SISSA

Gravothermalizing into Primordial Black Holes, Boson Stars, and Cannibal Stars

Takeshi Kobayashi

2410.18948 w/ Pranjal Ralegankar, Daniele Perri

BeyondWIMPs, Oxford

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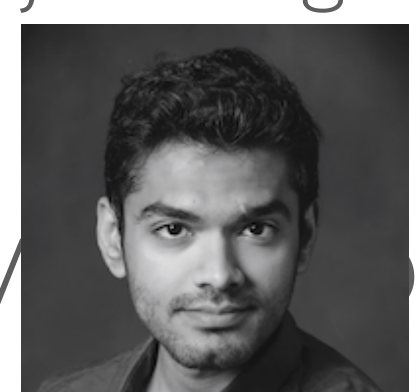
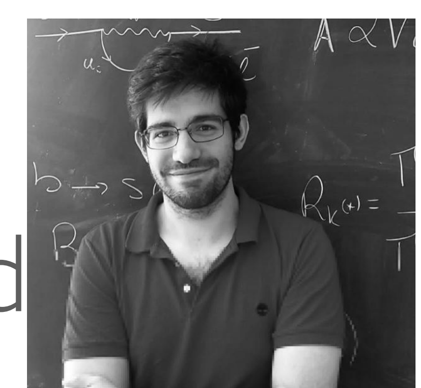
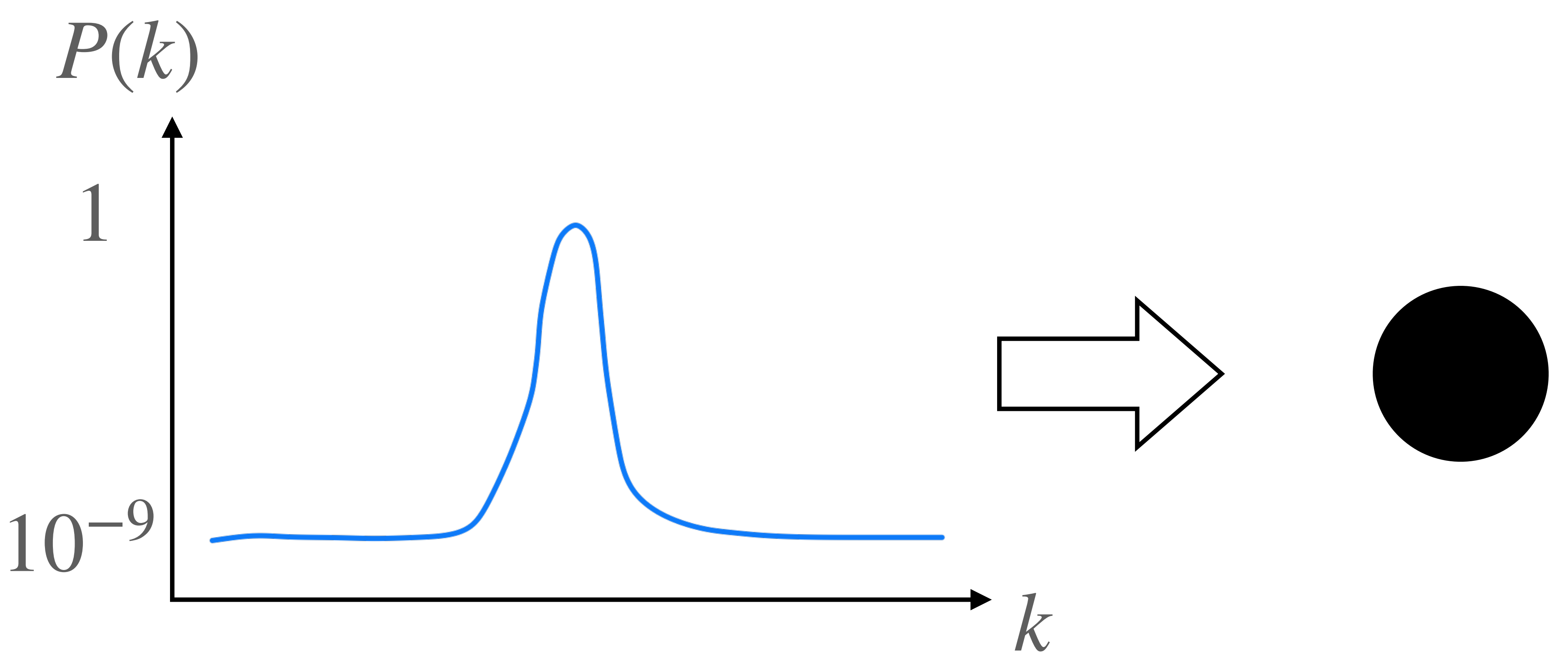
BeyondV  Oxford 

PBH FORMATION - THE USUAL STORY

Ingredient: enhanced density perturbation on small scales

Perturbations collapse into PBHs upon horizon re-entry



PBH FORMATION - A NEW STORY

Ingredient: early universe epoch dominated by non-relativistic particles with self-interactions

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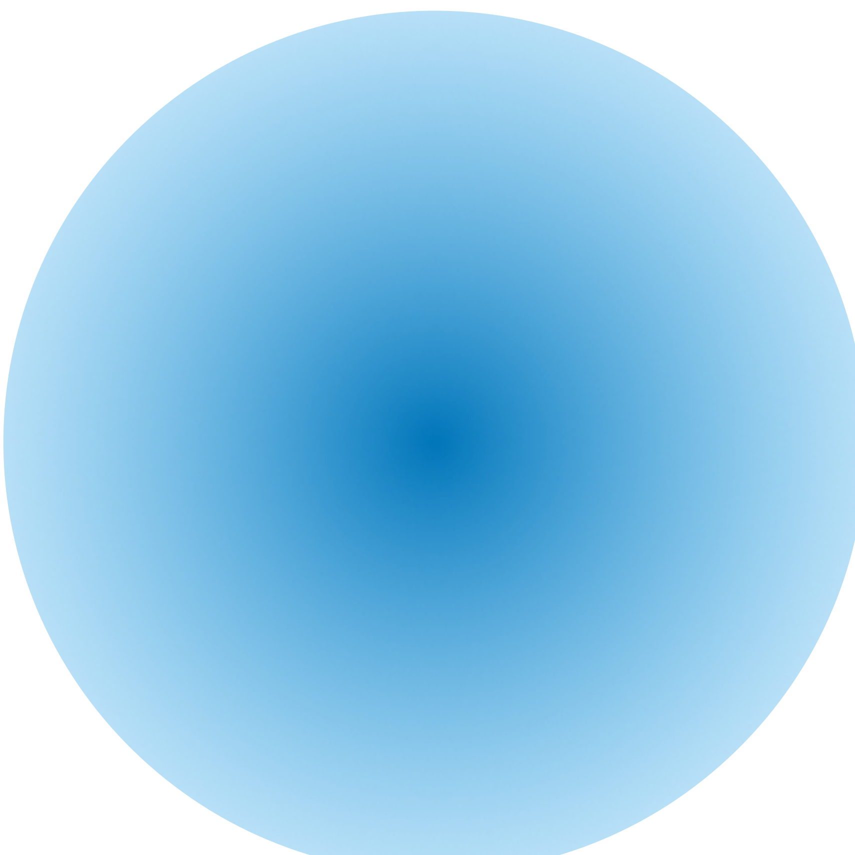
Halo forms,



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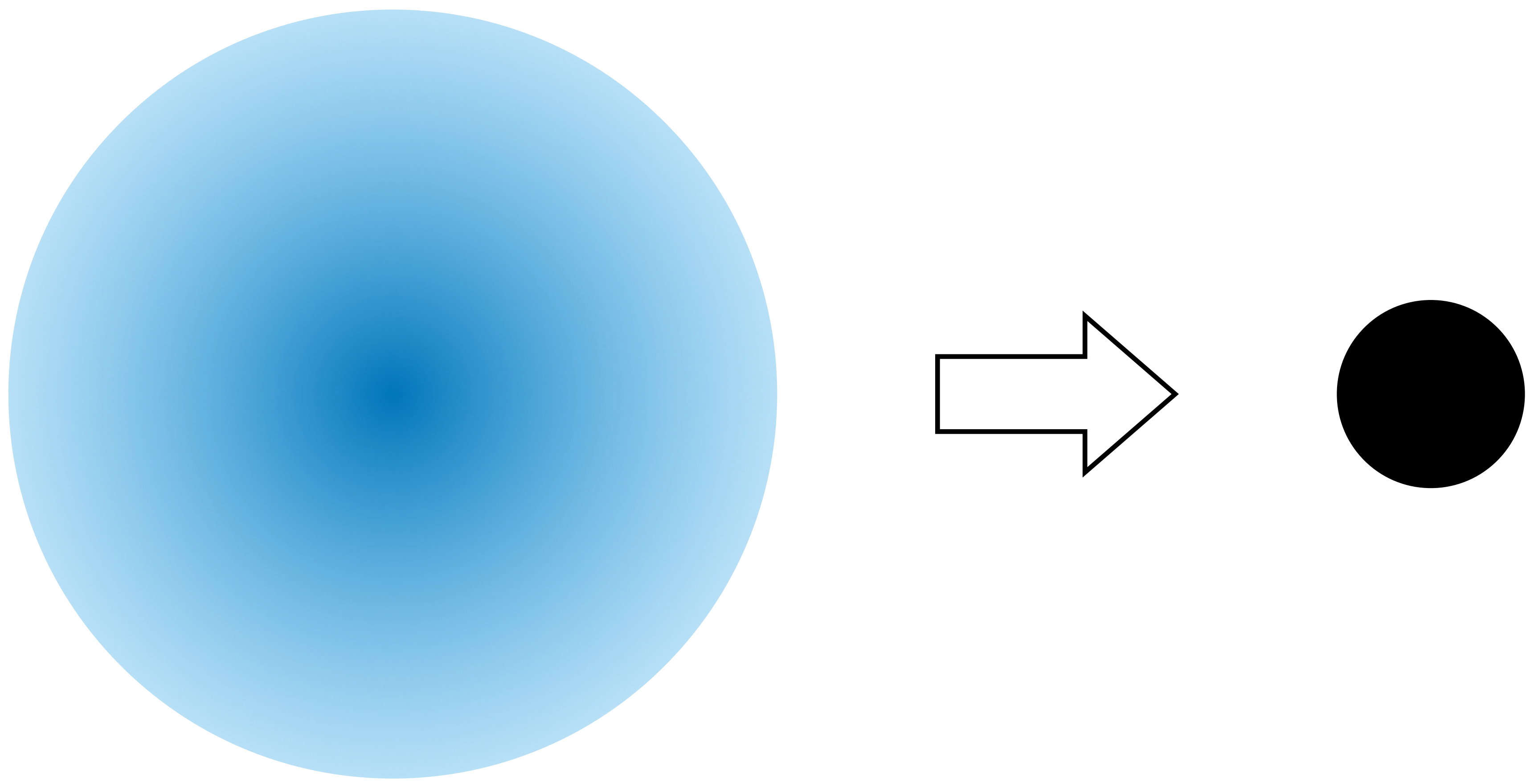
Halo forms, then undergo a gravothermal collapse into PBHs



OUTLINE

1. Gravothermal catastrophe
2. PBHs from gravothermal catastrophe
3. Toy model

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GRAVOTHERMAL CATASTROPHE

Lynden-Bell, Eggleton ‘80

Gravitationally bound systems in virial equilibrium have negative heat capacities

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Gets hotter by losing energy

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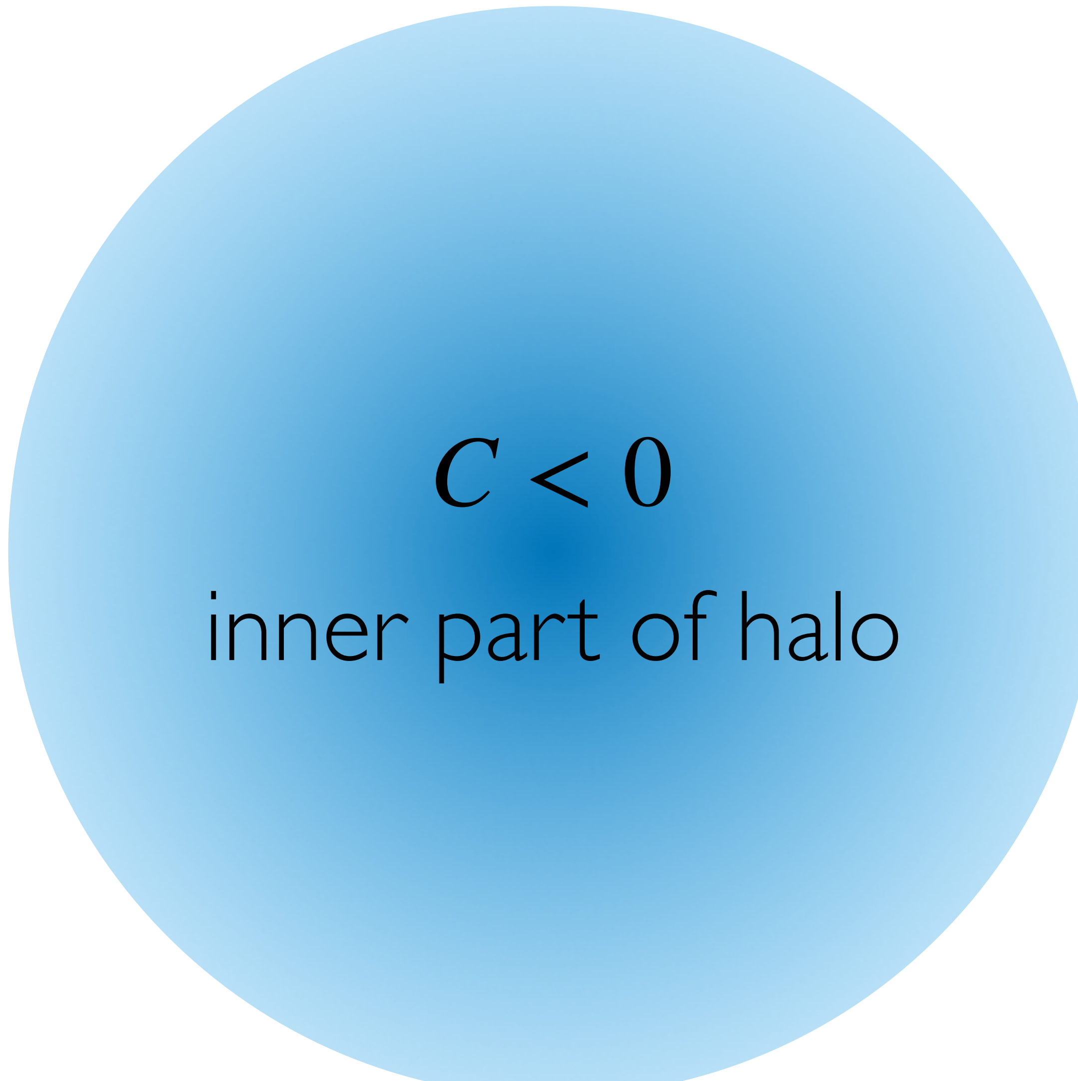

$C > 0$

outside (heat bath)

GRAVOTHERMAL CATASTROPHE

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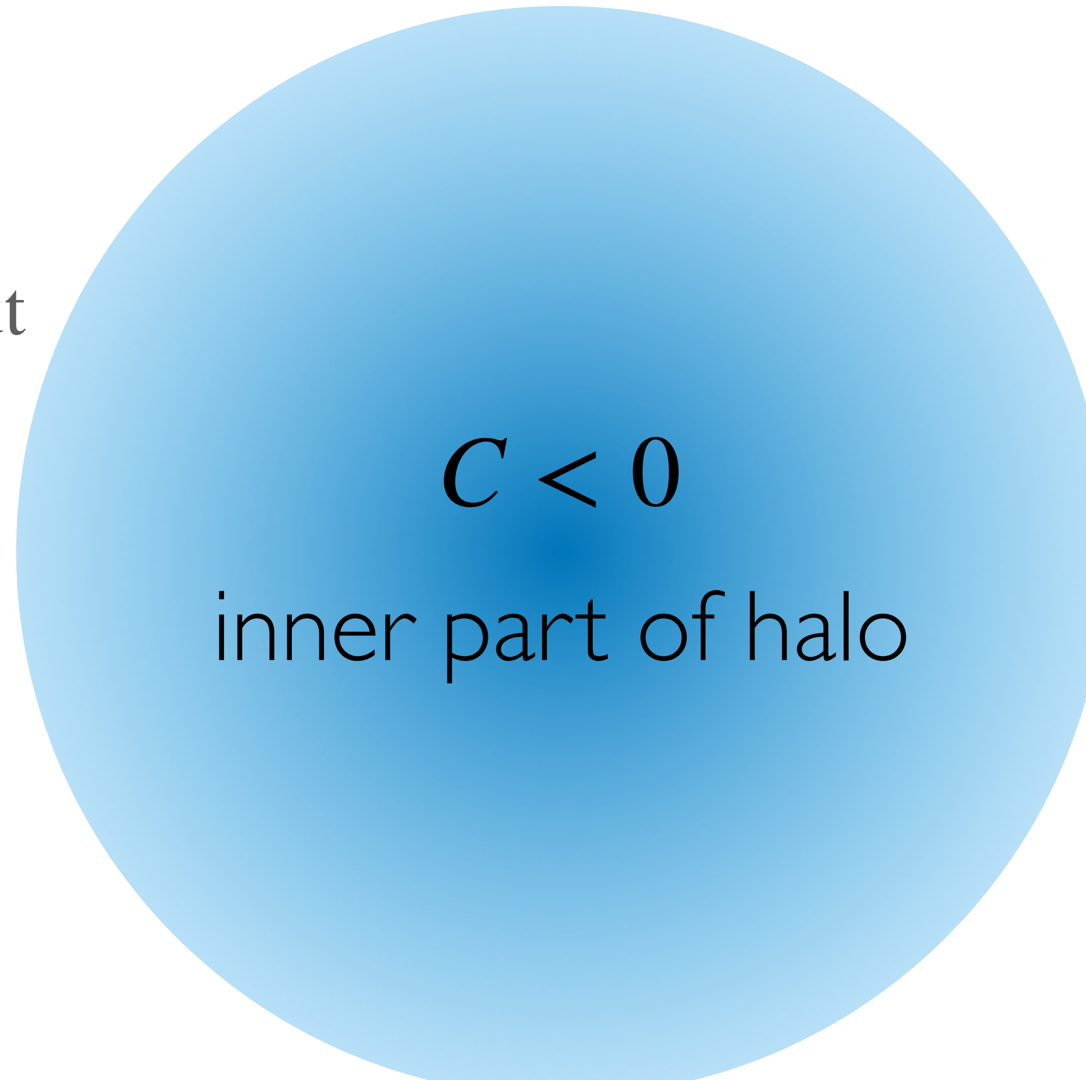
If initially $T_{\mathrm{in}} > T_{\mathrm{out}}$



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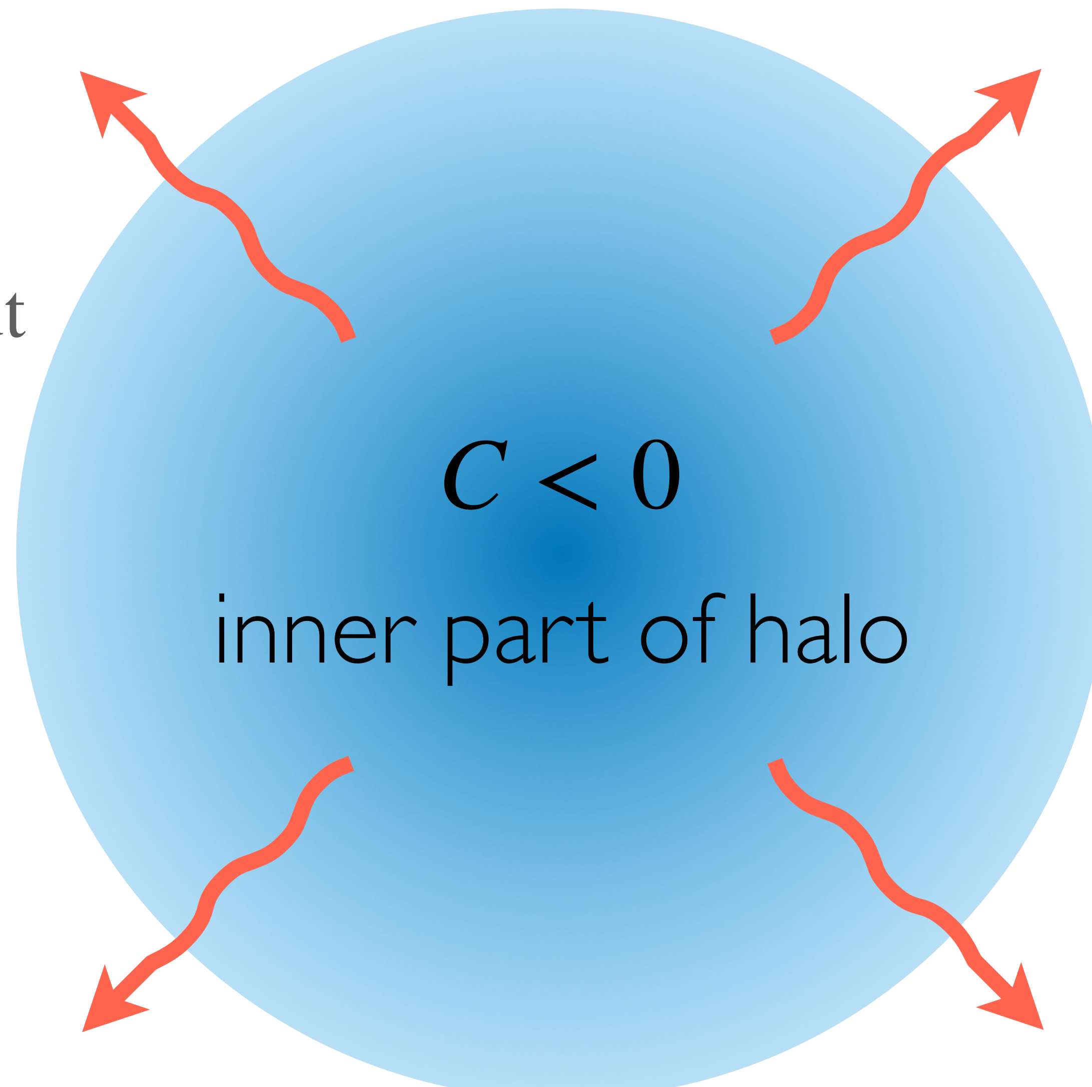

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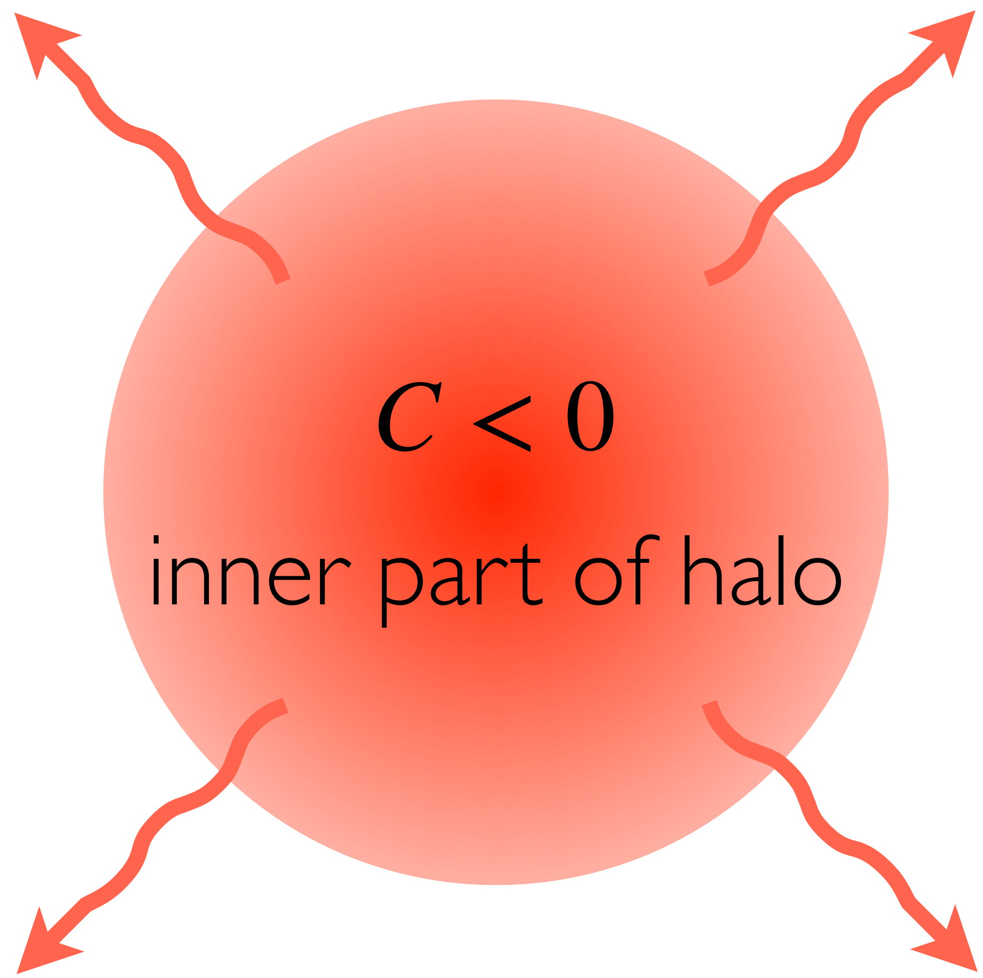

inner part becomes hotter unboundedly

$C > 0$

outside (heat bath)

DARK MATTER

Gravothermal evolution of DM halo only with gravitational interactions is slow

SELF-INTERACTING DARK MATTER

Gravothermal evolution of DM halo only with gravitational interactions is slow… but speeds up with self-scatterings

$$\tau_{\mathrm{r}} = \frac{\lambda}{v} \sim 10^9\,\mathrm{yr}\left(\frac{10^{-3}}{v}\right)\left(\frac{1\,\mathrm{GeV/cm^3}}{\rho}\right)\left(\frac{1\,\mathrm{cm^2/g}}{\sigma/m}\right)$$

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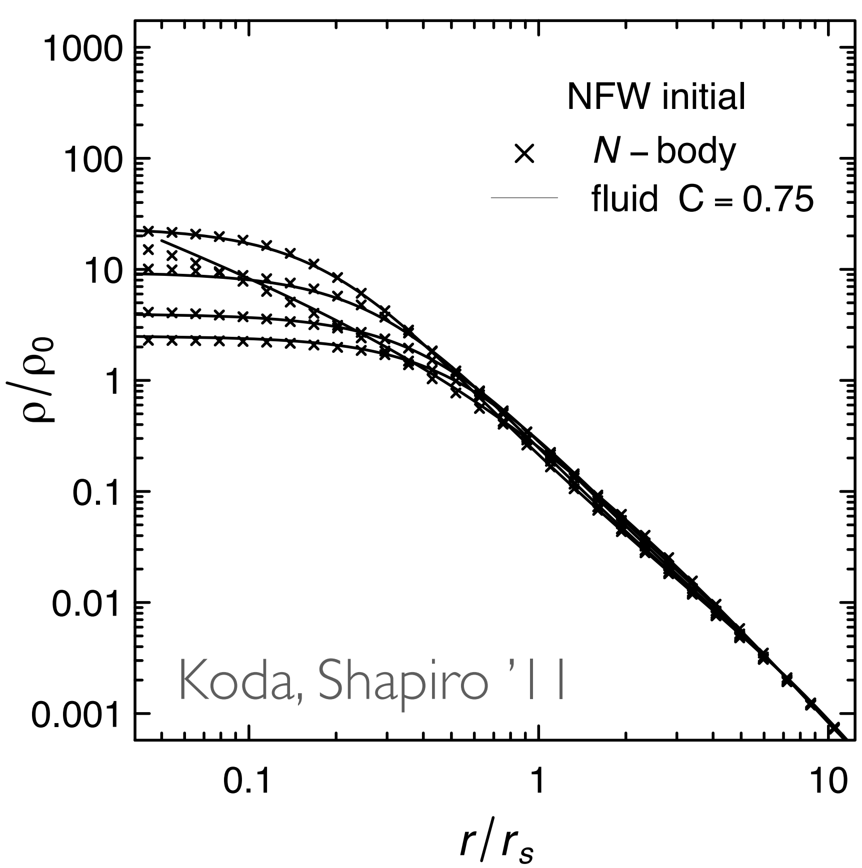
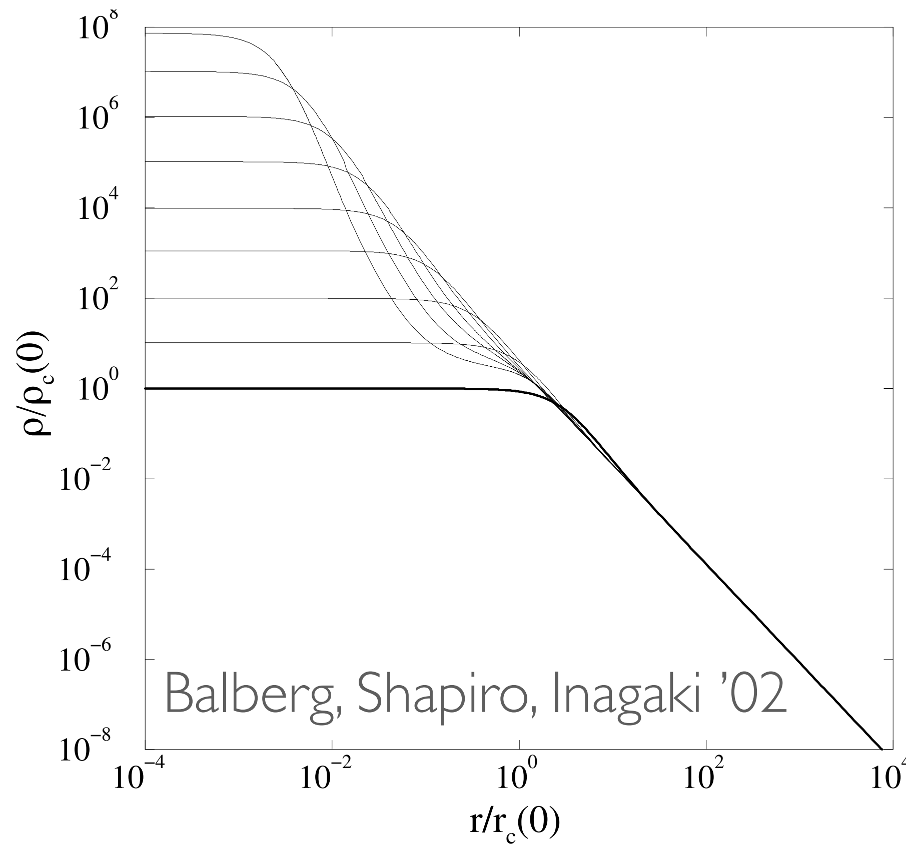
After $\sim \tau_{\rm r}$: core formation



After $\sim 100\tau_{\rm r}$: collapse into BH



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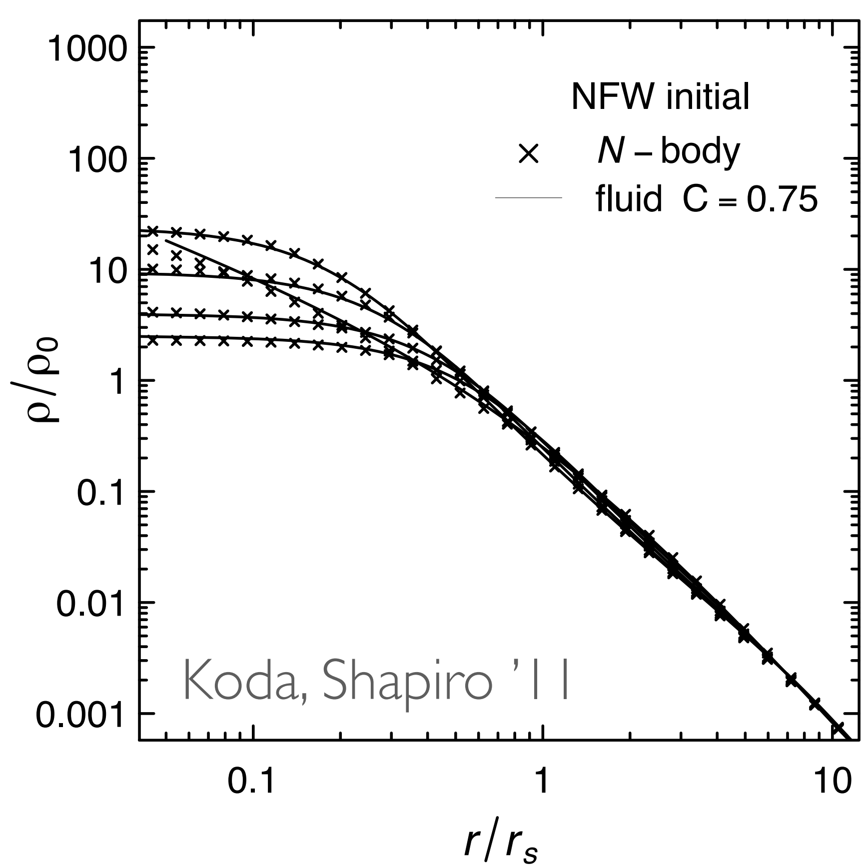

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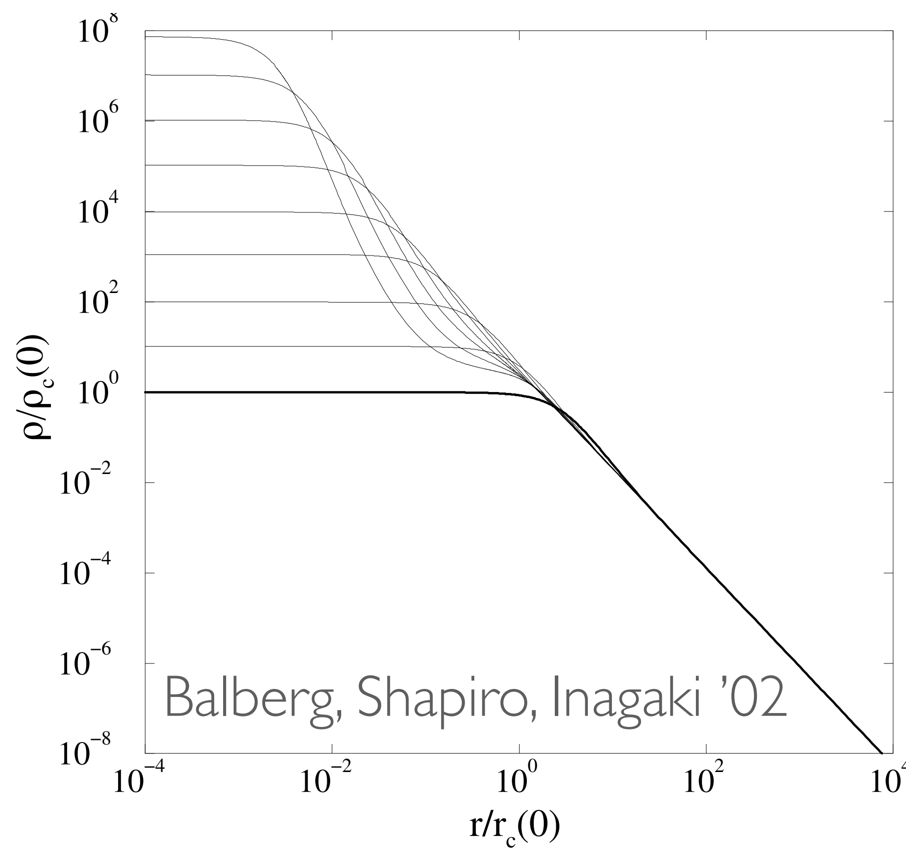


SIDM may solve core-cusp problem, but does not form BHs

OUTLINE

1. Gravothermal catastrophe
2. PBHs from gravothermal catastrophe
3. Toy model

GRAVOTHERMAL CATASTROPHE DURING EARLY MATTER DOMINATION

- Consider an early universe epoch dominated by non-relativistic particles (e.g. inflaton, modulus, but not DM), which eventually decay and reheat the universe
- If this epoch lasts long enough ($a_f/a_i > 10^5$), halos form
- If the particles have self-interactions, halos undergo gravothermal collapse into BHs

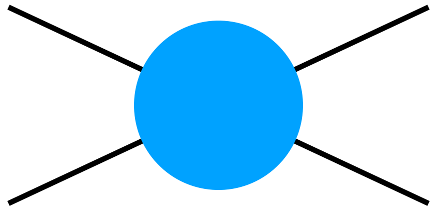
SPECIFIC FEATURES

- Halos from early matter domination are dense:
  $\rho_s \propto \bar{\rho} c^3$ with $c \sim 30$ Zhao, Jing, Mo, Boerner '09

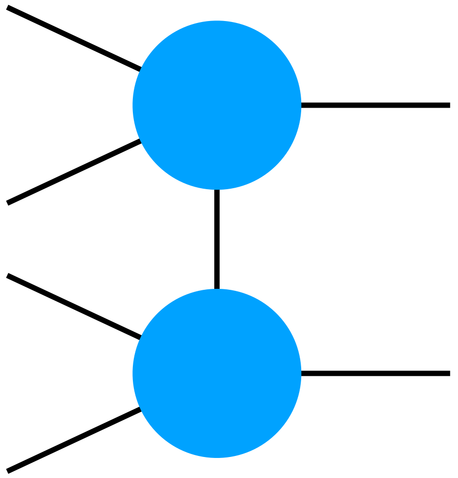
- Combination with a long early matter domination prompts gravothermal evolution

- But it's not just BHs forming (cannibalism & condensation)

CANNIBALISM



2→2 scattering



4→2 annihilation

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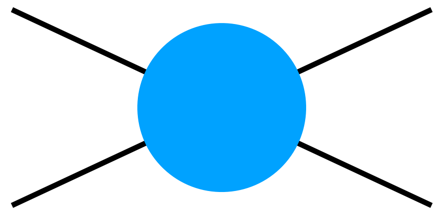

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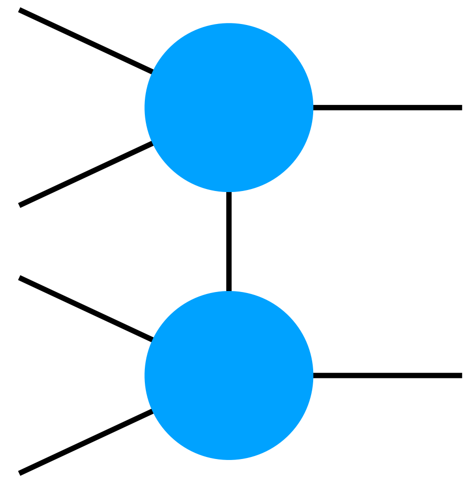
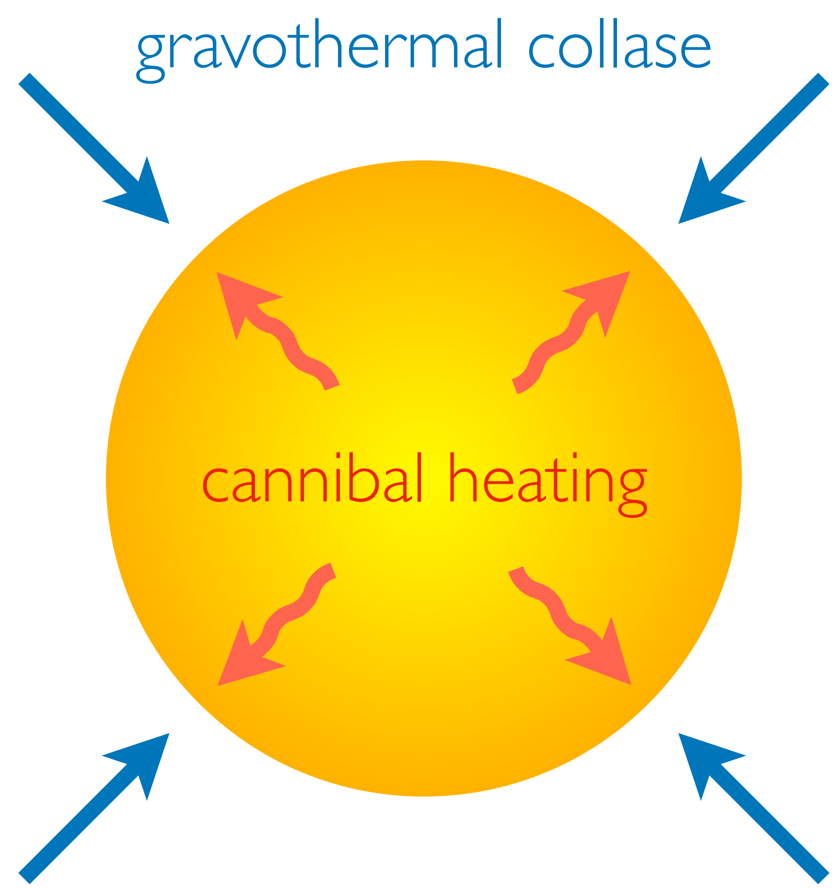


4→2 annihilation

Number-changing process produces heat, which can stop the collapse and form a cannibal star



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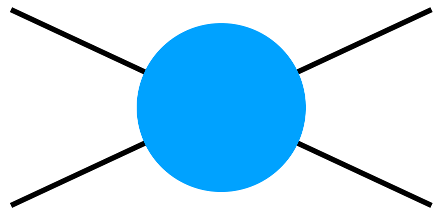

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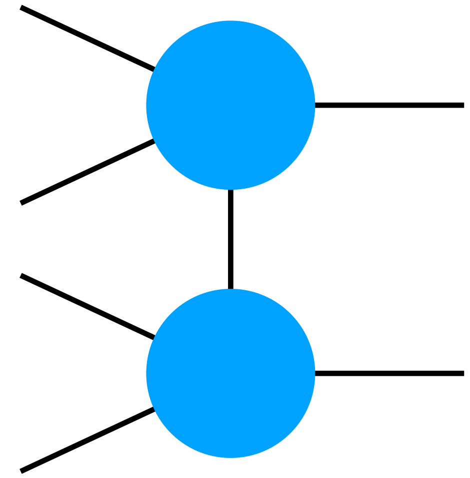

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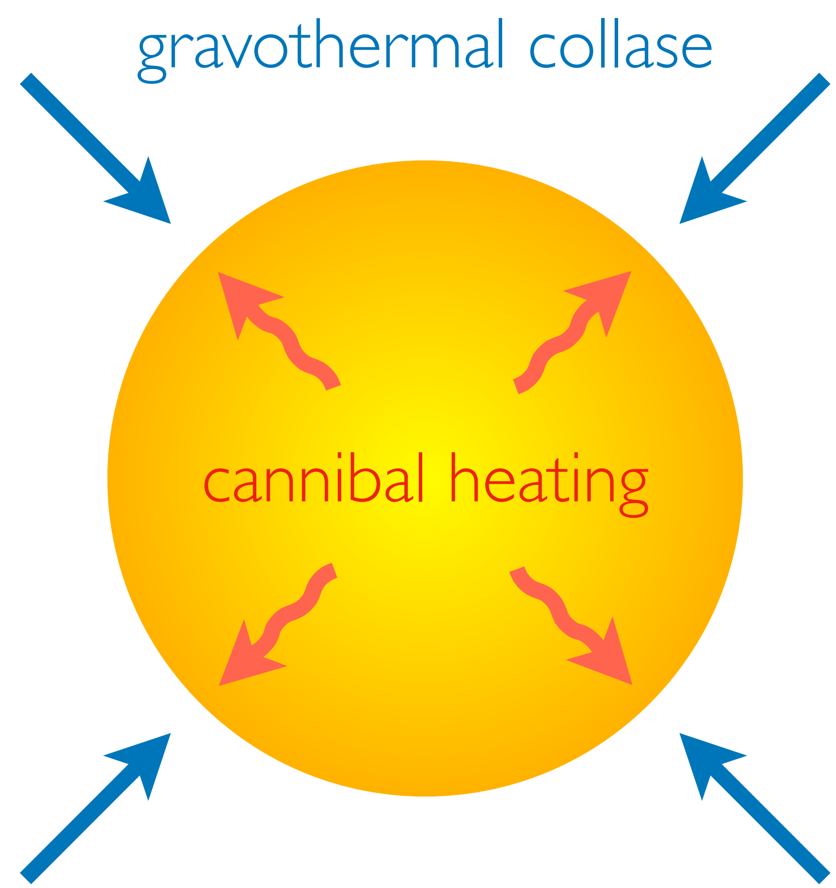

* Cannibal annihilations can be switched off
if the particles carry charge,
e.g. complex scalar with global U(1)

CONDENSATION

If the particles are bosons, a BEC forms when $\lambda_{\mathrm{dB}} \sim n^{-1/3}$

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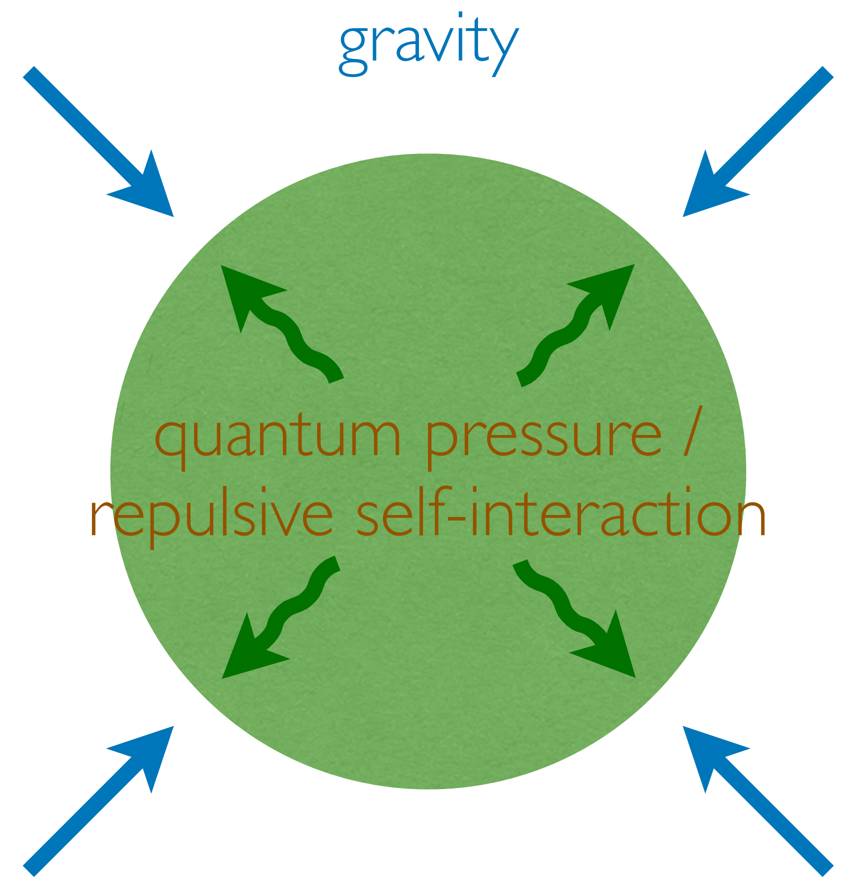
The condensed core can continue to contract, and turn into a boson star supported by quantum pressure and/or self-interaction



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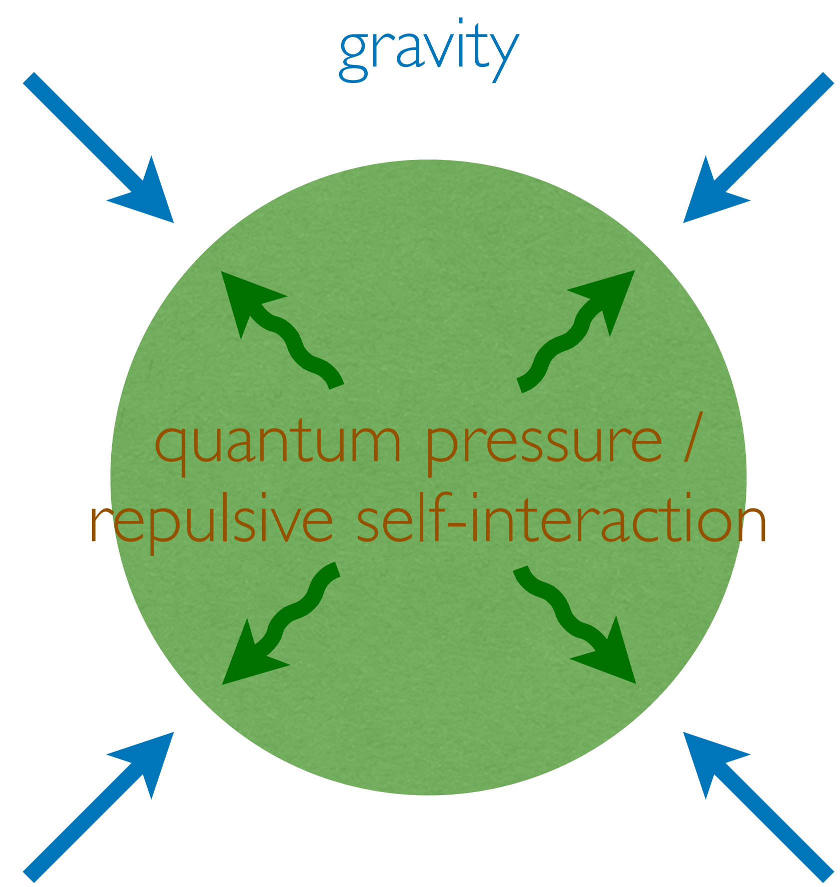


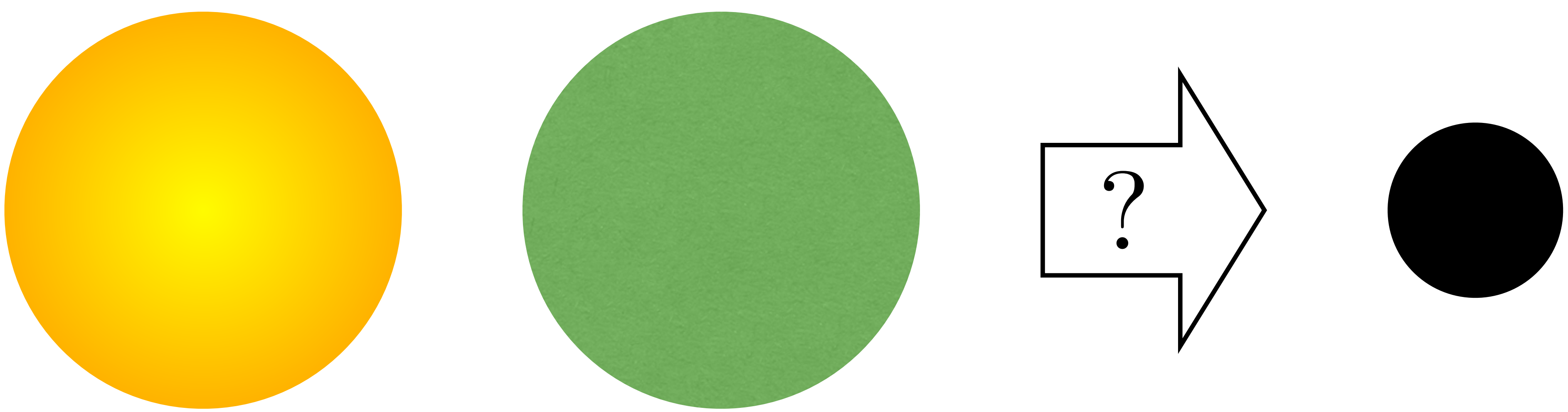
* Boson stars with attractive self-interactions can end up in a bosenova

Levkov, Panin, Tkachev '17

FATE OF STARS

- Cannibal and boson stars can grow with gravothermal accretion, and eventually collapse into BHs

- Otherwise they disappear at the end of matter domination as the particles decay



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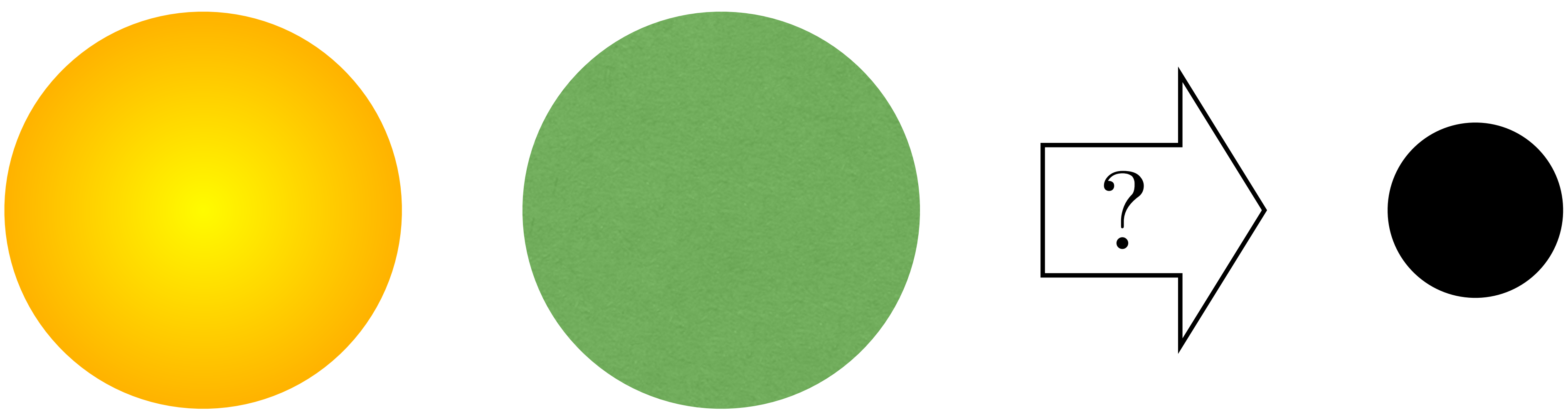


How effective is the accretion?

ACCRETION

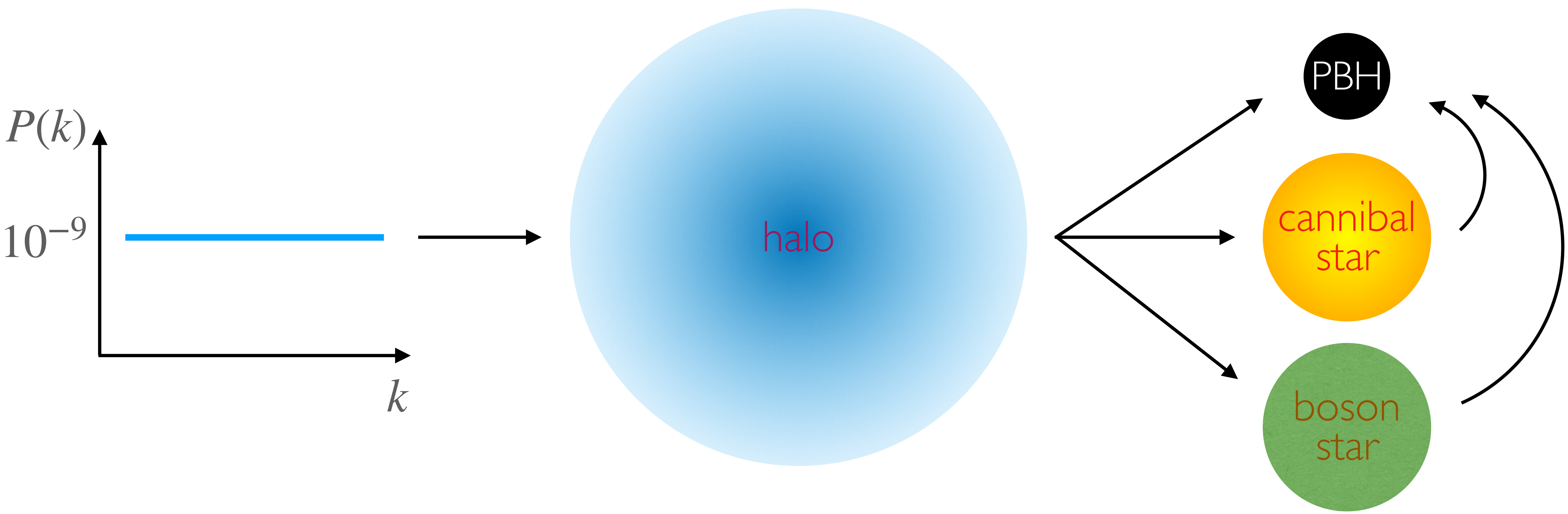
- The mass fraction of the halo that ends up in a BH is highly uncertain

- It can lie between $10^{-16} \lesssim M_{\rm BH}/M_{\rm halo} \lesssim 10^{-3}$, with the upper limit set by energy conservation*

- We treat this fraction as a free parameter

* Lower limit from the minimum mass in short mean free path regime.
Upper limit can change with Bondi accretion.

OVERALL PICTURE



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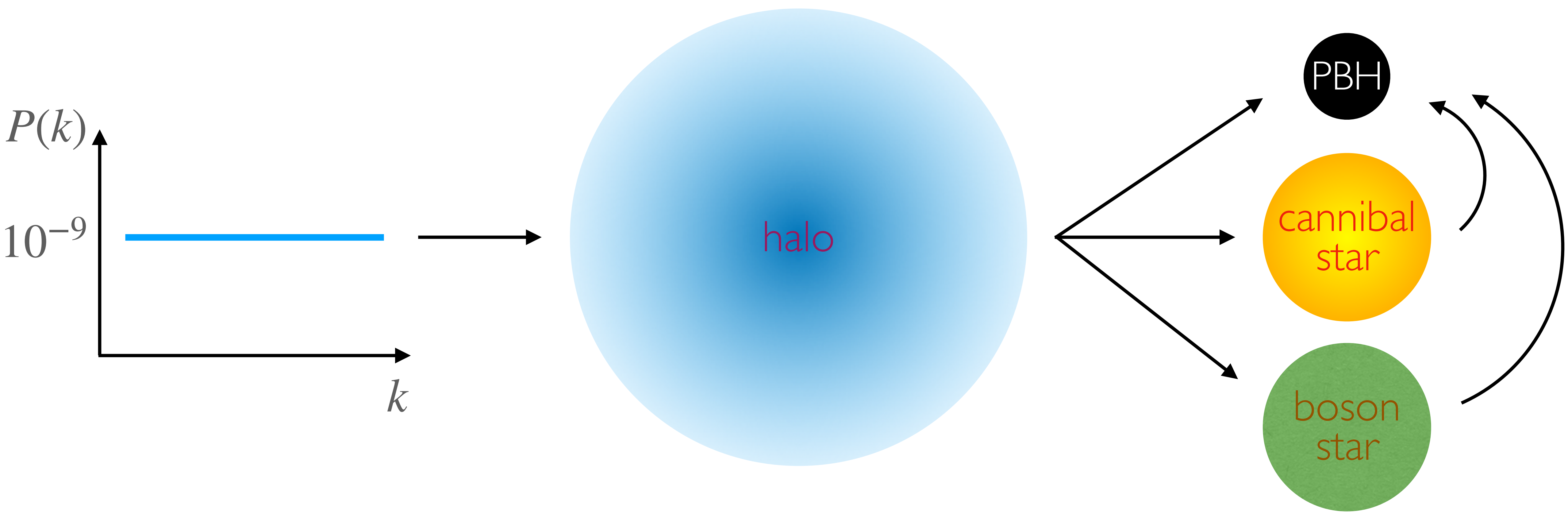

technical specifications:

- halo abundance estimate with Press-Schechter (ignore subhalo collapse)
- gravothermal evolution: $\rho_c \propto r_c^{-\alpha}$ with $\alpha \approx 2.2 \to 2.5$
- star formation thresholds can be estimated
- star evolution requires some guesswork

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EARLY MATTER DOMINATION (EMD) SCALAR TOY MODEL

$$L = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4 + \text{(coupling to SM)}$$

$$(\lambda > 0)$$

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Thermally distributed ϕ dominates the early universe:

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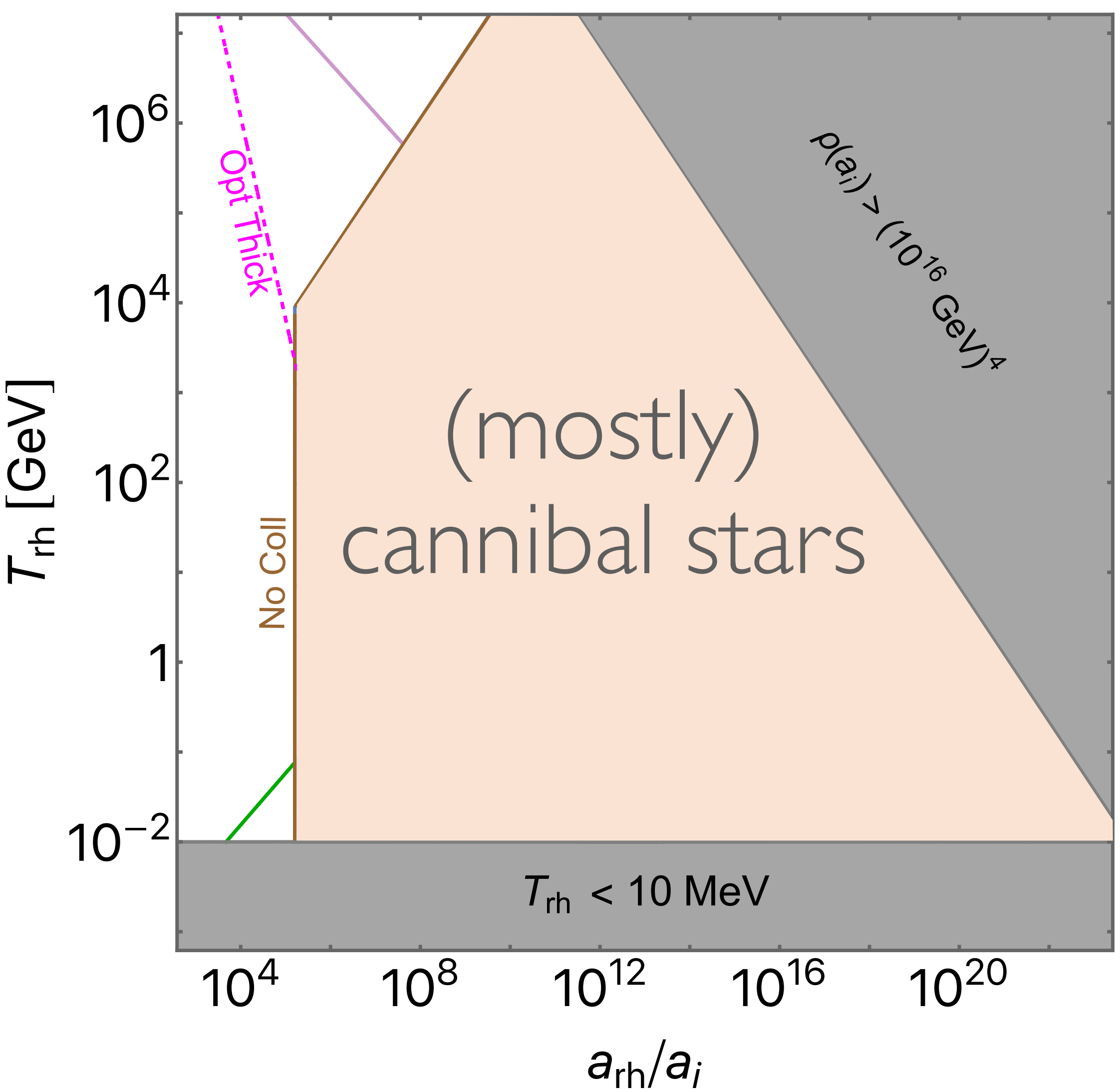
free parameters: $\{m,\ \Gamma,\ \lambda\}$

or $\{a_{\mathrm{rh}}/a_{\mathrm{i}},\ T_{\mathrm{rh}},\ \tau_{\mathrm{relax}}\}$

NEGLIGIBLE ACCRETION

PBHs produced only from direct collapse of halo core

$\lambda = 1$



NEGLIGIBLE ACCRETION

PBHs produced only from direct collapse of halo core

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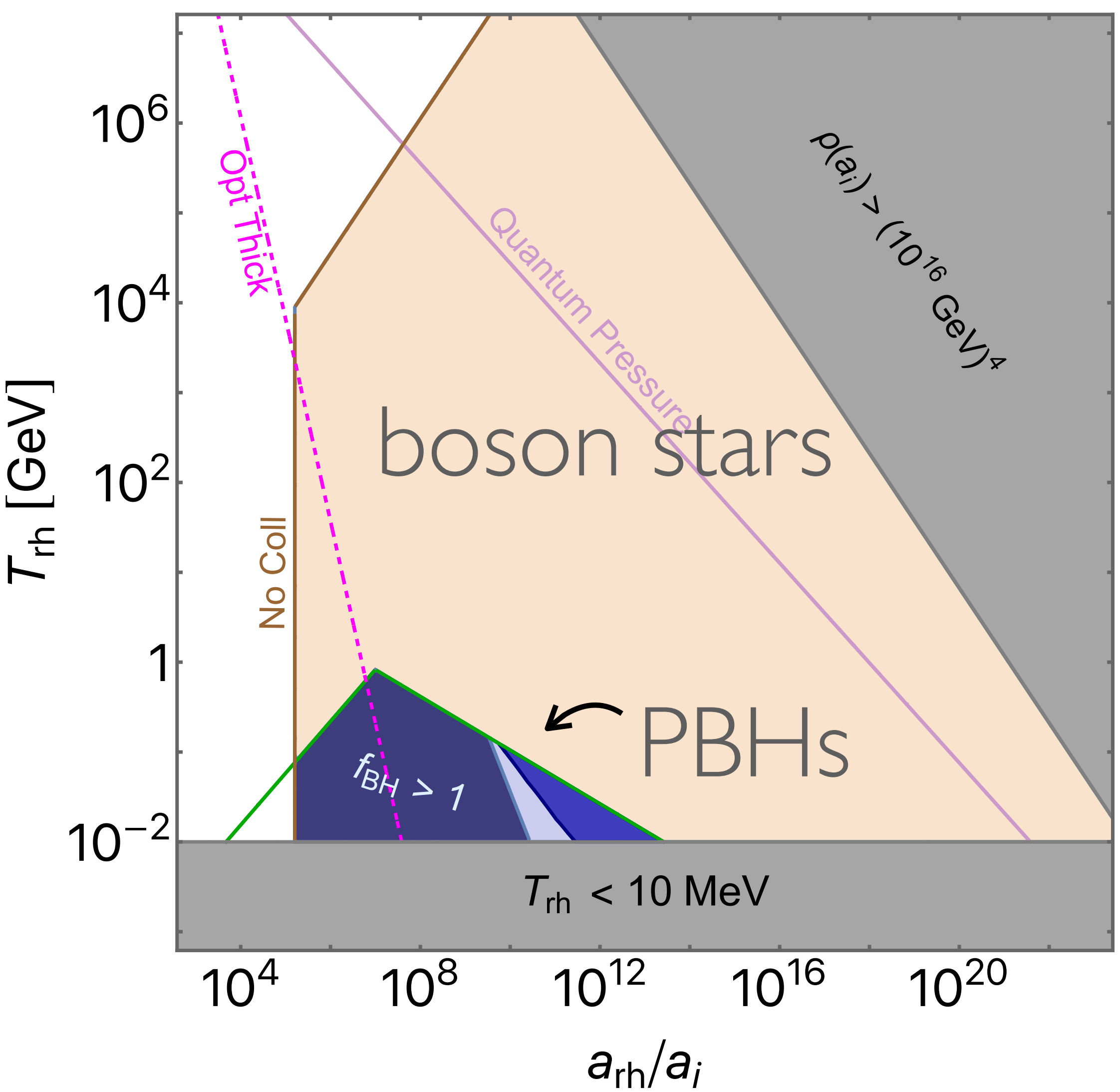

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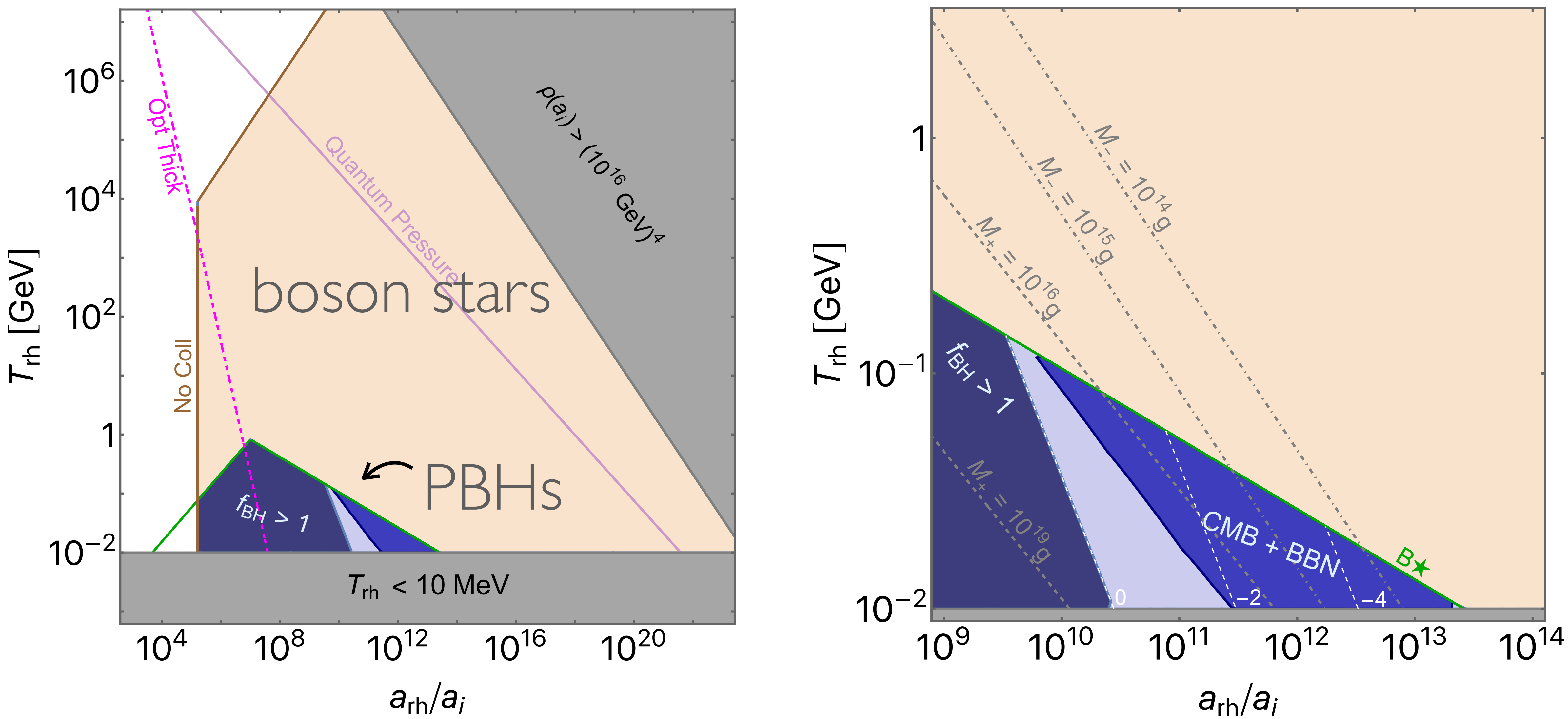

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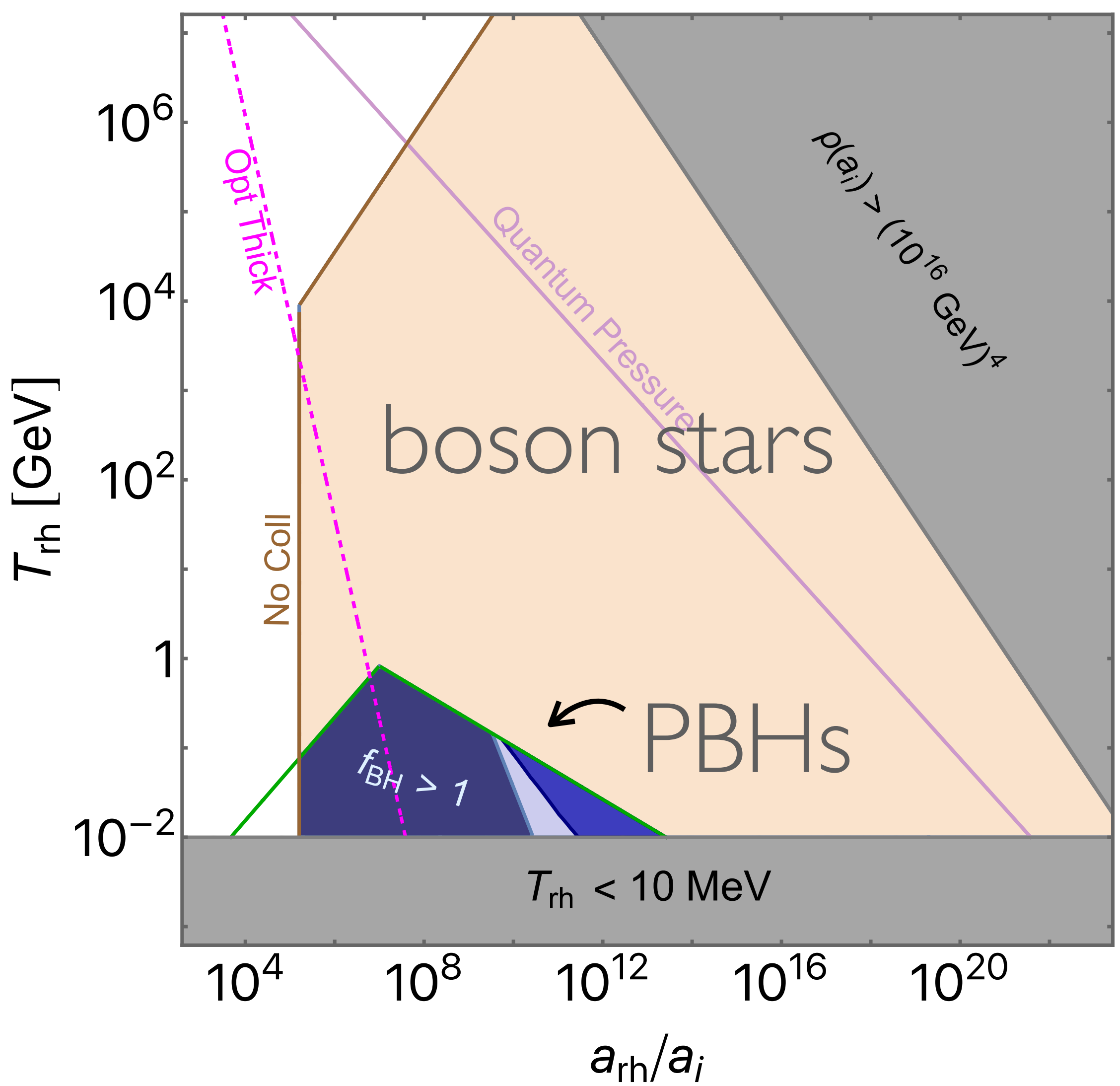

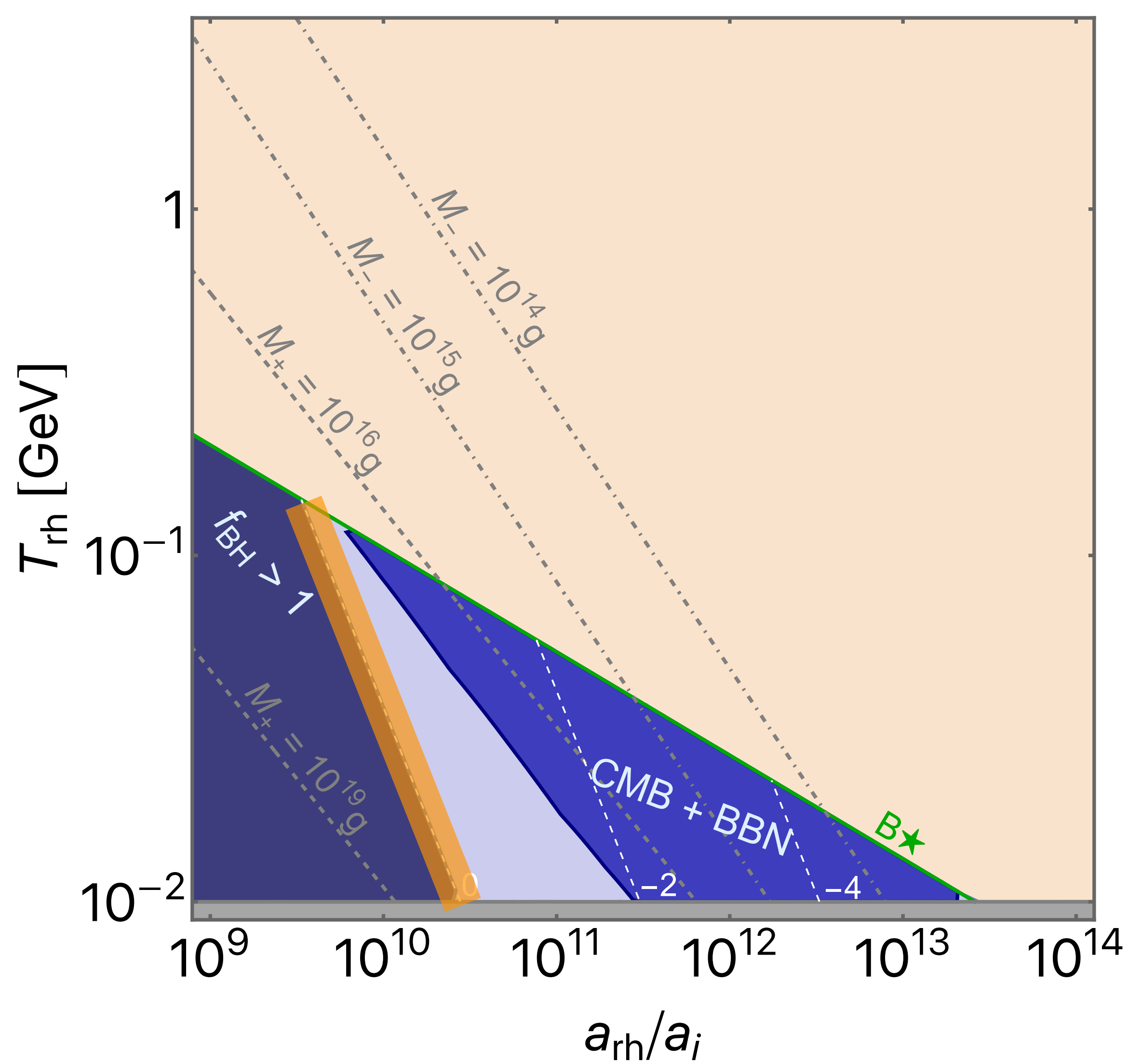

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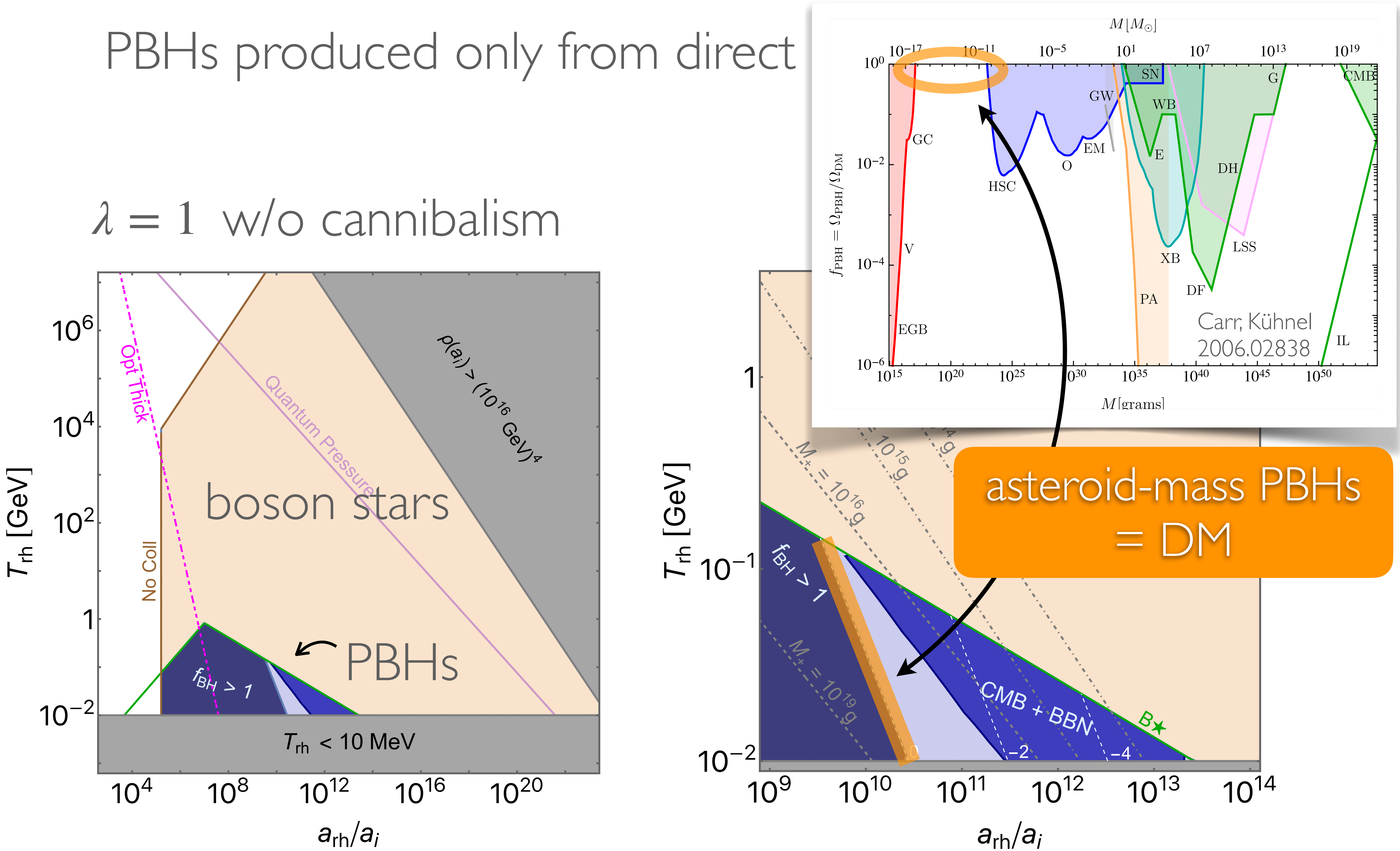
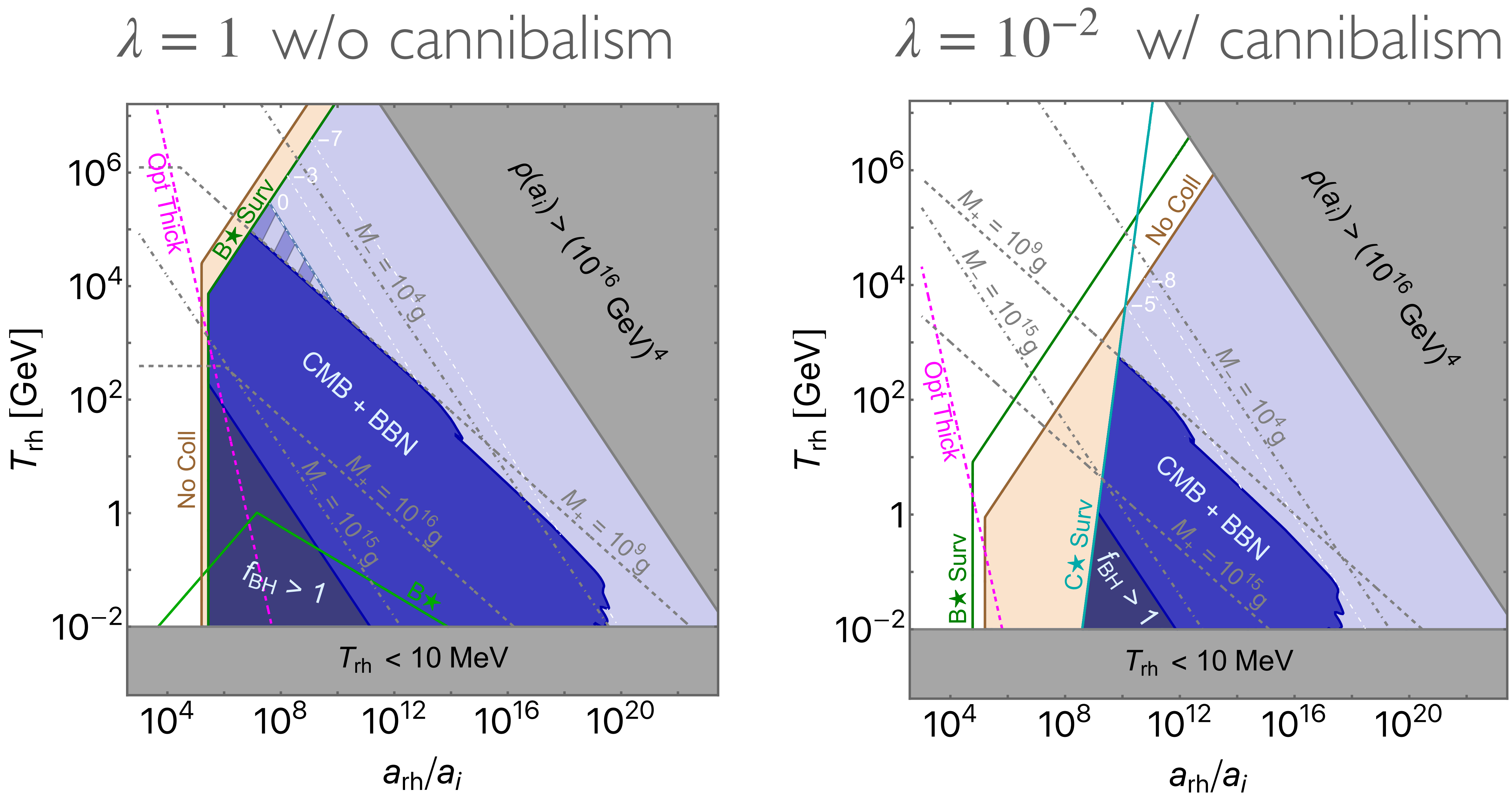


MAXIMAL ACCRETION $(M_{\rm BH}/M_{\rm halo} \sim 10^{-3})$

PBHs produced from direct collapse of halo core, and from collapse of cannibal/boson stars



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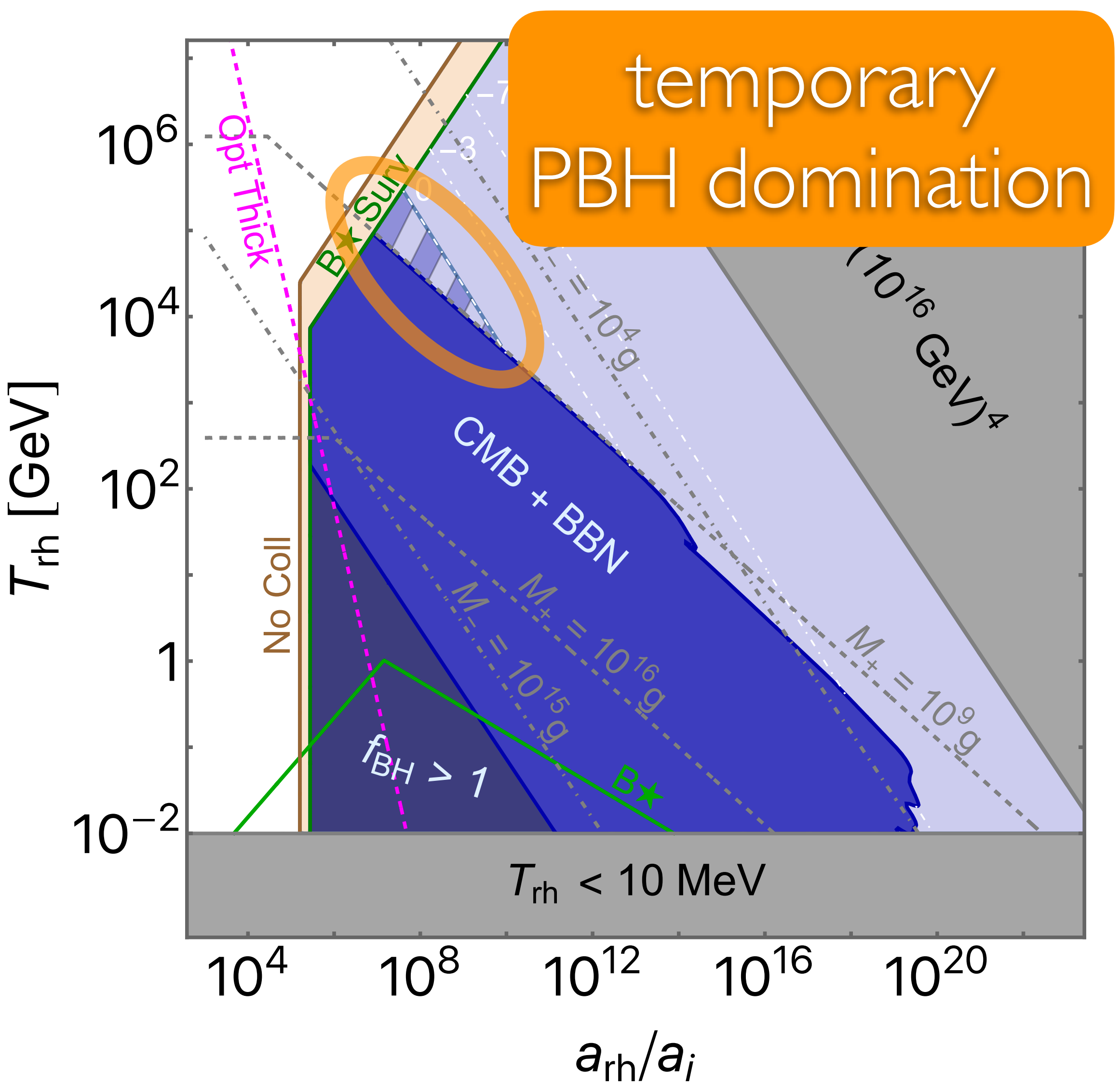
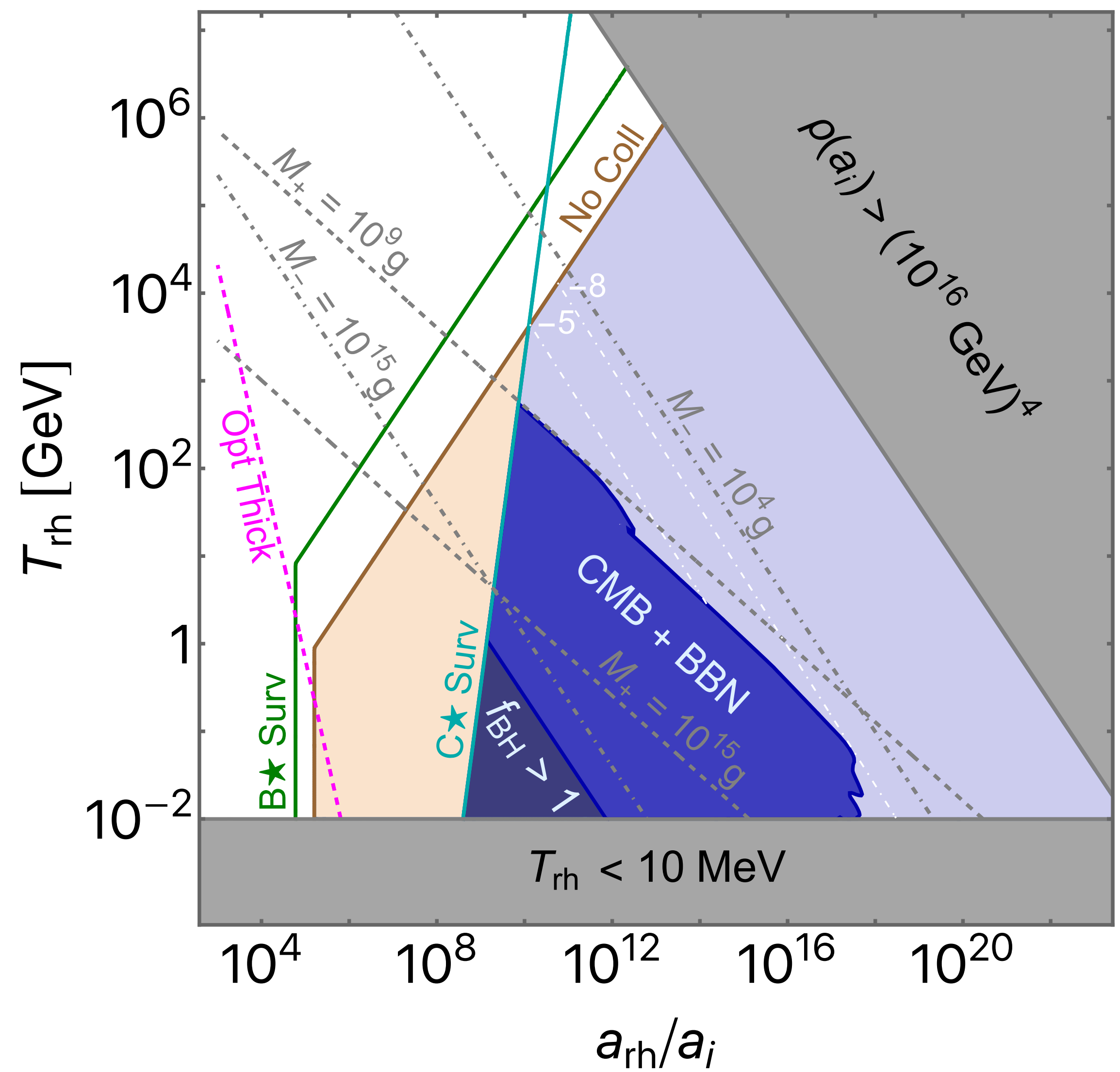


$\lambda = 10^{-2}$ w/ cannibalism



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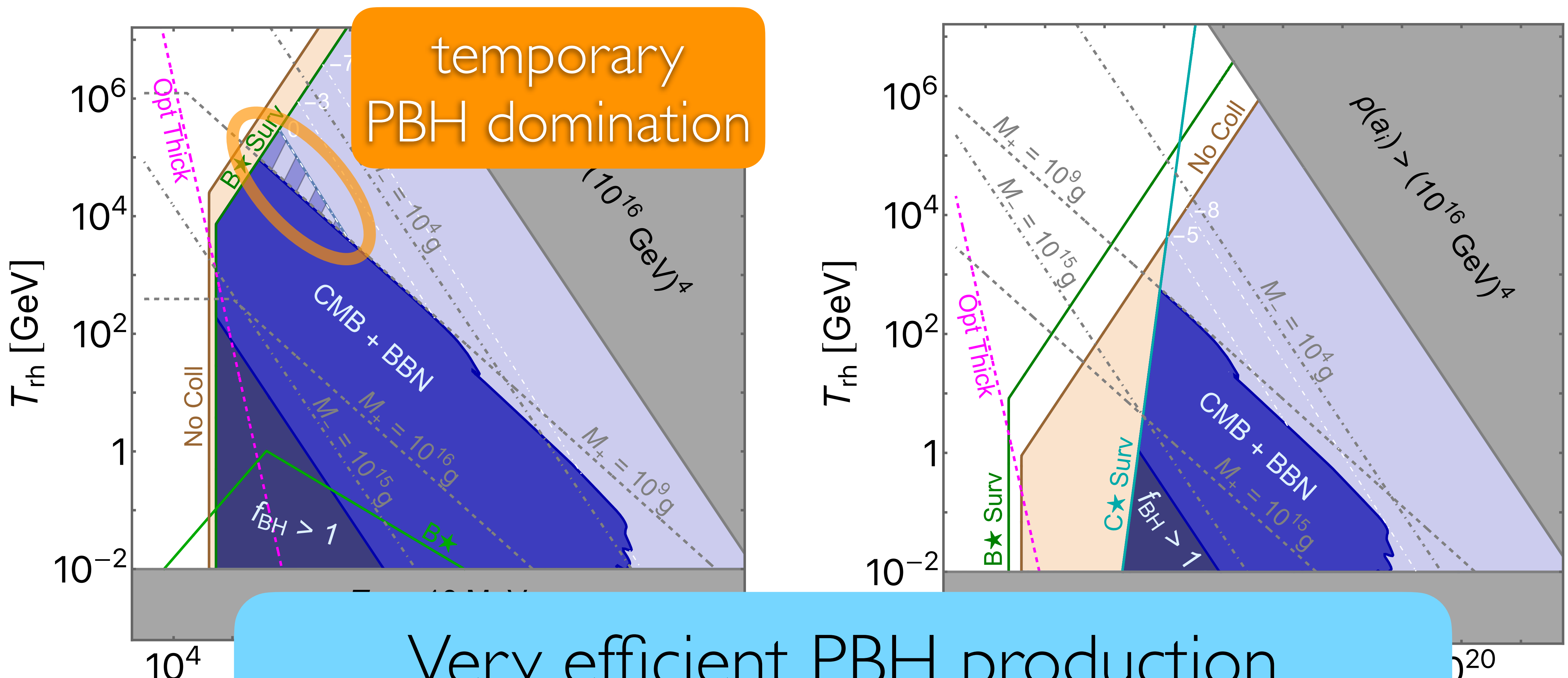


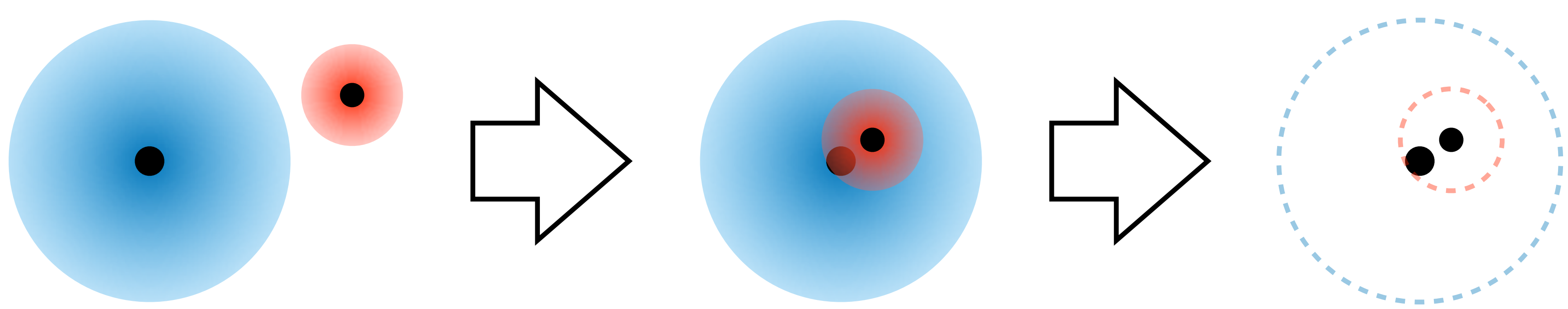
Very efficient PBH production
(can also be used to probe EMD)

SUMMARY

- Gravothermal effects during early matter domination produces PBHs (e.g. asteroid-mass range), and boson/cannibal stars

- Relic PBHs can be used to probe early matter domination, e.g. reheating epoch

- Formation of PBH binaries?



- Extremely rich astrophysics emerges from simple particle models during early matter domination, and we've just seen the tip of the iceberg

BACKUP SLIDES

BBN & CMB CONSTRAINTS