# The Inner Dark Matter Distribution in Hydrodynamic Simulations

Abdelaziz Hussein

In collaboration with: Lina Necib, Manoj Kaplinghat, Viraj Pandya, Stacy Kim, Justin Read

DPF-PHENO 2024

**5/16/2024**

Massachusetts Institute of Technology


Milky Way
Credit: ESO

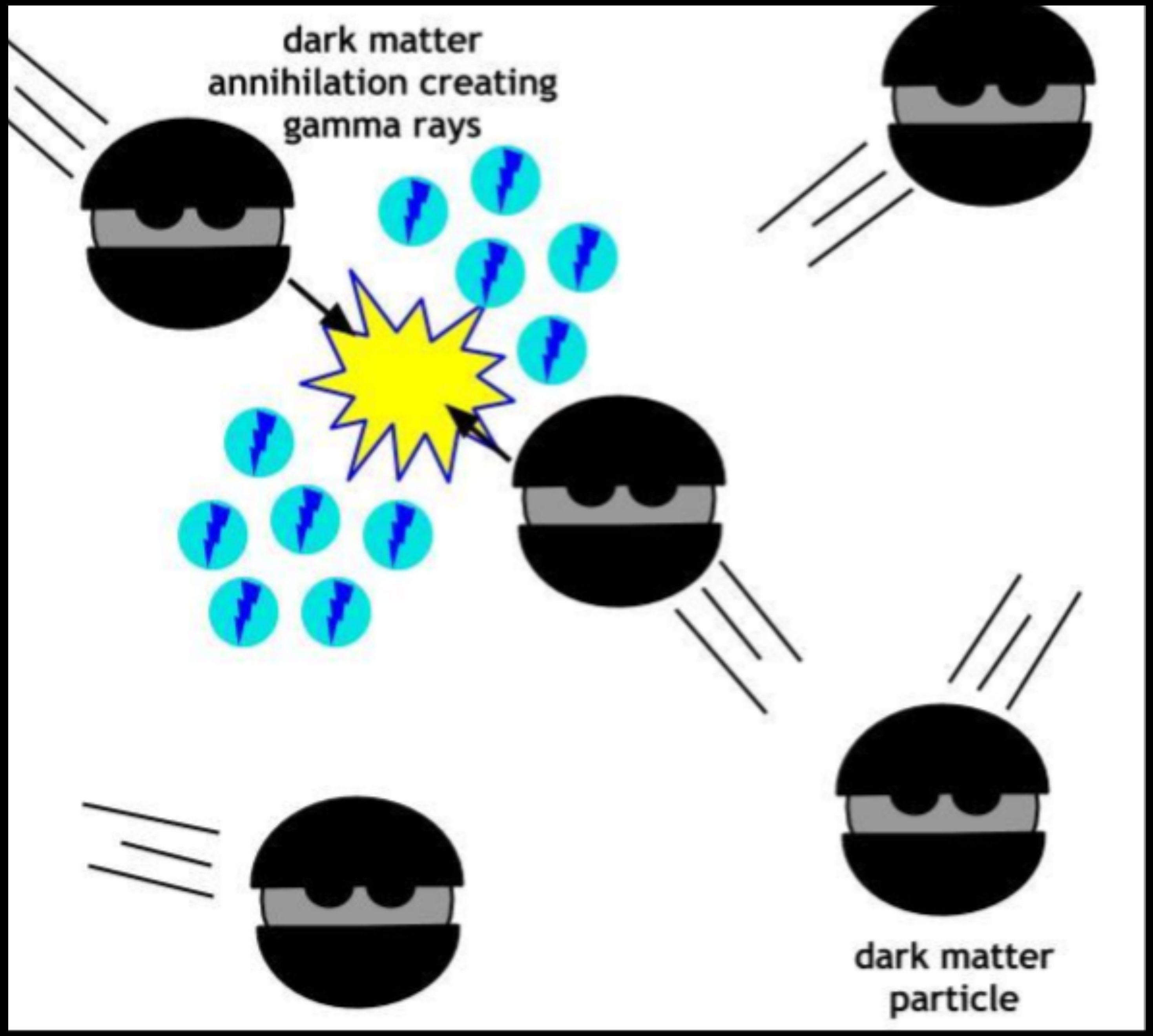

Synthetic survey of a baryonic simulation
(Sanderson et al. 2020)

# Outline:

- Why care about the density distribution?
- Cosmological simulations overview
- DM Distribution in different simulation suites
- Adiabatic contraction overview
- Calculation overview
- Results

# Why care about the density distribution?

- **For some DM models (ex: WIMPs) we get $\gamma$-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.**

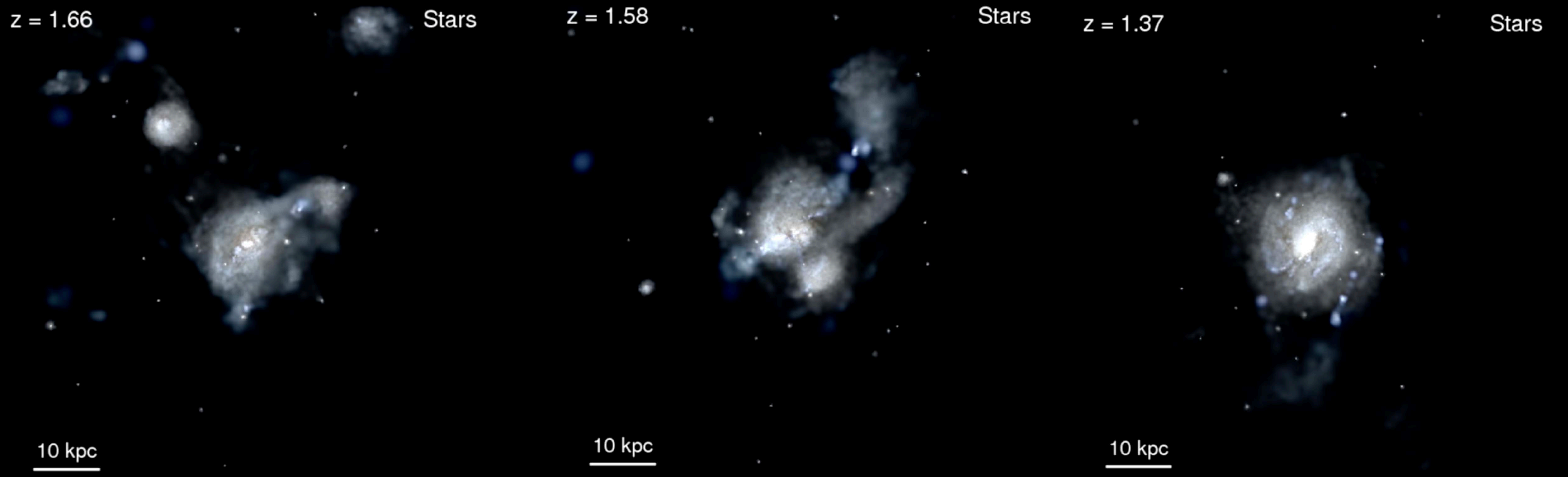



(Credit: Andrea Albert)

# Cosmological simulations overview:

(credit: Phil Hopkins)

# Cosmological simulations overview:



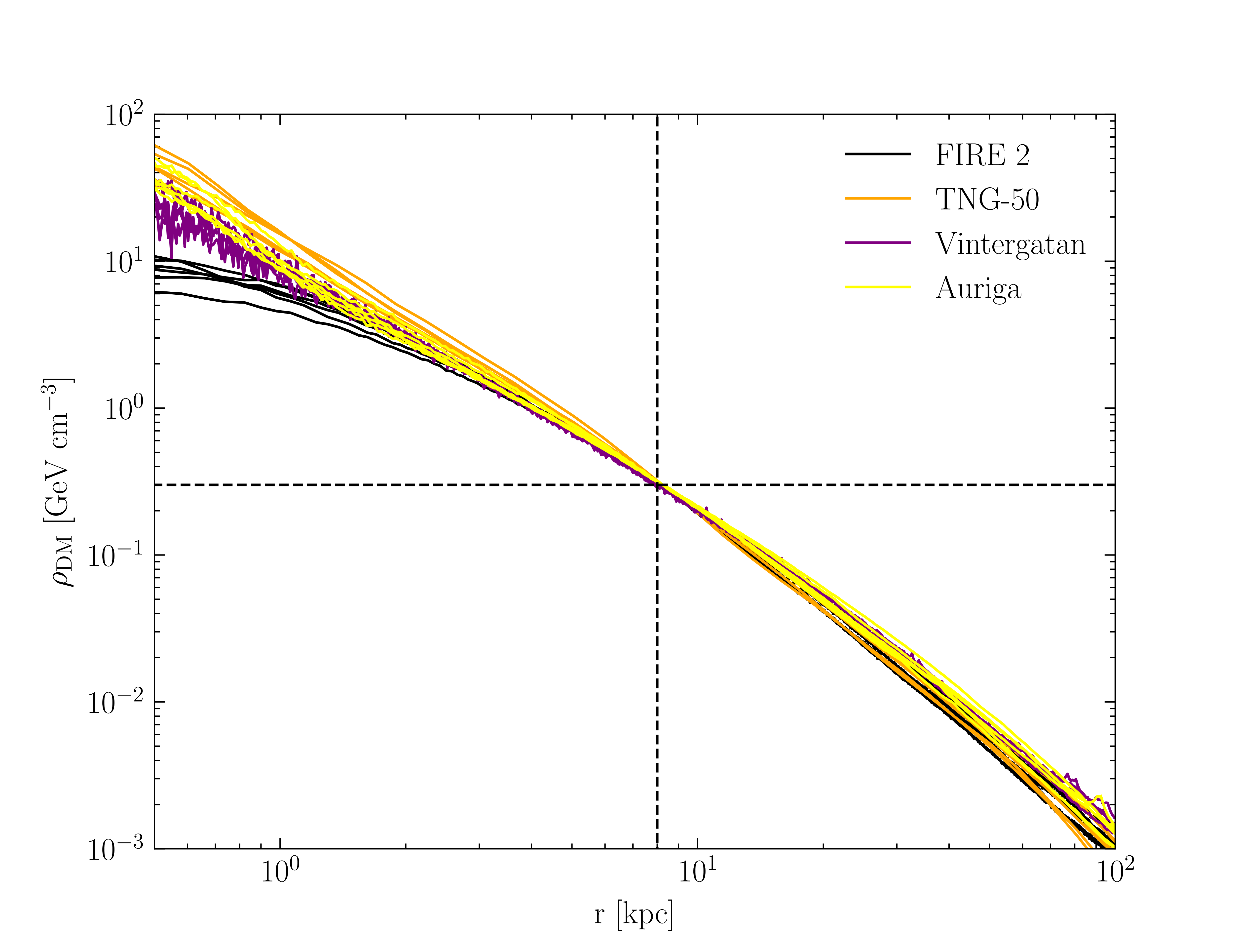

(credit: Phil Hopkins)

# 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 |

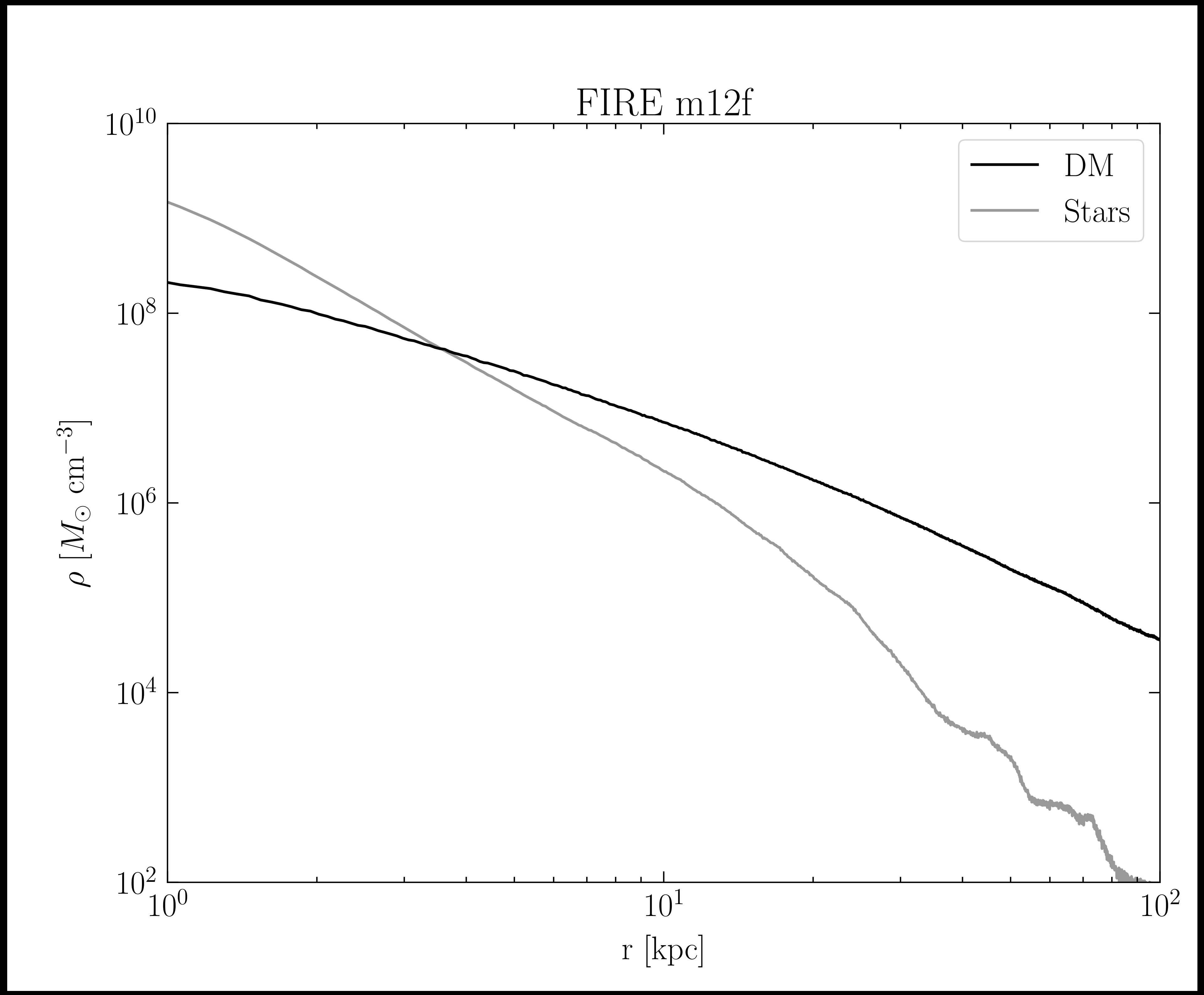
# DM Distribution in different simulation suites:

- **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.**



# Adiabatic contraction input:

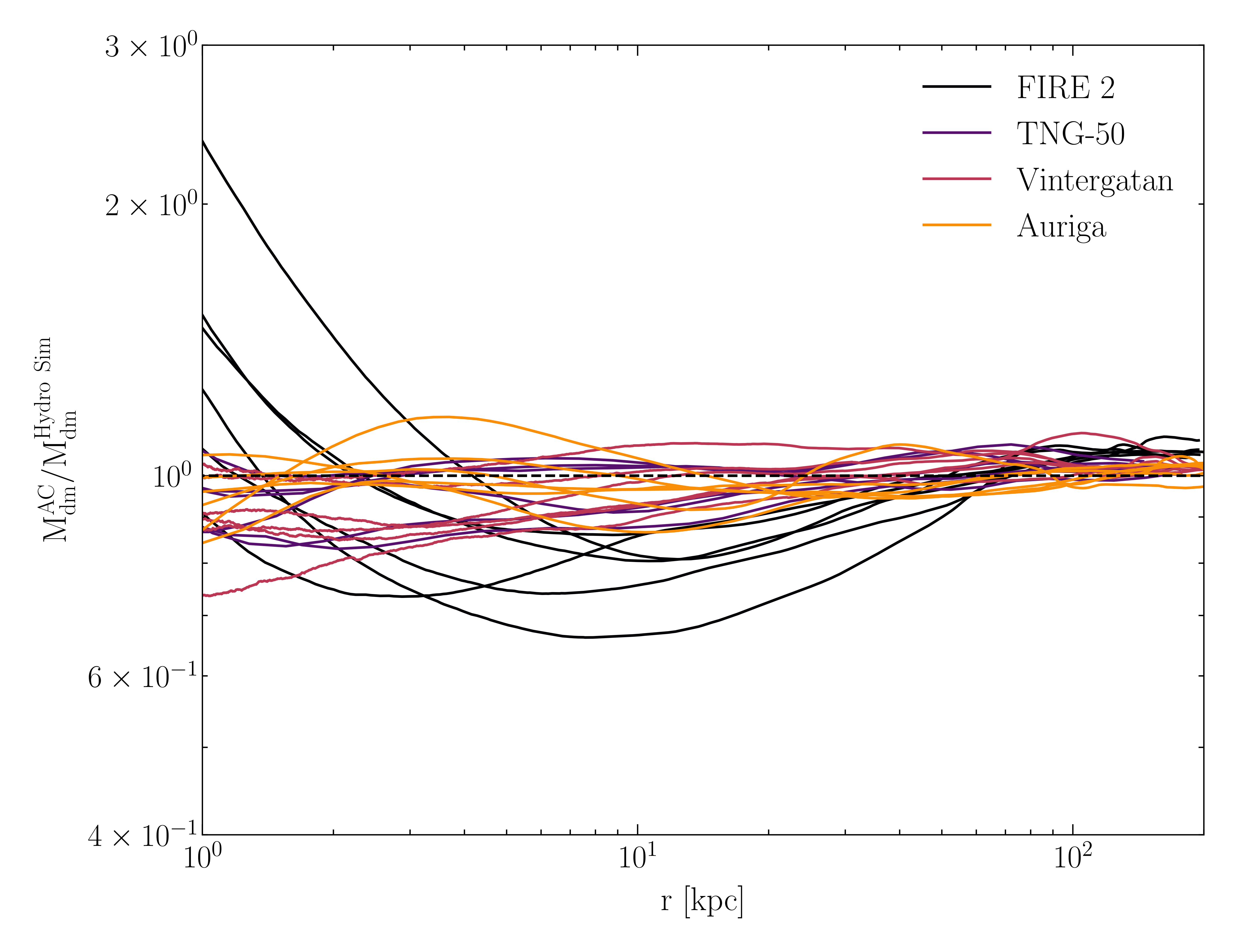
$$M_{\rm DM}^{\rm inital}(r_{\rm inital}) = M_{\rm DM}^{\rm final}(r_{\rm final})$$

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

- **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**

# 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

# Calculation overview:

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

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

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

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

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

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

**Find fixed point**

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

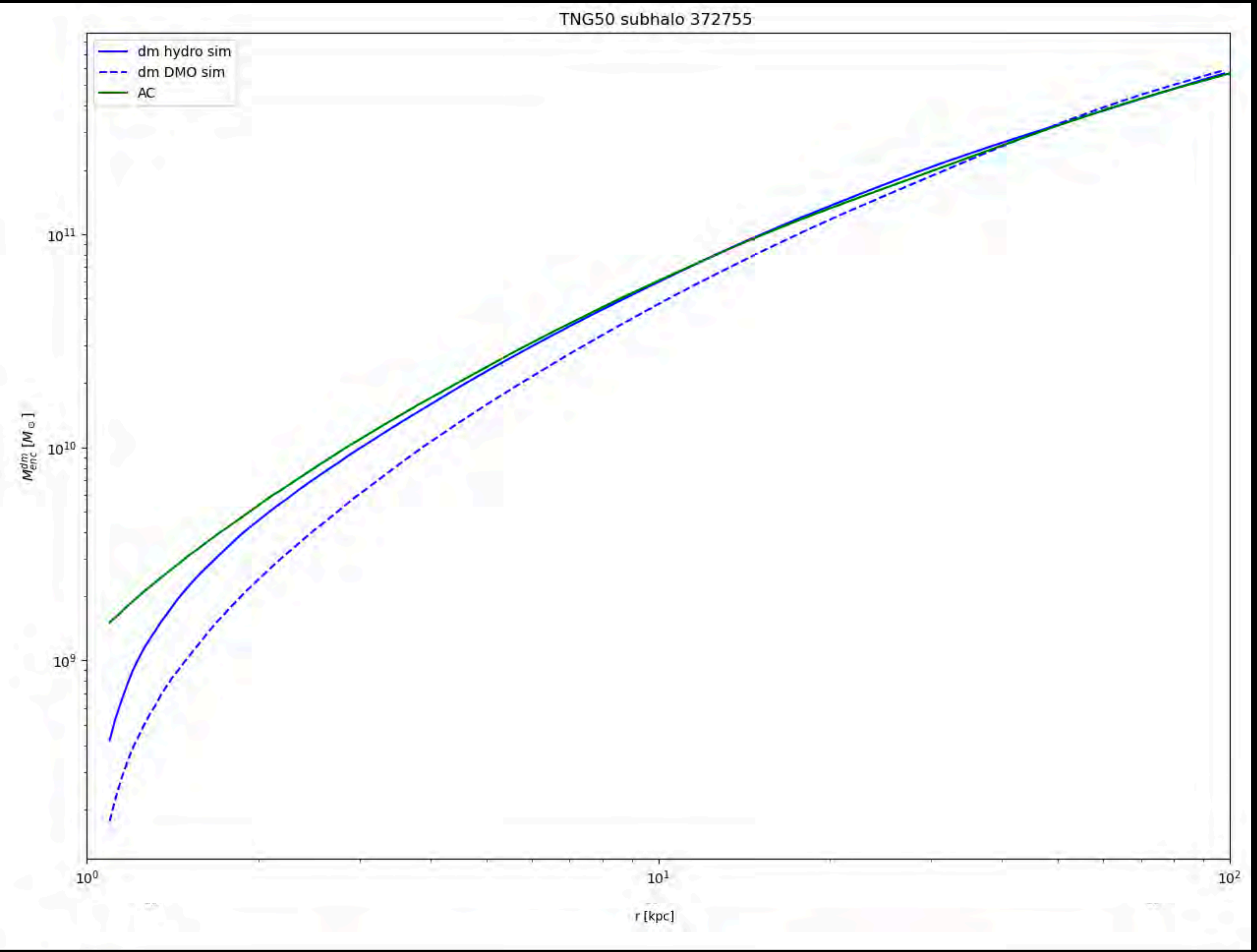
**tested by (Gustafsson et al 2007)**

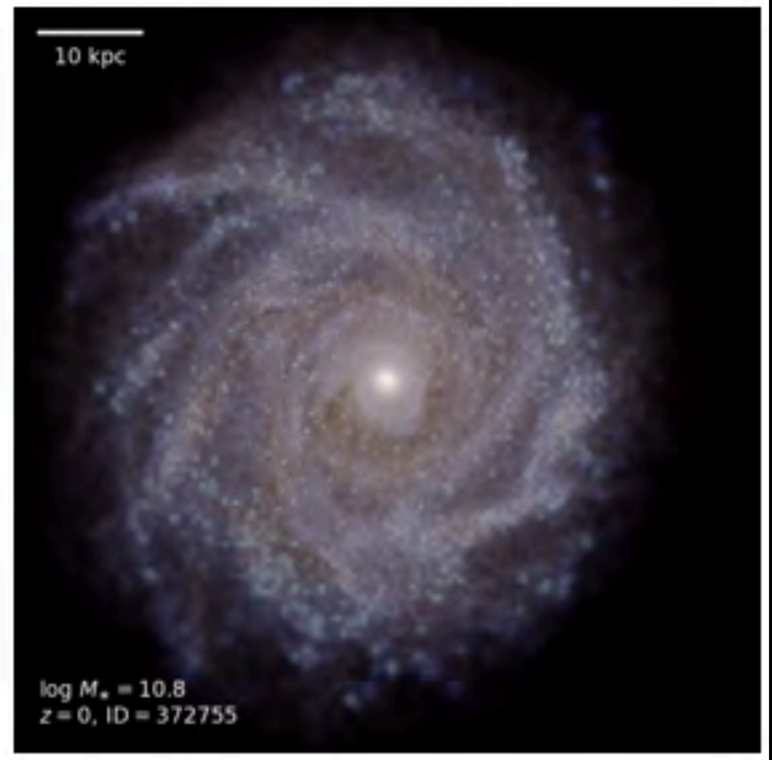
**Given such a wide eccentricity distribution, the orbit-averaged radius varies for particles at a given current radius r depending on the orbital phase. Nevertheless, the mean relation can be described by a power law function.**

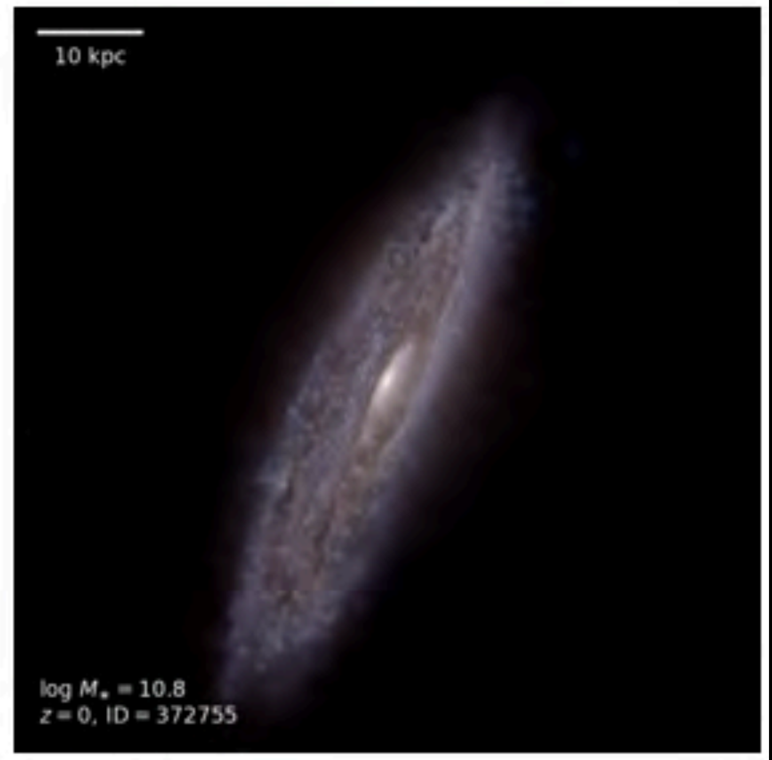
# Adiabatic contraction overview:

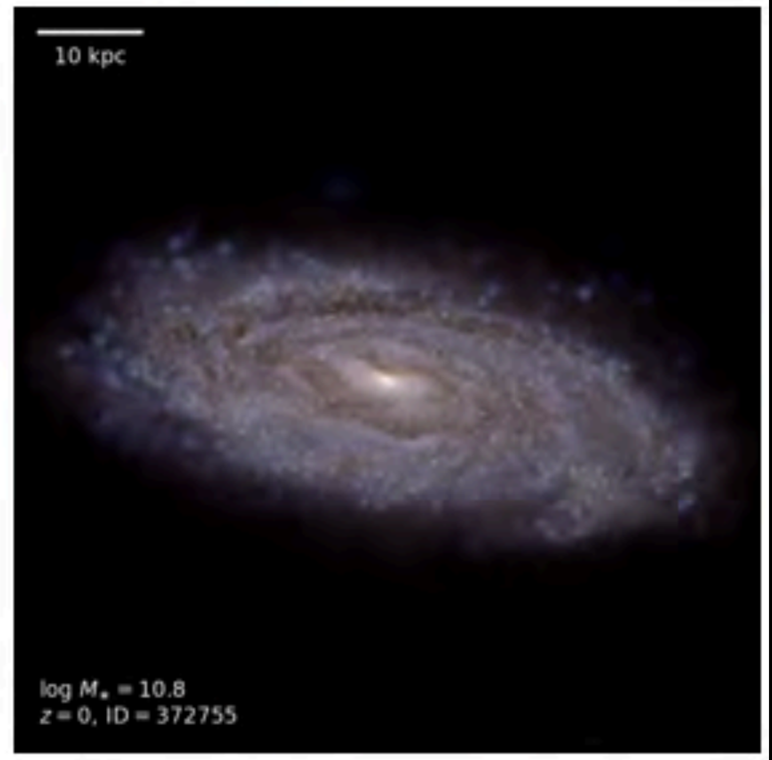
- **Assumptions:**
  - **Eccentric orbits (Ghigna et al. 1998)**
    - **Orbits have a wide distribution of eccentricities which should be taken to account.**
    - **Take this distribution into account by averaging over the population of orbits at a given radius:**
      - $\bar{r} = r_{vir} \; A(\frac{r}{r_{vir}})^{w}$
  - **Spherical symmetry**
  - **Conservation of angular momentum**
  - **Assume homologous contraction**

# Adiabatic Contraction in TNG50:



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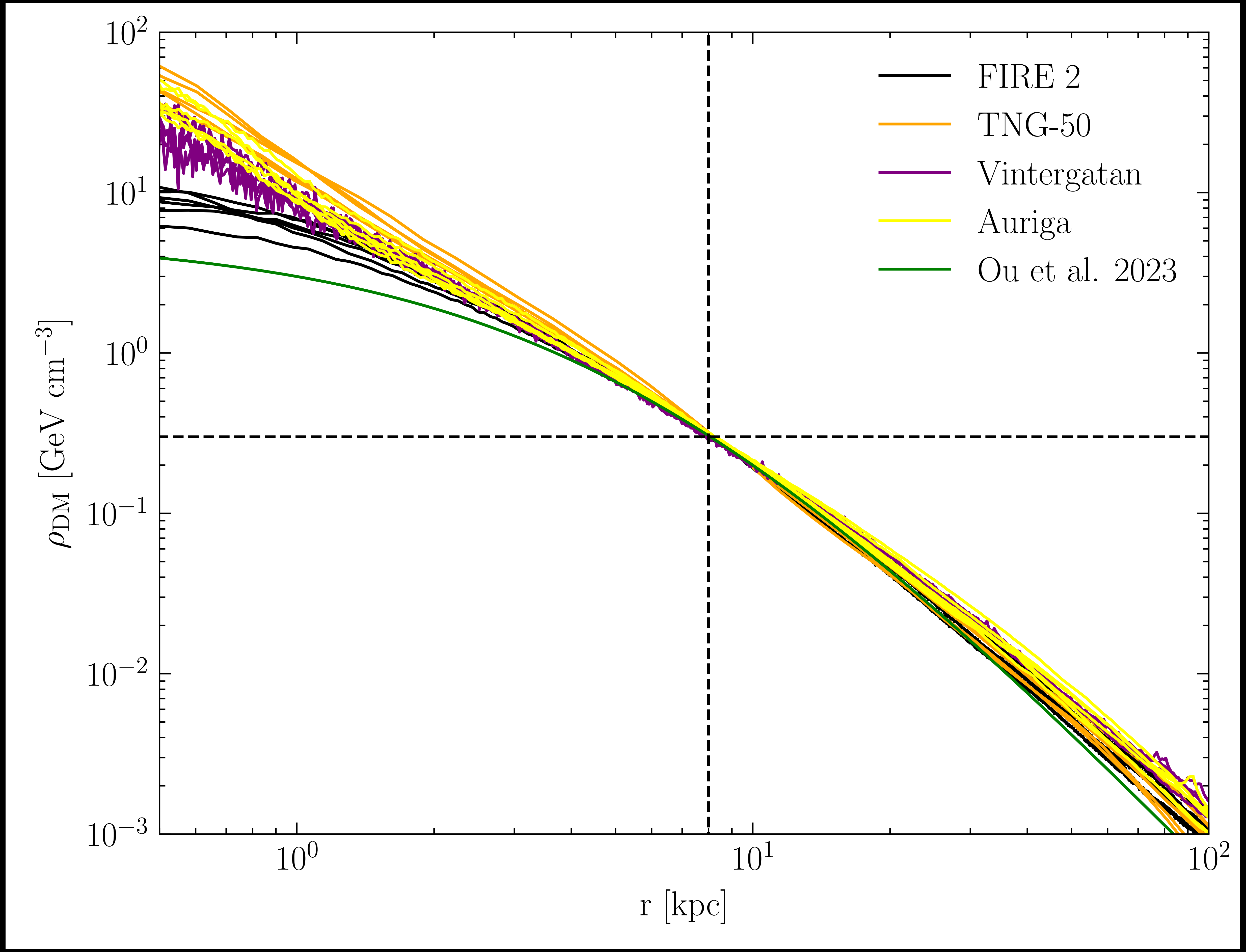
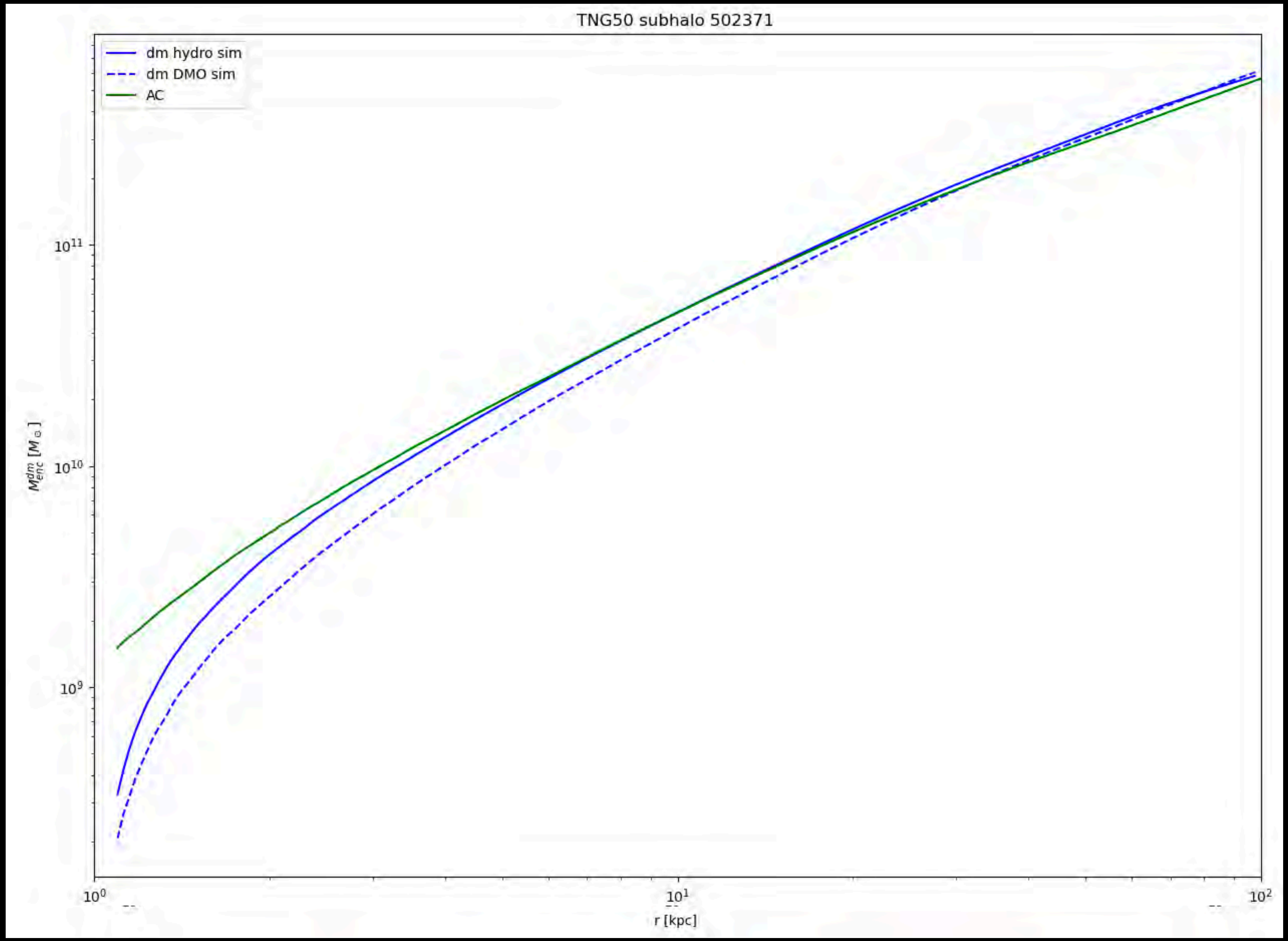
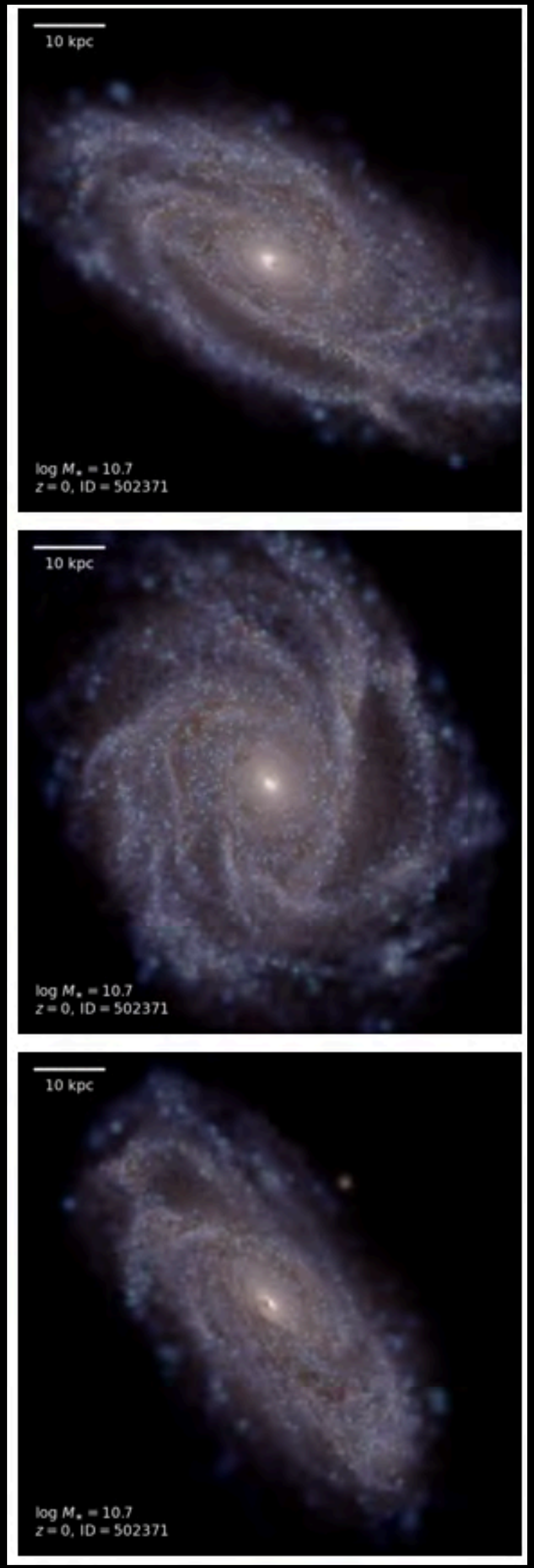
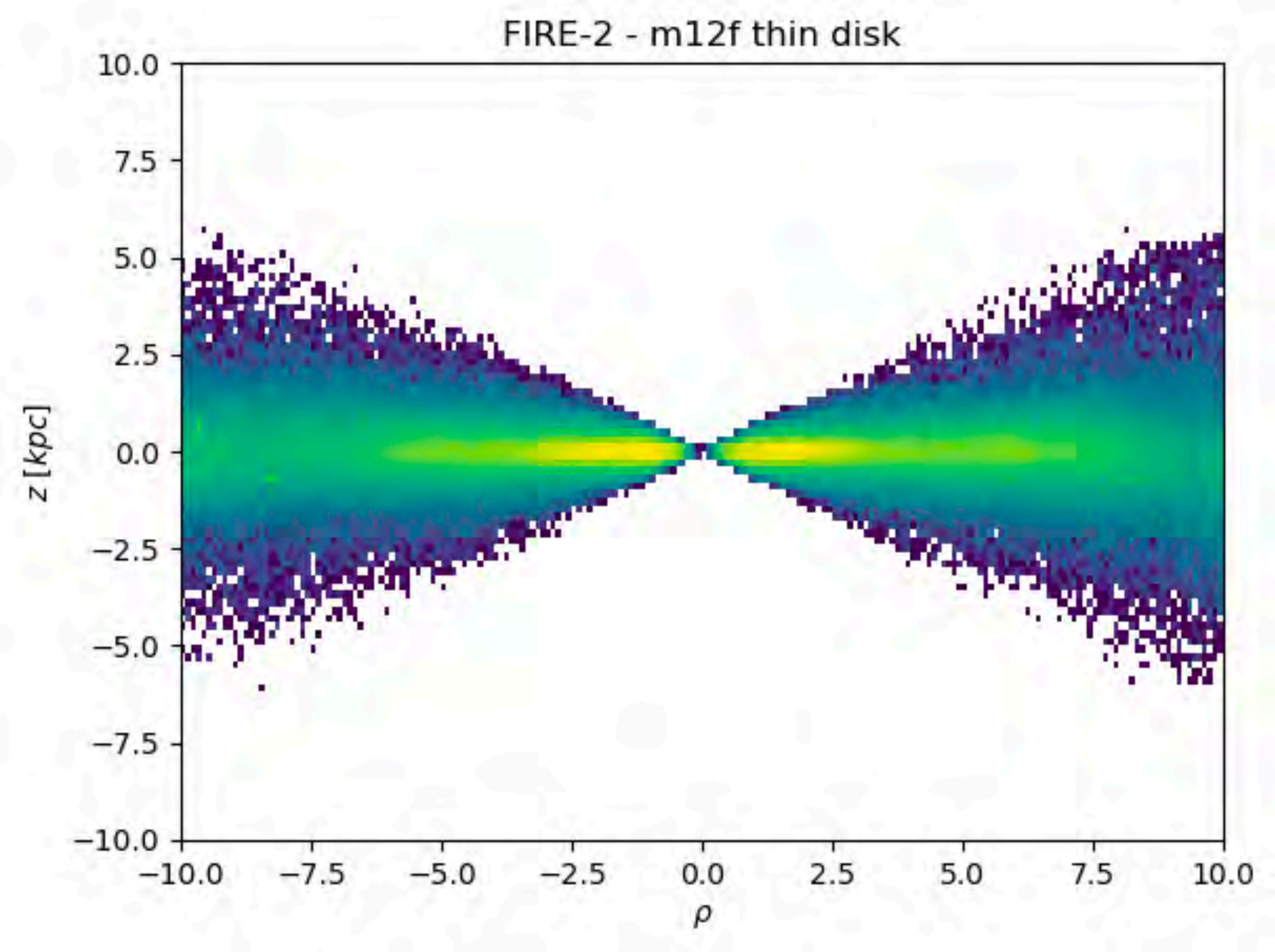


# Adiabatic Contraction in TNG50:

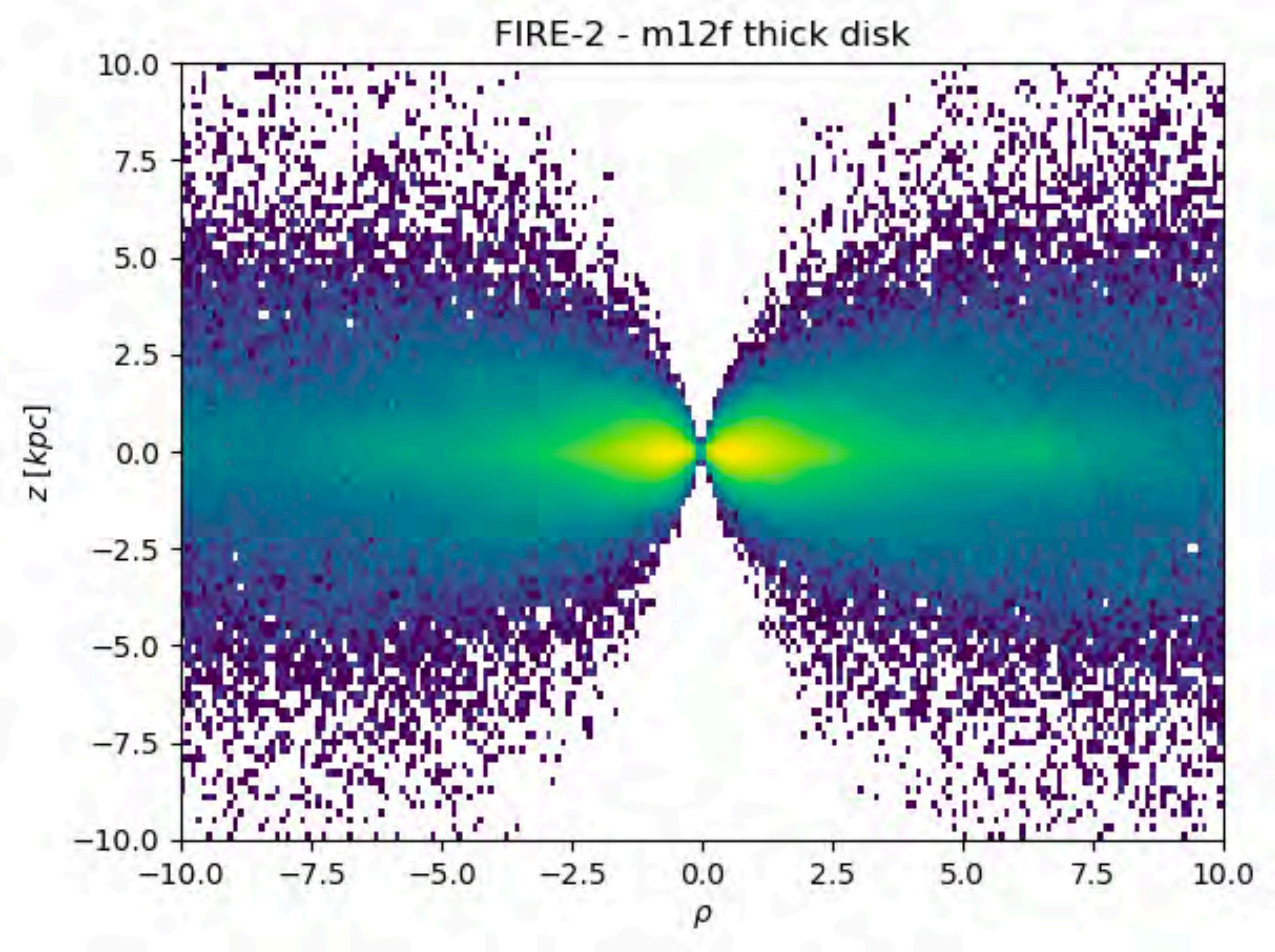


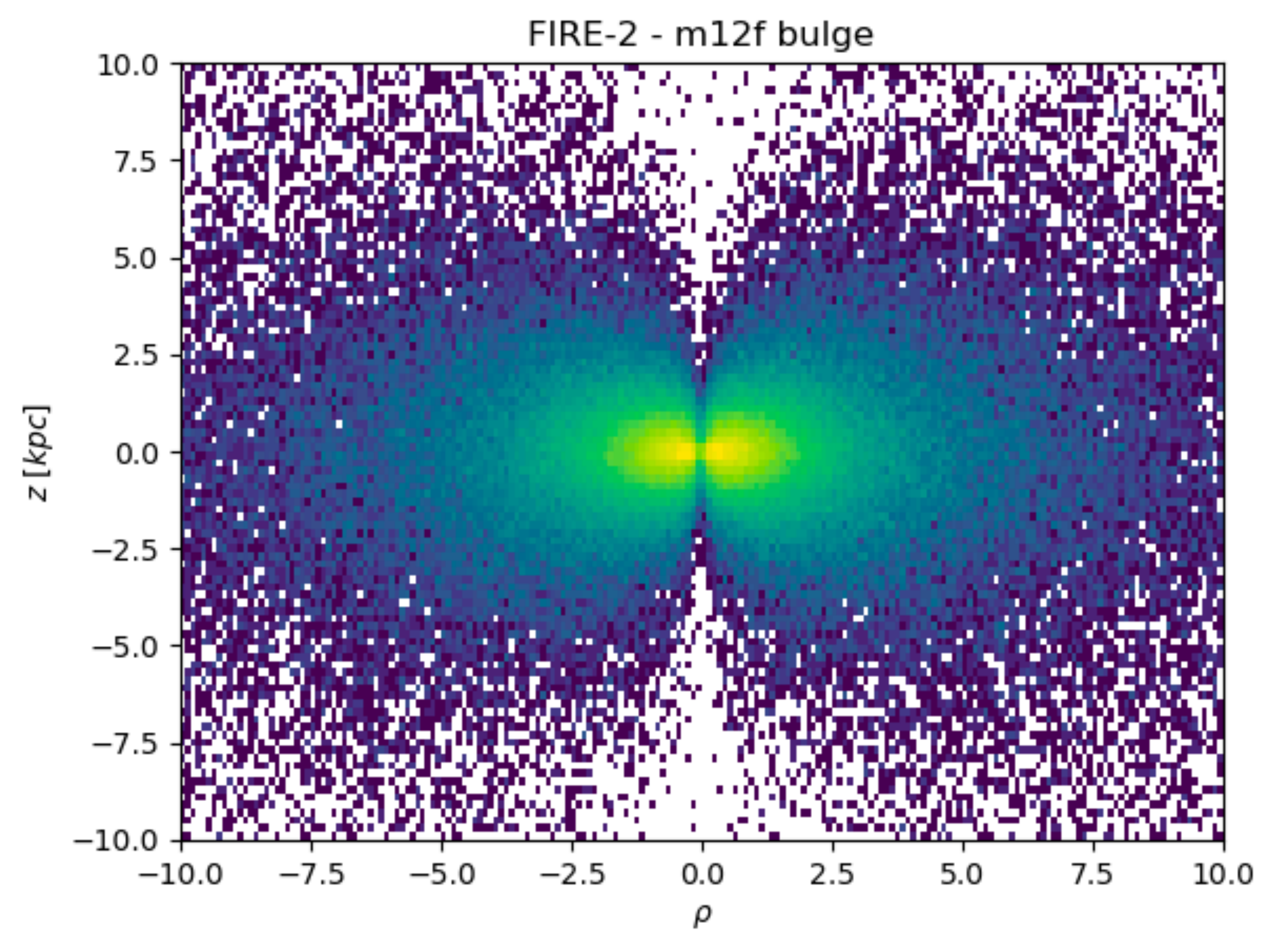
Thin disk




Thick disk

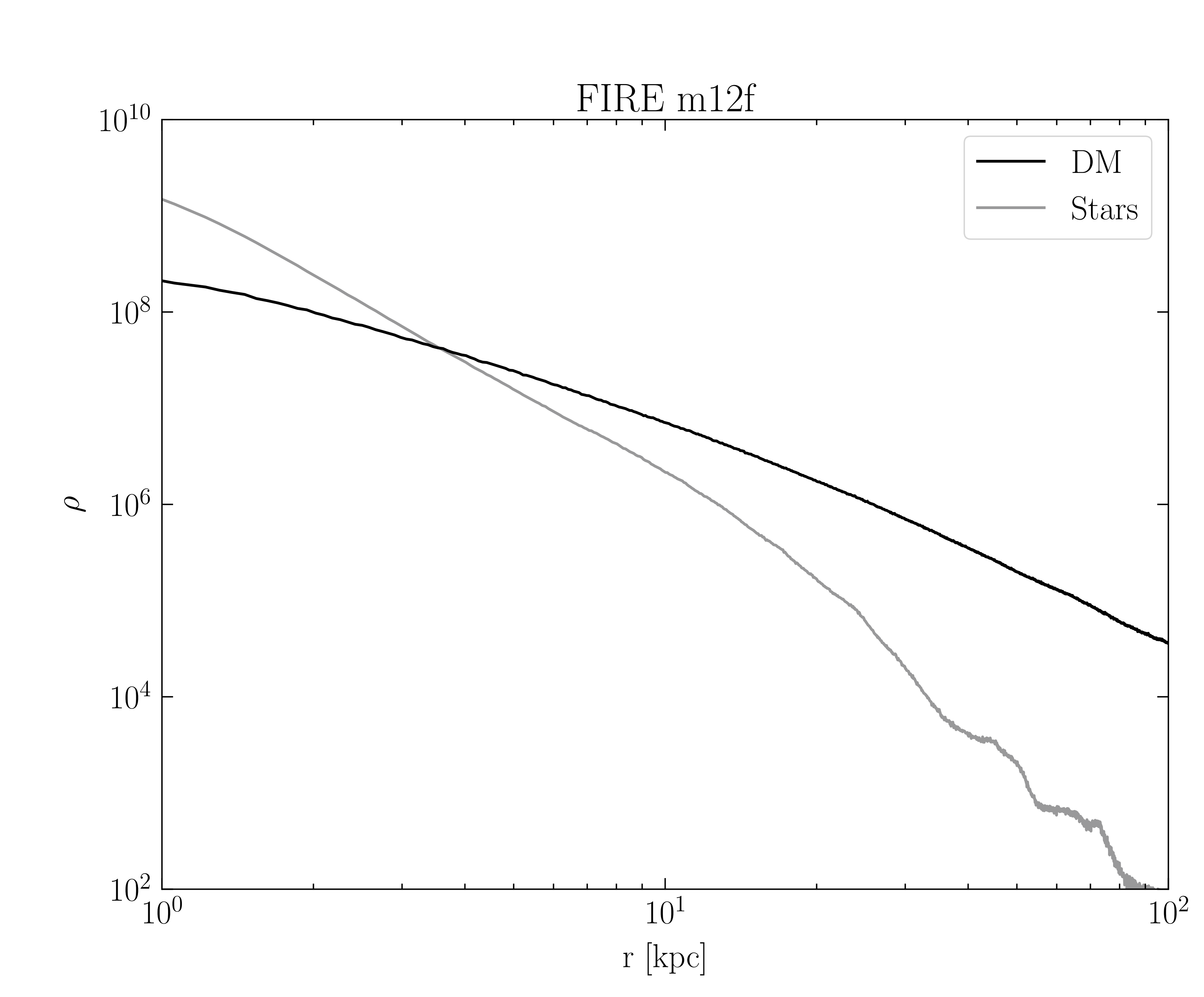



Bulge



# Adiabatic contraction overview:

- Although dark matter exceeds baryonic matter by a factor of $\Omega_b \simeq 5\Omega_{DM}$
  - The gravitational field in the central regions of galaxies is dominated by stars.
  - As the baryons condense in the center, they pull the dark matter particles inward thereby increasing their density in the central region.
- The conserved quantities for eccentric orbits
  - the angular momentum $J$
  - the radial action $I_r \equiv \dfrac{1}{\pi}\displaystyle\int_{r_p}^{r_a} v_r \, dr$
    - (Gnedin et al. 2004) argued that the conserved quantity $r\ M(\bar{r})$ is a better proxy for the radial action.

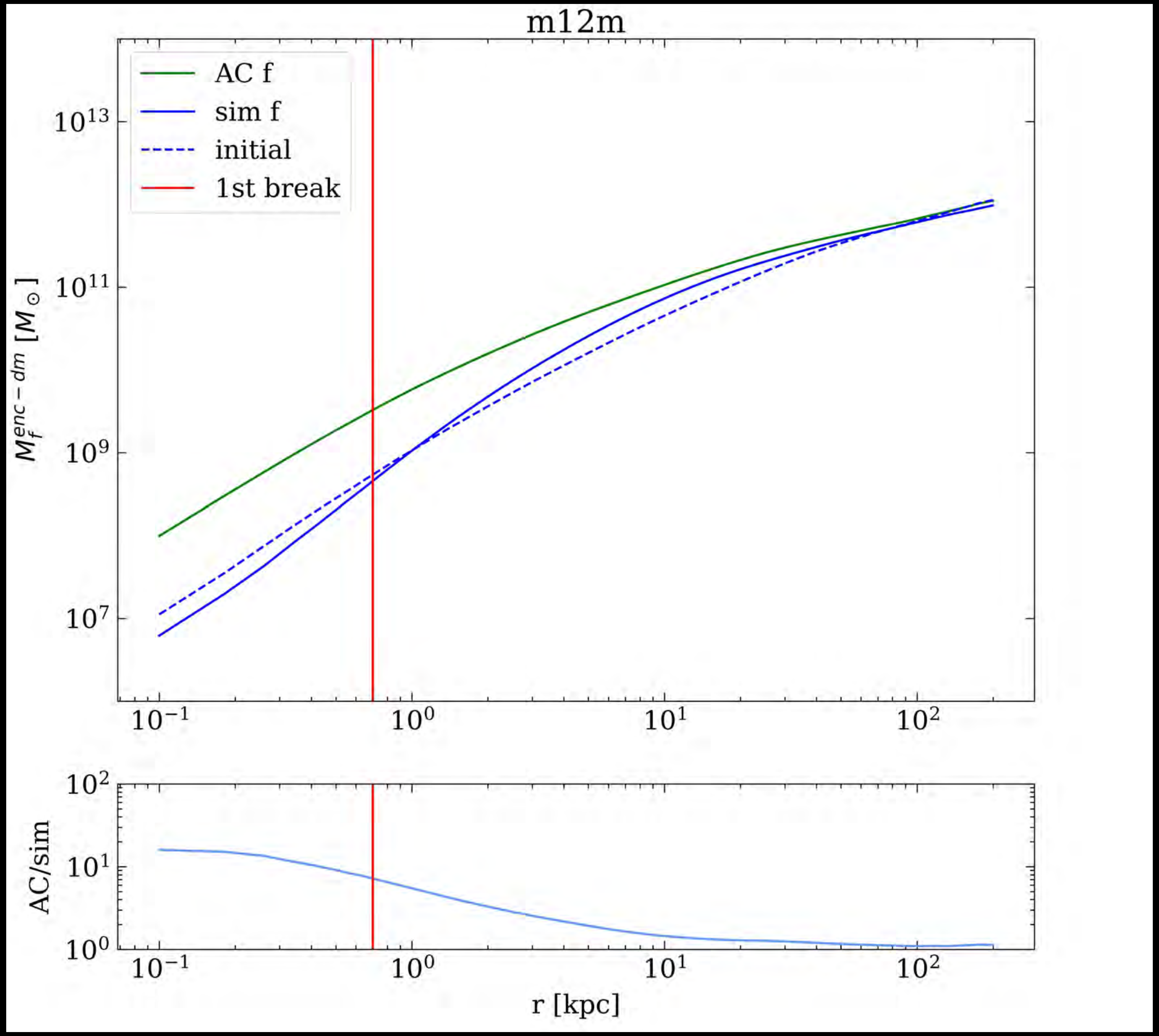


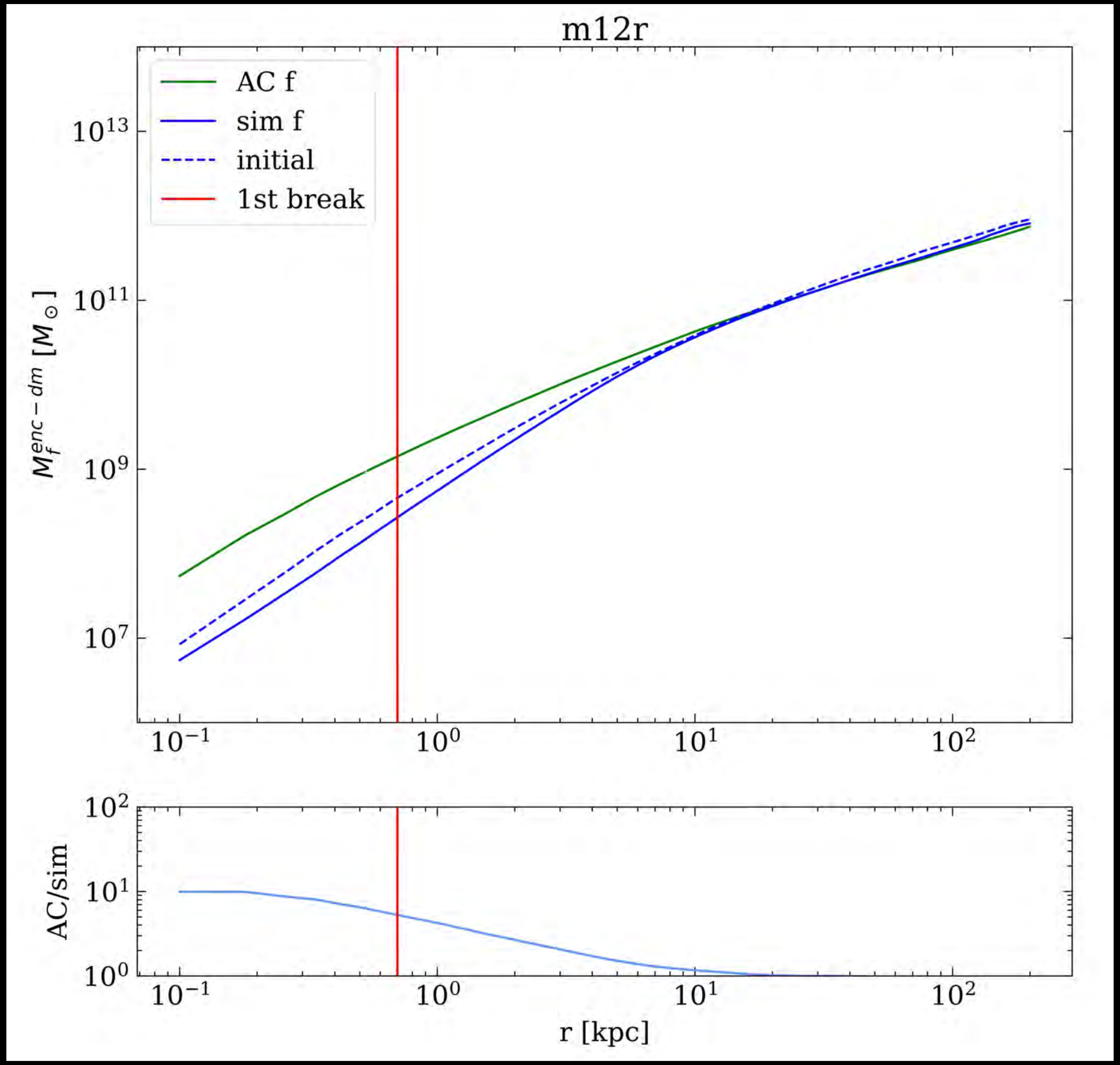
# Adiabatic Contraction in FIRE m12s

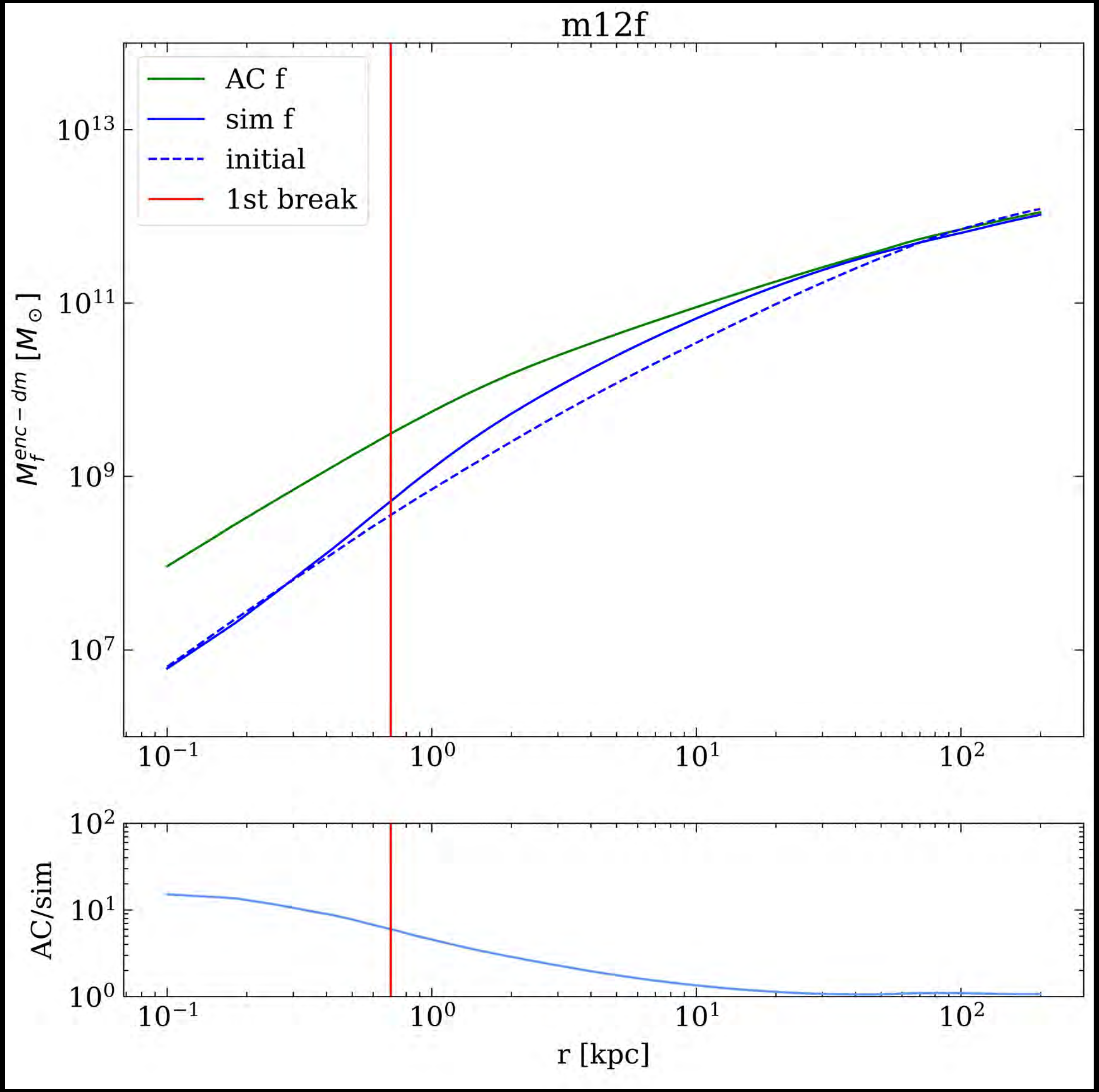
(Gnedin et al. 2004)

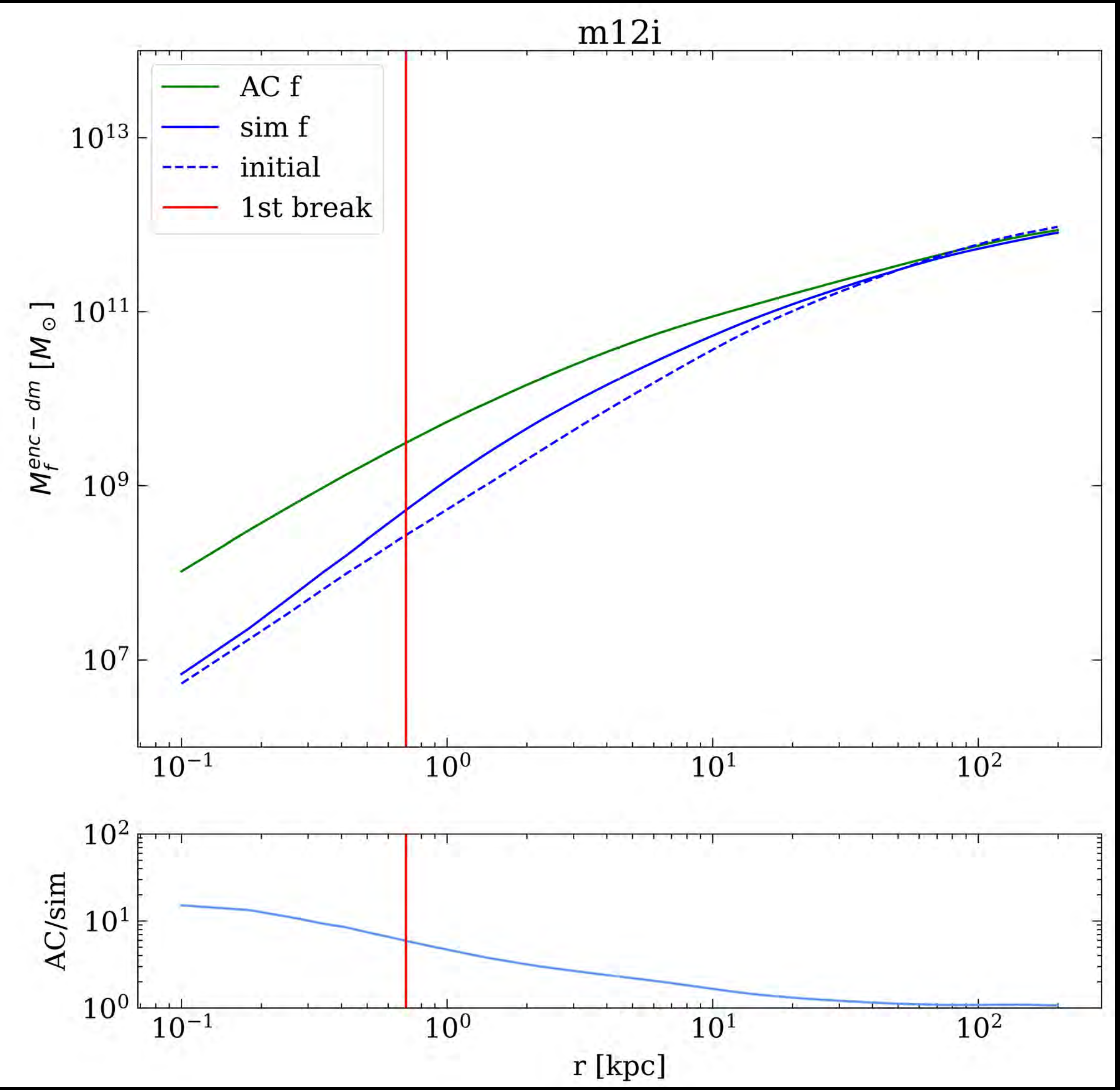
$$r\ M(\bar{r}) = const$$

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

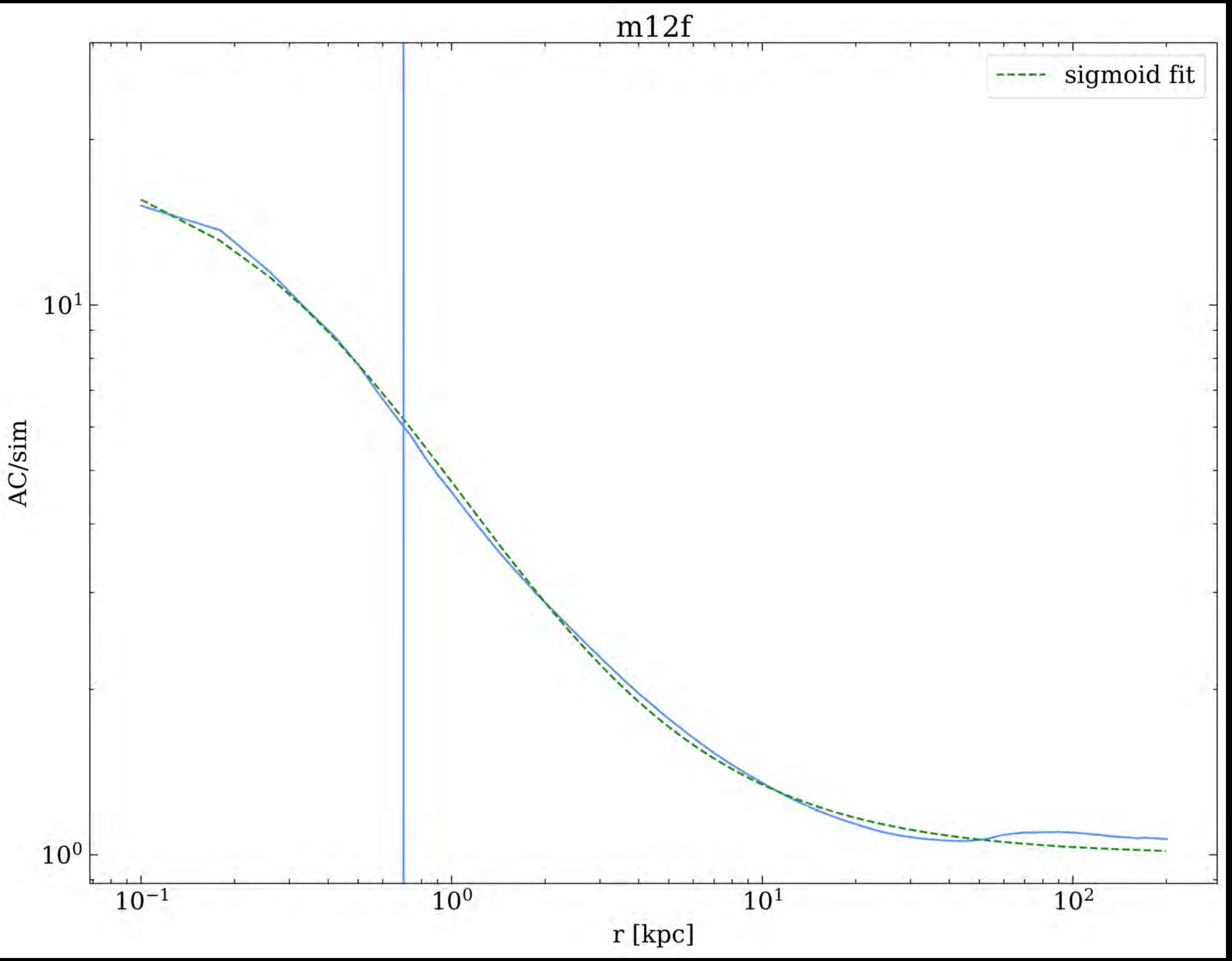


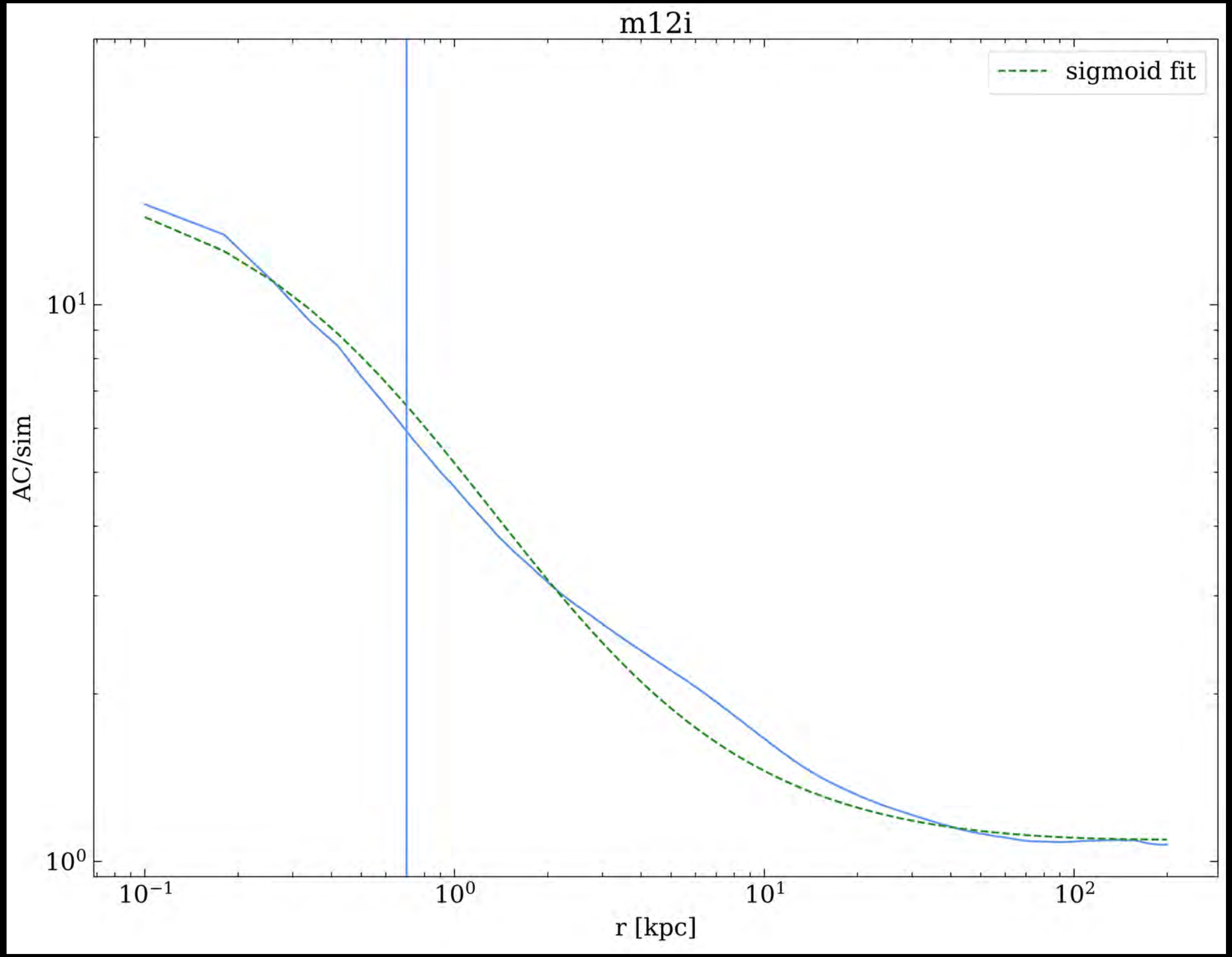




m12f
AC f
sim f
initial
1st break
$M_f^{enc-dm}$ [$M_\odot$]
$10^{13}$
$10^{11}$
$10^{9}$
$10^{7}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
AC/sim
r [kpc]

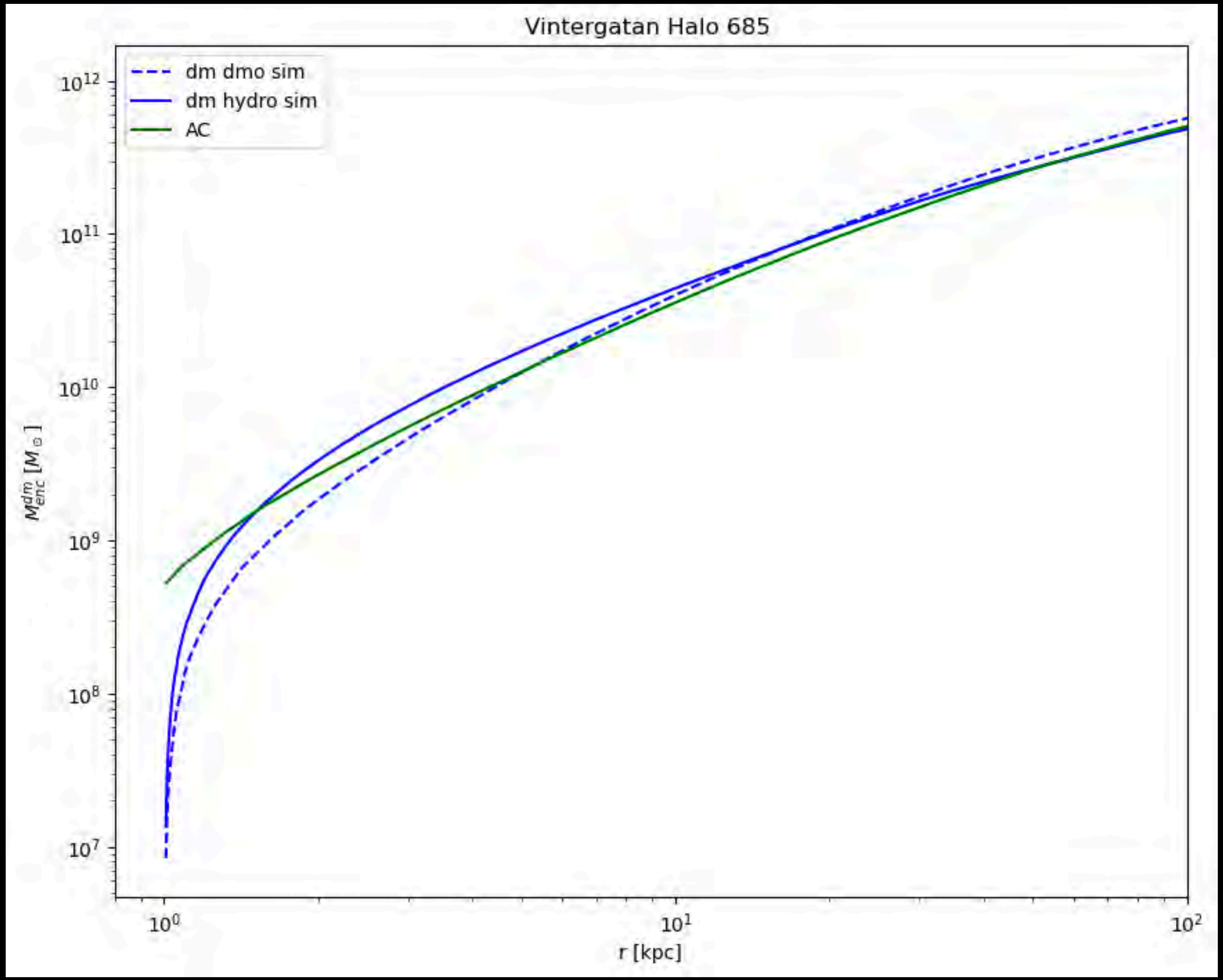

m12i
AC f
sim f
initial
1st break
$M_f^{enc-dm}$ [$M_\odot$]
$10^{13}$
$10^{11}$
$10^{9}$
$10^{7}$
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$
AC/sim
r [kpc]

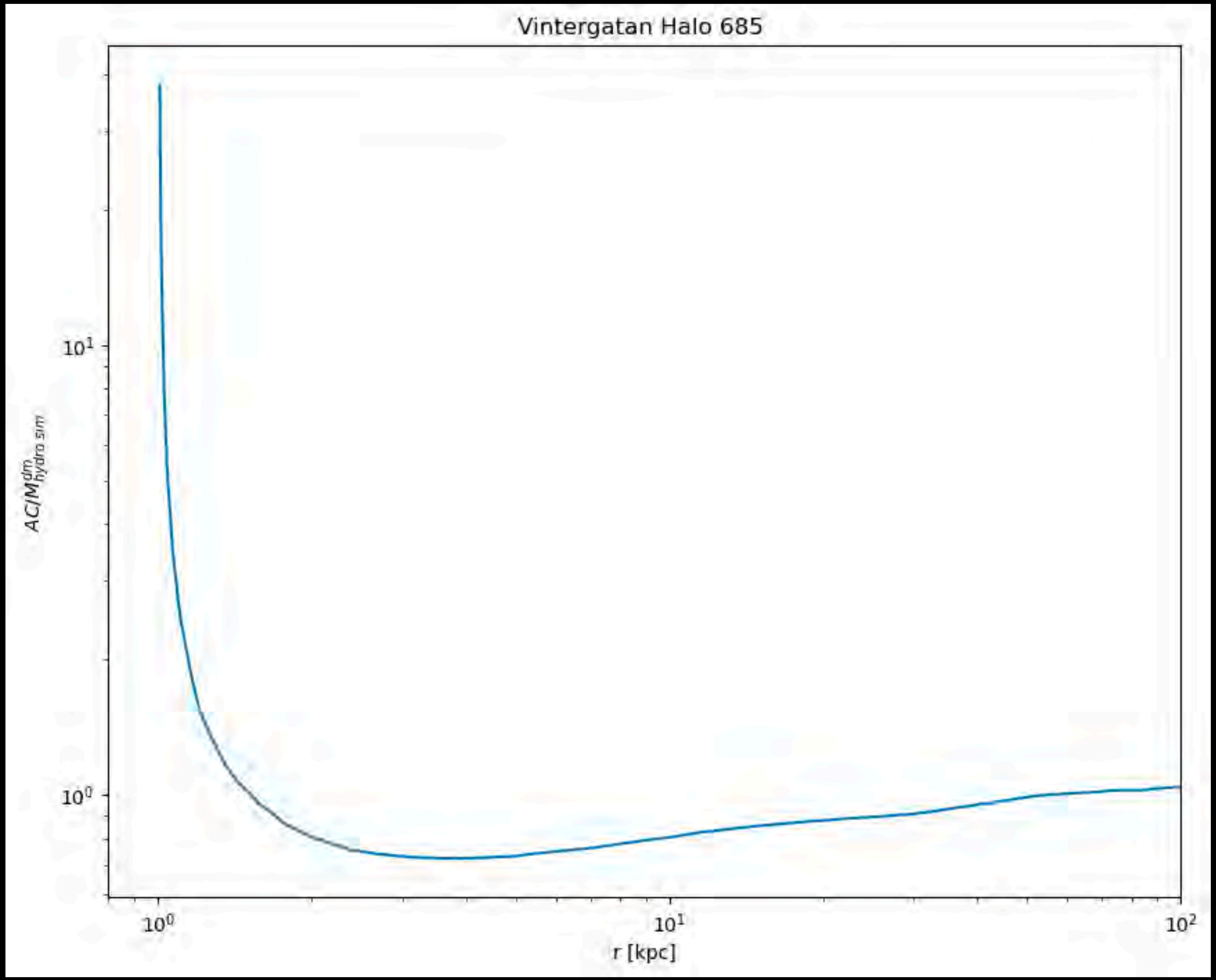
# Looking at transformation

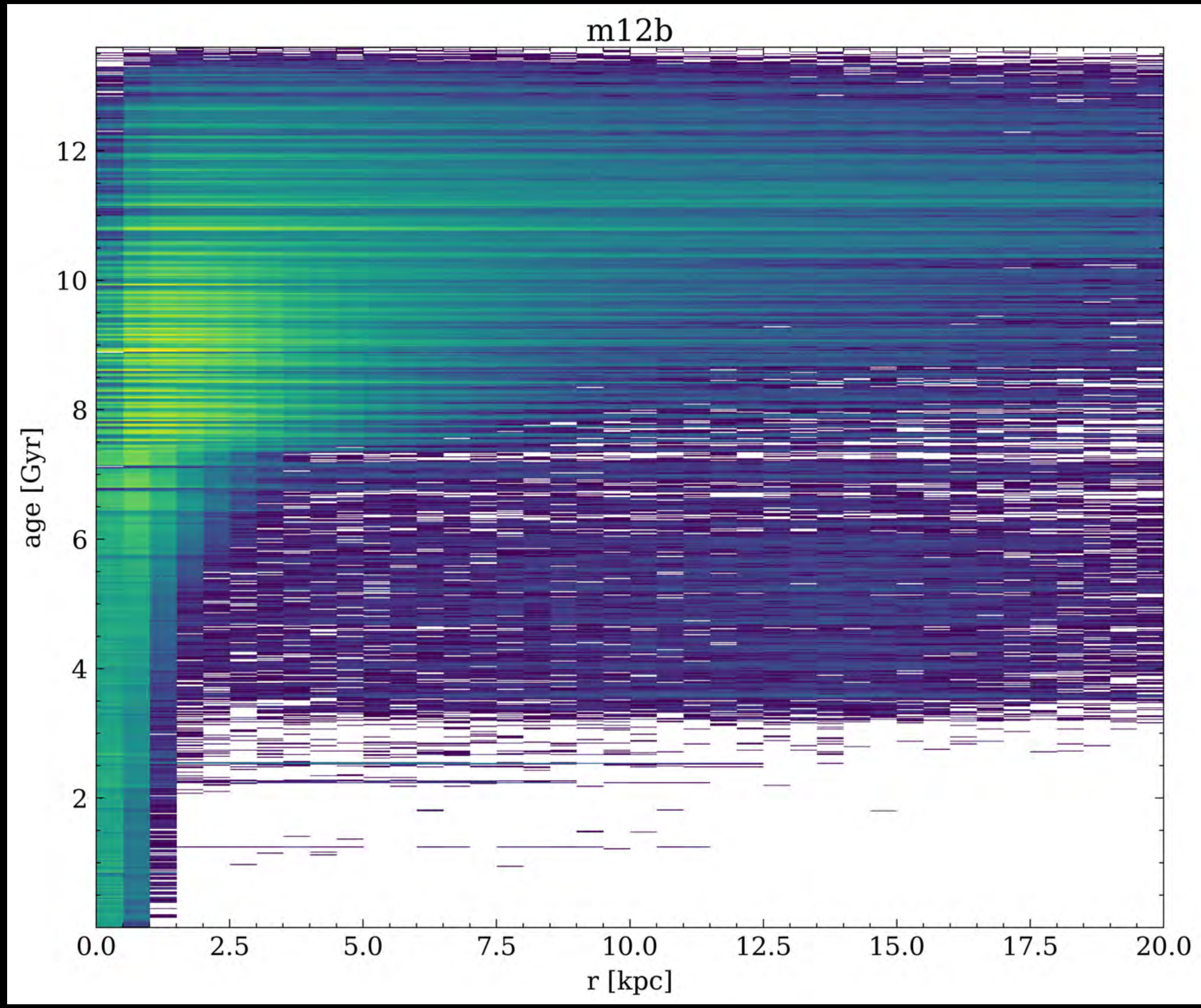


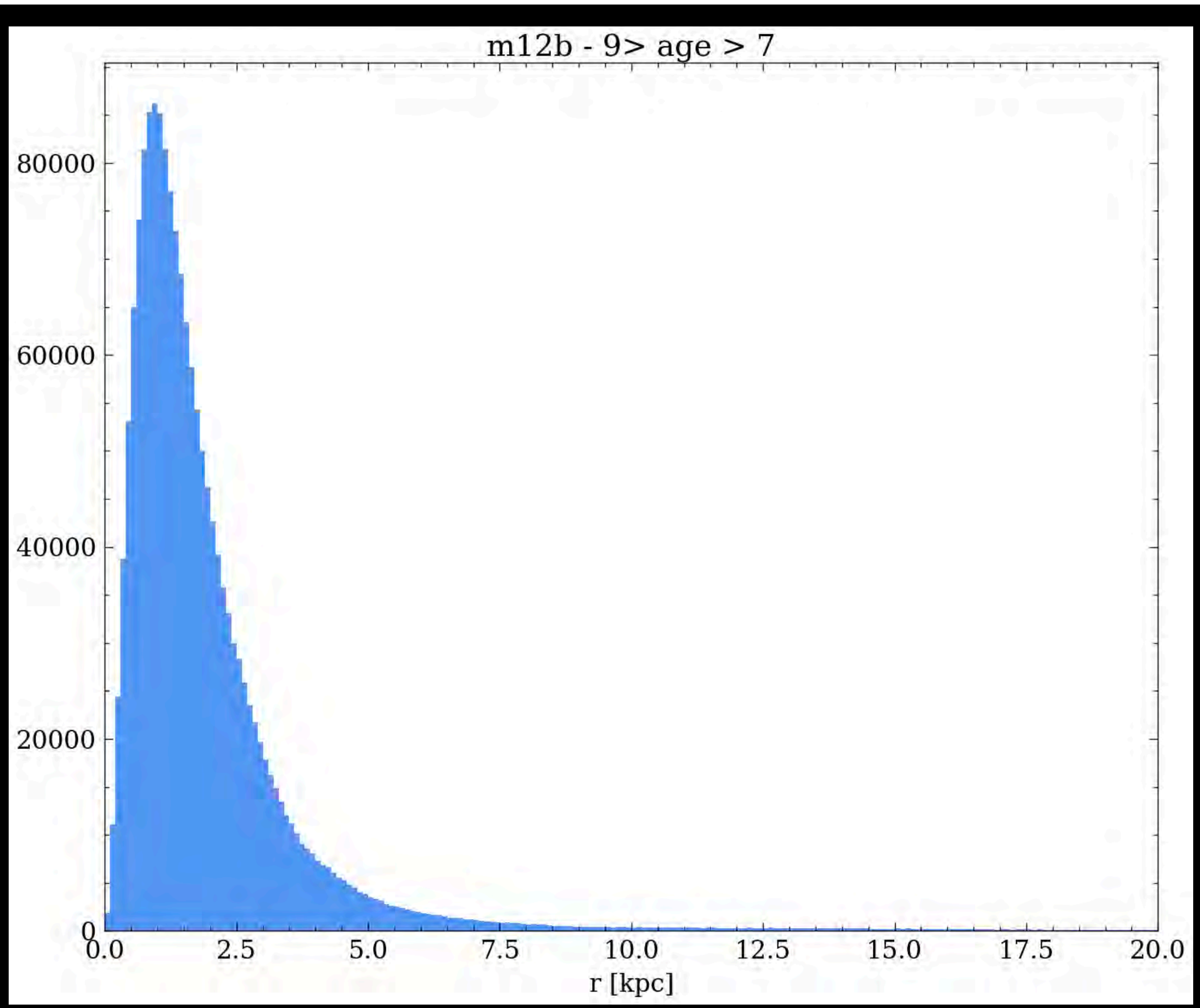



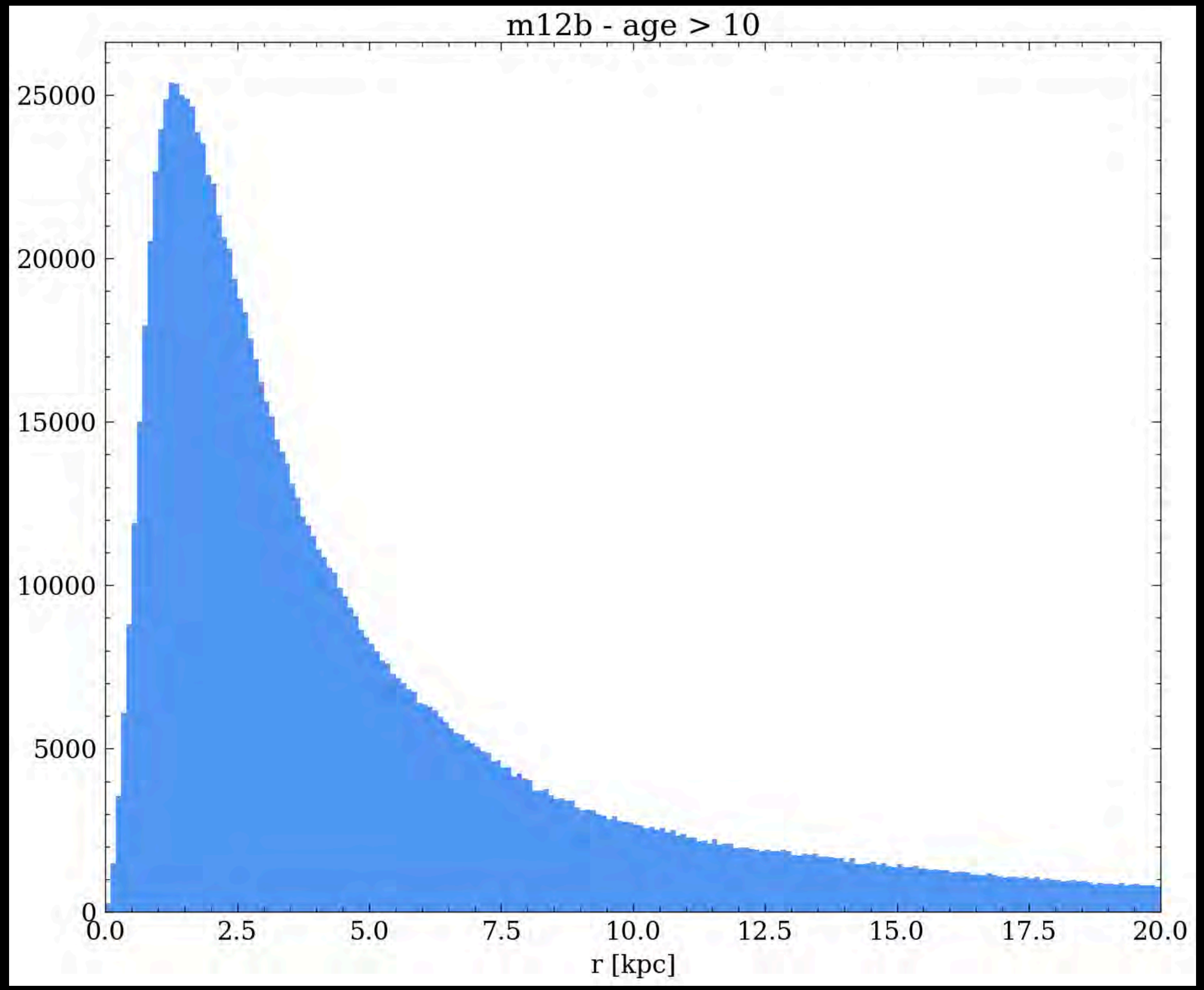
# Adiabatic Contraction in Vintergatan Halo 685

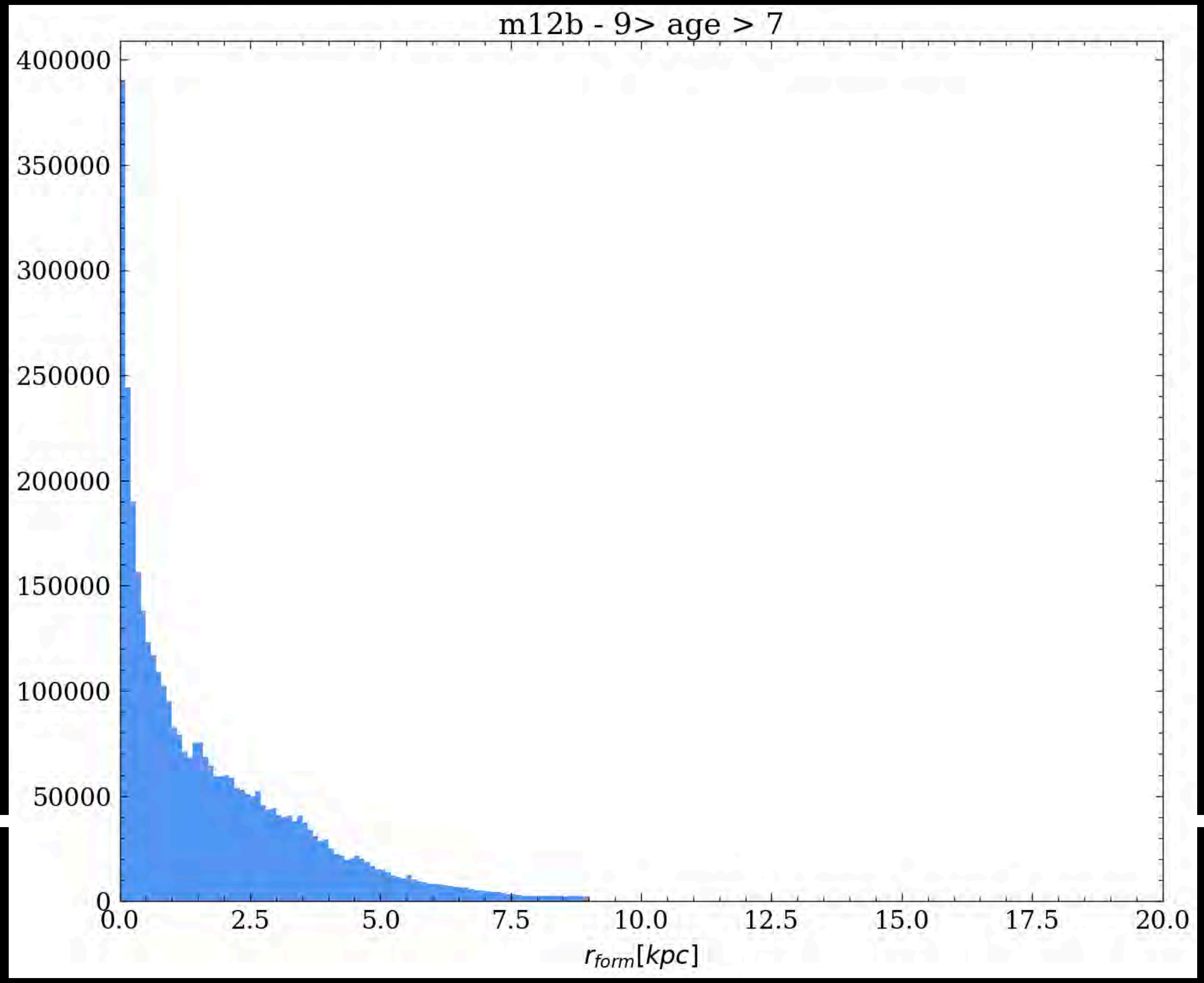


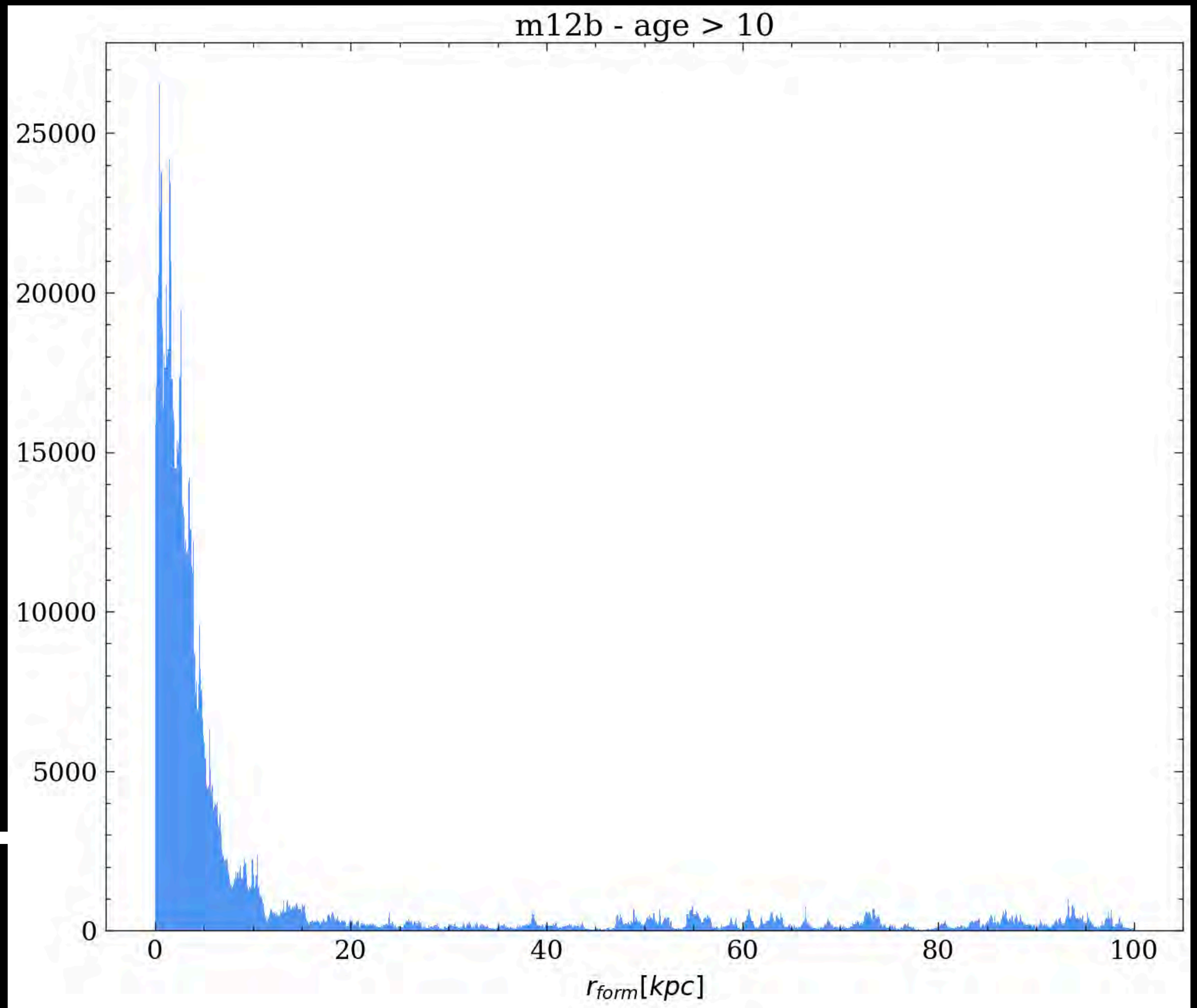



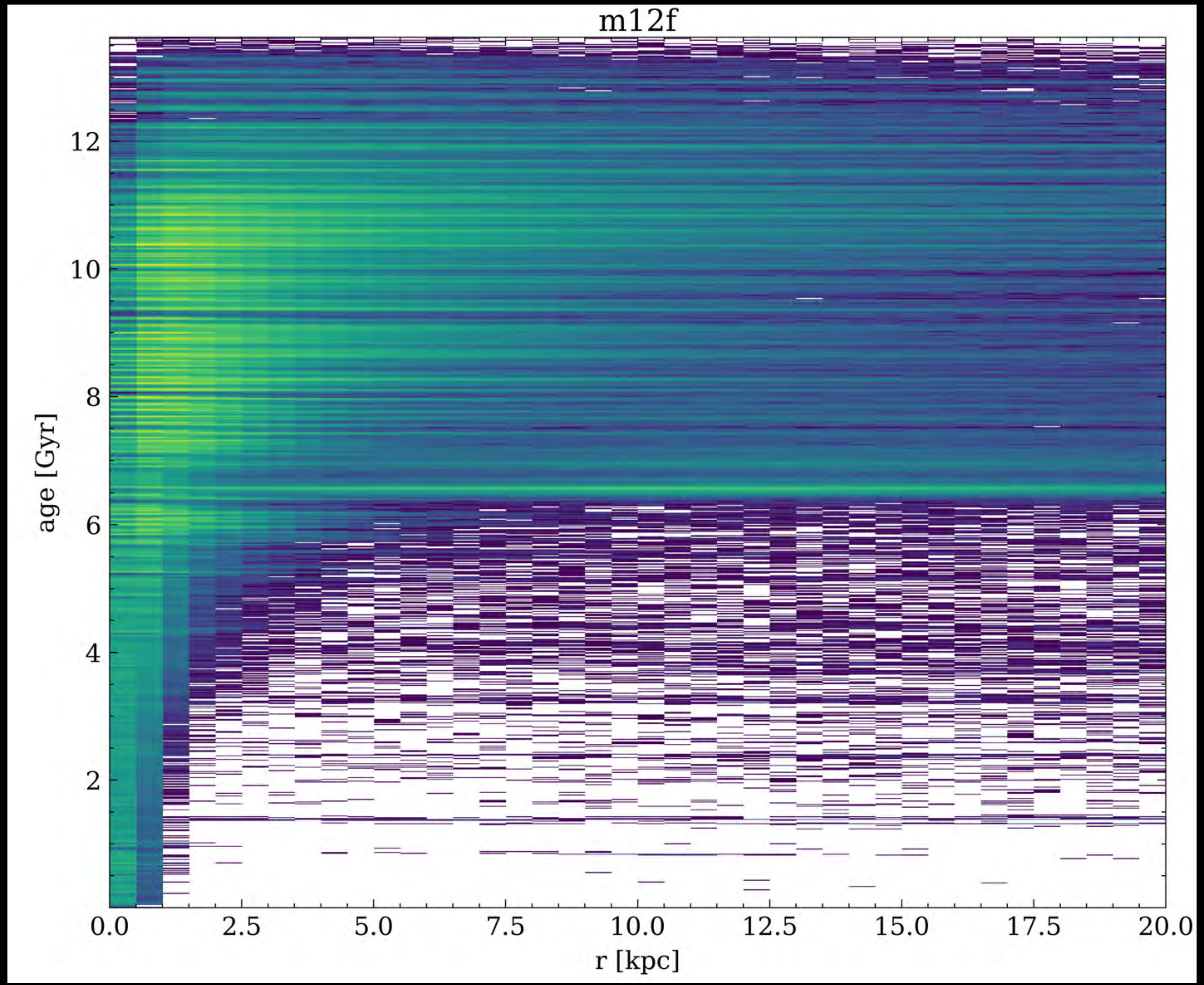

m12b
age [Gyr]
r [kpc]

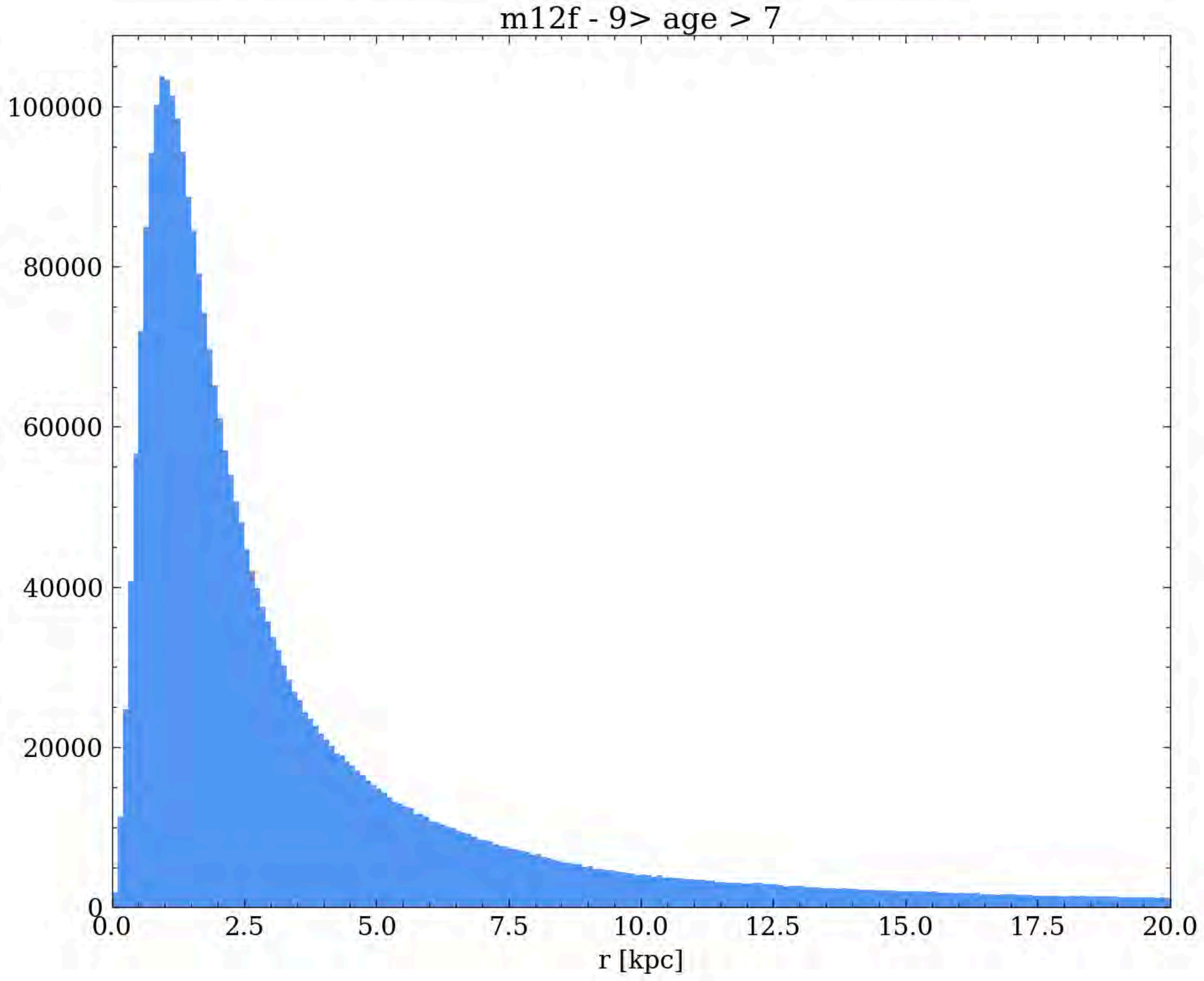

m12b - 9> age > 7
r [kpc]

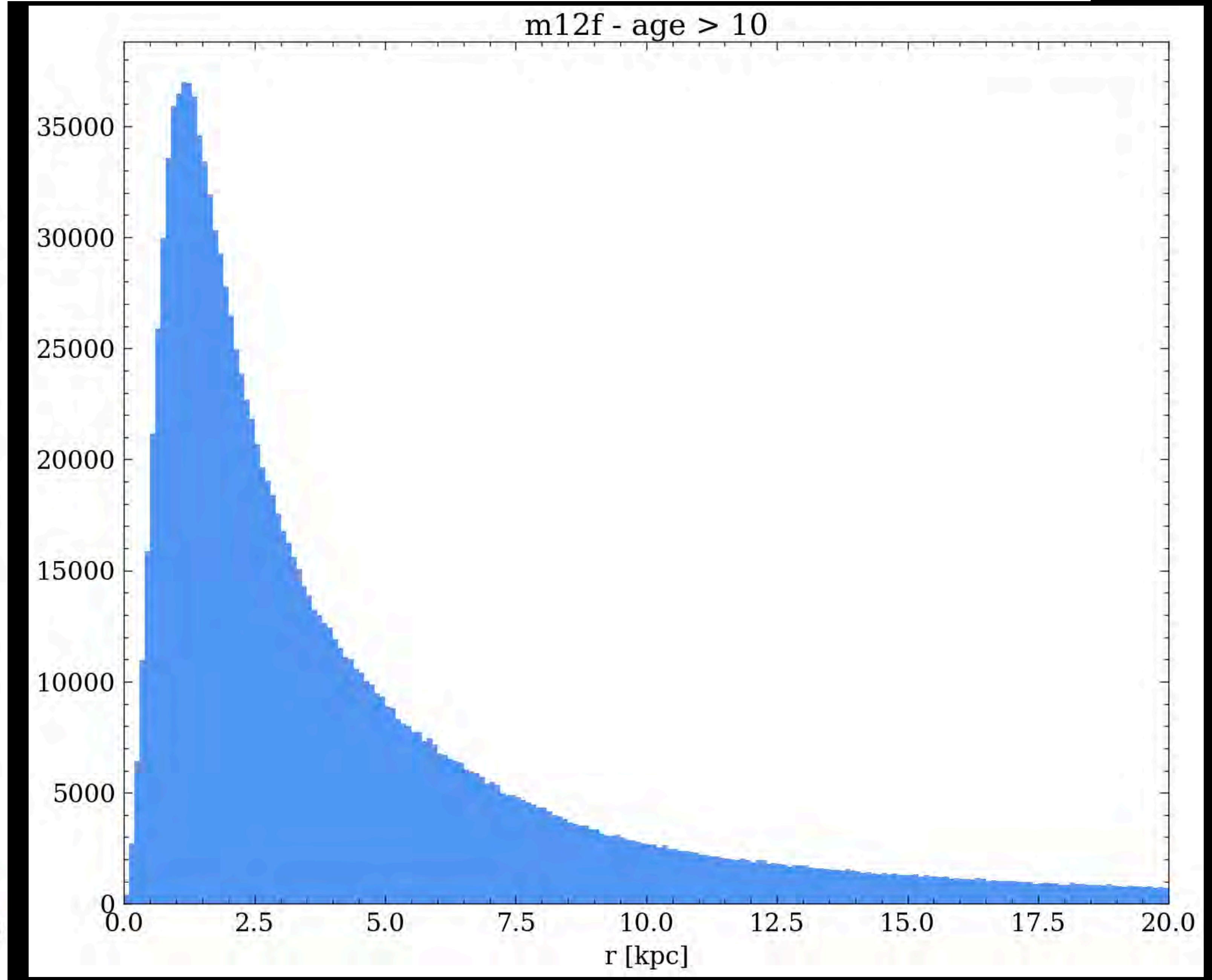

m12b - age > 10
r [kpc]

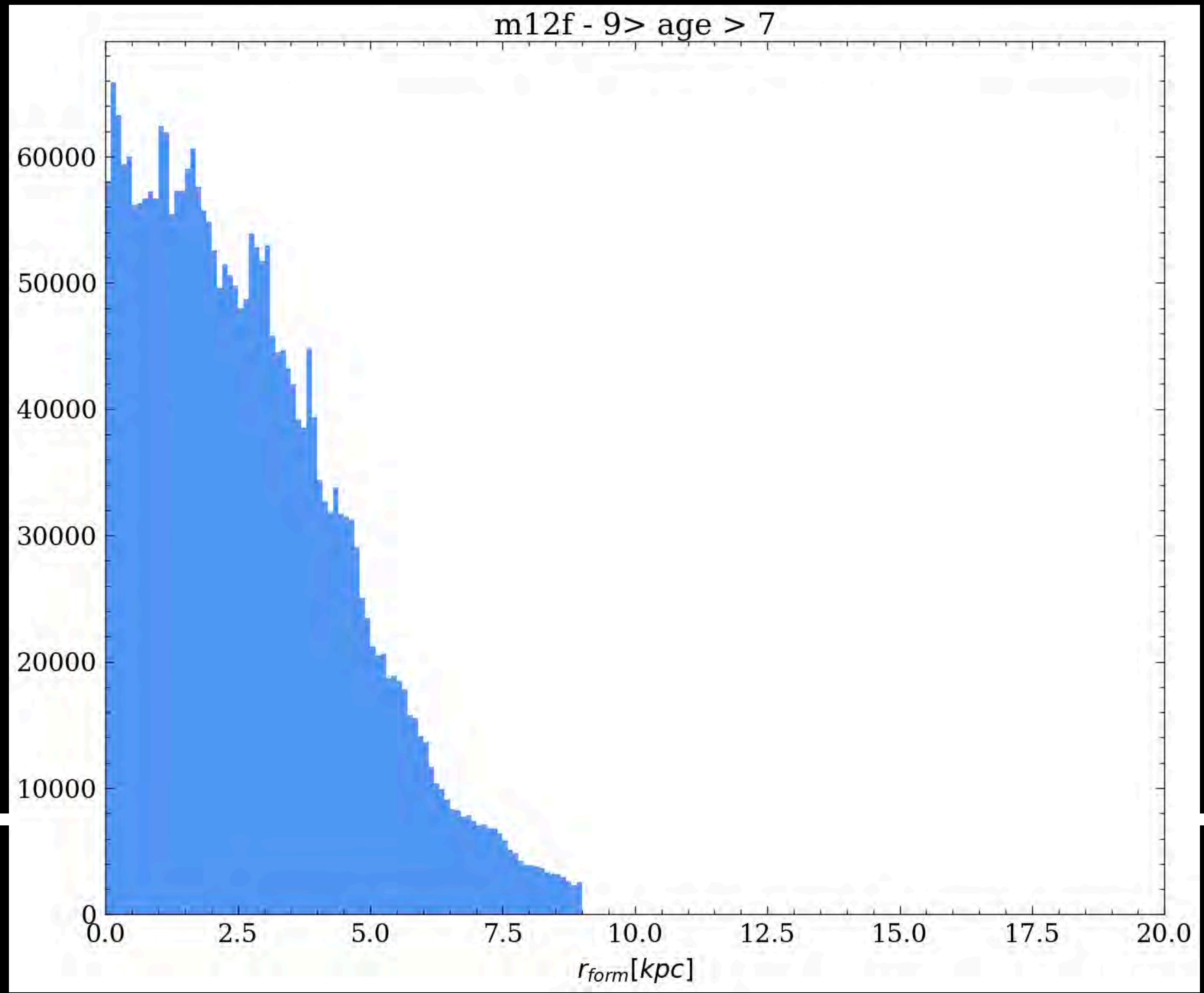

m12b - 9> age > 7
$r_{form}[kpc]$

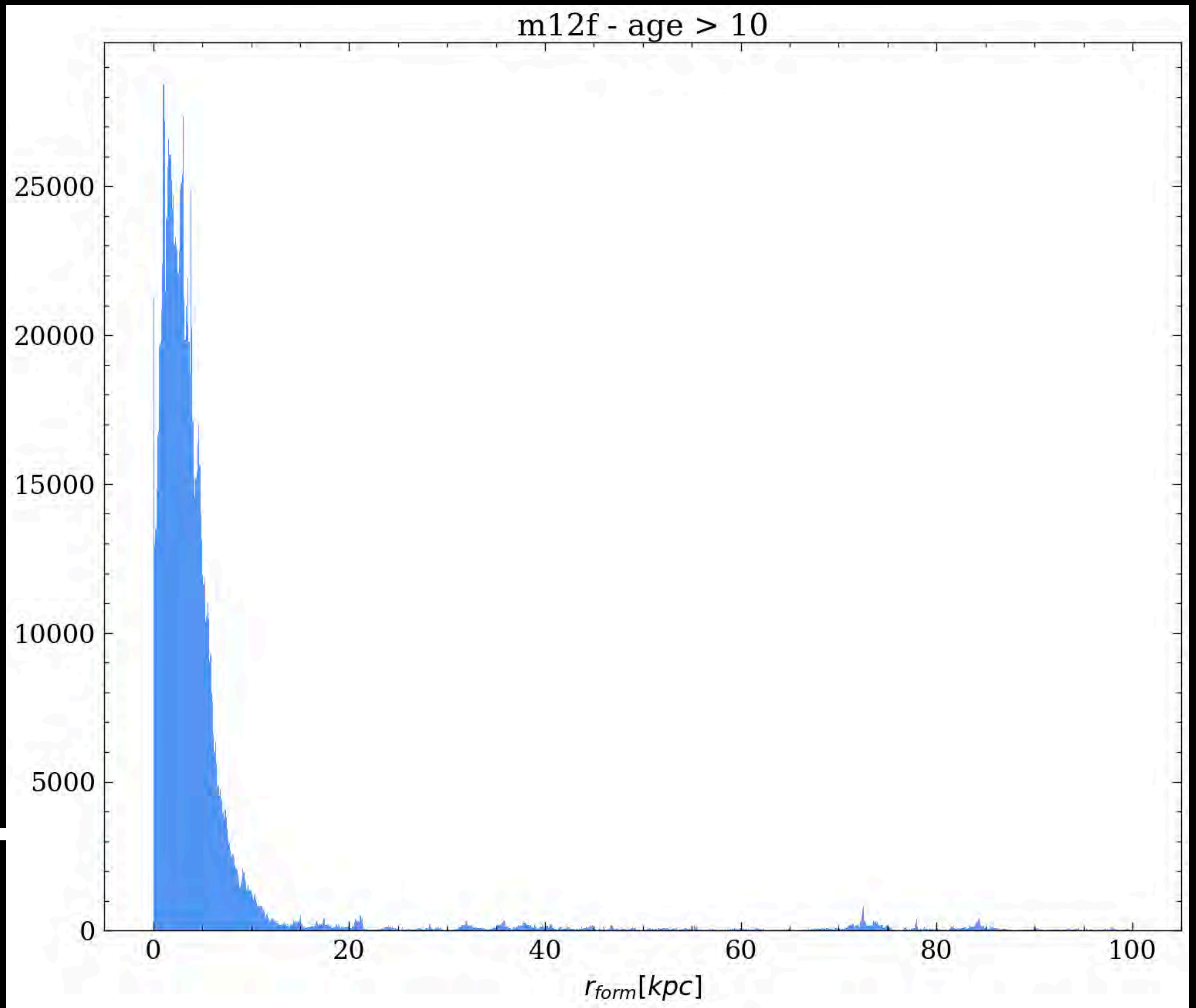

m12b - age > 10
$r_{form}[kpc]$


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
$r_{form}[kpc]$