Cascades of high-energy particles and non-thermal DM production in the pre-thermal phase

Masaki Yamada
Tohoku University

Based on

K. Mukaida, M.Y. JHEP 10 (2022) 116 (hep-ph/2208.11708)

See also

K. Harigaya, K. Mukaida, M.Y. JHEP 07 (2019) 059 (hep-ph/1901.11027)

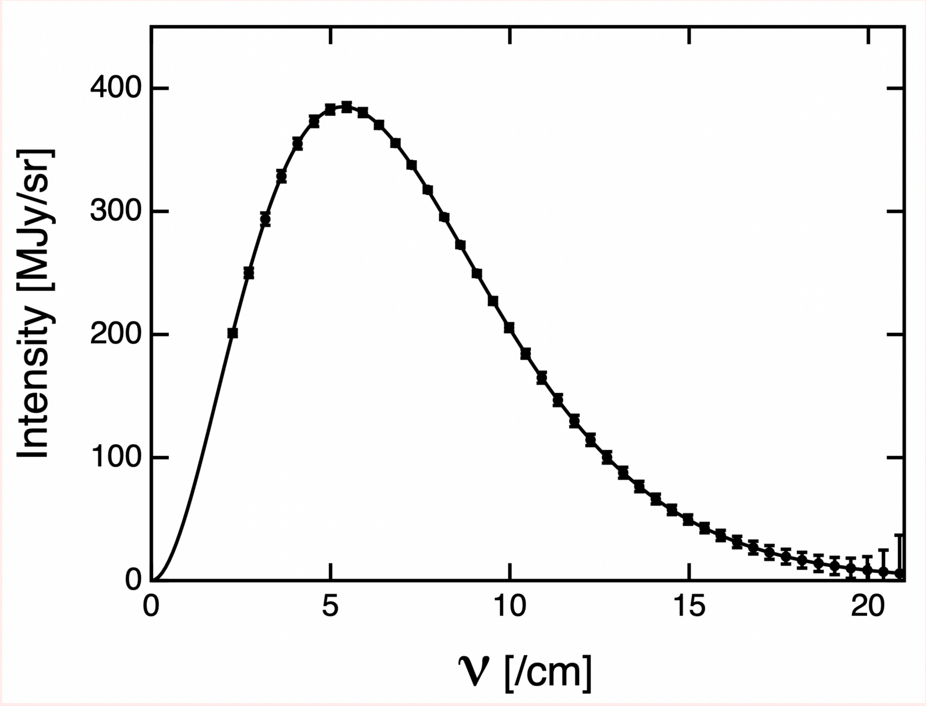
K. Mukaida, M.Y. JCAP 02 (2016) 003 (hep-ph/1506.07661)

K. Harigaya, M. Kawasaki, K. Mukaida, M.Y. Phys.Rev.D 89 (2014) 4, 043510 (hep-ph/1404.3138)

Thermal history of the Universe

13.8 Gyr — Present

Recombination (thermal eq.)



CMB spectrum

Smoot '97

O(1) min — BBN epoch (thermal eq.)

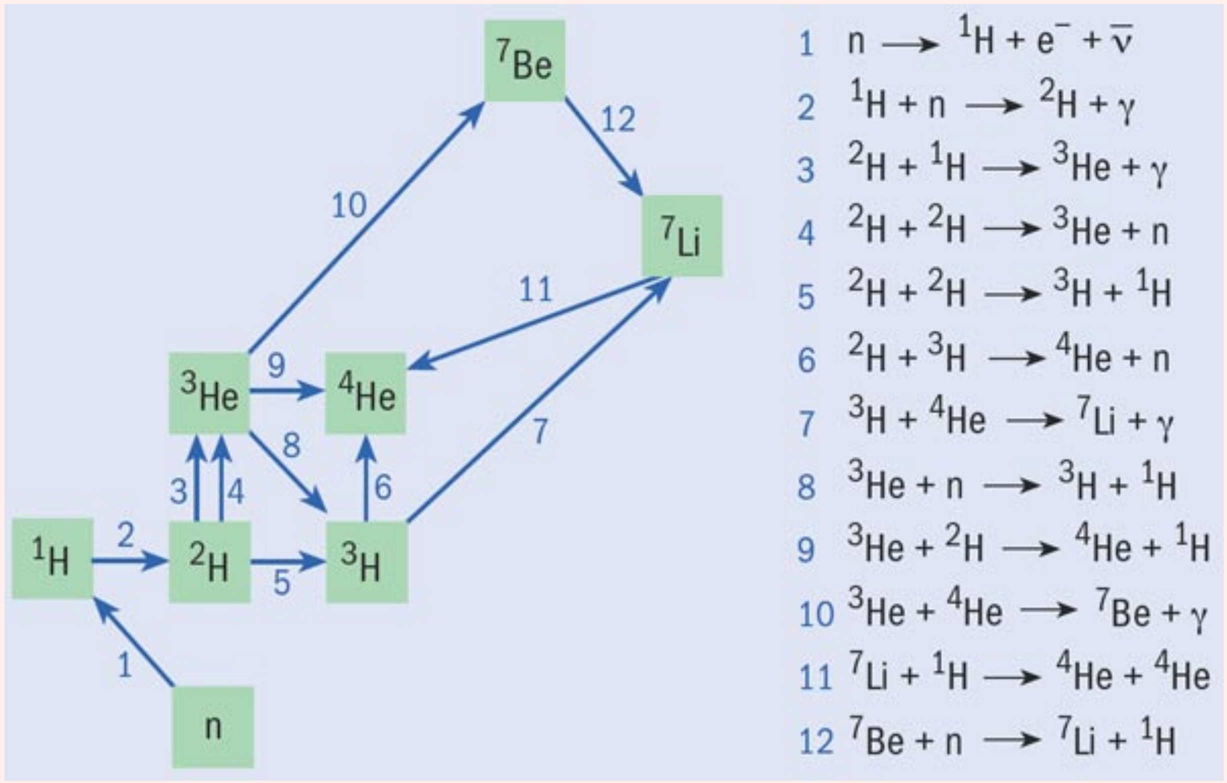
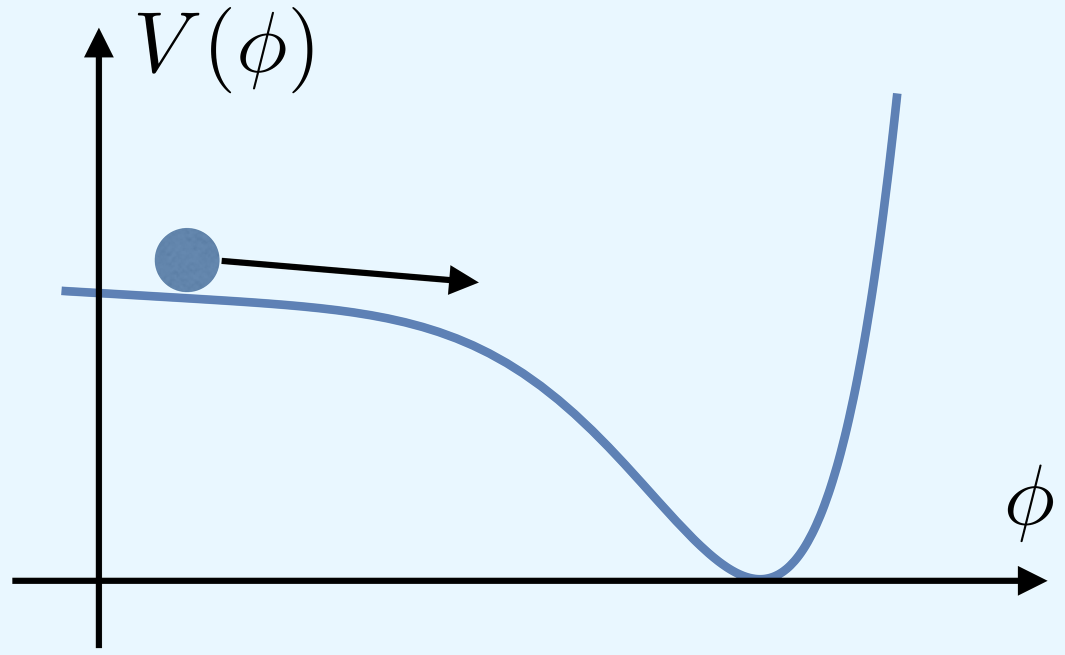


image from https://physicsworld.com/a/testing-the-elements-of-the-big-bang/

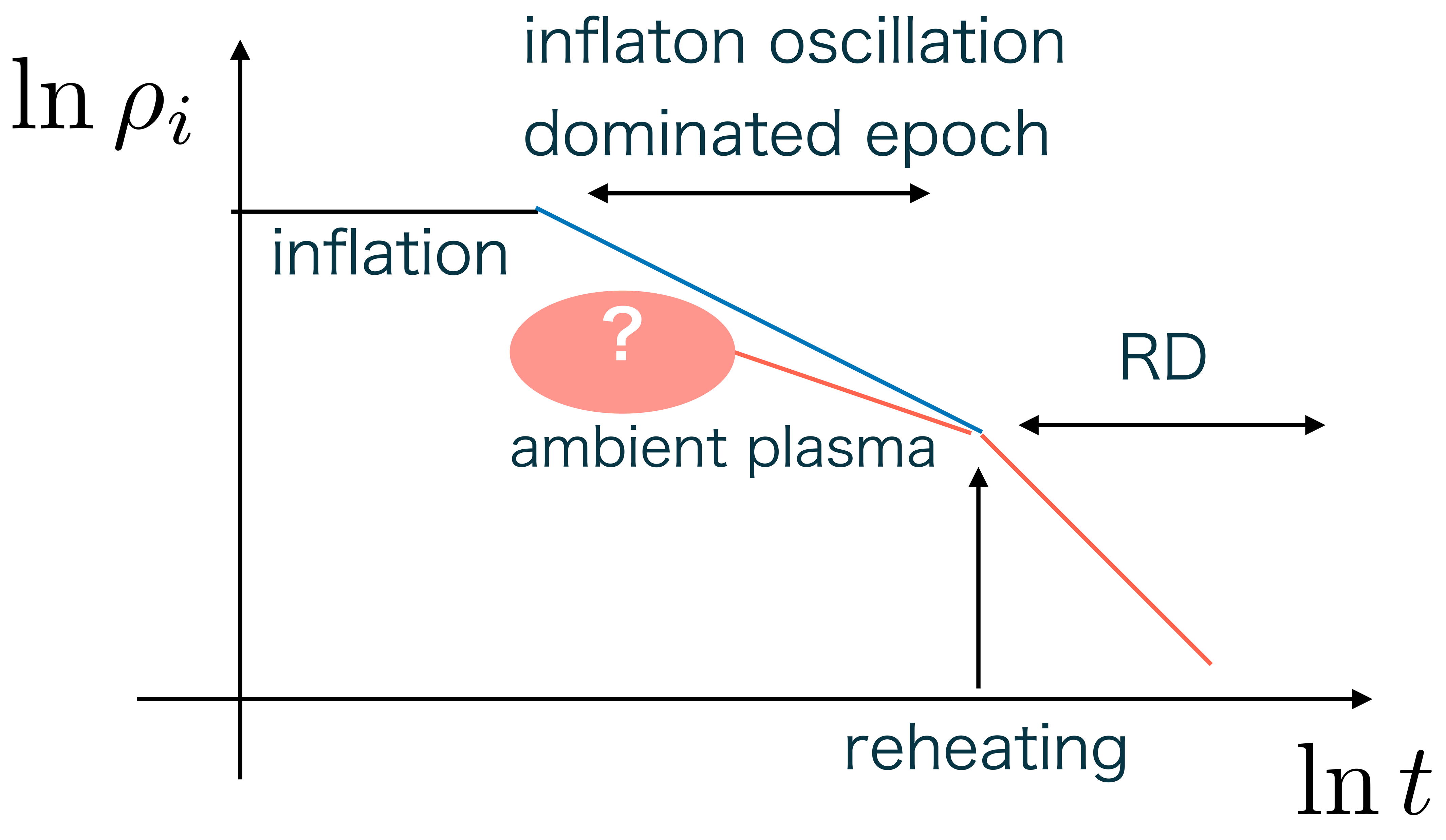
How does it reach the thermal equilibrium?

Inflation (far from thermal eq.)

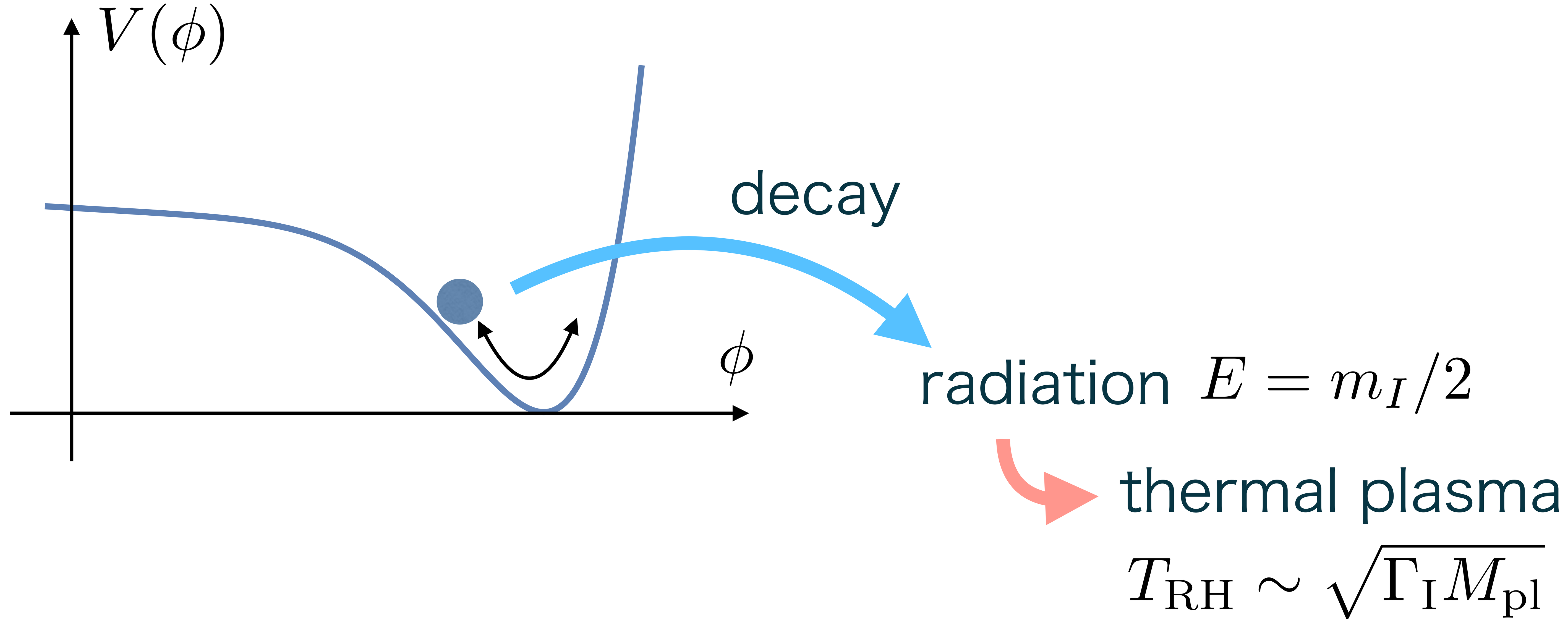


Thermal history of the Universe

- Inflaton starts to oscillate after inflation and decays into high-energy particles.
- We want to understand thermalization of inflaton-decay products during reheating era.



(In this talk, we particularly consider the case that inflaton decays via a Planck-suppressed dimension 5 operator or weaker one.)



Thermalization of a high-energy particle

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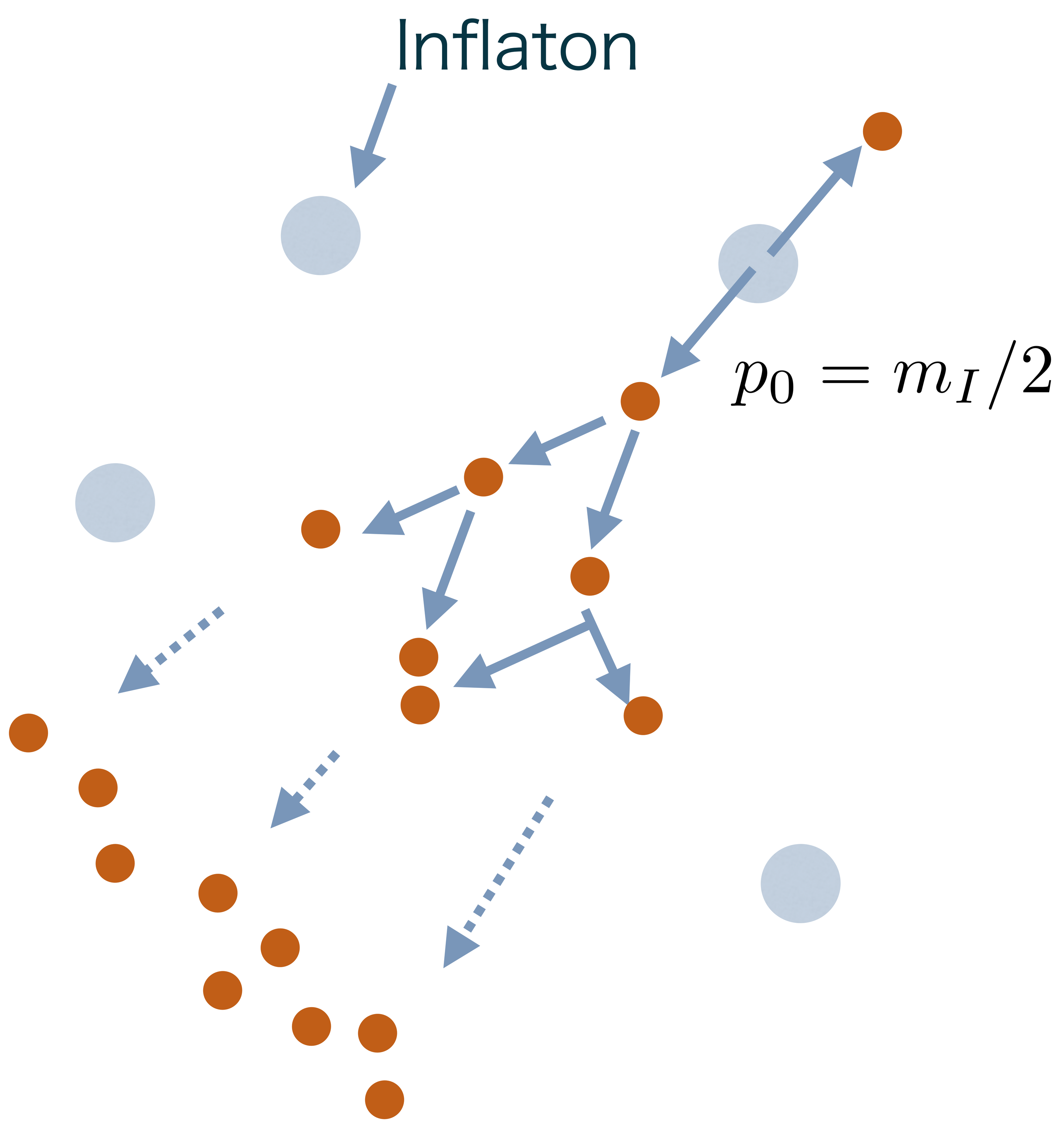
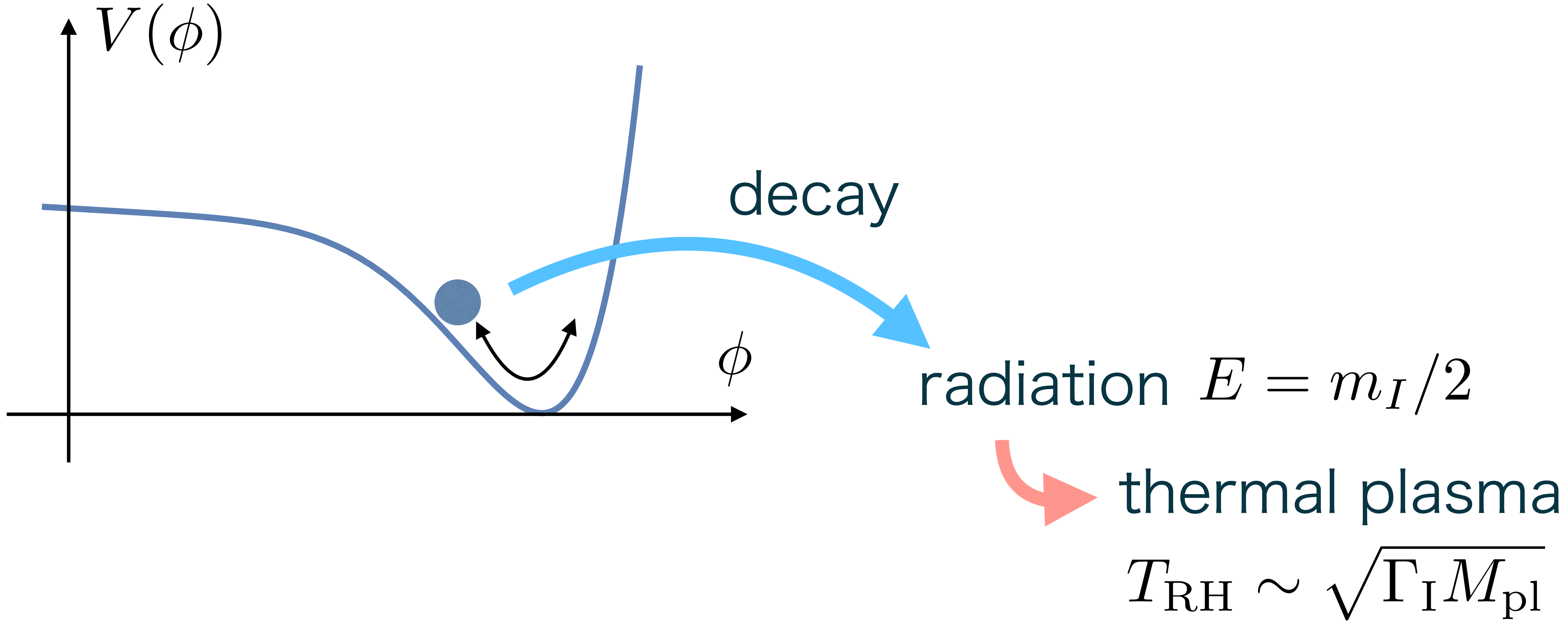
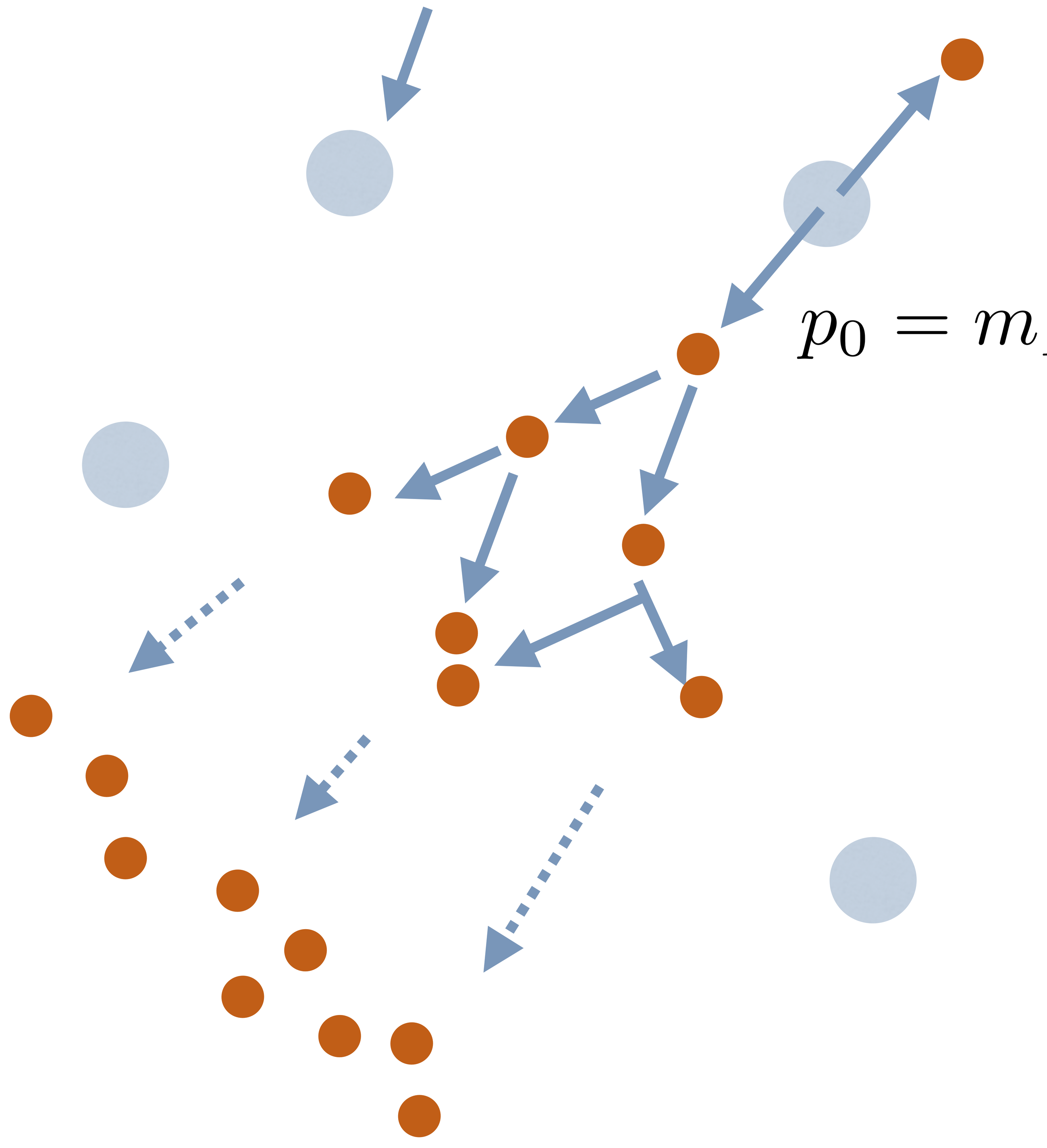


Harigaya and Mukaida '13, Mukaida, M.Y. '15



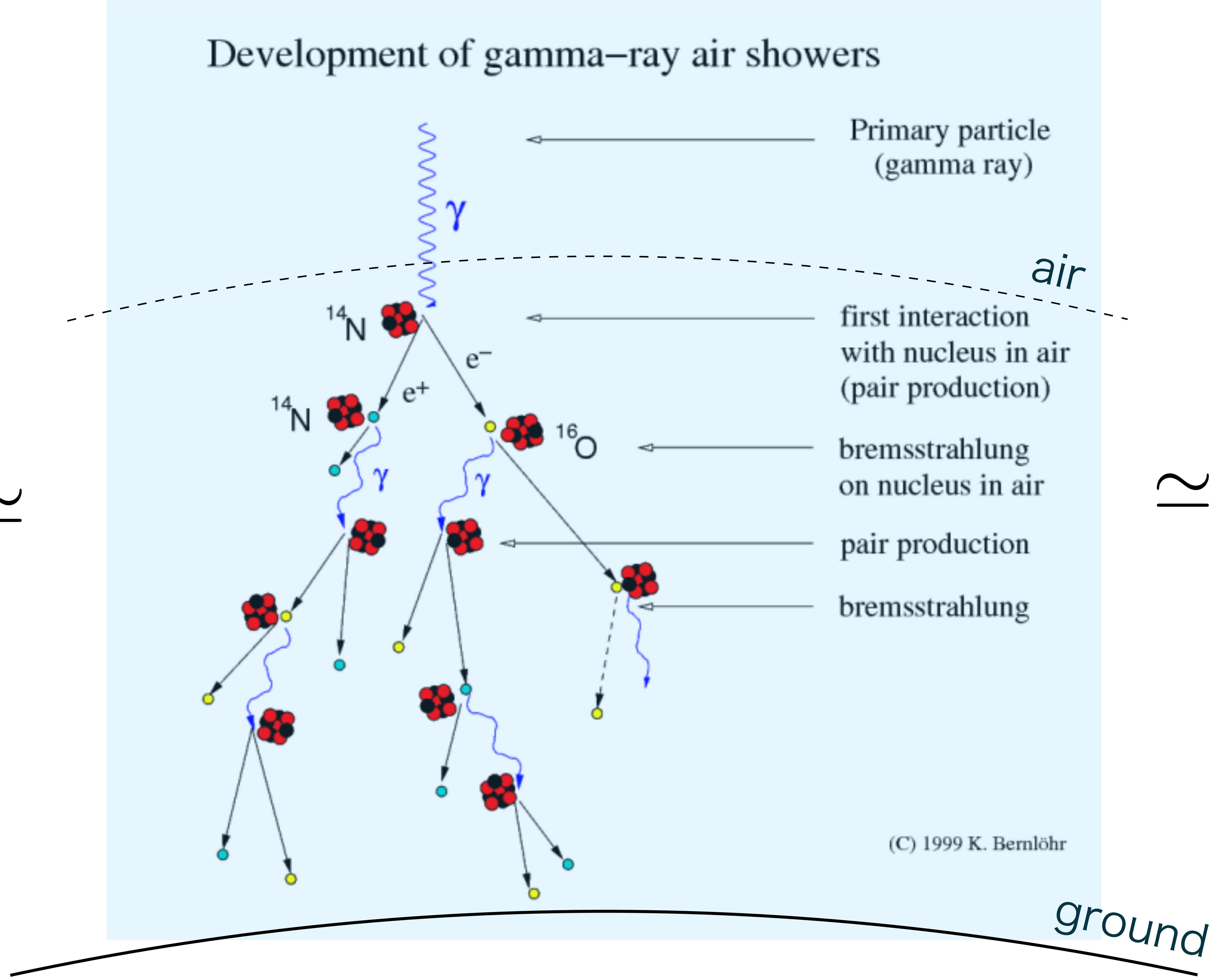
Thermalization of a high-energy particle

- Thermalization can be understood similarly to cosmic-ray air shower and heavy-ion collisions.



Harigaya and Mukaida '13, Mukaida, M.Y. '15

$\simeq$



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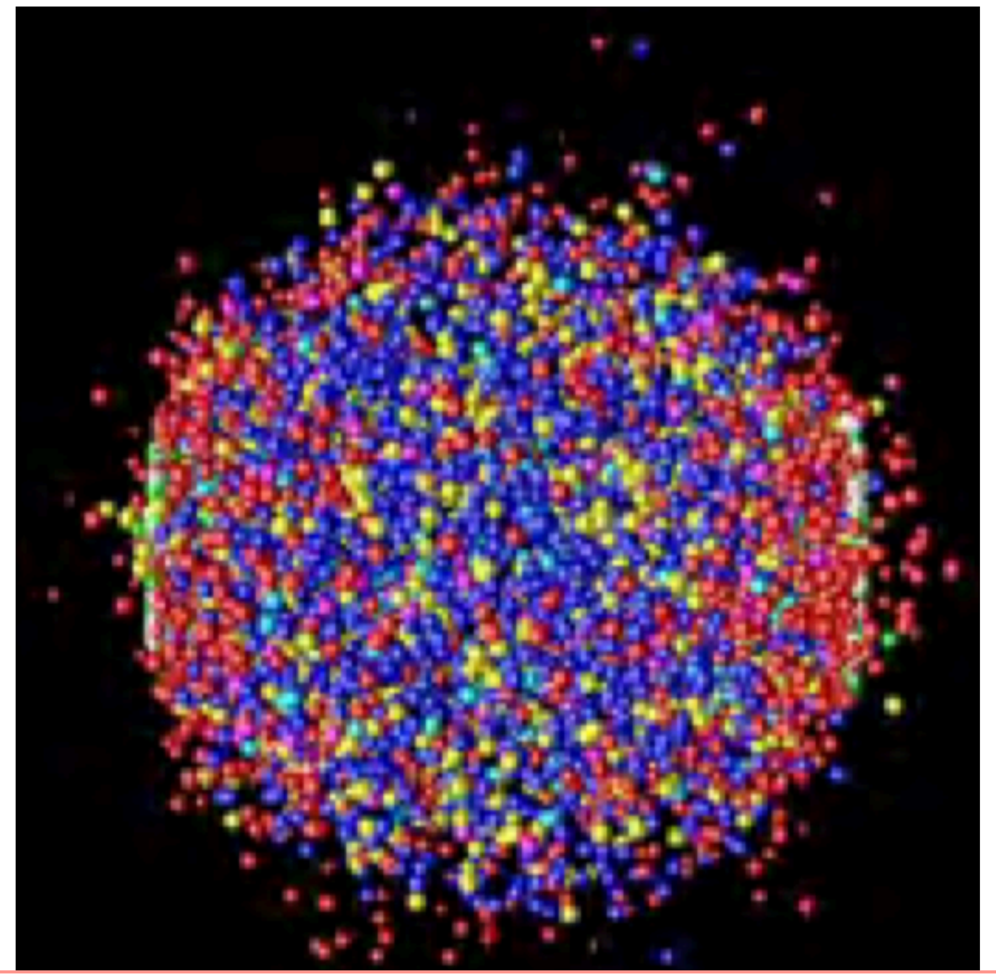

Thermalization after heavy-ion collisions

Davidson and Sarkar '00, Arnold, Moore, Yaffe '03, Kurkela and Moore '11,

Thermalization of a high-energy particle

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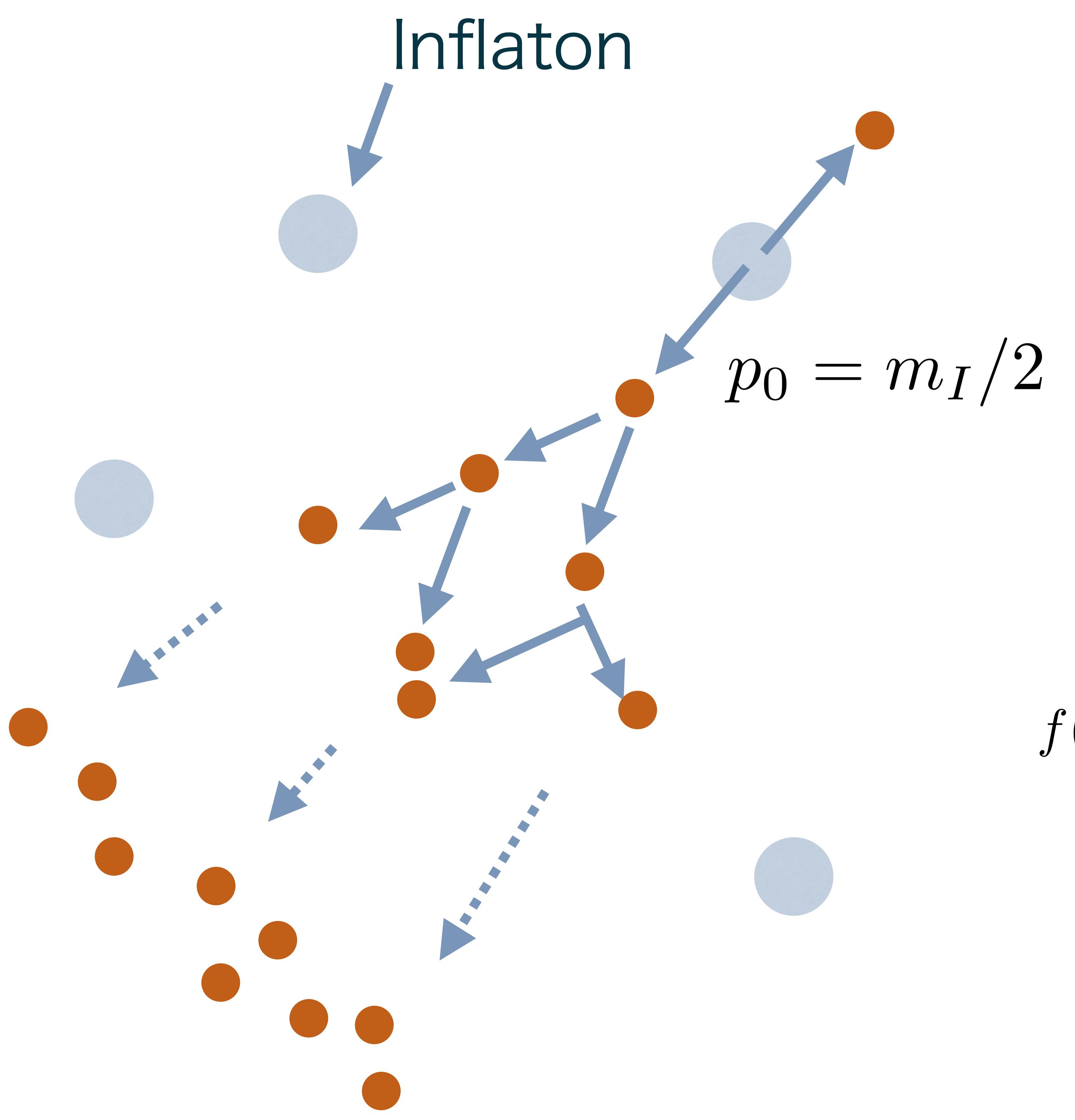
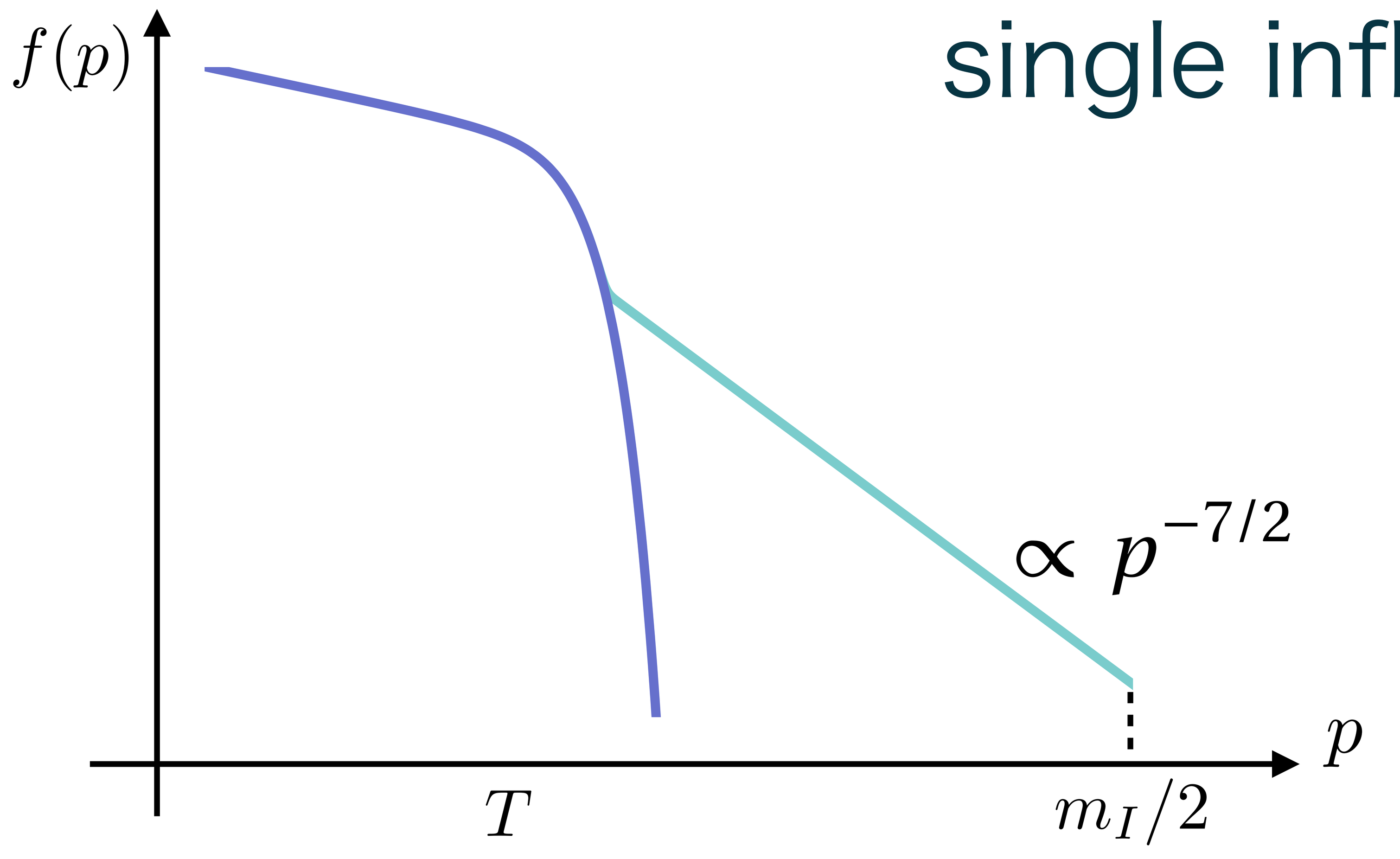


Harigaya and Mukaida '13, Mukaida, M.Y. '15



- If a high-energy particle splits into N particles, their typical energy is $< p >\sim m_I/N$.
- Once the energy becomes as low as the temperature of the ambient plasma, they will be thermalized.
- Since $m_I \gg T$, lots of particles are produced from a single inflaton.

Numerical simulations for thermalization in the SM

- The above qualitative picture can be confirmed by solving the Boltzmann equations.
- We have written down all relevant interactions in the SM, including the LPM effect.

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$$\frac{\partial}{\partial t} f_g(p,t) = -\frac{(2\pi)^3}{p^2 \nu_g} \int_0^p \mathrm{d}k \left[\gamma_{g\leftrightarrow gg} + \sum_f \left(\gamma_{g\leftrightarrow u_f \bar{u}_f} + \gamma_{g\leftrightarrow d_f \bar{d}_f} + 2\gamma_{g\leftrightarrow Q_f \bar{Q}_f} \right) \right] f_g$$
$$+ \frac{(2\pi)^3}{p^2 \nu_g} \int_0^\infty \mathrm{d}k \left[2\gamma_{g\leftrightarrow gg} f_g + \sum_f \left(\gamma_{u_f \leftrightarrow g u_f} f_{u_f} + \gamma_{d_f \leftrightarrow g d_f} f_{d_f} + 2\gamma_{Q_f \leftrightarrow g Q_f} f_{Q_f} \right) \right].$$

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

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

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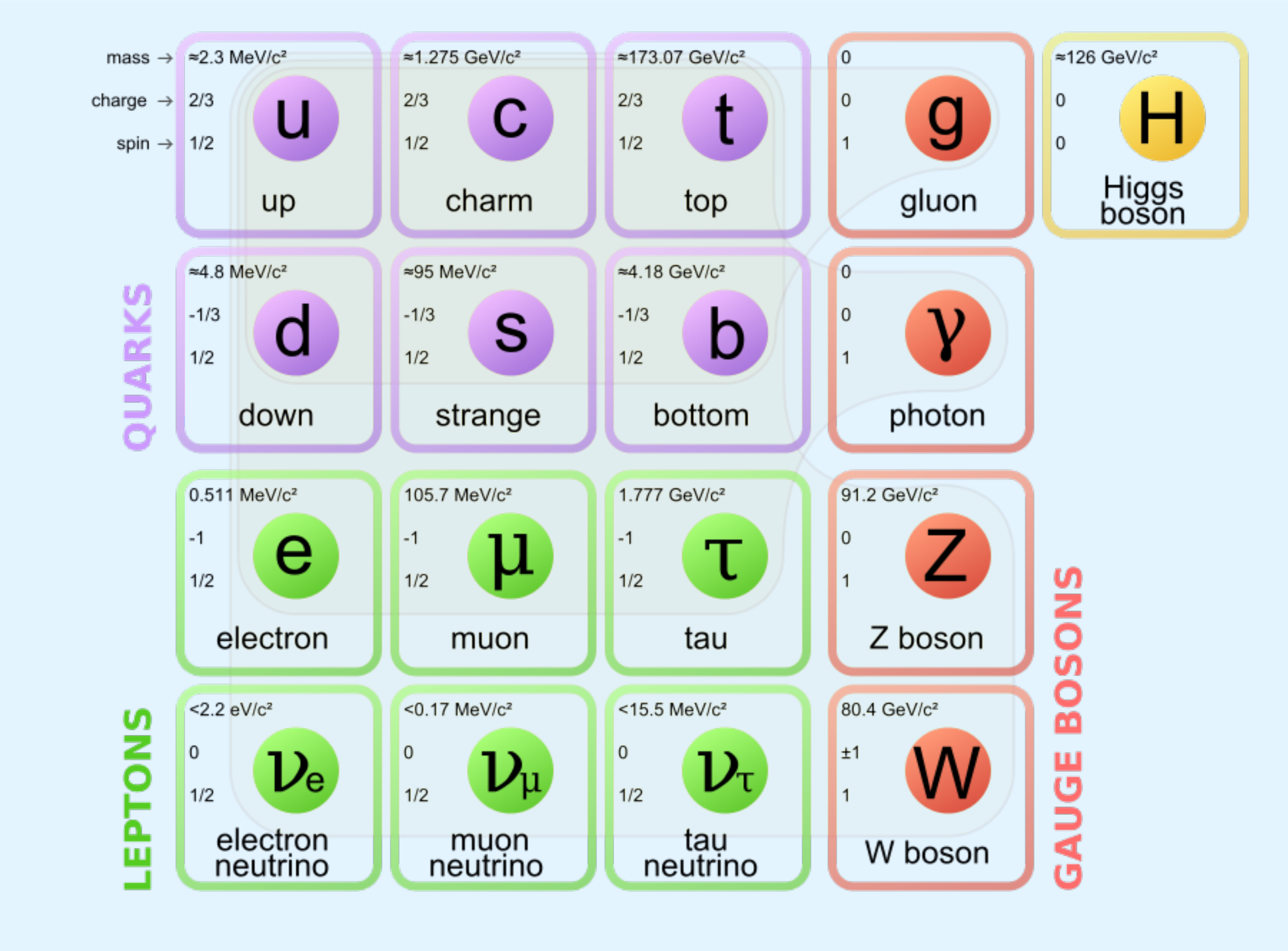

Numerical simulations for thermalization in the SM

- The above qualitative picture can be confirmed by solving the Boltzmann equations.
- We can simplify the equation when the expansion rate is much smaller than the thermalization rate.

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$$\frac{\partial}{\partial t} f_g(p,t) = -\frac{(2\pi)^3}{p^2 \nu_g} \int_0^p \mathrm{d}k \left[\gamma_{g\leftrightarrow gg} + \sum_f \left(\gamma_{g\leftrightarrow u_f \bar{u}_f} + \gamma_{g\leftrightarrow d_f \bar{d}_f} + 2\gamma_{g\leftrightarrow Q_f \bar{Q}_f} \right) \right] f_g$$
$$+ \frac{(2\pi)^3}{p^2 \nu_g} \int_0^\infty \mathrm{d}k \left[2\gamma_{g\leftrightarrow gg} f_g + \sum_f \left(\gamma_{u_f \leftrightarrow g u_f} f_{u_f} + \gamma_{d_f \leftrightarrow g d_f} f_{d_f} + 2\gamma_{Q_f \leftrightarrow g Q_f} f_{Q_f} \right) \right].$$

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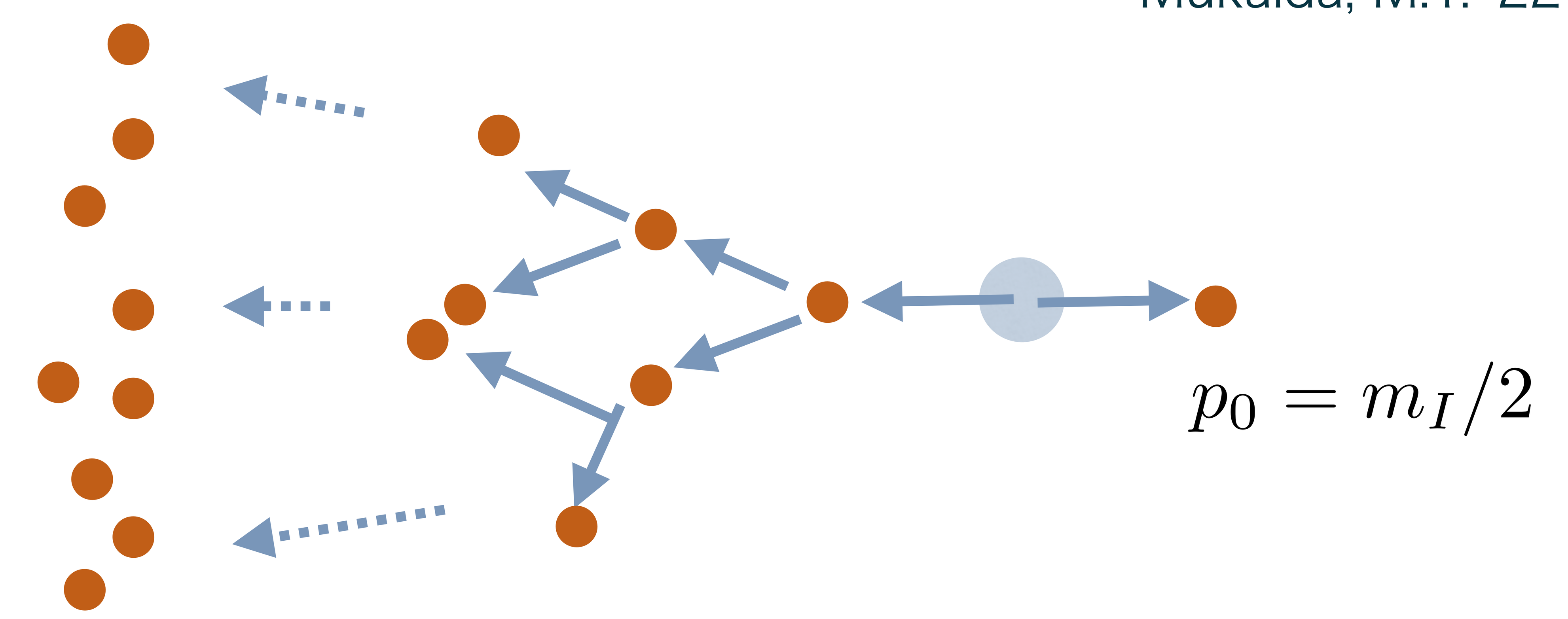
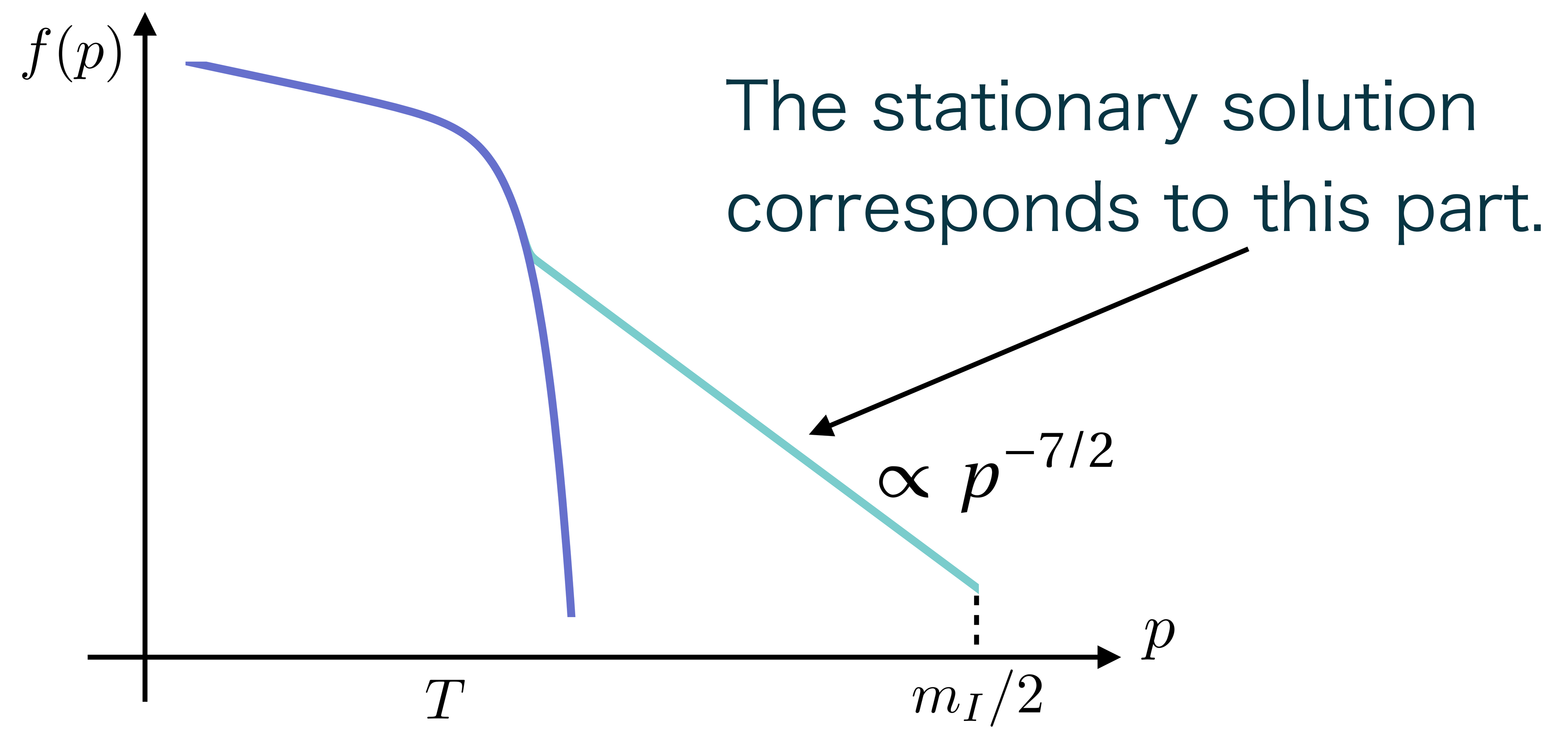
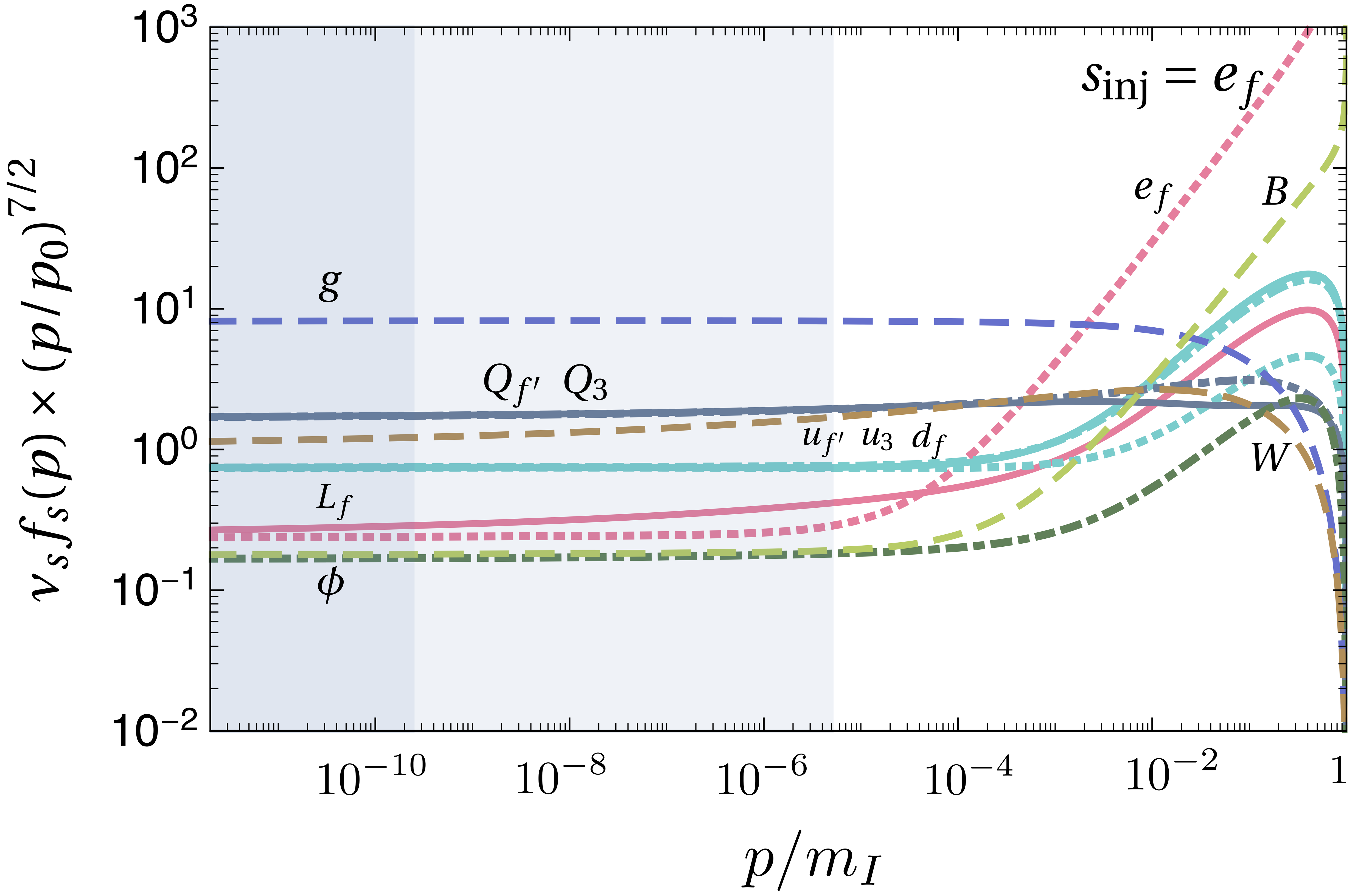


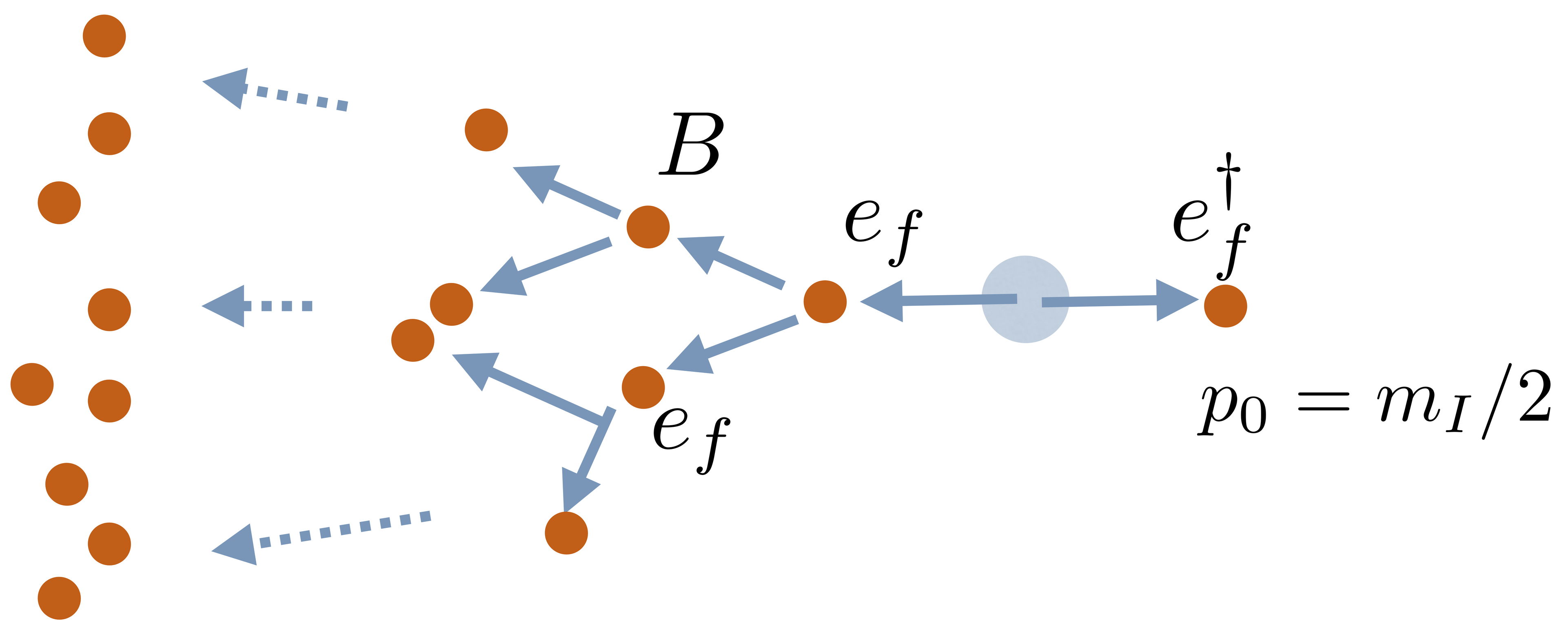


Numerical simulations for thermalization in the SM

- Spectra of SM particles can be determined by the numerical calculations.

  - Case with inflaton decay into right-handed leptons:





typical energy of particles after splittings into N particles:

$$< p > \sim m_I/N$$

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Those results particularly show that the amount of particles produced by particle shower is independent of the initial conditions. In other words, it does not depend on the details of inflaton decay. The attractor solution is reached before the complete thermal equilibrium.

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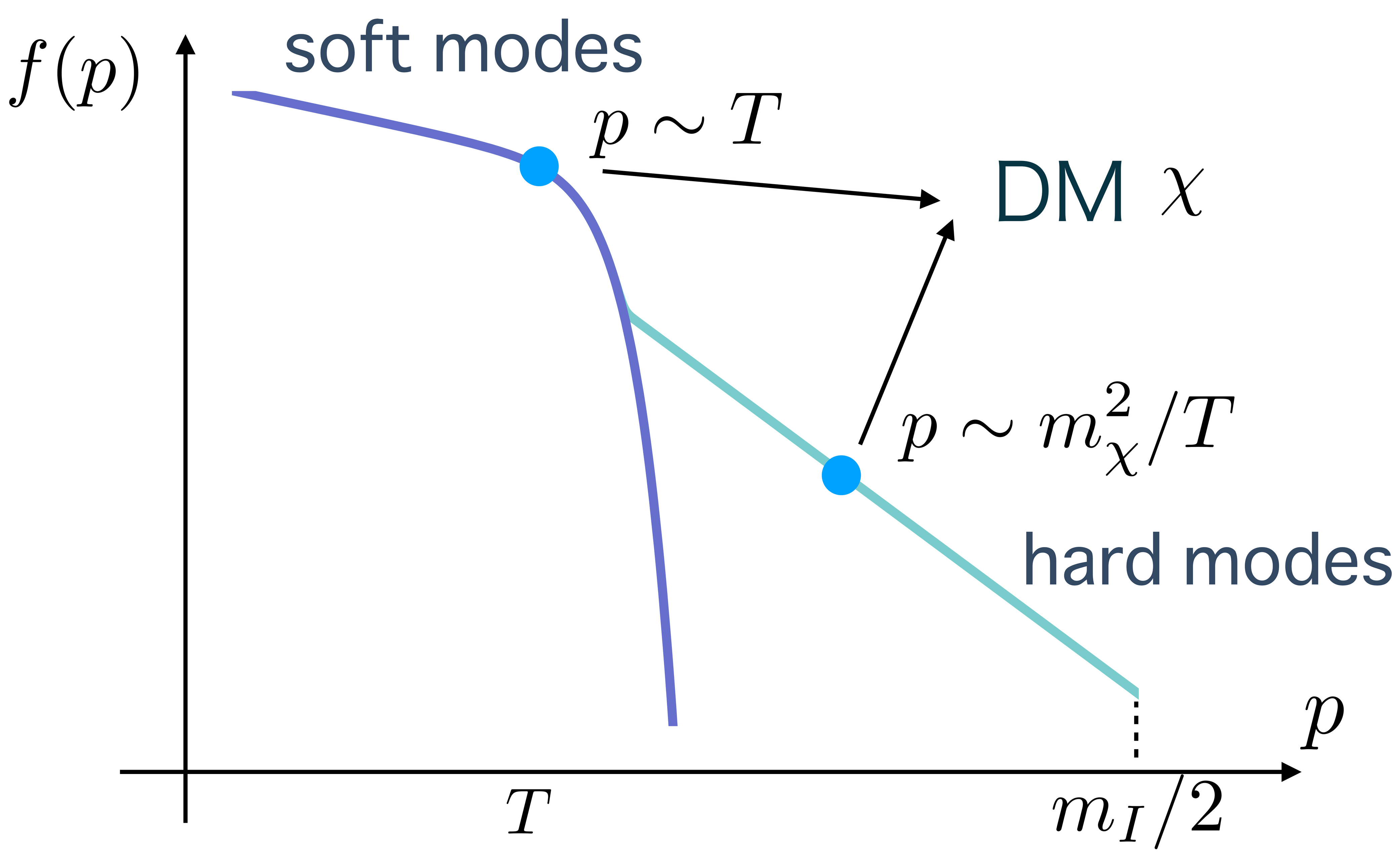
Non-thermal DM production



Once we have determined the SM spectra, we can calculate the amount of DM that is produced from scattering between

(A): hard modes

(B): a hard mode and a soft mode

(C): soft modes (this is considered in standard freeze-in scenarios.)

Kawasaki, Harigaya, Mukaida, M.Y. '14, Garcia, Amin '18, Harigaya, Mukaida, M.Y. '19, Mukaida, M.Y. '22

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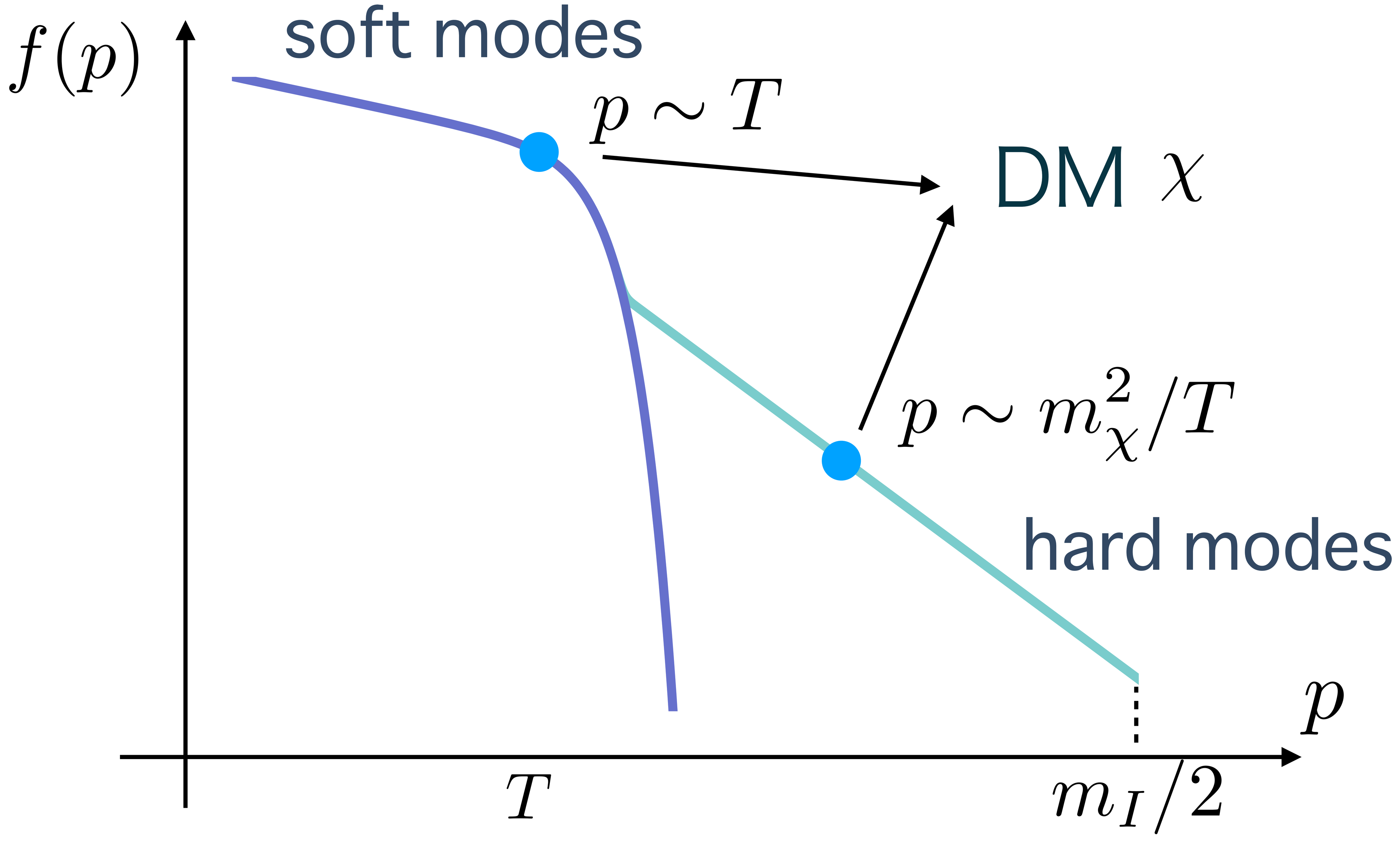

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$$\frac{\rho_\chi}{s} \sim m_\chi \frac{\sigma_\chi n_T}{\Gamma_{\text{inela}}} \frac{n_h}{s}$$

$n_T \sim T^3$, $\Gamma_{\text{inela}} \sim \alpha_s^2 \sqrt{\frac{T^3}{p}}$

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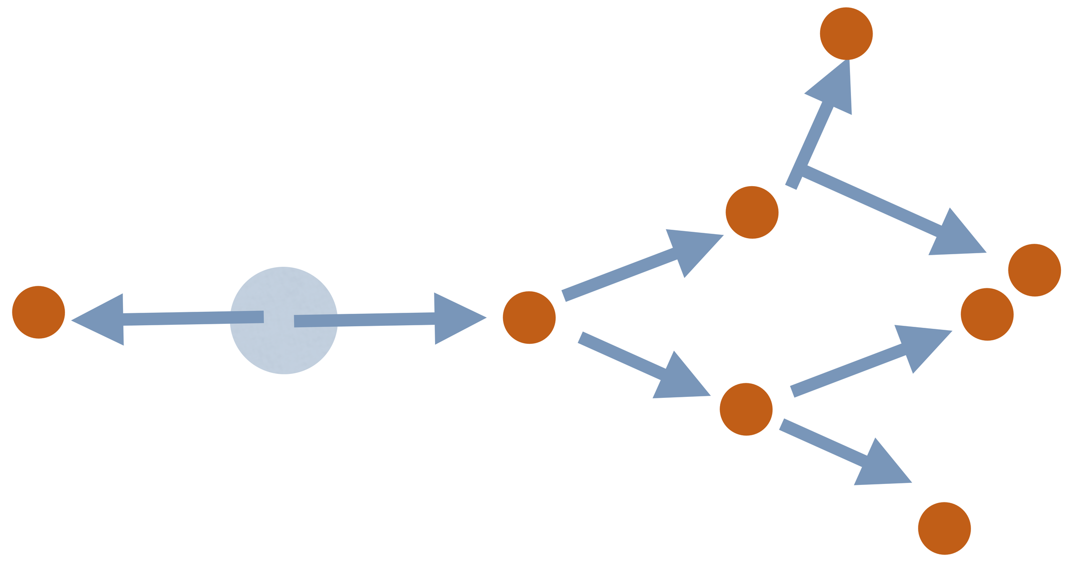
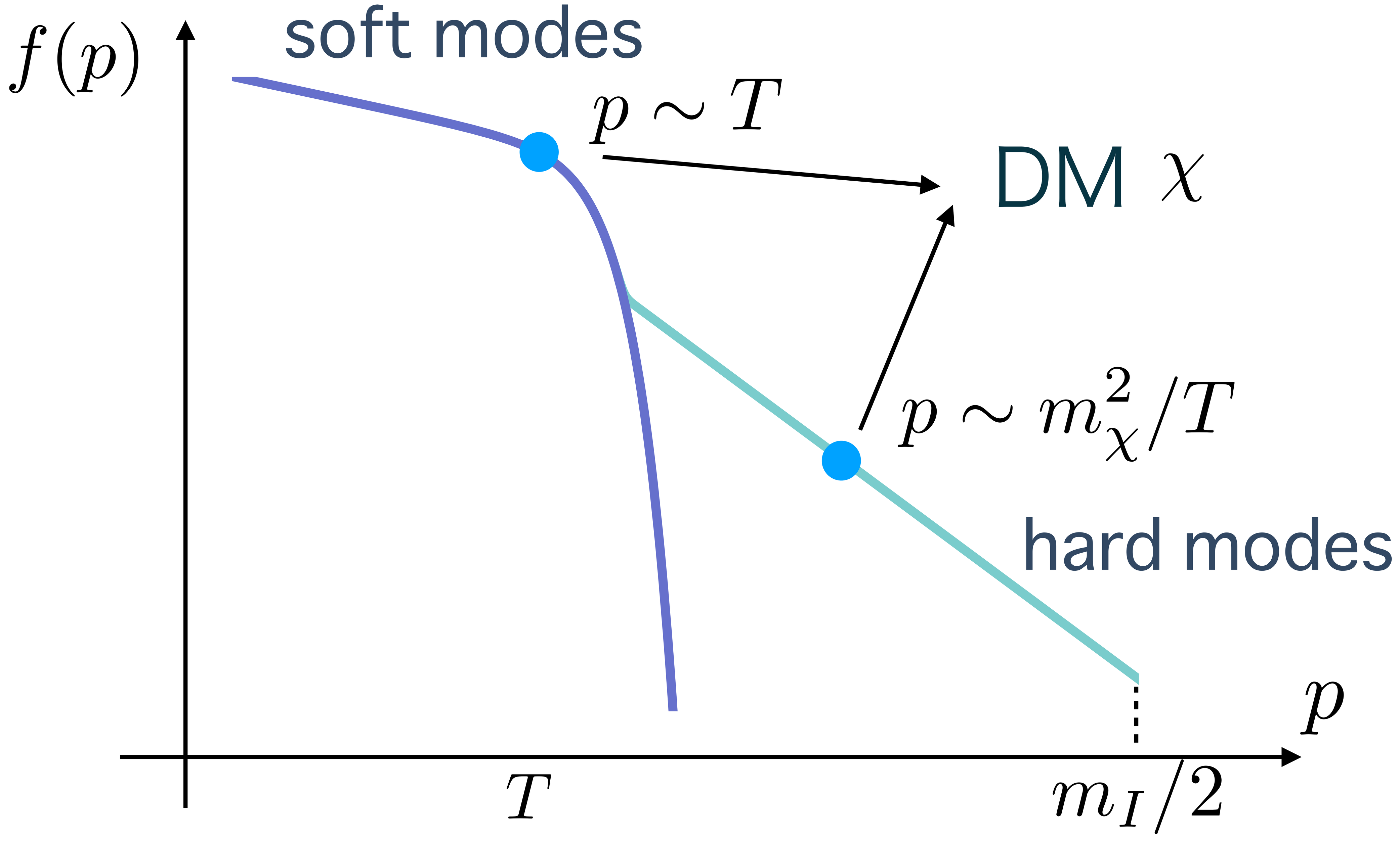


$$n_h \sim \frac{m_I}{p} n_I \sim \frac{H^2 M_{\text{pl}}^2}{p}$$

$n_I \sim 3H^2 M_{\text{pl}}^2 / m_I$

Non-thermal DM production



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$$\frac{\rho_\chi}{s} \sim m_\chi \frac{\sigma_\chi n_T}{\Gamma_{\rm inela}} \frac{n_h}{s}$$

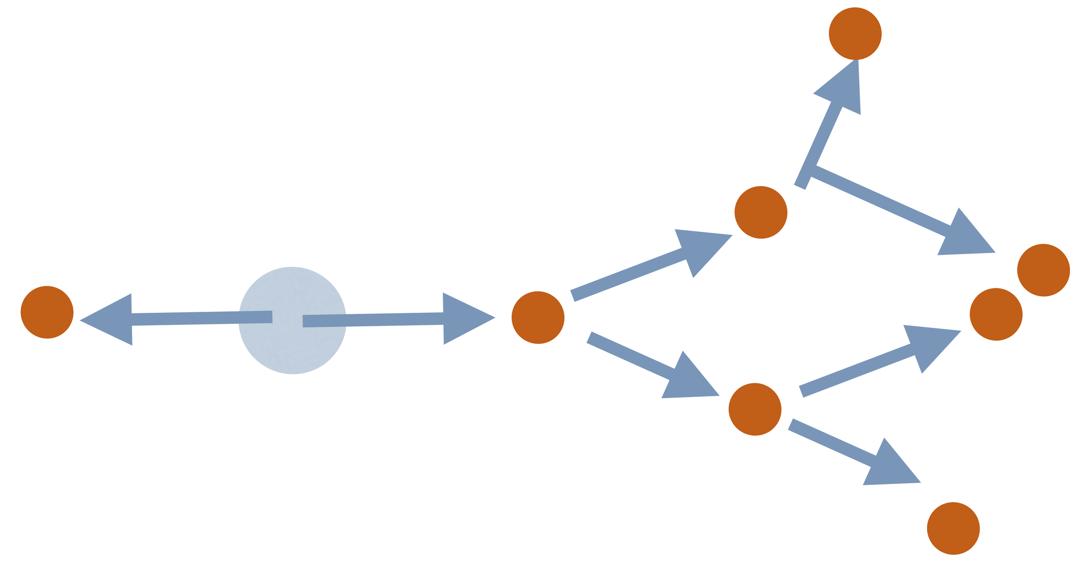
$n_T \leftarrow T^3$, $\quad \Gamma_{\rm inela} \leftarrow \alpha_s^2 \sqrt{\frac{T^3}{p}}$

Kawasaki, Harigaya, Mukaida, M.Y. '14, Garcia, Amin '18, Harigaya, Mukaida, M.Y. '19, Mukaida, M.Y. '22

$p \sim m_\chi^2/T$

$T = T_{\rm RH}$

$$\simeq 0.33\, \alpha_\chi^2 \frac{T_{\rm RH}^3}{m_\chi^2} \quad \text{for} \quad \sigma_\chi = \frac{\alpha_\chi^2}{s}$$



$$n_h \sim \frac{m_I}{p} n_I \sim \frac{H^2 M_{\rm pl}^2}{p}$$

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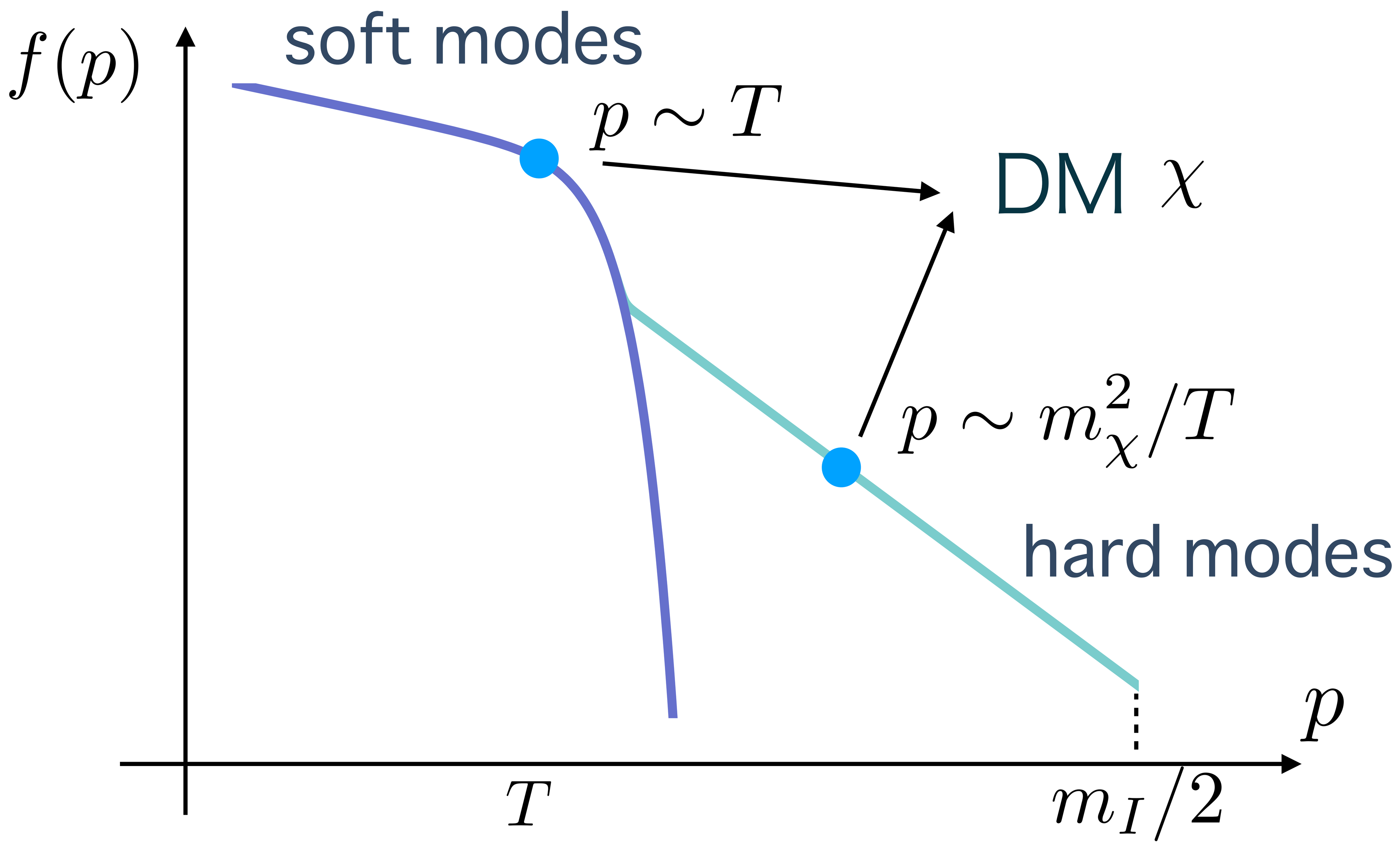
Non-thermal DM production



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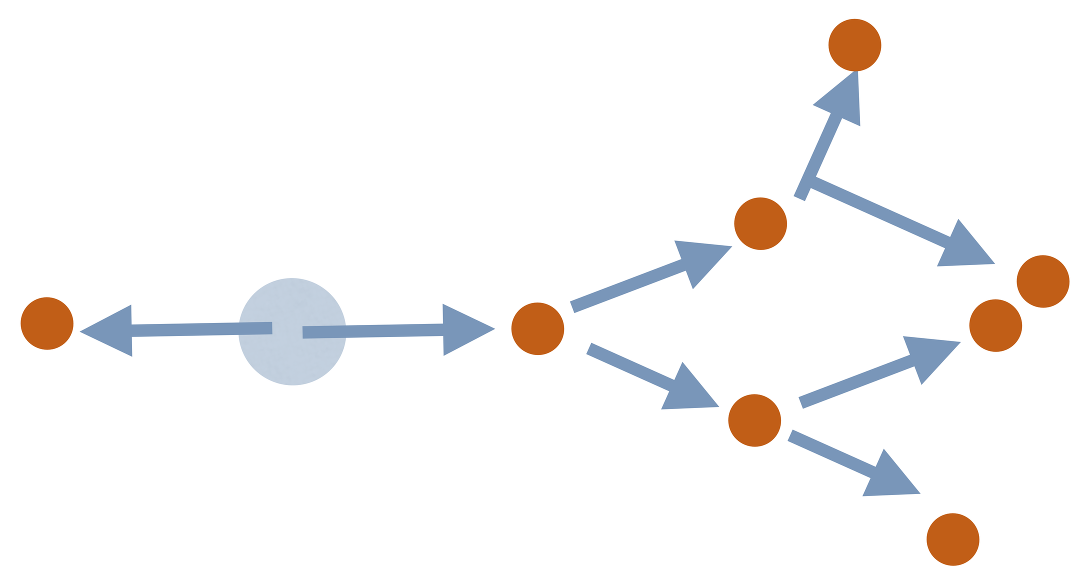
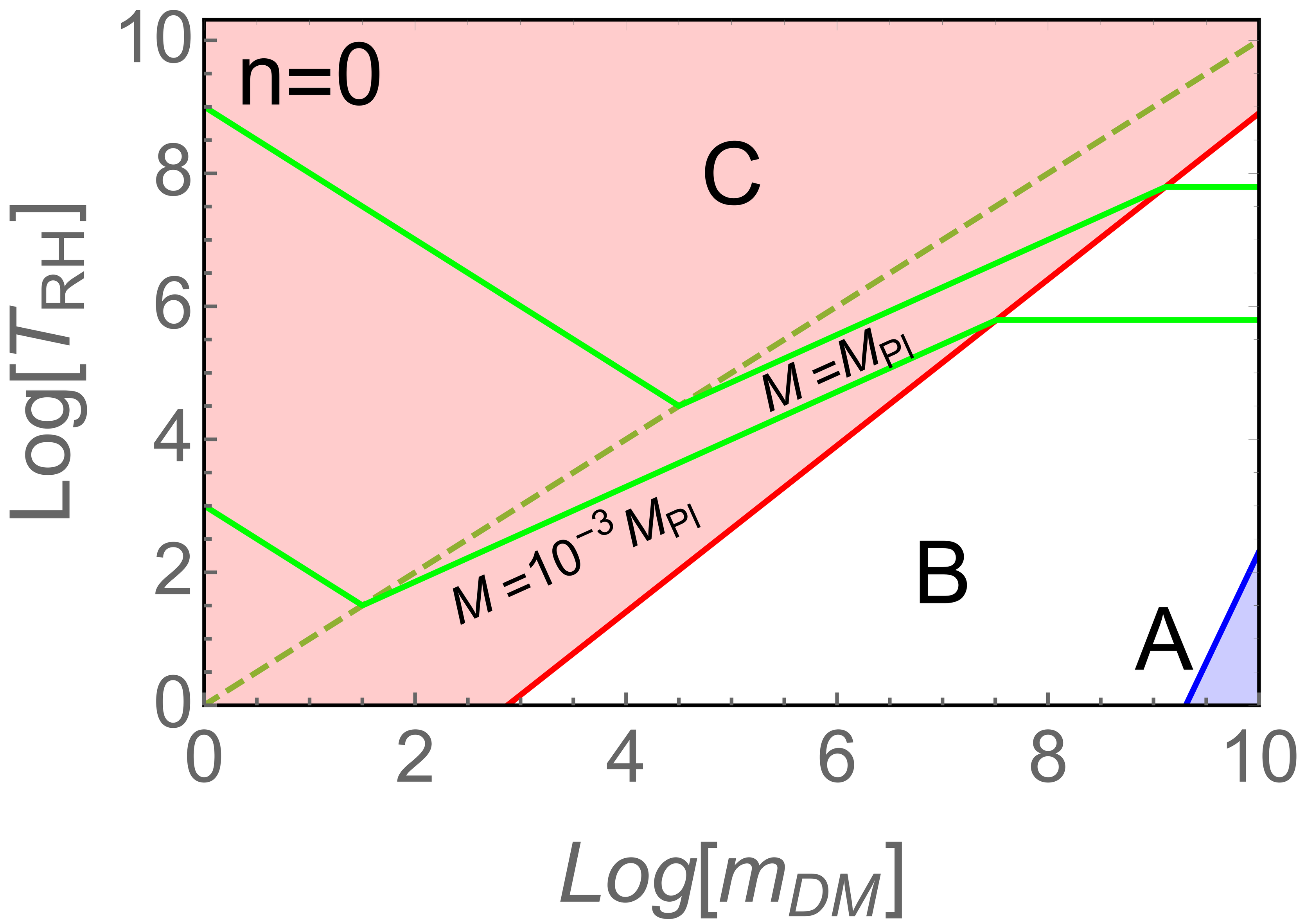


Case with non-renormalizable interaction:

$$\frac{\rho_\chi}{s} \sim \frac{T_{\rm RH}^3}{M^2} \quad \text{for} \quad \sigma_\chi = \frac{1}{M^2}$$

$$\frac{\rho_\chi}{s} \sim \frac{T_{\rm RH}^3 m_\chi^2}{M^4} \quad \text{for} \quad \sigma_\chi = \frac{s}{M^4}$$

Harigaya, Mukaida, M.Y. '19,



Summary

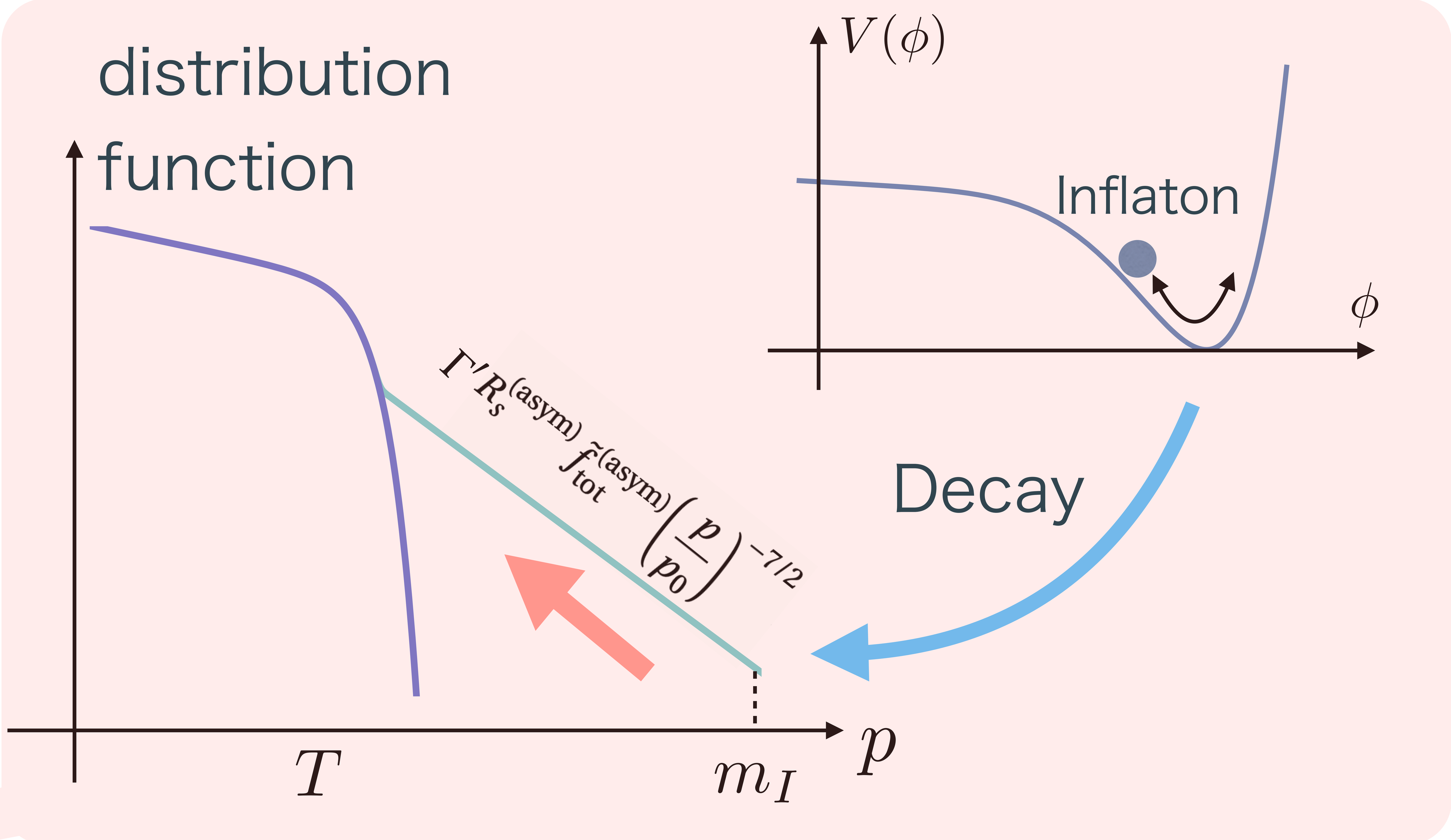
Present

Recombination (thermal eq.)

BBN epoch (thermal eq.)

We have investigated the thermal history of the Universe in the pre-thermal phase.

Inflation (far from thermal eq.)



Non-thermal DM abundance:

$$\frac{\rho_\chi}{s} \simeq 0.33\,\alpha_\chi^2 \frac{T_{\mathrm{RH}}^3}{m_\chi^2} \quad \text{for } \sigma_\chi = \frac{\alpha_\chi^2}{s}$$