The Inner Dark Matter Distribution in Hydrodynamic Simulations

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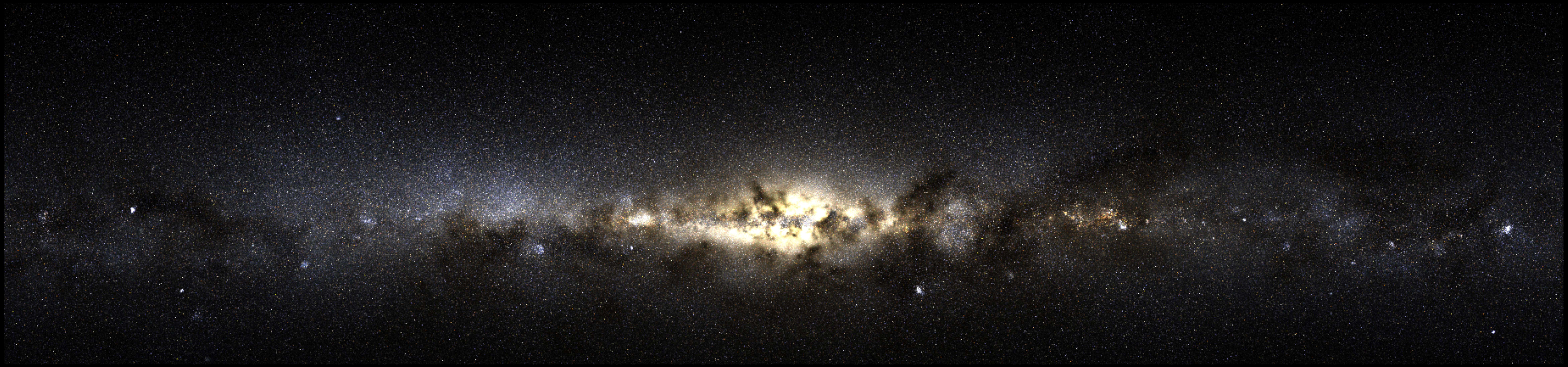
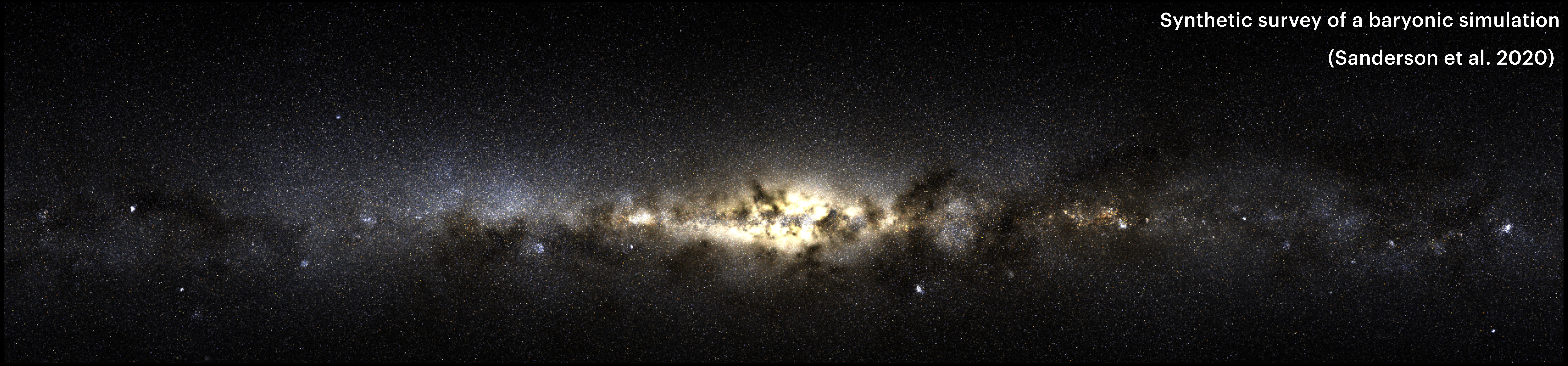
Massachusetts Institute of Technology

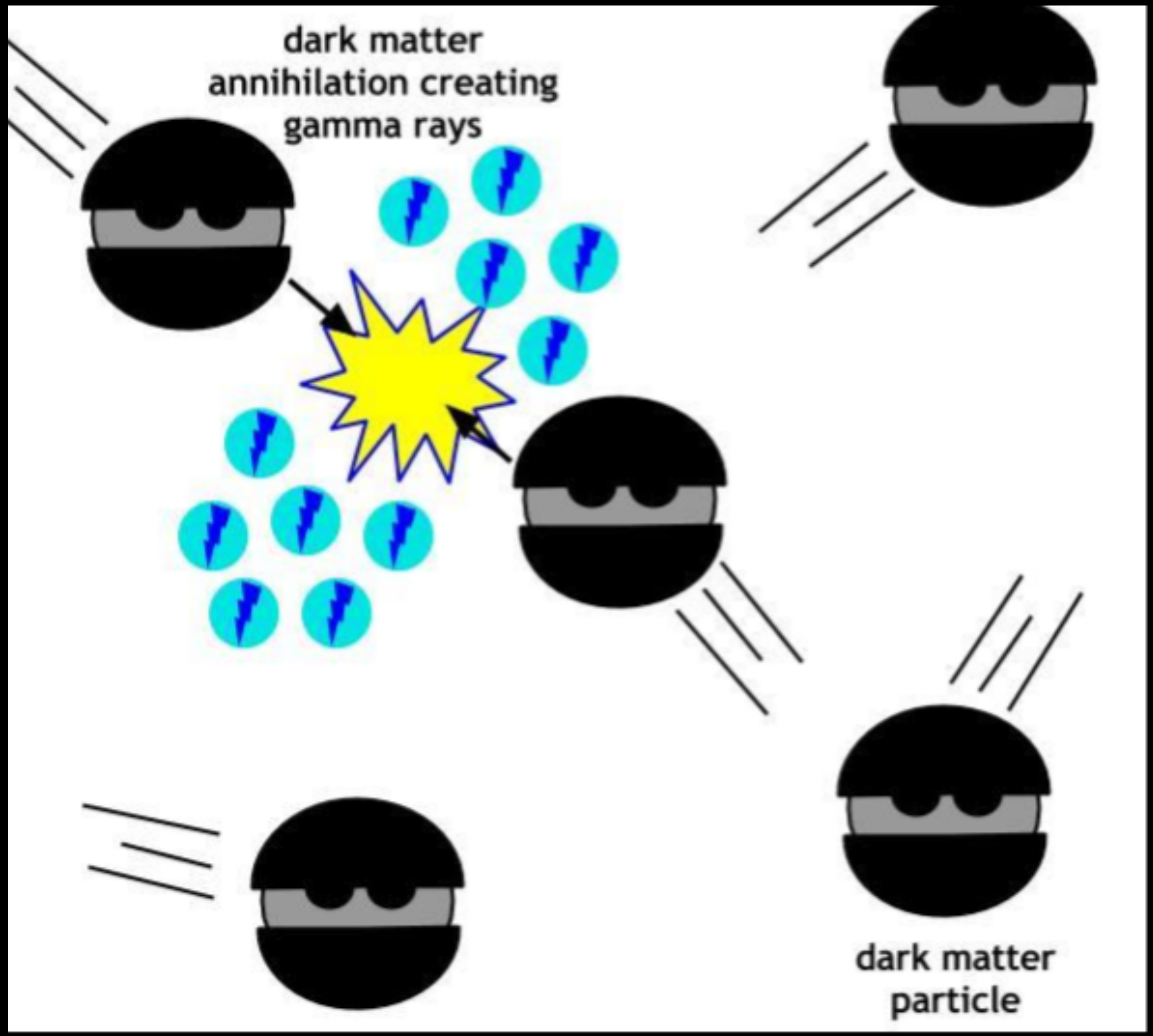



Milky Way
Credit: ESO


Synthetic survey of a baryonic simulation
(Sanderson et al. 2020)

Why care about the density distribution?

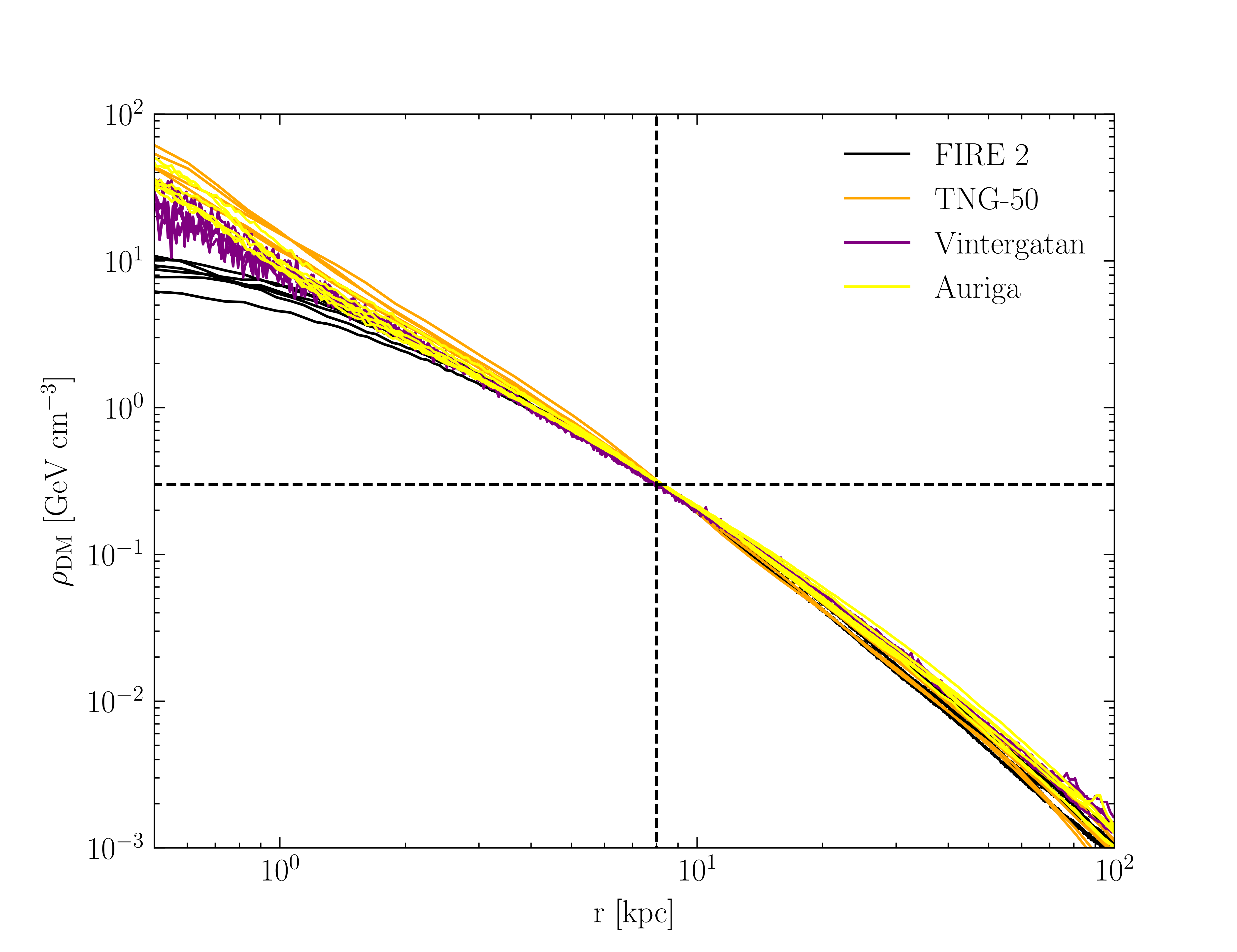
- For some DM models (ex: WIMPs) we get γ-ray emission from annhilation(Arcadi et al. 2018).
- The annihilation flux luminosity depends sensitively on $\rho_{\mathbf{DM}}$.
  - $\mathscr{L} \propto \rho^2_{\mathbf{DM}}$
- While traditionally a form for the DM density profile is assumed (NFW, Einasto,...), we can get a more informative result by using the density numerically calculated from the simulation.



(Credit: Andrea Albert)

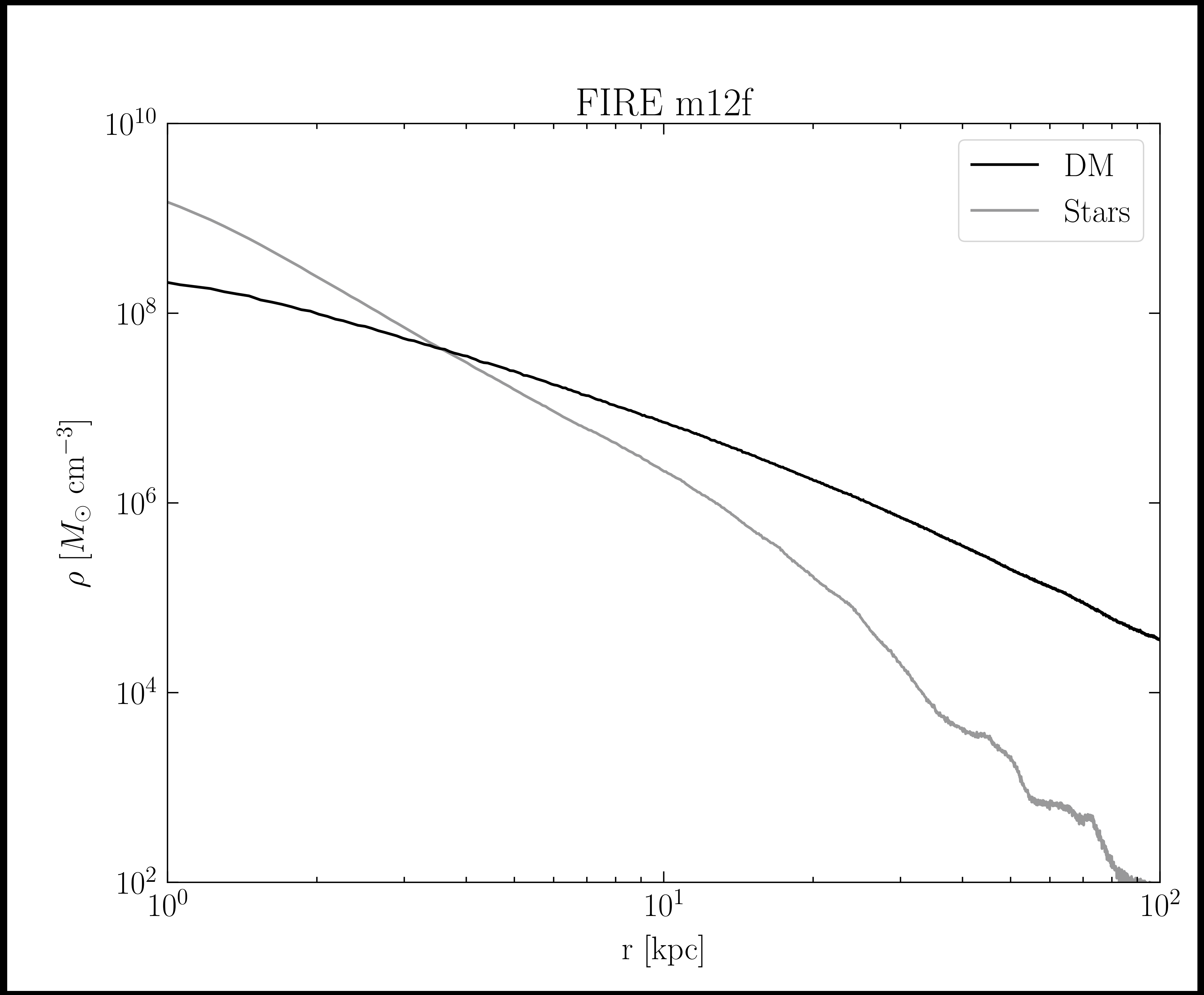
DM Distribution in different simulation suites:

- **Largest difference within 1 kpc**
- **Density similar for r > 1 kpc**
- **How can we quantify the difference?**
  - **Can any of these be modeled through adiabatic contraction?**



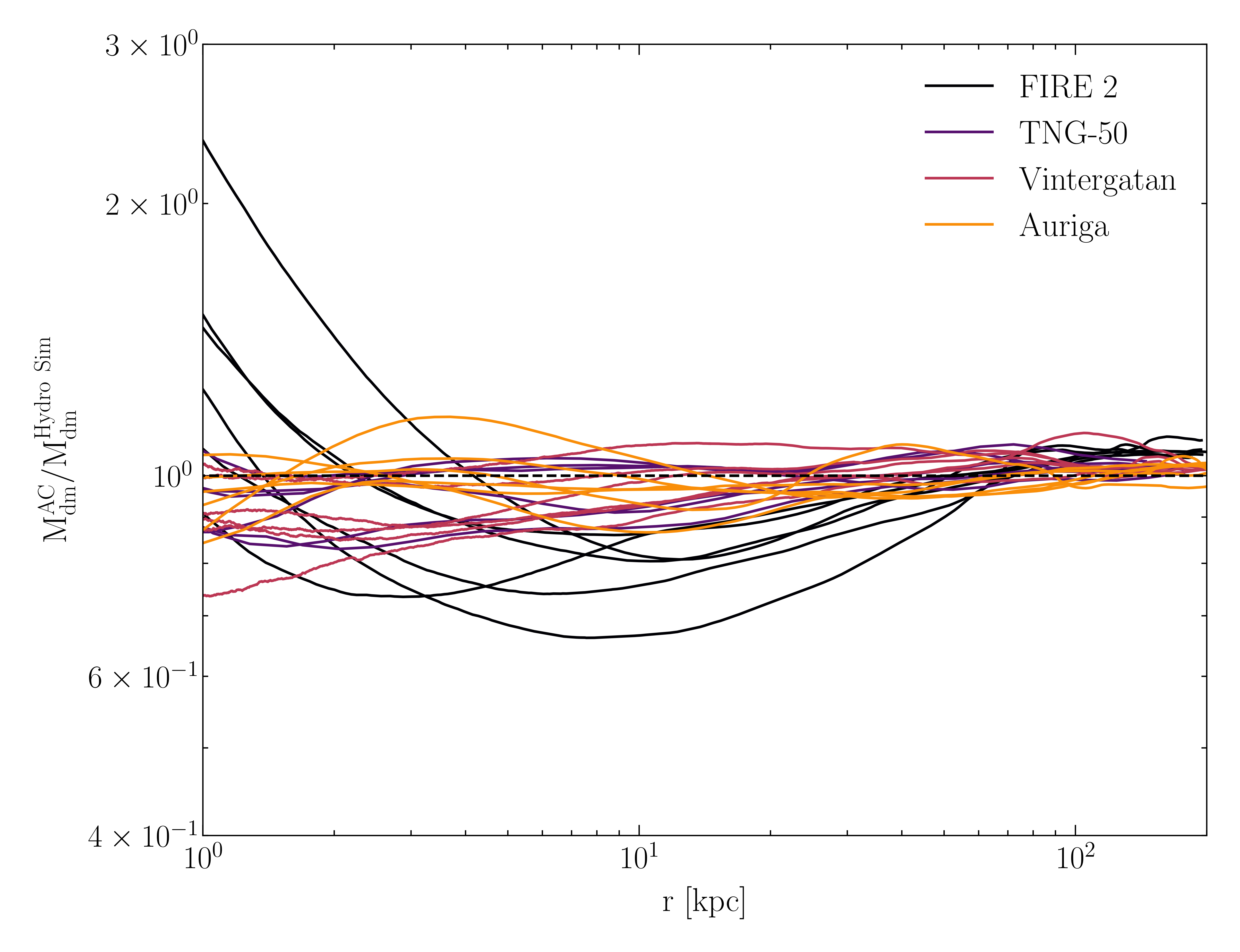
Adiabatic contraction overview:

- **The gravitational field in the central regions of galaxies is dominated by stars.**
- **The conserved quantities for eccentric orbits (Ghigna et al. 1998)**
  - **the radial action** $I_r \equiv \frac{1}{\pi}\int_{r_p}^{r_a} v_r \, dr$
    - **(Gnedin et al. 2004) argued that the conserved quantity** $r\ M(\bar{r})$ **is a better proxy for the radial action.**



Results:

- **The ratio deviates within 10 kpc from 1 for FIRE sims relative to TNG50, Vintergatan and Auriga**
- **Vintergatan, TNG50 and Auriga DM density profiles can be described using adiabatic contraction.**



Conclusion:

- Two possible solution:
  - Adiabatic contraction
  - Strong Feedback
- We will use AC to model the DM density profile of the MW
  - Obtain photon emission from DM annihilation signal.

Back up

Cosmological simulations overview:

Simulations	Year	Technique	SMBH Feedback	$m_{\text{DM}} (M_\odot)$	$m_{\text{baryon}} (M_\odot)$
Auriga L3	2017	Zoom in	Yes	5E+04	6E+03
FIRE-2	2017	Zoom in	No	3.5E+04	7.1E+03
Vintergatan	2020	Zoom in	No	3.5E+04	7.07E+03
TNG-50	2019	Uniform Resolution	Yes	4.5E+05	8E+04

Adiabatic contraction input:

$$M_{\rm DM}^{\rm inital}(r_{\rm inital}) = M_{\rm DM}^{\rm final}(r_{\rm final})$$

$$r_{\textbf{initial}}(M_{\textbf{DM}}^{\textbf{initial}}(\bar{r}_{\textbf{initial}}) + M_{\textbf{Stars}}^{\textbf{initial}}(\bar{r}_{\textbf{initial}})) = r_{\textbf{final}}(M_{\textbf{DM}}^{\textbf{final}}(\bar{r}_{\textbf{final}}) + M_{\textbf{Stars}}^{\textbf{final}}(\bar{r}_{\textbf{final}}))$$

- **Inputs (all z=0):**
    - **DM distribution from DMO sim**
    - **A stellar distribution that is self similar to the DMO distribution**
    - **Stellar density profile from hydro sim**

Cosmological simulations overview:

(credit: Phil Hopkins)

Calculation overview:

$$f_b = \frac{M_{Stars}^{hydro}(r_{200c})}{M_{DM}^{hydro}(r_{200c})} \quad (5)$$

$$f_{norm} = \frac{M_{DM}^{hydro}(r_{200c}) + M_{Stars}^{hydro}(r_{200c})}{M_{DM}^{DMO}(r_{200c})} \quad (6)$$

$$M_{\mathrm{DM}}^{\mathrm{initial}}(r) = (M_{DM}^{DMO}(r) \cdot f_{norm}) \cdot (1 - f_b) \quad (7)$$

$$M_{\mathrm{Stars}}^{\mathrm{initial}}(r) = (M_{DM}^{DMO}(r) \cdot f_{norm}) \cdot f_b \quad (8)$$

$$r_{\mathrm{initial}}(M_{\mathrm{DM}}^{\mathrm{initial}}(\bar{r}_{\mathrm{initial}}) + M_{\mathrm{Stars}}^{\mathrm{initial}}(\bar{r}_{\mathrm{initial}})) = r_{\mathrm{final}}(M_{\mathrm{DM}}^{\mathrm{final}}(\bar{r}_{\mathrm{final}}) + M_{\mathrm{Stars}}^{\mathrm{final}}(\bar{r}_{\mathrm{final}})) \quad (9)$$

$$M_{\mathrm{DM}}^{\mathrm{inital}}(r_{\mathrm{inital}}) = M_{\mathrm{DM}}^{\mathrm{final}}(r_{\mathrm{final}})$$

Find fixed point

$$\bar{r} = r_{vir}\ A(\frac{r}{r_{vir}})^w$$

tested by (Gustafsson et al 2007)

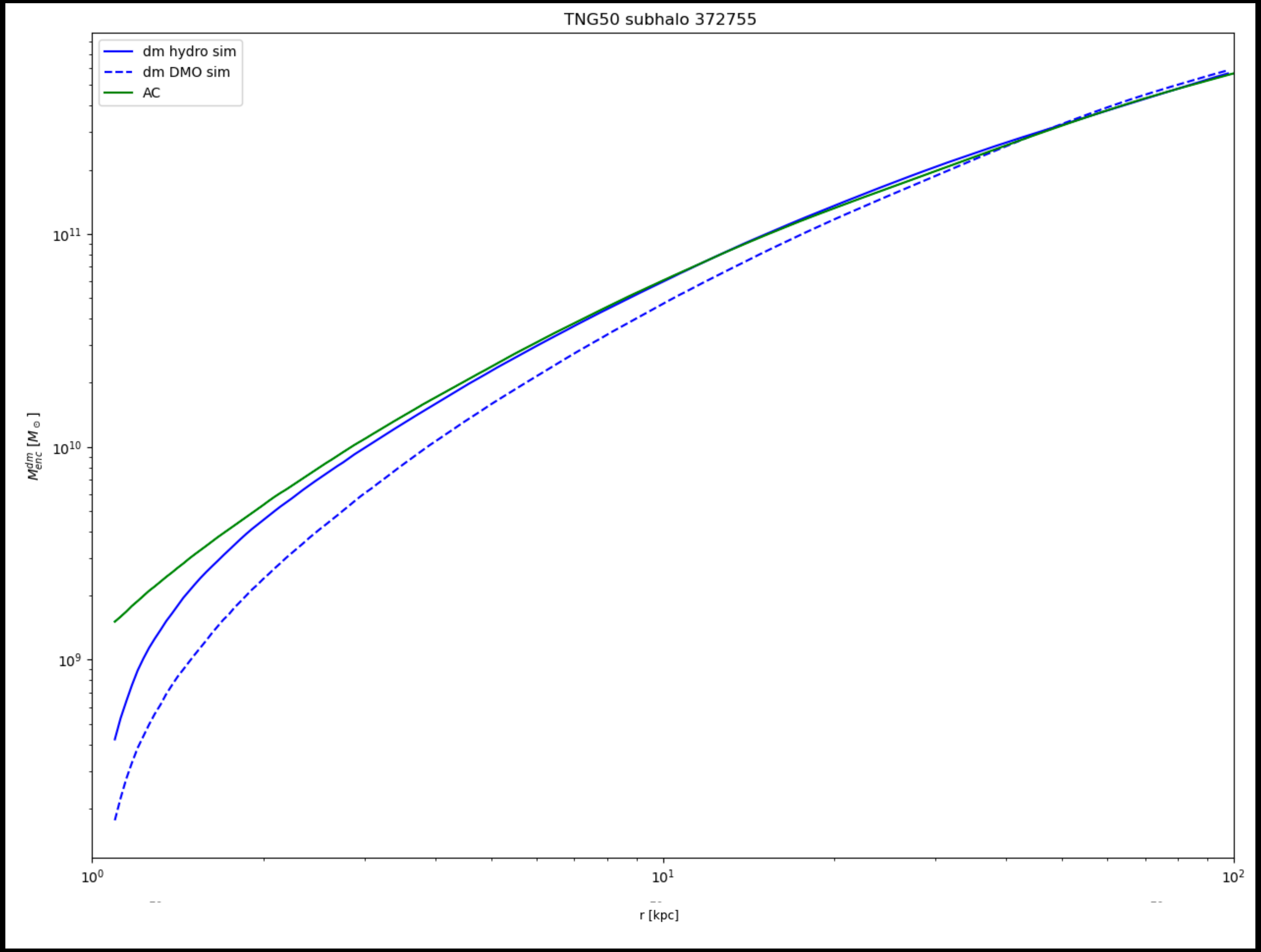
Given such a wide eccentricity distribution, the orbit-averaged radius varies for particles at a given current radius r depending on the orbital phase. Nevertheless, the mean relation can be described by a power law function.

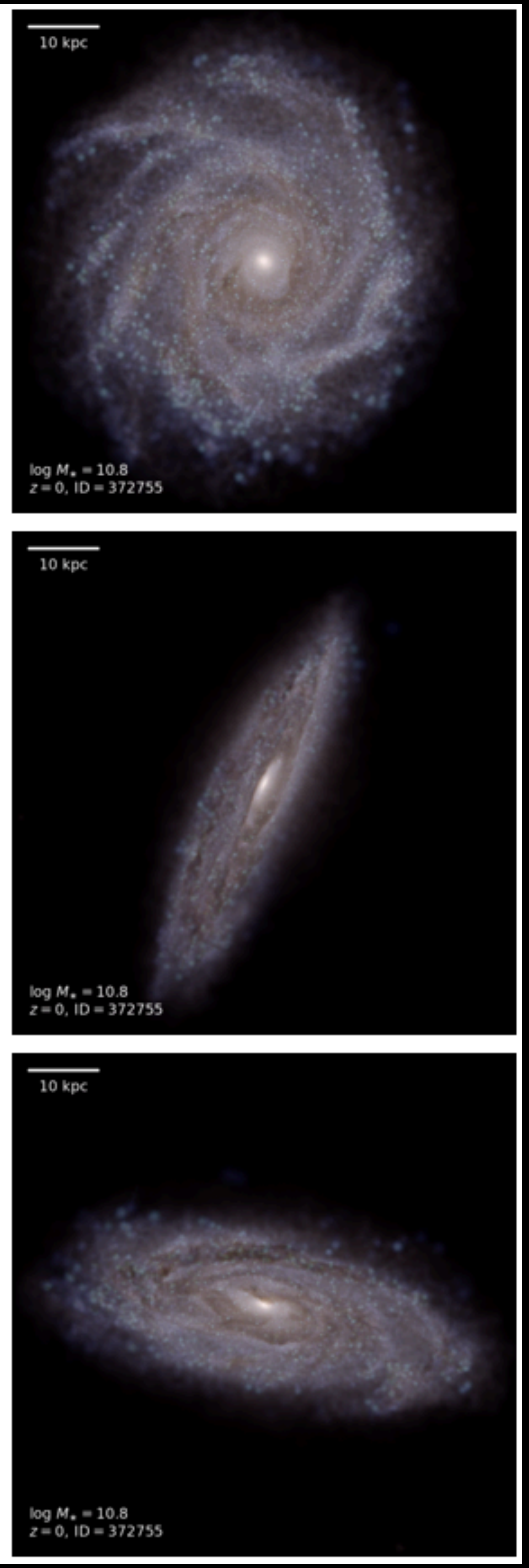
Density threshold:

Simulation	$\rho_{\rm th}$ (cm^{-3})
TNG_50	0.13
Auriga	0.13
Vintergatan	100
FIRE	1000

Table 7. Density threshold ρ_{th} for star formation

Adiabatic Contraction in TNG50:





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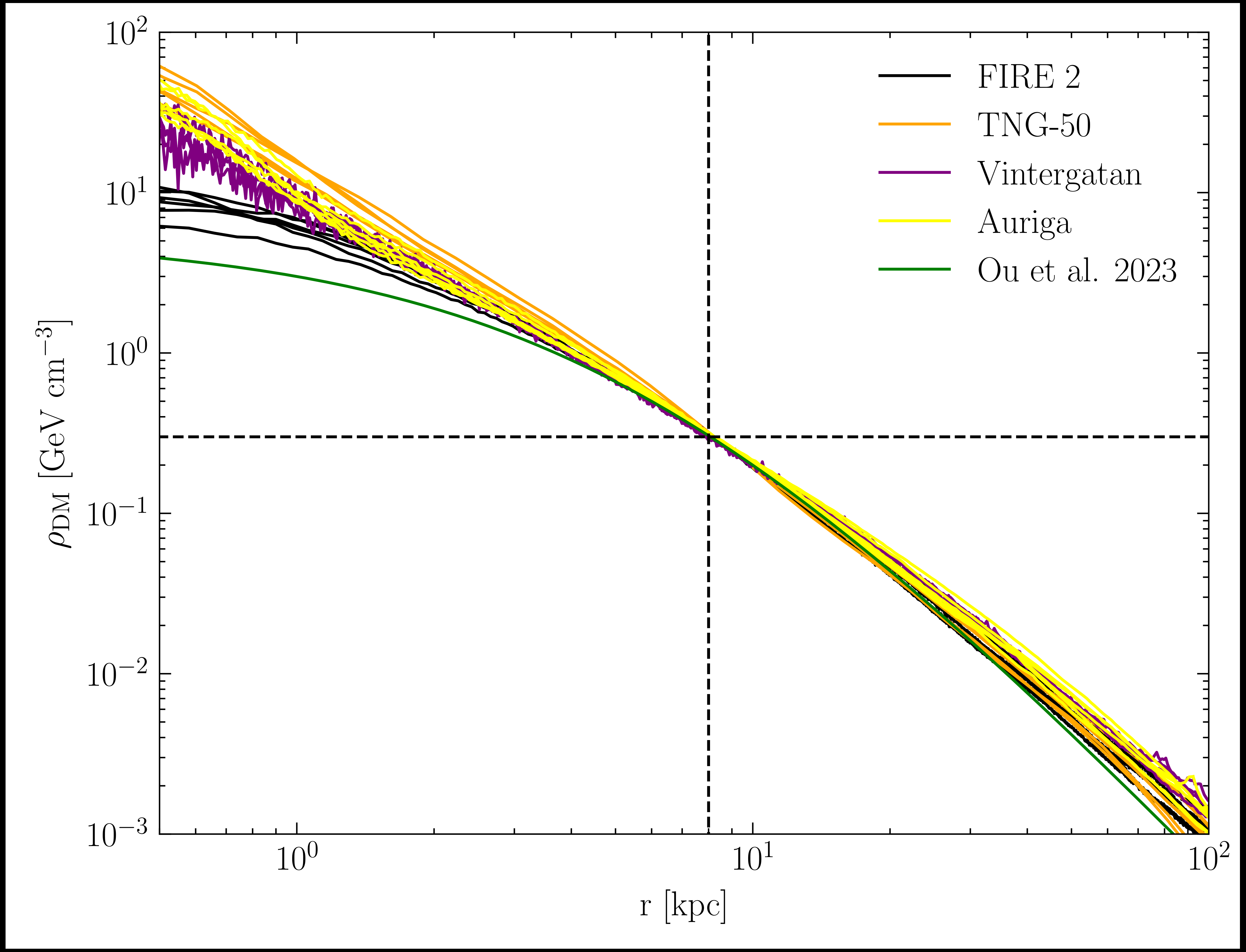
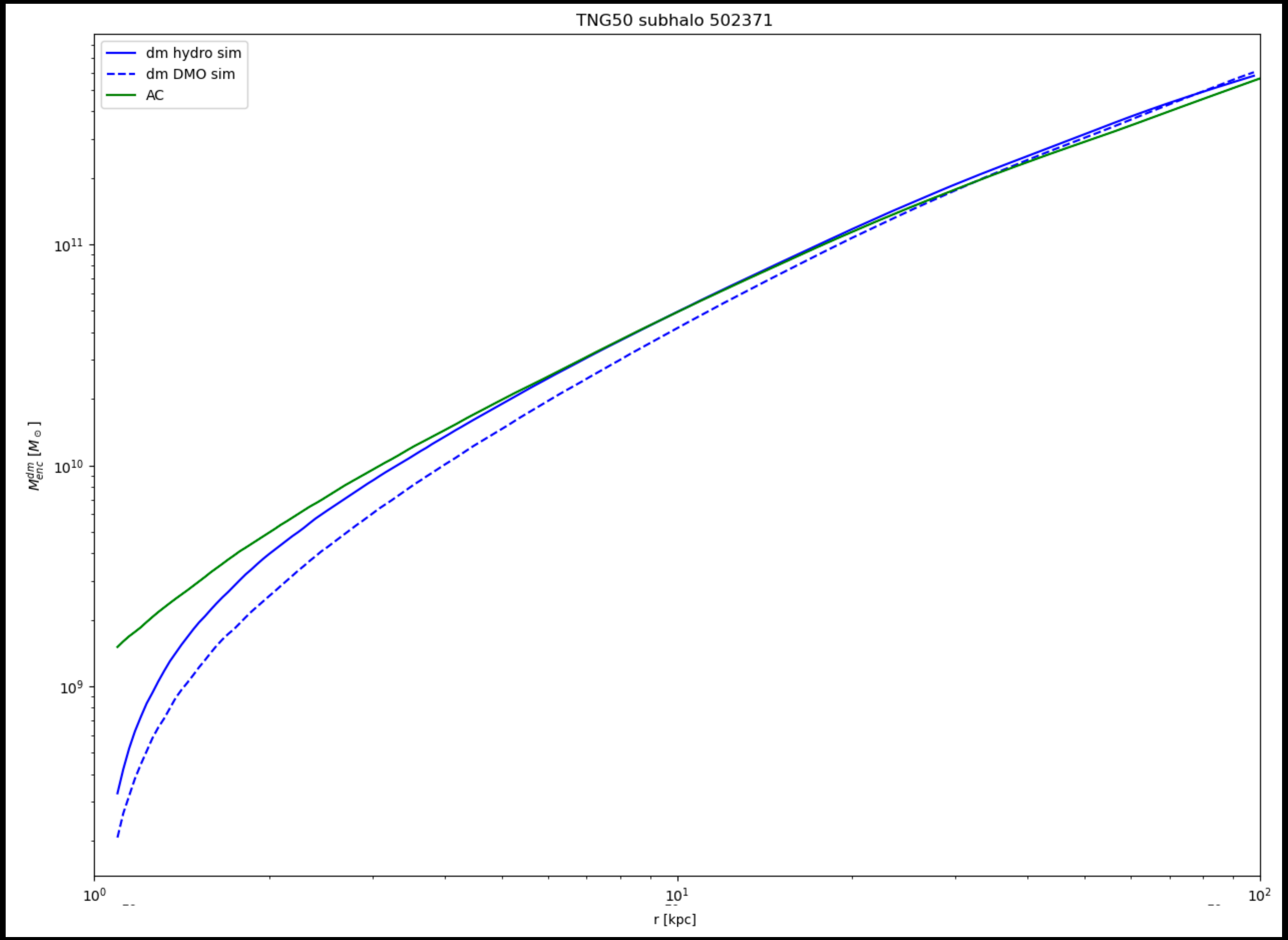
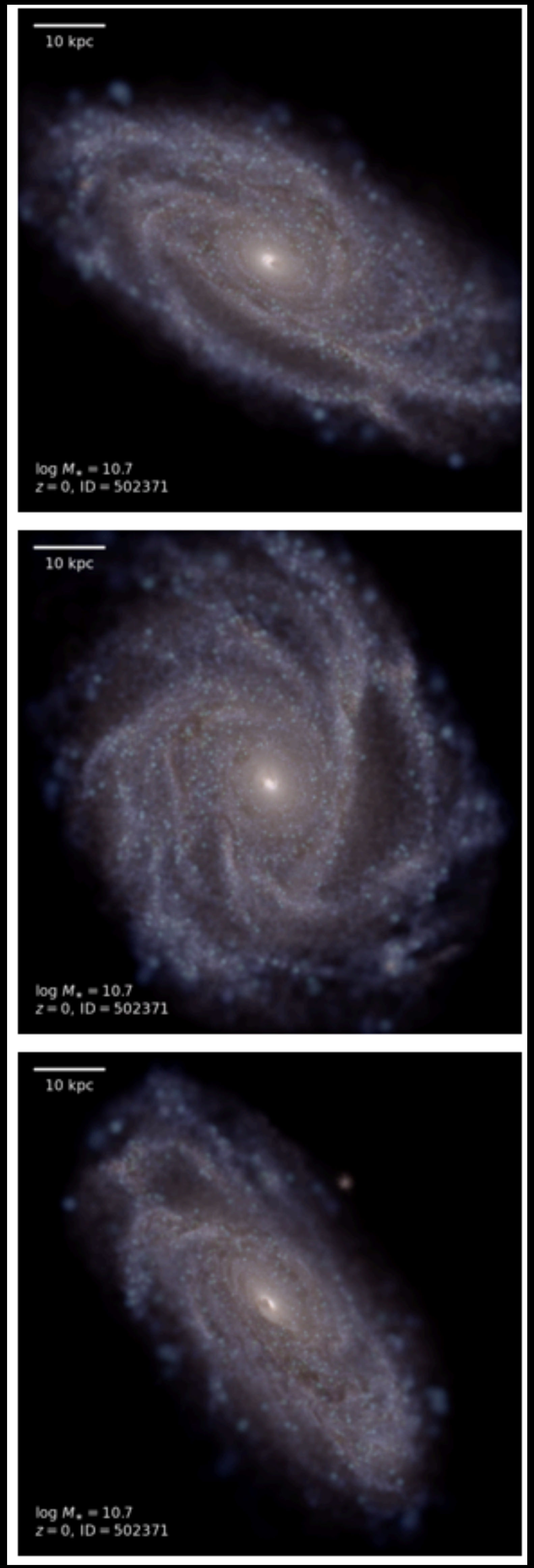


Adiabatic Contraction in TNG50:



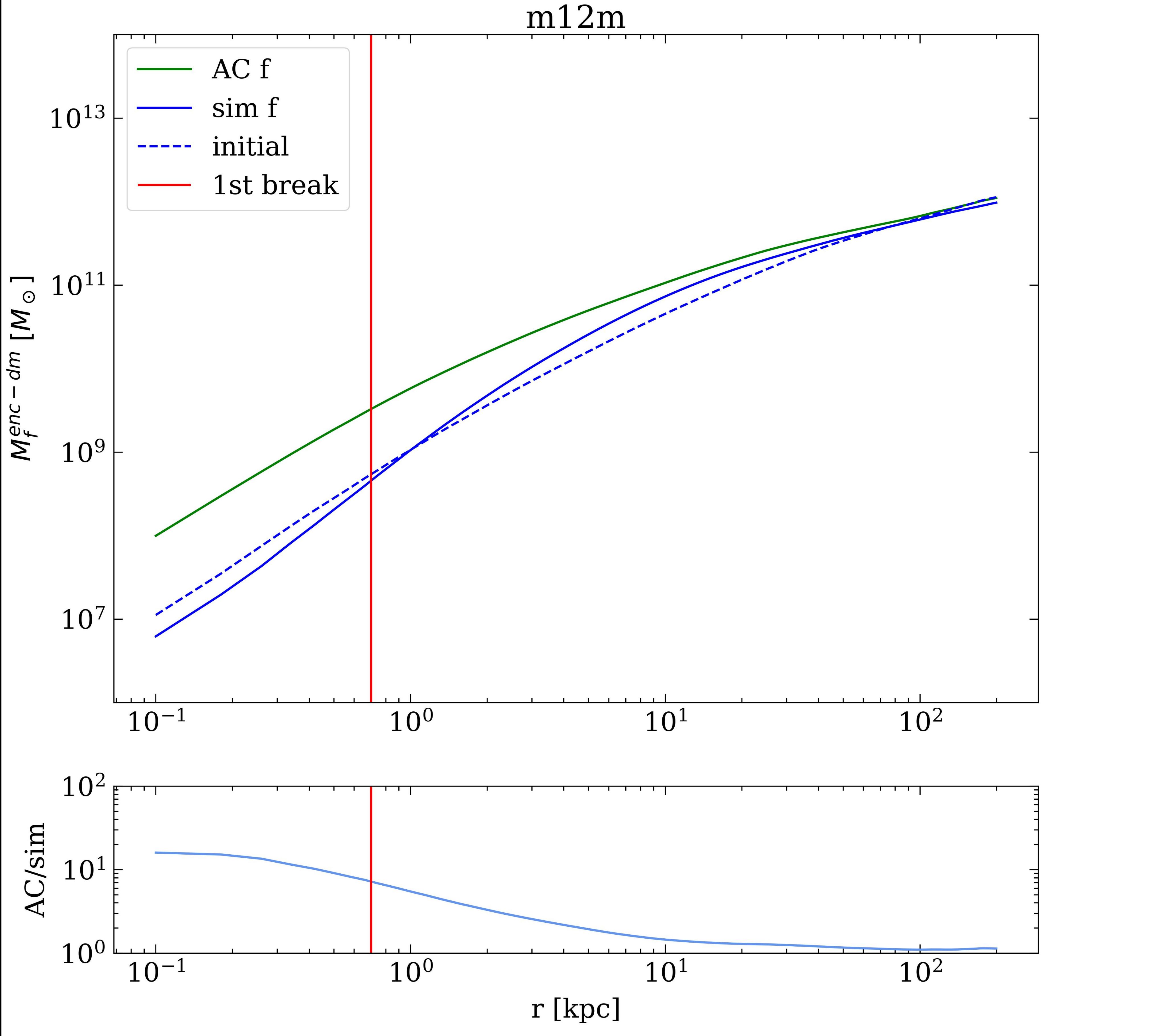


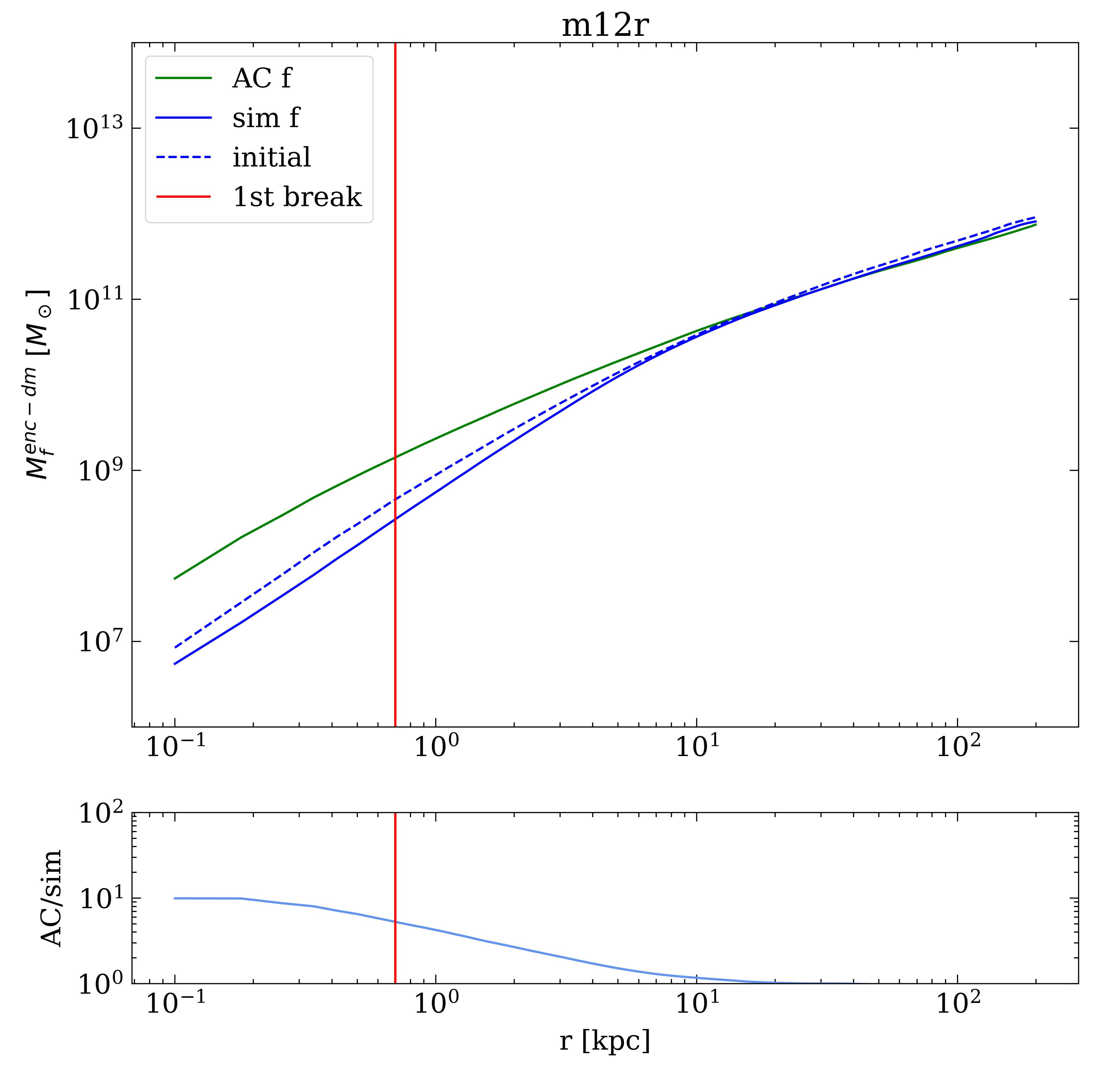
Adiabatic Contraction in FIRE m12s

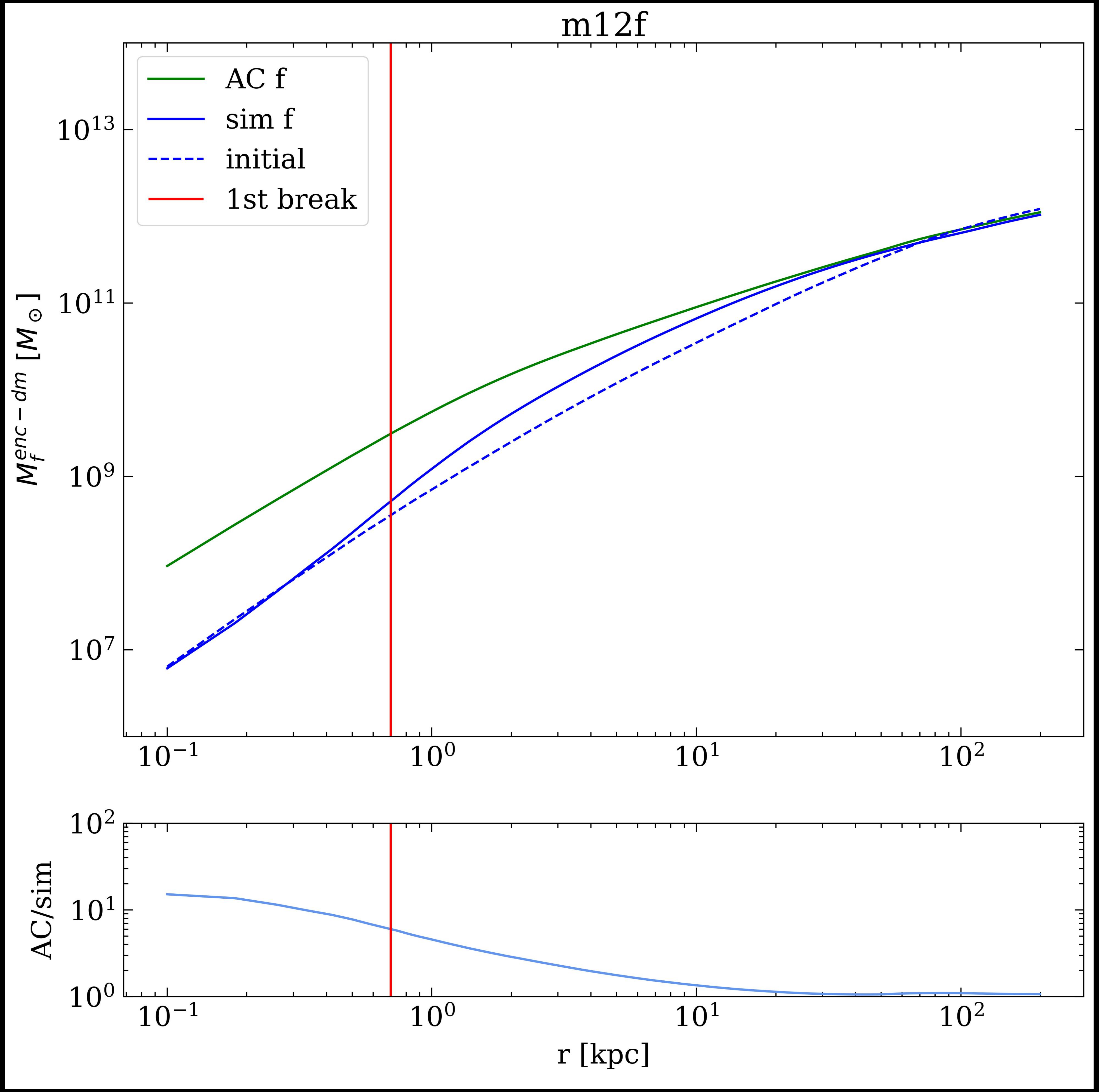
(Gnedin et al. 2004)

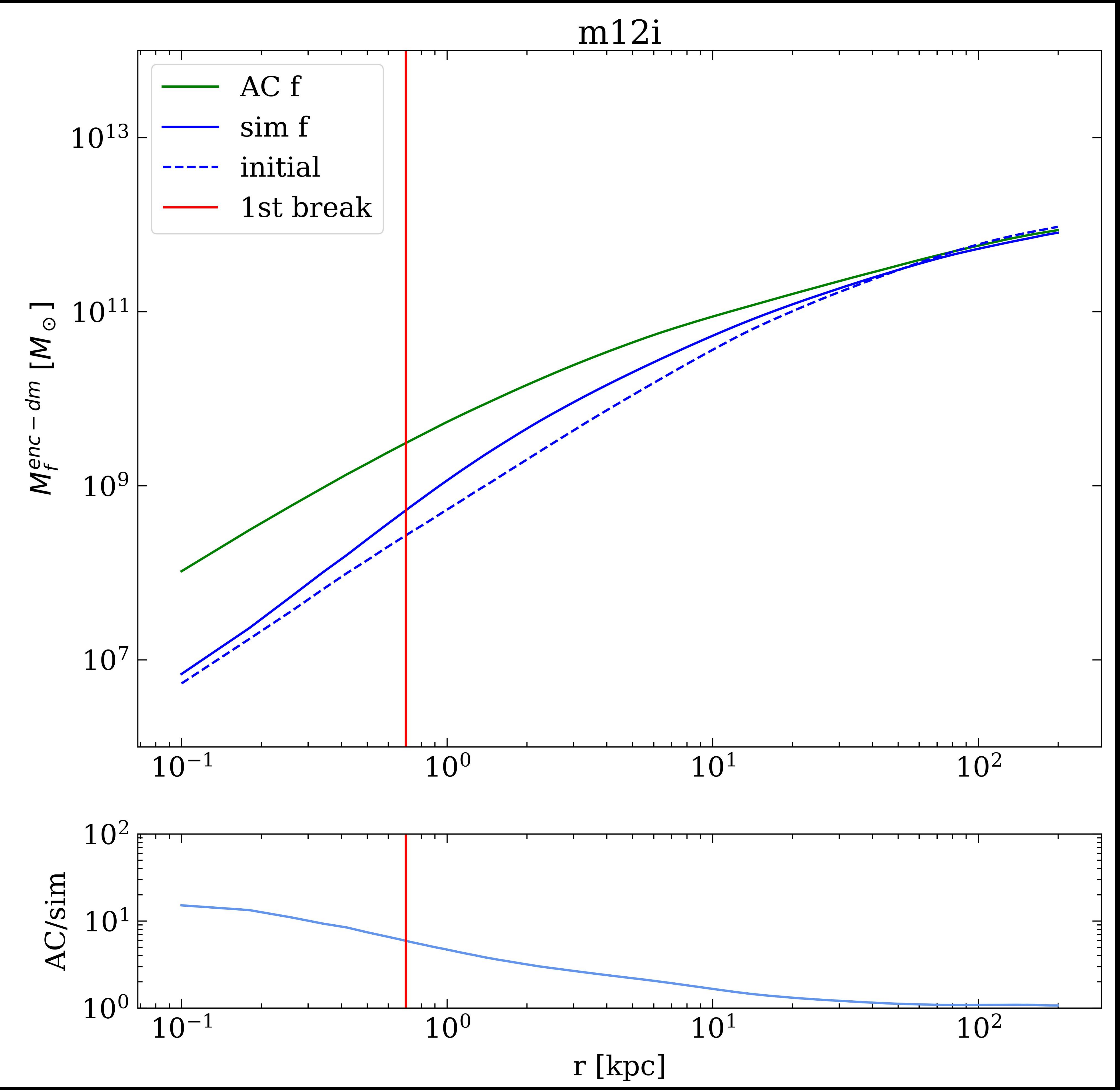
$$r\ M(\bar{r}) = const$$

$$\bar{r} = r_{vir}\ A(\frac{r}{r_{vir}})^{w} \qquad A = 0.85,\ w = 0.8$$

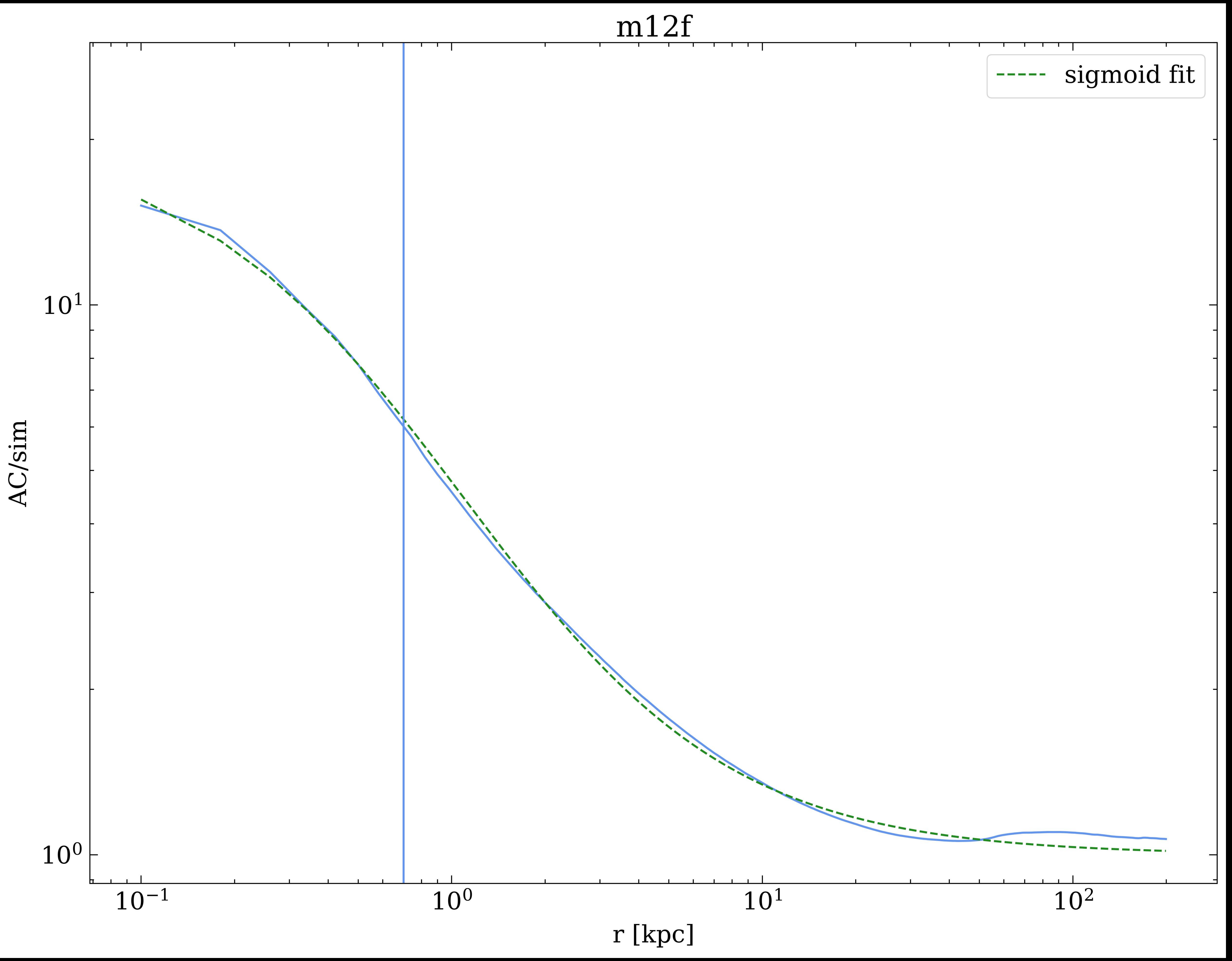


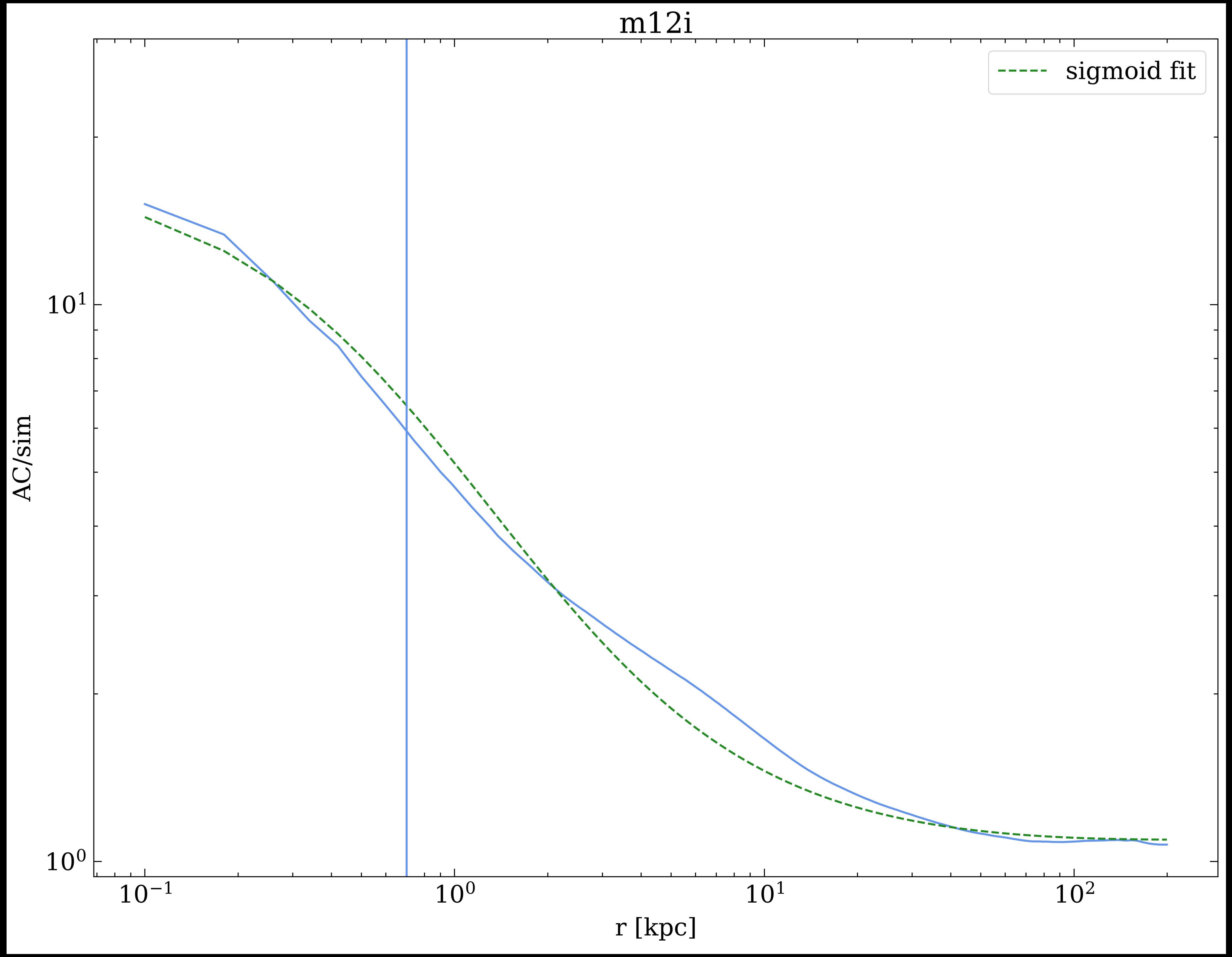



m12f
AC f
sim f
initial
1st break
M_f^{enc-dm} [$M_\odot$]
AC/sim
r [kpc]

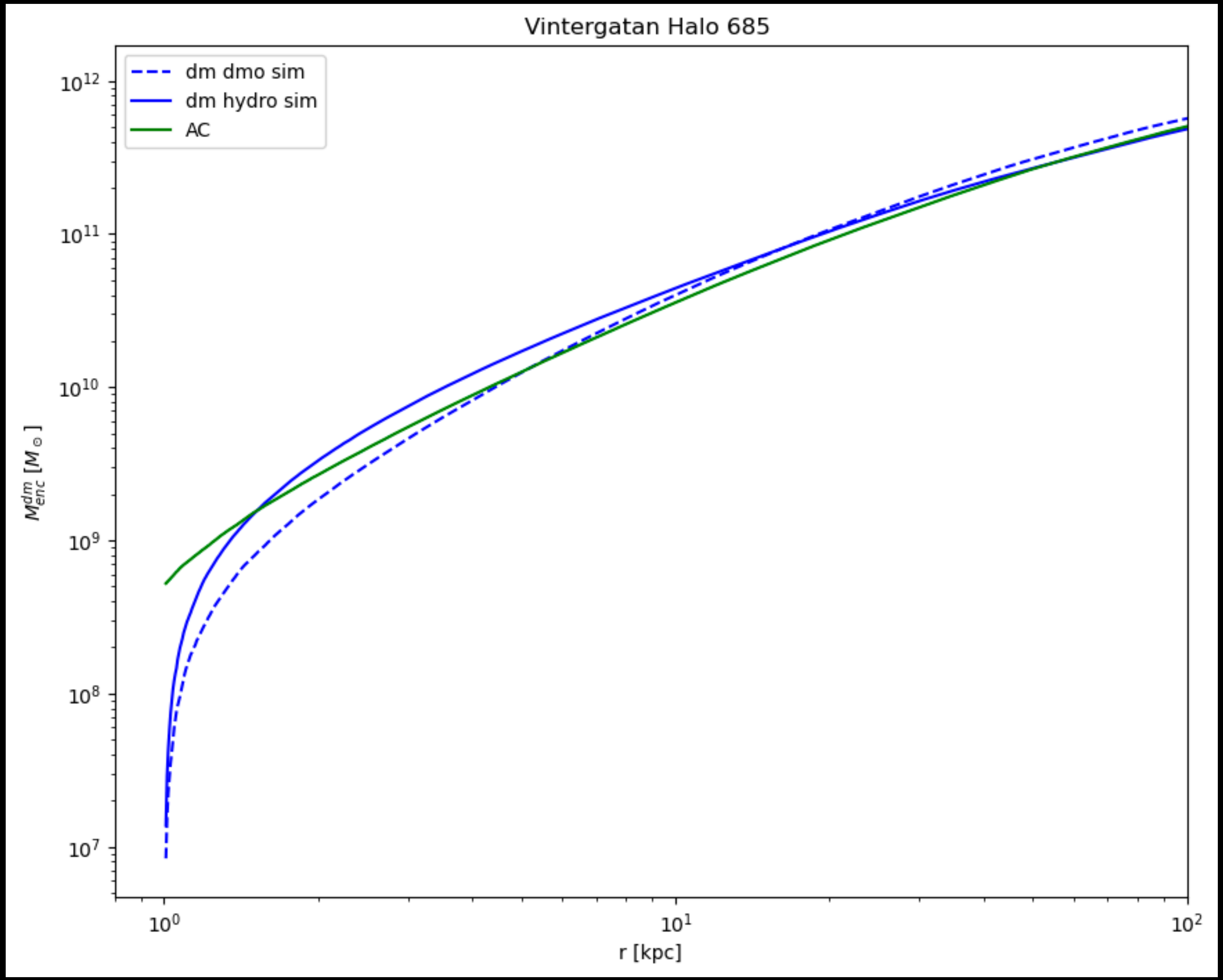

m12i
AC f
sim f
initial
1st break
M_f^{enc-dm} [$M_\odot$]
AC/sim
r [kpc]

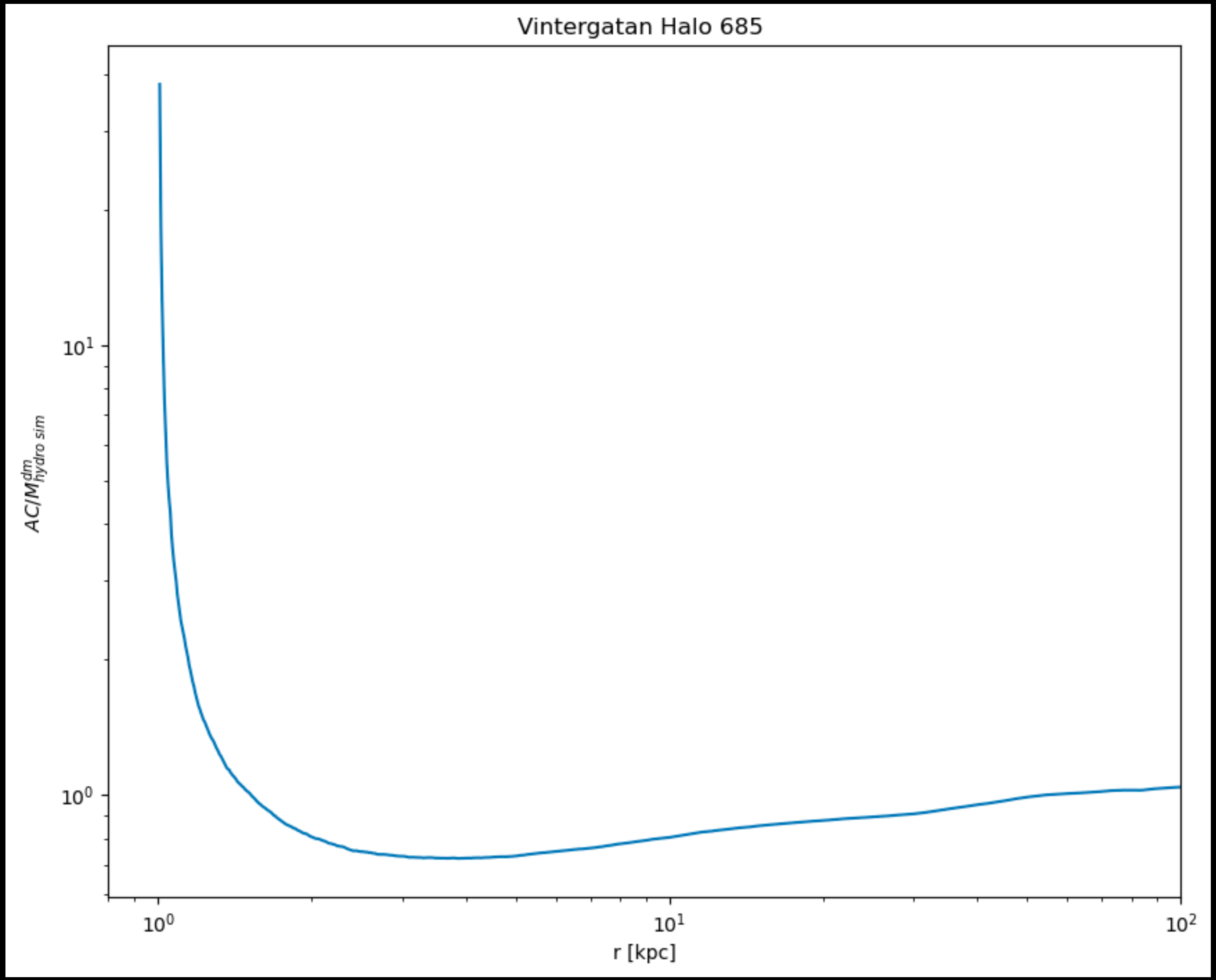
Looking at transformation

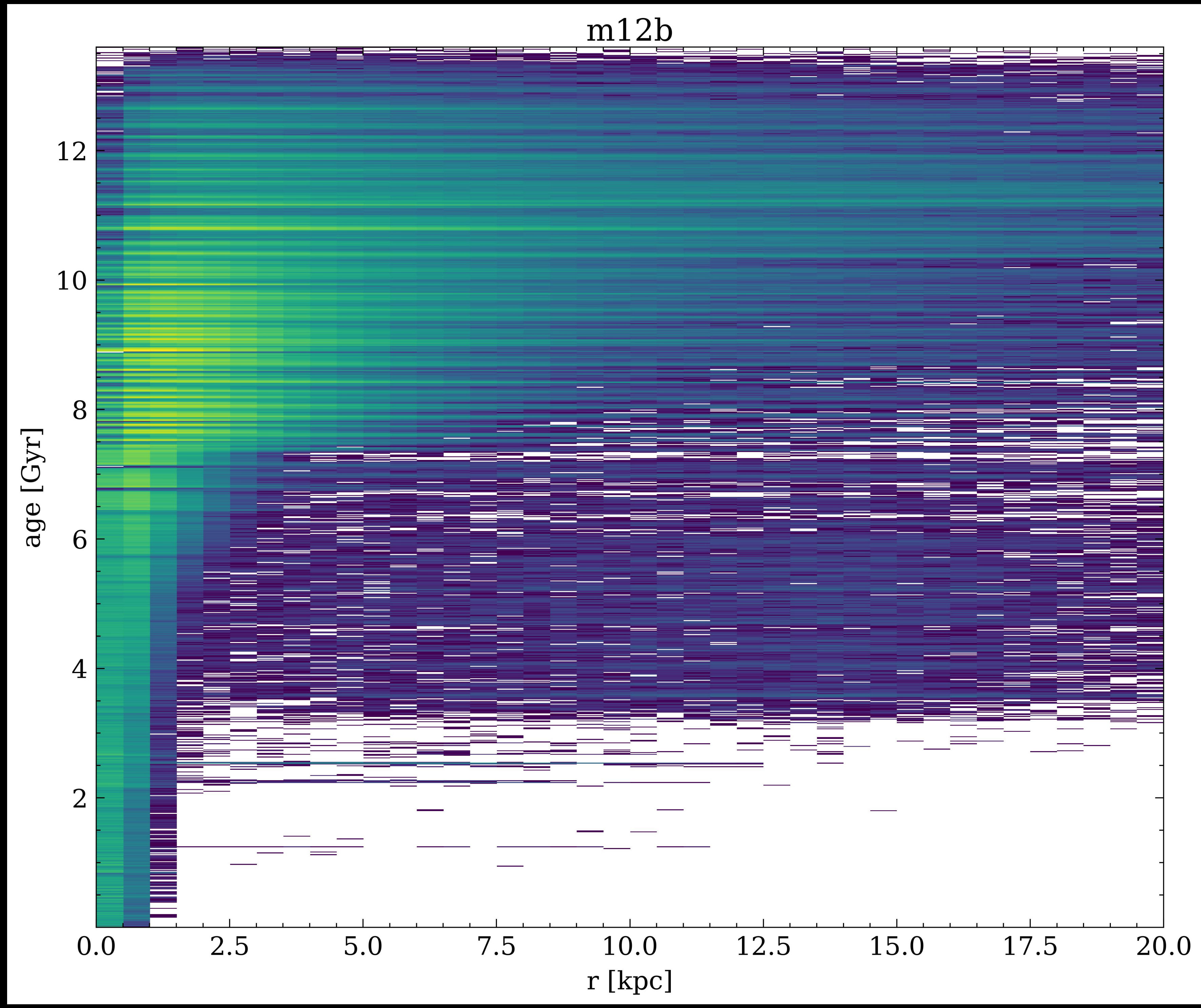


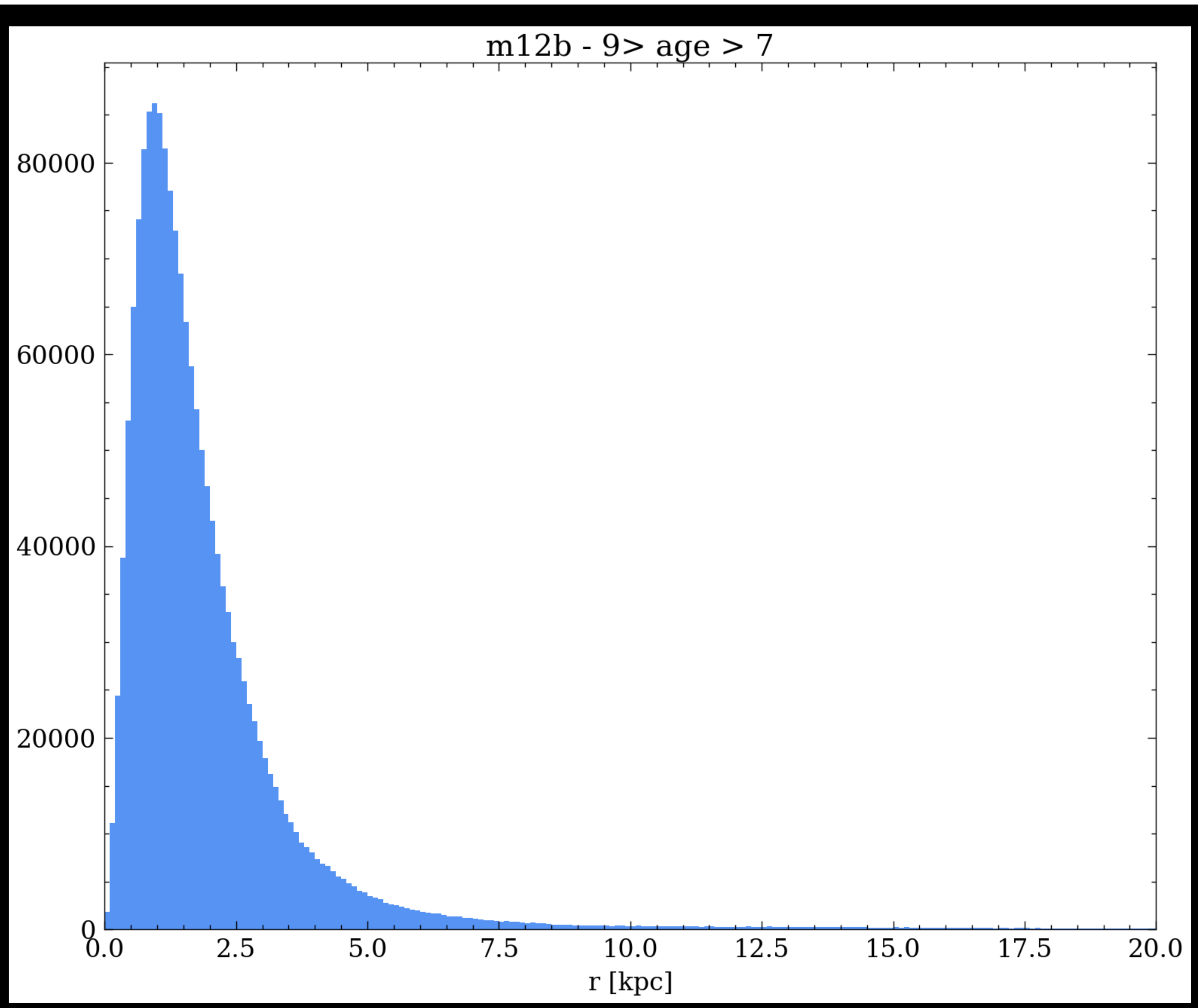


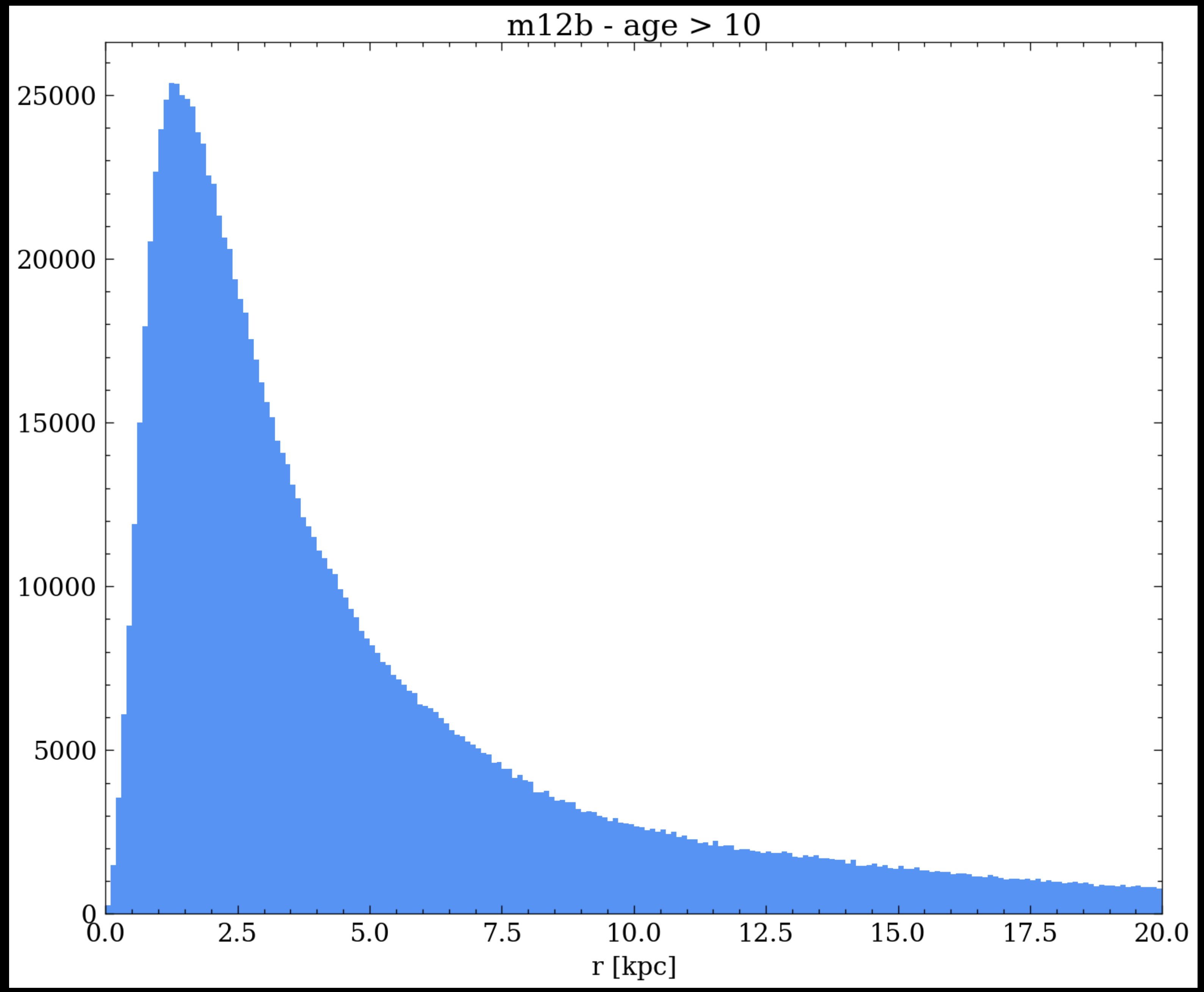
Adiabatic Contraction in Vintergatan Halo 685

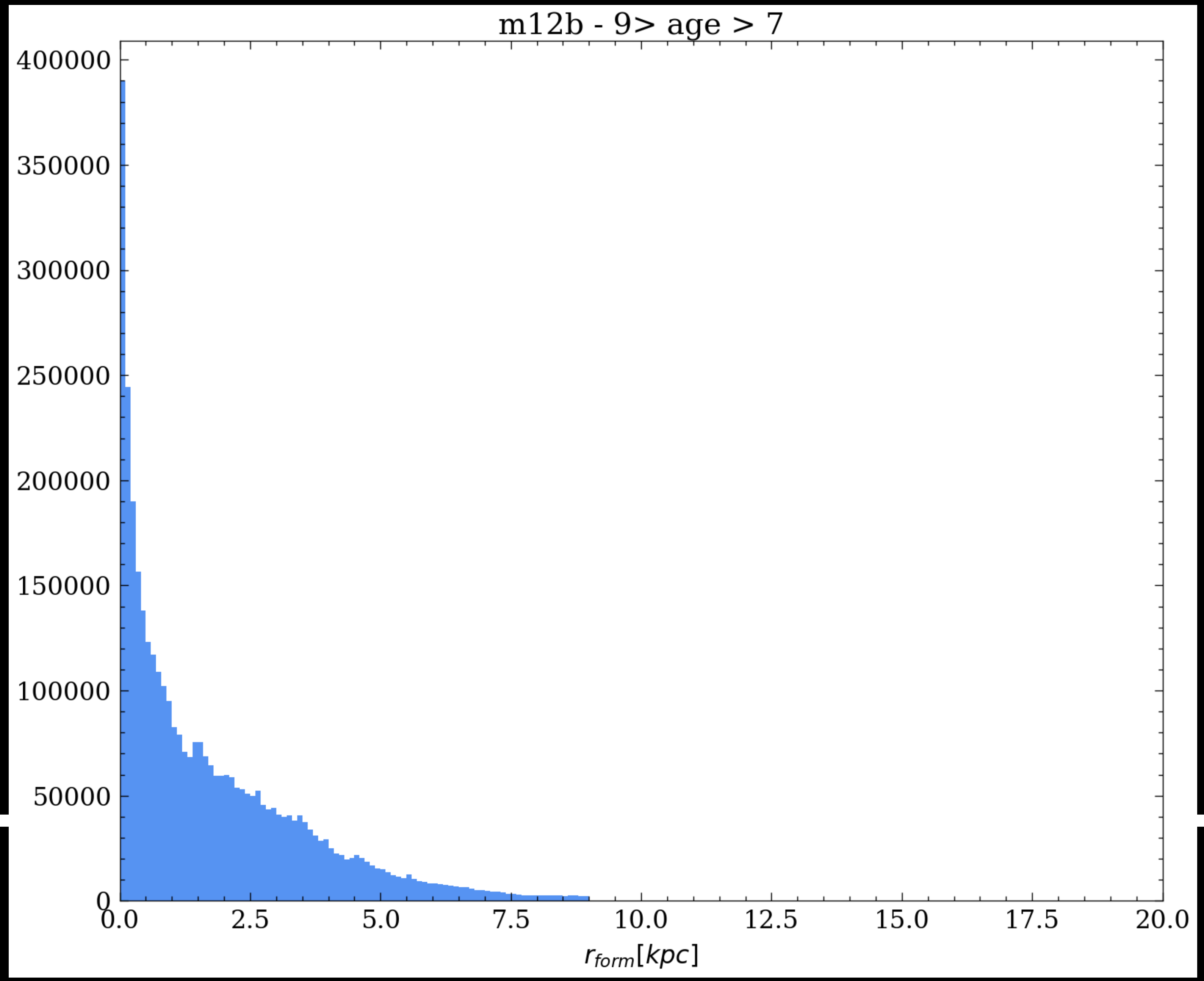


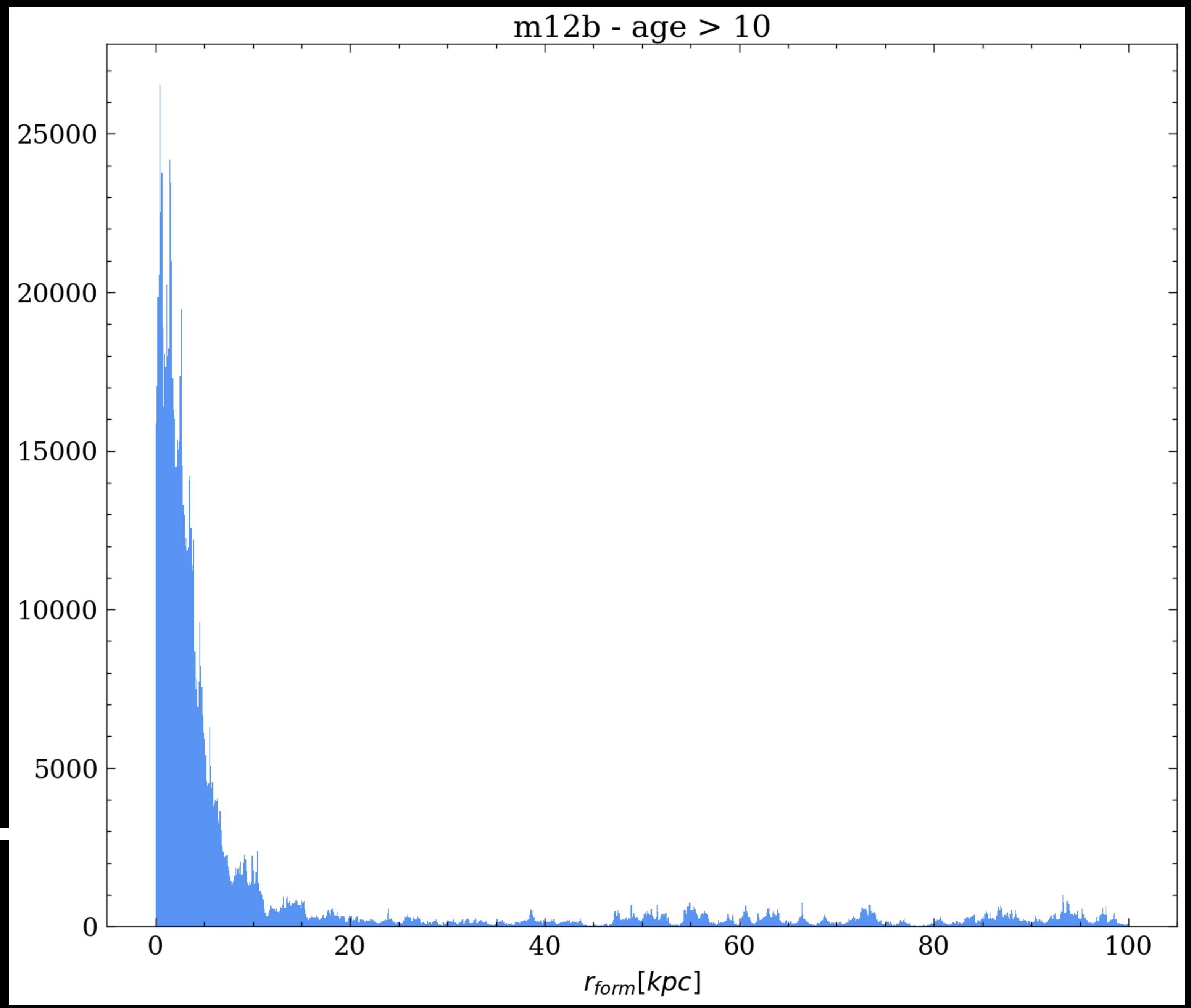


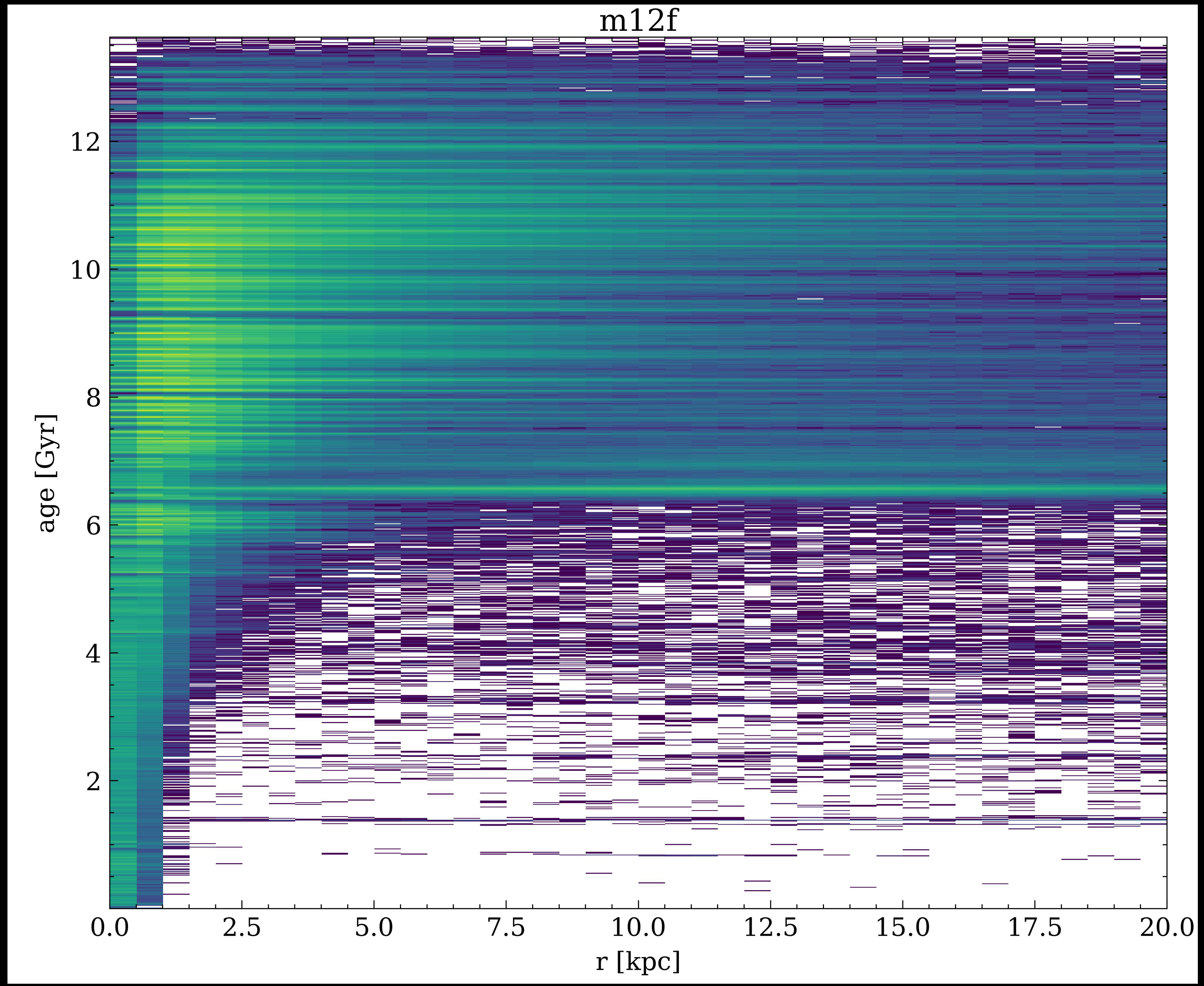

m12b
age [Gyr]
12
10
8
6
4
2
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
r [kpc]

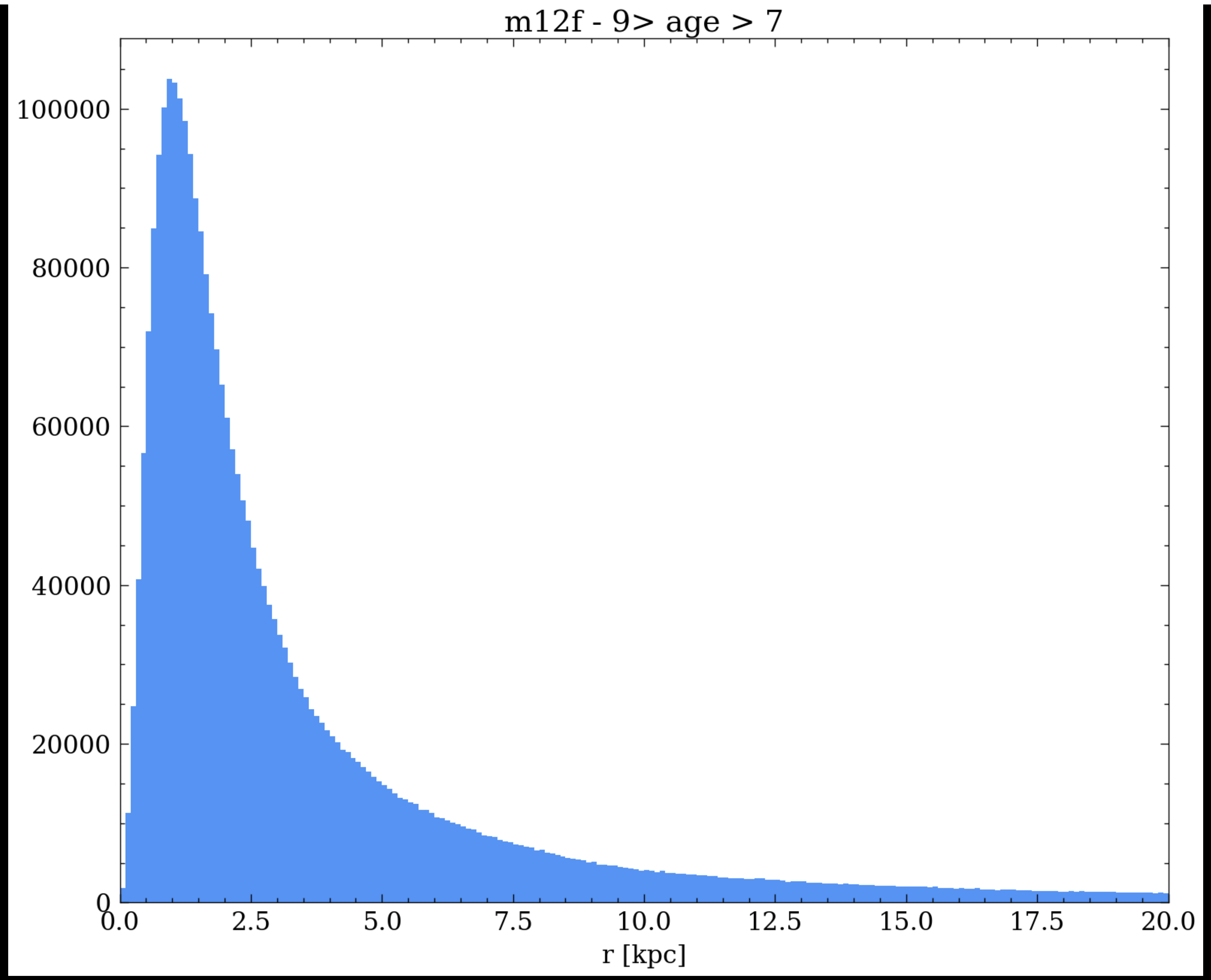

m12b - 9> age > 7
80000
60000
40000
20000
0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
r [kpc]

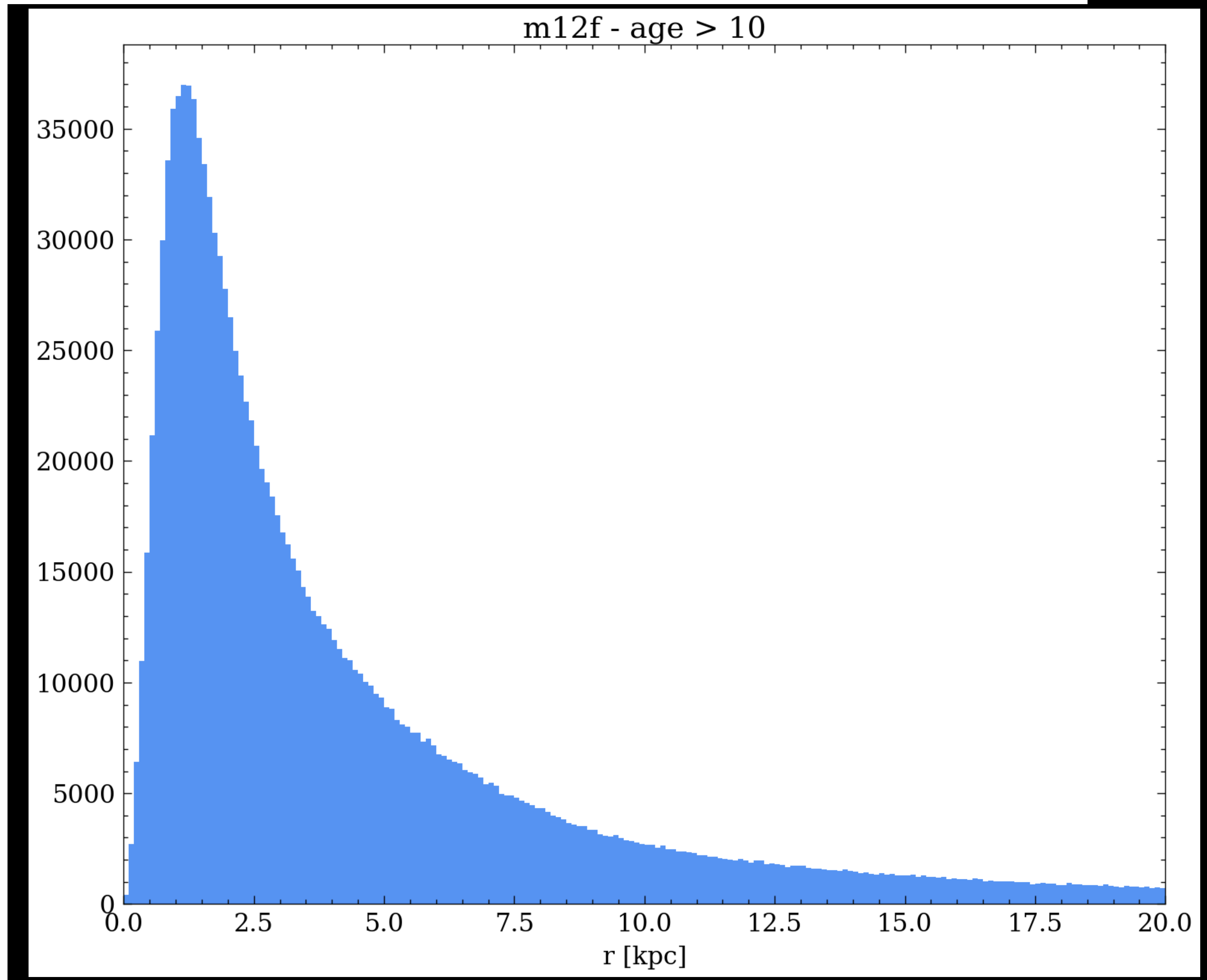

m12b - age > 10
25000
20000
15000
10000
5000
0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
r [kpc]

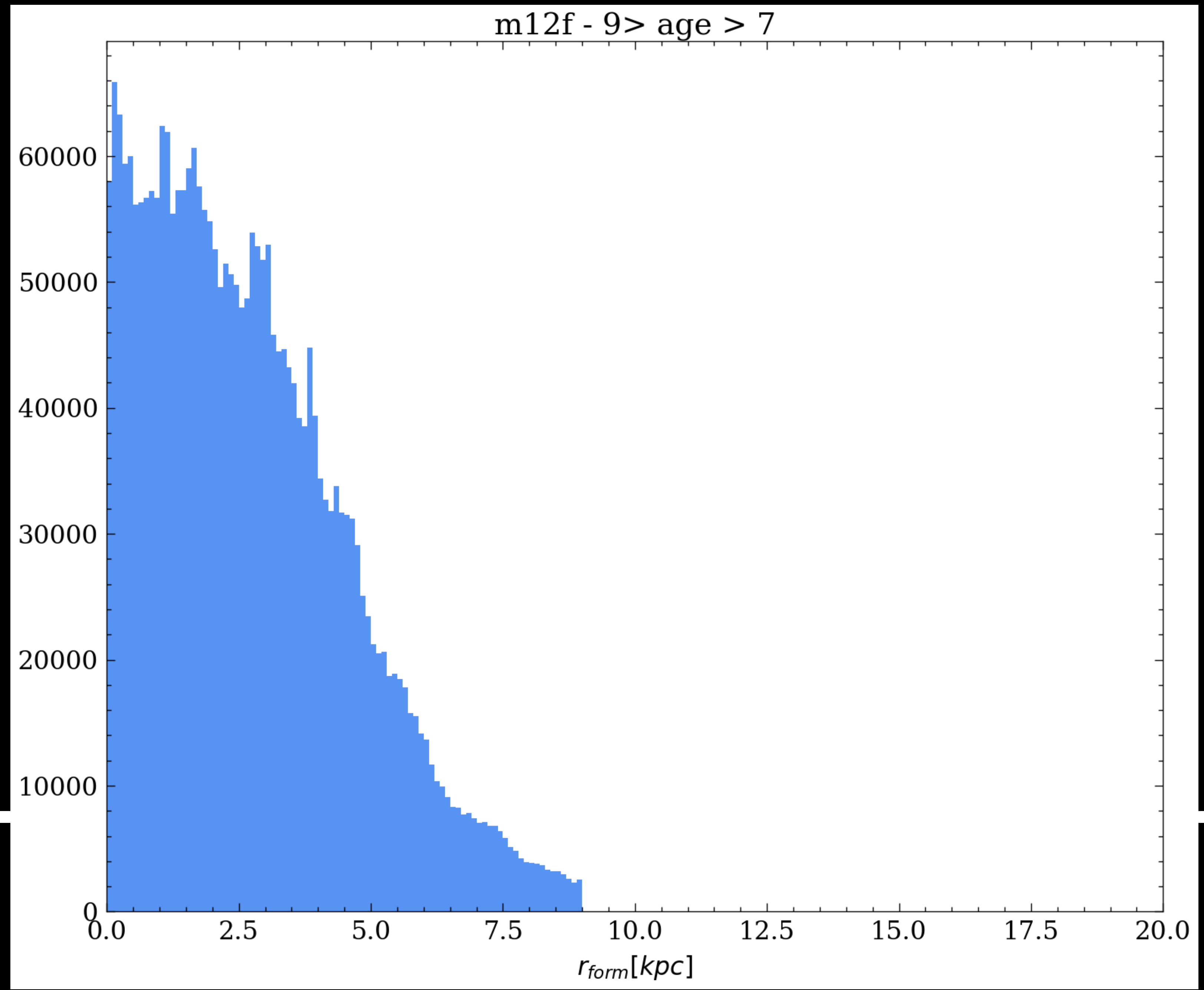

m12b - 9> age > 7
400000
350000
300000
250000
200000
150000
100000
50000
0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
$r_{form}[kpc]$

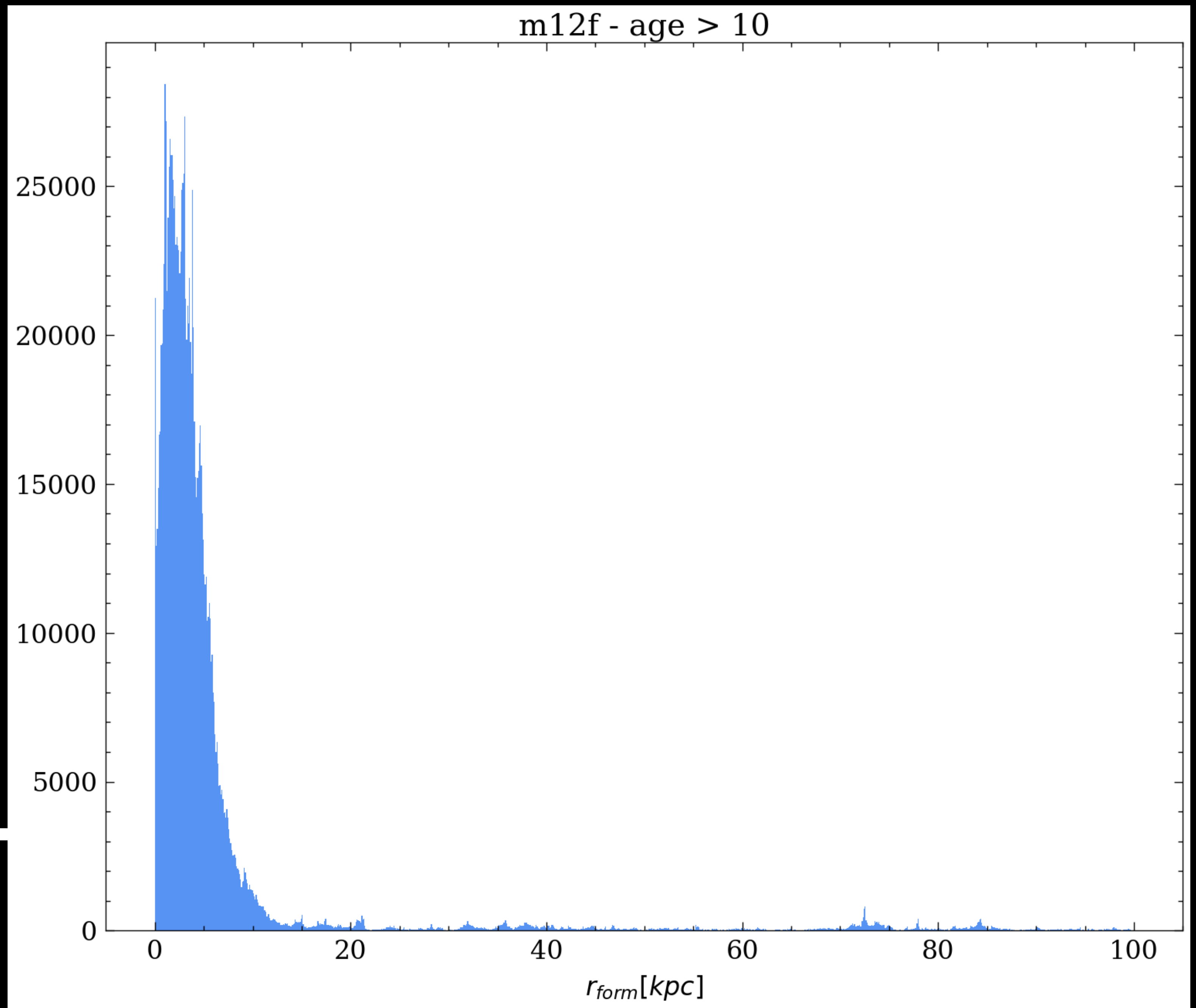

m12b - age > 10
25000
20000
15000
10000
5000
0
0
20
40
60
80
100
$r_{form}[kpc]$


m12f
age [Gyr]
r [kpc]


m12f - 9> age > 7
r [kpc]


m12f - age > 10
r [kpc]


m12f - 9> age > 7
$r_{form}[kpc]$


m12f - age > 10
$r_{form}[kpc]$