KEK 大学共同利用機関法人 高エネルギー加速器研究機構

素粒子原子核研究所
Institute of Particle and Nuclear Studies

Fire Balls from Primordial Black Hole Explosion

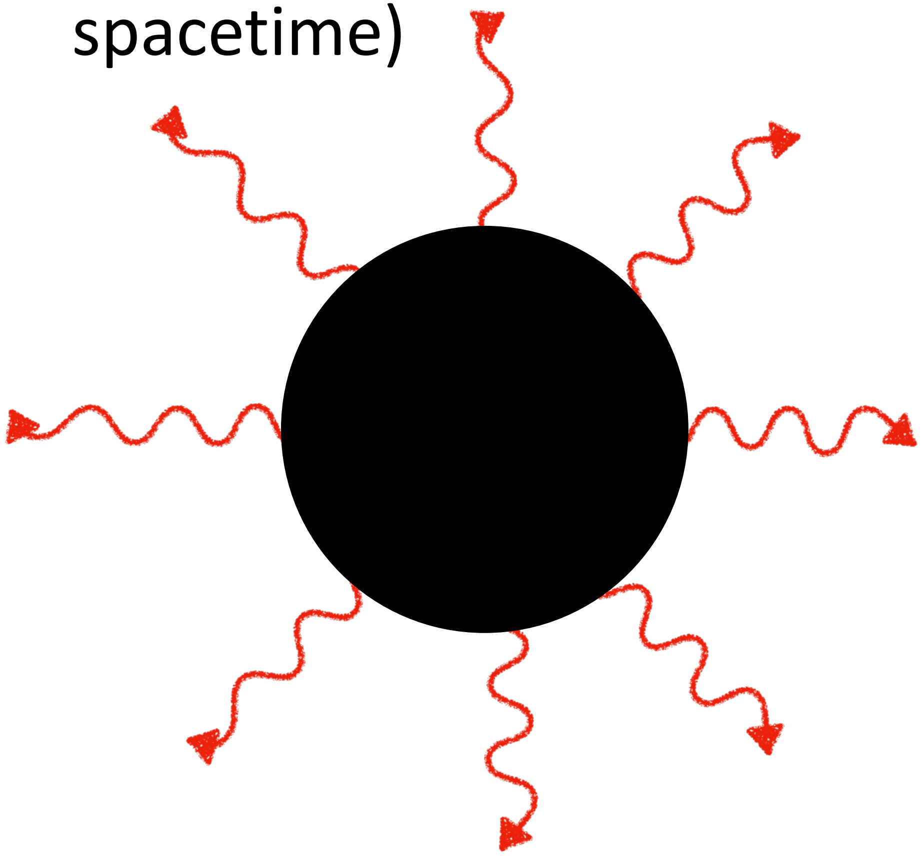
Speaker: Minxi He (何 敏熙)

2023/05/05@CAS-ITP

MH, Kazunori Kohri, Kyohei Mukaida, Masaki Yamada, JCAP 01 (2023) 027 [arXiv: 2210.06238].

Introduction

- Black holes (BHs) emit Hawking radiation: an effect of particle production from vacuum fluctuations around a black hole (curved spacetime)



1. (Nearly) blackbody spectrum
2. $T_{\mathrm{BH}} \propto M^{-1}$ (insignificant for astrophysical BHs)
3. T_{BH} can be as high as Planck scale

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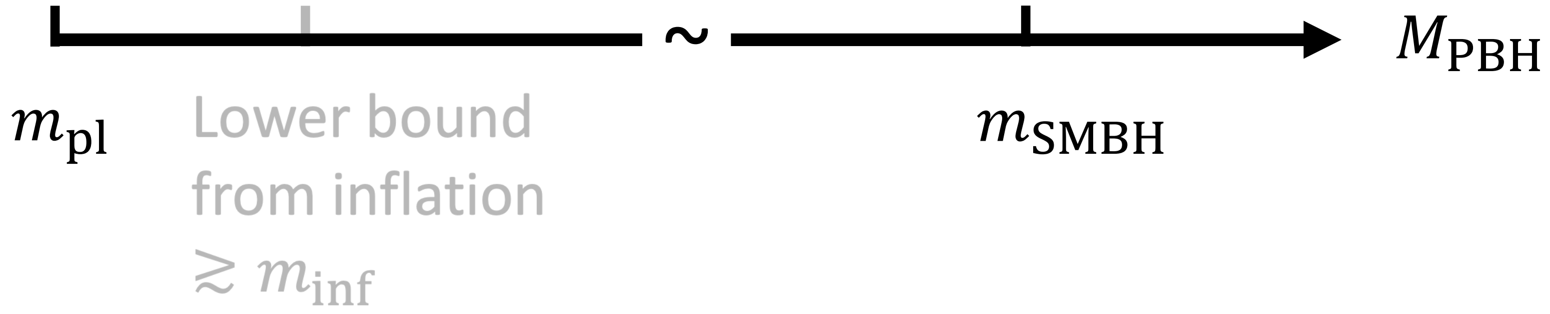
- It could be important for (small) primordial BHs (PBHs)



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Examples:
1. PBHs survive until today: $\gtrsim 10^{15}\mathrm{g}$ ($\sim 10^{15}\mathrm{g}$ severly constrained)
2. PBHs completely evaporate by BBN (radiation-domination): $\lesssim 10^{9}\mathrm{g}$

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- The emitted Hawking radiation at late stage of evaporation is extremely energetic, which can induce interesting phenomena.

For example, heating up the ambient plasma (rad-dom), which involves the thermalization process of Hawking radiation.

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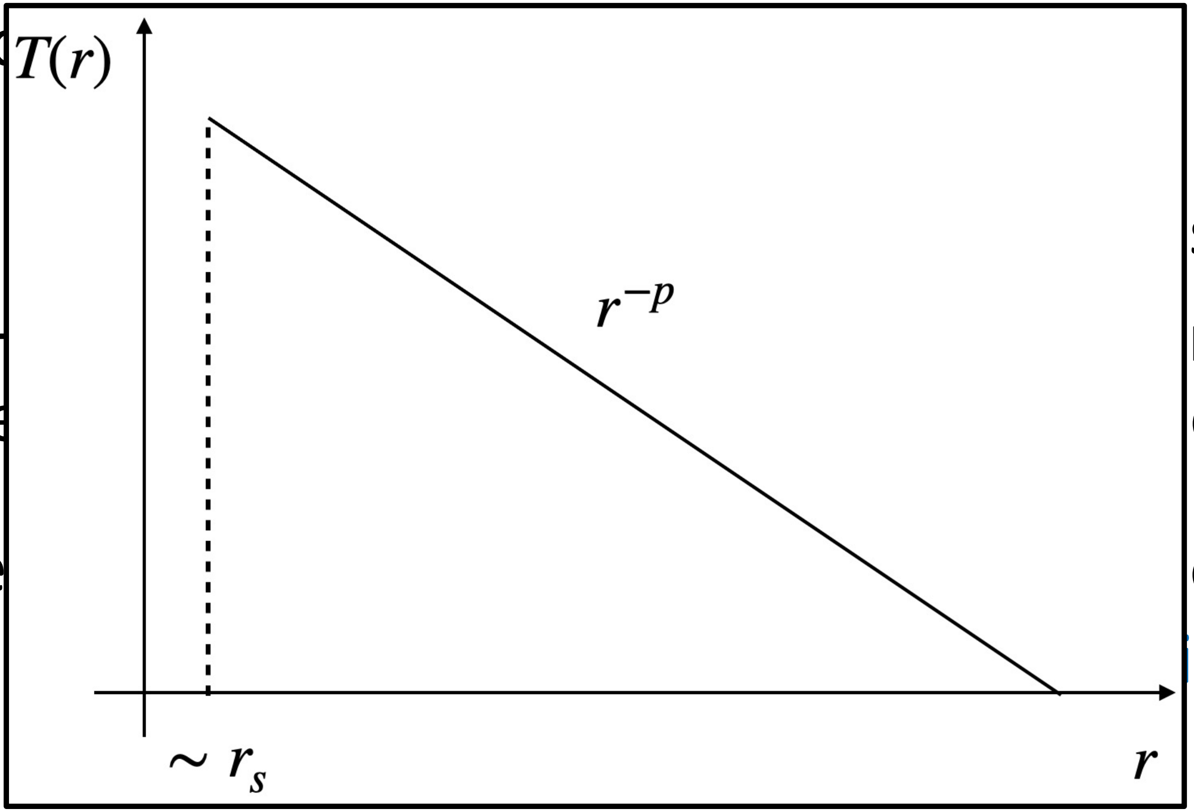

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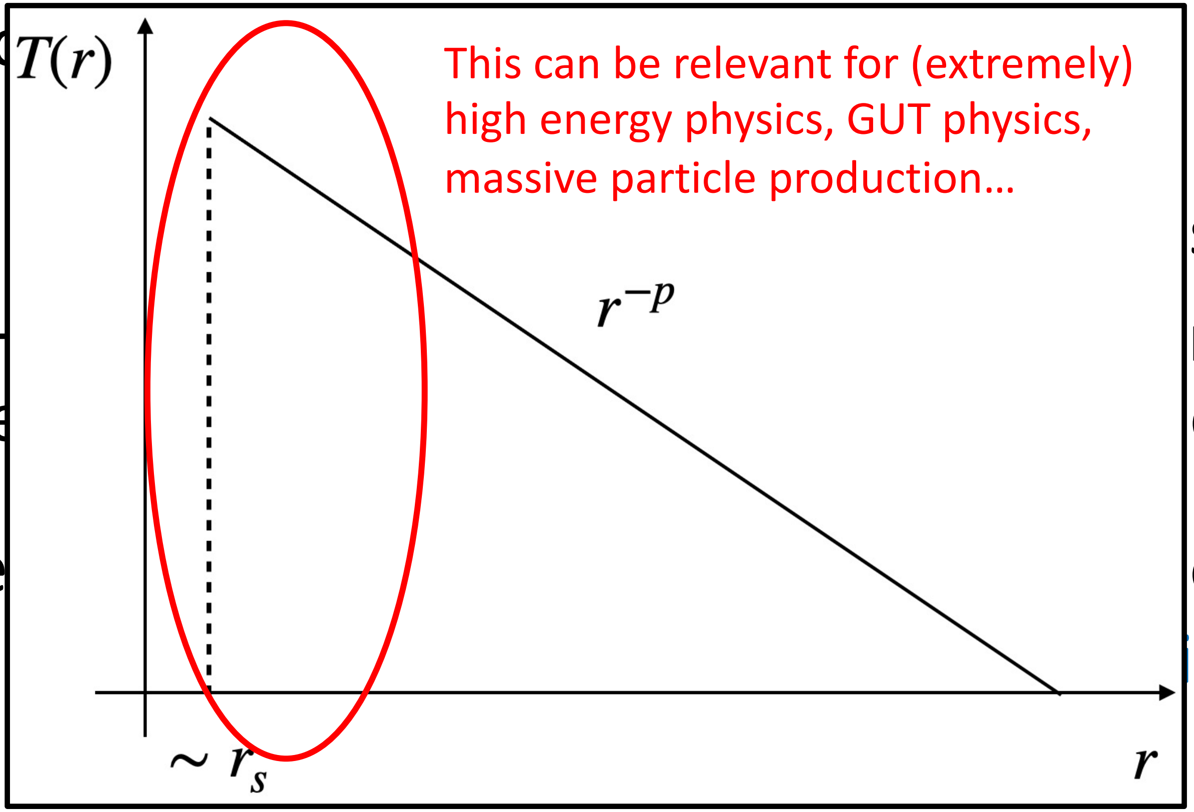

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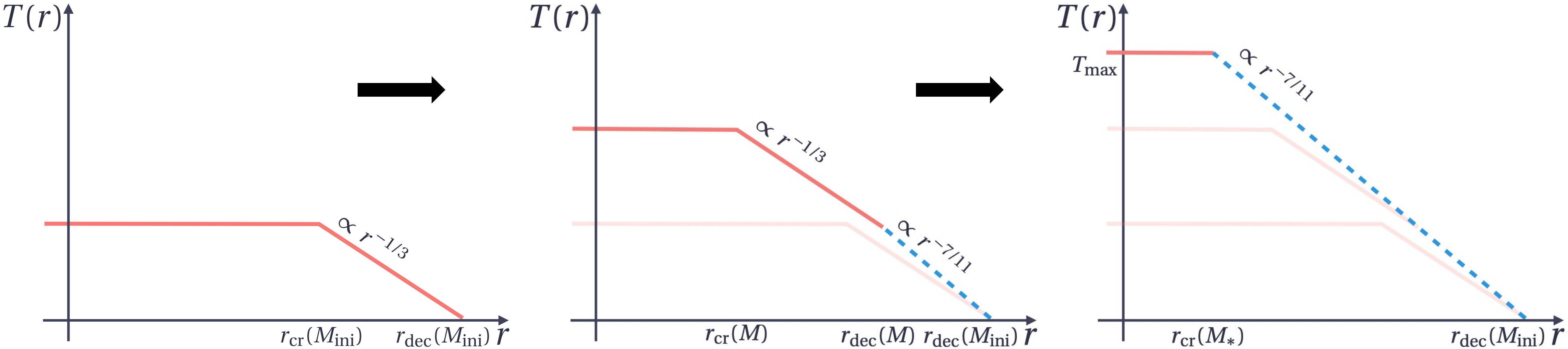
For example, heating up the ambient plasma (rad-dom), which involves the thermalization process of Hawking radiation. Usually assumed to be instantaneous which is NOT always true, especially at the late stage of evaporation.

Introduction

- Introduce the Landau-Pomeranchuk-Migdal (LPM) effect which is essential in the thermalization process of high-energy particles in low-temperature plasma
- Show the interplay among black hole evaporation, LPM effect, and diffusion of energy in the plasma
- Show the resulting temperature profile around a PBH
- Discuss possible implications to cosmology



$T(r)$
$\propto r^{-1/3}$
$r_{\rm cr}(M_{\rm ini})$
$r_{\rm dec}(M_{\rm ini})$
r
$T(r)$
$\propto r^{-1/3}$
$\propto r^{-7/11}$
$r_{\rm cr}(M)$
$r_{\rm dec}(M)$
$r_{\rm dec}(M_{\rm ini})$
r
$T(r)$
$T_{\rm max}$
$\propto r^{-7/11}$
$r_{\rm cr}(M_*)$
$r_{\rm dec}(M_{\rm ini})$
r

Plan of the talk

- Primordial black hole (PBH) and Hawking evaporation
- Landau-Pomeranchuk-Migdal (LPM) effect and diffusion
- Temperature profile around a primordial black hole
- Summary

Hawking radiation

- Black holes emit nearly blackbody radiation with Hawking temperature

$$T_{\rm BH} = M_{\rm pl}^2/M \simeq 1.1 \times 10^4 {\rm GeV} (M/10^9 {\rm g})^{-1}$$

The typical energy of the emitted particle is therefore $\sim T_{\rm BH}$

- Mass loss rate is inversely proportional to M^2

→ evaporation process accelerates
Hawking temperature increases with time

$$-d(\ln M)/dt \propto M^{-1}$$

$$t_{\rm ev} \simeq 0.41 \ {\rm sec} \ \left(M/10^9 {\rm g}\right)^3$$

Hawking (1974)

→ First time scale: PBH evaporation

Hawking radiation

- Big Bang nucleosynthesis (BBN) time $\sim 1 \text{ sec}$ (T_{BBN}~4 MeV)

  Kawasaki, Kohri, Sugiyama (2000)

  Compare with $t_{\mathrm{ev}} \simeq 0.41 \text{ sec } (M/10^9\mathrm{g})^3$

  ➡ A black hole with a mass $\lesssim 10^9 \text{ g}$ formed in the very early Universe completely evaporates by BBN.

- Primordial black holes (PBHs) can have such properties.

Hawking (1974)

Primordial black holes from early Universe

- Quantum fluctuations during inflation ⟶ $\delta \equiv \delta\rho/\rho$

$$\delta > \delta_c \quad \Rightarrow \quad \text{PBH}$$

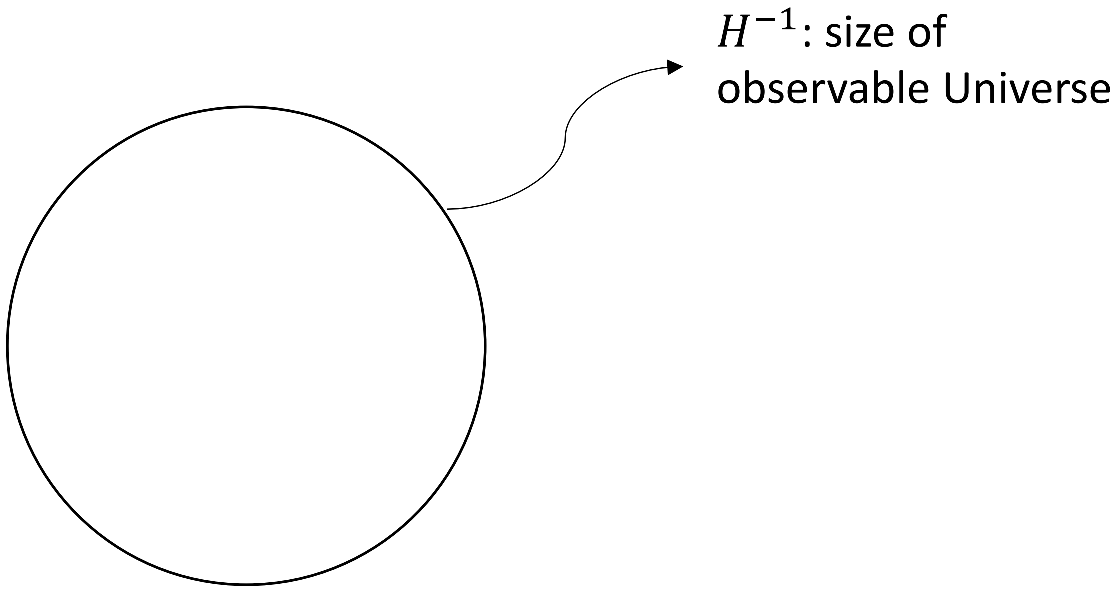
- Many ways to produce many large density fluctuations: ultra-slow-roll, change of slope in the inflaton potential, resonance…

- Other mechanisms that produce PBHs at late Universe…(not discussed here)

Zel'dovich, Novikov (1974), Hawking (1971), Carr, Hawking (1974), Carr (1975)

Primordial black holes from early Universe

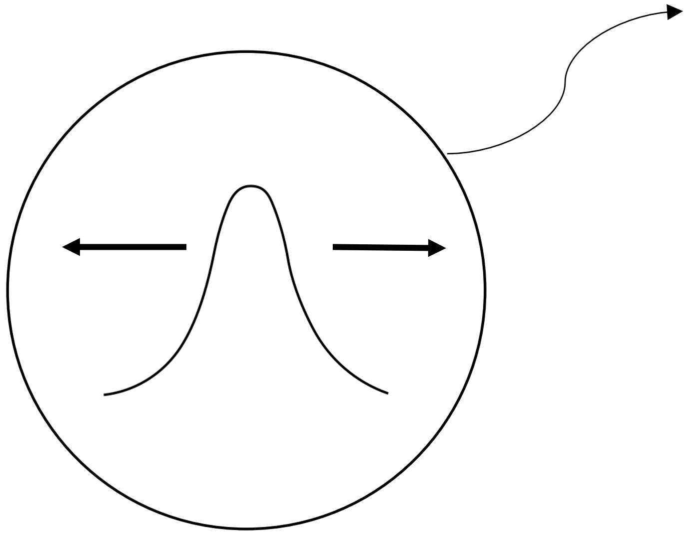
- Inflation: accelerated expansion of the Universe



Starobinsky, Guth, Linde, Mukhanov…

Primordial black holes from early Universe

- Inflation: accelerated expansion of the Universe
- Density fluctuations



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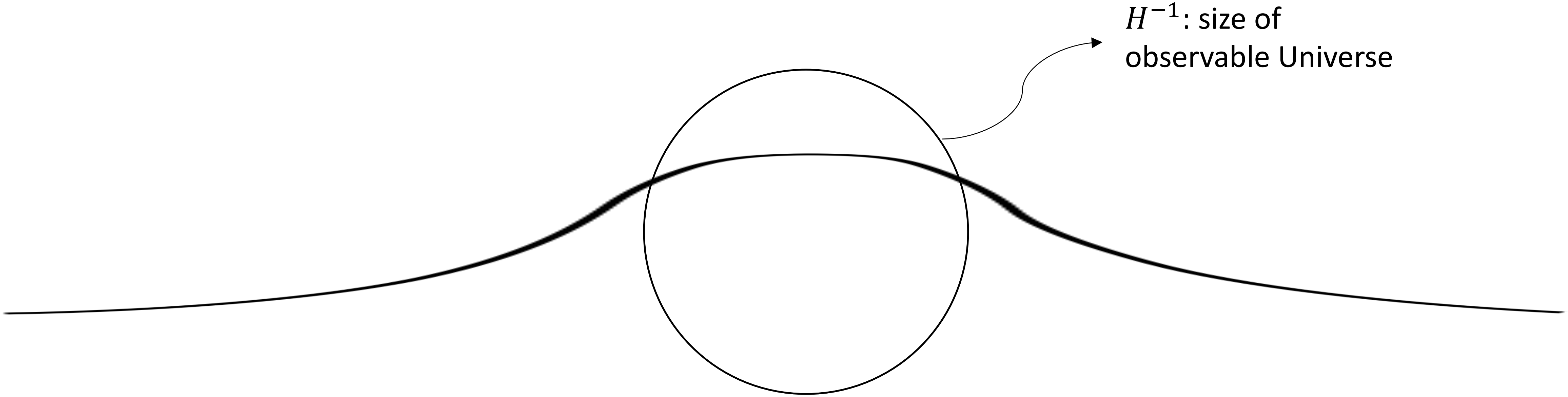

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Primordial black holes from early Universe

- Inflation: accelerated expansion of the Universe
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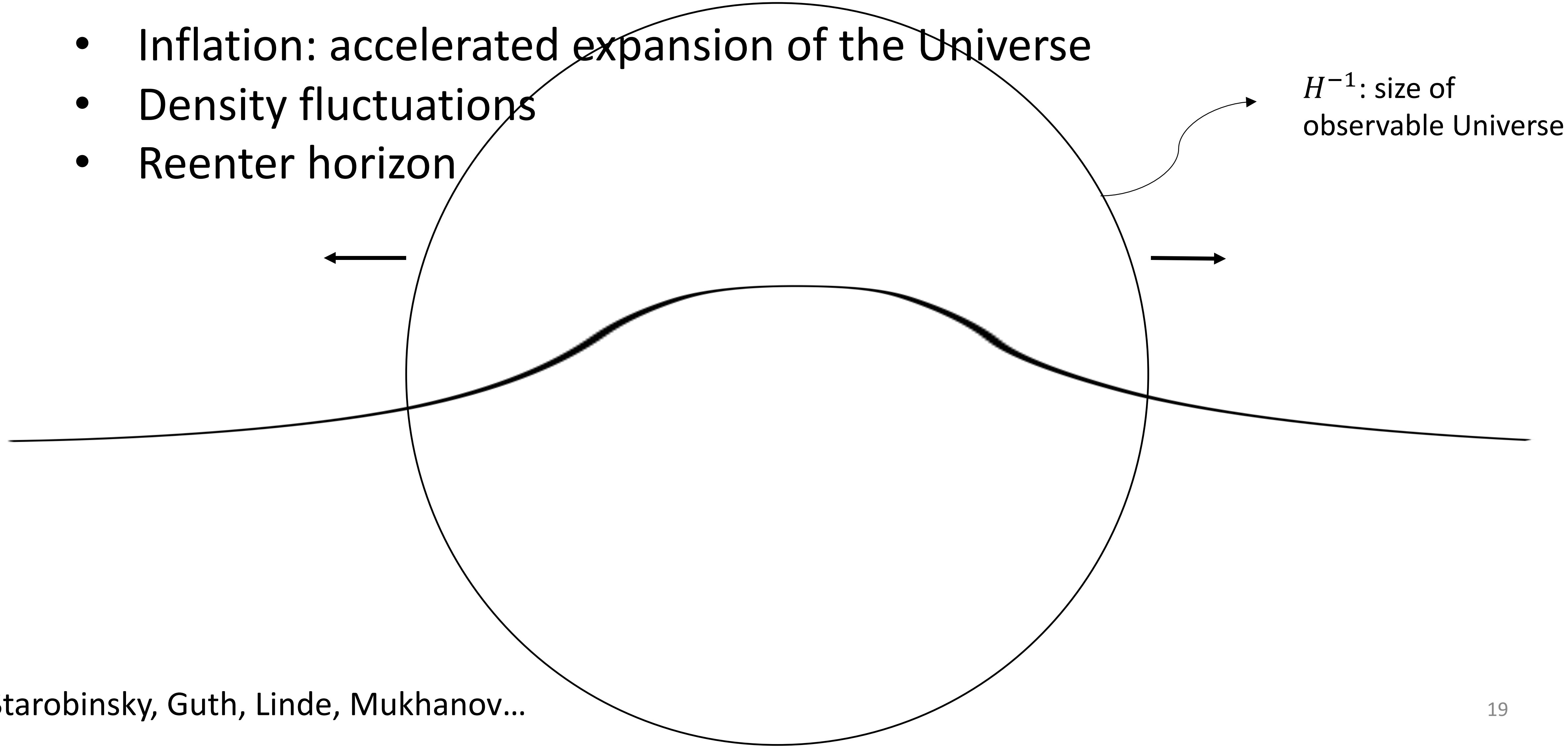
- Reenter horizon



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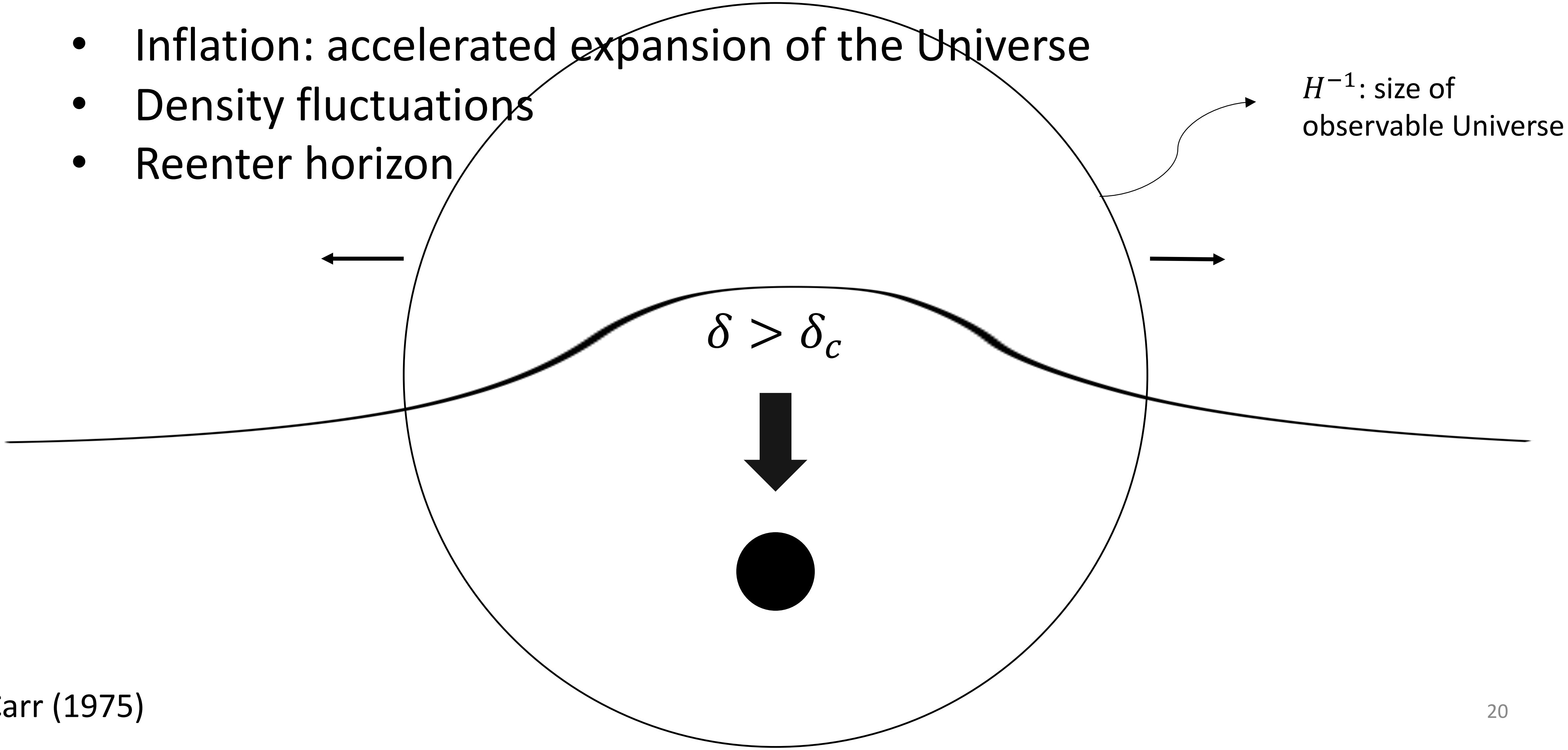
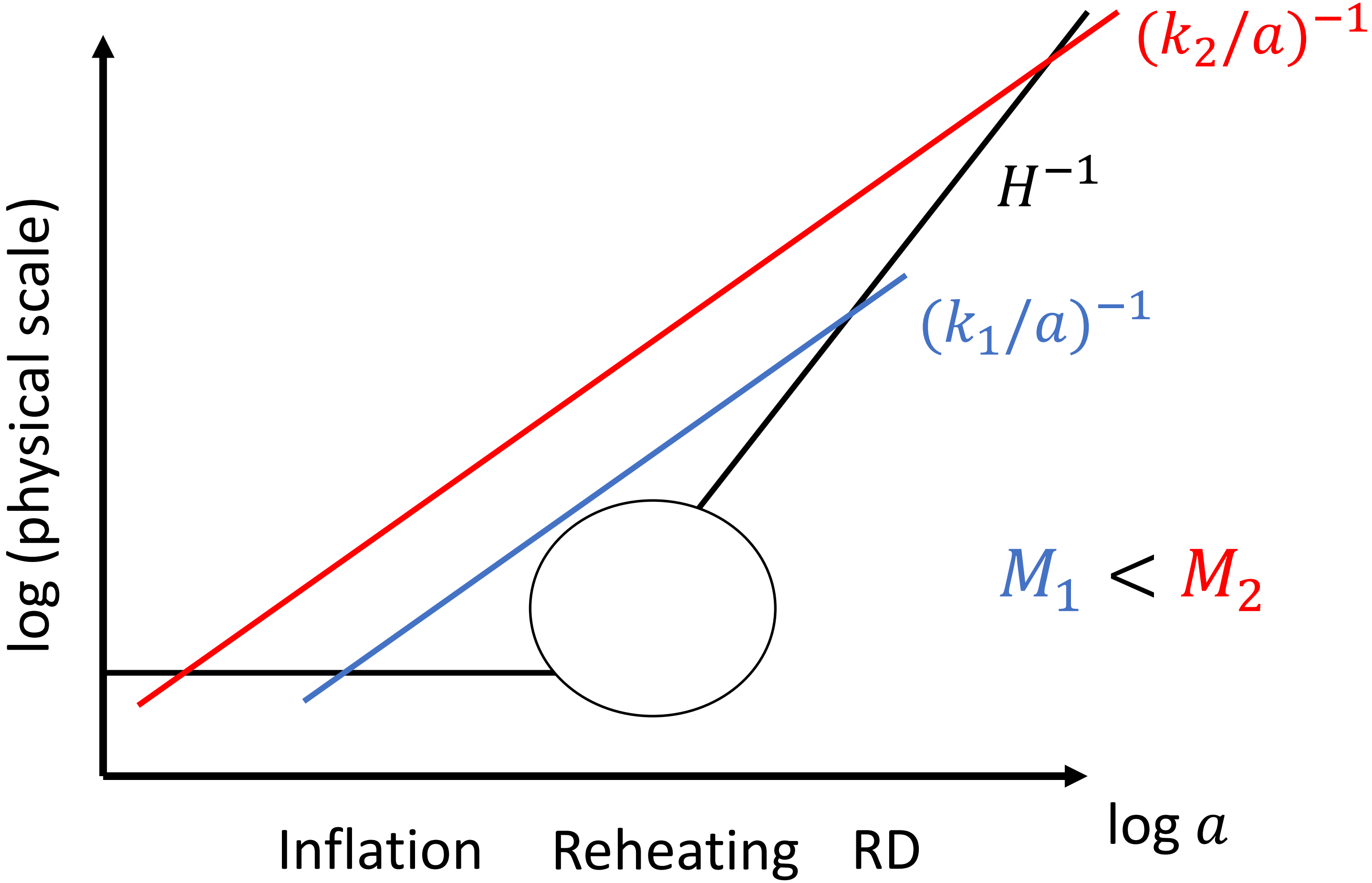


Carr (1975)

Primordial black holes from early Universe

- PBH mass depends on formation time (here focus on the PBHs form in RD era).



$M_1 < M_2$

PBH mass at formation is proportional to the horizon mass

$$M_{\rm ini} = \gamma \frac{4\pi \rho_{\rm ini}}{3H_{\rm ini}^3} = 4\pi\gamma \frac{M_{\rm pl}^2}{H_{\rm ini}} \propto t_{\rm ini}$$

Primordial black holes from early Universe

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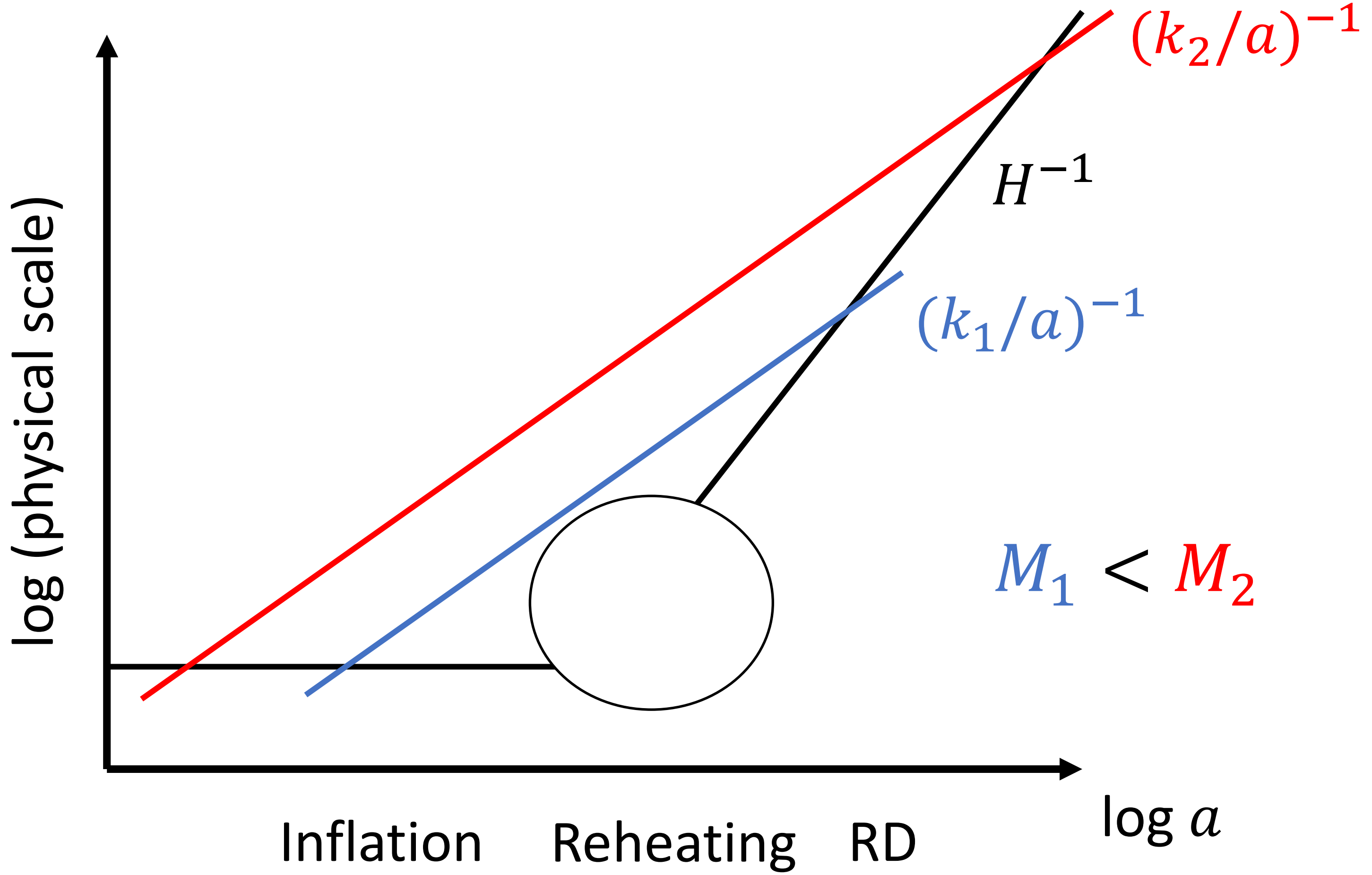

PBH mass at formation is proportional to the horizon mass

Upper bound on inflation scale

⬇

Lower bound on PBH mass $\gtrsim 0.4$ g

Primordial black holes from early Universe

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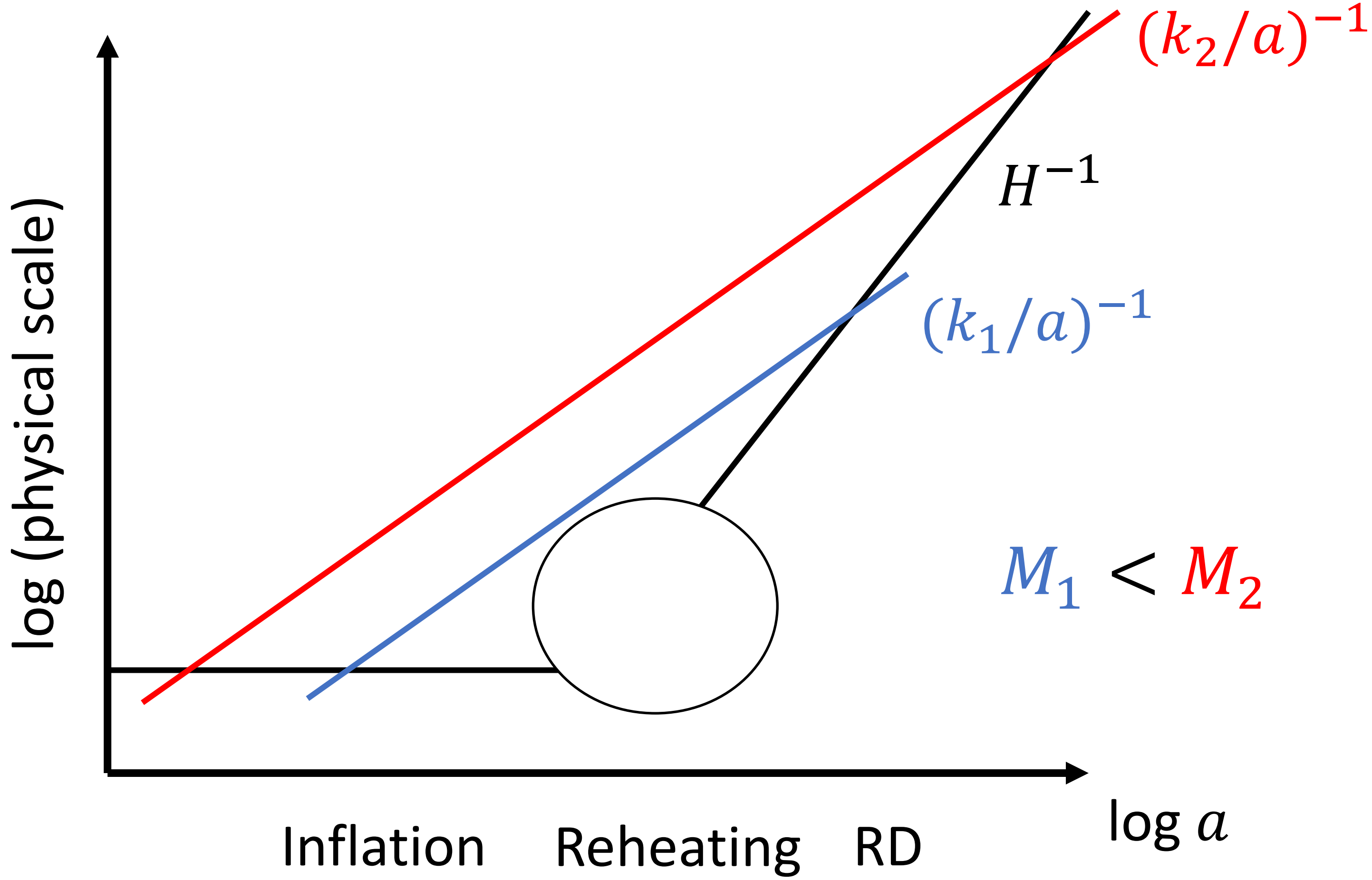


PBH mass at formation is proportional to the horizon mass

$$M_{\rm ini} \sim 10^9 {\rm g} \left(\frac{\gamma}{0.2}\right)\left(\frac{t_{\rm ini}}{10^{-29}{\rm s}}\right)$$

Primordial black holes from early Universe

- Assume RD right after the PBH evaporation. Then, using the lifetime of these PBHs, one can estimate the temperature of the Universe at evaporation

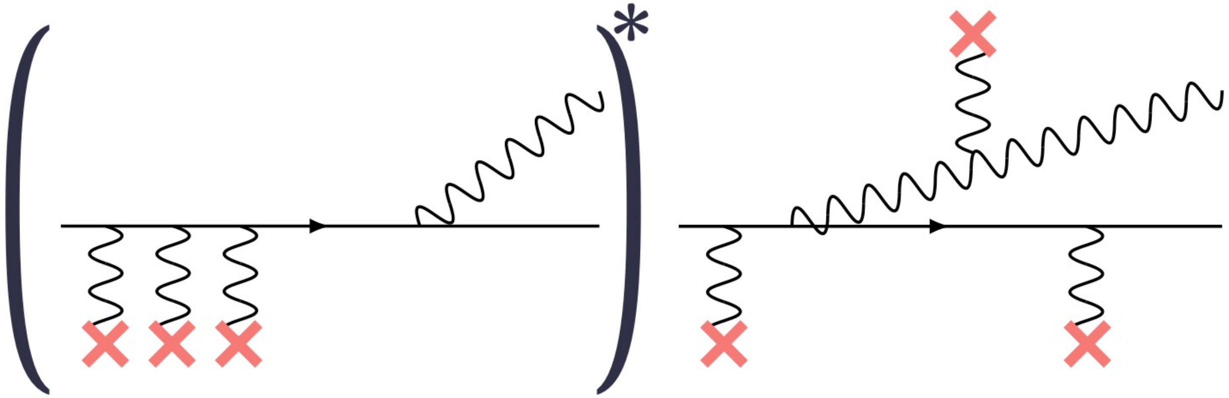
$$T_{\rm ev} \sim \mathcal{O}(1)\mathrm{MeV}\left(\frac{M_{\rm ini}}{10^9\mathrm{g}}\right)^{-3/2}$$

$$\ll \quad T_{\rm BH} = M_{\rm pl}^2/M \simeq 1.1 \times 10^4 \mathrm{GeV}(M/10^9\mathrm{g})^{-1}$$

➡ Before evaporation, the Hawking temperature will become much higher than the temperature of the ambient plasma. This fact is essential for the discussion of thermalization of the Hawking radiation from these PBHs.

Landau-Pomeranchuk-Migdal (LPM) effect

- Thermalization process of a high-energy particle is dominated by the emission of soft daughter particles. For $E_{\mathrm{particle}} \gg T_{\mathrm{plasma}}$, the thermalization process is suppressed by the LPM effect.

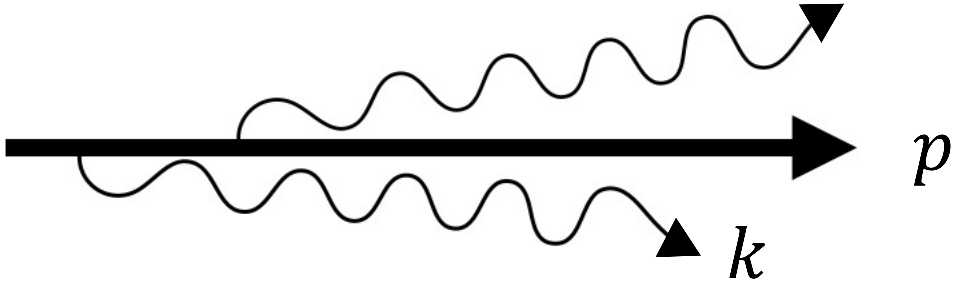


- destructive quantum interference

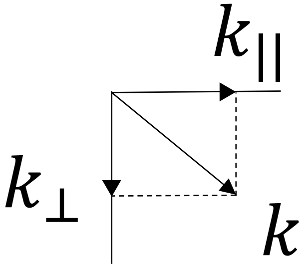
Landau, Pomeranchuk (1953), Migdal (1956)
Gyulassy, Wang (1994), Arnold, Moore, Yaffe (2001a,2001b,2002a,2002b), Besak, Bodeker (2010), Kurkela, Wiedmann (2014)

Landau-Pomeranchuk-Migdal (LPM) effect

- More intuitive understanding (relevant regime $p \gg T$)



Almost colinear so cannot separate from the mother particle



- Typical size of wave packet $\sim 1/k_\perp$
- Transverse velocity $\sim k_\perp/k$

Typical time scale to separate and form such a quantum $\sim t_{\mathrm{form}} \gtrsim k/k_\perp^2$

Landau, Pomeranchuk (1953), Migdal (1956)
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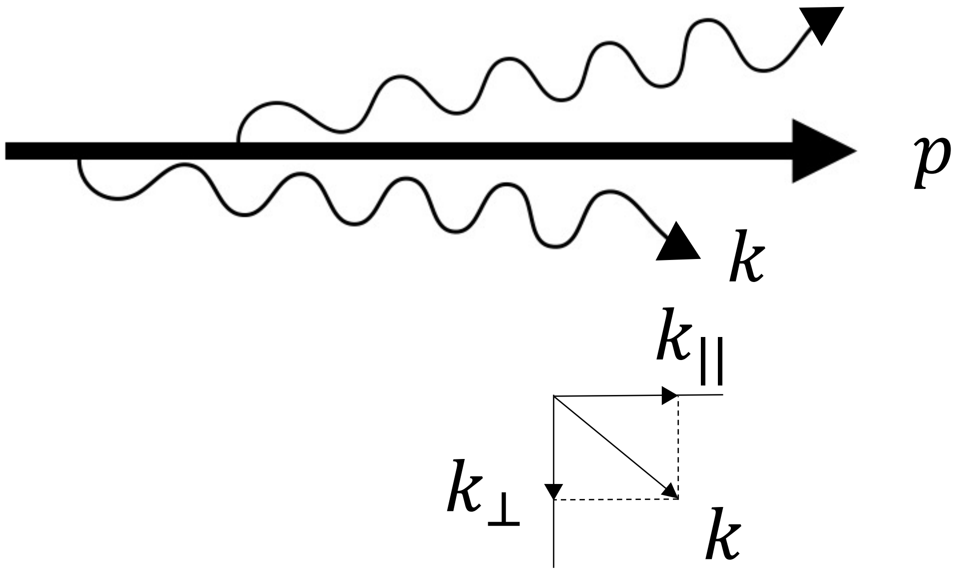

Almost colinear so cannot separate from the mother particle

- $t_{\text{form}} \gtrsim k/k_\perp^2$
- $k_\perp$ experiences Brownian motion in the medium

α: collective notation for small fine structure constant

$$\langle k_\perp^2 \rangle \sim \alpha^2 T^3 t$$

Landau, Pomeranchuk (1953), Migdal (1956)
Gyulassy, Wang (1994), Arnold, Moore, Yaffe (2001a,2001b,2002a,2002b),
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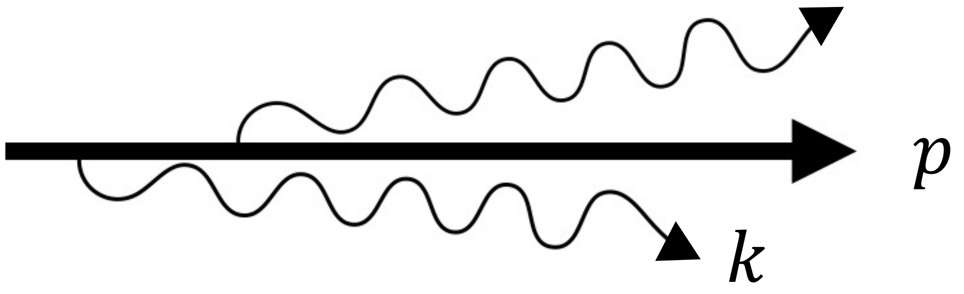

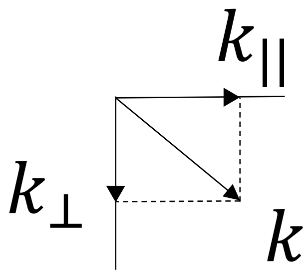

Almost colinear so cannot separate from the mother particle

$$t_{\rm form} \sim \alpha^{-1}\sqrt{k/T^3}$$

Momentum of the daughter particle

Landau, Pomeranchuk (1953), Migdal (1956)
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- More intuitive understanding (relevant regime $p \gg T$)

$$t_{\rm form} \sim \alpha^{-1}\sqrt{k/T^3}$$

In a weakly coupled theory, this only means that there is a probability $\sim\alpha$ to emit such a particle.

$$\Gamma_{\rm LPM}(\boxed{k}, T) \equiv \alpha\ t_{\rm form}^{-1} \sim \alpha^2\sqrt{T^3/k}$$

Momentum of the daughter particle

Landau, Pomeranchuk (1953), Migdal (1956)
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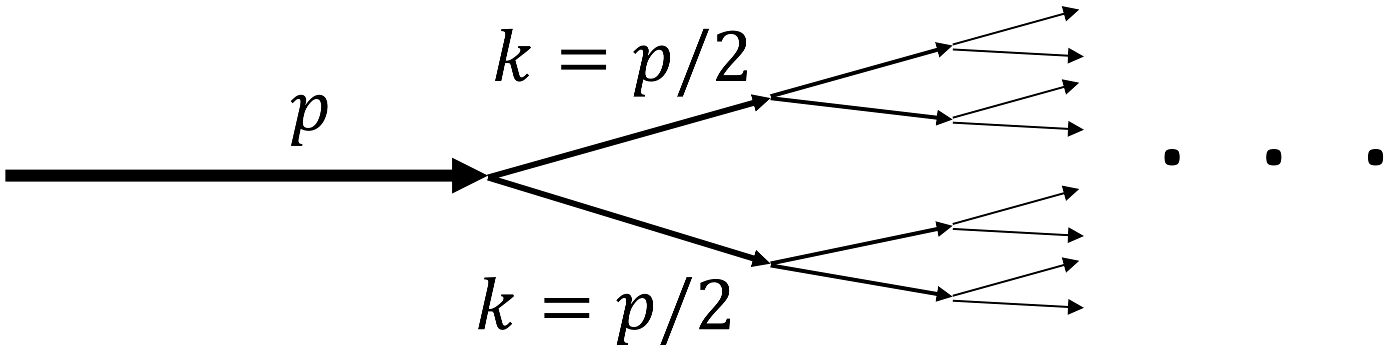

Need a series of splittings with subsequent splittings take shorter time. Estimate as $t_{\mathrm{th}}(p,T) \equiv 1/\Gamma_{\mathrm{LPM}}(p,T)$

Momentum of hard primary

Landau, Pomeranchuk (1953), Migdal (1956)
Gyulassy, Wang (1994), Arnold, Moore, Yaffe (2001a,2001b,2002a,2002b),
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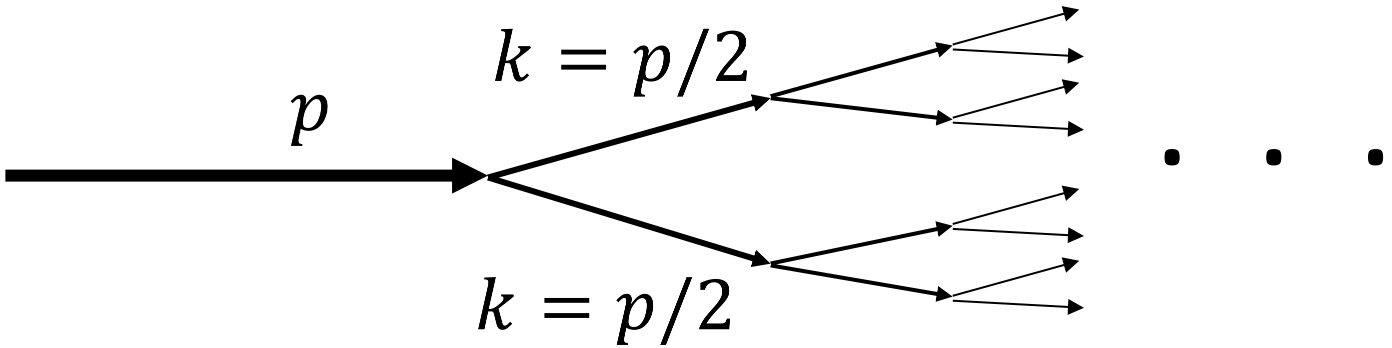


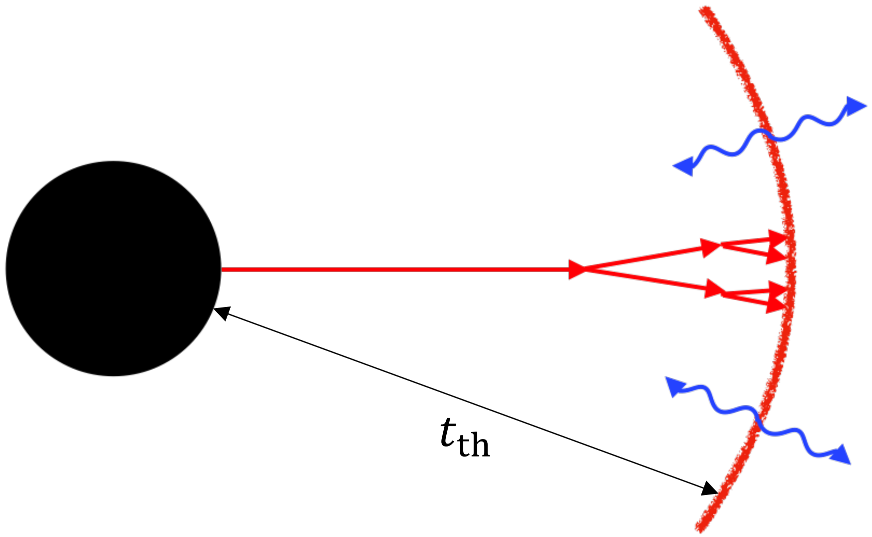
Need a series of splittings with subsequent splittings take shorter time. Estimate as $t_{\rm th}(p,T) \equiv 1/\Gamma_{\rm LPM}(p,T)$ Not instantaneous

Second time scale: thermalization (LPM rate)

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

Diffusion

- For $t \gtrsim t_{\rm th}$, the high energy particles from the PBH get thermalized and deposit their energy into the shell $r \simeq t_{\rm th}$ (before that the particle travels with speed of light). This energy will then diffuse (random walk process) into other part of the ambient plasma.



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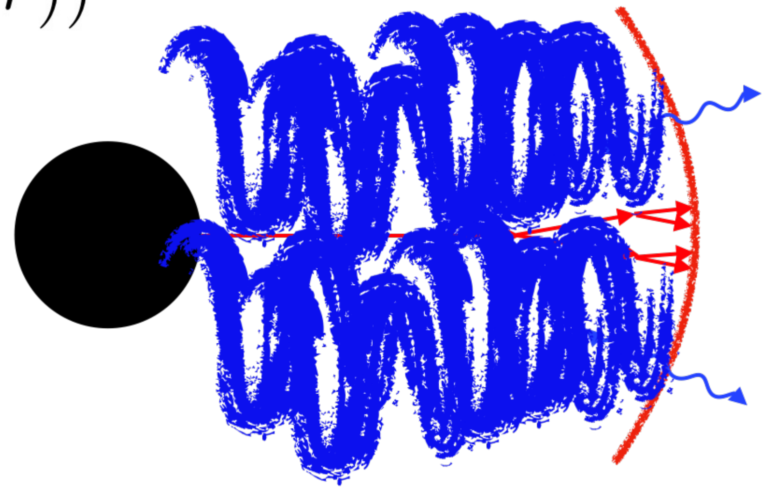
Diffusion length $r_{\rm d}(t, T(r)) \sim \sqrt{t/(\alpha^2 T(r))}$

→ Two important more scales



1. $r_{\rm d}(t_{\rm d}, T) = t_{\rm th}(T_{\rm BH}(M), T)$

Time scale for diffusion to cover $t_{\rm th}$.

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➡ Two important more scales

1. $r_{\rm d}(t_{\rm d}, T) = t_{\rm th}(T_{\rm BH}(M), T)$
   Time scale for diffusion to cover $t_{\rm th}$.

2. $r_{\rm dec}$ ⬅ $r_{\rm d} = r_{\rm d}(t_{\rm ev}(M), T(r_d))$
   Max distance that diffusion can cover within a given BH lifetime (or M).

Temperature profile around a PBH

- Regime 1: $t \lesssim t_{\rm ev}(M_{\rm ini})$

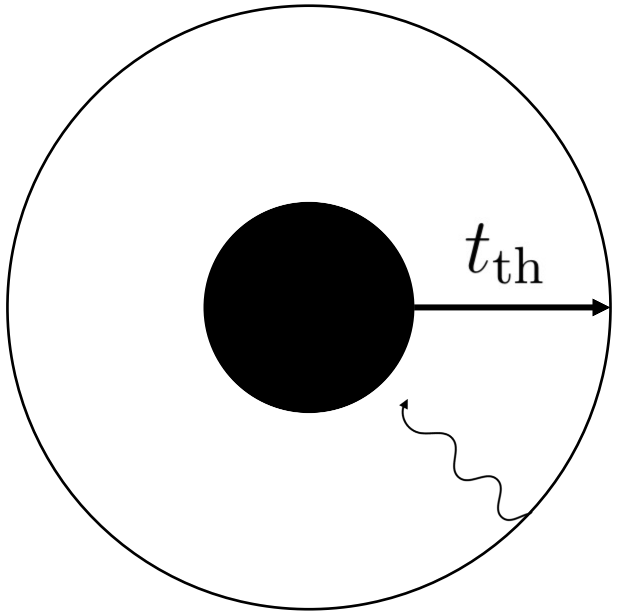
Black hole mass is almost unchanged.

If $t_{\rm d} < t_{\rm ev}$, the diffusion can cover $t_{\rm th}$

➡ A core in equilibrium

$M > M_* \simeq 0.8\ {\rm g}$

c.f. Lower bound on PBH mass $\gtrsim 0.4$ g



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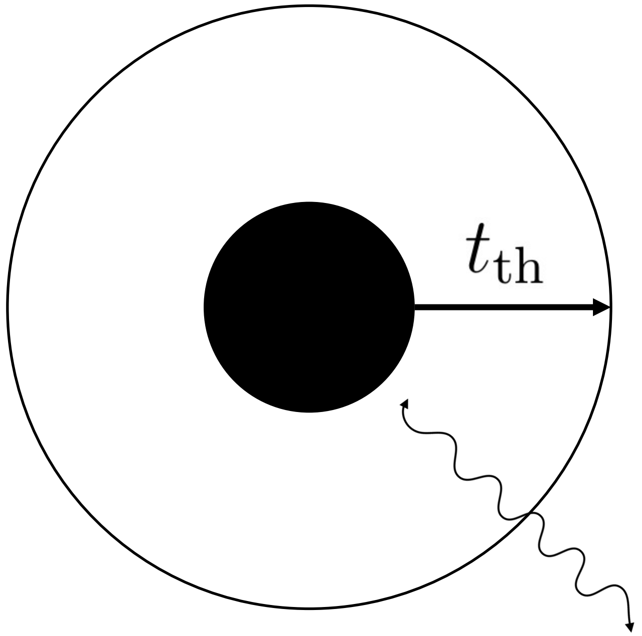

Energy conservation

⟹ $T(r \gtrsim t_{\mathrm{th}}) \propto r^{-1/3}$

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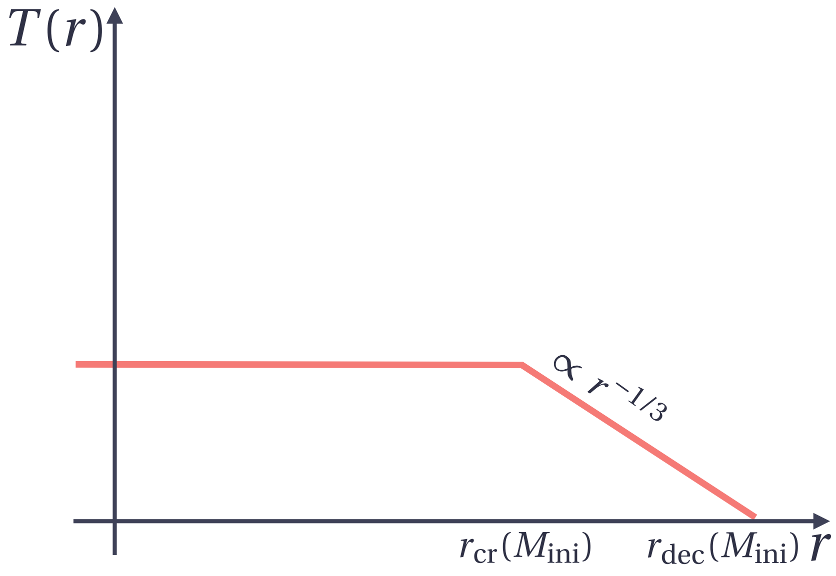
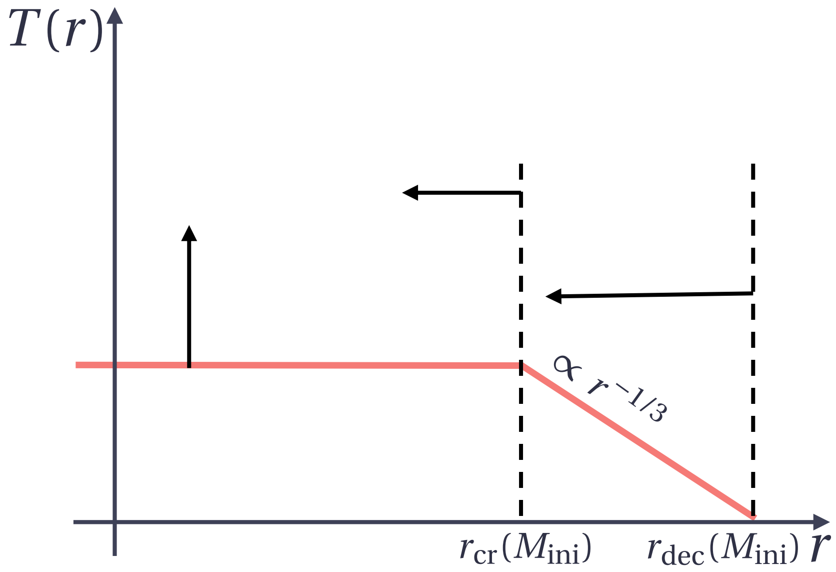


Temperature profile around a PBH

- Regime 2: $M_* \lesssim M \lesssim M_{\rm ini}$ $\quad$ ($M > M_* \simeq 0.8\ {\rm g}$ still satisfied)

Change of black hole mass is not neglibile. Simply change the previous analysis by replacing the constant mass with a time-dependent mass.



➡

$$r_{\rm cr} \propto M$$

$$r_{\rm dec} \propto M^{11/5}$$

➡ $\propto r^{-1/3}$ regime is getting narrower

Temperature profile around a PBH

- Regime 2: $M_* \lesssim M \lesssim M_{\rm ini}$ $({\color{blue} M > M_* \simeq 0.8\ \mathrm{g}}$ still satisfied)

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$$r_{\rm cr} \propto M$$

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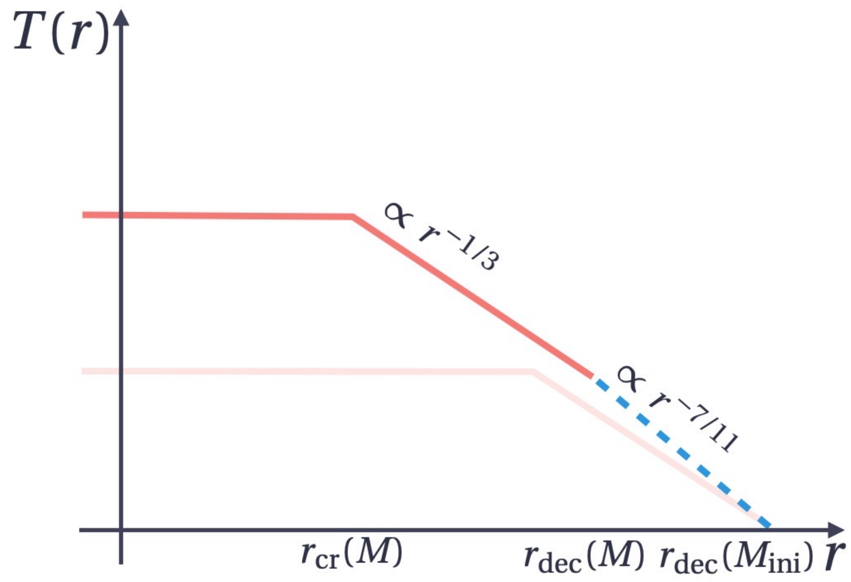
$$T \propto r^{-7/11}$$



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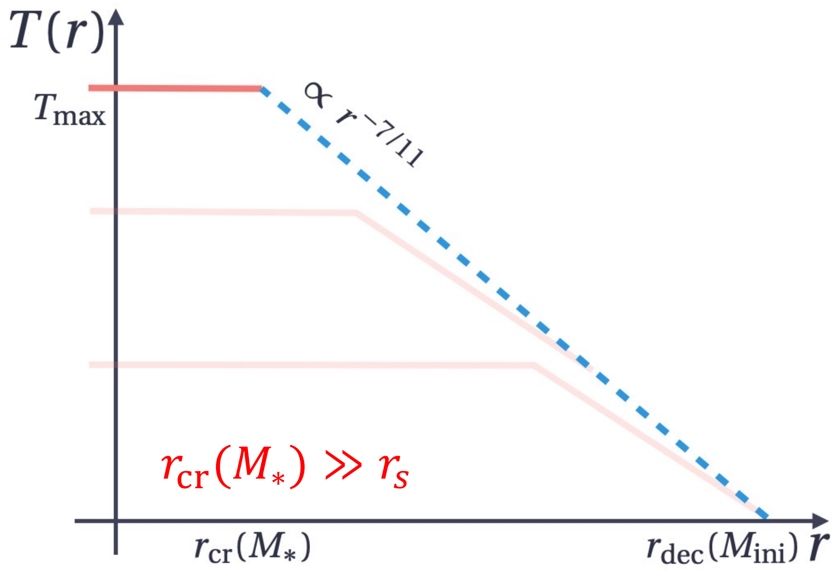


$$T_{\rm max} \equiv T(r < r_{\rm cr})|_{M_*} \simeq 2 \times 10^9 \,{\rm GeV} \left(\frac{\alpha}{0.1}\right)^{\frac{19}{3}} \left(\frac{g_*}{106.75}\right)^{-\frac{4}{3}} \left(\frac{g_{H*}}{108}\right)^{\frac{5}{6}}$$ at $M = M_*$

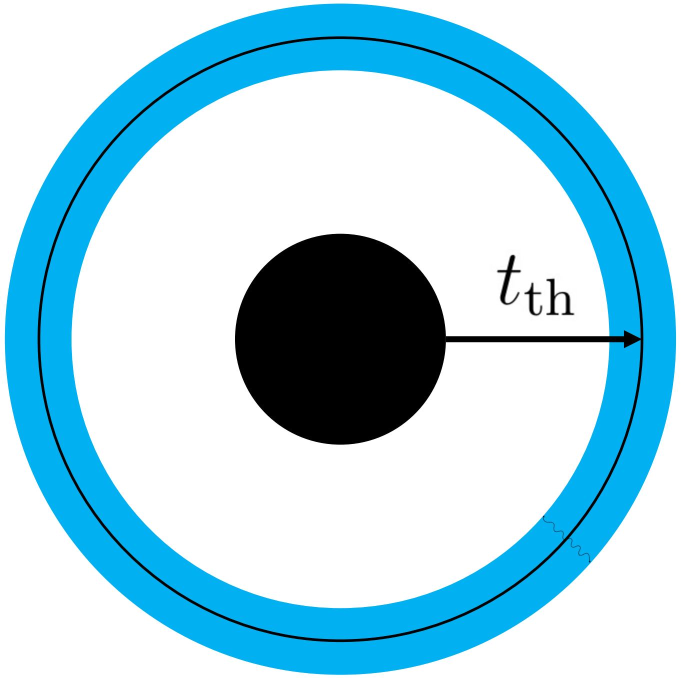
Independent of the initial black hole mass

Temperature profile around a PBH

- Regime 3: $M < M_*$

Diffusion can no longer cover the core.

➡ High-temperature shell at $t_{\rm th}$?



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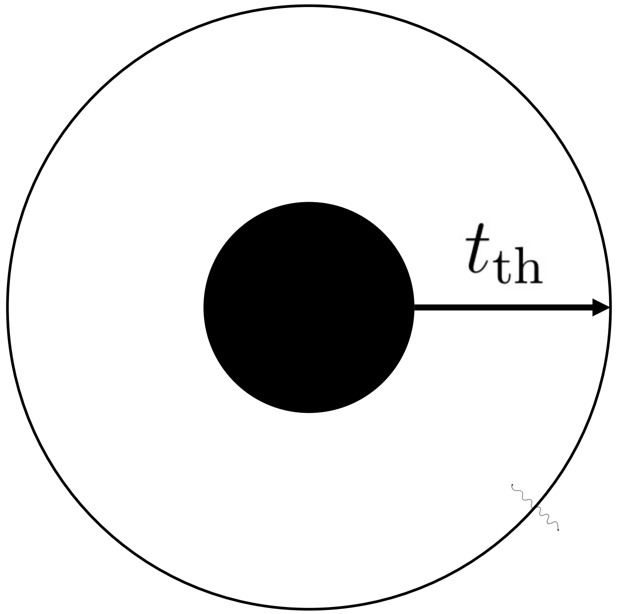


Actually no because

1. Hawking temperature is higher at later time

➡ more LPM-suppressed

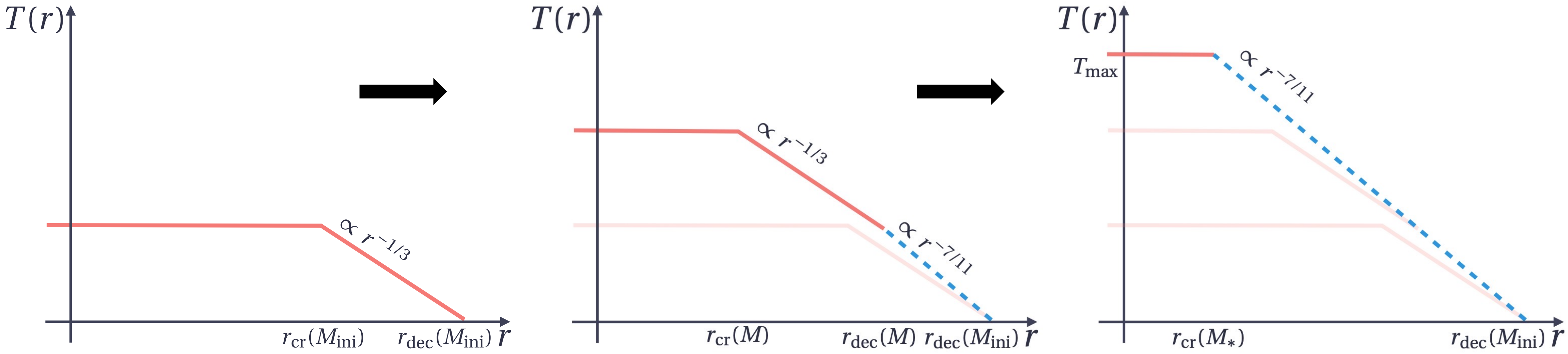
➡ energy deposited in larger radius

2. Less total energy at later time as the black hole mass is getting smaller

➡ Smaller energy density hence smaller $T \propto \rho^{1/4}$

Summary

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



Discussion

- Sphaleron and baryon asymmetry
    - Estimation of the volume fraction
    - Lepton number
- Symmetry restoration and topological defects
    - E.g. dark monopoles (c.f. Das, Hook (2021) GUT monopoles)
    - Vacuum decay
- Heavy particle production
    - E.g. dark matter
    - Heavy right-handed neutrinos

Thank you for your attention!

Back up

LPM effect vs small-angle elastic scattering

Energy loss rate

- LPM

$$\frac{1}{E}\,\frac{\mathrm{d}E}{\mathrm{d}t}\bigg|_{\mathrm{inel}} \sim \frac{1}{E}\int^{E/2} \mathrm{d}k\,\Gamma_{\mathrm{LPM}}(k,T) \sim \alpha^2 T\sqrt{\frac{T}{E}}$$

- Small angle scattering

$$\frac{1}{p}\,\frac{\mathrm{d}p}{\mathrm{d}t}\bigg|_{\mathrm{el}} \sim \frac{\alpha T}{p} \times \alpha T \sim \alpha^2 T\sqrt{\frac{T}{p}} \times \sqrt{\frac{T}{p}}$$

Harigaya, Kawasaki, Mukaida, Yamada (2014)

LPM effect vs small-angle elastic scattering

Energy loss rate

- LPM

$$\frac{1}{E}\,\frac{\mathrm{d}E}{\mathrm{d}t}\bigg|_{\mathrm{inel}} \sim \frac{1}{E}\int^{E/2} \mathrm{d}k\,\Gamma_{\mathrm{LPM}}(k,T) \sim \alpha^2 T\sqrt{\frac{T}{E}}$$

Dominant!

$\gg$

- Small angle scattering

$$\frac{1}{p}\,\frac{\mathrm{d}p}{\mathrm{d}t}\bigg|_{\mathrm{el}} \sim \frac{\alpha T}{p} \times \alpha T \sim \alpha^2 T\sqrt{\frac{T}{p}} \times \sqrt{\frac{T}{p}}$$

Harigaya, Kawasaki, Mukaida, Yamada (2014)