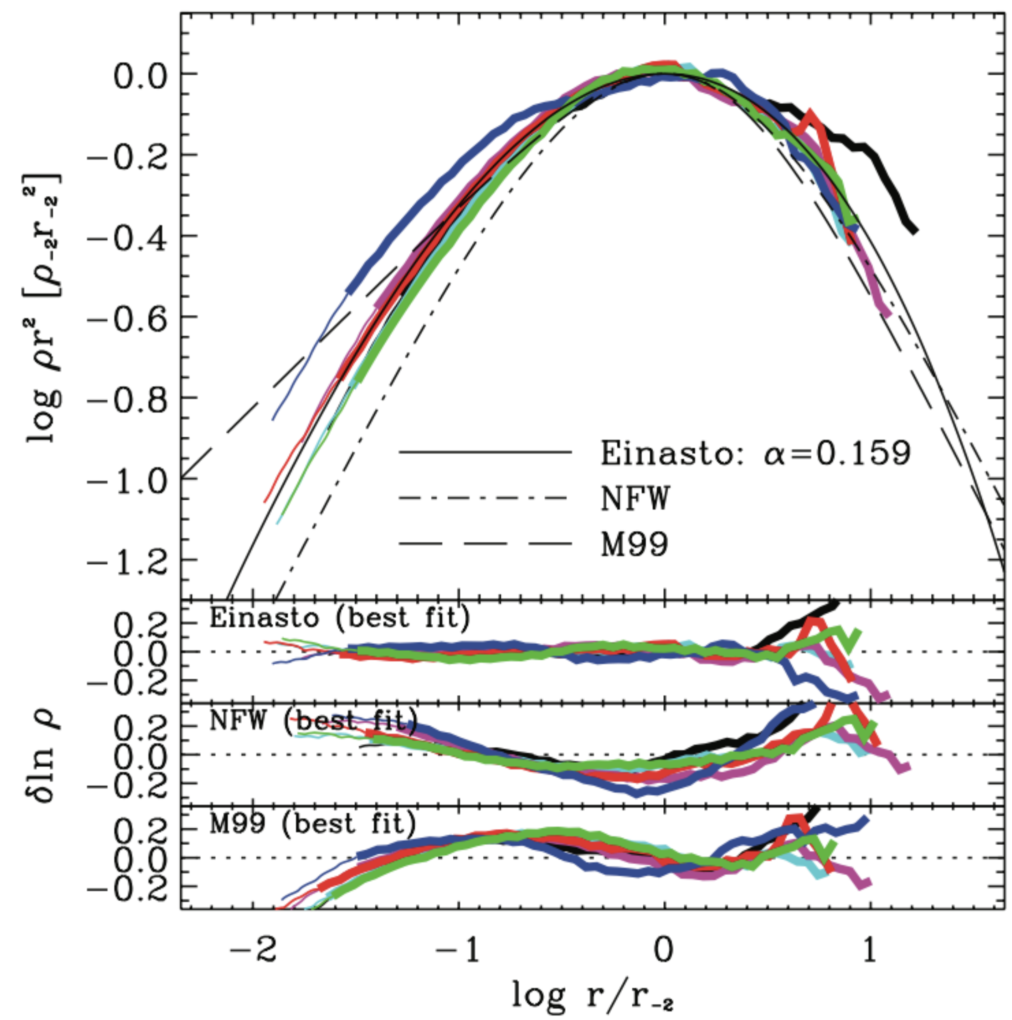
(Boldrini et al. in prep)



(Navarro et al. 2010)

Cores prevail

Group	Scenario	T_{core}/T_{sim}	T_{cusp}/T_{sim}
	HH + SH_{v1}	0.96	0.04
Different initial velocity	HH + SH_{v2}	0.81	0.19
	HH + SH_{v3}	0.73	0.27
	HH + SH_{v4}	0.35	0.65
Different initial radii	HH + SH_{r2}	0.96	0.04
	HH + SH_{r3}	0.96	0.04
Different initial masses	HH + SH_{m1}	0.01	0.99
	HH + SH_{m2}	0.96	0.04
Different initial number of subhalos	HH + SH_{v1} + SH_{r2}	0.95	0.05
	HH + SH_{v1} + SH_{r2} + SH_{r3}	0.96	0.04

(Boldrini et al. in prep)

Cores prevail

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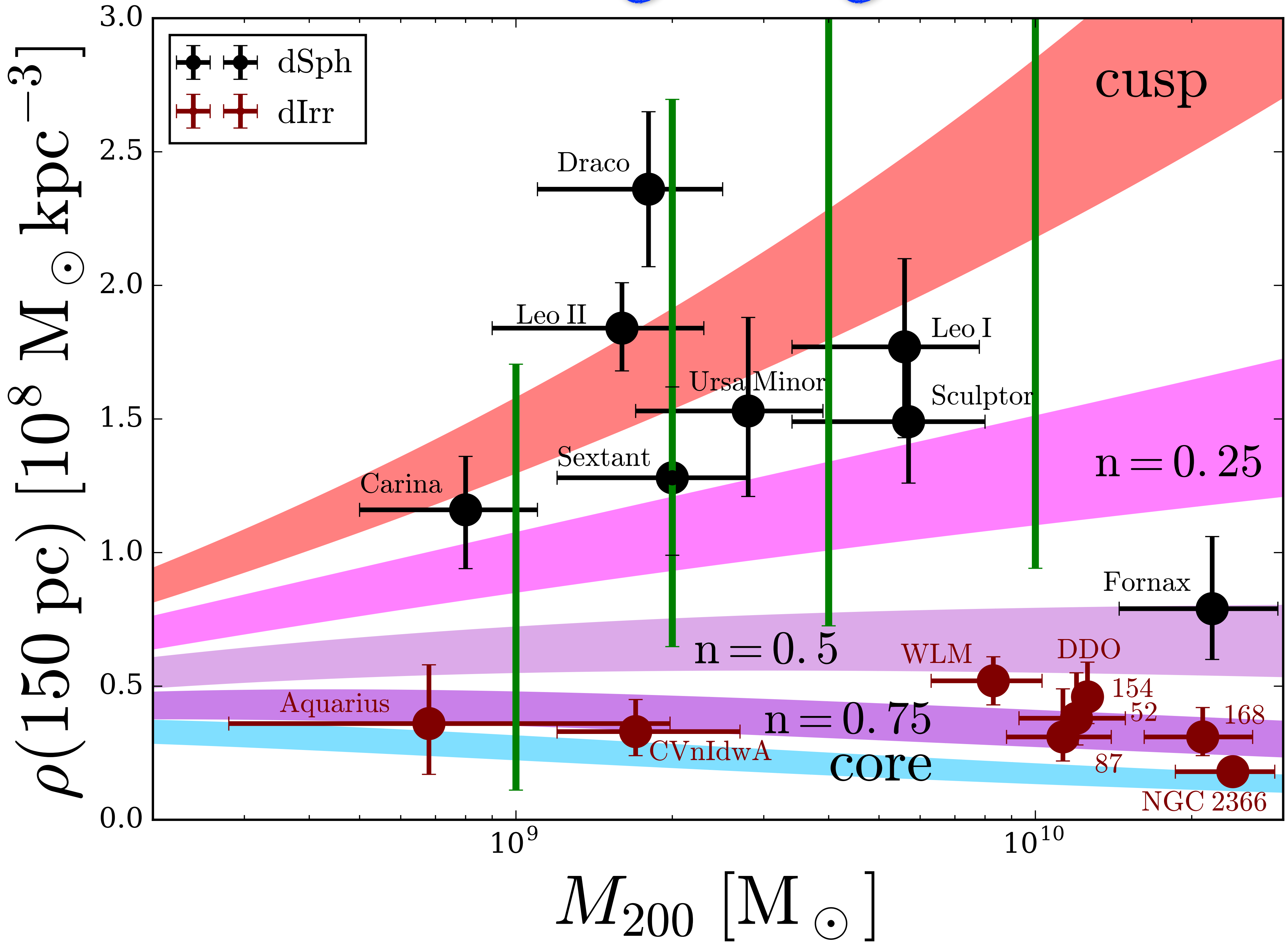
Cores prevail!

(Boldrini et al. in prep)

Inner density of dSph galaxies

Fully cuspy $0 < n \leqslant 1$ **Fully core**



CoreNFW model

(Read et al. 2016)

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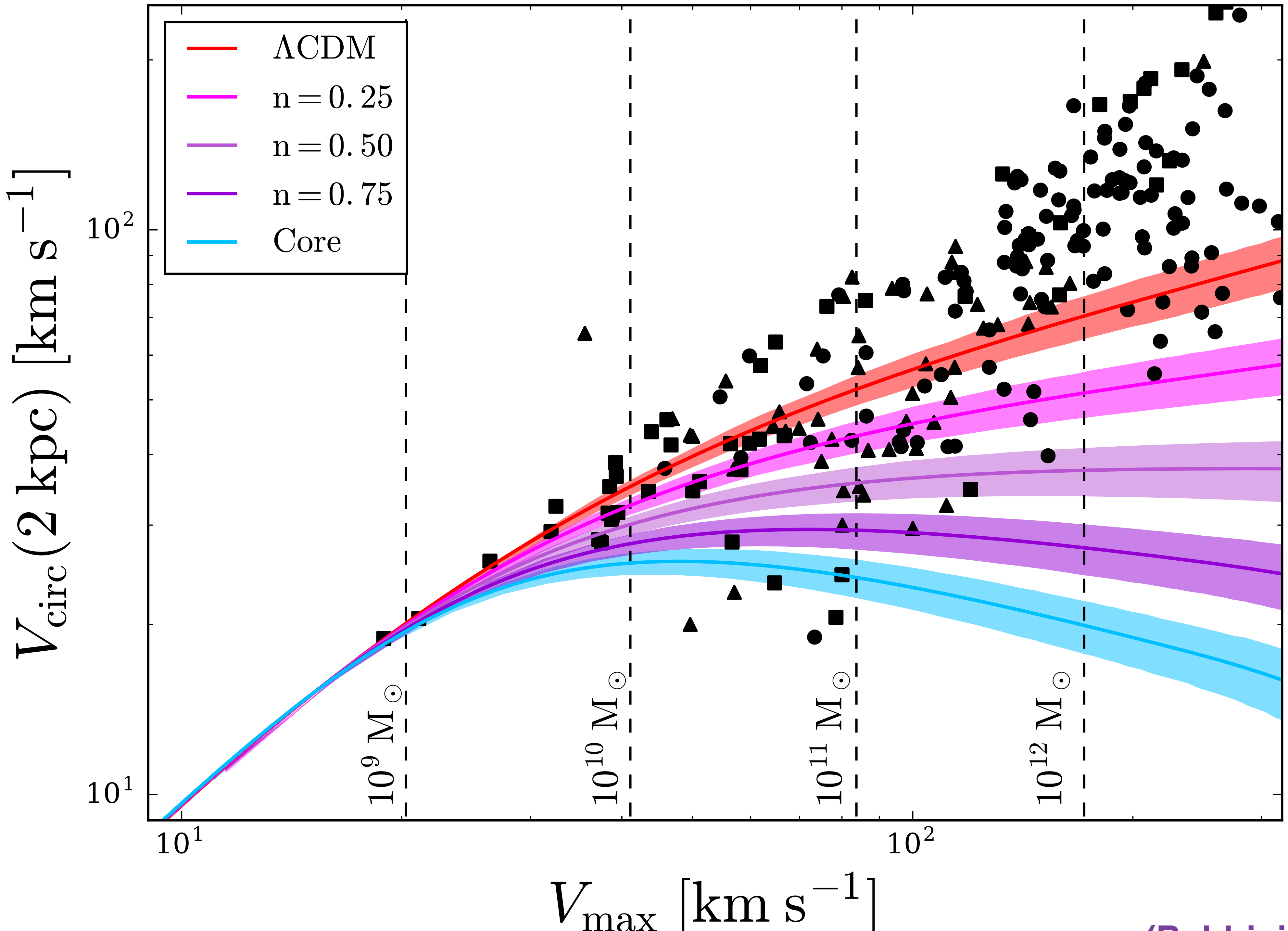
Diversity problem?



(Boldrini et al. in prep)

(Oman et al. 2015)

Transient core diversity

Fully cuspy $0 < n \leqslant 1$ **Fully core**

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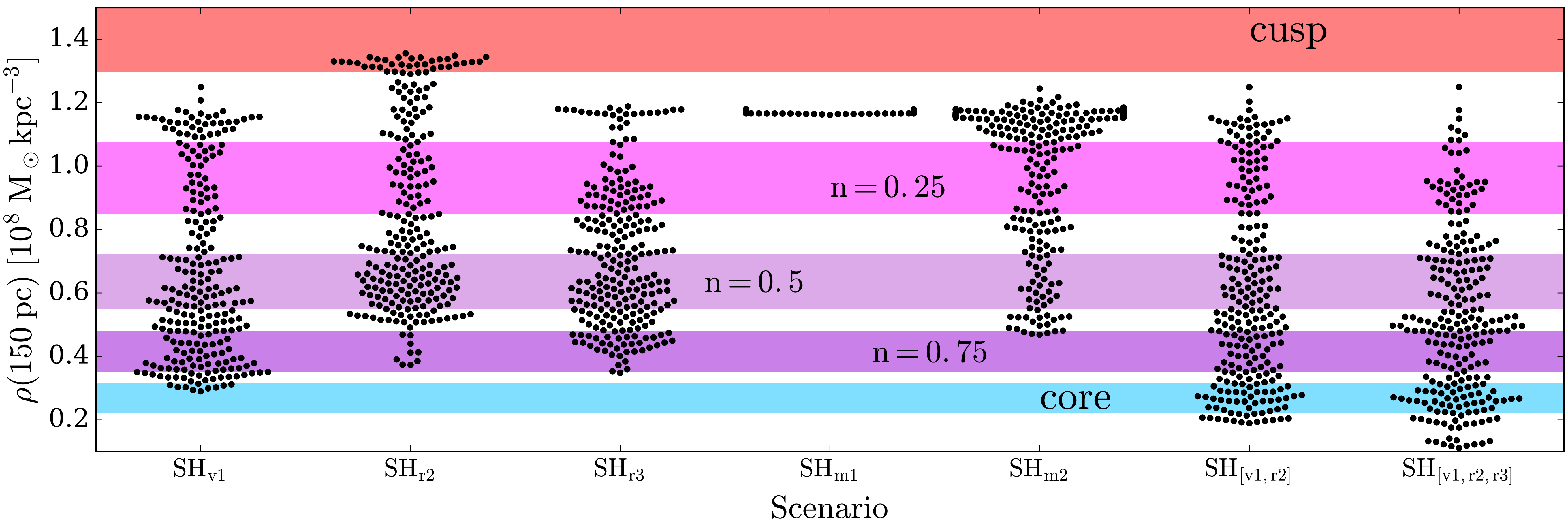

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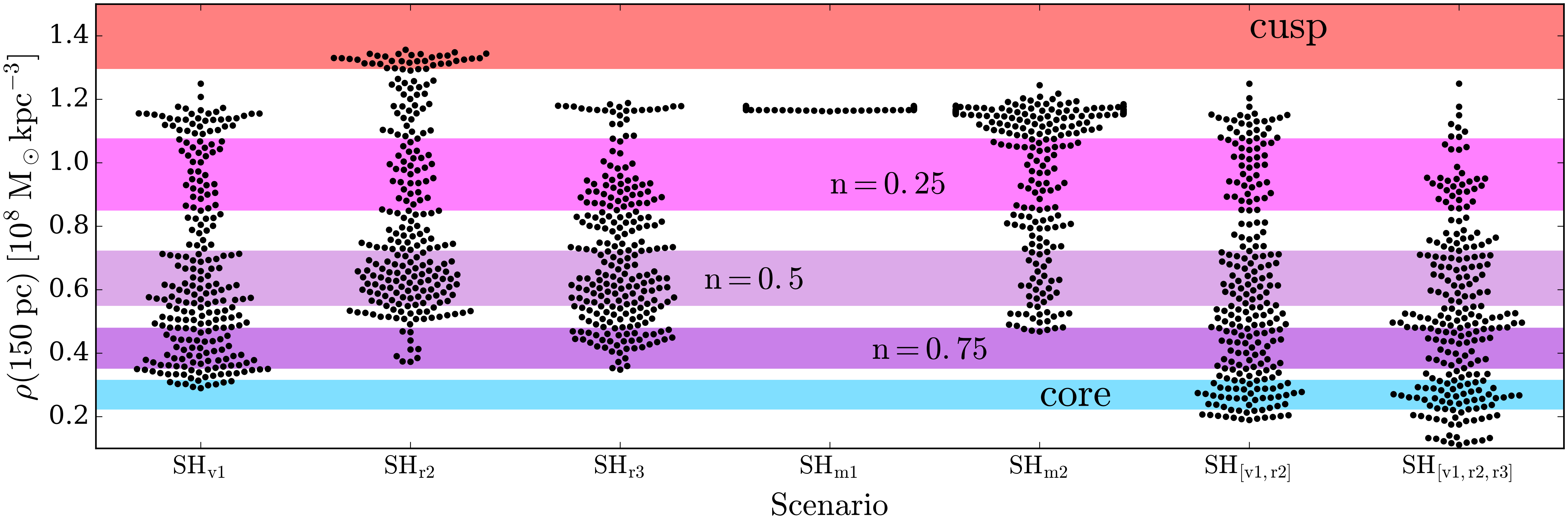
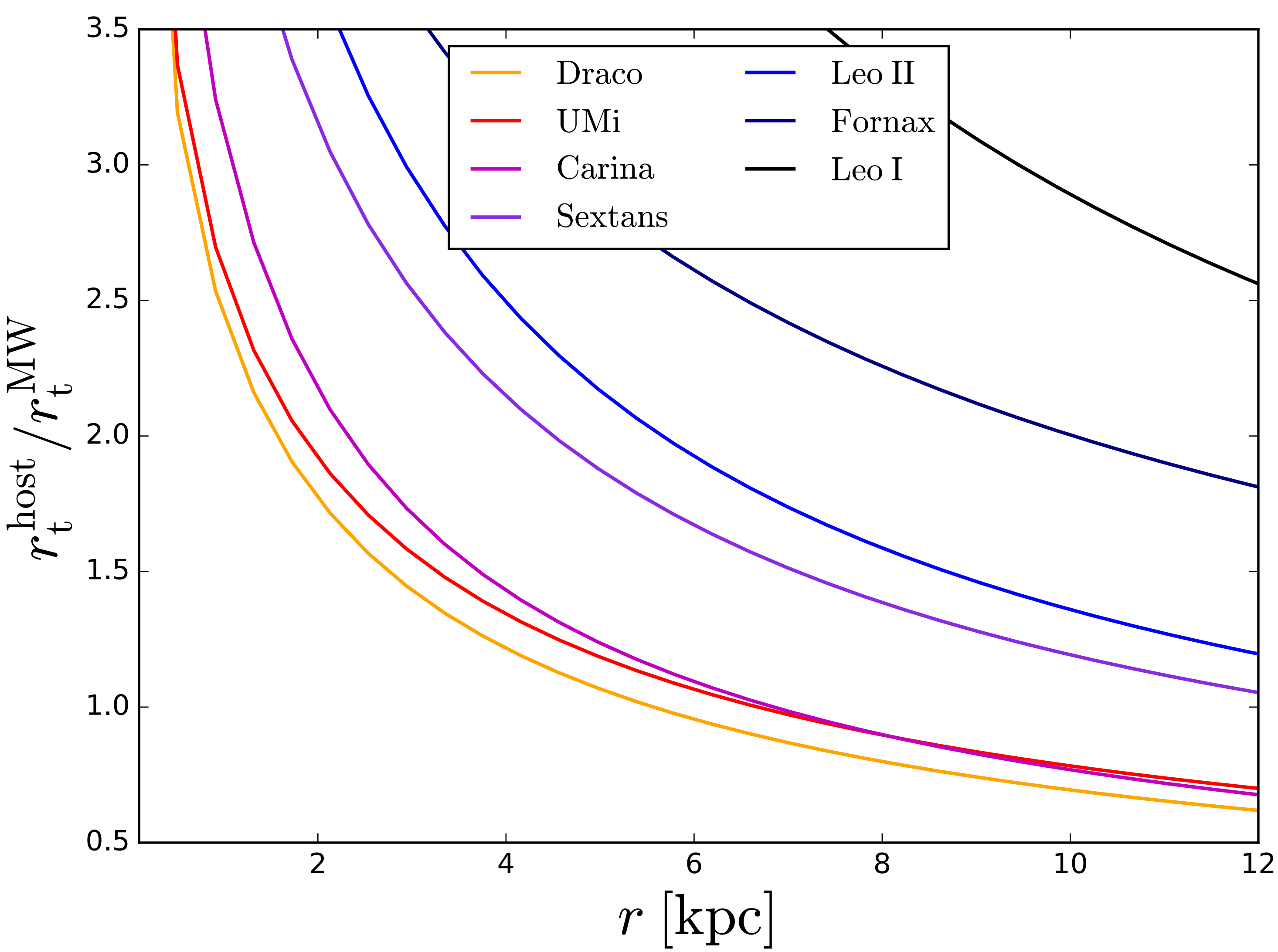


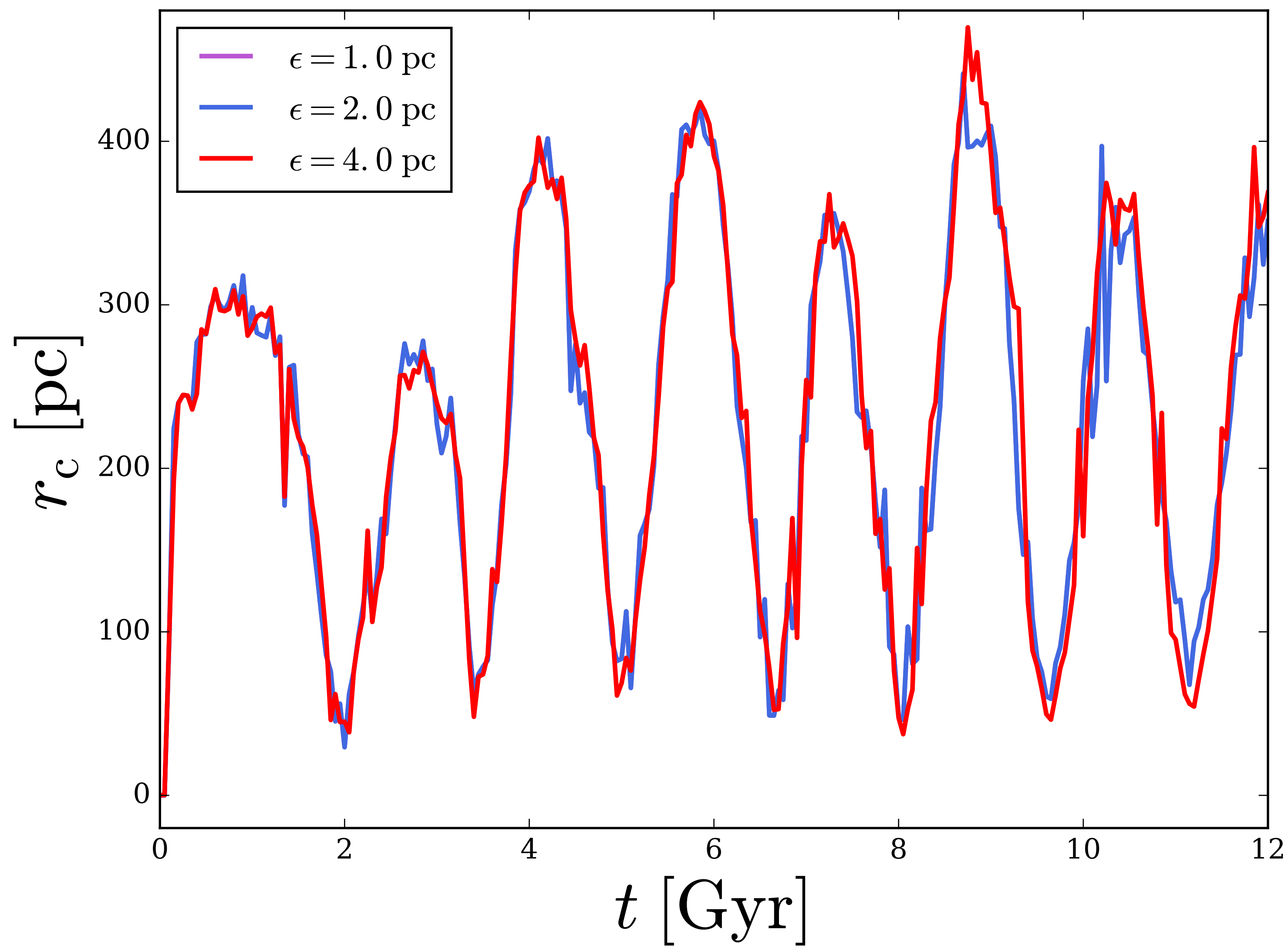
Diversity of transient cores in ΛCDM

(Boldrini et al. in prep)

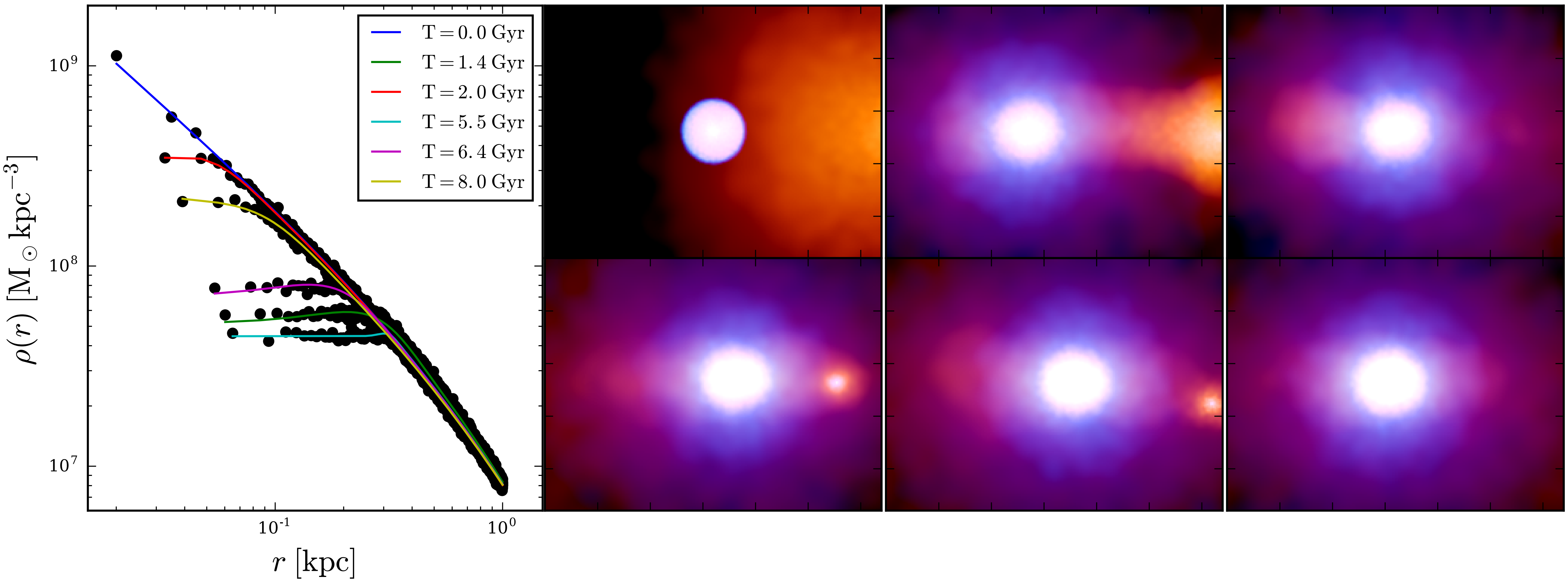
Isolated system



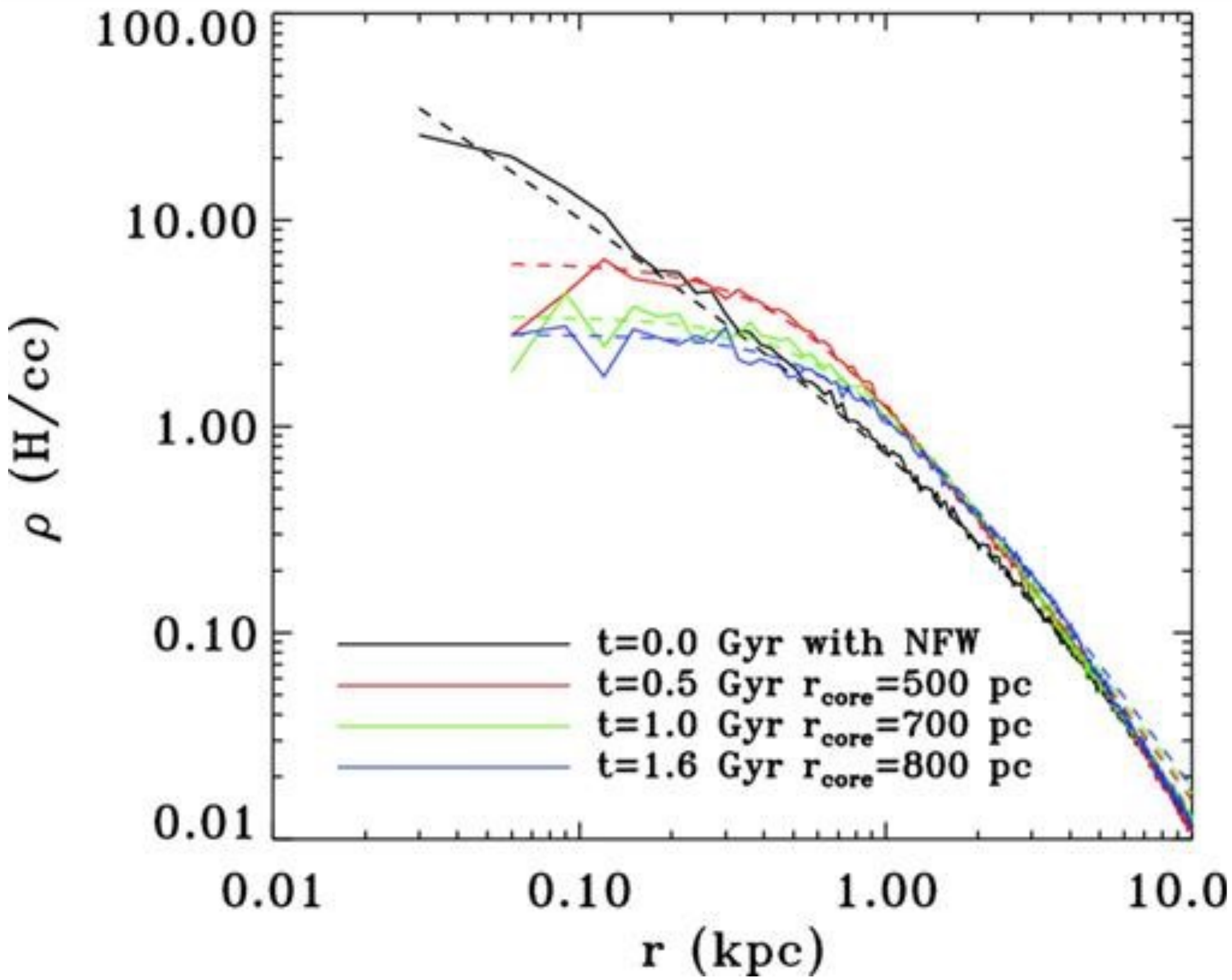
Softening convergence



Fitted DM profiles



Involving baryons

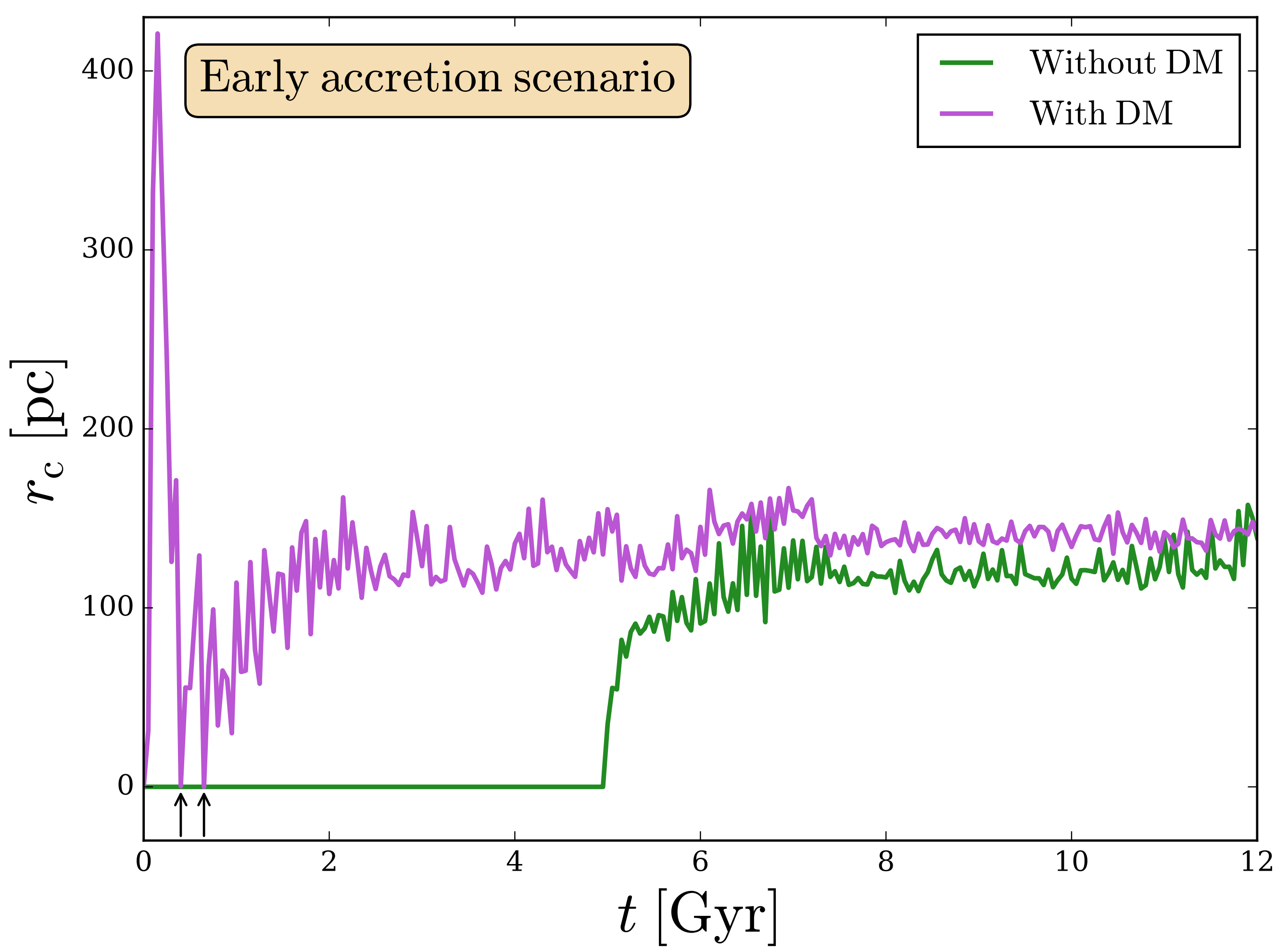


Stellar feedback

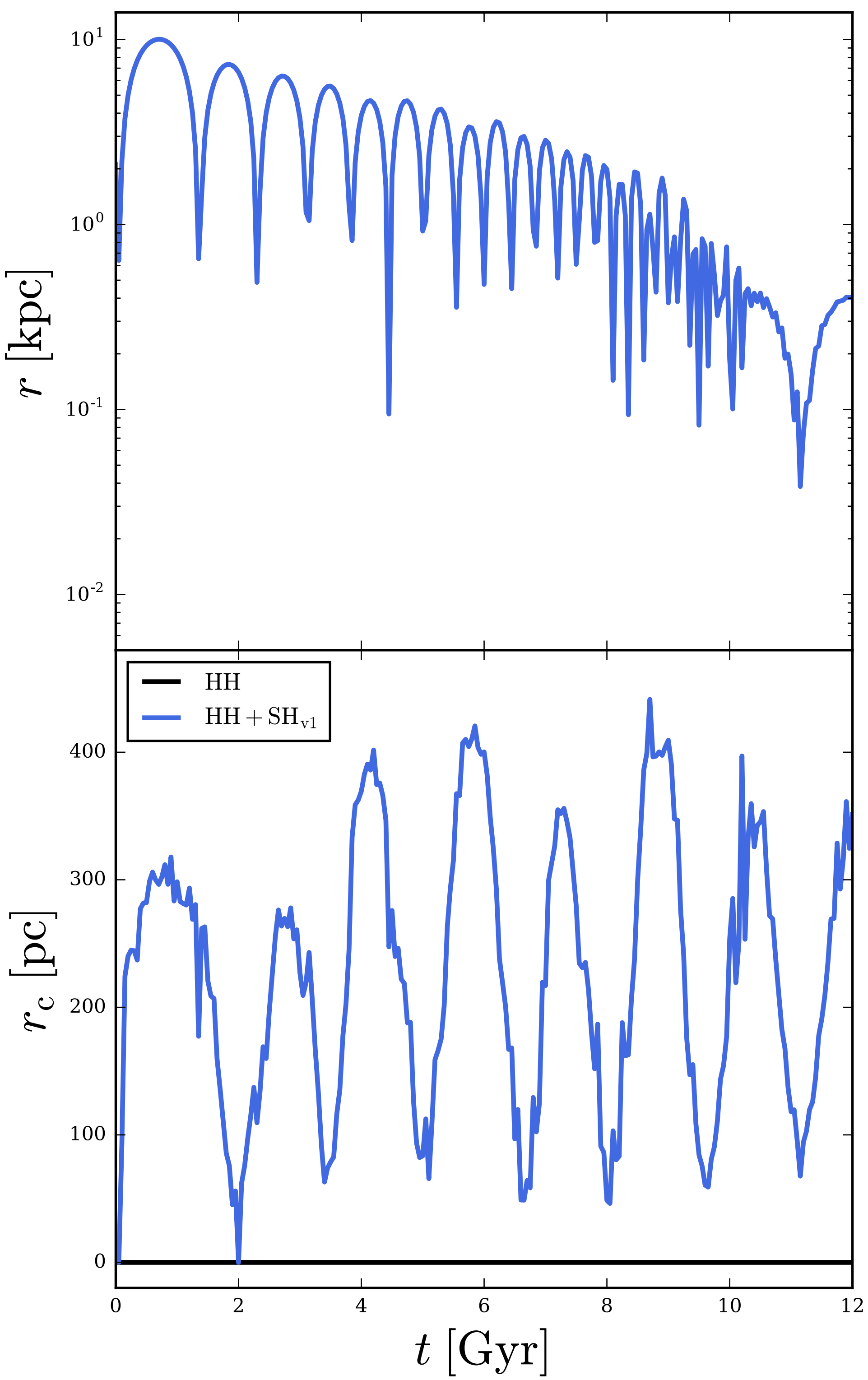
(Teyssier et al. 2013)

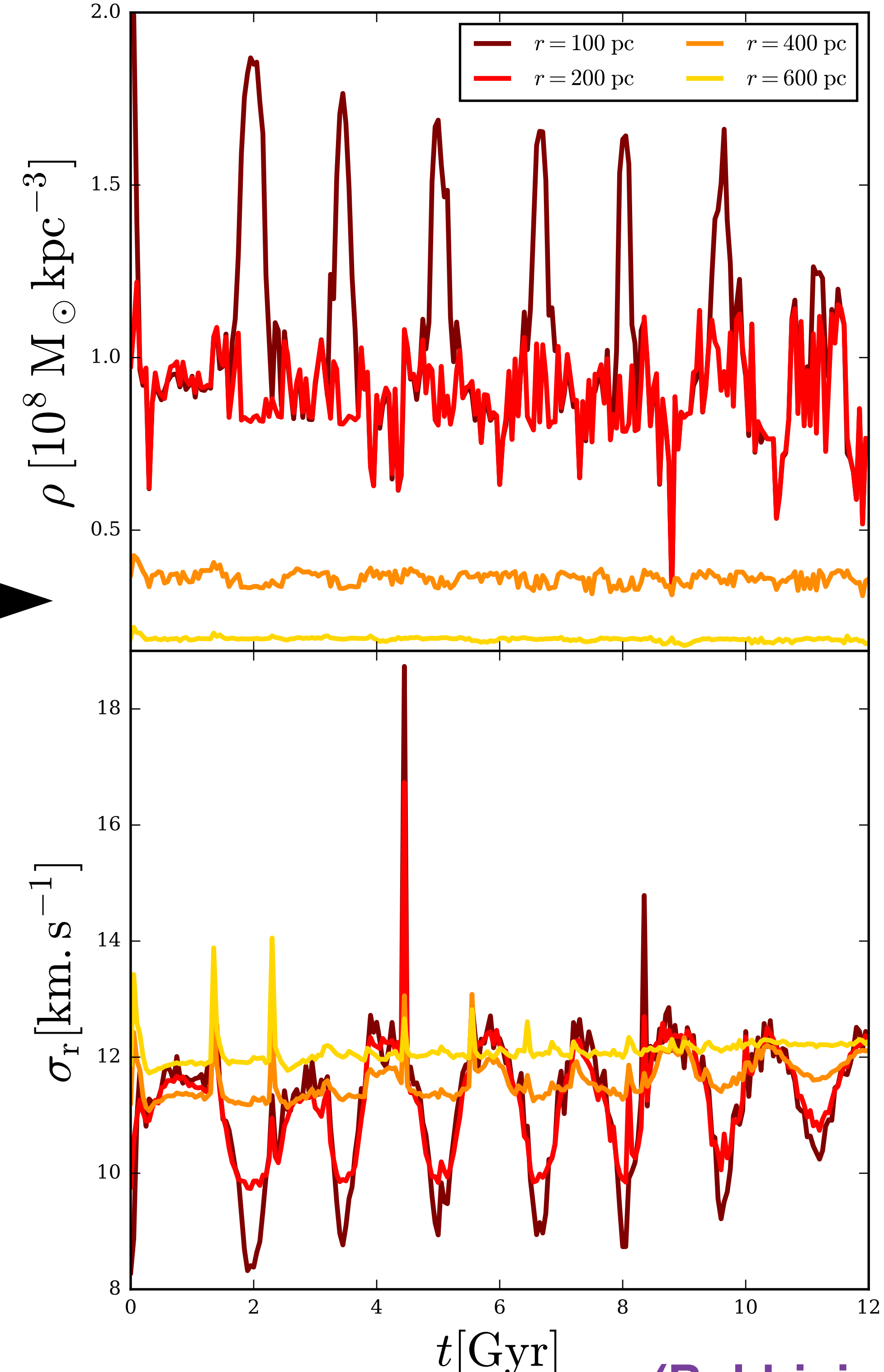
GCs with DM minihalos

(Boldrini et al. 2019)



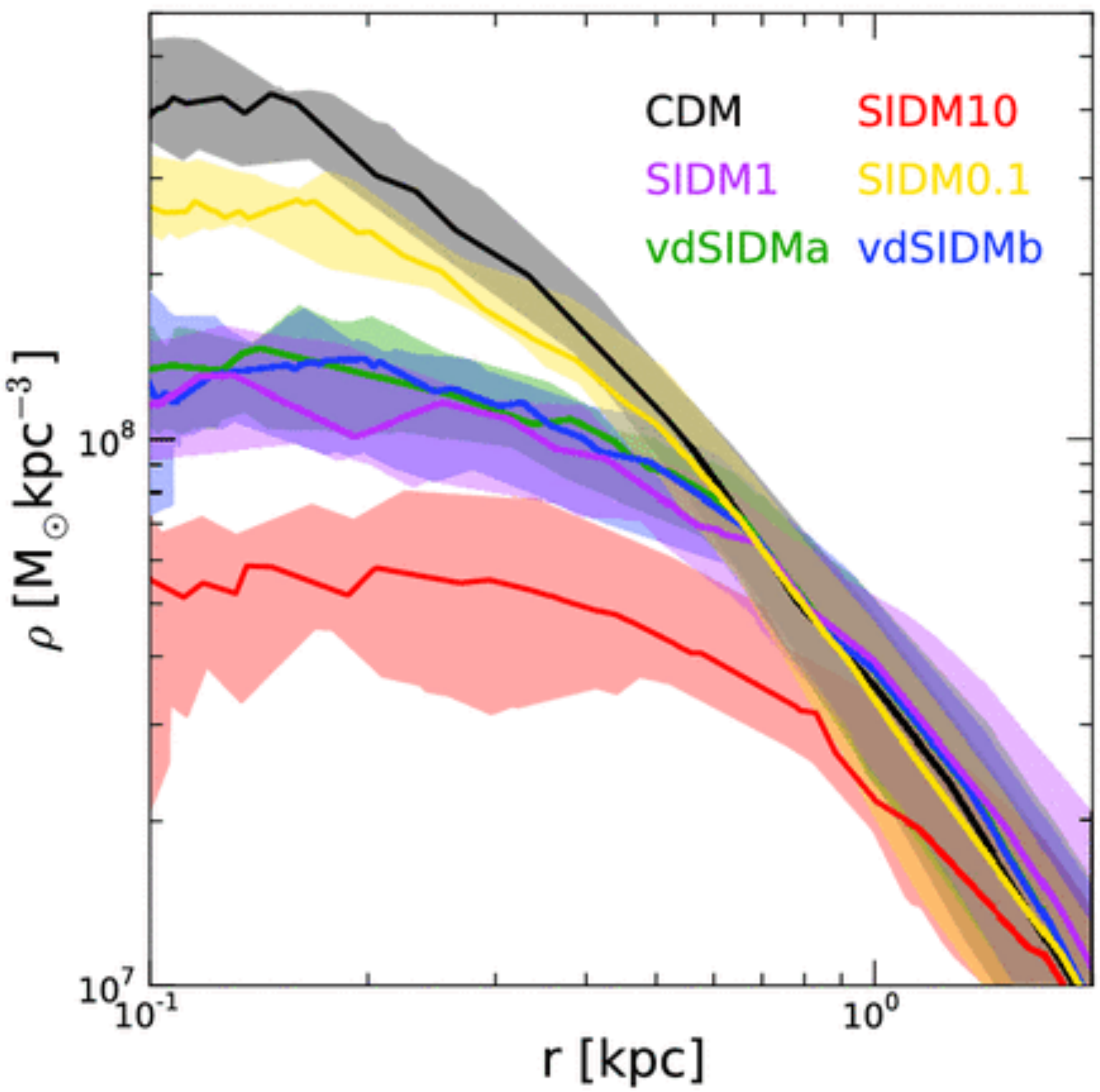
Halo centre heated





(Boldrini et al. in prep)

Nature of dark matter

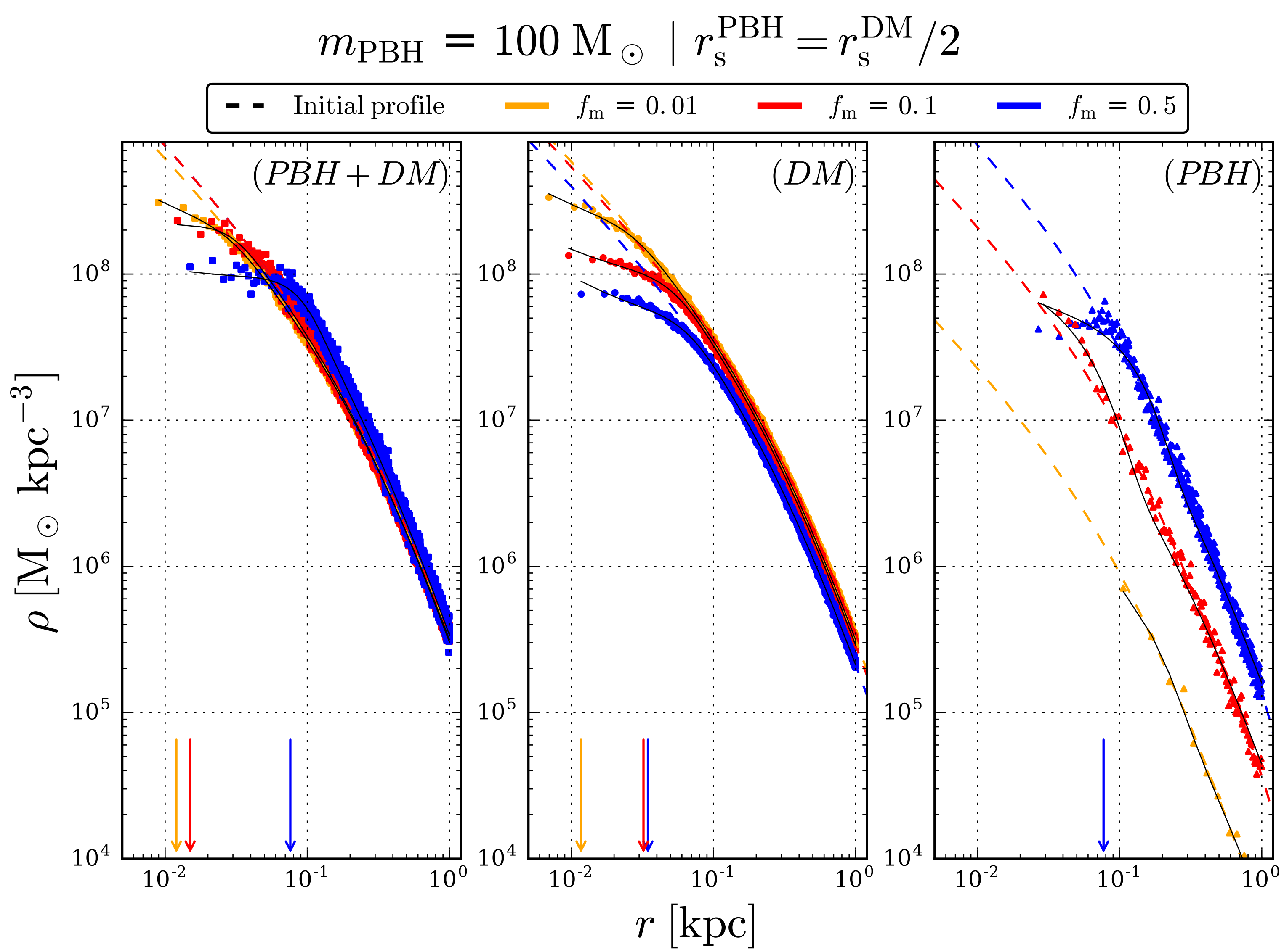


SIDM cores

(Zavala et al. 2013)

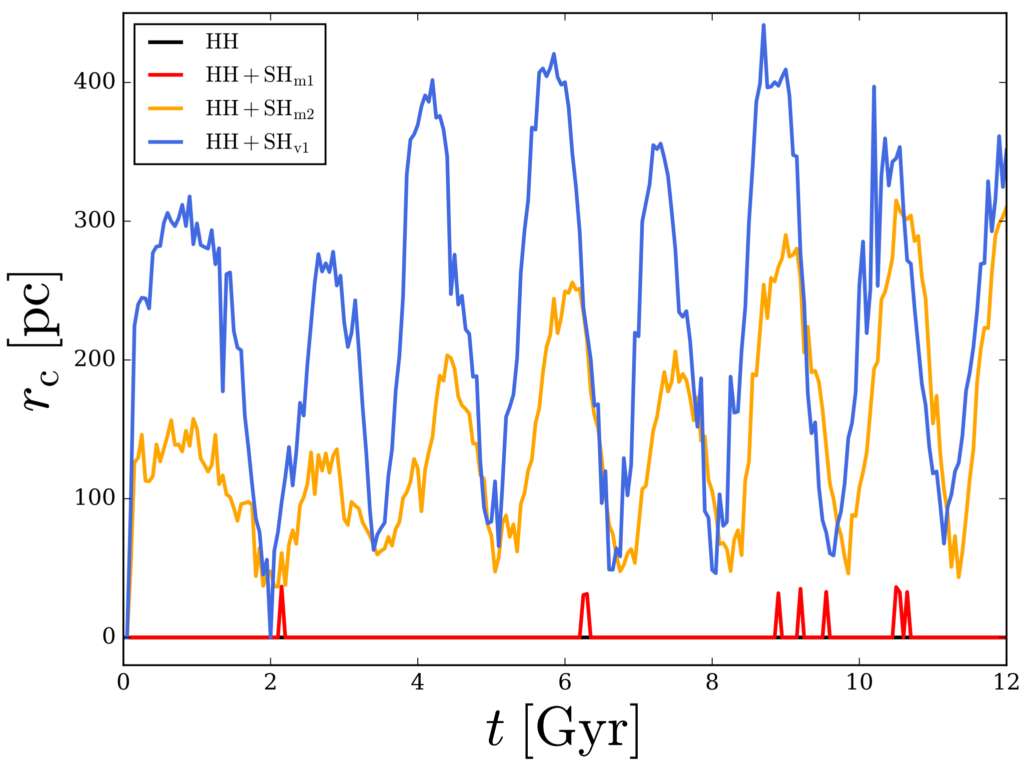
PBH-DM cores

(Boldrini et al. 2019)

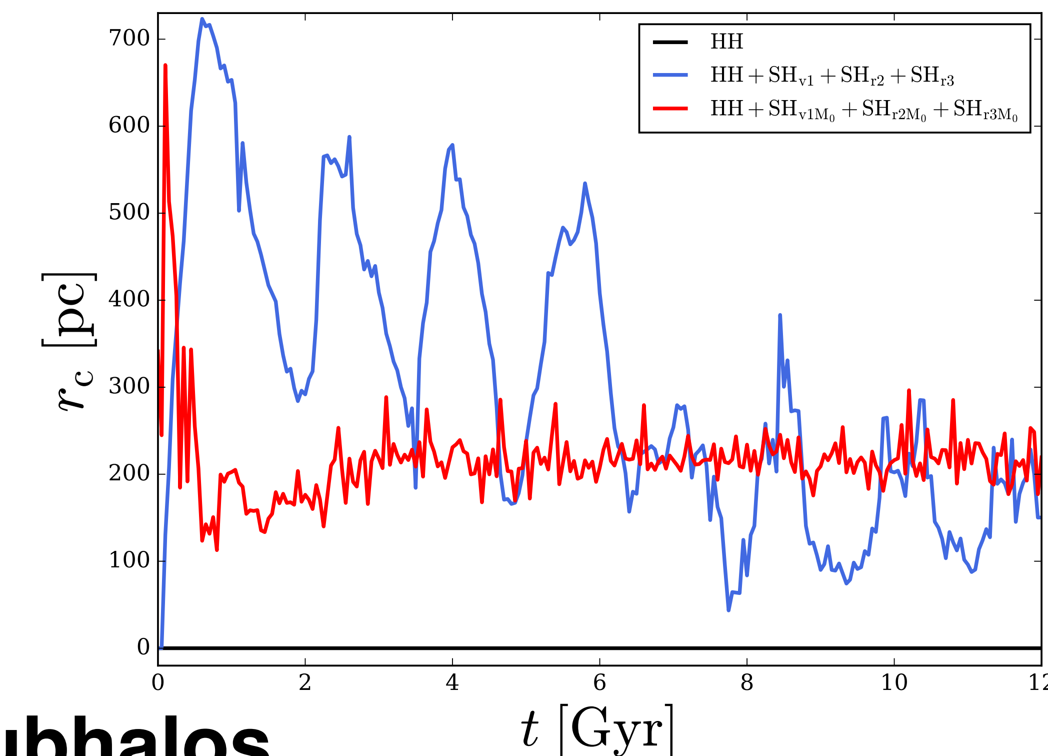


Scenarios

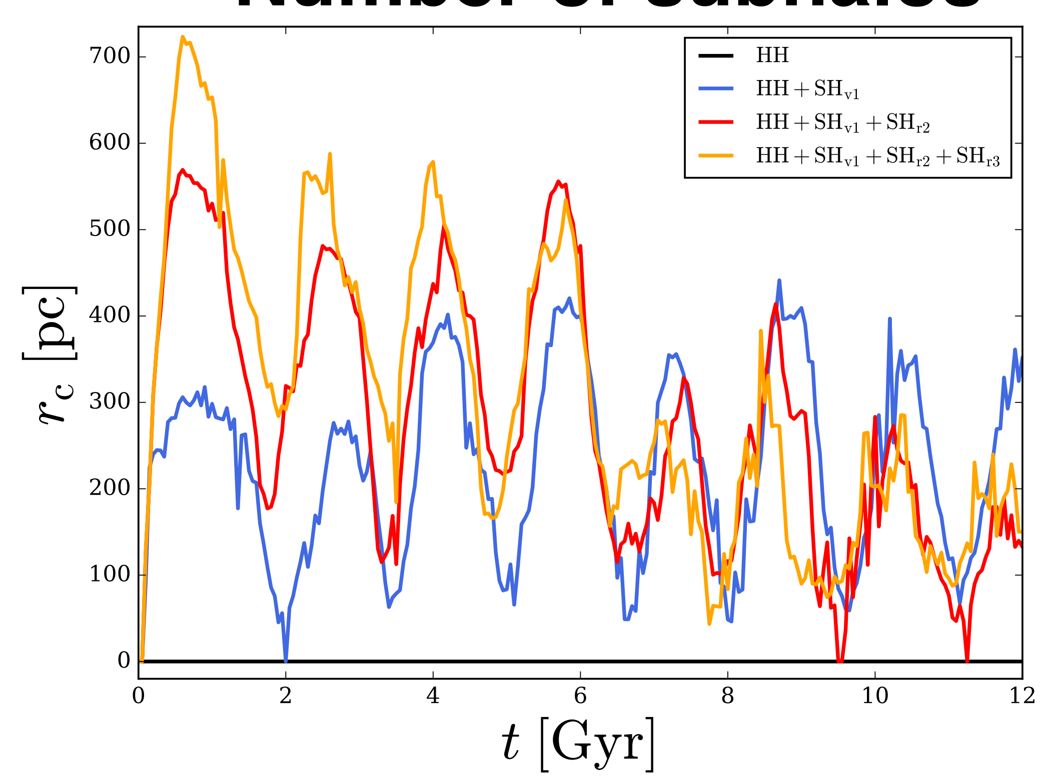
- **Subhalo mass**



- **Host halo mass**



- **Number of subhalos**



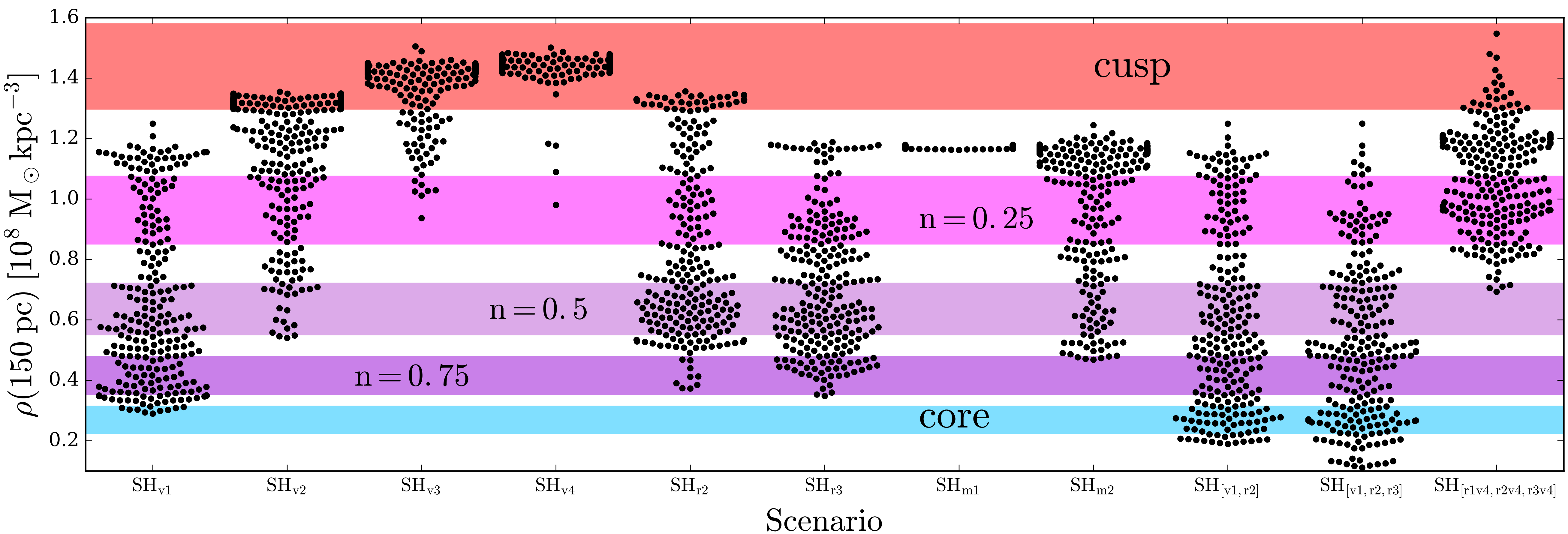
(Boldrini et al. in prep)

Transient core diversity

- **CoreNFW model** (Read et al. 2016)

$$\rho_{\rm cNFW} = f^n \rho_{\rm NFW} + \frac{n f^{n-1}(1-f^2)}{4\pi r^2 r_c} M_{\rm NFW} \qquad f^n = \left[\tanh\left(\frac{r}{r_c}\right)\right]^n$$

Fully cuspy $0 < n \leqslant 1$ **Fully core**



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Host halo + subhalo scenario

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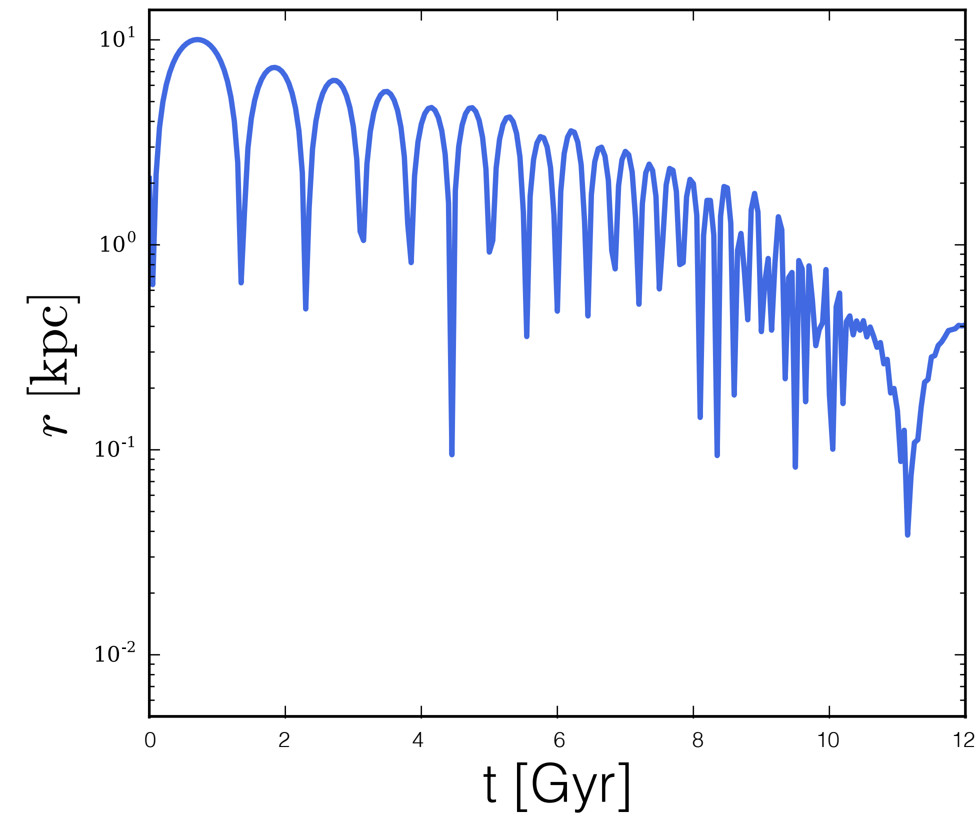

- **Fit model for subhalo+host**

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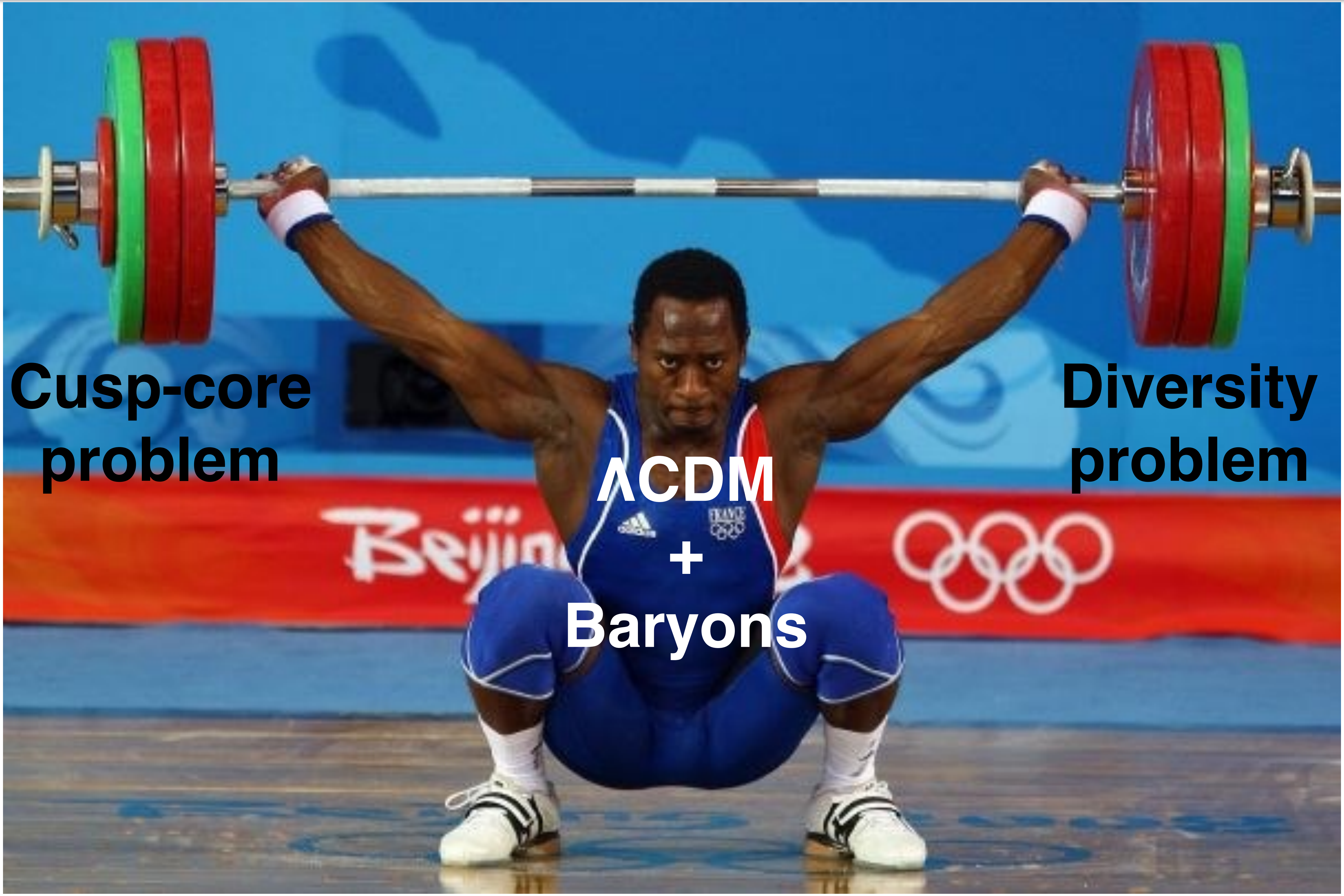
$$2W(r) = 1 - \mathrm{erf}\left(\frac{r - r_c}{2\delta}\right)$$

- $r_c > 20\text{-}30$ pc ⟶ • CCT with r_c
- $r_c < 20\text{-}30$ pc ⟶ • No CCT ($r_c = 0$)

Solutions?

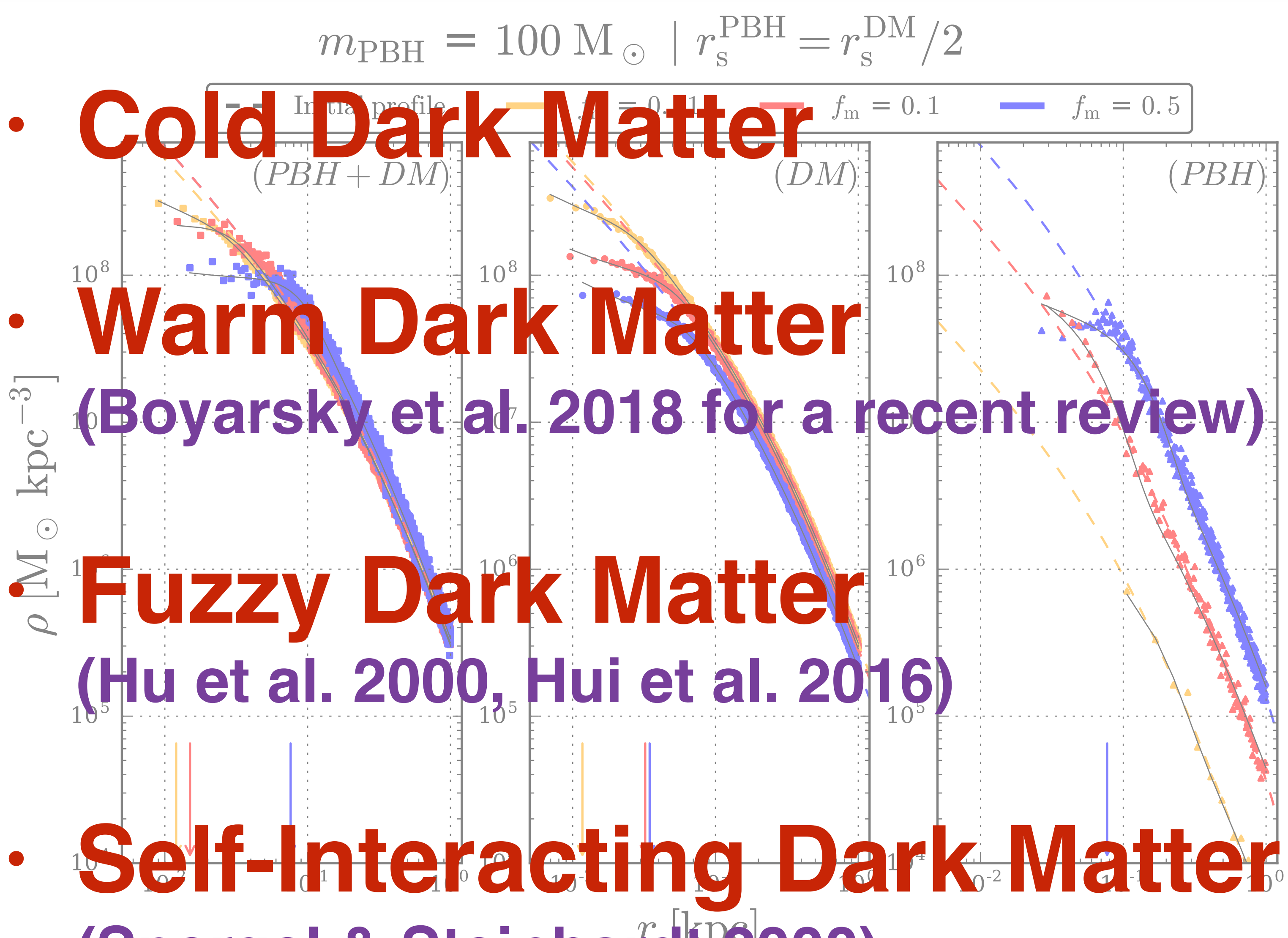
Solutions?

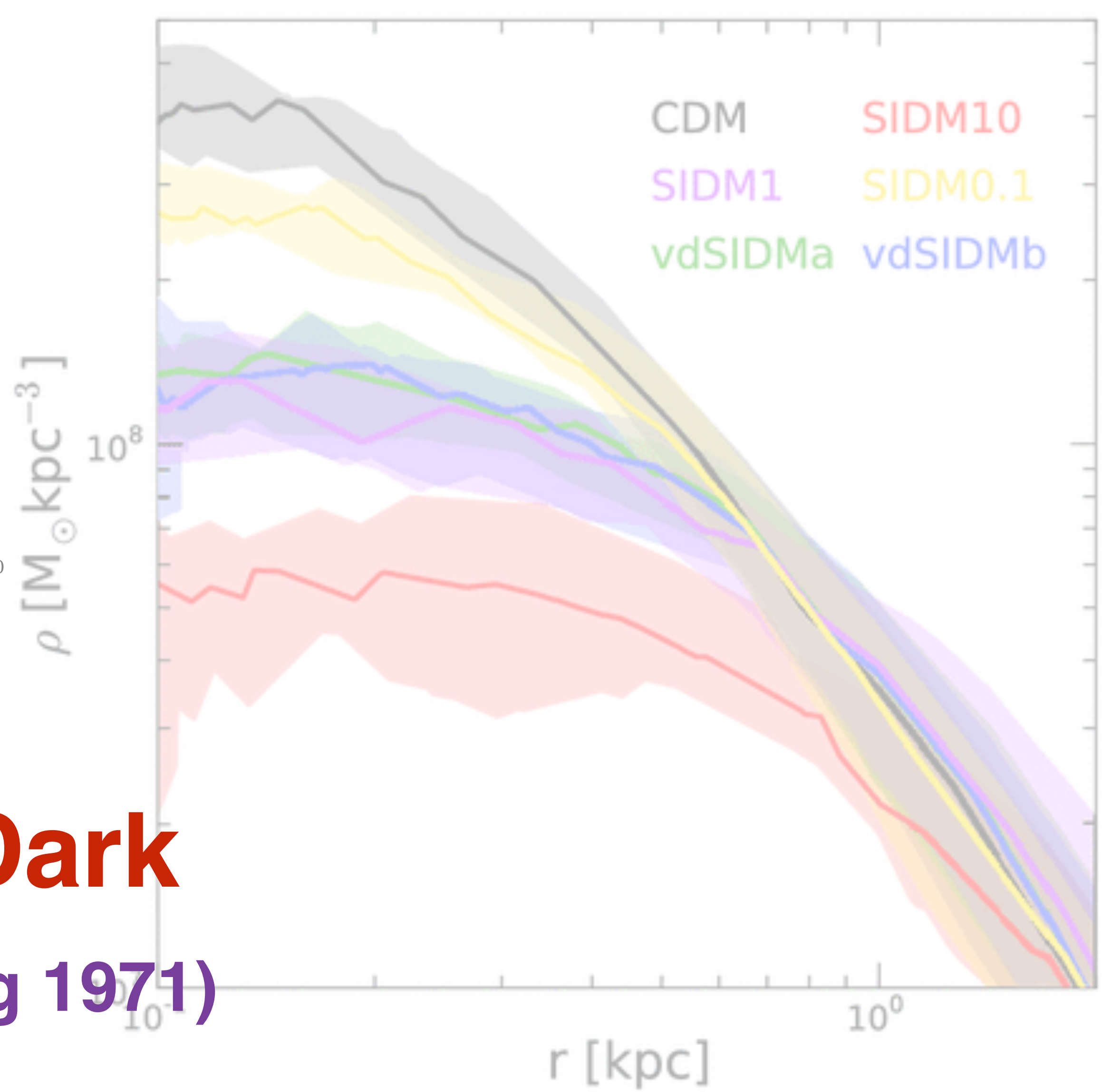
Baryons are halfway



Baryons are halfway

Nature of dark matter

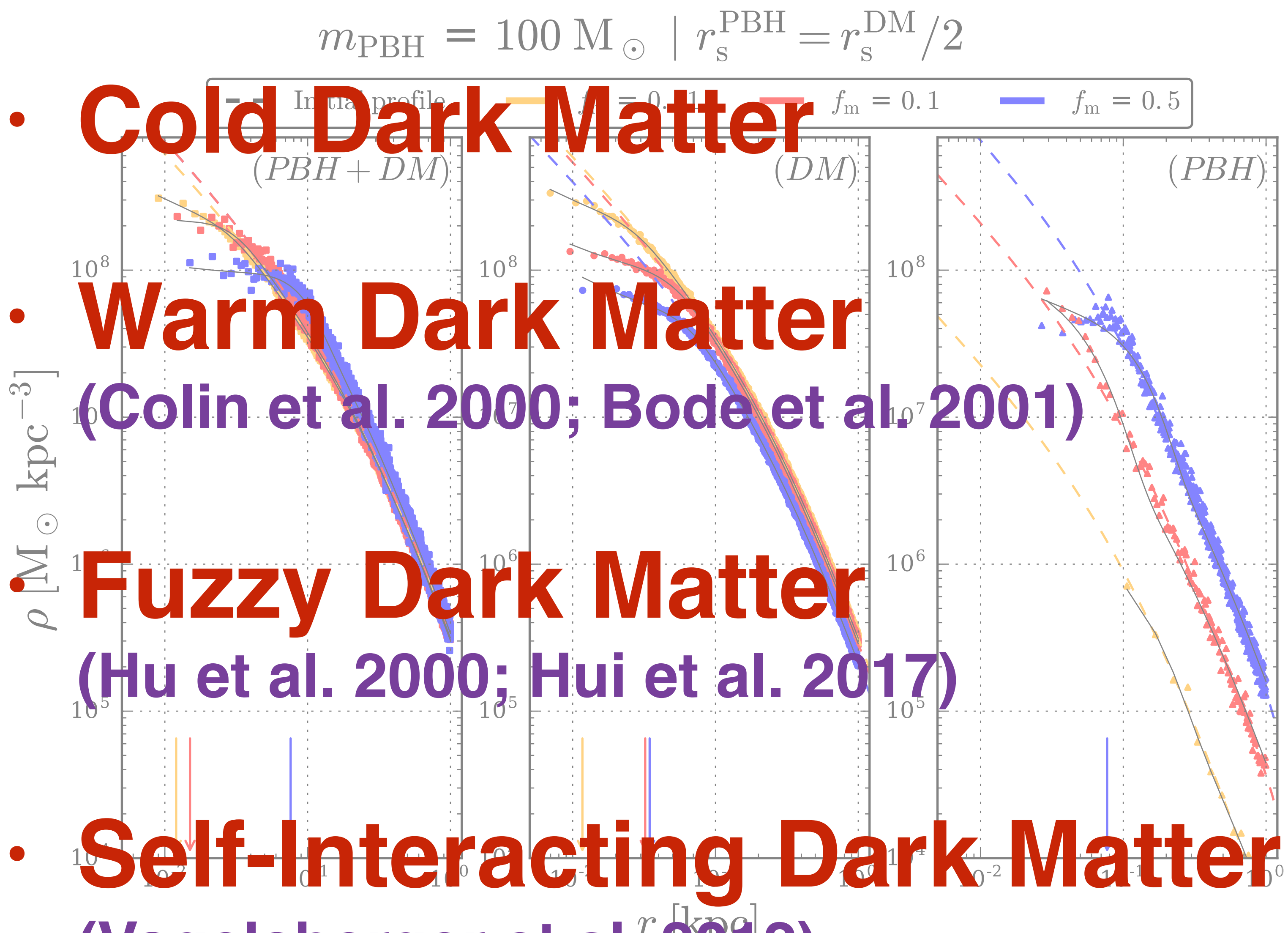


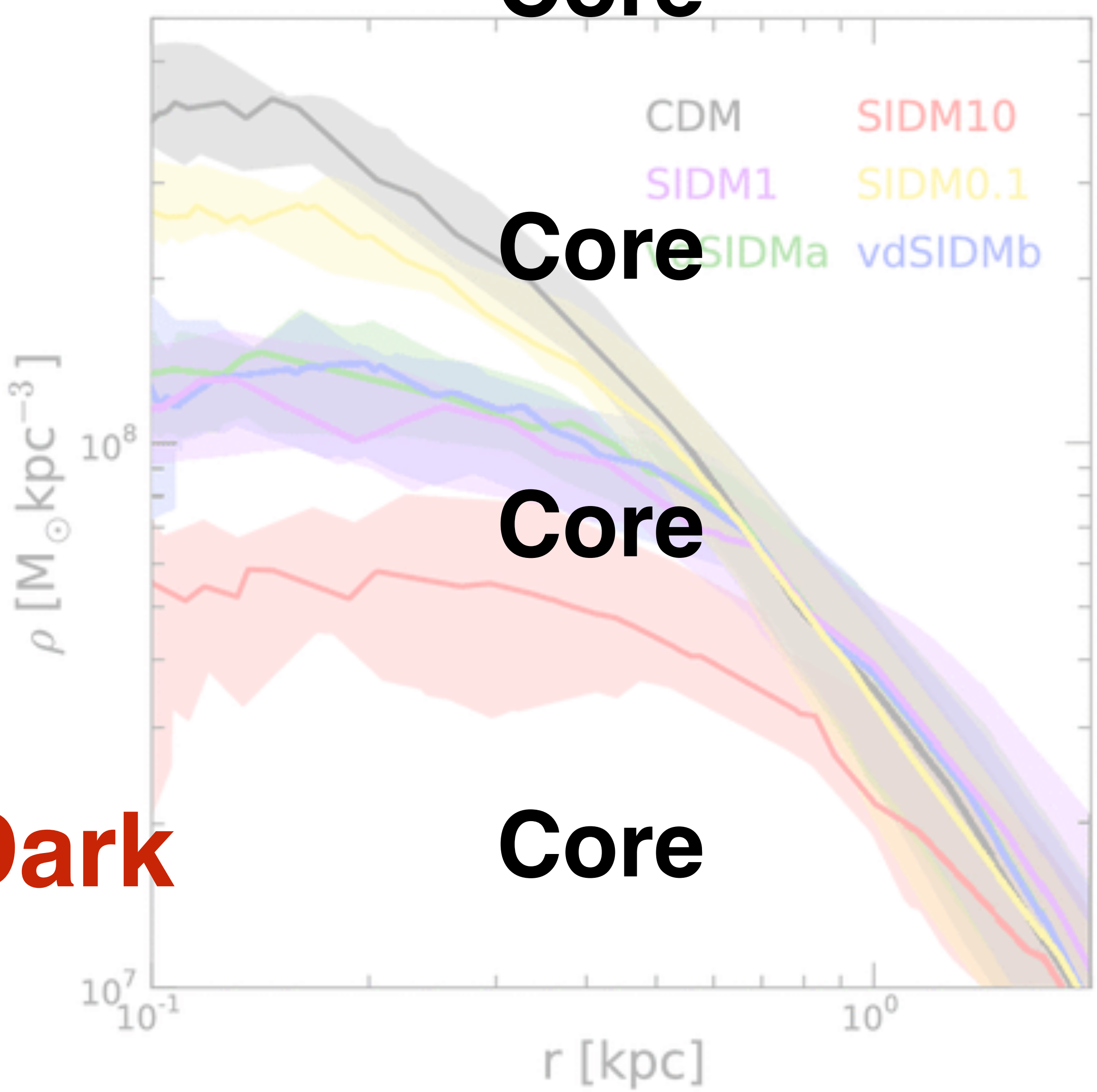


- **Cold Dark Matter**
- **Warm Dark Matter**
  (Boyarsky et al. 2018 for a recent review)
- **Fuzzy Dark Matter**
  (Hu et al. 2000, Hui et al. 2016)
- **Self-Interacting Dark Matter**
  (Spergel & Steinhardt 2000)
- **Primordial Black Holes as Dark Matter** (Zel'dovich et al 1967; Hawking 1971)

Nature of dark matter

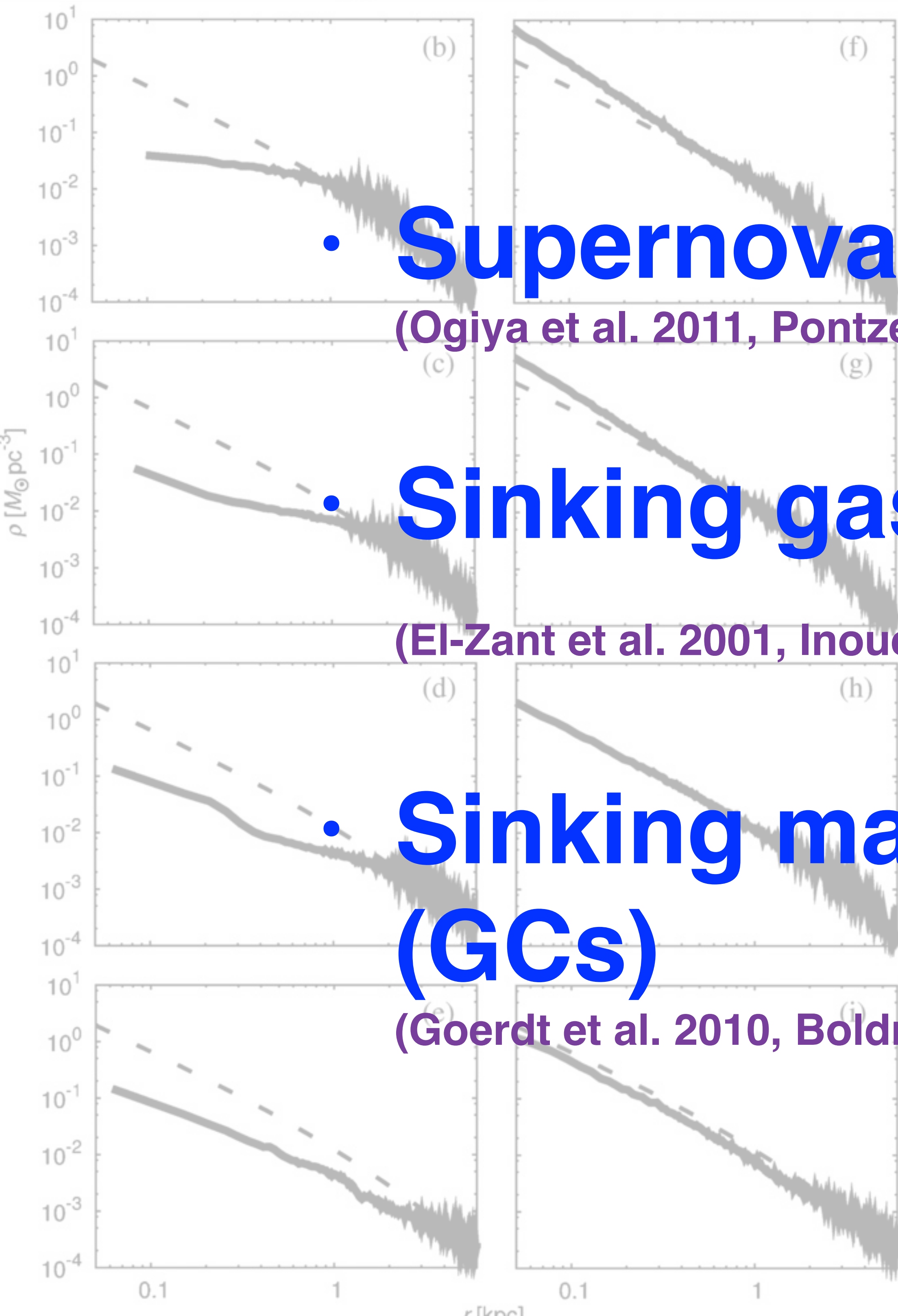
- **Cold Dark Matter** — **Cusp**
- **Warm Dark Matter** (Colin et al. 2000; Bode et al. 2001) — **Core**
- **Fuzzy Dark Matter** (Hu et al. 2000; Hui et al. 2017) — **Core**
- **Self-Interacting Dark Matter** (Vogelsberger et al. 2012) — **Core**
- **Primordial Black Holes as Dark Matter** (Boldrini et al. 2019) — **Core**



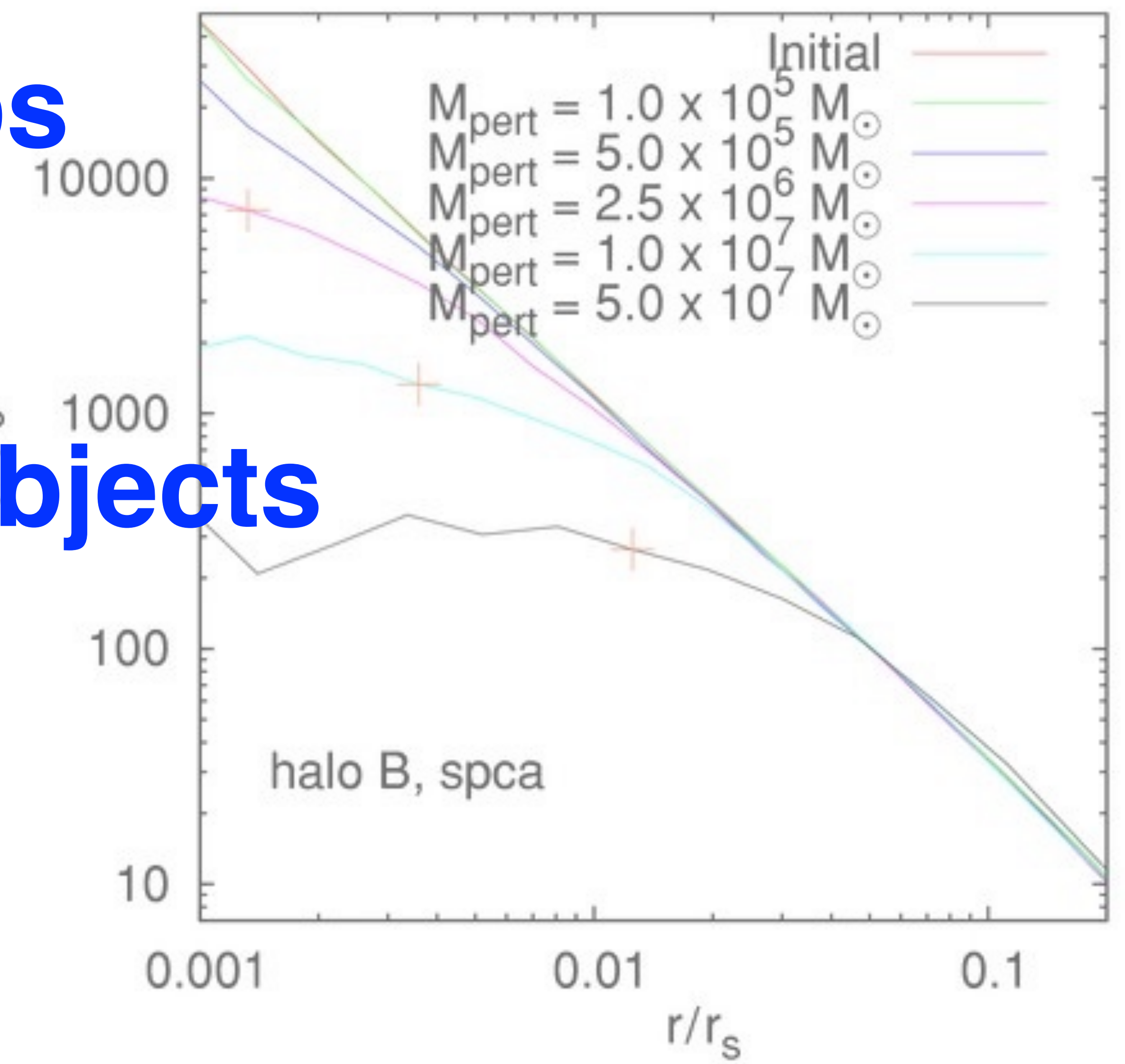


Alternative theories?

Involving baryons



- **Supernova feedback**
  (Ogiya et al. 2011, Pontzen et al. 2012)
- **Sinking gas clumps**
  (El-Zant et al. 2001, Inoue et al. 2011)
- **Sinking massive objects (GCs)**
  (Goerdt et al. 2010, Boldrini et al. 2019)

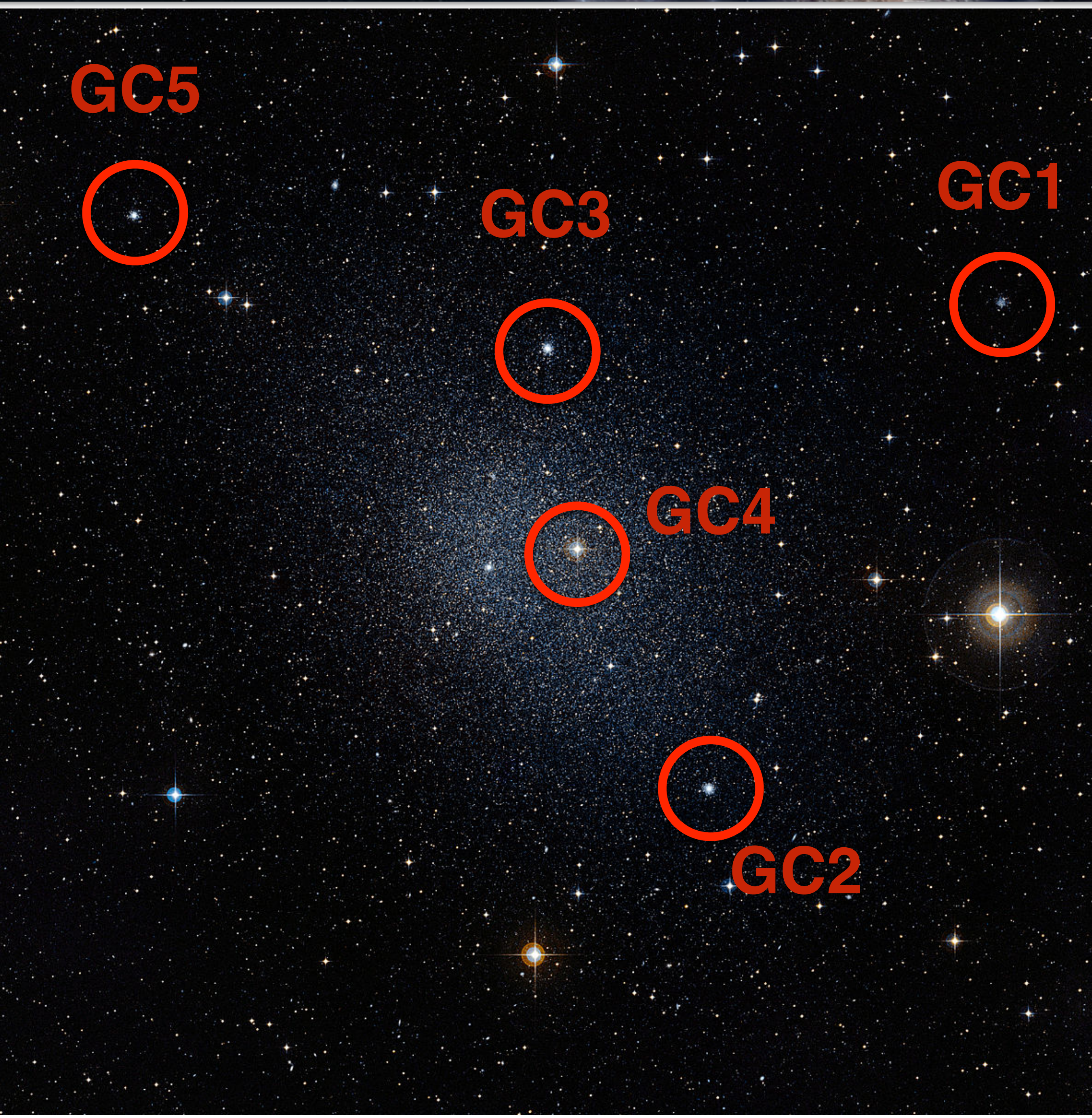


Fornax

Credit: ESO/Digitized Sky Survey 2

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

Fornax: cusp or core?



Credit: ESO/Digitized Sky Survey 2

Cusp or core?

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- **Globular cluster data (positions, masses)**