Efficiency of Primordial Black Hole Evaporation into Dark Matter

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Based on C. Kolda, M. Kwok[1], BZ (to appear)

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Overarching question

Can evaporating primordial black holes (PBHs) make a substantial fraction — or even all — of today's cold dark matter, assuming a WIMP-like dark matter particle?

- PBHs emit into **all kinematically allowed states**, even if those states couple only very weakly to the Standard Model.
- That makes PBHs an attractive **non-thermal engine** for dark-matter production.
- But the same fact creates the bottleneck: emission into any *one* final state is usually only a small fraction of the total PBH energy budget.

Previous work: PBH evaporation and dark matter

- Green, Anne M. "Supersymmetry and primordial black hole abundance constraints." Physical Review D 60.6 (1999): 063516.
- Allahverdi, Rouzbeh, James Dent, and Jacek Osinski. "Nonthermal production of dark matter from primordial black holes." Physical Review D 97.5 (2018): 055013.
- Lennon, Olivier, et al. "Black hole genesis of dark matter." Journal of Cosmology and Astroparticle Physics 2018.04 (2018): 009-009.
- Hooper, Dan, Gordan Krnjaic, and Samuel D. McDermott. "Dark radiation and superheavy dark matter from black hole domination." Journal of High Energy Physics 2019.8 (2019): 1.
- Morrison, Logan, Stefano Profumo, and Yan Yu. "Melanopogenesis: Dark Matter of (almost) any Mass and Baryonic Matter from the Evaporation of Primordial Black Holes weighing a Ton (or less)." Journal of Cosmology and Astroparticle Physics 2019.05 (2019): 005-005.
- Masina, Isabella. "Dark matter and dark radiation from evaporating primordial black holes." The European Physical Journal Plus 135.7 (2020): 1-27.
- Baker, Michael J., and Andrea Thamm. "Black hole evaporation beyond the Standard Model of particle physics." Journal of High Energy Physics 2023.1 (2023): 63.

Where this talk fits

This work extends the PBH-evaporation dark matter program by including the full heavy SUSY spectrum, scalar-enhanced emission, and cascade decays into the final LSP.

Minimal SUSY as a model dark sector

Useful intuition

The goal is to determine how much of the initial PBH mass ends up in the final dark-matter population, rather than being lost to Standard Model particles or excess kinetic energy.

Beyond the usual simplified picture

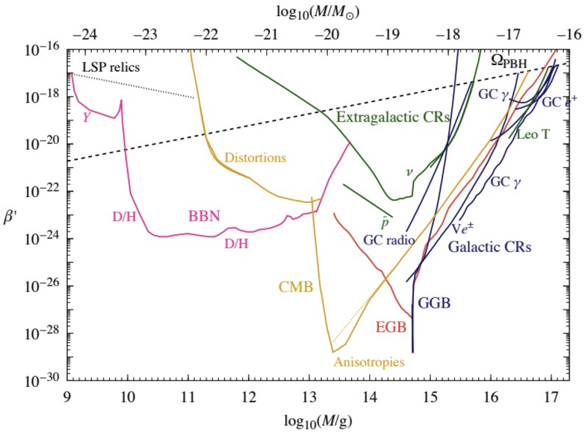
- Go beyond treating dark matter as a single isolated particle species
- Include the **full heavy SUSY sector** and cascade decays to the LSP
- Improve the treatment of **massive-particle emission** from PBHs
- Track the role of **scalar-rich spectra** and greybody effects near threshold

Working idea

If dark matter lives inside a larger SUSY-like sector, the final DM yield can be much larger than in a single-particle dark-matter model.

Why revisit the standard claim?

The commonly quoted bound says PBHs cannot make enough weak-scale SUSY dark matter without an early PBH-dominated era. This talk checks whether that conclusion survives more realistic assumptions, and allows for extension to more general dark sectors.



Carr, Bernard, et al. "Constraints on primordial black holes." Reports on Progress in Physics 84.11 (2021): 116902.

Our assumptions

- Very little DM produced by freeze-out/freeze-in.
- All/most DM are from PBH decay.
- PBH mass function narrowly peaked around some intitial $M_{\rm BH}$.
- Ignoring question of memory burden in BH decays.
- All "dark sector"/ SUSY states except DM are degenerate.
- Heavy dark states decay to SM particles + 1 LSP/DM particle (e.g., R-parity).
- PBHs never dominate universe's energy density.

How the calculation works

- Inputs:

$$\left.\begin{aligned} M_{\rm BH} &= \text{initial PBH mass}, \\ m_{\rm DM} &= \text{DM (or LSP) mass} \\ m_{\rm heavy} &= \text{mass of rest of SUSY states} \end{aligned}\right\} \quad \alpha = \text{compression} \equiv \frac{m_{\rm DM}}{m_{\rm heavy}} \leq 1.$$

- Start from Hawking emission from a PBH of a given initial mass.
- Compute how many heavy SUSY states and LSPs are emitted over the black hole lifetime.
- Convert that into a dark matter production efficiency η: how much of the PBH mass ends up in dark matter mass.
- Compare our derived semi-analytic approximation directly to a modified `BlackHawk` calculation.

Output

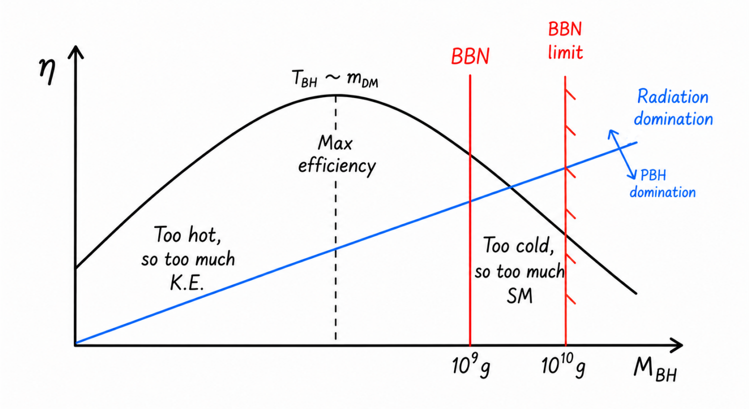
Two questions matter in the end: **Can PBHs make enough dark matter?** and **Can they do it without disrupting the ΛCDM cosmology, i.e., without requiring an early matter domination?**

Dark-matter production efficiency

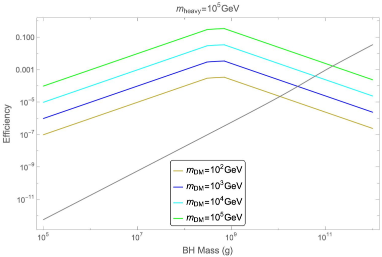
We define the efficiency η of the production of DM particles of mass $m_{\rm DM}$ by a PBH of mass $M_{\rm BH}$ as

$$\eta \equiv \frac{N_{\rm DM}\, m_{\rm DM}}{M_{\rm BH}},$$

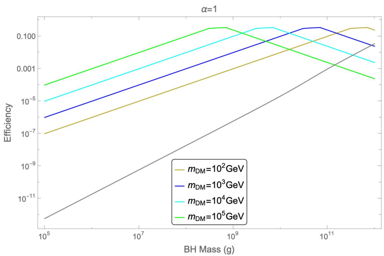
where $N_{\rm DM}$ is the total number of DM particles produced by the PBH.



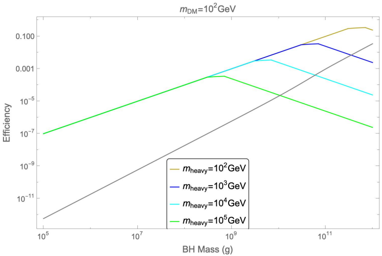
Dark-matter production efficiency



Fixed heavy-state mass
colored curves vary $m_{\rm DM}$



Fixed compression
colored curves vary the mass scale



Fixed dark-matter mass
colored curves vary $m_{\rm heavy}$

- The gray curve is the minimum efficiency needed to avoid an early PBH-dominated era.
- Colored curves above the gray curve are potentially viable before applying the full BBN constraints.

Main takeaway

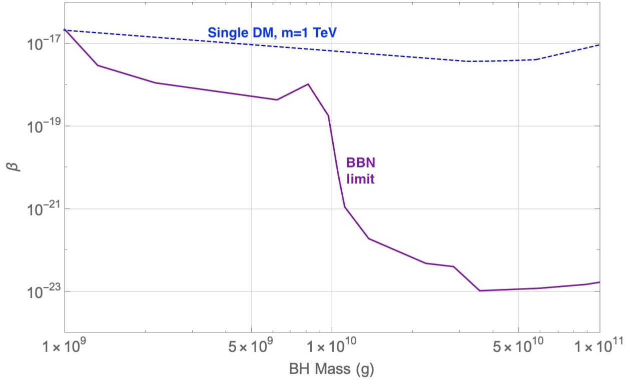
Heavy SUSY states and cascade decays can substantially increase the final LSP yield to avoid an early PBH-dominated era, especially when the PBH temperature is well matched to the SUSY mass scale.

Zooming in on BBN constraints

PBH mass fraction at formation time t_{f}: t_{f} as $\beta \equiv \rho_{\mathrm{PBH}}(t_{\mathrm{f}})/\rho_{\mathrm{R}}(t_{\mathrm{f}})$.

What the figure shows

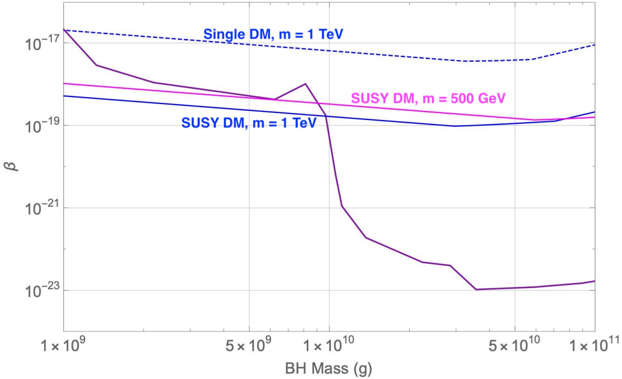
- The region above BBN limit is ruled out.
- Single-particle dark matter is strongly constrained.



Zooming in on BBN constraints

What the figure shows

- The region above BBN limit is ruled out.
- Single-particle dark matter is strongly constrained.
- A SUSY-like spectrum lowers the PBH abundance needed to match the relic density.



Representative result

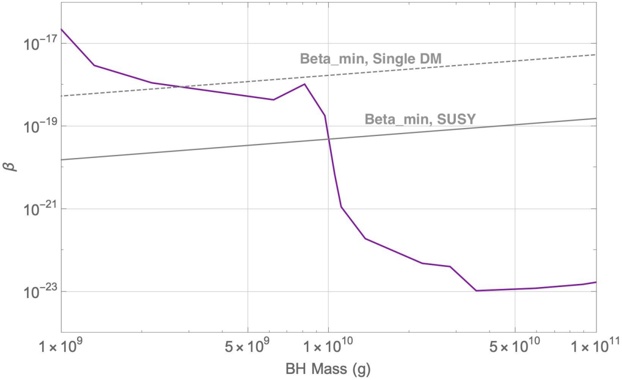
For $\alpha \sim 1$, PBHs up to about 10^{10} g can produce LSP dark matter down to roughly 500 GeV while remaining BBN-safe and avoiding an early PBH-dominated era.

Zooming in on BBN constraints

The minimum values of β required to produce all of the cold DM for a given PBH mass $M_{\rm BH}$ regardless of DM mass:

$$\beta_{\text{min}}^{\text{Single DM}}(M_{\rm BH}) \approx 1.72\times10^{-23}\left(\frac{M_{\rm BH}}{\rm g}\right)^{\frac{1}{2}};$$

$$\beta_{\text{min}}^{\rm SUSY}(M_{\rm BH}) \approx 4.93\times10^{-25}\left(\frac{M_{\rm BH}}{\rm g}\right)^{\frac{1}{2}}.$$



Take-home messages and outlook

Take-home messages

- PBHs remain viable **non-thermal sources** of weak-scale dark matter.
- Realistic heavy spectra and scalar-rich sectors can substantially increase the final DM yield.
- Once these effects are included, viable SUSY parameter space remains after cosmological constraints are applied.

Outlook

The next step is to extend this picture beyond the MSSM toward broader hidden-sector spectra and PBH formation scenarios tied to the same mass scale that makes evaporation efficient.

Thank you!