Probing ultralight and degenerate dark matter with galactic dynamics

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2205.00289, 2102.11522, 1805.00122

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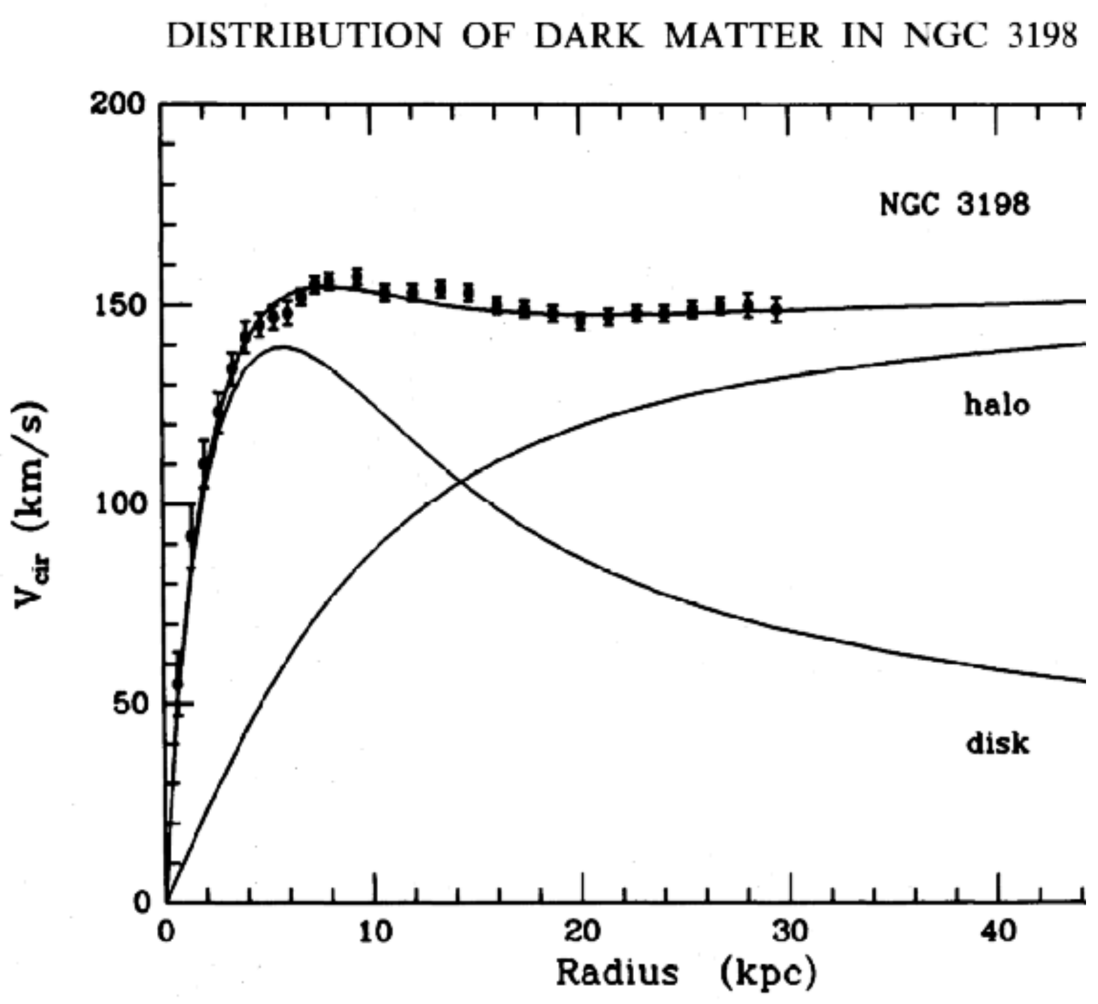
Some effects of DM on baryons @ galactic scales



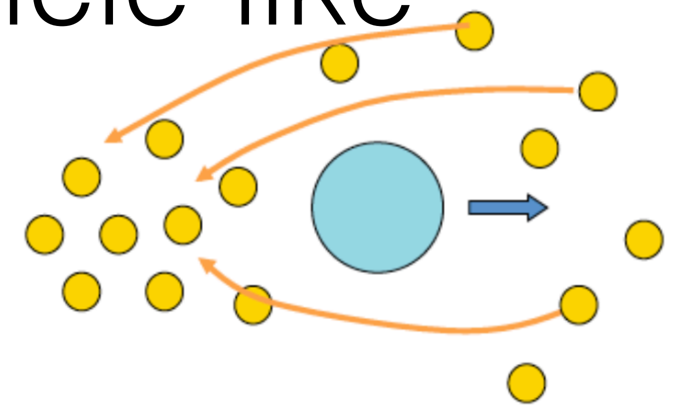
Galactic rotation curves probe the gravitational potential Φ

One of the most direct evidences of existence of DM halo

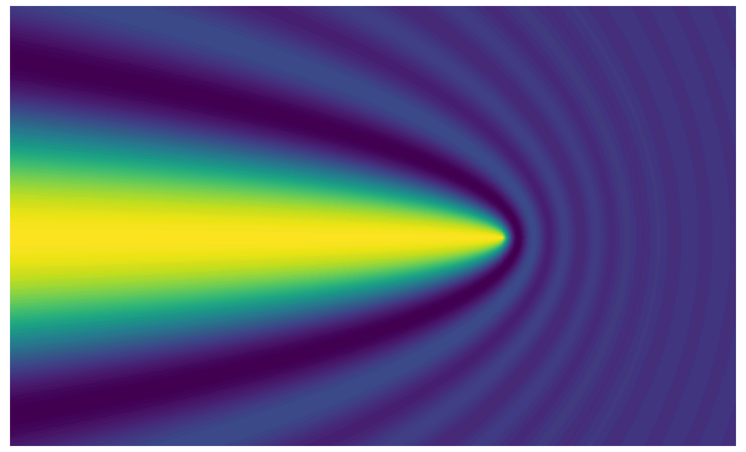
The presence of a 'dynamical medium' has many other effects on baryons: e.g. tidal disruption, dynamical friction, dynamical heating…

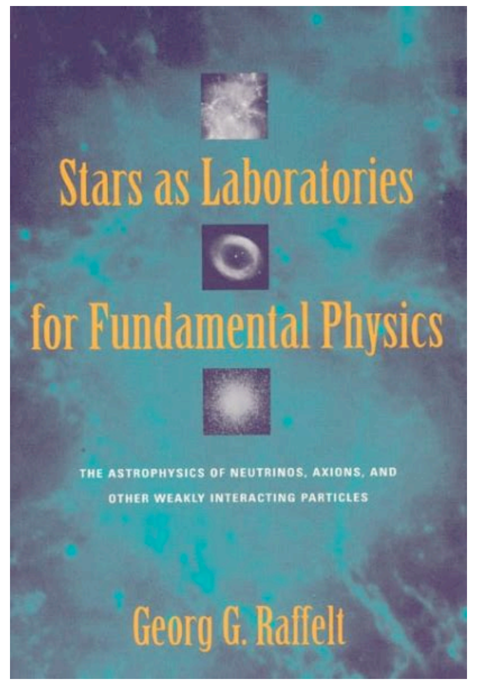
They depend on the nature of DM!!

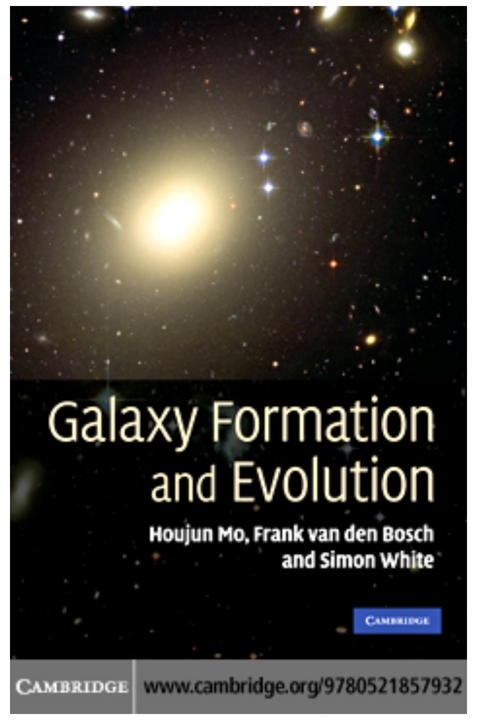
Particle-like

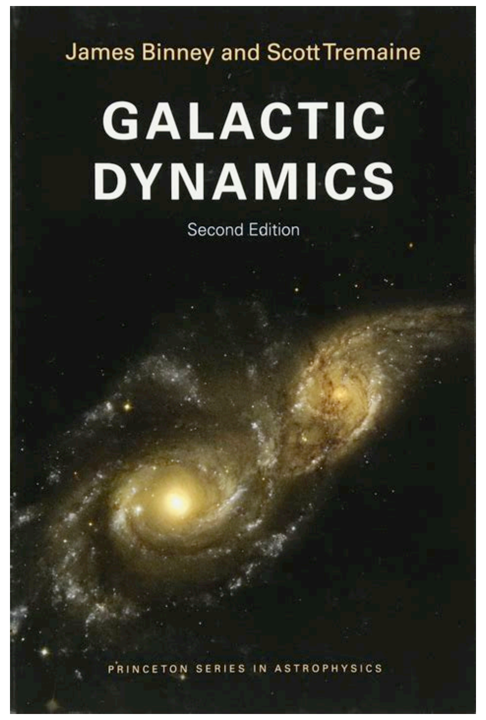


Wave-like









A systematic study is still missing (e.g. extend results in Benito's talk)

This talk: two extremes

Galactic rotation curves to test *ultra-light* **bosonic** DM

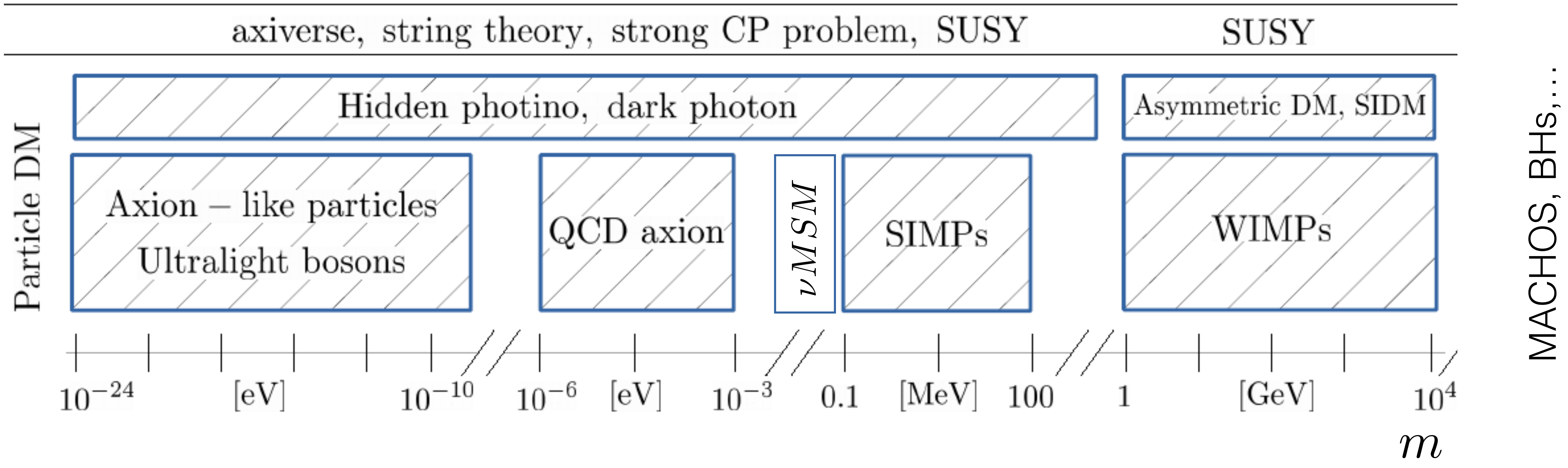
***** for *ultra-light* **fermionic** DM e.g.

Alvey, Sabti, DB, Escudero et al 2010.03572

Dynamical friction to test *ultra-light* **fermionic** DM

The mass landscape

Can we bound **the mass of DM?** (in a more or less model indep. way)



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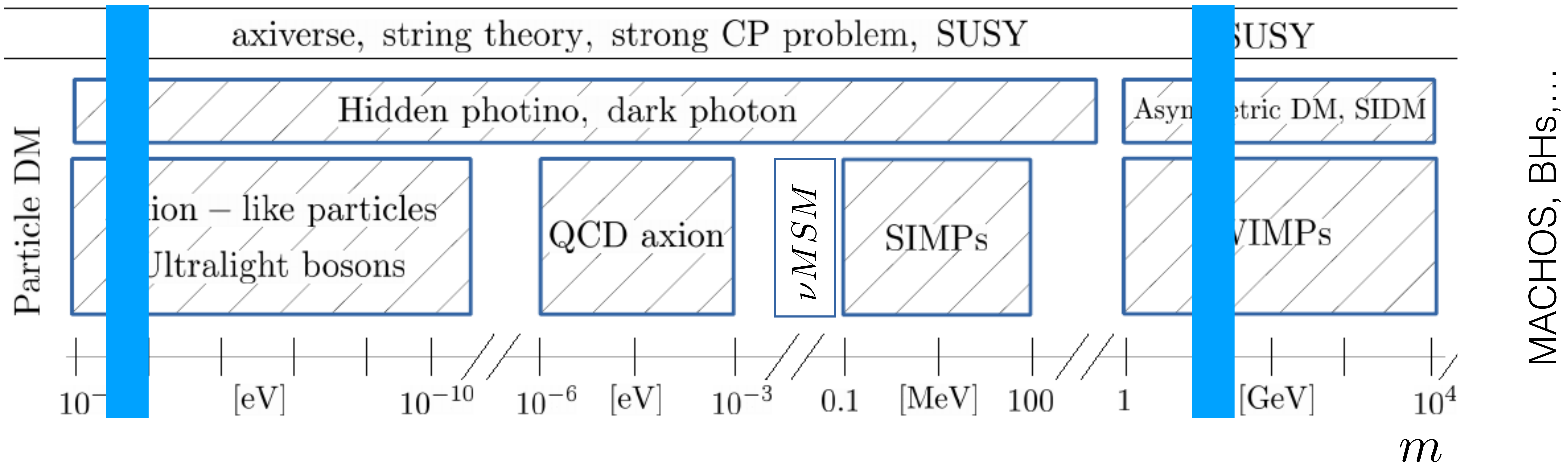

$\lesssim 10^{-22}\,\mathrm{eV}$

Bosons: they need to fit in the smallest galaxies (*behaviour as waves*, with large wavelength)

$\lesssim 100\,\mathrm{eV}$

Fermions: they need to be bounded in shallow galaxies (*Fermi surface*)

This talk: two extremes

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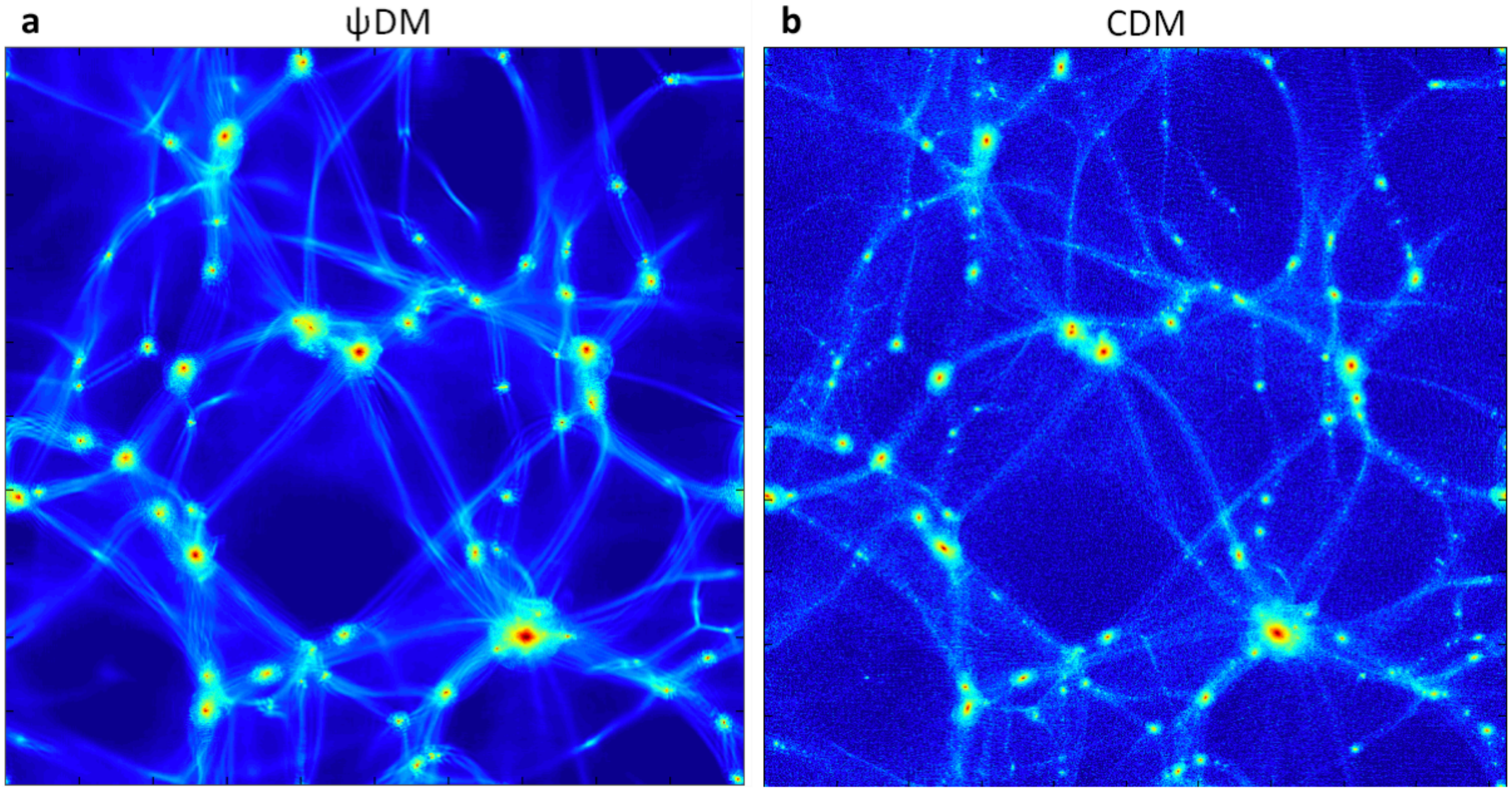
Alvey, Sabti, DB, Escudero et al 2010.03572

Dynamical friction to test *ultra-light* **fermionic** DM

ULDM behaves like CDM at large-scales

$$\lambda_{\rm dB} \sim \frac{10^{-22}{\rm eV}}{m}\frac{10^{-3}}{v}{\rm kpc}$$

Scale of ~30 Mpc, Schive et al. 1406.6586

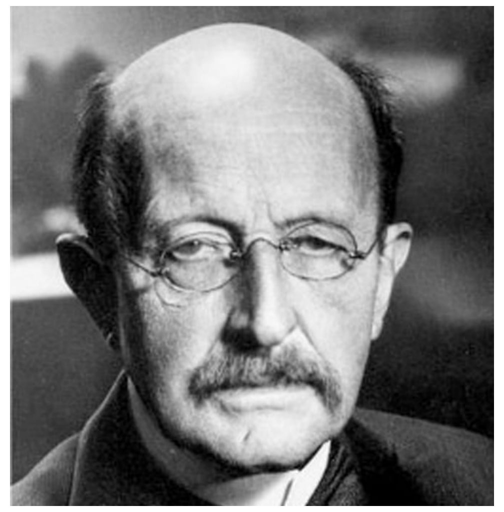


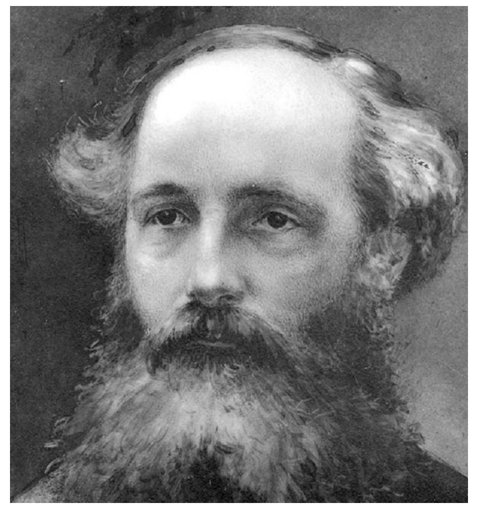
$m \sim 10^{-22}\,{\rm eV}$

ULDM **does not** behaves like CDM at small-scales

Description as a particle, as a classical field or as DF?

$\hbar\omega$





$F_{\mu\nu}$

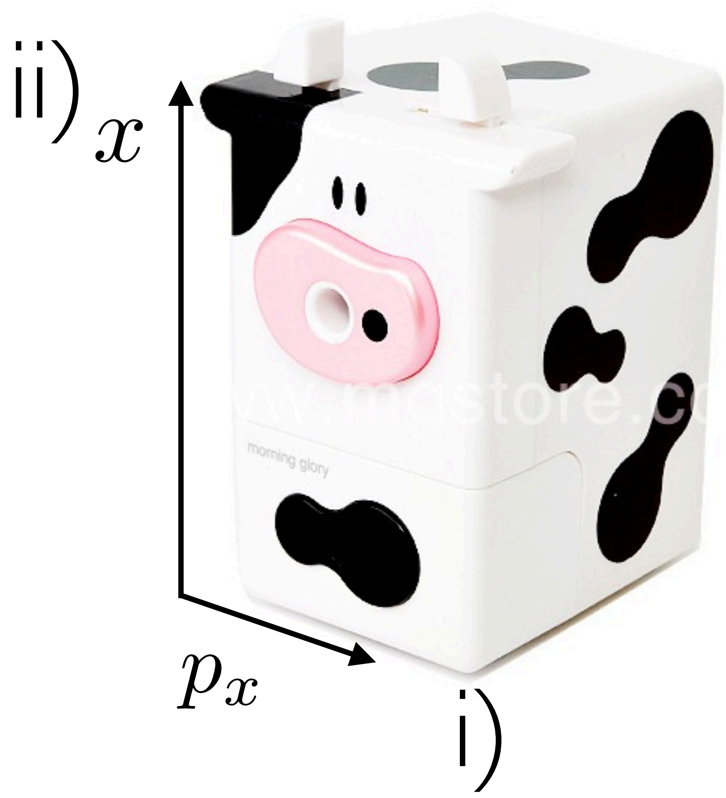
We need to understand the occupation number and (uncorrelated) phases

e.g. Milky way DM halo

i) escape velocity $\sim 2 \times 10^{-3} c$ ii) size 100 kpc

$$\Delta x \Delta p \gtrsim \hbar \rightarrow N_s \sim 10^{75} \left(\frac{m}{\mathrm{eV}}\right)^3$$

particles per state $N_p = \frac{M_{MW}}{N_s m} \sim 10^3 \left(\frac{\mathrm{eV}}{m}\right)^4$

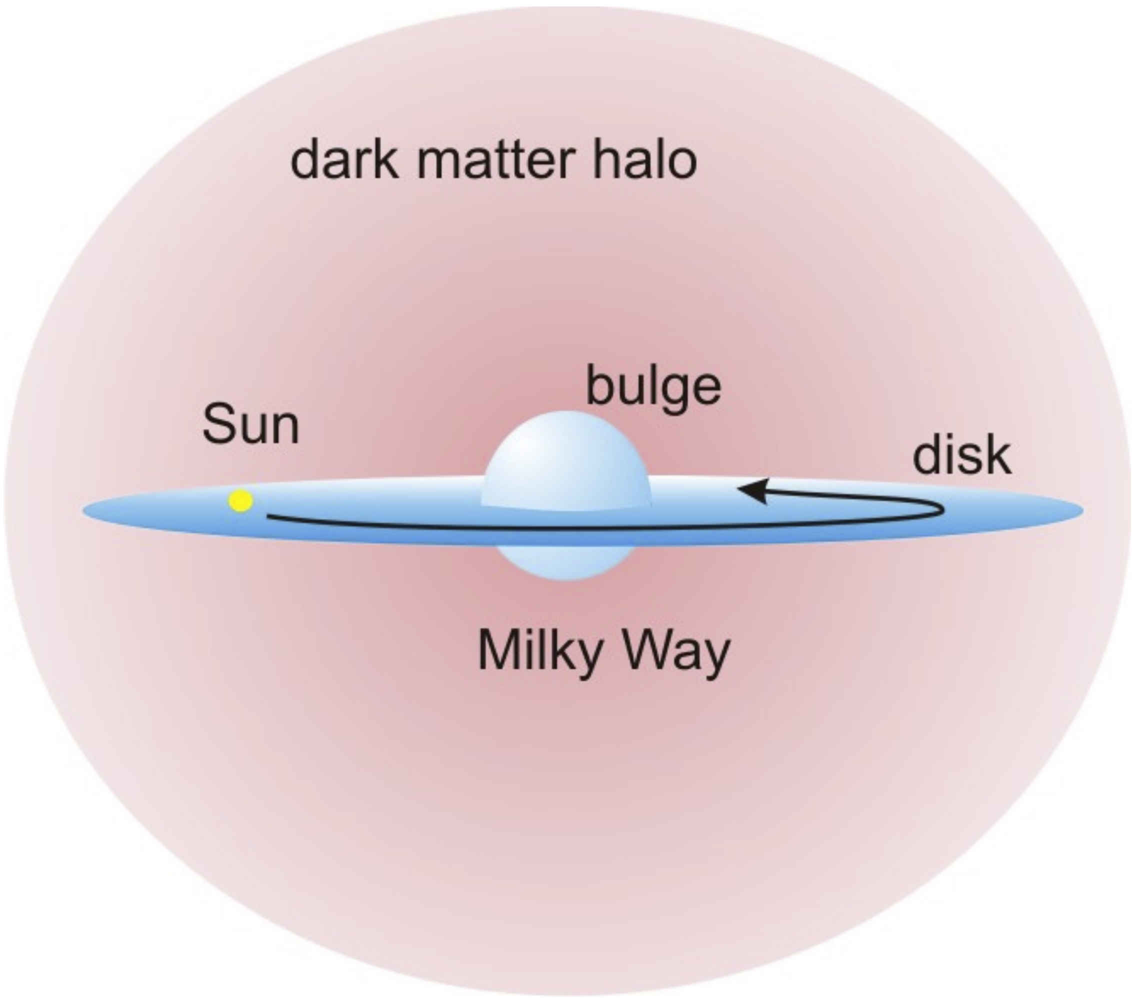


For low bosonic masses it can be considered as a classical field

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] \quad + \text{gravity}$$

ULDM **does not** behaves like CDM at small-scales

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] \quad + \text{gravity}$$



$$\phi_k \sim e^{i(\omega t - kx)}$$

Virialized configuration: collection of waves
with distribution determined by properties from the galaxy

$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3 v \, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c.$$

$\sigma_0 \sim 10^{-3} c$ in the MW

free wave

The DM potential has coherent oscillations in λ_{db}

$$t \sim \frac{10^6}{m}\left(\frac{10^{-6}}{\sigma_0^2}\right)$$

Close to λ_{db}
In terms of **fluid variables (e.g. $\rho \propto m^2\phi^2$):**

gravitational potential

$$\dot{\rho} + 3H\rho + \frac{\nabla}{a}(\rho\,\vec{v}) = 0$$

$$\dot{\vec{v}} + H\vec{v} + \left(\vec{v}\cdot\frac{\nabla}{a}\right)\vec{v} = -\frac{\nabla}{a}\left(V - \frac{1}{2m^2a^2}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

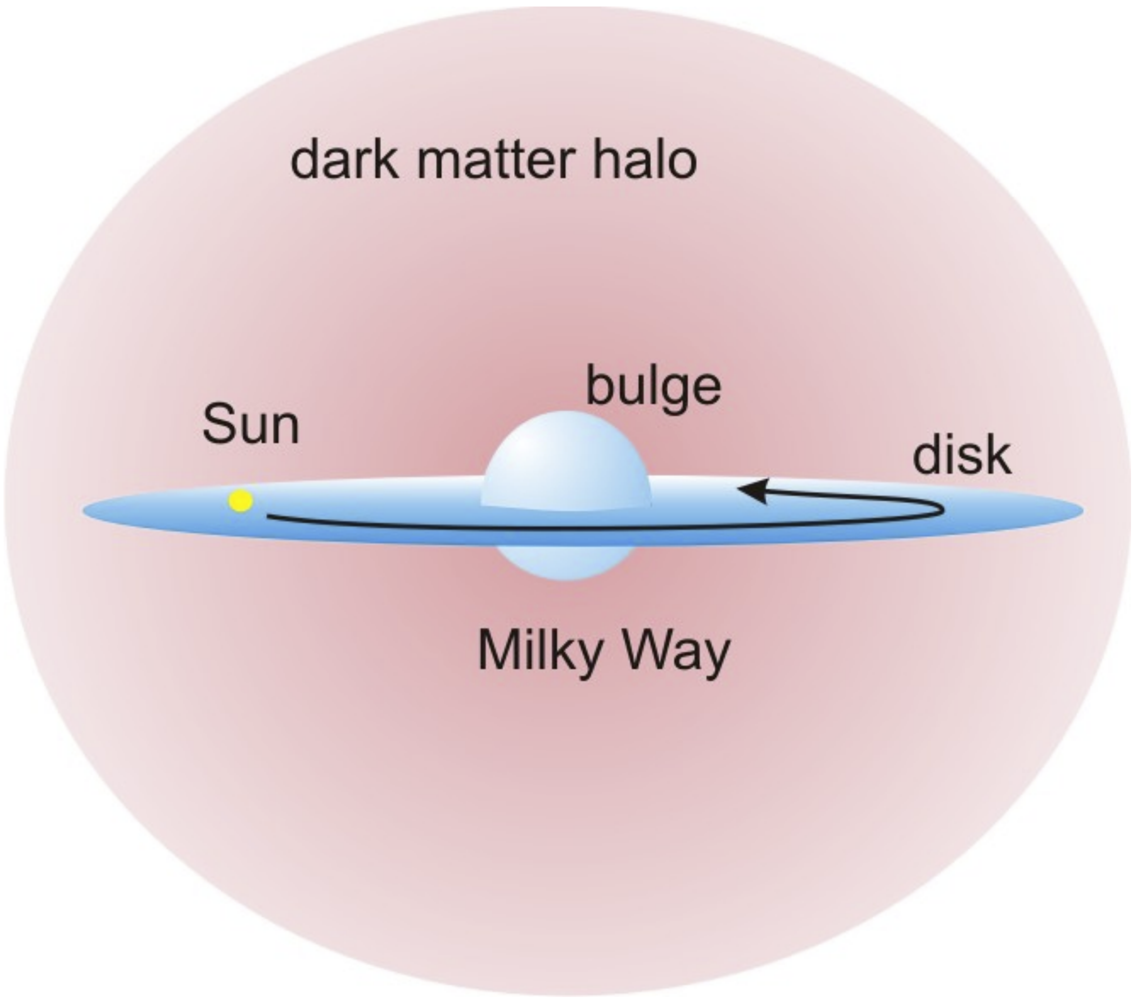
pure CDM part

new phenomena at small scales!
(repulsive effect: “quantum pressure”)

$$\lambda_{\rm dB} \sim \frac{10^{-22}\text{eV}}{m}\frac{10^{-3}}{v}\text{kpc}$$

ULDM **does not** behaves like CDM at small-scales

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right]$$ + gravity



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free wave

The DM potential has coherent oscillations in λ_{db}

Marsh, Niemeyer 18
Dalal , Kravtsov 22
Ban-Or et lal 19

e.g. this heats up the halo

Close to λ_{db}
In terms of **fluid variables (e.g.** $\rho \propto m^2\phi^2$**):**

gravitational potential

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pure CDM part

new phenomena at small scales!
(repulsive effect: "quantum pressure")

e.g. this changes dynamics at smaller scales

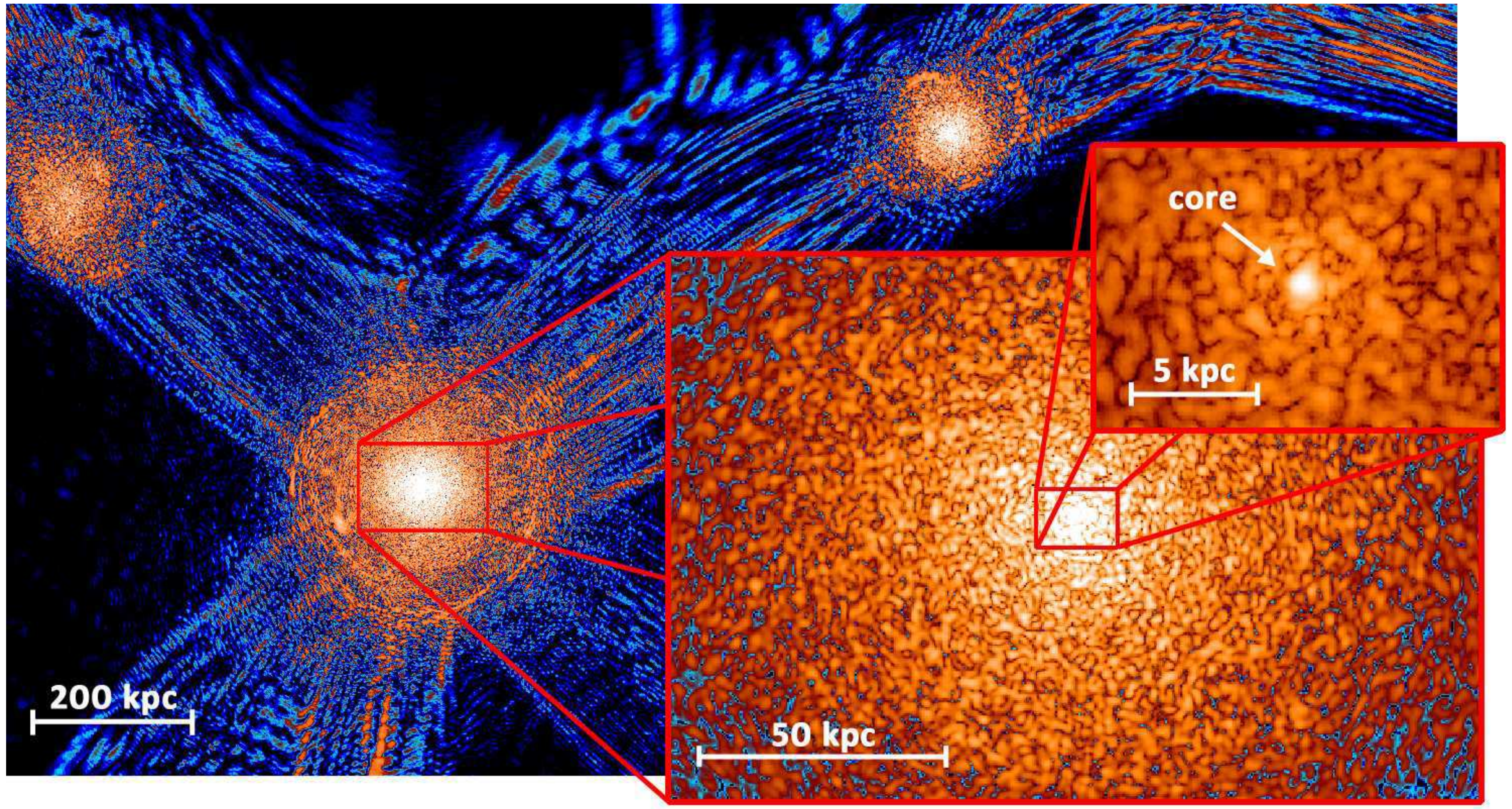
$\frac{10^{-3}}{v}\mathrm{kpc}$

ULDM **does not** behaves like CDM at small-scales

From simulations

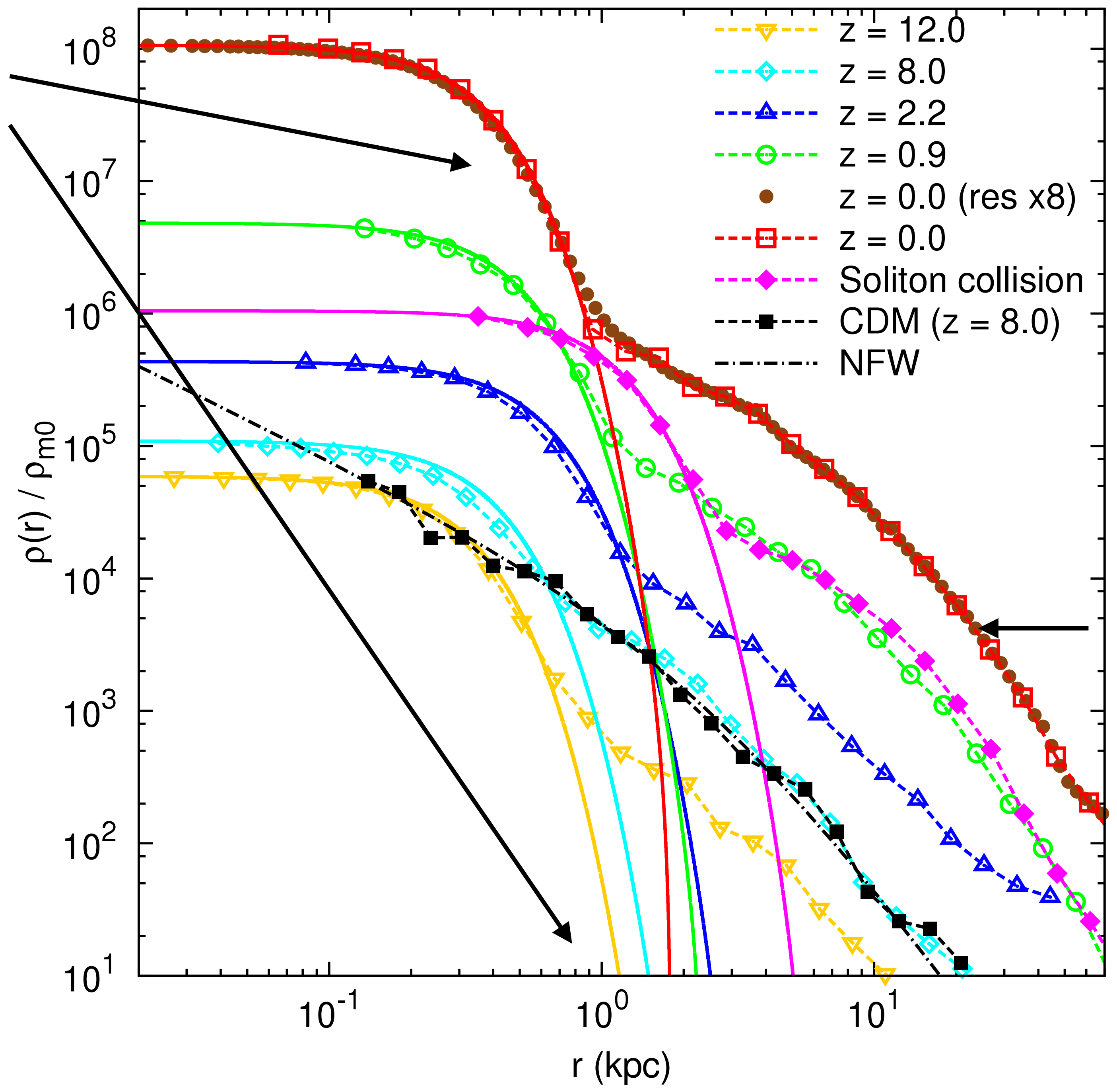
DM in the center of the halo
relaxes to solitons ("boson stars")

Schive et al.1406.6586



Schive et al.1407.7762

soliton



halo

Properties of the soliton

$$\phi(x,t) = \frac{1}{\sqrt{2m}} e^{-imt}\psi(x,t) + c.c.$$

$$v \ll c,\ \omega \ll m$$

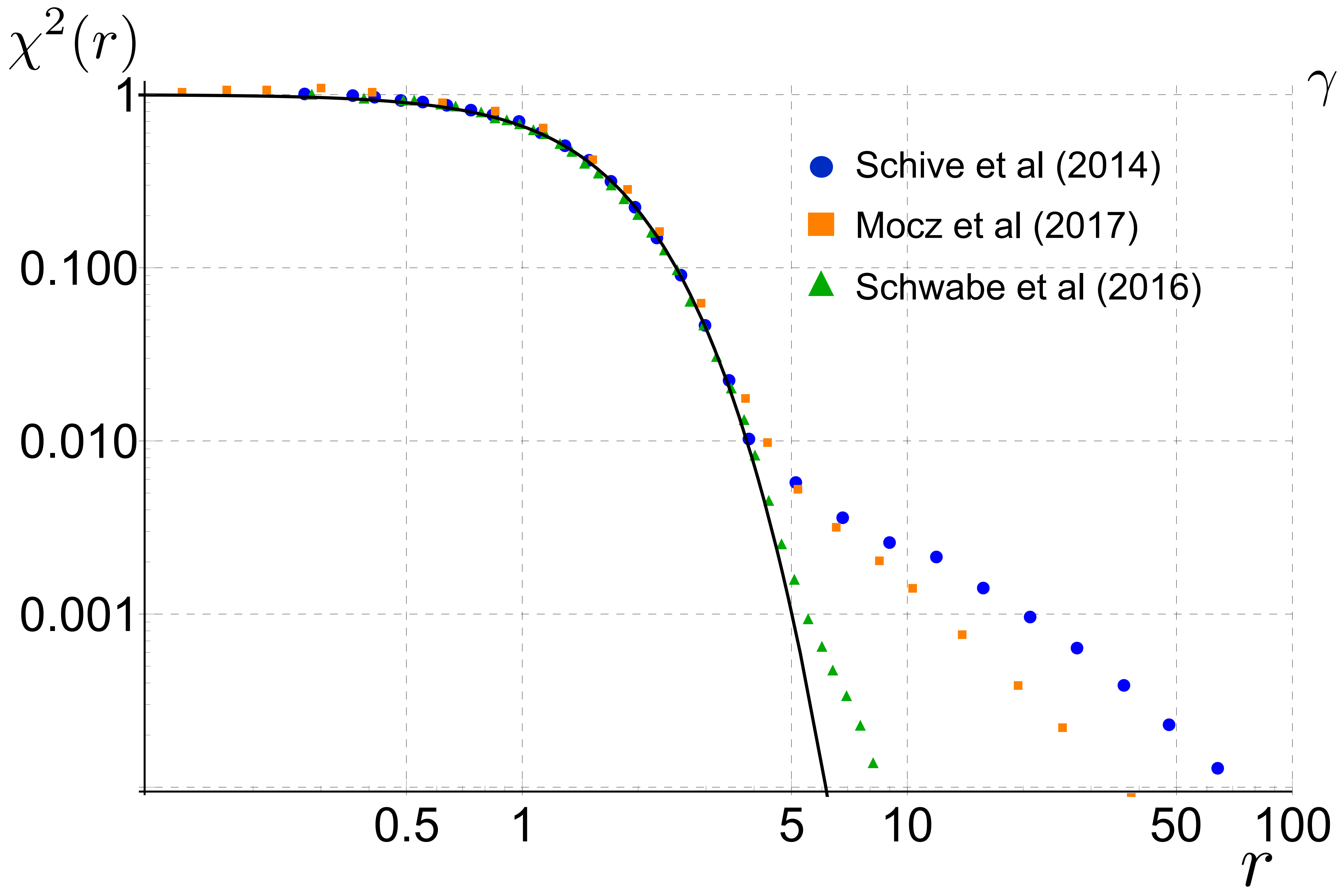
$$i\partial_t \psi = -\frac{1}{2m}\Delta\psi + m\Phi_N \psi$$

$$\Delta\Phi_N = 4\pi G|\psi|^2$$

spherically symmetric stationary, non-relativistic solution:

e.g. Bar, DB, Blum, Sibiryakov 18

$$\phi(x,t) = \frac{M_{pl}}{2\sqrt{2\pi}} e^{-imt} e^{-i\gamma t}\chi(x) + h.c.$$



$\gamma = -0.69$

scaling solution

$$\chi_\lambda(r) = \lambda^2\chi_1(\lambda r)$$

$$x_{c\lambda} = \lambda^{-1}x_{c1}$$

$$M_\lambda = \lambda M_1$$

$$\gamma_\lambda = \lambda^2\gamma$$

$$\rho_{c\lambda} = \lambda^4\rho_{c1}$$

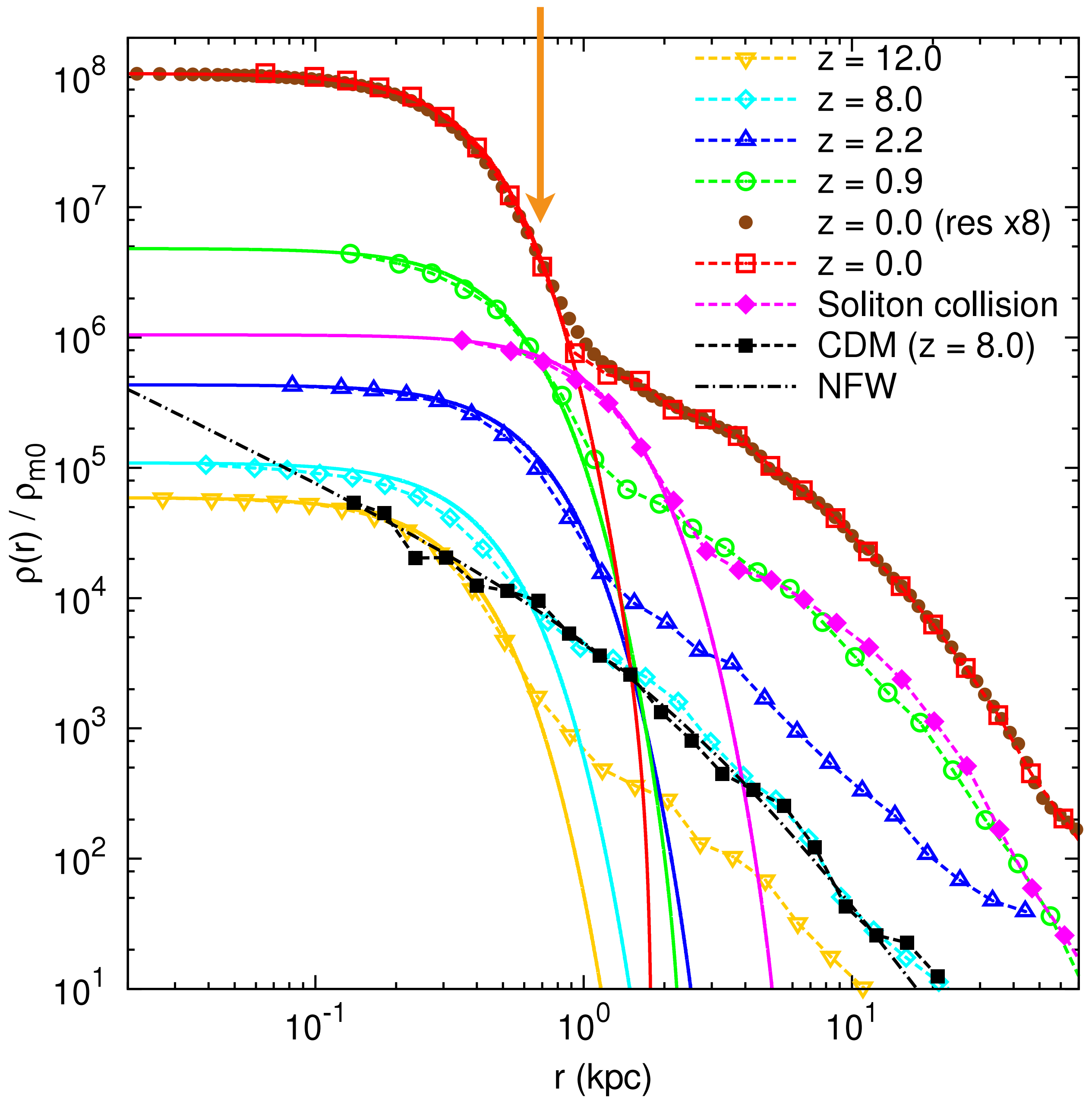
What fixes γ?

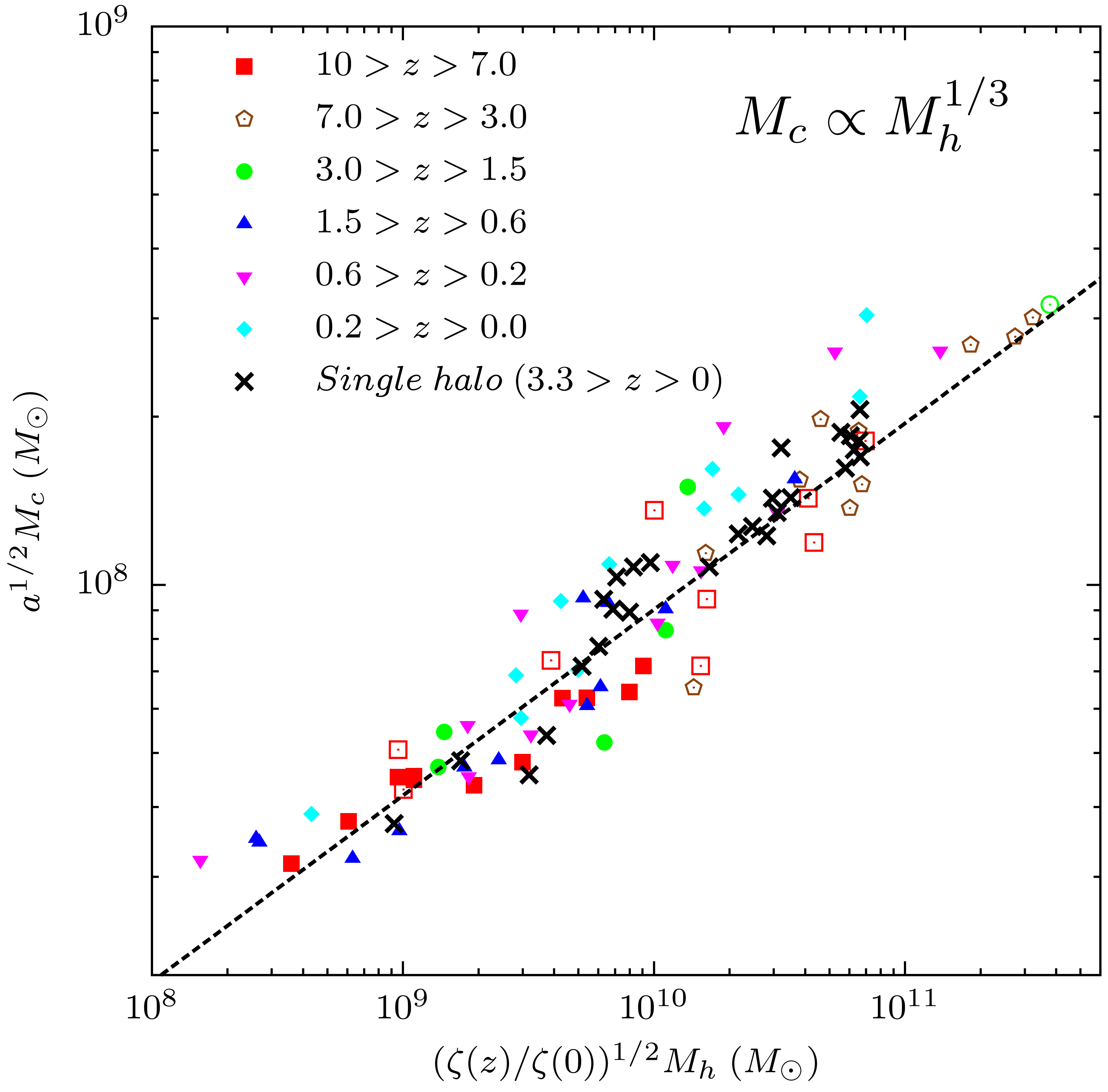
Solitons in a host-halo

What fixes γ? What fixes the size?

Schive et al 1407.7762

$$M_c \approx \alpha \left(\frac{|E_h|}{M_h}\right)^{1/2} \frac{M_{pl}^2}{m}$$





Solitons in a host-halo

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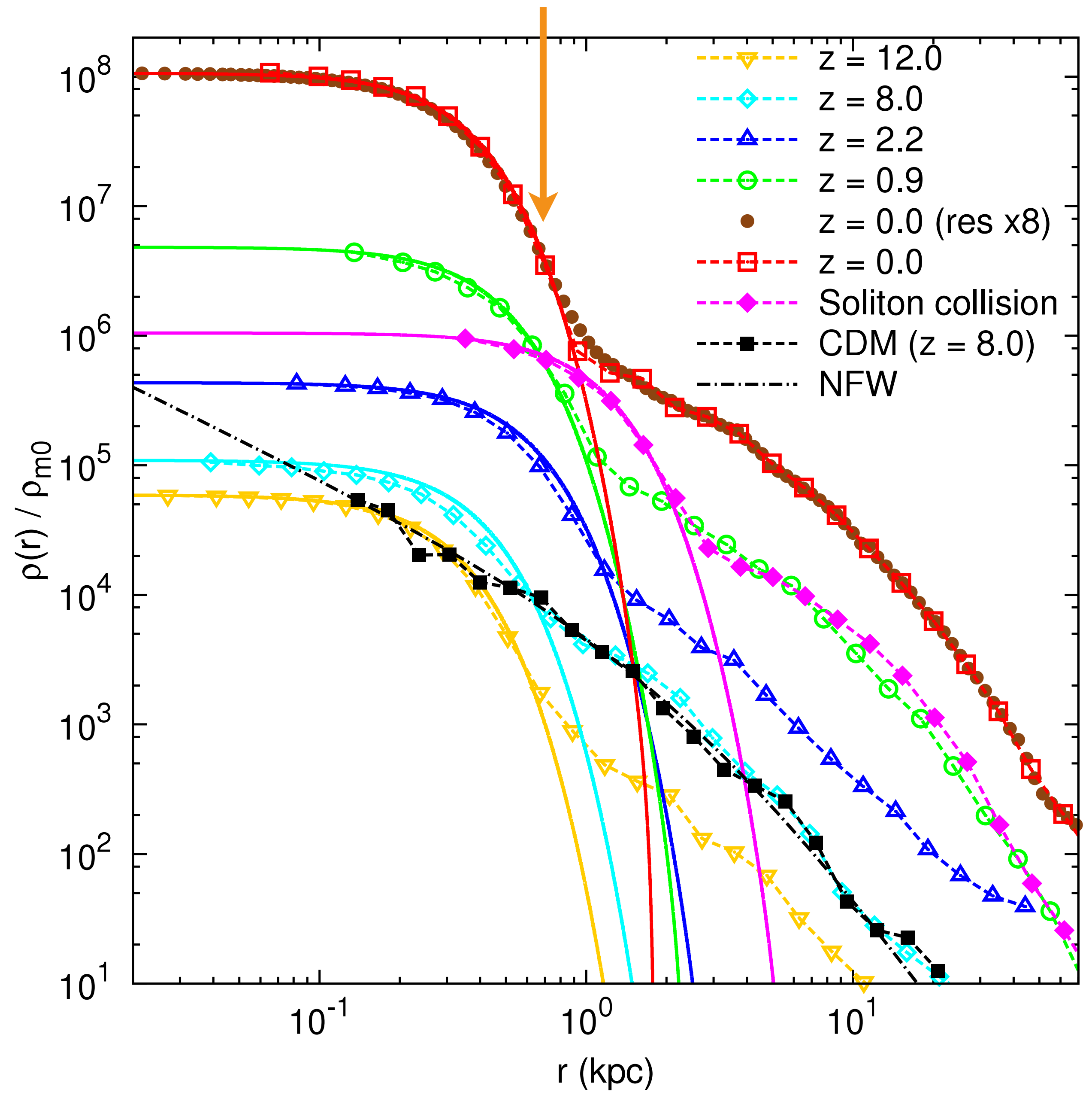
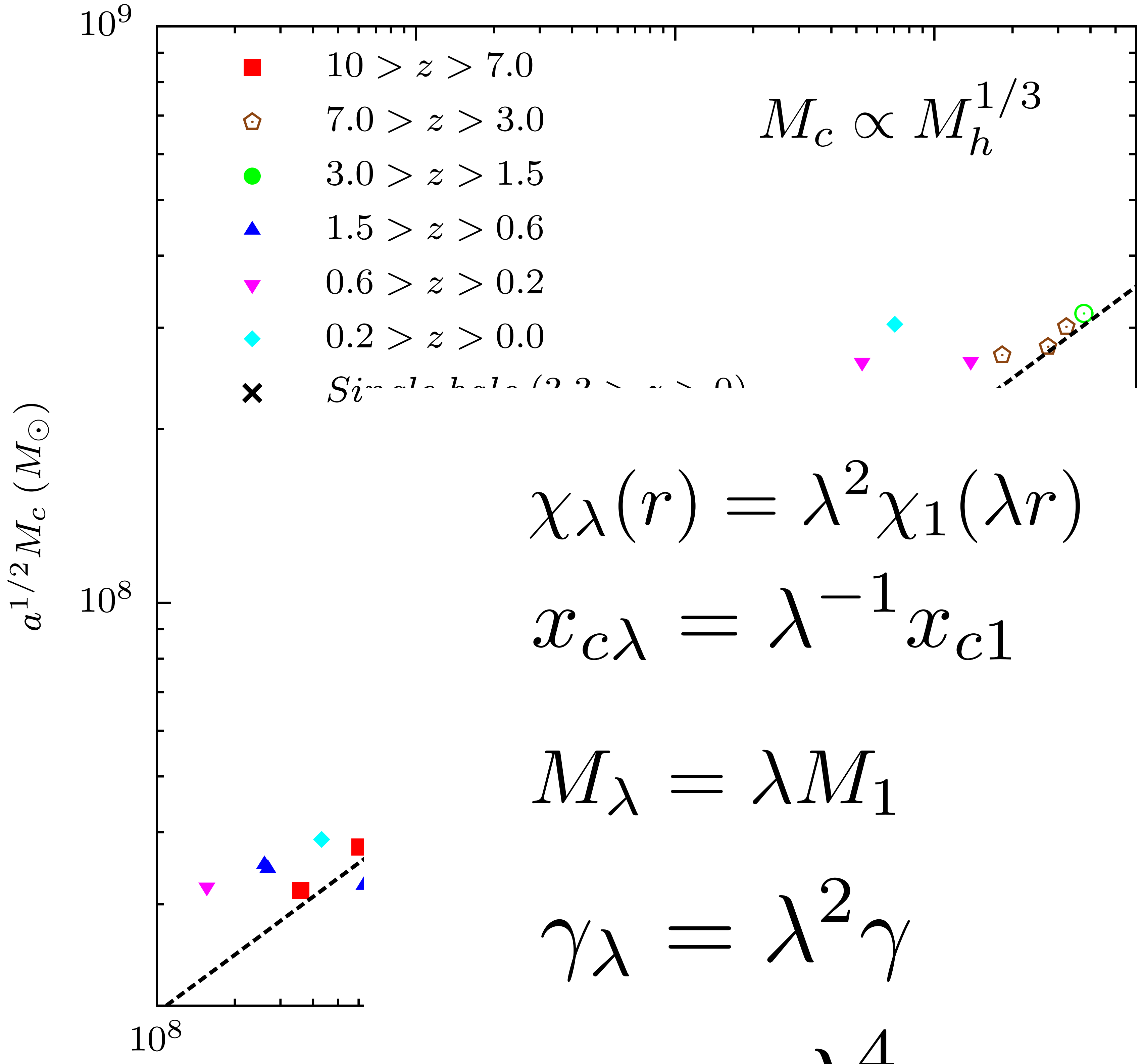




$$\chi_\lambda(r) = \lambda^2 \chi_1(\lambda r)$$

$$x_{c\lambda} = \lambda^{-1} x_{c1}$$

$$M_\lambda = \lambda M_1$$

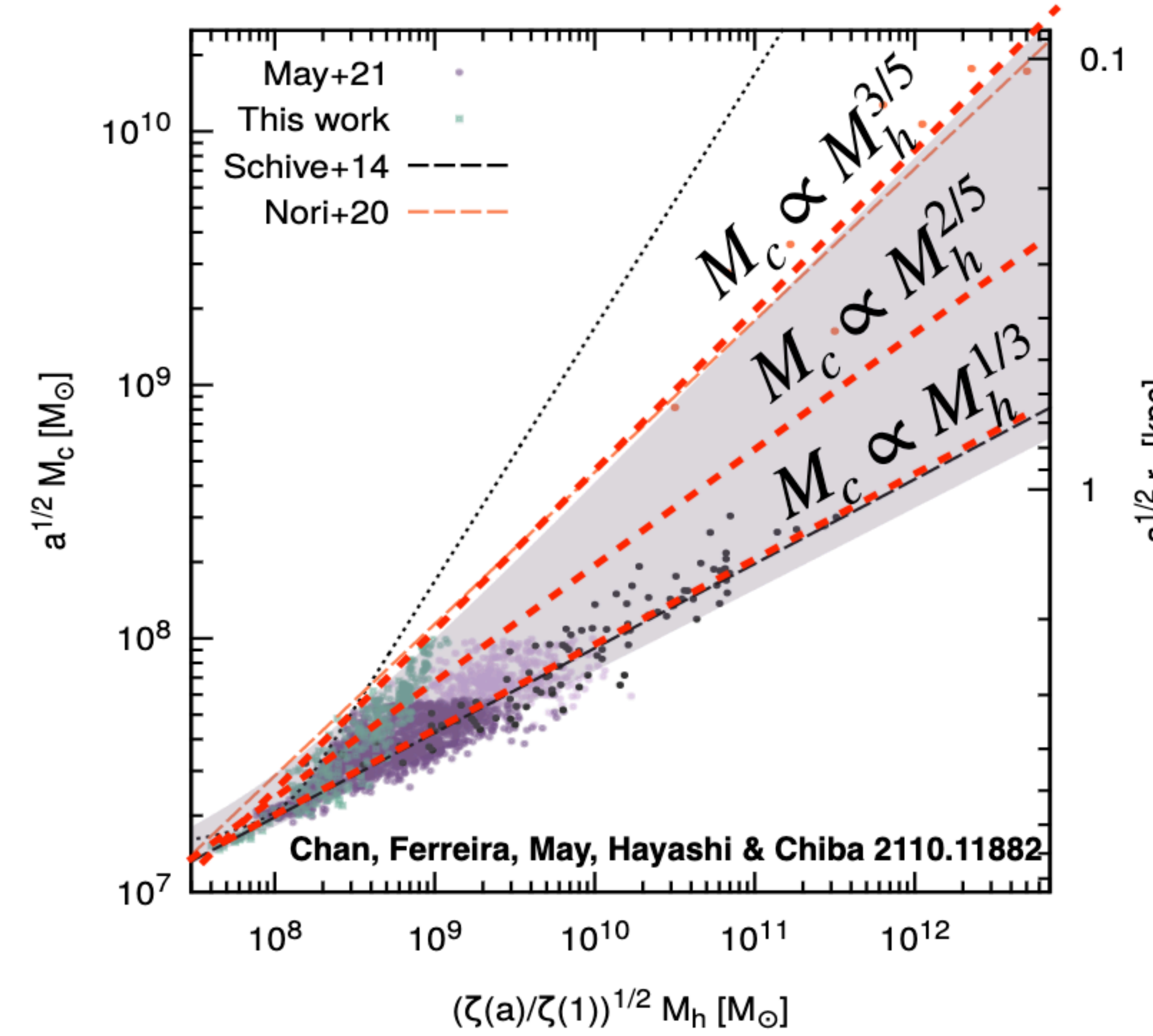
$$\gamma_\lambda = \lambda^2 \gamma$$

$$\rho_{c\lambda} = \lambda^4 \rho_{c1}$$

Schive et al 1407.7762

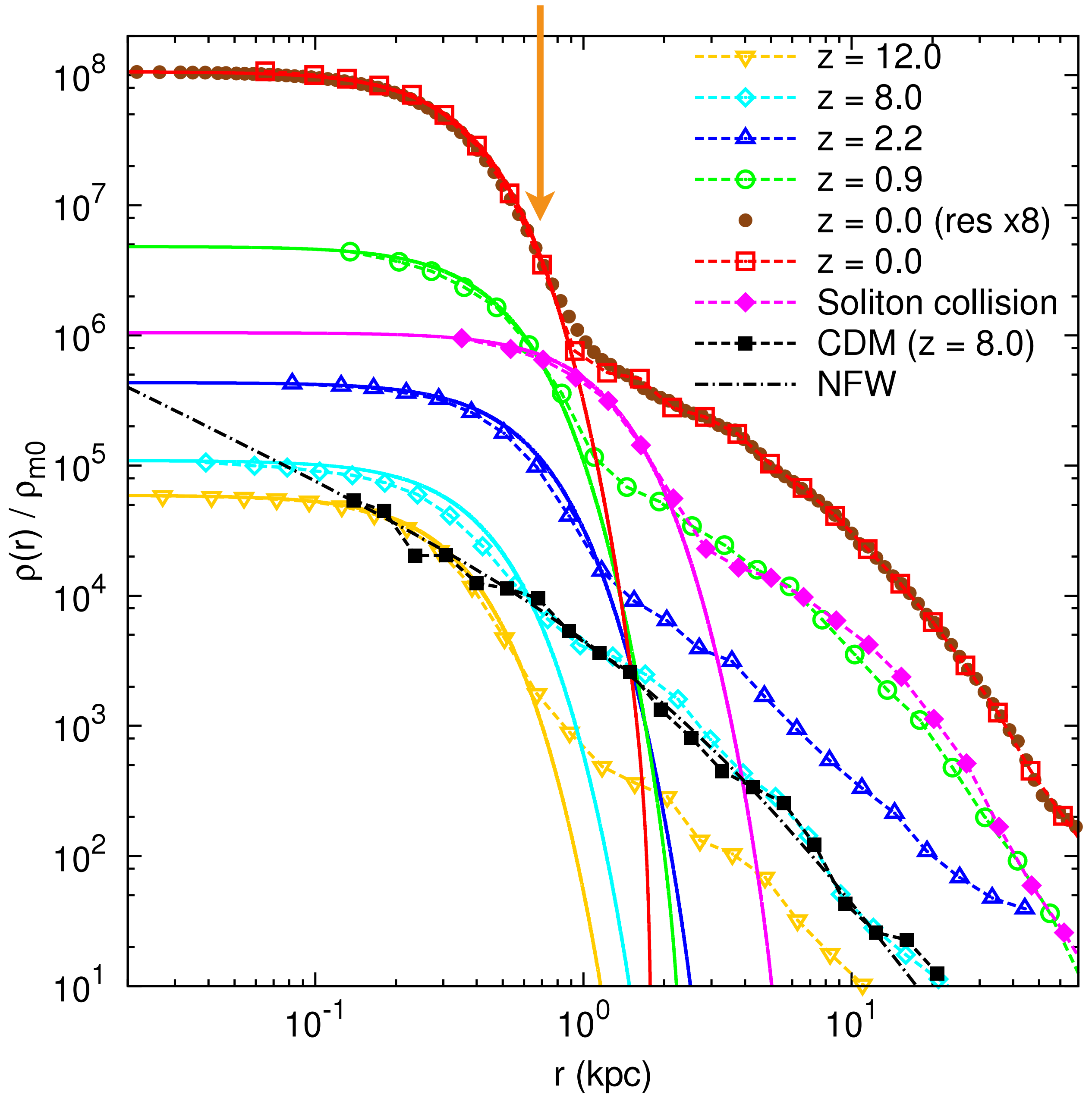
$$M_c \approx \alpha \left(\frac{|E_h|}{M_h} \right)^{1/2} \frac{M_{pl}^2}{m}$$

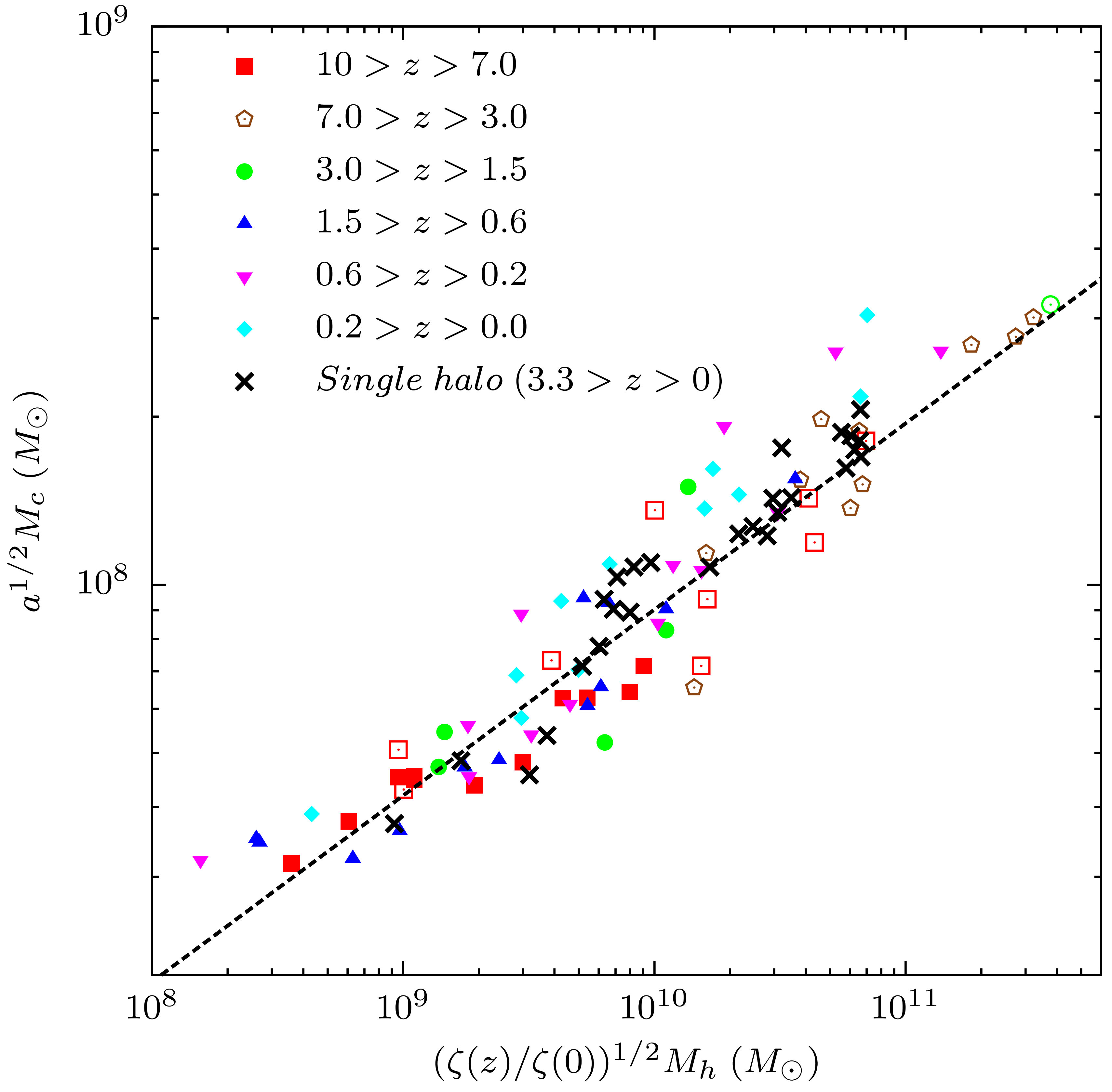
But, they may be denser



Solitons in a host-halo

What fixes γ? What fixes the size?





Schive et al 1407.7762

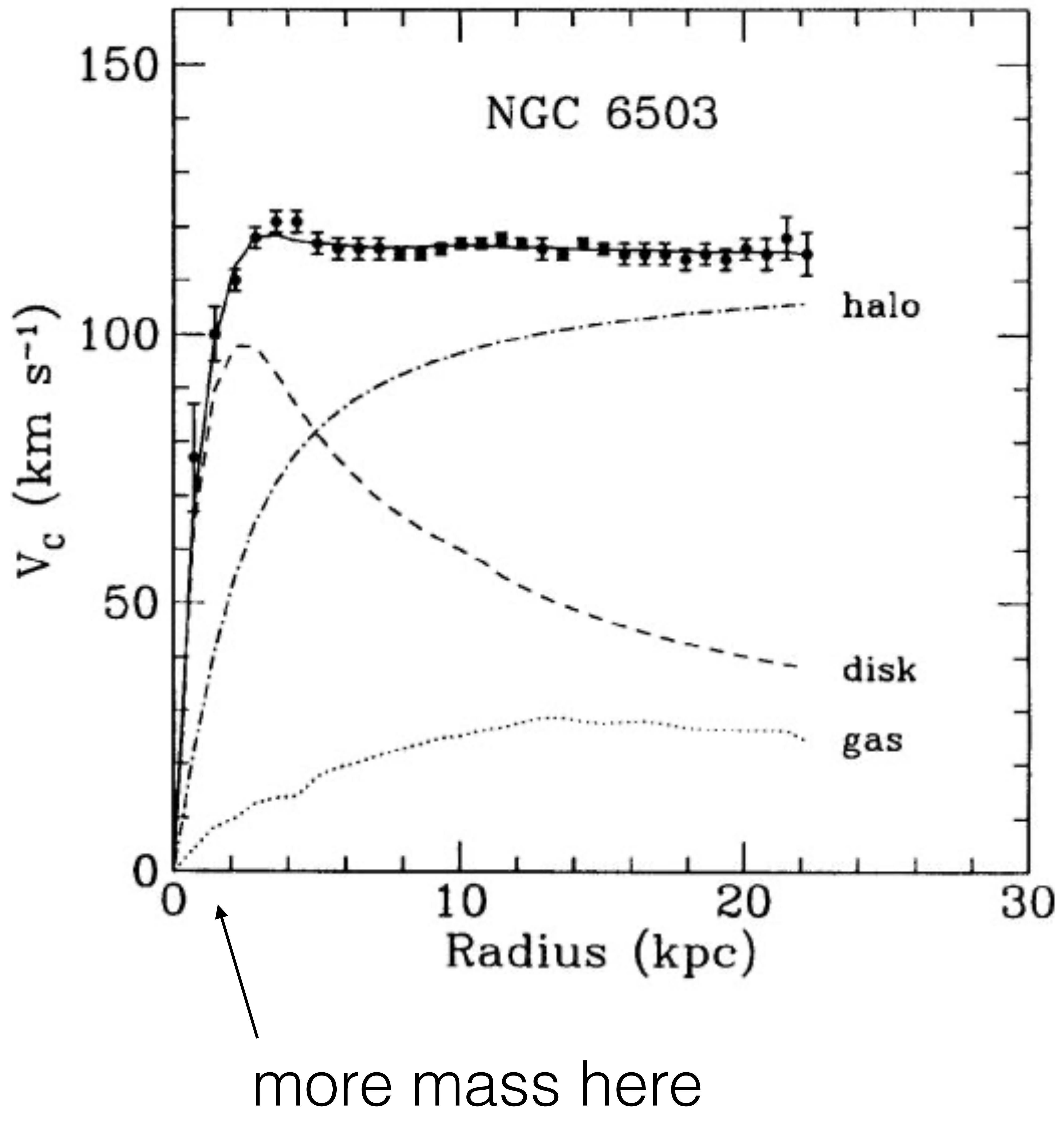
$$M_c \approx \alpha \left(\frac{|E_h|}{M_h} \right)^{1/2} \frac{M_{pl}^2}{m}$$

Bar, DB, Blum, Sibiryakov 1805.00122

$$\left.\frac{E}{M}\right|_{\rm sol} = \left.\frac{E}{M}\right|_{\rm halo}$$

a relaxed soliton in some sort of equilibrium with a virialized distribution?

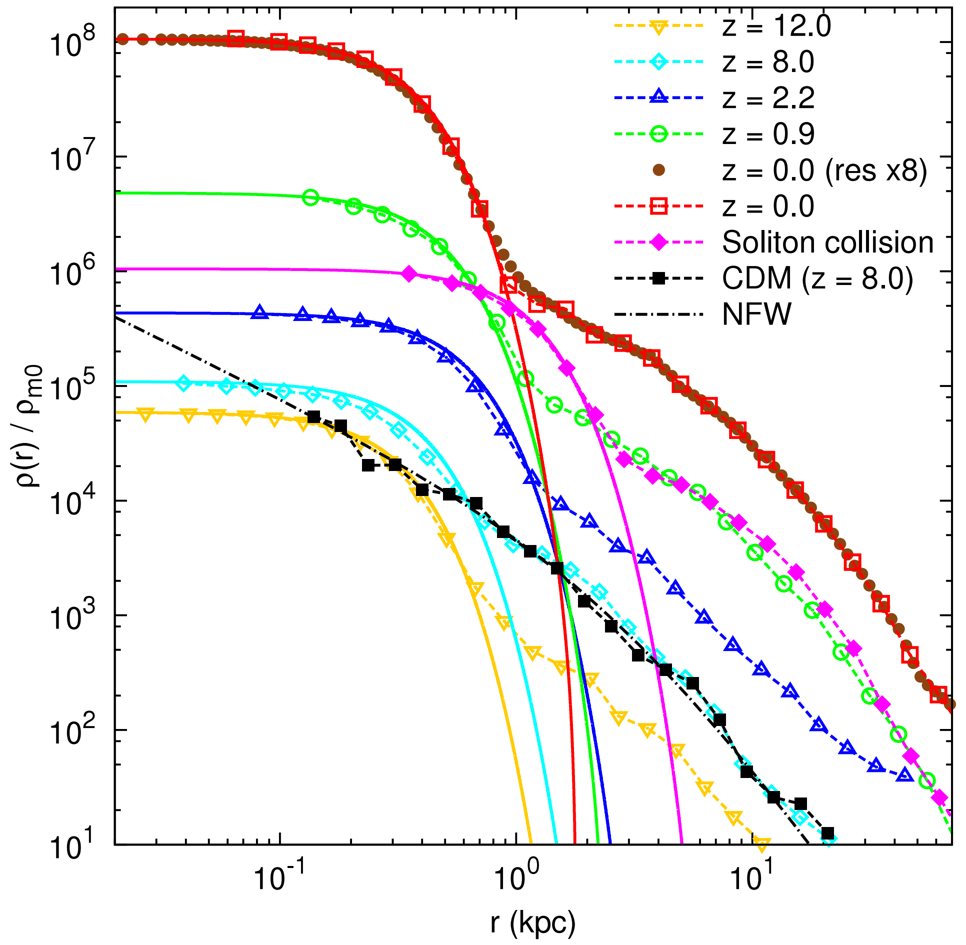
Rotation curves including the soliton

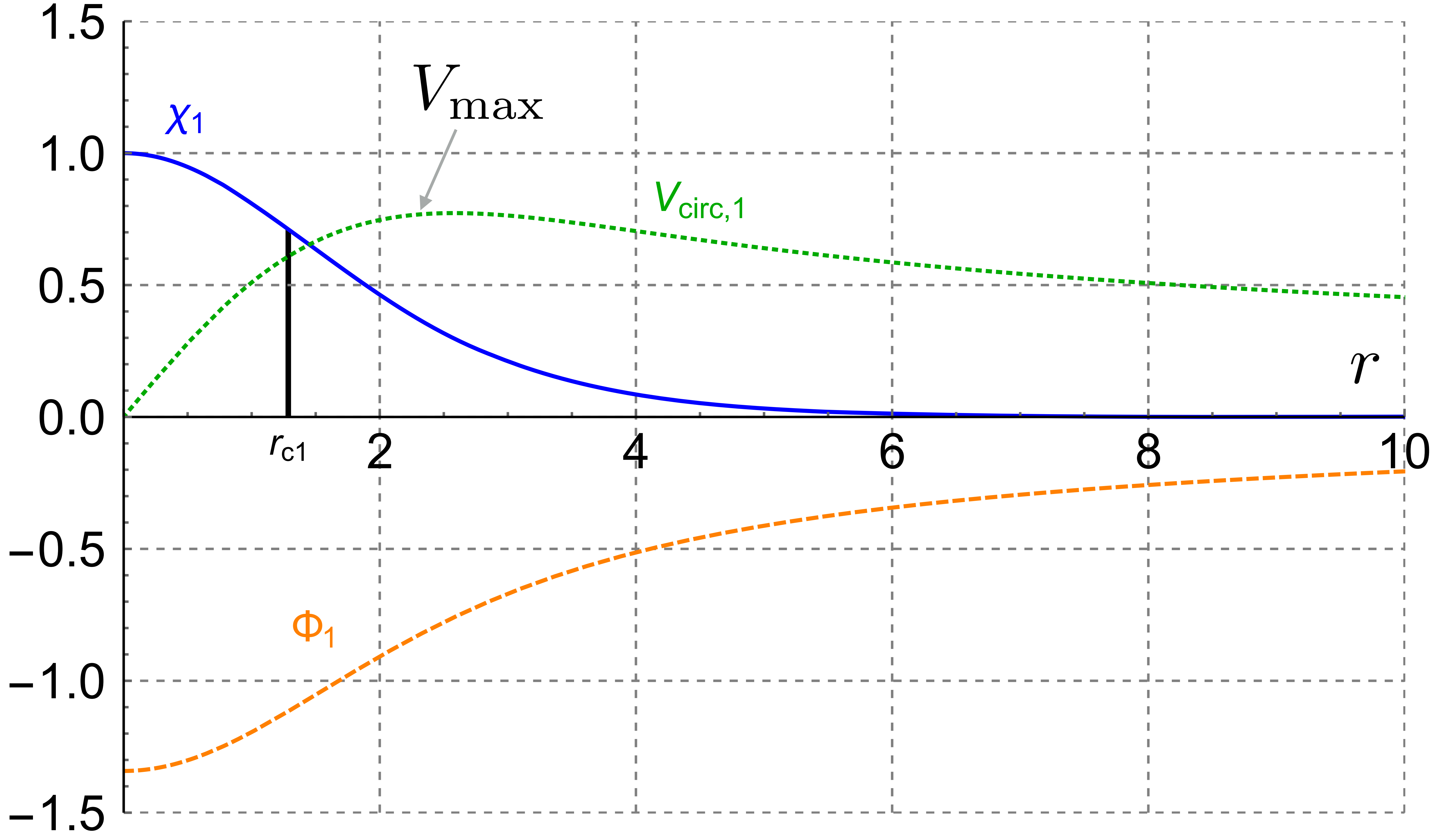


Circular velocities for the soliton

$$V_{\rm circ}^2 = r\partial_r\Phi(r)$$

Bar, DB, Blum, Sibiryakov 1805.00122





Halo + Soliton

a ‘realistic’ profile for the halo: NFW

$$\rho_{NFW} = \frac{\rho_{c,NFW}\delta_{c,NFW}}{\frac{x}{R_s}\left(1+\frac{x}{R_s}\right)^2}$$

radius

concentration

$$\rho_{c,NFW} = \frac{3H^2(z)}{8\pi G} \qquad \delta_{c,NFW} = \frac{200}{3}\frac{c^3}{\ln(1+c)-\frac{c}{1+c}}$$

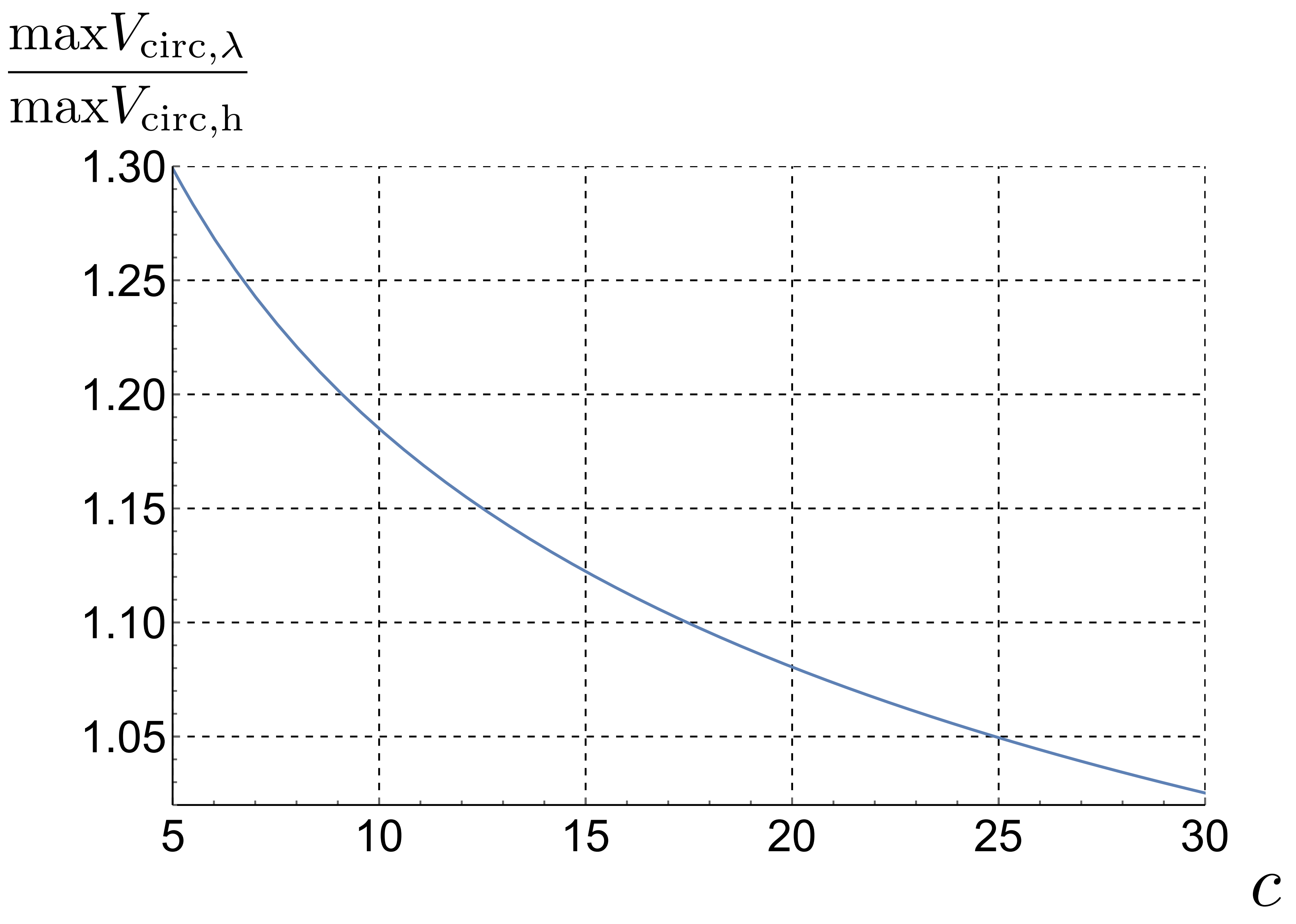
the corresponding soliton

$$\left.\frac{E}{M}\right|_{\rm sol} = \left.\frac{E}{M}\right|_{\rm halo}$$

$$\Phi_N = \Phi_{\rm halo} + \Phi_{\rm sol}$$

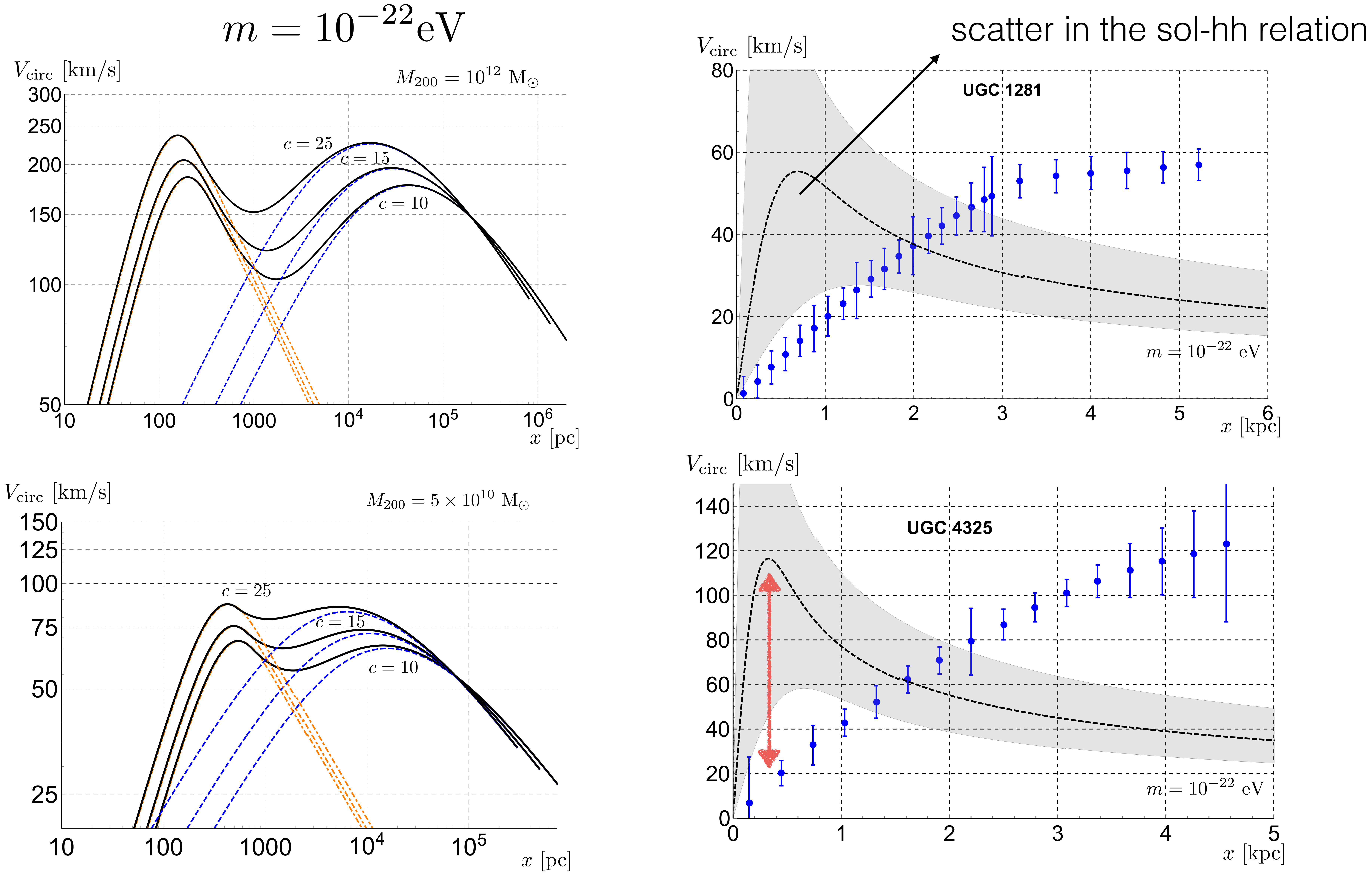
$$V^2_{\rm circ} = r\partial_r\Phi(r)$$

the max velocities are similar!

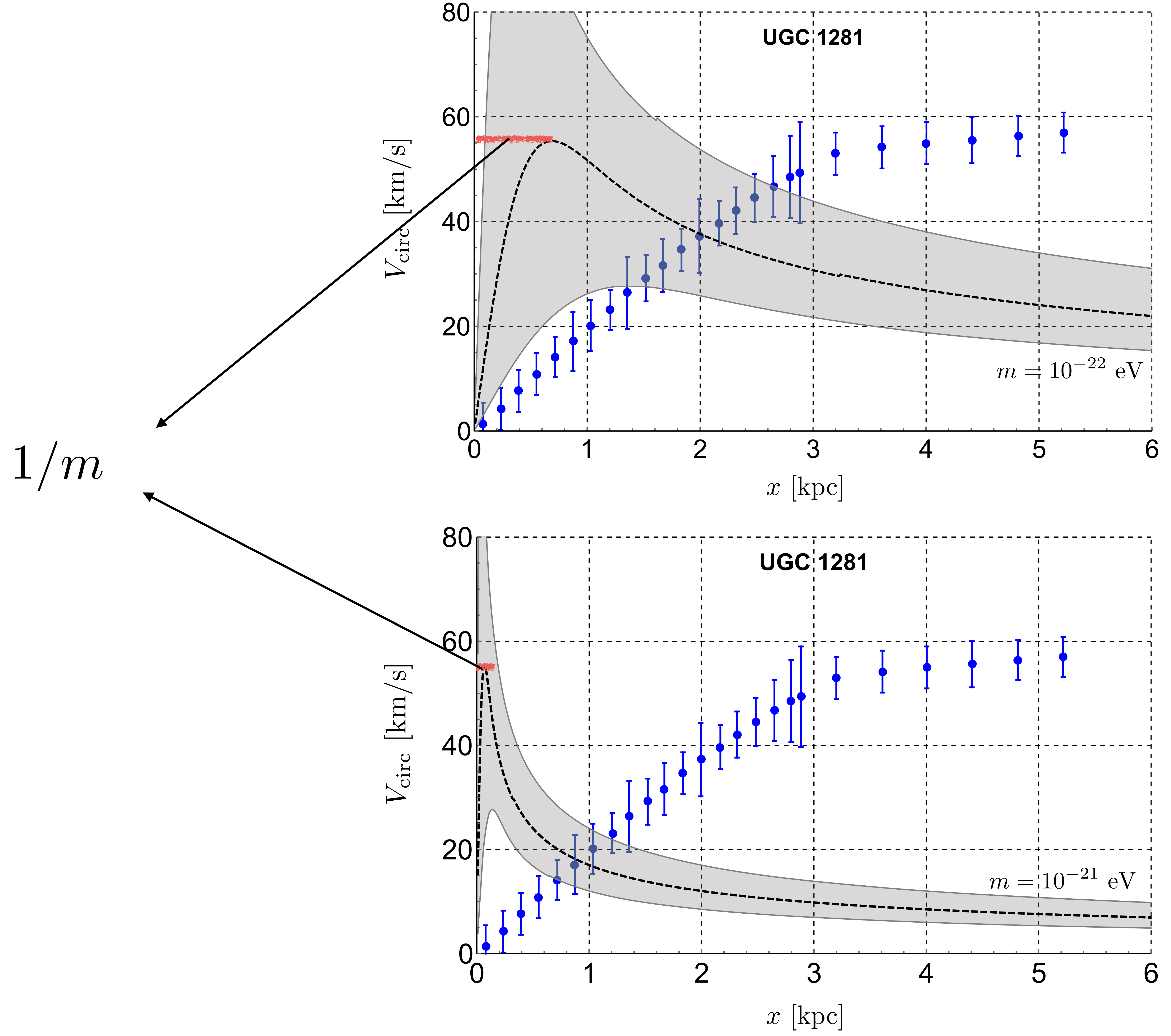


Soliton-host halo relation vs data

Lelli et al. SPARC 1606.0925



As a function of mass



Robustness

i) Baryons:

for these galaxies the photometric data implies a small baryonic effect.

simulations with stars show a more compact and massive soliton!

Chan et al. 1712.01947

can be confirmed 'analitically'

$$i\frac{\partial\psi}{\partial t} = -\frac{1}{2m}\nabla^2\psi + m\Phi_{self}\psi \rightarrow -\frac{1}{2m}\nabla^2\psi + m(\Phi_{self} + \Phi_{baryon})\psi$$

also Bar et al. 1903.03402
1905.11745

ii) Are we considering outliers?

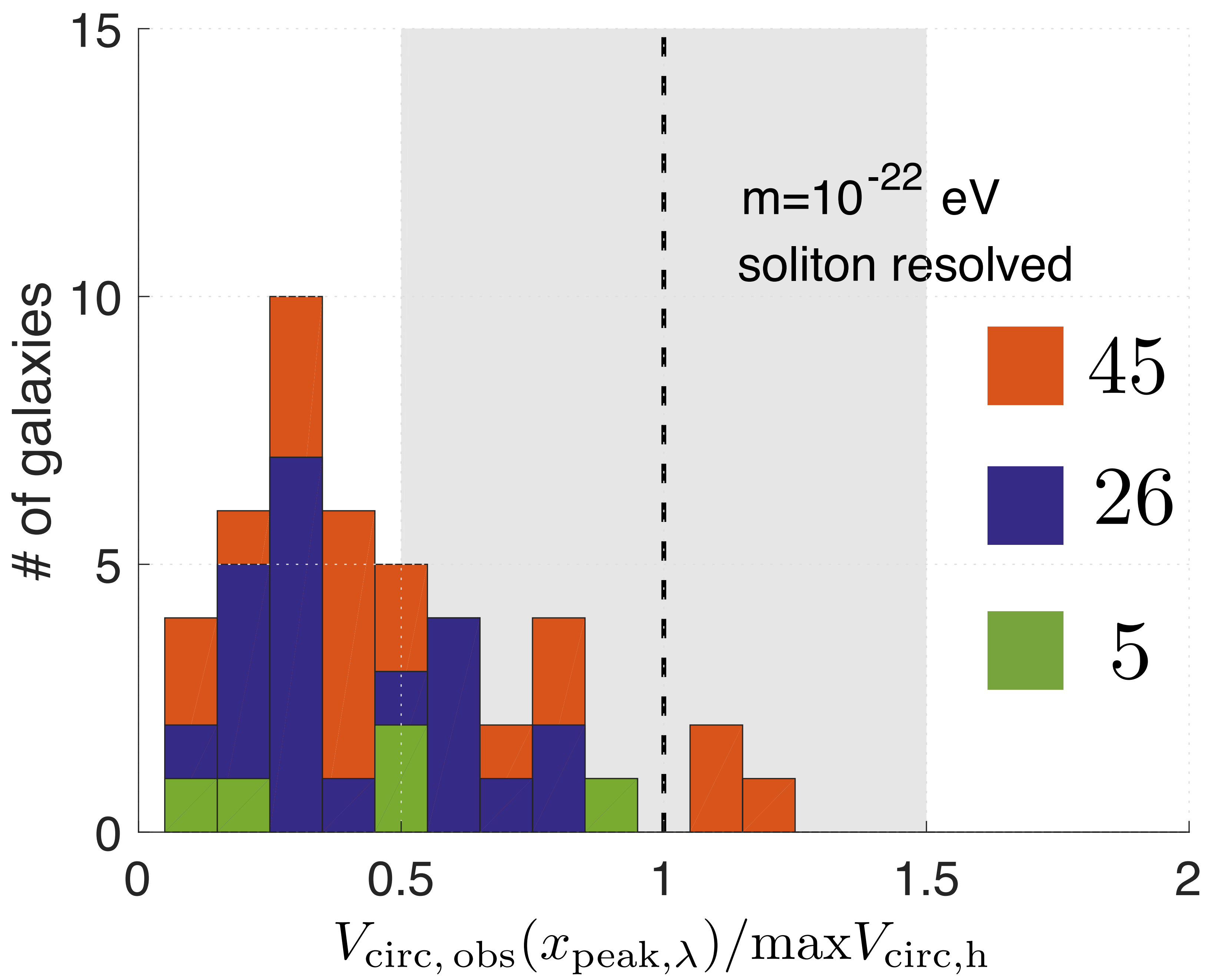
Comparison with SPARC data

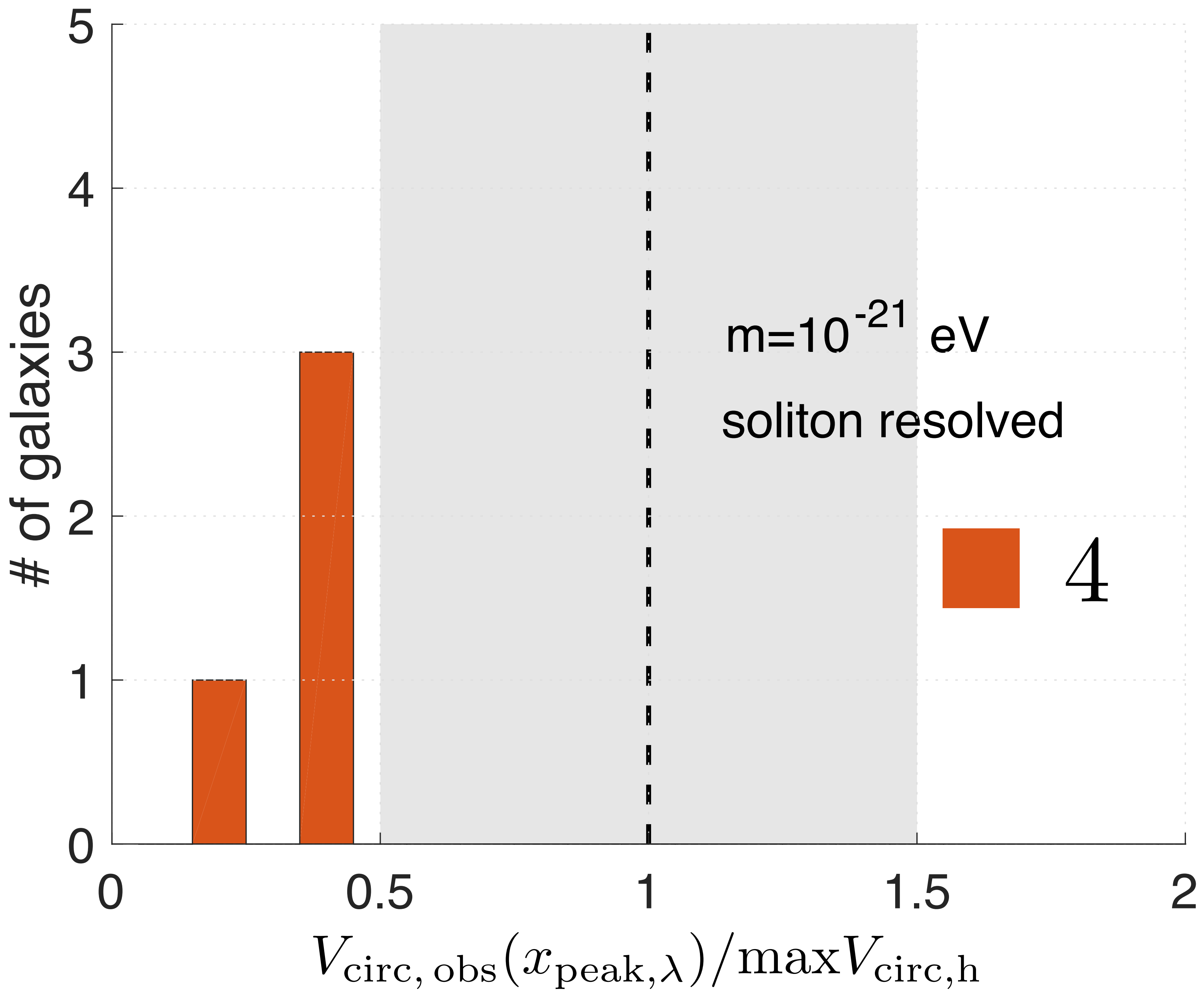
175 high resolution rotation curves

cuts:

- $5 \times 10^8 \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-\frac{3}{2}} M_\odot < M_{\rm halo} < 5 \times 10^{11} M_\odot$

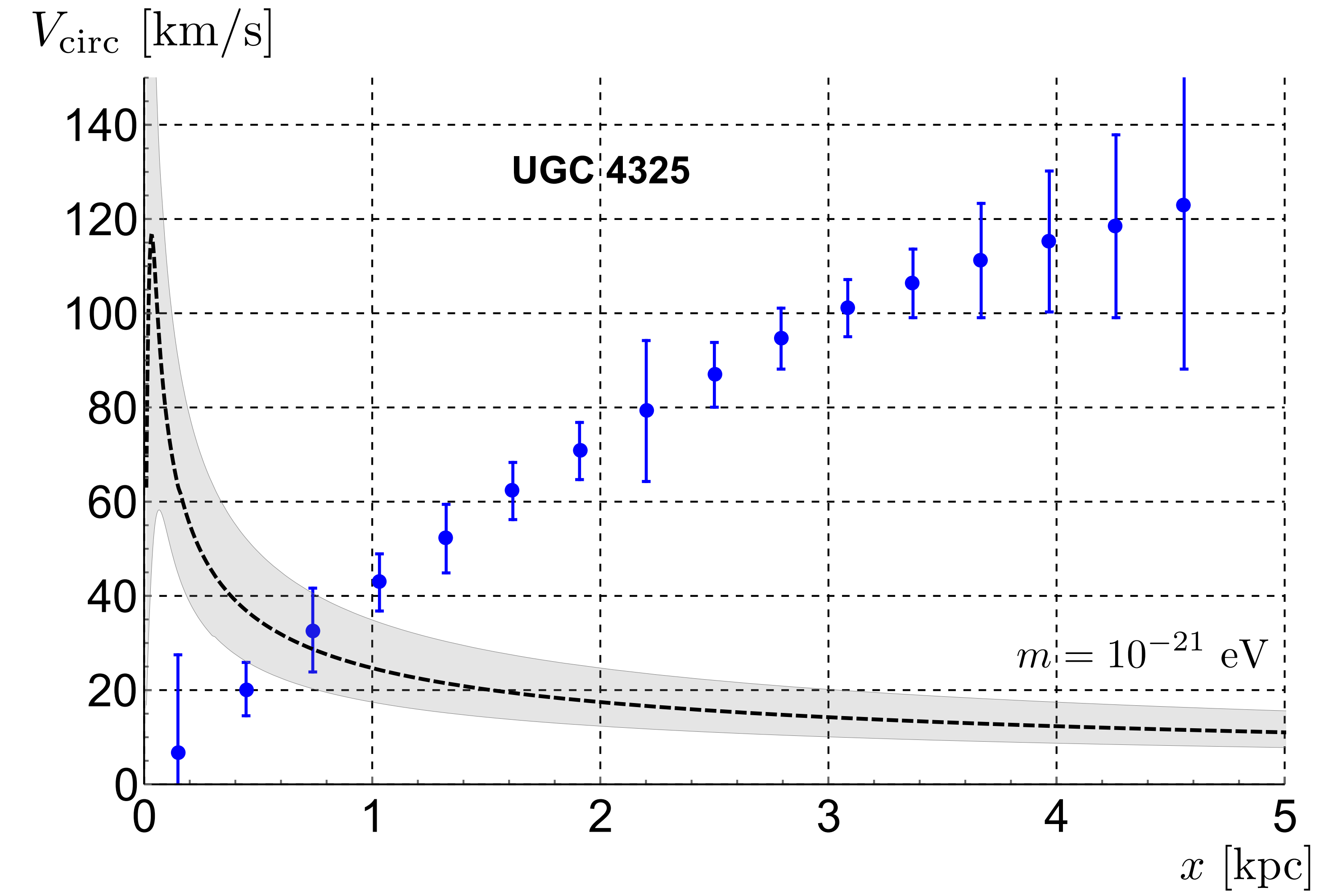
- $f_{\rm bar2DM} = \frac{V^{(\rm bar)}_{\rm circ,h}}{V^{(\rm DM)}_{\rm circ,h}}$ < 1 < 0.55 < 0.33



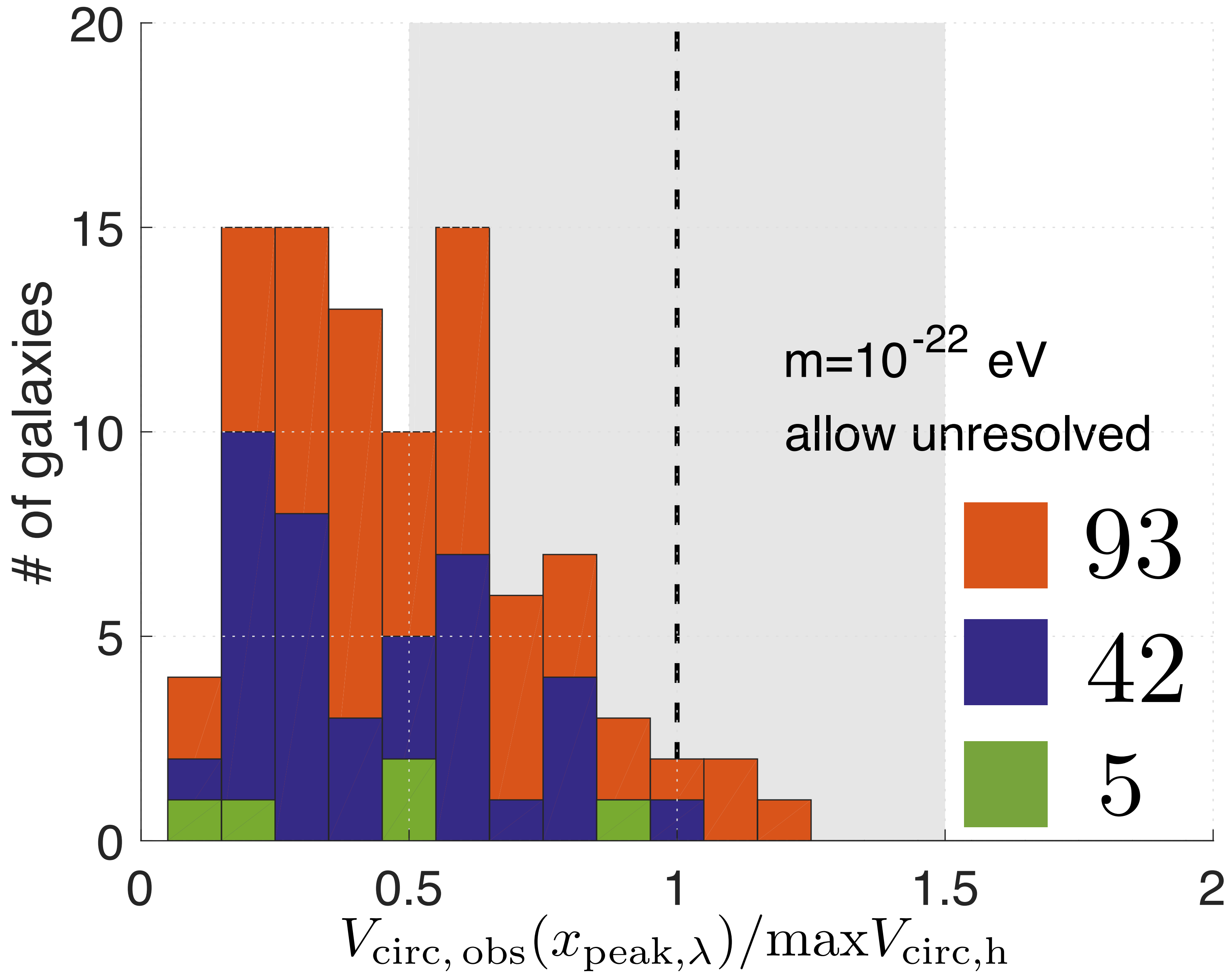


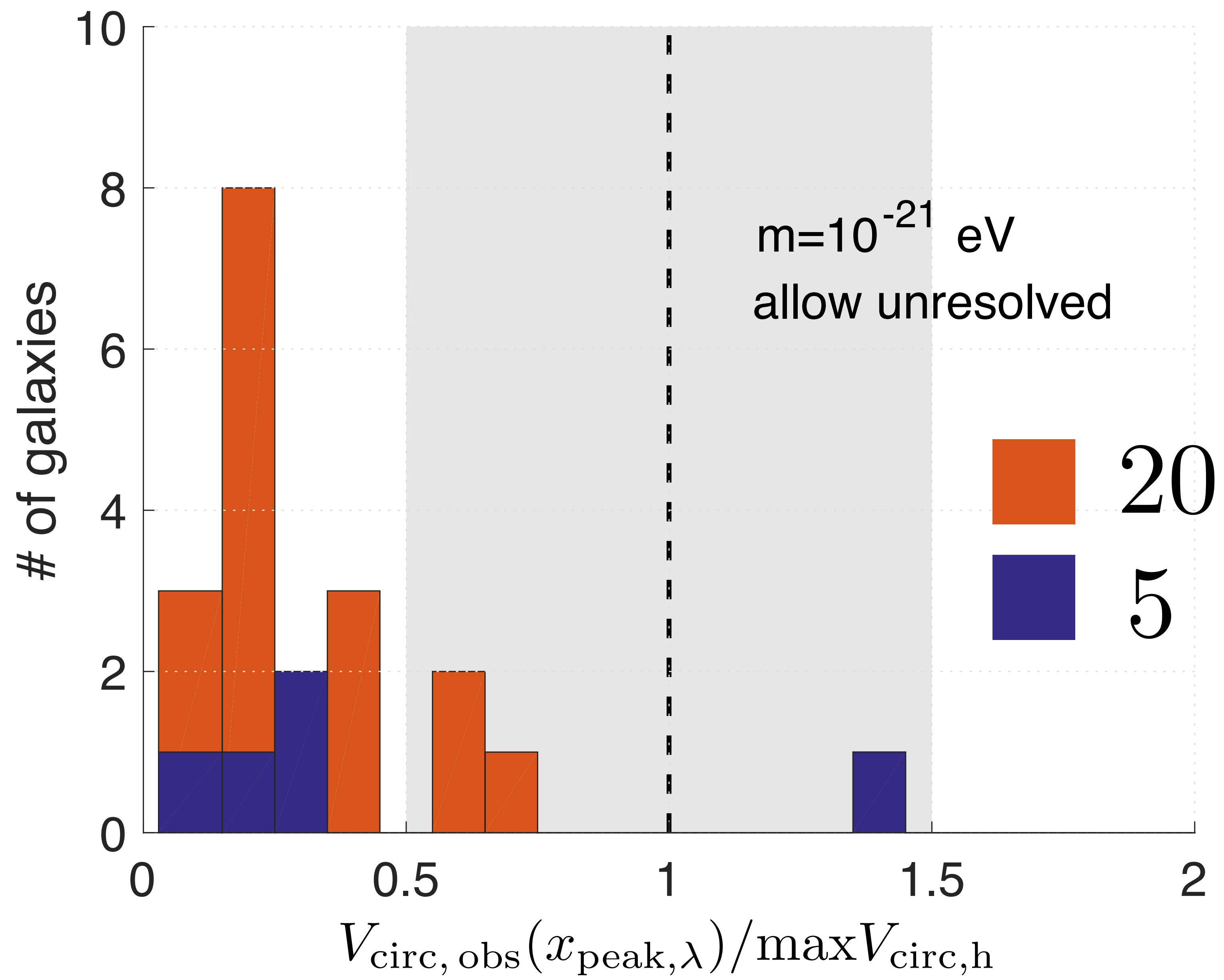
Comparison with SPARC data II

if soliton peak inside the innermost point



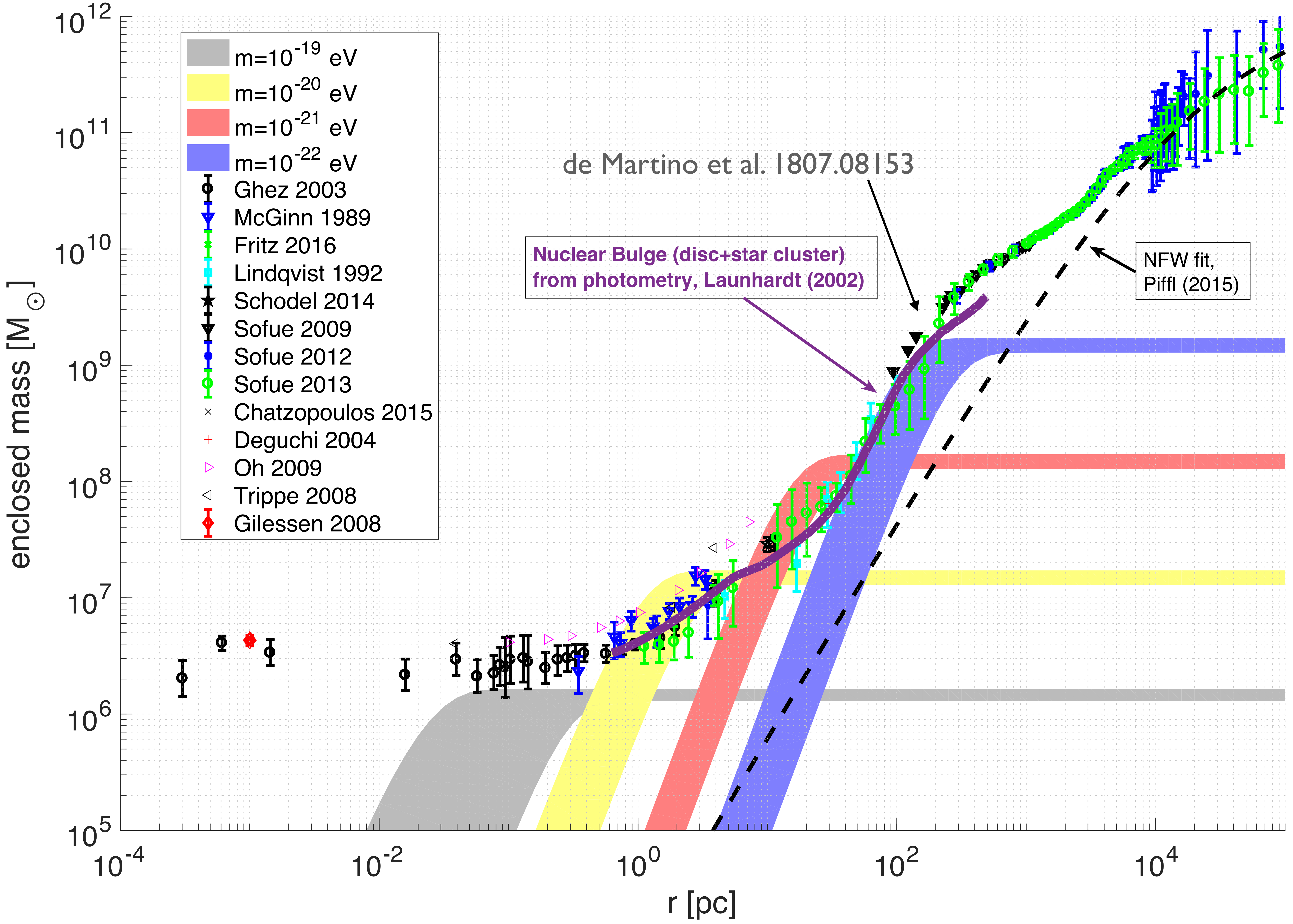
$$\frac{V_{\rm circ,\,obs}(x_{{\rm peak},\lambda})}{\max V^{\rm (DM)}_{\rm circ,h}} \to \frac{V_{\rm circ,\,obs}(x_{\rm min,data})}{\max V^{\rm (DM)}_{\rm circ,h}} \times \sqrt{\frac{x_{\rm min,data}}{x_{{\rm peak},\lambda}}}$$





Smaller masses: center of the Milky Way

the MW has a 'bump' in mass…most likely baryonic



TBD!

Conclusions I

Galactic rotation curves to test *ultra-light* Bosonic DM

- These models incorporate new ingredients
  - Soliton at the center of galaxies fixed by halo properties modifies the velocity curves: tension for masses

$$m \sim 10^{-22} \div 10^{-21}\,\mathrm{eV}$$

  - study of the MW center may constrain larger masses

This talk: two extremes

Galactic rotation curves to test *ultra-light* Bosonic DM

* for *ultra-light* Fermionic DM e.g.

Alvey, Sabti, DB, Escudero et al 2010.03572

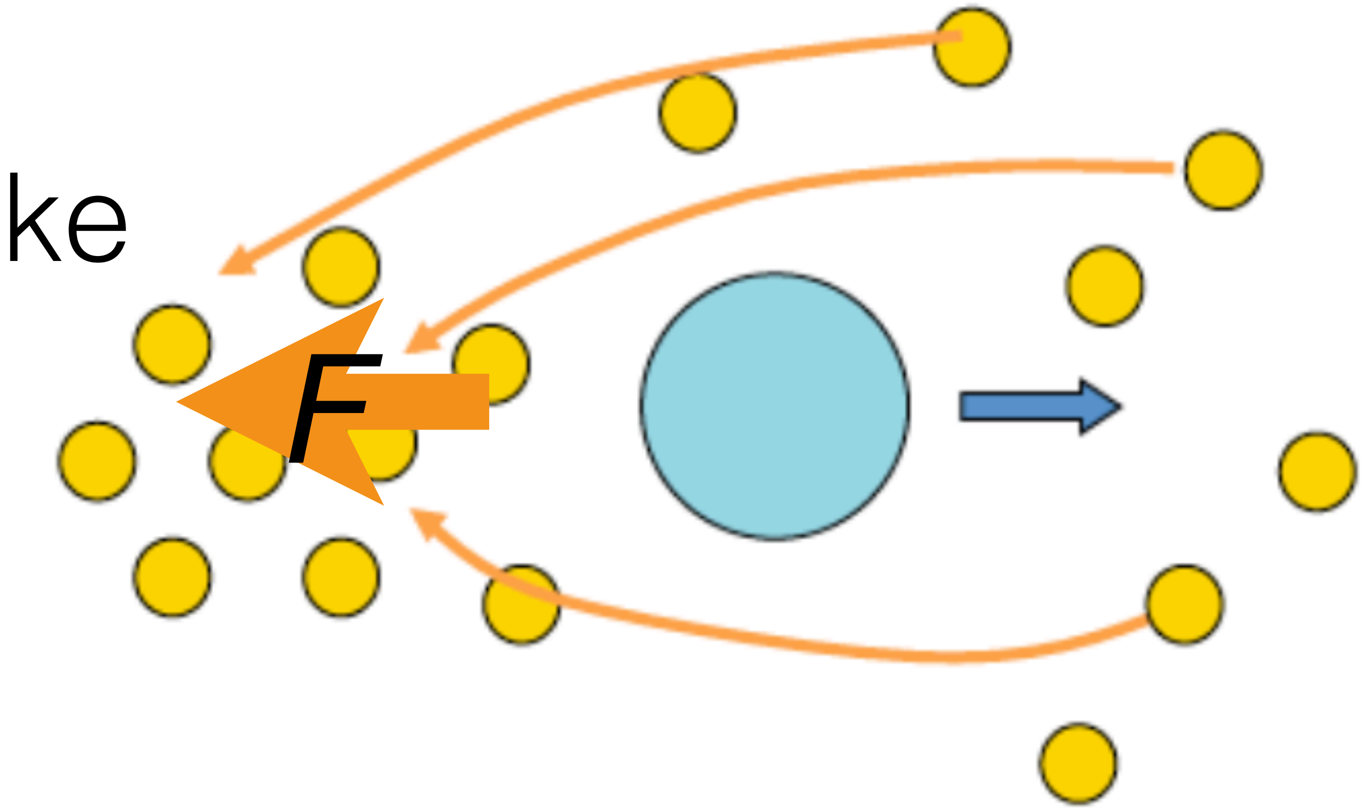
Dynamical friction to test *ultra-light* Fermionic DM

Dynamical friction - general intuition

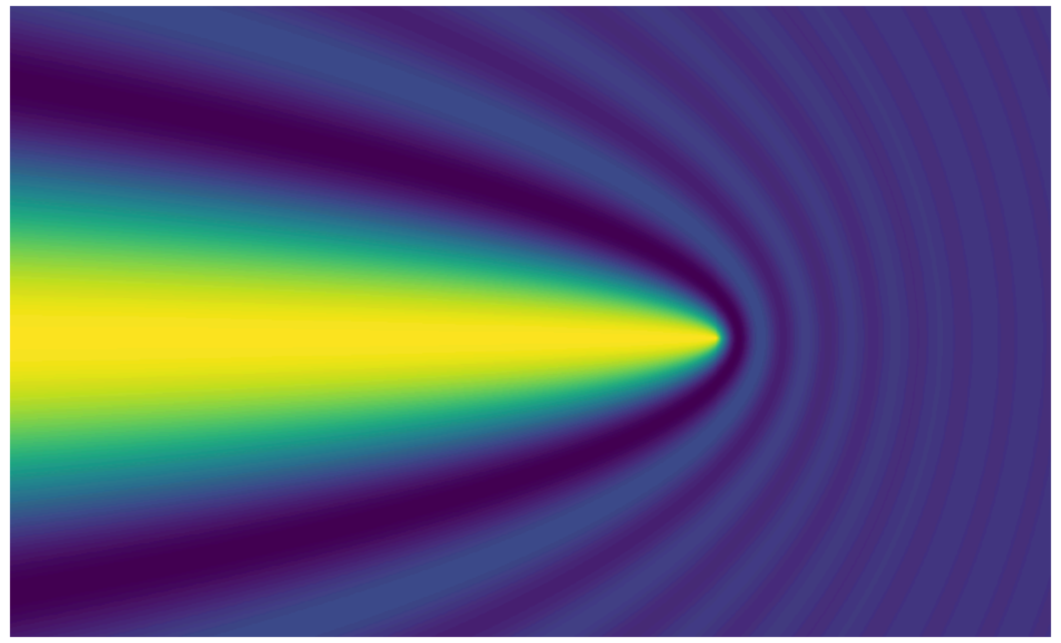
As mass M **moves** in a medium of particles with mass m

weak gravitational scatterings create over-density (wake) and a net force F opposite to velocity's direction: **friction** (~ v)

Particle-like



Wave-like



Lancaster et al 1909.06381

if M orbiting: lost of K makes it fall to the center

Dynamical friction - general intuition

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weak gravitational scatterings create over-density (wake) and a net force *F* opposite to velocity's direction: **friction** (~ v)

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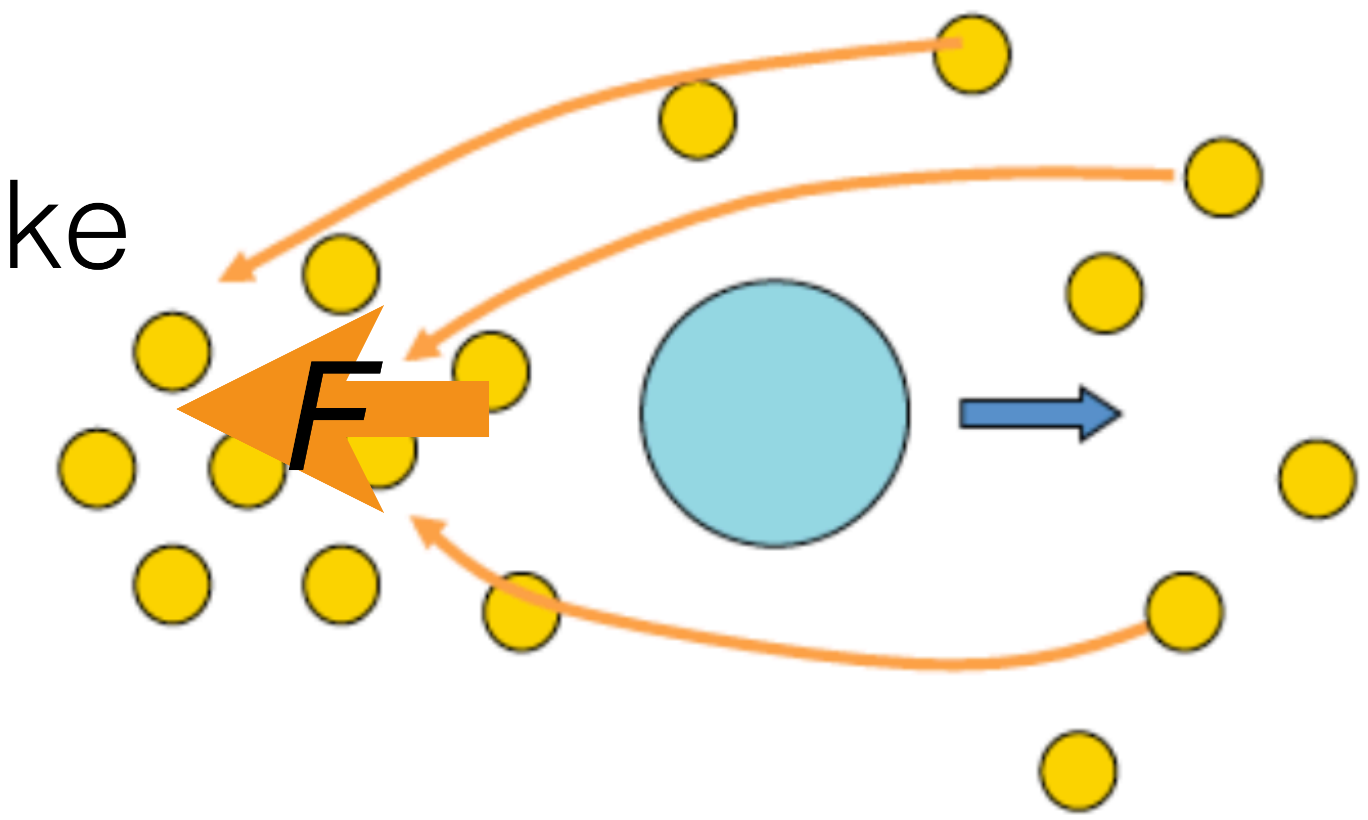

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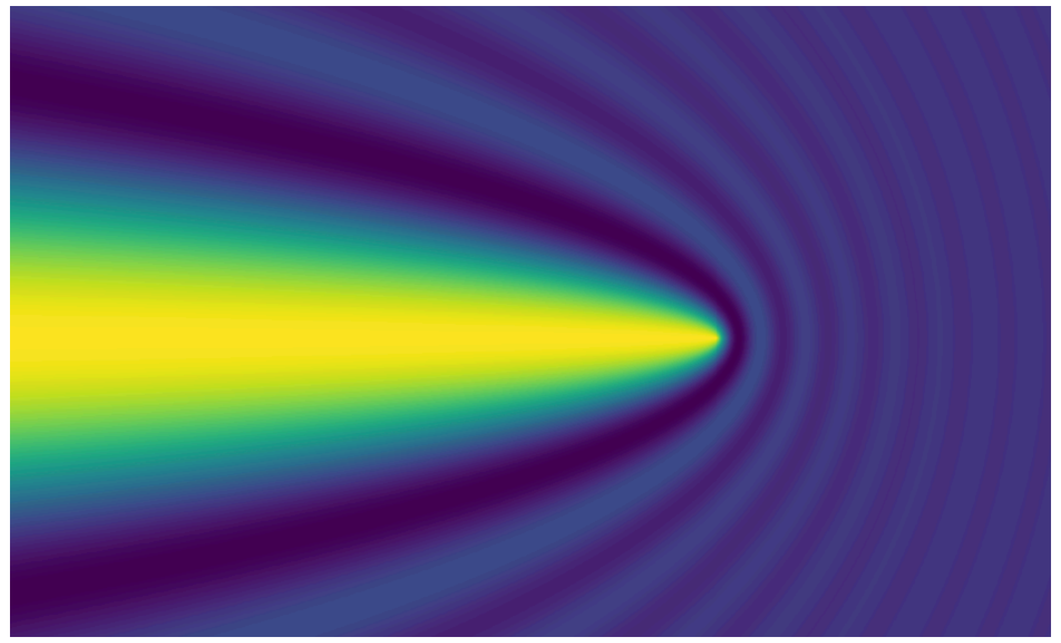
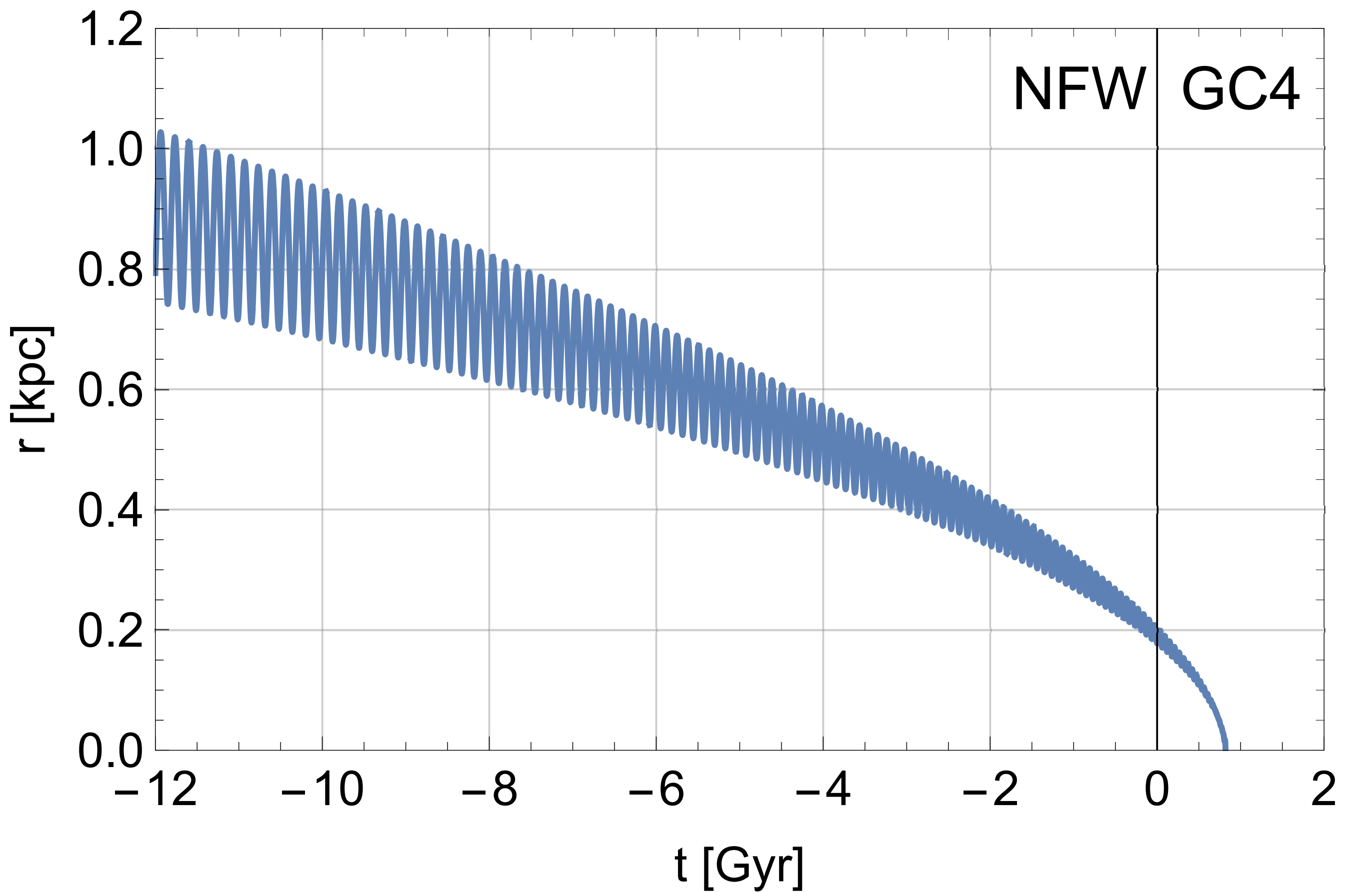


Lancaster et al 1909.06381

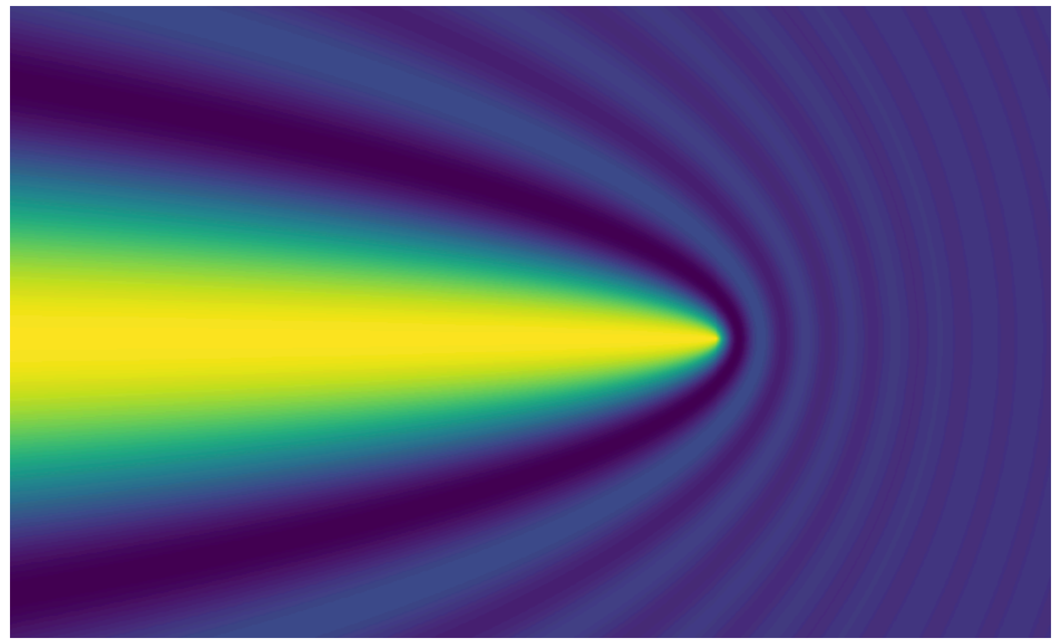


if *M* orbiting: lost of *K* makes it fall to the center

Dynamical friction - ULDM

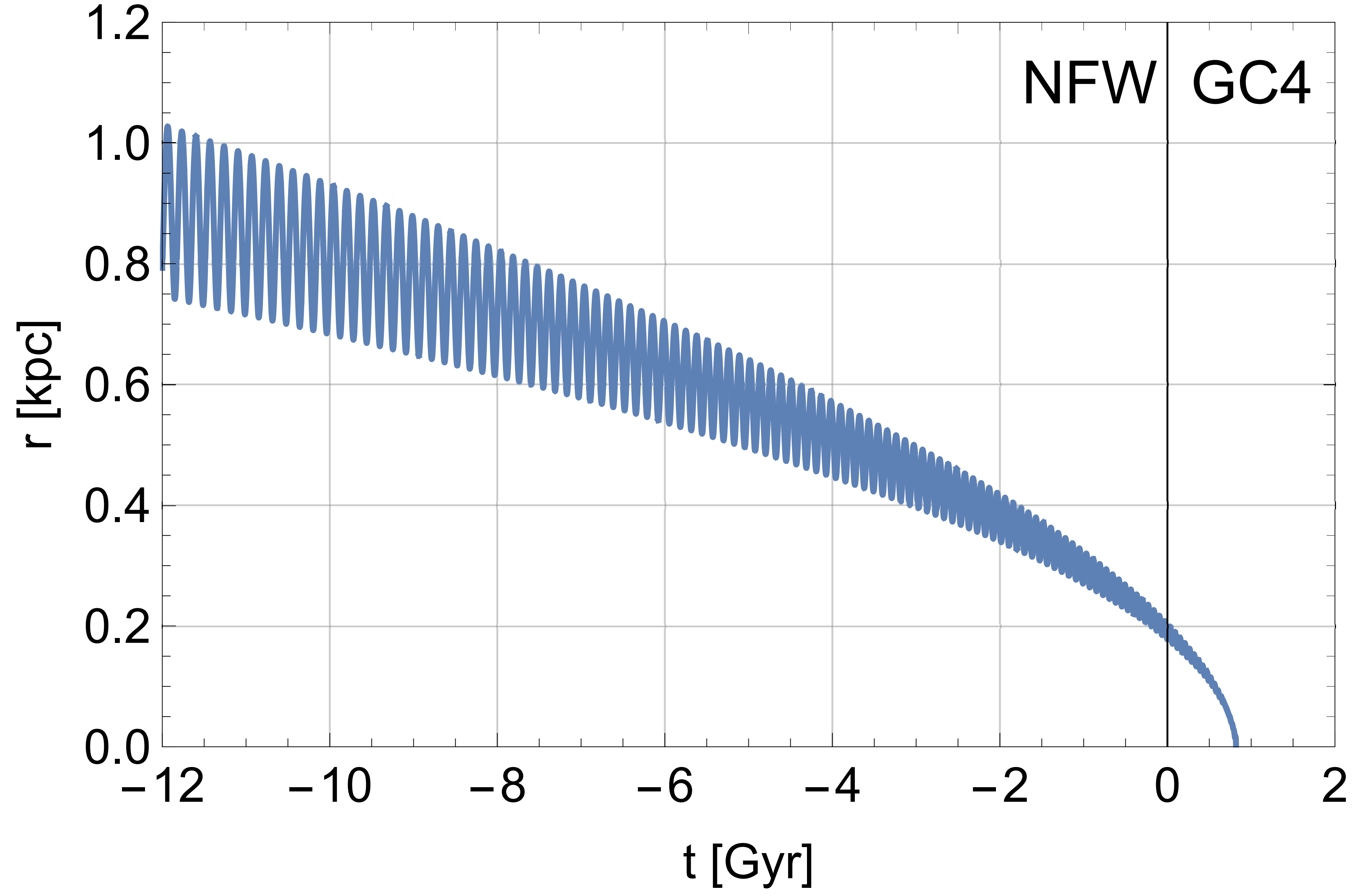
Wave-like

Lancaster et al 1909.06381

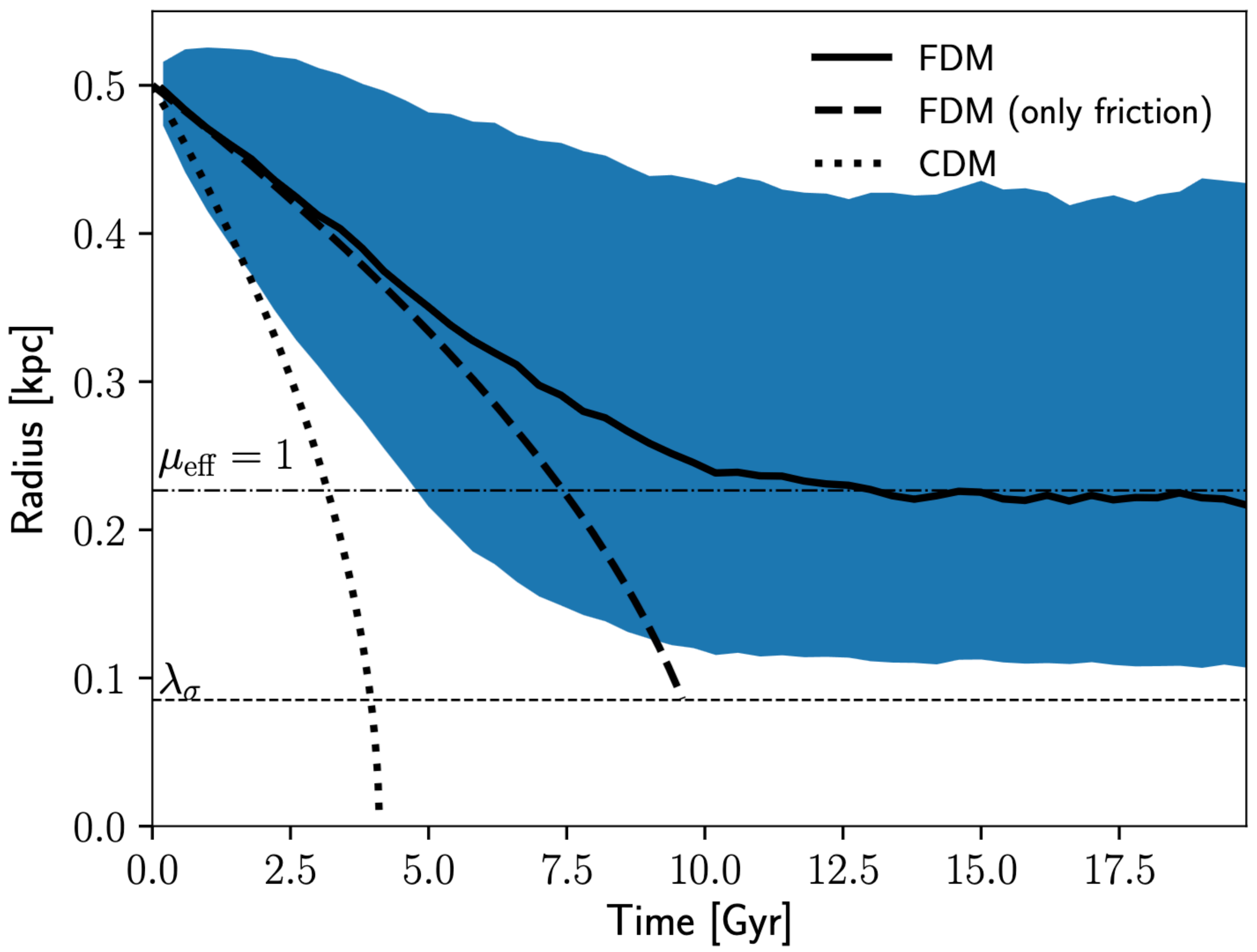


Several studies: friction reduced (wake bounces back at λ_{db}), but careful with other effects such as heating.

Lancaster et al 1909.06381
Hui et al 1610.08297
Bar-Or et al 1809.07673
Vicente et al 2201.08854
Wang et al 2110.03428…



Bar-Or et al 1809.07673



May find applications in the Fornax "problem"

- Very luminous nearby (~ 147 kpc away) dwarf satellite
- ~ $4 \times 10^7\ M_\odot$ stellar mass on ~ 1 kpc scale
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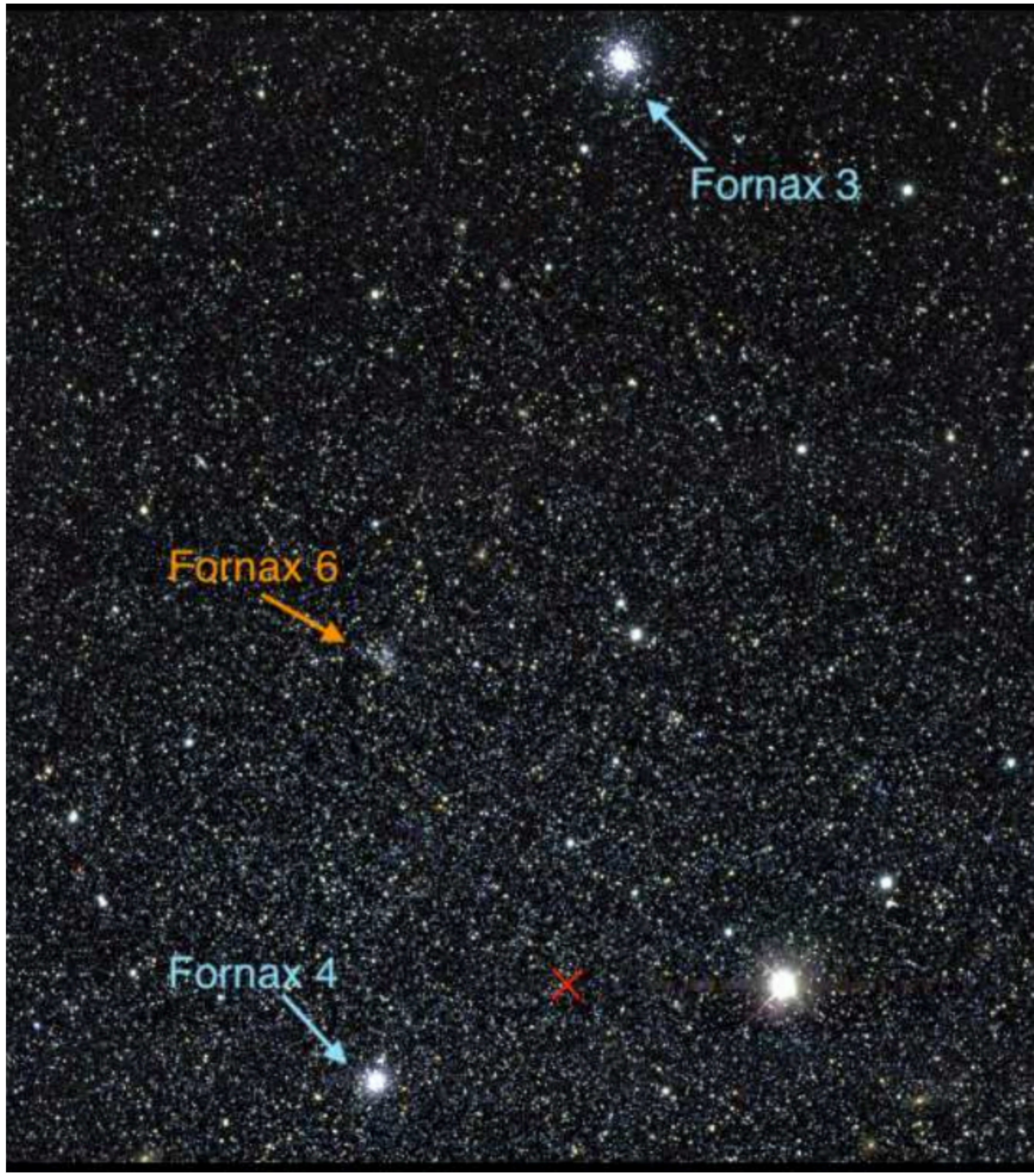

Bar et al 2102.11522

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SIDM, Fermi gas (**DDM**) or 'Bose' gas (**ULDM**)

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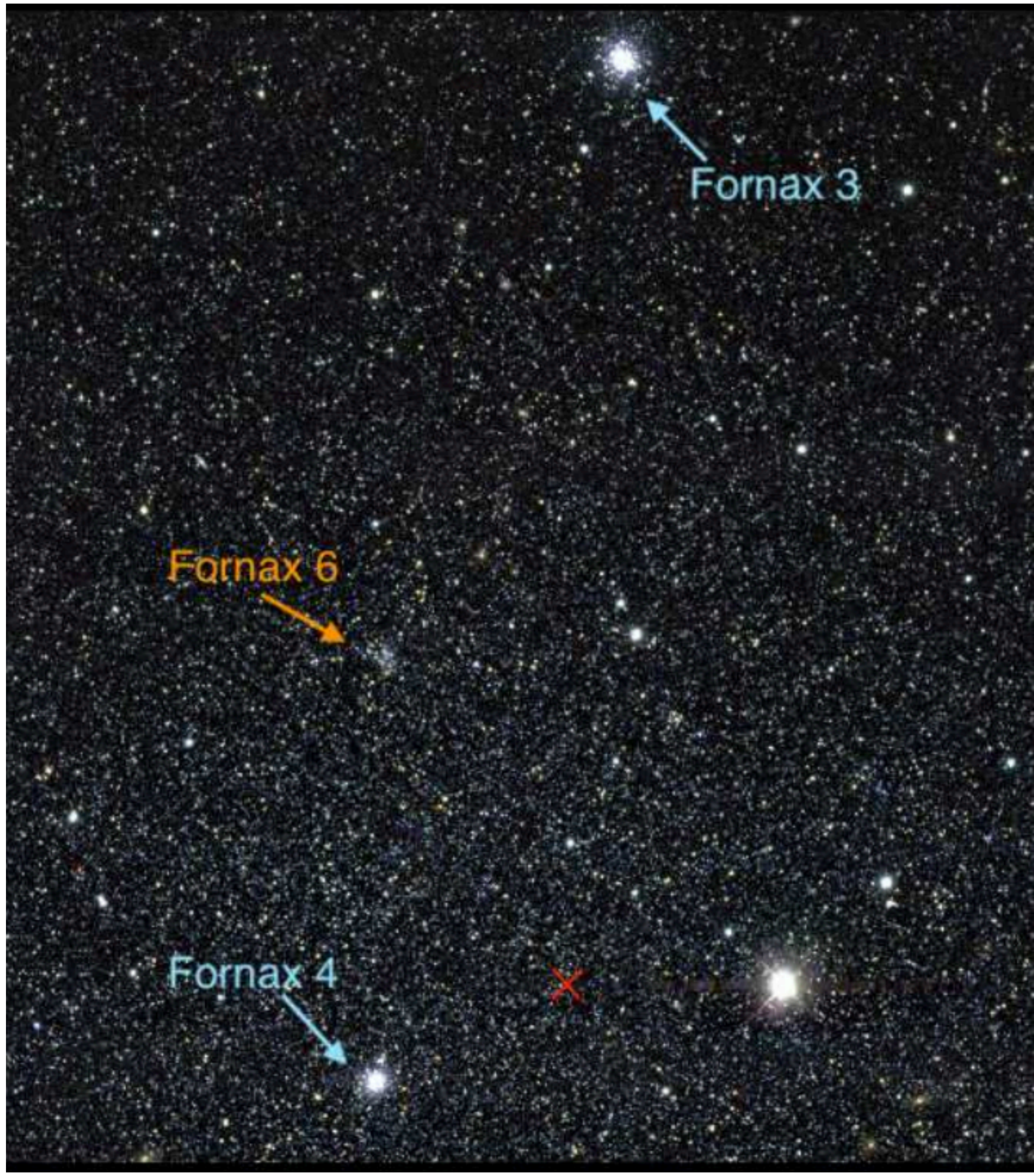

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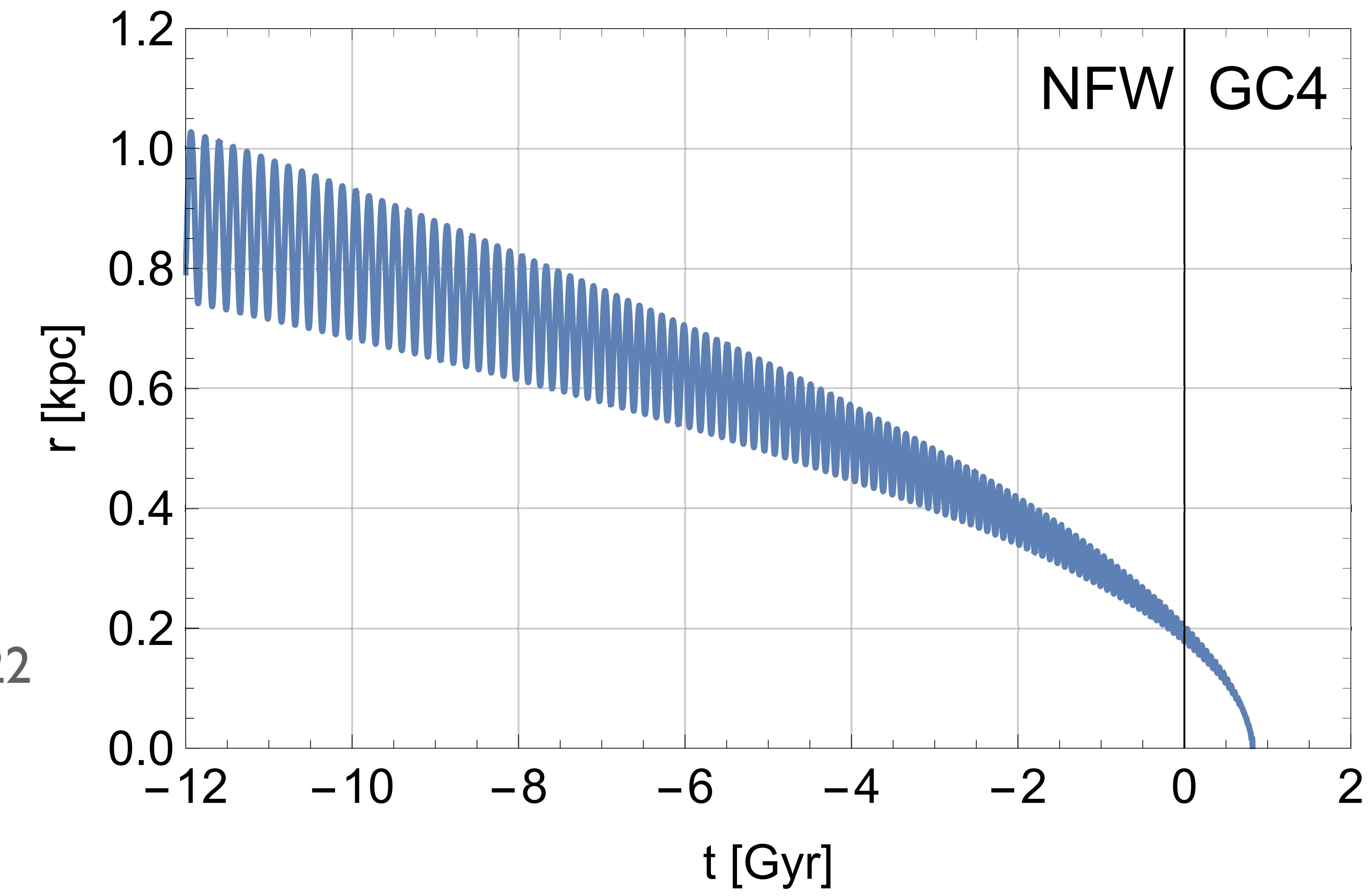
	projected radius	cluster mass	CDM	
n	$r_\perp$ (kpc)	$m_{\rm cl}$ ($M_\odot$)	C	τ (Gyr)
1	1.6	3.7×10^4	4.29	112
2	1.05	1.82×10^5	3.32	9.7
3	0.43	3.63×10^5	2.45	0.62
4	0.24	1.32×10^5	2.50	0.37
5	1.43	1.78×10^5	3.46	21.3



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Hui, Tremaine, Ostriker & Witten 2016

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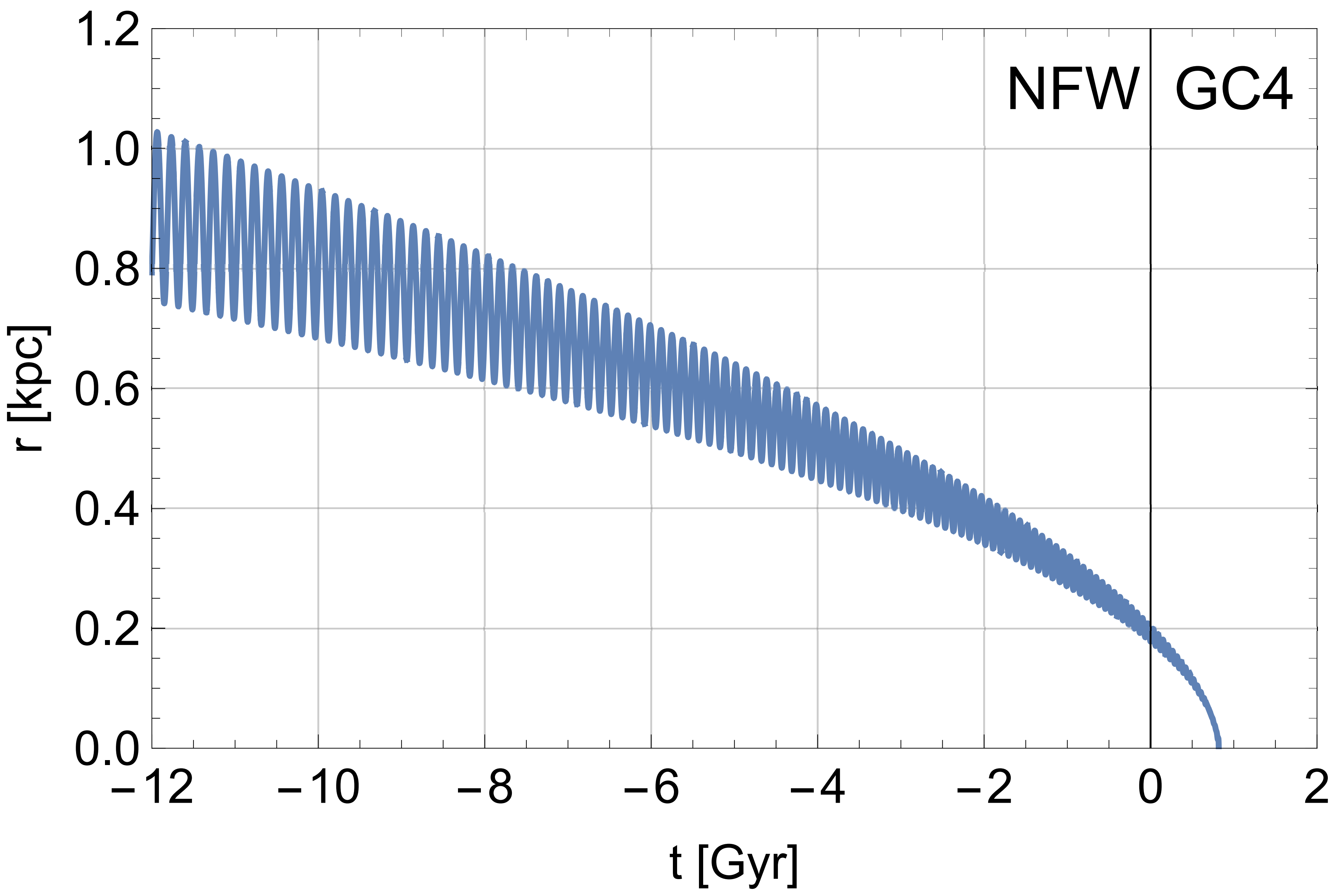


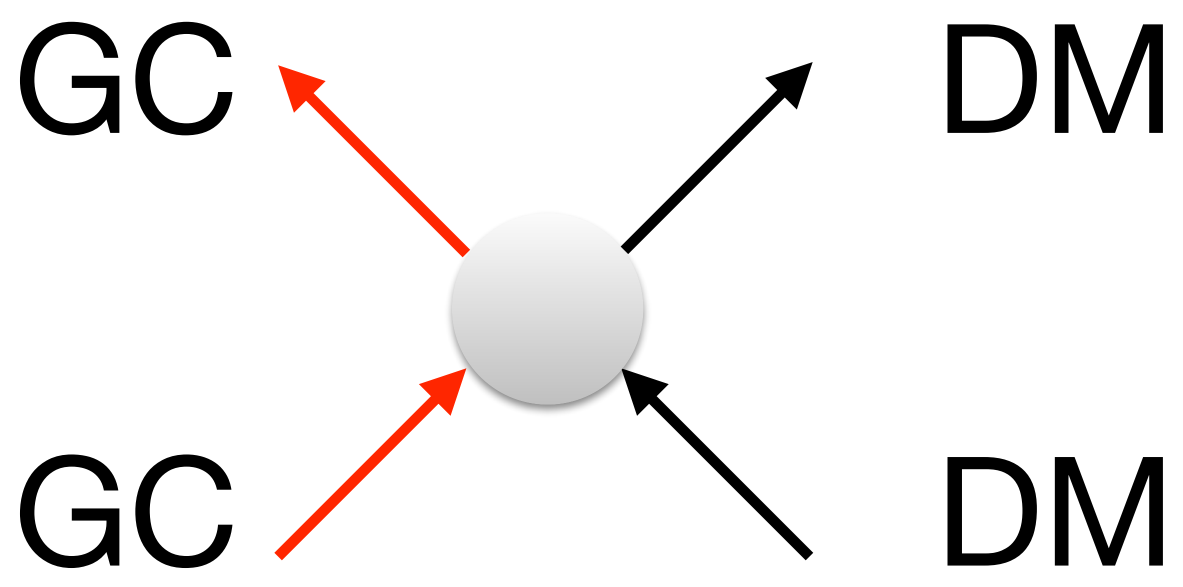
Bar et al 2102.11522

Dynamical friction derived from Fokker-Planck

Fokker-Planck: dynamical friction as diffusion in momentum space.

From Boltzmann equation with collision term between perturbers (GCs) and DM

$$\frac{df_1}{dt} = C[f_1],$$



$$|\overline{\mathcal{M}}|$$

$$C[f_1] = \frac{(2\pi)^4}{2E_p}\int d\Pi_{k,p',k'}\,\delta^{(4)}(p+k-p'-k')\,|\overline{\mathcal{M}}|^2\Big[f_1(p')f_2(k')(1\pm f_1(p))(1\pm f_2(k)) - f_1(p)f_2(k)(1\pm f_1(p'))(1\pm f_2(k'))\Big]$$

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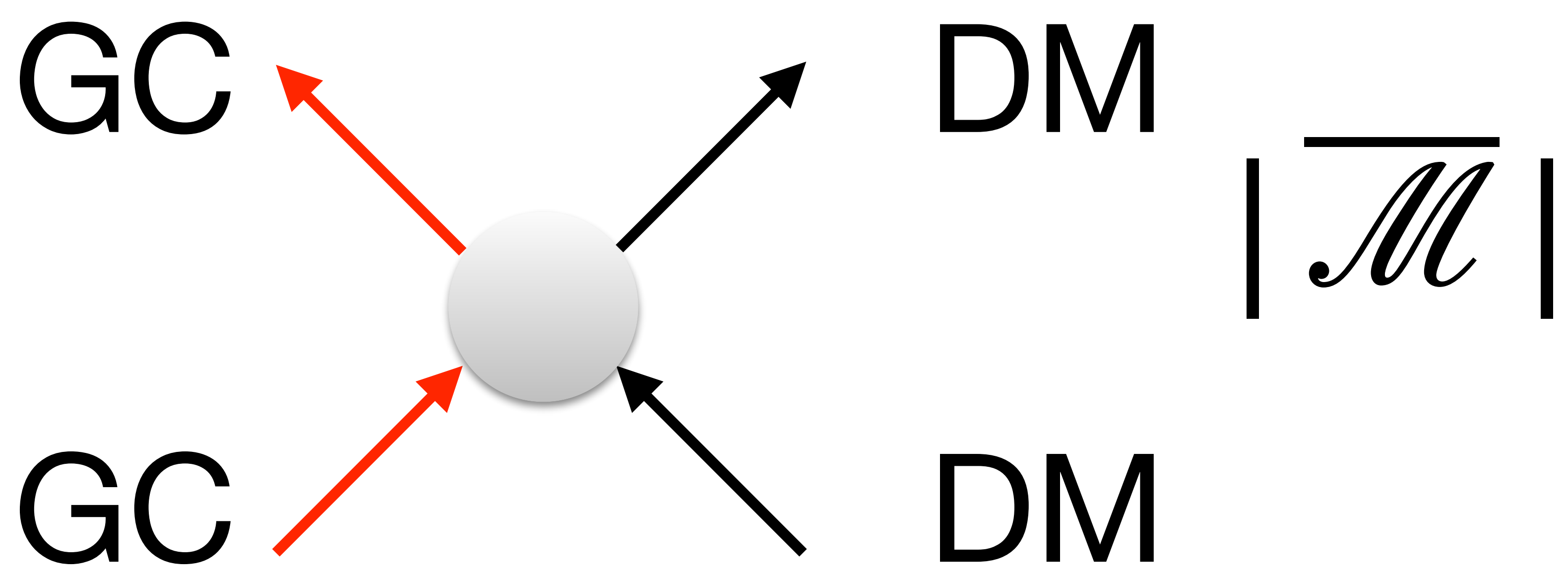

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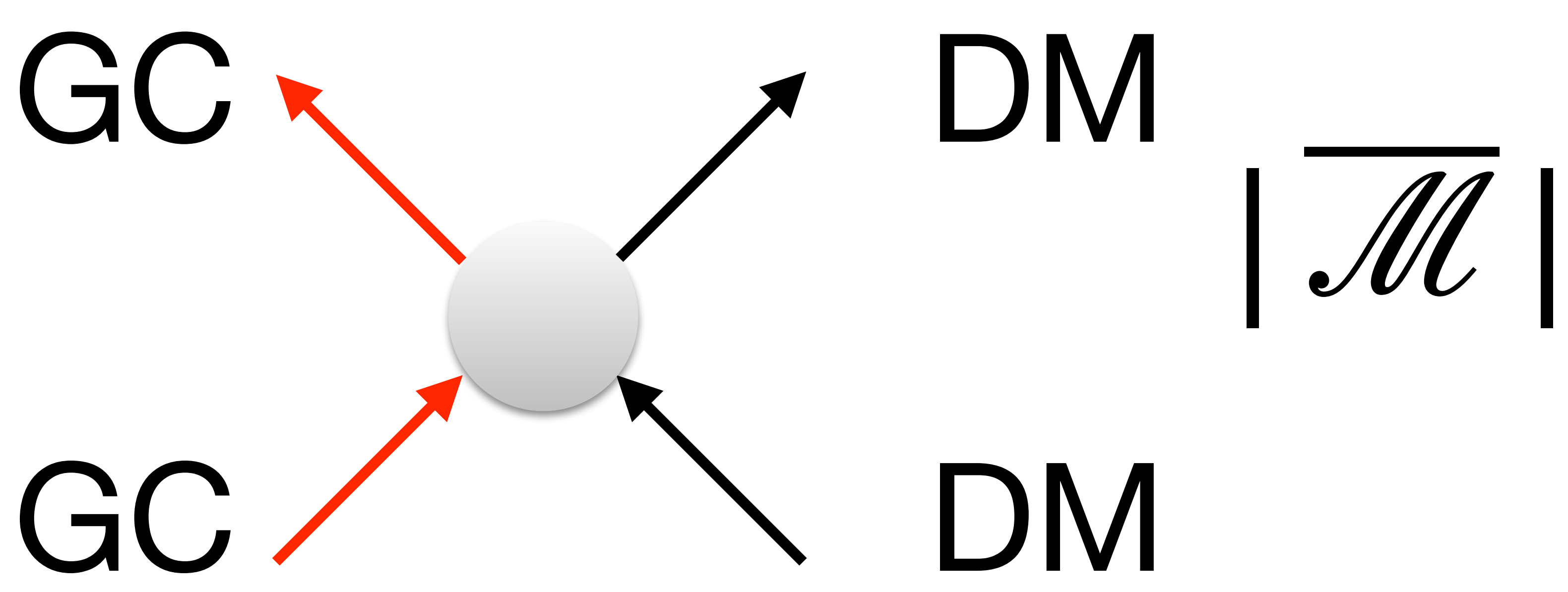

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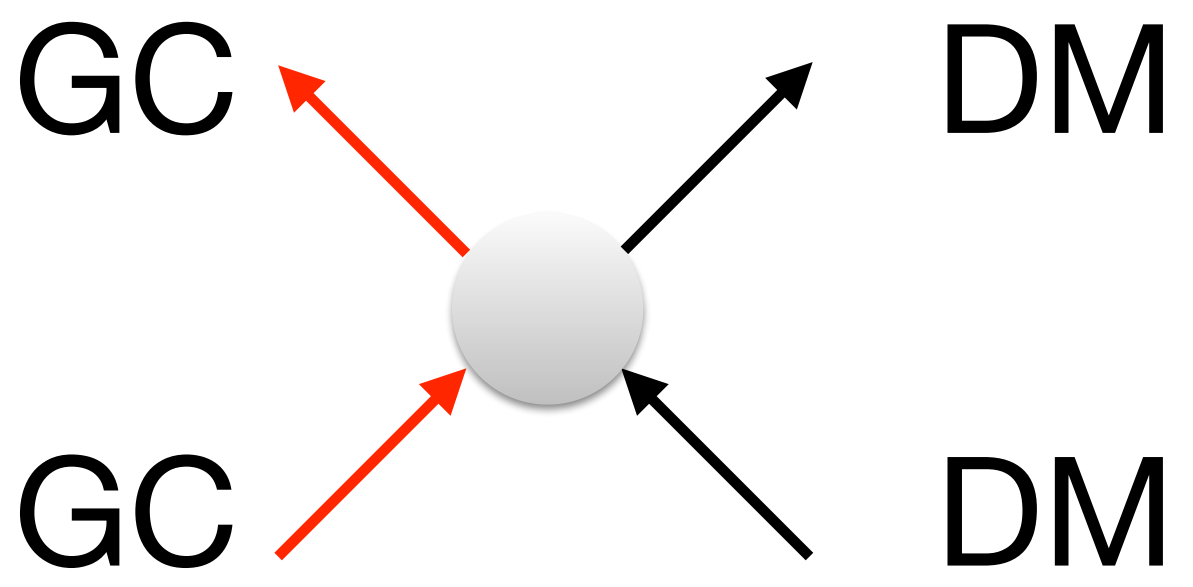

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$m_{DM} \lesssim 10^{-22}\,\mathrm{eV}$ may work , but in tension with other constraints (other coherent effects appear in ULDM)

Orbital deceleration (Chandrasekhar's formula)

$$\frac{d\mathbf{V}}{dt} = \frac{D}{M}\hat{V} = -\frac{4\pi G^2 \rho M \ln \Lambda}{V^3} \underbrace{C(V/\sigma)}_{O(1)} \mathbf{V}$$

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For a given halo, it depends on radius and velocity of object.

Assuming a circular orbit: Effective function of radius.

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- G^2 effect: G^2
- Background fluid density (core/cusp): ρ
- Perturber mass: M
- Coulomb logarithm: $\ln\Lambda$
- Microphysics (both C and sigma): $C(V/\sigma)$

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Time-scale

$$\tau \equiv \frac{|\mathbf{V}|}{|d\mathbf{V}/dt|} \sim 1.8 \left(\frac{V}{12\ \mathrm{km/s}}\right)^3 \frac{2\times 10^7 \frac{M_\odot}{\mathrm{kpc}^3}}{\rho}\ \mathrm{Gyr}$$

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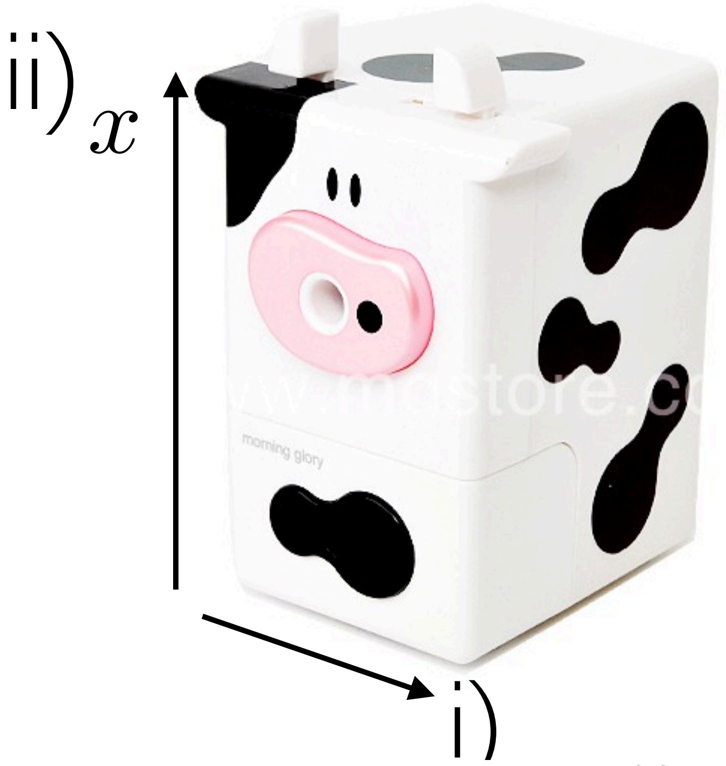
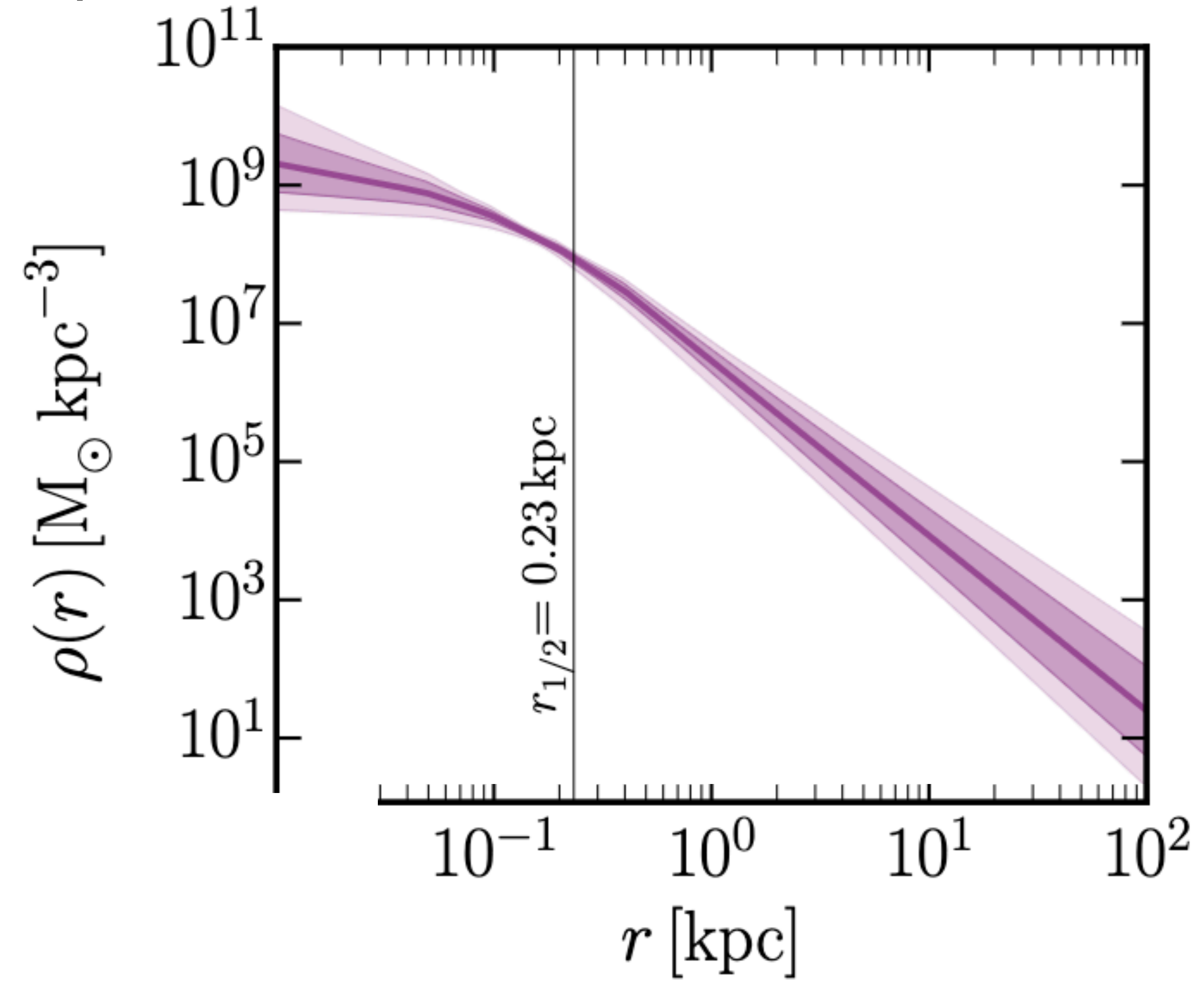
For classical Maxwellian $C_{\mathrm{Max}} \to \ln\Lambda \begin{cases} 1 & V \gg \sigma \\ \frac{\sqrt{2}}{3\sqrt{\pi}}\frac{V^3}{\sigma^3} & V \ll \sigma \end{cases},$

How to change ρ, σ or microphysics?

"extreme masses"

e.g. Milky way DM halo





i) escape velocity $\sim 2\times 10^{-3}c$ ii) size $100\ \mathrm{kpc}$

$$\Delta x \Delta p \gtrsim \hbar \rightarrow N_s \sim 10^{75}\left(\frac{m}{\mathrm{eV}}\right)^3$$

particles per state $N_p = \dfrac{M_{MW}}{N_s m} \sim 10^3 \left(\dfrac{\mathrm{eV}}{m}\right)^4$

Fermionic DM necessarily $N_p \lesssim 1$

When done for dSph $m \gtrsim \mathrm{keV}$

Alvey, Sabti, DB, Escudero et al 2010.03572

Close to the limit: degenerate fermions $P \sim \rho^{5/3} m_f^{-8/3}$

core+Fermi blocking! (like a huge DM white dwarf)

Models of dark matter with different microphysics predict different densities and dispersions

- Vanilla CDM - NFW profile — *Cusp*
- CDM - isothermal (ISO) profile
- DDM - degenerate fermionic dark matter
- SIDM - self-interacting dark matter: thermalised core

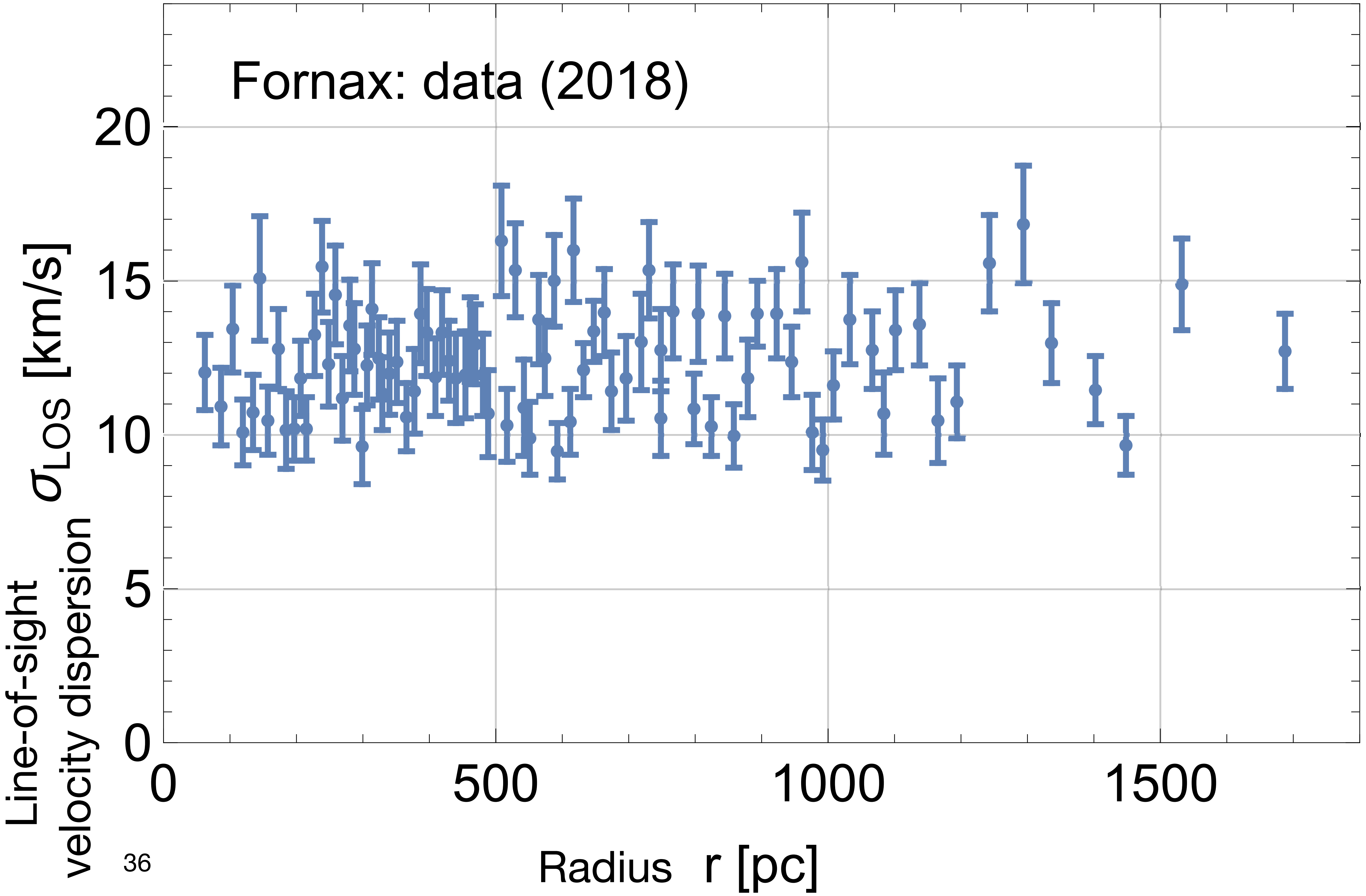
} *Large core (~1 kpc)*

- CDM with baryonic feedback (coreNFW) — *Mid-way core*

- DDM $r_c \sim 681 \left(\frac{\rho_0}{10^7\ \mathrm{M}_\odot/\mathrm{kpc}^3} \right)^{-\frac{1}{6}} \left(\frac{g\, m^4}{2 \times (120\ \mathrm{eV})^4} \right)^{-\frac{1}{3}} \mathrm{pc}$ — Ly-a?
- SIDM $r_c \sim \frac{m}{\rho\sigma} = 48 \frac{10^8 M_\odot/\mathrm{kpc}^3}{\rho} \frac{1\ \mathrm{cm}^2/\mathrm{gr}}{\sigma/m} \mathrm{kpc}$

All these models fit the kinematic data

Kinematic data: line-of-sight velocities of ~2500 stars. No proper motion. Many models fit OK; “velocity anisotropy degeneracy”.



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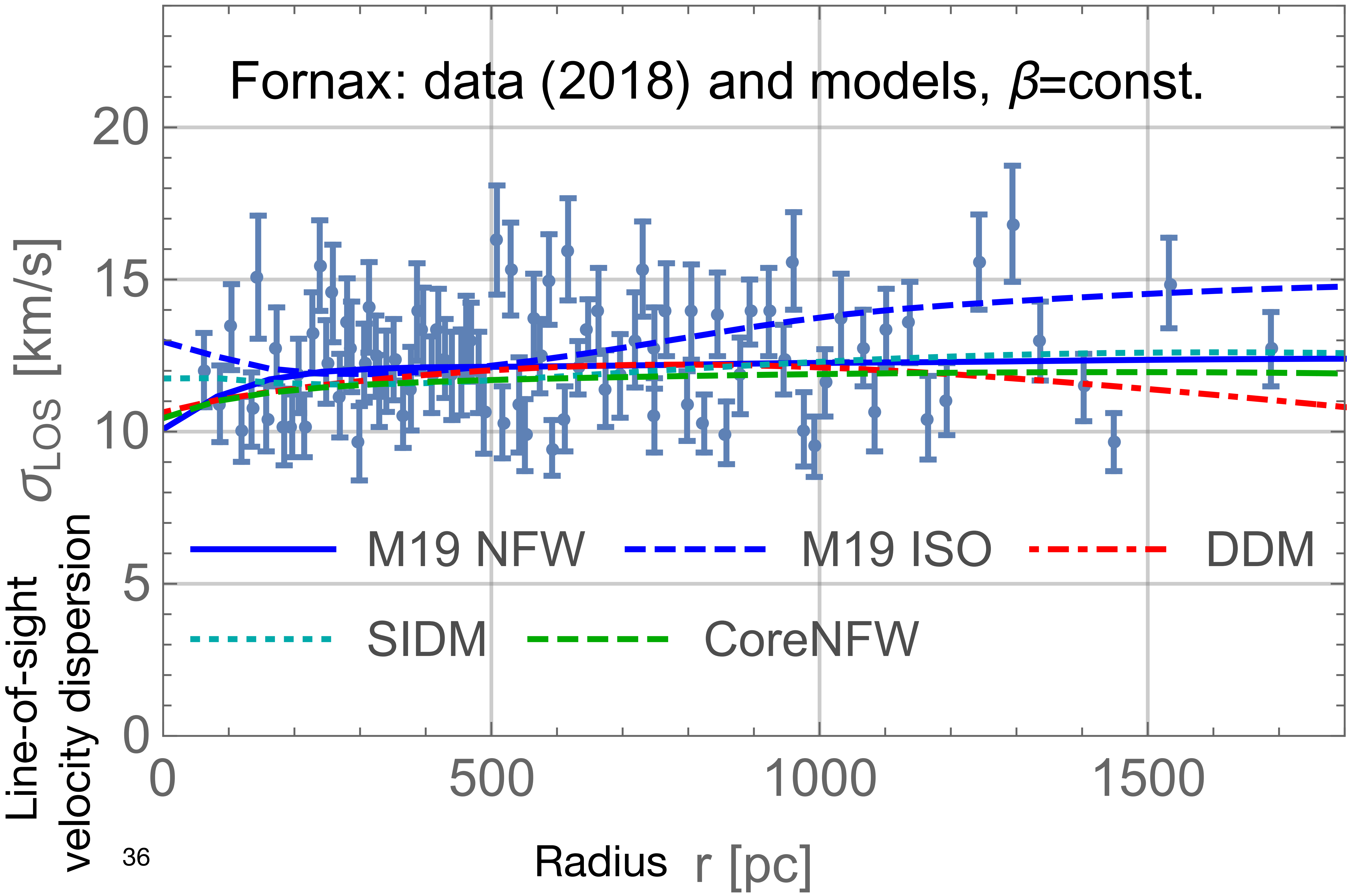

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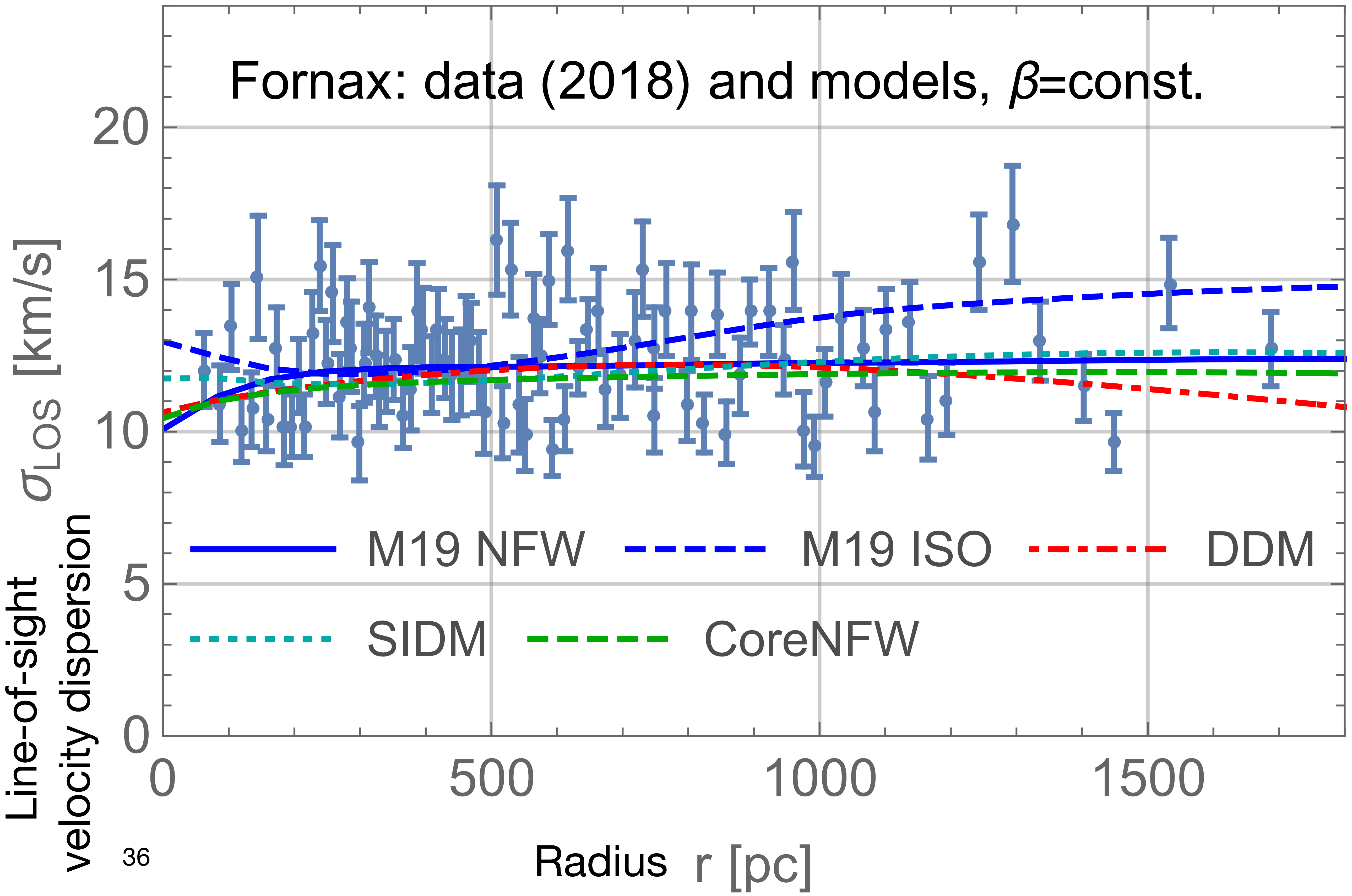
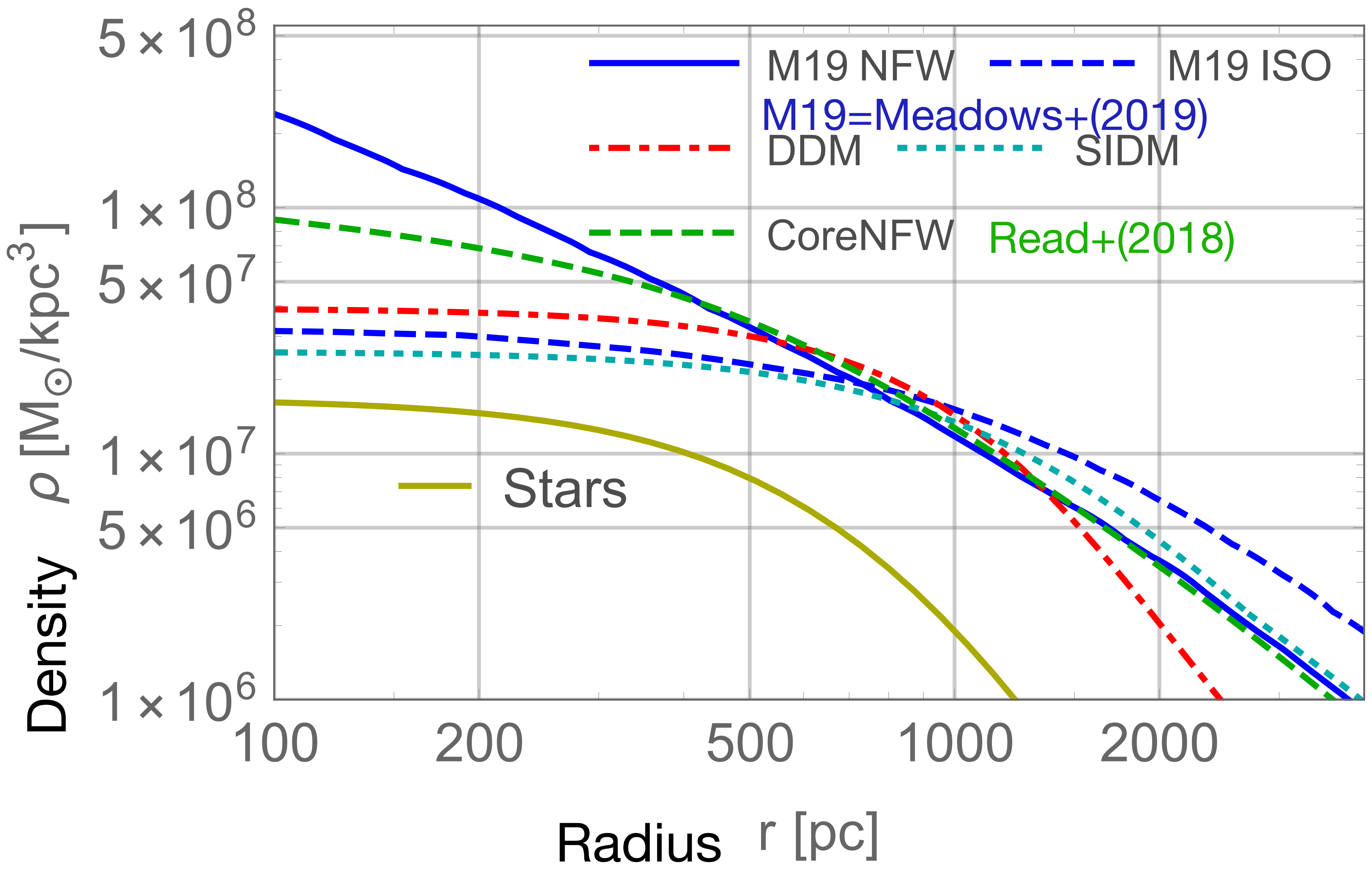
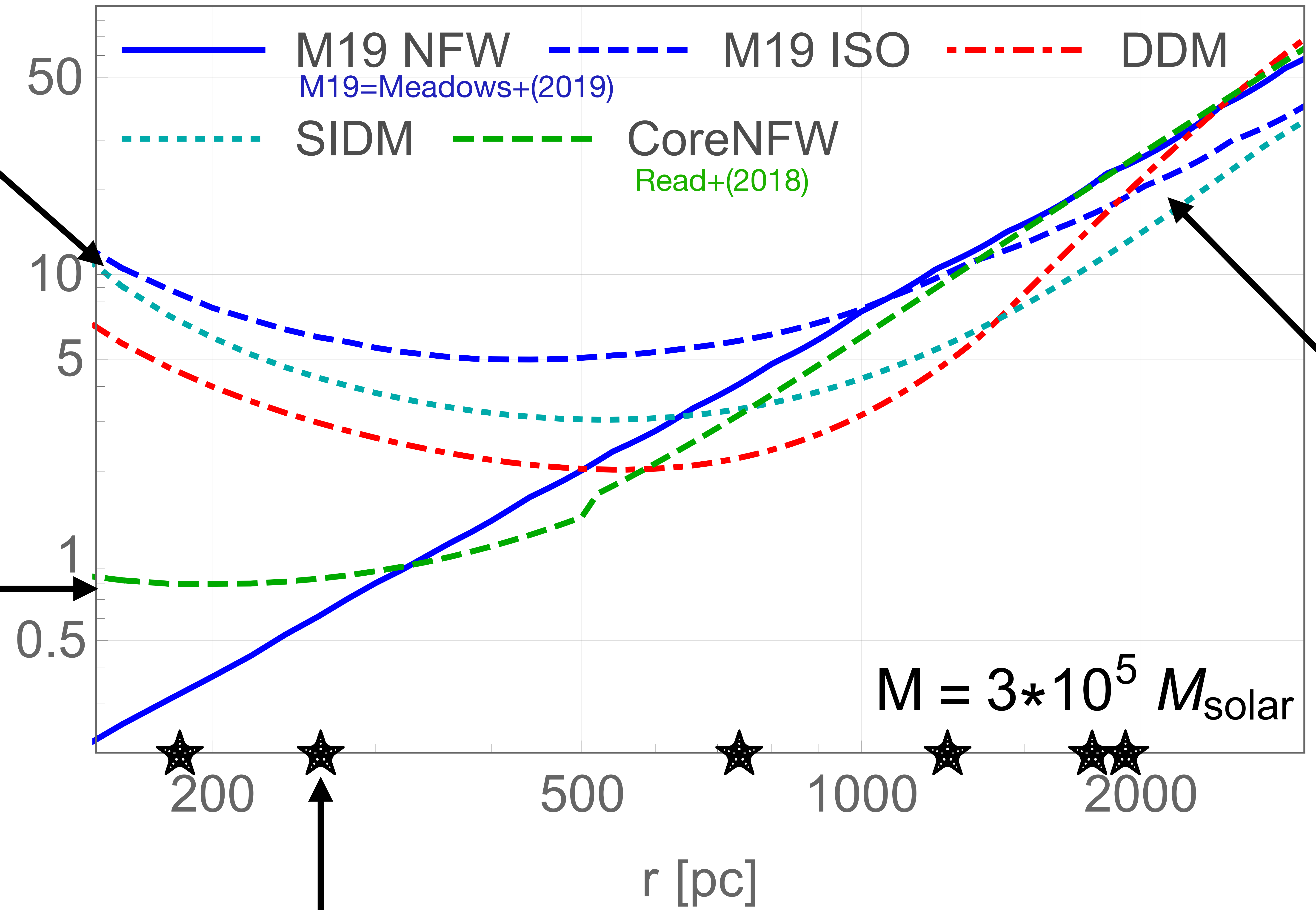




Dynamical friction time demonstrates core stalling

~1 kpc cores lengthen time! (problem for DDM from Ly-a constraints)

Smaller core stalls inner GC to few Gyr



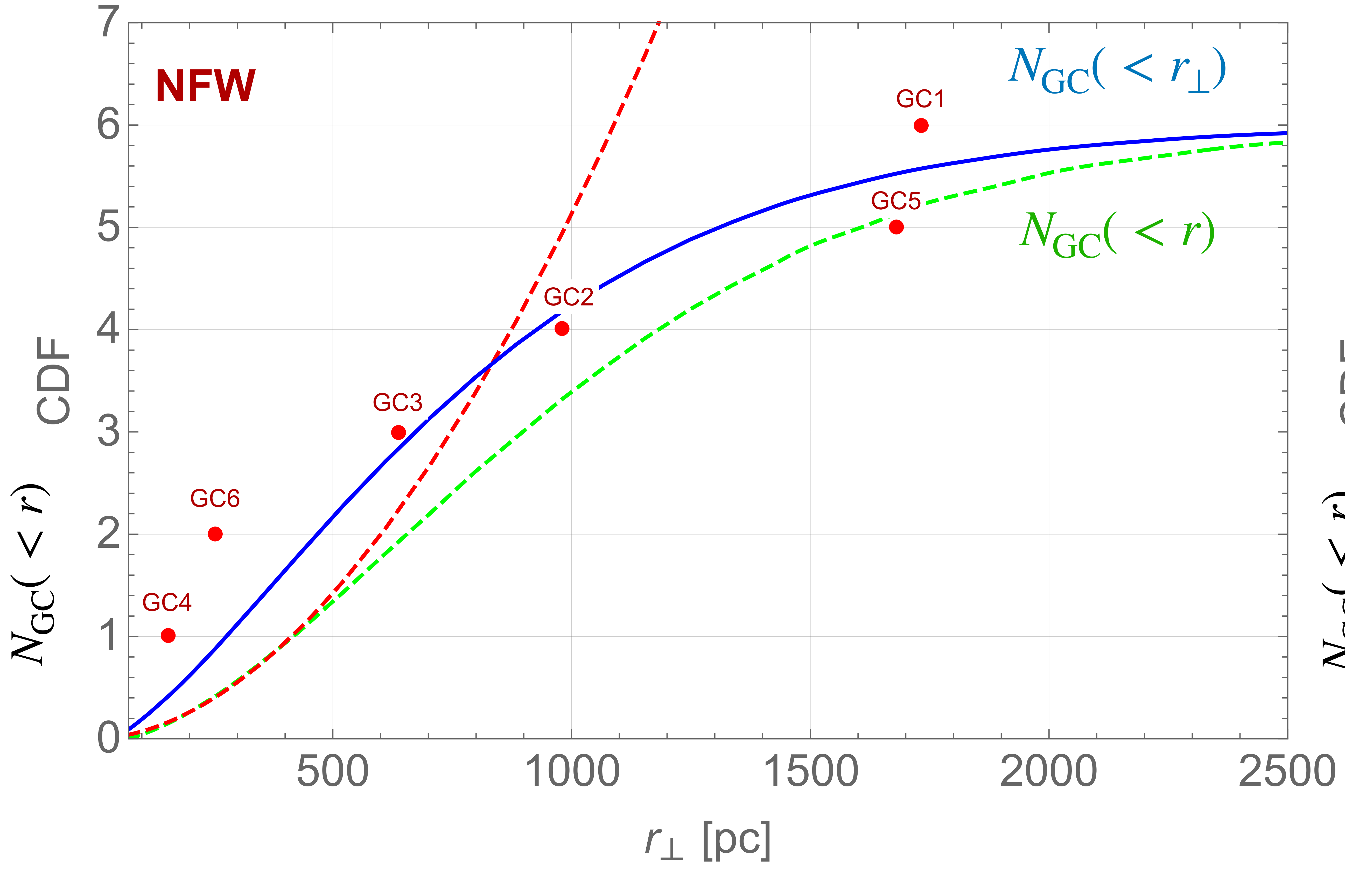
Agreement on halo outskirts

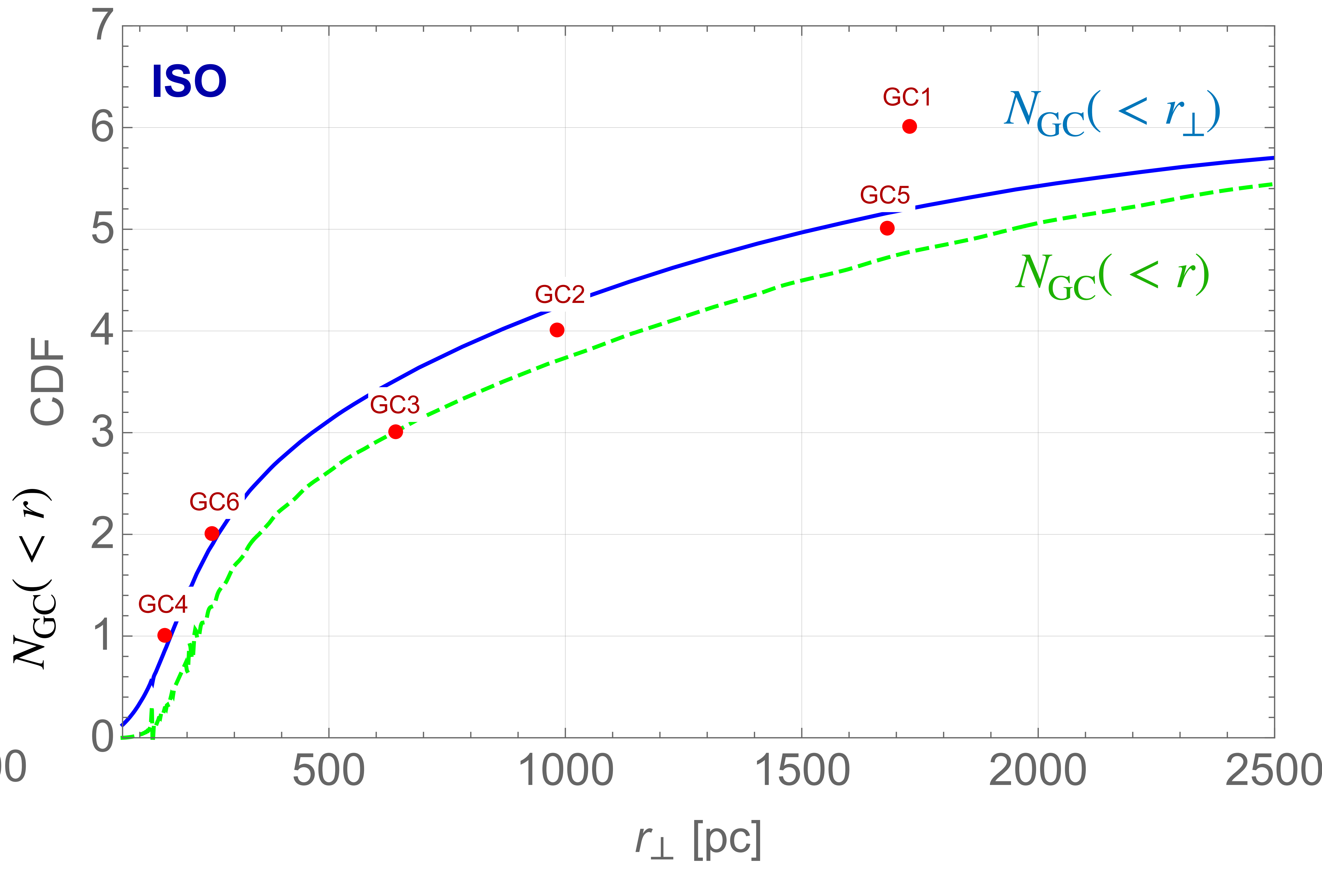
Cusp predicts rapid infall of inner GCs

Did we solve anything? Initial cond.

Quantifying distribution of GCs

When starting from a ‘natural distribution’ of GCs, today we expect



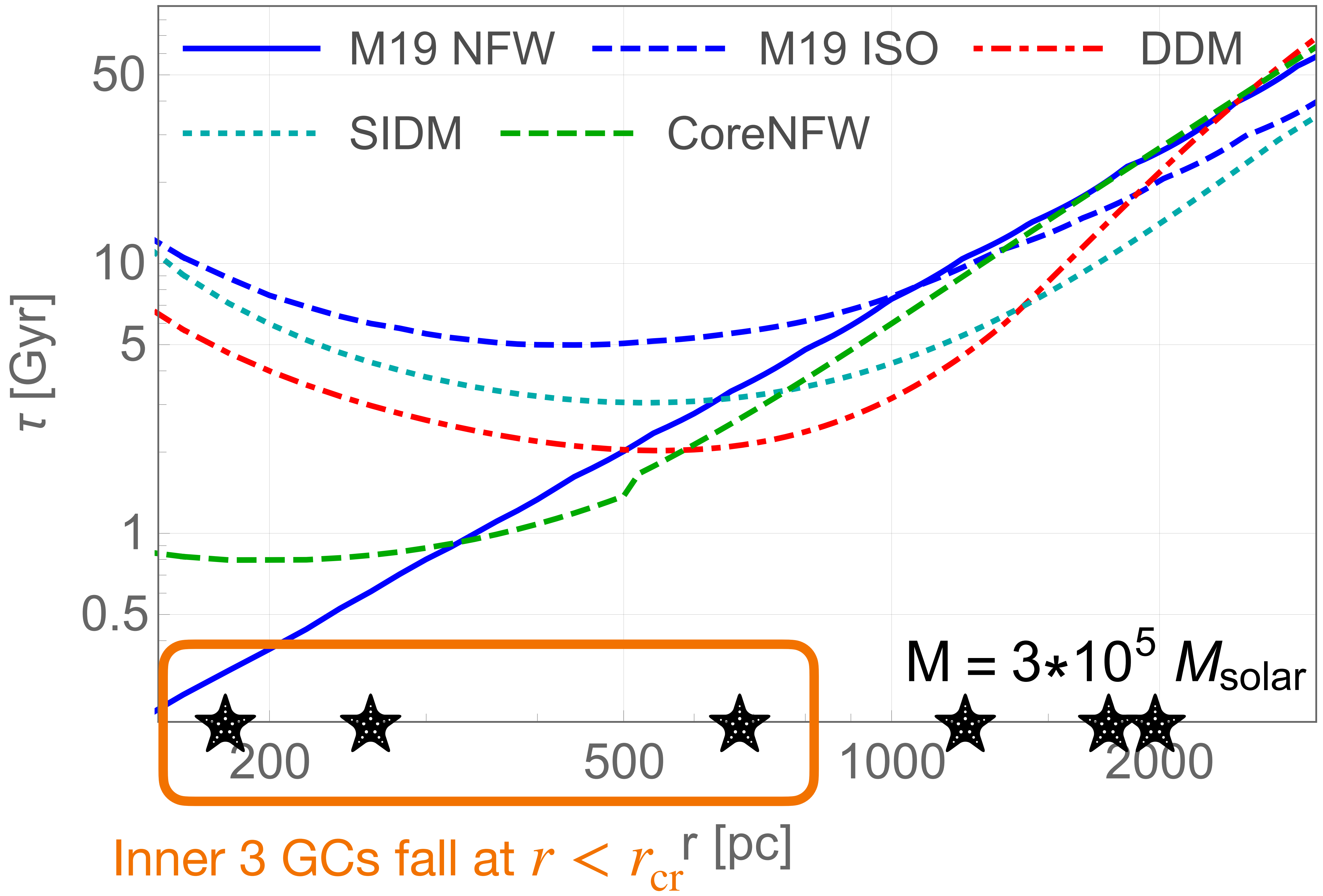


Confronted with data, a cusp is mildly tuned

For a cusp, $\tau(r) \propto r^{1.85}$

The sparse data (3 applicable GCs) favors a shallower profile, but certainly allow a cusp:

We find a Poisson probability $\sim 25\,\%$.



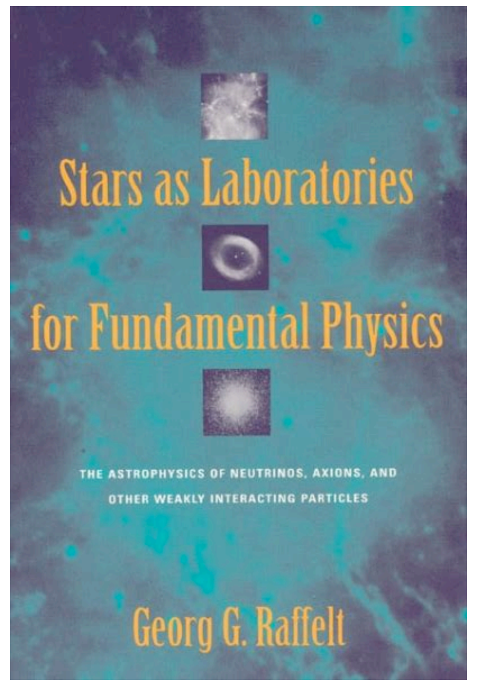
Summary

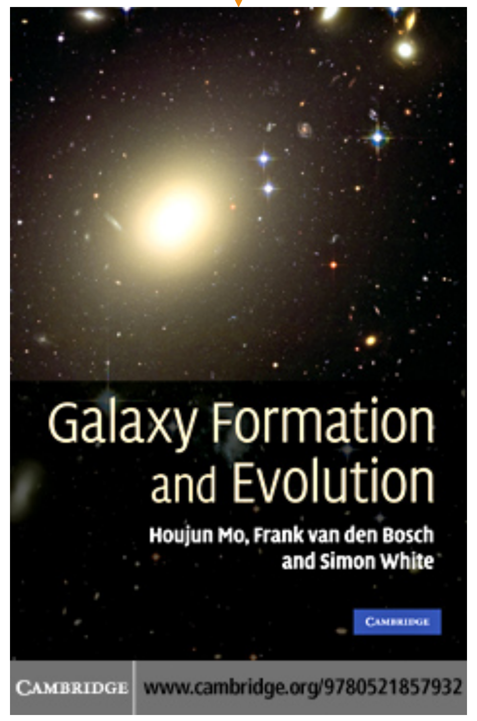
Dynamical friction to test *ultra-light* Fermionic DM

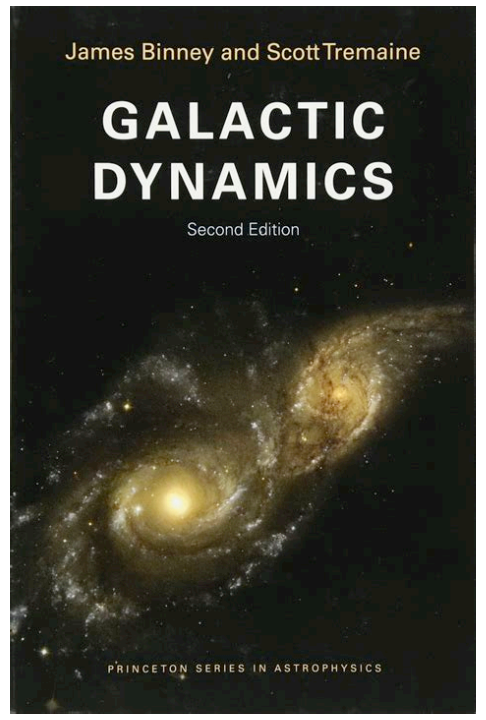
- Different DM models predict different DF: Fornax problem?
- A **small core** due to baryonic feedback may alleviate some tension.
- A **large core** (**SIDM, DDM**) predicts little dynamical friction: GC distribution depends strongly on initial conditions. (It requires some tuning for observed radial velocity of GC4).

- Can we apply the analytical cusp prediction to more extensive data?

Conclusions







- Galactic dynamics is modified for "extreme" DM (e.g. ULDM or DDM)
  - many "classical aspects" modified (not fully explored!)
- ULDM: for $m \lesssim \mathrm{eV}$ occupation number of DM states in MW $O(1)$
  - wavy halo: coherent oscillating patches (modified heating, DF, grav scattering)
  - soliton: extra features at galactic centres. Can be probed with dynamics
- Degenerate DM: for $m \lesssim \mathrm{keV}$ occupation number of DM states in dSph $O(1)$. Fermionic DM will be close to degeneracy
  - degeneracy pressure: presence of core.
  - filled Fermi surface: gravitational scattering modified (DF, heating…)

Backups

Conclusions and outlook on DM cusp in Fornax

- DM cusp predicts a power-law CDF of GCs in the center of the halo, with little dependence on initial conditions.
- Fornax requires a mild $\sim 25\ \%$ tuning to agree with this.
- Dynamical friction: $\mathcal{O}(40\%)$ of GCs to fall to the center of Fornax.

To do:

- Surface brightness modelling does not seem to predict enough light in the center of Fornax to account for fallen & disrupted GCs.
- Proper prediction of GCs in the center of Fornax would require N-body simulation.

Quantifying distribution of GCs

First, we find that the time it takes a GC on circular orbit to inspiral from r_0 to r_f is

$$\Delta t(r_i; r_f) = \int_{r_f}^{r_0} \frac{dr}{2r} \left(1 + \frac{d\ln M}{d\ln r}\right) \tau(r, v_{\rm circ}(r))$$

Can easily be evaluated for const. or power law τ.

Then, given initial distribution $n_{GC}(r, t=0)$, one can find final distribution

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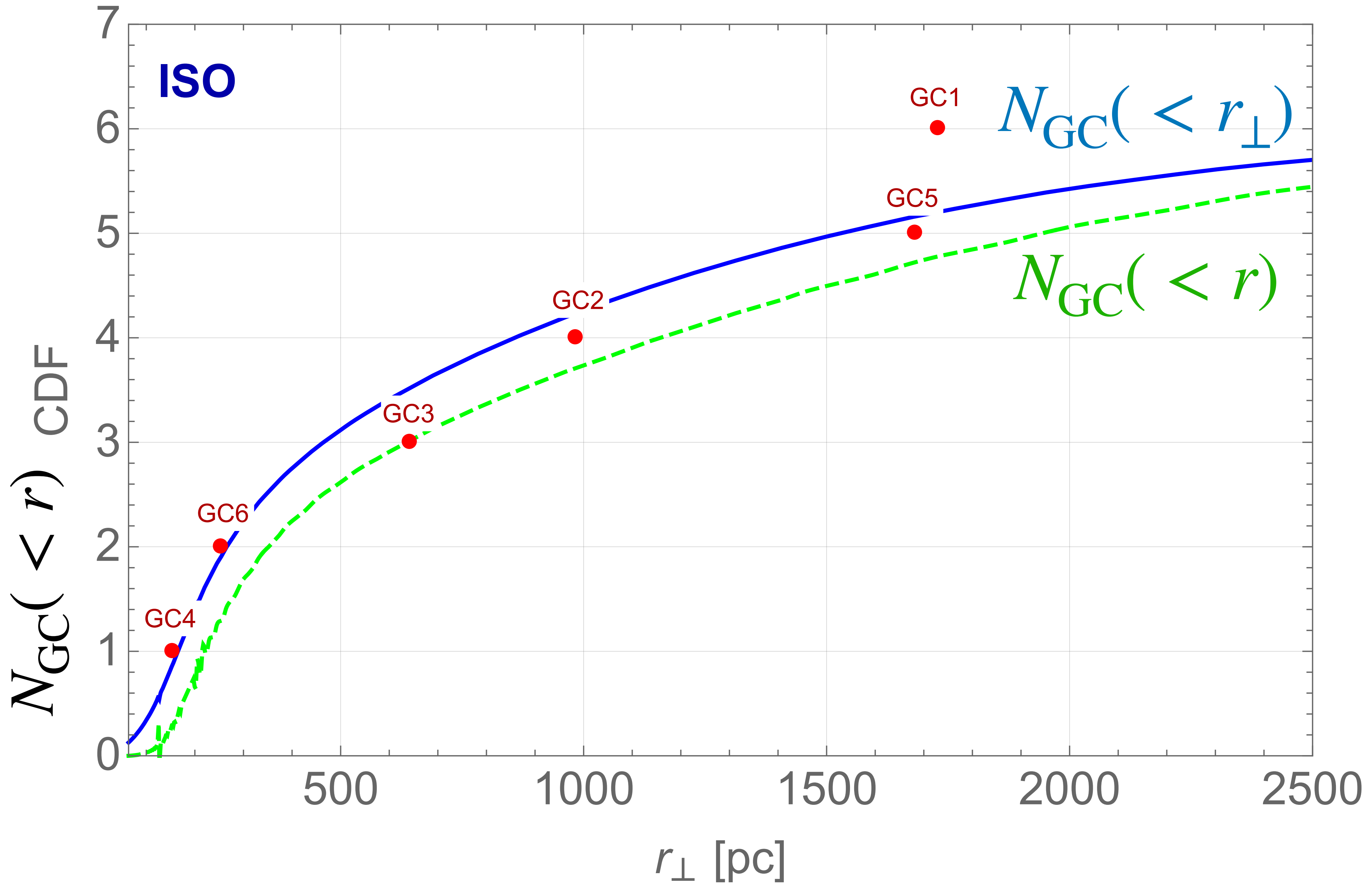

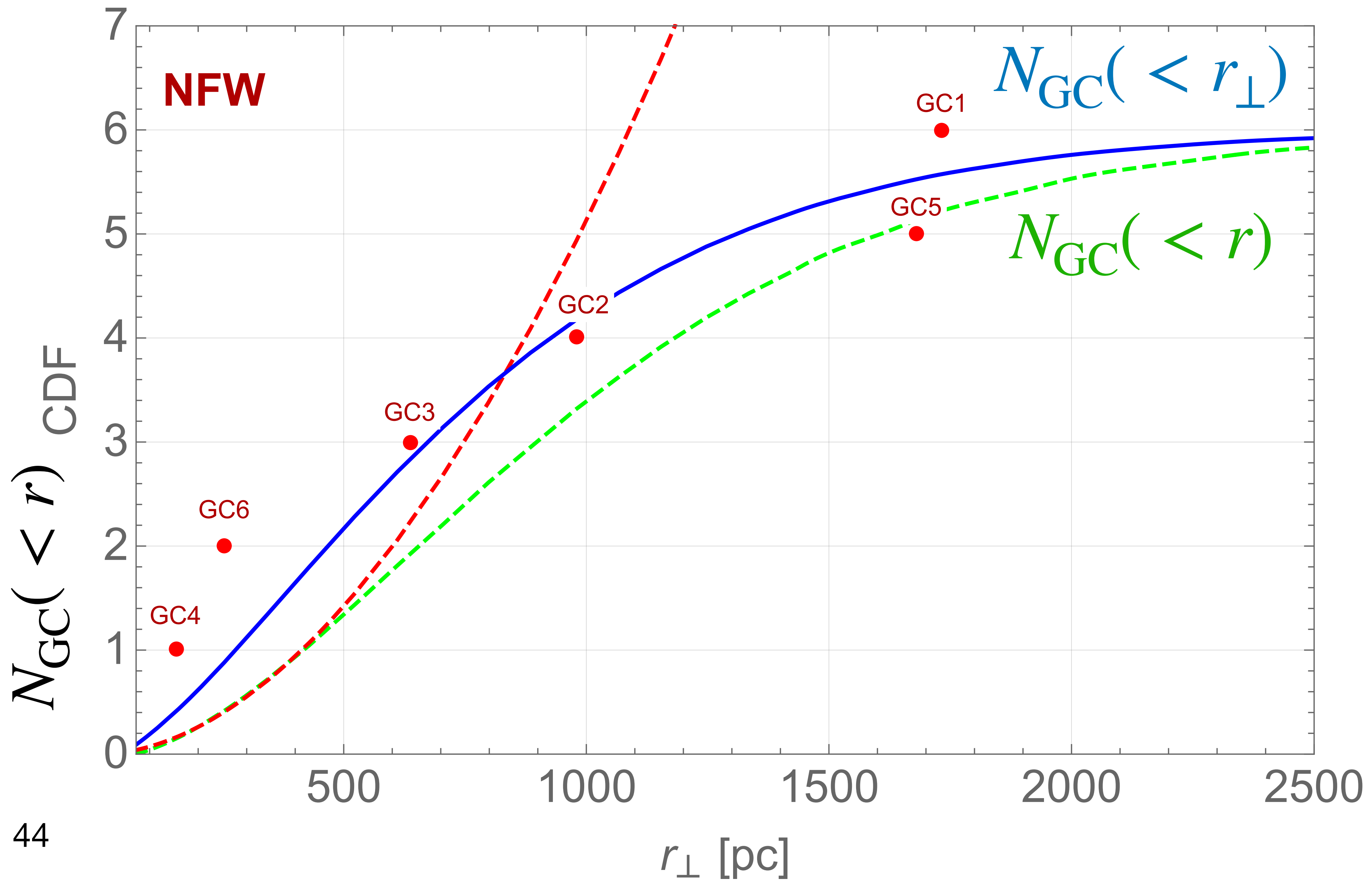

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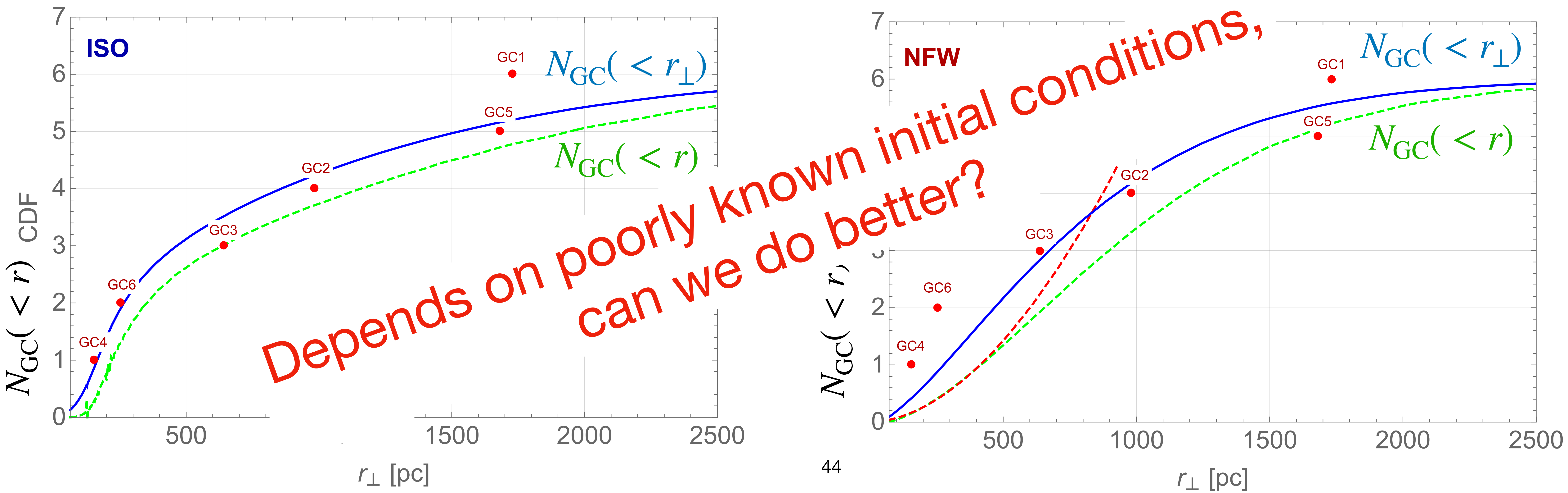

Is this enough? Where are the GCs that fell to the center?

In taking an initial distribution that roughly reproduces the GC distribution in Fornax, some $30\% - 50\ \%$ of GCs should fall to the center by today's time.

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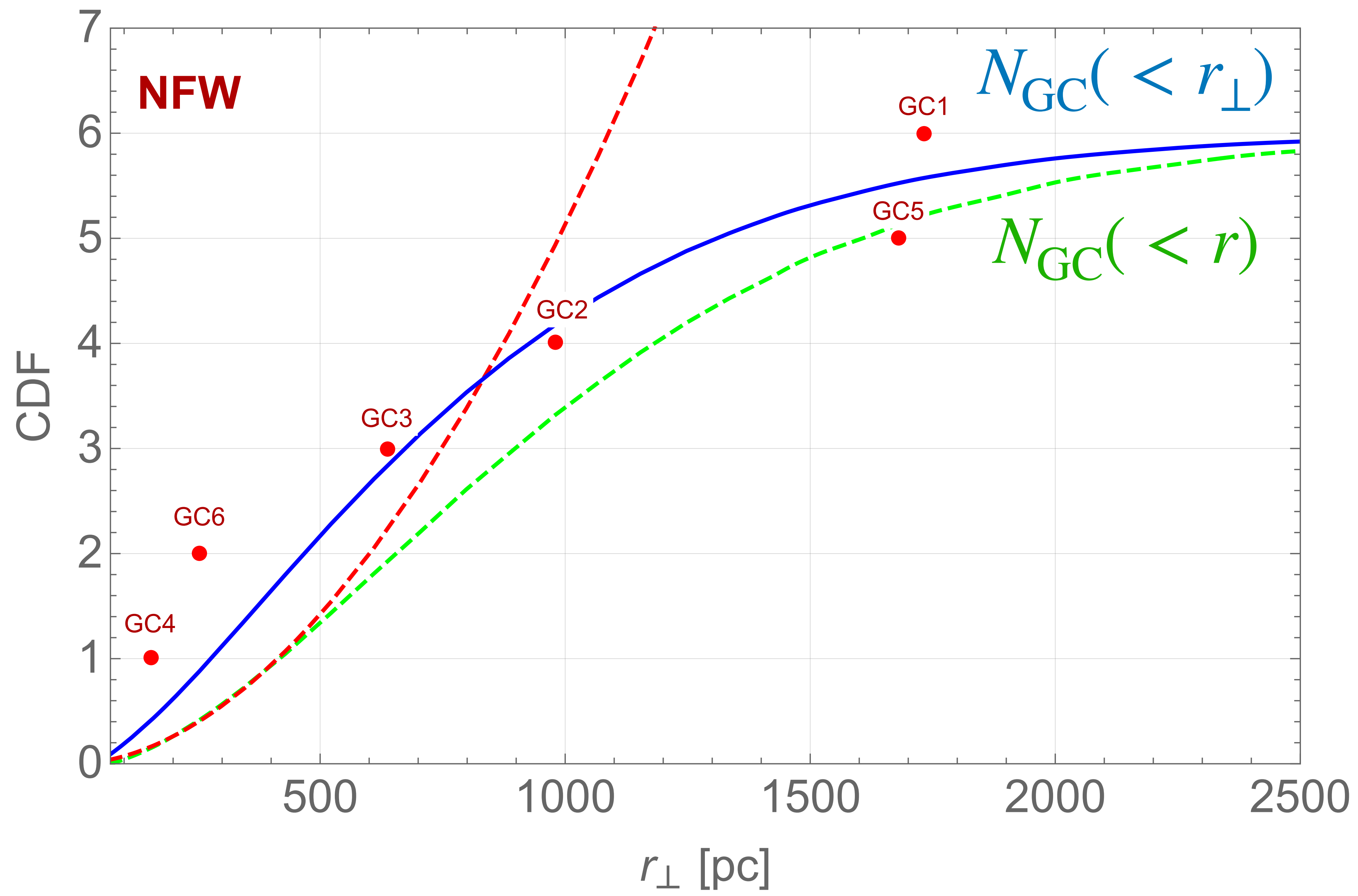

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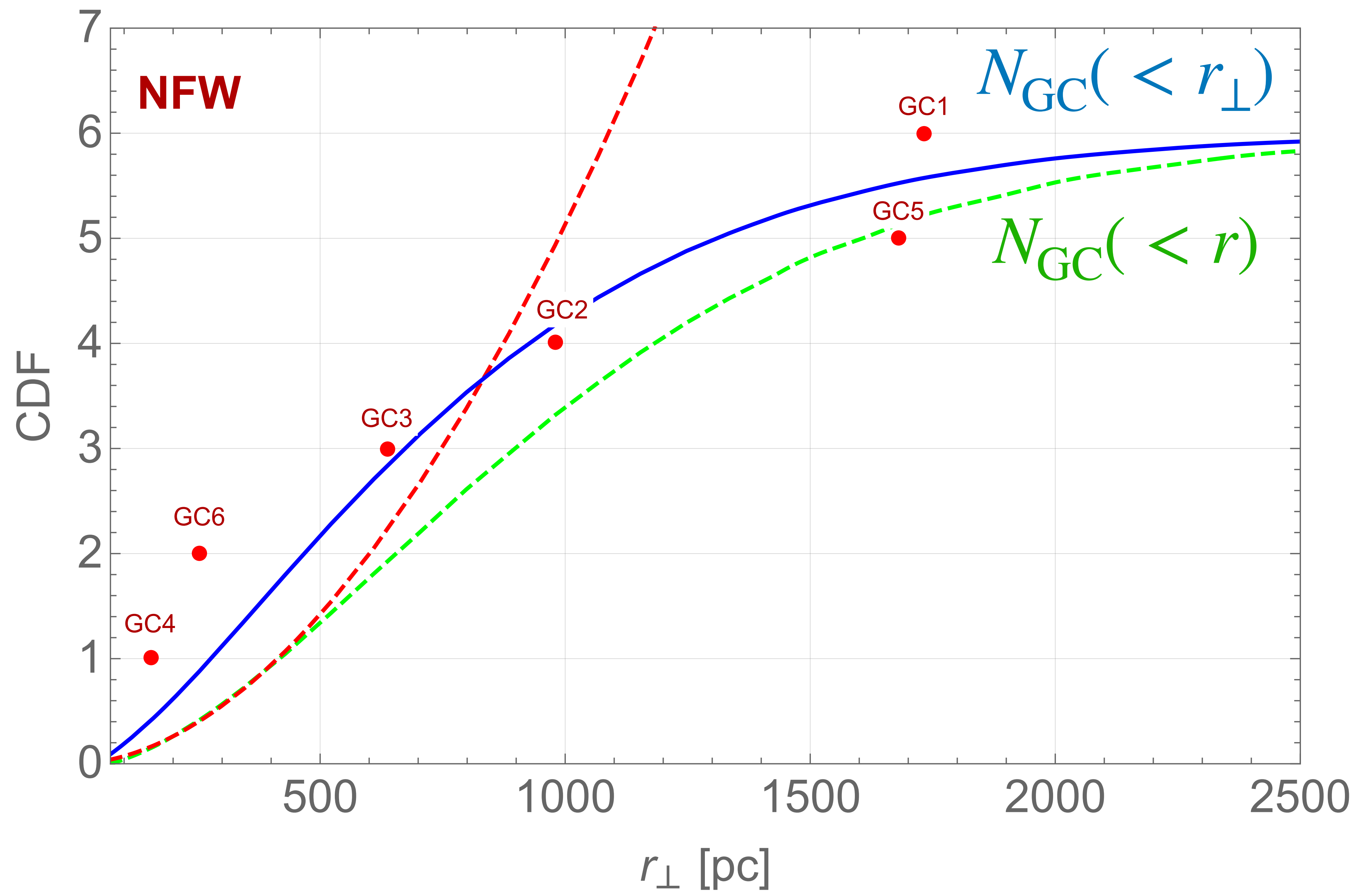

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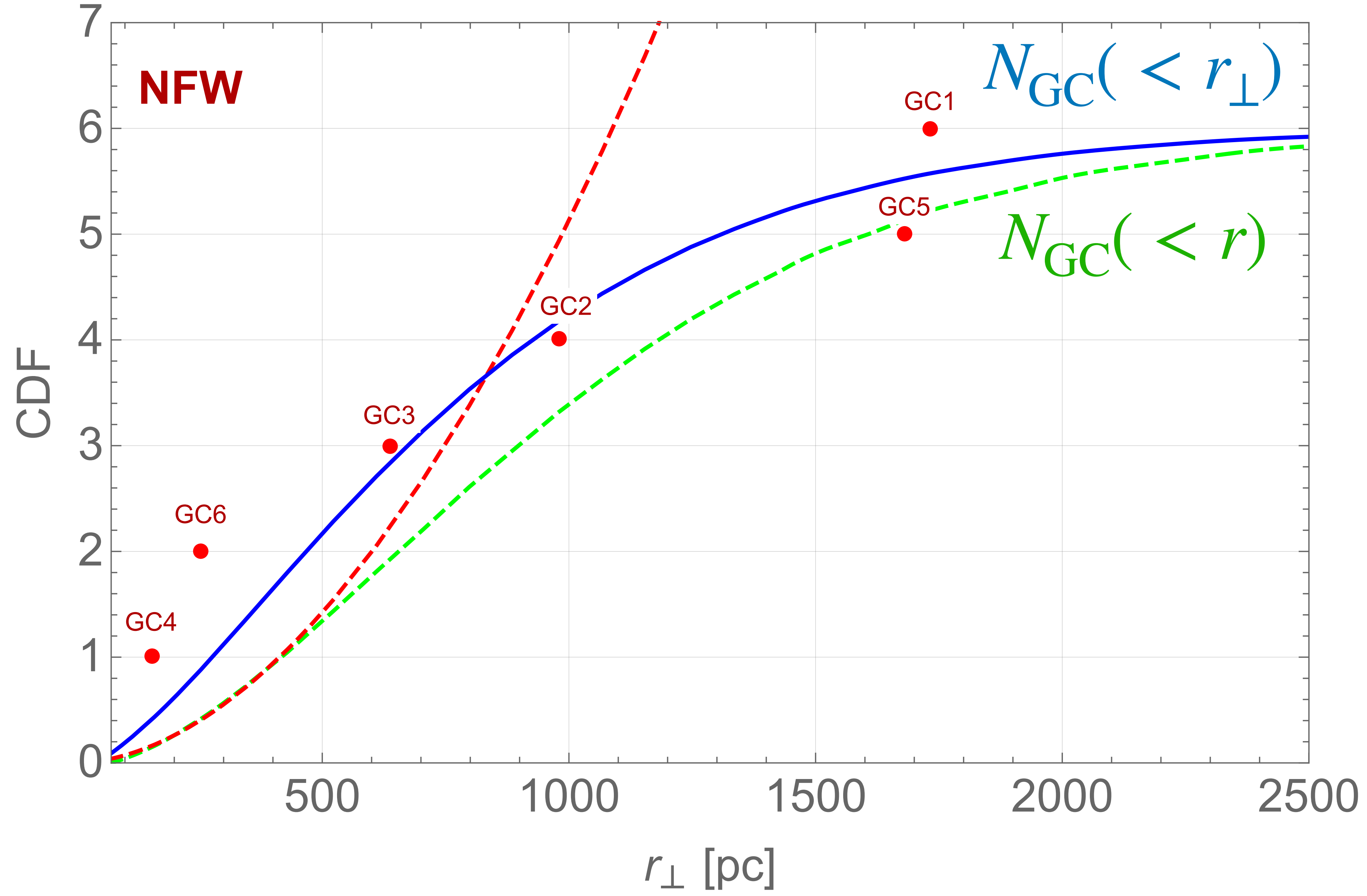

THE FORMATION OF THE NUCLEI OF GALAXIES. II. THE LOCAL GROUP

SCOTT D. TREMAINE
Joseph Henry Laboratories, Physics Department, Princeton University
Received 1975 March 12; revised 1975 April 28

The small relaxation times in Fornax and NGC 185 seem to be inconsistent with the absence of visible nuclei in these systems. A possible explanation of this discrepancy lies in the early history of their nuclei. The first two clusters which spiral to the center will form a binary pair. When the third cluster spirals in, the resulting three-body system tends to be unstable: the binary acts as an energy source, expelling the pair and the third cluster in opposite directions (Valtonen 1974). This instability is more important in low-density systems like Fornax or NGC 185 than in M31, since the cluster motion is dominated by forces from the other clusters (rather than the galaxy) at much larger radii. Moreover, to avoid the formation of the M31

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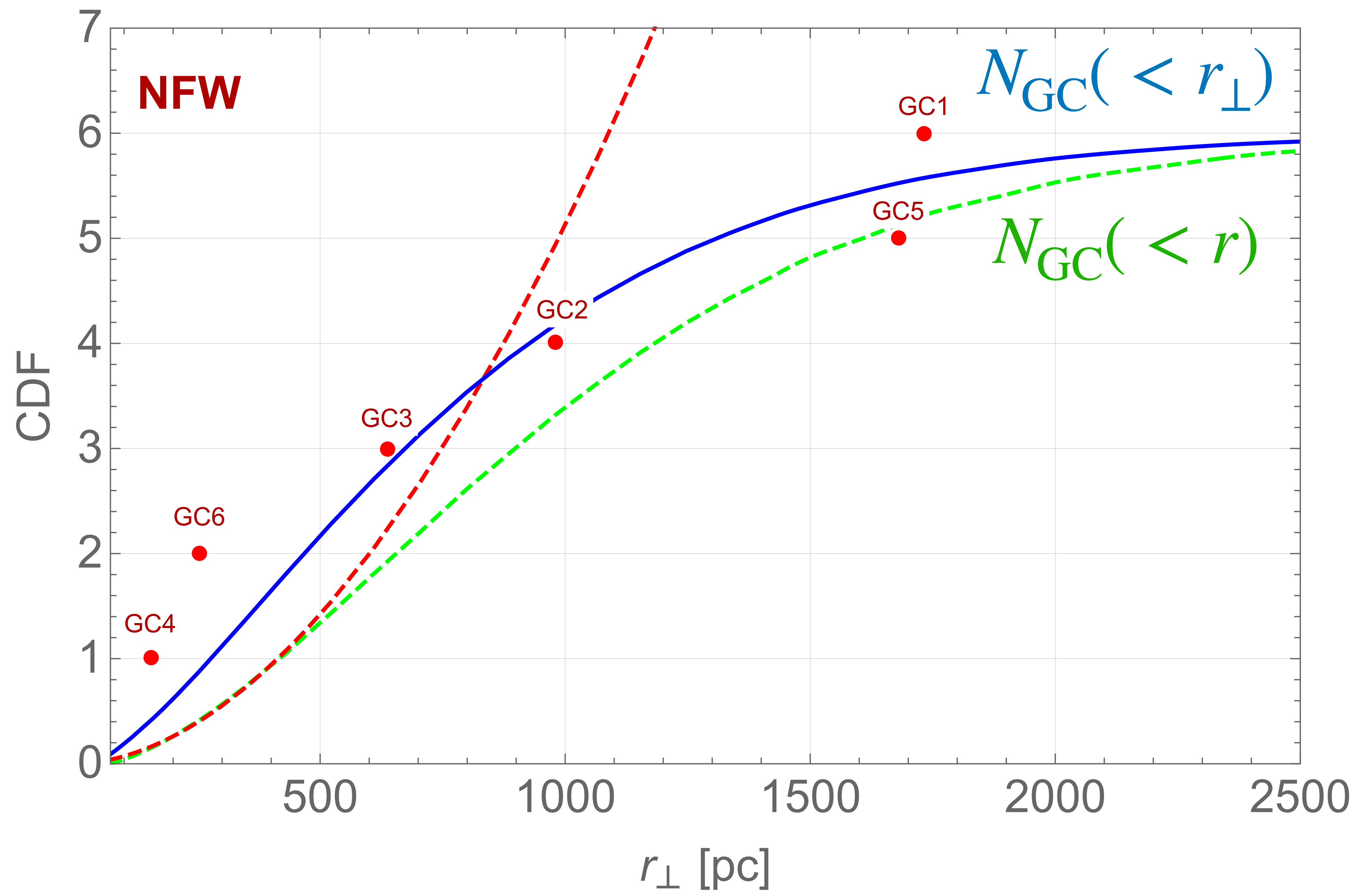

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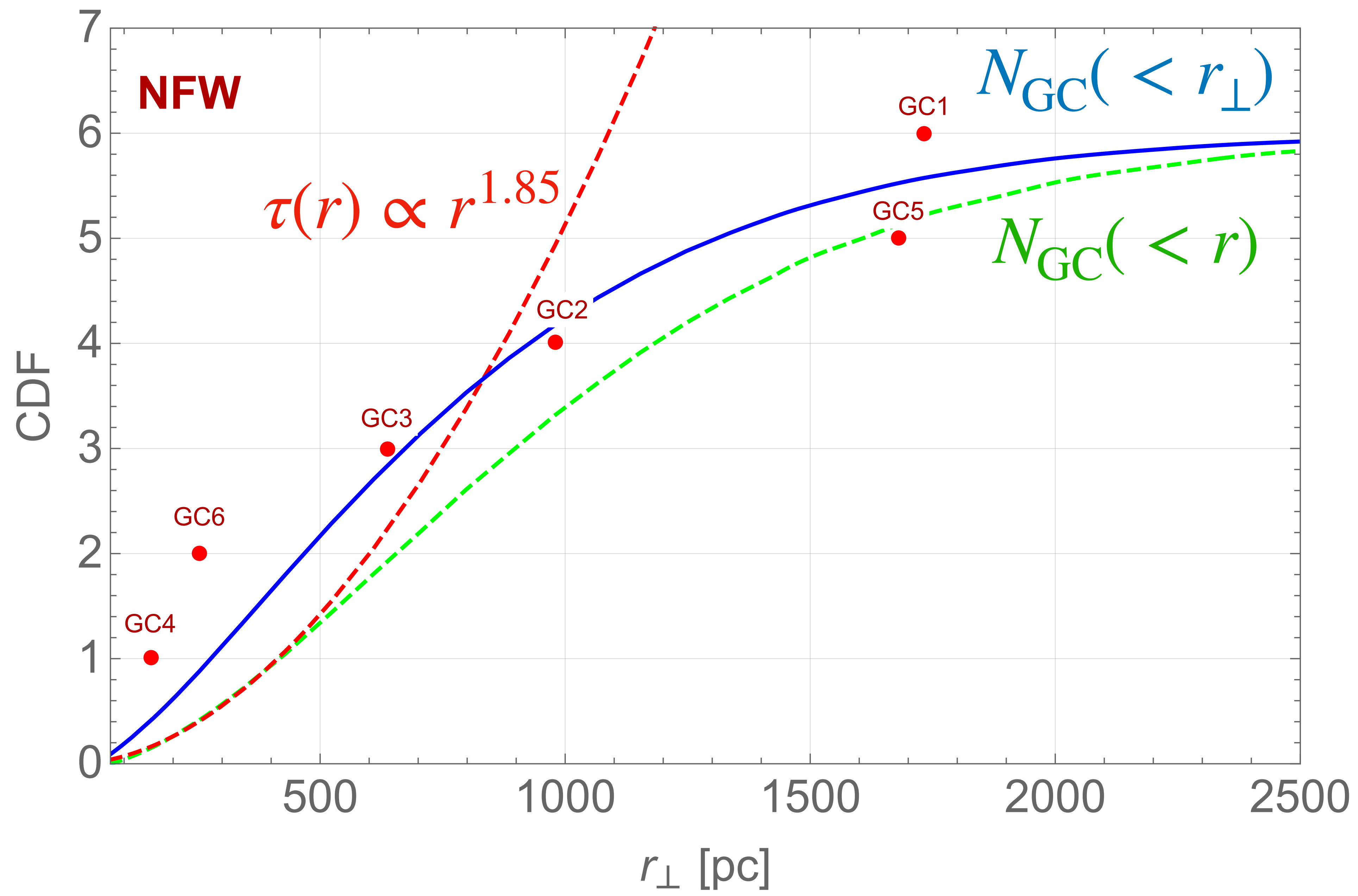

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Conclusions and outlook on DM cusp in Fornax

- DM cusp predicts a power-law CDF of GCs in the center of the halo, with little dependence on initial conditions.
- Fornax requires a mild $\sim 25\ \%$ tuning to agree with this.
- Dynamical friction: $\mathcal{O}(40\%)$ of GCs to fall to the center of Fornax.

To do:

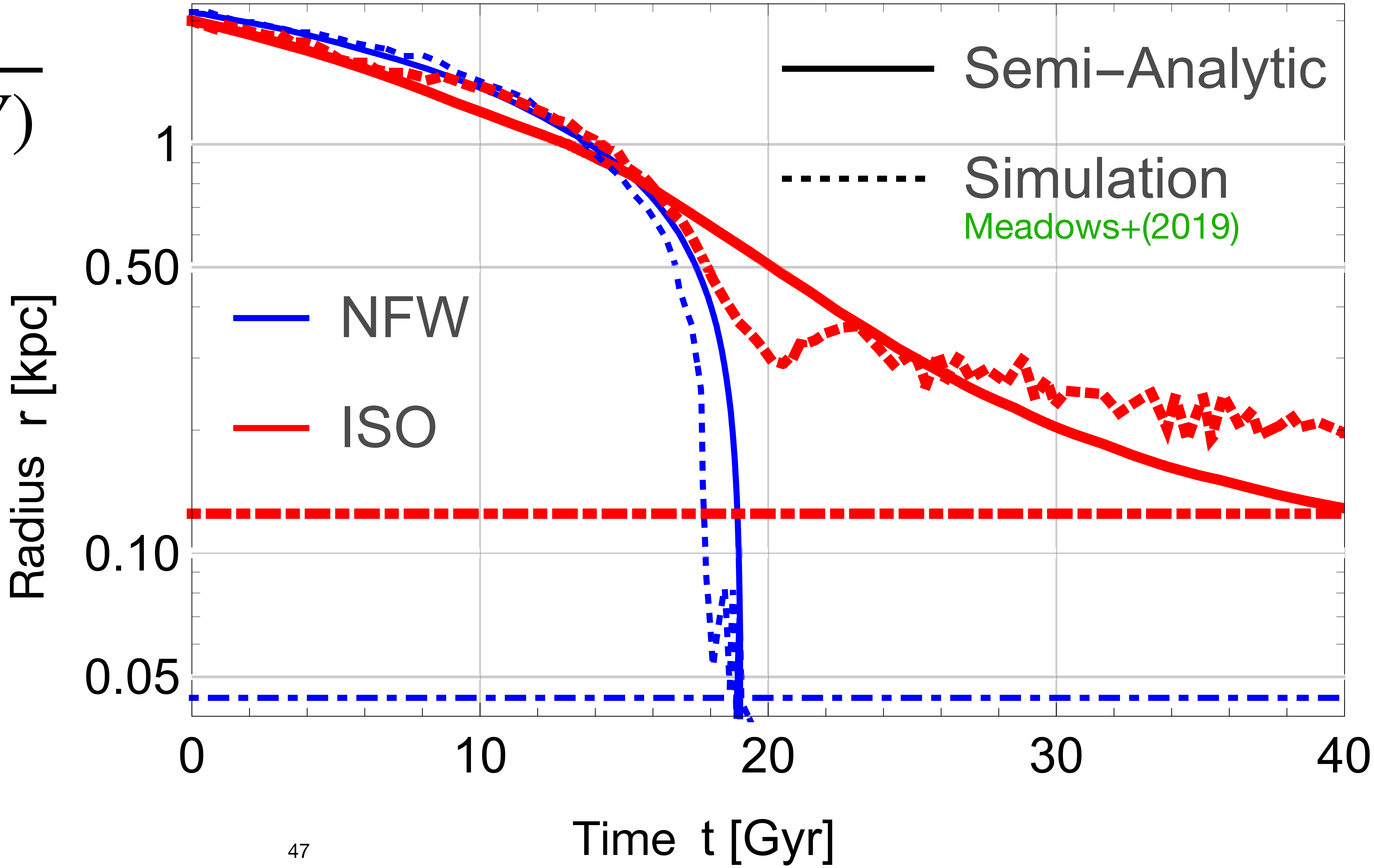
- Surface brightness modelling does not seem to predict enough light in the center of Fornax to account for fallen & disrupted GCs.
- Proper prediction of GCs in the center of Fornax would require N-body simulation.

Analytical treatment can roughly reproduce N-body simulations

Semi-analytic integration:

$$\frac{d\mathbf{V}}{dt} = -\frac{GM(r)}{r^2}\hat{r} - \frac{\mathbf{V}}{\tau(r, V)}$$

Coulomb logarithm needs to be calibrated.

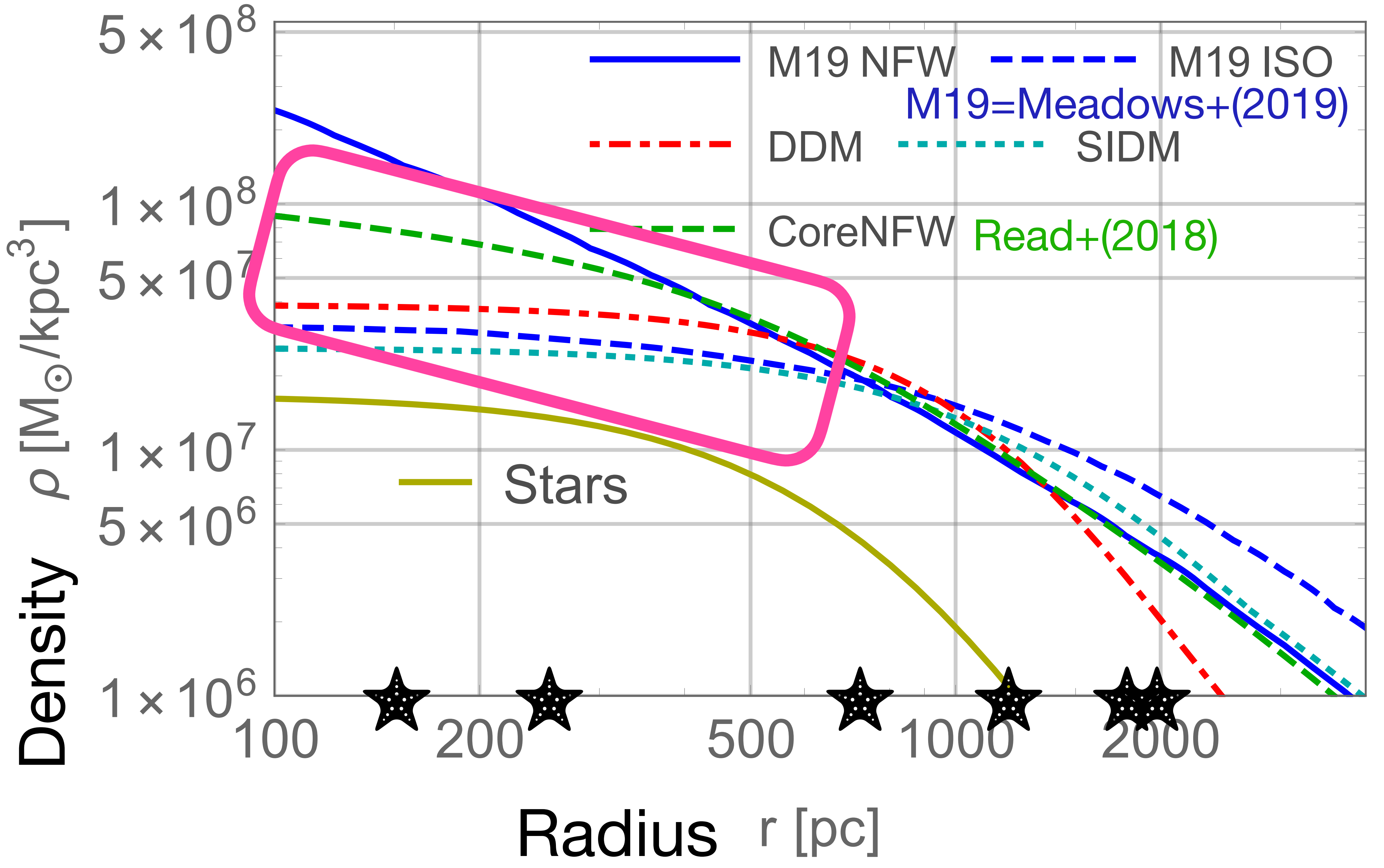


Why conclusions more mild than previous studies?

- Center of galaxy shifted a little.
- New kinematic data favors a more massive halo with less dynamical friction.
- Mass estimates of GCs were updated.
- A more accurate treatment of dynamical friction in realistic halos.
- A prediction of GC distribution for a cusp gave something concrete to test on.

Can globular cluster distribution hint to cusp vs. core?

Vanilla CDM-only simulations predict “cusp” — 1/r density.
Some indicators may hint otherwise



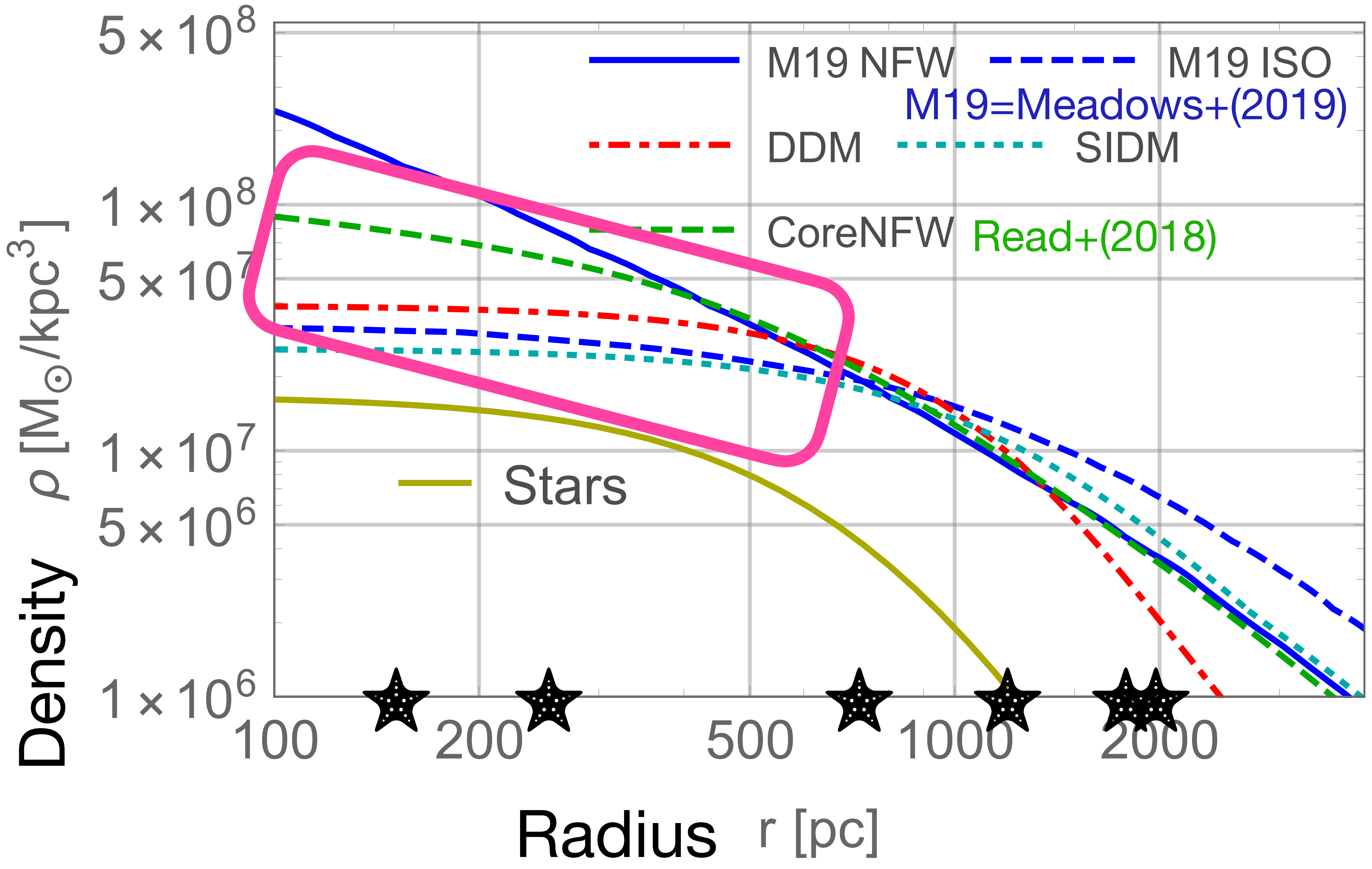
Can globular cluster distribution hint to cusp vs. core?

Vanilla CDM-only simulations predict “cusp” — 1/r density.
Some indicators may hint otherwise

Does the Fornax dwarf spheroidal have a central cusp or core? (MNRAS 2006)

Tobias Goerdt,[1★] Ben Moore,[1] J. I. Read,[1] Joachim Stadel[1] and Marcel Zemp[1,2]

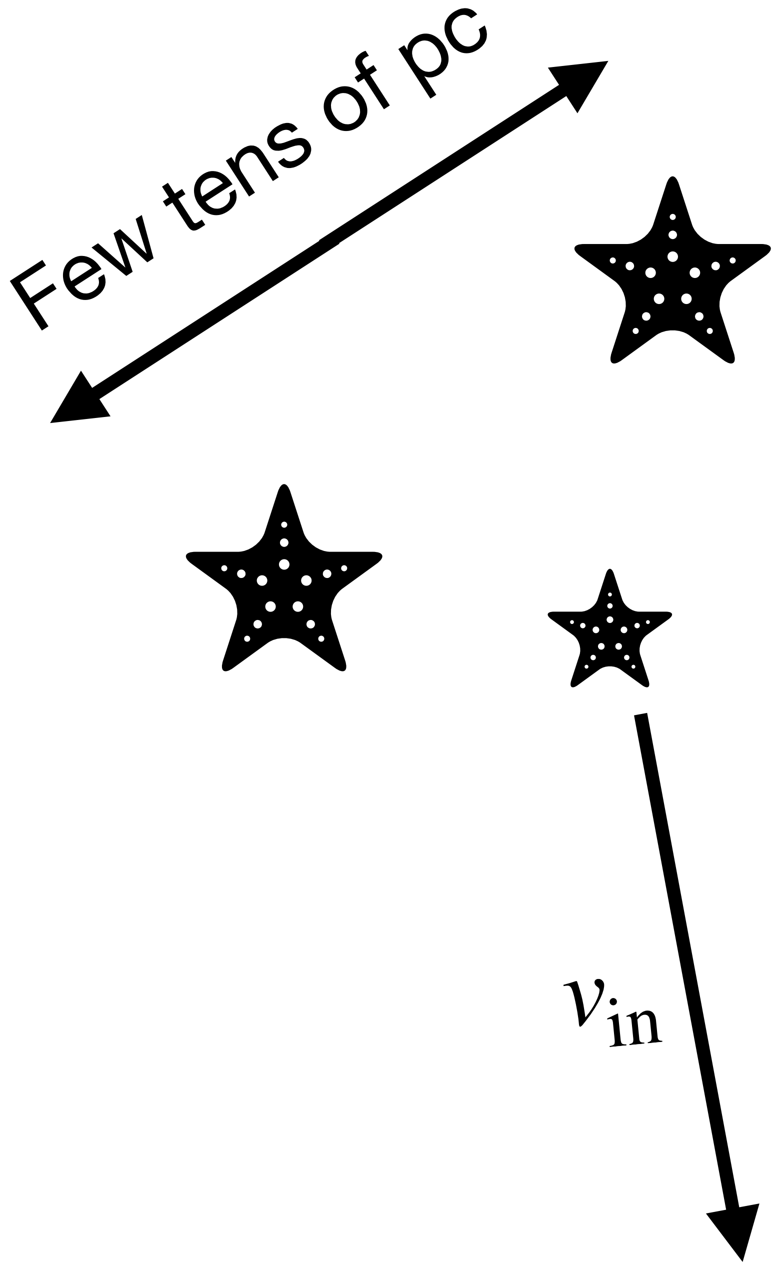
ABSTRACT
The dark matter dominated Fornax dwarf spheroidal has five globular clusters orbiting at ~1 kpc from its centre. In a cuspy cold dark matter halo the globulars would sink to the centre from their current positions within a few Gyr, presenting a puzzle as to why they survive undigested at the present epoch. We show that a solution to this timing problem is to adopt a cored dark matter halo. We use numerical simulations and analytic calculations to show that, under these conditions, the sinking time becomes many Hubble times; the globulars effectively stall at the dark matter core radius. We conclude that the Fornax dwarf spheroidal has a shallow inner density profile with a core radius constrained by the observed positions of its globular clusters. If the phase space density of the core is primordial then it implies a warm dark matter particle and gives an upper limit to its mass of ~0.5 keV, consistent with that required to significantly alleviate the substructure problem.



GCs are unlikely to be ejected from center by N-body interactions

The velocity scale is on the edge of the GC is

$$V \sim \sqrt{\frac{GM_{\rm GC}}{r_h}} = 12\sqrt{\frac{M_{\rm GC}}{10^5\ M_\odot}\frac{3\ \rm pc}{r_h}}\ \frac{\rm km}{\rm s}\ .$$



Ejecting an object from a cusp is not that easy:

$$r_{\rm eject} = \frac{v_{\rm in}^2}{4\pi G\rho_0 r_s} \sim 100\left(\frac{v_{\rm in}}{12\ \rm km/s}\right)^2\ \rm pc\ .$$

Mass of the center of Fornax consistent with stars of no more than $\sim 2-3$ GCs

Mass scale of GC $10^5\ M_\odot$.

	$m_\star$ $[10^5 M_\odot]$
GC1	0.42 ± 0.10
GC2	1.54 ± 0.28
GC3	4.98 ± 0.84
GC4	0.76 ± 0.15
GC5	1.86 ± 0.24
GC6	~ 0.29

Fornax mass inside 100 pc or so uncertain because of

(i) Surface brightness modeling (Plummer, Sersic, etc.)

(ii) Stellar mass uncertainty.

As a very crude estimate, $0.3-3\times 10^5\ M_\odot$ inside <100 pc

Very dilute GCs may be tidally disrupted in the center

$$r_t \sim 40 \left(\frac{R_G}{100 \text{ pc}} \right)^{1/3} \left(\frac{M_{\text{GC}}}{10^5 \, M_\odot} \right)^{1/3} \text{ pc}$$

where R_G is the distance of the GC to the halo's center.

These are very large radii, much larger than other of other GCs in Fornax.

Ly-a bounds

- Instantaneous DM free streaming is given by $k_{FS} \simeq \sqrt{\frac{3}{2}\frac{\mathscr{H}(z)}{\sigma(z)}}$
- A small core due to baryonic feedback may alleviate some tension.
- A large core predicts little dynamical friction, therefore GC distribution depends strongly on initial conditions.
  Large core also requires some tuning because of the observed radial velocity of GC4.
- Can we apply the analytical cusp prediction to more extensive data? Looking into that.

Cusp predicts 30-50% GCs fall to center — where are they?

Stellar mass in central $100\ \mathrm{pc}$ is fairly uncertain: assuming factor of two uncertainty of total mass around $4.3 \times 10^7\ M_\odot$ and different density profiles, Plummer/Sersic, we find

$$0.3 - 3 \times 10^5\ M_\odot$$

GC masses, on the other hand, is about $10^5\ M_\odot$.

Mass budget of the center of Fornax consistent with stars of no more than $\sim 2-3$ GCs

Luminosity of a GC about $\sim 10^{4.7} = 5 \times 10^4\ L_\odot$

At* $M_V = -14.3 \pm 0.3, L_{\rm Fornax} \sim 4.5 \times 10^7\ L_\odot$

* Wang+(2018,DES)

Cluster	log L_∞ $(L_\odot)^{b,c}$	log L_m $(L_\odot)^b$
Fornax 1	4.07 ± 0.13	4.07 ± 0.13
Fornax 2	4.76 ± 0.12	4.75 ± 0.12
Fornax 3	5.06 ± 0.12	5.00 ± 0.11
Fornax 4	4.69 ± 0.24	$4.67^{+0.23}_{-0.24}$
Fornax 5	4.76 ± 0.20	$4.67^{+0.17}_{-0.18}$

Mackey & Gilmore (2003)

Surface brightness modeling predicts

$0.24 \pm 0.1\ \%$ of luminosity within inner 100 pc $\sim 10^5\ L_\odot$

Roughly the amount of two GCs.

Mass modelling roughly agrees.

GC details in the paper

TABLE I. Some details of Fornax GCs. For the galactic center of Fornax we use an updated measurement [22], based on surface brightness modelling. This estimate is ≈ 160 pc off relative to the center defined by previous works [1, 3, 18, 20, 32, 34], leading to different projected radii of GCs. We set the distance to Fornax as 147 ± 4 kpc [19]. We estimate the error on $r_\perp$ by propagating the distance error, added in quadrature with a 13 pc [22] uncertainty on the center. For relative radial velocities Δv_r, we use the galactic radial velocity $\mathrm{RV}_{\mathrm{Fornax}} = 55.46 \pm 0.63$ km/s [51] and set $\Delta v_r = \mathrm{RV}_{\mathrm{GC}} - \mathrm{RV}_{\mathrm{Fornax}}$, adding errors in quadrature. For GC6, the values correspond to a small sample of stars, likely contaminated by background [16]. $r_{c/h}$ refers to King radius for GC1-GC5 and half-light radius for GC6. The CDM instantaneous DF time (Eq. (10)) estimates are based on the NFW profile of [18]. The instantaneous DF time of DDM and SIDM are based on Secs. IV and V.

	$m_\star$ [$10^5 M_\odot$]	$r_\perp$[kpc]	Δv_r[km/s]	$r_{c/h}$ [pc]	Refs.	τ_{CDM} [Gyr]	$\tau_{\mathrm{DDM}}^{(135)}$ [Gyr]	τ_{SIDM} [Gyr]
GC1	0.42 ± 0.10	1.73 ± 0.05	3.54 ± 1.18	10.8 ± 0.3	[19, 20, 51–53]	119	122	79.3
GC2	1.54 ± 0.28	0.98 ± 0.03	3.9 ± 0.7	6.2 ± 0.2	[19, 20, 53, 54]	14.7	7.12	8.82
GC3	4.98 ± 0.84	0.64 ± 0.02	4.94 ± 0.66	1.7 ± 0.1	[19, 20, 55, 56]	2.63	1.48	2.21
GC4	0.76 ± 0.15	0.154 ± 0.014	-8.26 ± 0.64	1.9 ± 0.2	[19, 20, 55, 56]	0.91	10.7	14.8
GC5	1.86 ± 0.24	1.68 ± 0.05	3.93 ± 0.77	1.5 ± 0.1	[19, 20, 51, 55, 56]	32.2	30.1	20
GC6	~ 0.29	0.254 ± 0.015	-1.56 ± 1.36	12.0 ± 1.4	[1, 16]	5.45	16.1	22

Orbital deceleration (Chandrasekhar's formula)

$$\frac{d\mathbf{V}}{dt} = \frac{D}{M}\hat{V} = -\frac{4\pi G^2 \rho M \ln\Lambda}{V^3} \underbrace{C(V/\sigma)}_{O(1)} \mathbf{V}$$

Orbital deceleration (Chandrasekhar's formula)

G^2 effect

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- Perturber mass
- Coulomb logarithm
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For a given halo, it depends on radius and velocity of object.

Assuming a circular orbit:
Effective function of radius.

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Time-scale

$$\tau \equiv \frac{|\mathbf{V}|}{|d\mathbf{V}/dt|} \sim 1.8 \left(\frac{V}{12\ \mathrm{km/s}}\right)^3 \frac{2 \times 10^7 \frac{M_\odot}{\mathrm{kpc}^3}}{\rho}\ \mathrm{Gyr}$$

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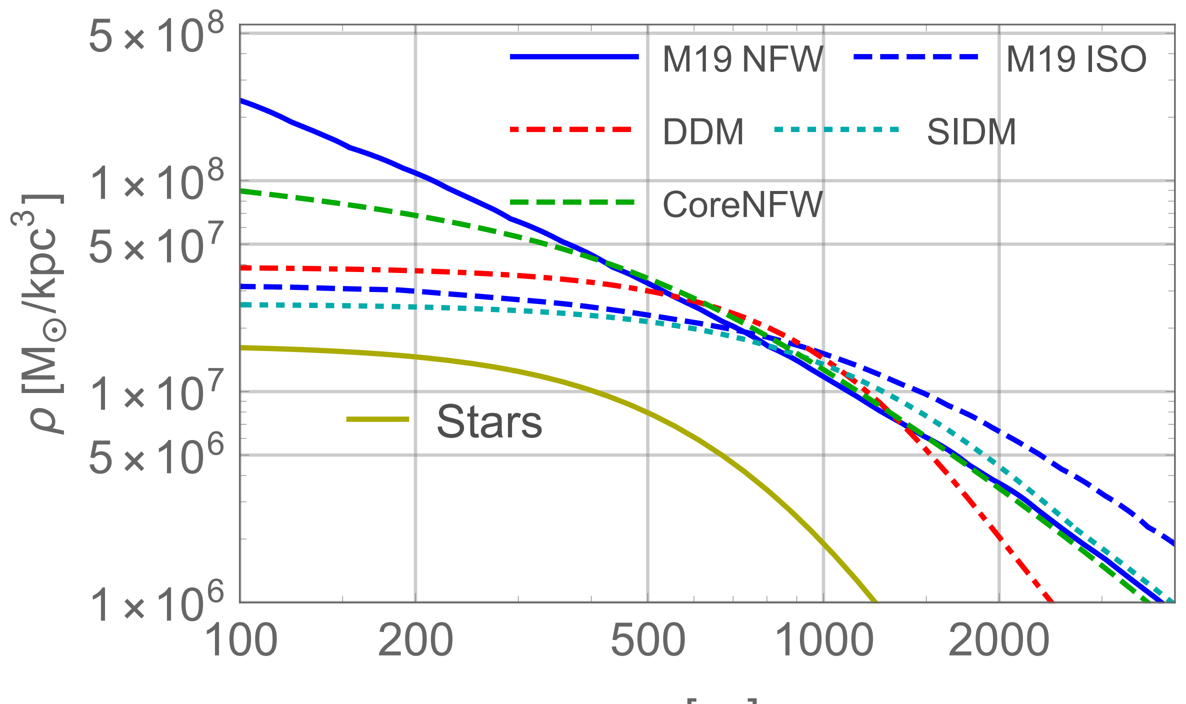

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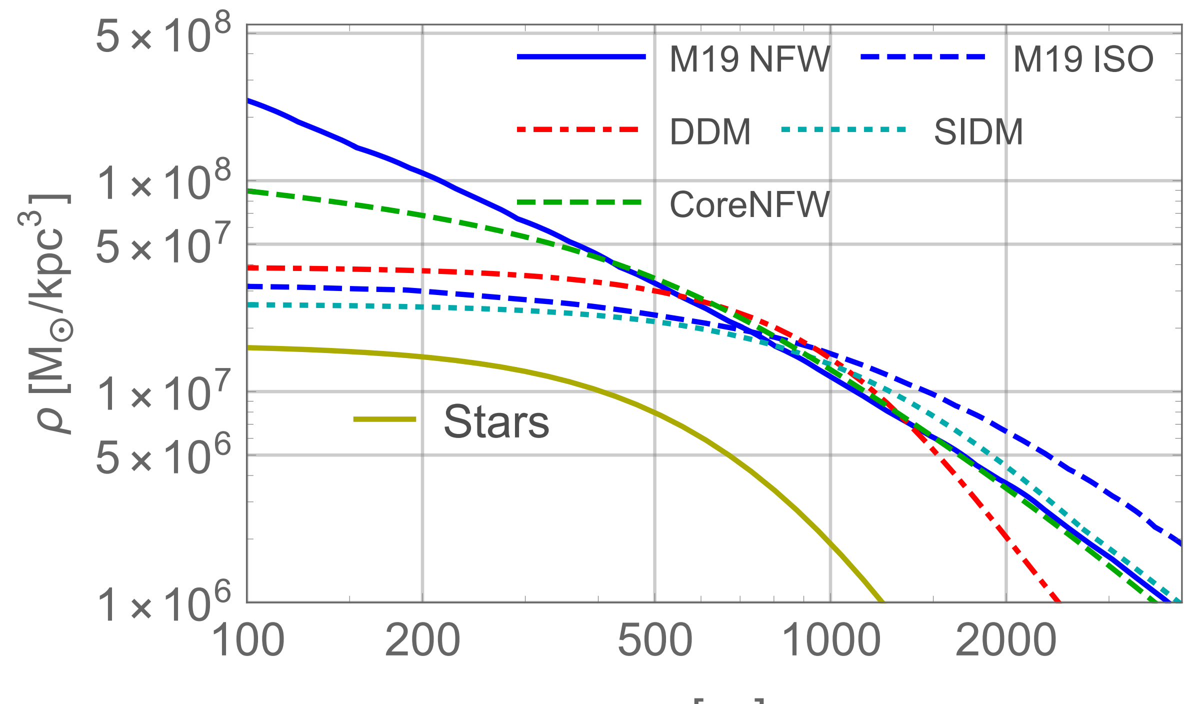
For classical Maxwellian $C_{\mathrm{Max}} \to \ln\Lambda \begin{cases} 1 & V \gg \sigma \\ \frac{\sqrt{2}}{3\sqrt{\pi}}\frac{V^3}{\sigma^3} & V \ll \sigma \end{cases},$



Analytic insight into GC distribution in a cusp

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- For $r < r_{\rm cr}$, where $\Delta t(r_i = r_{\rm cr}; r_f = 0) = t_{\rm GC-age}$, GCs must fall to the galactic center. Then, it turns out that $N_{\rm GC}(<r)$ has an analytic approximation
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where A is a normalization factor.

- Projection effects correct this, but roughly keep the dependence
$$N_{\rm GC}(< r_{\perp}, \Delta t) \approx \widetilde{A}\ \frac{\tau(r_{\perp})}{\Delta t}$$
New analytic prediction.

Self-gravitating systems using Jeans equations

- In spherical symmetry, $\overline{v_\theta^2} = \overline{v_\phi^2}$ and equilibrium equation is $\frac{1}{\nu}\frac{d}{dr}(\nu \overline{v_r^2}) + 2\frac{\beta \overline{v_r^2}}{r} = -\frac{GM}{r^2}$, where $\beta = 1 - \overline{v_\theta^2}/\overline{v_r^2}$
- When $\beta \to 1$: $\overline{v_\theta^2} = \overline{v_\phi^2} = 0$, highly radial orbits
- When $\beta \to -\infty$: $\overline{v_r^2} = 0$, highly circular orbits
- $\beta = 0$: isotropic system.

New data used

- New estimate of galactic center, based on DES photometry.
- Revised GC mass estimates.
- Existence of GC6.
- New radial velocity measurements.

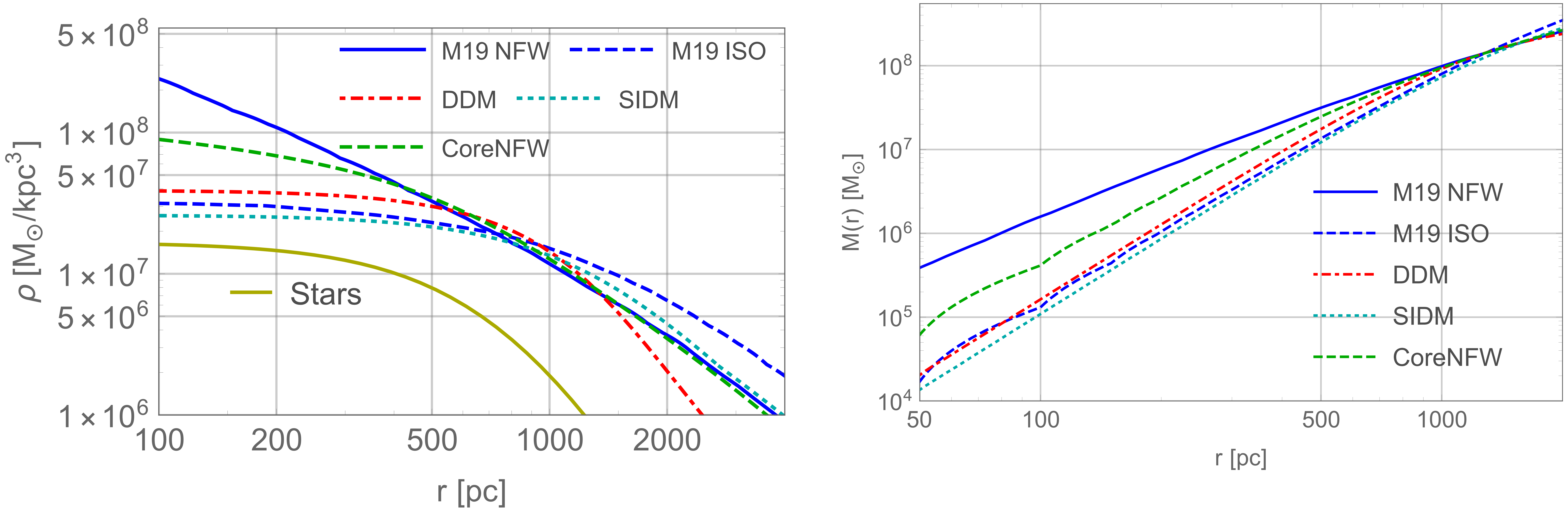
Properties of other dSph

Read+2018 arXiv: 1808.06634

Galaxy	Type	D (kpc)	M_* (10^6 $M_\odot$)	M_{gas} (10^6 $M_\odot$)	$R_{1/2}$ (kpc)	R_{gas} (kpc)	M_{200} ($10^9 M_\odot$)	Sample size	t_{trunc} (Gyrs)	$\rho_{DM}(150\,pc)$ ($10^8 M_\odot\,kpc^{-3}$)	$\gamma_{DM}(150\,pc)$	Refs.
UMi	dSph	76 ± 3	0.29	–	0.181 ± 0.027 [0.306]	–	2.8 ± 1.1	430	12.4	$1.53^{+0.35}_{-0.32}$	$-0.71^{+0.28}_{-0.29}$	3,5
Draco	dSph	76 ± 6	0.29	–	0.221 ± 0.019 [0.198]	–	1.8 ± 0.7	504	11.7	$2.36^{+0.29}_{-0.29}$	$-0.95^{+0.25}_{-0.25}$	3,4
Sculptor	dSph	86 ± 6	2.3	–	0.283 ± 0.045 [0.248]	–	5.7 ± 2.3	1,351	11.8	$1.49^{+0.28}_{-0.23}$	$-0.83^{+0.3}_{-0.25}$	3,6
Sextans	dSph	86 ± 4	0.44	–	0.695 ± 0.044 [0.352]	–	2.0 ± 0.8	417	10.6	$1.28^{+0.34}_{-0.29}$	$-0.95^{+0.36}_{-0.41}$	3,7
Leo I	dSph	254 ± 15	5.5	–	0.251 ± 0.027 [0.298]	–	5.6 ± 2.2	328	3.1	$1.77^{+0.33}_{-0.34}$	$-1.15^{+0.33}_{-0.37}$	3,8
Leo II	dSph	233 ± 14	0.74	–	0.176 ± 0.042 [0.194]	–	1.6 ± 0.7	186	6.3	$1.84^{+0.17}_{-0.16}$	$-1.5^{+0.35}_{-0.31}$	3,8
Carina	dSph	105 ± 6	0.38	–	0.250 ± 0.039 [0.242]	–	0.8 ± 0.30	767	2.8	$1.16^{+0.20}_{-0.22}$	$-1.23^{+0.39}_{-0.35}$	3,9
Fornax	dSph	138 ± 8	43	–	0.710 ± 0.077 [0.670]	–	21.9 ± 7.4	2,573	1.75	$0.79^{+0.27}_{-0.19}$	$-0.30^{+0.21}_{-0.28}$	3,10

Much more stellar mass than the rest — over abundance of GCs not unexpected

Mass profiles



DF in MOND - general

- Addressed in previous works: Ciotti & Binney 2004, Sanchez-Salcedo+2006, Angus & Diaferio 2009. We did not revisit it.
- Generally said to have quick orbital decay.
- Plummer star mass profile $M(r) = \dfrac{M_0 r^3}{(r^2 + a^2)^{3/2}}$ with $M_0 = 4.3 \times 10^7\ M_\odot$ and $a = 0.85\ \mathrm{kpc}$ roughly agrees with MOND ($v_{\rm circ} \approx (GMa_0)^{1/4} \sim 15\ \mathrm{km/s}$).
- The acceleration in Fornax is $a_{\rm gal} = \dfrac{v_{\rm circ}^2}{r} \approx 0.1 a_0 \dfrac{v_{\rm circ}^2}{(15\ \mathrm{km/s})^2} \dfrac{0.6\ \mathrm{kpc}}{r}$: indeed Mondian
- Note that $a_{\rm GC} = \dfrac{GM_{\rm GC}}{r^2} \approx a_0 \dfrac{M_{\rm GC}}{10^5\ M_\odot} \left(\dfrac{11\ \mathrm{pc}}{r}\right)^2$, hinting that essentially everywhere, stars scatter on GCs in the deep Mondian regime.

Orbital characteristics of Fornax

A&A 619, A103 (2018)
https://doi.org/10.1051/0004-6361/201833343

Astronomy & Astrophysics

Gaia DR2 proper motions of dwarf galaxies within 420 kpc

Orbits, Milky Way mass, tidal influences, planar alignments, and group infall

T. K. Fritz[1,2], G. Battaglia[1,2], M. S. Pawlowski[3,⋆], N. Kallivayalil[4], R. van der Marel[5,6], S. T. Sohn[5], C. Brook[1,2], and G. Besla[7]

Satellite	peri(1.6)(kpc)	apo(1.6)(kpc)	ecc(1.6)(kpc)	peri(0.8)(kpc)	apo(0.8)(kpc)	ecc(0.8)(kpc)
FnxI	58^{+26}_{-18}	147^{+9}_{-7}	$0.42^{+0.14}_{-0.13}$	100^{+28}_{-33}	168^{+55}_{-17}	$0.28^{+0.14}_{-0.05}$

Depends on MW potential. $(1.6) = 1.6 \times 10^{12} M_{\odot}$. Similarly (0.8).

Distance, mass to Fornax, GCs

RR Lyrae stars 1510.05642
Tip of red giant see refs in 1510.05642
Inside GCs: Mackey & Gilmore 2003 (also metallicity there)

Mass of GCs: updated in 1510.05642, using CMD and metallicity

Total mass Fornax 1510.05642

Equipartition of energy

See Binney & Tremaine (2008), Eq. 7.90 for balance of dynamical friction and dynamical heating when energy equipartition is satisfied.

The rate of change of the kinetic energy of the subject star is

$$\begin{aligned} D[\Delta E] &= m\sum_{i=1}^{3}\left(v_i D[\Delta v_i] + \tfrac{1}{2}D[\Delta v_i \Delta v_i]\right) \\ &= m\left(vD[\Delta v_\parallel] + \tfrac{1}{2}D[(\Delta v_\parallel)^2] + \tfrac{1}{2}D[(\Delta \mathbf{v}_\perp)^2]\right) \\ &= 16\pi^2 G^2 m m_a \ln\Lambda \left[m_a \int_v^\infty \mathrm{d}v_a\, v_a f_a(v_a) - m\int_0^v \mathrm{d}v_a\, \frac{v_a^2}{v} f_a(v_a)\right]. \end{aligned} \tag{7.90}$$

Coulomb logarithm calibration

In NFW case

$$\ln\Lambda_{\rm NFW} = \ln\frac{b_{\rm max}\sigma^2}{GM},\ b_{\rm max} = 0.5\ {\rm kpc}.$$

In Core case

$$\ln\Lambda_{\rm ISO} = \ln\frac{2rV^2}{GM}$$

Roughly agreeing with earlier definitions, but not exactly. To avoid small logarithm problems, we replace

$$\ln\Lambda \rightarrow \frac{1}{2}\ln(1+\Lambda^2)$$

(minor?) Caveats

the time of formation of solitons is not known for the higher masses

$$m \gtrsim 10^{-21}\,\mathrm{eV}$$

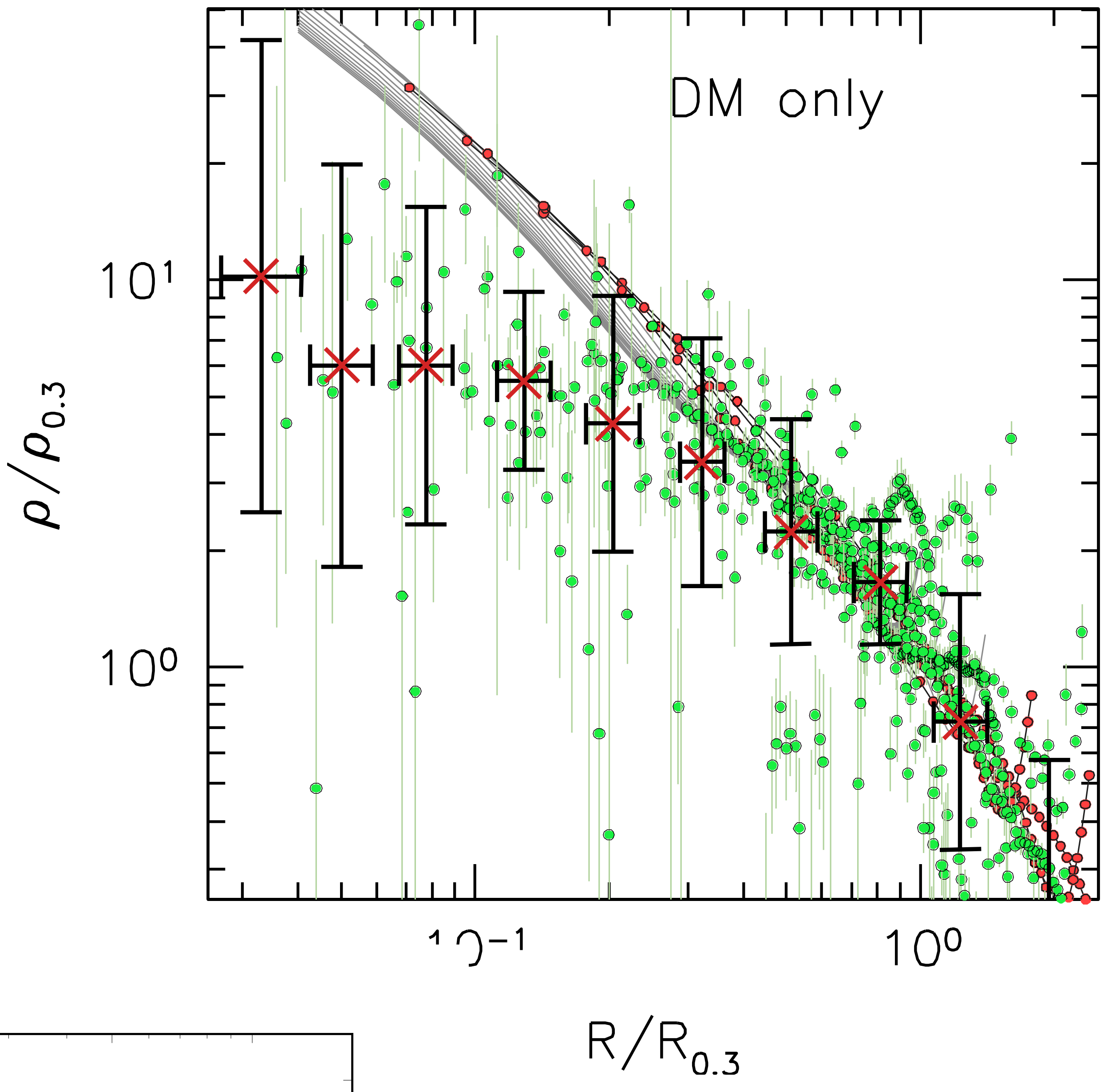
a SMBH may absorb the soliton (not relevant for our constraints)

self-interaction may change the picture (though there are natural choices that don't)

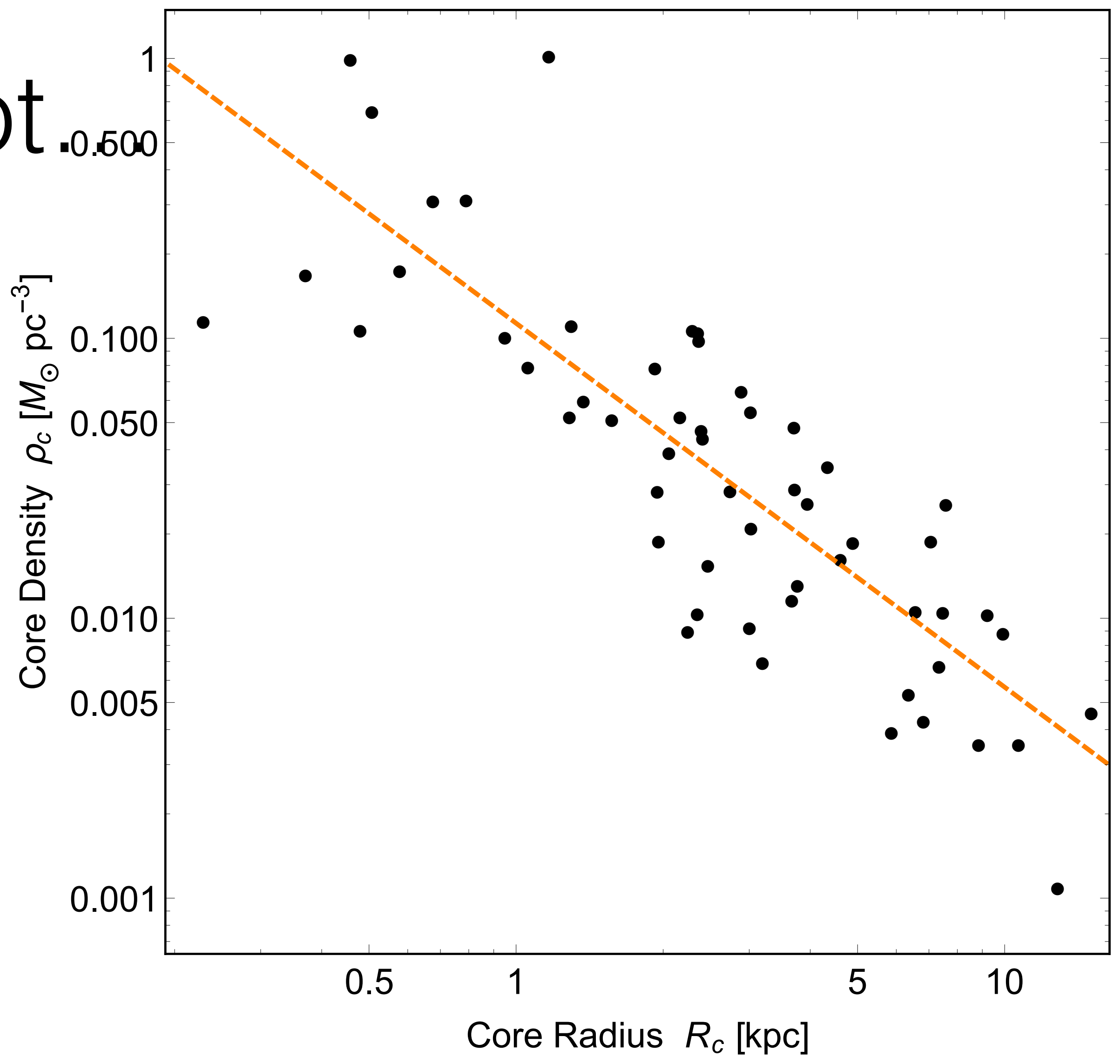
Any connection to core vs cusp?

Oh et al. 1502.01281

centers of dwarf galaxies
flatter than CDM only



probably not



Deng et al. 1804.05921

data

$$\rho_c \propto R_c^{-1.3}$$

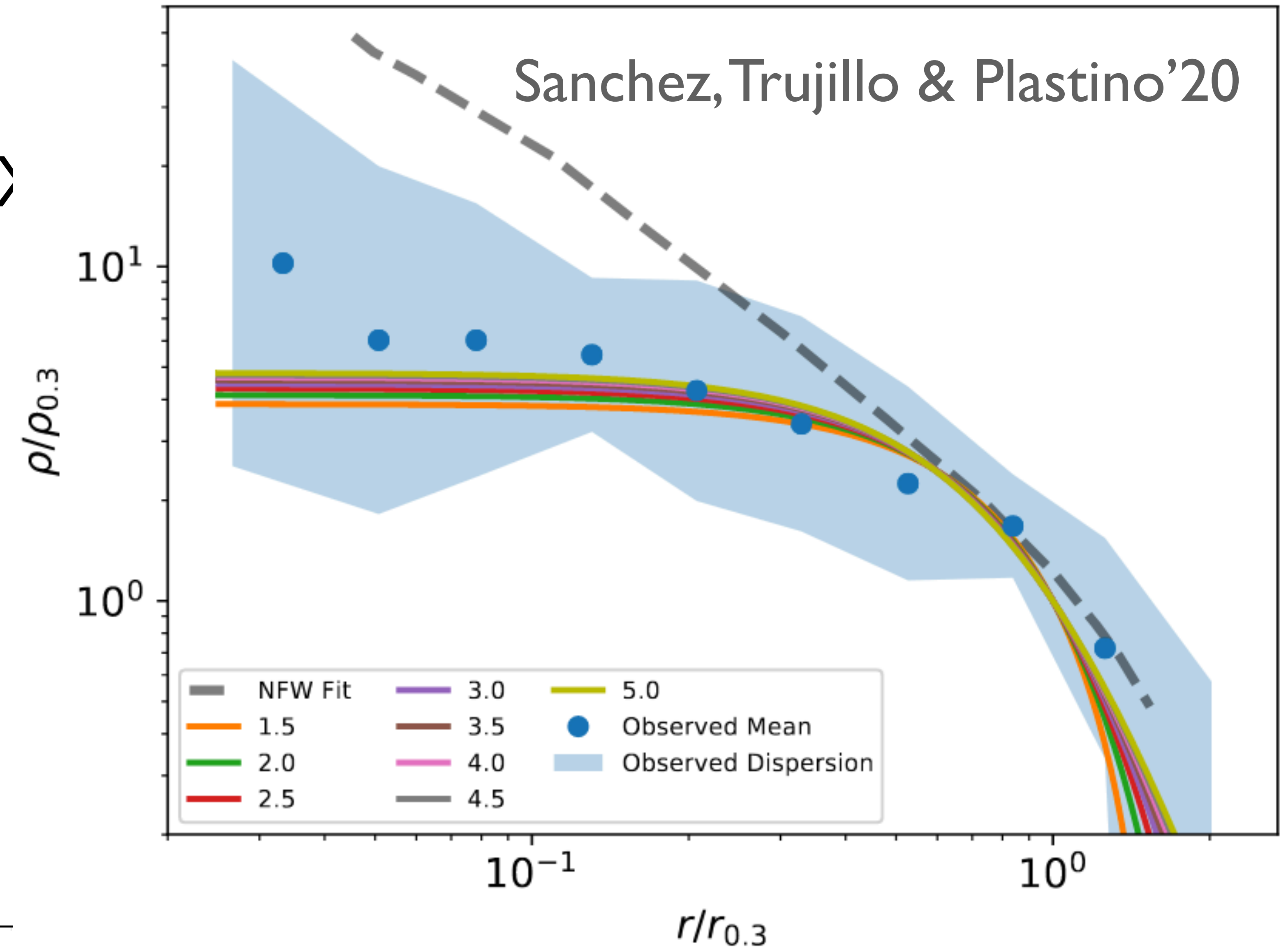
ULDM solitons

$$\rho_c \propto R_c^{-4}$$

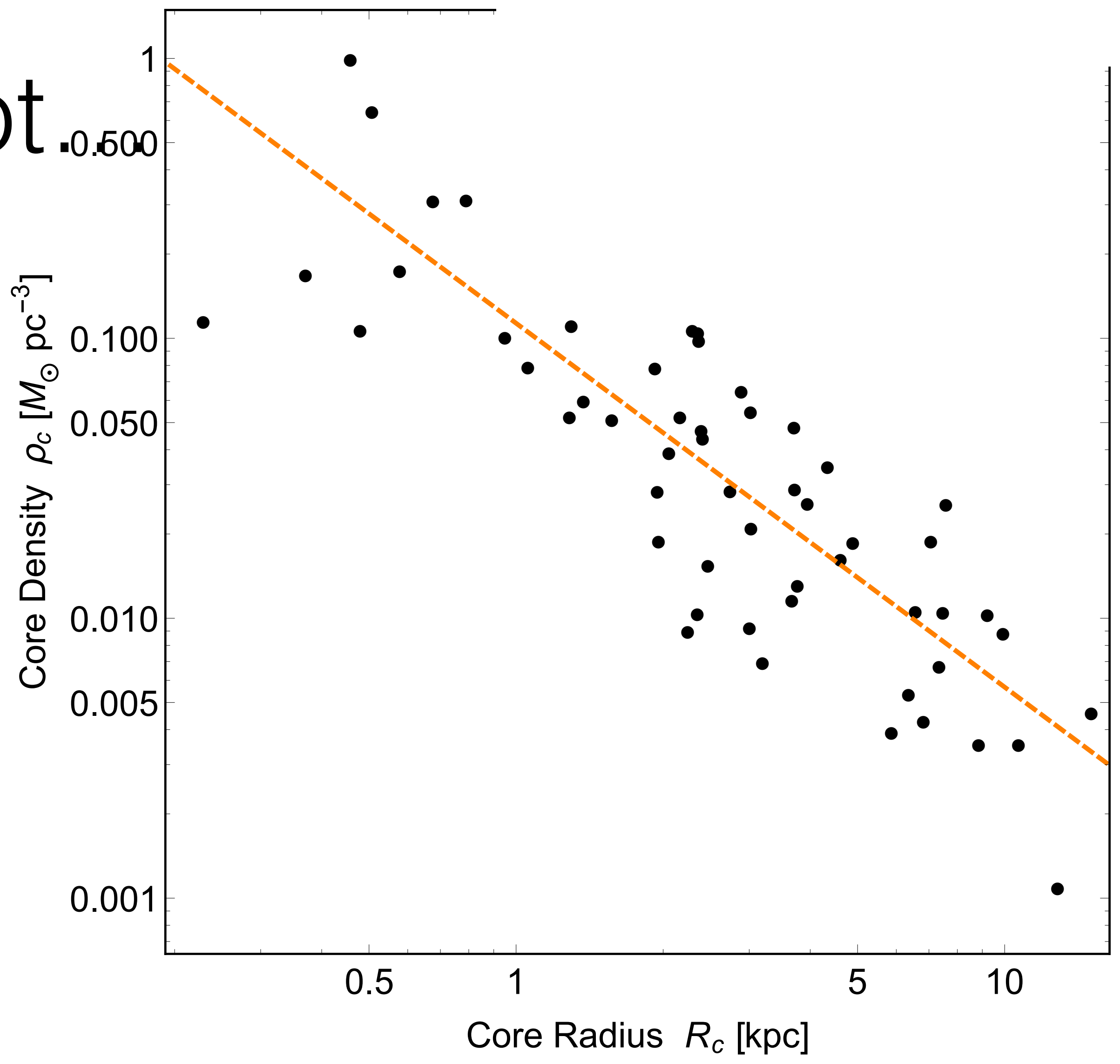
Any connection to core vs cusp?

Oh et al. 1502.01281

centers of dwarf galax
flatter than CDM on



probably not



Deng et al. 1804.05921

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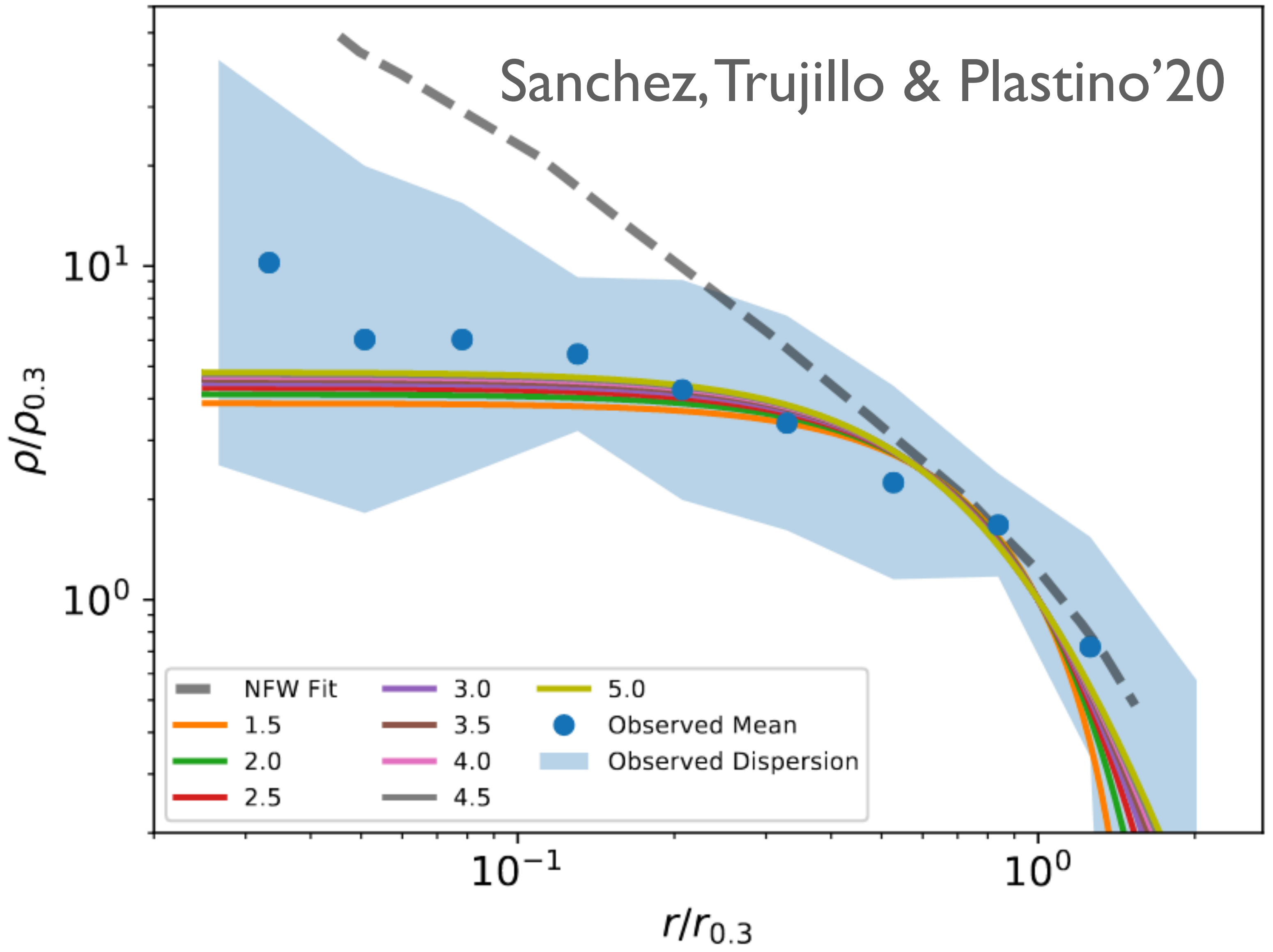
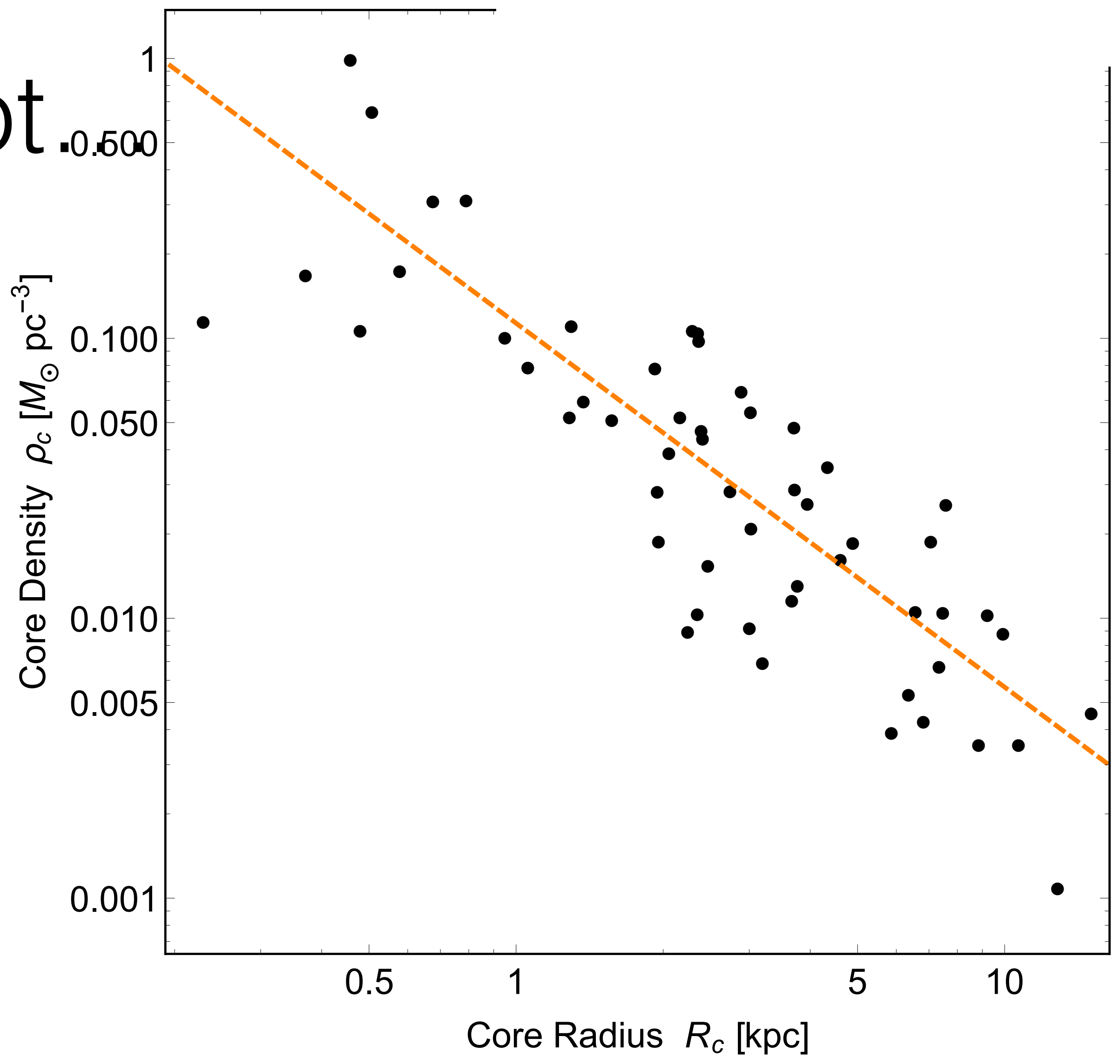


probably not.



Deng et al. 1804.05921

data

$$\rho_c \propto R_c^{-1.3}$$

ULDM solitons

$$\rho_c \propto R_c^{-4}$$

baryons? PBH?
SIDM? Degenerate DM?