Hotspot Formation around Evaporating Primordial Black Holes

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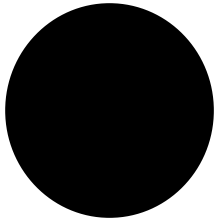
2025/04/28@CUBES-7, Gurye

MH, Kazunori Kohri, Kyohei Mukaida, Masaki Yamada, JCAP 01 (2023) 027 [arXiv: 2210.06238]
MH, Kazunori Kohri, Kyohei Mukaida, Masaki Yamada, JCAP 10 (2024) 080 [arXiv: 2407.15926]

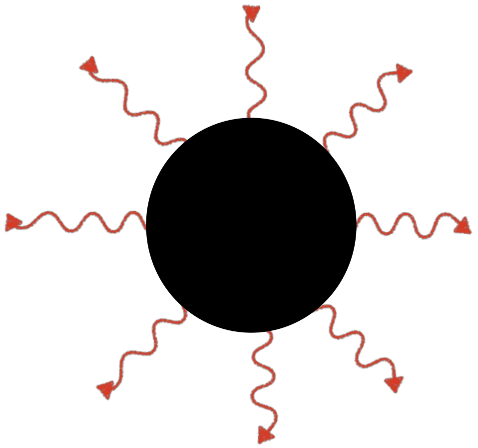
Overview

- Small primordial black hole (PBH)



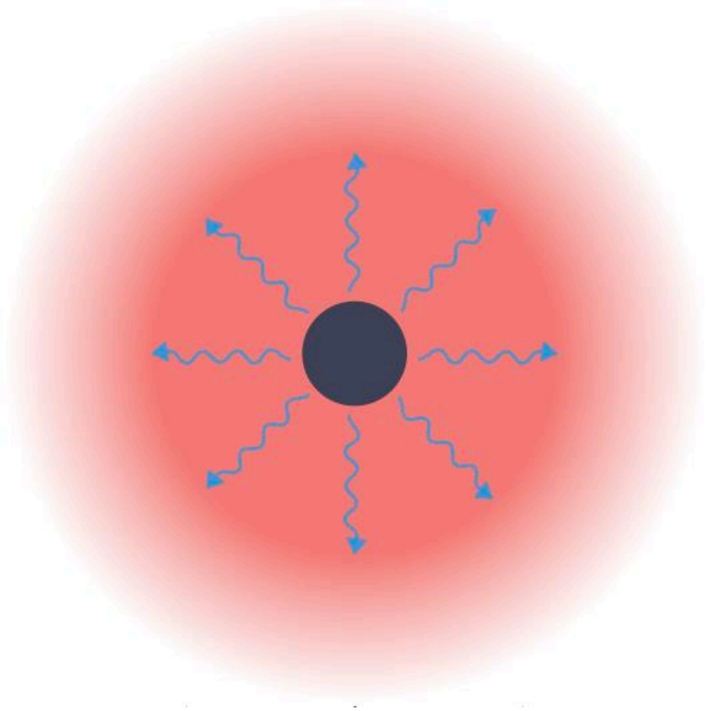
Overview

- Small primordial black hole (PBH)
- Hawking radiation



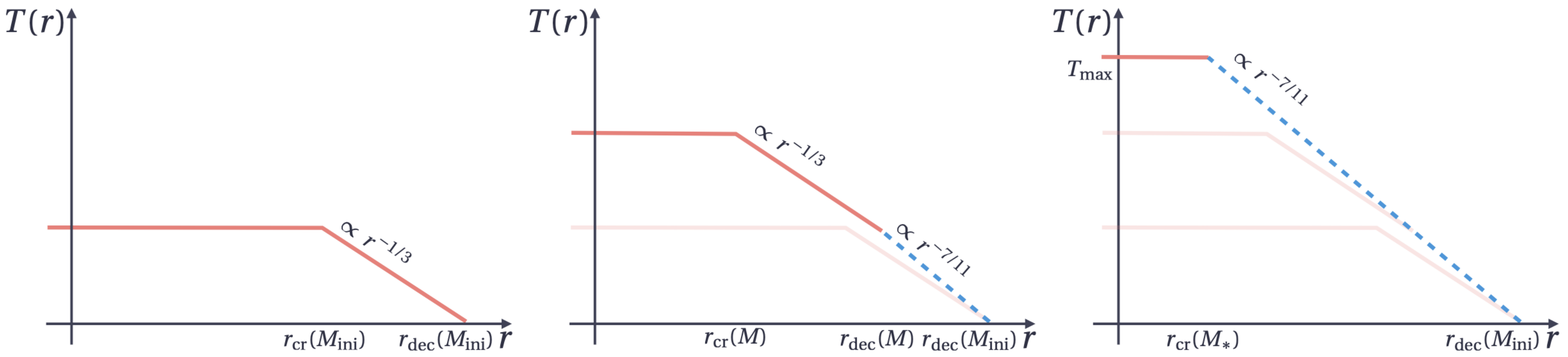
Overview

- Small primordial black hole (PBH)
- Hawking radiation
- Heating plasma and hotspot



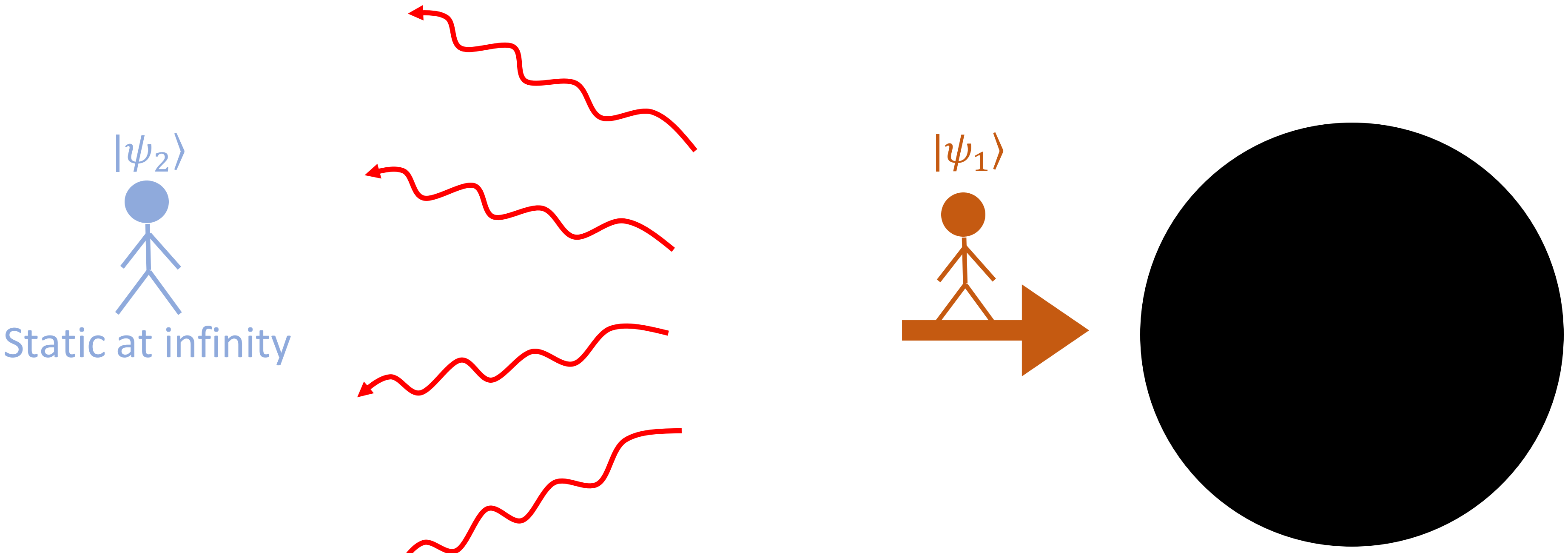
Overview

- Small primordial black hole (PBH)
- Hawking radiation
- Heating plasma and hotspot
- Temperature profile



Hawking radiation Hawking (1974, 1975)

- Particle production in curved spacetime

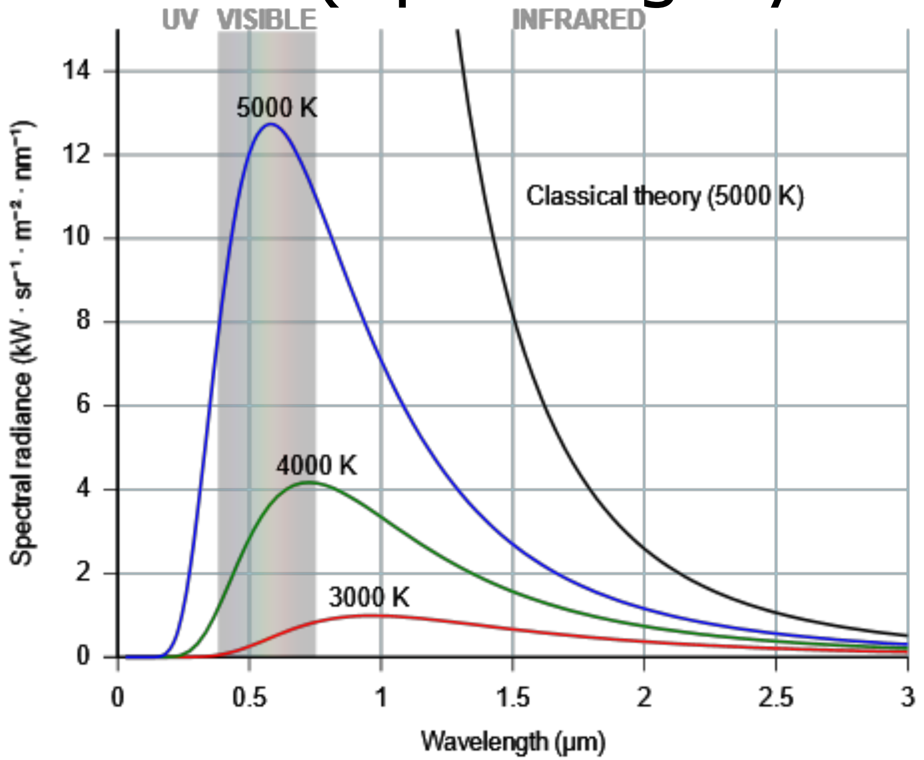


$a|\psi_2\rangle \neq 0$ $a|\psi_1\rangle = 0$

Hawking radiation

Hawking (1974, 1975)

- Particle production in curved spacetime
  - Blackbody spectrum (up to a greybody factor)



Credit: Wikipedia

Hawking radiation

Hawking (1974, 1975)

- Particle production in curved spacetime
  - Blackbody spectrum (up to a greybody factor)
  - Hawking temperature $T_{\rm BH} \propto M_{\rm Pl}^2/M$
    - Solar mass $M_\odot = 2 \times 10^{33}\rm g$: $T_{\rm BH} = M_{\rm Pl}^2/M_\odot \approx 5 \times 10^{-21}\rm GeV{\sim}10^{-8}K$
    - Planck mass:

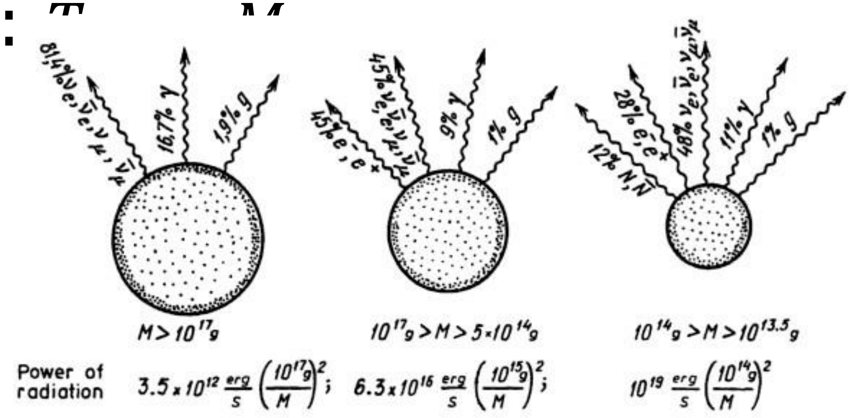


Figure 10.7: Quantum decay of a non-rotating black hole. The fractions of gravitons (g), photons (γ), neutrinos (ν) and other elementary particles are given in percent of the total number of particles emitted by black holes of different masses.

Frolov and Novikov (1998)

Hawking radiation

Hawking (1974, 1975)

- Particle production in curved spacetime
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  - Hawking temperature $T_{\mathrm{BH}} \propto M_{\mathrm{Pl}}^2/M$
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    - Planck mass: $T_{\mathrm{BH}} = M_{\mathrm{Pl}}$
  - Black

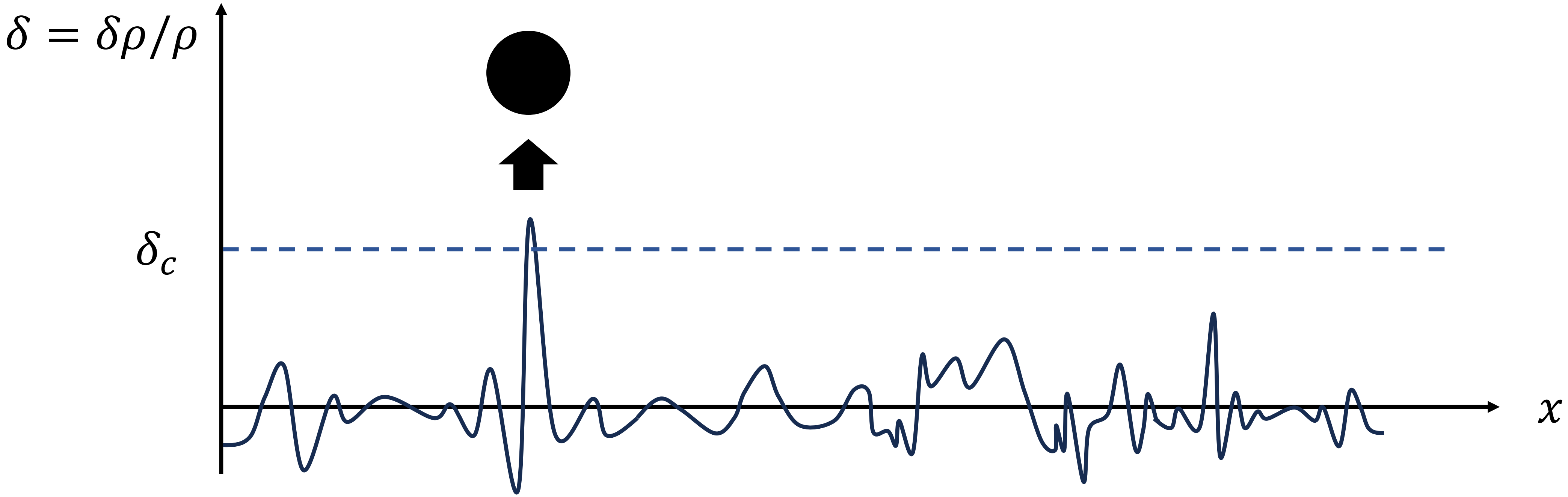
$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{\pi \mathcal{G} g_{H*}(T_{\mathrm{H}})}{480} \frac{M_{\mathrm{Pl}}^4}{M^2} \qquad t_{\mathrm{ev}}(M) = \frac{160}{\pi \mathcal{G} g_{H*}(T_{\mathrm{H}})} \frac{M^3}{M_{\mathrm{Pl}}^4}$$

    - Evaporated by today: $\lesssim 10^{15}\mathrm{g}$
    - Evaporated by BBN (~1s after Big Bang): $\lesssim 10^{9}\mathrm{g}$

Primordial black hole

Zel'dovich and Novikov (1967); Hawking (1971); Carr and Hawking (1974); Carr (1975)

- Collapse of primordial density fluctuation

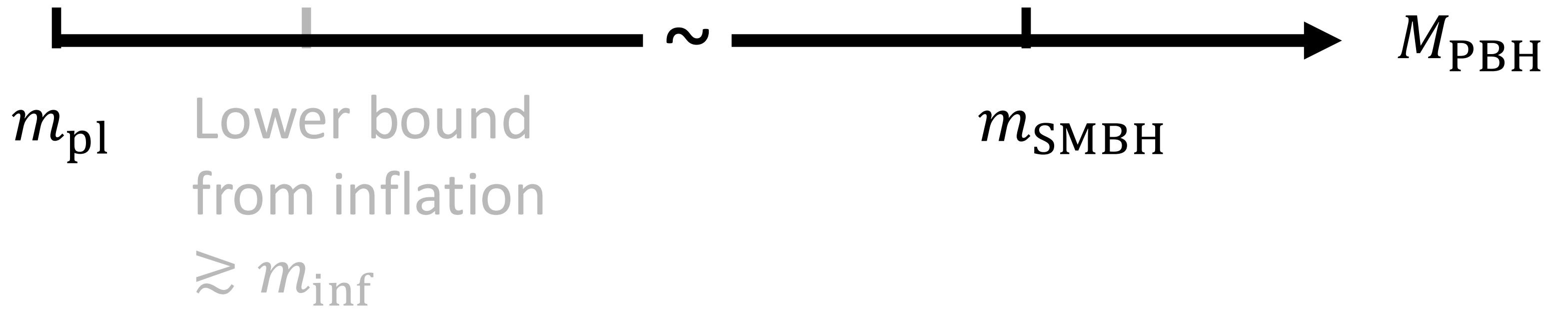


Primordial black hole

Zel'dovich and Novikov (1967); Hawking (1971); Carr and Hawking (1974); Carr (1975)

- Collapse of primordial density fluctuation
  - PBH mass and formation time

$$M_{\rm ini} = \gamma \frac{4\pi\rho}{3H_{\rm ini}^3} = 4\pi\gamma \frac{M_{\rm Pl}^2}{H_{\rm ini}} \simeq 0.4\,{\rm g}\,\left(\frac{\gamma}{0.2}\right)\left(\frac{H_{\rm ini}}{6\times 10^{13}\,{\rm GeV}}\right)^{-1}$$



- $M_{\rm ini} = 10^9{\rm g}$: $H_{\rm ini} \sim 10^5{\rm GeV} \implies t_{\rm ini} \sim 10^{-30}{\rm s}$

Primordial black hole

Zel'dovich and Novikov (1967); Hawking (1971); Carr and Hawking (1974); Carr (1975)

- Collapse of primordial density fluctuation
  - PBH mass and formation time
  - Plasma temperature at evaporation (assumed RD)

$$T_{\rm ev} \simeq 1\,{\rm MeV} \left(\frac{g_*(T_{\rm ev})}{10.75}\right)^{-\frac{1}{4}} \left(\frac{g_{H*}(T_{\rm H})}{108}\right)^{\frac{1}{2}} \left(\frac{M_{\rm ini}}{10^9\,{\rm g}}\right)^{-\frac{3}{2}}$$

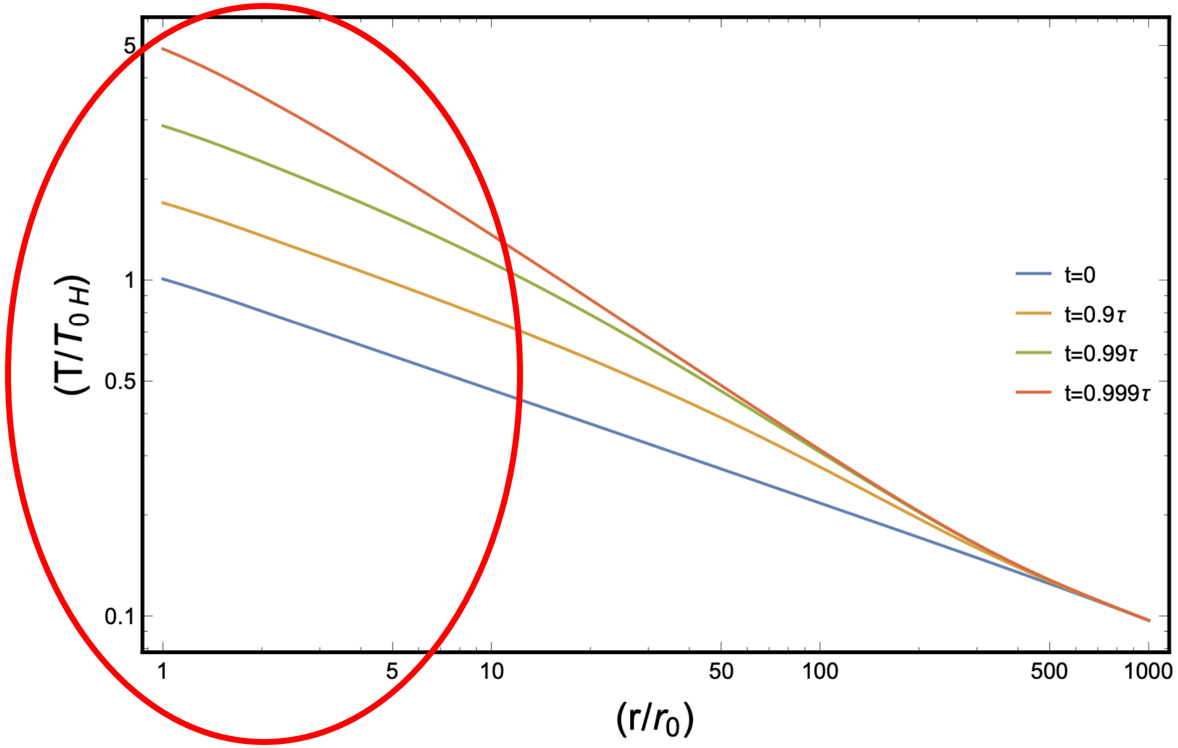
- $M_{\rm ini} = 10^9{\rm g}$: $T_{\rm BH} \sim 10^4{\rm GeV} \gg T_{\rm ev} \sim 1{\rm MeV}$

Hotspot formation

- Thermalization of Hawking radiation

Hotspot formation

- Thermalization of Hawking radiation
  - Instantaneous thermalisation?

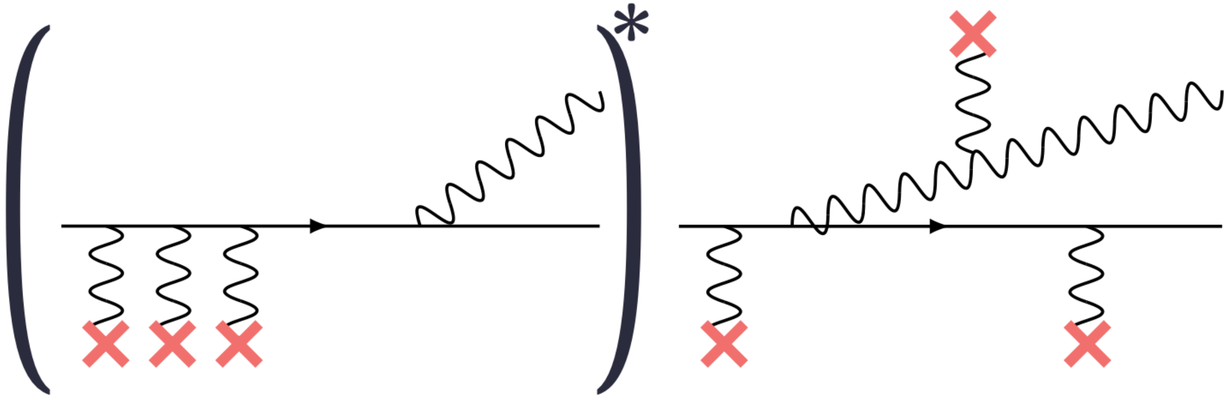


Das and Hook, (2021)

Hotspot formation

- Thermalization of Hawking radiation
  - Instantaneous thermalisation?
  - $p \sim T_{\mathrm{BH}} \gg T_{\mathrm{ev}}$: Landau-Pomeranchuk-Migdal (LPM) effect

Landau, Pomeranchuk (1953), Migdal (1956)
Gyulassy, Wang (1994), Arnold, Moore, Yaffe (2001a,2001b,2002a,2002b),
Besak, Bodeker (2010), Kurkela, Wiedmann (2014)

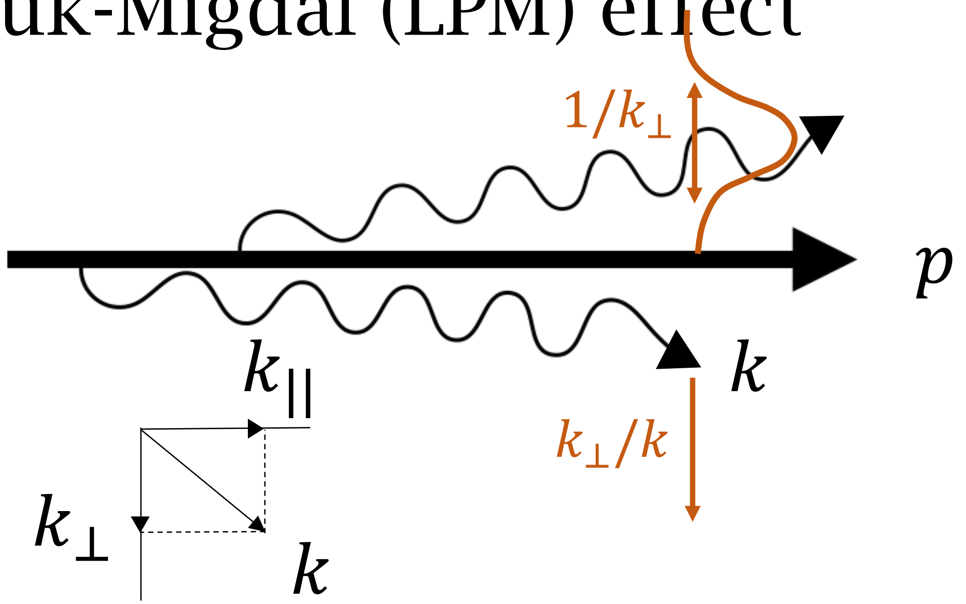


- Destructive interference between diagrams

Hotspot formation

- Thermalization of Hawking radiation
  - Instantaneous thermalisation?
  - $p \sim T_{\mathrm{BH}} \gg T_{\mathrm{ev}}$: Landau-Pomeranchuk-Migdal (LPM) effect
    - Destructive interference
    - Nearly collinear emission
    - $t_{\mathrm{form}} \sim k/k_\perp^2$
    - $\langle k_\perp^2 \rangle \sim \alpha^2 T^3 t_{\mathrm{form}}$
    - $\Gamma_{\mathrm{LPM}}(k, T) \sim \alpha\, t_{\mathrm{form}}^{-1} \sim \alpha^2 T \sqrt{T/k}$

Momentum of daughter particle



Hotspot formation

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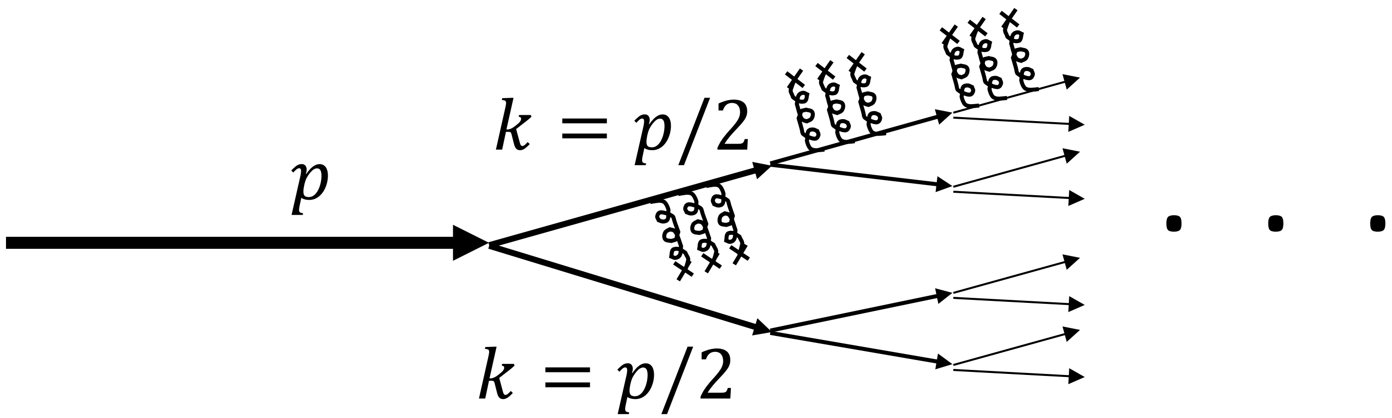
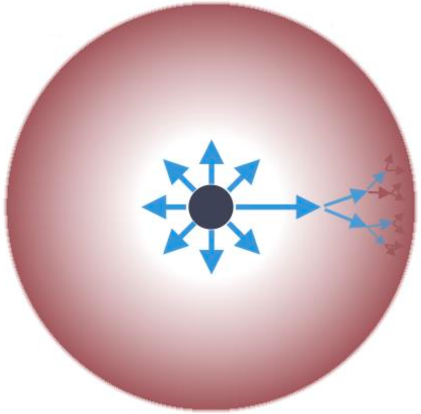


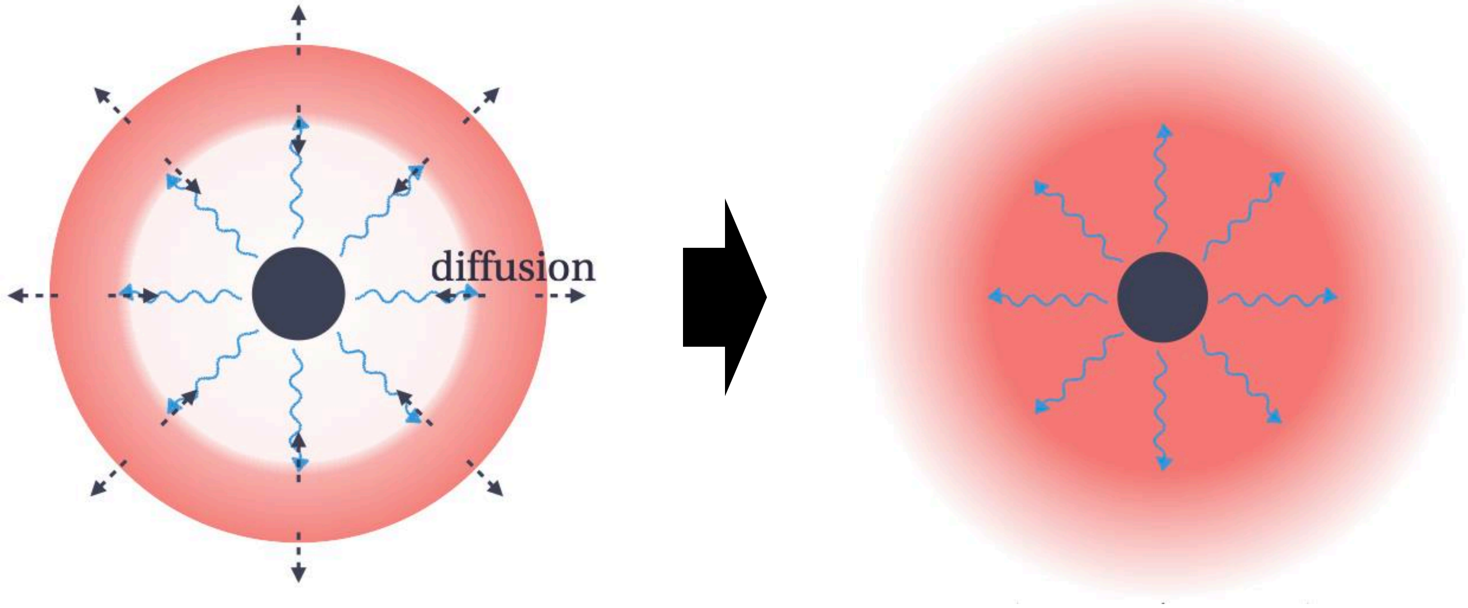


$$t_{\rm th}(p, T) \equiv 1/\Gamma_{\rm LPM}(p, T)$$

Momentum of mother particle

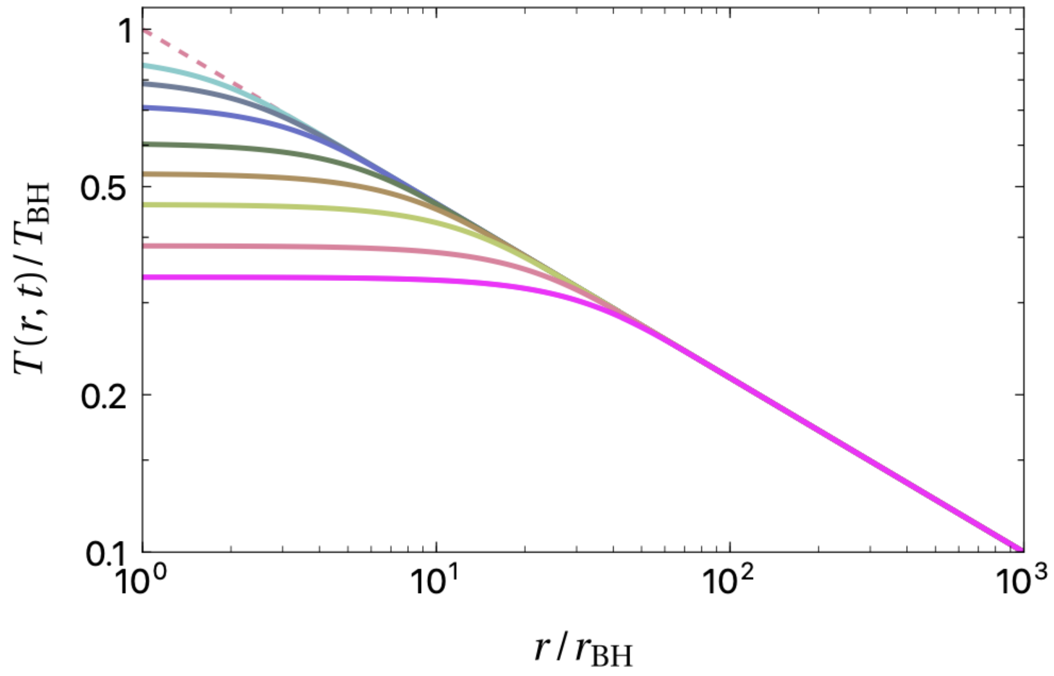
Hotspot formation

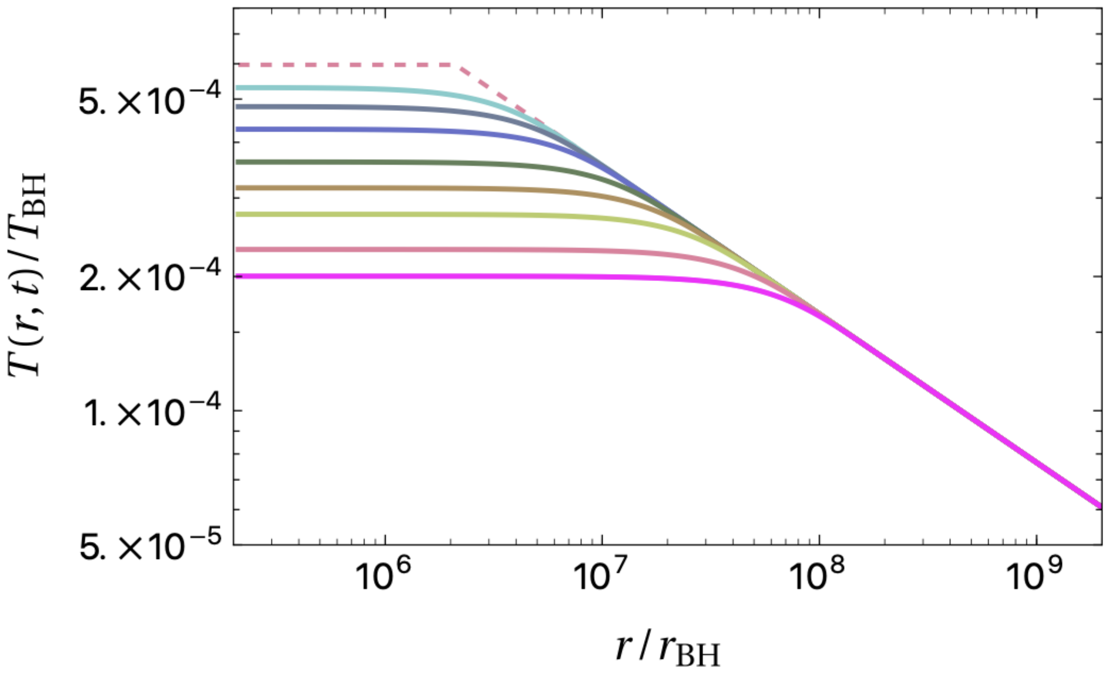
- Thermalization of Hawking radiation
- Diffusion $r_{\mathrm{d}}(t, T(r)) \sim \sqrt{t/(\alpha^2 T(r))}$ ⟶ $t_{\mathrm{d}}(M, T)$



Hotspot formation

- Result

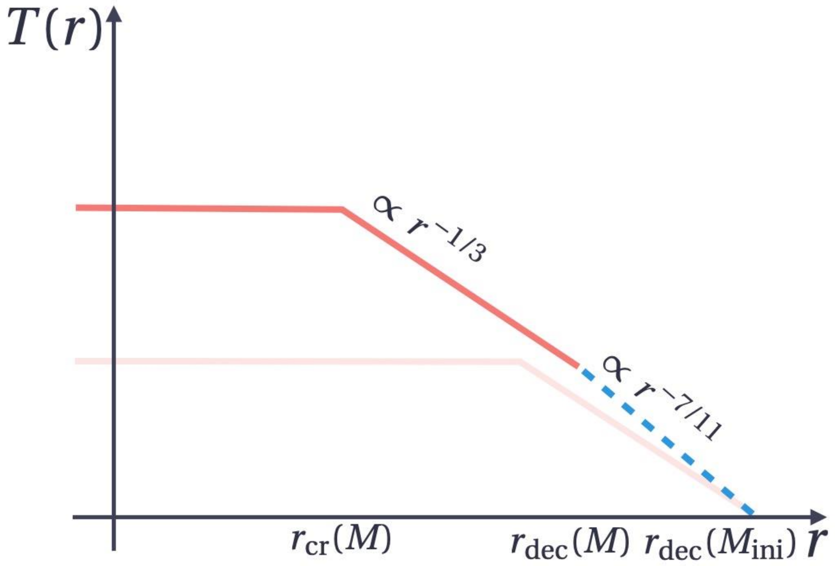


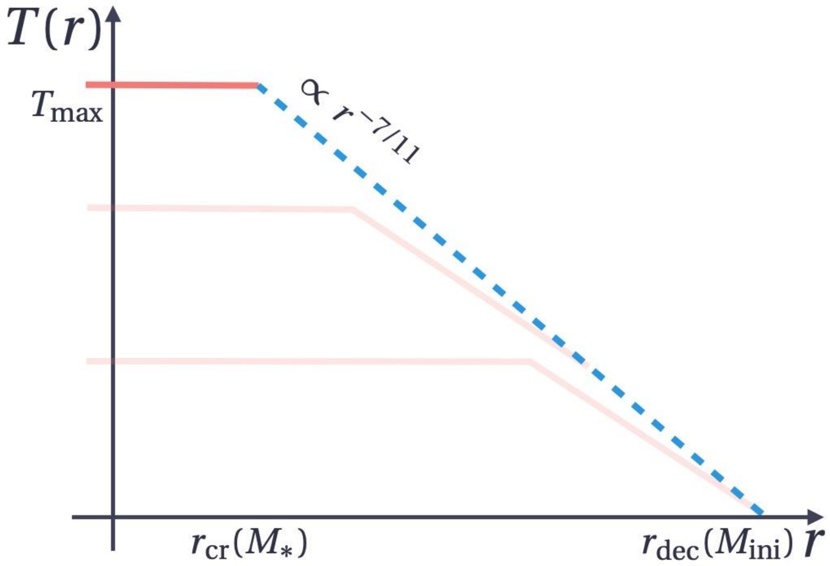


Hotspot formation

- Result

$T_{\rm max}$ is determined by $t_{\rm d} = t_{\rm ev}$

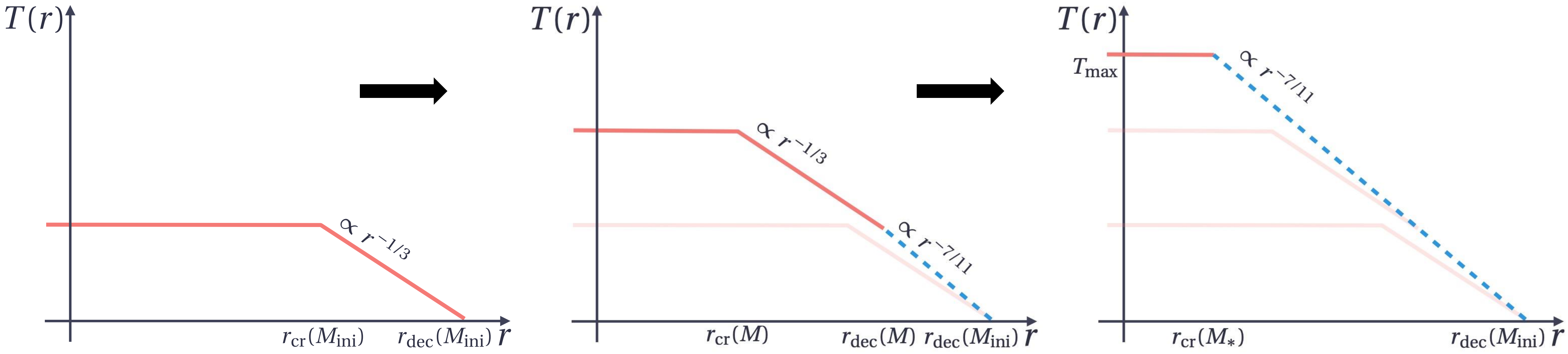




$$T_{\rm max} \equiv T(r < r_{\rm cr})|_{M_*} \simeq 2 \times 10^9\,{\rm GeV} \left(\frac{\alpha}{0.1}\right)^{\frac{19}{3}} \left(\frac{g_*}{106.75}\right)^{-\frac{4}{3}} \left(\frac{g_{H*}}{108}\right)^{\frac{5}{6}}$$

Summary

- We consider the Hawking radiation from small PBHs in the early Universe
- Take into account the LPM effect and diffusion
- Result: a hotspot ($T_{\rm max}$) with radius much larger than r_s.



Discussion

- Sphaleron and baryon asymmetry
- Symmetry restoration and topological defects
- Heavy particle production

Thank you for your attention!