

# Gravothermalizing into Primordial Black Holes

**Speaker:**  
**Daniele Perri**



Pranjal Ralegankar, **DP**,  
Takeshi Kobayashi  
[arXiv:2410.18948](https://arxiv.org/abs/2410.18948)



**NEHOP'25 - 21/05/25**

# Contents of the Talk

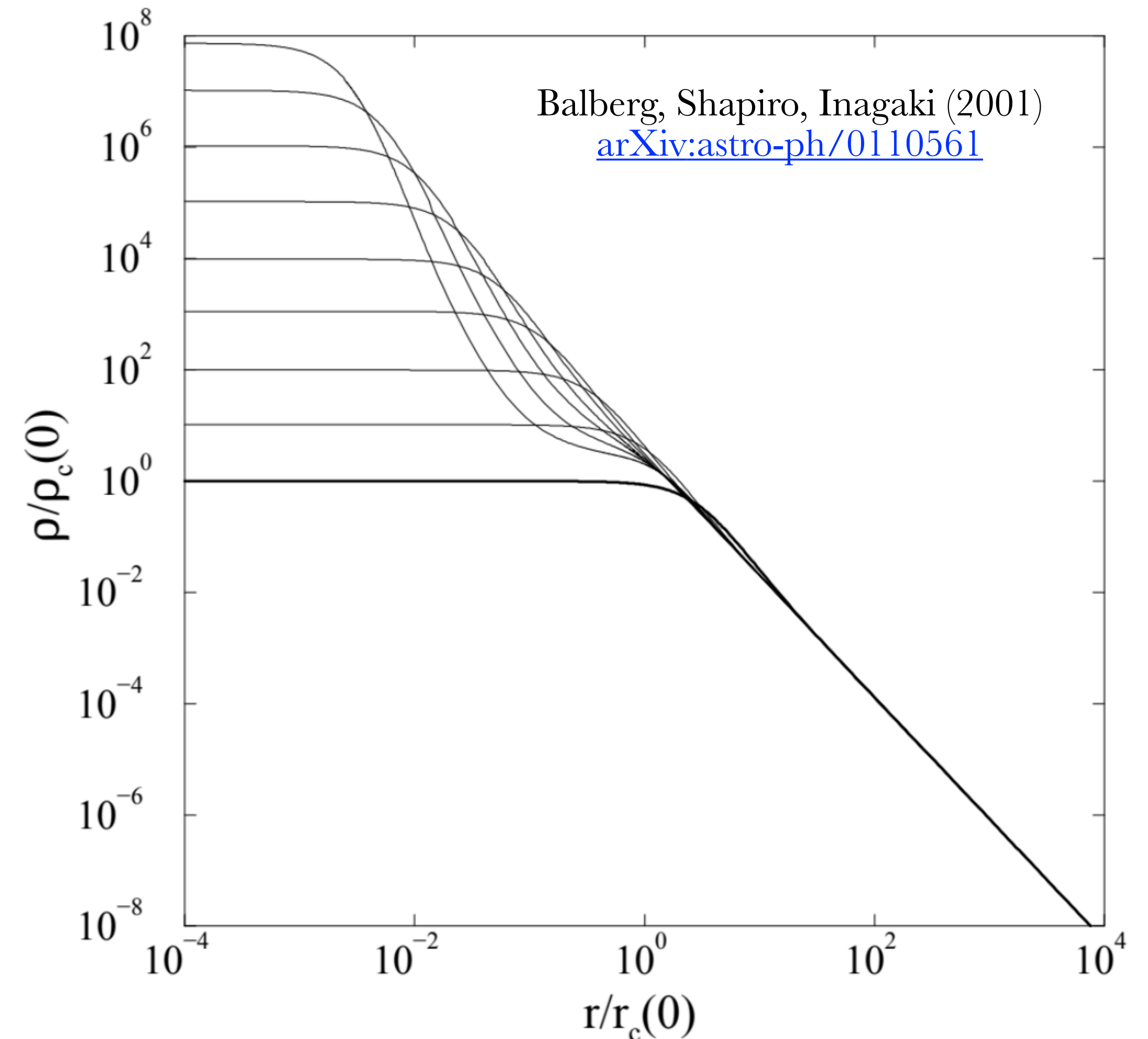
- ✓ SIDM and gravothermal collapse.
- ✓ Gravothermal collapse in an EMDE.
- ✓ PBHs spectrum and constraints.
- ✓ Conclusion.

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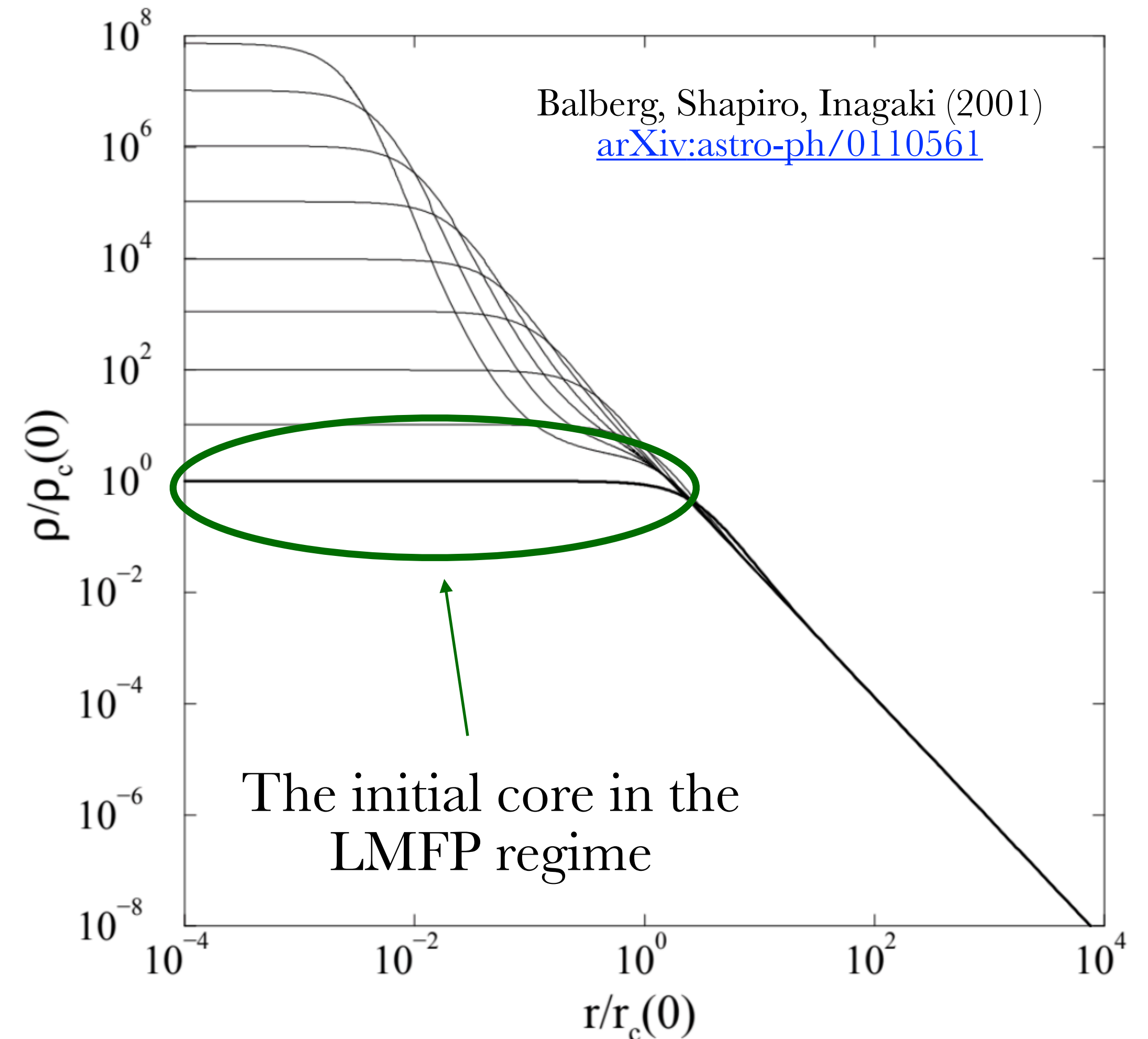
# Gravothermal collapse and SIDM

- A halo of self-interacting dark matter (SIDM) exhibits a core at its center due to self-interactions.
  - SIDM particles lose heat from the surface of the core, reducing the kinetic energy.
  - An inner core is formed at larger densities in the strongly interacting regime.
- Without mechanisms that stabilize the core, the inner core collapses into a BH.



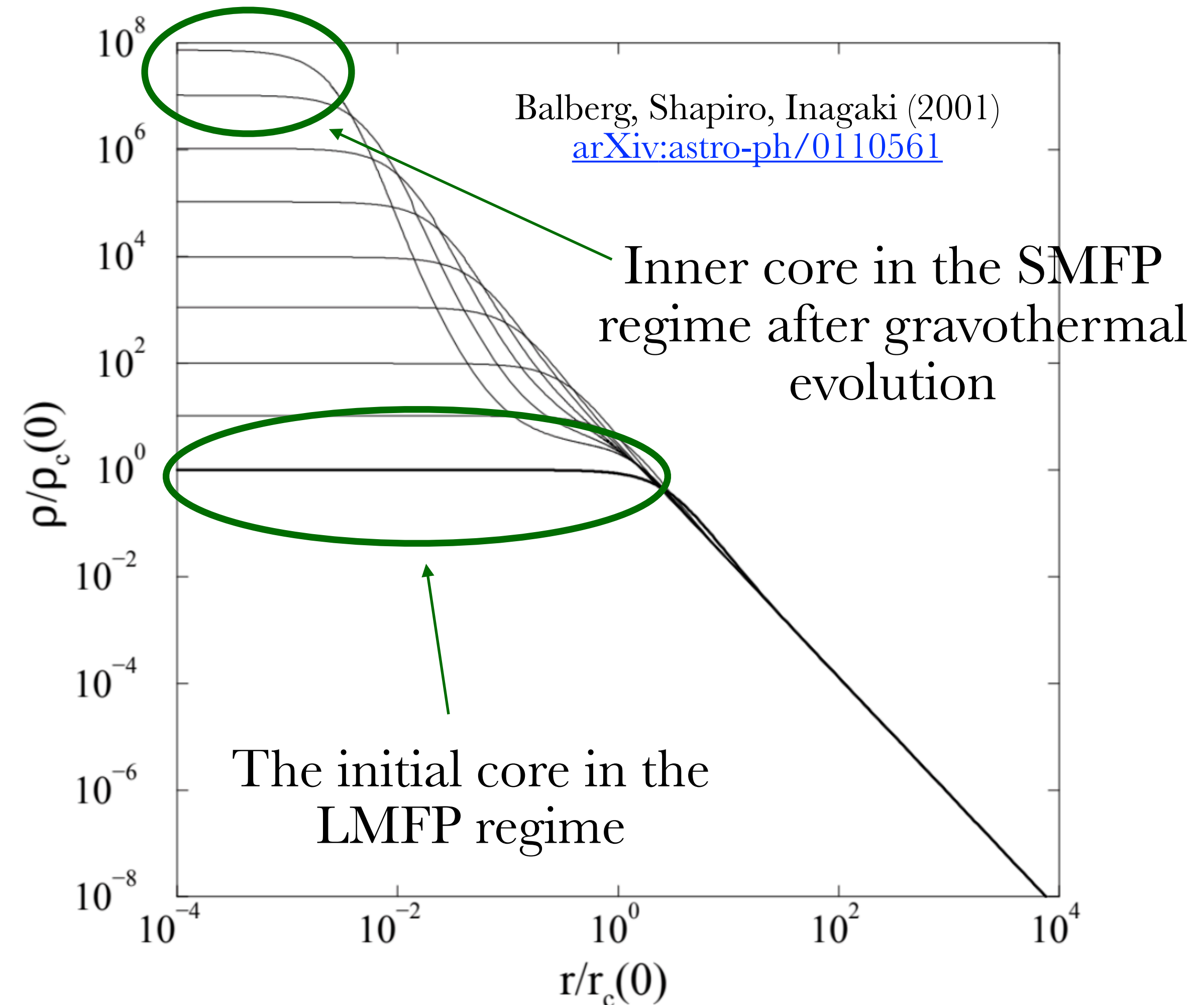
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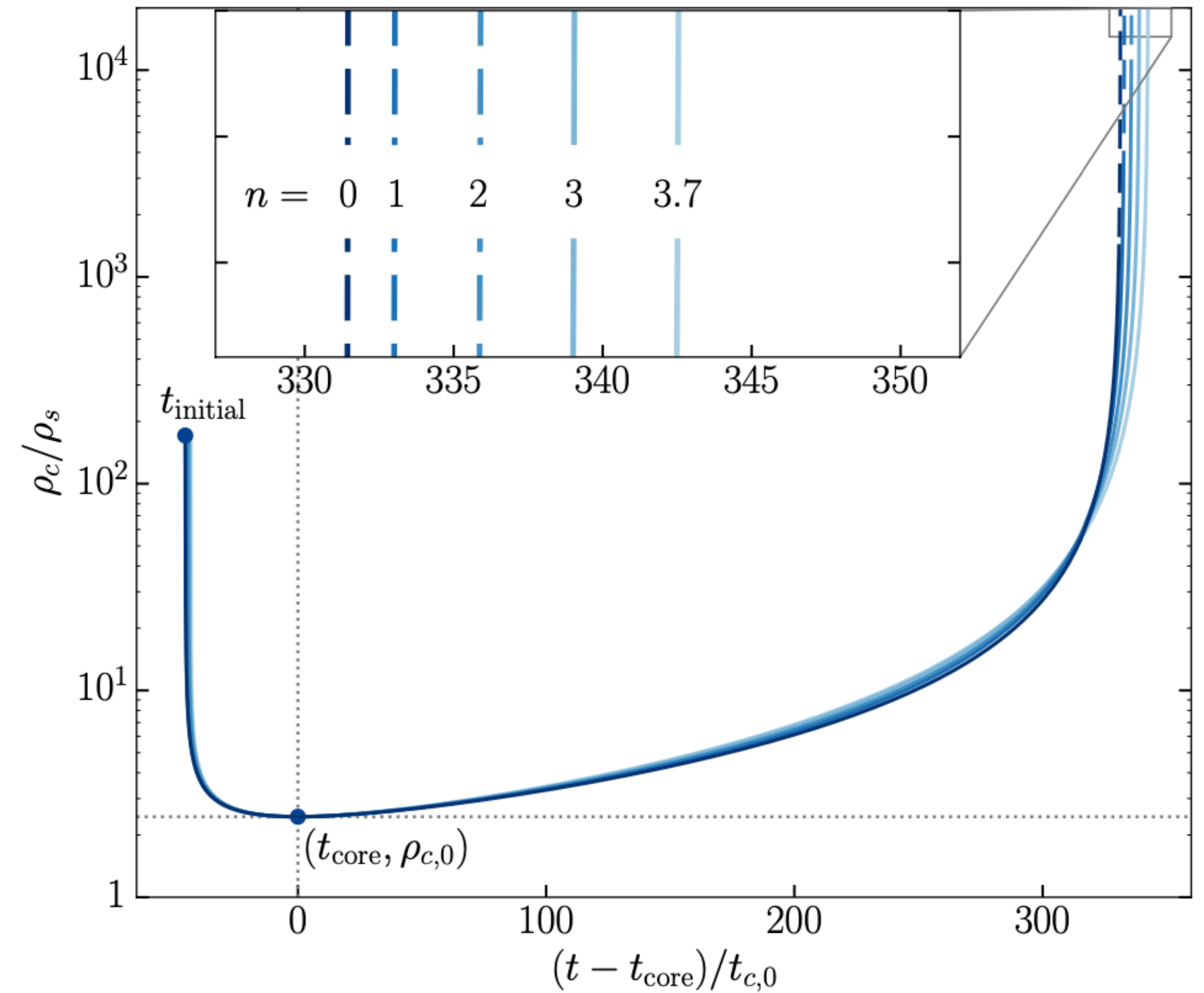
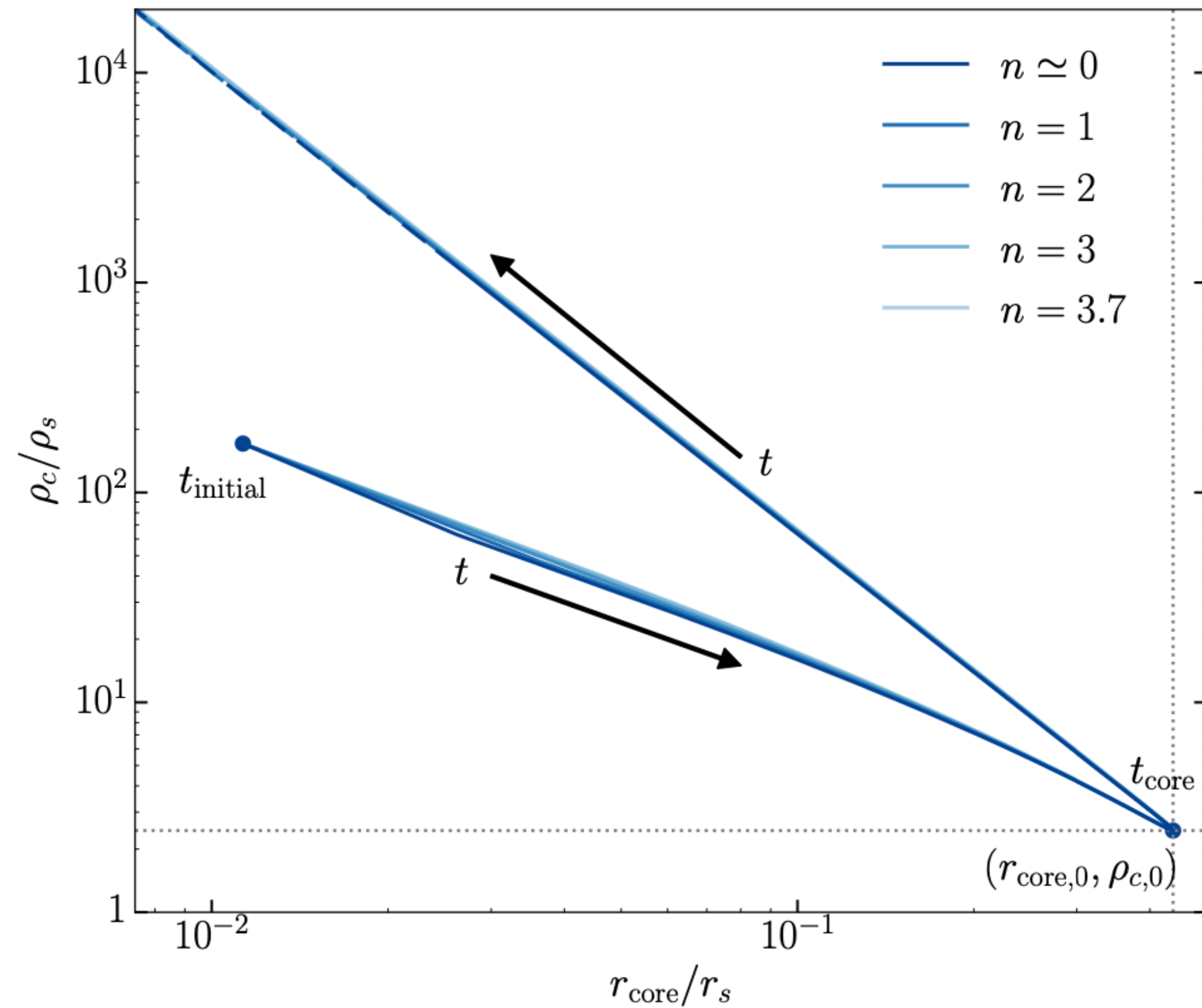


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# Gravothermal collapse and SIDM



Outmezguine, Boddy, Gad-Nasr, Kaplinghat, Sagunski (2022)  
[arXiv:2204.06568](https://arxiv.org/abs/2204.06568)

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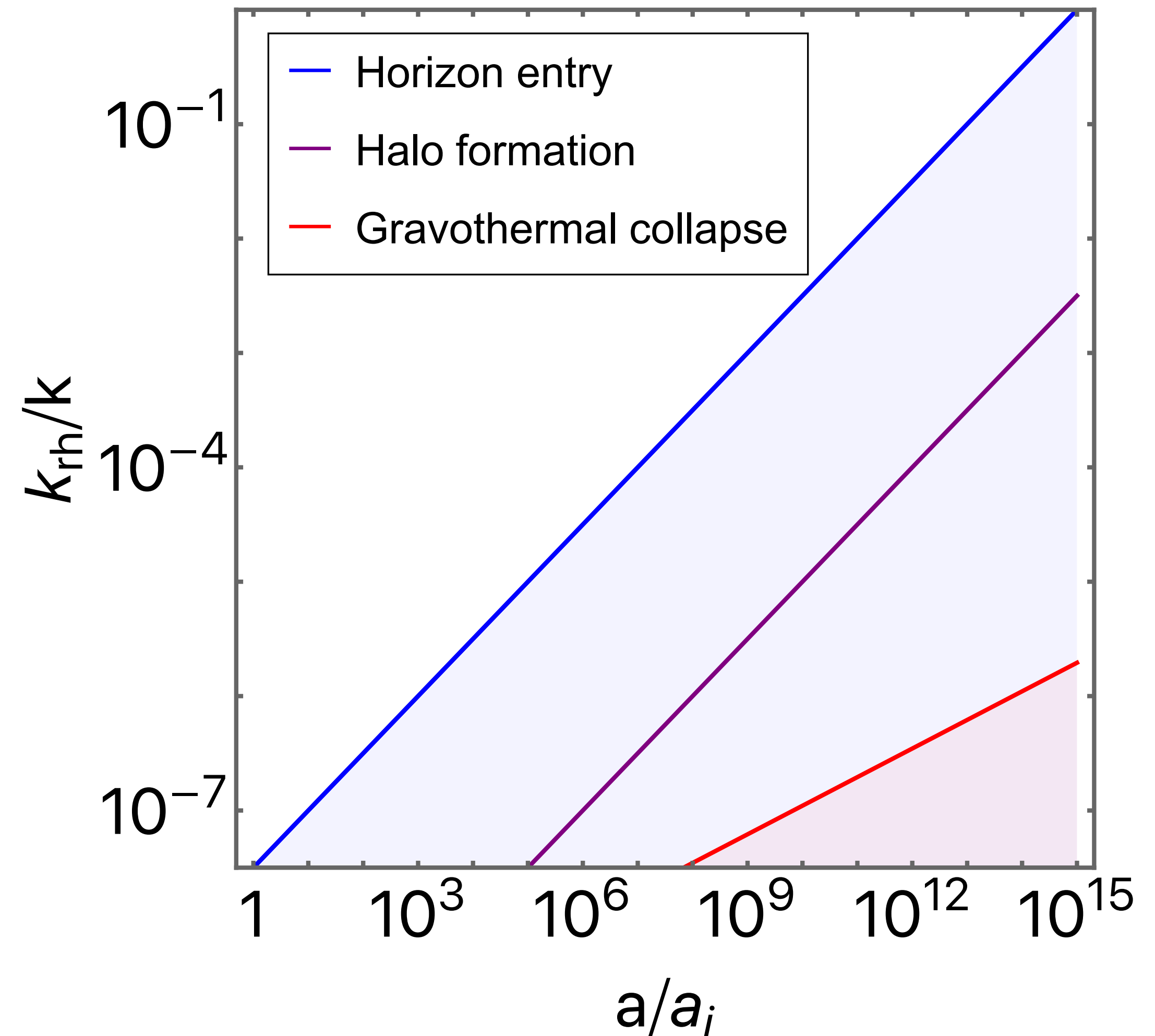
# Gravothermal collapse in an EMDE

- A simple model of self-interacting nonrelativistic scalar particles dominating the universe after inflation and then decaying into SM:

$$V(\varphi) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4!}\varphi^4 \quad m \sim 10 \cdot T_{rh} \left( \frac{a_{rh}}{a_i} \right)^{3/4}$$

- Gravothermal collapse allows the production of PBHs from primordial halos.

- The biggest PBH is formed at the end of the EMDE (reheating).
- The smallest PBH corresponds to the mode entering the horizon at the beginning of the EMDE.



$$\lambda = 10^{-1}, a_{rh}/a_i = 10^{15}, T_{rh} = 100 \text{ MeV}$$

# Self-Interaction Pressure and Boson Stars

- During the collapse, the inner core can be so dense that quantum effects become important.
- If the typical separation of the particles in the core  $d \sim (m/\rho_{\text{core}})^{1/3}$  becomes smaller than their de Broglie wavelength  $l_{\text{dB}} \sim \frac{1}{mv_{\text{core}}}$ , the collapse is stopped.
- If before rel instability  $l_{\text{dB}} < d \rightarrow$  ***boson star*** at the center of the halo.

# 4-to-2 Interactions and Cannibal Stars

- During the collapse, the inner core can be so dense that 4-to-2 interactions become important.
- If the heat gained via cannibal interactions is more than the heat loss due to self-interactions, the collapse is stopped.

$$Q_{cool} \sim 4\pi r_{core}^2 \frac{v_{core}}{\sigma} \frac{\partial v^2}{\partial r}(r_{core})$$

$$Q_{heat} = \frac{\rho_{core}^4}{m^4} \frac{\langle \sigma_{4 \rightarrow 2} v^3 \rangle}{2} \times \frac{4\pi}{3} r_{core}^3 \times 2m$$

$$\langle \sigma_{4 \rightarrow 2} v^3 \rangle = \frac{1}{2048\sqrt{3}\pi} \frac{\lambda^4}{m^8}$$

- If before rel instability  $Q_{cool} < Q_{heat}$   $\rightarrow$  **cannibal star** at the center of the halo.

*4-to-2 interactions can be turned off in models with particle number conservation.*

# Computing the BH mass: Seed PBH

- Following the gravothermal evolution of the core, we estimated the amount of matter that collapses at relativistic instability,  $\eta_{\min}$ :

$$\eta_{\min} \sim 6 \times 10^{-7} \lambda^{1.0} \left( \frac{a_{\text{rh}}/a_i}{10^{10}} \right)^{-1.2} \left( \frac{k/k_{\text{rh}}}{10^4} \right)^{1.6} \times \left( \frac{T_{\text{rh}}}{100 \text{ MeV}} \right)^{-0.52}$$

$$\eta \equiv \frac{M_{\text{BH}}}{M_{\text{halo}}}$$

- This accounts for the available matter for the *seed PBH* at the center of the halo.

*The estimate is very conservative and does not take into account BH accretion.*

# Computing the BH mass: Accretion

- The gravothermal process proceeds even after the first collapse.
- The mass of the seed BH increases, cannibal and bosonic stars can collapse into new PBHs.
- The accretion process works until the kinetic energy of the particles at relativistic instability is smaller than the total energy of the original NFW halo:

$$K_{\text{NFW}} > K_{\text{BH}} \sim \frac{1}{2} M_{\text{BH}} \left( \frac{1}{3} \right)^2$$



$$\eta_{\text{max}} \sim 20 \cdot v_{\text{vir}}^2 \sim 10^{-3}$$

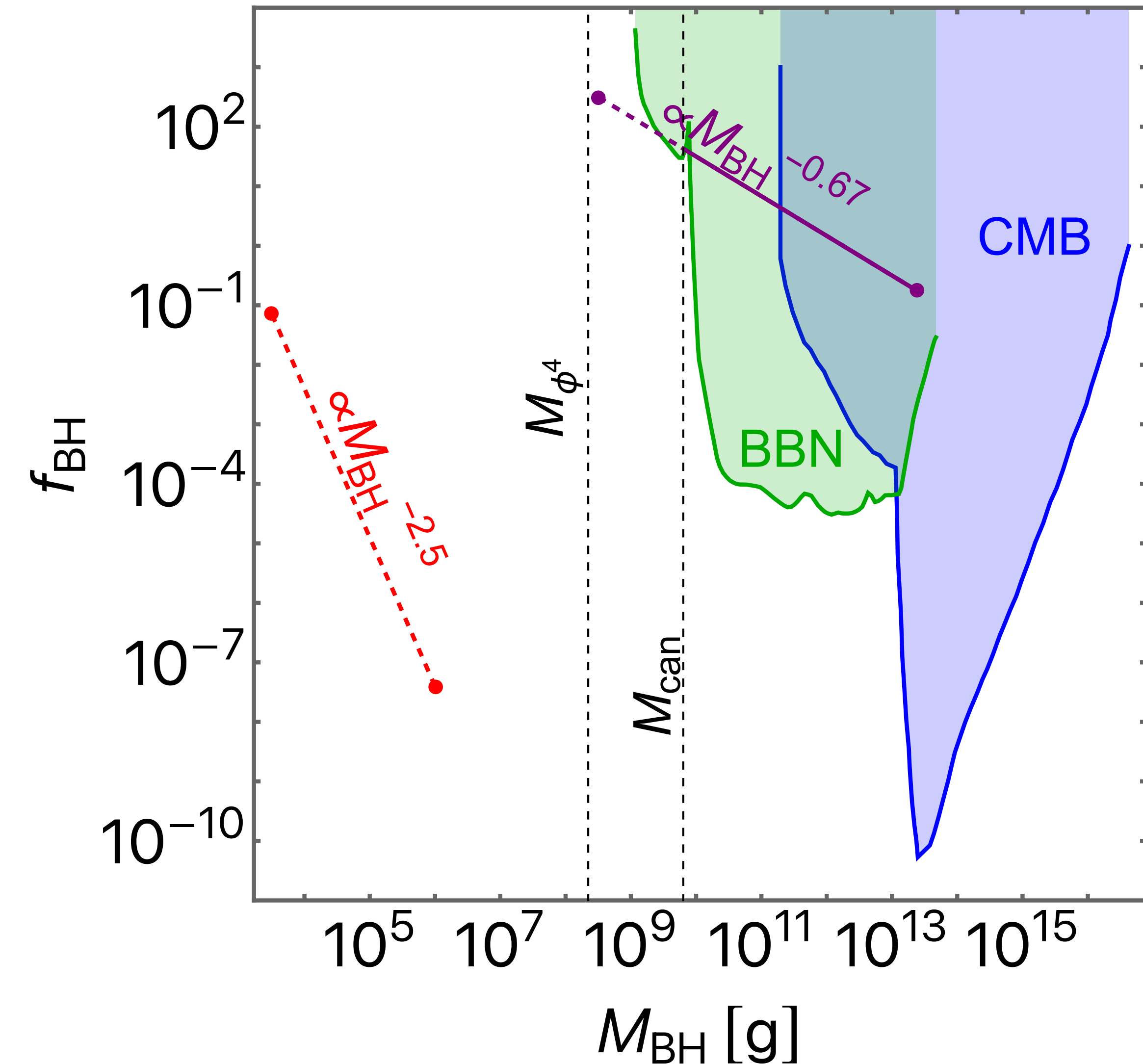
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# PBH spectrum and constraints



- We obtained a conservative estimate for  $f_{\text{BH}}$  by assuming PBHs can form only in isolated halos in the *Press-Schechter formalism*.
  - ▶ The spectrum can spread over very different BH masses (up to asteroid-mass range).
  - ▶ In the presence of 4-to-2 interactions, accretion is necessary to produce any BH.

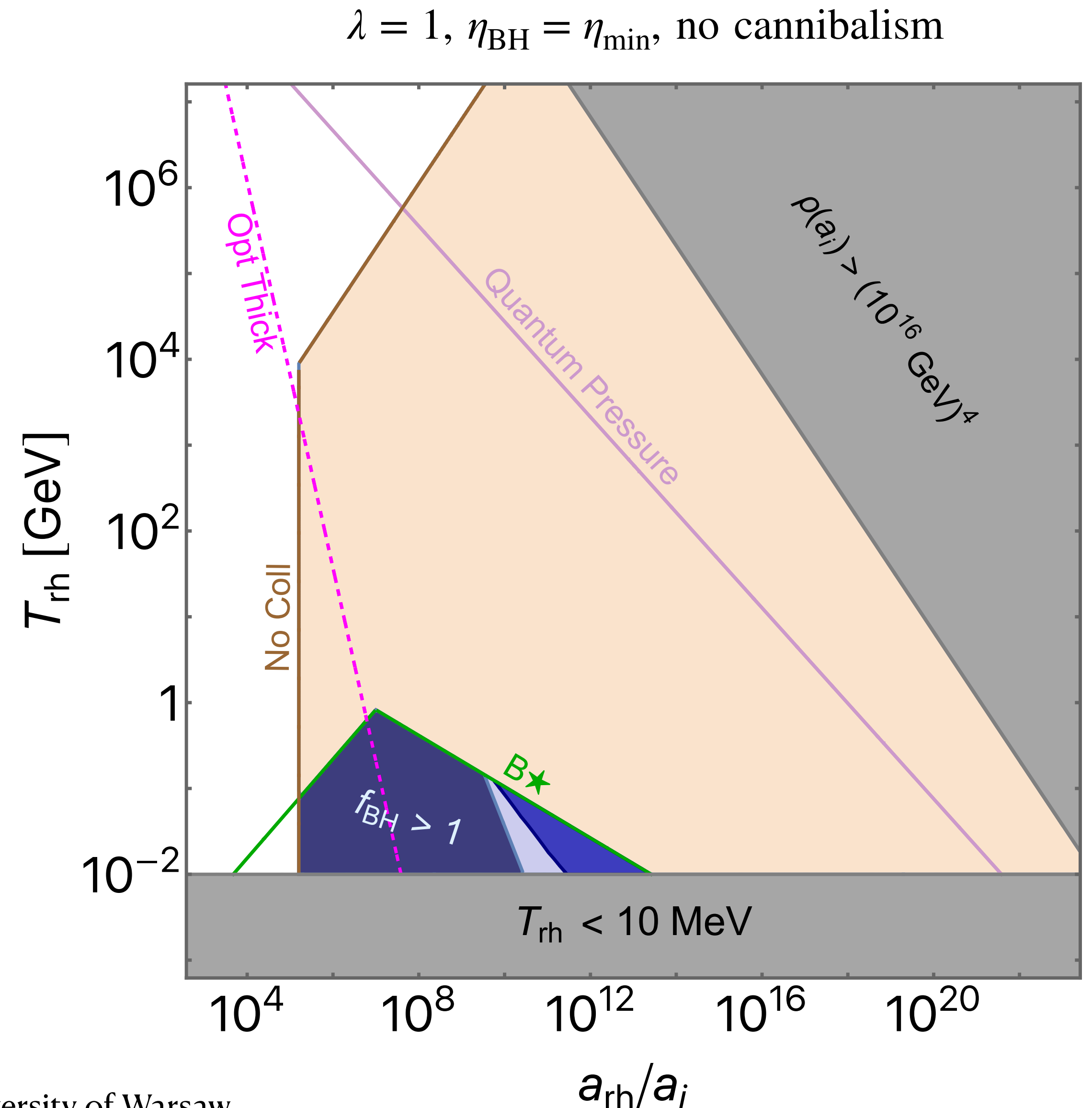
# Parameter space and abundance

## 1. Seed BH without cannibalism

The results strongly depend on the self-coupling of the particles.

The process of PBH production is very (too much) efficient!!

- ▶ We can exclude large regions of parameters with the constraints on PBHs in a very conservative way.



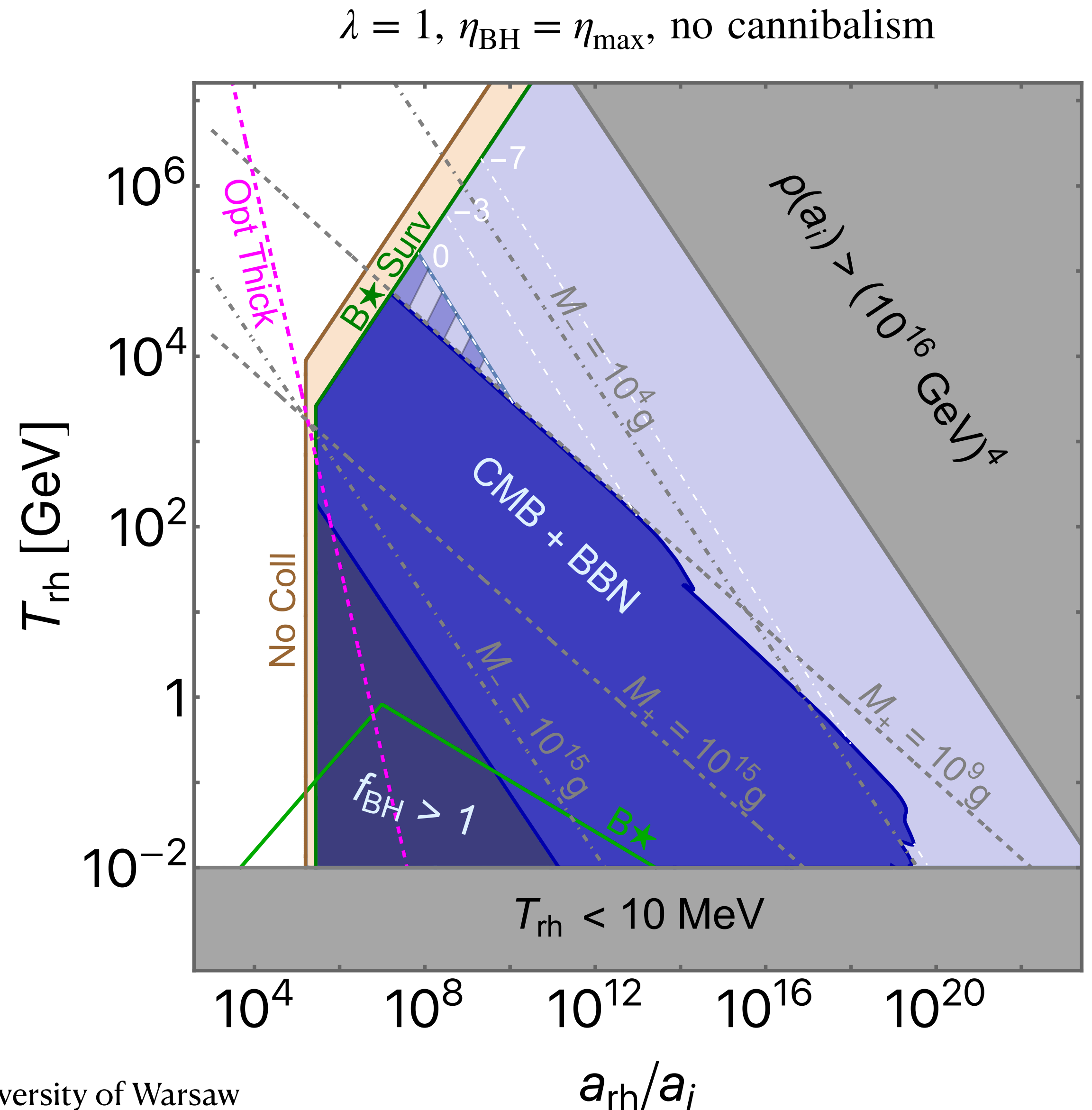
# Parameter space and abundance

## 1. Accreted BH without cannibalism

The results strongly depend on the self-coupling of the particles.

The process of PBH production is very (too much) efficient!!

- ▶ In some regions of parameters PBHs dominate the universe before evaporating (PBH reheating)



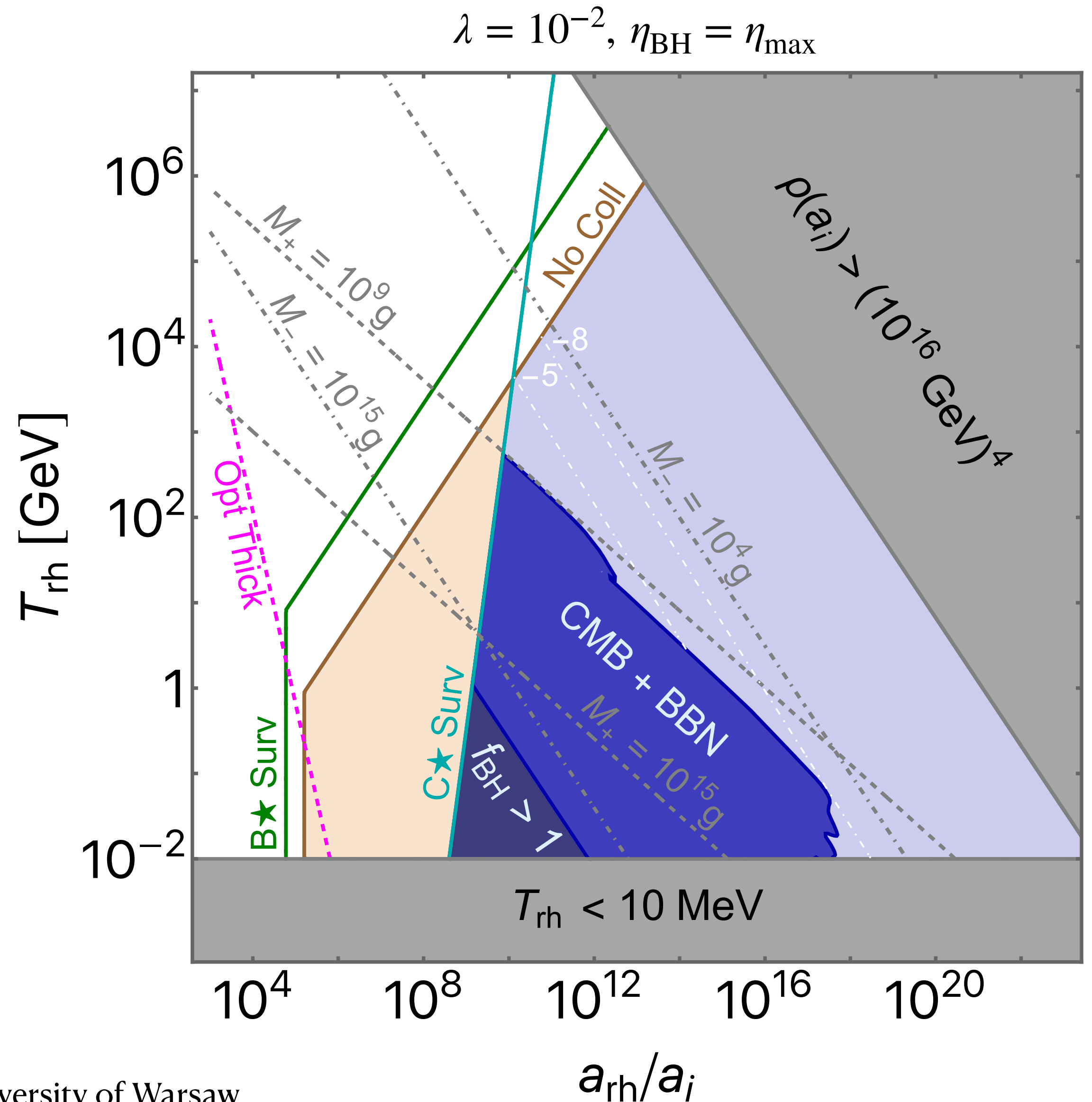
# Parameter space and abundance

## 1. Accreted BH with cannibalism

The results strongly depend on the self-coupling of the particles.

The process of PBH production is very (too much) efficient!!

- ▶ After considering PBH accretion, even with 4-to-2 interactions, it is possible to produce a significant amount of PBHs.



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# Conclusion

- ▶ *Gravothermal collapse* in a EMDE can be a (too much) efficient way of PBH production.
  1. There are allowed regions where PBHs survive until today and are a significant fraction of DM.
  2. We have been able to exclude large regions of parameters constraining EMDEs.
  3. There is space for light PBHs that dominate the universe before evaporating.
    - ▶ 4-to-2 interactions and quantum effects can lead to *cannibal* and *boson stars*.
- ▶ Still searching for possible signals from gravothermal-produced PBHs (ex. GW from evaporation, PBH merging).
  - ▶ Still to look at different EMDE scenarios (ex. inflaton or curvaton condensates).
  - ▶ Still a lot to do with non-isolated halos, simulations of accretion, model building...



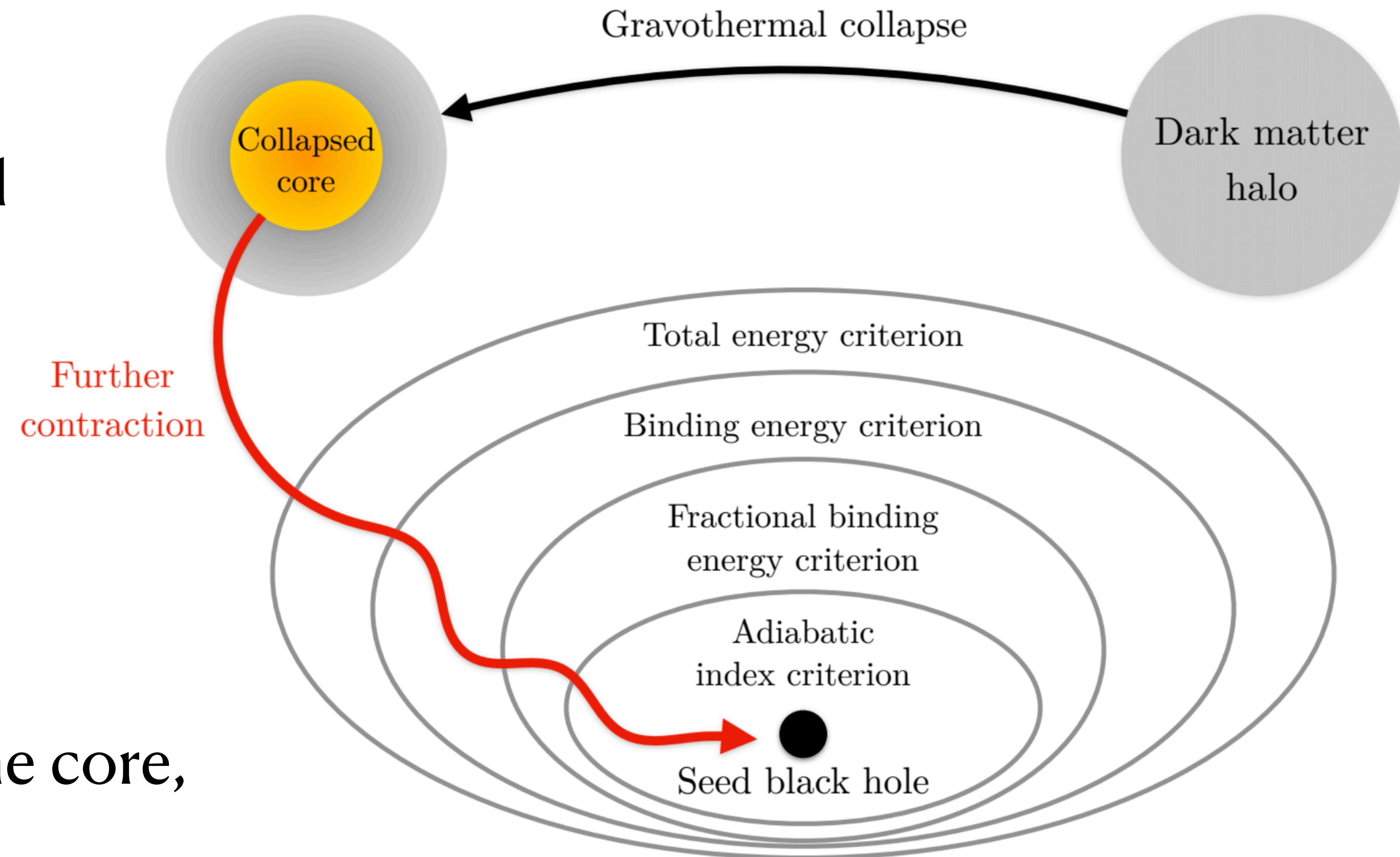
# Thank You!!



# Gravothermal collapse and SIDM

- A halo of SIDM shows a core at its center because of self-interactions.

- SIDM particles lose heat from the surface of the core reducing the total energy.
- An inner core is formed at larger densities in the strongly interacting regime.
- Without mechanisms that stabilize the core, the inner core collapses into a BH.



Feng, Yu, Zhong (2021)  
[arXiv:2108.11967](https://arxiv.org/abs/2108.11967)

# PBH spectrum and constraints

## 1. Accreted BH with cannibalism

The parameters of EMDE for which PBH formation is allowed strongly depend on the self-coupling of the particles.

The process of PBH production is very (too much) efficient!!

Decreasing the value of  $\lambda$  there is a region where PBHs survive until today and can be a significant fraction of DM.

$$\lambda = 10^{-5}, \eta_{\text{BH}} = \eta_{\text{max}}$$

