Gravothermalizing into Primordial Black Holes

Speaker:
Daniele Perri

UNIWERSYTET WARSZAWSKI

Pranjal Raleganker, **DP,**
Takeshi Kobayashi
arXiv:2410.18948

Contents of the Talk

- ✓ <u>SIDM and gravothermal collapse.</u>
- ✓ Gravothermal collapse in an EMDE.
- ✓ PBHs spectrum and constraints.
- ✓ Conclusion.

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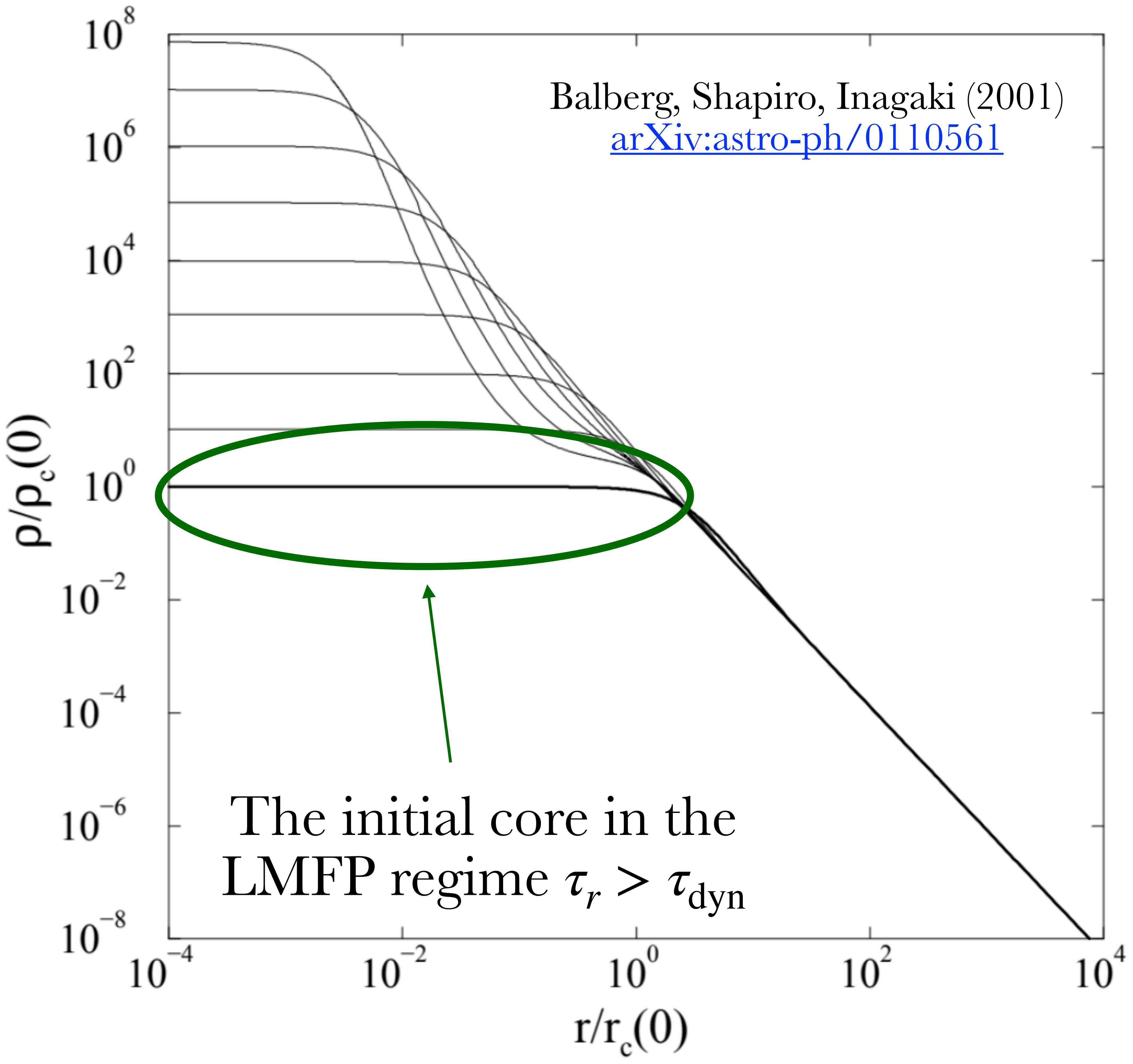
Gravothermal collapse and SIDM

- A halo of self-interacting dark matter (SIDM) exhibits a core at its center due to self-interactions.

$$\tau_{\text{dyn}} = \frac{1}{\sqrt{4\pi G\rho_s}} \qquad \tau_r = \frac{1}{\rho_s v_s \sigma}$$

- 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 BH.



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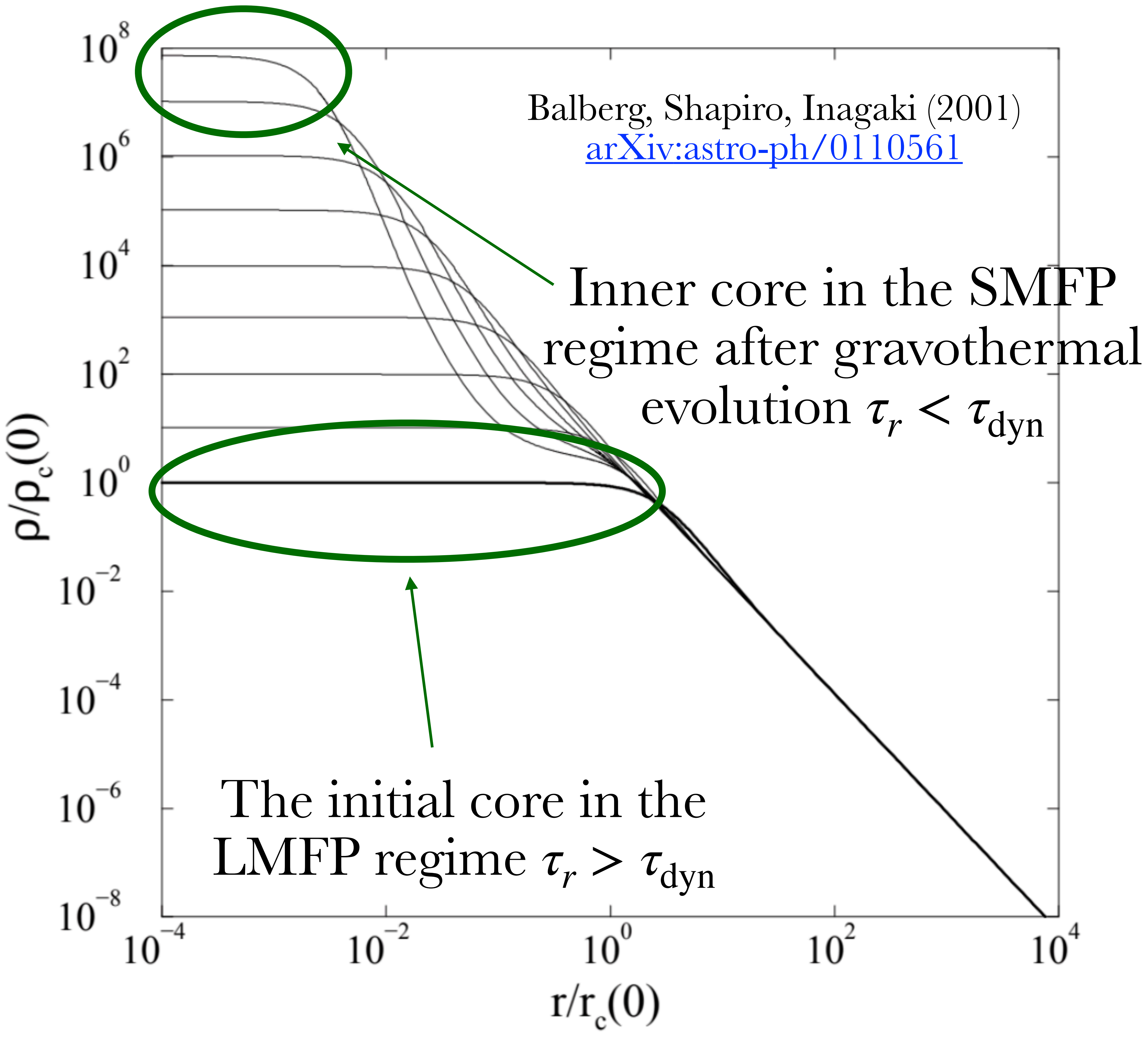
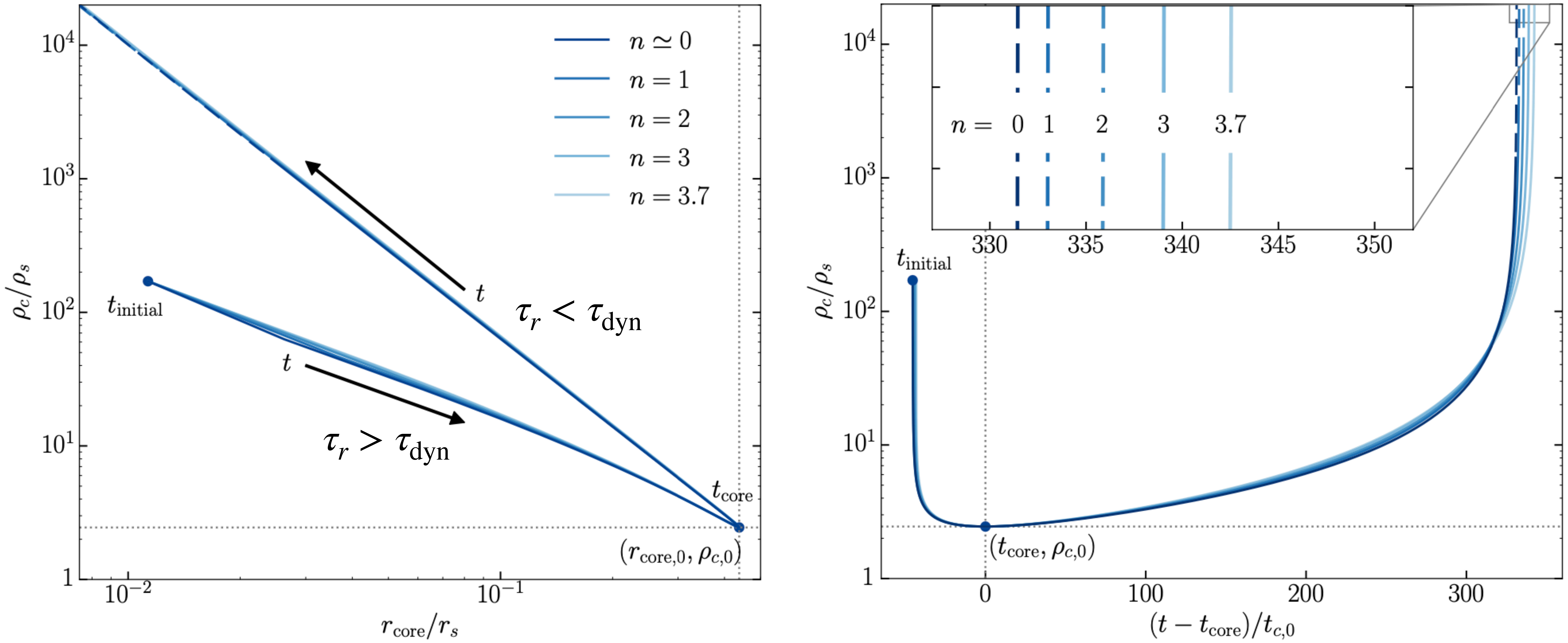


Gravothermal collapse and SIDM



Outmezguine, Boddy, Gad-Nasr, Kaplinghat, Sagunski (2022)
arXiv:2204.06568

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Gravothermal collapse in an EMDE

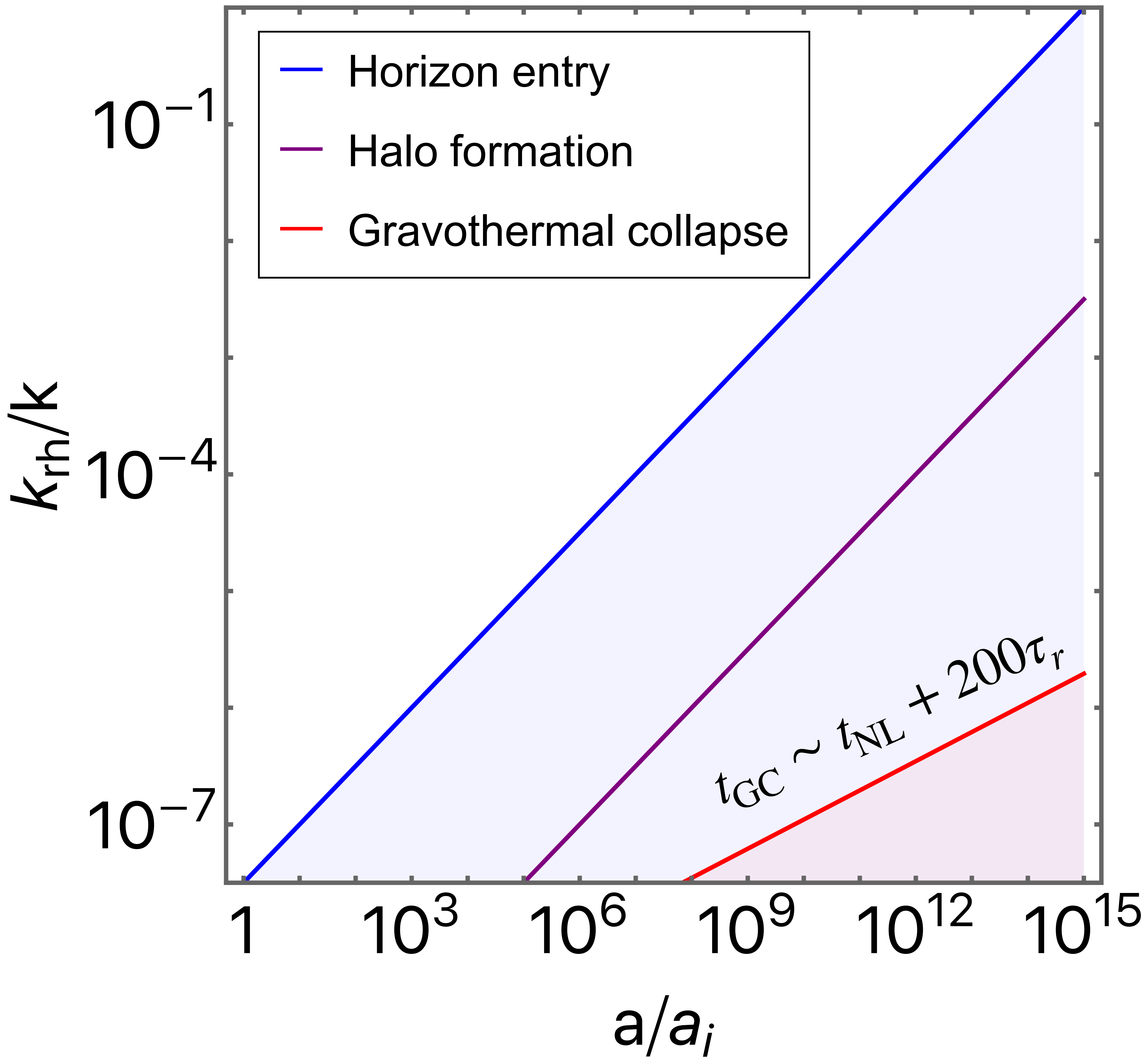
- A simple model of self-interacting nonrelativistic scalar particles dominating the universe after inflation and then decaying into SM:

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

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

  1. The biggest PBH is formed at the end of the EMDE (reheating).

  2. The smallest PBH corresponds to the mode entering the horizon at the beginning of the EMDE.



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

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 $l_{\rm dB} \sim \dfrac{1}{mv_{\rm core}}$, the collapse is stopped.

- If before rel instability $l_{\rm dB} > r_c$ → ***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 rel instability $\frac{1}{2}m^2\phi_c^2 \gtrsim \frac{\lambda}{4!}\phi_c^4$

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.

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

$$Q_{heat} = \frac{\rho_{\rm core}^4}{m^4} \frac{< \sigma_{4\to2} v^3 >}{2} \times \frac{4\pi}{3} r_{\rm core}^3 \times 2m$$

$$\langle \sigma_{4\to2} v^3 \rangle = \frac{1}{2048\sqrt{3}\pi} \frac{\lambda^4}{m^8}$$

- If before rel instability $Q_{\rm cool} < Q_{\rm heat}$ → ***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, $\eta_{\rm min}$:

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

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

- 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:

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

$$\Downarrow$$

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

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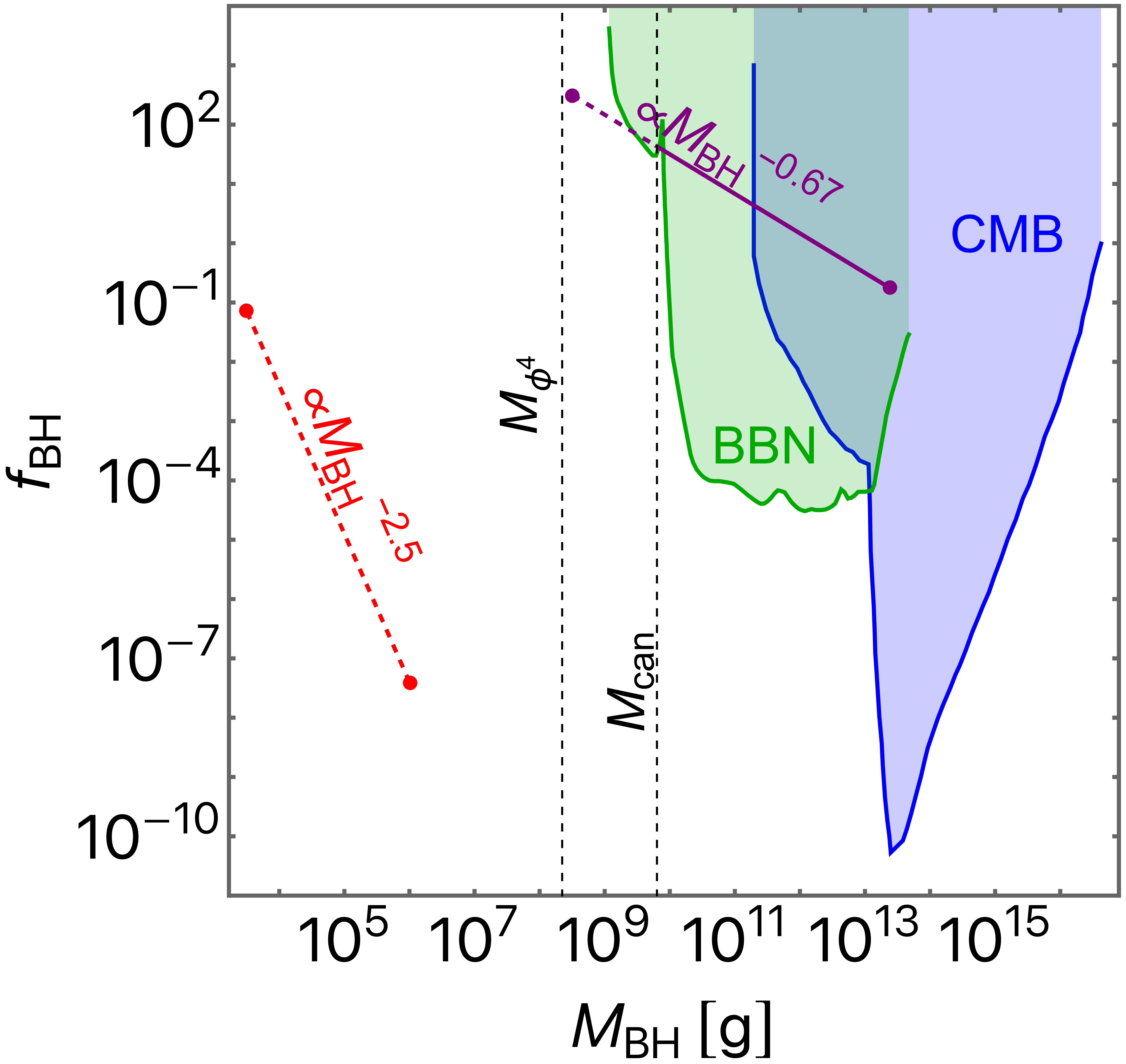
PBH spectrum and constraints



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

- 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).
  - In the presence of 4-to-2 interactions, accretion is necessary to produce any BH.

Parameter space and abundance

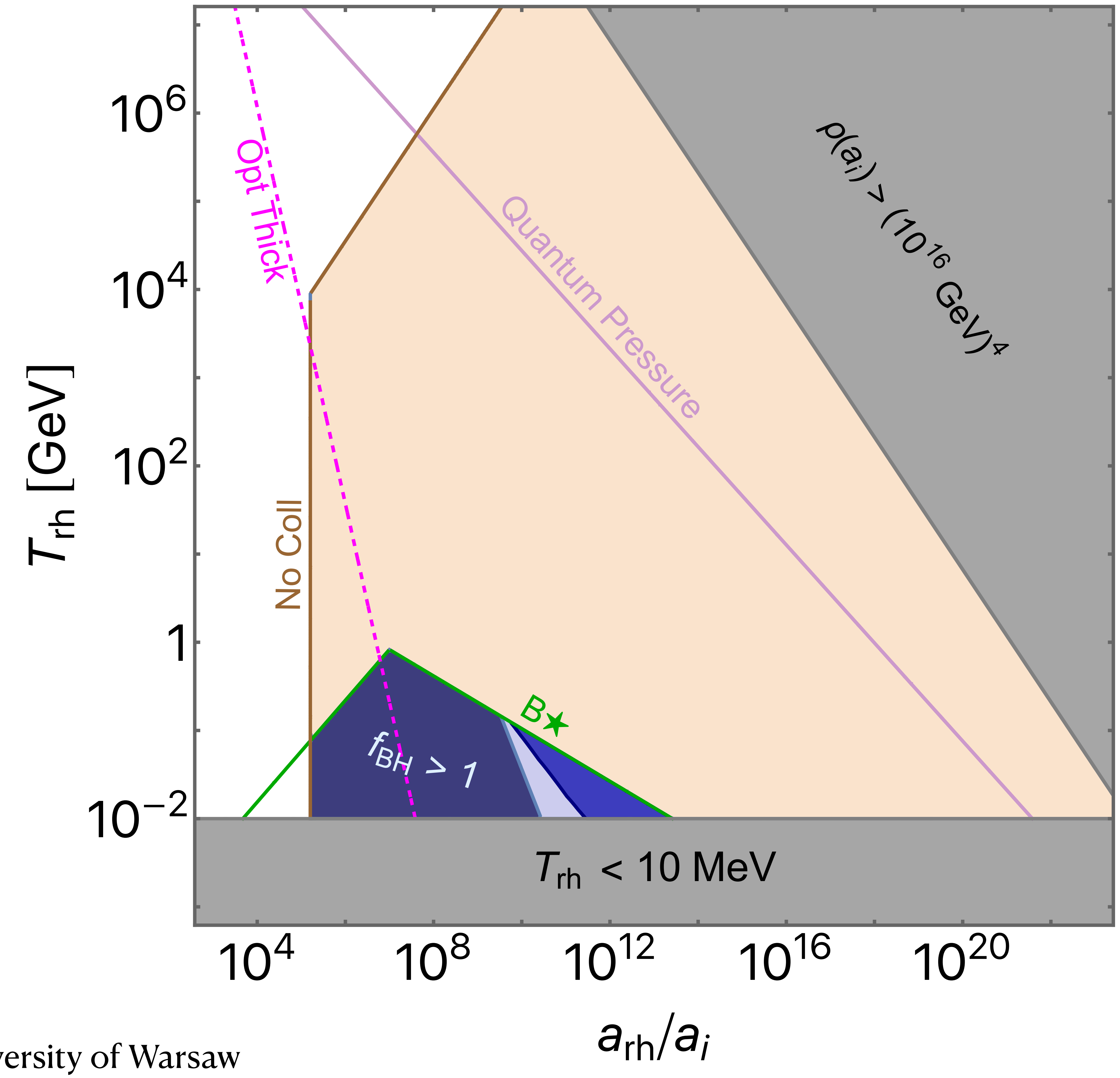
1. Seed BH without cannibalism

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.

$\lambda = 1,\ \eta_{\rm BH} = \eta_{\rm min}$, no cannibalism



Parameter space and abundance

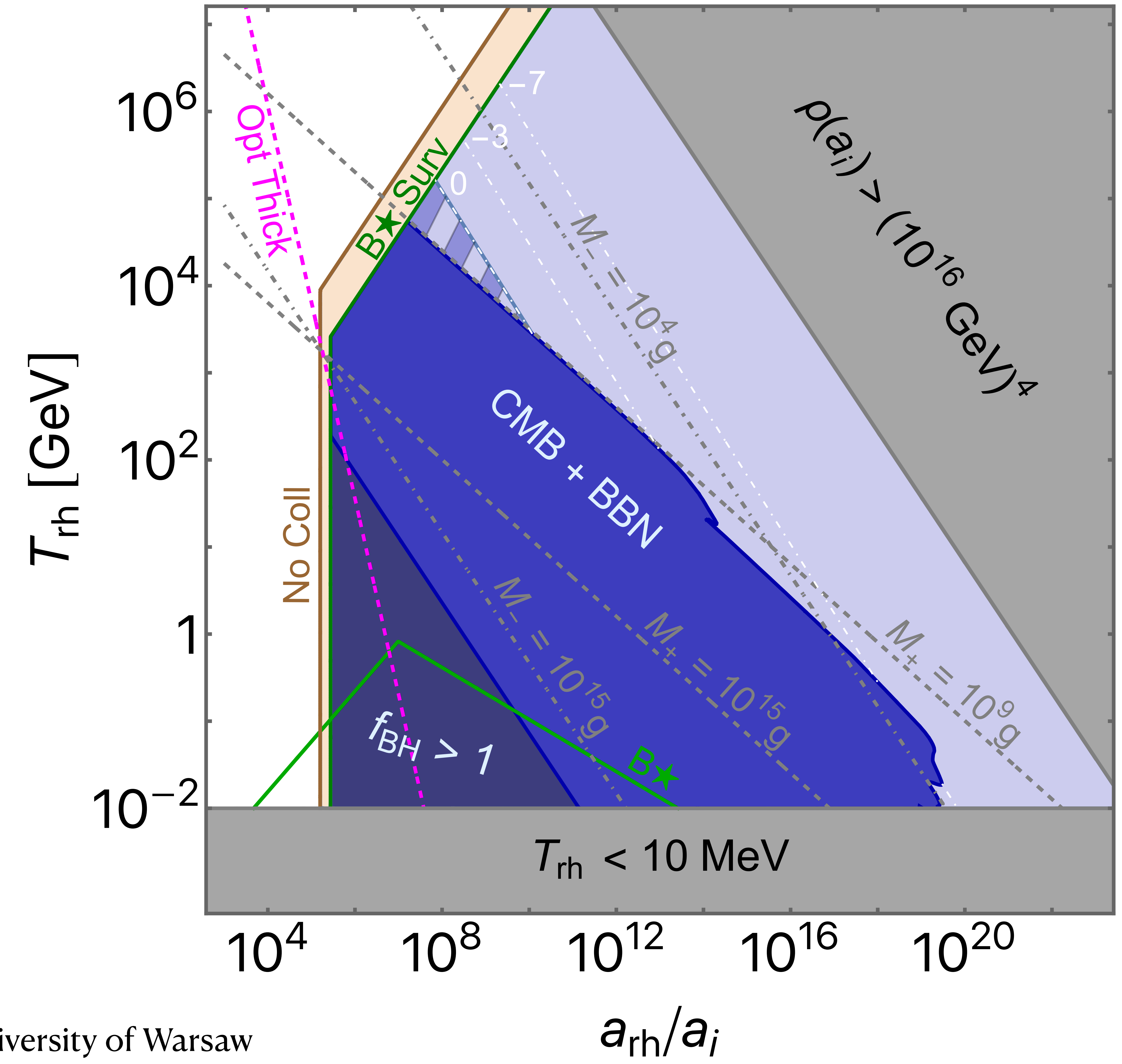
1. Accreted BH without cannibalism

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)

$\lambda = 1,\ \eta_{\rm BH} = \eta_{\rm max}$, no cannibalism



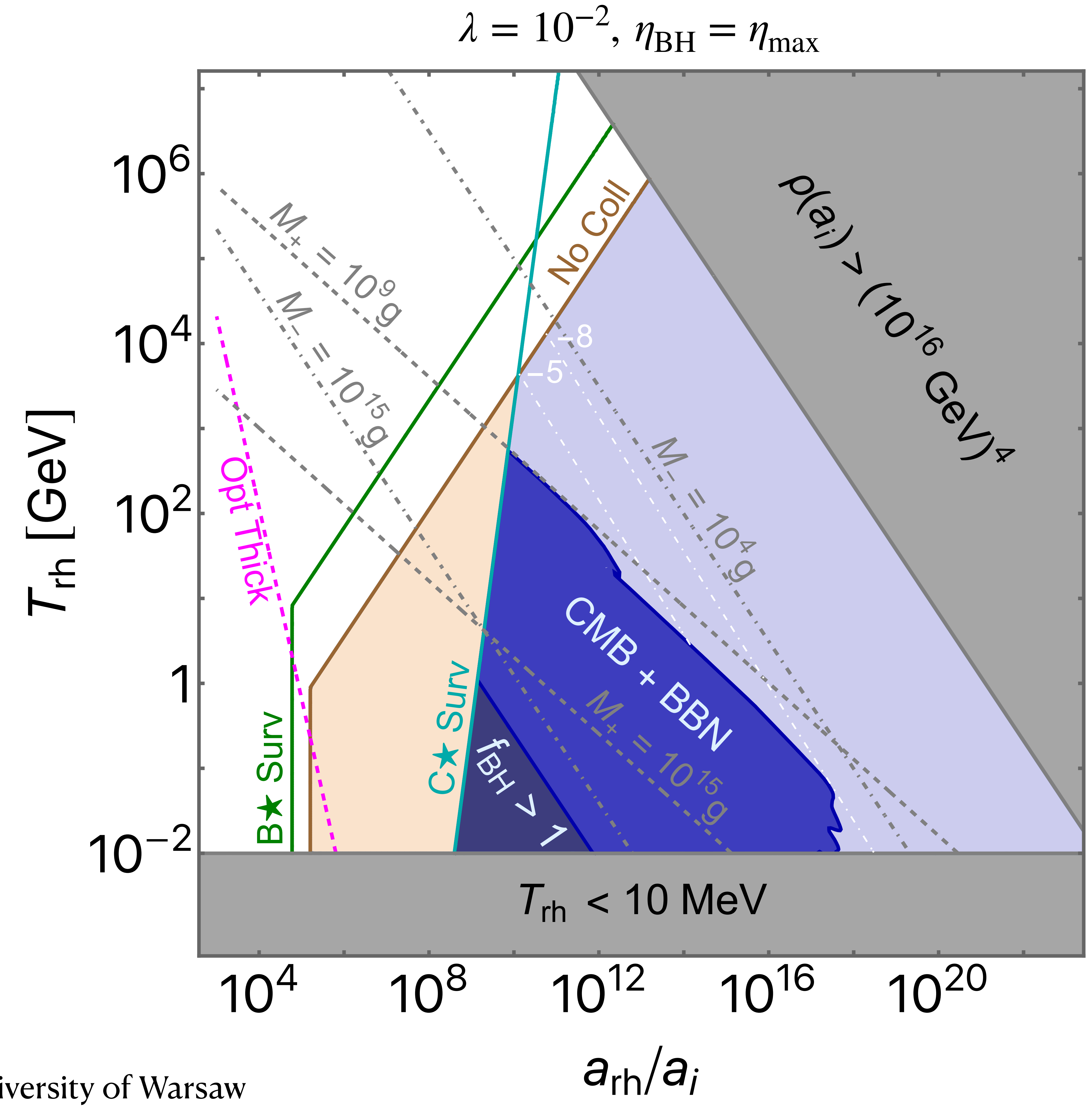
Parameter space and abundance

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...

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Thank You!!

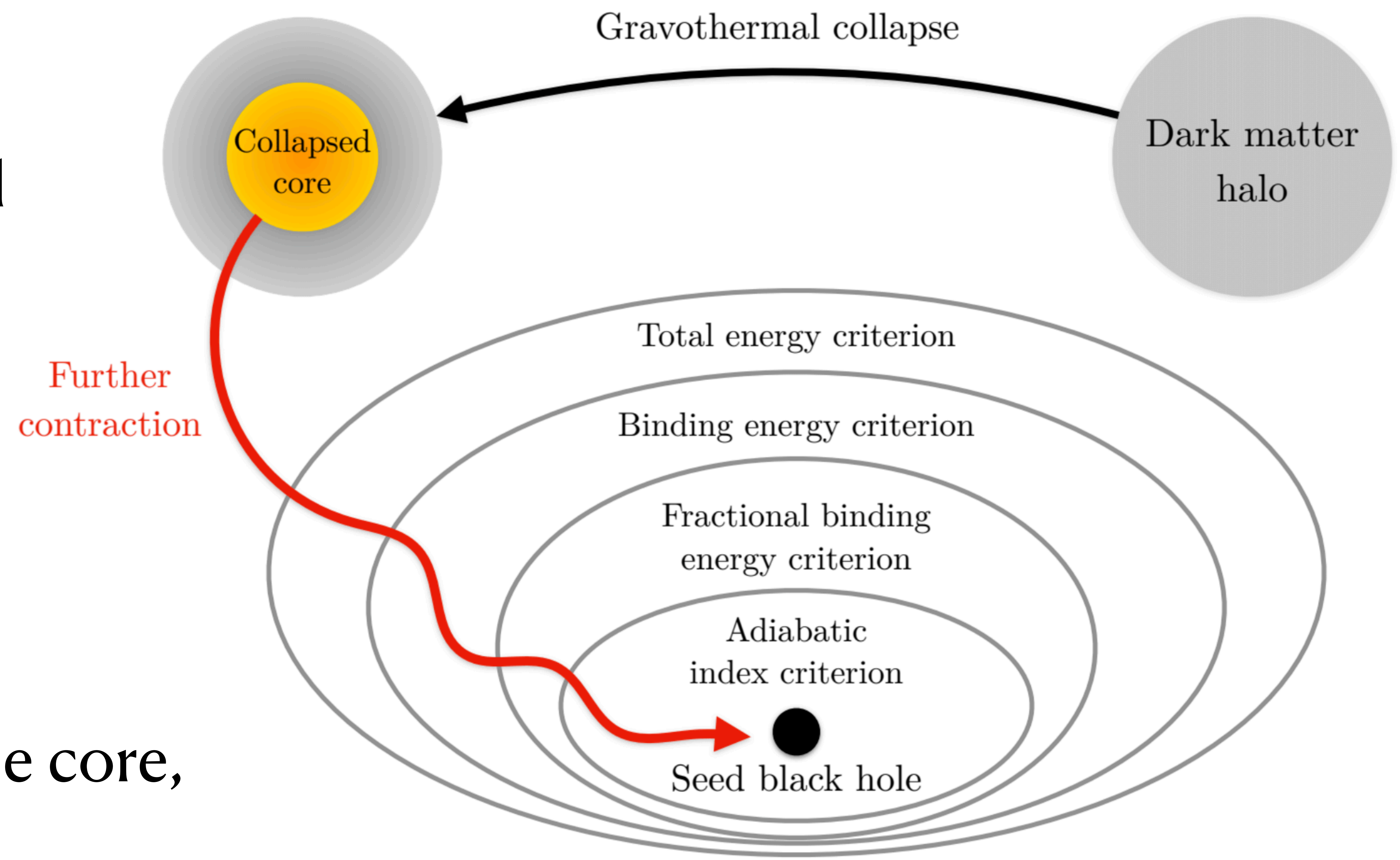
Gravothermal collapse and SIDM

- 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

Quantum Nature and Gravothermal Evolution

- 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 $d \sim (m/\rho_{\rm core})^{1/3}$ becomes smaller than their de Broglie wavelength $l_{\rm dB} \sim \dfrac{1}{m v_{\rm core}}$, the gravothermal evolution is modified.

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

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 λ there is a region where PBHs survive until today and can be a significant fraction of DM.

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