Hot Spots around Small PBHs

via In-medium Cascades of High-energy particles

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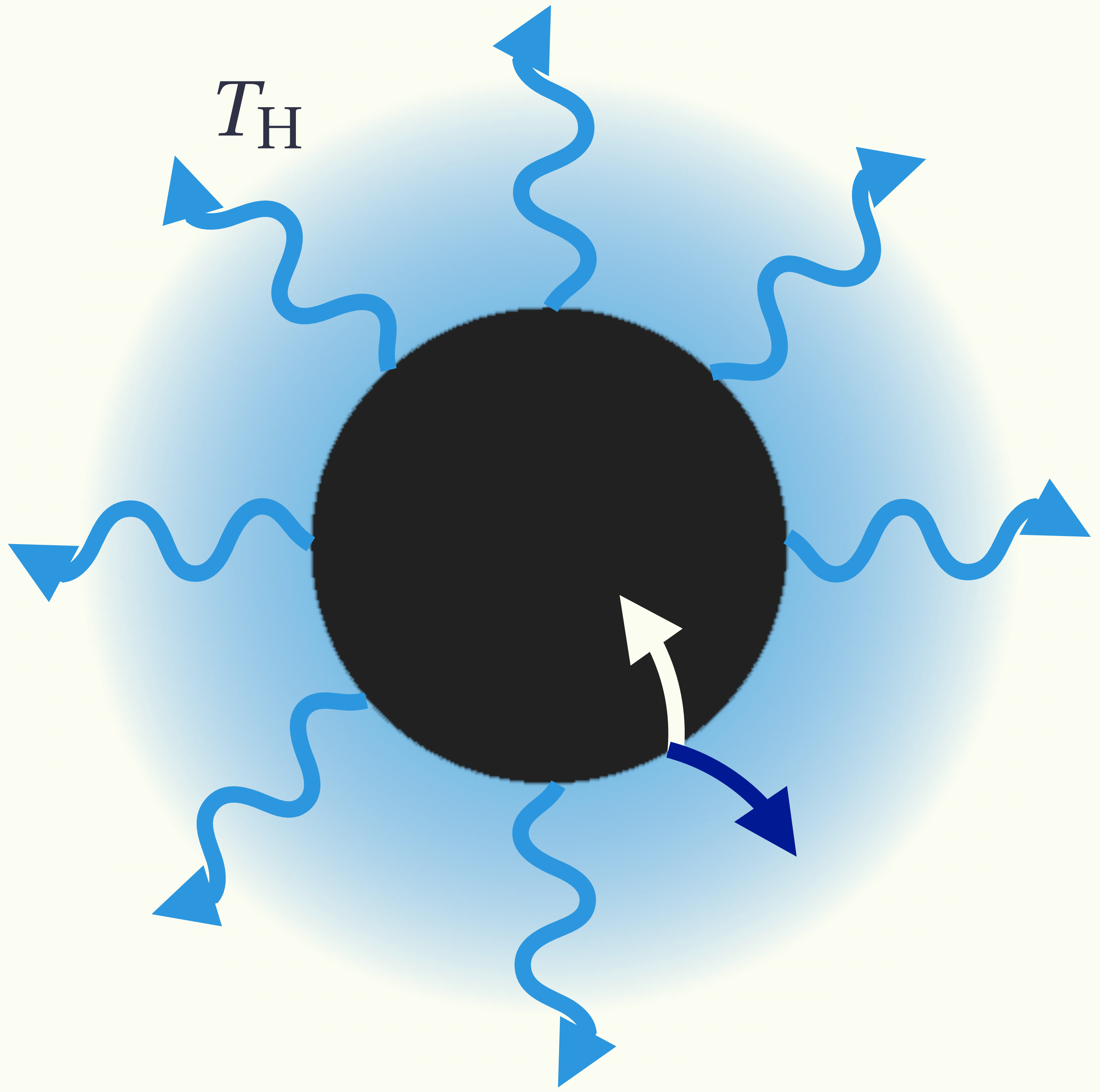
Introduction

Hawking radiation in a nutshell

- Hawking Temperature

$$T_{\mathrm{H}} = \frac{M_{\mathrm{Pl}}^2}{M} \simeq 10^4 \mathrm{GeV} \left(\frac{M}{10^9\ \mathrm{g}} \right)^{-1}$$

▶ particles w/ $\mathbf{T_H}$ emitted



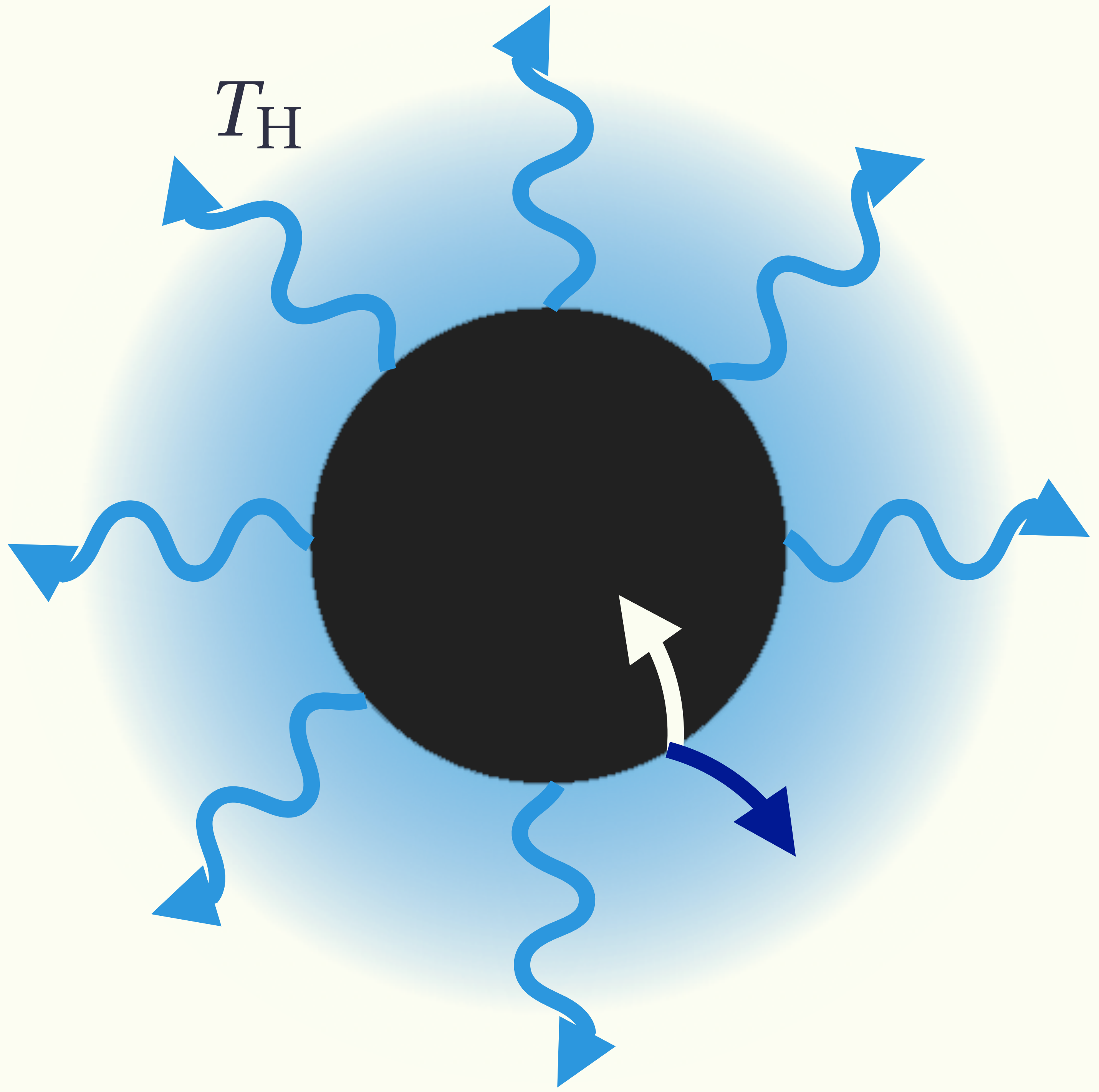
- Stefan-Boltzmann like radiation

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\mathcal{G} \frac{\pi^2}{120} g_{H*}(T_{\mathrm{H}}) T_{\mathrm{H}}^4 \times 4\pi r_{\mathrm{S}}^2 = -\frac{\pi \mathcal{G} g_{H*}(T_{\mathrm{H}})}{480} \frac{M_{\mathrm{Pl}}^4}{M^2}$$

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

Various mass range of Primordial Black Holes

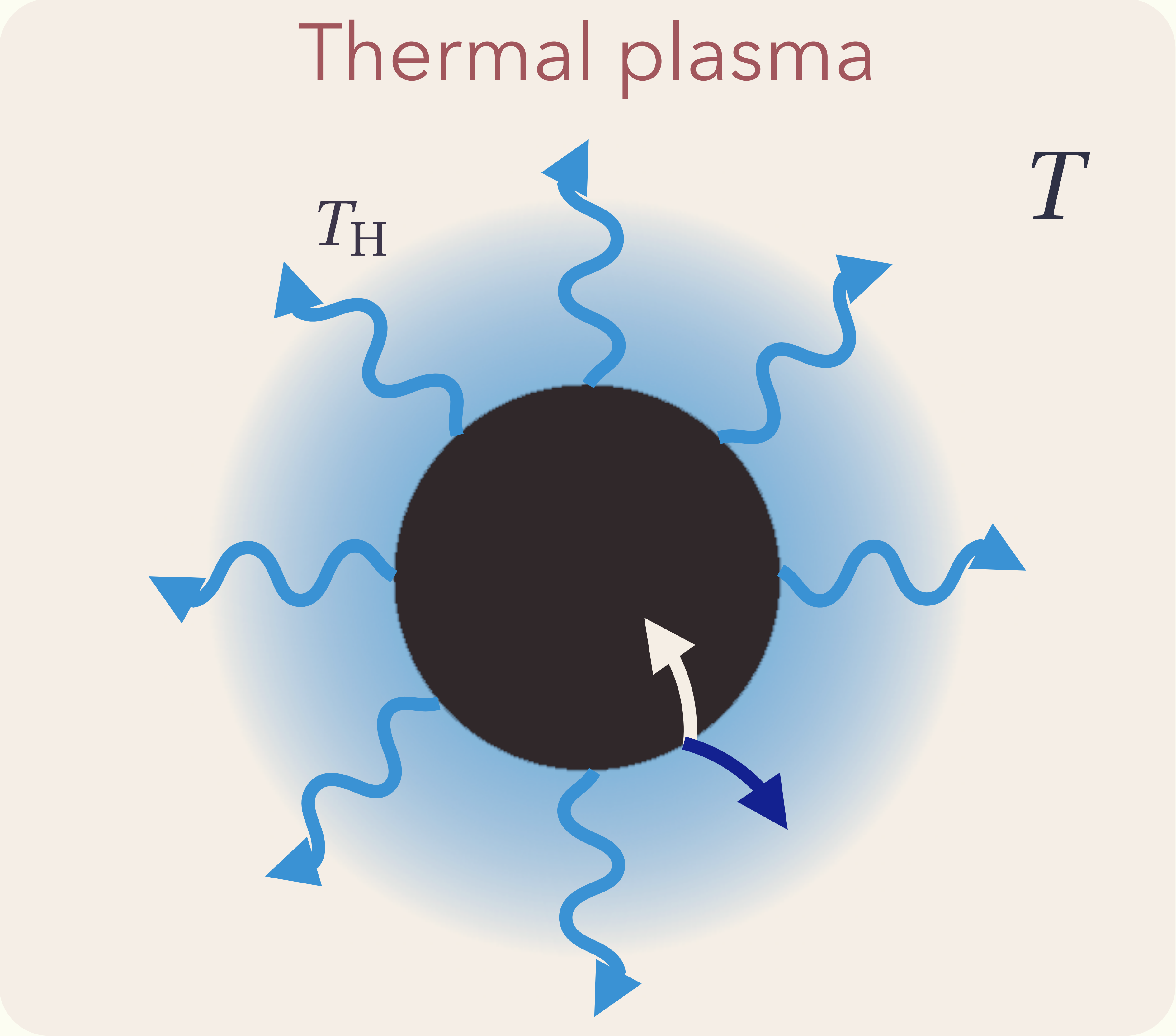
- Long-lived for mass > 10^{15} g
  - Dark Matter, BH-mergers, SMBH,…
- Evaporated by now for (10^9 g <) mass < 10^{15} g
  - extragalactic γ-ray bkg, CMB distortion, BBN distortion,…
- Evaporated before **BBN** for mass < 10^9 g
  ↪ "**Small**" PBHs
  - DM production, Baryo/Leptogenesis, enhanced GWs, induced vacuum decay,…



Small Primordial Black Holes

- **Extremely Hot Heater** in the primordial thermal plasma

[Das, Hook '21; He, Kohri, **KM**, Yamada 2210.06238]



- Energy of emitted particles

$$T_{\rm H} = \frac{M_{\rm Pl}^2}{M} \simeq 10^4 {\rm GeV} \left(\frac{M}{10^9\ {\rm g}}\right)^{-1}$$

↗ **Increases** by time

$\gg$

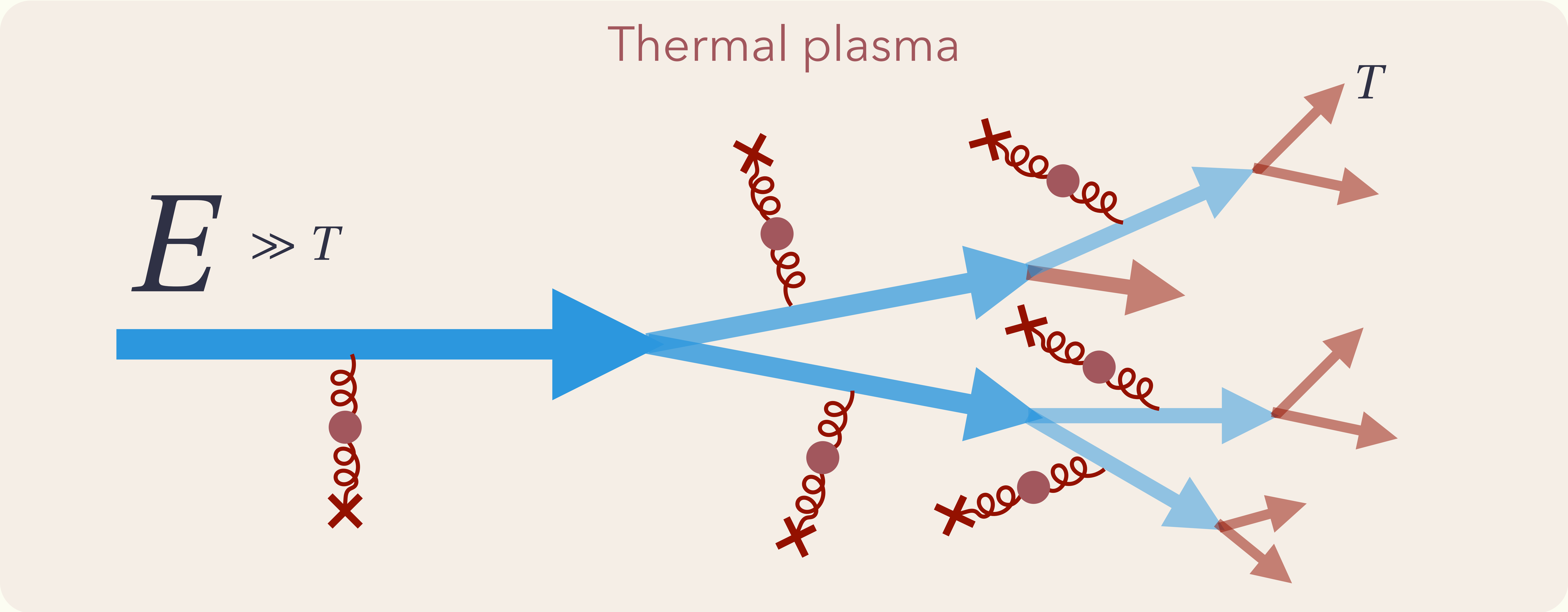
- Temperature of ambient plasma

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

Formation of Hot Spot

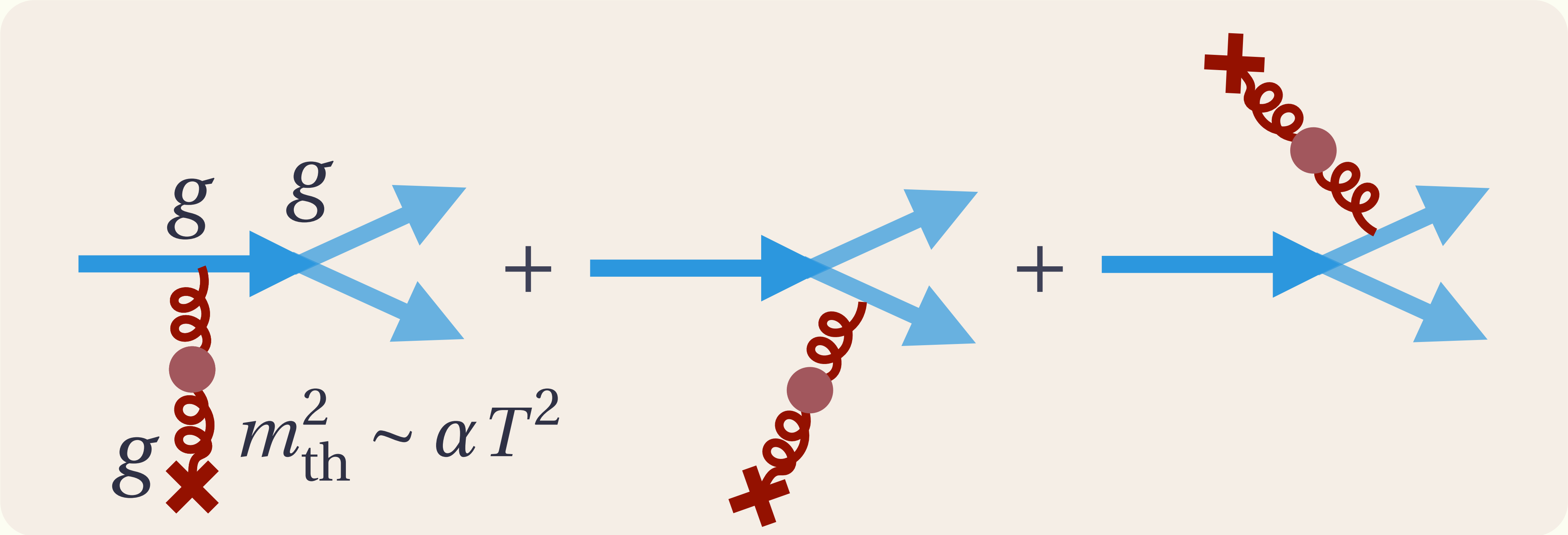
In-medium Cascade of High Energy Particles

- Cascades via multiple splittings



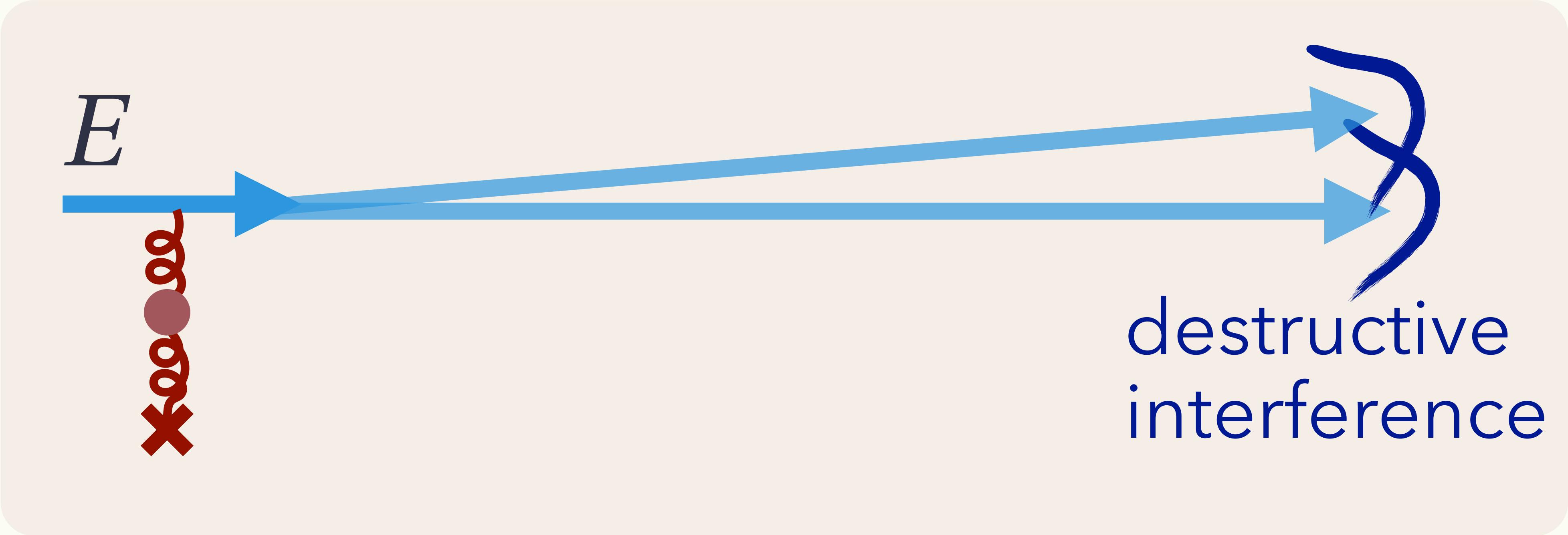
In-medium Cascade of High Energy Particles

- Bether-Heitler v.s. Landau-Pomeranchuk-Migdal
  - Bether-Heitler formula



$$\Gamma_{\mathrm{BH}} \sim \frac{\alpha^3}{m_{\mathrm{th}}^2} \times n_{\mathrm{th}} \sim \alpha^2 T \quad \text{(up to log)}$$

  - **Landau-Pomeranchuk-Migdal** suppression

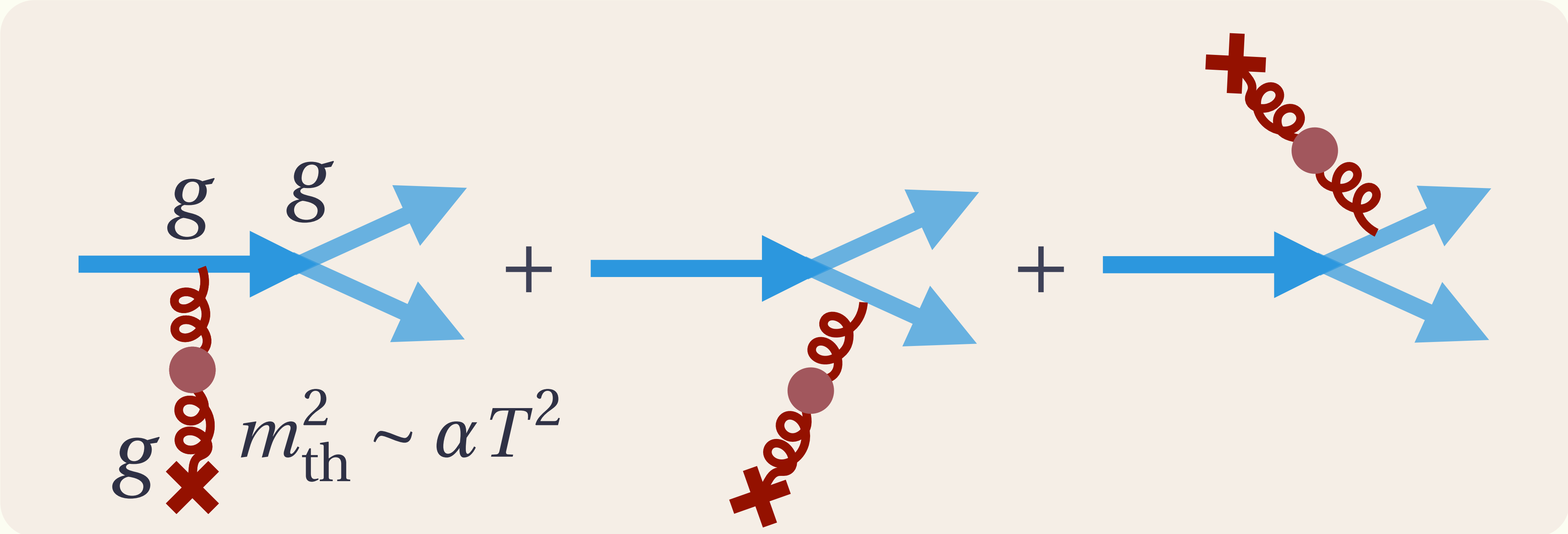


In-medium Cascade of High Energy Particles

- Bether-Heitler v.s. Landau-Pomeranchuk-Migdal

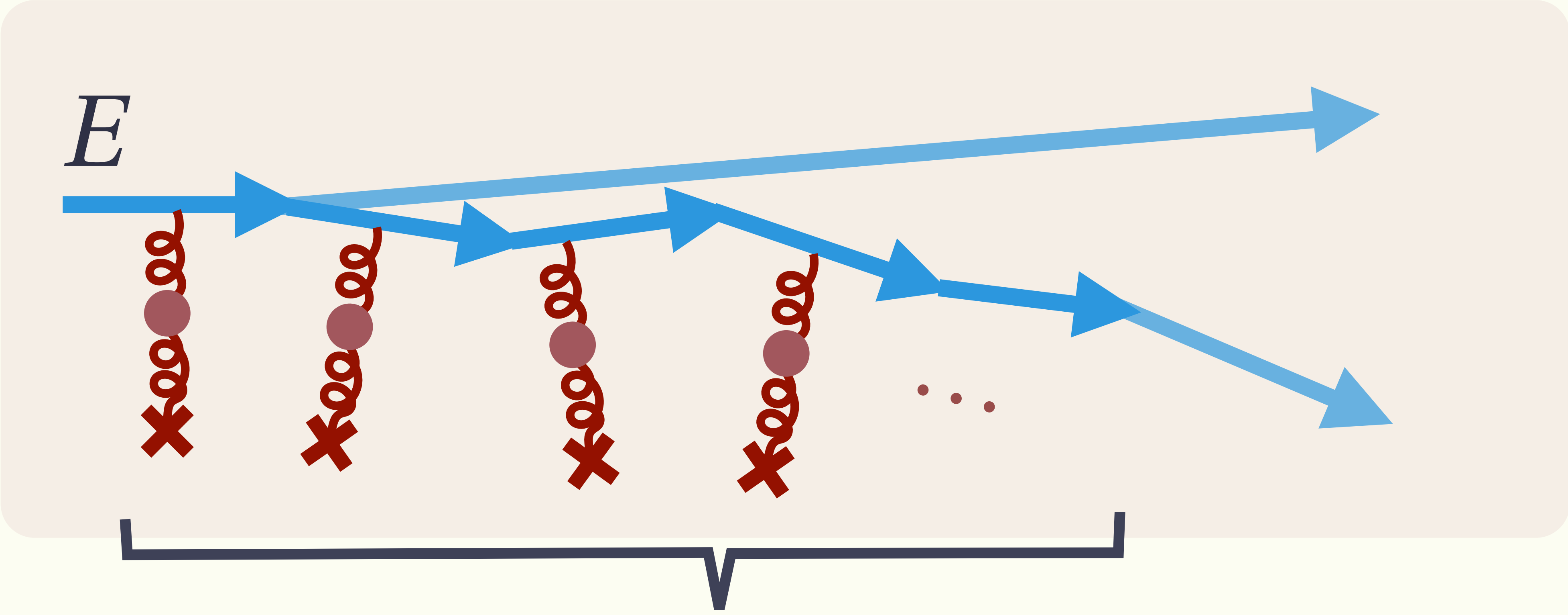
[Landau, Pomeranchuk; Migdal]

- Bether-Heitler formula



$$\Gamma_{\rm BH} \sim \frac{\alpha^3}{m_{\rm th}^2} \times n_{\rm th} \sim \alpha^2 T \quad \text{(up to log)}$$

- **Landau-Pomeranchuk-Migdal** suppression



Formation time $t_{\rm form} \sim \sqrt{E/(\alpha^2 T^3)}$

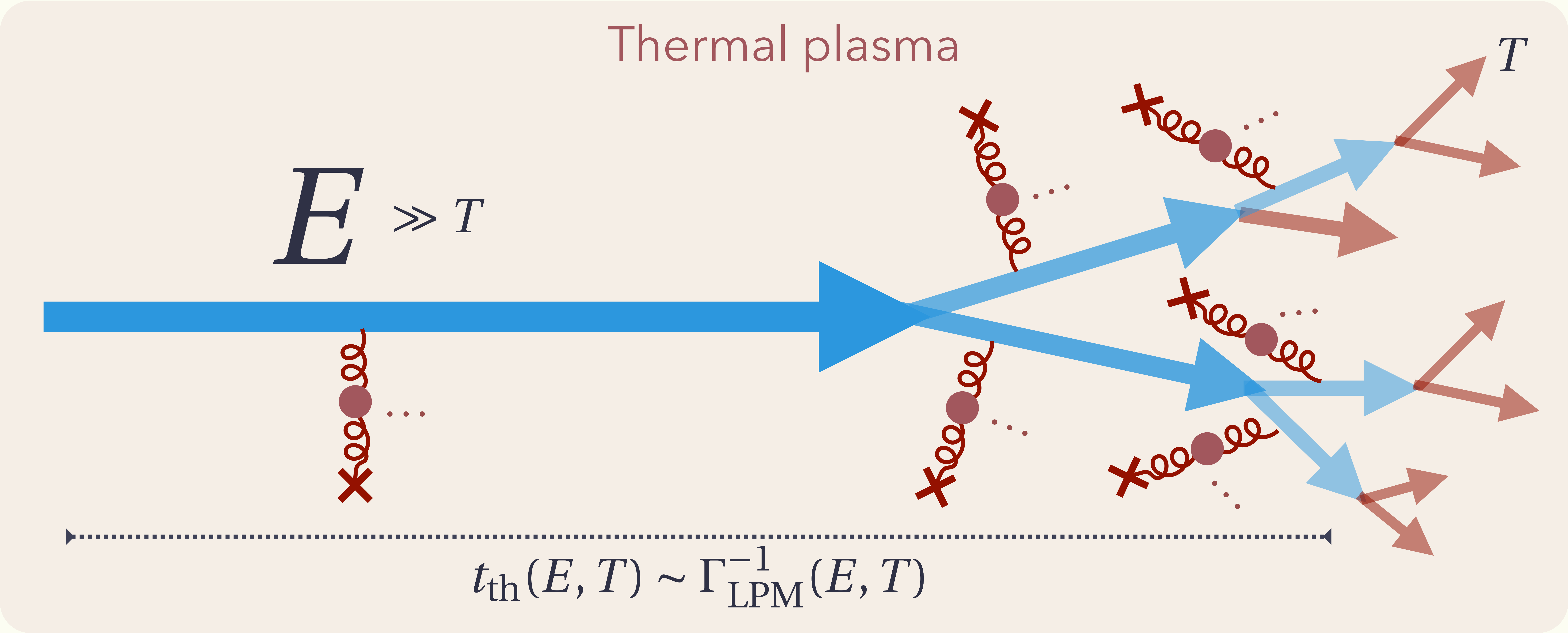
$$\Gamma_{\rm LPM} \sim \alpha\, t_{\rm form}^{-1} \sim \alpha^2 T \sqrt{T/E} \quad \text{(up to log)}$$

[Arnold, Morre, Yaffe '01,'02,'03; (**KM**+ 2208.11708 for SM)]

↪ Rate increases via the course of splittings

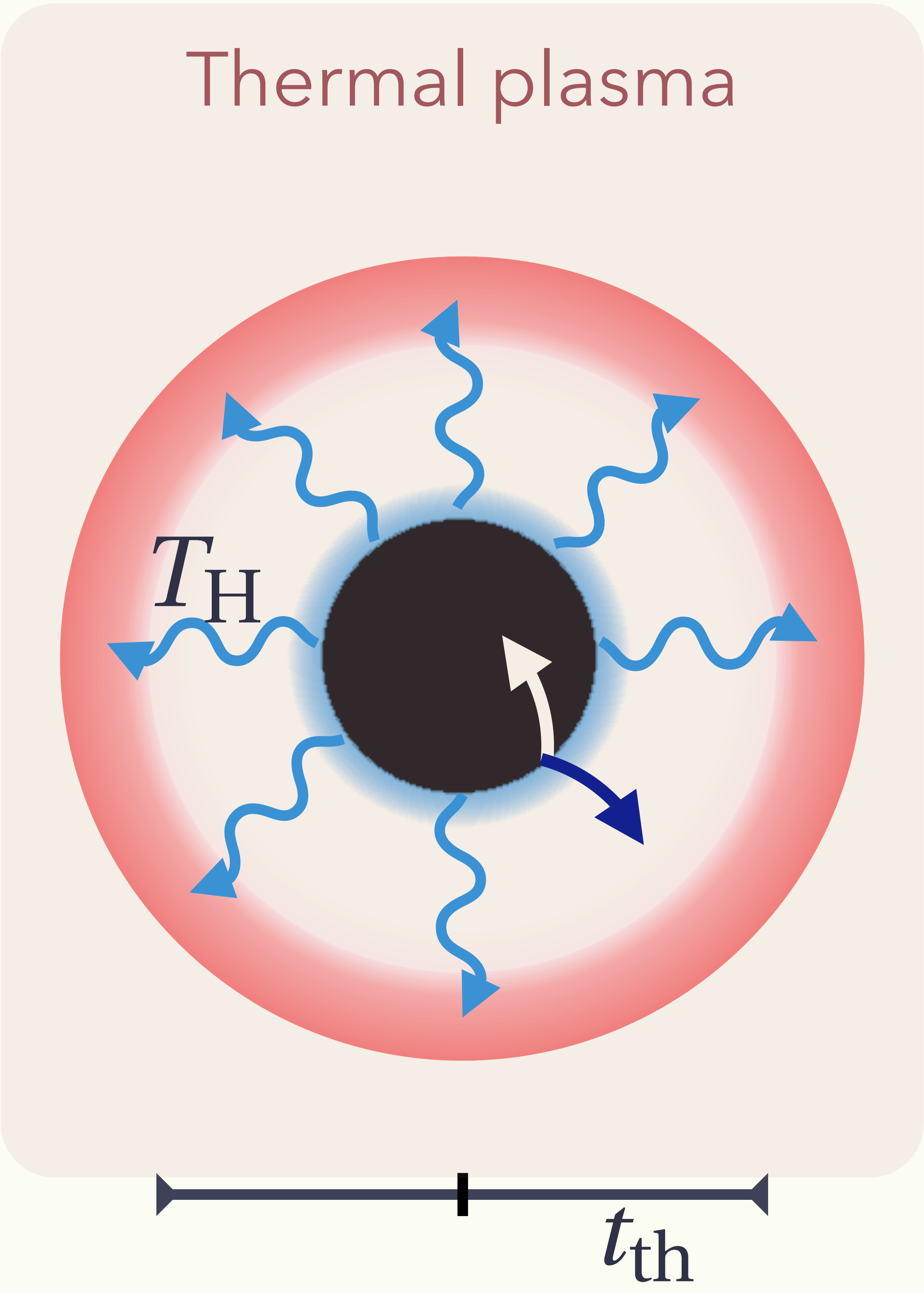
In-medium Cascade of High Energy Particles

- Cascades via multiple LPM-suppressed splittings



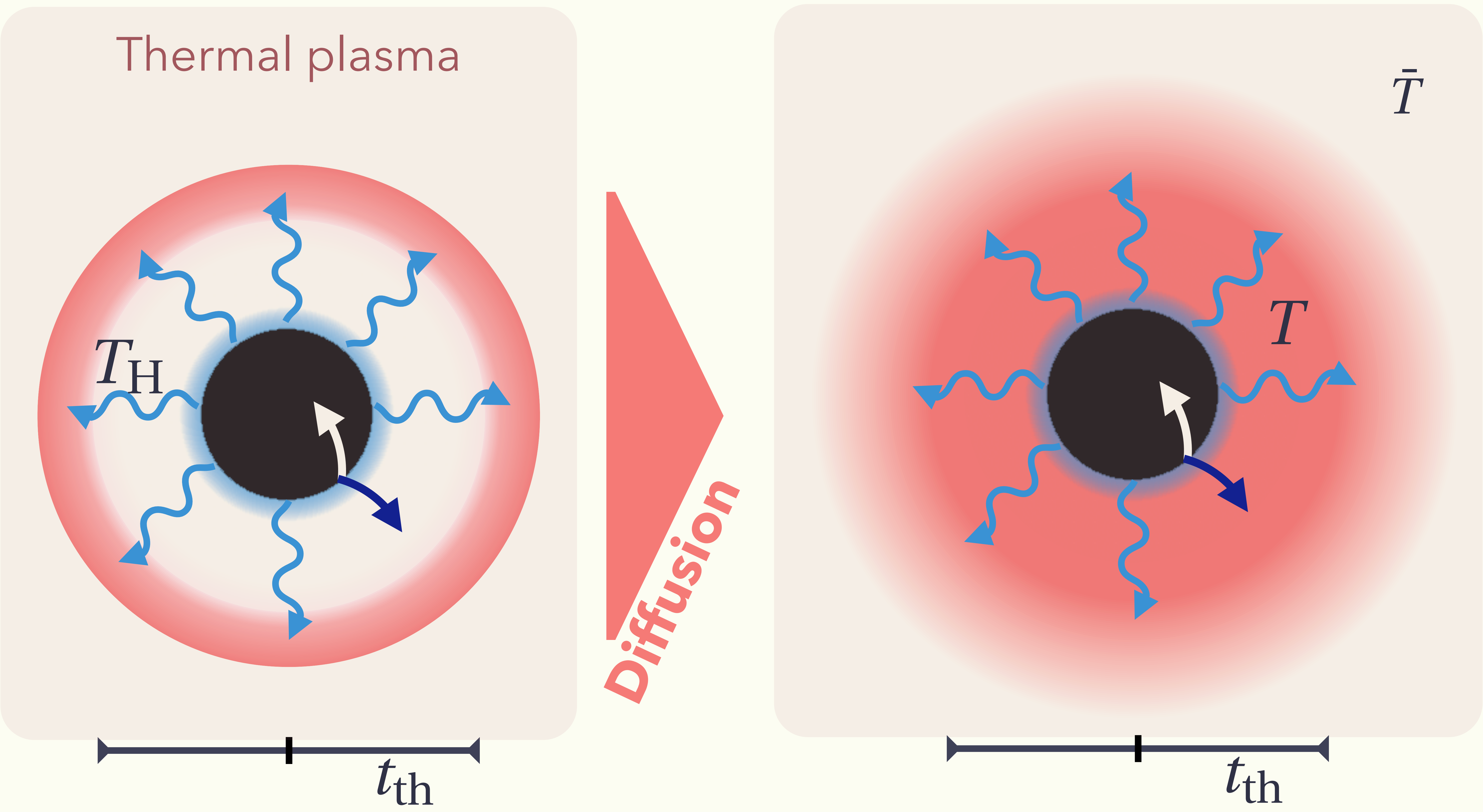
[He, Kohri, **KM,** Yamada **2210.06238**]

Cartoon of Hot-Spot Formation



Cartoon of Hot-Spot Formation

- LPM-suppression gives a cored T-profile



Diffusion via elastic scat.

$$t_{\rm th}^2 \sim (\alpha^2 T)^{-1} t_{\rm d} \quad \text{w/in } r < t_{\rm th}$$

Hot-spot formation

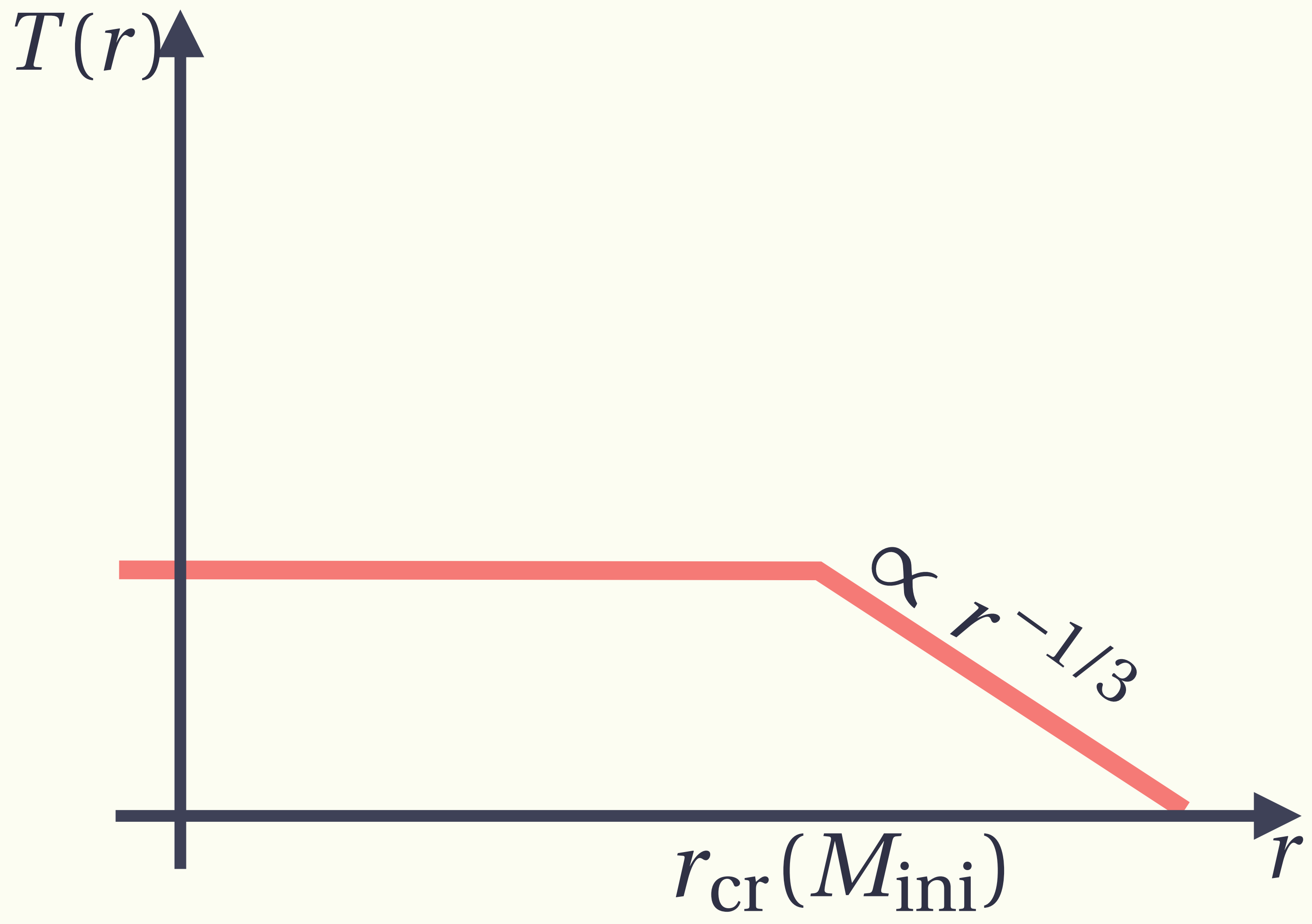
$$\frac{\pi^2 g_*}{30} T^4 \times \frac{4\pi}{3} t_{\rm th}^3 \simeq -t_{\rm d} \frac{dM}{dt}$$

$$\hookrightarrow T \sim 10^{-4} \left(\frac{\alpha}{0.1}\right)^{\frac{8}{3}} T_{\rm H} \ll T_{\rm H}$$

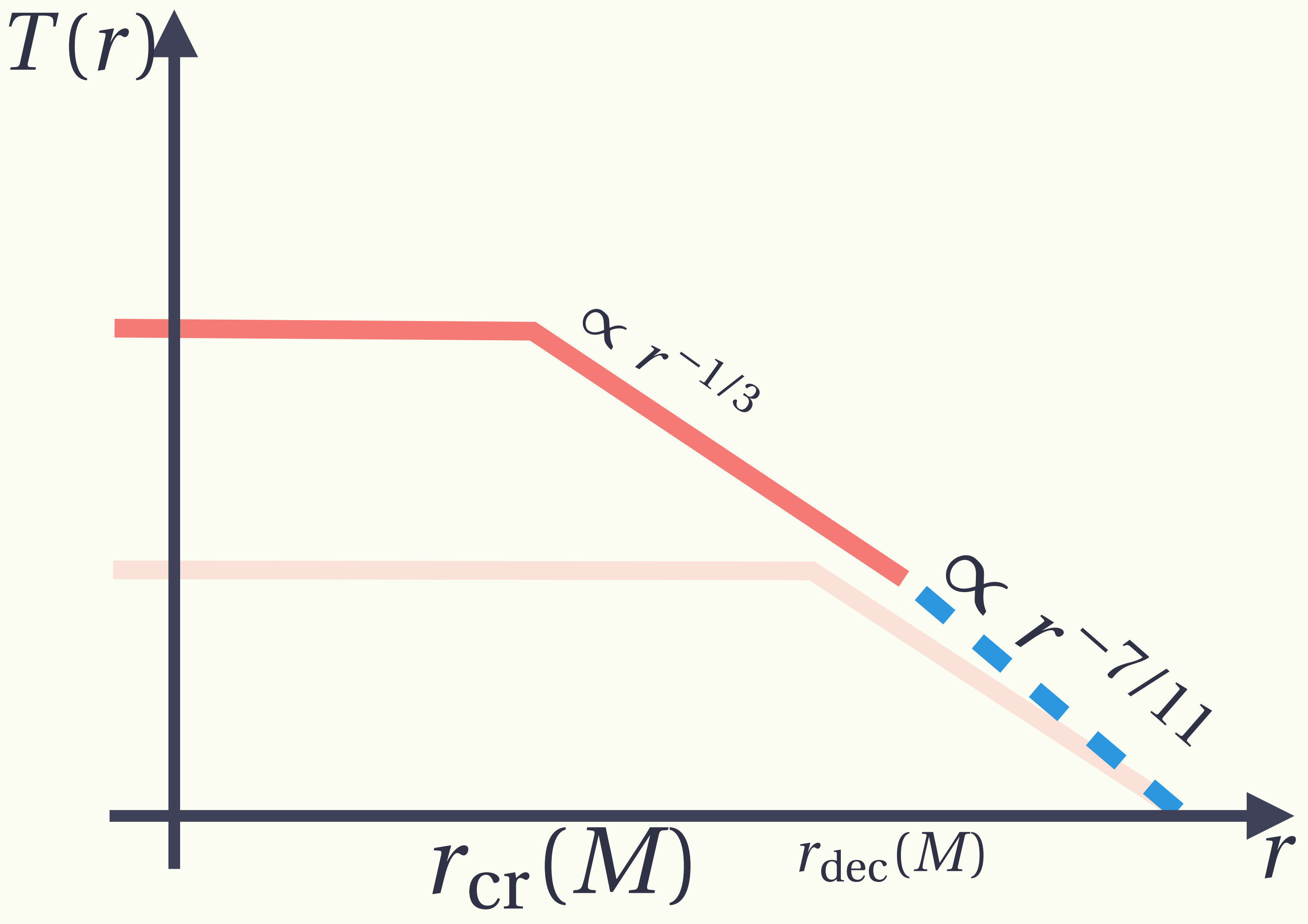
[He, Kohri, **KM,** Yamada **2210.06238**]

Cartoon of Hot-Spot Formation

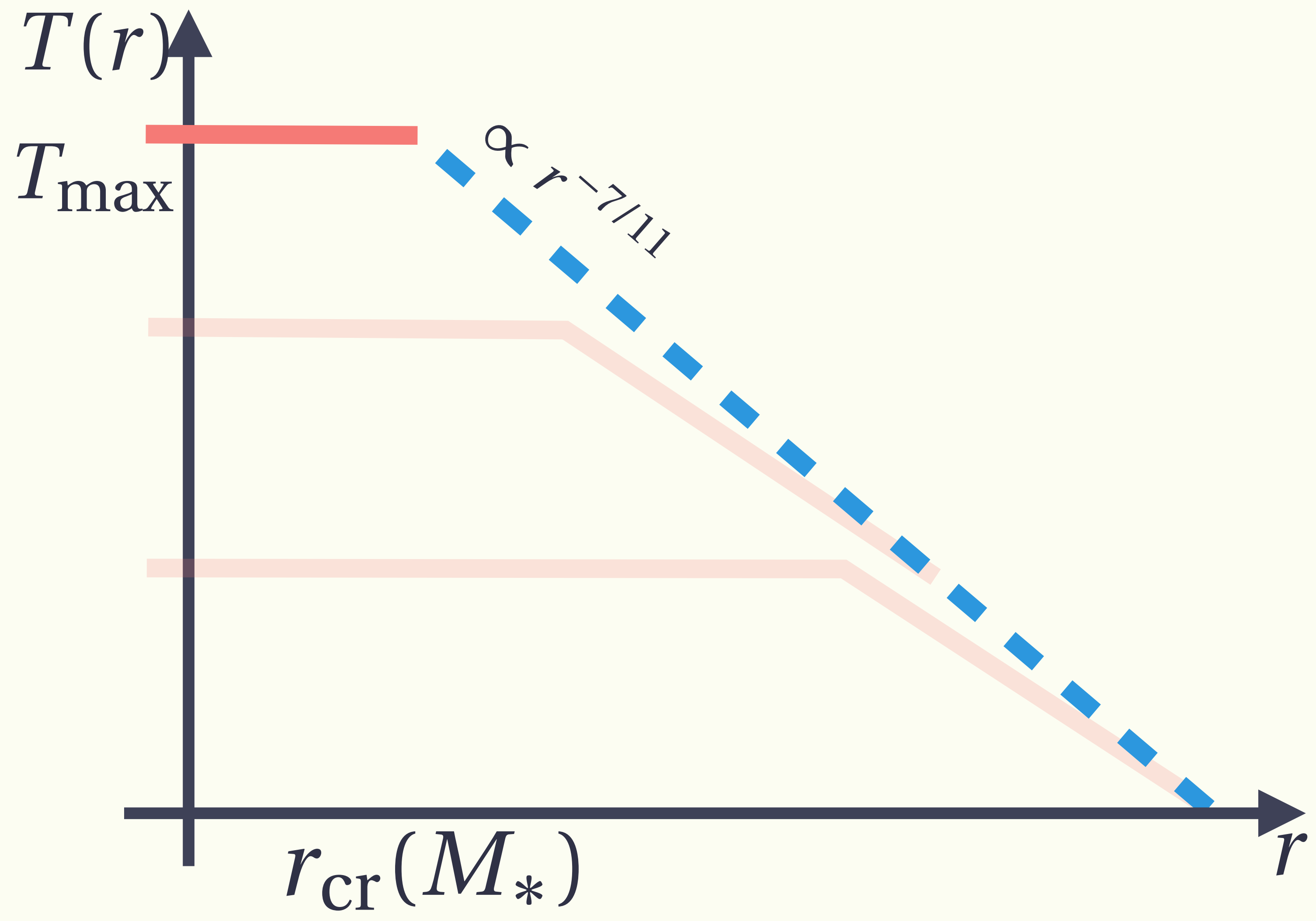
- LPM-suppression gives a cored T-profile
  - time < evaporation
  - evaporation < time < t*
  - t* < time



$$r_{\rm cr} \sim t_{\rm th} \sim 10^9 \left(\frac{\alpha}{0.1}\right)^{-6} r_S(M)$$



$$T_{\rm core} \sim 10^{-4} \left(\frac{\alpha}{0.1}\right)^{\frac{8}{3}} T_H(M)$$



$$T_{\rm max} \sim 10^9\,{\rm GeV} \left(\frac{\alpha}{0.1}\right)^{\frac{19}{3}}$$

Phenomenological Implications?

- Symmetry restoration, Topological defects, Vacuum decay
  - Monopole production, induced vacuum decay…

[Das, Hook '21]

- Baryogenesis/Leptogenesis
  - Locally **re-activate** B/L-violating interactions

E.g., Sphaleron

$$\frac{\mathrm{Volume}_{T\gtrsim 10^2\,\mathrm{GeV}}}{\mathrm{Total\ Volume}} \sim 10^{-12}\, f_{\mathrm{PBH}}^{(\mathrm{ev})} \left(\frac{\alpha}{0.1}\right)^{\frac{6}{7}} \left(\frac{M_{\mathrm{ini}}}{10^7\,\mathrm{g}}\right)^7$$

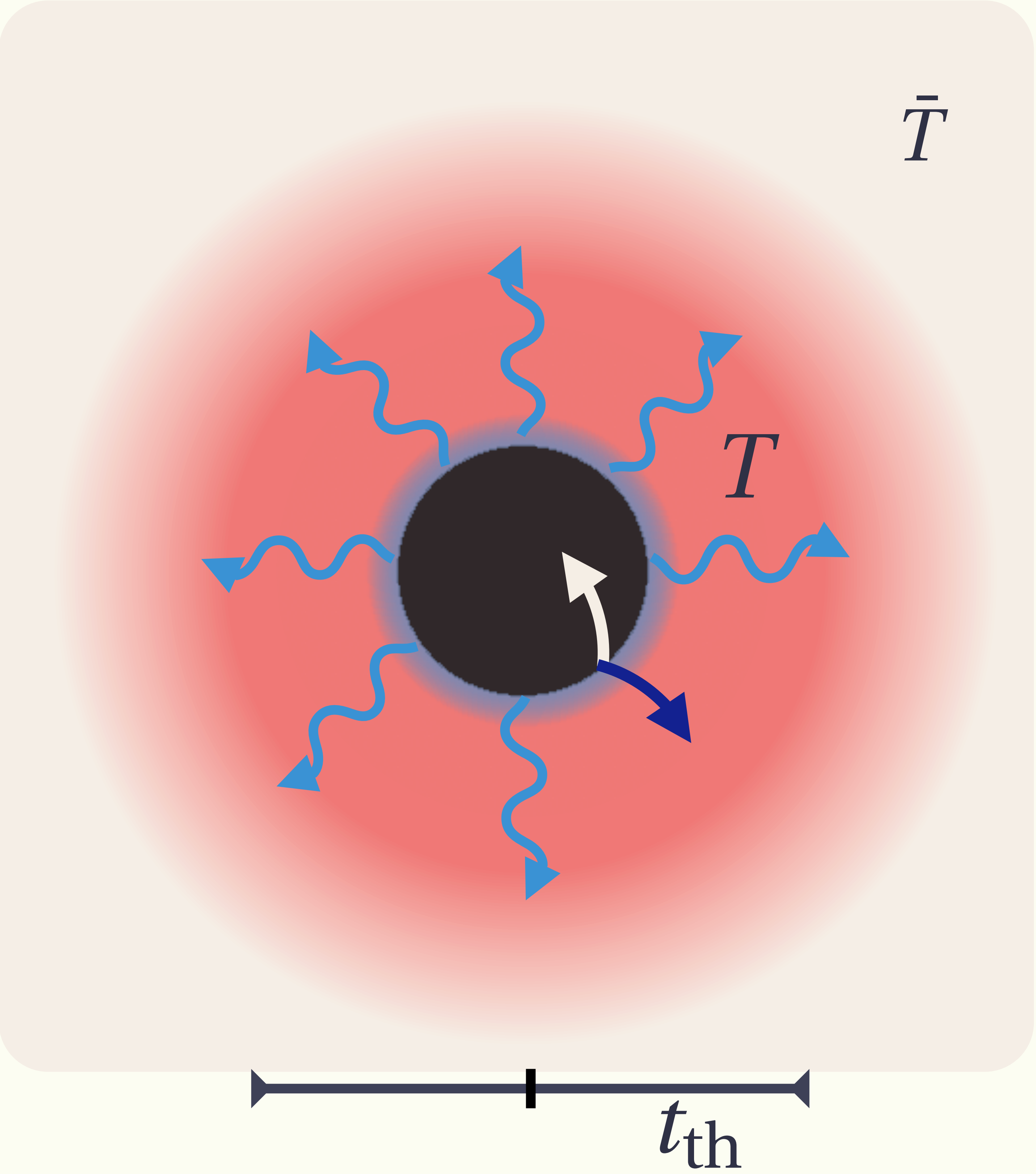
* PBH formation via large curvature perturbs.

- Dark Matter production
  - Though typically direct production through Hawking radiation dominates

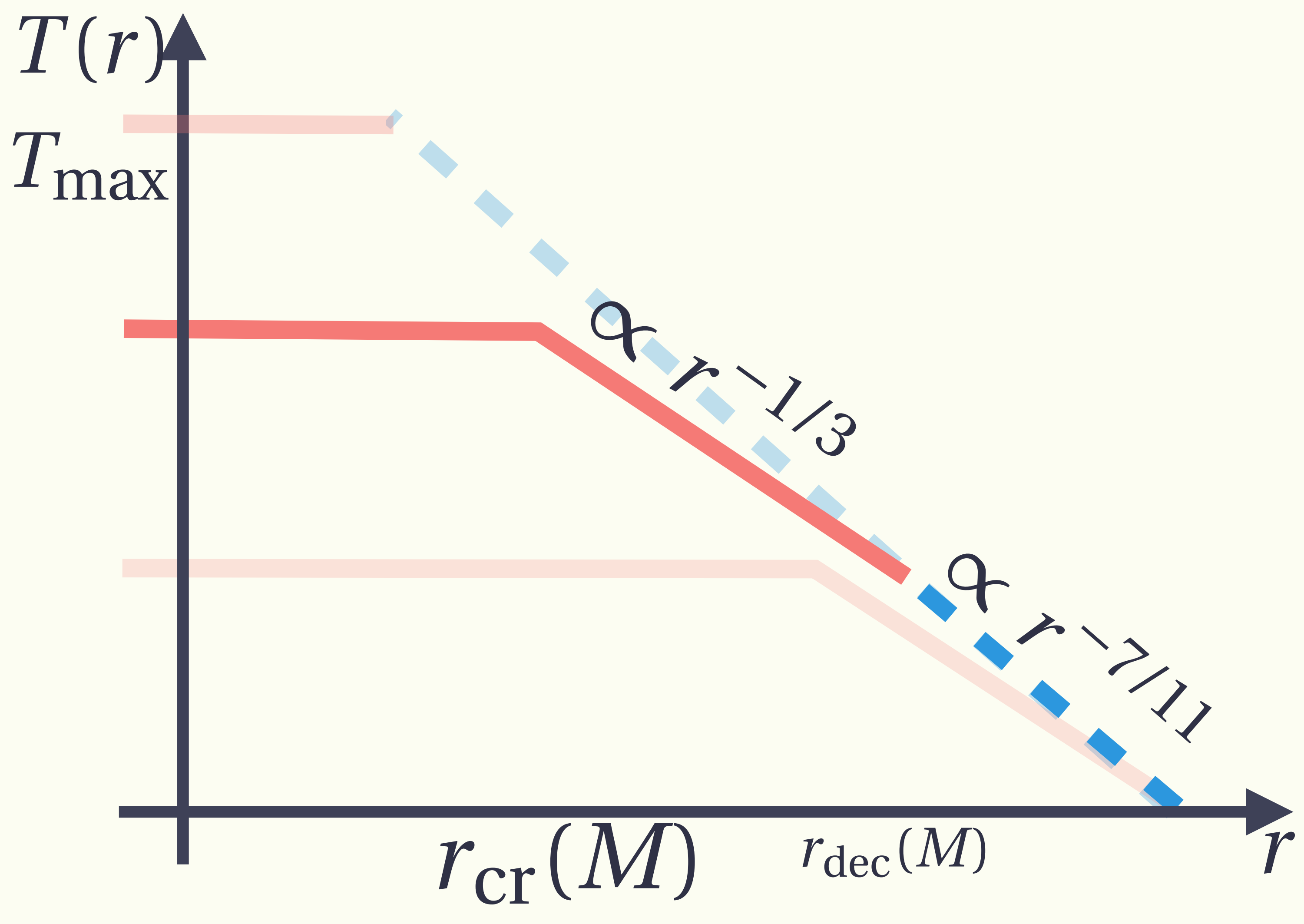
[He, Kohri, **KM,** Yamada **2210.06238**]

Summary

- Small PBHs are **extremely hot heaters** in the primordial plasma



- Cored T-profile by LPM effect



$$T_{\rm core} \sim 10^{-4}\left(\frac{\alpha}{0.1}\right)^{\frac{8}{3}} T_{\rm H}(M)$$

$$\lesssim 10^9\,{\rm GeV}\left(\frac{\alpha}{0.1}\right)^{\frac{19}{3}}$$

<u>Unconventional cosmology</u>

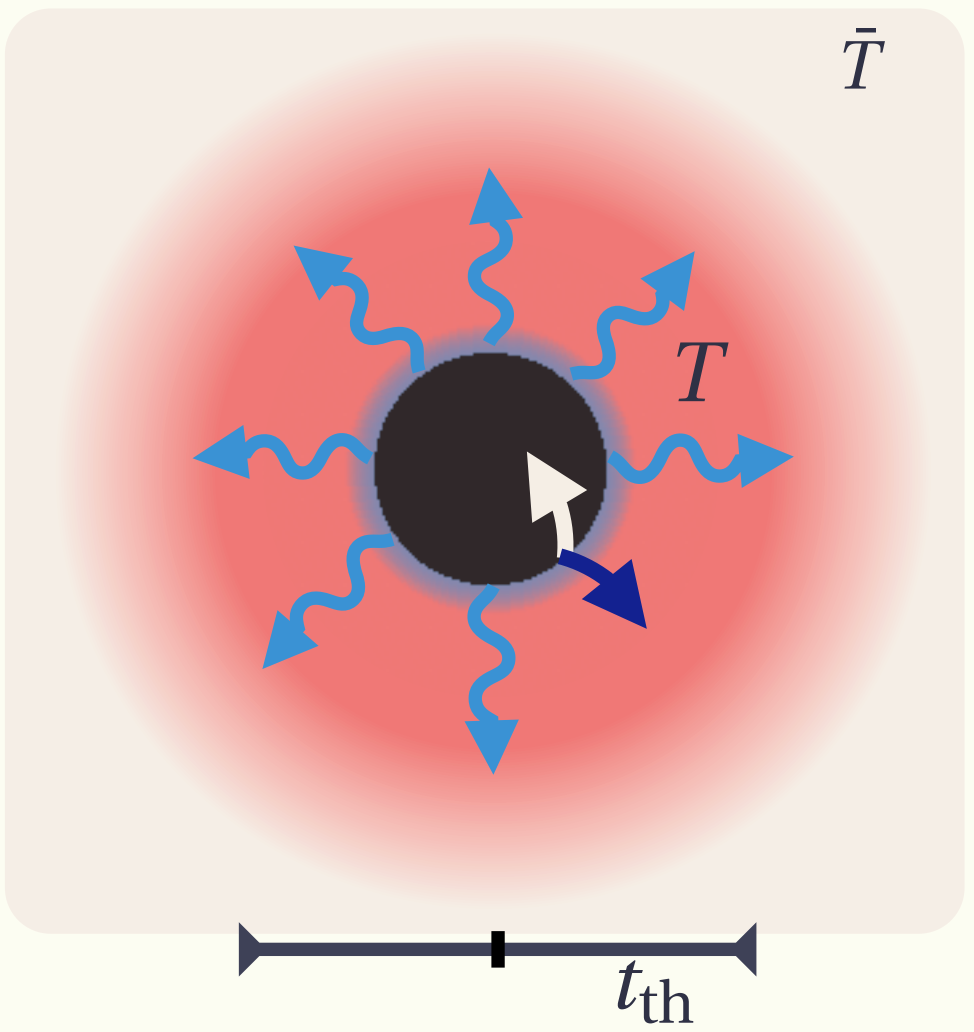
- **Local** phase transition
- **Local** Baryo/Leptogenesis
- …

Backup

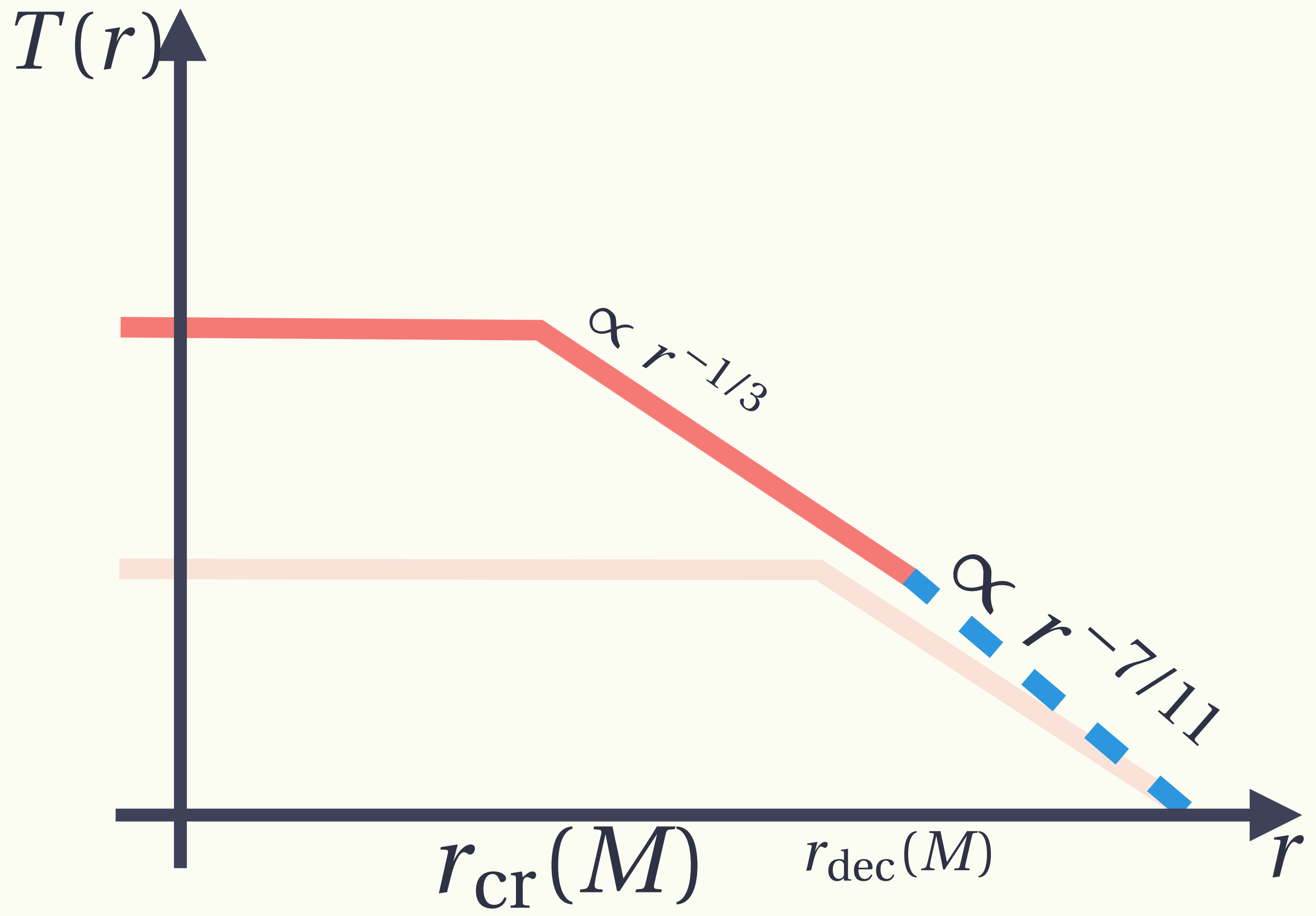
Some details

- Comparison of time scales

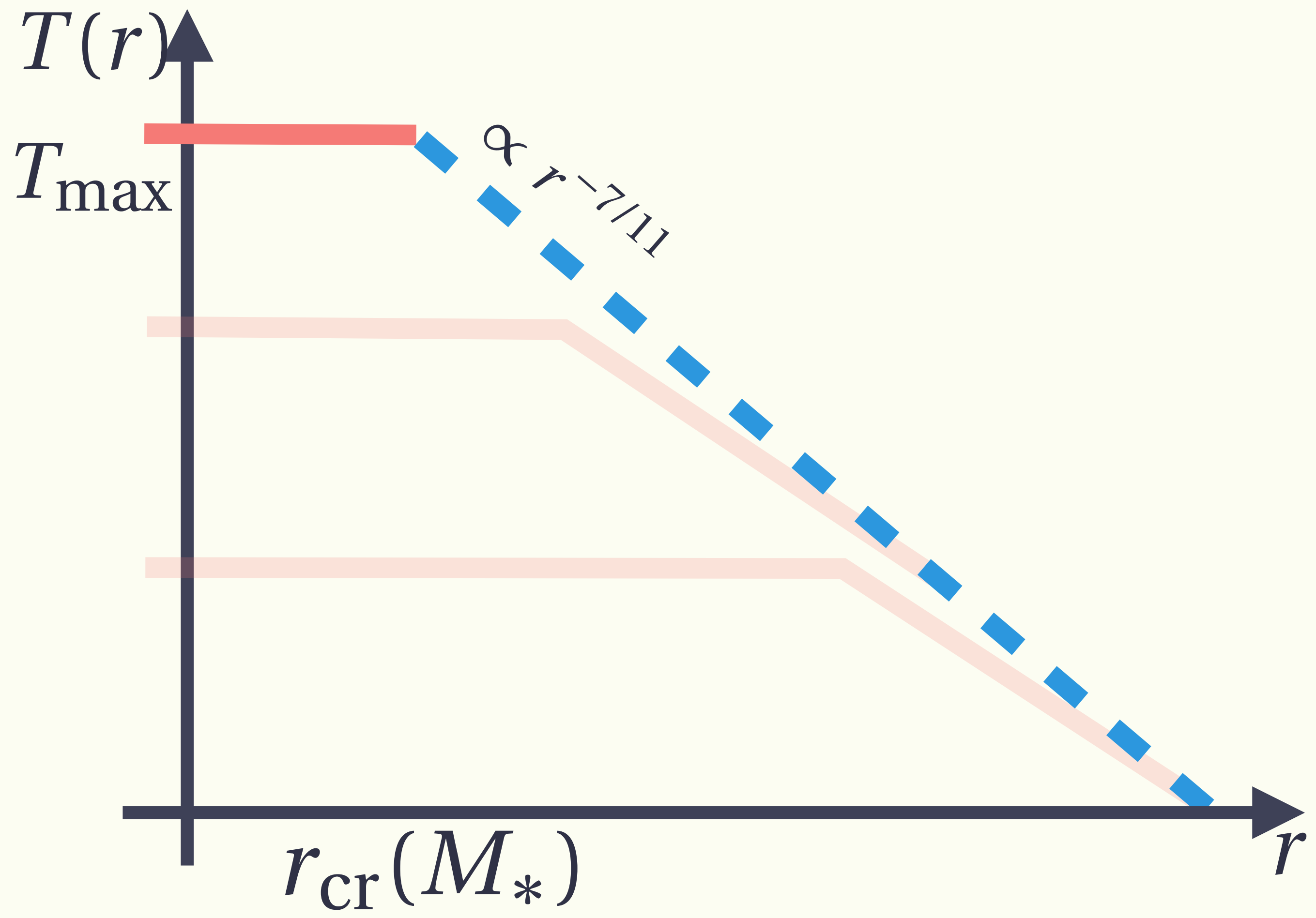
$$t_{\rm th} \sim \alpha^{-2} T^{-1} \sqrt{T_{\rm H}/T} \quad \lesssim \quad t_{\rm d} \sim \alpha^{-2} T^{-1} (T_{\rm H}/T) \quad ? \quad t_{\rm ev} \sim M_{\rm Pl}^2 / T_{\rm H}^3$$



i), ii) $t_{\rm d} < t_{\rm ev}$



iii) $t_{\rm d} > t_{\rm ev}$



Some details

- Comparison of time scales

$$t_{\rm th} \sim \alpha^{-2} T^{-1} \sqrt{T_{\rm H}/T} \quad \lesssim \quad t_{\rm d} \sim \alpha^{-2} T^{-1} (T_{\rm H}/T) \quad \lesssim \quad t_{\rm ev} \sim M_{\rm Pl}^2 / T_{\rm H}^3 \quad \text{for i), ii)}$$

- What is $\mathbf{r_{dec}}$? → diffusion length @ $t \sim t_{\rm ev}$: $\quad r_{\rm dec} \sim 10\,{\rm cm} \left(\frac{\alpha}{0.1}\right)^{-\frac{8}{5}} \left(\frac{T_{\rm H}}{10^4\,{\rm GeV}}\right)^{-\frac{11}{5}}$

  → local thermal eq. w/in $r < r_{\rm dec}$