Thermalization after/during Reheating

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Based on **1312.3097** with **Keisuke Harigaya (Kavli IPMU)**

Introduction

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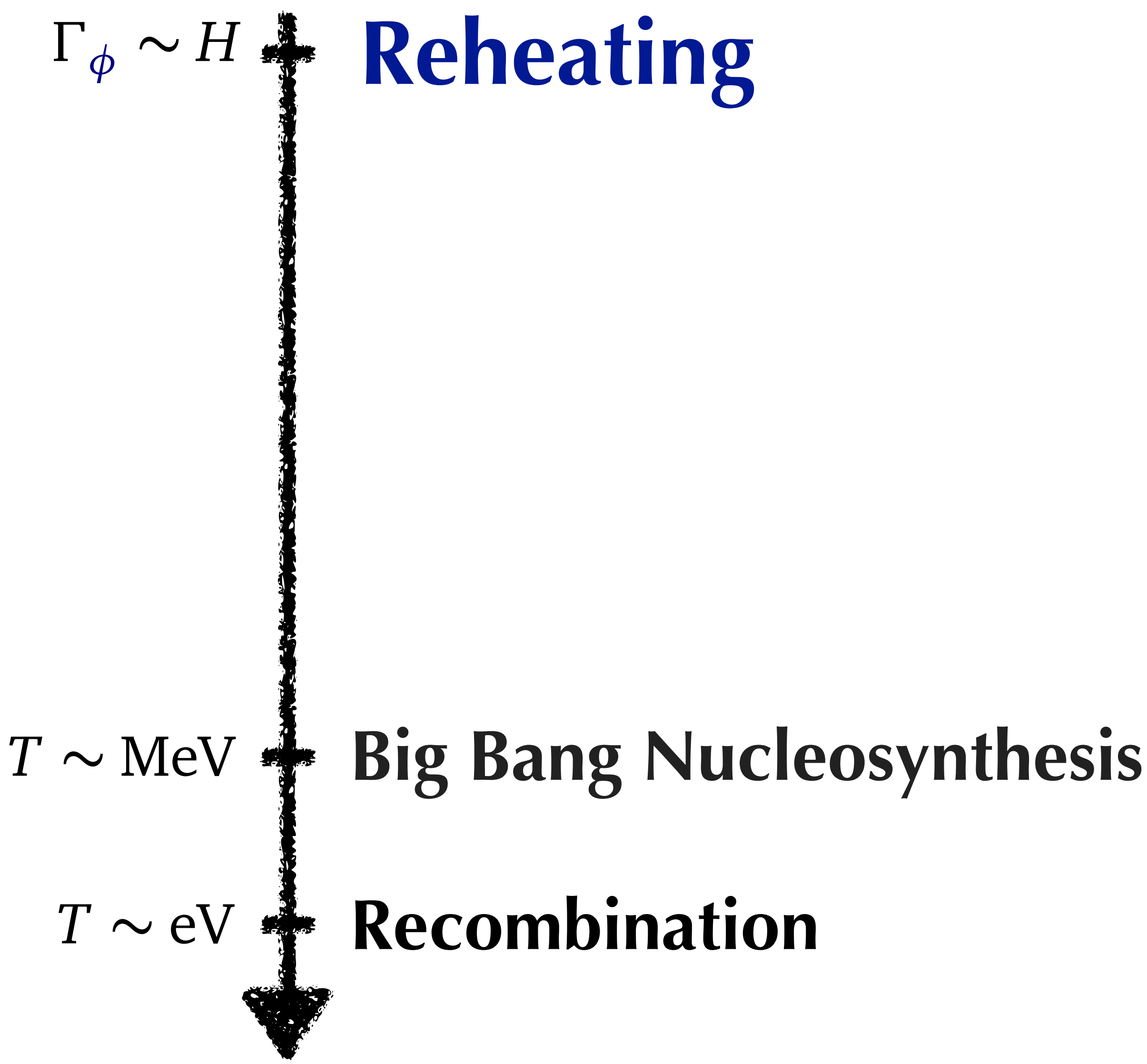
- Inflaton should convert its energy to radiation: **reheating**.
- Rough sketch of time evolution after the **reheating**:



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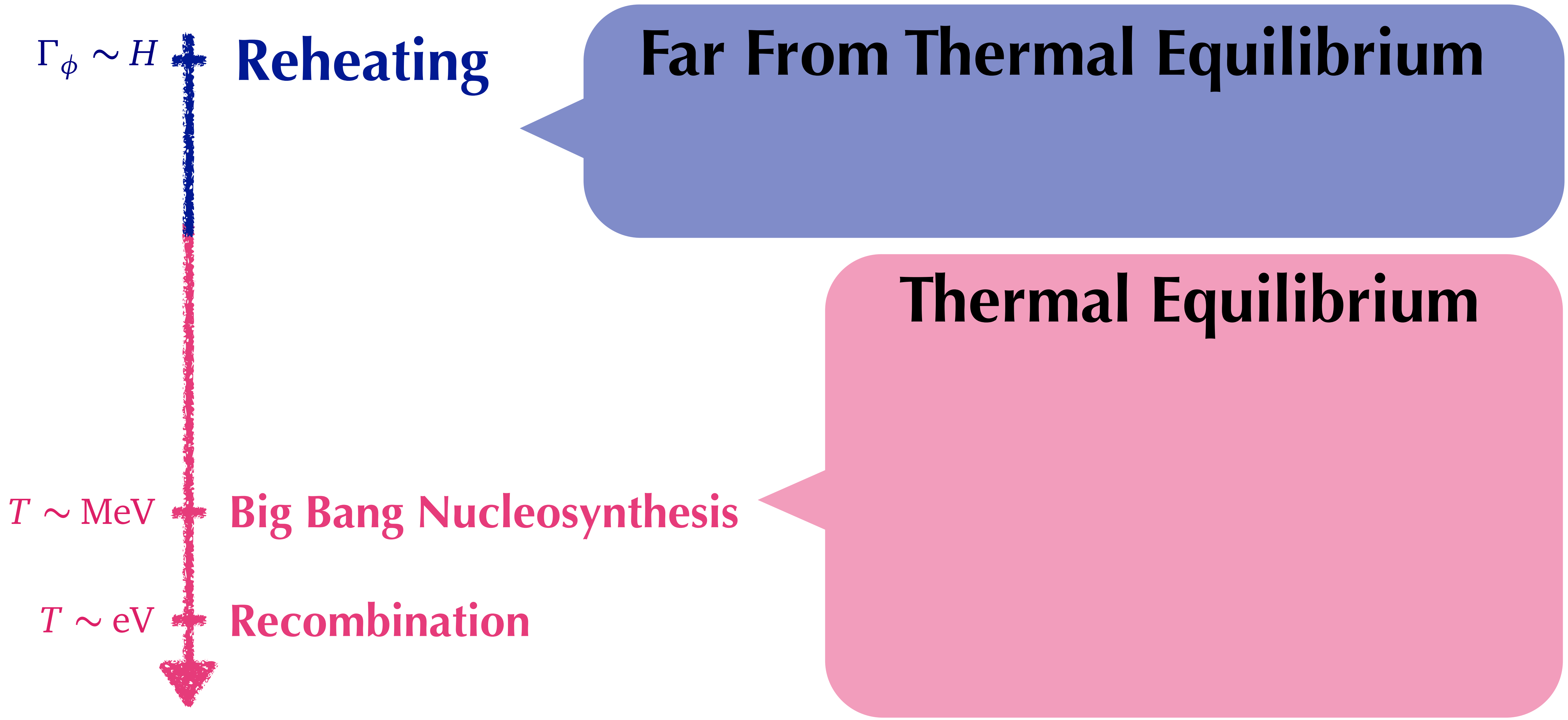

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- Rough sketch of time evolution after the **reheating**:

$\Gamma_\phi \sim H$ — **Reheating**

$T \sim M_{\rm N}$ — Thermal Leptogenesis??

⋮

$T \sim m_{\rm DM}$ — Thermal DM production??

⋮

$T \sim {\rm MeV}$ — **Big Bang Nucleosynthesis**

$T \sim {\rm eV}$ — **Recombination**

Far From Thermal Equilibrium

Thermal Equilibrium

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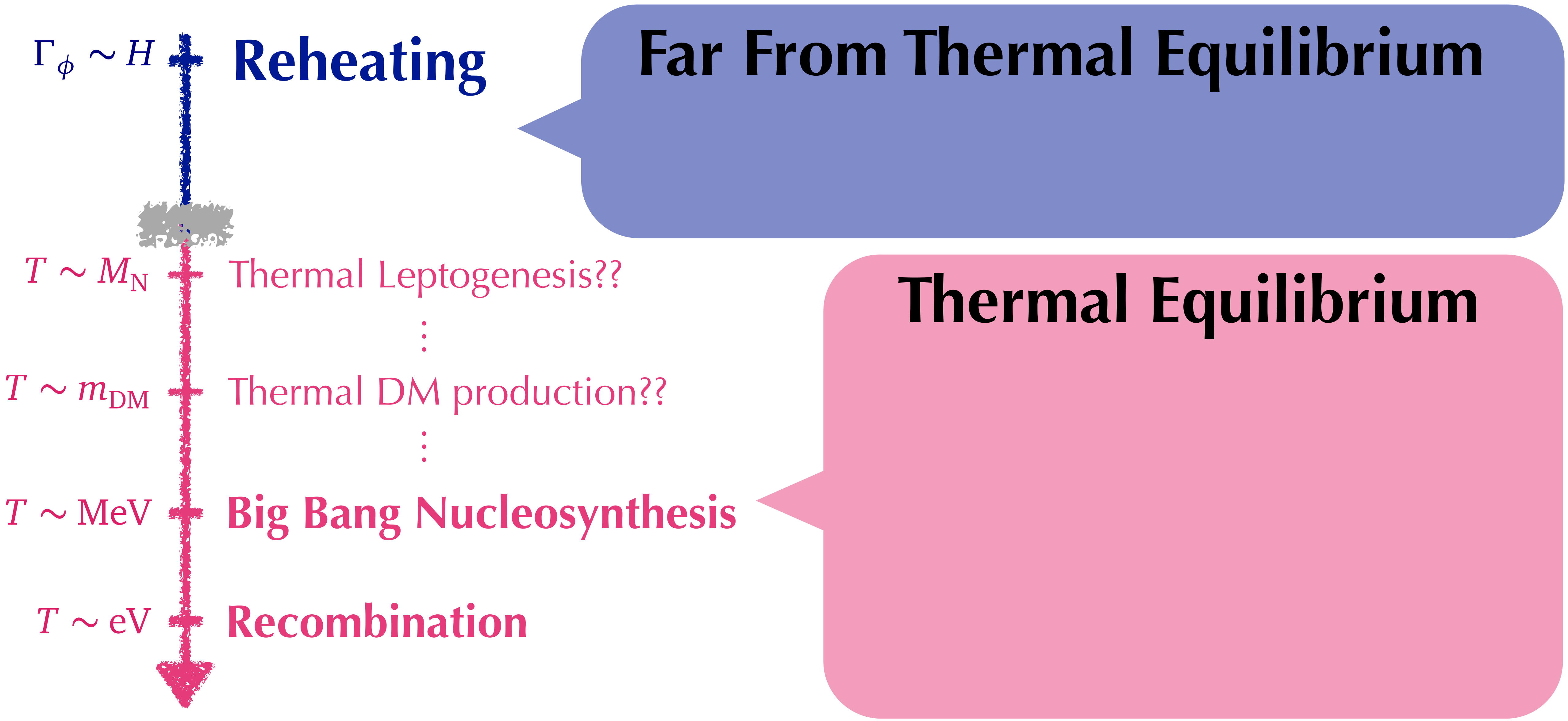

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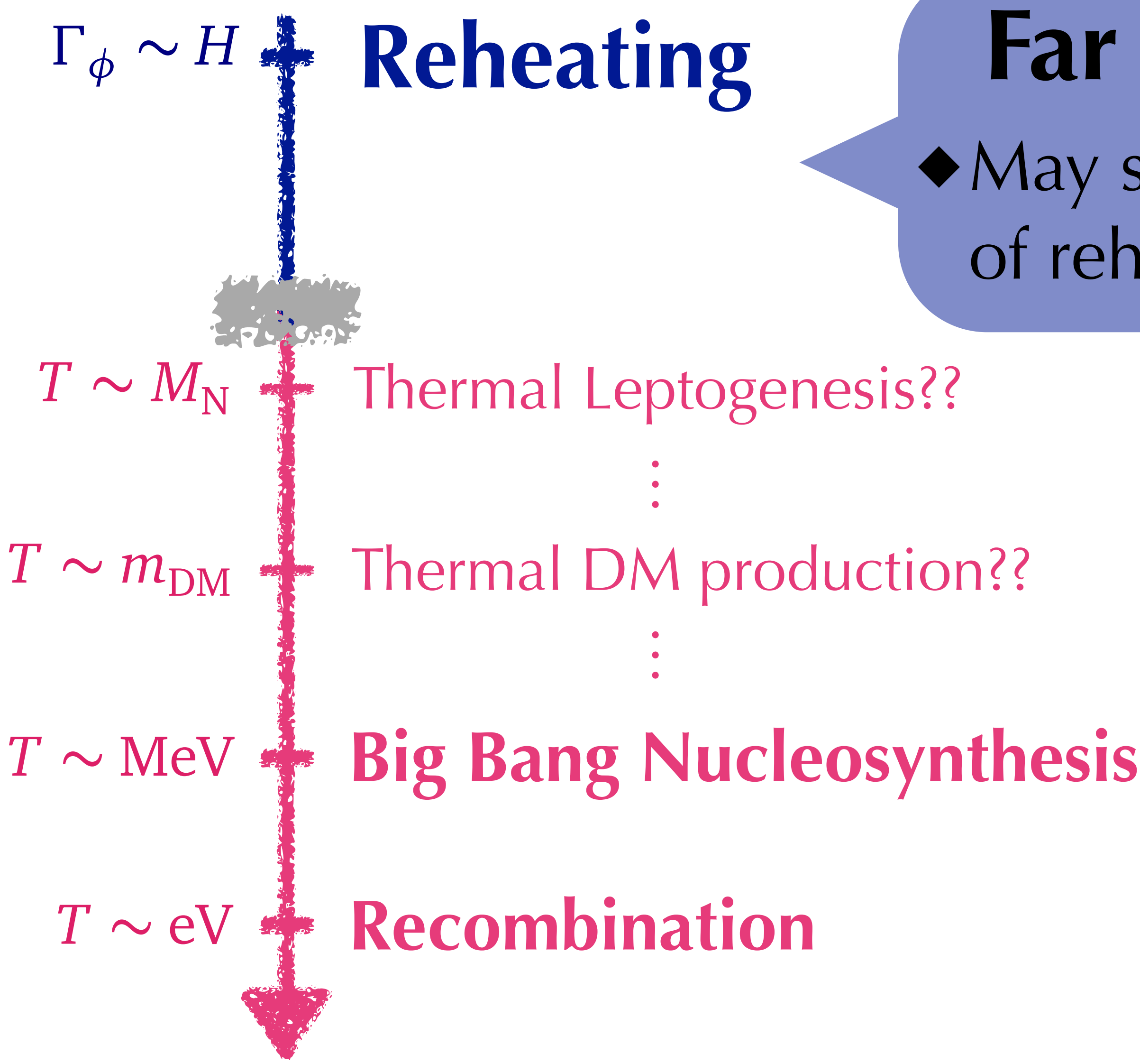


Far From Thermal Equilibrium

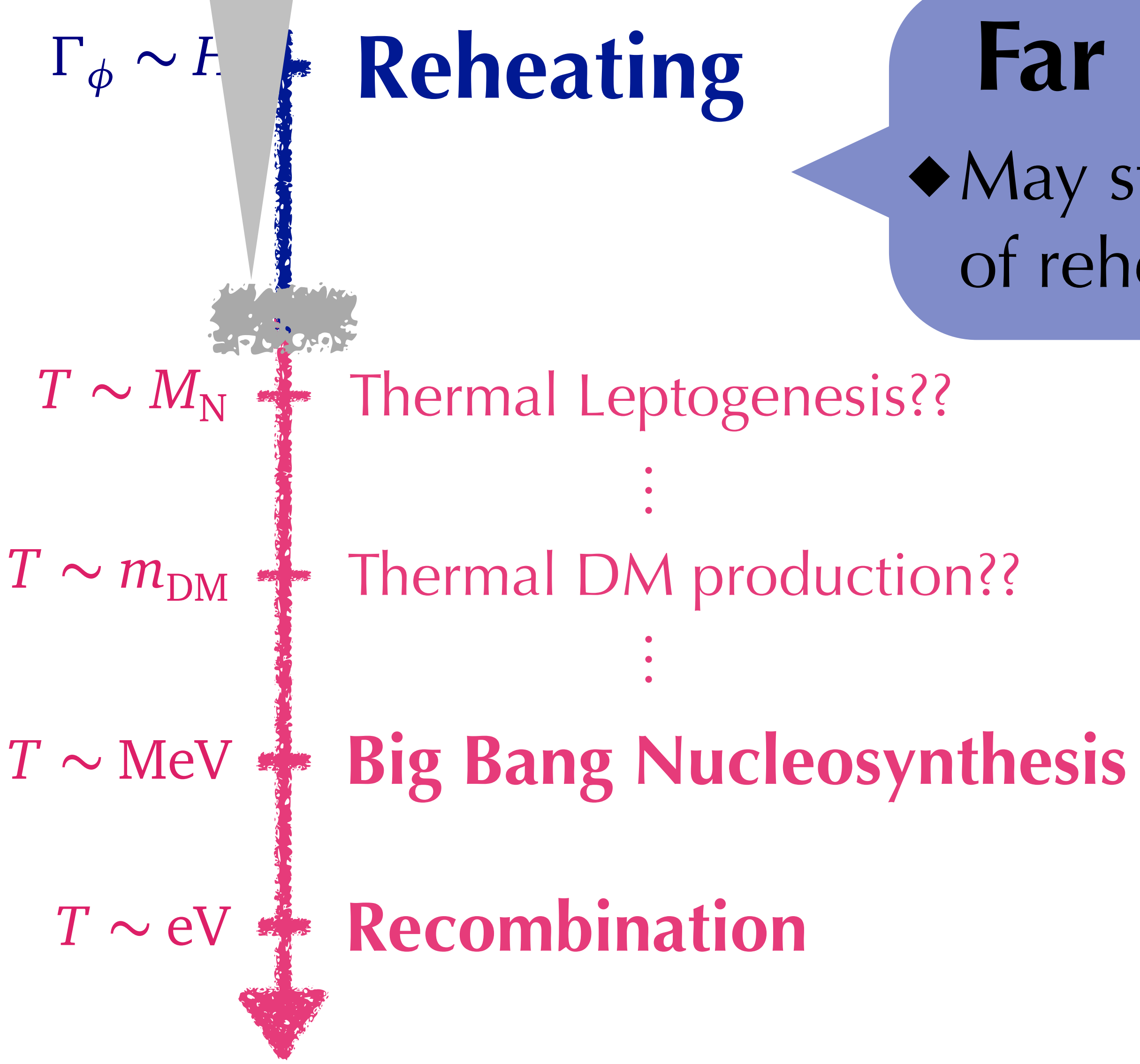
- May strongly depend on details of the process of reheating…

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

When do the produced light particles Thermalize ???



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Outline

- Introduction
- Reheating
- Thermalization (Main Topic)
- Summary

Reheating

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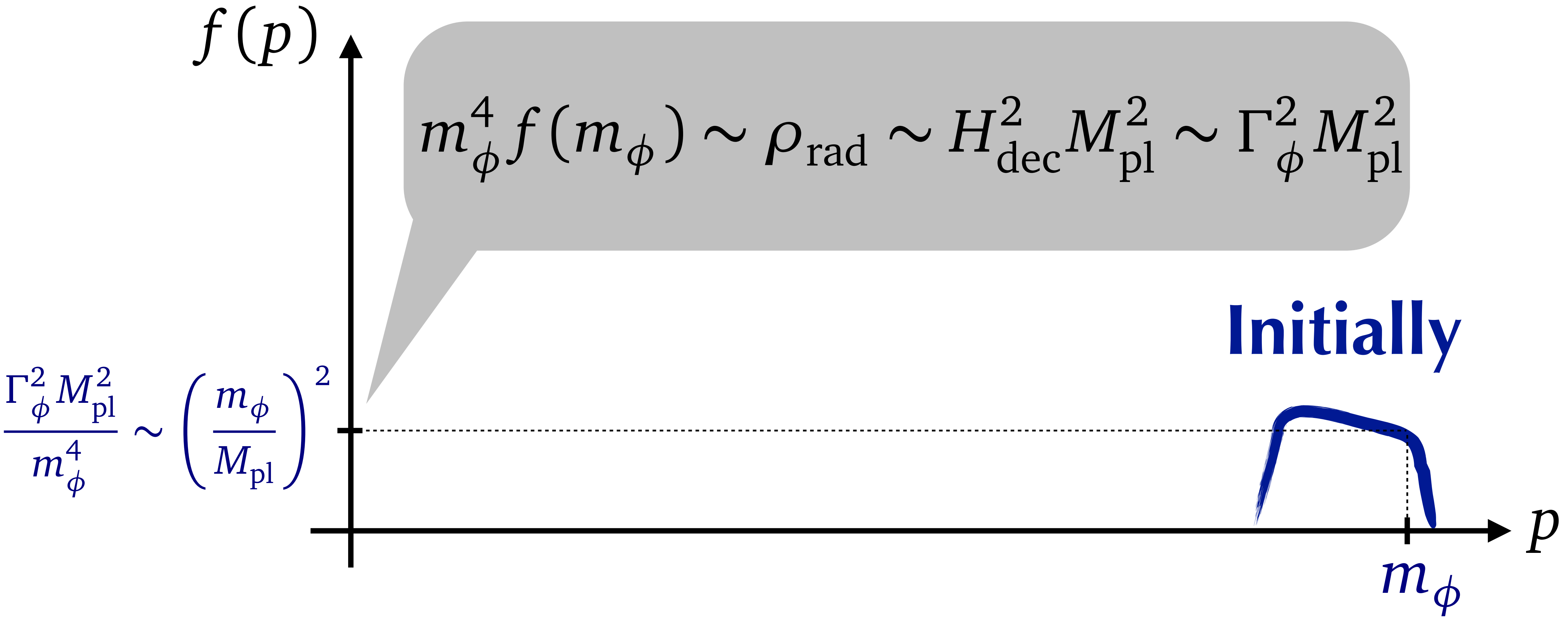
- Inflaton decays into radiation completely at $\Gamma_\phi \sim H$.
- Distribution of decay products (right after the decay):
  - Let us consider a **small decay rate**: e.g., $\Gamma_\phi = \kappa^2 m_\phi \sim \dfrac{m_\phi^3}{M_{\rm pl}^2}$. [cf. Terada san's Talk]



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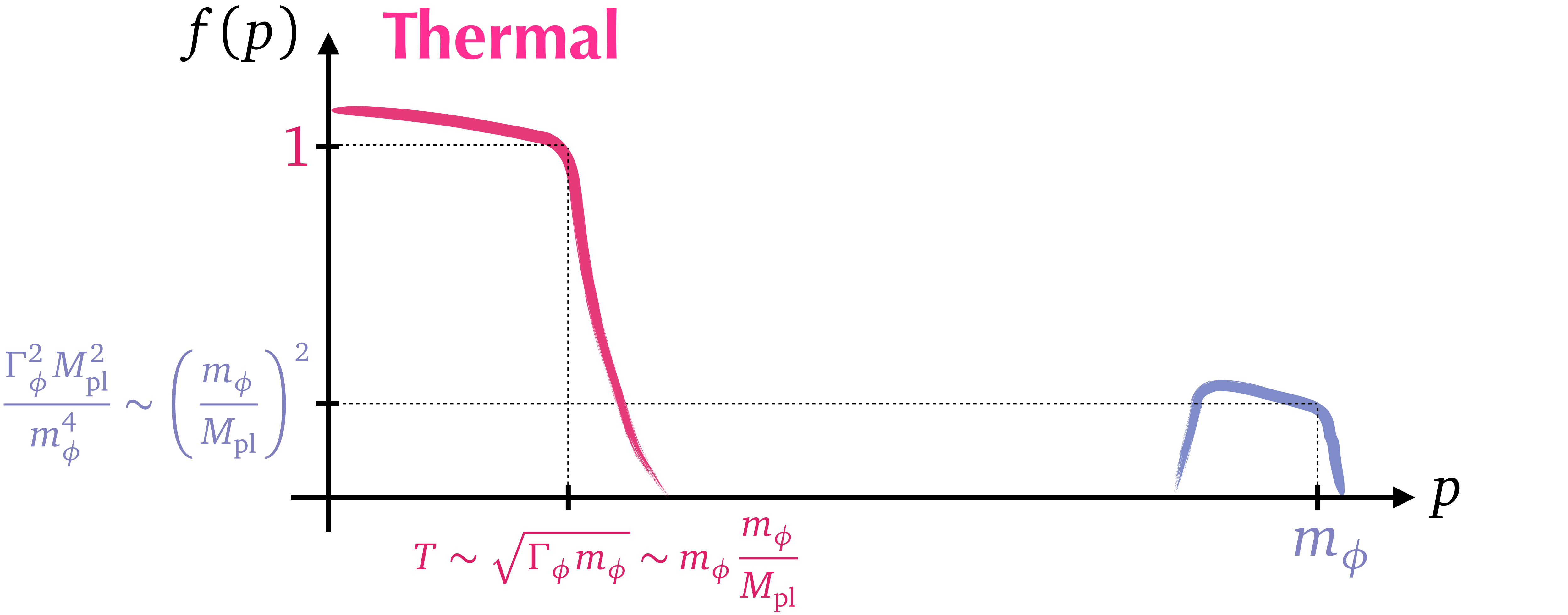

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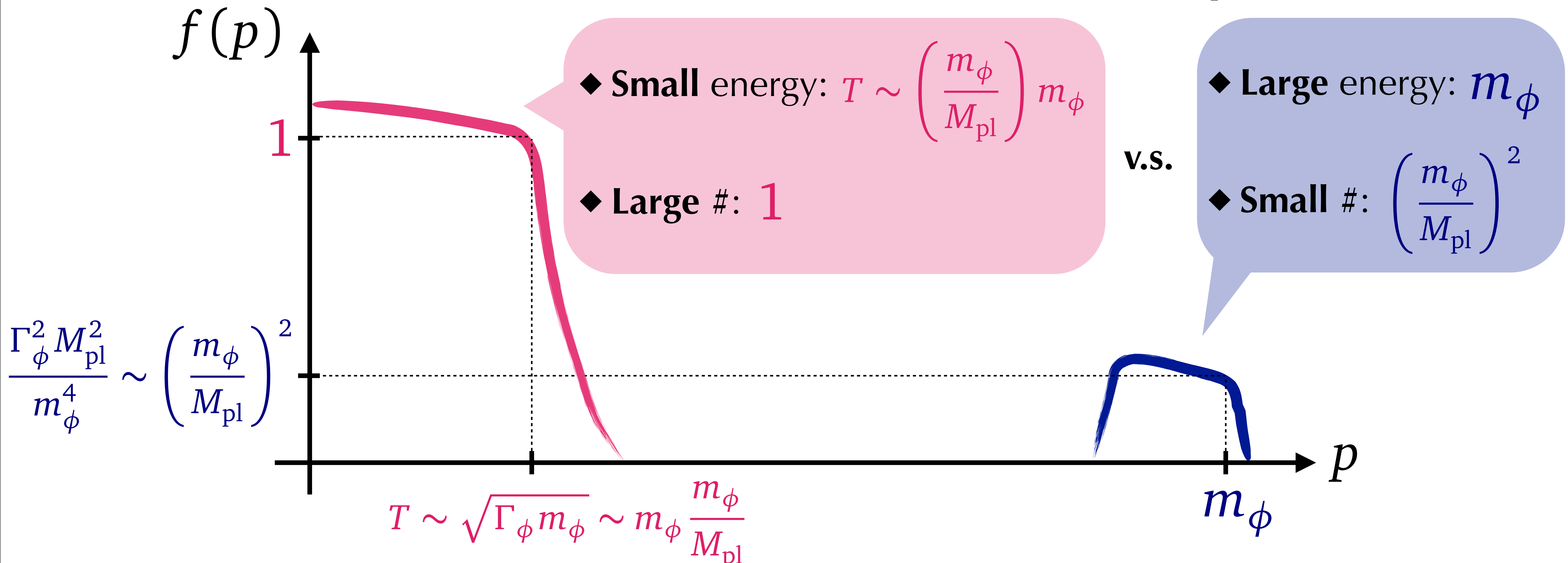

Reheating

#-violating processes play crucial roles!

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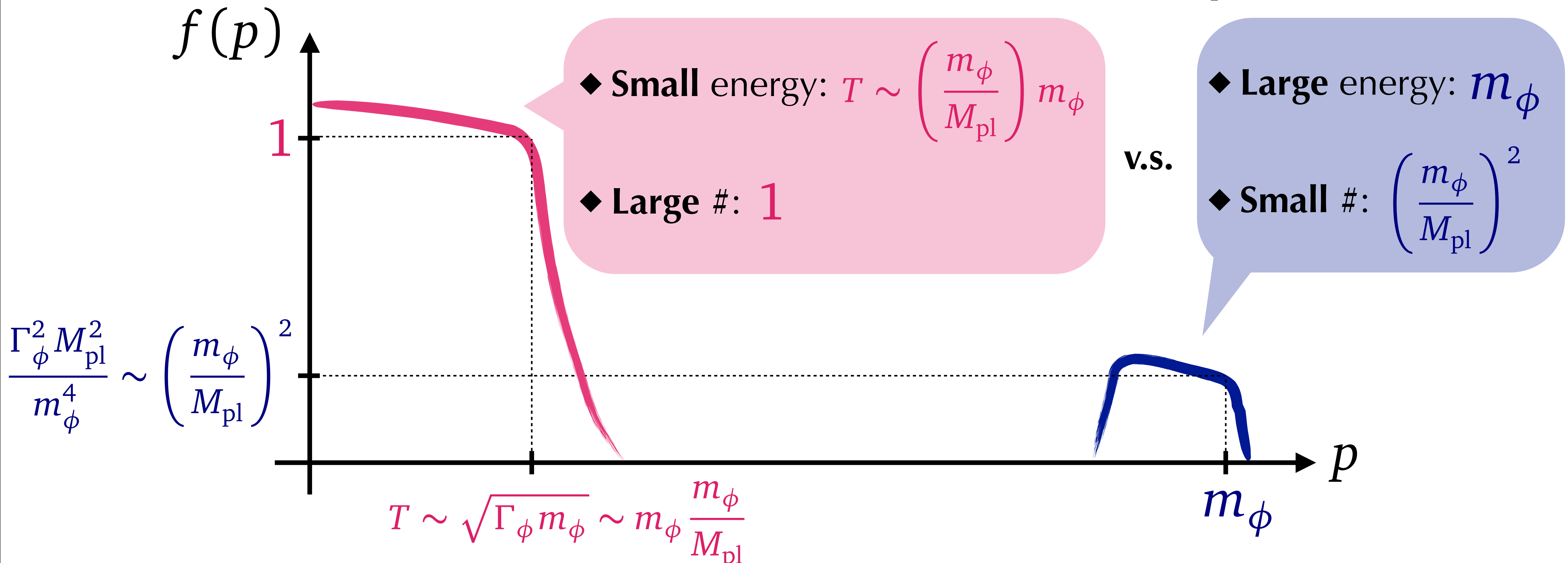
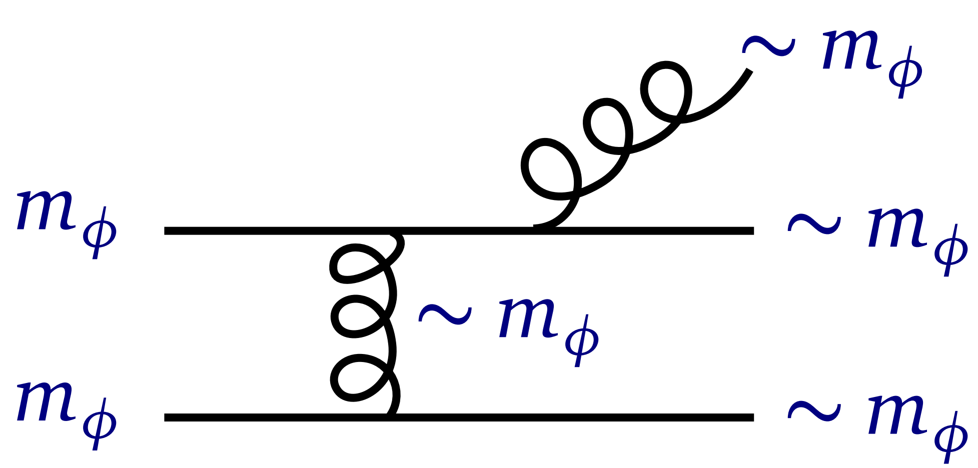


Thermalization

Thermalization

- ***Naively***, #-violating **"hard"** processes increase #/reduce the energy per one-particle efficiently.
- However, the rate is small due to the small #/large energy.



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

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

◆Delayed thermalization??: [Ellis et al.,1987; Mcdonald, '00; Allahverdi, '00]

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

Thermalization

- **"Soft"** processes play crucial roles, though they cannot reduce the energy per one-particle efficiently. [Davidson, Sarkar, '00]
- Similar situation is well studied in the context of QGP.
- The process is dubbed as "**bottom-up thermalization**"; thermalization proceeds from the IR. [Baier et al., '00; Kurkela, Moore, '11]

◆ **What we did:** [K. Harigaya and KM, 1312.3097]

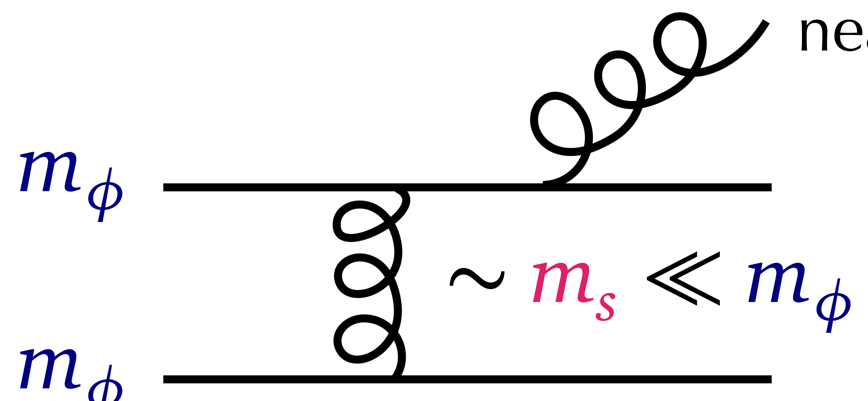
Apply **"bottom-up thermalization"** to **thermalization after/during reheating**

Thermalization

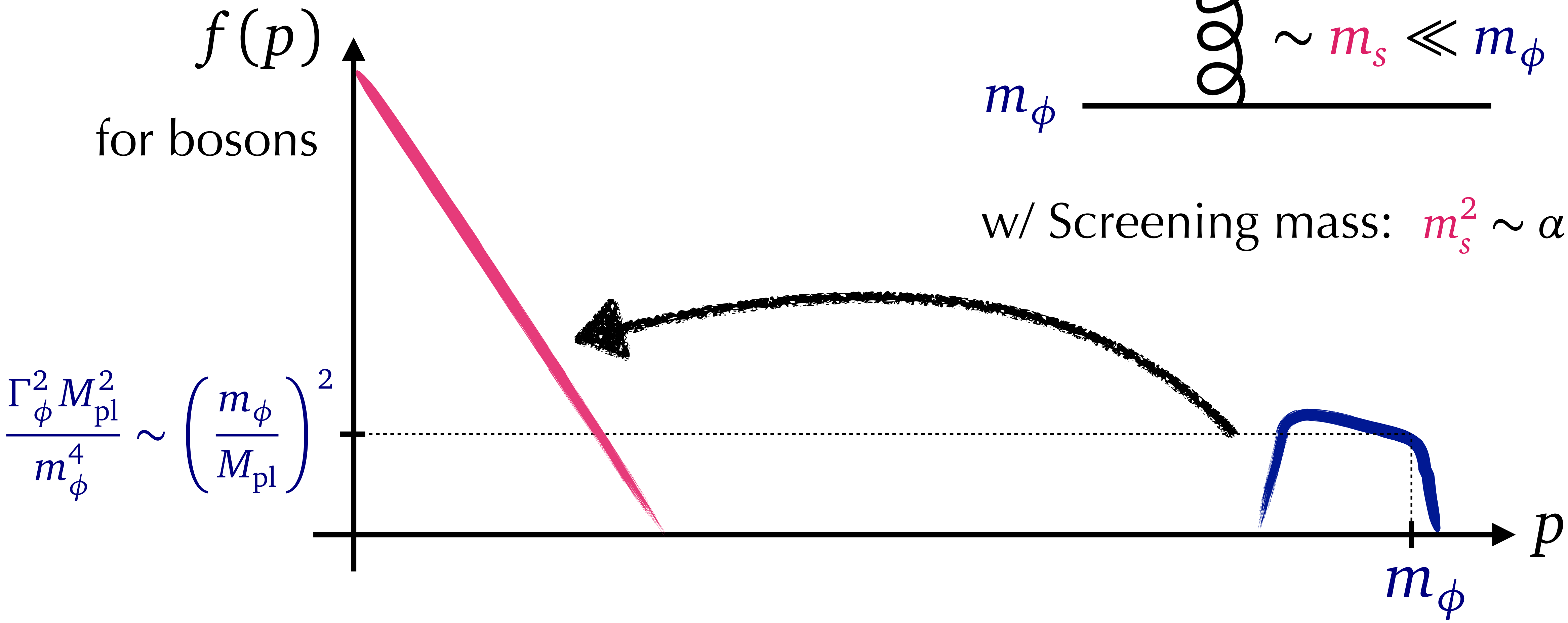
- Rough sketch of **bottom-up thermalization**:

  I. Soft particles are produced via the nearly collinear emission.

  - Much faster than H^{-1} for most cases.



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

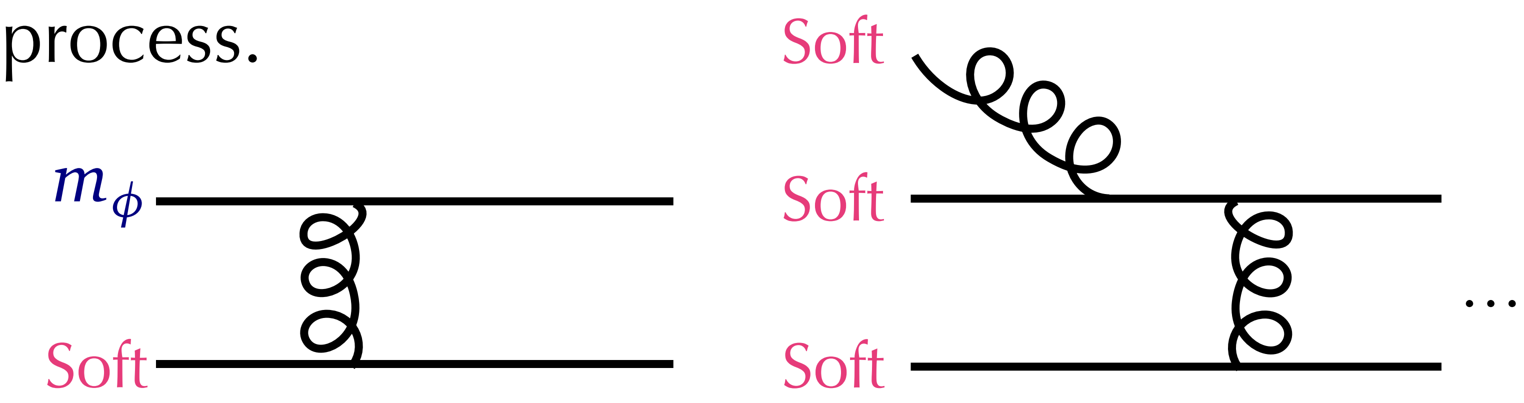


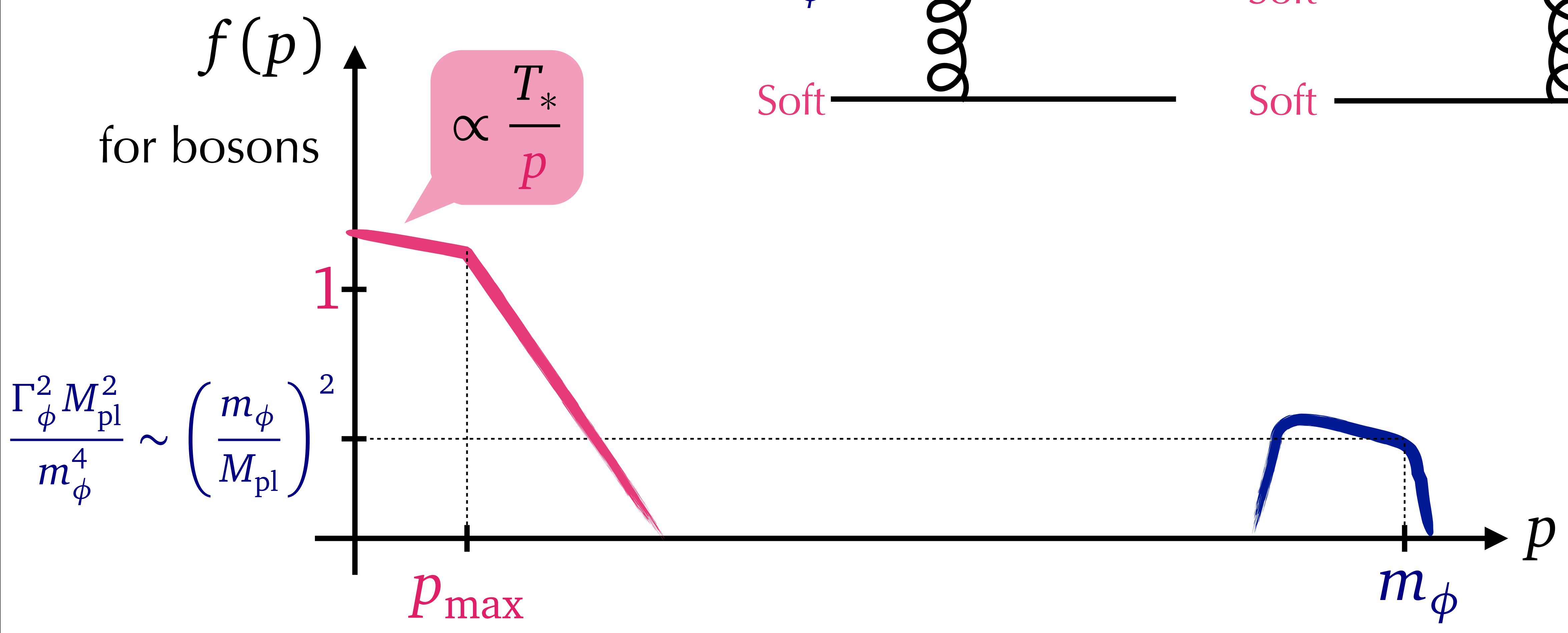
Thermalization

- Rough sketch of **bottom-up thermalization**:

II. Soft particles fall into a thermal-like distribution below p_{max}.

- ◆ Much faster than the 1st process.





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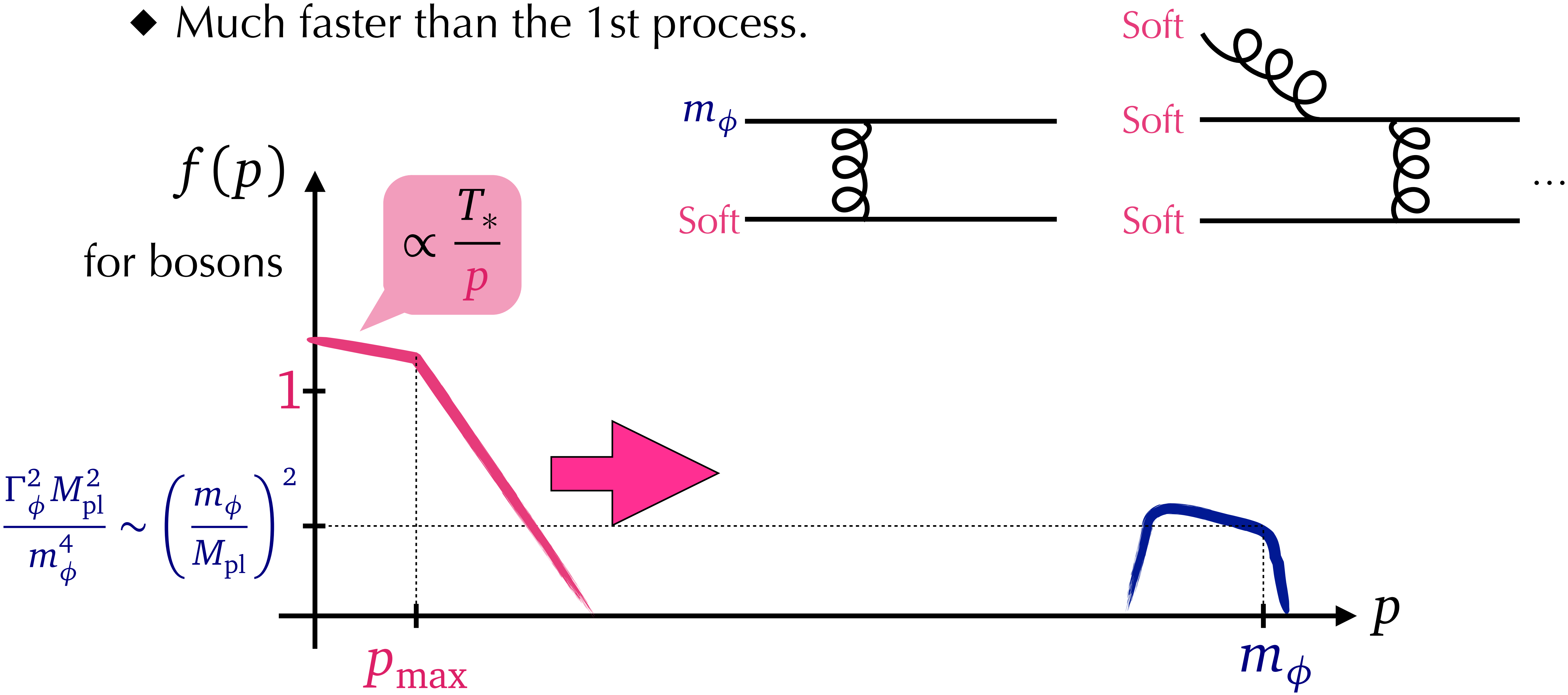
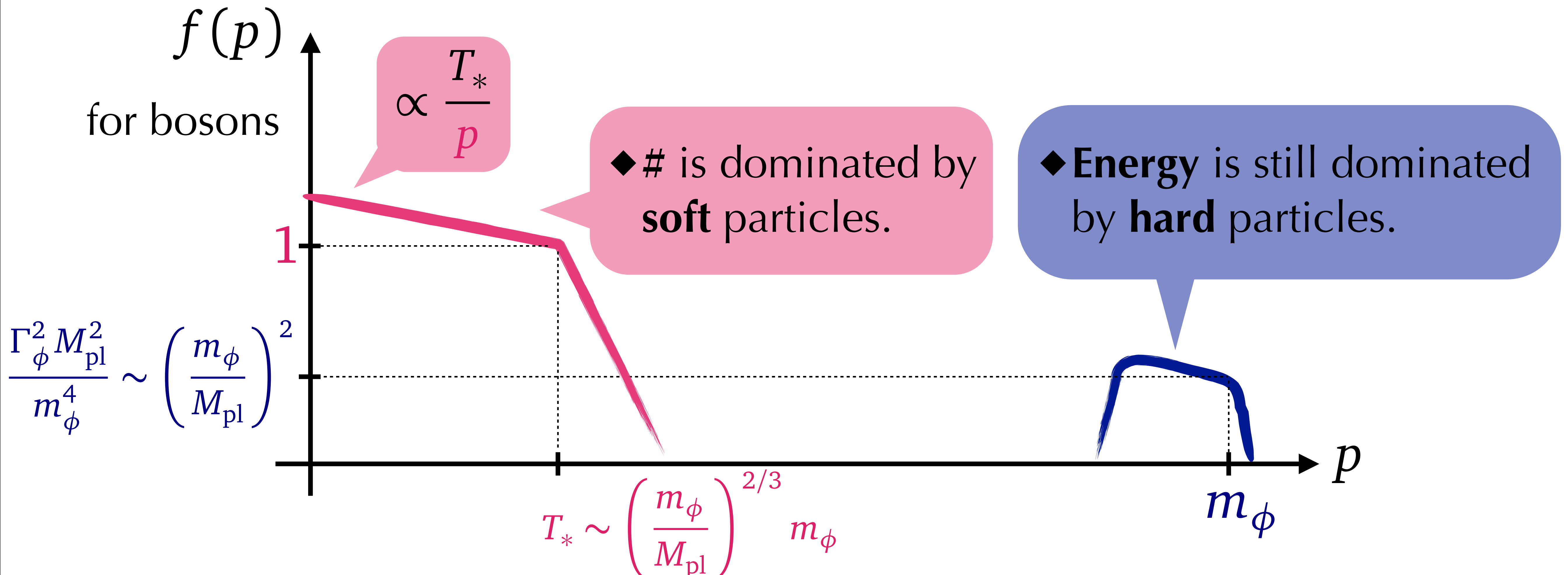


Thermalization

- Rough sketch of **bottom-up thermalization**:

III. p_{max} evolves towards UV, and soft particles "thermalize" eventually via interactions among themselves.

- v.s. Hubble parameter: $1 \gg \frac{\langle \sigma v n_{soft} \rangle_{soft}}{H} \sim \alpha^2 \frac{T_*}{\Gamma_\phi} \to \alpha \gg 2.6 \times 10^{-4} \left(\frac{m_\phi}{10^{13}\,\mathrm{GeV}} \right)^{2/3}$ for dim-5

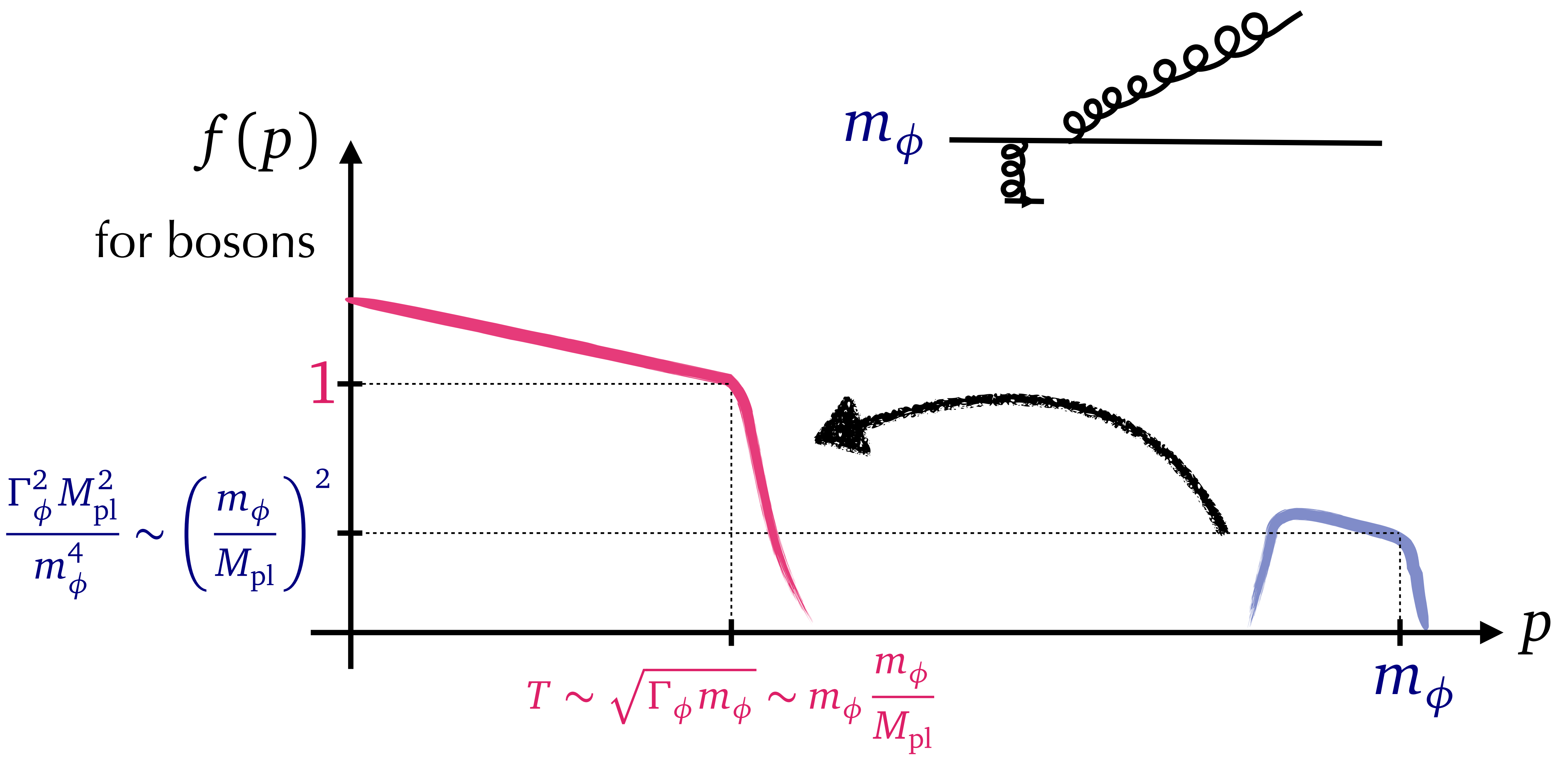


Thermalization

- Rough sketch of **bottom-up thermalization**:

IV. Finally, **hard** particles lose their energy via multiple splittings.

◆ This is the bottleneck!!



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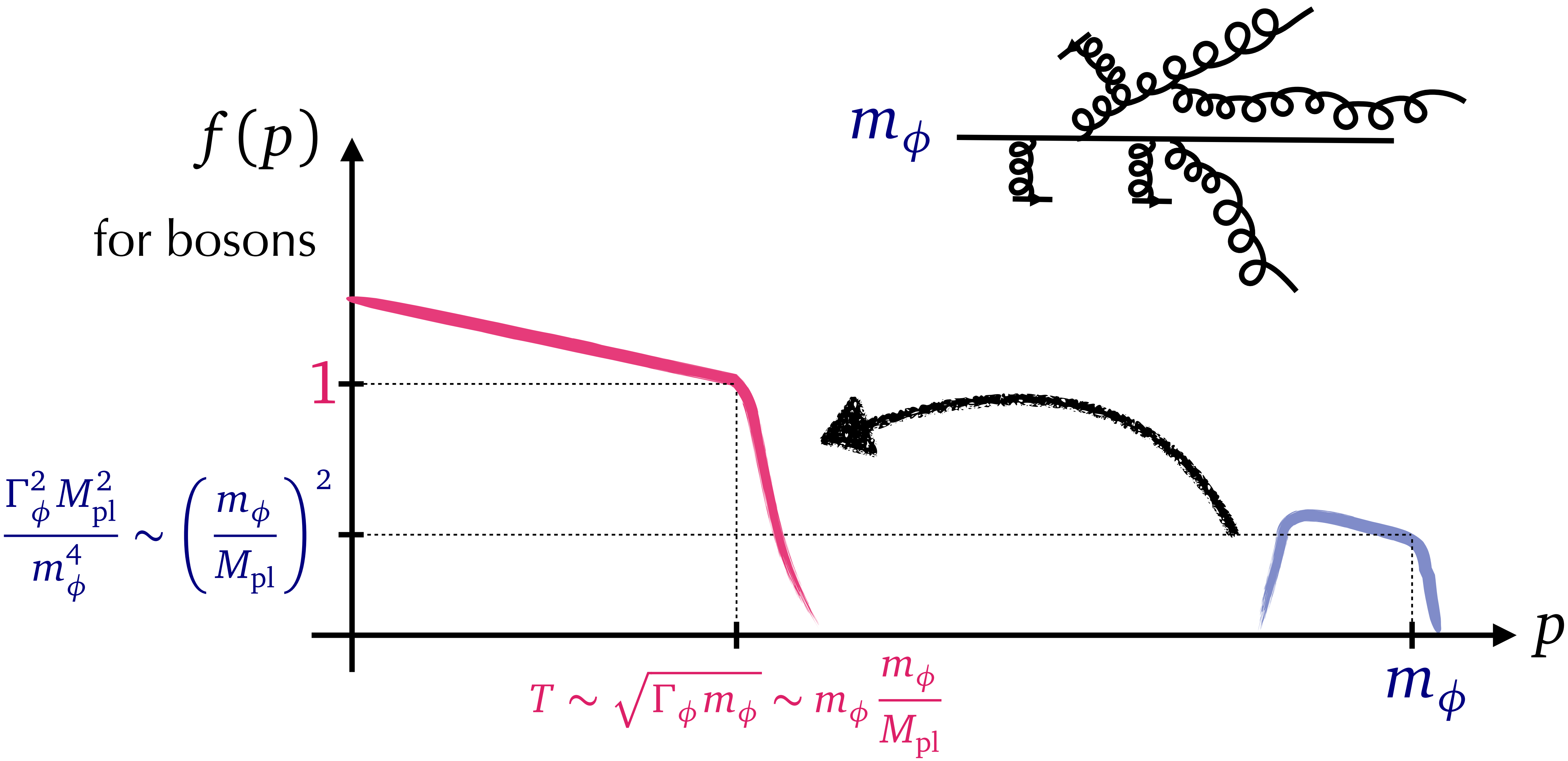

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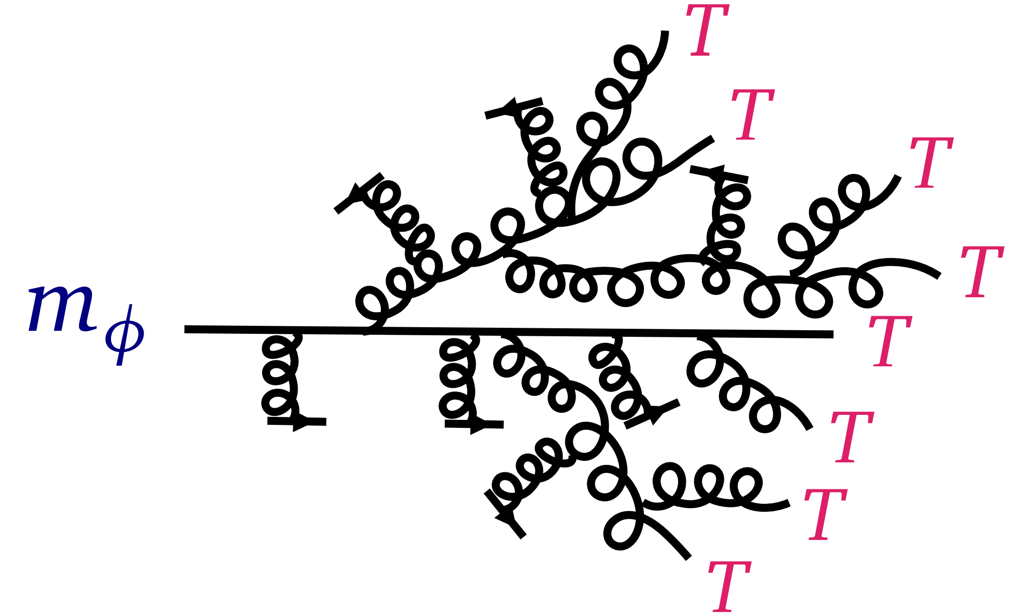

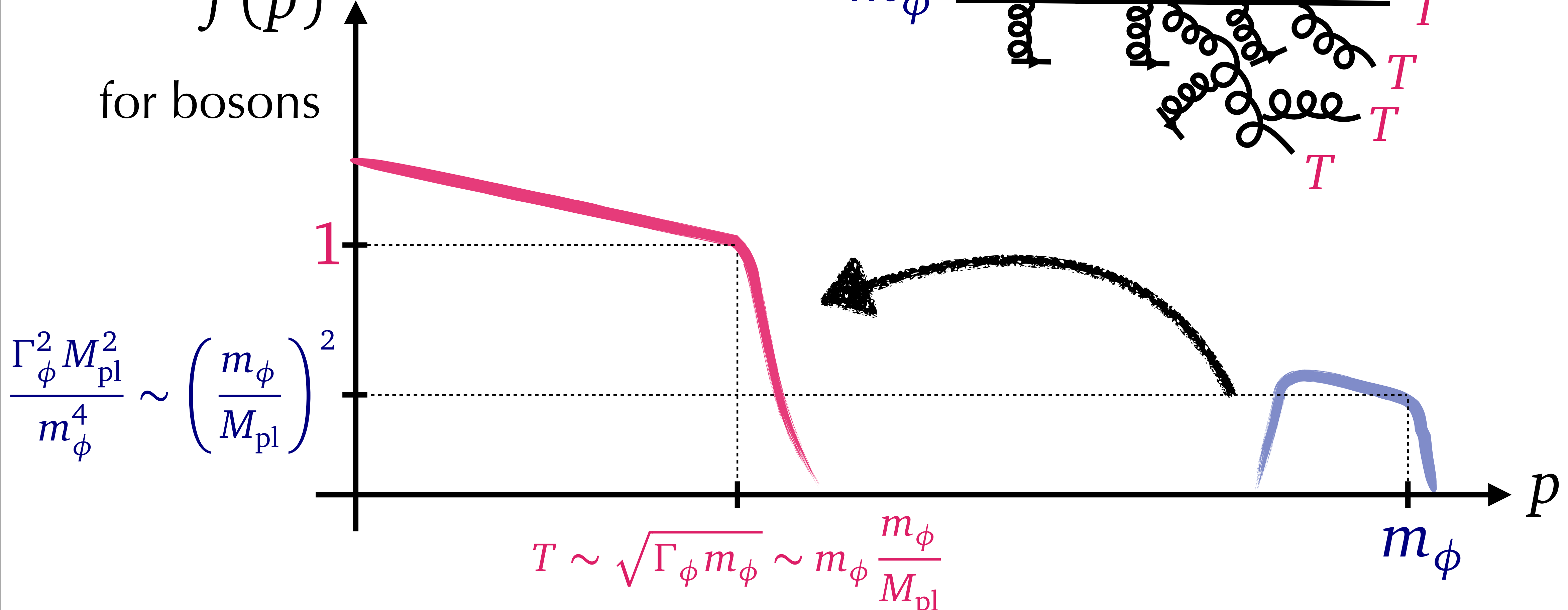

Thermalization

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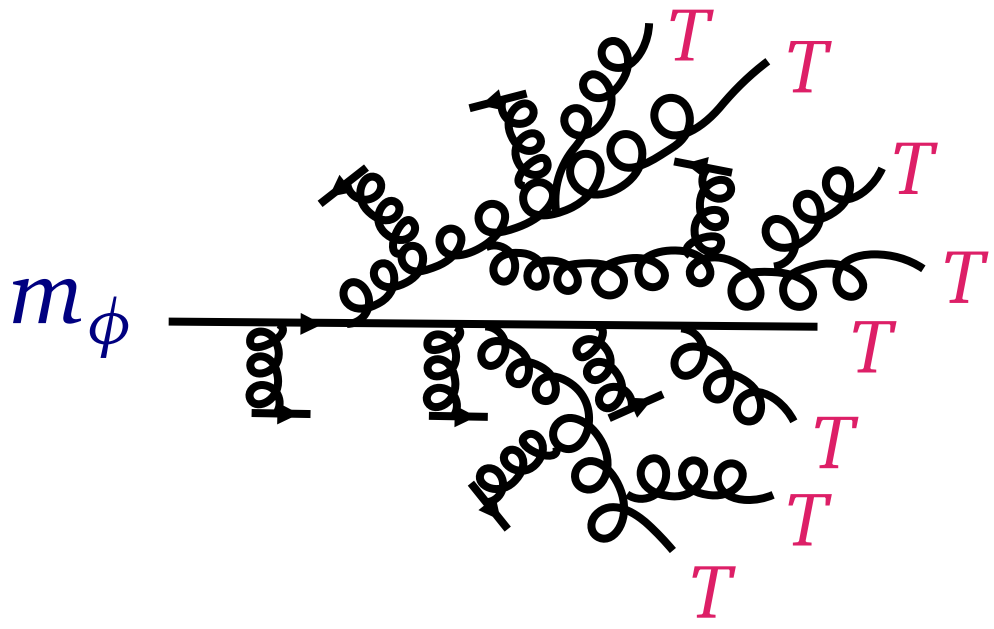
◆ Energy loss rate of multiple splittings (w/ LPM effect):



$$\frac{dE}{dt} \sim \alpha^2 T^2 \sqrt{\frac{E}{T}}$$ (at the last moment)

[Baier et al., '97; Kurkela, Moore, '11]

➡ Hard particles (~m_Φ) completely lose their energy within

$$t_{\rm split} \sim (\alpha^2 T)^{-1} \sqrt{\frac{m_\phi}{T}}.$$

◆ v.s. Hubble parameter:

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

Thermalization

- Rough sketch of **bottom-up thermalization**:

IV. Finally, **hard** particles lose their energy via multiple splittings.

◆Energy loss rate of multiple splittings (w/ LPM effect):

- **More instantaneous** for a **smaller** decay rate.
- Radiation thermalizes **instantaneously** in most cases.
- Discussion on T_{max} → **See our paper!**

◆v.s. Hubble parameter:

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Summary

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- A **small decay rate** of inflaton (e.g., Planck-suppressed one) results in a **small # 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 $\mathbf{T_{max}}$ → See our paper.
- Application: In a low T_R scenario, hard decay products ($\sim m_\Phi$) may create DM w/ **M > T**, when they lose their energy via multiple-splittings. → See our yesterday's paper!

[K.Harigaya, M. Kawasaki, KM, M. Yamada; 1402.2846]