Bottom-up Thermalization during/after Reheating and Dark Matter Production

Kyohei Mukaida

UNIVERSITY OF TOKYO

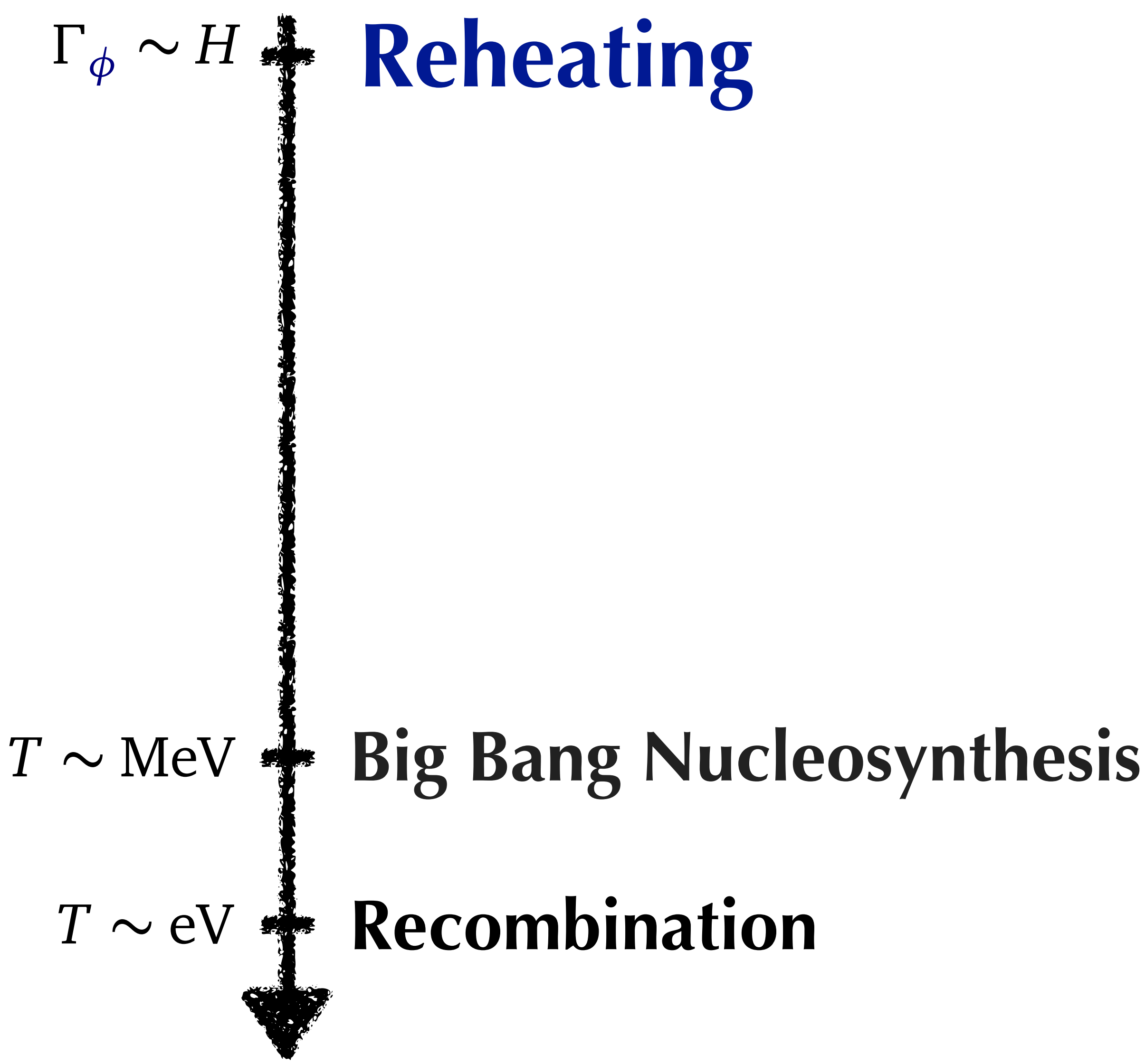
based on 1312.3097 and 1402.2846
w/ Harigaya, Kawasaki, Yamada

Introduction

Introduction

■ Reheating after Inflation

- Inflaton should convert its energy into radiation.
- **Rough sketch of thermal history** after the inflation:



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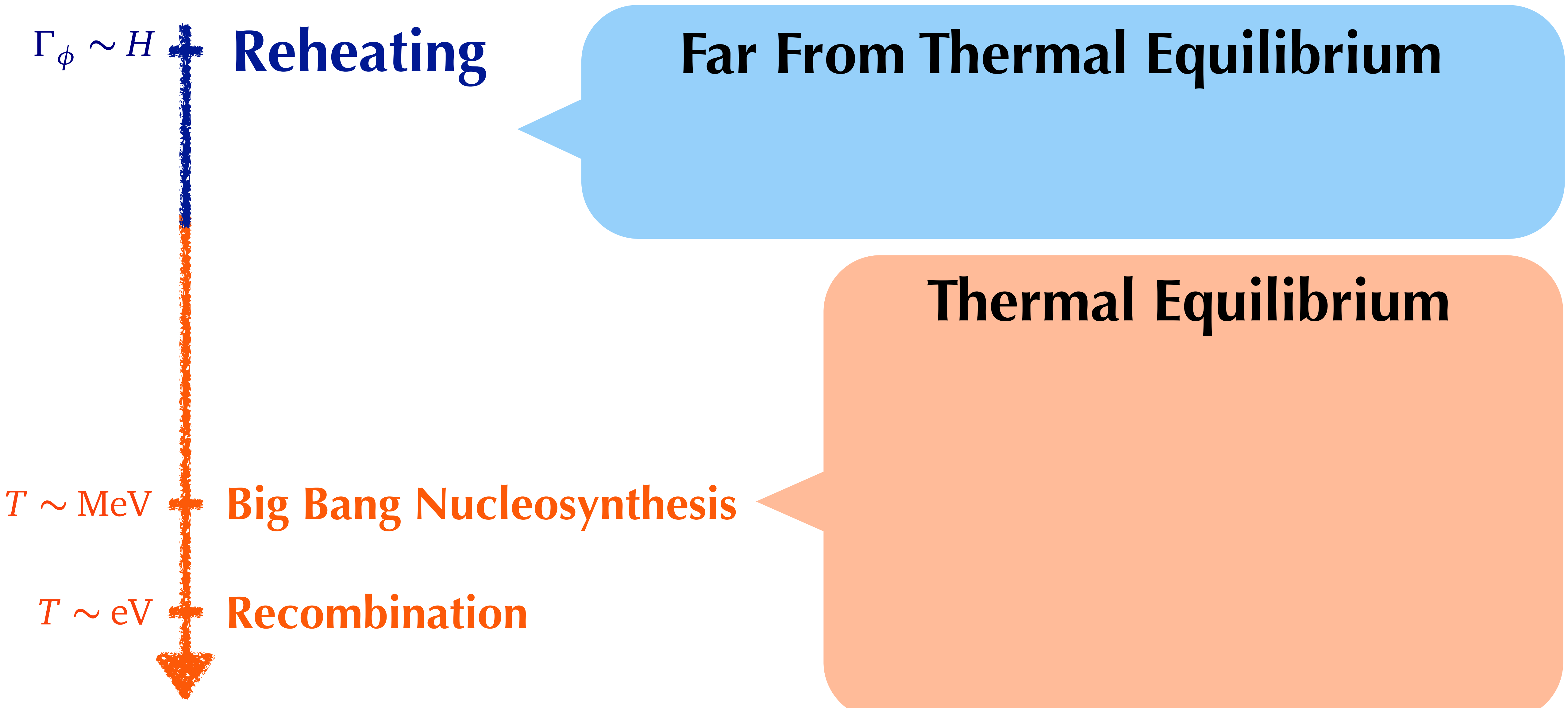

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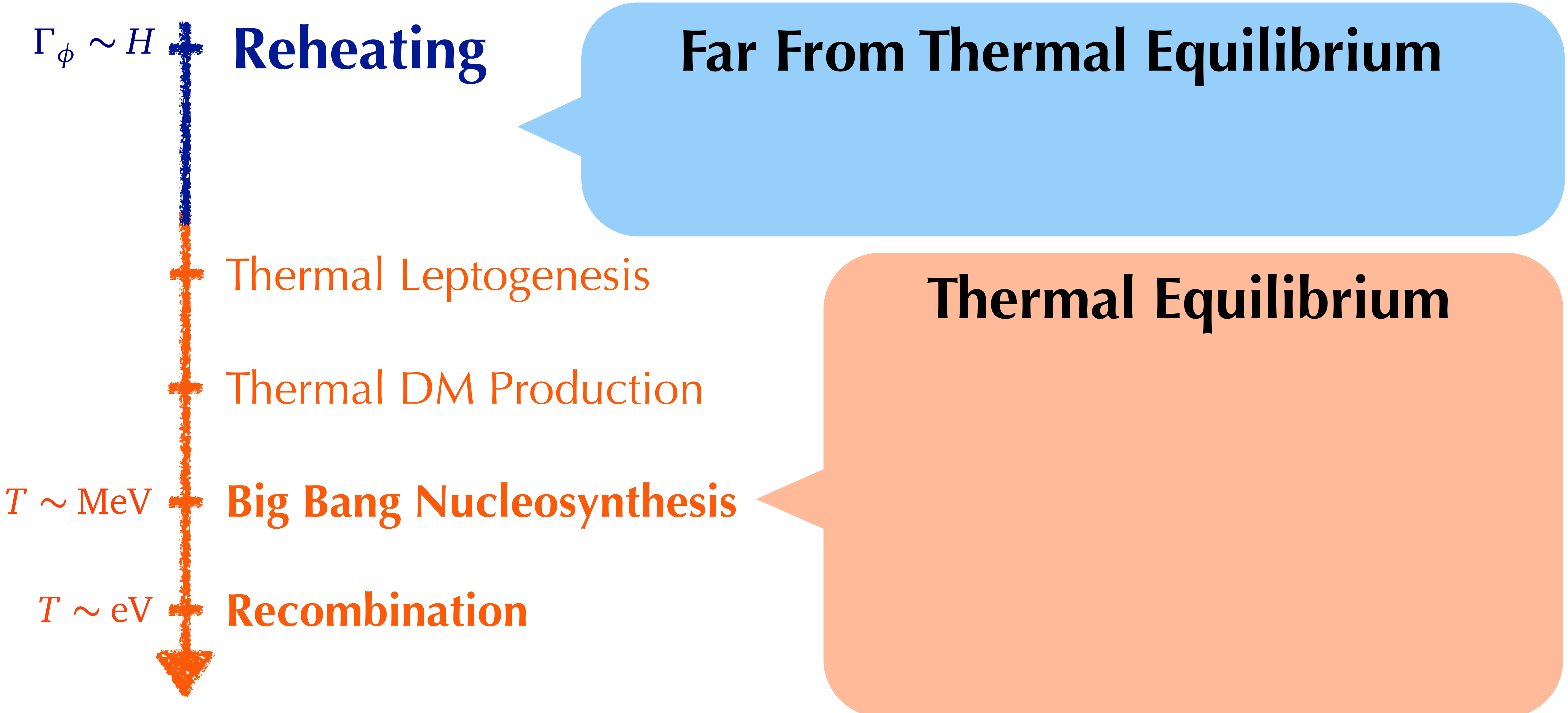

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- ◆**Rough sketch of thermal history** after the inflation:

$\Gamma_\phi \sim H$ **Reheating**

Far From Thermal Equilibrium

- ◆May strongly depend on details of the process of reheating.

Thermal Leptogenesis

Thermal DM Production

$T \sim \mathrm{MeV}$ **Big Bang Nucleosynthesis**

$T \sim \mathrm{eV}$ **Recombination**

Thermal Equilibrium

- ◆Tend to lose information:

  e.g., initial conditions, details of the process of reheating…etc

- ◆Simply characterized by the temperature.
- ◆Restricted (More predictable).

Introduction

■ Goal of This Talk

1. Thermalization: when and how ???

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AD-mechanism

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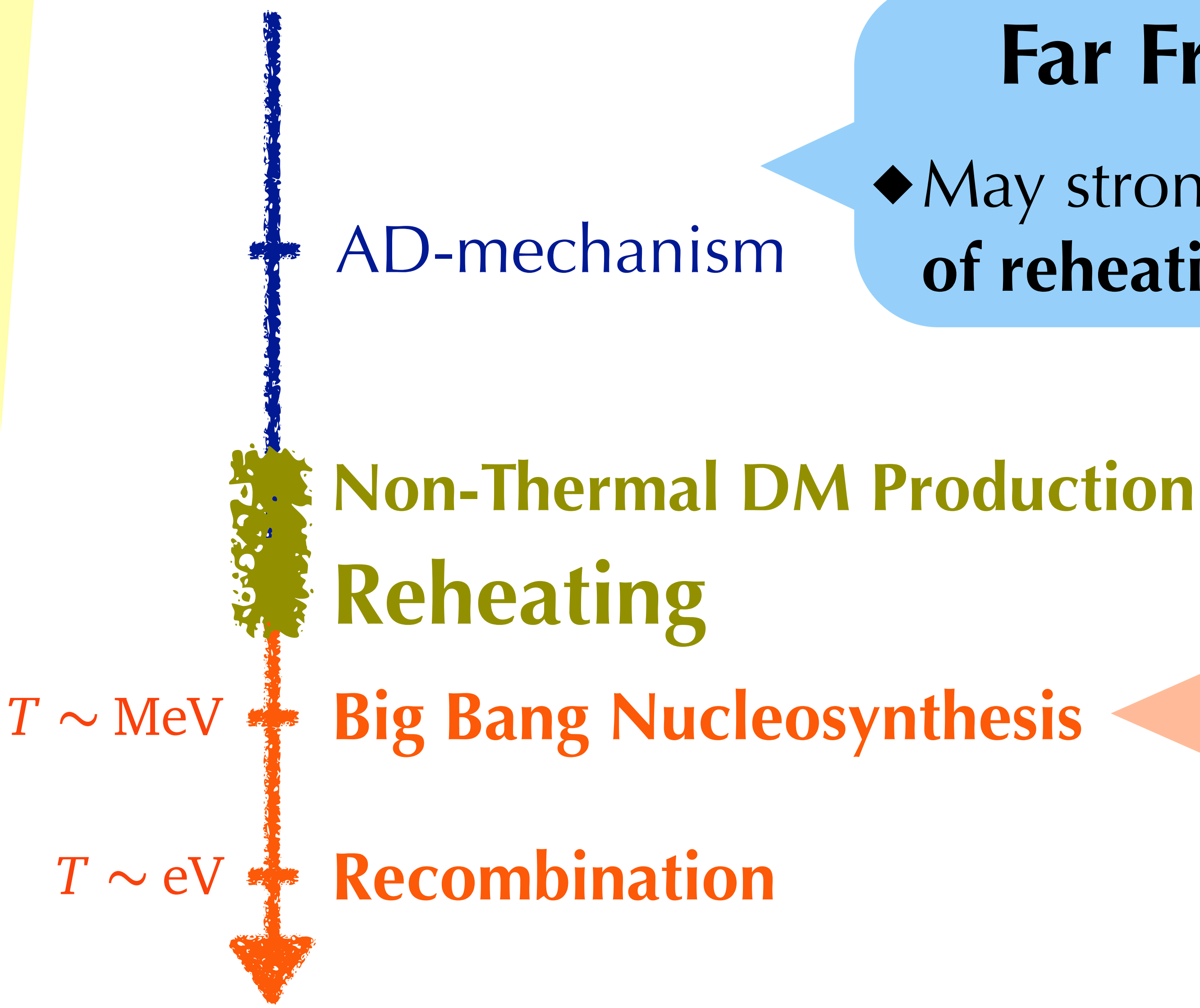
2. Non-thermal DM production in the thermalization.



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Outline

- Introduction
- Naive Estimation
- Bottom-up Thermalization
- DM Production
- Conclusion

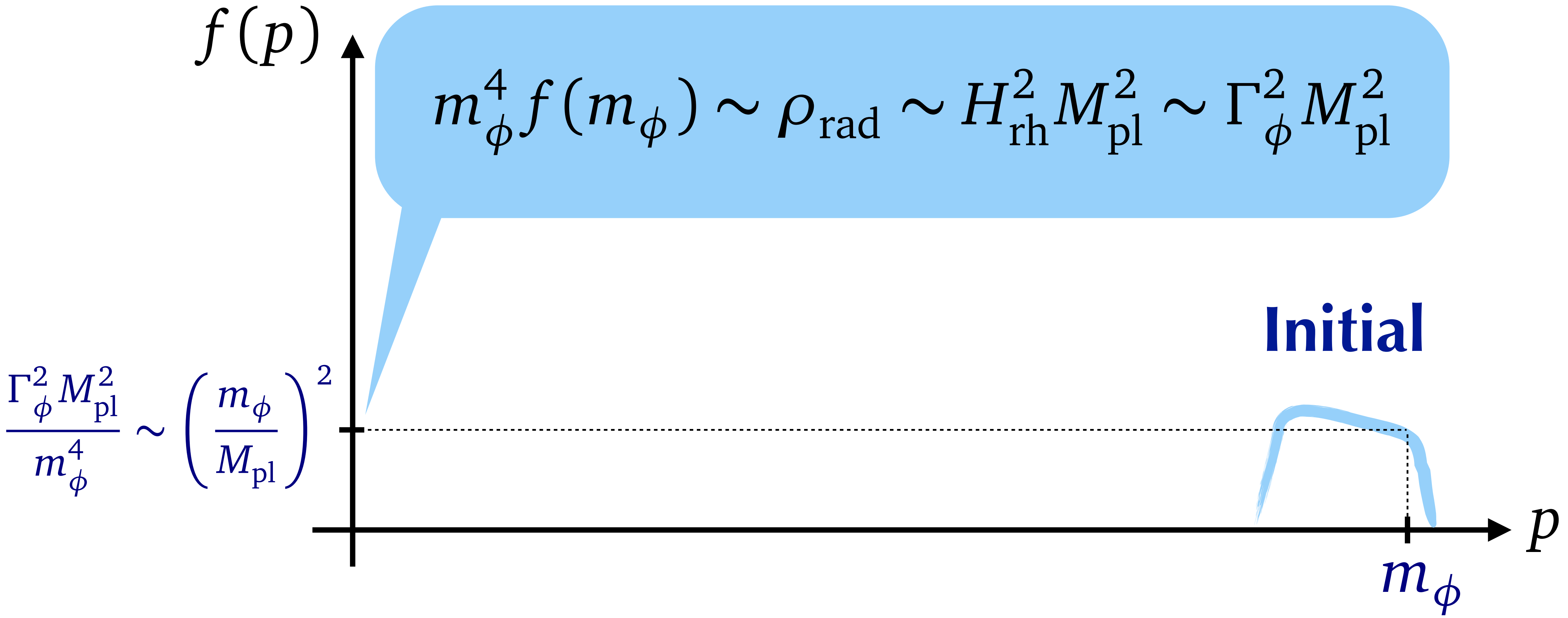
Naive Estimation

Naive Estimation

■ Reheating via Planck-suppressed Decay

- ◆Reheating can be described by a perturbative decay. [*e.g.*, $\Gamma_\phi^{(\text{dim }5)} \sim m_\phi^3/M_{\text{pl}}^2$]
- ◆As an illustration, let us study **right after the reheating**: $\Gamma_\phi \sim H$.

➡Typical distribution function, f(p), is…



Naive Estimation

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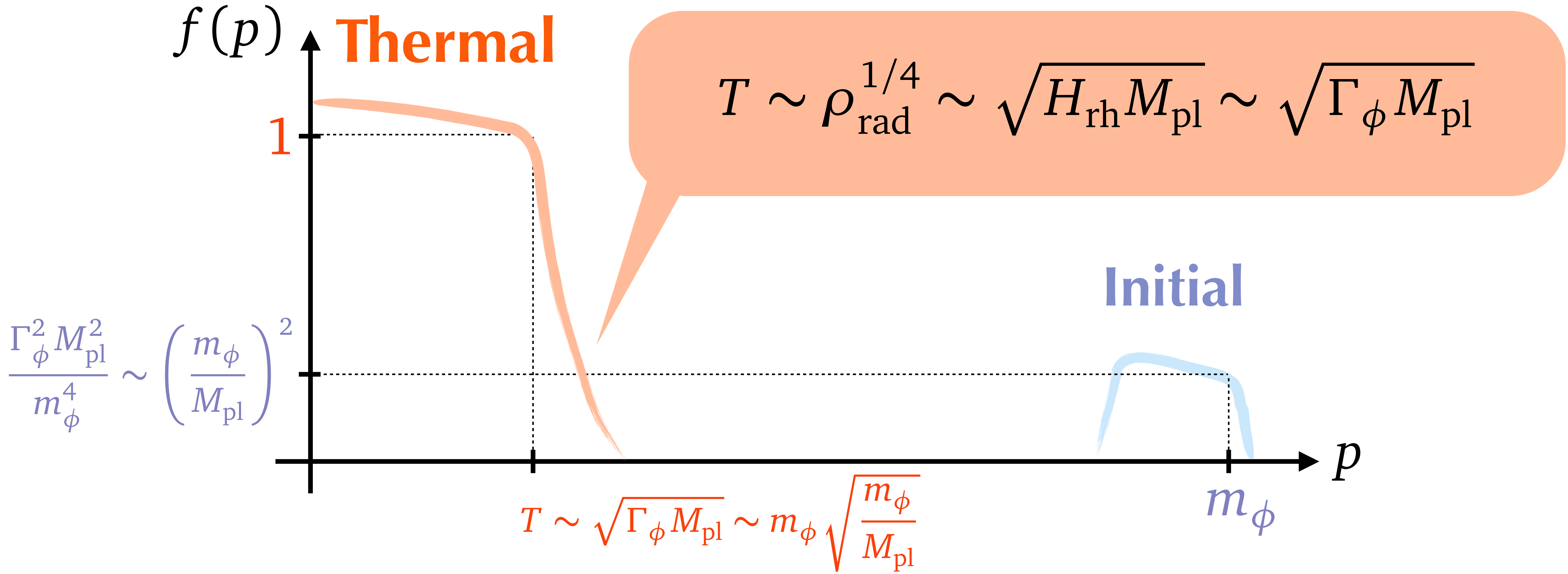


Naive Estimation

■ **Reheating via Planck-suppressed Decay**

➡ **Number violating processes play crucial roles !!!**

Thermal

◆ **Small** energy: $T \sim m_\phi \sqrt{\frac{\Gamma_\phi M_{\rm pl}}{m_\phi^2}}$

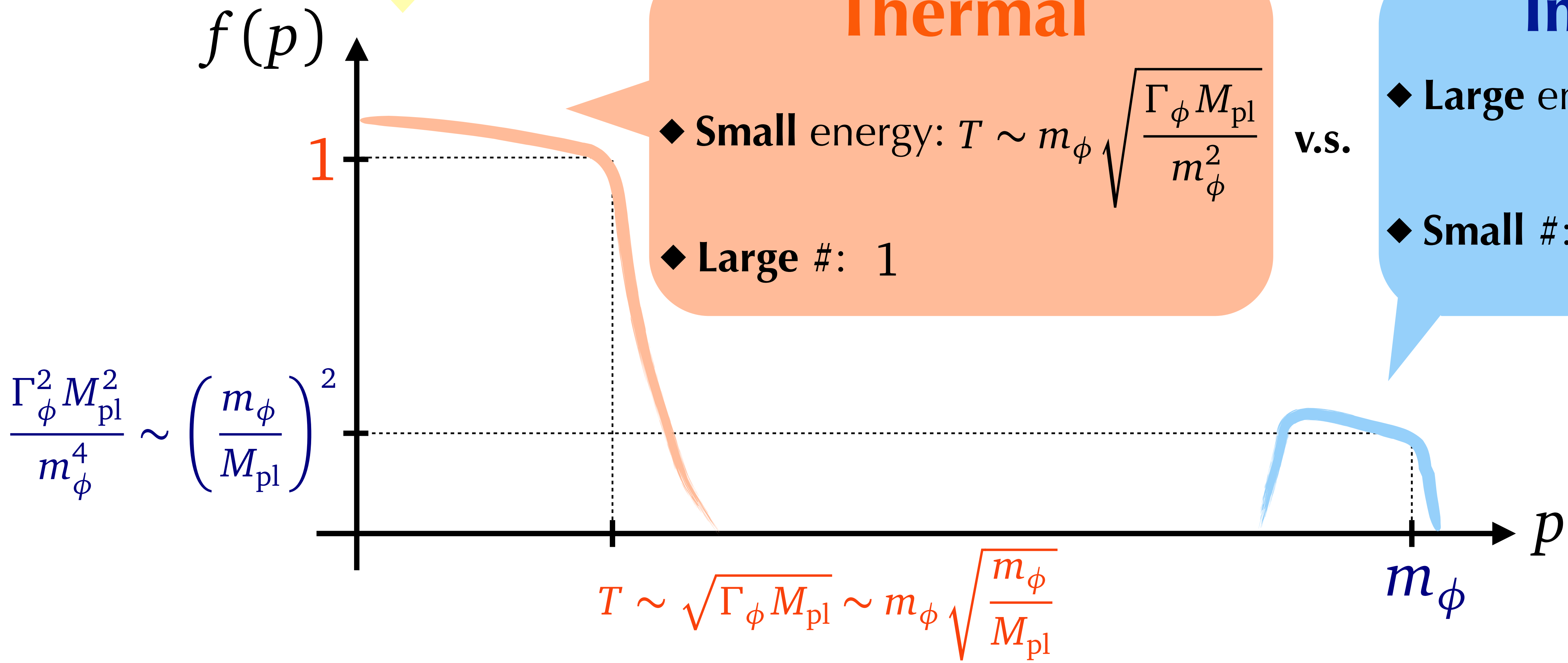
◆ **Large** #: 1

v.s.

Initial

◆ **Large** energy: m_ϕ

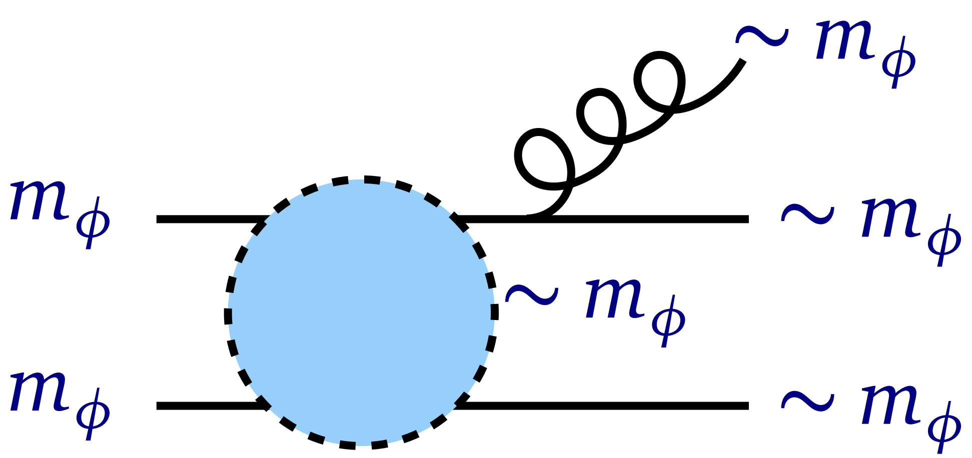
◆ **Small** #: $\left(\frac{\Gamma_\phi M_{\rm pl}}{m_\phi^2}\right)^2$



Naive Estimation

■ Number Violating Processes (*naive estimation*)

◆Apparently, number violating "**hard**" processes seem to efficiently **increase #/reduce energy** per one-particle…



$$\sigma v n \sim \frac{\alpha^3}{m_\phi^2} \times \frac{\Gamma_\phi^2 M_{\rm pl}^2}{m_\phi^4} m_\phi^3 \sim \alpha^3 m_\phi \frac{\Gamma_\phi^2 M_{\rm pl}^2}{m_\phi^4}$$

$$\sim \alpha^3 m_\phi \left(\frac{m_\phi}{M_{\rm pl}}\right)^2 \quad \text{for dim 5}$$

➡ **Delayed thermalization ???**

$$\frac{\langle \sigma v n \rangle}{H} \sim \alpha^3 \frac{\Gamma_\phi M_{\rm pl}^2}{m_\phi^3} \ll 1$$

$$\sim \alpha^3 \quad \text{for dim 5}$$

Naive Estimation

- **Number Violating Processes** (*naive estimation*)
  - Apparently, number violating "**hard**" processes seem to efficiently [redacted] **#/reduce energy** per one-particle…

$\sim m_\phi$

$\sigma v n$ [redacted] $\frac{\quad_{\rm pl}}{m_\phi^4}$

m_ϕ [redacted]

m_ϕ [redacted] $\frac{\quad}{M_{\rm pl}}\Big)$ for dim 5

WRONG !!!

➡ **De**[redacted]:

[redacted] $\frac{\quad v n\rangle}{H} \sim \alpha^3 \frac{\Gamma_\phi M_{\rm pl}^2}{m_\phi^3}$ $\ll 1$

$\sim \alpha^3$ for dim 5

Bottom-up Thermalization

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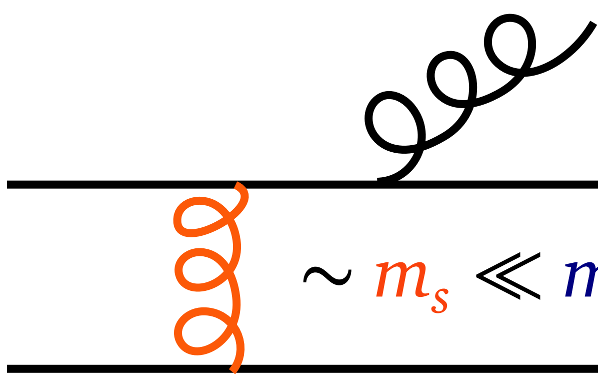
■ "Soft" Number Violating Processes

◆t-channel enhancement of "soft" processes:



w/ $m_s^2 \sim \alpha \int_{\boldsymbol{p}} \frac{f(p)}{p}$

$$\frac{\sigma v n}{H} \sim \alpha^3 \frac{\Gamma_\phi M_{\rm pl}^2}{m_\phi^3} \frac{m_\phi^2}{m_s^2} \sim \alpha^2 \frac{m_\phi}{\Gamma_\phi} \sim \left(\alpha \frac{M_{\rm pl}}{m_\phi}\right)^2 \quad \text{for dim 5} \quad \gg 1$$

➡ **Soft particles are created rapidly !!!**

■ Bottom-up Thermalization; studied in the context of QGP

[Baier et al., '00; Kurkela, Moore, '11,'14]

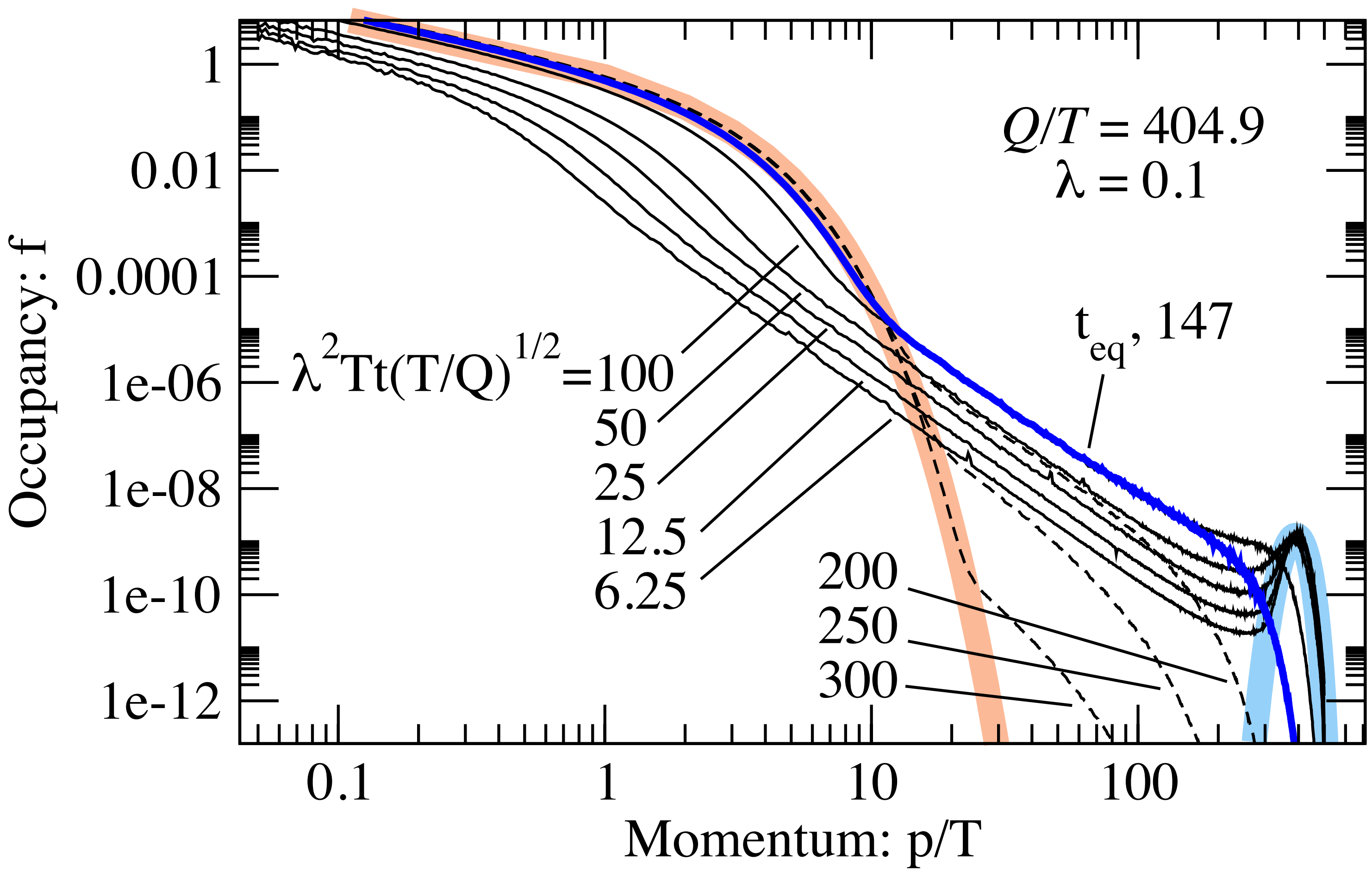
◆Thermalization proceeds from the **soft sector**.

◆**Soft sector**: evolves towards UV and thermalizes separately.

Bottom-up Thermalization

[Baier et al., '00; Kurkela, Moore, '11,'14]

- **Bottom-up Thermalization;** studied in the context of QGP
  - ◆Numerical simulation is recently performed by **Kurkela, Lu, 1405.6318**.



$$\begin{cases} Q \simeq m_\phi \\ \lambda = N_c g^2 \end{cases}$$

➡ **Bottleneck process:** energy loss of remaining **hard particles**, which still **dominates the energy density**.

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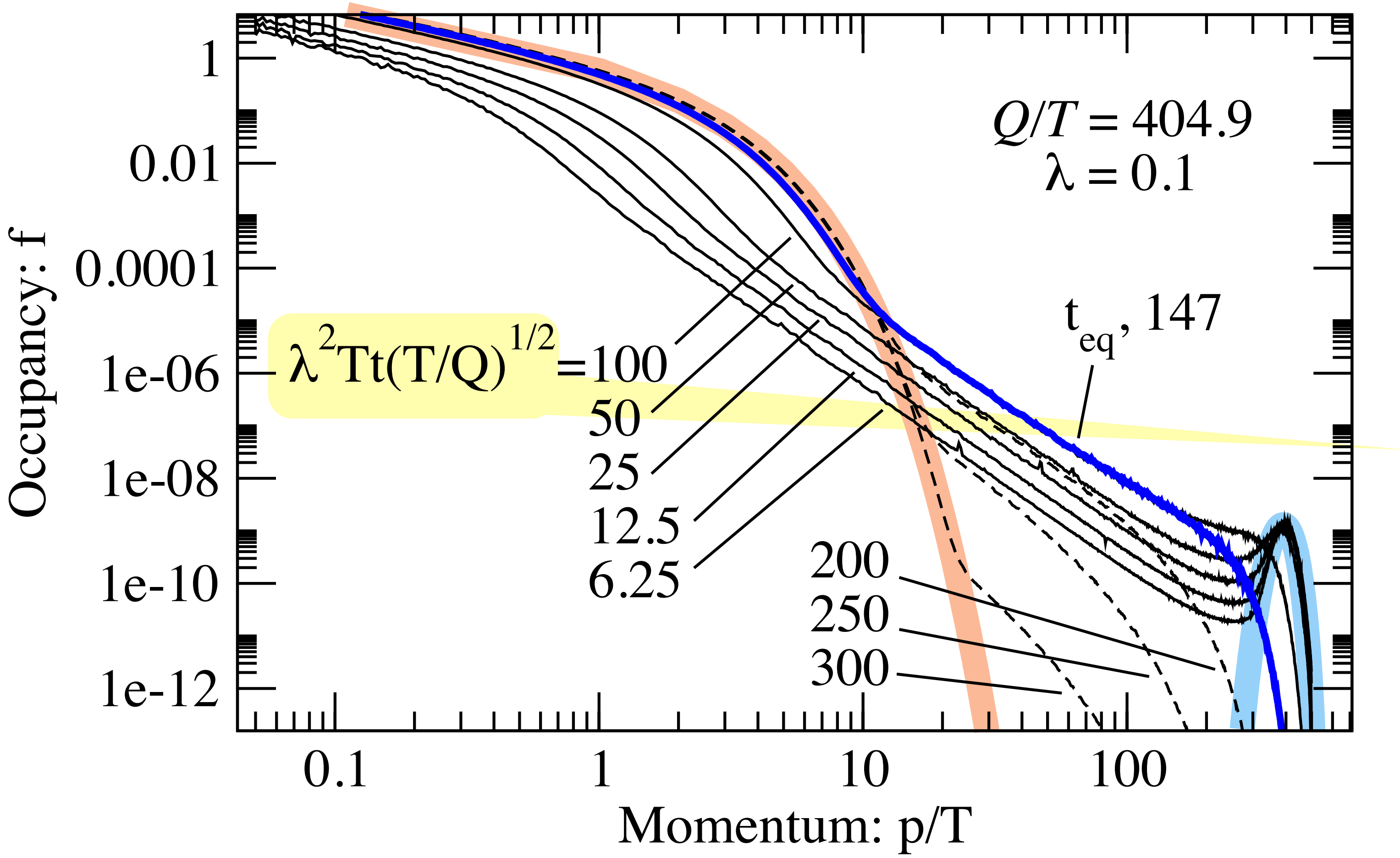

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$$t_{\text{typ}} \sim (\alpha^2 T^2)^{-1} \sqrt{\frac{m_\phi}{T}}$$

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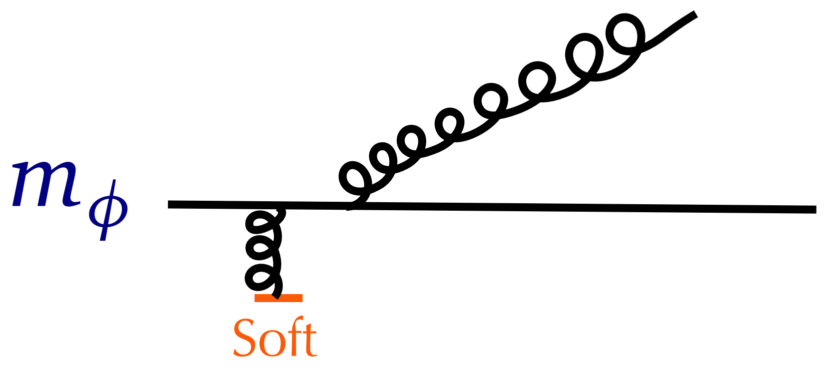
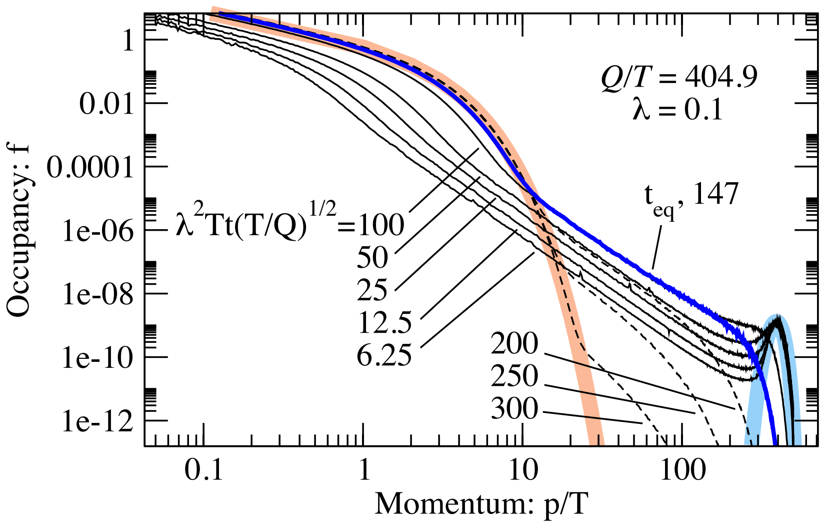
Bottom-up Thermalization

[Baier et al., '00; Kurkela, Moore, '11,'14]

- **Bottleneck process: splitting of hard particles**





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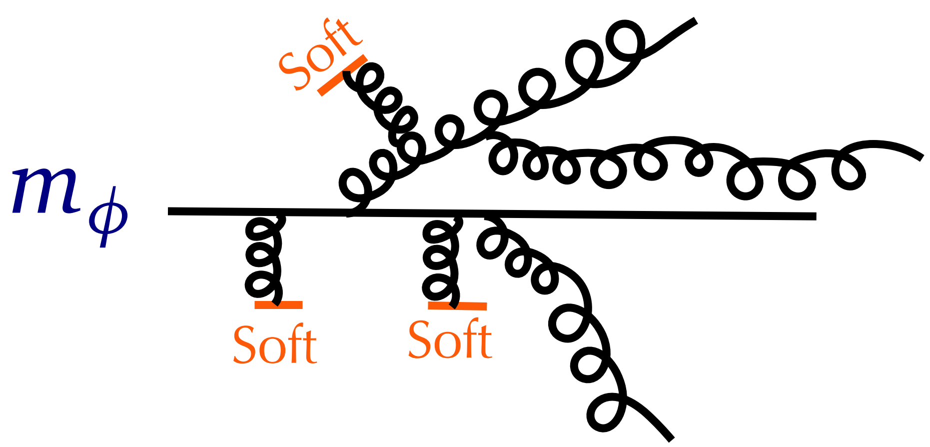

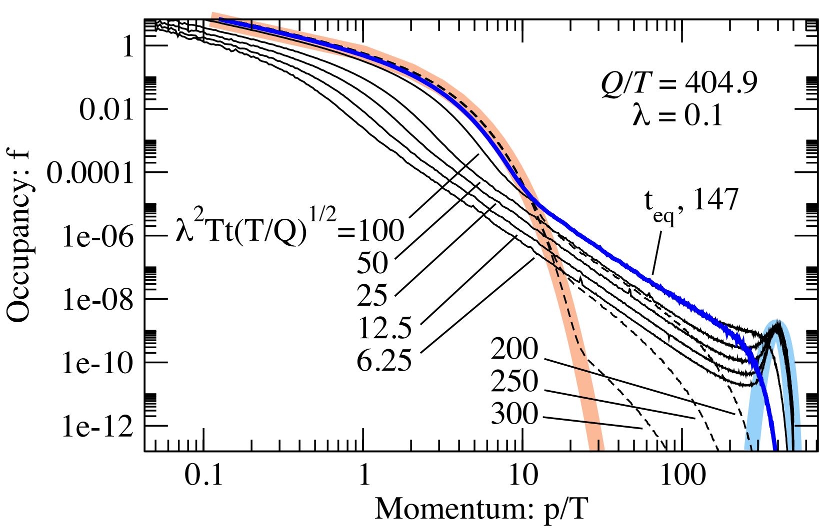

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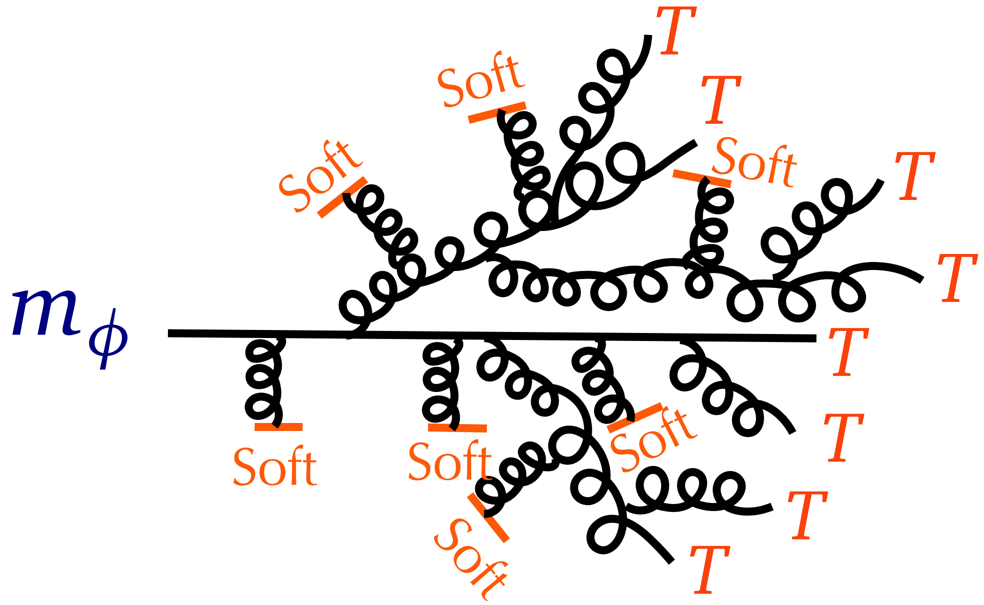

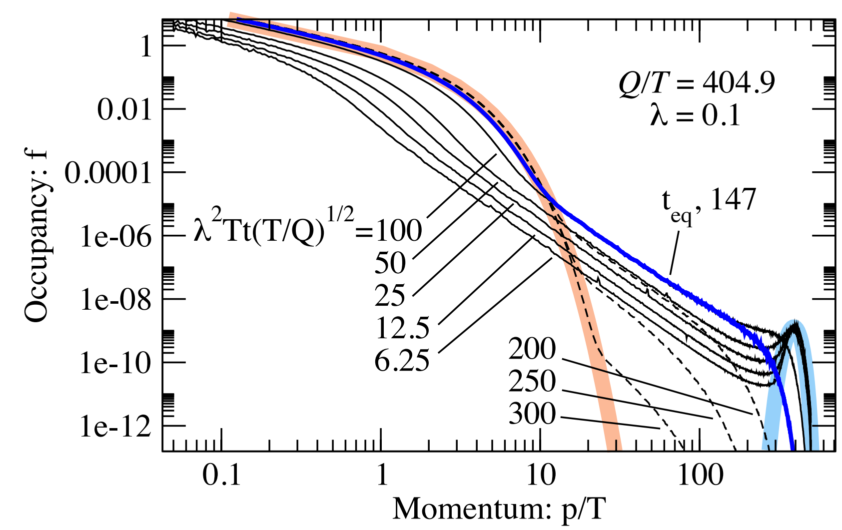

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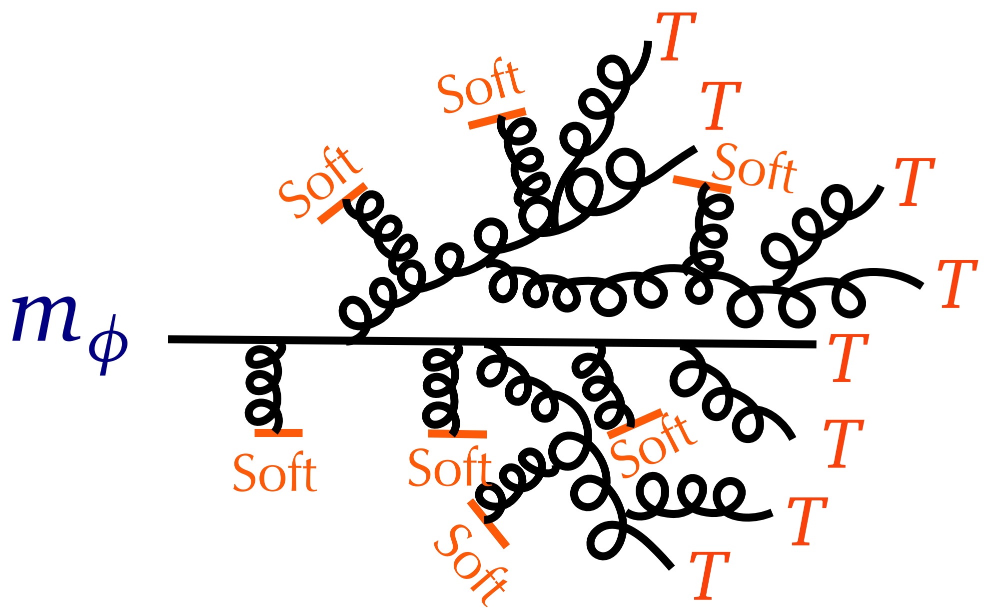

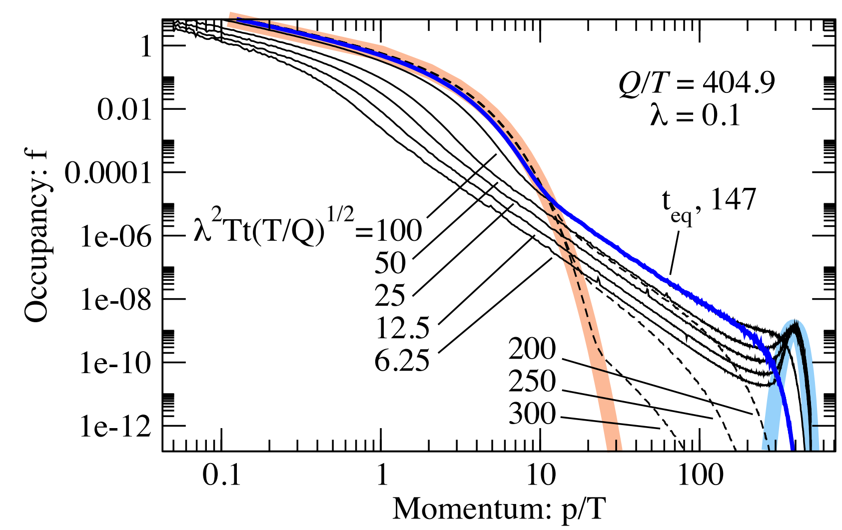

$$\begin{cases} Q \simeq m_\phi \\ \lambda \simeq \alpha \end{cases}$$

- Energy loss rate of hard particles ~ m_ϕ (w/ LPM effect):

$$\frac{dE_{\rm hard}}{dt} \sim \alpha^2 T^2 \sqrt{\frac{E_{\rm hard}}{T}} \Longrightarrow t_{\rm split} \sim \left(\alpha^2 T\right)^{-1} \sqrt{\frac{m_\phi}{T}}$$

➡ **Instantaneous thermalization in most cases:** [K. Harigaya and KM, 1312.3097]

$$\frac{1}{H t_{\rm split}} \gg 1 \leftrightarrow \alpha \gg \left(\frac{m_\phi}{M_{\rm pl}}\right)^{5/8} \left(\frac{\Gamma_\phi M_{\rm pl}^2}{m_\phi^3}\right)^{1/8} \Longrightarrow \alpha \gg 4 \times 10^{-4} \left(\frac{m_\phi}{10^{13}\,{\rm GeV}}\right)^{5/8} \quad \text{for dim 5}$$

DM Production

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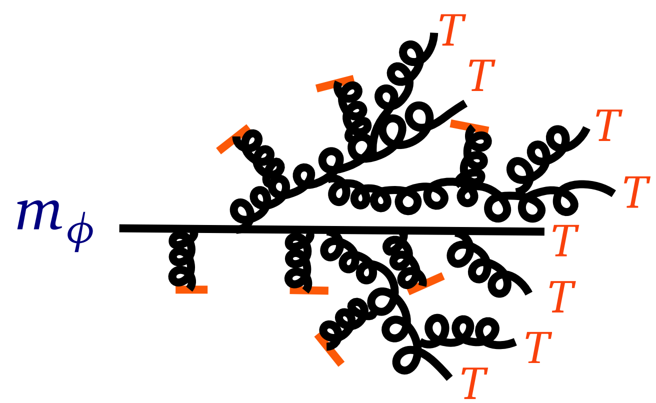
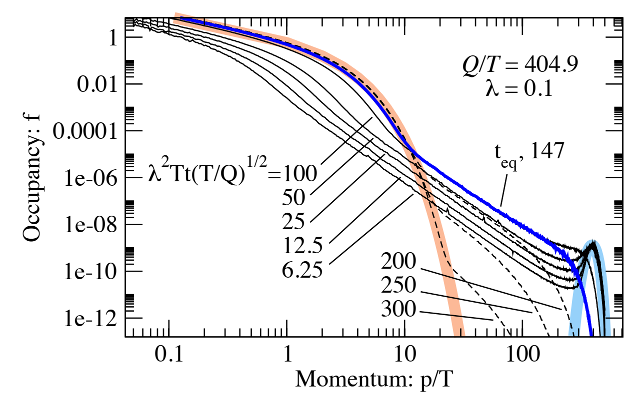
2. **Non-thermal DM production in the thermalization.**





$$\begin{cases} Q \simeq m_\phi \\ \lambda \simeq \alpha \end{cases}$$

Non-Thermal DM Production w/ $m_{\rm DM} \gg T_{\rm R}$

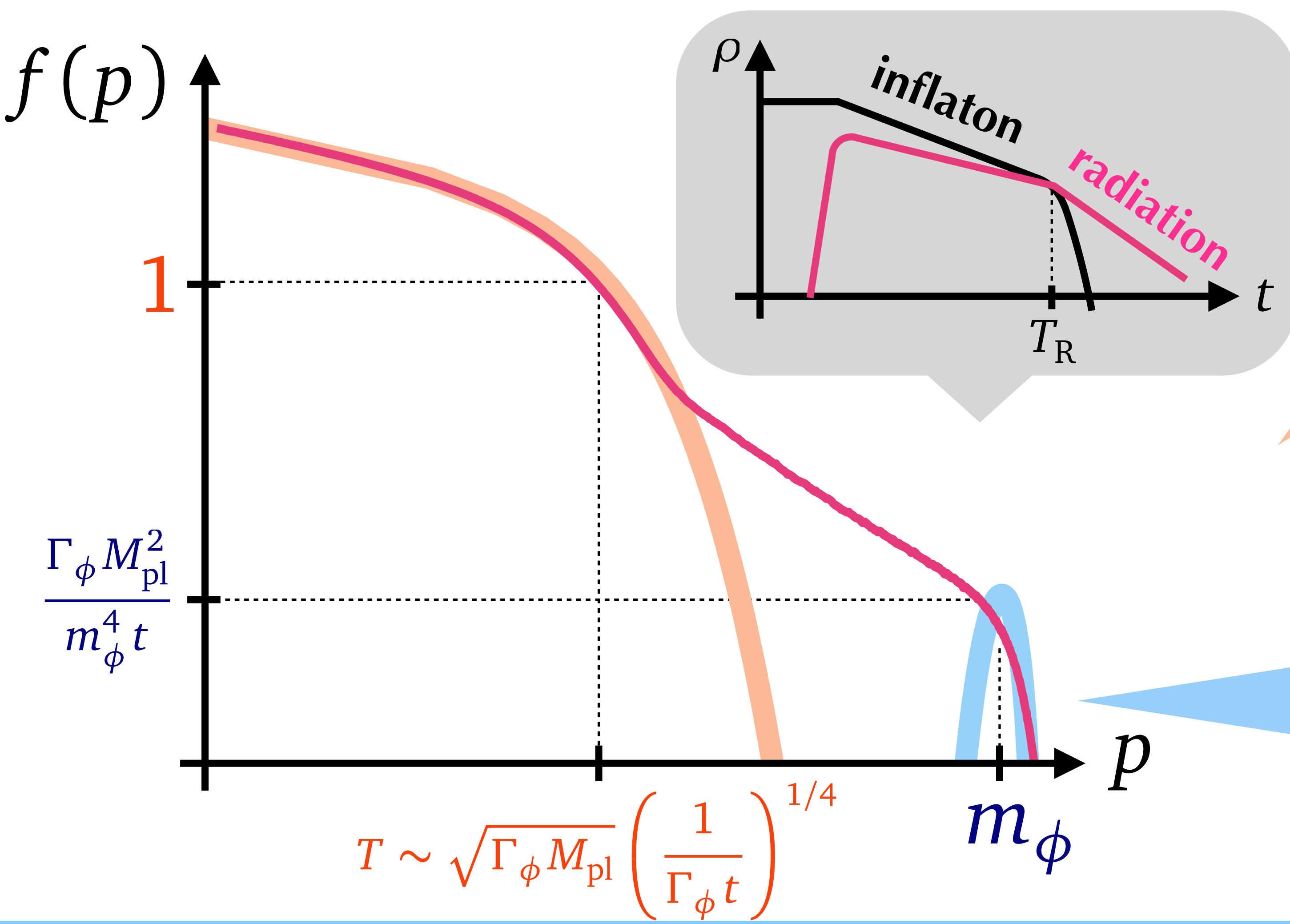
$T_{\rm R}$ **Reheating**

$T \sim \text{MeV}$ **Big Bang Nucleosynthesis**

$T \sim \text{eV}$ **Recombination**

DM Production

- **DM production processes w/ $m_{\rm DM} \gg T_{\rm R}$**
  - Non-thermal production from direct inflaton decay
  - Non-thermal/Thermal production from background plasma



Thermal Plasma

- Red-shift: $T \propto t^{-1/4}$
- Dominates number/energy
- Soft: p ~ T

Hard Particles

- Red-shift: $f(m_\phi) \propto 1/t$
- Small number
- Hard: p ~ m_ϕ

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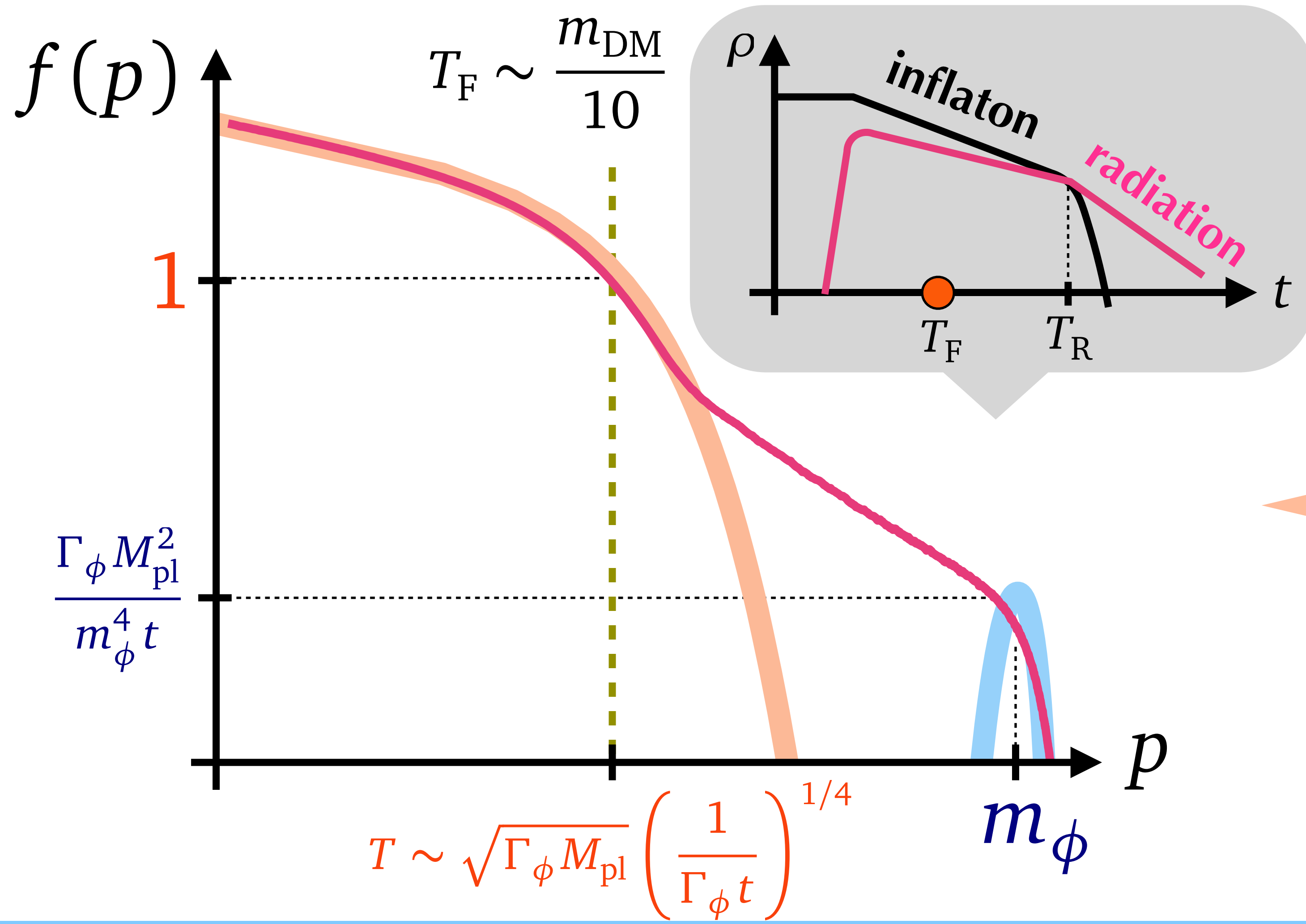

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- ◆ Soft: p ~ T

➡ Thermal Freeze-out

$$\left.\frac{\rho_{\rm DM}^{\rm th}}{s}\right|_{\rm now} \simeq \left.\frac{\rho_{\rm DM}^{\rm th}}{s}\right|_{\rm F} \left(\frac{T_{\rm RH}}{T_{\rm F}}\right)^5$$

$$\left[\left.\frac{\rho_{\rm DM}^{\rm th}}{s}\right|_{\rm now} \simeq \left.\frac{\rho_{\rm DM}^{\rm th}}{s}\right|_{\rm F,\,ordinary} \left(\frac{T_{\rm RH}}{T_{\rm F}}\right)^3\right]$$

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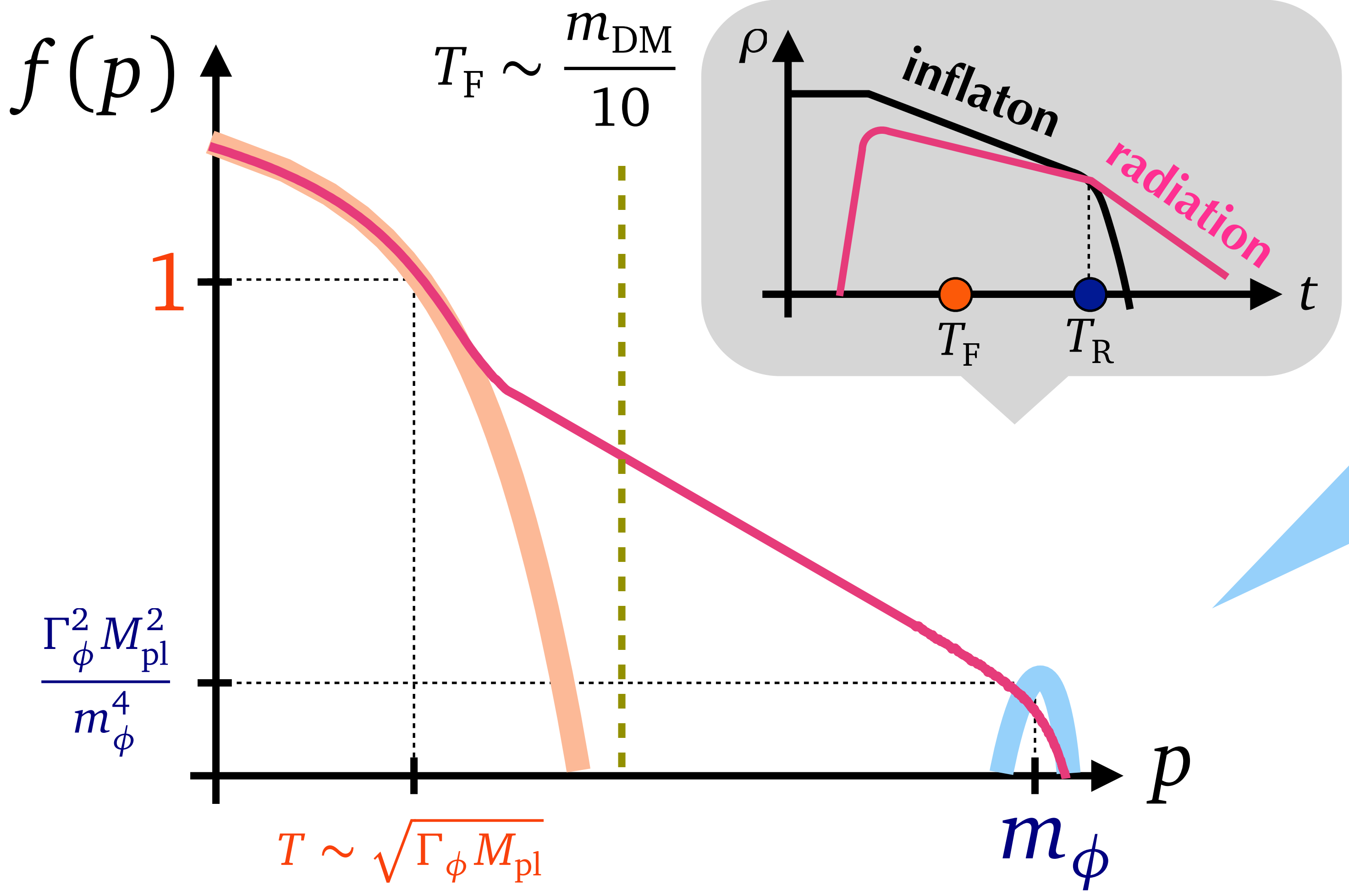

Hard Particles

- ◆Red-shift: f(m_Φ)∝1/t
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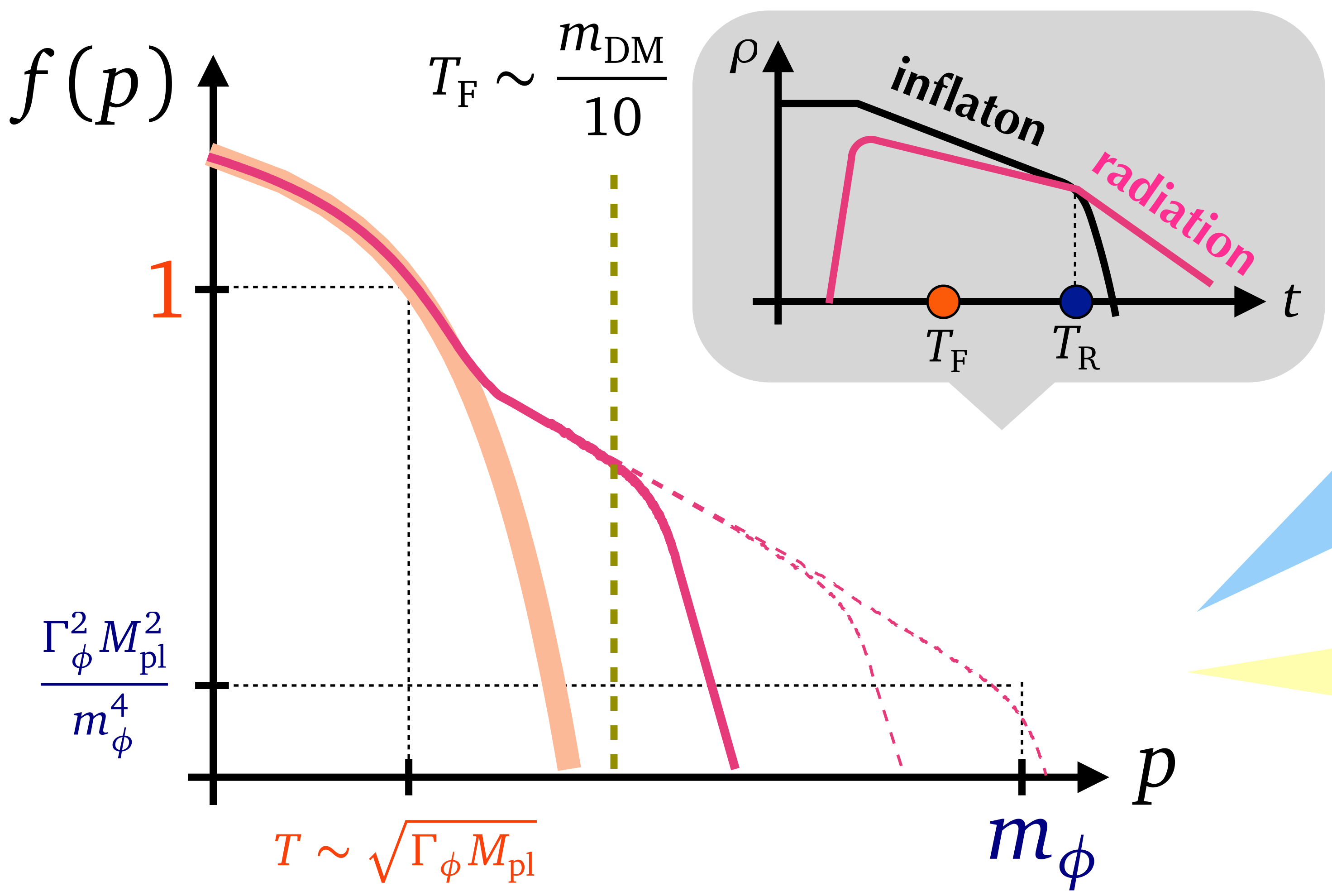


Hard Particles

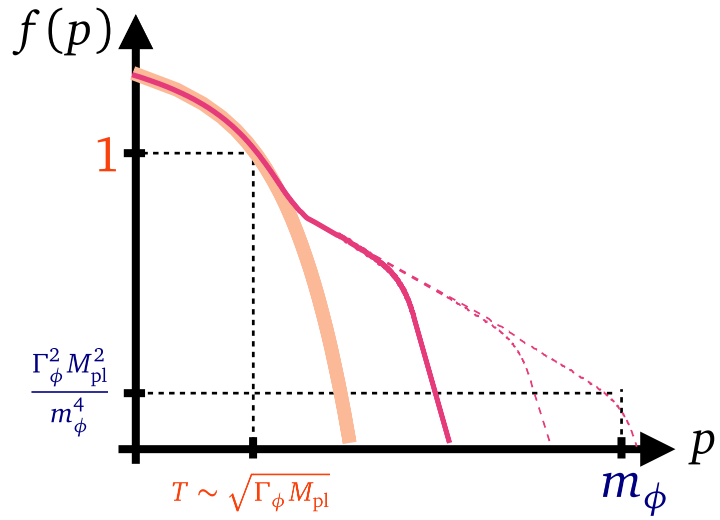
- ◆ Red-shift: $f(m_\Phi) \propto 1/t$
- ◆ Small number
- ◆ Hard: $p \sim m_\Phi$
- ◆ **Breakup completely @ T_{R}**

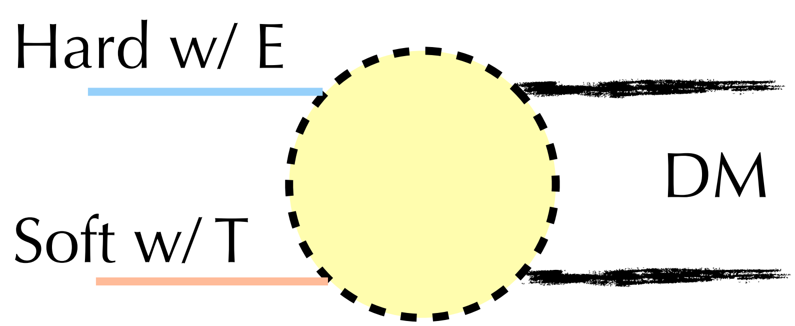
➡**DM production thru interactions btw Hard and Soft particles !**

DM Production

■ DM production during thermalization

◆DM can be produced even at $m_{\rm DM} \gg T$.





$$\sigma_{\rm DM} v \sim \frac{\alpha_{\rm DM}^2}{4ET}; \quad \text{w/ } E \gtrsim \frac{m_{\rm DM}^2}{T}$$

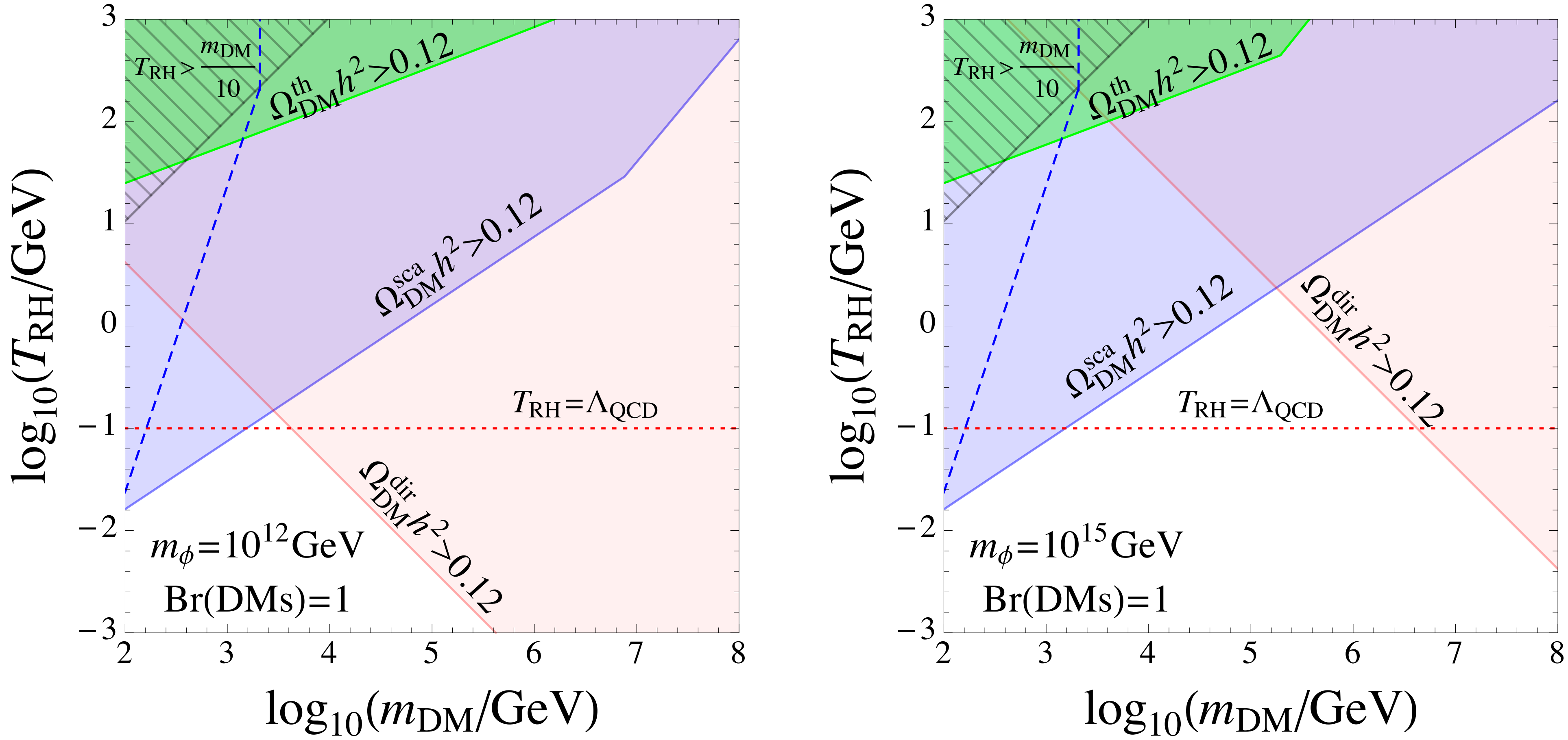
$$n_h \sim \frac{m_\phi}{E} \frac{\Gamma_\phi^2 M_{\rm pl}^2}{m_\phi}$$

➡ Most efficient at $E \sim \dfrac{m_{\rm DM}^2}{T_{\rm R}}$; $n_{\rm DM} \sim \dfrac{\alpha_{\rm DM}^2 T_{\rm R}^3}{m_{\rm DM}^2} n_h \Gamma_{\rm split}^{-1}(m_{\rm DM}^2/T_{\rm R})$; $\Gamma_{\rm split}(E) \sim \alpha^2 T_{\rm R} \sqrt{\dfrac{T_{\rm R}}{E}}$

$$\left.\frac{\rho_{\rm DM}}{s}\right|_{\rm now} \sim \frac{\alpha_{\rm DM}^2}{\alpha^2} \frac{T_{\rm R}^3}{m_{\rm DM}^2} \quad \text{for } m_\phi \gtrsim \frac{m_{\rm DM}^2}{T_{\rm R}} \qquad \left[\left.\frac{\rho_{\rm DM}}{s}\right|_{\rm now} \sim \frac{\alpha_{\rm DM}^2}{\alpha^2} \frac{T_{\rm R}^5 m_\phi^2}{m_{\rm DM}^6} \quad \text{for } \frac{m_{\rm DM}^2}{T_{\rm R}} \gtrsim m_\phi \gg \frac{m_{\rm DM}^2}{T_{\rm max}} \right]$$

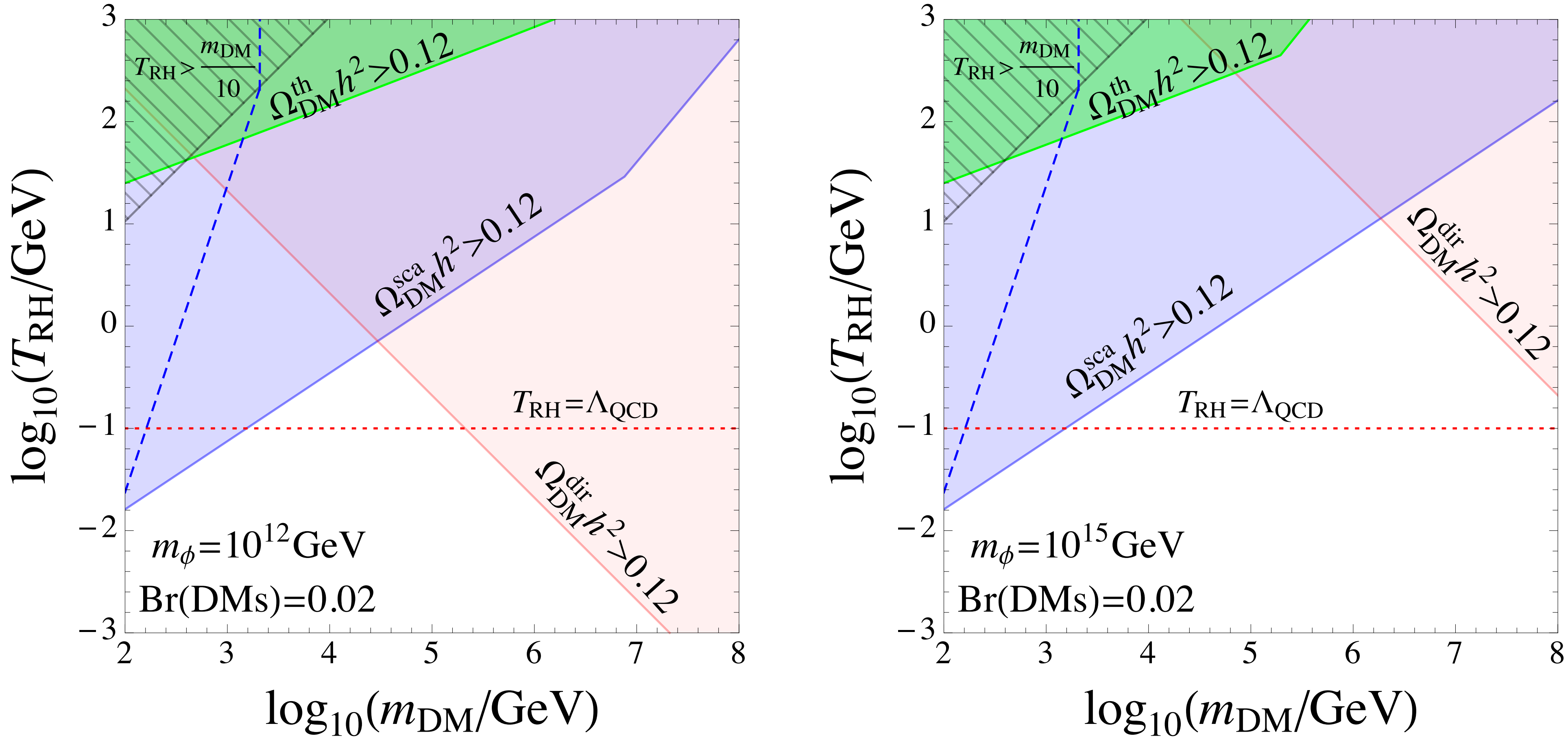
DM Production

- **Contour plot of DM density as a function of T_R and m_Φ**



Br(inflaton → DMs) = 1

- **Contour plot of DM density as a function of T_R and m_Φ**



Br(inflaton → DMs) = 0.02

Summary

Summary

- A **small decay rate** of inflaton (e.g., Planck-suppressed one) results in a **small number density** of decay products initially.
- We found the **condition for instantaneous thermalization**, which is satisfied in most cases: $\alpha \gg (m_\phi / M_{\rm pl})^{5/8} (M_{\rm pl}^2 \Gamma_\phi / m_\phi^3)^{1/8}$.
- Discussion on **during reheating** and $T_{\rm max}$ → See our paper.
- For $m_\Phi \gg T_R$, DM is efficiently produced through interactions btw **hard** and **soft** particles.

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