KEK

Perturbative Reheating & Thermalization

via cascades of energetic SM particles

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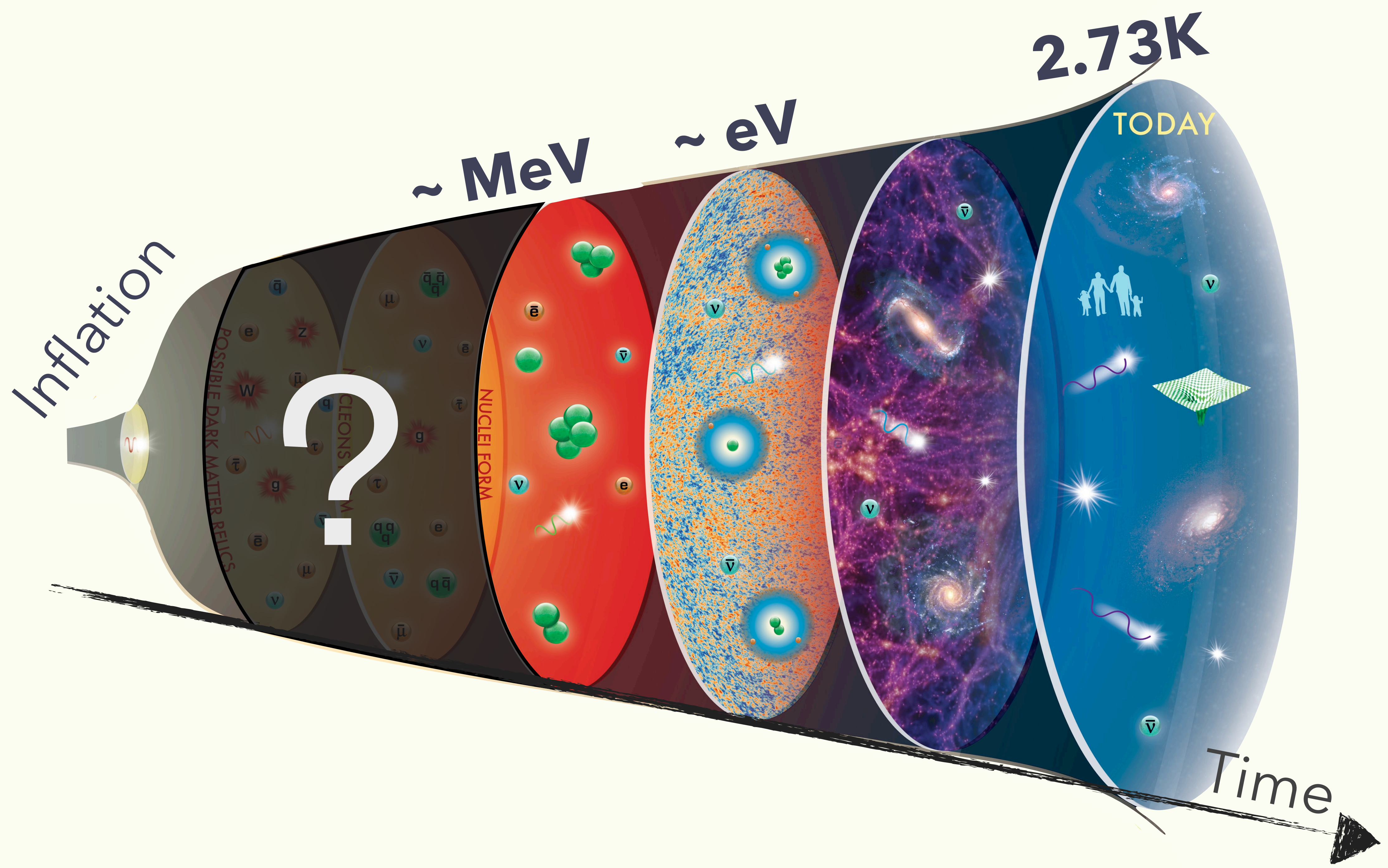
w/ K.Harigaya, M.He, K.Kohri, M.Yamada

1312.3097, 1402.2846, 1901.11027,
2208.11708, **2402.14054**, **2407.15926**

Introduction

Beginning of Hot Universe?

- Cosmic inflation (accelerated expansion)
  - Solves Horizon/Flatness problem
  - Provides the origin of density fluctuations
  - ◉ **Dilutes everything** including baryons, dark matter…



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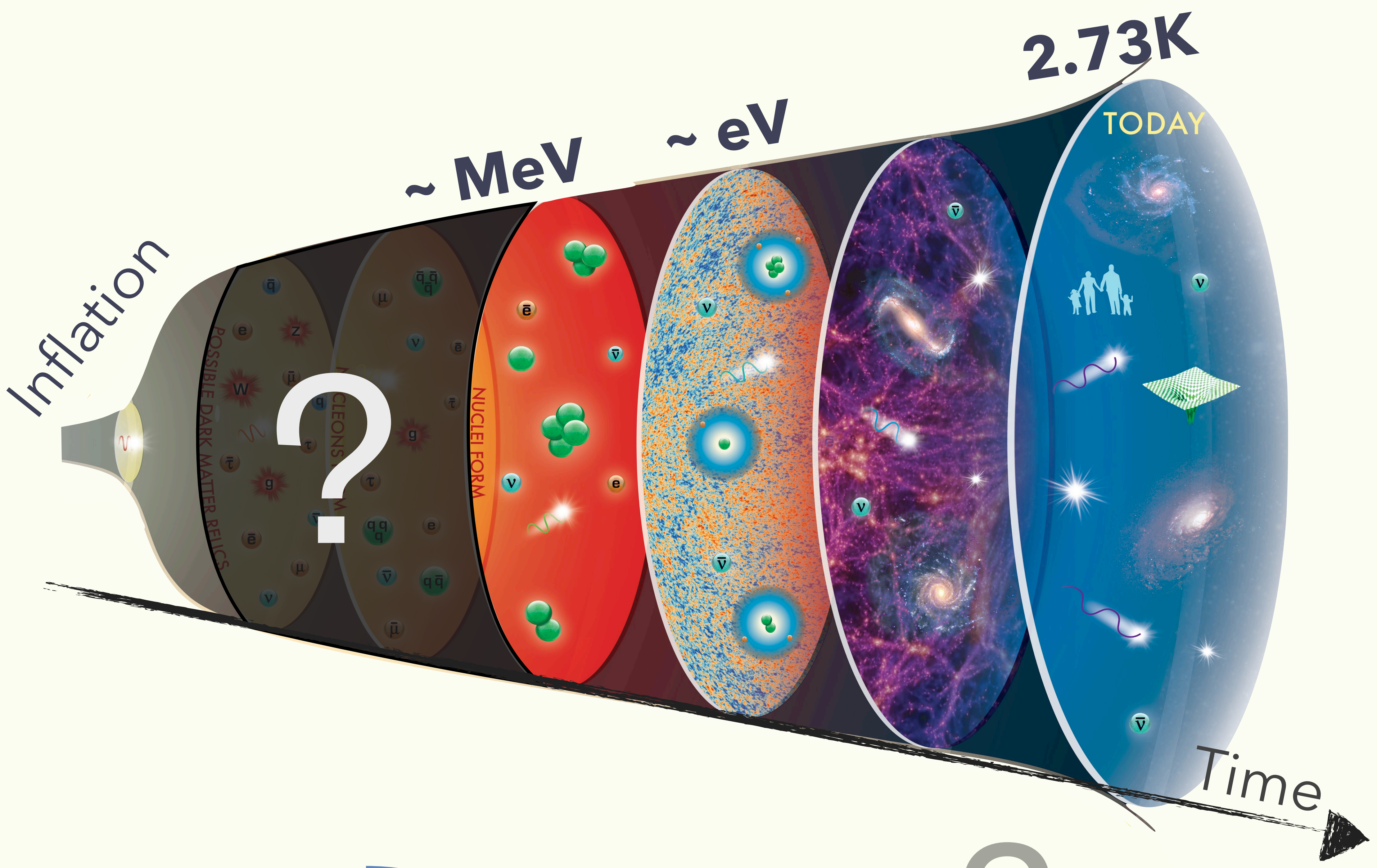
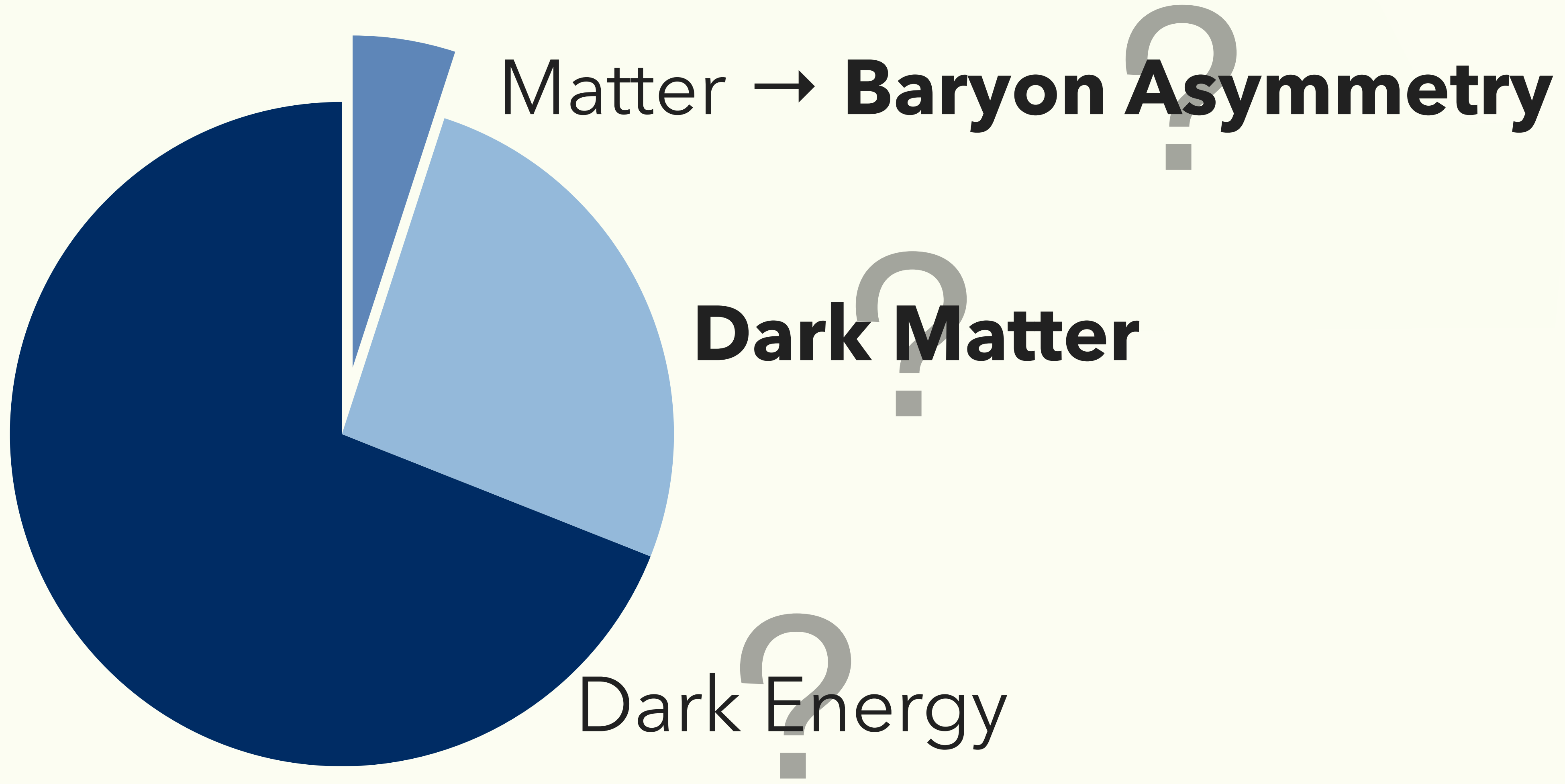


Hot Universe

- Big Bang Nucleosynthesis
- Cosmic Microwave Background



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Reheating

?

Hot Universe

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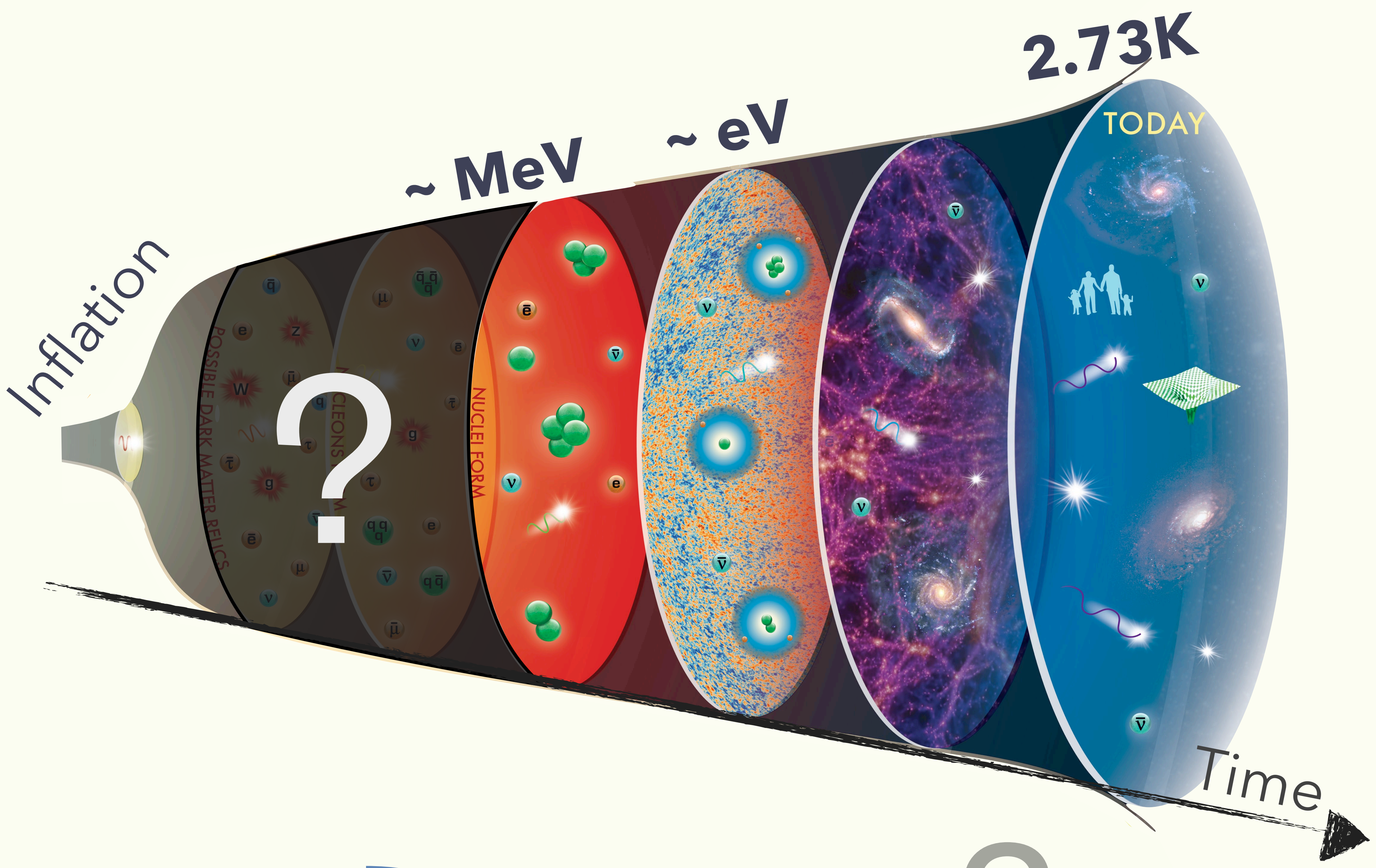
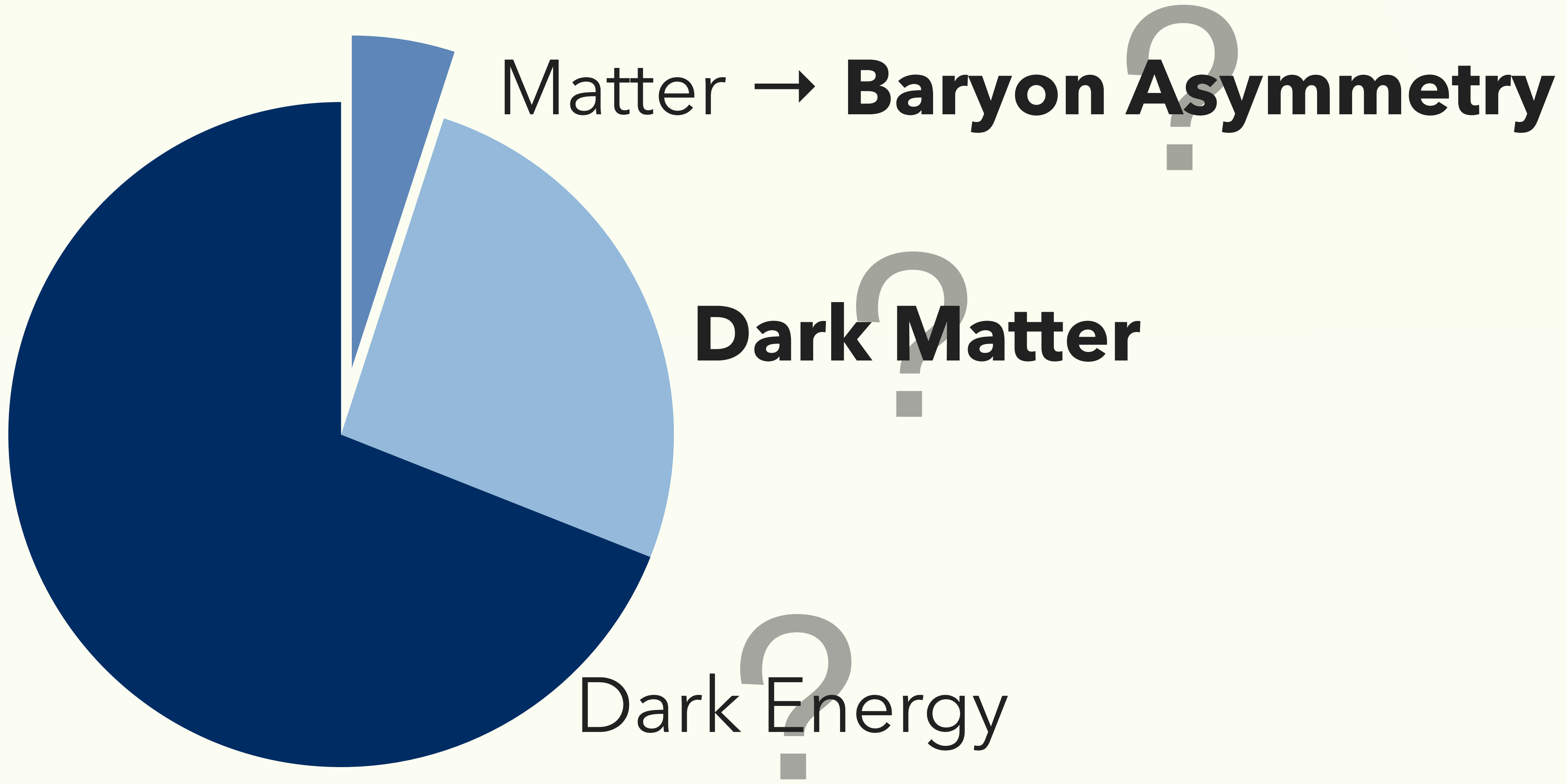
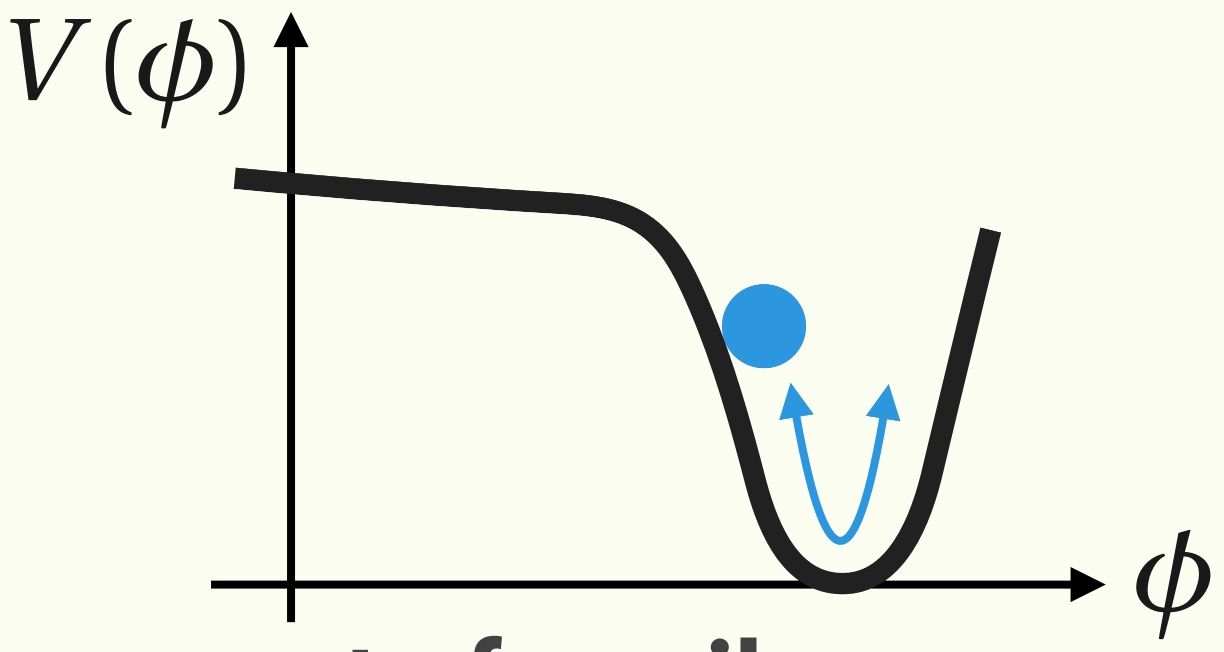
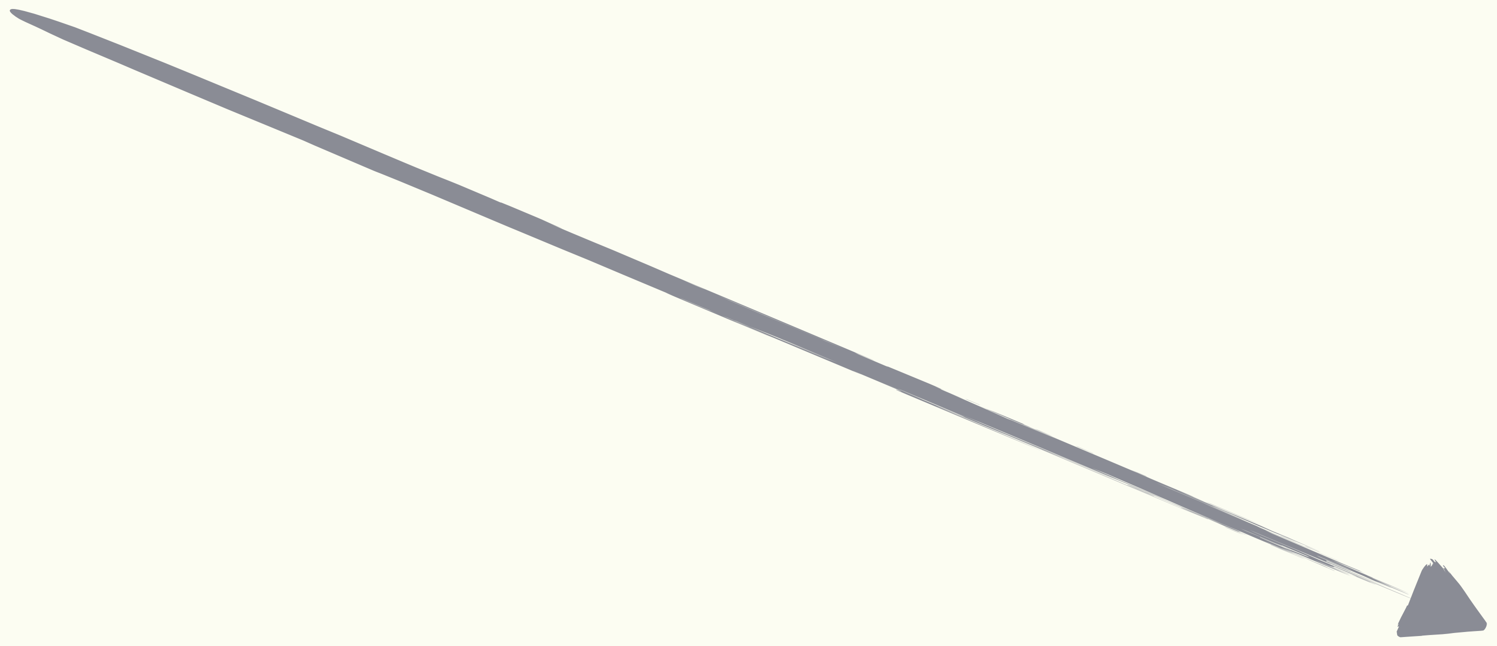




Reheating and Thermalization



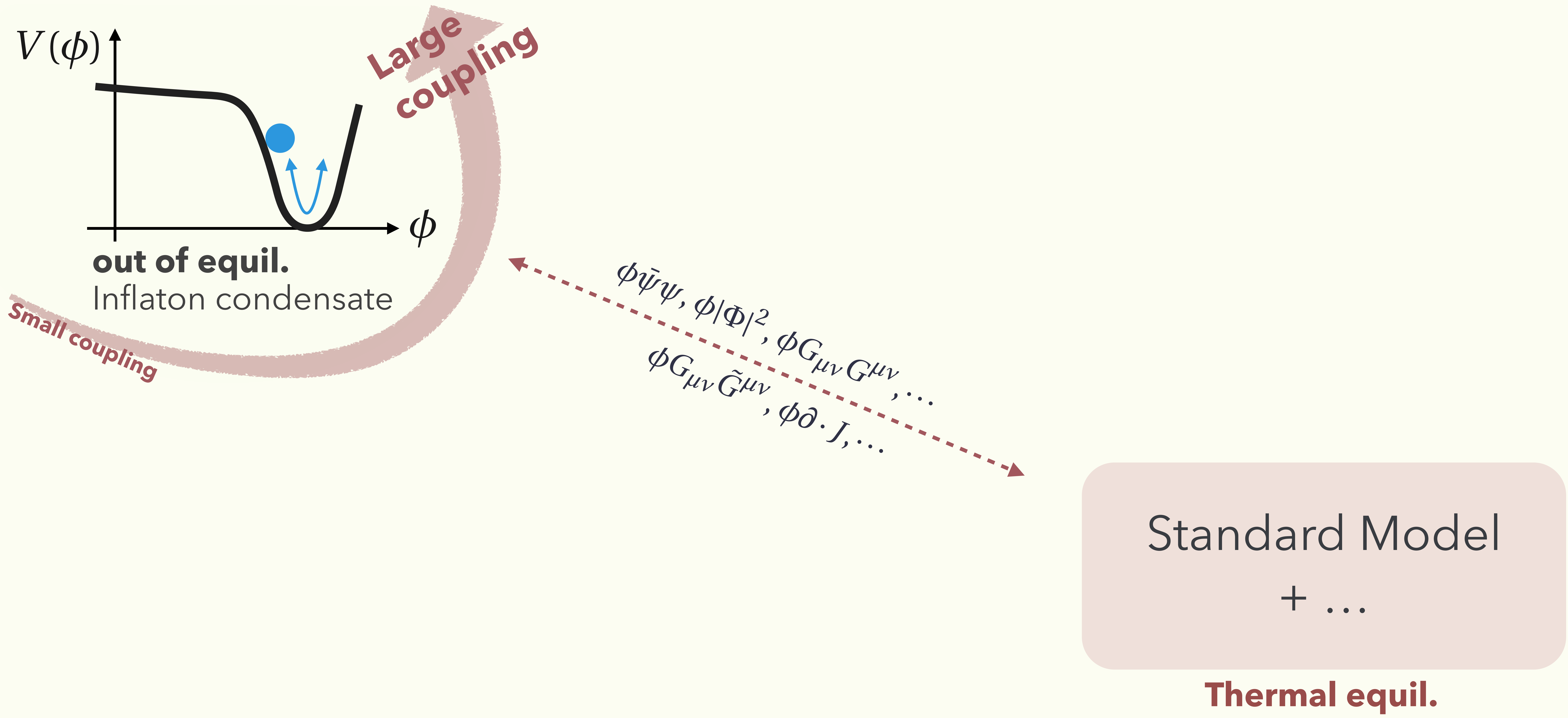
out of equil.
Inflaton condensate



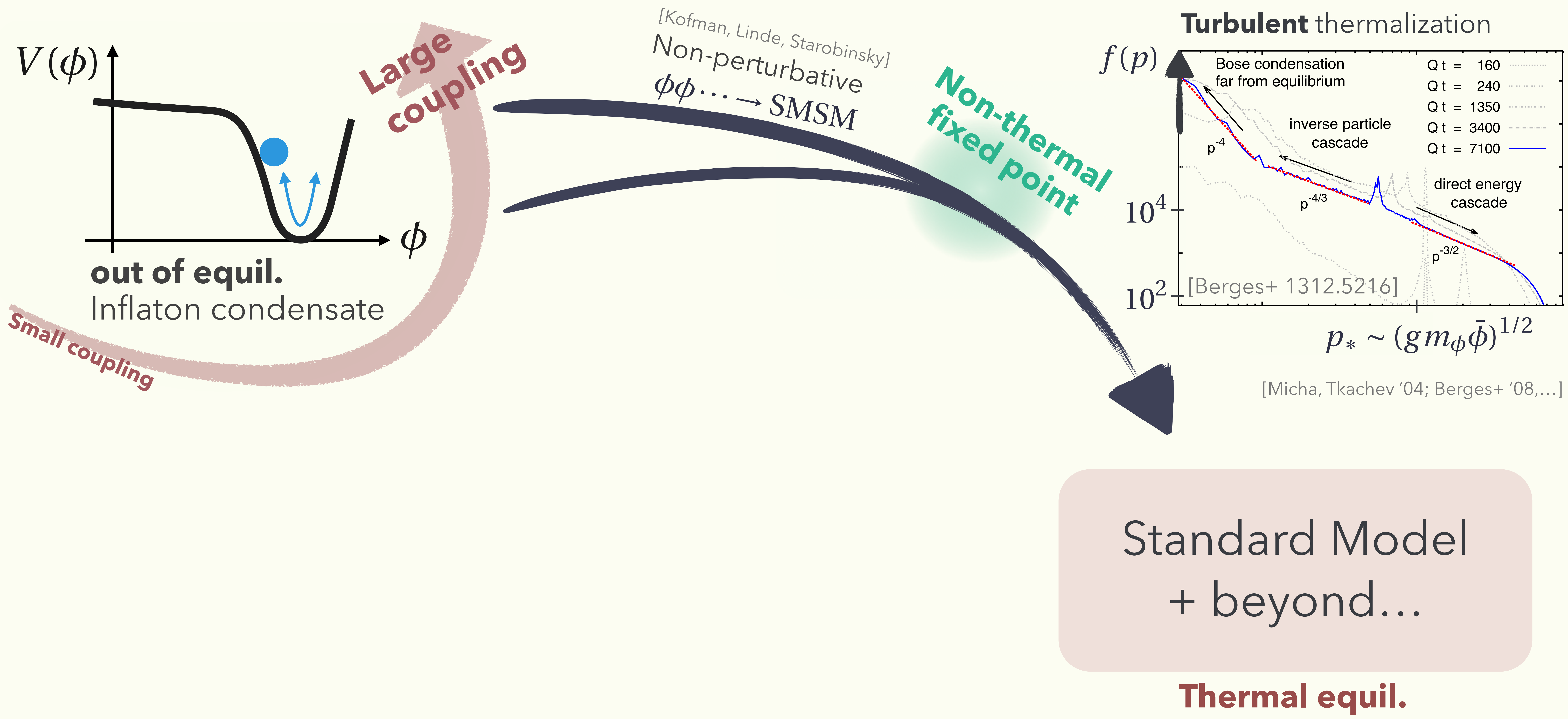
Standard Model
+ ...

Thermal equil.

Reheating and Thermalization



Reheating and Thermalization



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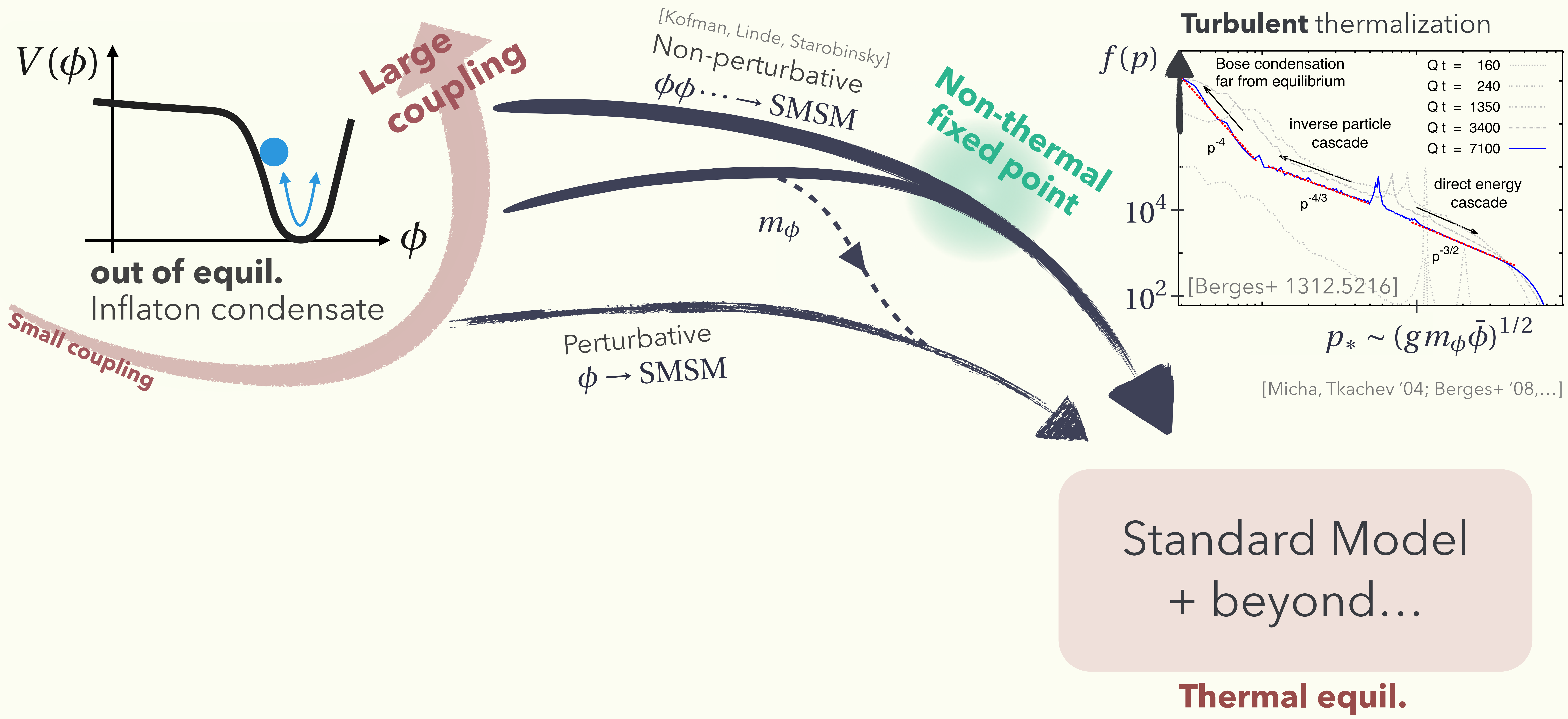
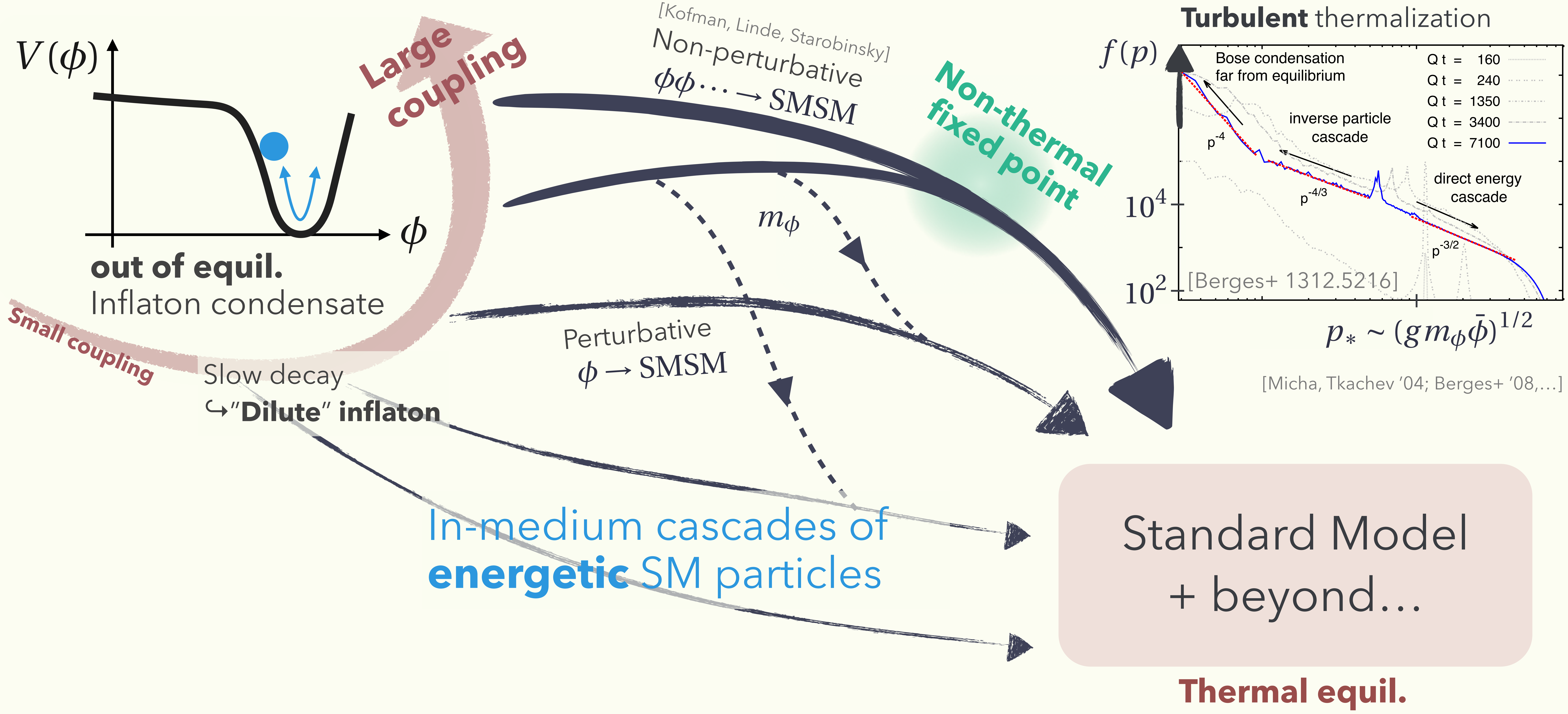
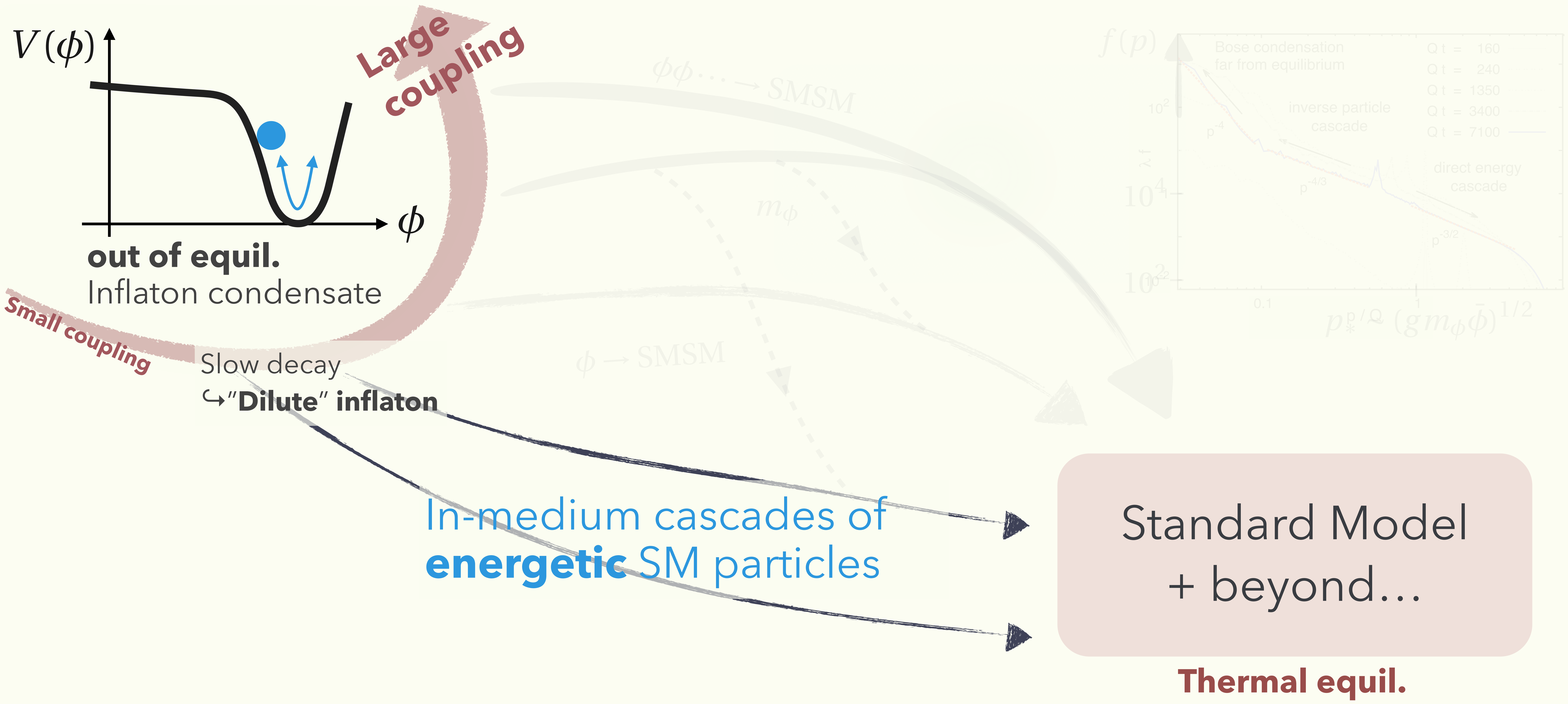


Reheating and Thermalization



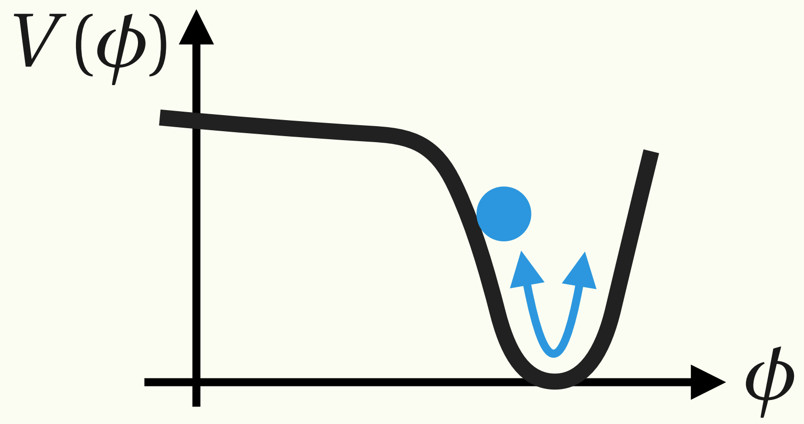
Reheating and Thermalization

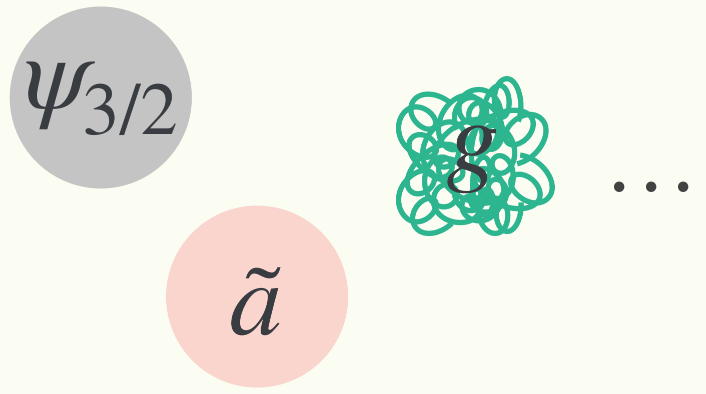


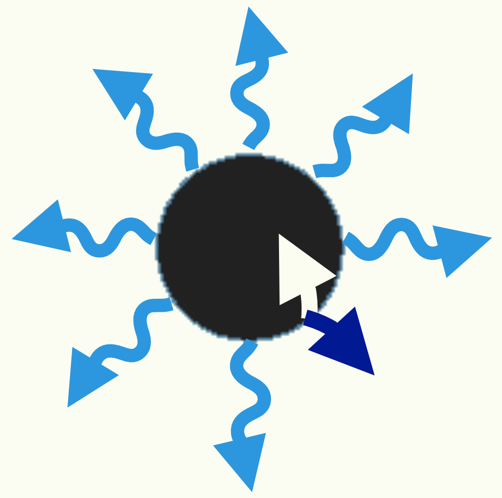
Heavy Long-lived Matter in the early Universe

- Candidates are ubiquitous in BSMs

Inflaton Moduli BSM particles Primordial Black Hole (PBH) …





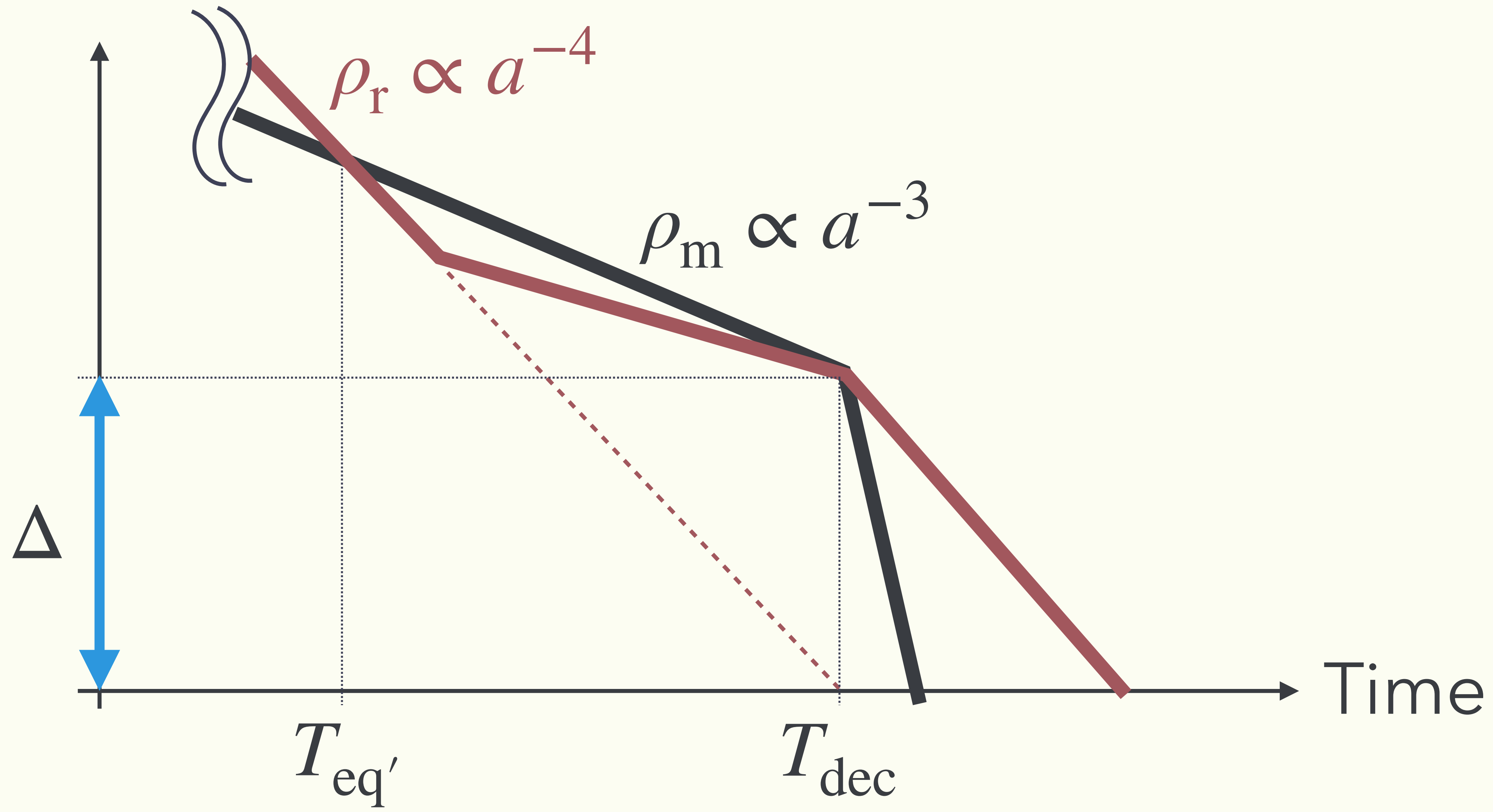


- Implications?
  - (possible) matter domination

$$\rho_r \propto a^{-4} \qquad \rho_m \propto a^{-3}$$

  - Entropy dilution

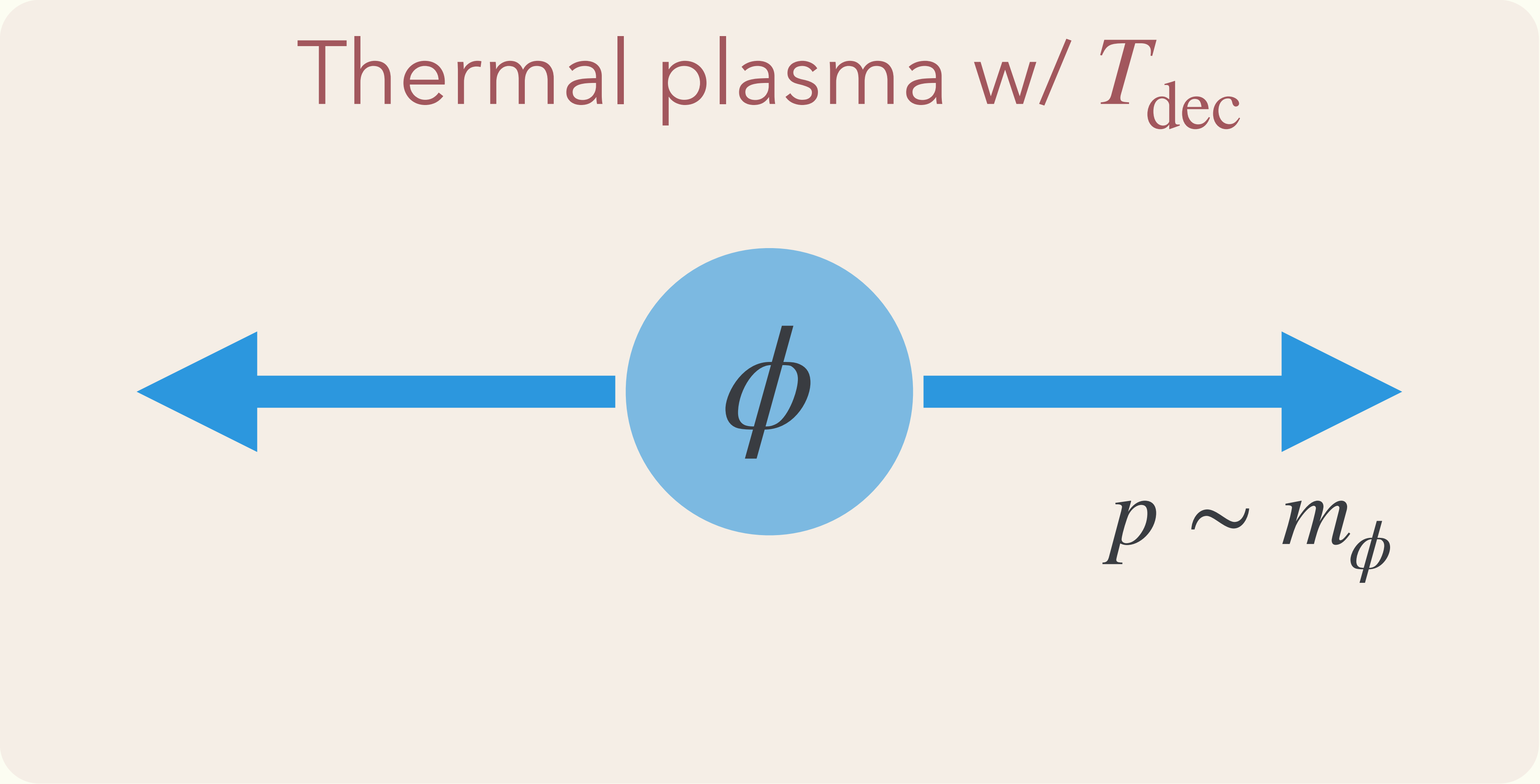
$$\Delta = T_{eq'}/T_{dec}$$



Heavy Long-lived Matter in the early Universe

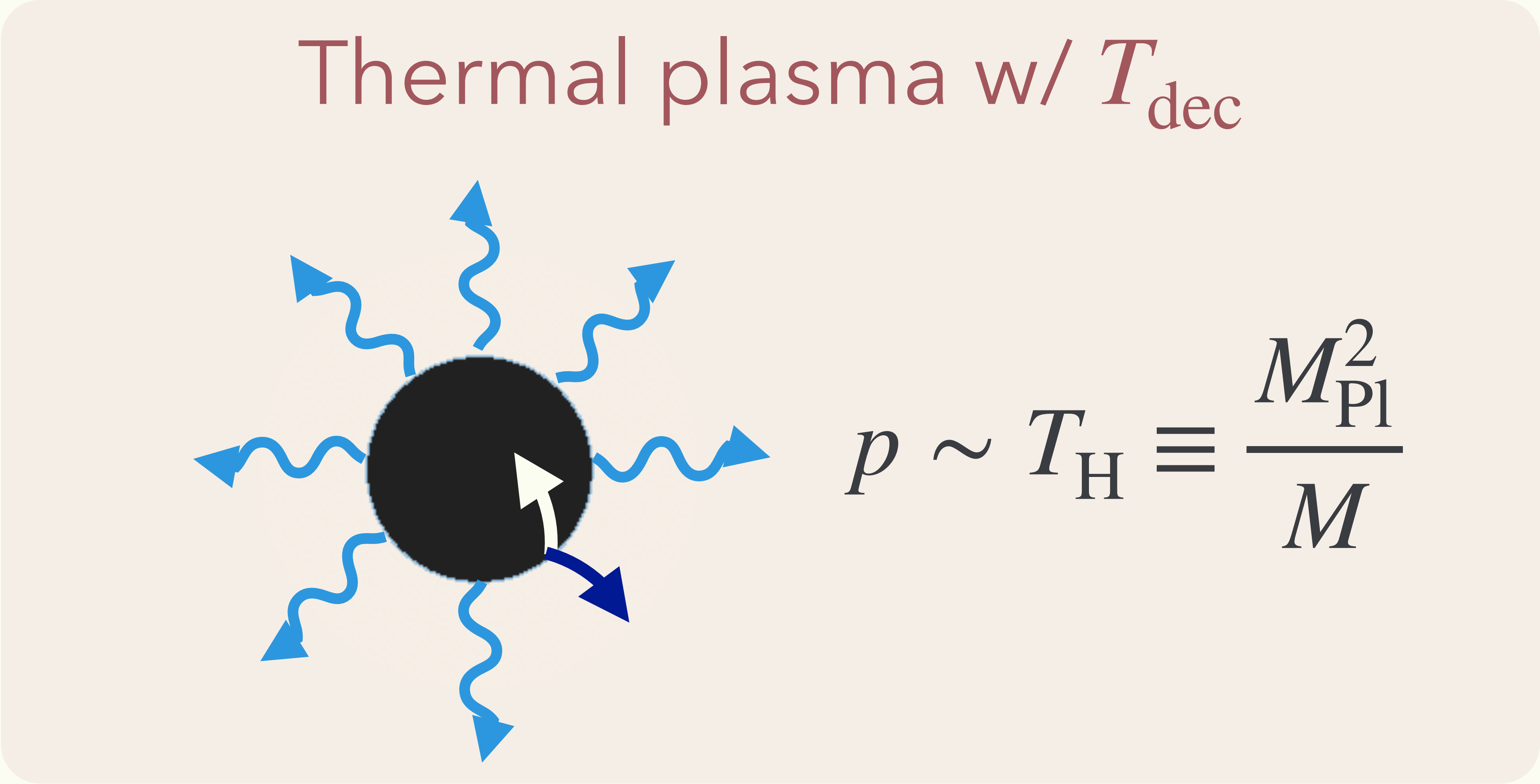
- Production of "**energetic**" particles

- Planck-suppressed decay of Inflaton/Moduli



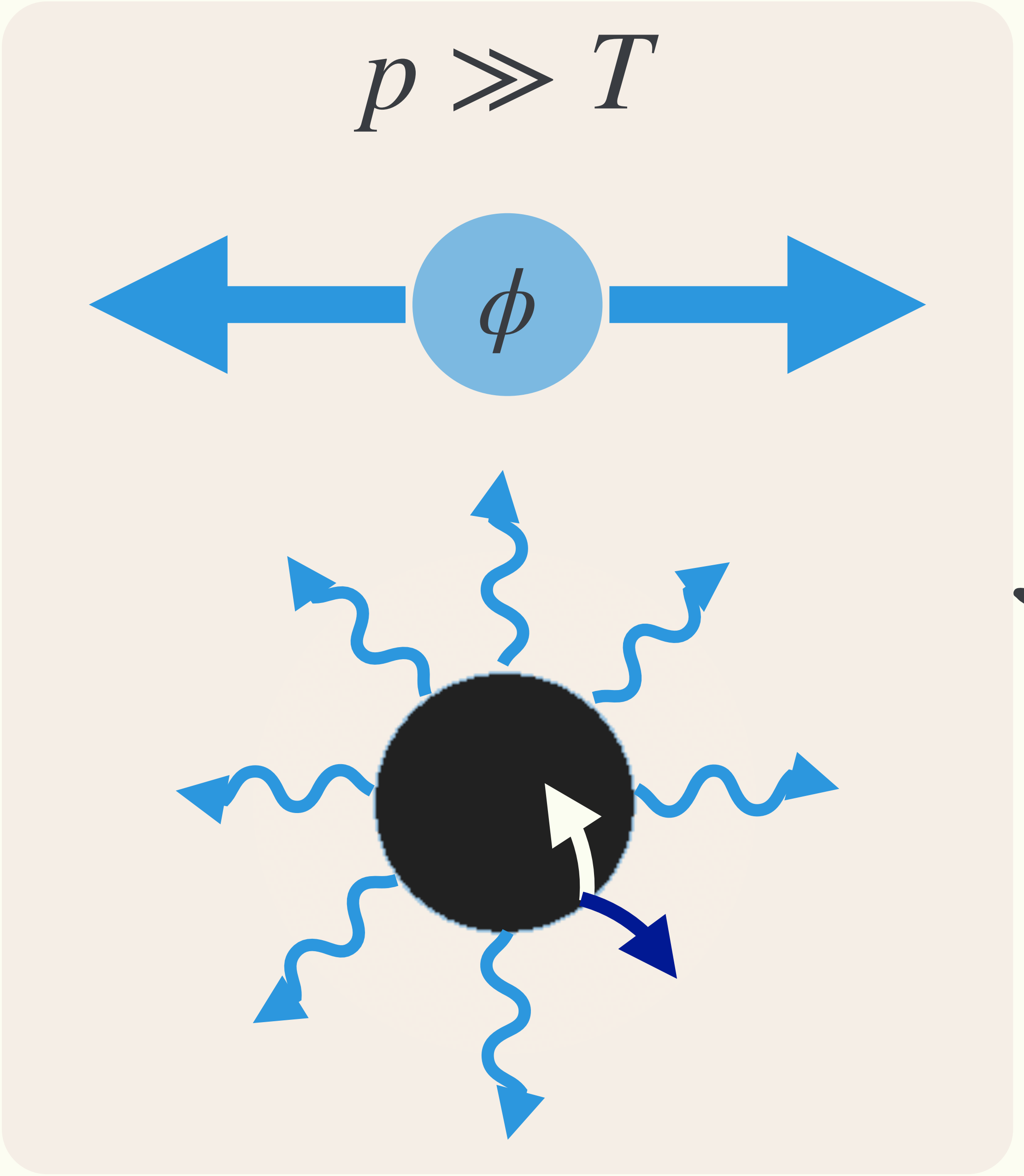
$$T_{\rm dec} \sim \sqrt{\Gamma_\phi M_{\rm Pl}} \sim \sqrt{\frac{m_\phi^n}{M_{\rm Pl}^n}}\, m_\phi \ll m_\phi$$

- Evaporating PBH w/ $10^9\,{\rm g} \gtrsim M \gg M_{\rm Pl}$



$$T_{\rm dec} \sim \sqrt{\Gamma_{\rm PBH} M_{\rm Pl}} \sim \sqrt{\frac{M_{\rm Pl}}{M}}\, T_{\rm H} \ll T_{\rm H}$$

Heavy Long-lived Matter in the early Universe



Decay of heavy long-lived matter

→ **energetic** particles

?

Dark Matter production?

Baryogenesis?

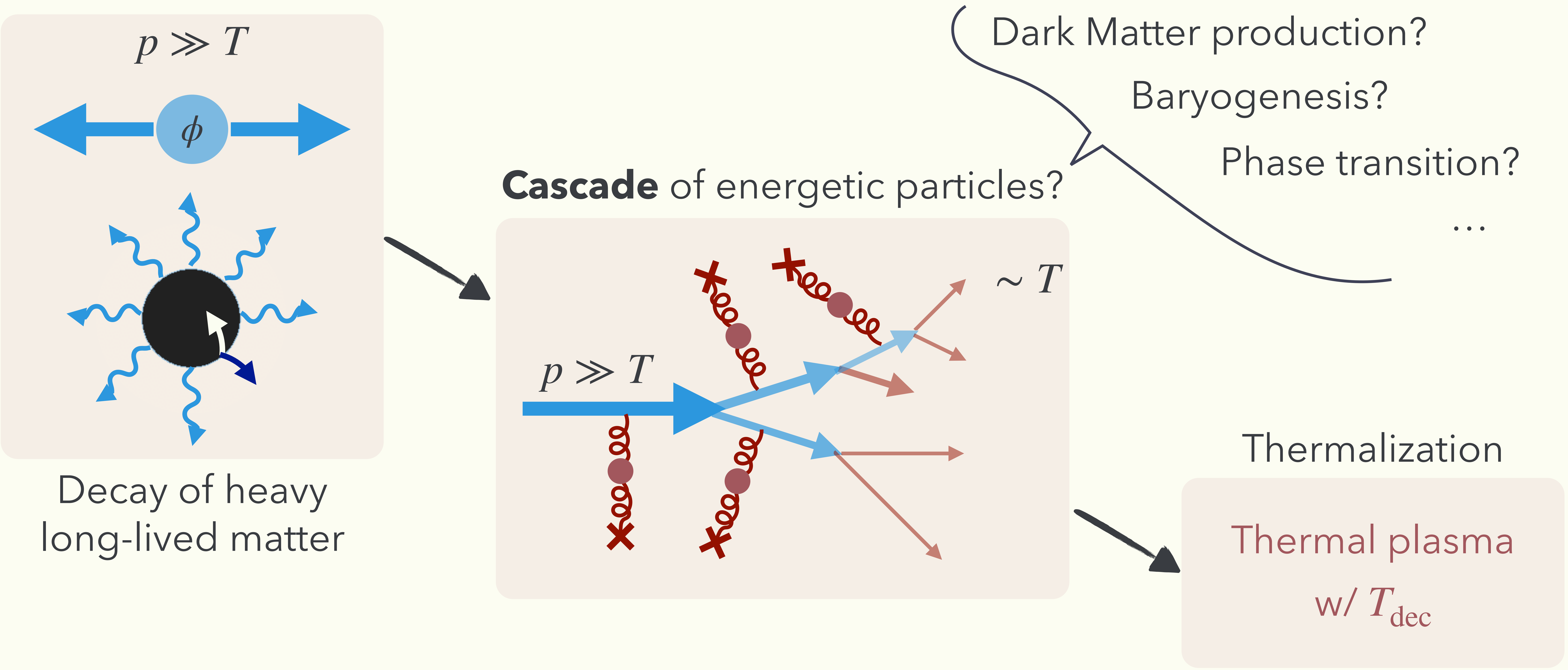
Phase transition?

…

Thermalization

Thermal plasma w/ T_{dec}

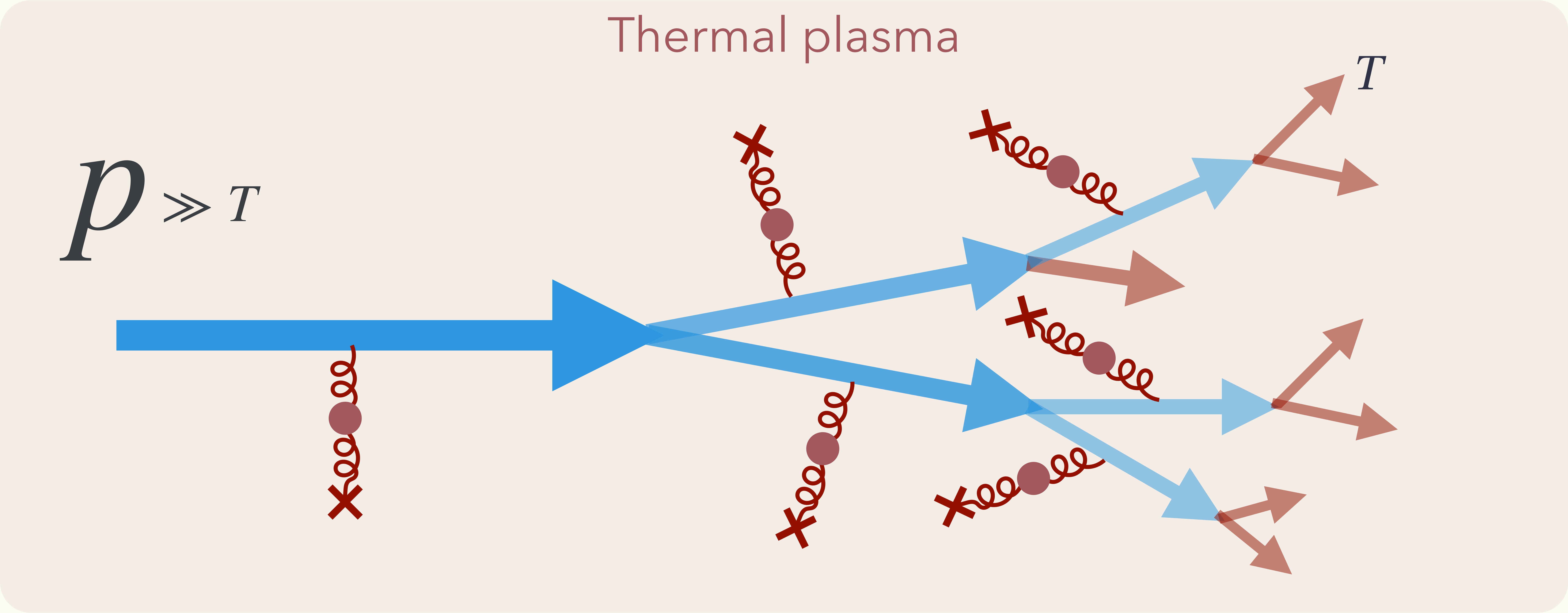
Heavy Long-lived Matter in the early Universe



Cascade of energetic particles in thermal plasma

In-medium Cascade of Energetic Particles

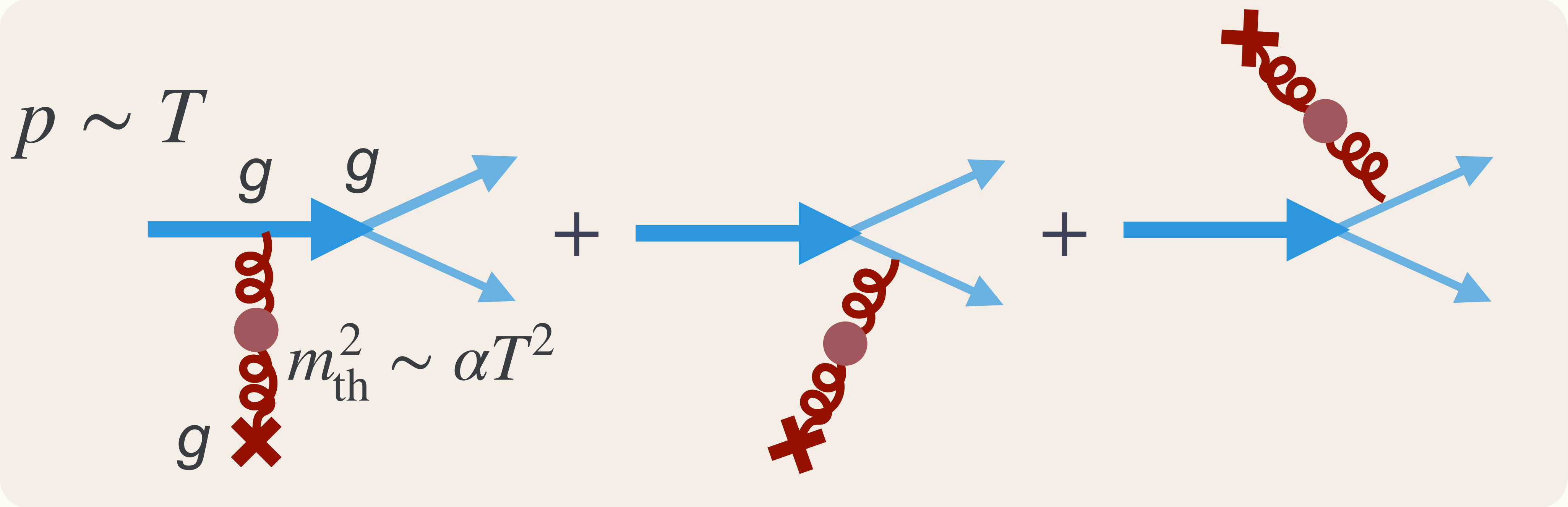
- Cascade via multiple splittings



In-medium Cascade of Energetic Particles

- Bethe–Heitler v.s. Landau–Pomeranchuk–Migdal (LPM)

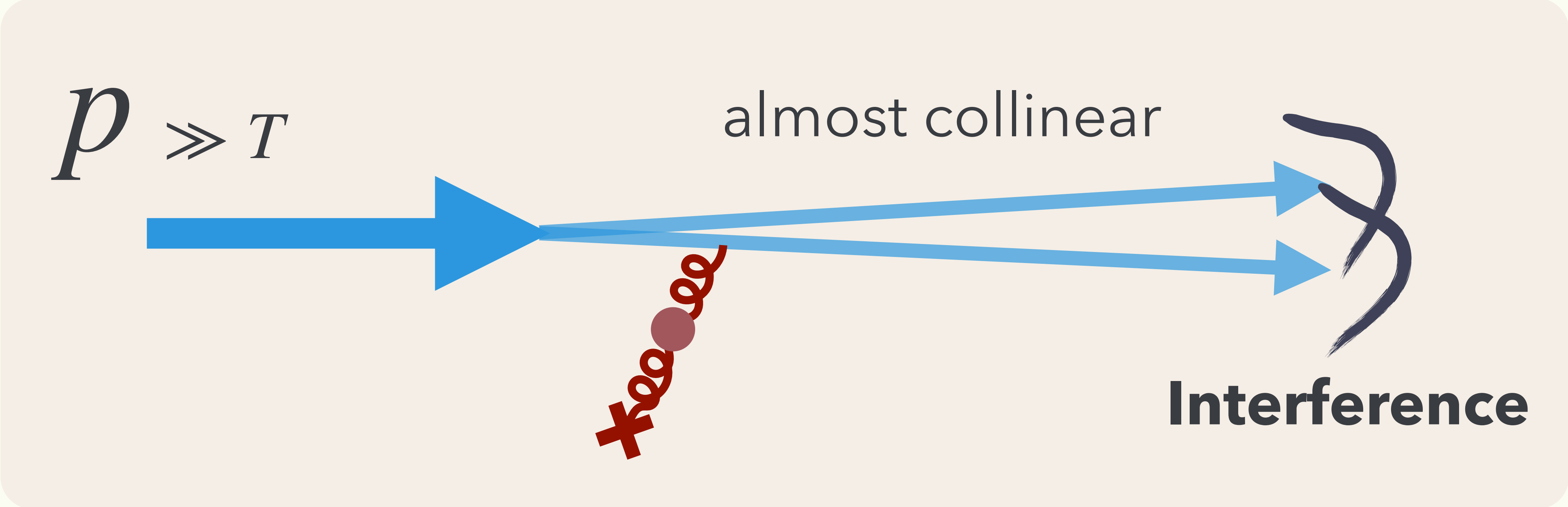
  - Bethe–Heitler formula



Scale-independent splitting

$$\Gamma_{\rm BH} \sim \alpha^3 \frac{T^3}{m_{\rm th}^2} \sim \alpha^2 T$$

  - **LPM** suppression [Landau, Pomeranchuk; Migdal]



coherent multiple scatterings

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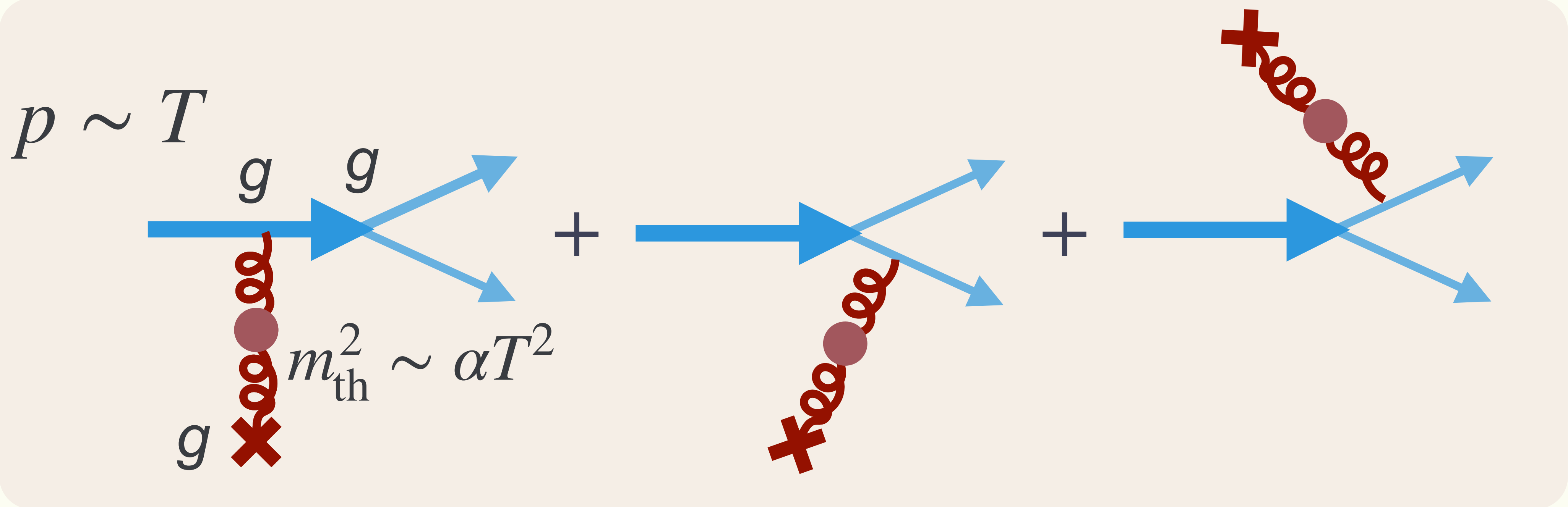

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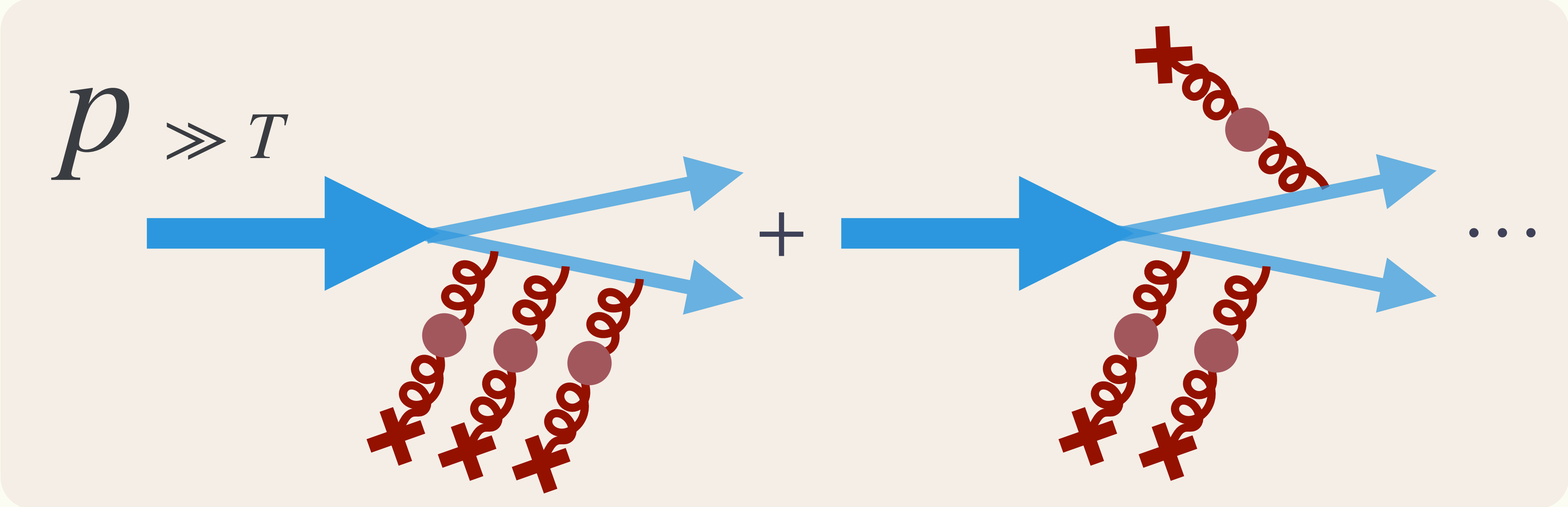


coherent multiple scatterings

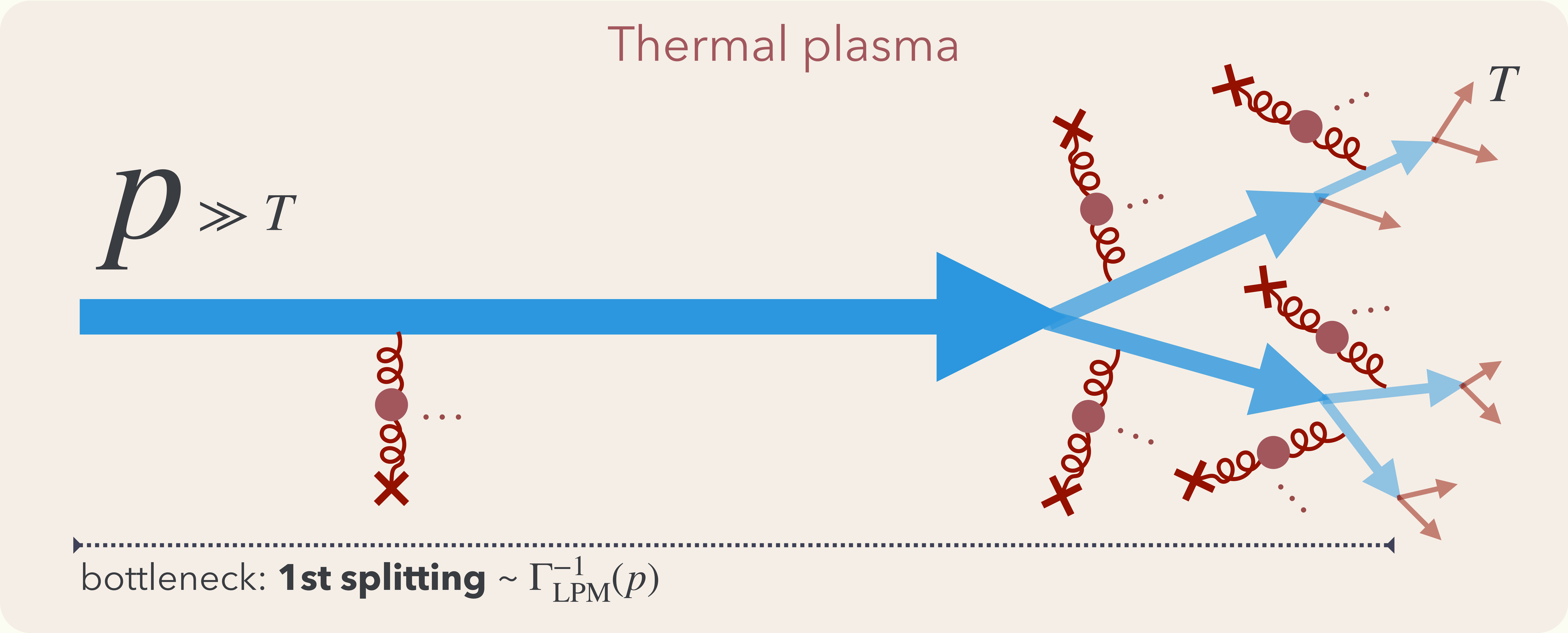
p-dependent splitting, i.e., **LPM suppression**

$$\Gamma_{\rm LPM} \sim \alpha\, t_{\rm form}^{-1}(p) \sim \alpha^2 T \times \sqrt{\frac{T}{p}}$$

[Arnold, Moore, Yaffe '01,'02,'03; Arnold, Dogan '08]

In-medium Cascade of Energetic Particles

- Cascade via LPM-suppressed multiple splittings



Effective Kinetic Theory of SM

- LPM-suppressed splitting function for SM

[**KM**, Yamada 2208.11708;
Arnold, Morre, Yaffe '01,'02,'03; Arnold, Dogan '08]

- Kinetic equation

$$\mathcal{L} f_s(\boldsymbol{x}, \boldsymbol{p}, t) = \mathcal{S} + \mathcal{C}_{2\leftrightarrow 2}[f_s] + \mathcal{C}_{``1\leftrightarrow 2"}[f_s]$$

w/ $s = e_f, L_f, u_f, d_f, Q_f, \phi, B, W, g$

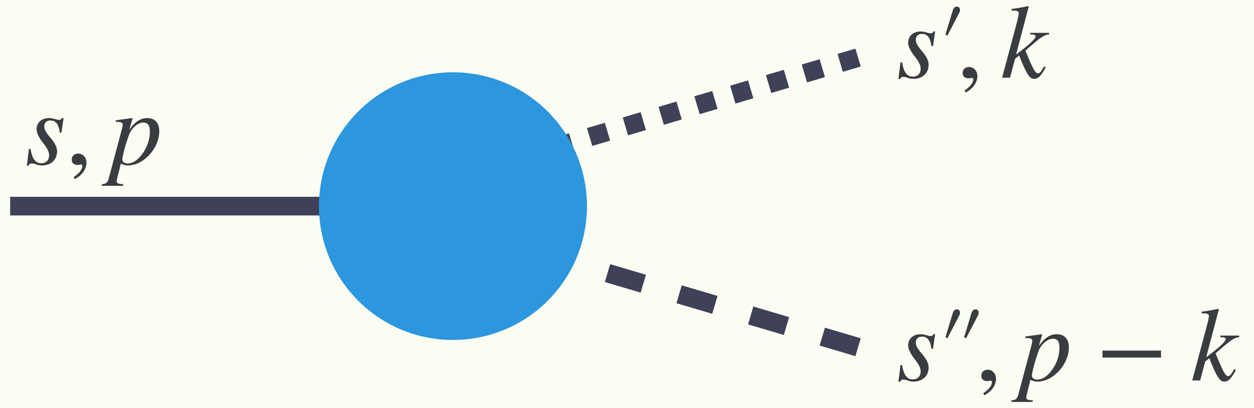
Source (e.g., inflaton, PBHs) | Elastic scat. | **LPM-suppressed** splitting

- **Splitting function** for effective "1 to 2" processes

$$\mathcal{C}_{``1\leftrightarrow 2"}[f_s] \supset -\frac{(2\pi)^3}{p^2 \nu_s} \sum_{s', s'} \int_0^p \mathrm{d}k \, \gamma_{s\leftrightarrow s's''}(p; k, p-k) f_s(p)$$

$$+(\text{inverse})$$

Splitting function



Effective Kinetic Theory of SM (cont'd)

- LPM-suppressed splitting function for SM

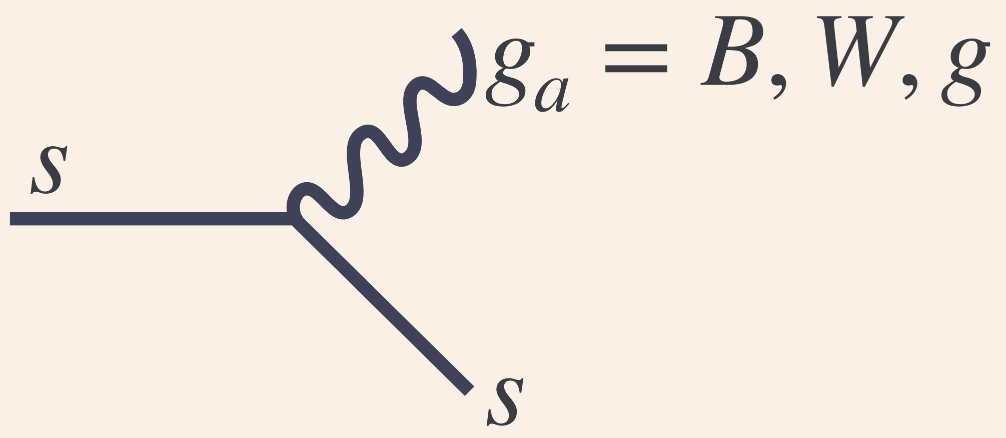
[**KM**, Yamada 2208.11708; Arnold, Morre, Yaffe '01,'02,'03; Arnold, Dogan '08]

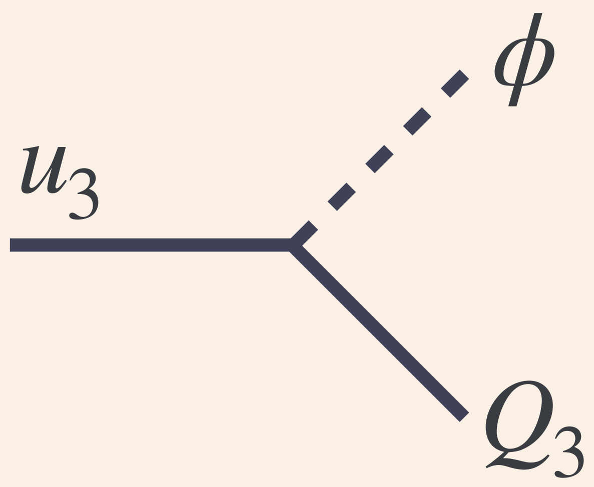
  - SM splitting function

$$\gamma_{s\to s's''}(p;xp,(1-x)p) = \frac{1}{2}\frac{\alpha_{ss's''}}{(2\pi)^4\sqrt{2}} \times \frac{P^{(\mathrm{vac})}_{s\to s's''}(x)}{x(1-x)} \times \mu_\perp^2(1,x,1-x;s,s',s'')$$

vacuum DGLAP splitting function

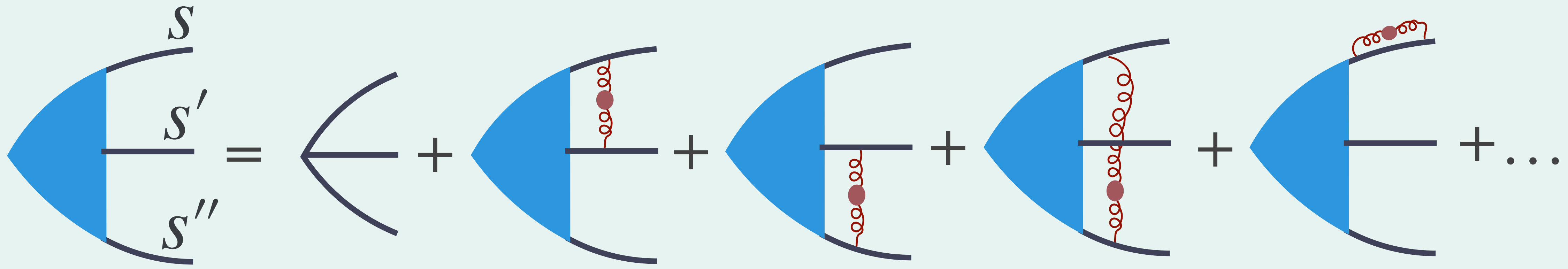
SM gauge + top Yukawa





$\alpha_{sg_as} = d^{(a)}_{\mathbf{R}_s} C^{(a)}_{\mathbf{R}_s} \alpha_a$ $\qquad$ $\alpha_{u_3\phi Q_3} = y_t^2/(4\pi)$

LPM suppression



i.e., self-consistent equation for vertex func.

Effective Kinetic Theory of SM (cont'd)

- LPM-suppressed splitting function for SM

[**KM**, Yamada 2208.11708;
Arnold, Morre, Yaffe '01,'02,'03; Arnold, Dogan '08]

  - SM splitting function

$$\gamma_{s\to s's''}(p; xp, (1-x)p) = \frac{1}{2}\frac{\alpha_{ss's''}}{(2\pi)^4\sqrt{2}} \times \frac{P^{(\mathrm{vac})}_{s\to s's''}(x)}{x(1-x)} \times \mu_\perp^2(1, x, 1-x; s, s', s'')$$

vacuum DGLAP splitting function

SM gauge + top Yukawa

$$\alpha_{sg_a s} = d^{(a)}_{\mathrm{R}_s} C^{(a)}_{\mathrm{R}_s} \alpha_a \qquad \alpha_{u_3\phi Q_3} = \alpha_t$$

	C_F	C_A	d_F	d_A	t_F	t_A
SU(3)	4/3	3	3	8	1/2	3
SU(2)	3/4	2	2	3	1/2	2
U(1)	q_Y^2	0	1	1	q_Y^2	0

LPM suppression

$$\mu_\perp^4(x_1, x_2, x_3; s_1, s_2, s_3) = \frac{2}{\pi} x_1 x_2 x_3 p \sum_a \frac{\alpha_a(m_{D,a}) - \alpha_a(Q_{\perp,a})}{-b_a/(64\pi^3)} \mathcal{N}_a \times \sum_{\sigma\in A_3} \frac{1}{2}\left[C^{(a)}_{R_{s_{\sigma(2)}}} + C^{(a)}_{R_{s_{\sigma(3)}}} - C^{(a)}_{R_{s_{\sigma(1)}}}\right] x^2_{\sigma(1)}$$

$$b_a = \begin{cases} -7 \\ -\frac{19}{6} \\ \frac{41}{6} \end{cases} \qquad \mathcal{N}_a = \begin{cases} 15\frac{\zeta(3)}{\pi^2}T^3 \\ 14\frac{\zeta(3)}{\pi^2}T^3 \\ 6\frac{\zeta(3)}{\pi^2}T^3 \end{cases} \qquad m^2_{D,a} = \begin{cases} 8\pi\alpha_3 T^2 & \text{for SU(3)} \\ \frac{22\pi}{3}\alpha_2 T^2 & \text{for SU(2)} \\ \frac{22\pi}{3}\alpha_1 T^2 & \text{for U(1)} \end{cases}$$

Effective Kinetic Theory of SM (cont'd)

$$\gamma_{g_a\leftrightarrow g_a g_a}(P;xP,(1-x)P) = \frac{1}{2}\frac{d_{\rm A}^{(a)}C_{\rm A}^{(a)}\alpha_a}{(2\pi)^4\sqrt{2}}\,\frac{1^4+x^4+(1-x)^4}{1^2\cdot x^2(1-x)^2}\,\mu_{\perp,a}^2(1,x,1-x;\,g_a,\,g_a,\,g_a)\,,$$

$$\gamma_{s\leftrightarrow g_a s}(P;xP,(1-x)P) = \frac{1}{2}\frac{d_{\rm F}^{(a)}C_{{\rm F}_s}^{(a)}\alpha_a}{(2\pi)^4\sqrt{2}}\,\frac{1^2+(1-x)^2}{1\cdot x^2(1-x)}\,\mu_{\perp}^2(1,x,1-x;\,s,g_a,s)\quad \text{for } s=(\text{fermion})\,,$$

$$\gamma_{g_a\leftrightarrow s\bar{s}}(P;xP,(1-x)P) = \frac{1}{2}\frac{d_{\rm F}^{(a)}C_{{\rm F}_s}^{(a)}\alpha_a}{(2\pi)^4\sqrt{2}}\,\frac{x^2+(1-x)^2}{1^2\cdot x(1-x)}\,\mu_{\perp}^2(1,x,1-x;\,g_a,s,s)\quad \text{for } s=(\text{fermion})\,,$$

$$\gamma_{\phi\leftrightarrow g_a\phi}(P;xP,(1-x)P) = \frac{1}{2}\frac{d_{\rm F}^{(a)}C_{{\rm F}_\phi}^{(a)}\alpha_a}{(2\pi)^4\sqrt{2}}\,\frac{2}{x^2}\,\mu_{\perp}^2(1,x,1-x;\,\phi,g_a,\phi)\,,$$

$$\gamma_{g_a\leftrightarrow \phi\phi^*}(P;xP,(1-x)P) = \frac{1}{2}\frac{d_{\rm F}^{(a)}C_{{\rm F}_\phi}^{(a)}\alpha_a}{(2\pi)^4\sqrt{2}}\,\frac{2}{1^2}\,\mu_{\perp}^2(1,x,1-x;\,g_a,\phi,\phi)\,,$$

$$\gamma_{u_3\leftrightarrow \phi Q_3}(P;xP,(1-x)P) = \frac{1}{2}\frac{\alpha_{\rm t}}{(2\pi)^4\sqrt{2}}\,\frac{1}{1\cdot(1-x)}\,\mu_{\perp}^2(1,x,1-x;\,u_3,\phi,Q_3)\,,$$

$$\gamma_{\phi\leftrightarrow u_3\bar{Q}_3}(P;xP,(1-x)P) = \frac{1}{2}\frac{\alpha_{\rm t}}{(2\pi)^4\sqrt{2}}\,\frac{1}{x(1-x)}\,\mu_{\perp}^2(1,x,1-x;\,\phi,u_3,Q_3)\,,$$

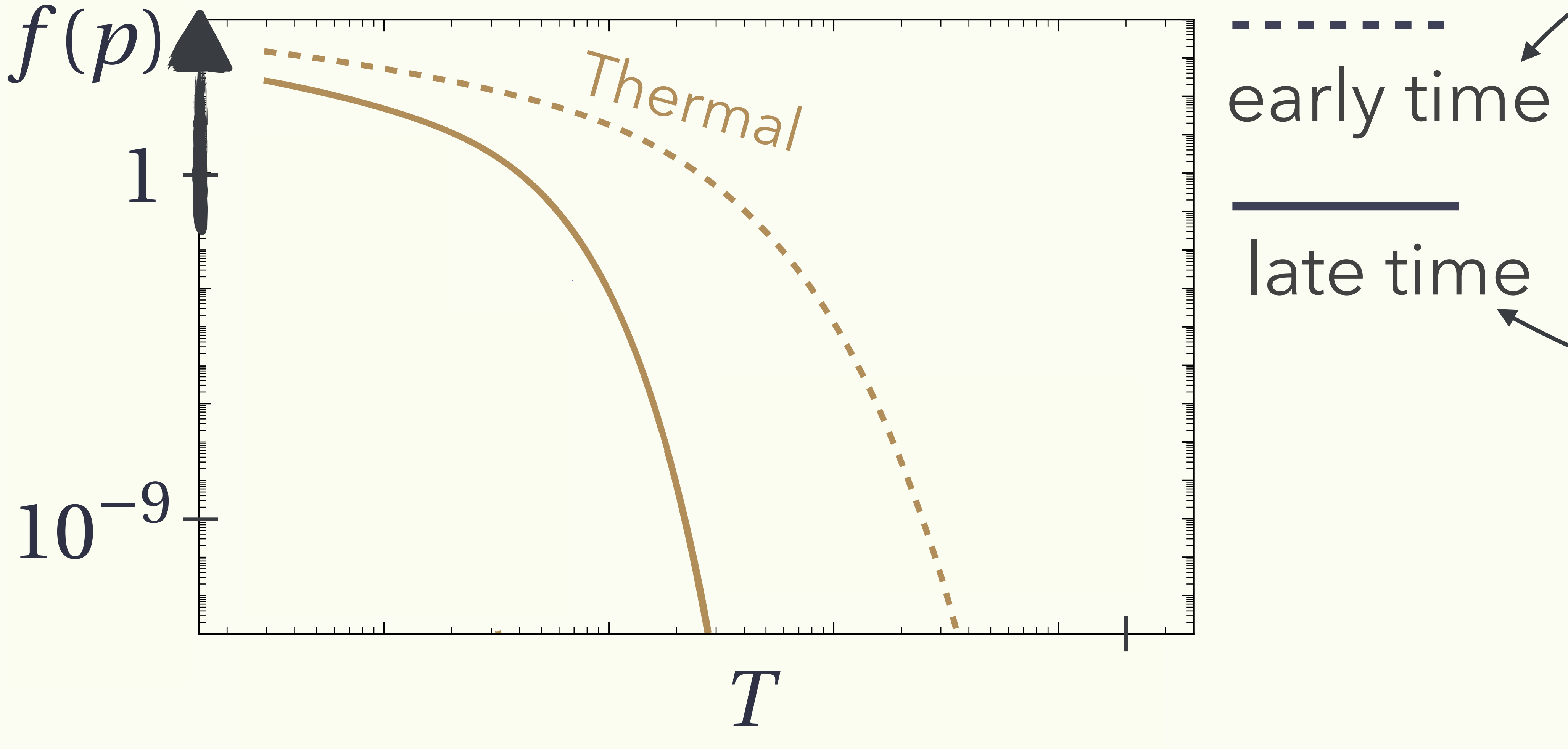
Reheating after Inflation

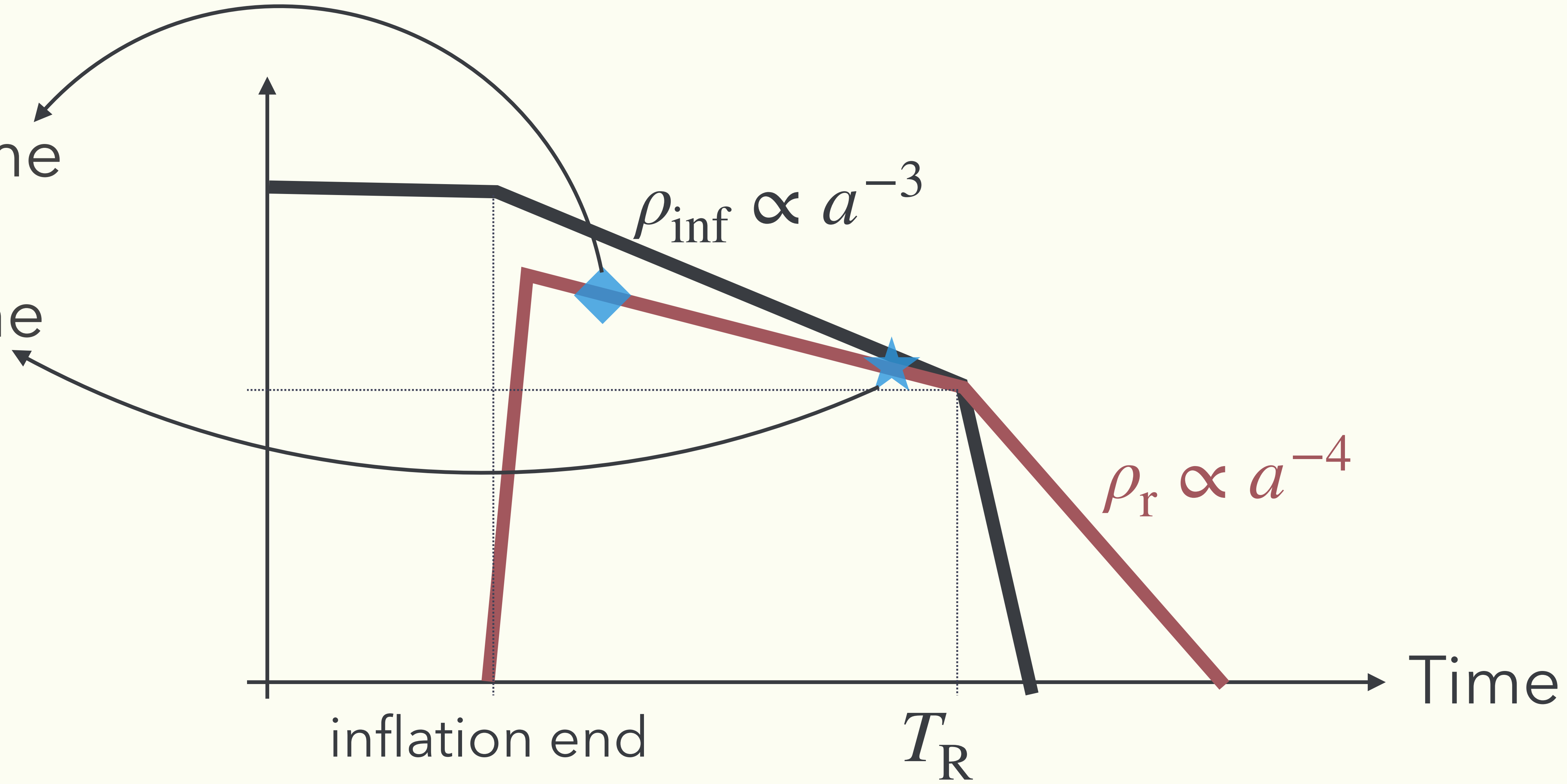
(i.e., Homogeneous source)

[**KM**, Harigaya 1312.3097; **KM**, Yamada 1506.07661, 2208.11708, 2402.14054]

Suppression of Maximal Temperature

- Instantaneous v.s. Finite-time thermalization for inflaton → gluon + gluon
  - Instantaneous thermalization





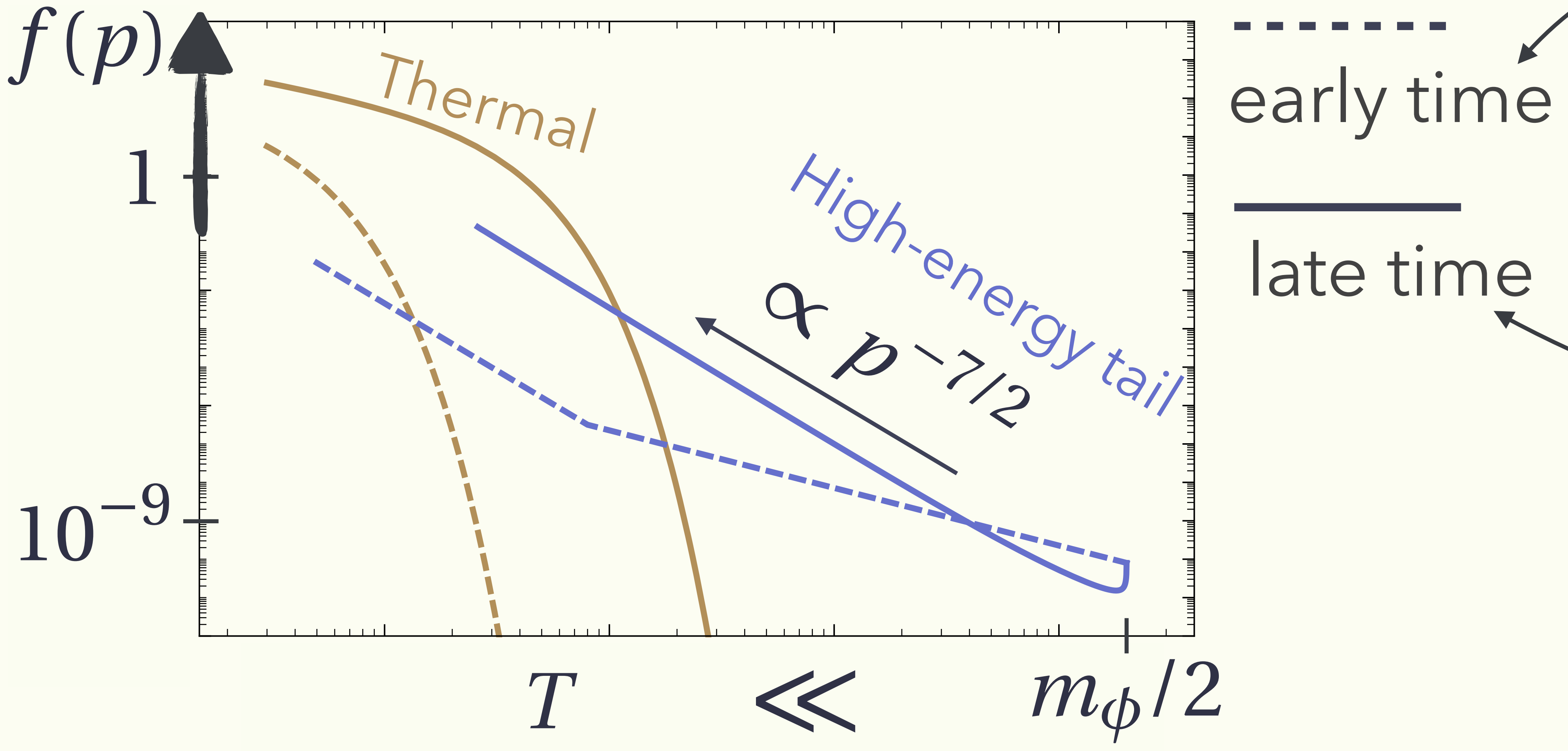
$$T_{\rm max}^{\rm (inst)} \sim \left(m_\phi T_{\rm R}^2 M_{\rm Pl}\right)^{1/4} \gg T_{\rm R}$$

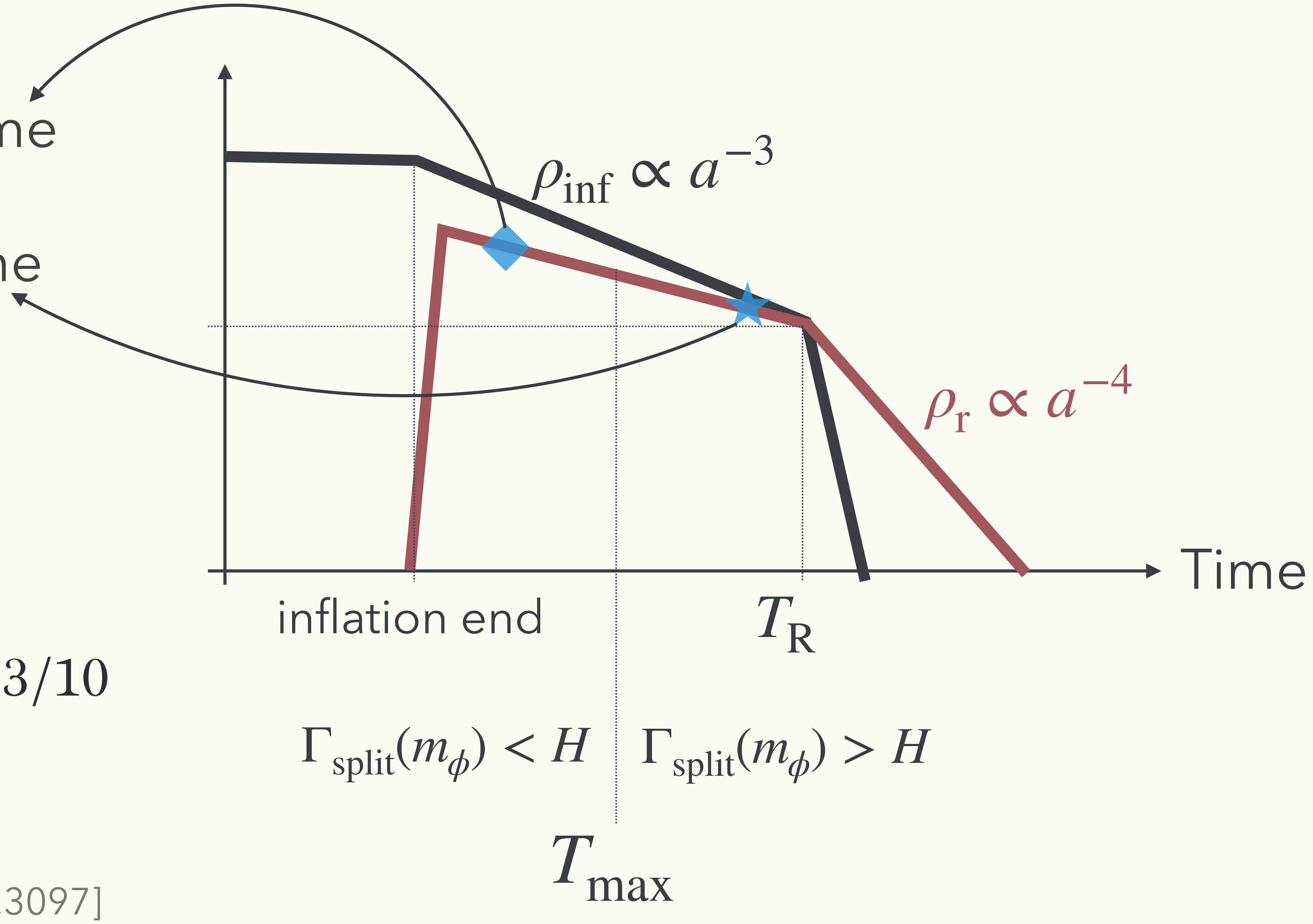
[Giudice, Kolb, Riotto hep-ph/0005123]

[**KM**, Harigaya 1312.3097; **KM**, Yamada 1506.07661, 2208.11708, 2402.14054]

Suppression of Maximal Temperature

- Instantaneous v.s. Finite-time thermalization for inflaton → gluon + gluon
  - **Finite-time** thermalization



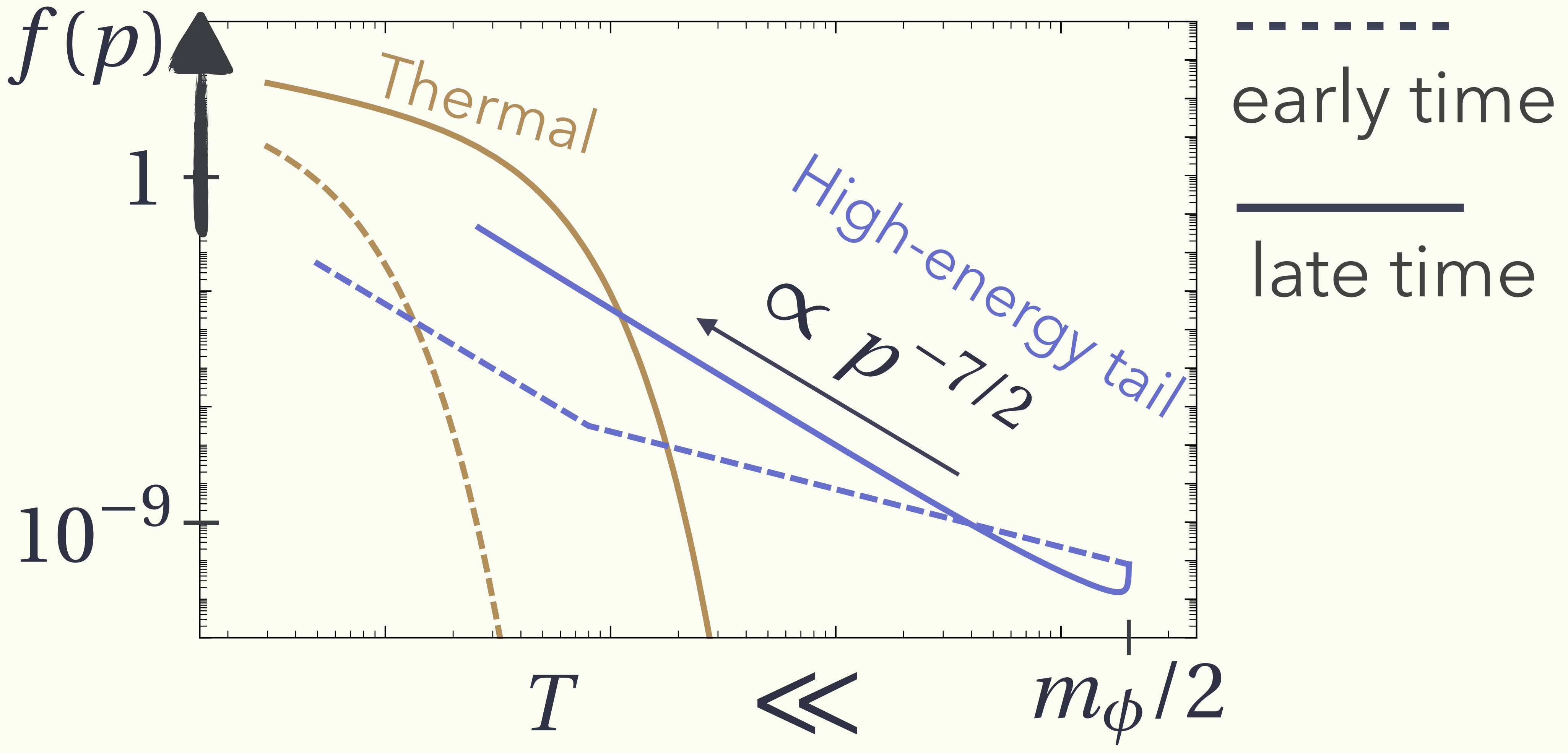


$$\frac{T_{\rm max}}{T_{\rm max}^{\rm (inst)}} \sim 10^{-3}\left(\frac{\alpha}{0.1}\right)^{4/5}\left(\frac{T_{\rm R}}{10^3\ {\rm GeV}}\right)^{3/10}$$

[**KM**, Harigaya 1312.3097]

Suppression of Maximal Temperature

- Attractor for $\Gamma_{\rm split}(m_\phi) \gtrsim H \gtrsim \Gamma_\phi$



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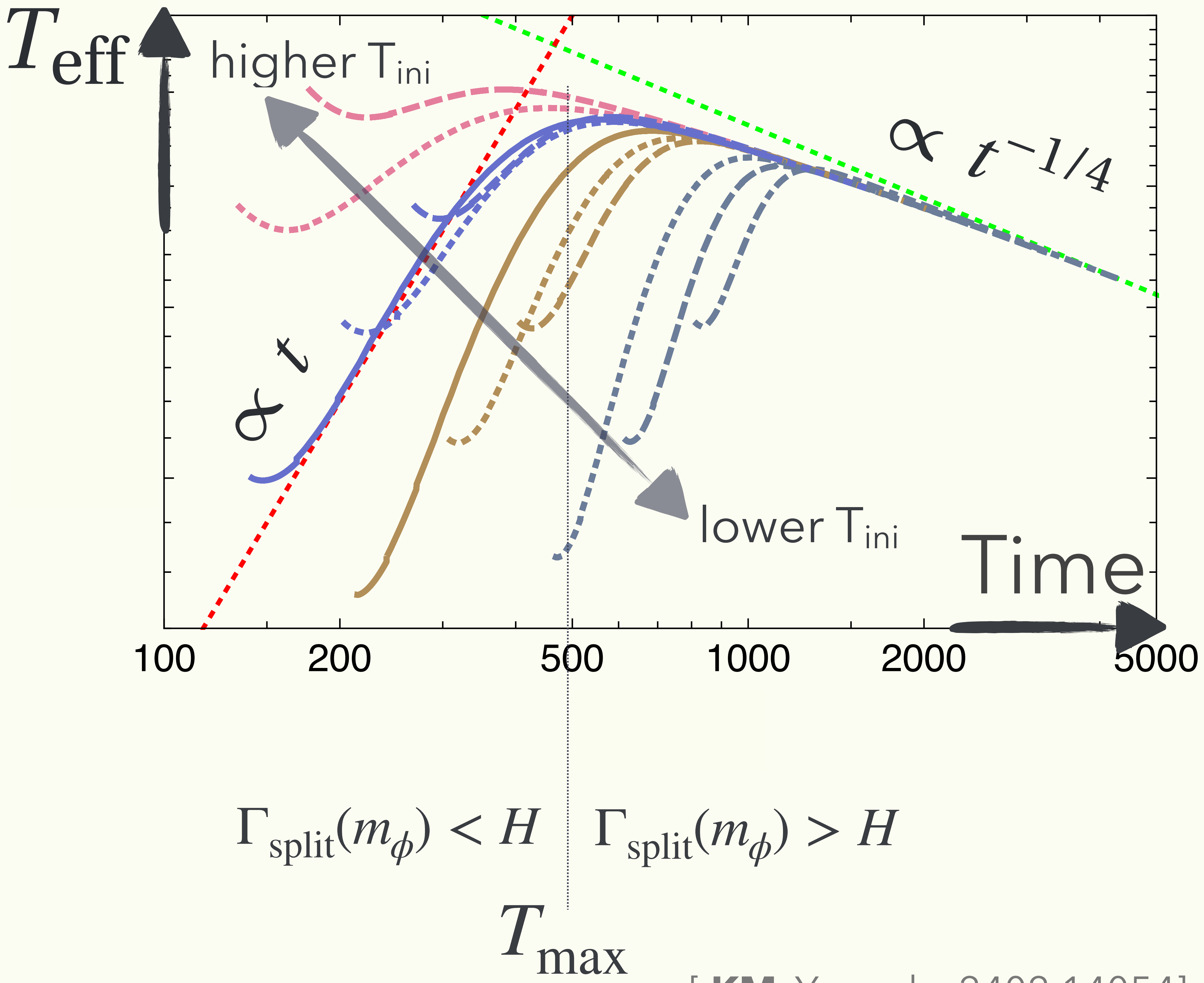
[KM, Harigaya 1312.3097]

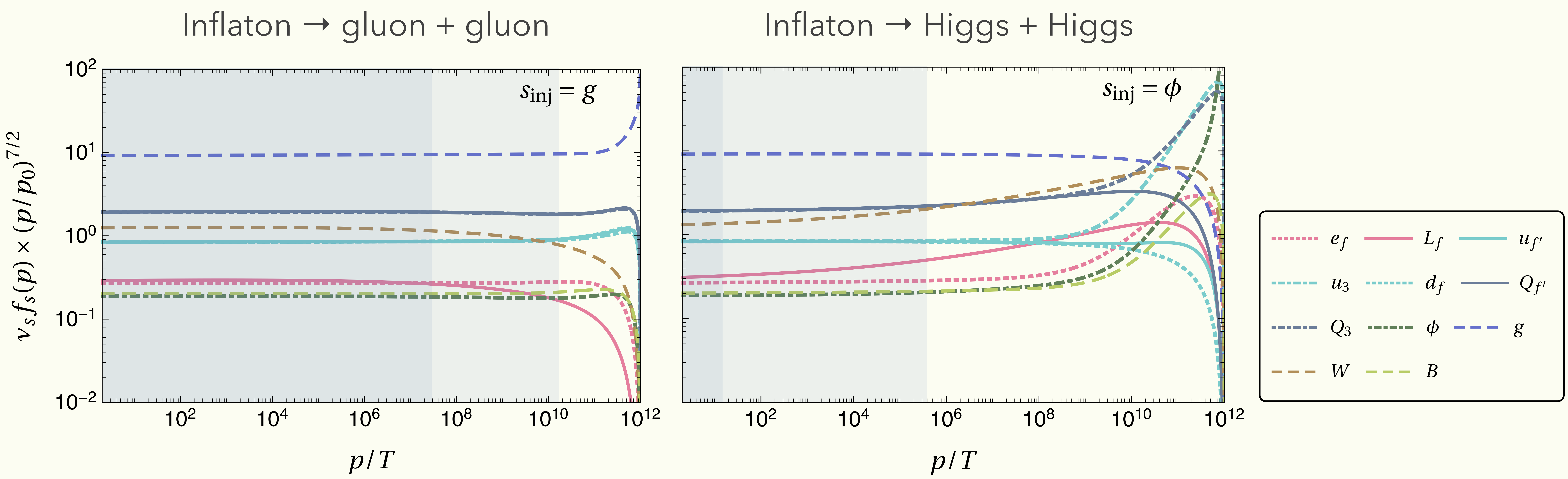


[KM, Yamada, 2402.14054]

Universality in the Spectrum

[**KM**, Yamada 2208.11708]

- Hardtail composition irrespective of inflaton-SM coupling



Universality in the Spectrum

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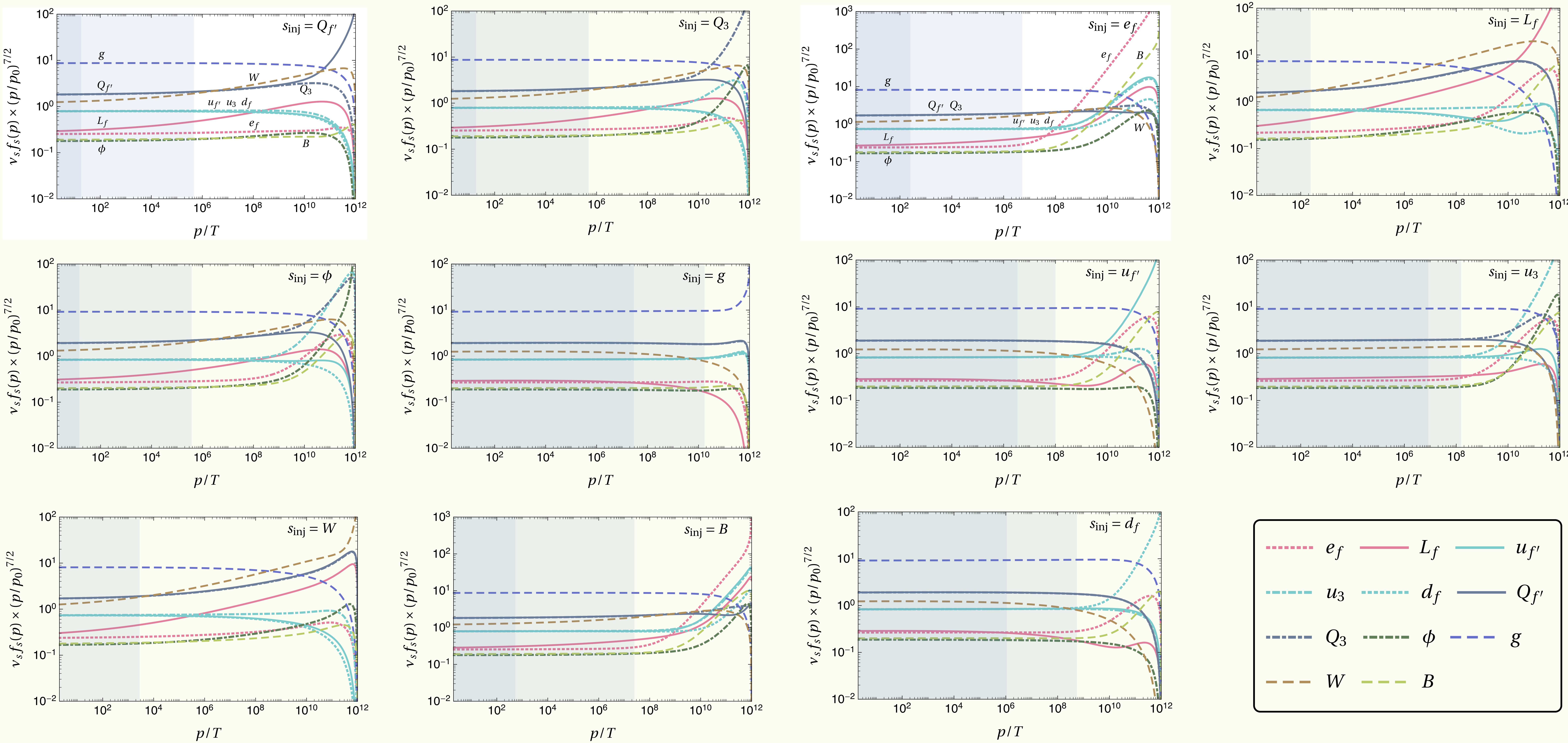
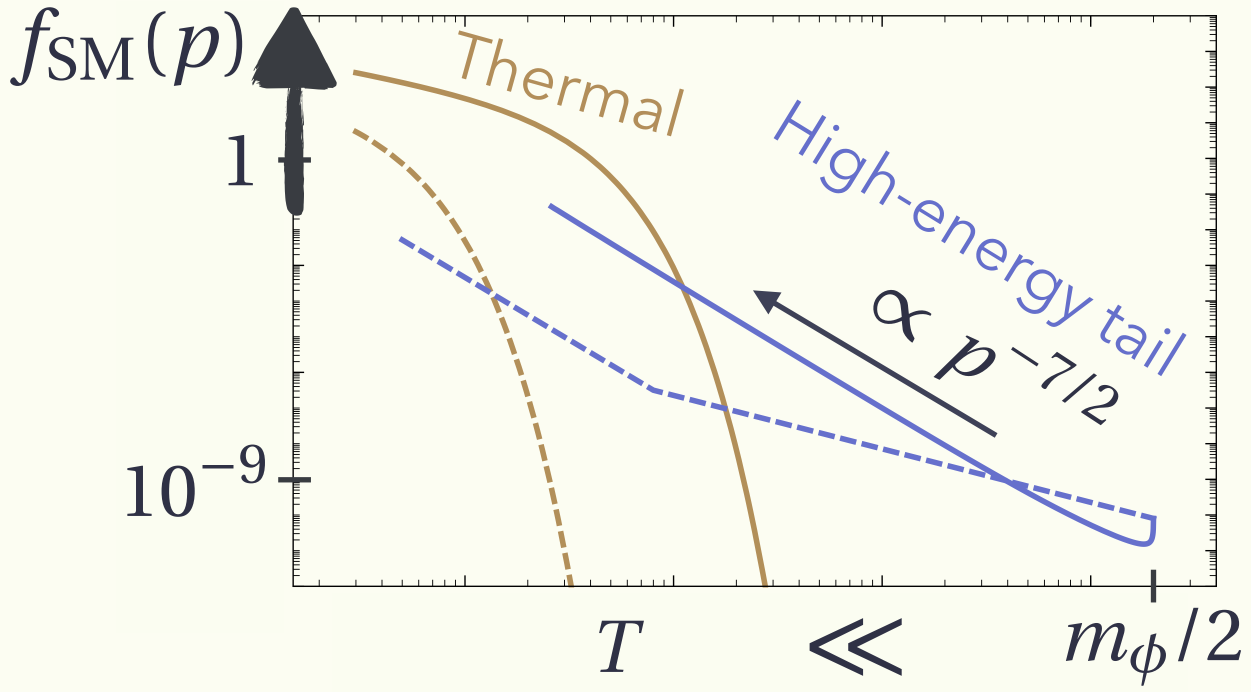
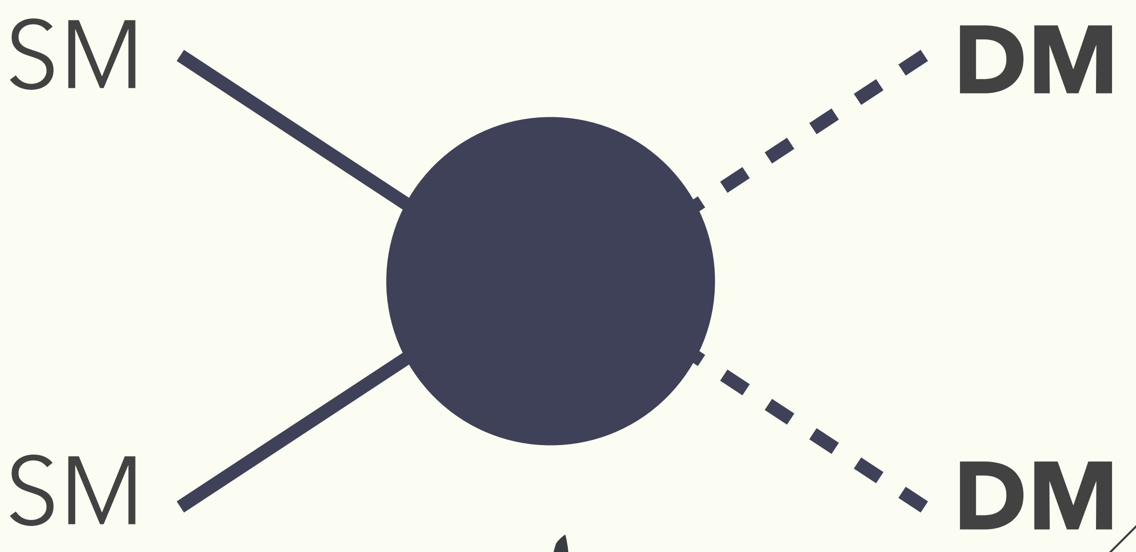


Implications of Suppressed $T_{\max}$ & Hardtail?

- Non-thermal Dark Matter production of $m_{\rm DM} > T_{\rm R}$

[**KM**+ 1402.2846, 1901.11027; Drees+; Garcia+]

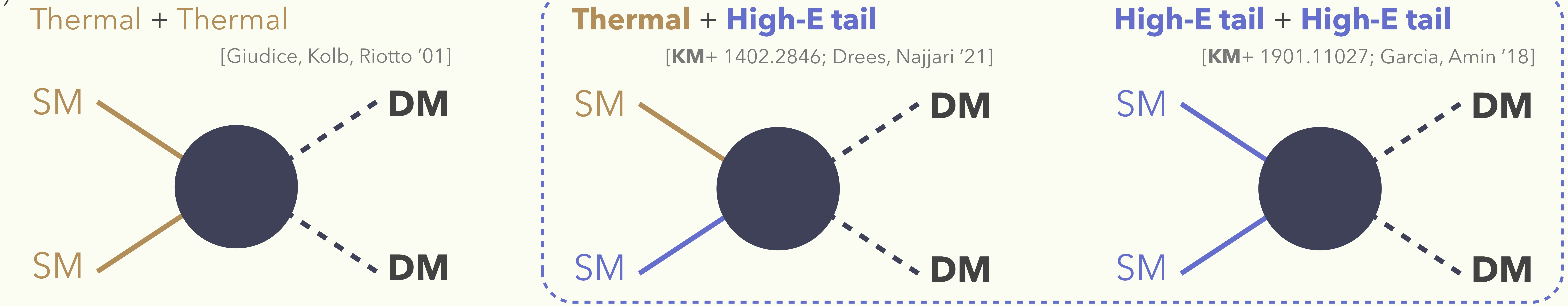




E.g. W W → DM DM

$$\langle \sigma v \rangle \simeq \frac{\alpha_{\rm DM}^2}{m_{\rm DM}^2} \quad \Rightarrow \quad \frac{\rho_{\rm DM}}{s} \simeq 0.11 \alpha_{\rm DM}^2 \frac{T_{\rm R}^3}{m_{\rm DM}^2}$$

"Universal" production



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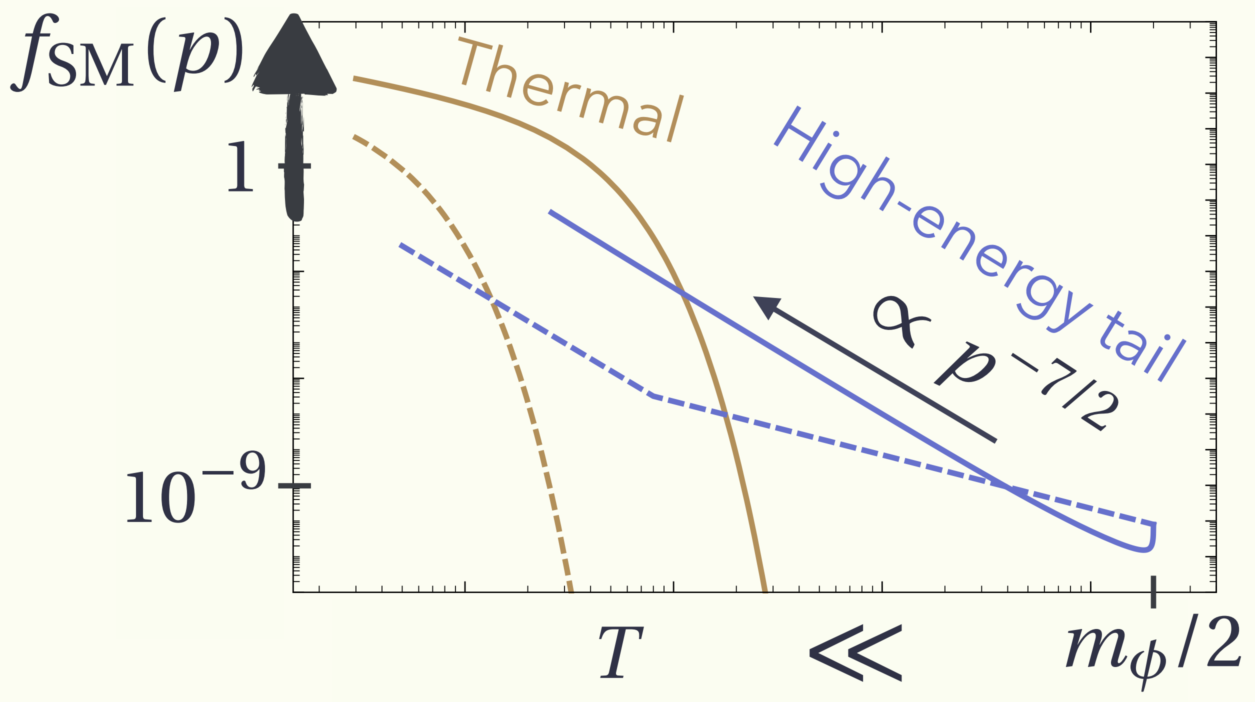
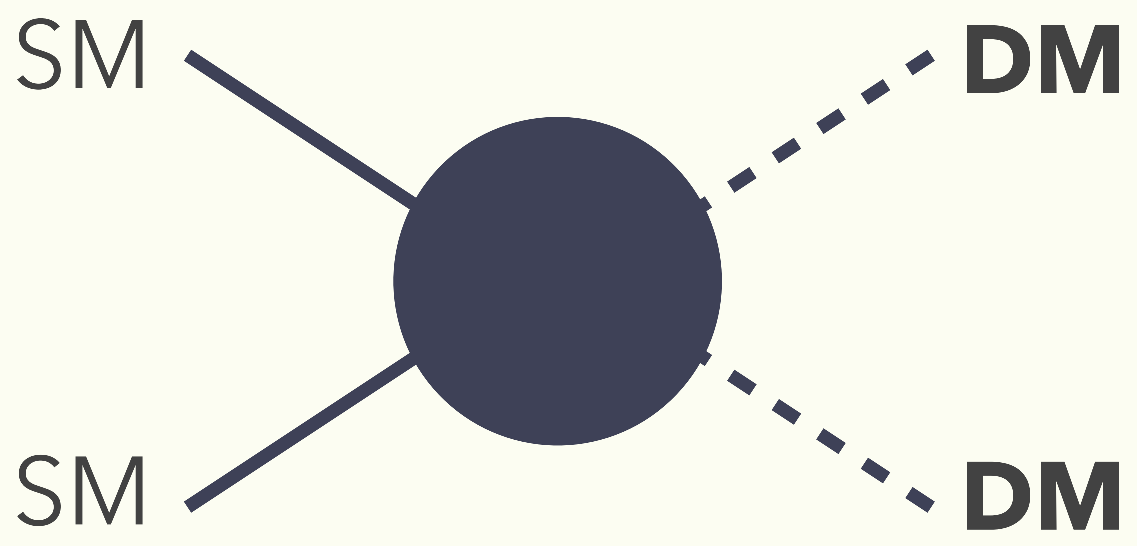
- Non-thermal Dark Matter production of $m_{\text{DM}} > T_{\text{R}}$

[**KM**+ 1402.2846, 1901.11027; Drees+; Garcia+]





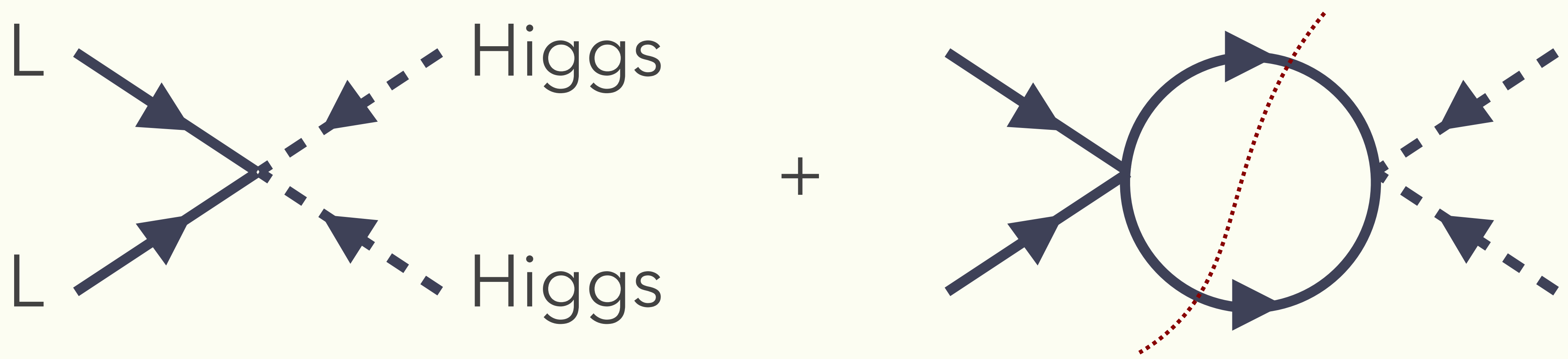
E.g. W W → DM DM

$$\langle \sigma v \rangle \simeq \frac{\alpha_{\text{DM}}^2}{m_{\text{DM}}^2} \quad \Rightarrow \quad \frac{\rho_{\text{DM}}}{s} \simeq 0.11 \alpha_{\text{DM}}^2 \frac{T_{\text{R}}^3}{m_{\text{DM}}^2}$$

"Universal" production

- Leptogenesis of $M_N > T_{\text{R}}$

[Hamada, Kawana 1510.05186, ...]



- Phase transition ...

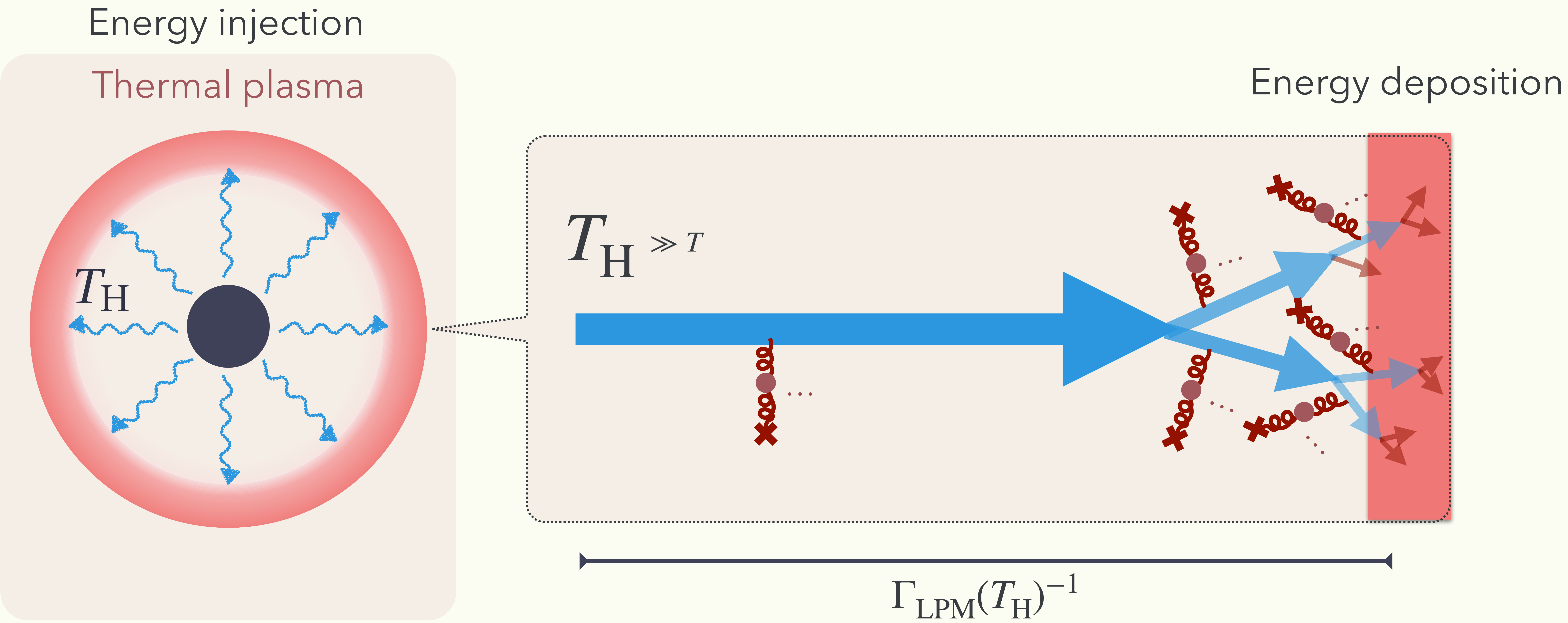
Evaporation of PBH

(i.e., Inhomogeneous source)

Formation of Hotspot

[He, Kohri, **KM,** Yamada 2210.06238, 2407.15926]

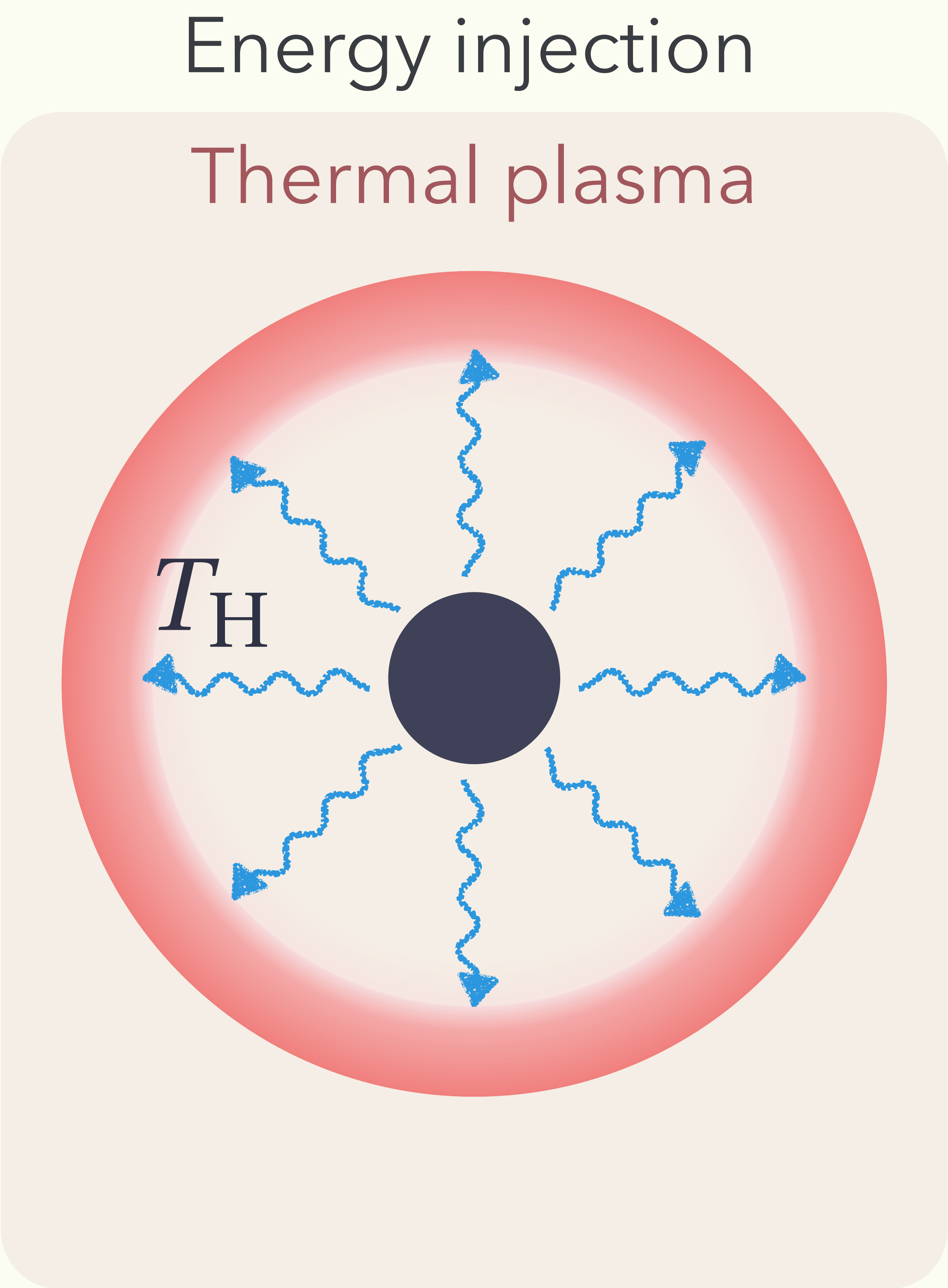
- Energy injection v.s. Diffusion

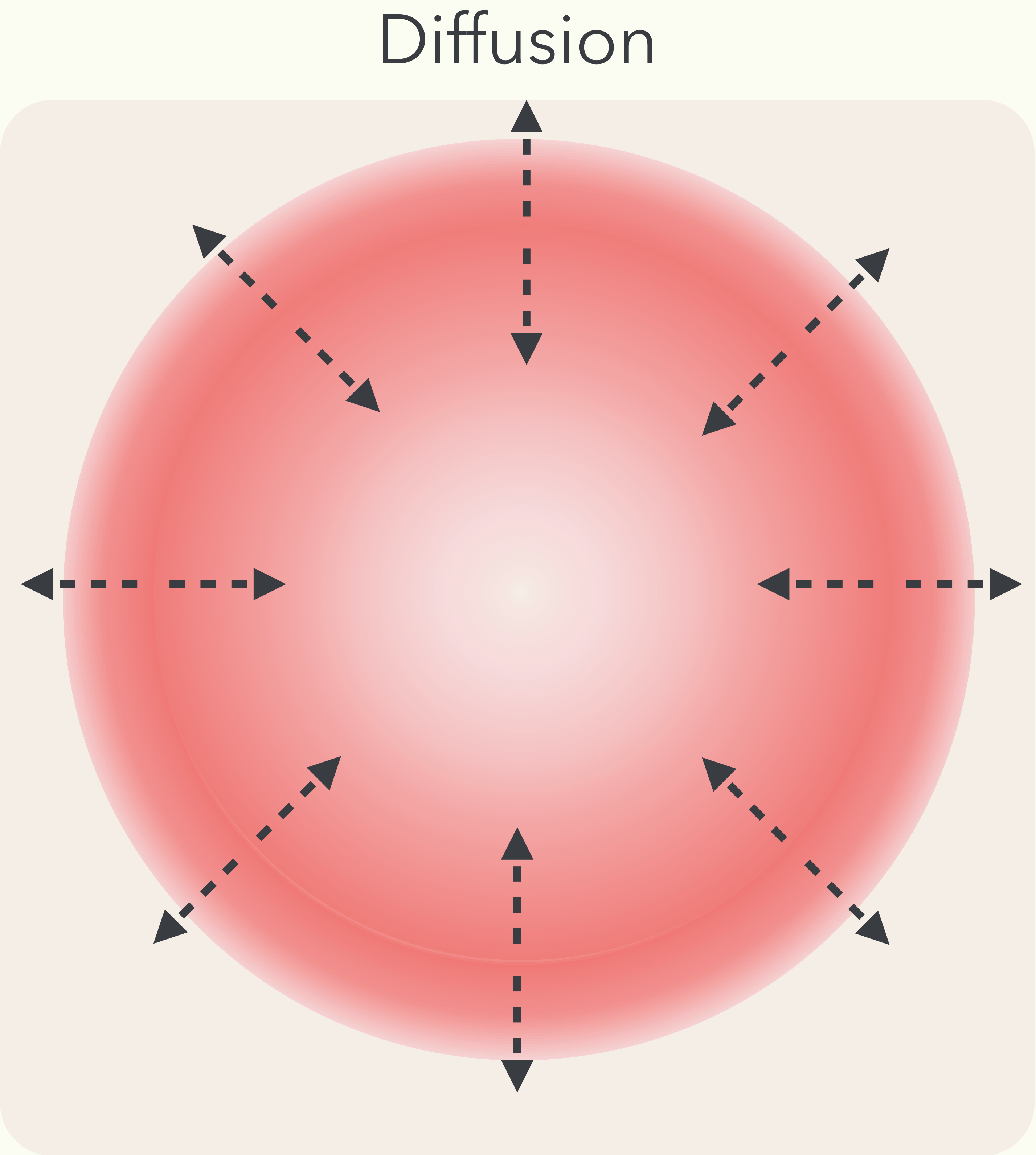


Formation of Hotspot

[He, Kohri, **KM,** Yamada 2210.06238, 2407.15926]

- Energy injection v.s. Diffusion

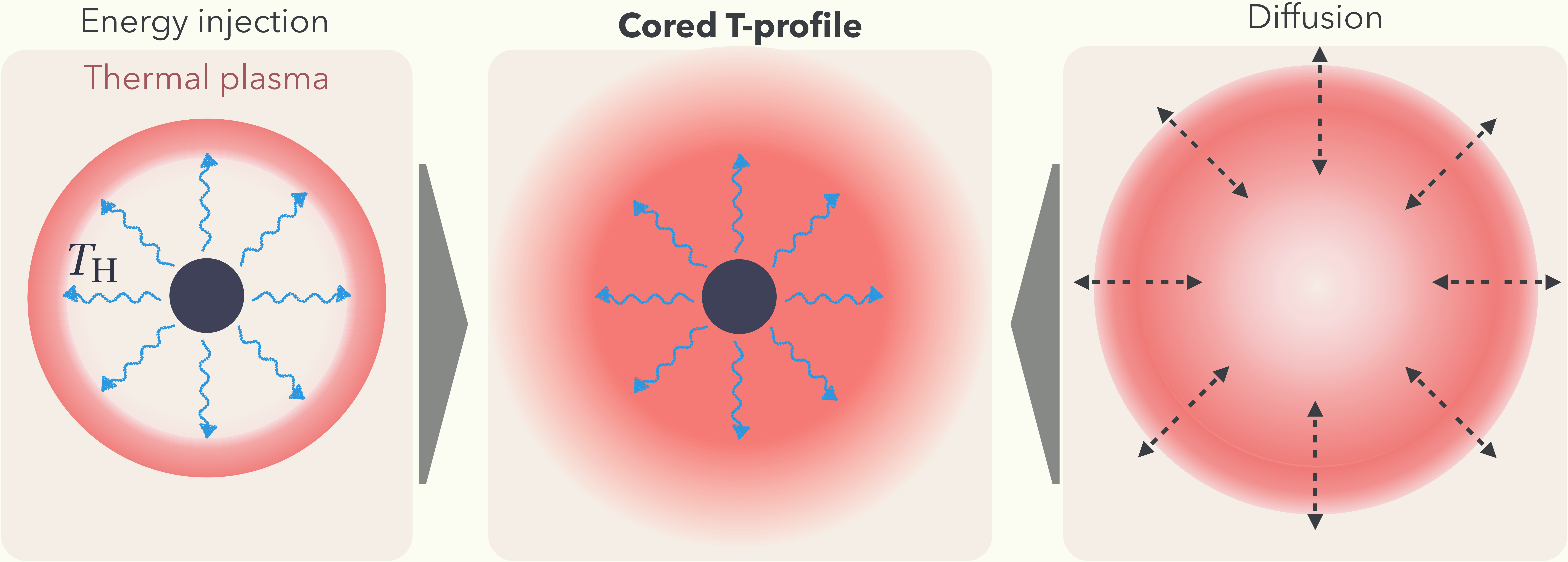




Formation of Hotspot

[He, Kohri, **KM,** Yamada 2210.06238, 2407.15926]

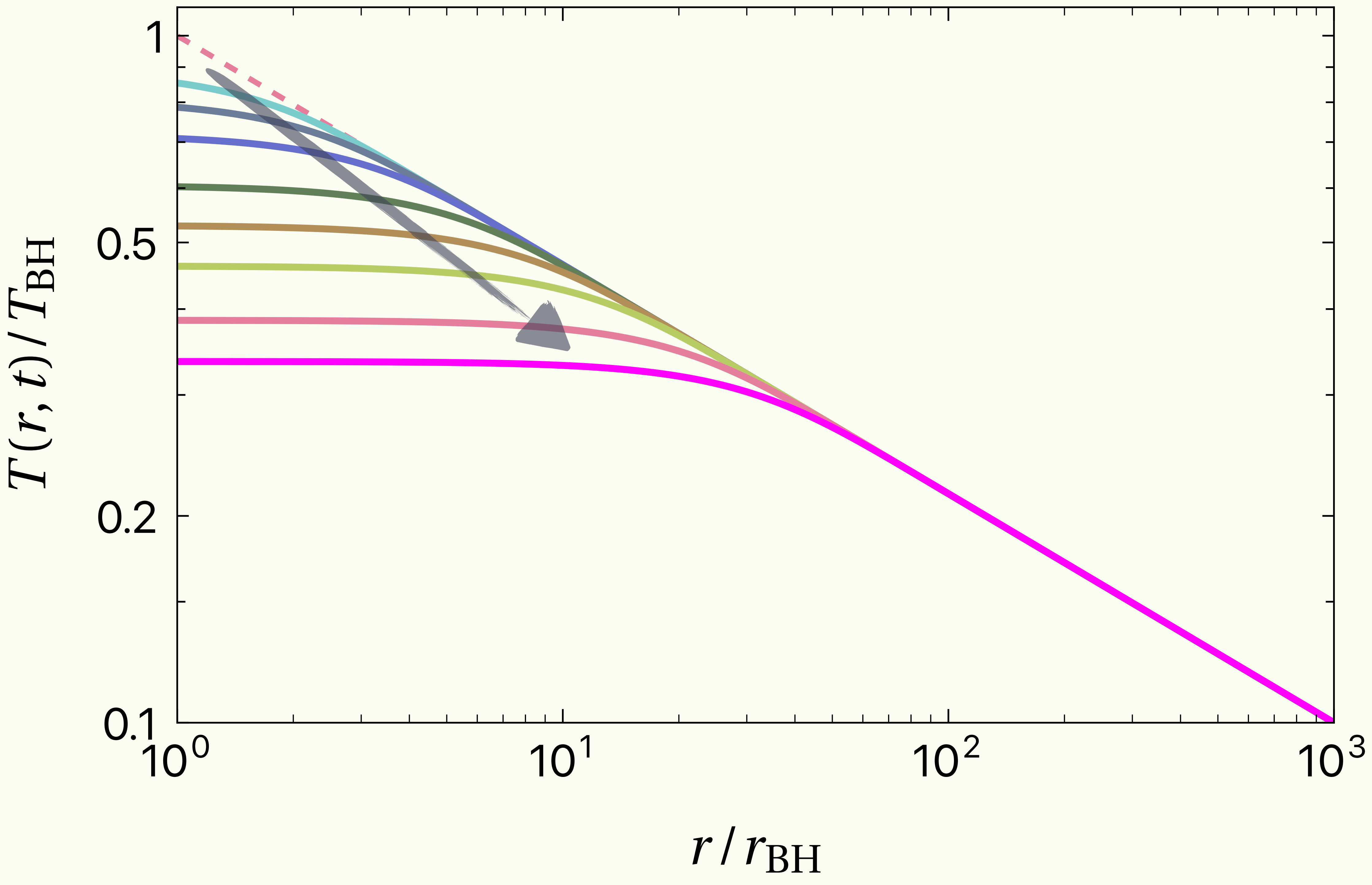
- Energy injection v.s. Diffusion

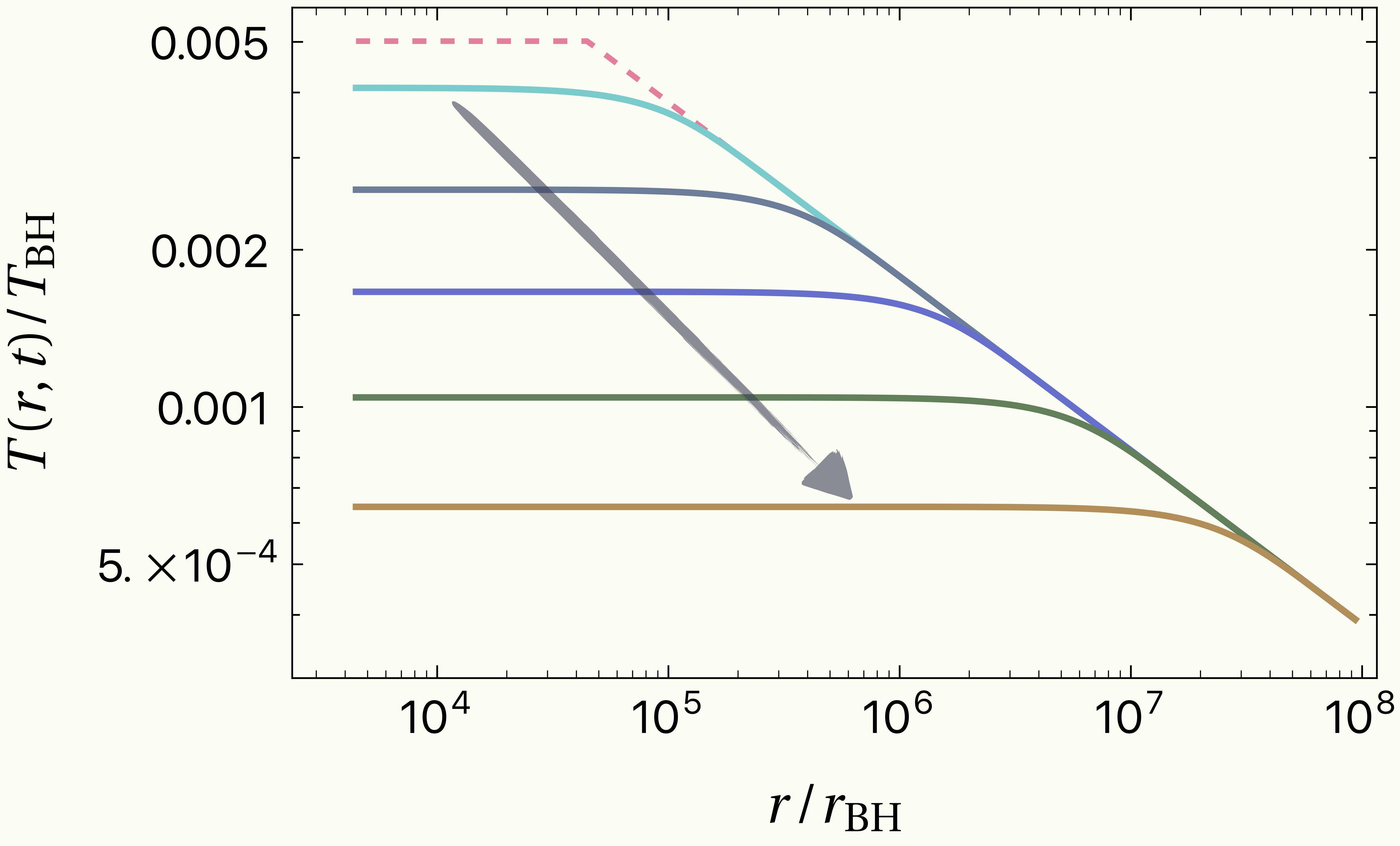


Formation of Hotspot

[He, Kohri, **KM,** Yamada 2210.06238, 2407.15926]

- Evolution towards the attractor

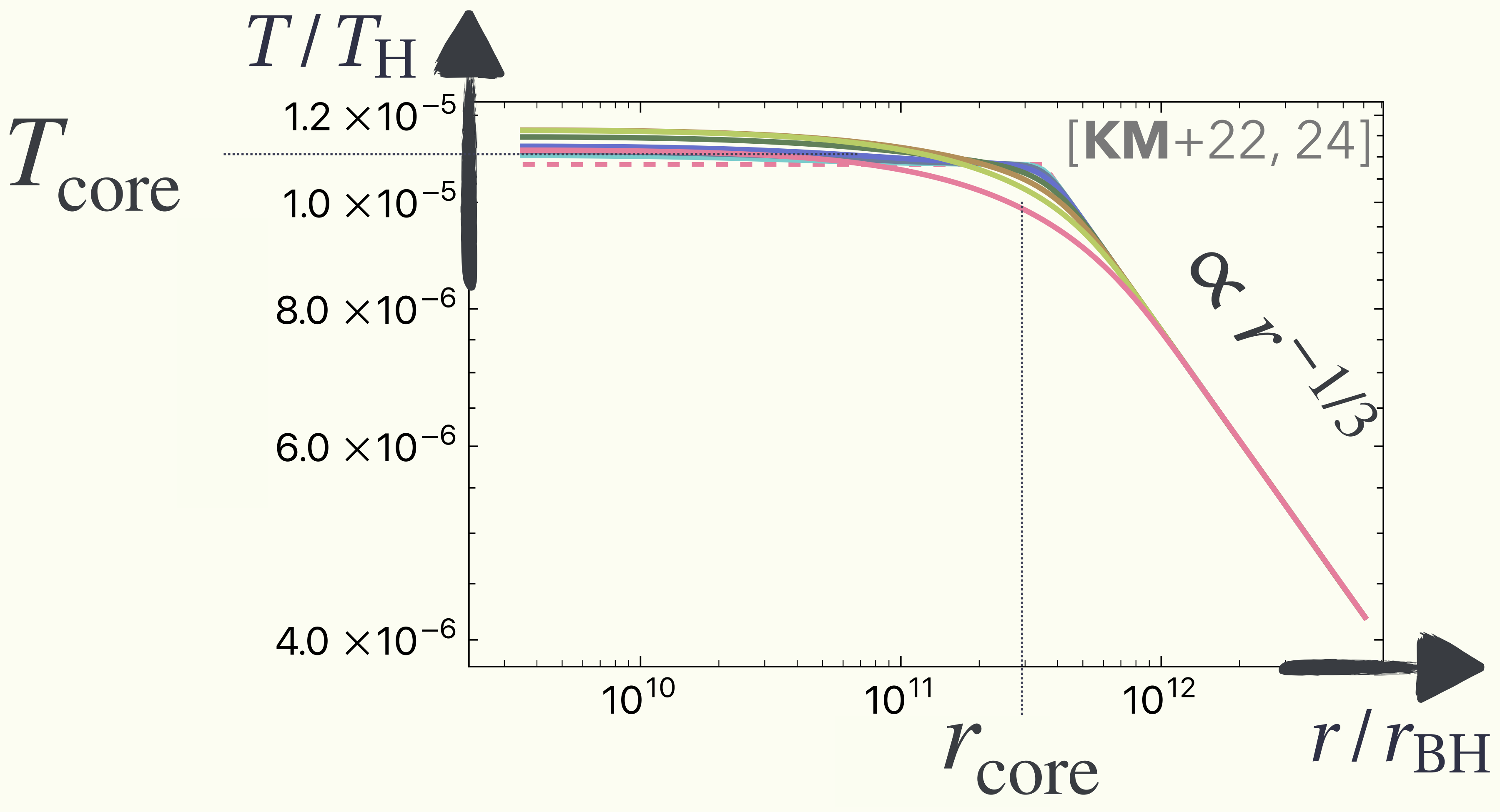




Formation of Hotspot

[He, Kohri, **KM,** Yamada 2210.06238, 2407.15926]

- **Cored temperature profile** from the LPM suppression

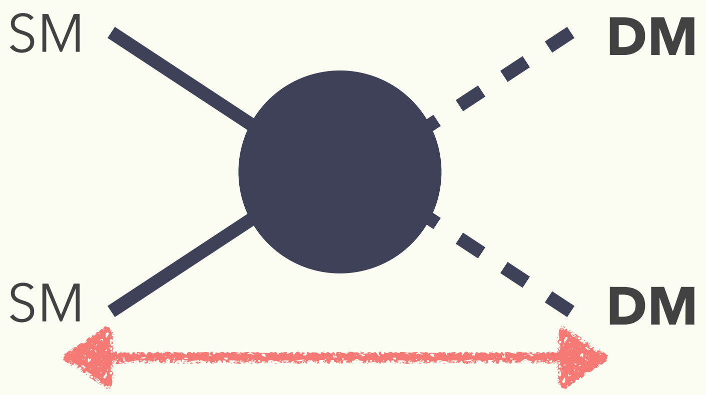


$$T_{\rm core} \sim 7\times10^{-6}\left(\frac{\alpha}{0.05}\right)^{8/3} T_{\rm H} \lesssim 10^{7}\,{\rm GeV}\left(\frac{\alpha}{0.05}\right)^{19/3}$$

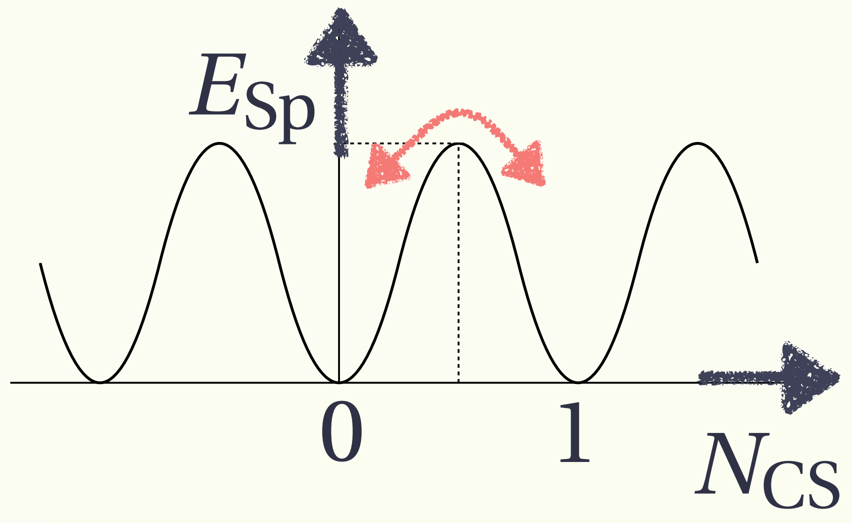
$$r_{\rm core} \sim 3\times10^{11}\left(\frac{\alpha}{0.05}\right)^{-6} r_{\rm BH}$$

- Potential impacts on physics of T if $\boldsymbol{T_{\rm core} > T > T_{\rm bkg}}$

Local DM **freeze-out** for $T_{\rm core} > \boldsymbol{T_{\rm FO}} > T_{\rm bkg}$

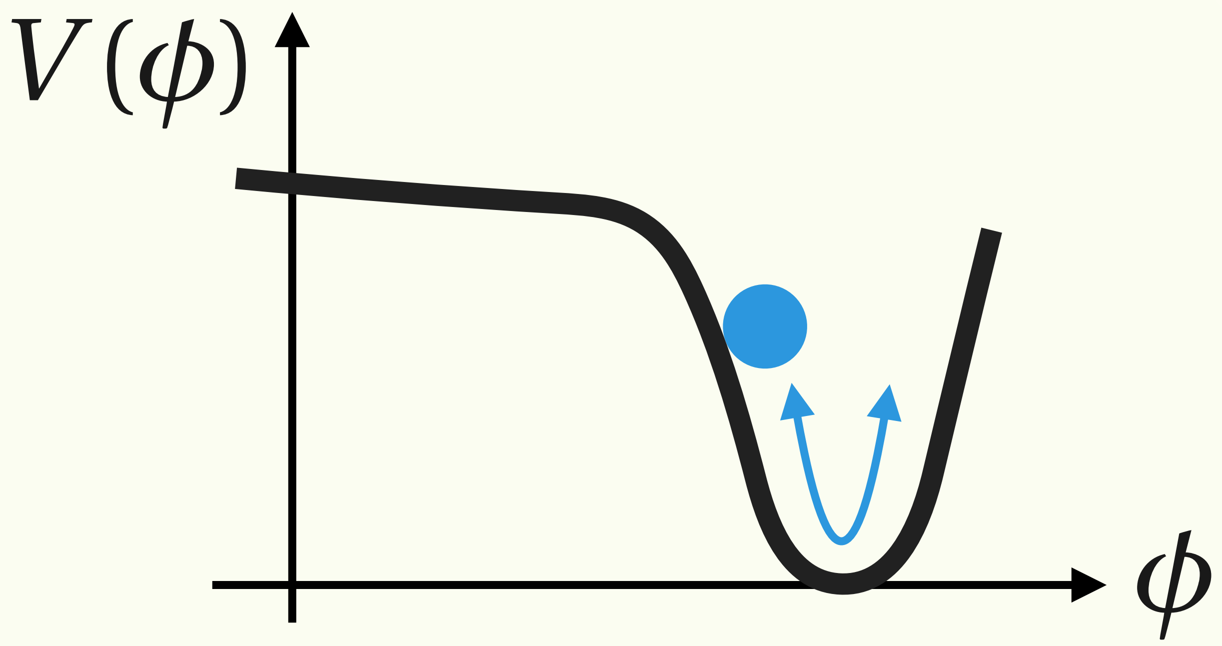


Local **sphaleron** for $T_{\rm core} > \boldsymbol{T_{\rm Sph}} > T_{\rm bkg}$

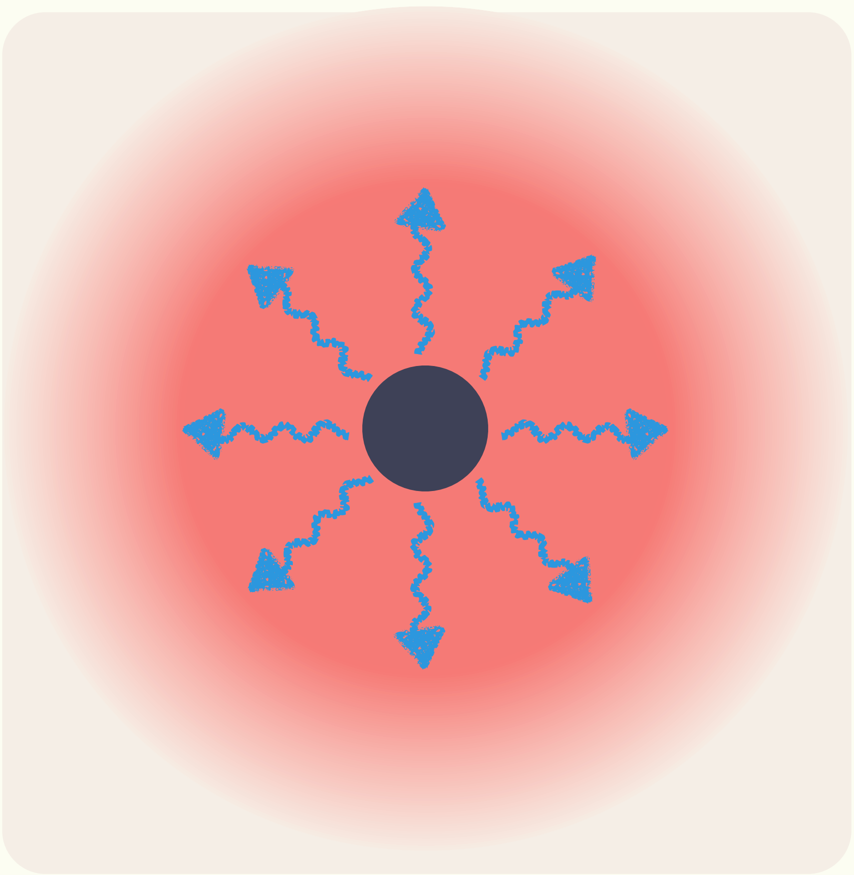


…

Summary



w/ **small coupling** to radiation

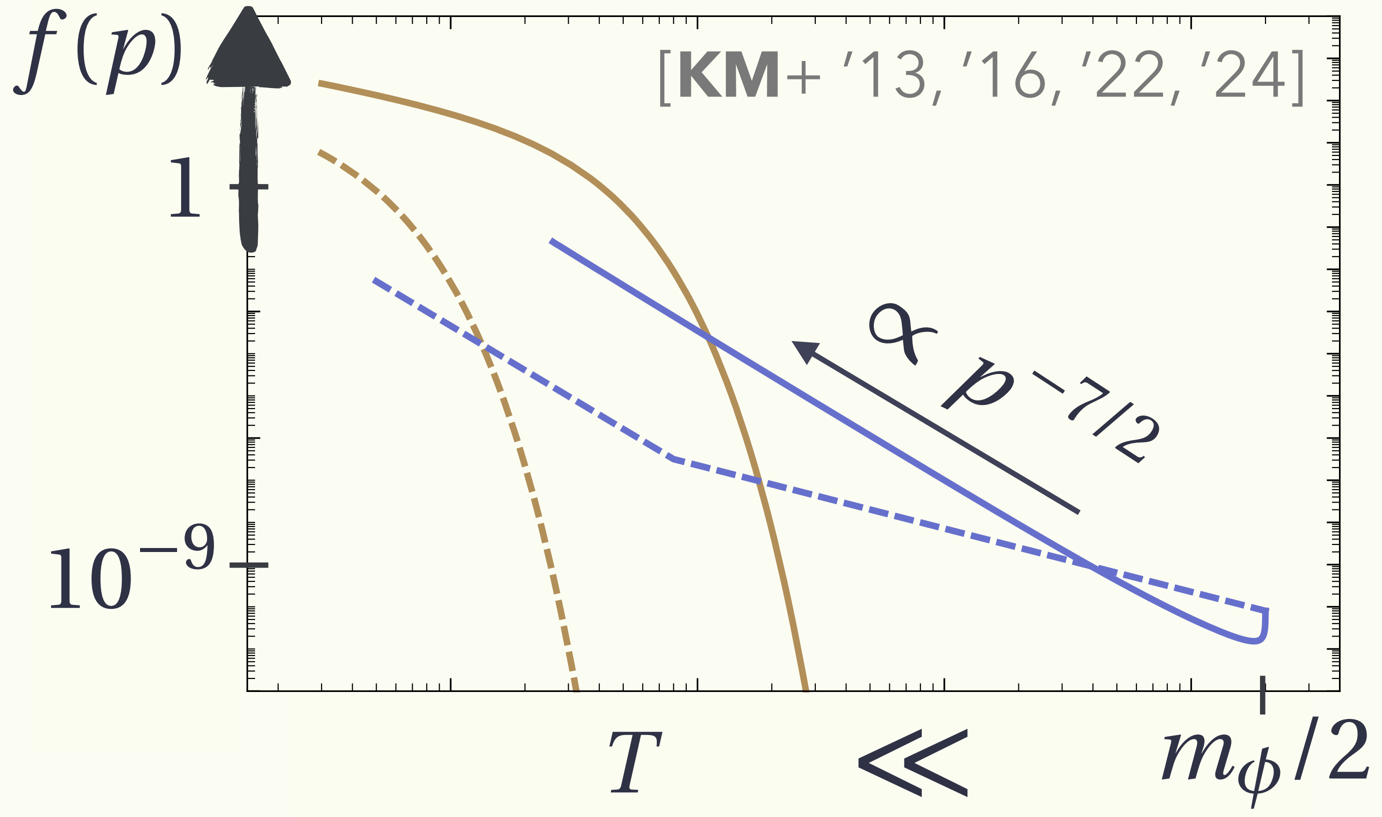


w/ life time ≪ 1s

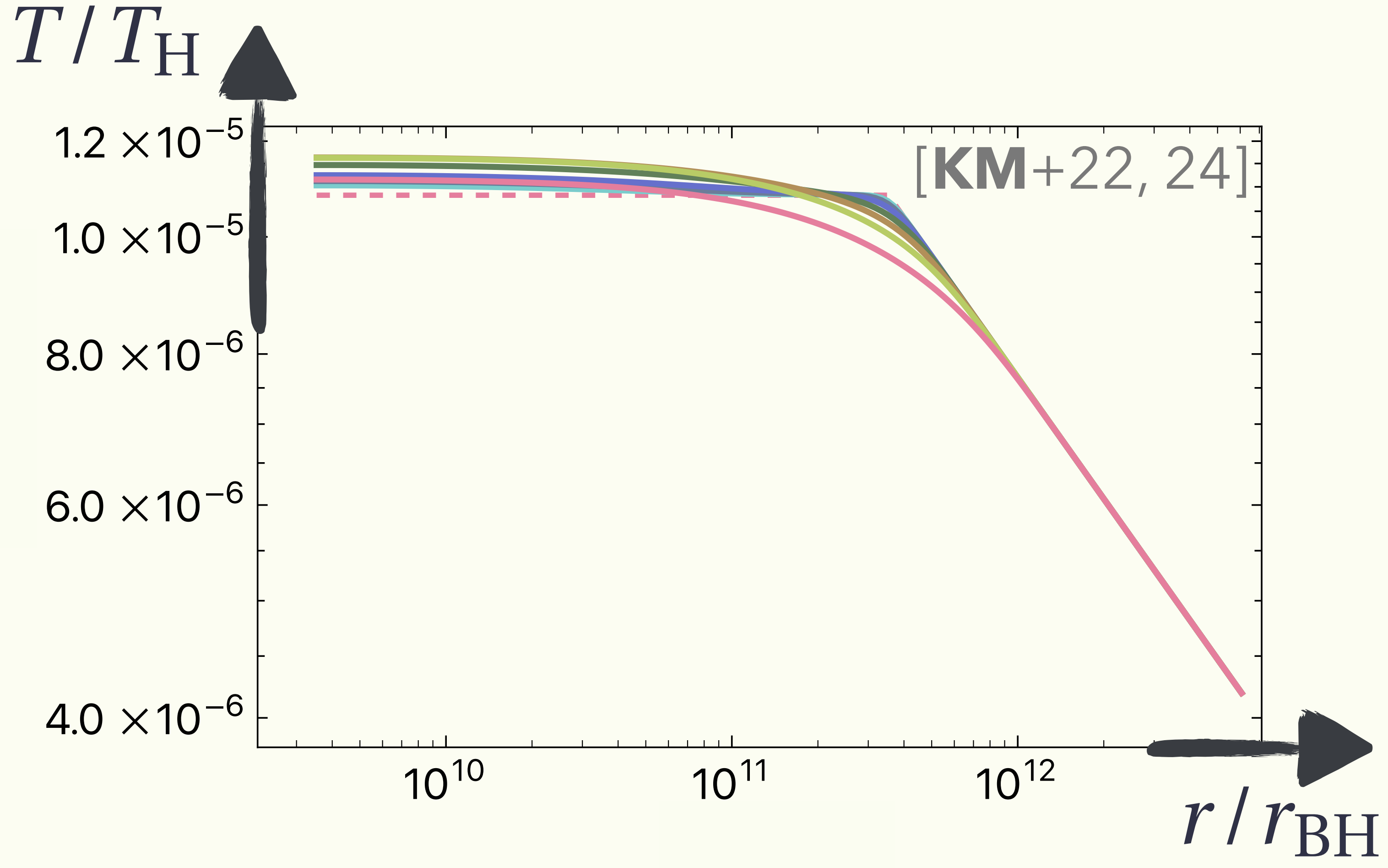
[**KM**, Harigaya 1312.3097; **KM**, Yamada 1506.07661, 2208.11708, 2402.14054]

In-medium cascades (LPM)

- Suppressed $T_{\rm max}$ & Universality



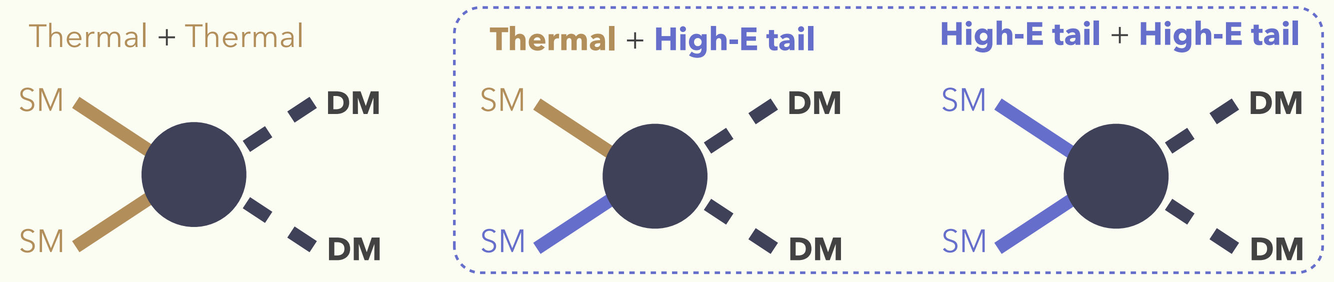
- Cored T-profile



Implications

- DM production

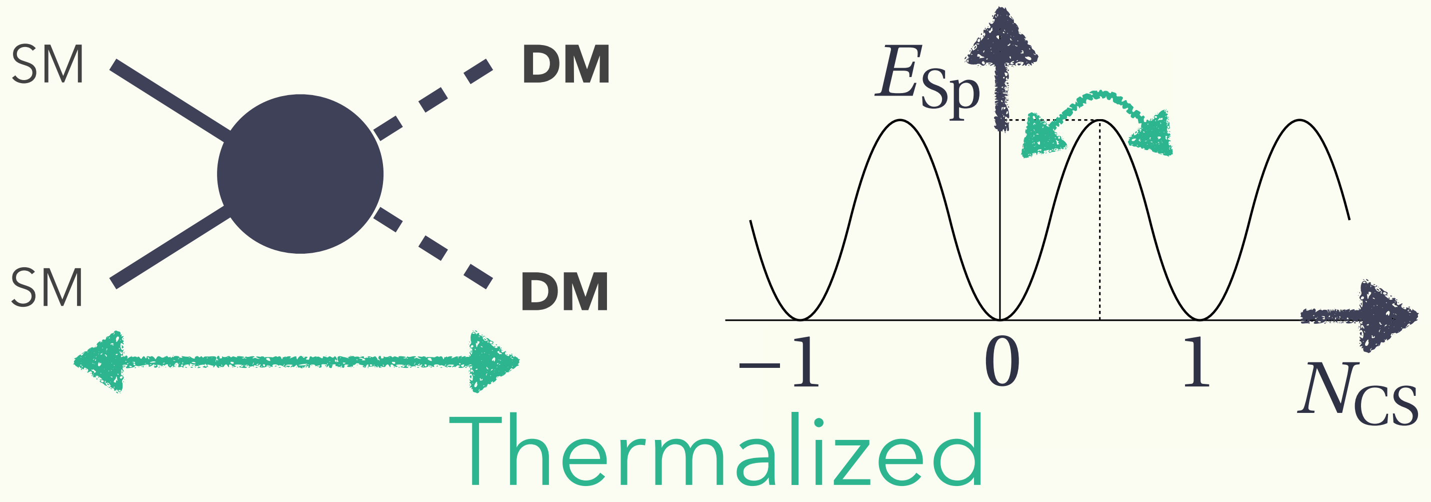
[**KM**+ 1402.2846, 1901.11027; Drees +; Garcia+]



- Baryogenesis
- …

- Local DM/baryon production

[**KM**+2210.06238, 2407.15926; Turner+]

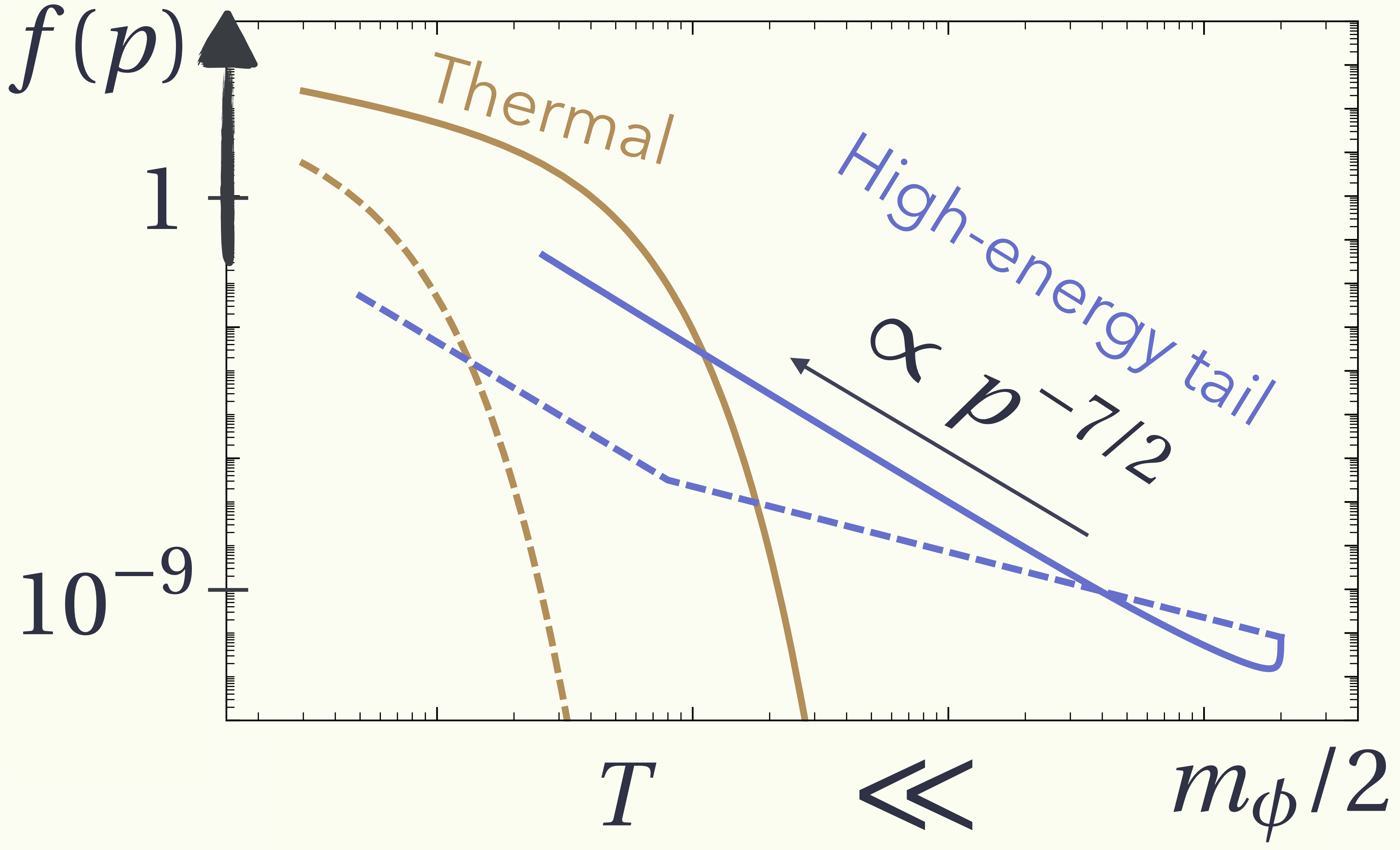


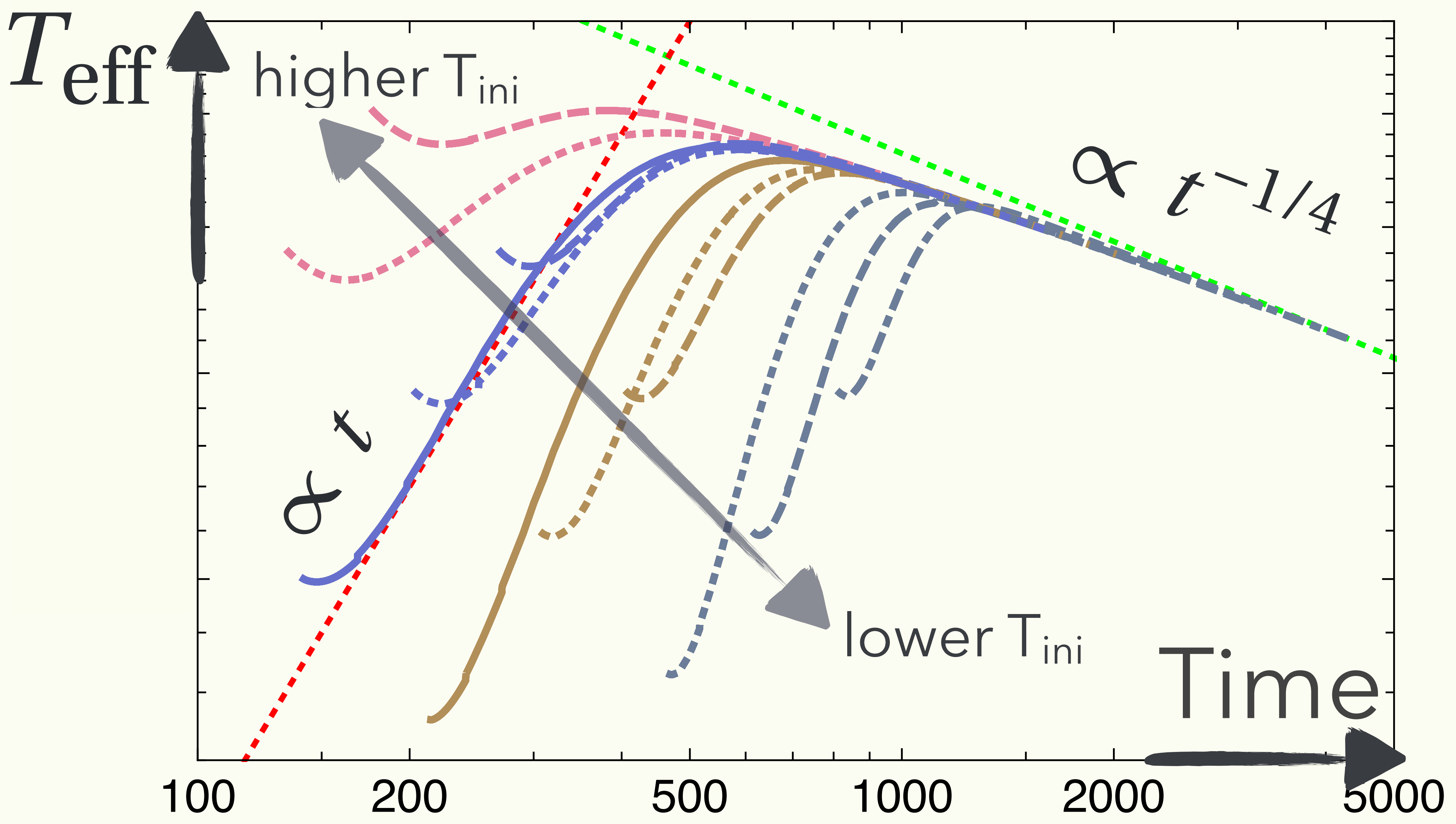
- …

Backup

Inflaton Decays into Pure YM

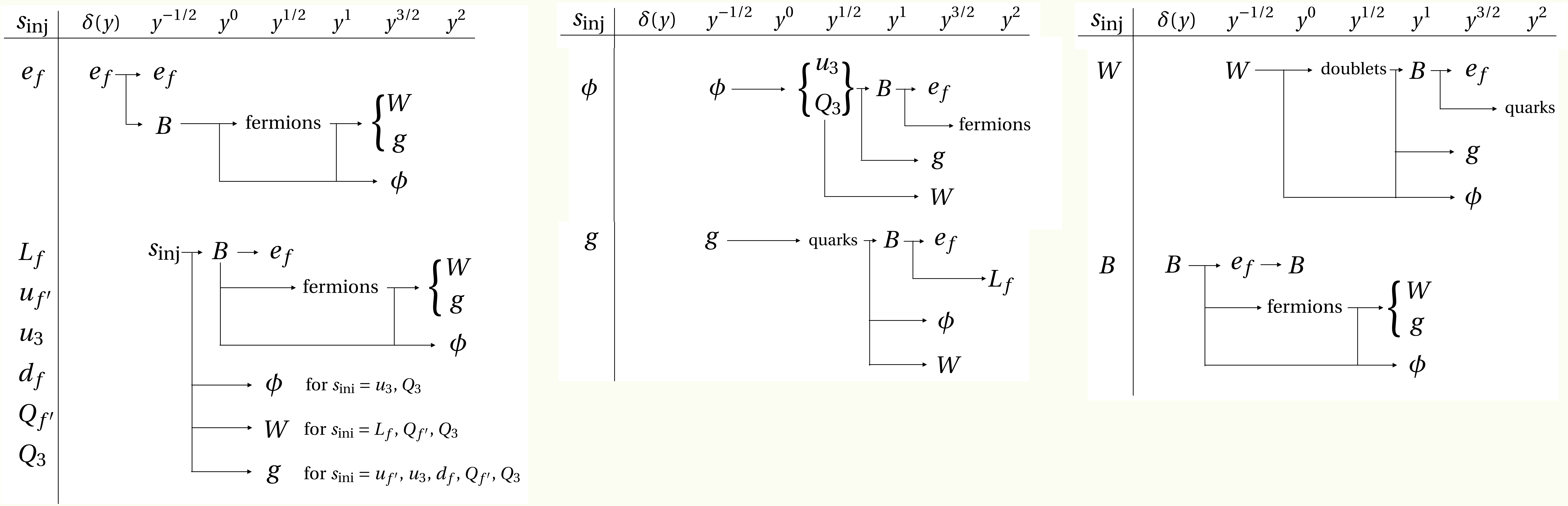
- Attractor for $\Gamma_{\text{split}}(m_\phi) \gg H \gtrsim \Gamma_\phi$





More on splitting functions

- **Splitting** channels in the SM



More on splitting functions

- IR divergence in the splitting kernel?

$$\mathscr{C}_s^{\text{“}1\to 2''} = -\frac{(2\pi)^3}{p^2\nu_s}\sum_{s',s''}\int_0^p \mathrm{d}k\,\gamma_{s\leftrightarrow s's''}(p;k,p-k)\,f_s(p) + \frac{(2\pi)^3}{p^2\nu_s}\sum_{s',s''}\int_0^\infty \mathrm{d}k\,\gamma_{s'\leftrightarrow ss''}(p+k;p,k)\,f_{s'}(p+k)$$

$$\gamma_{s\leftrightarrow s's''}(p;k,p-k) \propto k^{-3/2} \quad \text{for} \quad k \ll p$$

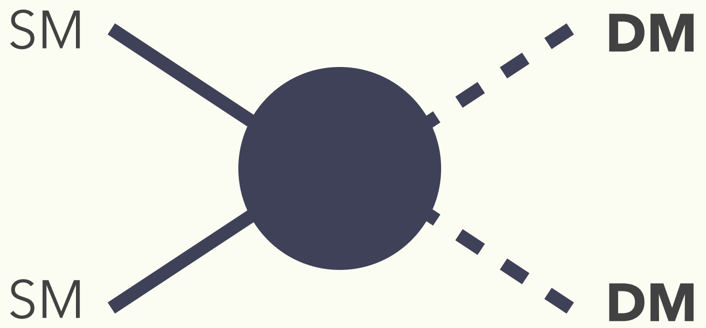
- **The collision term is IR safe!**

$$\int_0^{\epsilon p} \mathrm{d}k\,\gamma_{g\leftrightarrow gg}(p;k,p-k)\,f_g(p) - \int_0^{\epsilon p} \mathrm{d}k\,\gamma_{g\leftrightarrow gg}(p+k;p,k)\,f_g(p+k) \qquad \text{w/} \;\; f_g(p+k) \simeq f_g(p) + k f_g'(p)$$

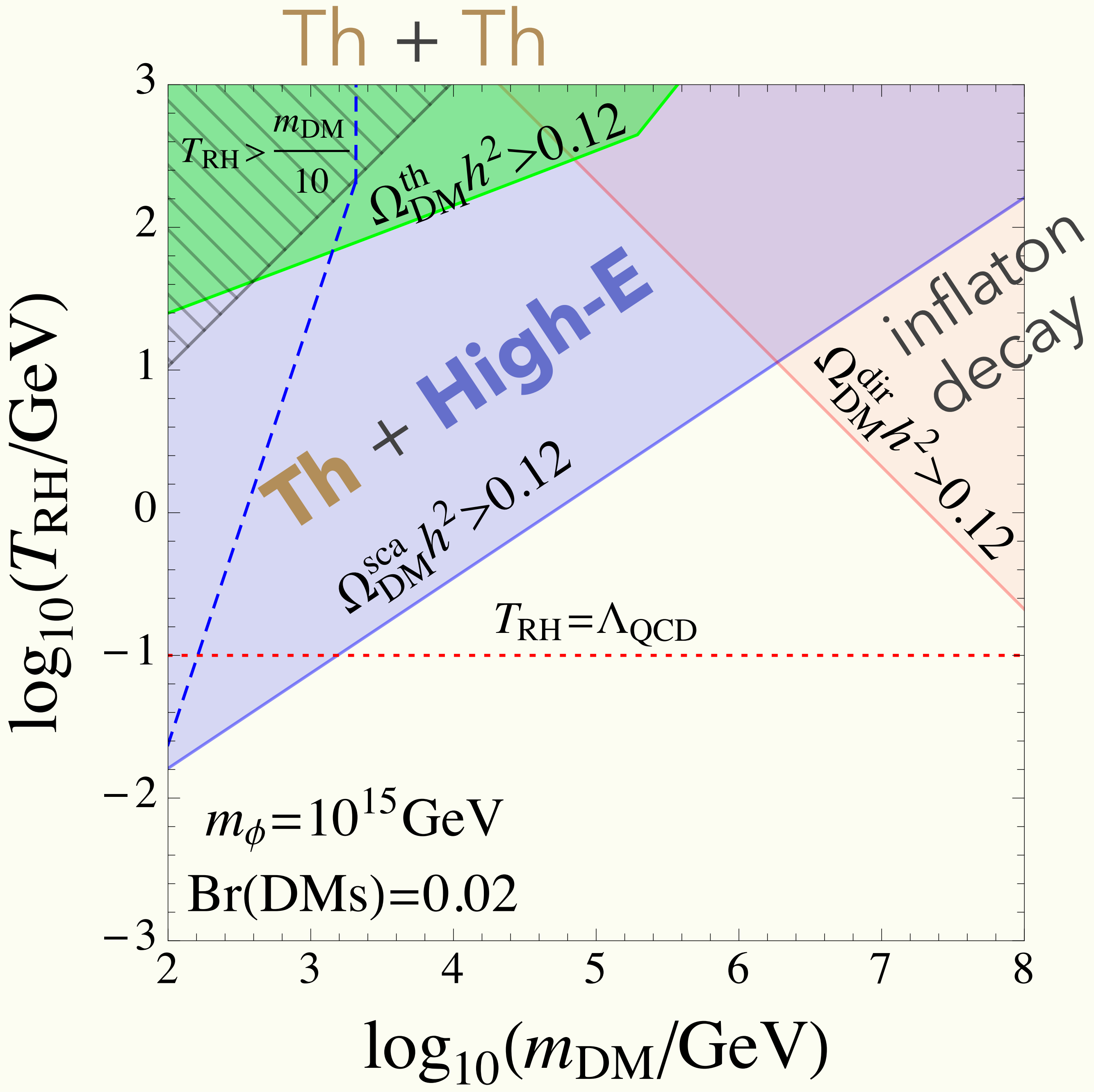
$$\simeq \quad f_g(p)\int_0^{\epsilon p} \mathrm{d}k\,[\gamma_{g\leftrightarrow gg}(p;k,p-k) - \gamma_{g\leftrightarrow gg}(p+k;p,k)] - f_g'(p)\int_0^{\epsilon p} \mathrm{d}k\,k\,\gamma_{g\leftrightarrow gg}(p+k;p,k).$$

Non-thermal DM Production

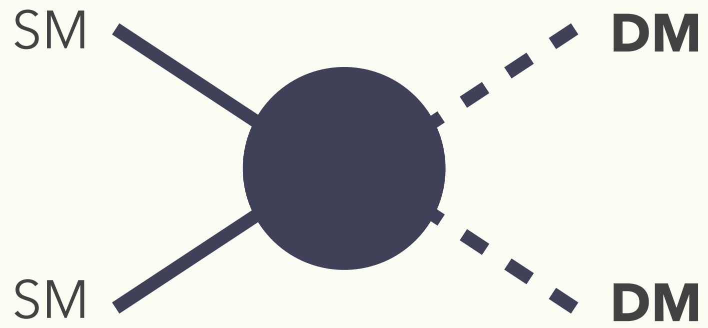
- Non-thermal DM production via SM SM to DM DM



$$\langle \sigma v \rangle \simeq \frac{\alpha_{\rm DM}^2}{m_{\rm DM}^2}$$

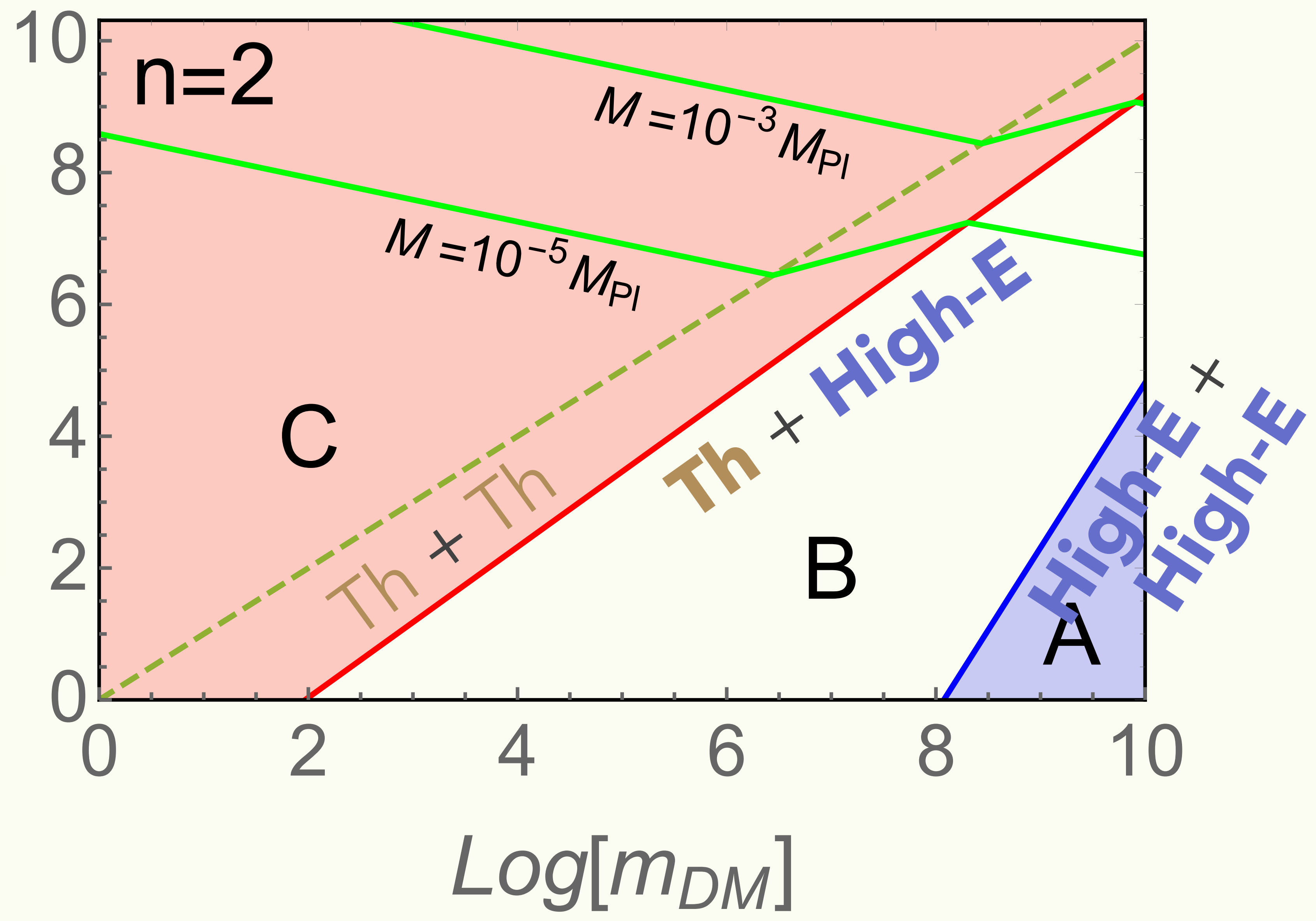


[**KM**+ 1402.2846]



$$\langle \sigma v \rangle = \frac{E_{\rm CM}^n}{M^{n+2}}$$

w/ $M \gtrsim m_{\rm inf}$



[**KM**+ 1901.11027]

Some details after $t \gtrsim t_{\rm ev}$

- Comparison of time scales during the hotspot formation

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

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

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