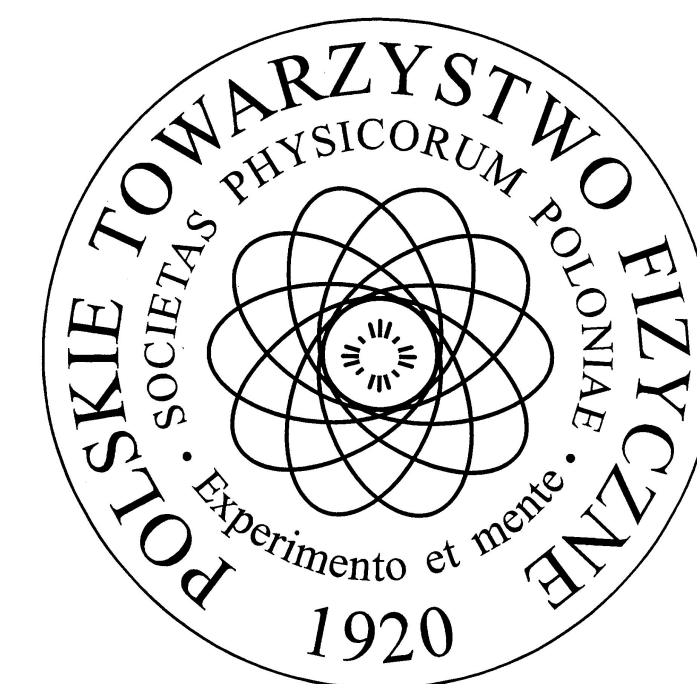


Gravothermalizing into Primordial Black Holes

Speaker:
Daniele Perri



Pranjal Ralegankar, **DP**,
Takeshi Kobayashi
Phys.Rev.D 112 (2025) 8, 083019



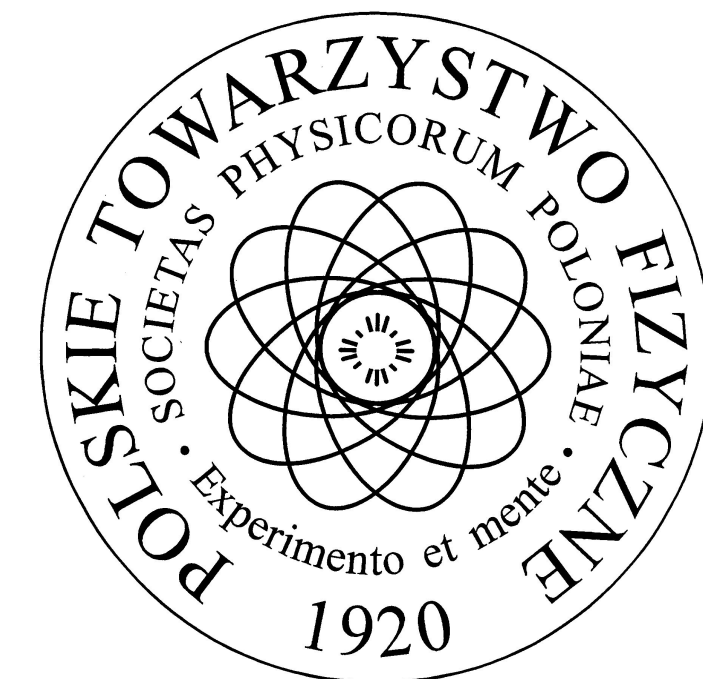
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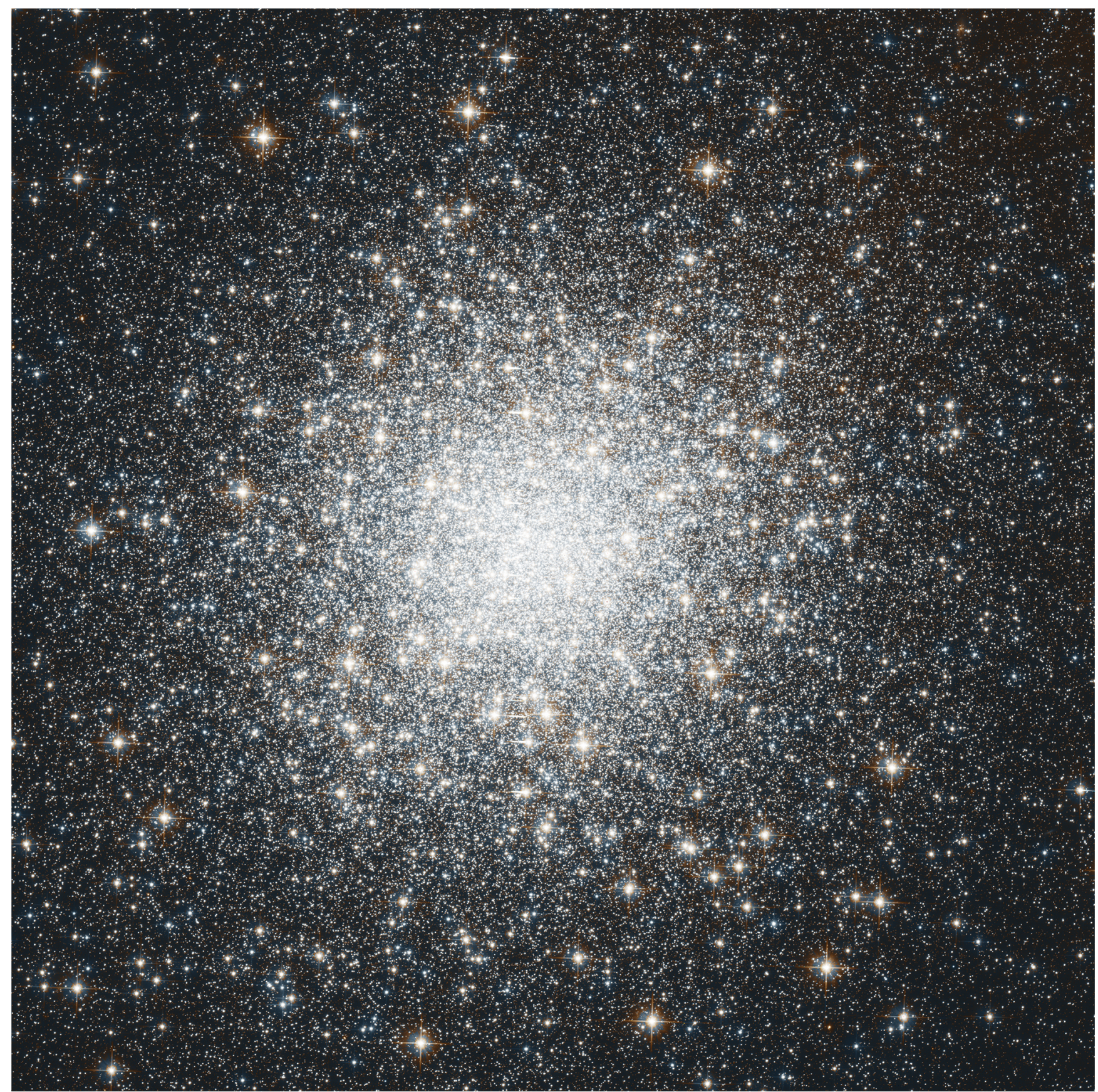
Contents of the Talk

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

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Gravothermal collapse in Globular Clusters



- In globular clusters, gravitational self-interaction between stars transfers heat from the inner to the outer region.
- The stars lose kinetic energy and migrate toward the center of the cluster -> *gravothermal collapse*.
- In globular clusters, the gravothermal evolution is eventually stabilized by the formation of binaries.

► For collisionless dark matter halos, gravothermal collapse does not occur because its time scale grows with the number of particles and significantly exceeds the age of the universe.

Self-interacting Dark Matter

- Self-interacting dark matter (SIDM) candidates have often been proposed as an alternative to Λ CDM.
- They have been used to explain deviation from the NFW profile of galaxies (but there are alternative explanations).
- SIDM is constrained by astrophysical observations (ex. Bullet Cluster).



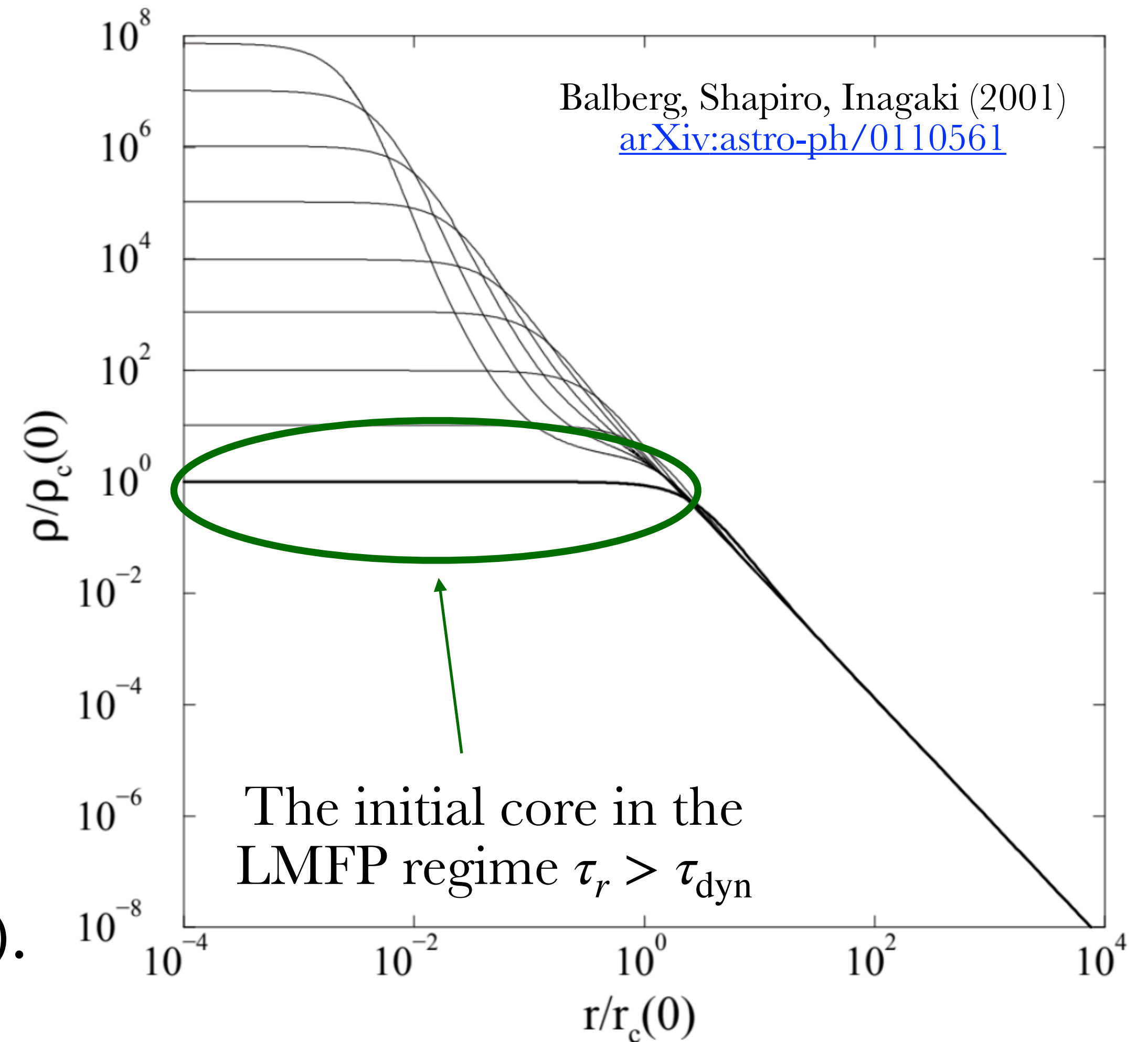
Self-interaction enhances the scattering rate of dark matter particles making gravothermal collapse possible.

Gravothermal collapse and SIDM

- A halo of SIDM exhibits a core at its center due to self-interactions.

$$\tau_{\text{dyn}} = \frac{1}{\sqrt{4\pi G\rho}} \quad \tau_r = \frac{1}{\rho v \sigma}$$

- 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 Black Hole (BH).

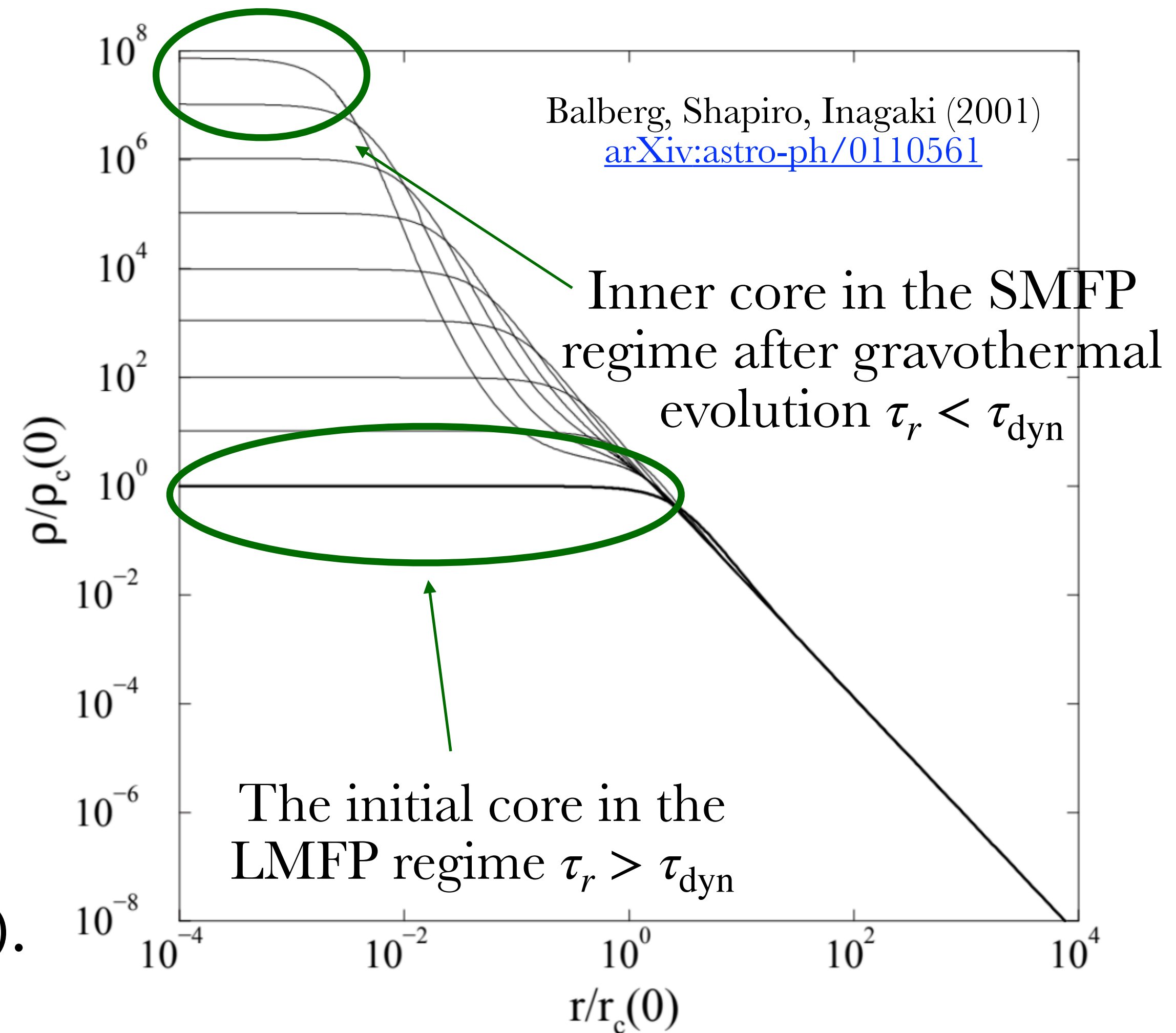


Gravothermal collapse and SIDM

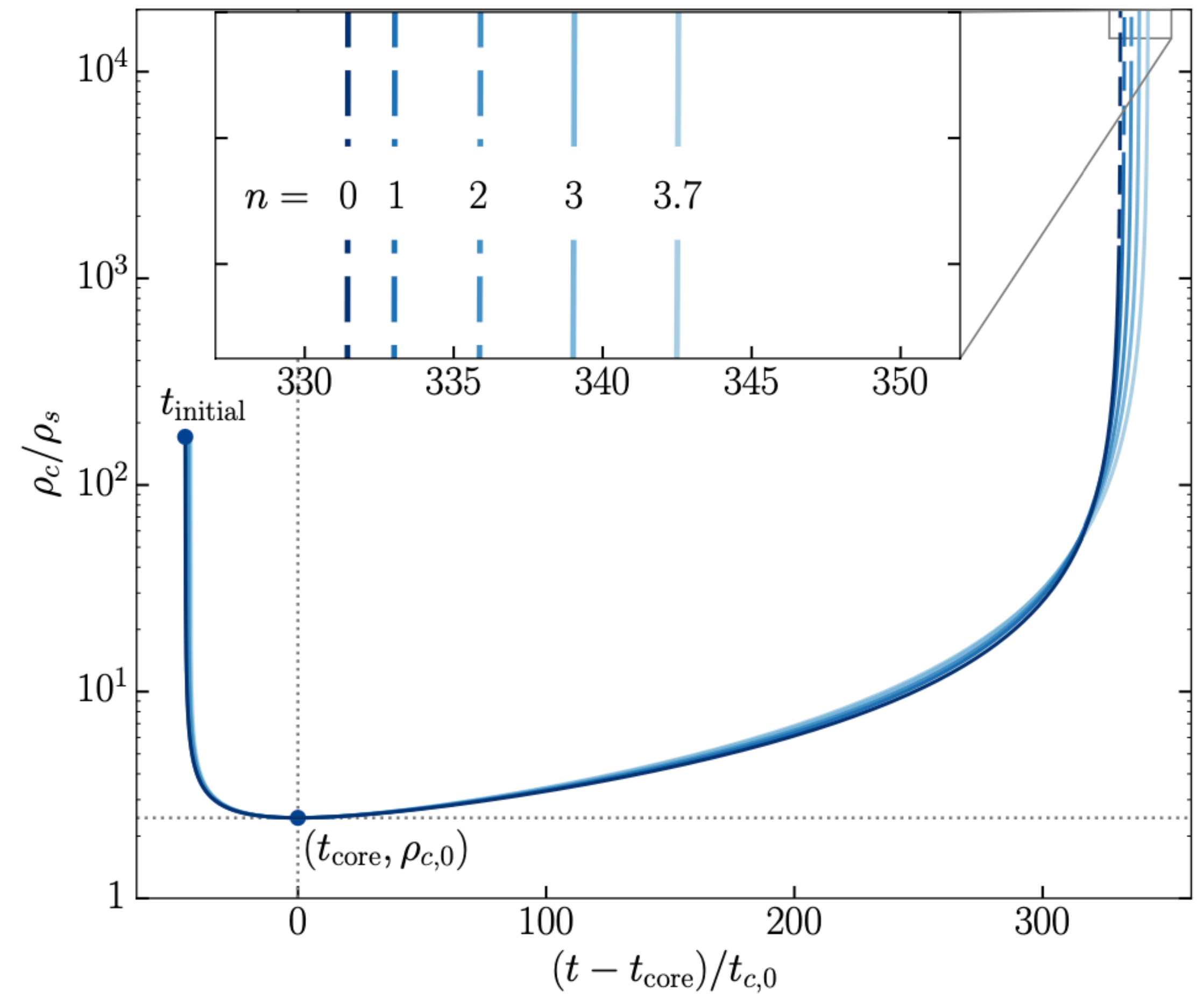
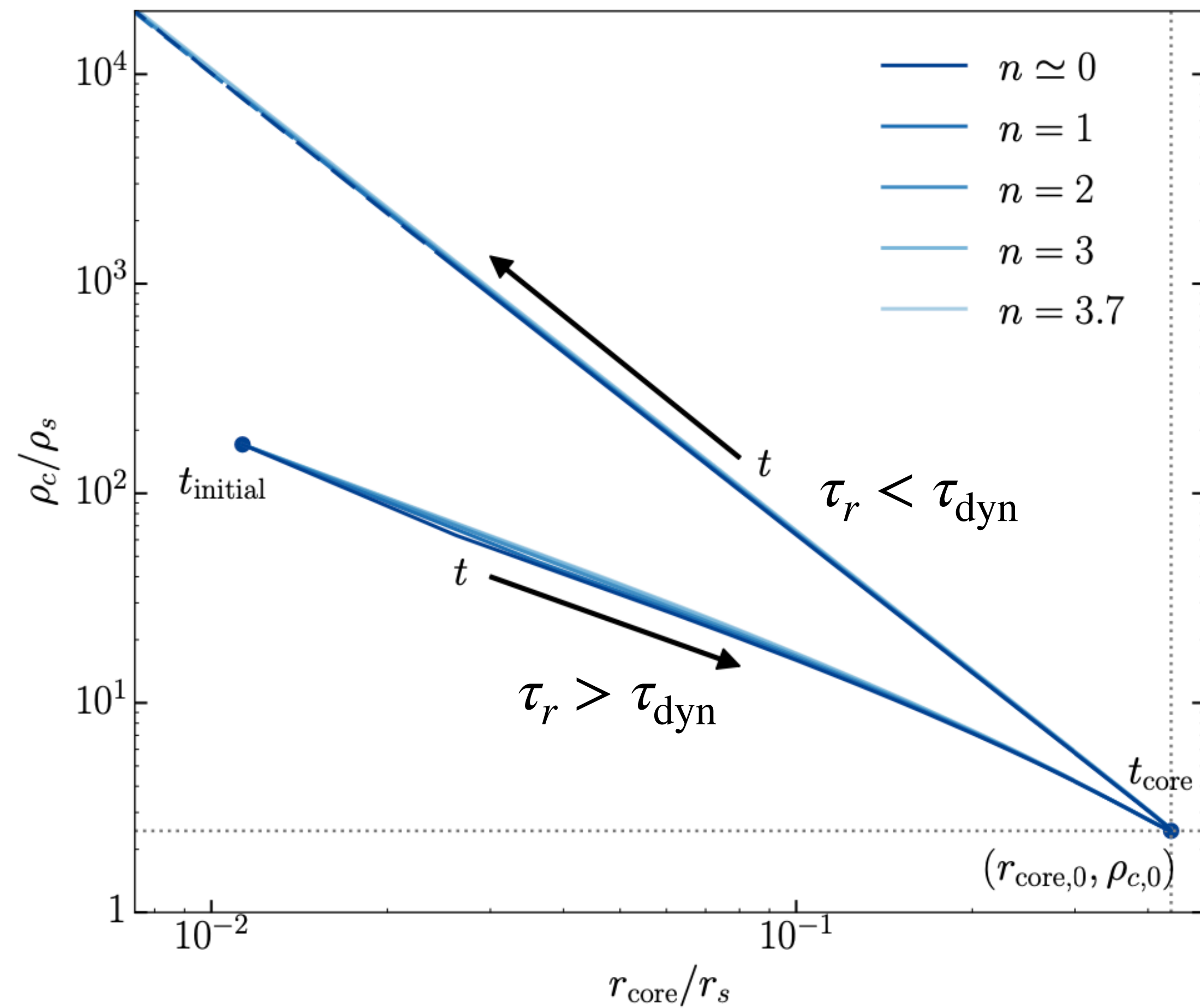
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Gravothermal collapse and SIDM



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

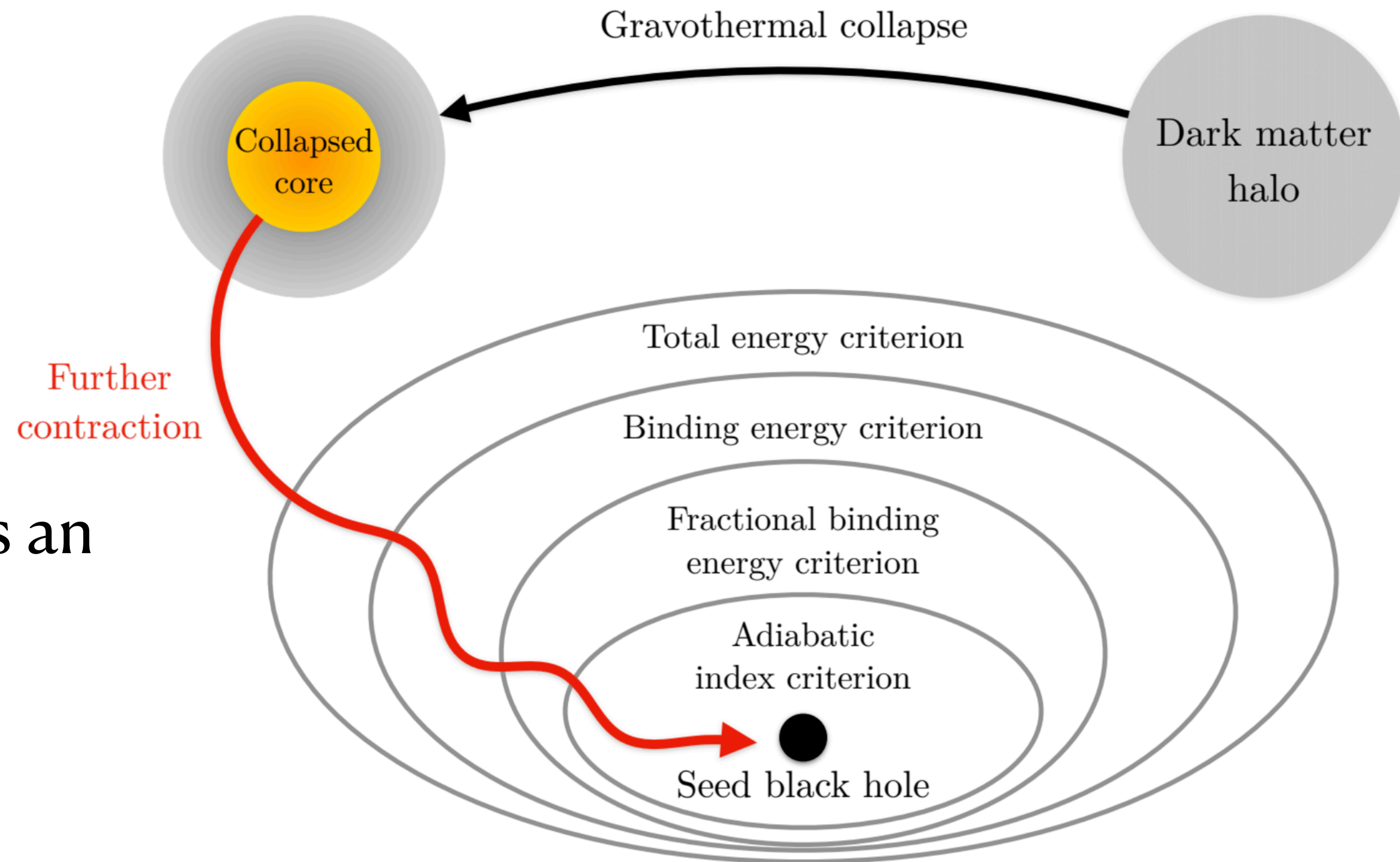
Gravothermal collapse and SIDM

- Different conditions can be used to verify if a gravothermalized halo collapses into a BH.

- Relativistic instability in the inner halo is an easy condition to apply to the collapse:

$$v_c \gtrsim 1/3$$

Current observational constraints on dark matter self-interaction limit the possibility of a collapse occurring by present time for most halos.

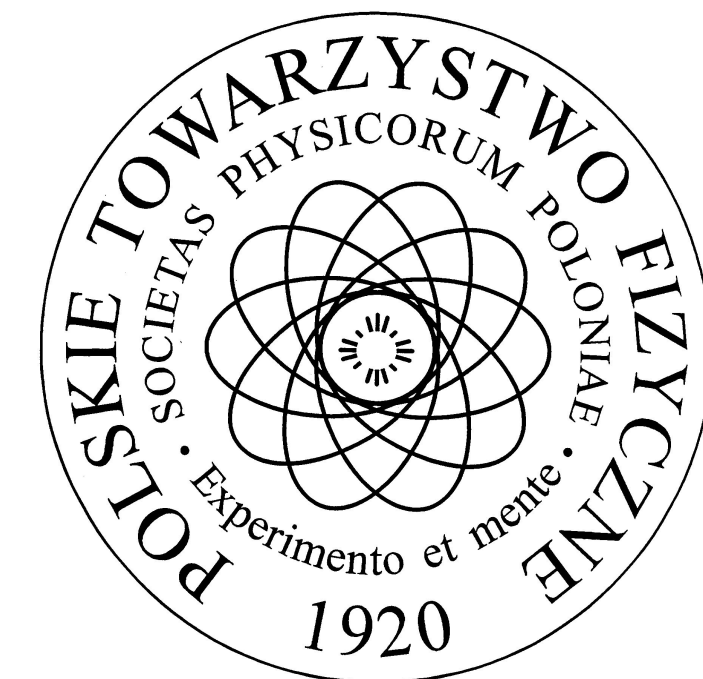


Feng, Yu, Zhong (2021)
[arXiv:2108.11967](https://arxiv.org/abs/2108.11967)

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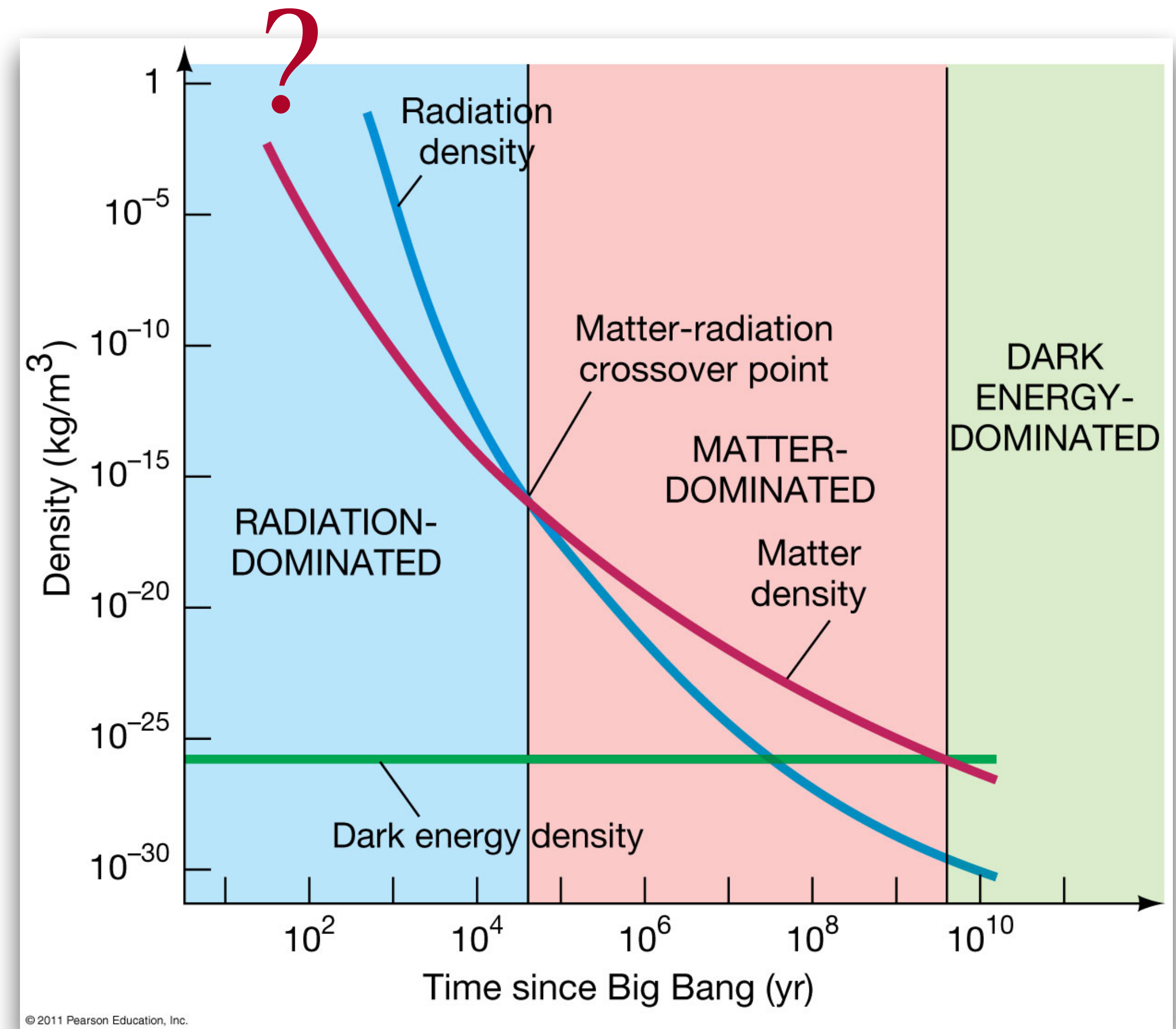


Early matter-dominated epoch models

- Cosmological evolution after Big Bang Nucleosynthesis (BBN) is strongly constrained by the results of precision cosmology.
- However, we have very little information on the history of the universe from the end of inflation to BBN.
- Such an intermediate era spans potentially up to 36 orders of magnitude in time.



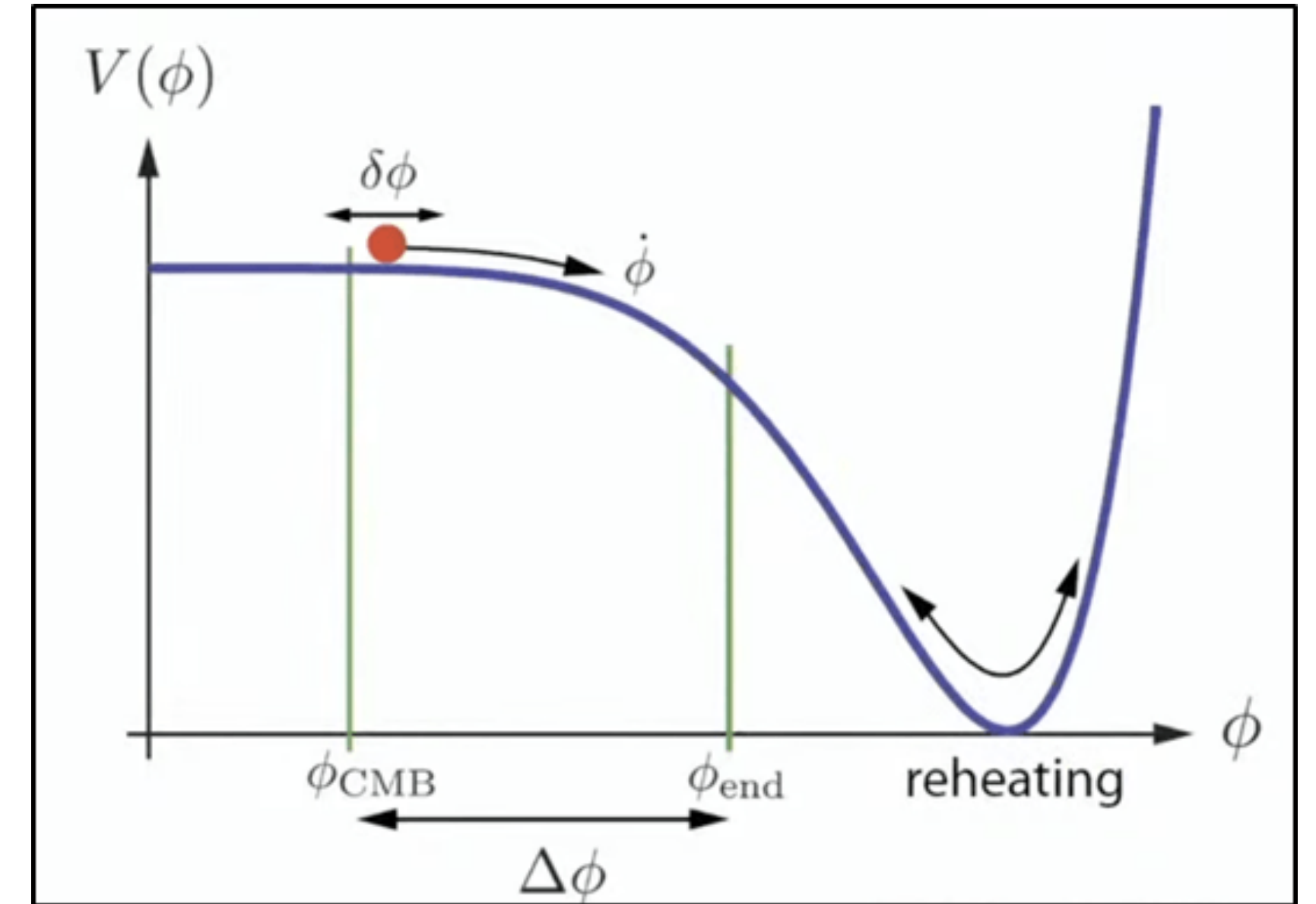
There is space for a “long” early matter domination



Early matter-dominated epoch models

- Many models of early matter-dominated epoch (EMDE) have been proposed in the literature:

1. Coherent oscillation of the inflaton field acts as an effective EMDE.
2. Hidden sectors decoupled from the Standard Model (massive particle lately decaying into the thermal bath).
3. **Choose your model**.



- If this epoch lasts longer than 12 e-folds, primordial perturbations become nonlinear, and early halos can form.

Gravothermal collapse allows the production of Primordial BHs (PBHs) from primordial halos.

Early matter-dominated epoch models

- We adopted a simple model of *self-interacting* nonrelativistic scalar particles dominating the universe after inflation and then decaying into Standard Model (SM) particles at the end of EMDE.

$$V(\varphi) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4!}\varphi^4$$

1. EMDE starts when the particles become non-relativistic ($t = t_i$): $\rho_\varphi(a_i) \approx \frac{\pi^2}{30} \left(\frac{m}{3}\right)^4$
2. The particles decay into SM particles (*reheating*, $t = t_{rh}$): $\rho_{SM}(a_{rh}) = \frac{\pi^2}{30} g_{*rh} T_{rh}^4$
3. The mass of the particles is fixed by the characteristics of the EMDE

$$\rho_{SM}(a_{rh}) \approx \rho_\varphi(a_i) \left(\frac{a_i}{a_{rh}}\right)^3 \quad \rightarrow \quad m \sim 10 \cdot T_{rh} \left(\frac{a_{rh}}{a_i}\right)^{3/4}$$

Early matter-dominated epoch models

- We adopted a simple model of *self-interacting* nonrelativistic scalar particles dominating the universe after inflation and then decaying into Standard Model (SM) particles at the end of EMDE.

$$V(\varphi) = \frac{1}{2}m^2\varphi^2 + \frac{\lambda}{4!}\varphi^4$$

Particle physics parameters: *mass, SM decay rate, self-interaction*

$$(m, \Gamma_{SM}, \lambda)$$



Cosmological EMDE parameters: *EMDE length, reheating temperature, self-interaction*

$$(a_{rh}/a_i, T_{rh}, \lambda)$$

Early matter-dominated epoch models

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Gravothermal collapse in an EMDE

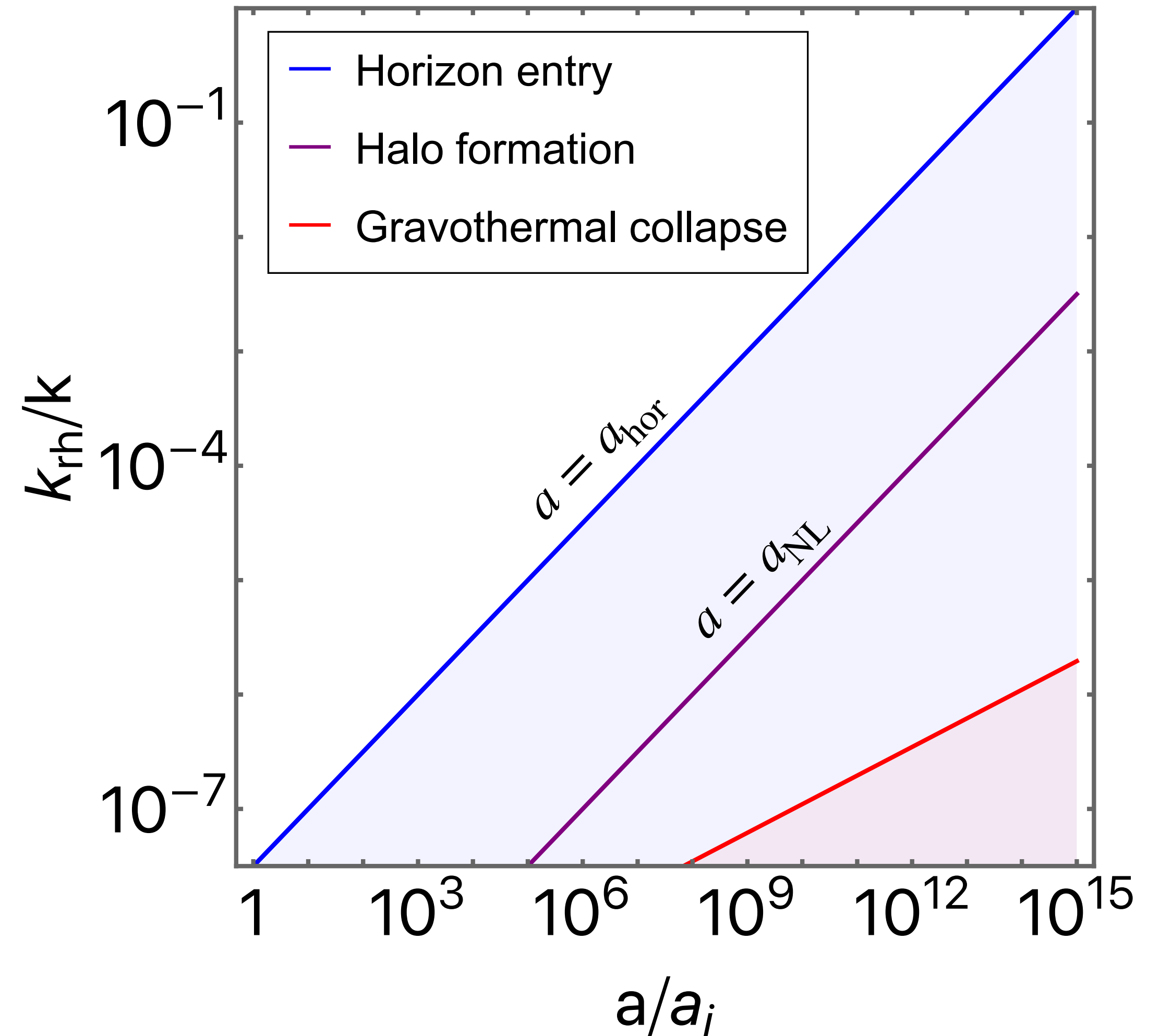
Gravothermal collapse allows the production of PBHs from SIDM primordial halos.

- Matter power spectrum for perturbations entering the horizon during matter domination:

$$\Delta_{\delta}^2(k, a) = \frac{4}{25} \left(\frac{a}{a_{\text{hor}}} \right)^2 \Delta_{\mathcal{R}}^2(k), \quad \Delta_{\mathcal{R}}^2(k) \sim 10^{-9}$$

- Halo formation occurs when perturbations become nonlinear, $\Delta_{\delta}(k, a_{\text{NL}}) = 1.686$:

$$a_{\text{NL}} \sim 1 \times 10^5 a_{\text{hor}} = 1 \times 10^5 a_{\text{rh}} \left(\frac{k_{\text{rh}}}{k} \right)^2$$



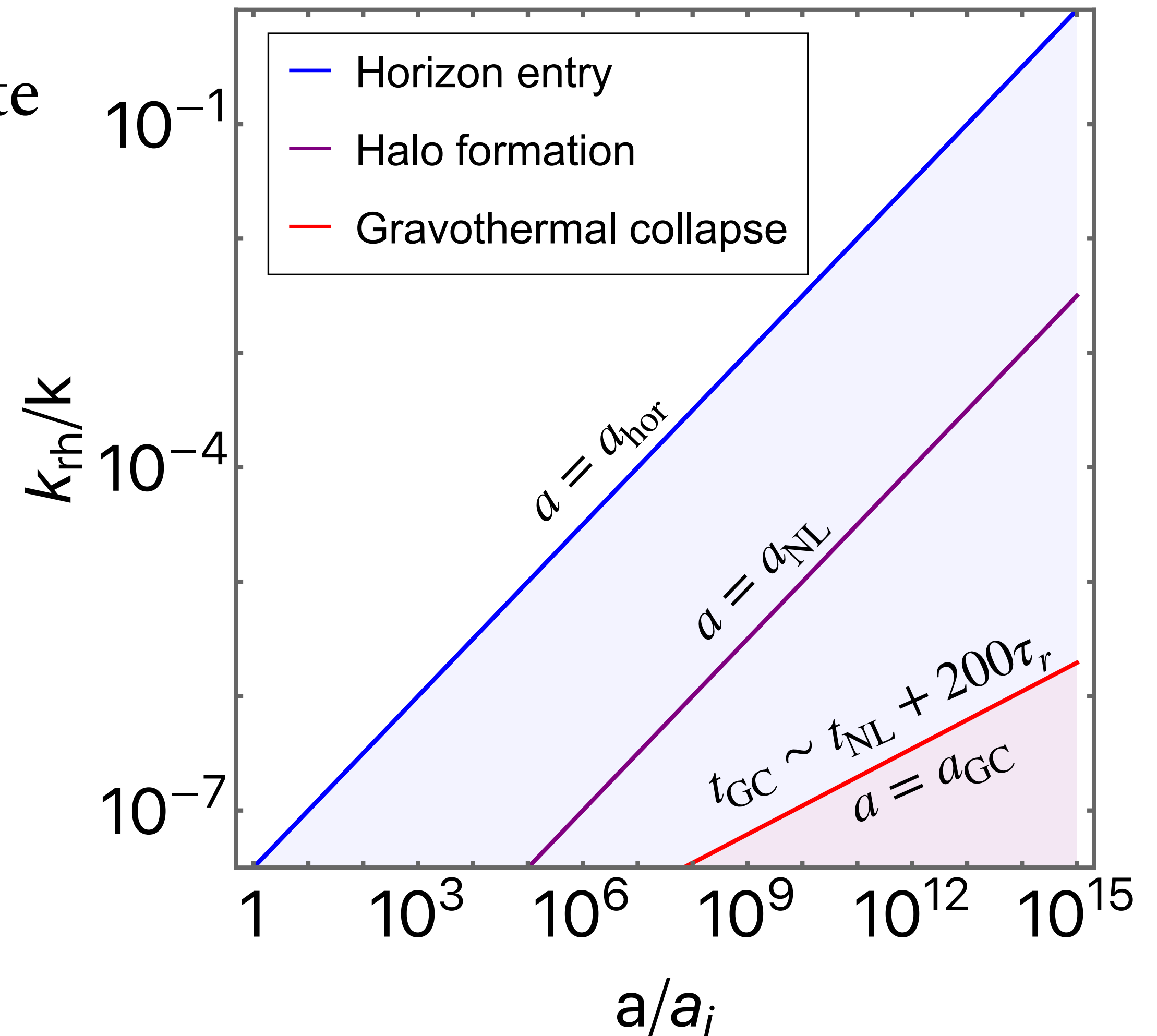
Gravothermal collapse in an EMDE

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

- Following the gravothermal evolution, we estimate the time at which the halo inner core collapse:

$$\frac{a_{\text{GC}}}{a_i} \sim \max \left[2 \times 10^8 \lambda^{-4/3} \left(\frac{k/k_{\text{rh}}}{10^4} \right)^{-4} \left(\frac{T_{\text{rh}}}{100 \text{ MeV}} \right)^{2/3} \left(\frac{a_{\text{rh}}/a_i}{10^{10}} \right)^{5/2}, \frac{a_{\text{NL}}}{a_i} \right]$$

1. The biggest PBH is formed at the end of the EMDE (the largest halo to collapse).
2. The smallest PBH corresponds to the mode entering the horizon at the beginning of the EMDE (the smallest halo).



Gravothermal collapse in an EMDE

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

- Differently from the late universe, density effects in the early universe can alter or stop gravothermal collapse:
 1. *Quantum and self-interaction pressure can stop the collapse of the inner core.*
 2. *Quantum effects can modify the gravothermal evolution of the halo.*
 3. *Cannibal 4-to-2 interactions in the inner core can be efficient enough to stop the collapse.*

Quantum Pressure and Boson Stars

- During the collapse, the inner core can be so dense that quantum effects become important.

- If the size of the core $r_c \sim GM_c/v_c^2$ becomes smaller than the particle de Broglie wavelength $l_{\text{dB}} \sim \frac{1}{mv_c}$, the collapse is stopped.



- If before rel instability $l_{\text{dB}} > r_c \rightarrow$ ***boson star*** at the center of the halo.

Self-Interaction Pressure and Boson Stars

- During the collapse, the inner core can be so dense that self-interaction pressure become important.
 - With positive self-coupling λ , the pressure can stop the collapse.

- If before relativistic instability $\frac{1}{2}m^2\phi_c^2 \lesssim \frac{\lambda}{4!}\phi_c^4$



boson star at the center of the halo.



Quantum Nature and Gravo-thermal Evolution

- Quantum effects in the inner core can become important even without stopping the collapse.
- 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 $l_{\text{dB}} \sim \frac{1}{mv_c}$, the gravo-thermal evolution might be modified.



We assume that this does not affect the results of our analysis.



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, η_{\min} :

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

- This accounts for the available matter for the *seed PBH* at the center of the halo.
- As the halo remains in virial equilibrium, the gravothermal evolution is expected to continue, accreting the collapsed core.

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

Computing the BH mass: Accretion

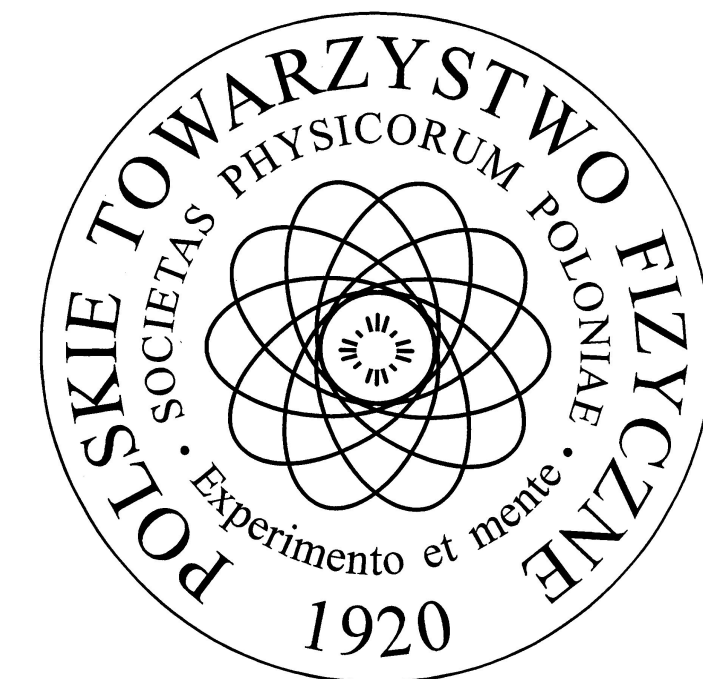
- The gravothermal process proceeds even after the first collapse, accreting mass around the collapsed core:
 1. Accretion increases the mass of the seed BH.
 2. Cannibal and bosonic stars can collapse into new BHs.
- The accretion process works until the kinetic energy of the particles computed at relativistic instability is smaller than the total energy of the original NFW halo:

$$K_{\text{NFW}} > K_{\text{BH}} \sim \frac{1}{2} M_{\text{BH}} \left(\frac{1}{3} \right)^2 \quad \longrightarrow \quad \eta_{\text{max}} \sim 20 \cdot v_{\text{vir}}^2 \sim 10^{-3}$$

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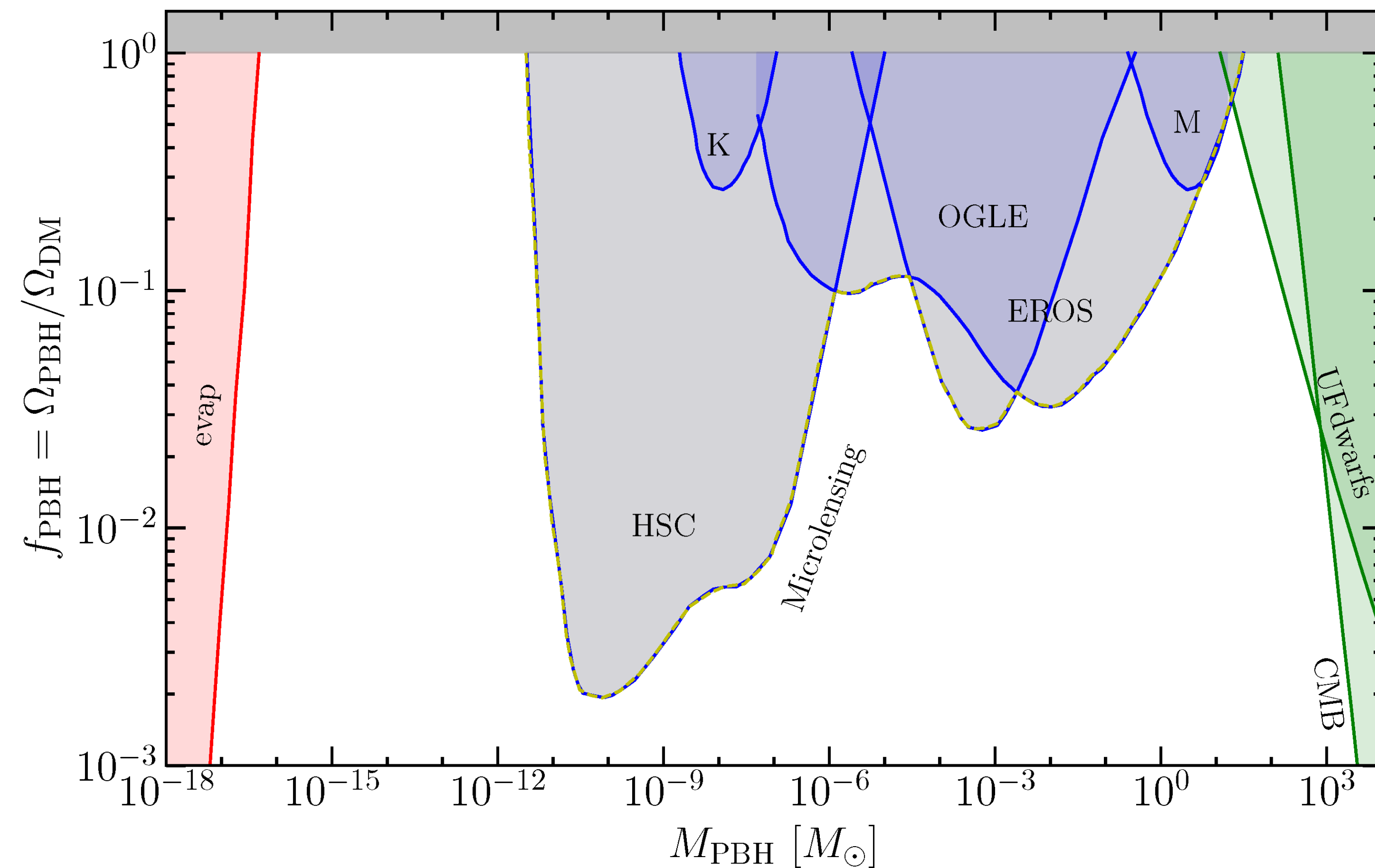
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PBH spectrum and constraints

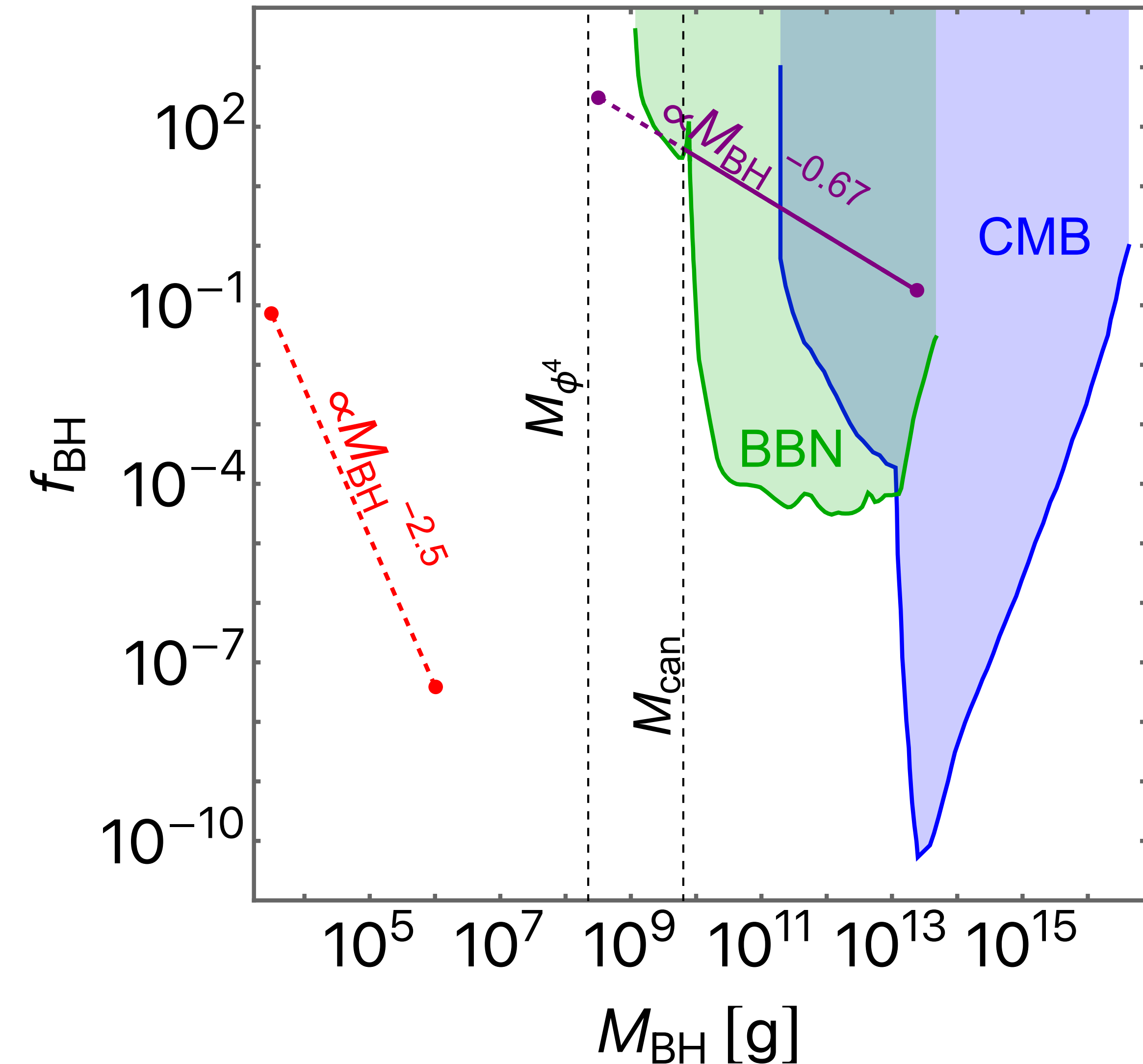
- ▶ Primordial black holes (PBHs) are constrained by different observations depending on the mass range.



1. Indirect constraints (large mass).
2. Abundance of dark matter (large abundance).
3. Black hole evaporation (small masses).

- ▶ We compute the PBH spectrum in our model and compare with the constraints.

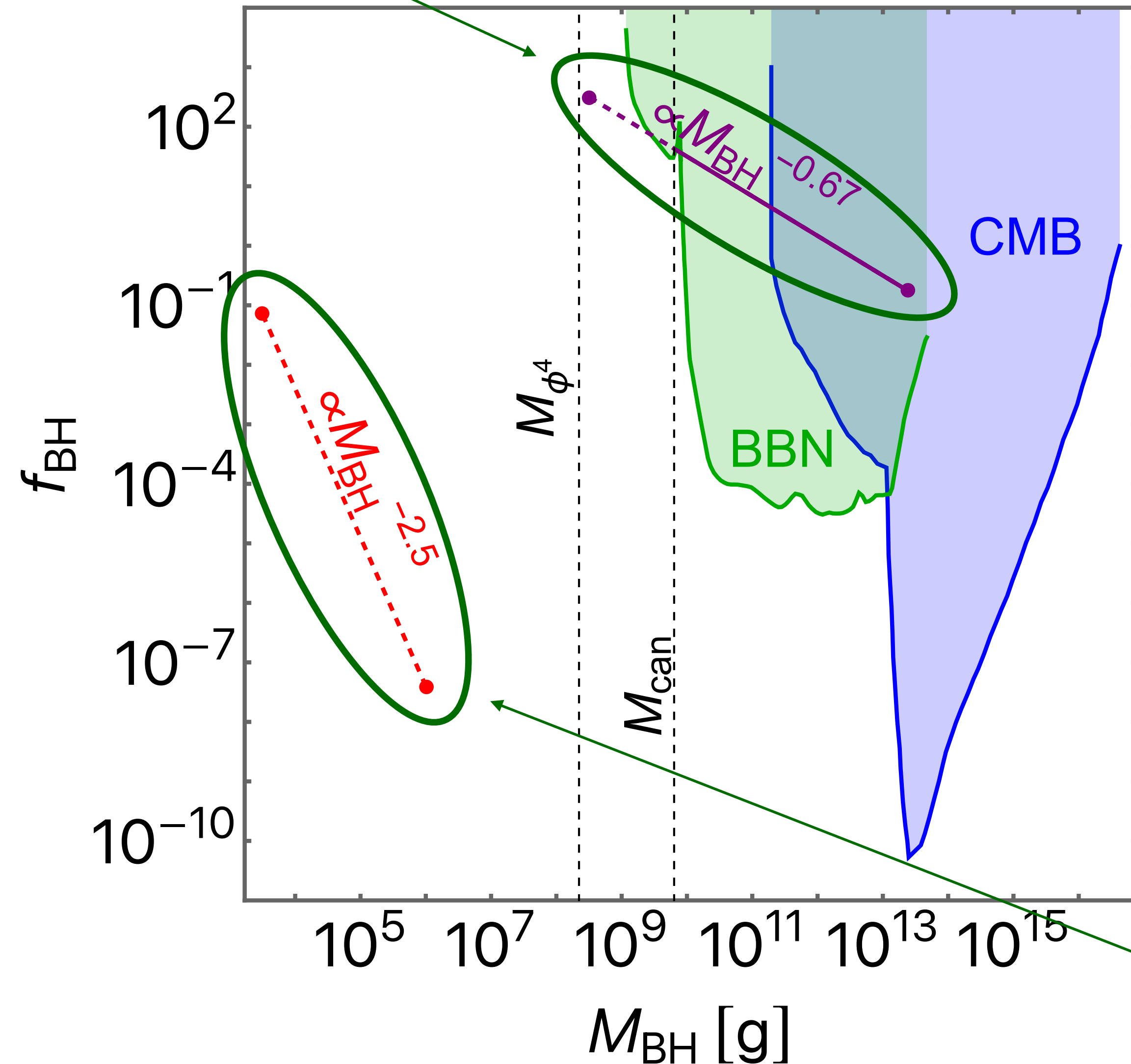
PBH spectrum and constraints



- We obtained a conservative estimate for f_{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).
 - ▶ Gravo-thermal-produced PBHs are mostly constrained by evaporation and DM abundance.

Accreted PBHs

PBH spectrum and constraints



- We obtained a conservative estimate for f_{BH} by assuming PBHs can form only in isolated halos in the *Press-Schechter formalism*.
 - Self-interaction pressure and cannibal interactions set lower bounds on the BH mass.
 - In the presence of 4-to-2 interactions, accretion is necessary to produce any BH.

Seed PBHs

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

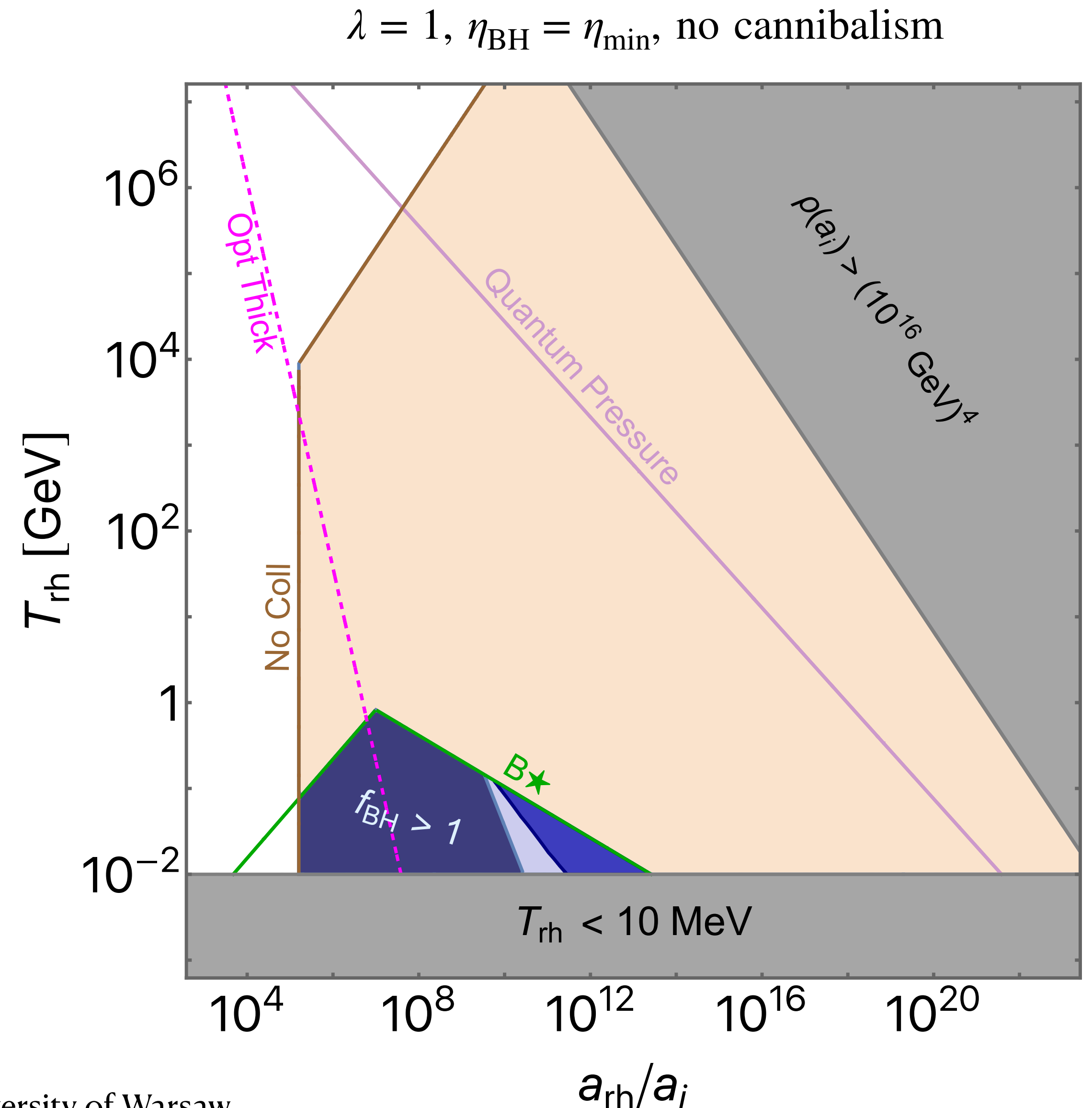
Parameter space and abundance

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.



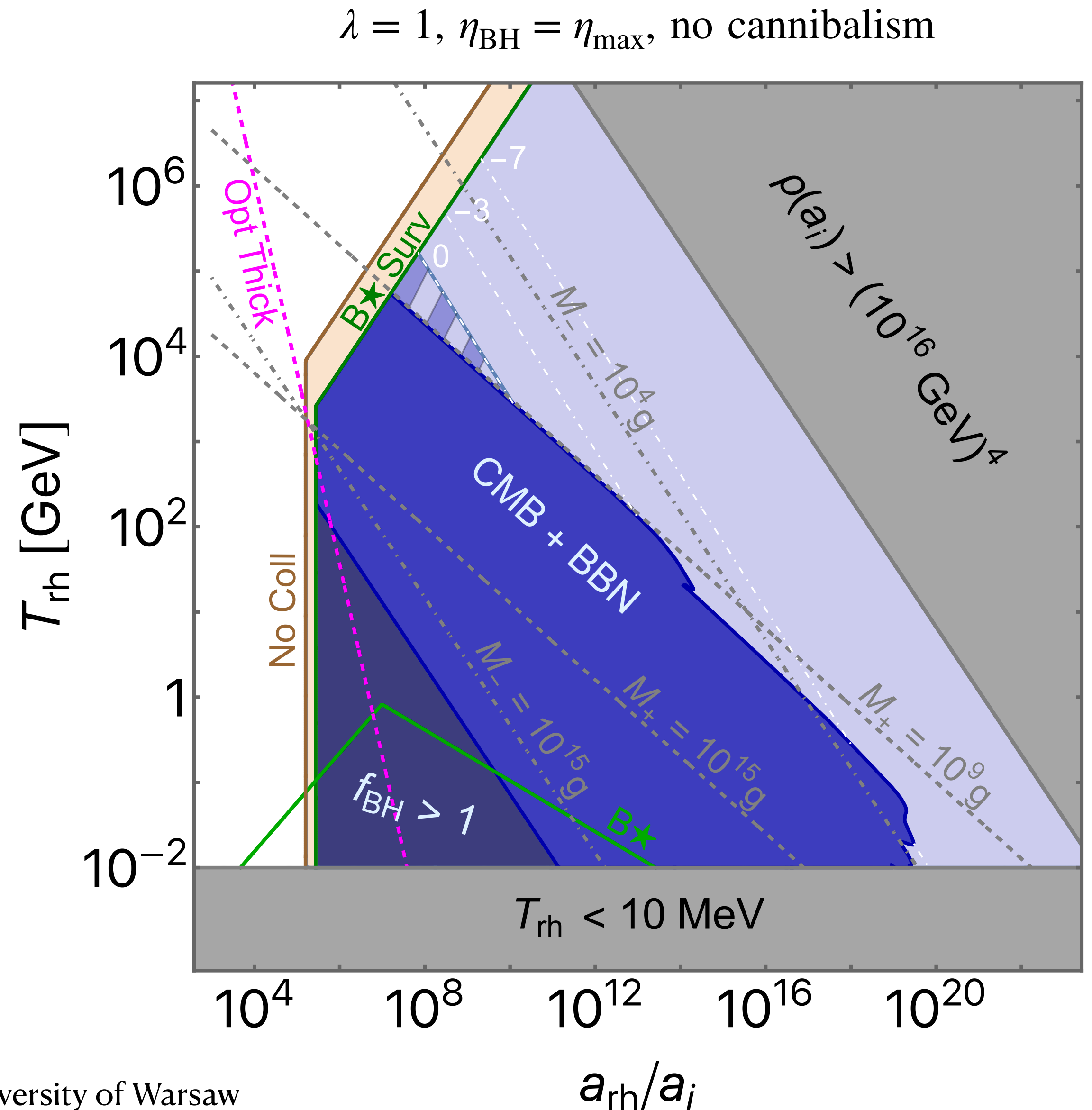
Parameter space and abundance

2. 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)



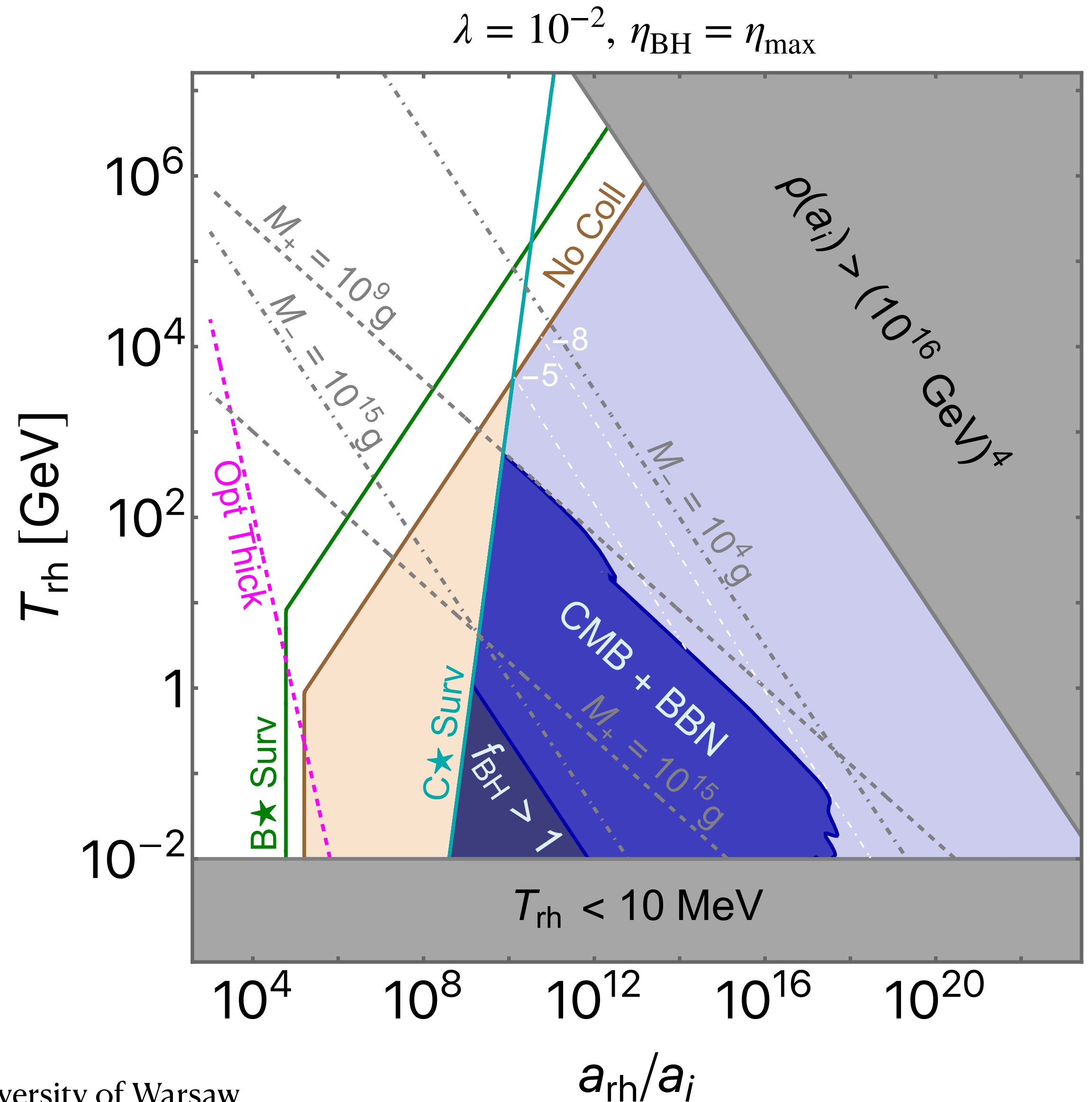
Parameter space and abundance

3. 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.



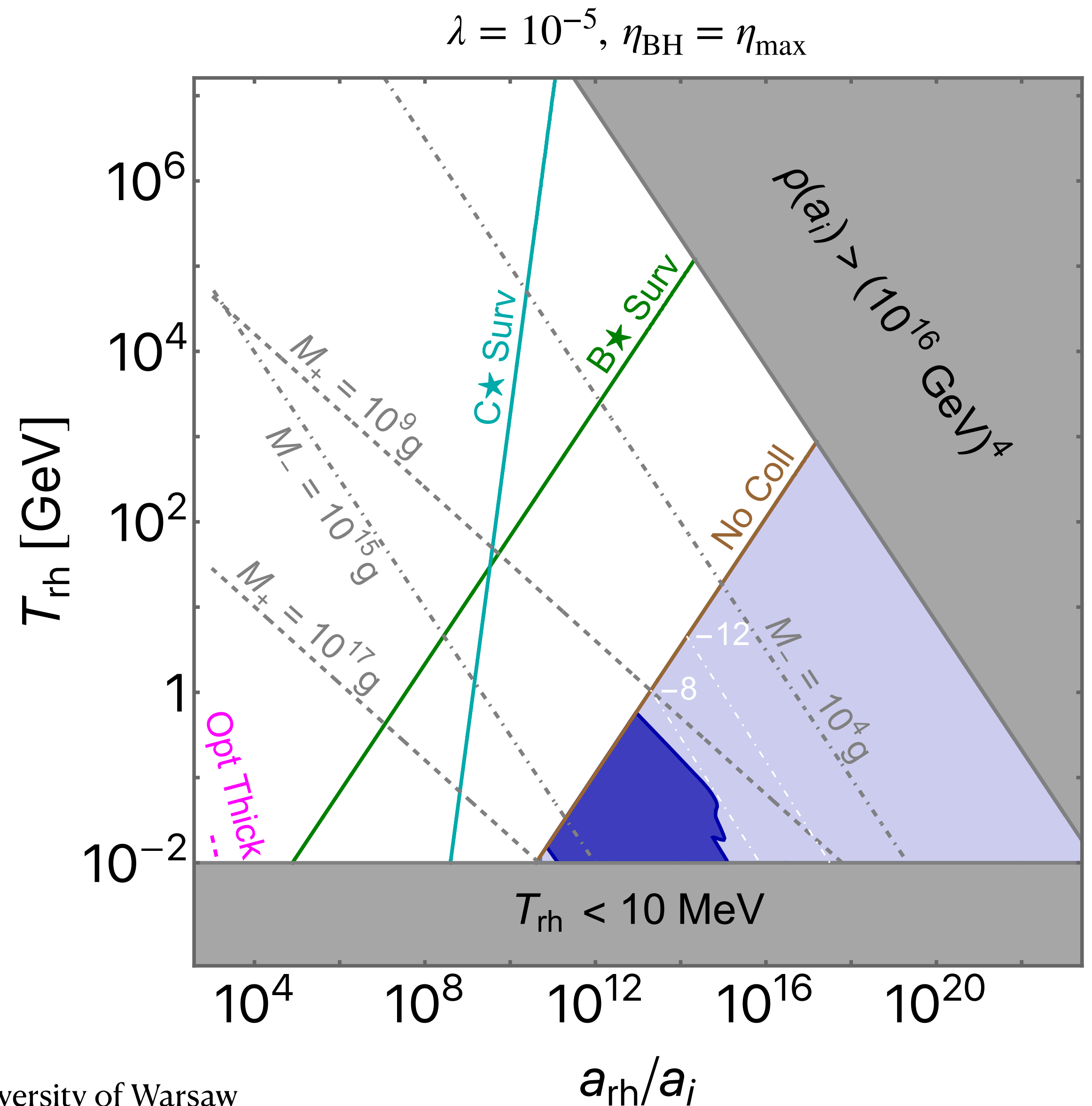
PBH spectrum and constraints

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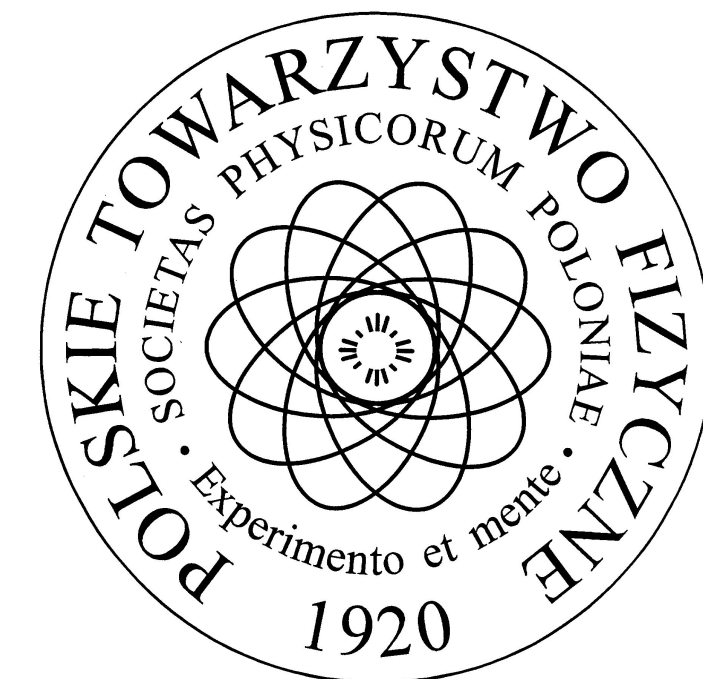
- ▶ Decreasing the value of λ there is a small region where PBHs survive until today and can be a significant fraction of DM.



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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!!

