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Primordial Black Hole Hotspots Beyond Flat Spacetime

Jong-Hyun Yoon
Chungnam National University

in collaboration with
Doojin Kim, TaeHun Kim, Jong-Chul Park

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Light primordial black holes evaporate

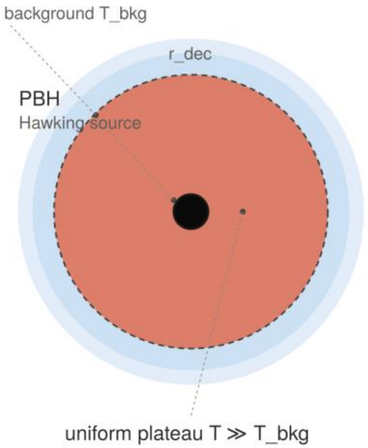
- Primordial black holes (PBHs): black holes formed in the early universe, spanning a huge mass range.
- Sufficiently light PBHs (M ≲ 10^9 g) evaporate before BBN, with a lifetime that grows as

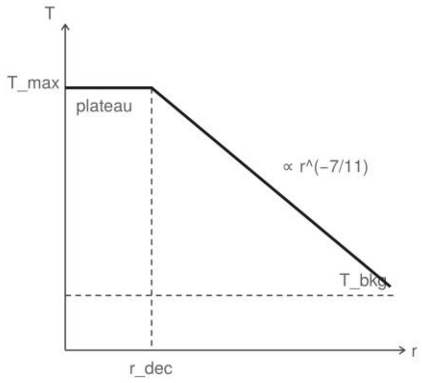
$$t_{\rm ev} \sim \frac{M^3}{M_{\rm Pl}^4}$$

- 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.
- ⇒ hotspots can modify early-universe observables.

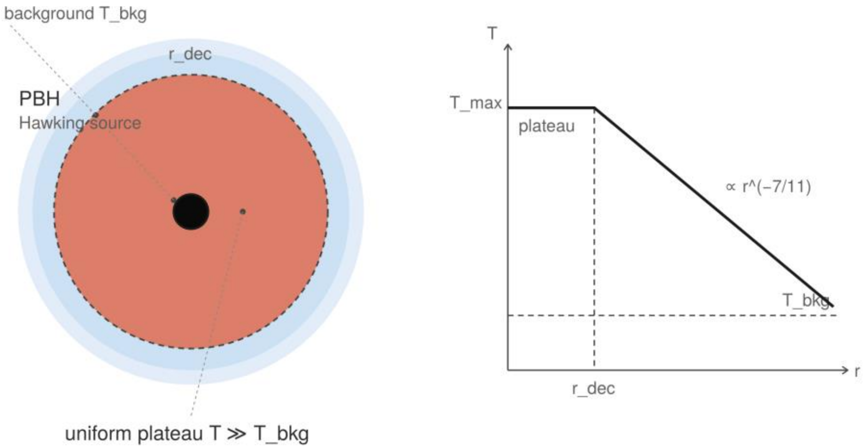




Studied so far by Das & Hook; He et al.; Gunn et al. (~2021–2024).

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.
- But a light PBH's lifetime is itself a Hubble time: $\tau_{\rm PBH} \simeq t_{\rm ev} \sim H^{-1}(t_{\rm ev})$
- It forms and cools over this timescale — expansion runs on the same clock.

⇒ Cosmic expansion is not a priori negligible. Does it change the picture?

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: $$\frac{\partial \rho}{\partial t} + 4H\rho = \frac{1}{a^2} \vec{\nabla}_c \cdot \left(\frac{\lambda v}{3} \vec{\nabla}_c \rho \right)$$
- 4Hρ — 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 2026)

Formation is robust against expansion

- Critical scale where Hubble overtakes diffusion: $R_H = \sqrt{\frac{\lambda v}{H}}$
- During radiation domination this coincides exactly with r_dec: the expansion boundary is the decoupling radius — a clean physical interpretation of r_dec.
- The envelope T ∝ r^−7/11 is essentially unchanged.
- Reason: most energy is emitted at the very end of evaporation, so the profile barely redshifts while forming.

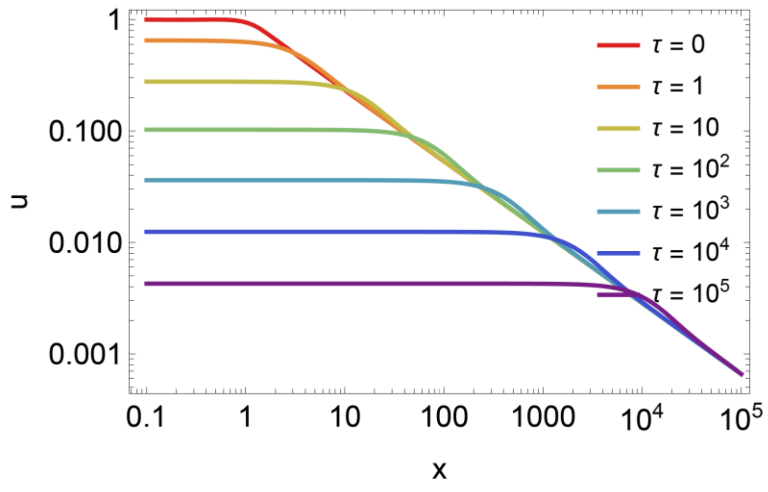
Cooling, after the PBH is gone

- Source switches off ⇒ pure cooling, governed by the same equation.

- Recast in dimensionless variables (u, τ, x): the equation and initial con dition become parameter-independent.

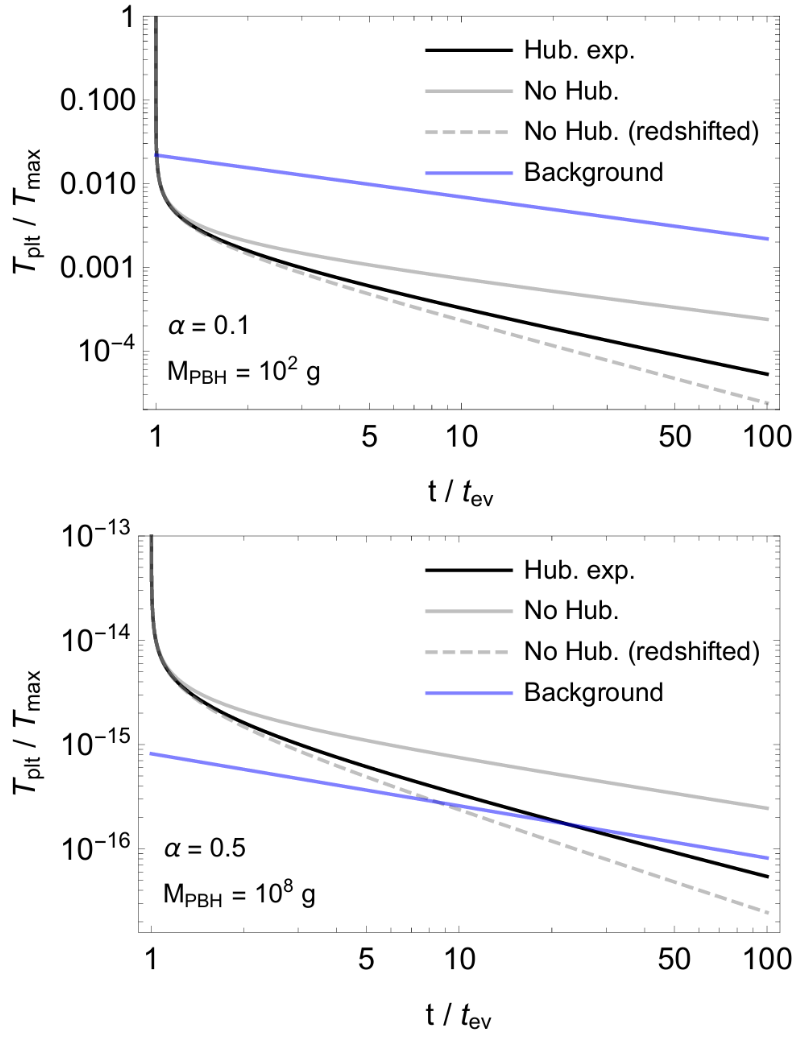
⇒ solve once; map back to any (M_PBH, α).

- Profiles keep their shape: plateau drops, envelope stays ∝ x^−7/11.



A steeper cooling law: t^(–11/15)

- Plateau temperature T_plt(t):
  - a rapid initial drop (many orders of magnitude), then
  - a power law $T_{\mathrm{plt}} \propto t^{-11/15}$
- 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

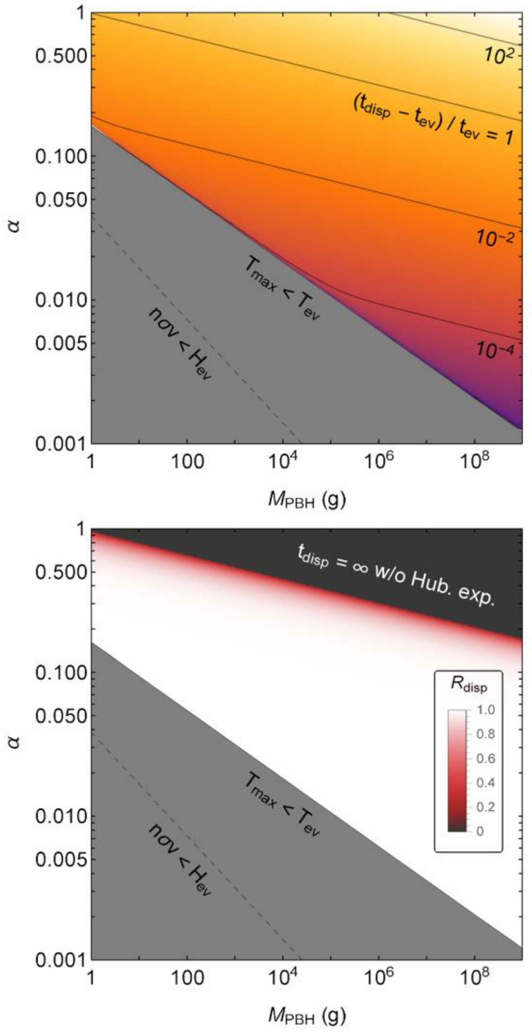
- Disappearance time t_disp: when T_plt falls to the background T_bkg ∝ t^−1/2.

- Flat result t^−7/15 falls slower than background

⇒ some hotspots would survive forever.

- Our t^−11/15 falls faster ⇒ every hotspot disappears in finite time.

- Difference matters mainly for heavy PBHs + large coupling.



Summary & outlook

What we did

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

What we found

- Formation robust: $R_H = r_{dec}$, profile unchanged.
- Cooling modified: $T_{plt} \propto t^{-11/15}$, finite lifetime — not reproducible by naive redshift.

Outlook

- Dark hotspots in a dark sector ($\alpha \to \alpha_D$).
- 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:

$$\mathcal{V} \equiv \frac{1}{\alpha^2 T^2} \left|\partial_t T + v\,\partial_r T\right| \lesssim \mathcal{O}(10^{-2})$$

- Many scatterings per Hubble time: nσv = v/λ > H.
- In the plateau nσv ~ α^2 T_plt, while T_bkg ~ sqrt(M_Pl H) ≫ H; so once nσv > H_ev holds at ev aporation, it holds until T_plt = T_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_diff ~ L^2/D, t_adv ~ L/v:

$$\mathrm{Pe} \equiv \frac{vL}{D(T)}, \qquad D(T) \sim 1/T. \qquad \begin{cases} \mathrm{Pe} \gg 1 & \text{advection wins} \\ \mathrm{Pe} \ll 1 & \text{diffusion wins} \end{cases}$$

- Kaiser et al. (2026) argue advection dominates for much of parameter space (M ≲ 10^6 g, T_H ≳ 10^7 GeV, T_b ~EW), challenging all diffusion-based hotspot work.

- Their 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):
- Tmax < Tev — 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).
- nσv = v/λ < H — emitted particles do not scatter often enough to thermalize within a Hubble time.

- Of the two, T_max > T_ev is the more stringent condition.

Backup — From u(τ) to Tplt ∝ t−11/15

- Dimensionless cooling equation (u ≡ U/Tmax, x ≡ rc/r0):

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

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

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

- Undoing the redshift definition T_plt = U tev/t with τ ∝ t at late times gives

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

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

Backup — Why hotspots matter (phenomenology)

- Inside a hotspot the local temperature can exceed thresholds unreachable in the smooth background:
  - Baryogenesis — local sphaleron / leptogenesis processes can be reactivated in the hot region.
  - Dark matter — local (re)thermalization or modified freeze-out can shift the relic abundance relative to the homogeneous calculation.
  - BBN / Neff — modified evaporation histories and energy injection.

- Our contribution fixes the cooling history (T_plt ∝ t^−11/15, finite lifetime), which sets how long each threshold stays open — a prerequisite for any of the above. Quantitative signals: future work.