



Light dark matter around eV mass range

Tohoku U.
Wen Yin

Based on 2301.08735

@Workshop on Very Light Dark Matter 2023
30/03/2023 Mario Royal Kaikan, Chino, Nagano

Motivations of eV DM

Theory

- ALP miracle: ALP=inflaton=DM predicts \sim eV **range ALP DM**
[Daido, Takahashi, WY, 1702.03284](#),[1710.11107](#),
- Hadrophobic GUT axion=inflaton=DM solving strong CP problem predicts \sim eV **range axion DM** [Takahashi, WY, 2301.10757](#)
- Thermal production [WY, 2301.08735](#)
e.g. Moroi, WY, 2011.09475, 2011.12285 for light DM from inflaton decay
Nakayama, WY, [2105.14549](#) from dark Higgs decay are possible but does not predict eV mass.

Experiment

- Anisotropic **cosmic infrared background excess** can be explained by **eV-range DM** decaying into photons.[Gong et al 1511.01577](#)
- The **attenuation of TeV gamma-ray** spectrum can be explained by **eV-range DM** decaying into photons.[Korochkin, et al, 1911.13291](#)
(LORRI excess, [Lauer et al, Astrophys. J. Lett. 927, L8 \(2022\)](#). [Bernal et al, 2203.11236](#). cannot be explained by DM [Nakayama, WY, 2205.01079](#))
- Probed by looking at dSphs via **infrared spectrographs**, e.g., WINERED @ Magellan, IRCS @ Subaru, or NIRSpec @ JWST, with **O(1) hours**.
[Bessho, Ikeda, WY, 2208.05975](#), [Hayashi, WY, XXXXX](#)

hints

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this talk

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hints

Hot DM paradigm (-1984)

e.g. Introduction of Davis et al, *Astrophys.J.* 292 (1985) 371-394

- eV-range DM was special and theoretically well motivated before WIMP paradigm.

$$\because T_{\text{matter-radiation equality}} \sim eV$$

$$\text{if } n_{\text{DM}} \sim T^3, \boxed{m_{\text{DM}} \sim eV}$$

- Hot DM production has $p_{\text{DM}} \sim T$.

$$\nu_{\text{DM}} \sim p_{\text{DM}}/m_{\text{DM}} \sim 1 @ \text{matter-radiation equality}$$

See the warm DM bound $m_{WDM} > O(1)\text{keV}$, Viel et al, 0501562; Irsic et al, 1702.01764.
is excluded. Freeze-in : $m_{DM} \gtrsim O(10)\text{keV}$, Kamada, Yanagi, 1907.04558; Ballesteros et al, 2011.13458

- Is “thermal production” of eV range DM excluded?

What I will talk about

WY 2301.08735

- Thermal production of eV-keV bosonic DM is possible.
- eV range DM is still special and theoretically well-motivated, a la hot DM paradigm.

Setup:

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$\chi_1 \rightarrow \chi_2\phi$. χ_1 is thermalized, while χ_2 and ϕ are absent initially.

χ_1 mass : $M_1 (\ll T)$ χ_2, ϕ : massless

Equations:

$$\frac{\partial f_i[p_i, t]}{\partial t} - p_i H \frac{\partial f_i[p_i, t]}{\partial p_i} = C^i[p_i, t],$$

$$C^\phi = \frac{1}{2E_\phi g_\phi} \sum \int d\Pi_{\chi_1} d\Pi_{\chi_2}$$

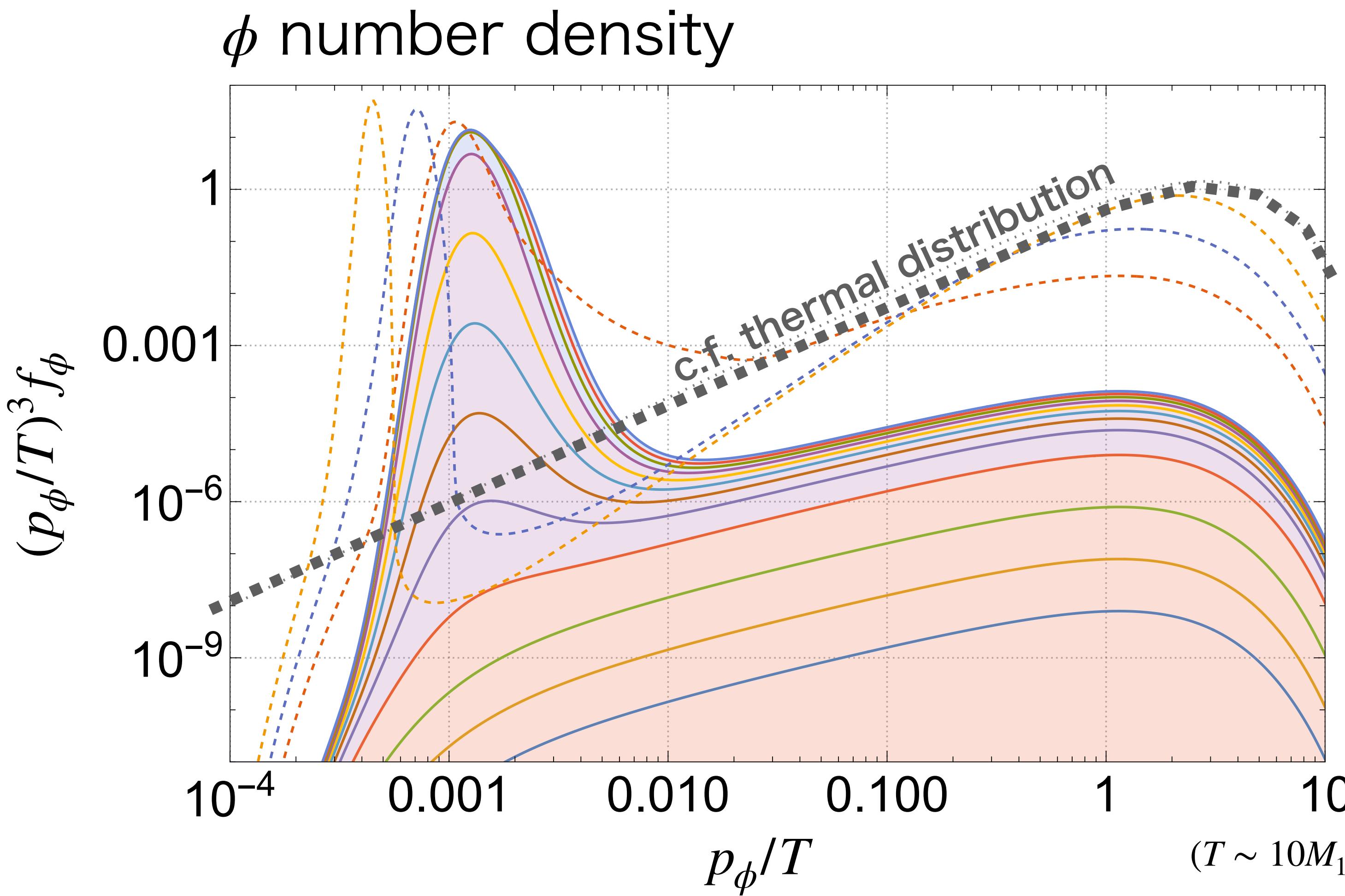
$$(2\pi)^4 \delta^4(p_{\chi_1} - p_\phi - p_{\chi_2}) \times |\mathcal{M}_{\chi_1 \rightarrow \chi_2\phi}|^2$$
$$\times S(f_{\chi_1}[p_{\chi_1}], f_{\chi_2}[p_{\chi_2}], f_\phi[p_\phi])$$

$$S \equiv f_{\chi_1}[p_{\chi_1}] (1 \pm f_{\chi_2}[p_{\chi_2}]) (1 + f_\phi[p_\phi])$$
$$- (1 \pm f_{\chi_1}[p_{\chi_1}]) f_\phi[p_\phi] f_{\chi_2}[p_{\chi_2}]$$

- f_{χ_2} is also solved together with f_ϕ .

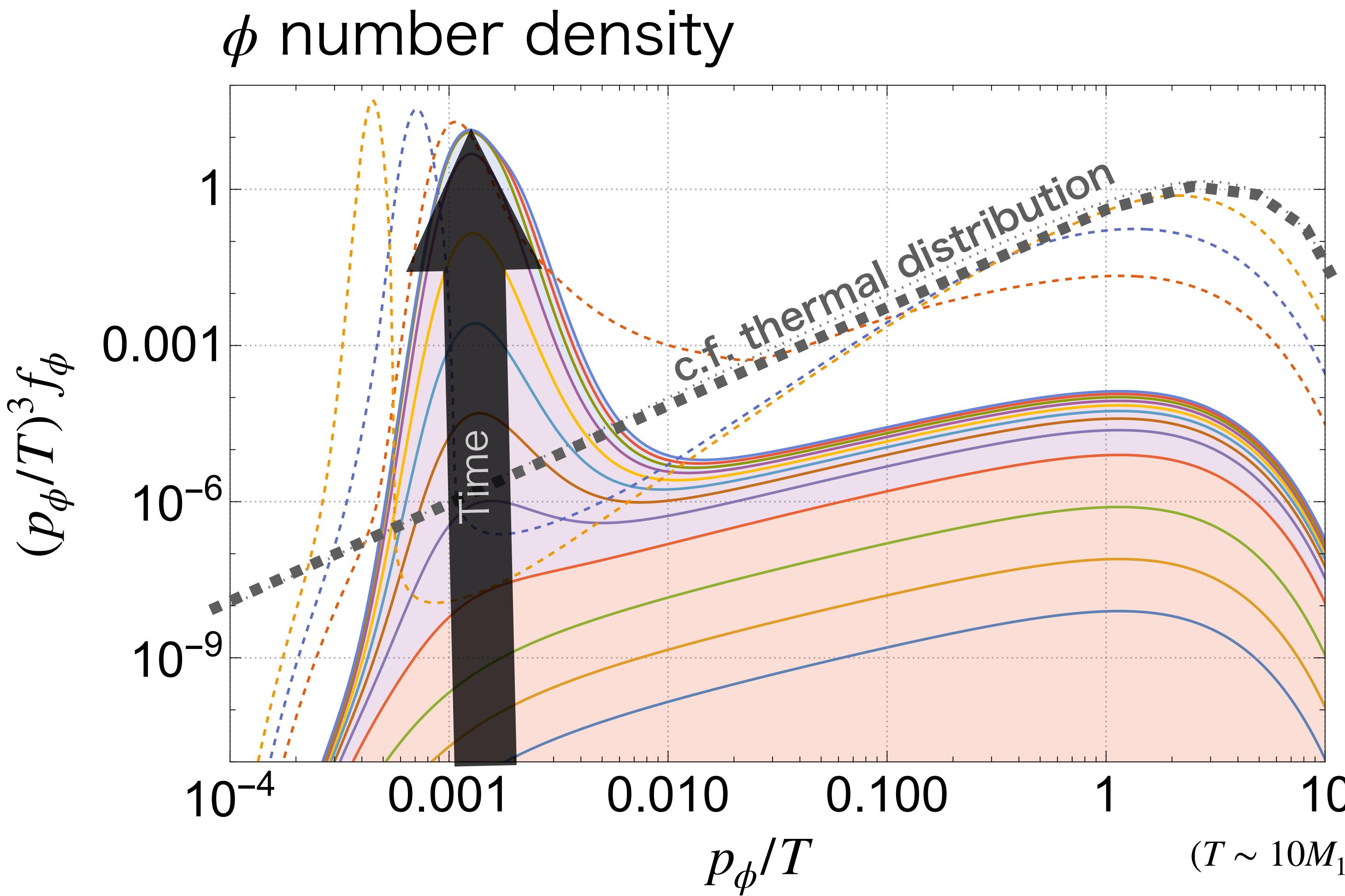
-Bose-enhancement/Pauli-blocking effect is included.

Burst production of DM ϕ turns out
thanks to bose enhancement.



Three stages of
burst production:
1. Ignition
2. Burst
3. Saturation

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Three stages of
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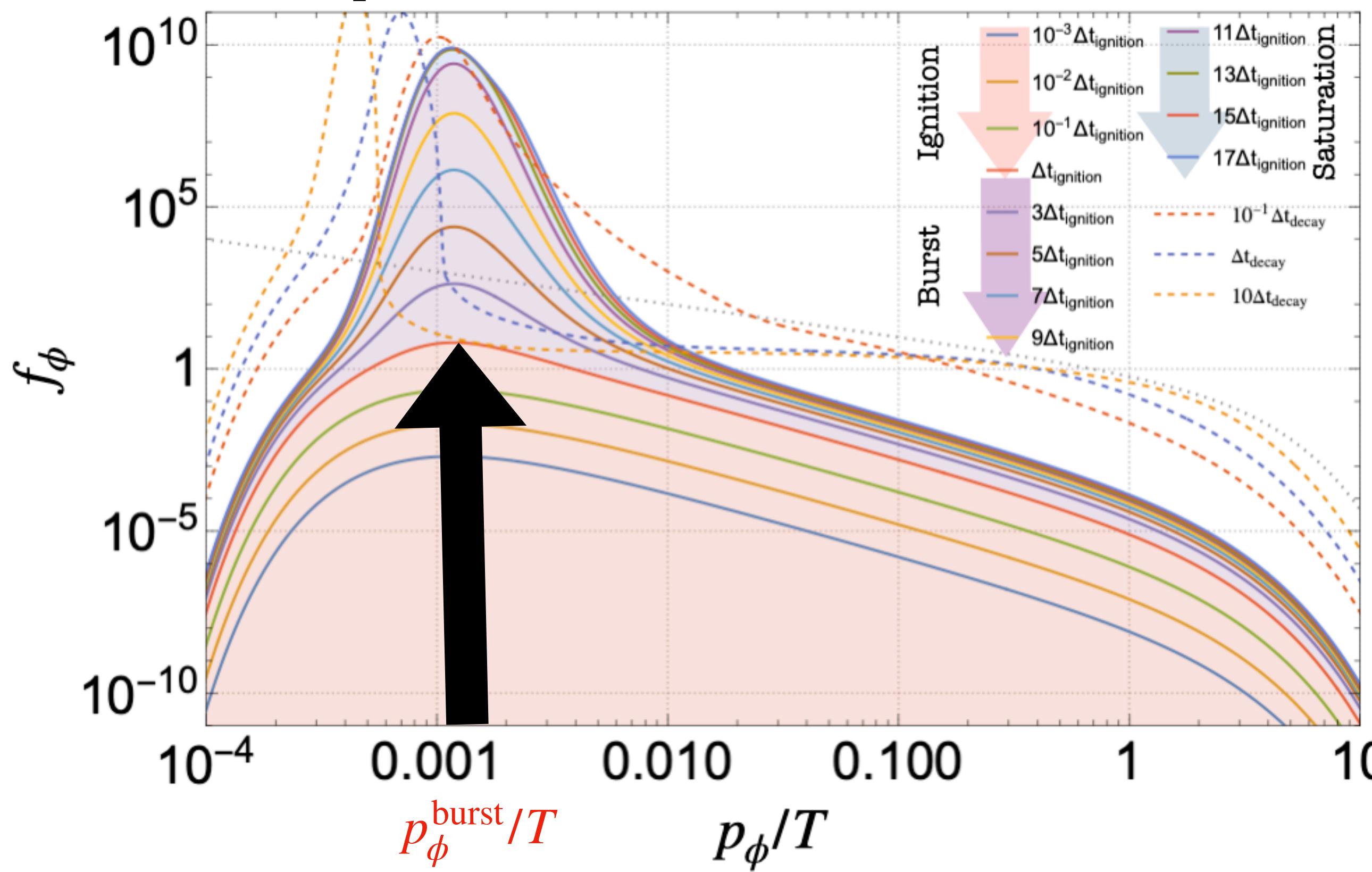
1. Ignition
2. Burst
3. Saturation

Stage 1: Ignition

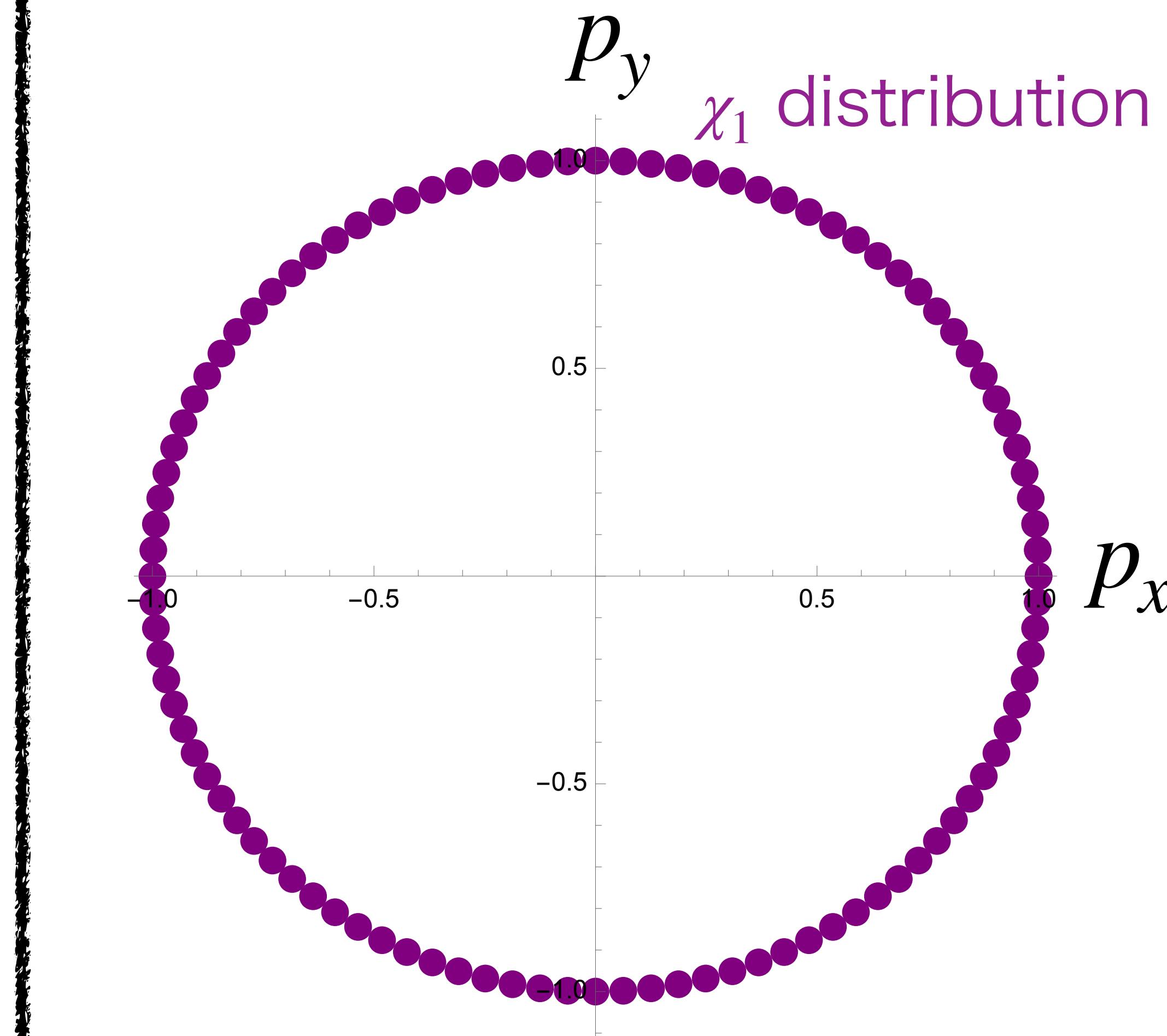
-Distribution function f_ϕ at $p_\phi \sim p_\phi^{\text{burst}} \sim M_1^2/T$ increases fastest.

- $f_\phi(p_\phi \ll p_\phi^{\text{burst}})$ is rarely produced.

Occupation number



Simplified model.

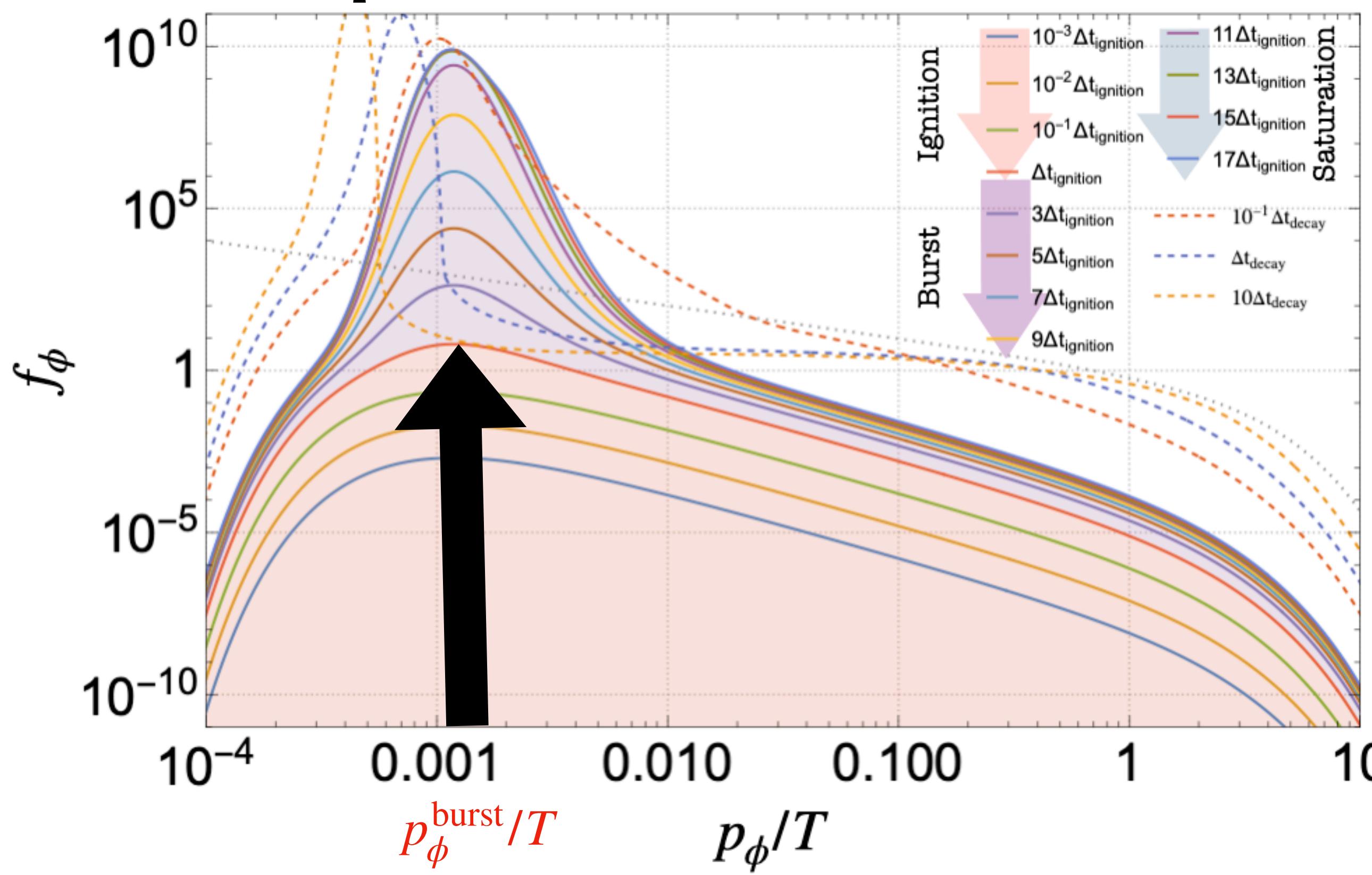


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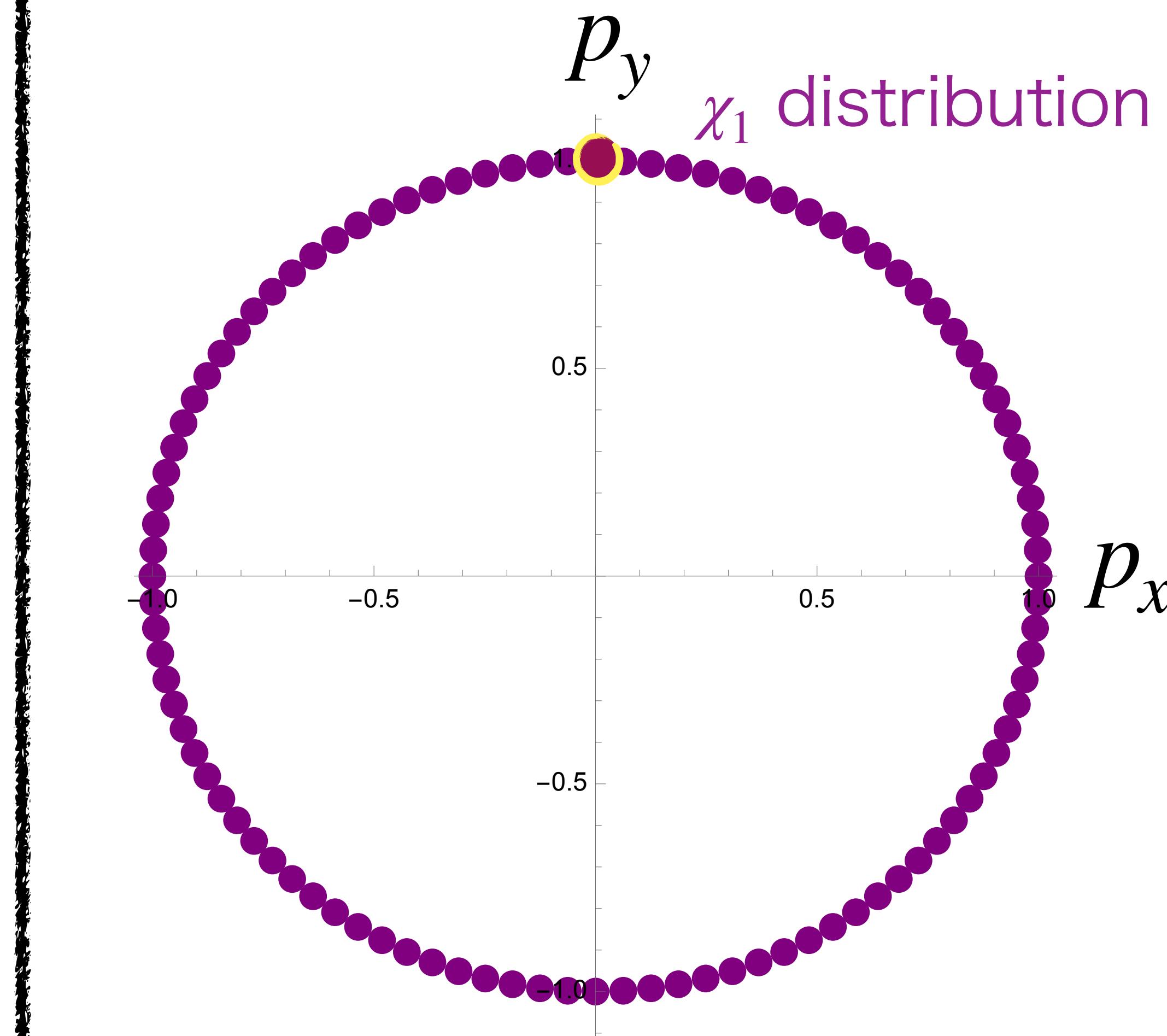
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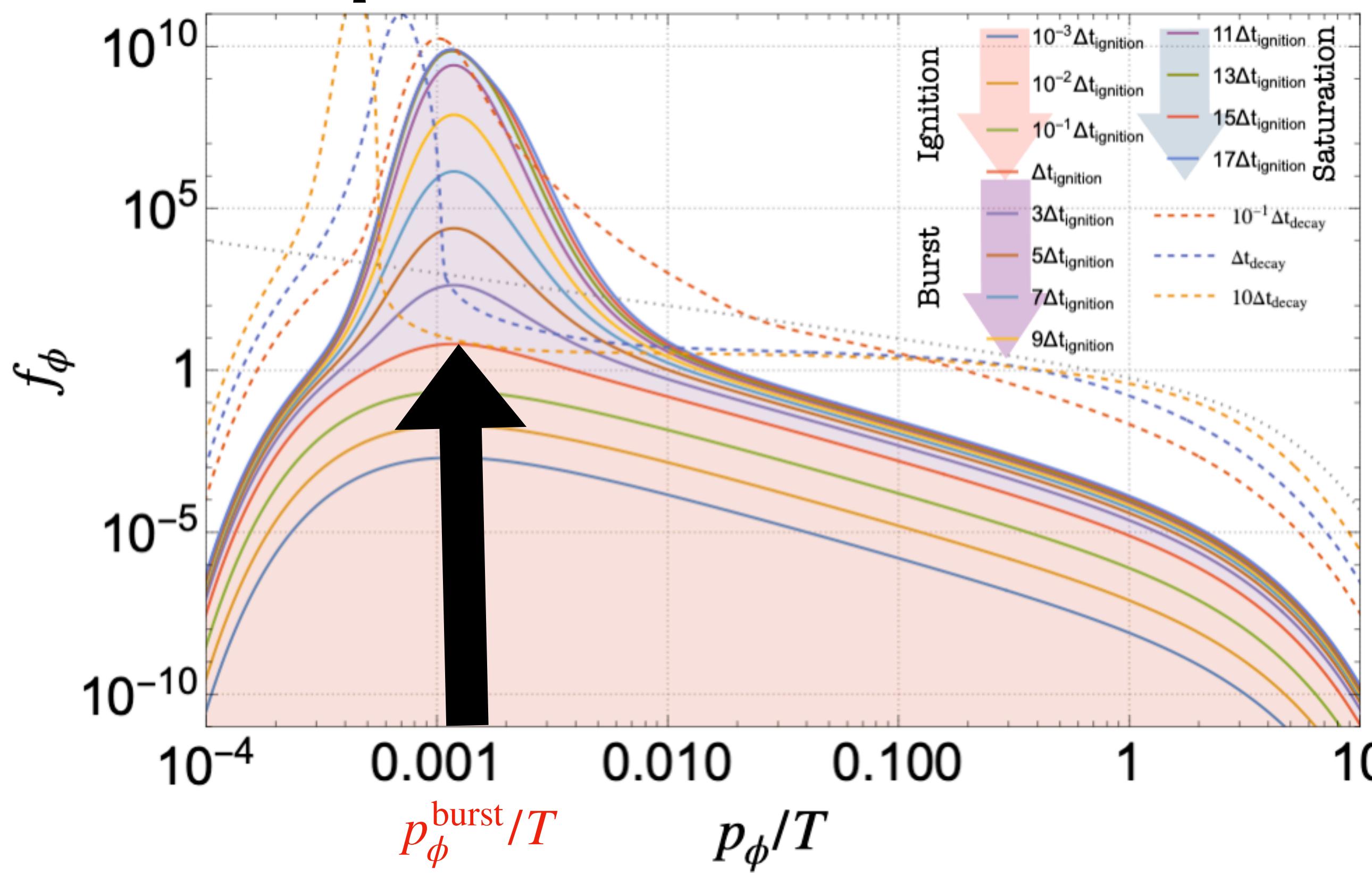


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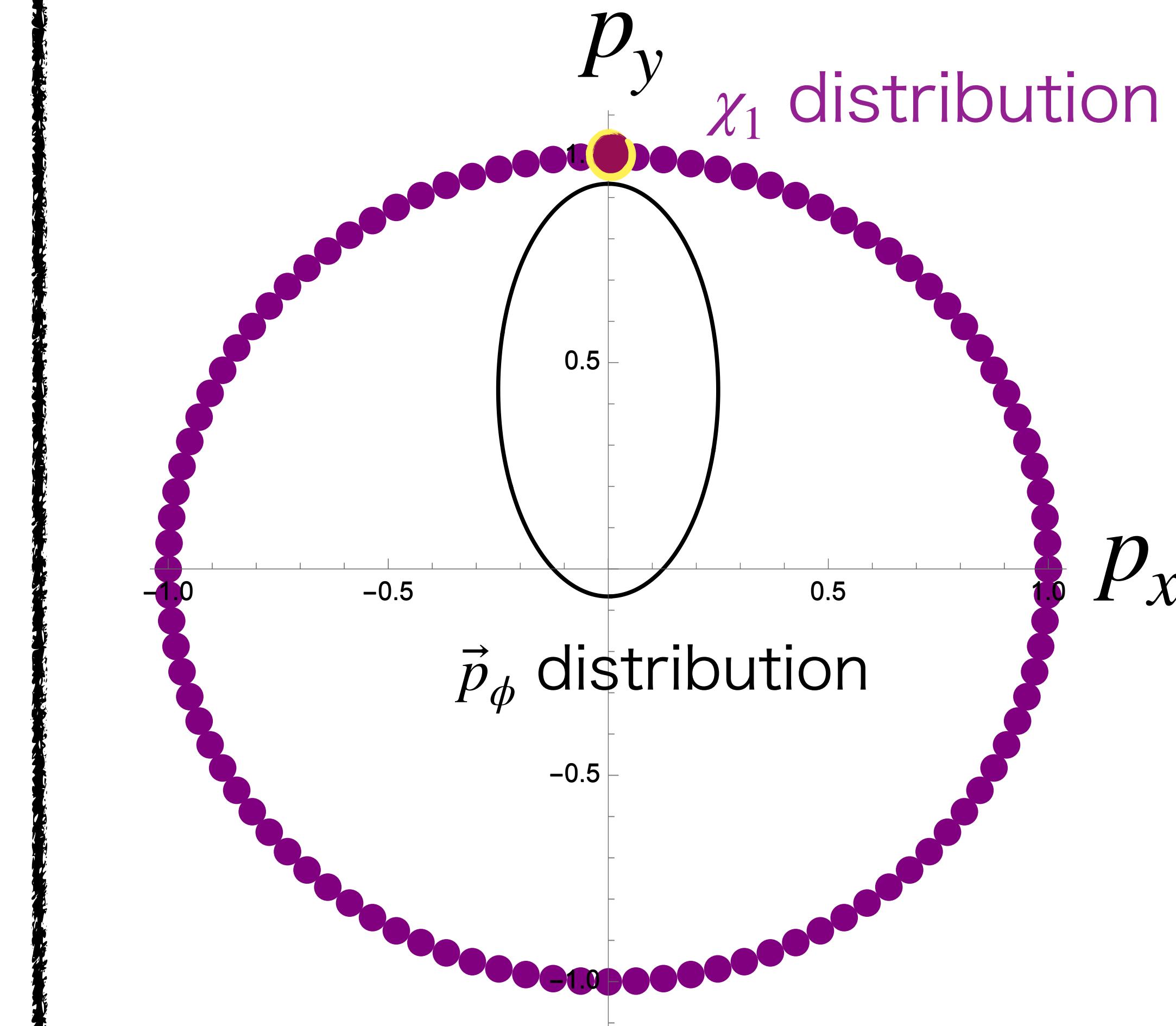
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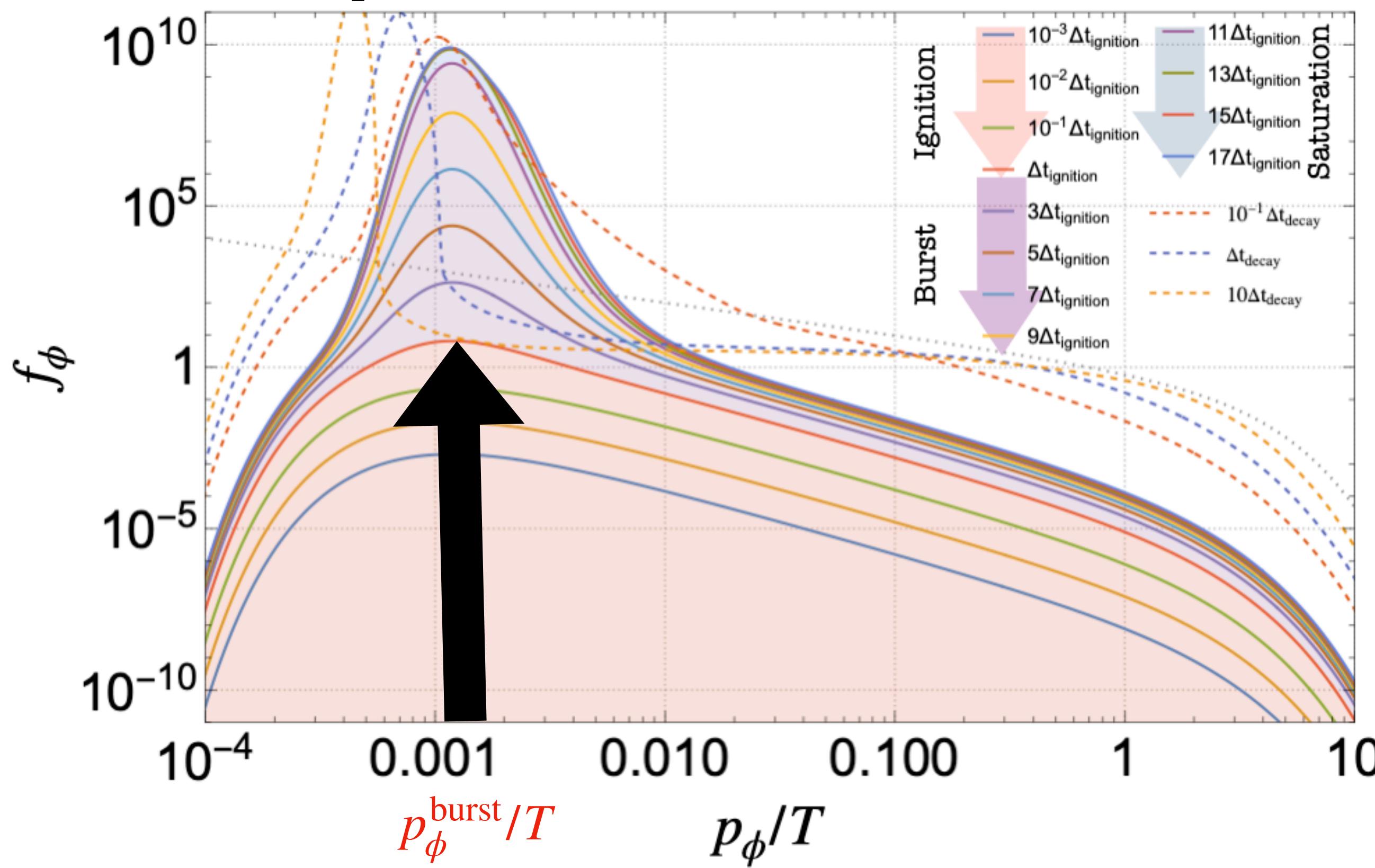


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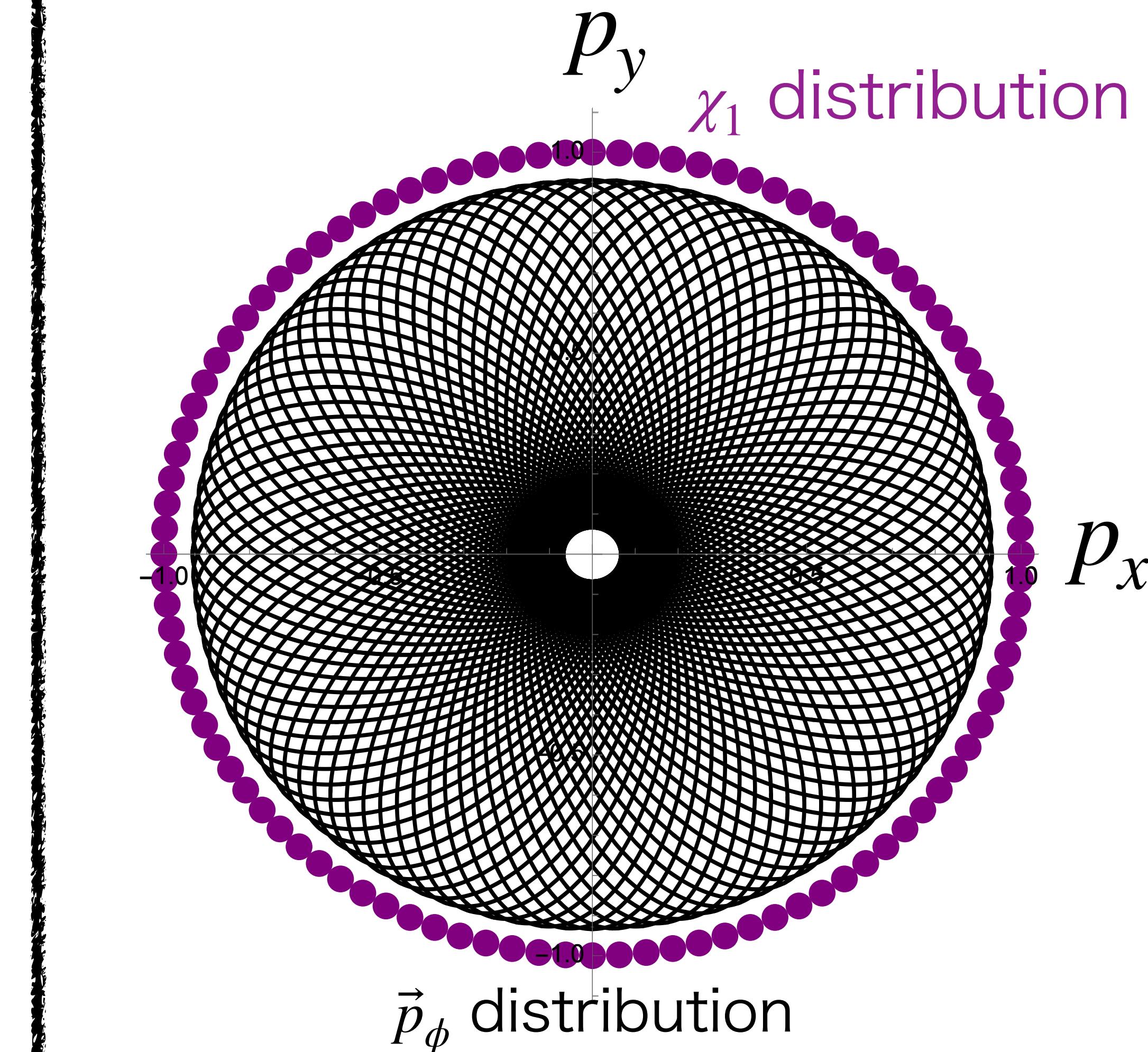
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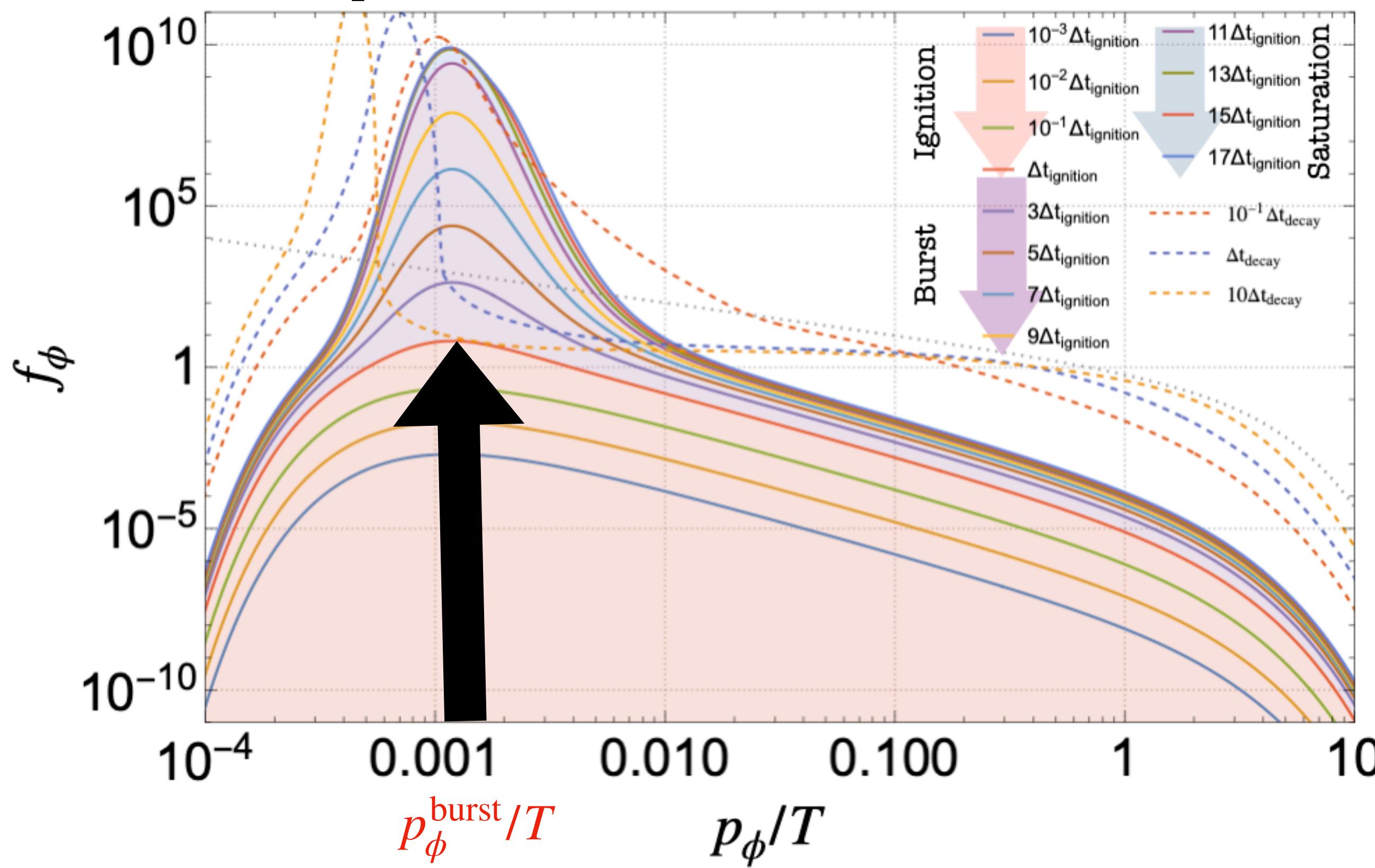


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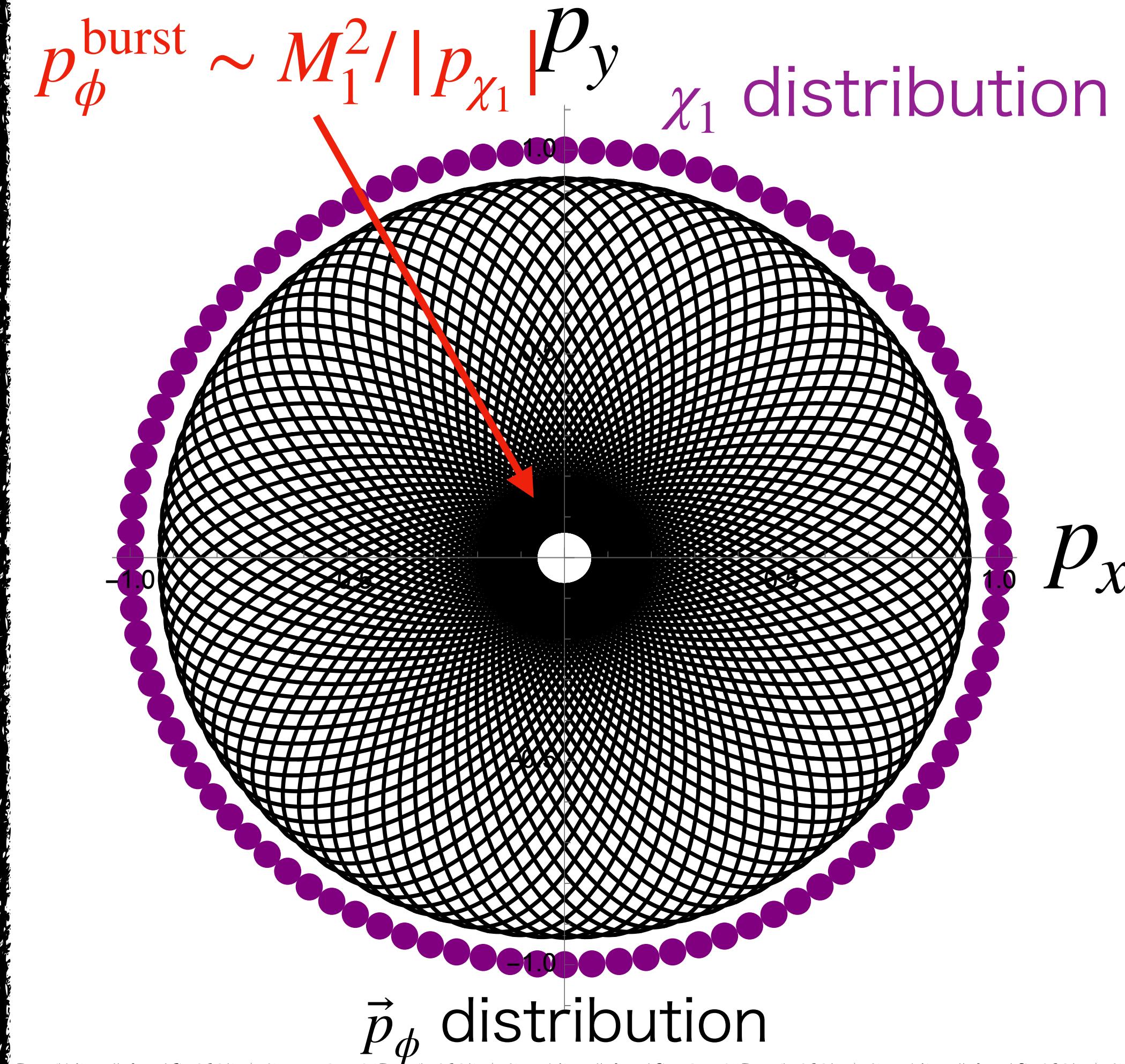
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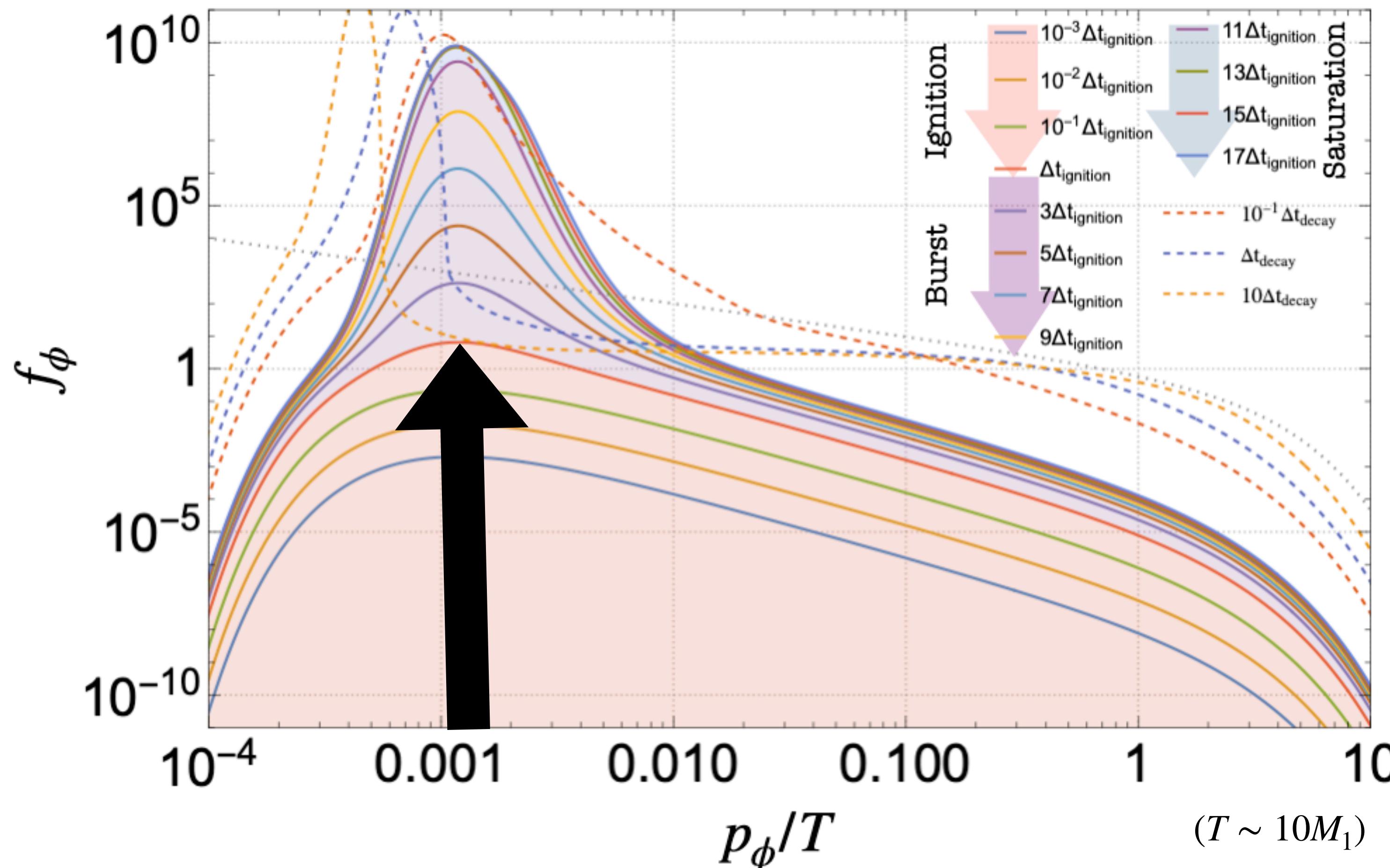


Stage 1: Ignition

Let the timescale that the occupation number of ϕ around

$p_\phi^{\text{burst}} \sim M_1^2/T$ reaches unity $\Delta t_{\text{ignition}}$:

$$\Delta t_{\text{ignition}}^{-1} \sim \frac{1}{(p_\phi^{\text{burst}})^3} \times T^3 \times \frac{p_\phi^{\text{burst}}}{T} \left(\frac{M_1}{T} \Gamma_{\text{decay}} \right)$$

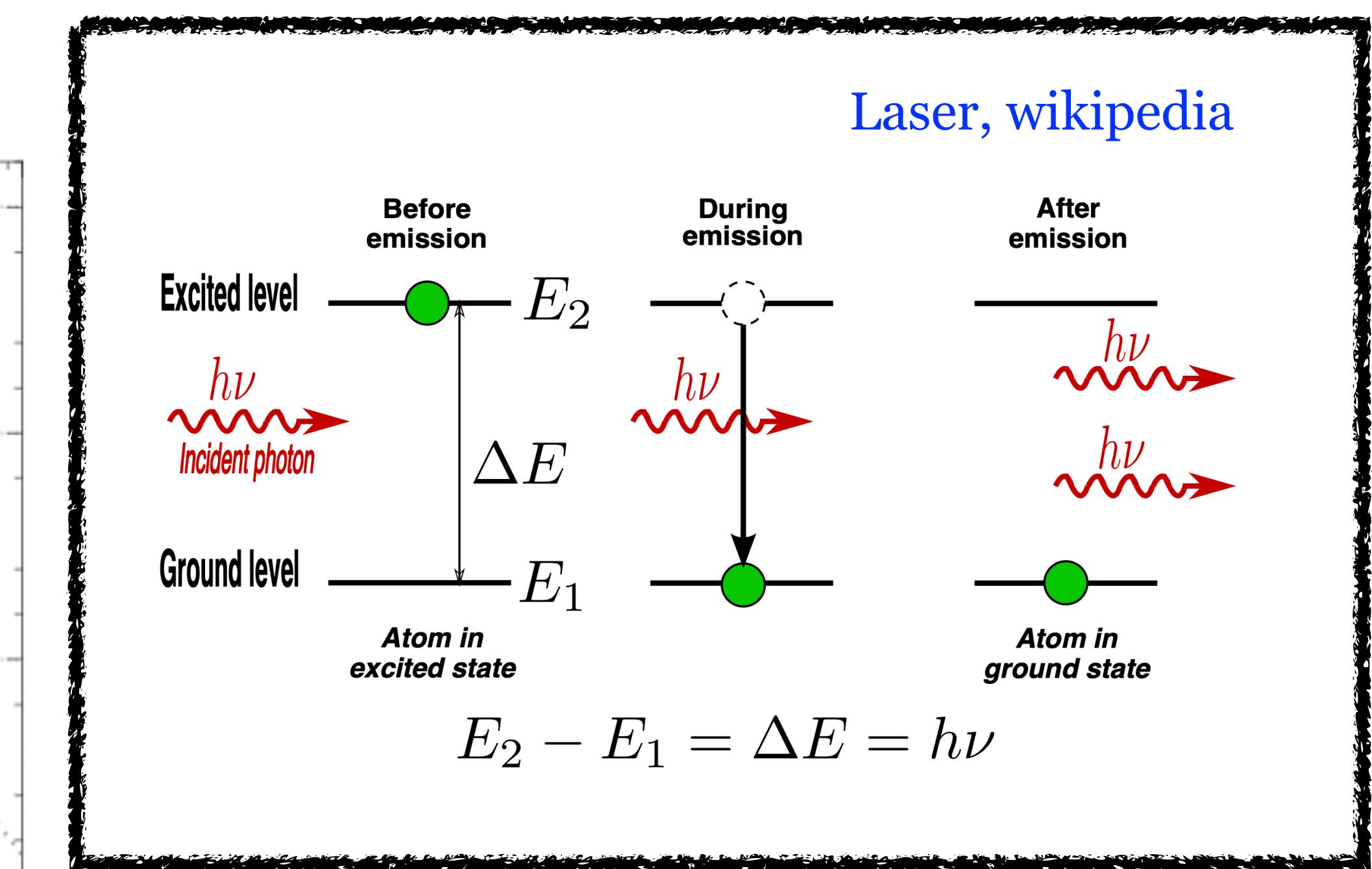
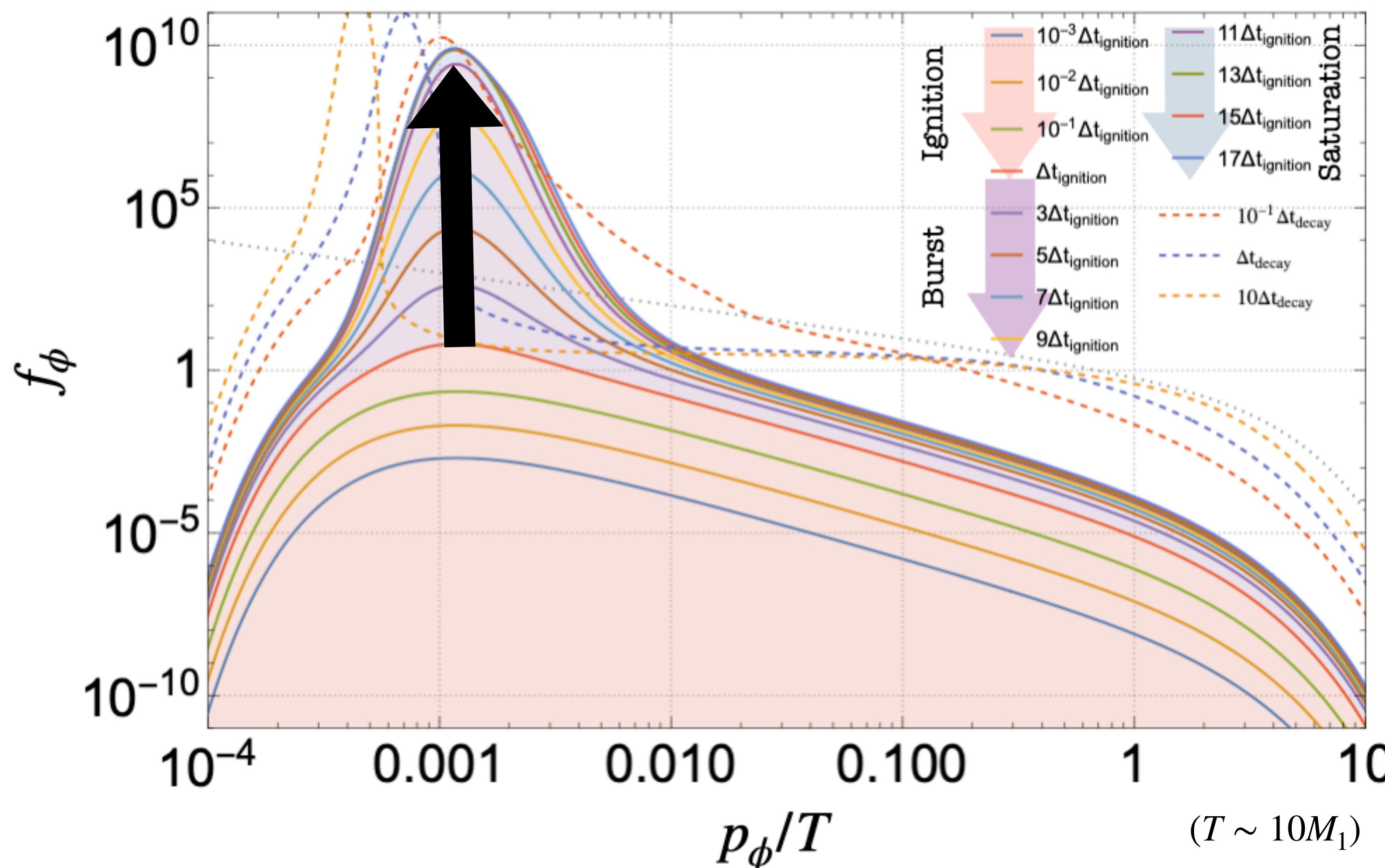


$$\sim \frac{T^4}{M_1^4} \times \left(\frac{M_1}{T} \Gamma_{\text{decay}}^{(\text{proper})} \right)$$

faster than the ordinary thermalization rate by T^4/M_1^4 .

Stage 2: Burst

p_ϕ^{burst} modes grow exponentially due to Bose enhancement. c.f. laser.

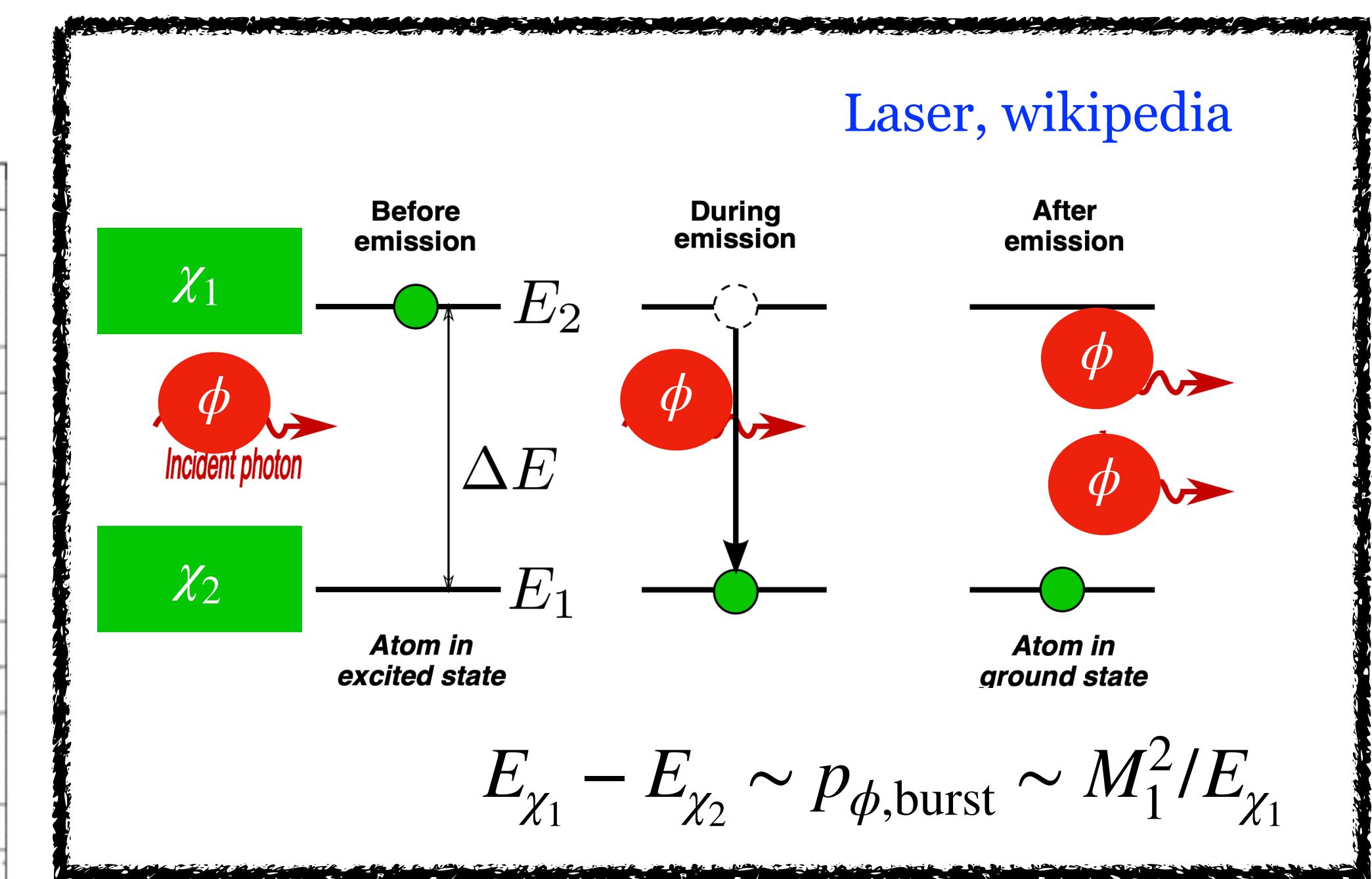
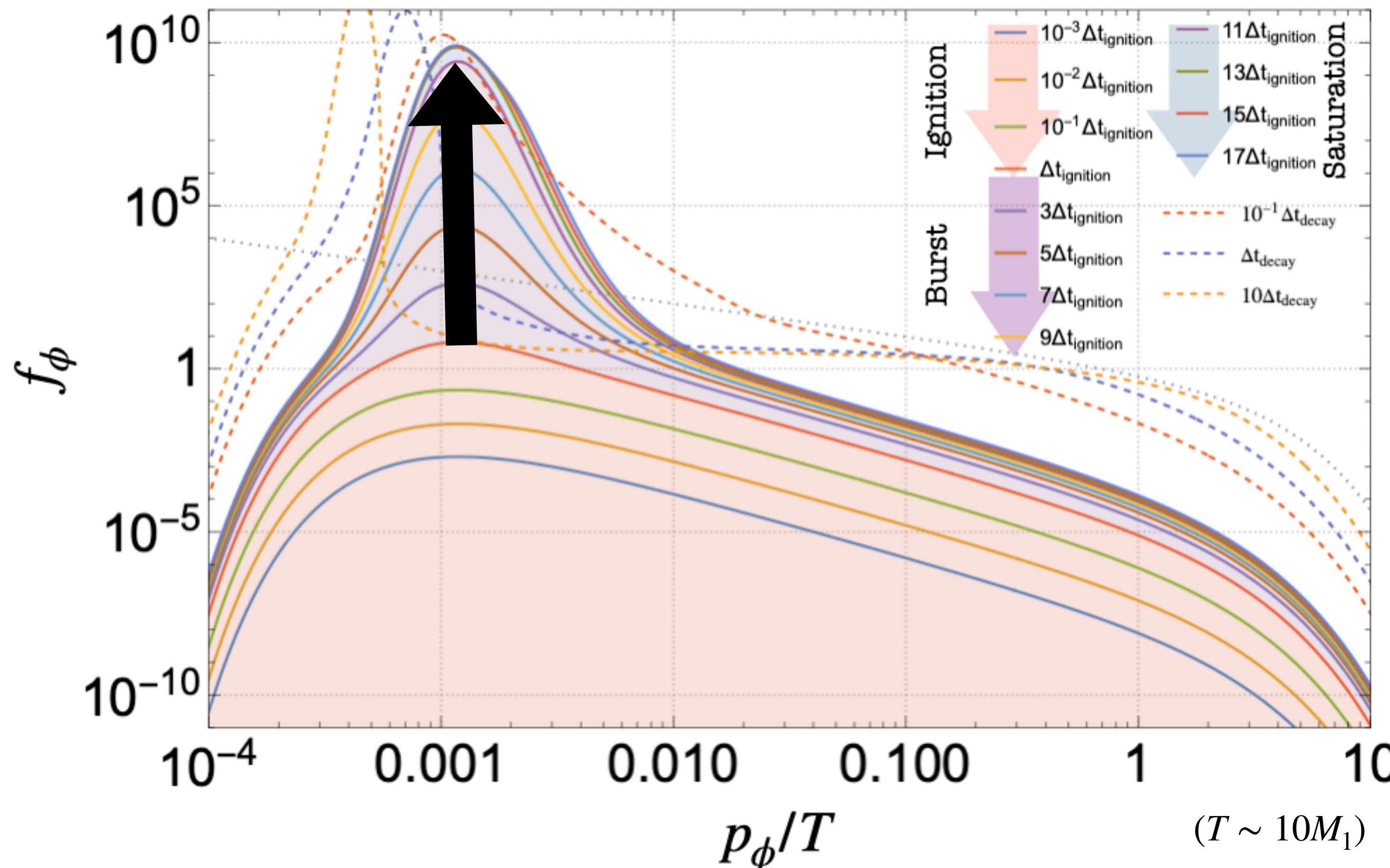


$$f_\phi[p_\phi \sim p_\phi^{\text{burst}}] \sim \exp[t/\Delta t_{\text{ignition}}]$$

$(T \sim 10M_1)$

Stage 2: Burst

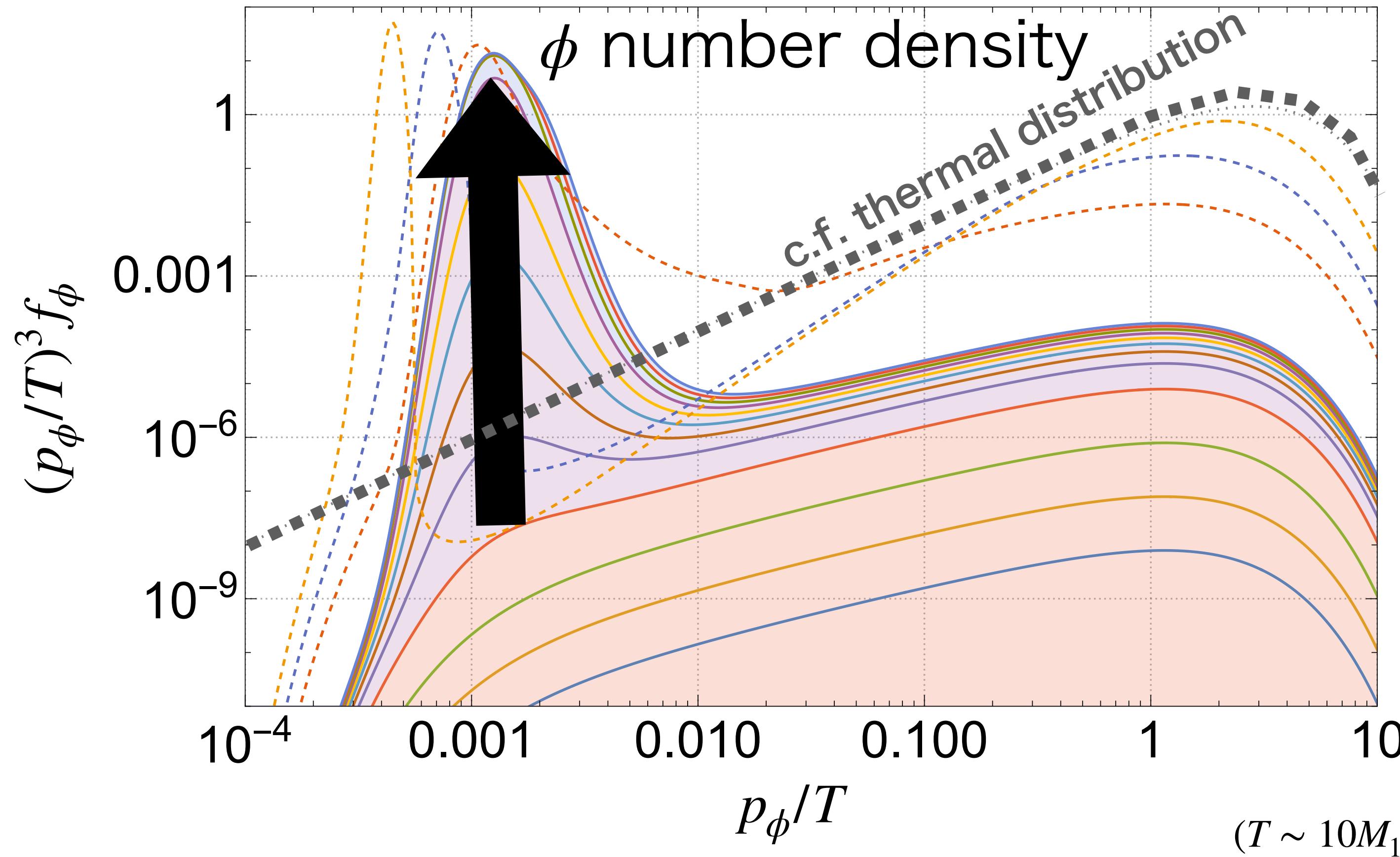
p_ϕ^{burst} modes grow exponentially due to Bose enhancement. c.f. laser.



$$f_\phi[p_\phi \sim p_\phi^{\text{burst}}] \sim \exp[t/\Delta t_{\text{ignition}}]$$

Stage 2: Burst

p_ϕ^{burst} modes grow exponentially due to Bose enhancement. c.f. laser. So does ϕ number density.



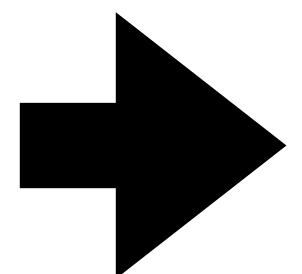
$$\begin{aligned} & (p_\phi^{\text{burst}})^3 f_\phi [p_\phi \sim p_\phi^{\text{burst}}] \\ & \sim (p_\phi^{\text{burst}})^3 \exp[t/\Delta t_{\text{ignition}}] \\ & \sim n_\phi[t] \end{aligned}$$

Stage 3: Saturation (quasi-equilibrium)

The burst production stops due to the inverse decay
when $f_{\chi_2}[p_{\chi_2} \sim T] \sim f_{\chi_1}[p_{\chi_1} \approx p_{\chi_2}]$, c.f. thermal equilibrium.

With $f_\phi[p \sim p_\phi^{\text{burst}}] \gg 1, f_{\chi_2}[p_{\chi_2} \sim T] \sim 1$

$$C^\phi = \frac{1}{2E_\phi g_\phi} \sum \int d\Pi_{\chi_1} d\Pi_{\chi_2} S \equiv f_{\chi_1}[p_{\chi_1} \sim T](1 \pm f_{\chi_2}[p_{\chi_2} \sim T]) \cancel{(1 + f_\phi[p_\phi \sim p_\phi^{\text{burst}}])}$$
$$(2\pi)^4 \delta^4(p_{\chi_1} - p_\phi - p_{\chi_2}) \times |\mathcal{M}_{\chi_1 \rightarrow \chi_2 \phi}|^2$$
$$\times \boxed{S(f_{\chi_1}[p_{\chi_1}], f_{\chi_2}[p_{\chi_2}], f_\phi[p_\phi])}$$
$$-(1 \pm f_{\chi_1}[p_{\chi_1} \sim T])f_\phi[p_\phi \sim p_\phi^{\text{burst}}] f_{\chi_2}[p_{\chi_2} \sim T]$$
$$\sim \boxed{\frac{[f_{\chi_1}[p_{\chi_1} \sim T] - f_{\chi_2}[p_{\chi_2} \sim T])f_\phi[p_\phi \sim p_\phi^{\text{burst}}]}{[f_{\chi_1}[p_{\chi_1} \sim T] + f_{\chi_2}[p_{\chi_2} \sim T])}}$$

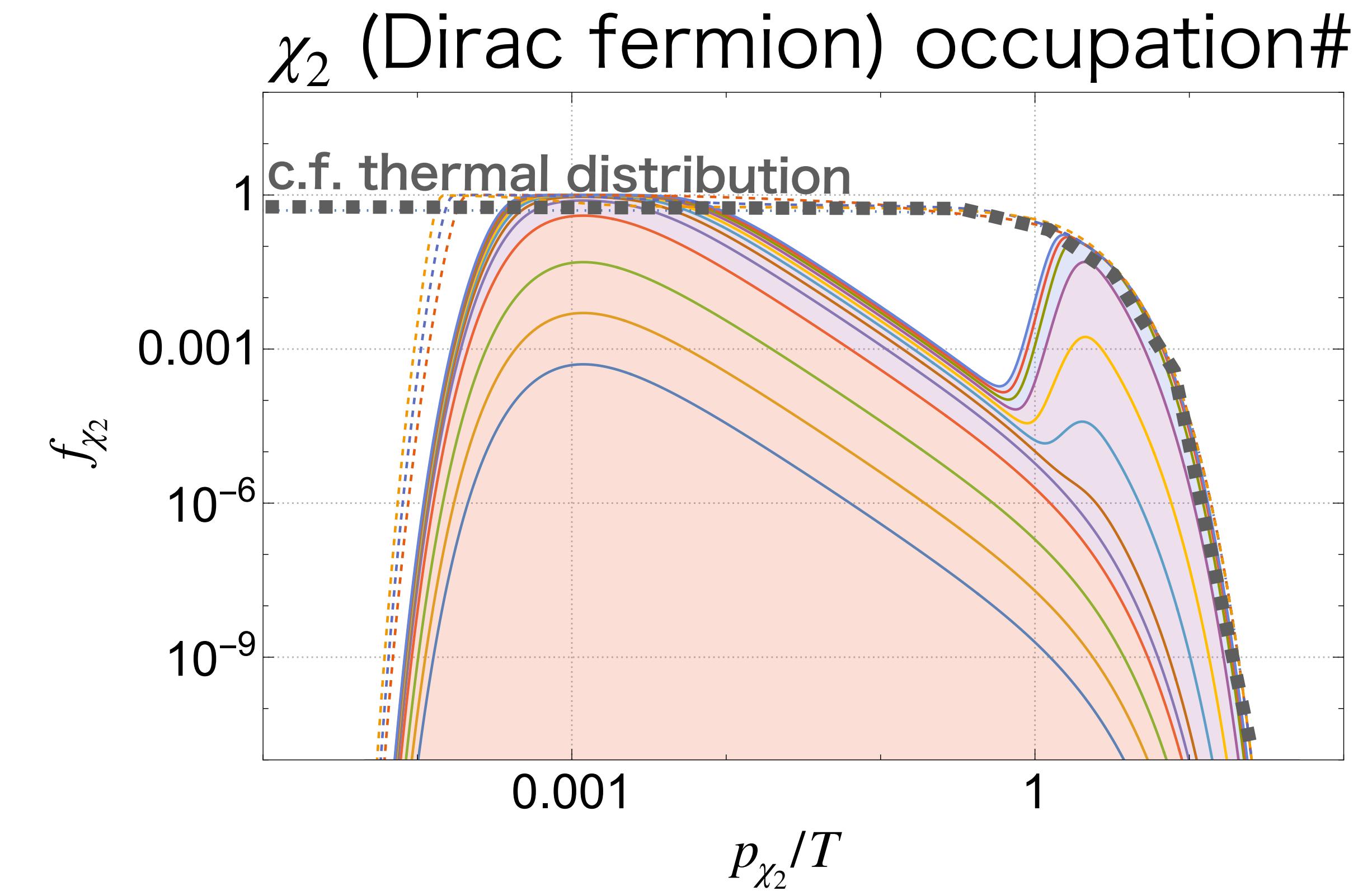
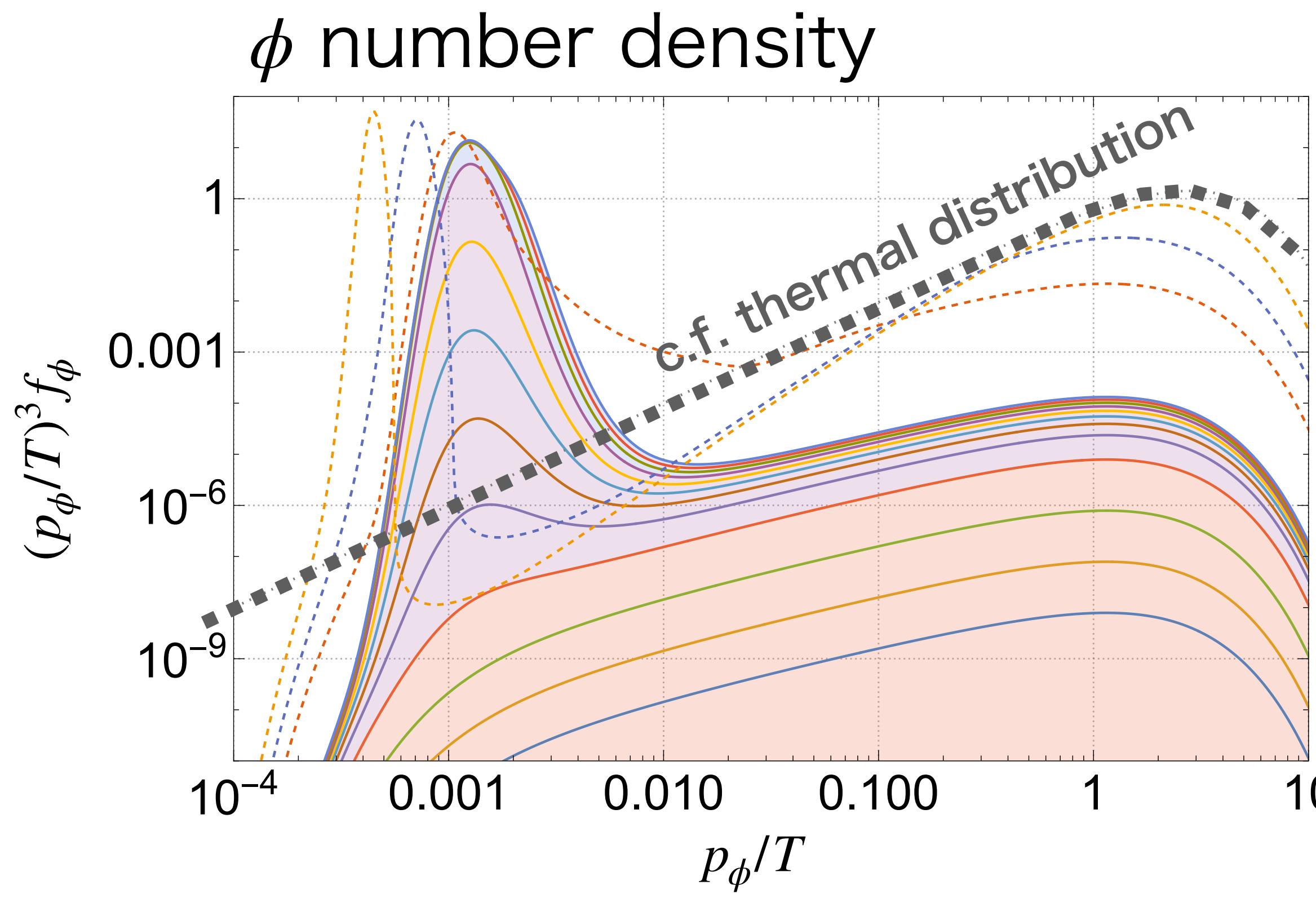


$$\dot{f}_\phi[p_\phi \sim p_\phi^{\text{burst}}] \sim 0$$

Stage 3: Saturation (quasi-equilibrium)

The number density of χ_2 at $p_{\chi_2} \sim T$ is T^3 . Since

$$\dot{n}_{\chi_2} = \dot{n}_\phi \text{ in } \chi_1 \leftrightarrow \chi_2 \phi,$$



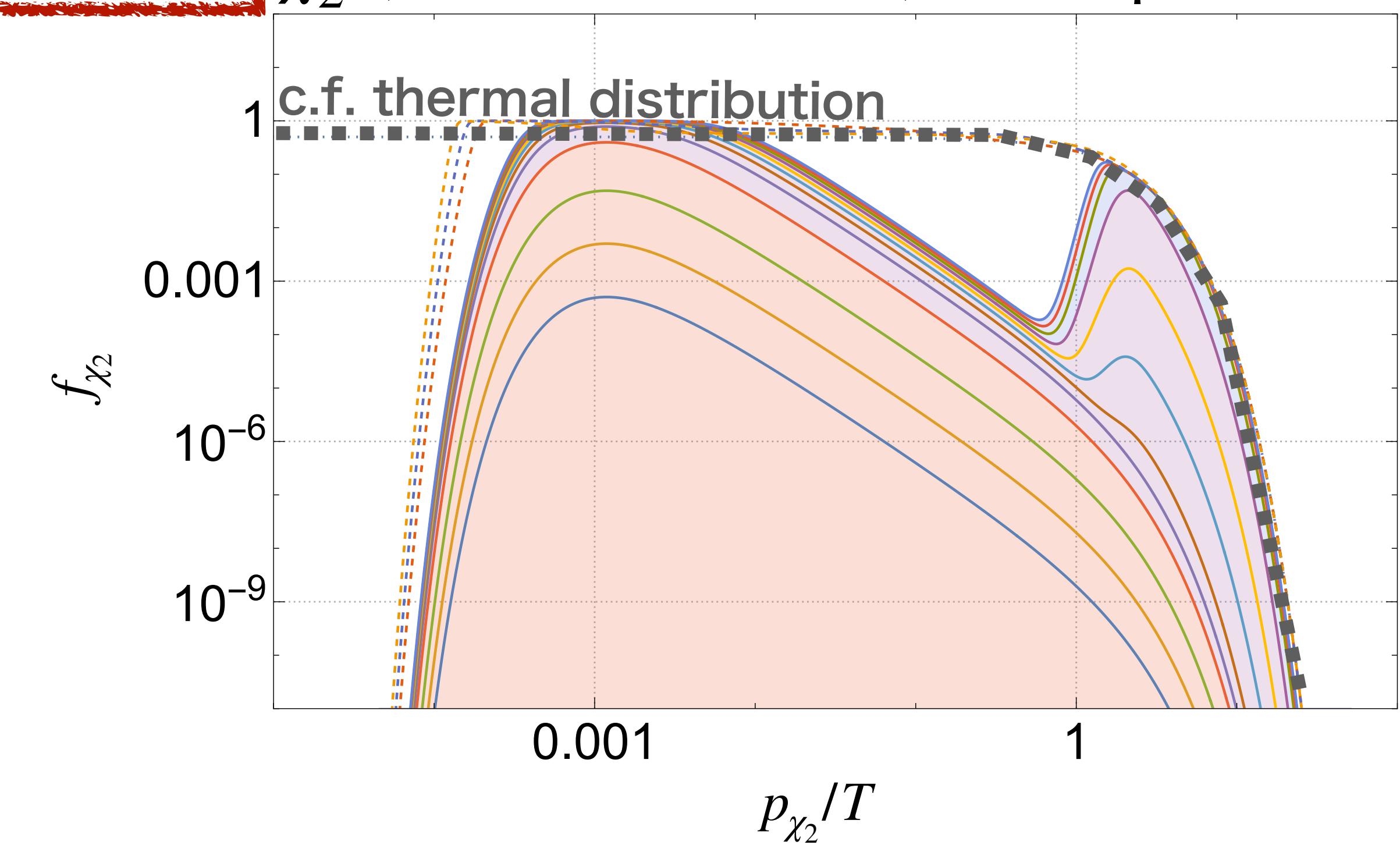
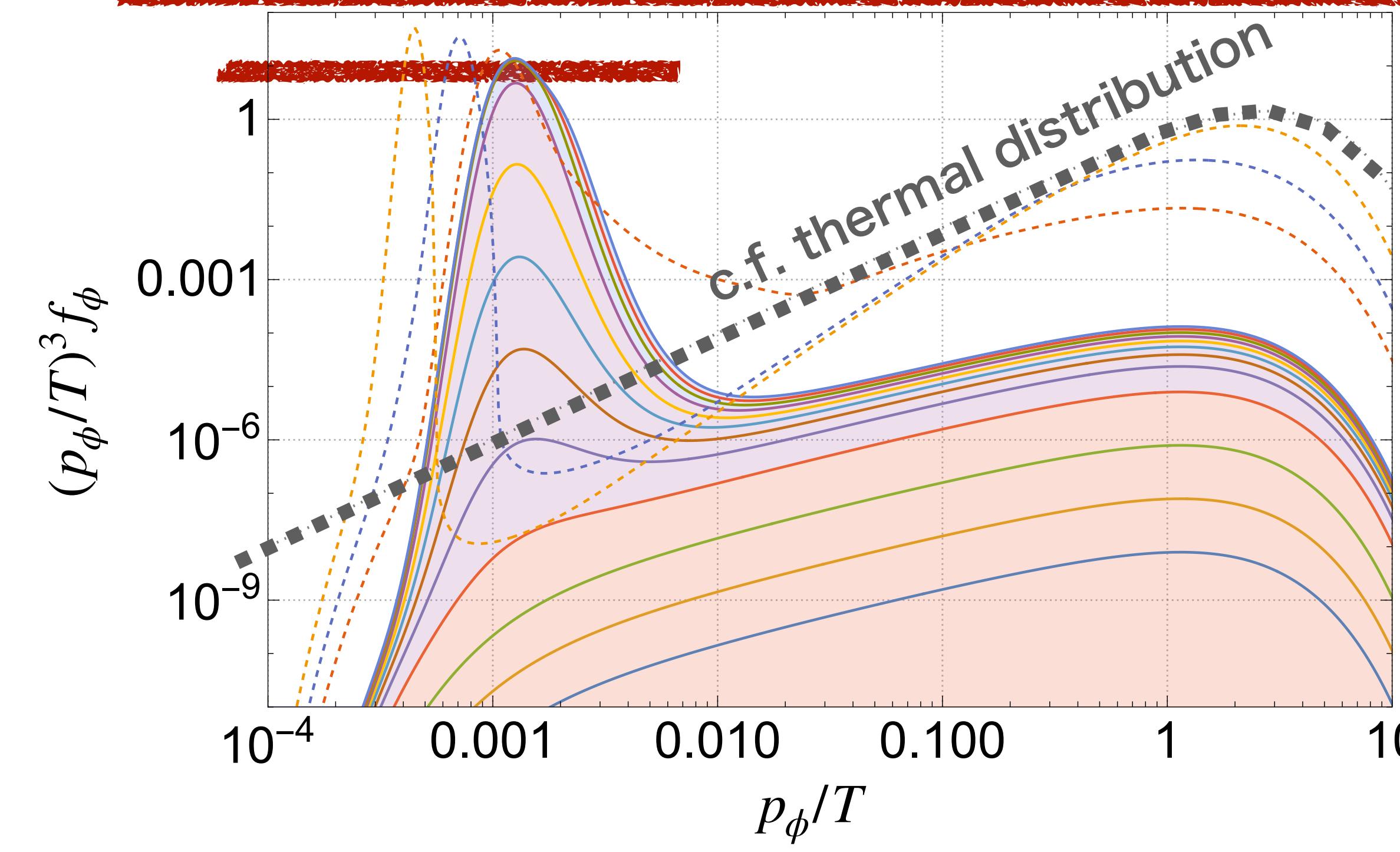
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$n_\phi \sim T^3, p_\phi \sim M_1^2/T$, which is cold

χ_2 (Dirac fermion) occupation#

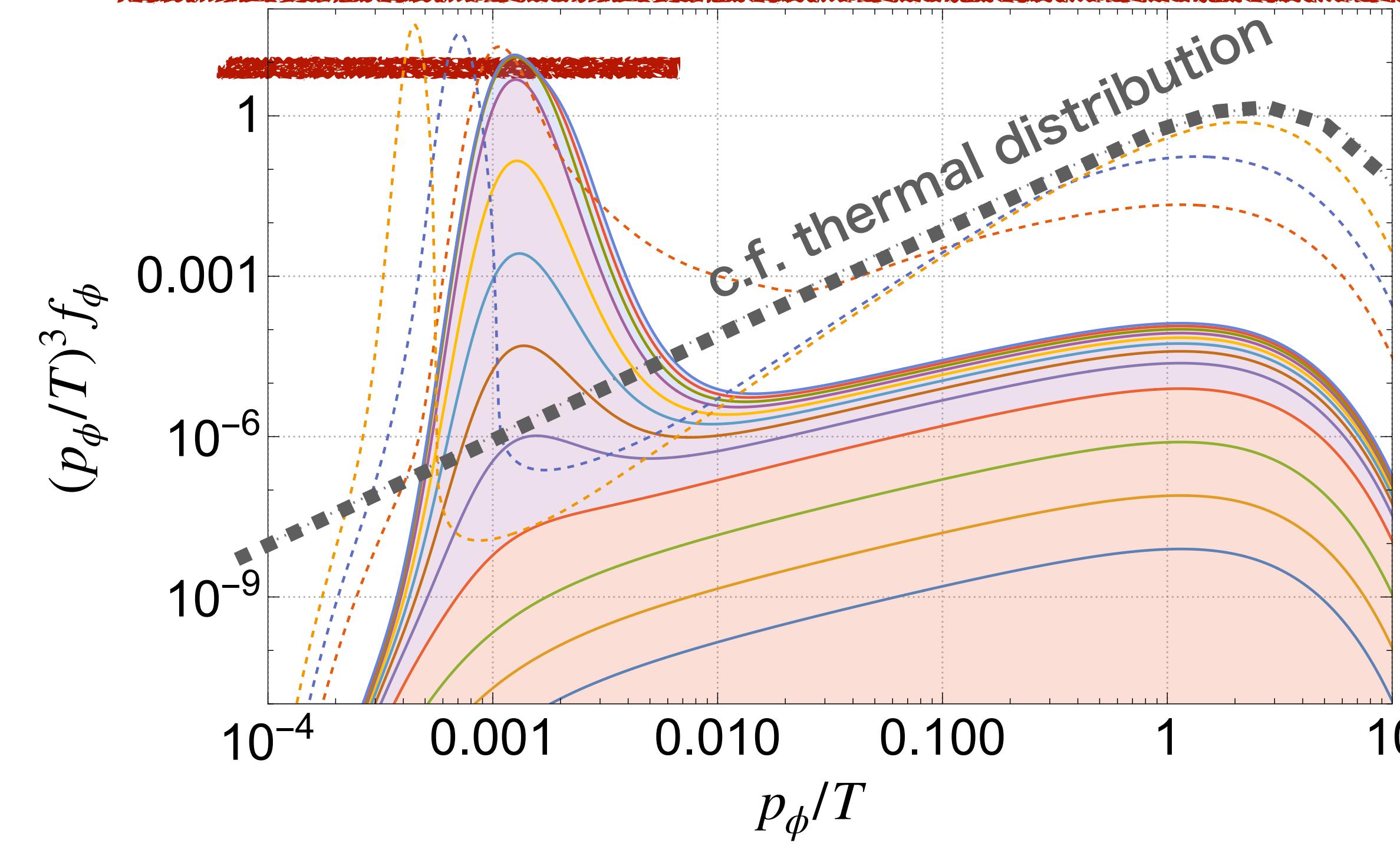


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The quasi-equilibrium is kept on a very long time scale until

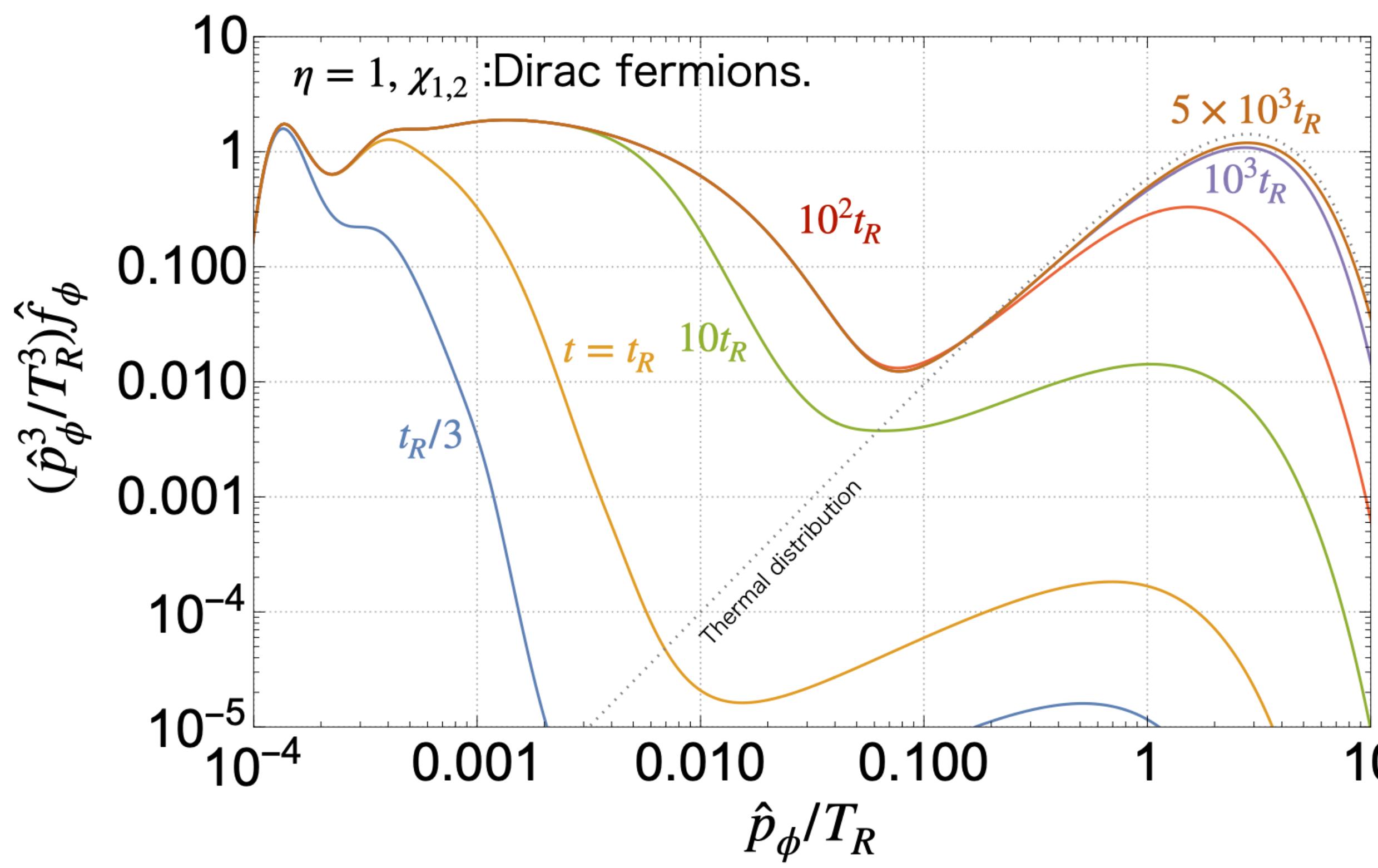
$$t \sim \left(\Gamma_{\text{decay}}^{(\text{proper})} \right)^{-1} \frac{T}{M_1} \sim \left(\frac{T}{M_1} \right)^4 \Delta t_{\text{ignition}}$$

Burst production in expanding Universe

If there is a period satisfying

$$\left(\frac{M_1}{T} \Gamma_{\text{decay}}^{\text{(proper)}} \right) \sim \frac{M_1^4}{T^4} 1/\Delta t_{\text{ignition}} \ll H \ll 1/\Delta t_{\text{ignition}},$$

the burst produced ϕ remains due to redshift and kinematics.



$$\therefore n_\phi \sim T^3$$

Prediction:
Cold DM
with

$$m_{\text{DM}} = 2\text{-}O(100)\text{eV}$$

Comparison of hot DM production and burst production in $\chi_1 \leftrightarrow \phi \chi_2$ system

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Hot DM paradigm (-1984):

- $\left(\frac{T}{M_1}\right)^3 \Gamma_{\chi_1 \rightarrow \chi_2 \phi}^{(\text{proper})} > \frac{M_1}{T} \Gamma_{\chi_1 \rightarrow \chi_2 \phi}^{(\text{proper})} > H$ for $T > M_1$
- $n_\phi \sim T^3$ from **thermal equilibrium**

=> eV mass for DM abundance
• Comoving momentum is

$$p_{\text{com}} \sim a_{\text{prod}} T_{\text{prod}}$$

=> hot

Burst production of DM

- $\left(\frac{T}{M_1}\right)^3 \Gamma_{\chi_1 \rightarrow \chi_2 \phi}^{(\text{proper})} > H > \frac{M_1}{T} \Gamma_{\chi_1 \rightarrow \chi_2 \phi}^{(\text{proper})}$ @ a period
- $n_\phi \sim T^3$ from **quasi-equilibrium** of
bose-enhancement dynamics
=> eV mass for DM abundance
• Comoving momentum is

$$p_{\text{com}} \sim a_{\text{prod}} M_1^2 / T_{\text{prod}}$$

=> cold

Conclusions: Bose enhancement in light DM production is very important.

WY 2301.08735

- eV range DM is still special and theoretically well-motivated, a la hot DM paradigm.
- Predictions of freeze-in scenarios $\chi_1 \rightarrow \chi_2 \phi$, $\Phi_1 \rightarrow \phi \phi$, may be significantly altered by this effect.

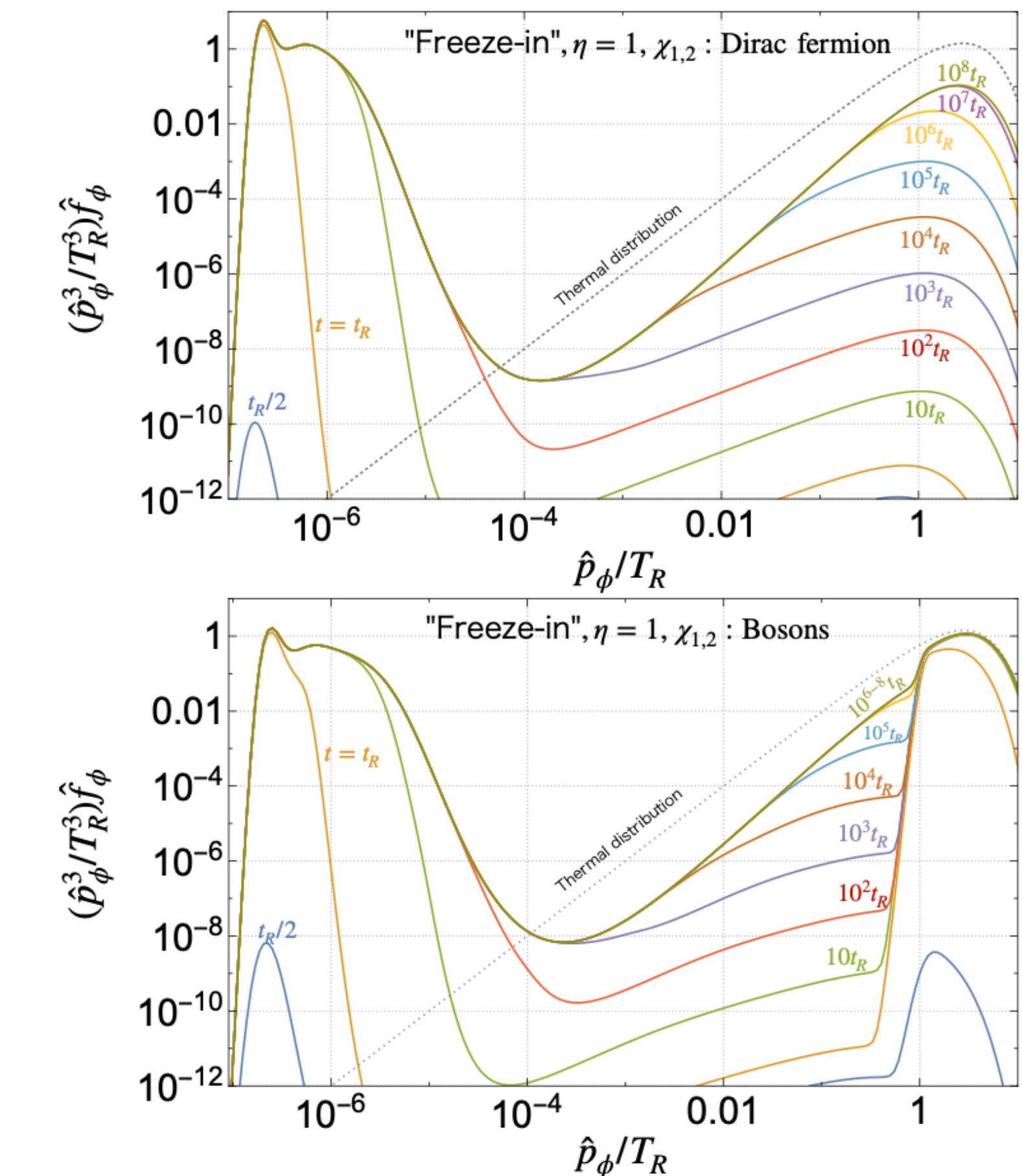
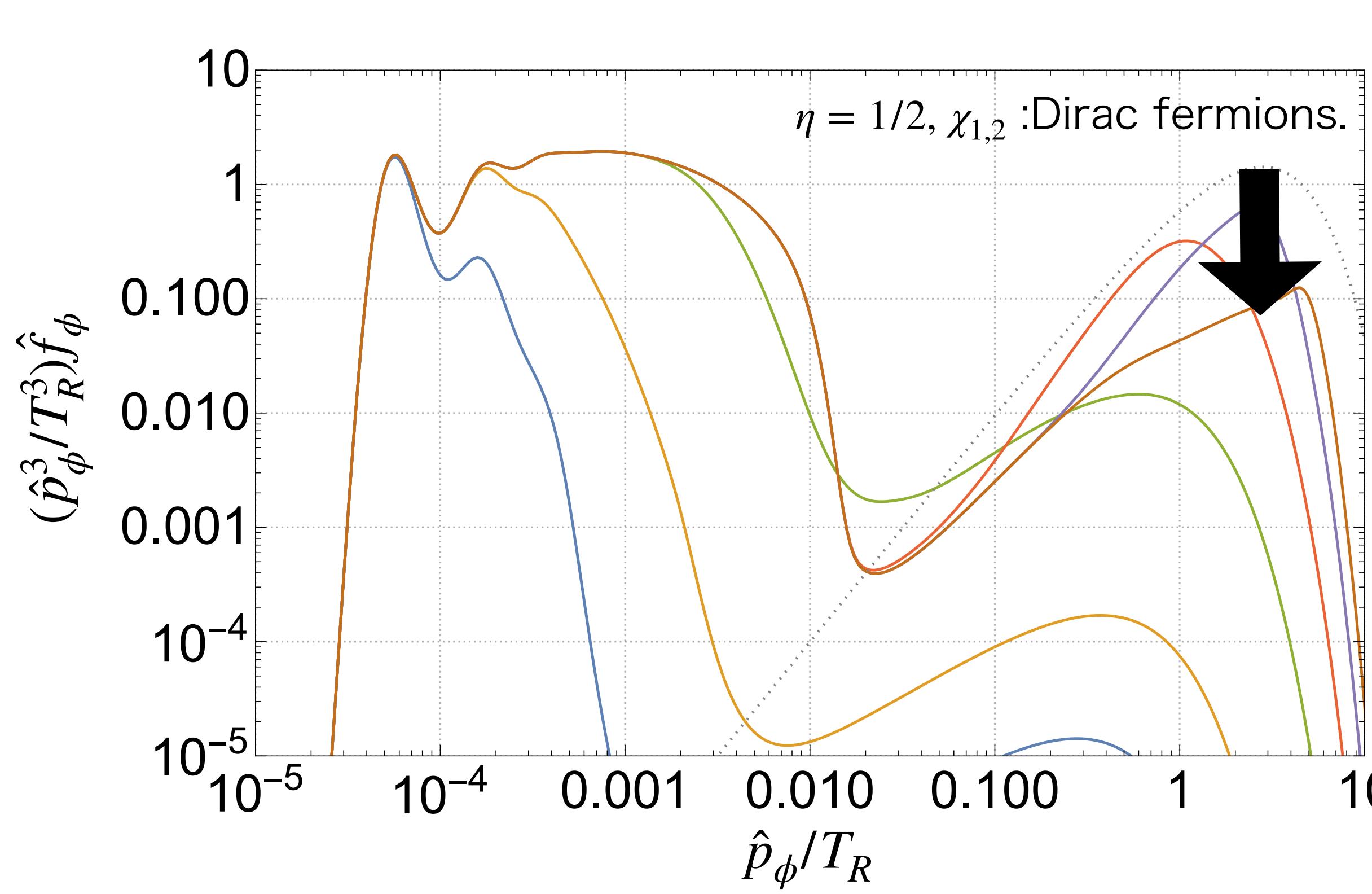
Only when $\chi_1^{thermal} \rightarrow \chi_2^{thermal} \phi$ the conventional analysis is a good approximation.

Non-trivial results in slightly different setups:

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Cooling of DM due to inverse decay
with slight mass degeneracy of mother
particles.

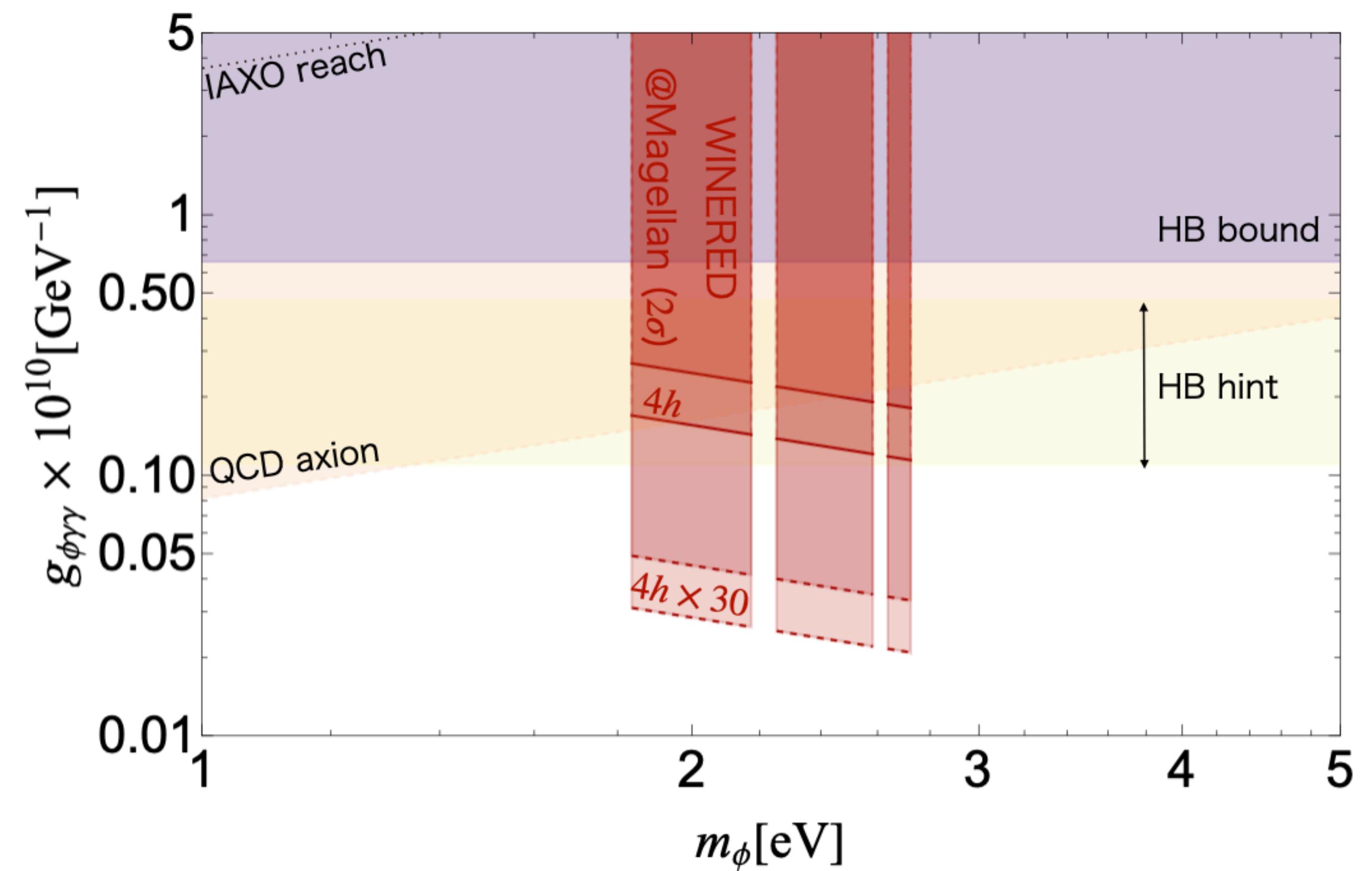
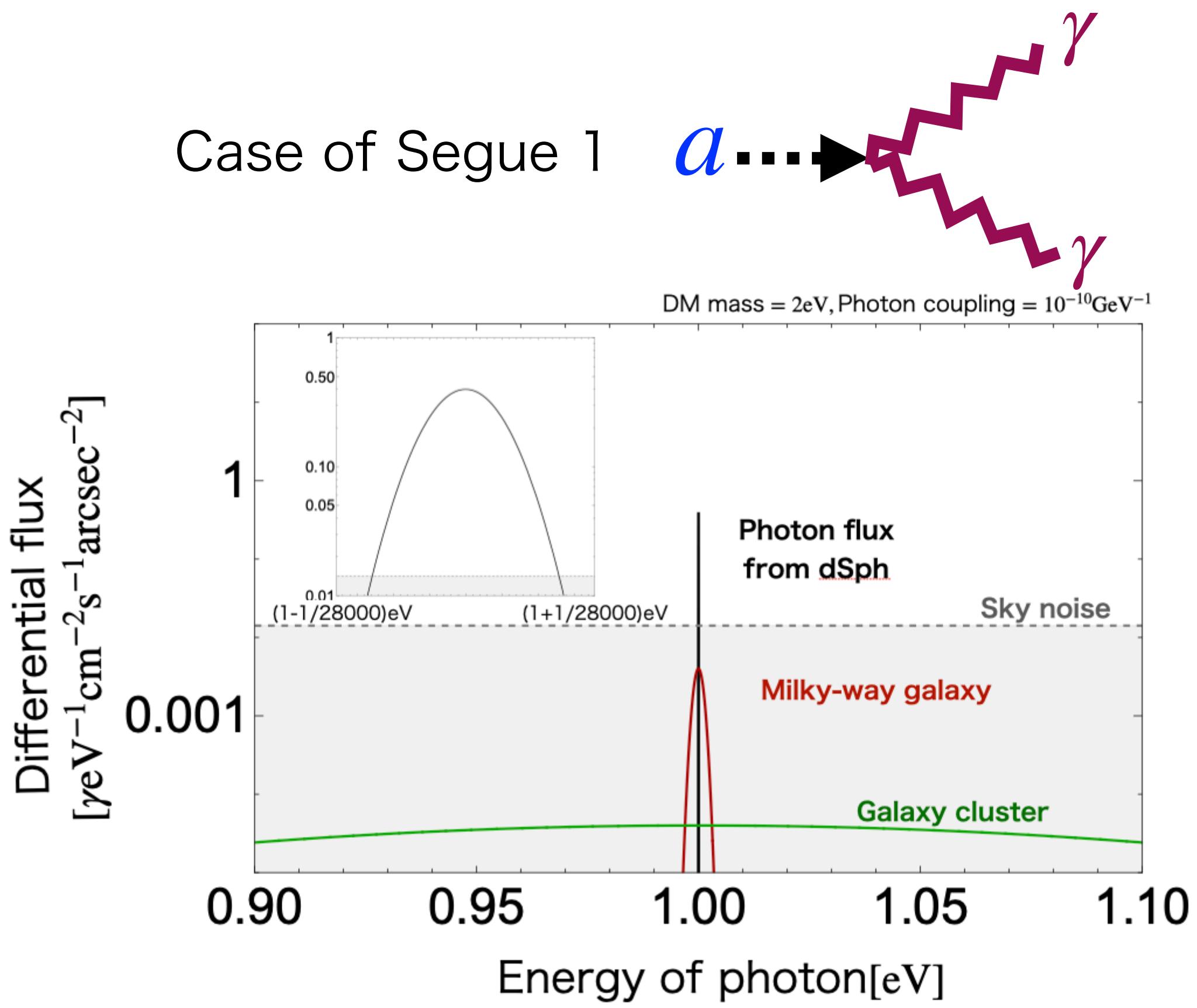
Freeze-in production of the DM may
have significantly different abundance
and free-streaming length from the
conventional estimations.



Indirect detection of ALP DM in infrared regime

Serious sky/thermal noise can be overcome by high-resolution
of infrared spectrographs.

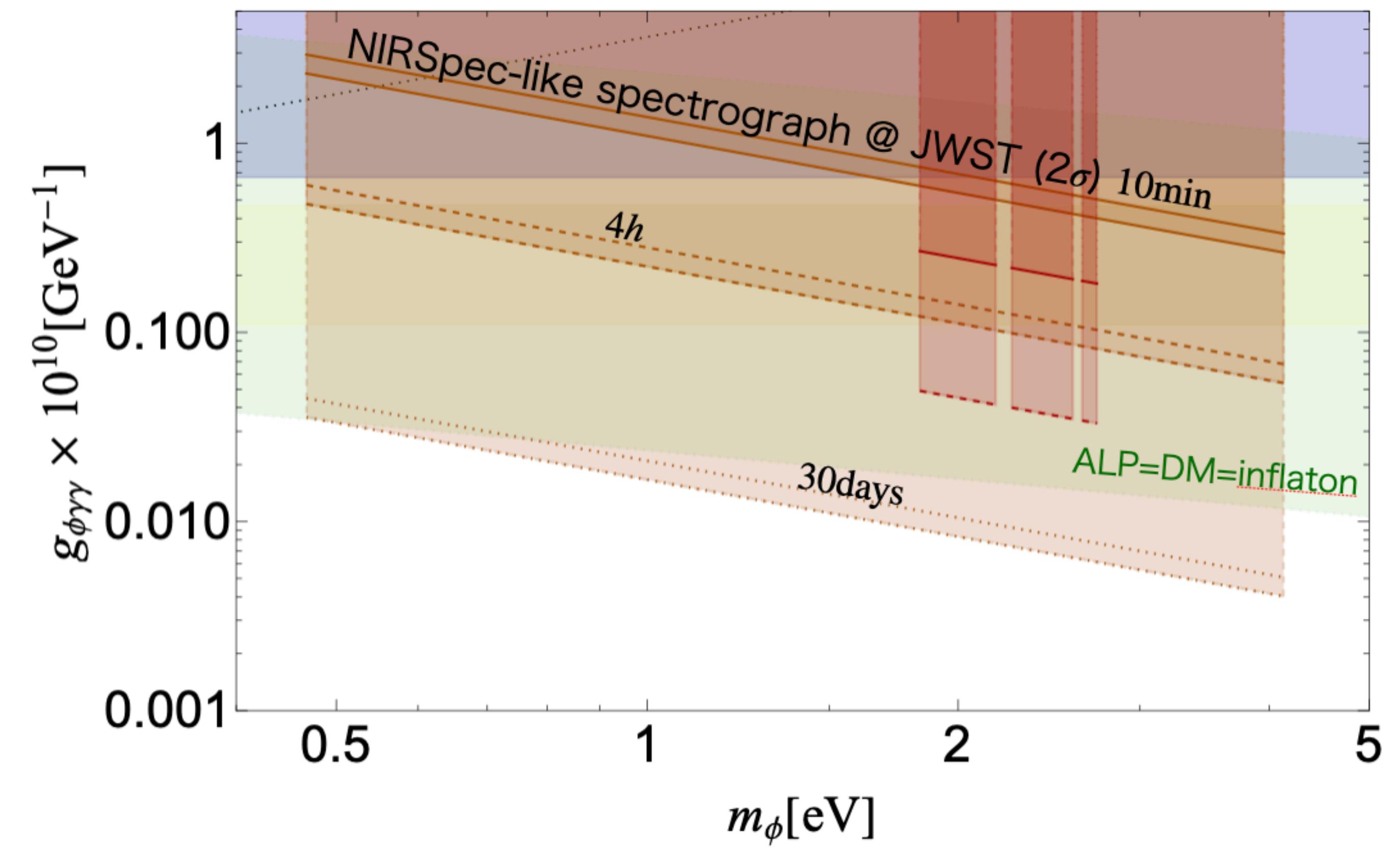
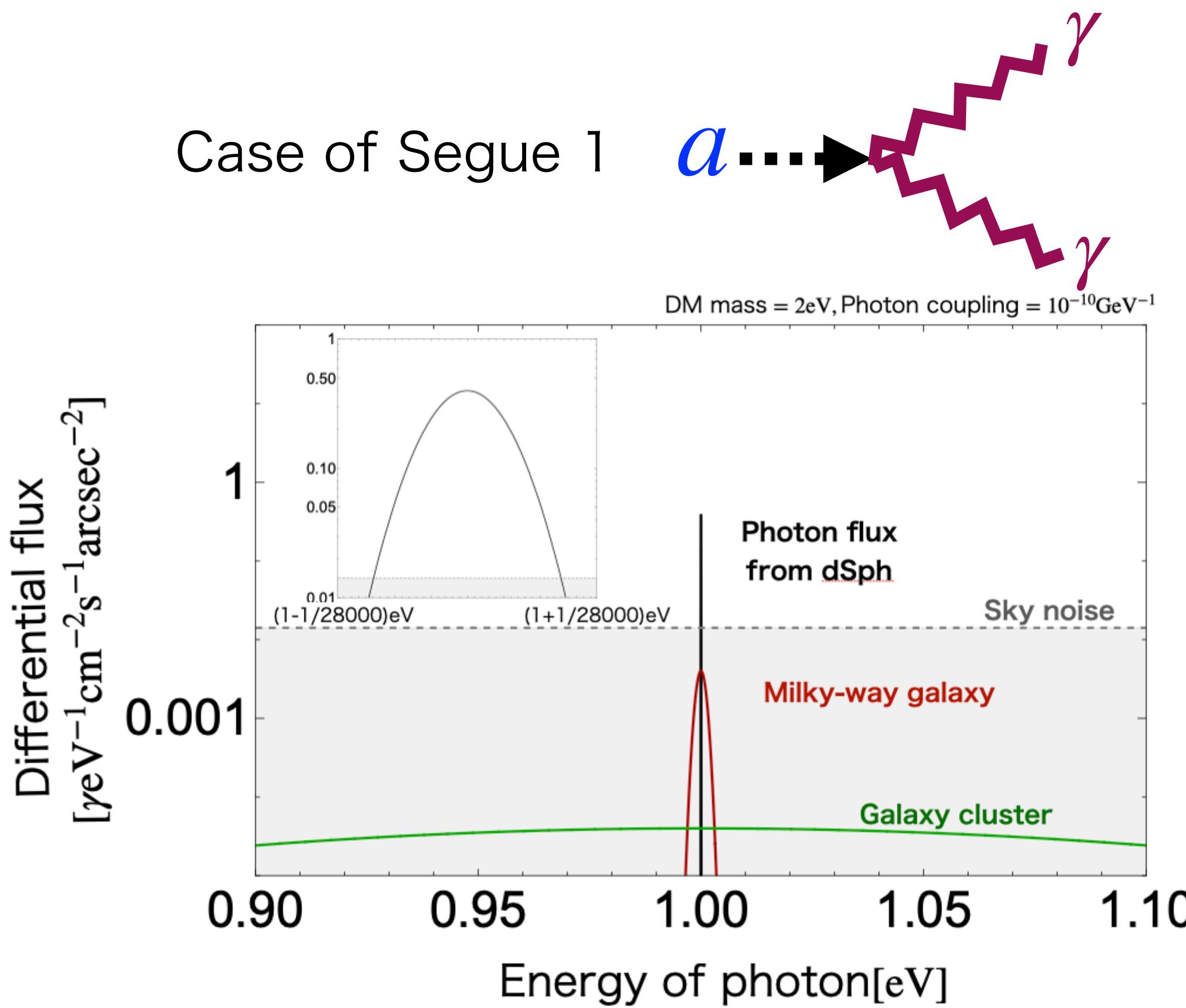
Bessho, Ikeda, WY, 2208.05975



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Bessho, Ikeda, WY, 2208.05975



Narrow parametric resonance \approx Boltzmann equation including Bose enhancement/Pauli-block factor. [Moroi, WY, 2011.12285](#)

-Analytical solution for DM distribution from condensate decays [Moroi, WY, 2011.09475, 2011.12285](#)

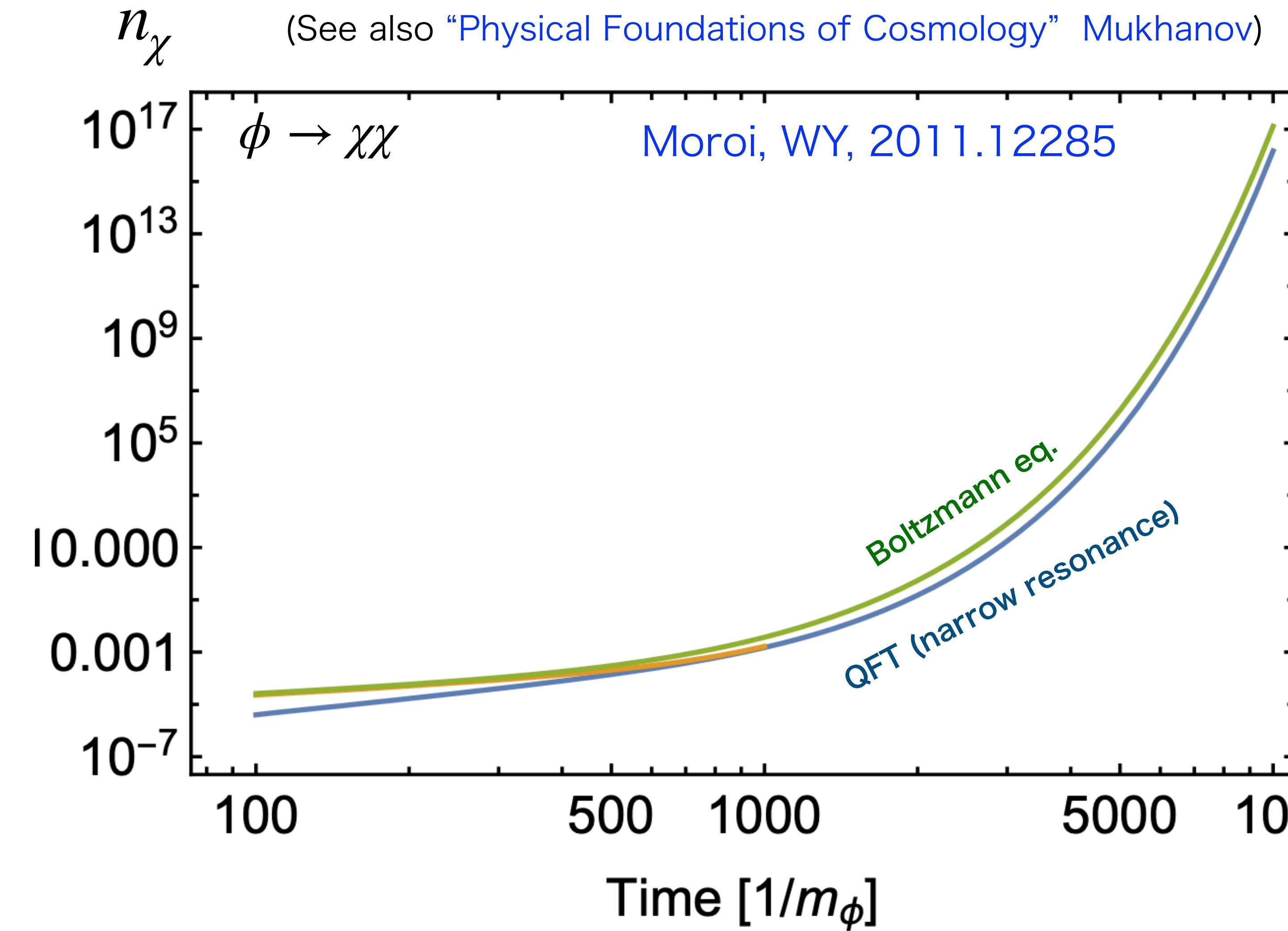
$$f_k(t \rightarrow \infty) = \pm \frac{1}{2} \left(e^{\pm 2\bar{f}(t_k)} - 1 \right) \theta(p_\chi - k),$$

$$\bar{f}(t_k) \equiv \frac{4\pi^2 \Gamma_{\phi \rightarrow \chi\chi}^{(0)} n_\phi}{H p_\chi^3} \Big|_{t=t_{\hat{k}}}$$

$$\sim q^2 \frac{m_\phi}{H} \frac{m_\phi^2}{4p_\chi^2} \lesssim \frac{m_\phi}{H} \frac{m_\phi^2}{4p_\chi^2}$$

-Model-building for $m_\phi > H$

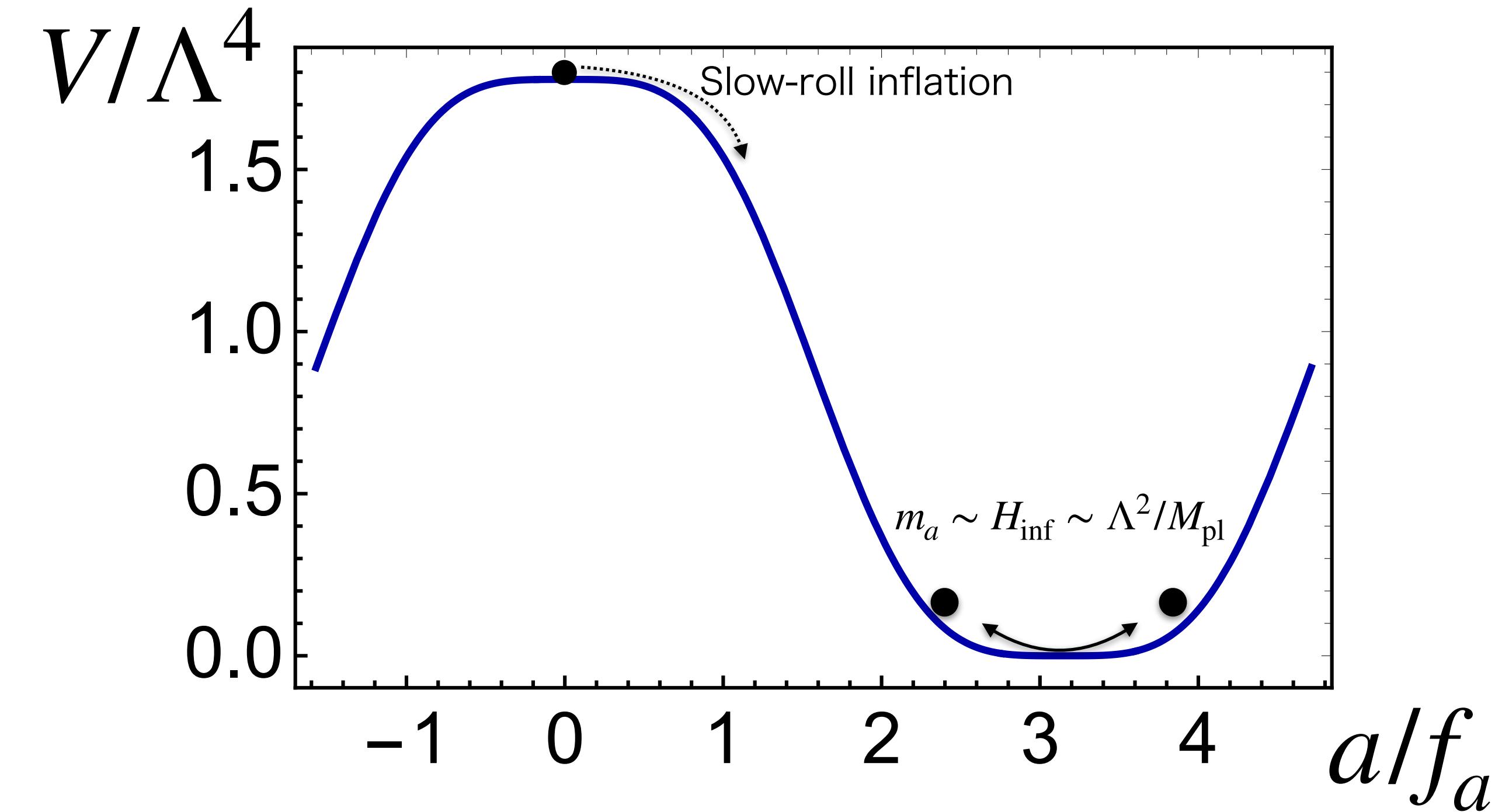
- Light DM from inflaton decay [Moroi, WY, 2011.09475, 2011.12285,](#)
- Light axion/hidden photon from dark (PQ) Higgs decay [Nakayama WY, 2105.14549](#)



The ALP miracle scenario: Inflaton = DM = ALP

Assumption:

- upside-down symmetric potential
- Hilltop inflation



Why is it light?

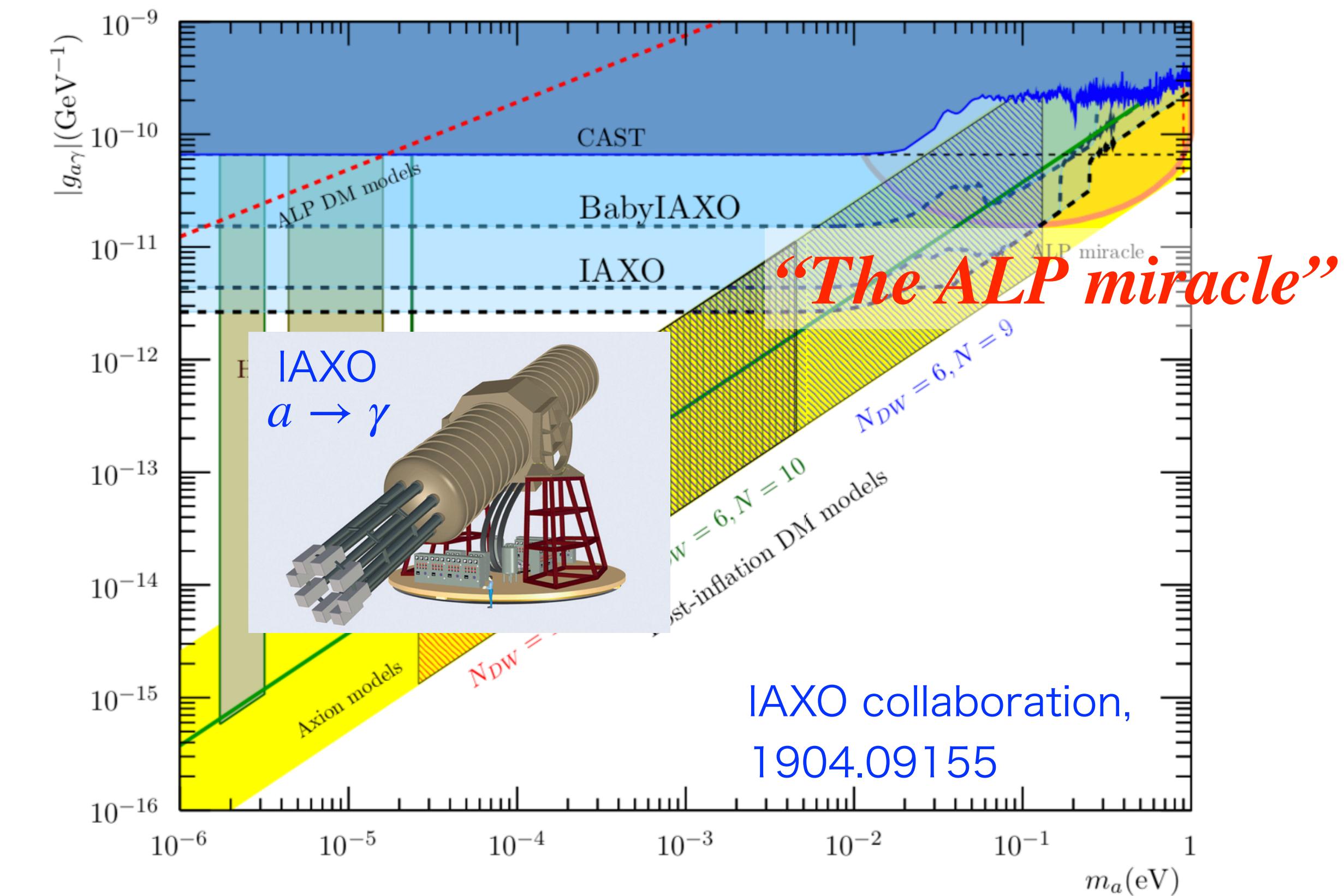
Slow-roll condition

+upside down symmetry

How to produce ALP DM?

Inflaton remains (built-in).

Daido, Takahashi, WY, 1702.03284, 1710.11107



The same ALP from sun, photon collider.

$\Delta N_{\text{eff}} \approx 0.03$. "indirect/direct detection",

Next part