Adiabatically compressed wave dark matter halo and intermediate-mass-ratio inspirals

Hyungjin Kim, Alessandro Lenoci, Isak Stomberg, Xiao Xue

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Speaker: Xiao Xue
University of Hamburg & DESY, Hamburg, Germany. Sponsored by Quantum Universe.
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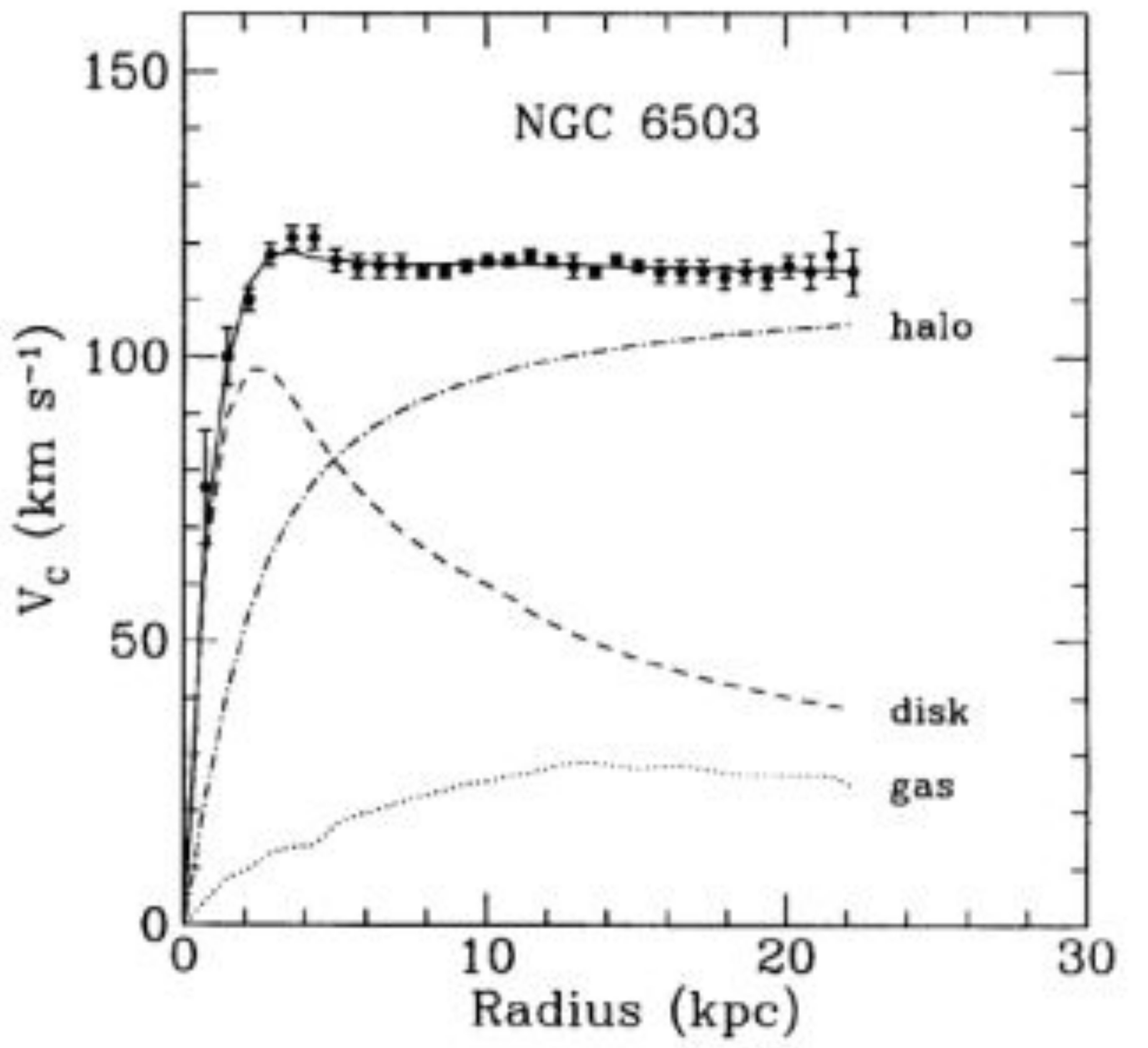
What We Know About Dark Matter

- It can not only explain "galaxy rotation curve” (Rubin, Ford and Thonnard 1980), but can also explain the “large scale structure” observed by the CMB.

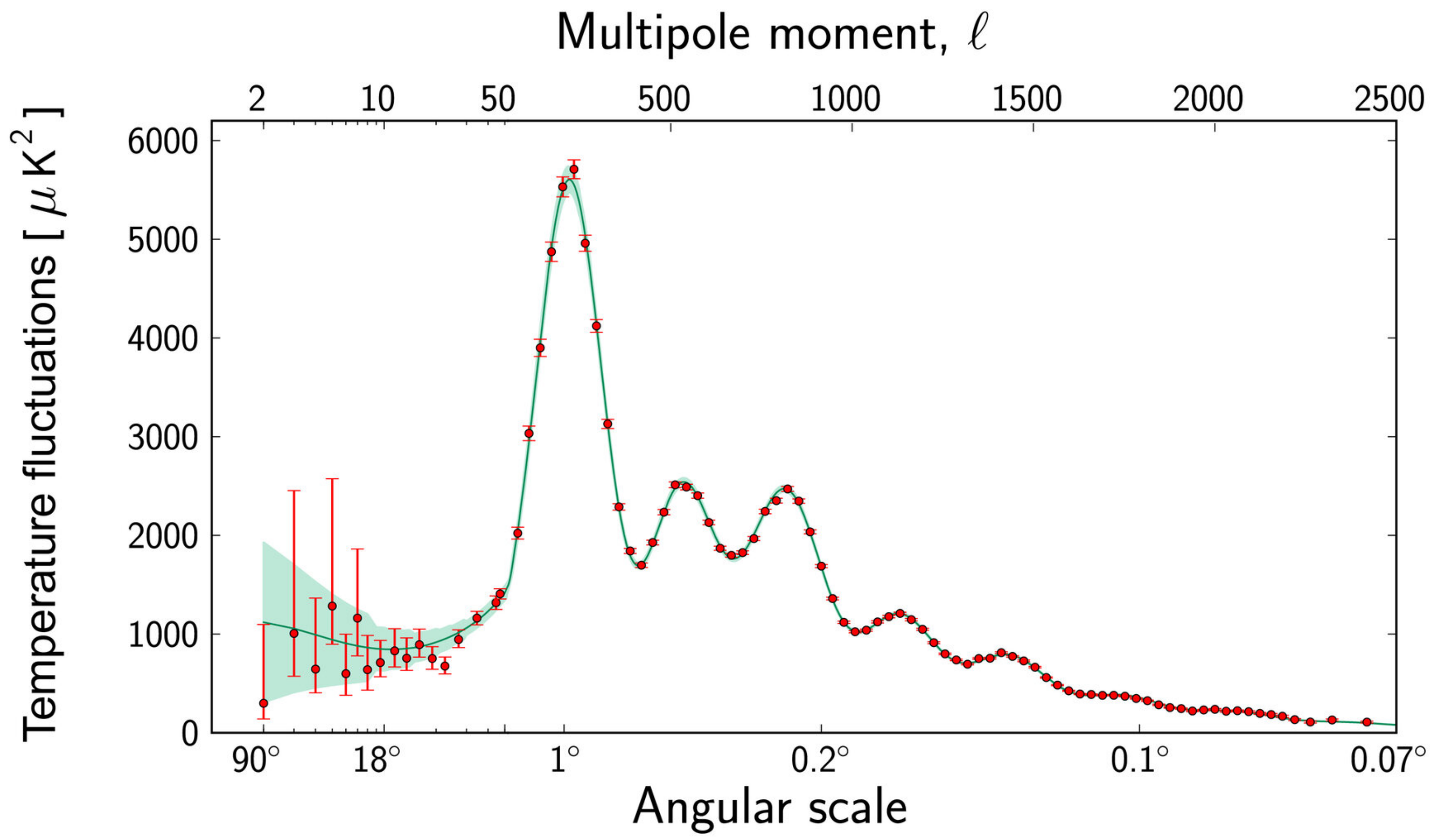
- It accounts for ~**84.5%** of the total mass of the current universe.

- Particle N-body collisionless simulation suggests a scale invariant **NFW** (Navarro–Frenk–White) density profile.

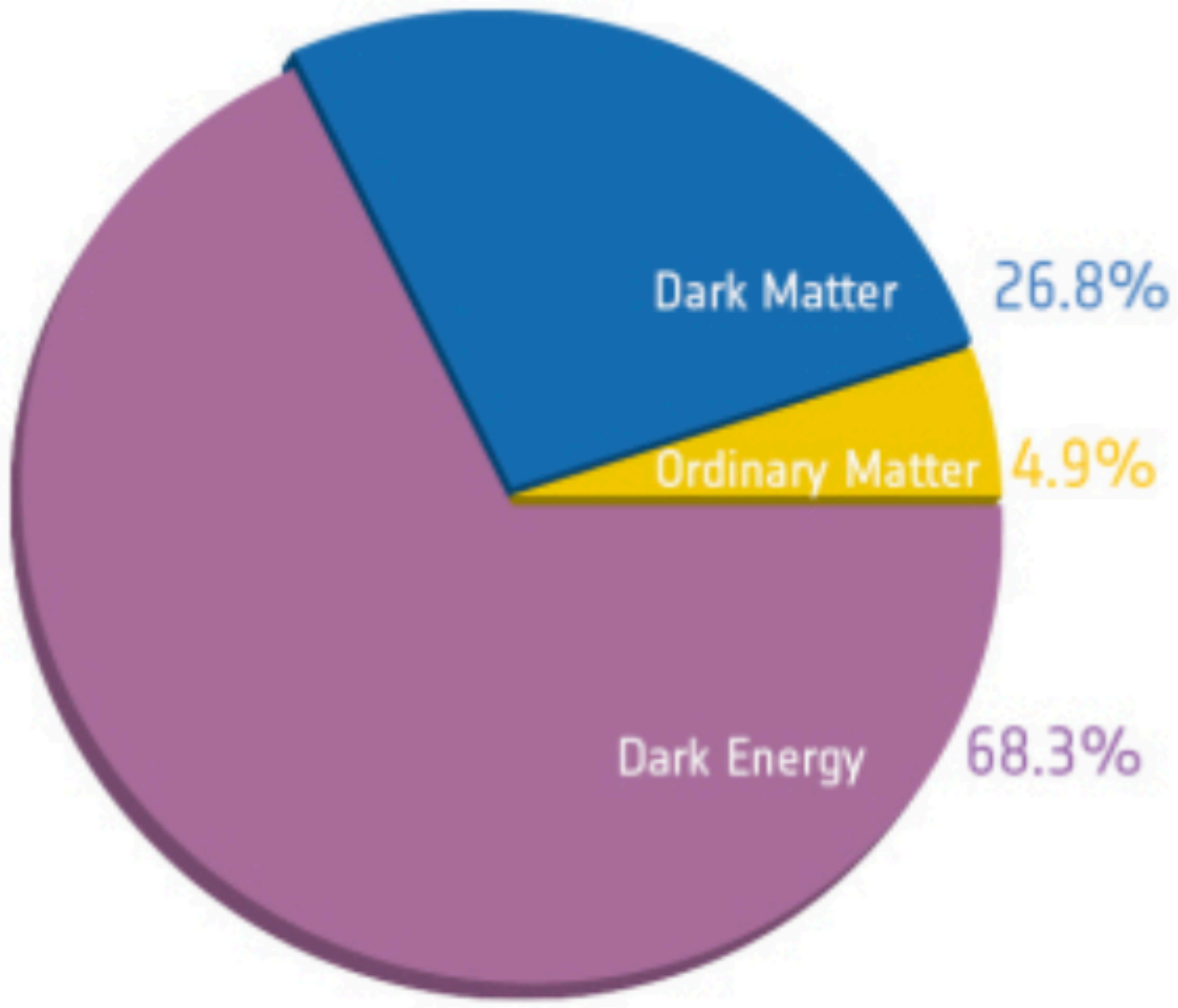
$$\rho_{\mathrm{NFW}}(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2} \propto \begin{cases} r^{-1}, & \mathrm{r} \ll \mathrm{r_s} \\ r^{-3}, & \mathrm{r} \gg \mathrm{r_s} \end{cases}$$



An example of the galaxy rotation curve
Begeman, Broeils and Sanders, 1991

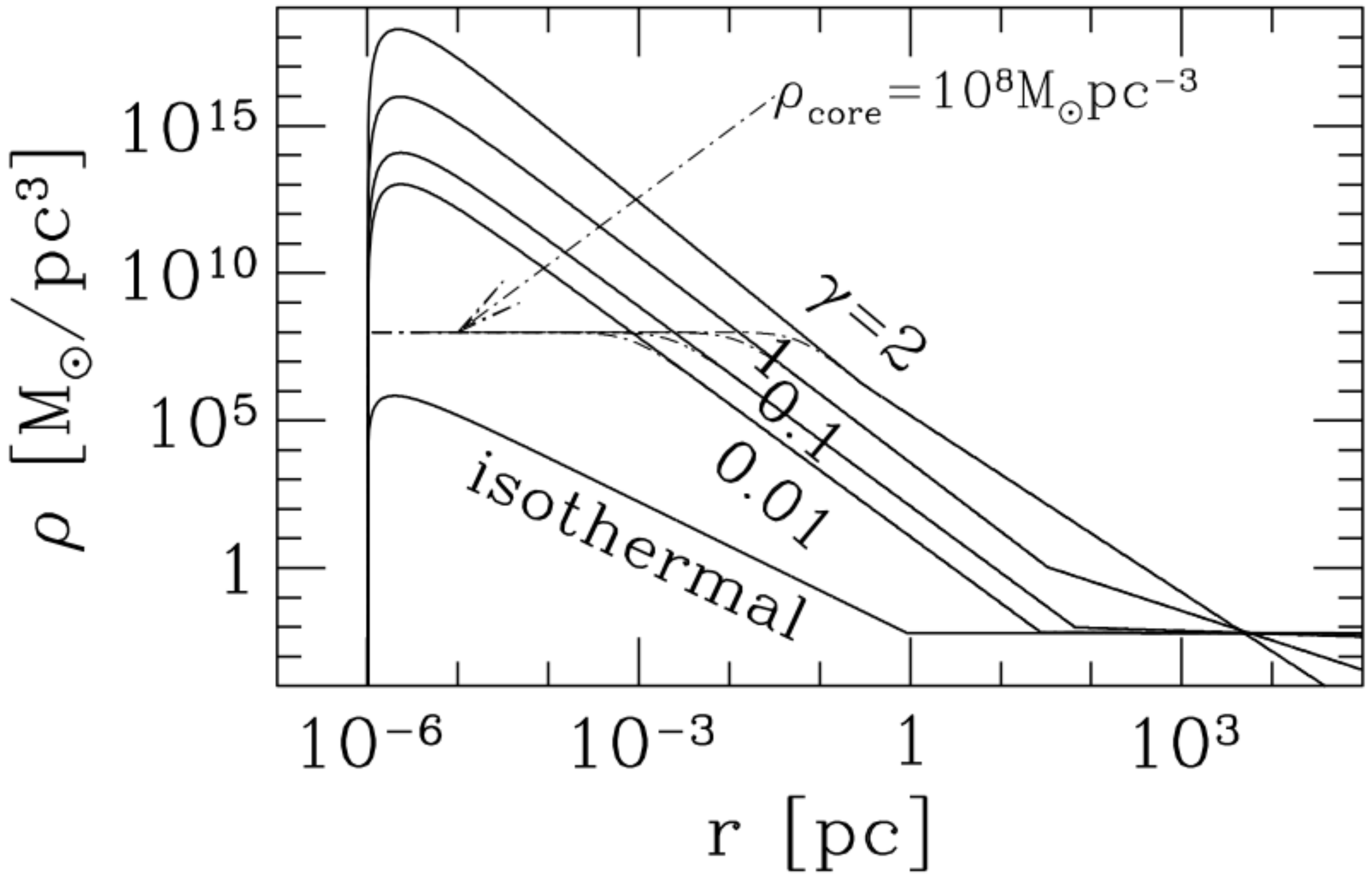
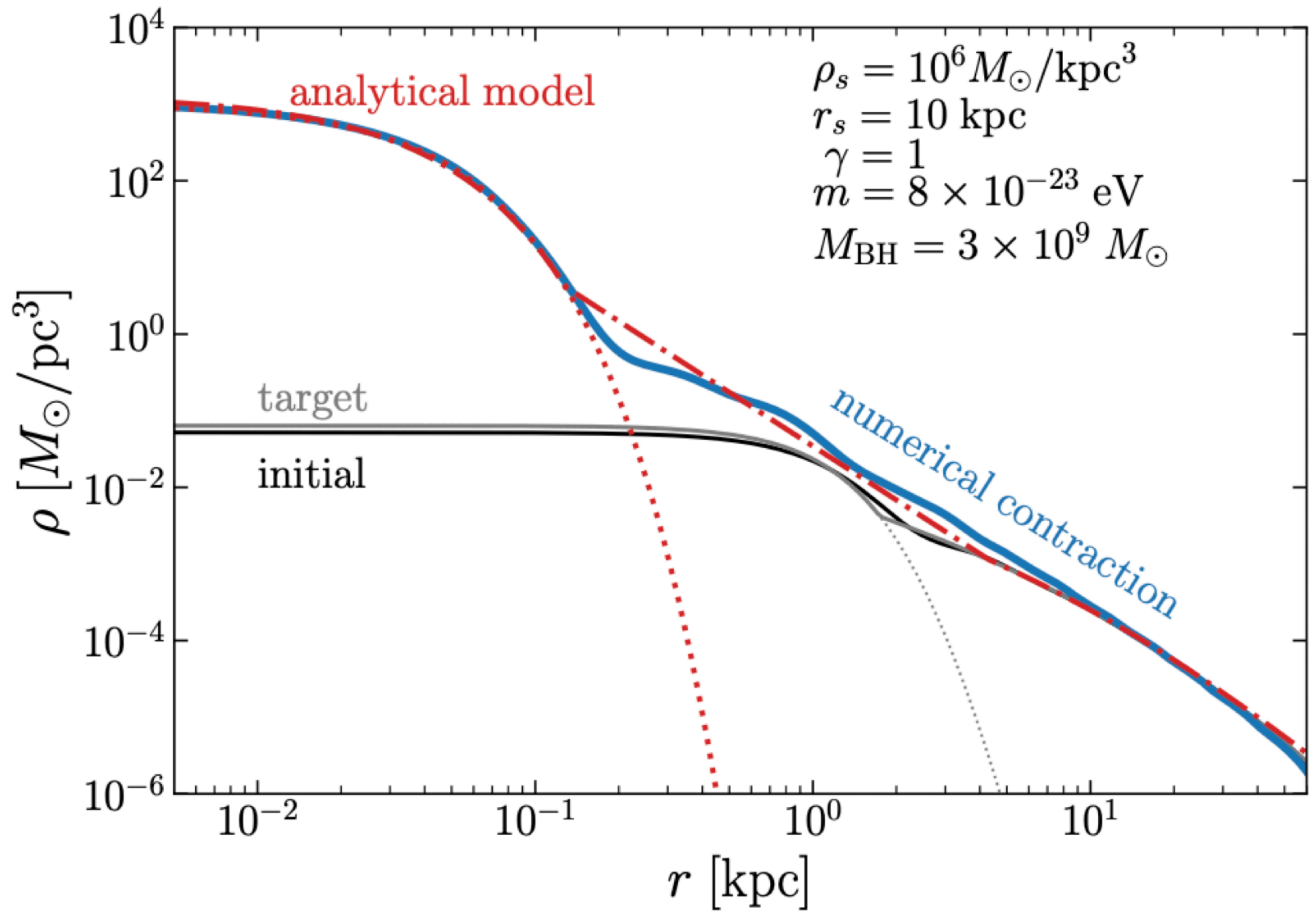


Planck CMB power spectrum (2013)



Dark matter density from Planck (2013)

Dark Matter Around a Black Hole

Black Hole Grows Adiabatically (Use supermassive BH as an example)	
Particle Dark Matter	**Wave Dark Matter**
	
Gondolo and Silk, **1999** (astro-ph/9906391)	Kim, Lenoci, Stomberg and Xue, **2022** (2212.07528) **(this work)**

Note: It is under the assumption that the black hole grows adiabatically in the center of the dark matter halo.

Adiabatic Compression of the Particle Dark Matter

Not the standard accretion

$$\rho_{\rm init}(r) = \rho_s (r/r_s)^{-\gamma}$$

$$\rho_{\rm final}(r) = \rho_{\rm sp}\left(\frac{r_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}\left(1-\frac{R_s}{2}\right)^{\gamma_{\rm sp}}$$

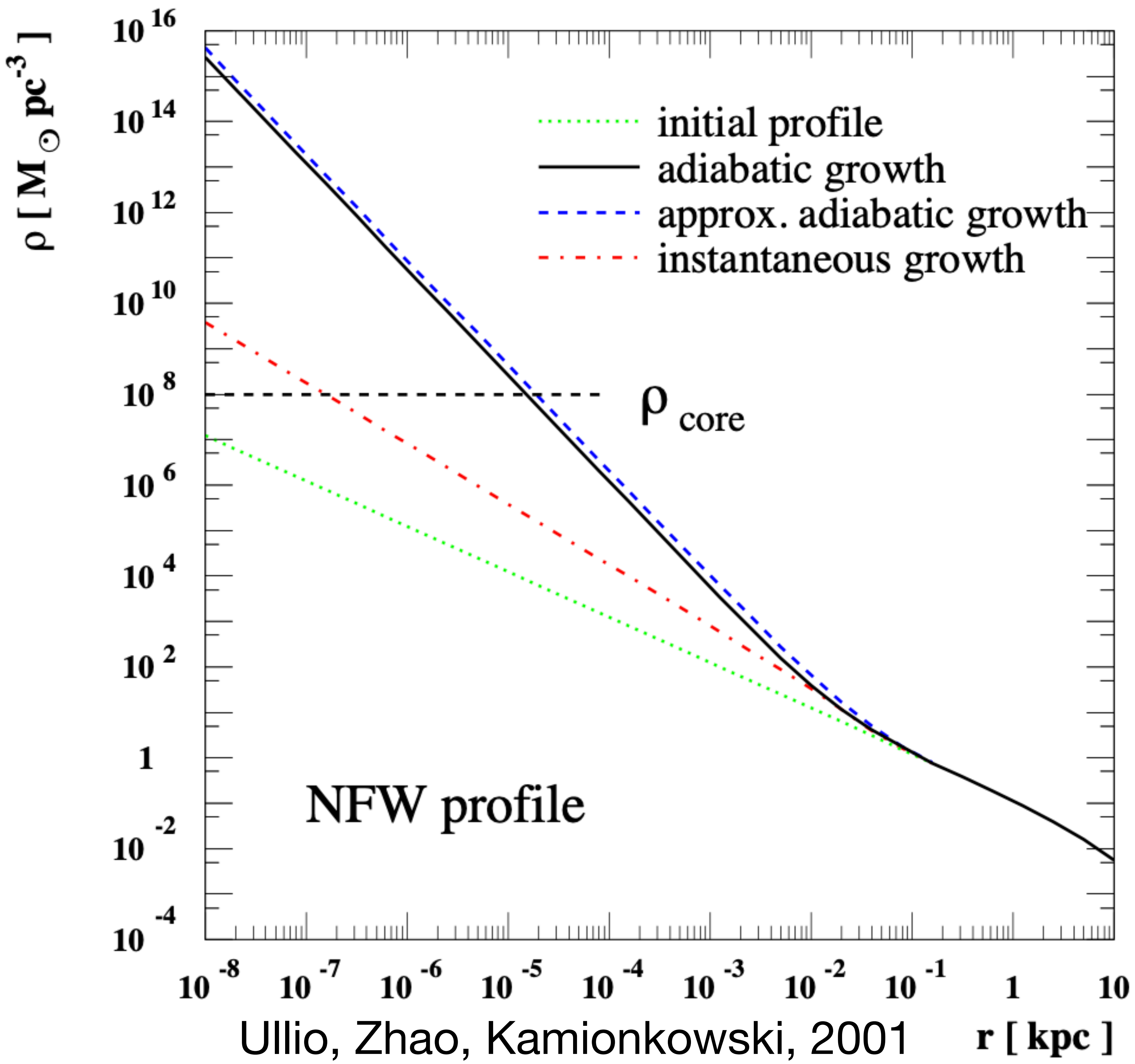
$$\gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma} \qquad R_s = 2GM_1$$

$$r_{\rm sp} = \left[\frac{(3-\gamma_{\rm sp})0.2^{3-\gamma_{\rm sp}}M_1}{2\pi\rho_{\rm sp}}\right]^{1/3}$$

$$\rho_{\rm sp} = \rho_{\rm init}(r_{\rm sp})$$

astro-ph/9906391 2212.07528

1. From initial $\rho_{\rm init}$, using Eddington's formula to find $f(E_i)$.
2. Angular momentum conservation can fix $L_i = L_f$.
3. Radial action conservation $J_i = J_f$ **(Because of adiabatic compression!)** can help finding a relation between E_i and E_f, $f(E_f, L_f) = f(E_i(E_f, L_f))$.
4. The final profile is $\rho_{\rm final} = \int dE_f \int dL_f \frac{4\pi L_f}{r^2 v_r} f(E_f, L_f)$.



Ullio, Zhao, Kamionkowski, 2001

$$\rho_{\rm final}(r) \propto r^{-7/3}$$

Adiabatic Compression of the Wave Dark Matter

- Schrödinger Poisson Equation

$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2\nabla^2}{2m} + m\Phi\right)\psi$$

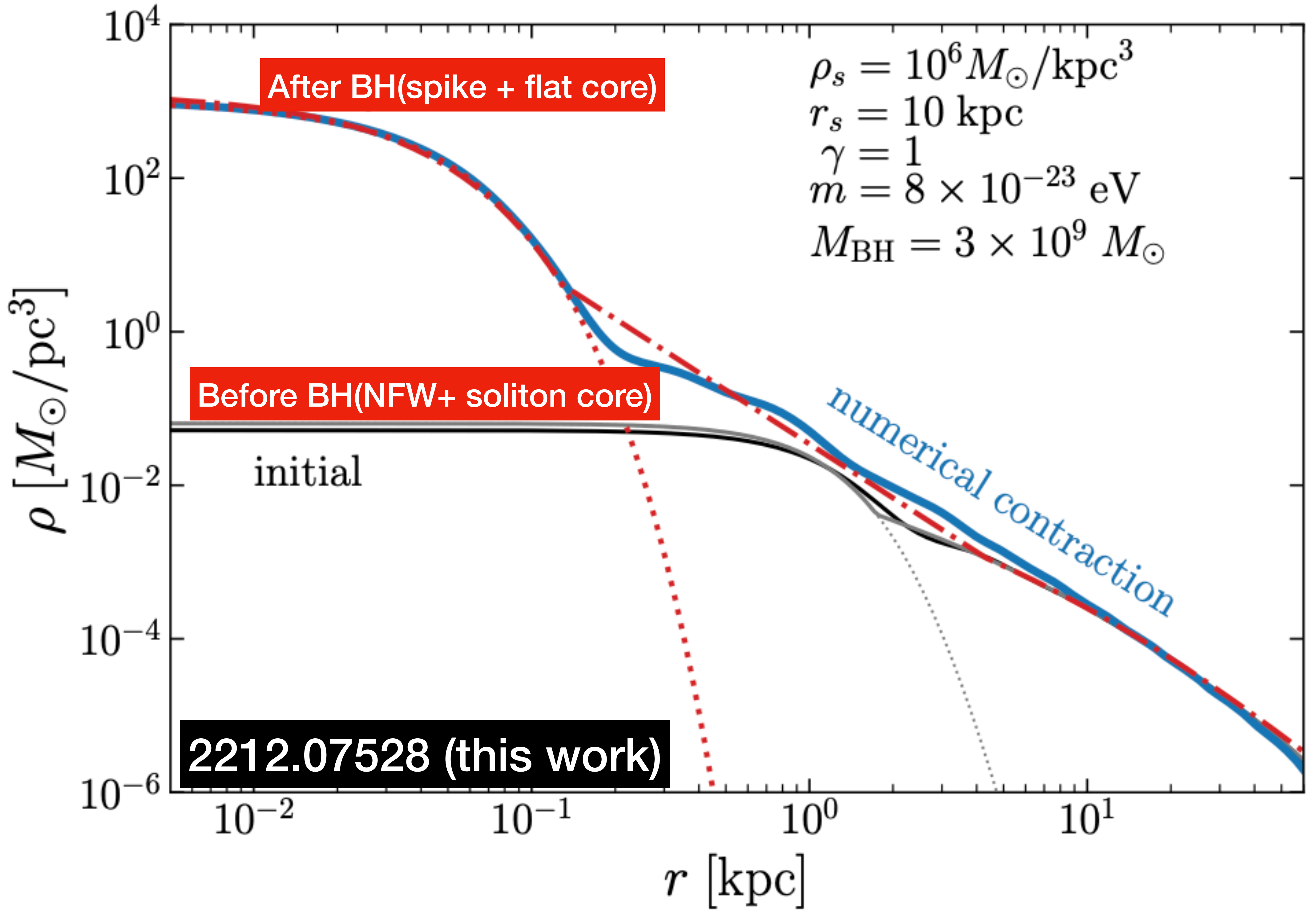
$$\nabla^2\Phi = 4\pi G|\psi|^2$$ **(before BH)**

$$\nabla^2\Phi = 4\pi G|\psi|^2 + 4\pi G M_1$$ **(after)**

- Adiabatic Theorem:

$$f^{\rm init}_{n\ell m} = f^{\rm final}_{n\ell m}$$

The size of the core and density of the "spike" depends on the dark matter mass.



An example for supermassive black hole

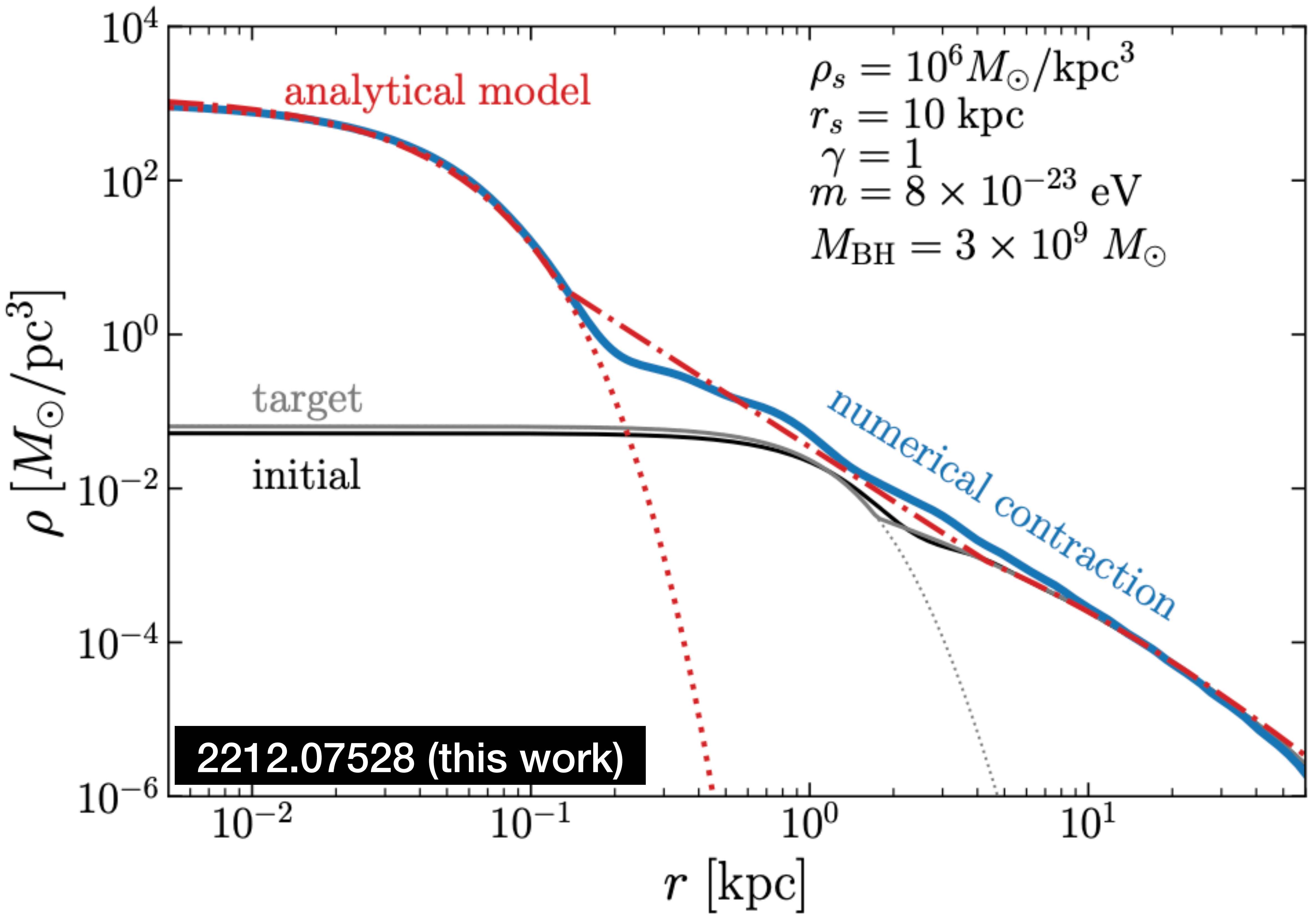
Adiabatic Compression of the Wave Dark Matter

The Pipeline

1. Using truncated NFW + soliton core profile to represent initial target halo, assuming that the halo is spherically symmetric (before BH appears).

2. For initial target halo, find $\Phi_{\text{init}}(r)$ numerically, then find the **eigenstates** $R^{\text{init}}_{n\ell}(r)$ of the Schrödinger equation. Decompose the initial halo with those eigenstates and find $f^{\text{init}}_{n\ell}$ (See Yavetz, Li, Hui, 2021)

3. Insert a black hole in the system and directly find $\Phi_{\text{final}}(r) = \Phi_{\text{init}}(r) - GM_{\text{BH}}/r$, then find the **eigenstates** $R^{\text{final}}_{n\ell}(r)$. The adiabatic theorem requires $f^{\text{init}}_{n\ell} = f^{\text{final}}_{n\ell}$, we can find out the final halo $\rho_{\text{final}}(r)$.



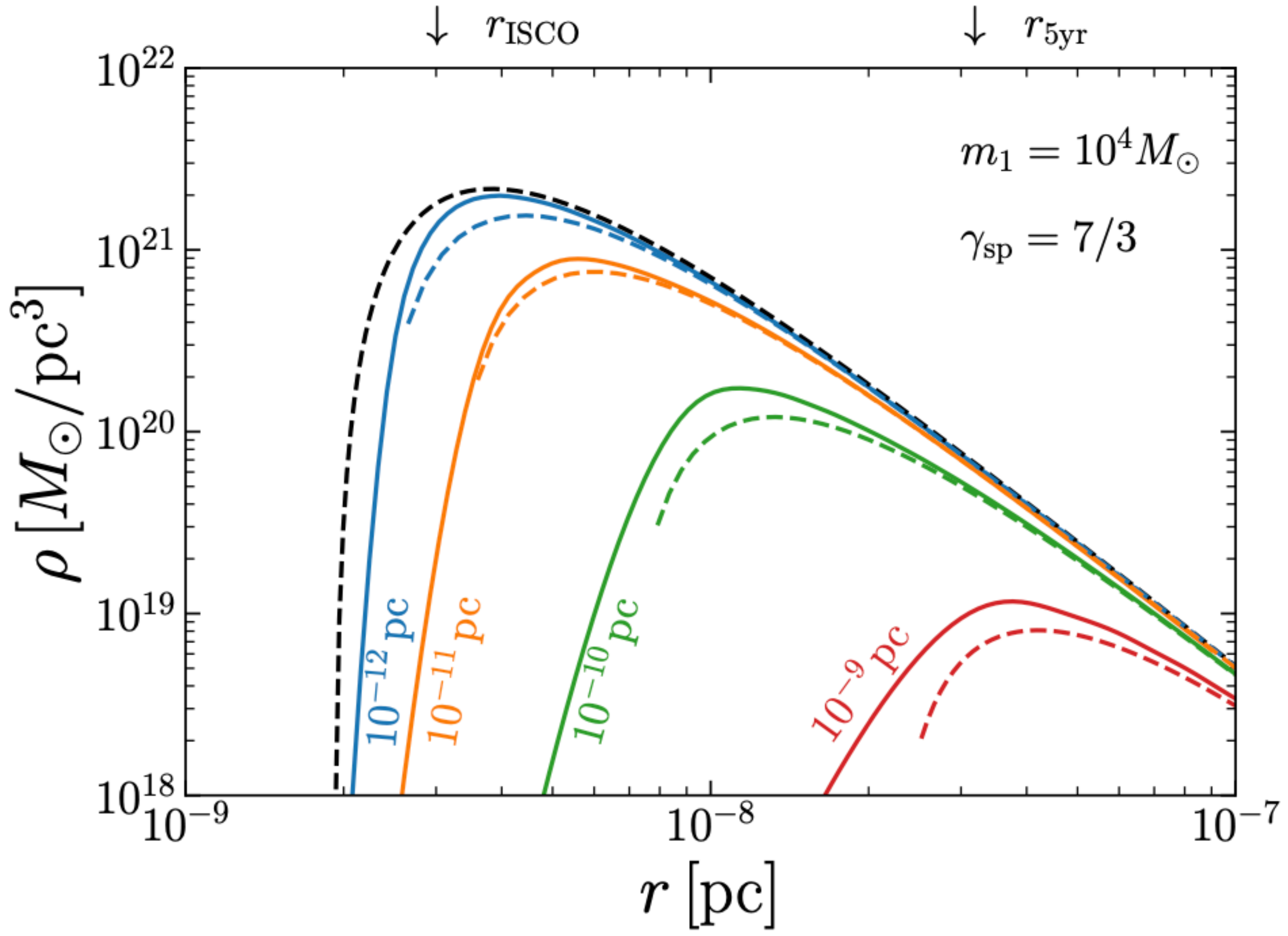
Intermediate Mass Black Hole

Survival of the soliton core

$$\Gamma_{nl} = m\alpha_G^{4\ell+5}\frac{2^{4\ell+3}(n+\ell)!}{n^{2\ell+4}(n-\ell-1)!}\left(\frac{\ell!}{(2\ell)!(2\ell+1)!}\right)^2\prod_{k=1}^{\ell}[k^2+(4\alpha_G)^2]$$

$$\rho_{\rm final}(r) = \frac{m}{4\pi}\sum_{n\ell}(2\ell+1)\,|R_{n\ell}^{\rm final}(r)|^2 e^{-2\Gamma_{nl}t_{\rm halo}}$$

$$\alpha_G \equiv GM_1 m$$



We find that in the previous SMBH case, the soliton core survives given that $t_{\rm halo} = 13{\rm Gyr}$. But for $M_1 \sim 10^4 M_\odot$ with dark matter mass $m \sim 10^{-14}{\rm eV}$, the soliton is **completely** absorbed by the BH.

Effects on the Intermediate Mass Ratio Inspirals

Dynamical Friction, Accretion of the companion mass, Halo feedback

$$\frac{dE_{\rm DF}}{dt} = \frac{4\pi G M_2^2 \rho(<v)}{v} C(v)$$

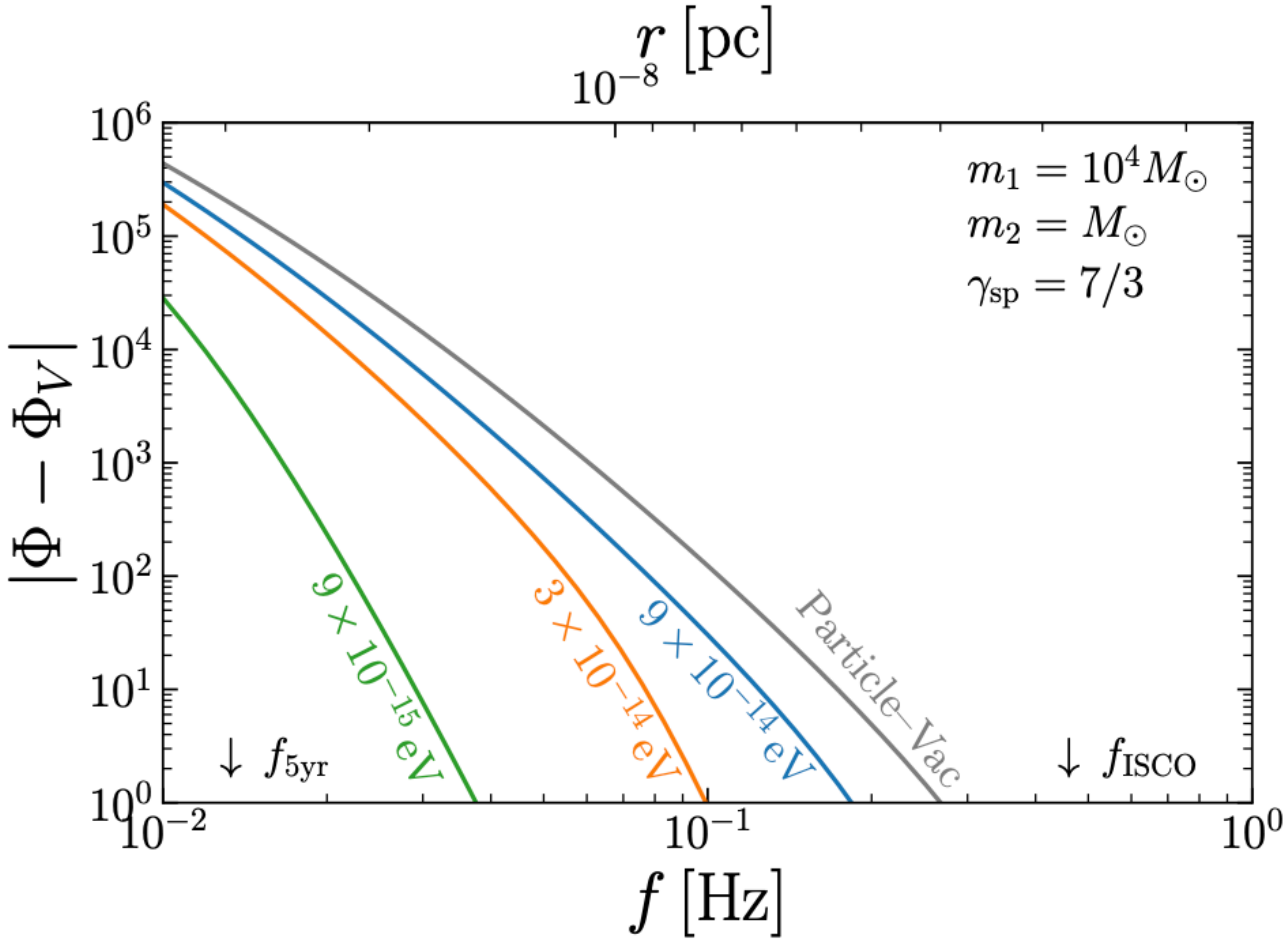
$$C_{\rm wave}(v) = \int_0^{2mvr} \frac{1-\cos(x)}{x} dx - 1 + \frac{\sin(2mvr)}{2mvr}$$

(Hui, Ostriker, Tremaine and Witten, 2016)

Consistent with Vincente and Cardoso, 2022, where the DF and accretion is treated in a consistent framework.

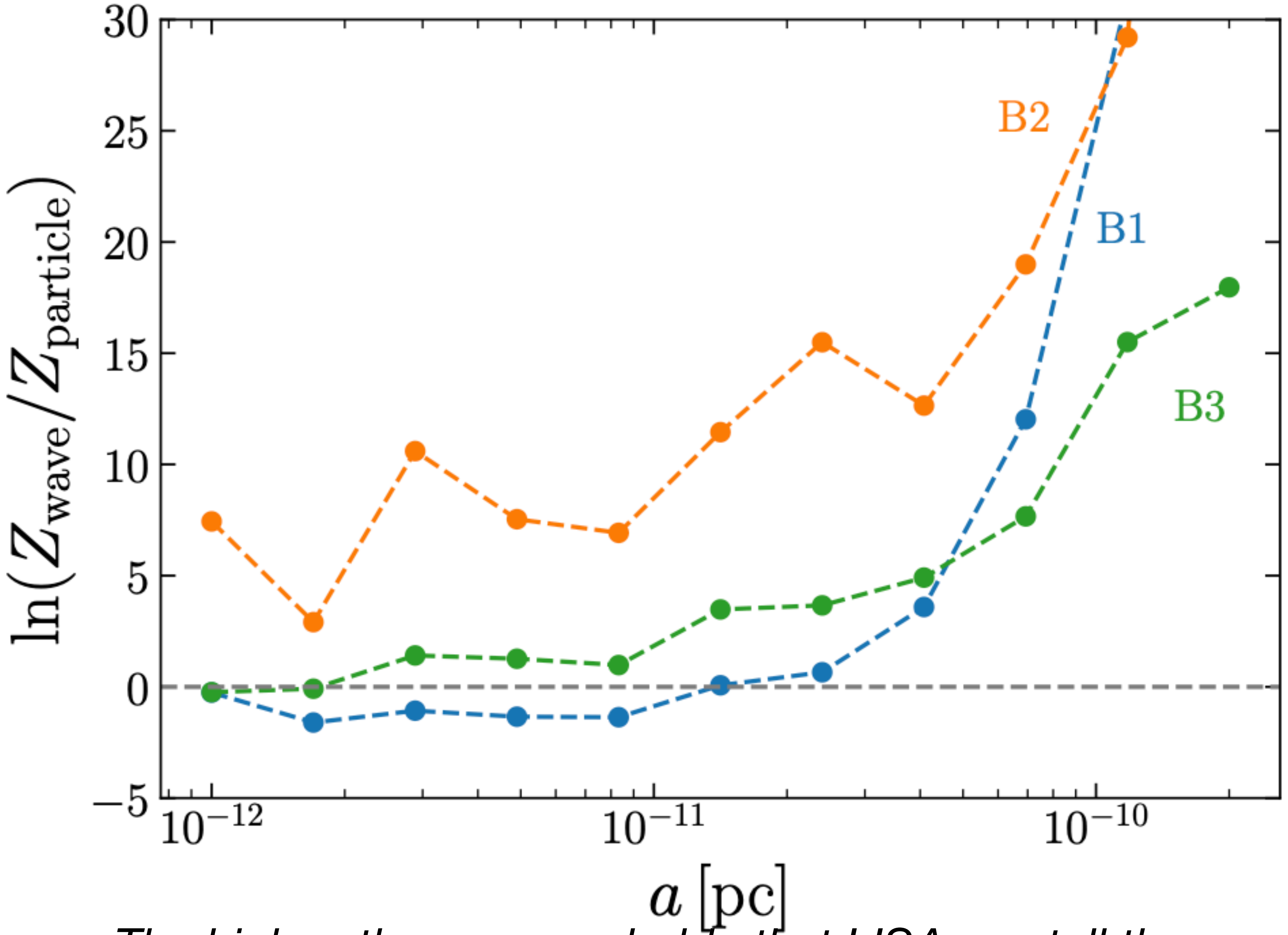
The feed back to halo is calculated from shell model (Kavanagh, Nichols, Bertone and Gaggero 2021)

$$\frac{dE_{\rm DF}}{dt} \to min\left(\frac{dE_{\rm DF}}{dt}, \frac{1}{2}\frac{dU}{dt}\right)$$



LISA Prospect

Can we tell the difference between wave “spike” and particle spike?



The higher, the more probable that LISA can tell the difference between the wave “spike” and the particle spike.

	$M_c\ [M_\odot]$	q	$\rho_6\ [10^{15} M_\odot/\mathrm{pc}^3]$	$\gamma_{\rm sp}$	D_L [Mpc]
B1	22.2	10^{-3}	6.8	7/3	83
B2	39.8	10^{-4}	25	7/3	203
B3	10^2	10^{-5}	120	7/3	750

1. We generated mock data with **wave “spike” model** using the **LISA** noise power spectral density.
2. We assume **5 years** of observation. In all cases, the signal strength **SNR = 15.** We constructed the likelihood function and use “dynesty” to calculate the evidence.
3. Model comparison is between the **wave “spike”** and the **particle spike**.

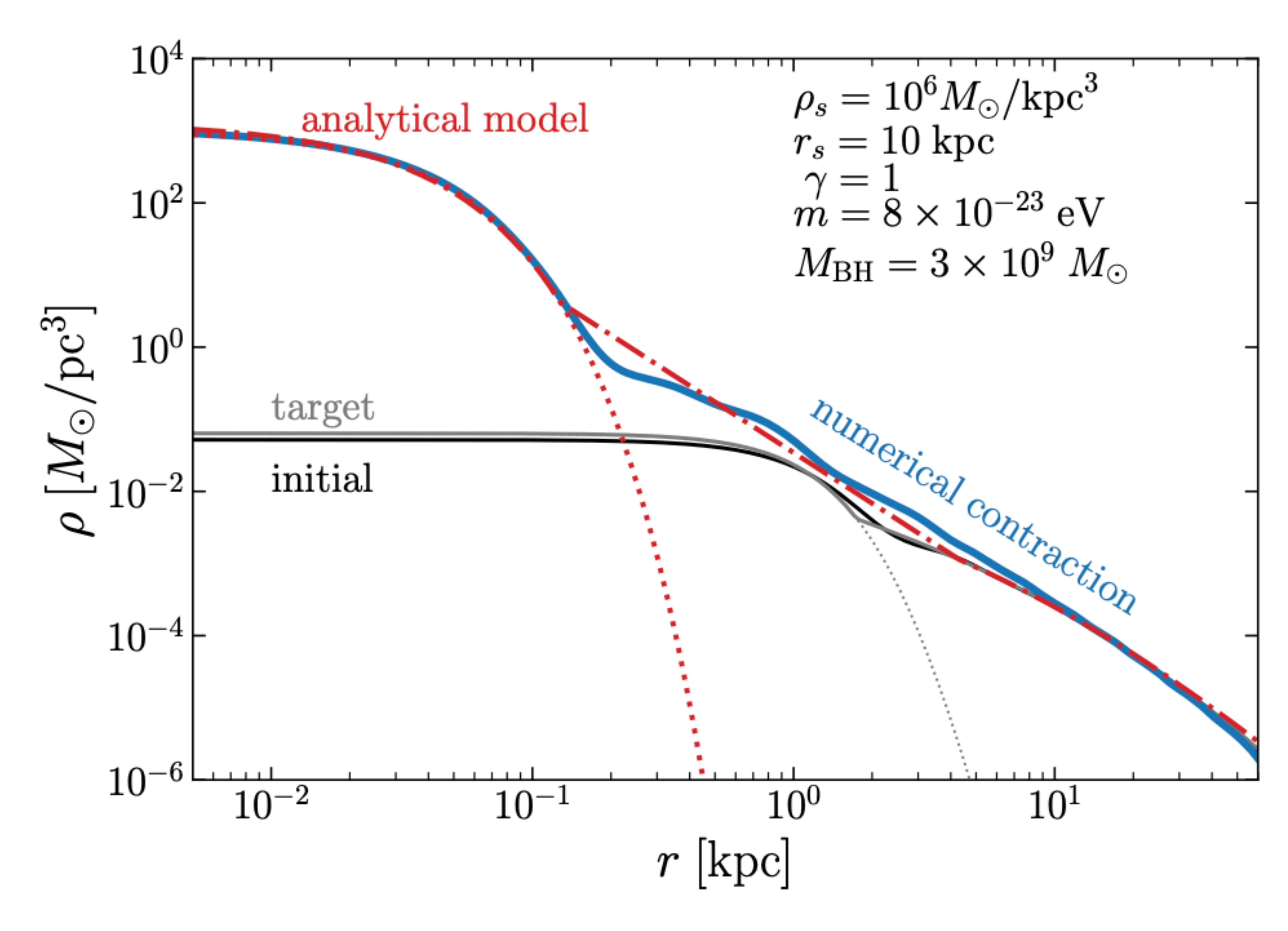
For particle spike vs vacuum, see Coogan, Bertone, Gaggero, Kavanagh and Nichols 2021.

Discussions

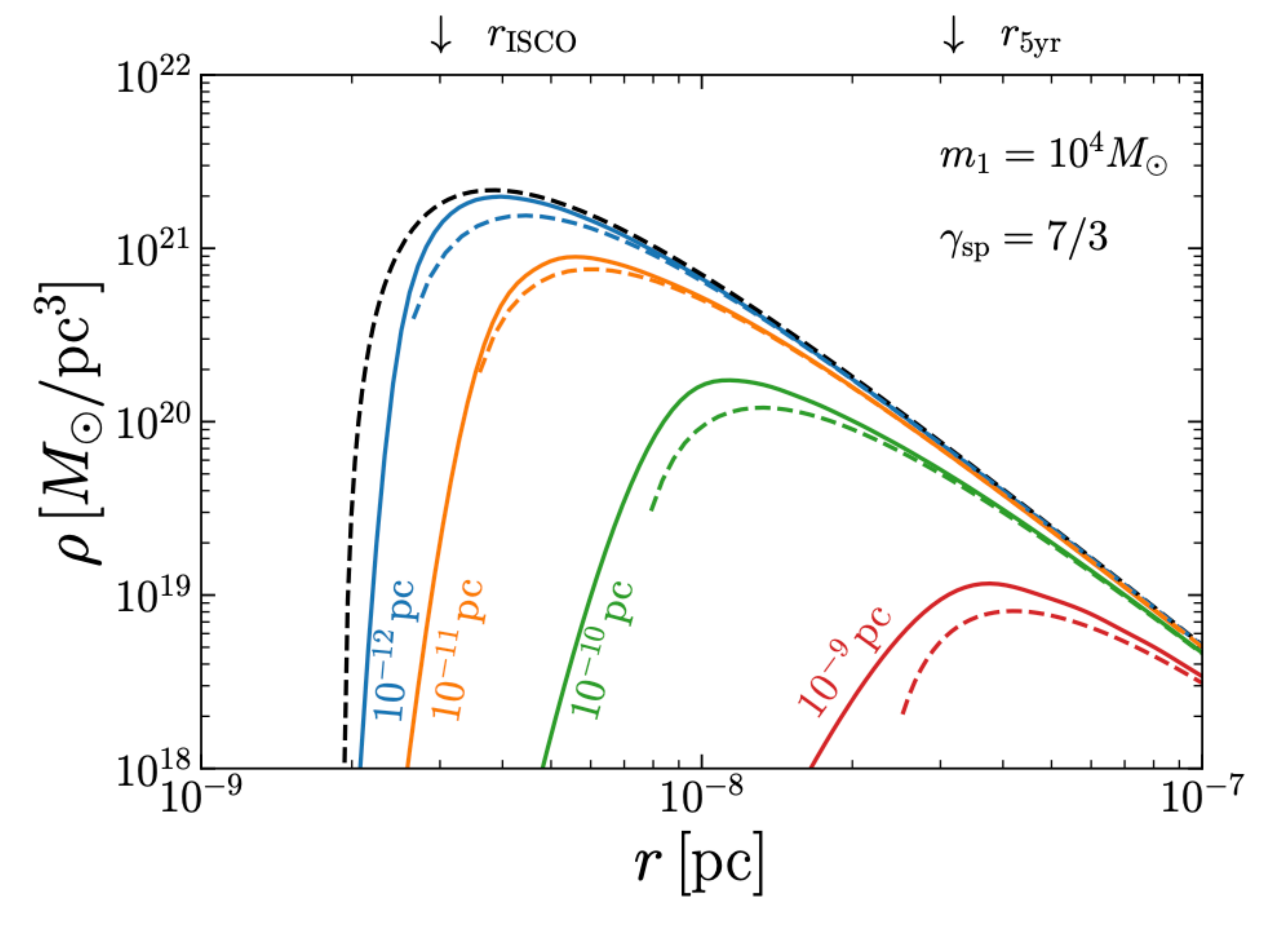
- The wave “spike” may survive during the galaxy merger because the wave “spike” co-rotates with the central BH.
  Ikeda, Bernard, Cardoso, Zilhão, 2020
  Bamber, Clough, Aurrekoetxea and Ferreira, 2022

- Intermediate mass ratio inspirals may also deplete the wave “spike”, but the depletion is small.
  Kavanagh, Nichols, Bertone and Gaggero 2021 (particle spike)
  Baumann, Bertone, Stout and Tomaselli, 2021 (gravitational atom)

Conclusions



Wave "spike" around a **supermassive** BH



Wave "spike" around a **intermediate mass** BH
Can be detected by LISA!

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Hyungjin Kim, Alessandro Lenoci, Isak Stomberg, Xiao Xue
DESY & University of Hamburg

Thank you for your attention!