

12th Workshop on Flavor Symmetries and Consequences in
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Primordial Black Hole Hotspots Beyond Flat Spacetime

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Light primordial black holes evaporate

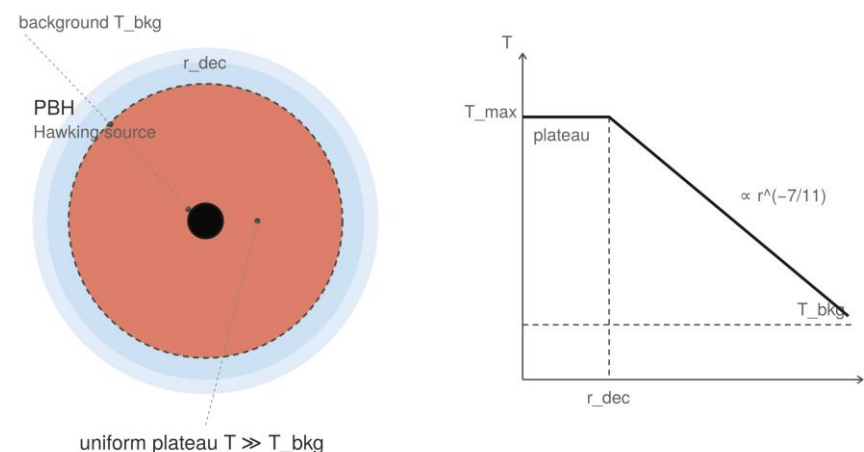
- Primordial black holes (PBHs): black holes **formed in the early universe**, spanning a huge mass range.
- Sufficiently light PBHs ($M \lesssim 10^9 \text{ g}$) **evaporate before BBN**, with a lifetime that grows as

$$t_{\text{ev}} \sim \frac{M^3}{M_{\text{Pl}}^4}$$

- Evaporation dumps **high-energy particles** into the surrounding plasma.
- Why it matters: a clean probe of the early universe, with implications for **dark matter** and **baryogenesis**.
- *One PBH = a tiny, intense, transient particle source.*

A PBH heats its neighborhood: a “hotspot”

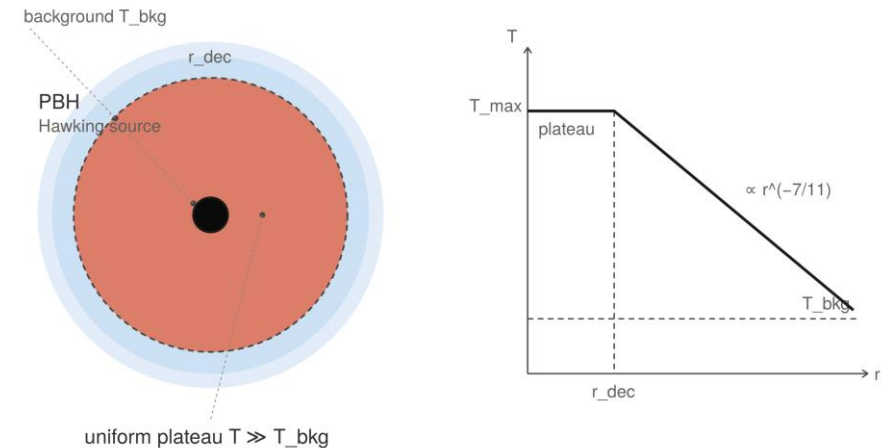
- The emitted particles deposit energy in the plasma **faster than it diffuses away**.
- Result: a localized region **far hotter** than the cosmological background — a **hotspot**.
- Inside, the temperature can cross thresholds for
 - sphaleron / leptogenesis processes,
 - dark-matter thermalization,
 - symmetry restoration.
- $\Rightarrow$ hotspots can **modify early-universe observables**.



Studied so far by Das & Hook; Kohri et al.; Gunn et al. ($\sim 2021\text{--}2024$).

The hotspot has a characteristic shape

- Energy transport in the plasma → treated as **diffusion**.
- During evaporation a quasi-steady profile forms:
 - a flat central **plateau**,
 - a power-law envelope $T \propto r^{-7/11}$.
- **Decoupling radius r_{dec}** : the farthest distance diffusion can reach within the PBH lifetime.



Does the expansion matter?

- A hotspot is far smaller than the Hubble radius — so naively, expansion looks irrelevant.
 - Critical scale where Hubble overtakes diffusion: $R_H = \sqrt{\frac{\lambda_\nu}{H}}$
 - During radiation domination this coincides exactly with r_{dec} : the expansion boundary is the decoupling radius
- ⇒ Cosmic expansion is not a priori negligible. Does it change the picture?

Formation is robust against expansion

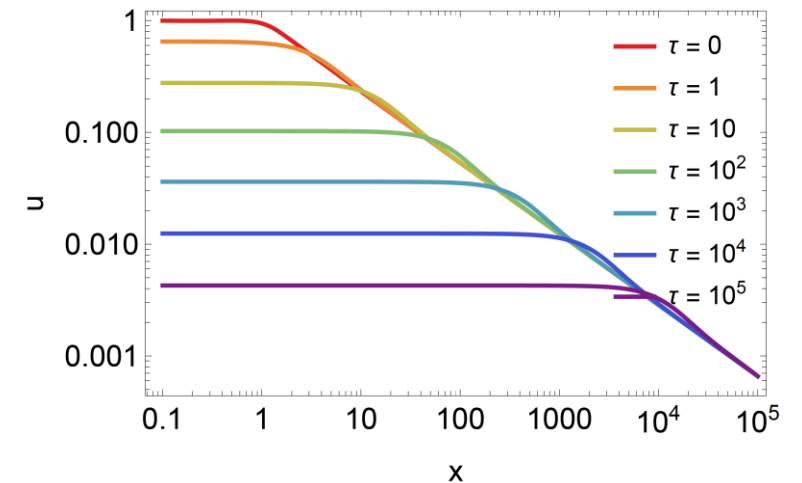
- A light PBH's **lifetime is itself a Hubble time**: $\tau_{\text{PBH}} \simeq t_{\text{ev}} \sim H^{-1}(t_{\text{ev}})$
- It forms and cools over this timescale — does the profile redshift away?
- The envelope $T \propto r^{-7/11}$ is **essentially unchanged**, because the energy injection rate grows as $1/M^2$, the hot inner profile forms only at the **very end** of evaporation, so the profile barely redshifts while forming.

Diffusion in an expanding universe

- Flat spacetime (previous work): $\frac{\partial \rho}{\partial t} = \vec{\nabla} \cdot \left(\frac{\lambda v}{3} \vec{\nabla} \rho \right)$
- In an FLRW background: $\frac{\partial \rho}{\partial t} + 4H\rho = \frac{1}{a^2} \vec{\nabla}_c \cdot \left(\frac{\lambda v}{3} \vec{\nabla}_c \rho \right)$
- $4H\rho$ — Hubble dilution: cooling by cosmological redshift.
- $1/a^2$ — expansion weakens diffusion by diluting spatial gradients.
- Valid where particles scatter many times per Hubble time, $v/\lambda \gg H$.
- Diffusion framework (as in all prior work) — advection may dominate instead (Kaiser et al. 2026)

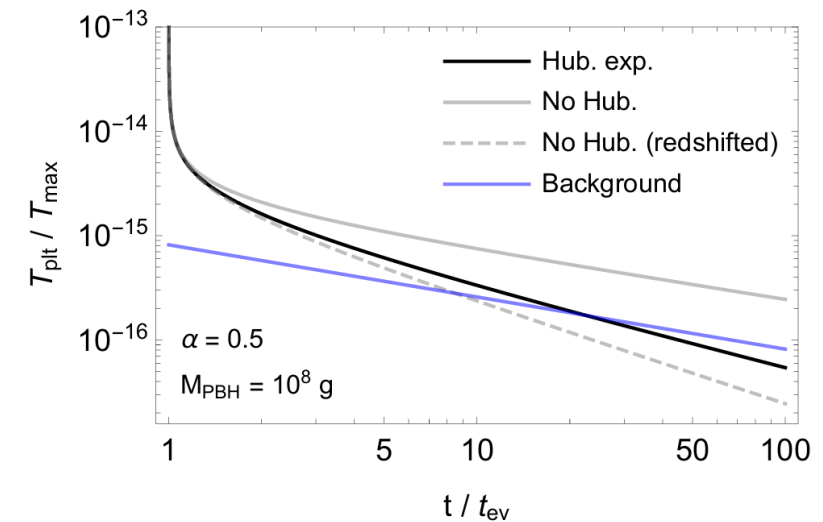
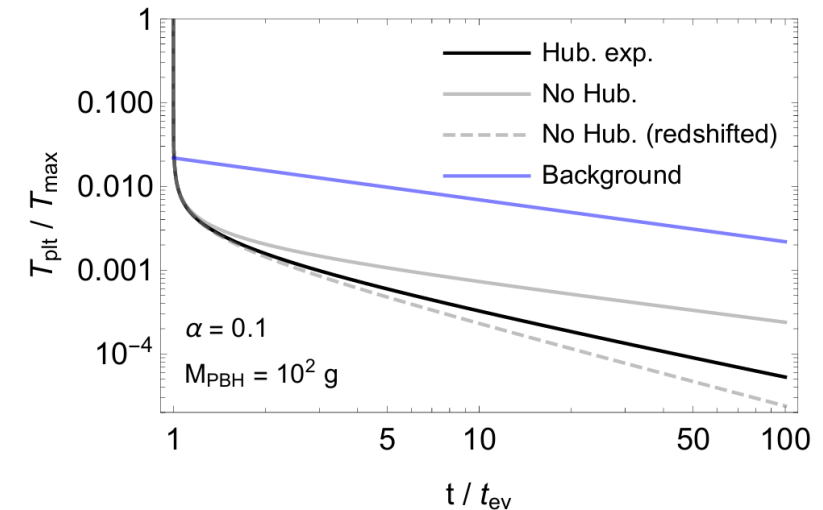
Cooling, after the PBH is gone

- Source switches off $\Rightarrow$ pure **cooling**, governed by the same equation.
- Recast in **dimensionless variables** (u, τ, x): the equation and initial condition become **parameter-independent**.
 $\Rightarrow$ solve **once**; map back to any (M_{PBH}, α) .
- Profiles keep their shape: plateau drops, envelope stays $\propto x^{-7/11}$.



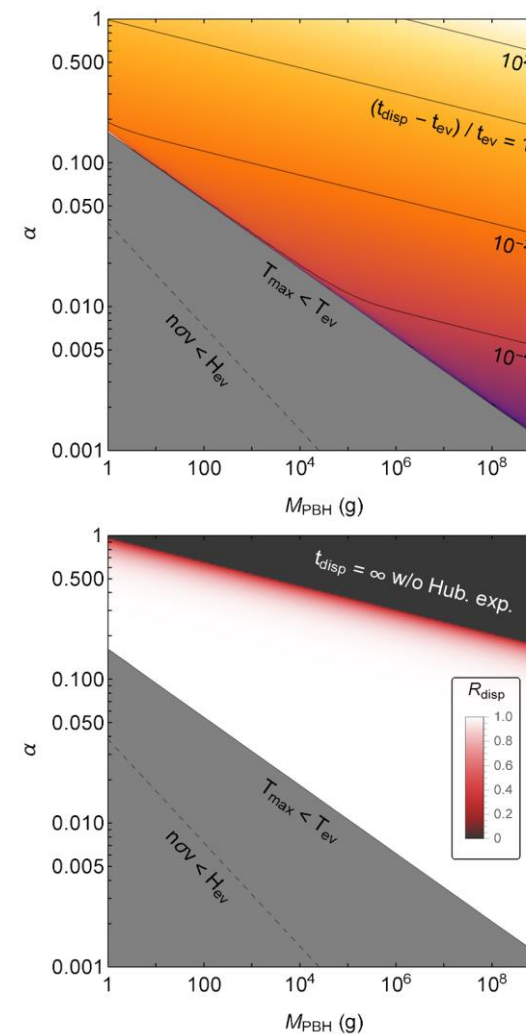
A steeper cooling law: $t^{-11/15}$

- Plateau temperature $T_{\text{plt}}(t)$:
 - a **rapid initial drop** (many orders of magnitude), then
 - a power law $T_{\text{plt}} \propto t^{-11/15}$
- Compare:
 - flat spacetime: $t^{-7/15}$
 - naive redshift of it: $t^{-29/30}$
- However, expansion redshifts and weakens diffusion ($1/a^2$), so you cannot recover it by redshifting a flat solution.



Consequence — every hotspot dies in finite time

- Disappearance time t_{disp} : when T_{plt} falls to the background
 $T_{\text{bkg}} \propto t^{-1/2}$.
- Flat result $t^{-7/15}$ falls **slower** than background
 $\Rightarrow$ some hotspots would survive **forever**.
- Our $t^{-11/15}$ falls **faster** $\Rightarrow$ **every hotspot disappears in finite time**.
- Difference matters mainly for **heavy PBHs + large coupling**.



Observational implications

- No direct detection — the black holes are gone before BBN. Everything is indirect, through what hotspots leave behind.
- Every such yield = a rate integrated over hotspot volume $\times$ lifetime $\rightarrow$ the input is $T(r, t)$ in the expanding universe.
- This work fixes that input — in particular t_{disp} : **finite** for every hotspot, where flat spacetime gave "**never**" for some.
- The rates inside a cooling hotspot, and the actual yields: **future work**.

Summary & outlook

What we did

- Formulated PBH-hotspot diffusion in an **expanding universe** ($4H\rho + 1/a^2$).

What we found

- **Formation robust**: initial profile unchanged.
- **Cooling modified**: $T_{\text{pl}} \propto t^{-11/15}$, finite lifetime — not reproducible by naive redshift.

Outlook

- **Dark hotspots** in a dark sector ($\alpha \rightarrow \alpha_D$).
- Phenomenology for baryogenesis / DM — future work.
- Advection / hydrodynamic transport to be included.

Backup — validity of the diffusion picture

- Diffusion is a coarse-grained account of many random walks. Two checks:
- Mean free path well defined over one scattering — temperature varies slowly on the scattering scale:
$$\mathcal{V} \equiv \frac{1}{\alpha^2 T^2} |\partial_t T + v \partial_r T| \lesssim \mathcal{O}(10^{-2})$$
- Many scatterings per Hubble time: $n\sigma v = v/\lambda > H$.
- In the plateau $n\sigma v \sim \alpha^2 T_{\text{plt}}$, while $T_{\text{bkg}} \sim \sqrt{M_{\text{Pl}} H} \gg H$; so once $n\sigma v > H_{\text{ev}}$ holds at evaporation, it holds until $T_{\text{plt}} = T_{\text{bkg}}$.
- This tests whether diffusion is well defined — not whether diffusion beats advection (next slide).

Backup — Diffusion vs. advection (Péclet number)

- Energy can move by diffusion (random walk) or advection (bulk flow). Compare timescales $t_{\text{diff}} \sim L^2/D$, $t_{\text{adv}} \sim L/v$:
$$\text{Pe} \equiv \frac{vL}{D(T)}, \quad D(T) \sim 1/T. \quad \begin{cases} \text{Pe} \gg 1 & \text{advection wins} \\ \text{Pe} \ll 1 & \text{diffusion wins} \end{cases}$$
- Kaiser et al. (2026) argue **advection dominates** for much of parameter space ($M \lesssim 10^6 \text{ g}$, $T_{\text{H}} \gtrsim 10^7 \text{ GeV}$, $T_{\text{b}} \sim \text{EW}$), challenging all diffusion-based hotspot work.
- The criterion is itself set in flat spacetime — settling diffusion vs advection with expansion included is left to future work.

Backup — Where the framework breaks down

- Gray region of the (MPBH, α) plane (excluded):
- $T_{\max} < T_{\text{ev}}$ — diffusion predicts a peak below the background, so no well-defined hotspot forms within this framework (localized deposition may still occur; left to future work).
- $n\sigma v = v/\lambda < H$ — emitted particles do not scatter often enough to thermalize within a Hubble time.
- Of the two, $T_{\max} > T_{\text{ev}}$ is the more stringent condition.

Backup — From $u(\tau)$ to $T_{\text{plt}} \propto t^{-11/15}$

- Dimensionless cooling equation ($u \equiv U/T_{\text{max}}$, $x \equiv rc/r_0$):

$$\frac{\partial u}{\partial \tau} = \frac{1}{u} \left(\frac{\partial^2 u}{\partial x^2} + \frac{2}{x} \frac{\partial u}{\partial x} \right) + \frac{2}{u^2} \left(\frac{\partial u}{\partial x} \right)^2, \quad u(x, 0) = \begin{cases} 1 & x \leq 1 \\ x^{-7/11} & x > 1 \end{cases}$$

- Universal (no physical parameters). Numerically, the plateau follows

$$u_{\text{plt}}(\tau) \sim \tau^{-7/15}$$

- Undoing the redshift definition $T_{\text{plt}} = U \sqrt{t_{\text{ev}}/t}$ with $\tau \propto \sqrt{t}$ at late times gives

$$T_{\text{plt}} \propto t^{p/2-1/2} \Big|_{p=-7/15} = t^{-11/15},$$

- steeper than the flat-space $t^{-7/15}$ (and not the naive redshift $t^{-29/30}$).