Thermal production of bosonic dark matter and Bose-enhancement

Tohoku U.
Wen Yin

@HPNP 2023 8th Jun 2023, Osaka

Mainly based on JHEP 05 (2023) 180, 2301.08735

Thermal production of bosonic dark matter and Bose-enhancement

Axion dark matter around eV for this talk

Tohoku U.
Wen Yin

@HPNP 2023 8th Jun 2023, Osaka

Mainly based on JHEP 05 (2023) 180, 2301.08735

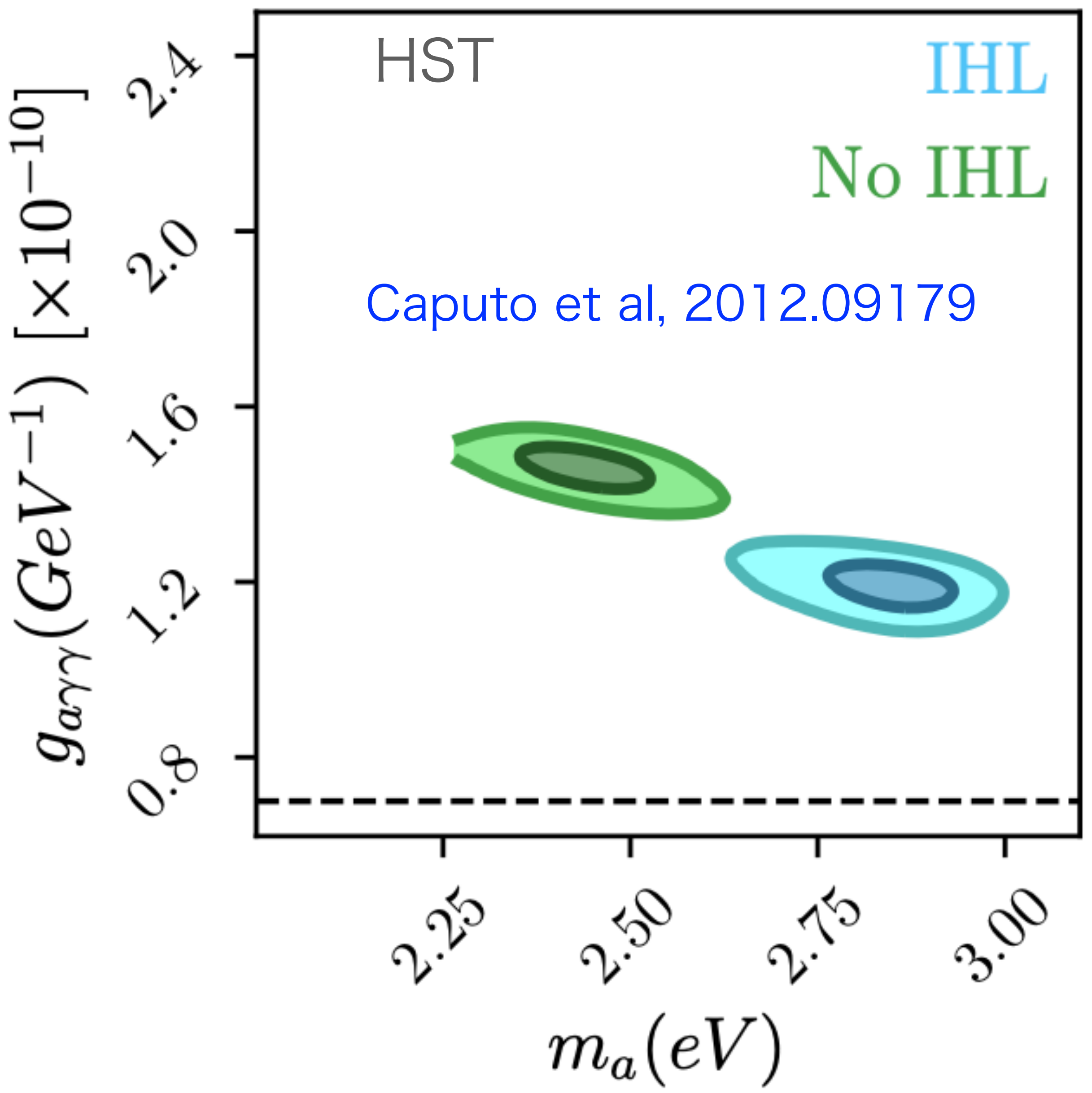
Hints for eV DM

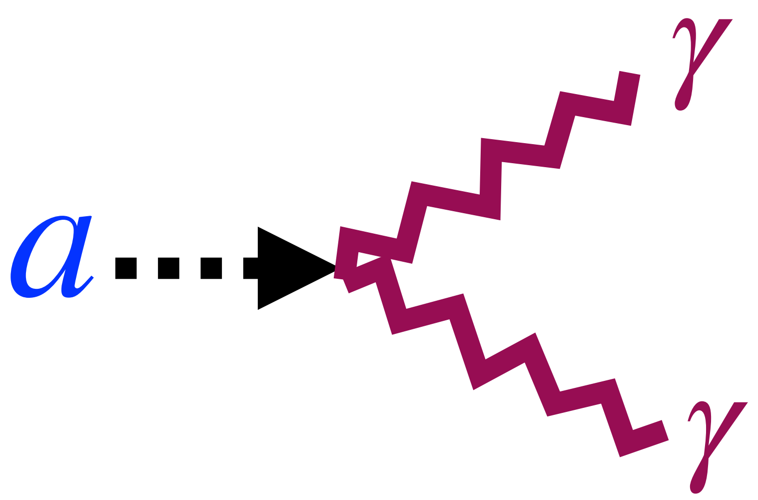
Possible DM mass spreads from $m_{\rm DM} = [10^{-22} eV - M_{\odot}]$. The coupling and spin are unknown. Interestingly, in the huge parameter region, we have coincidences

The **anisotropic cosmic infrared background (CIB)** data suggests a decaying DM with

$m_a \sim eV$, $g_{a\gamma\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$

Gong et al 1511.01577



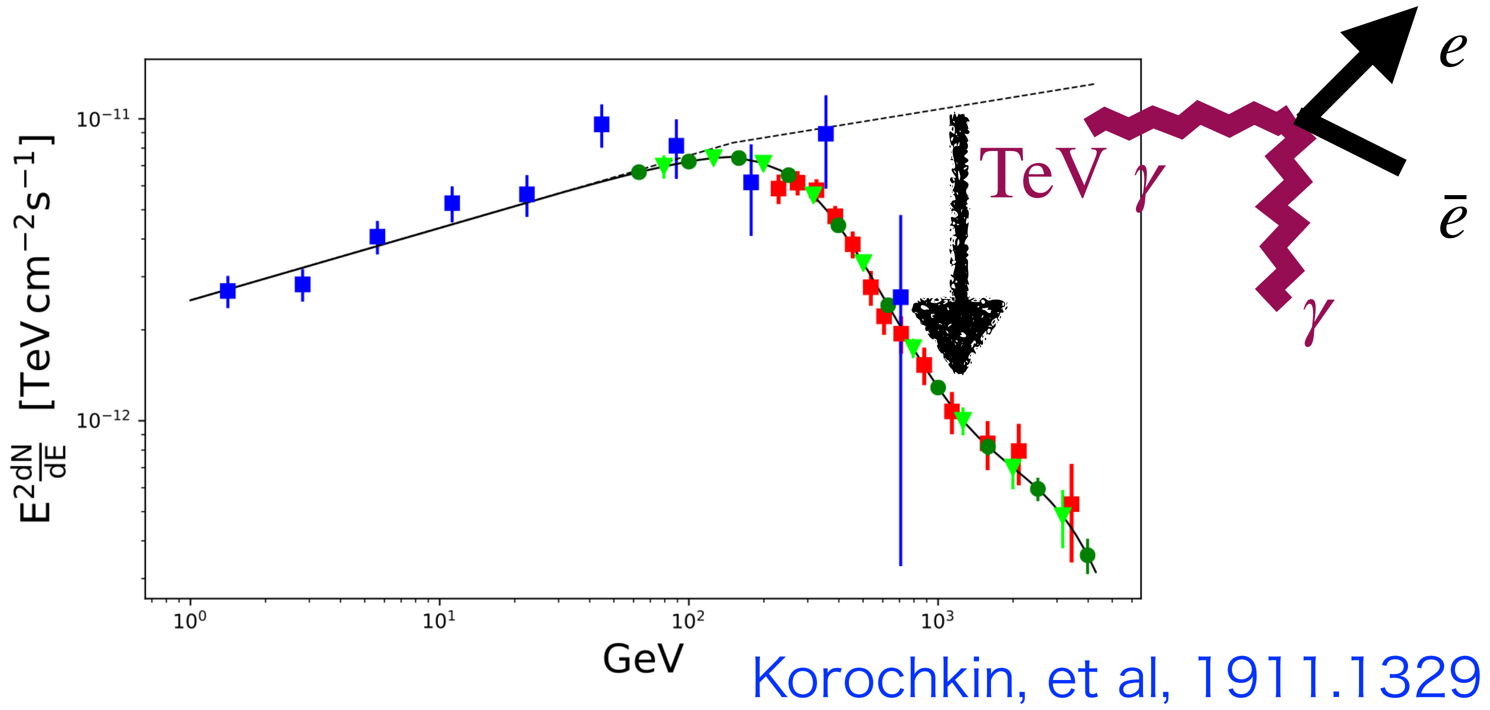


$m_a \sim eV$,

$g_{a\gamma\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$

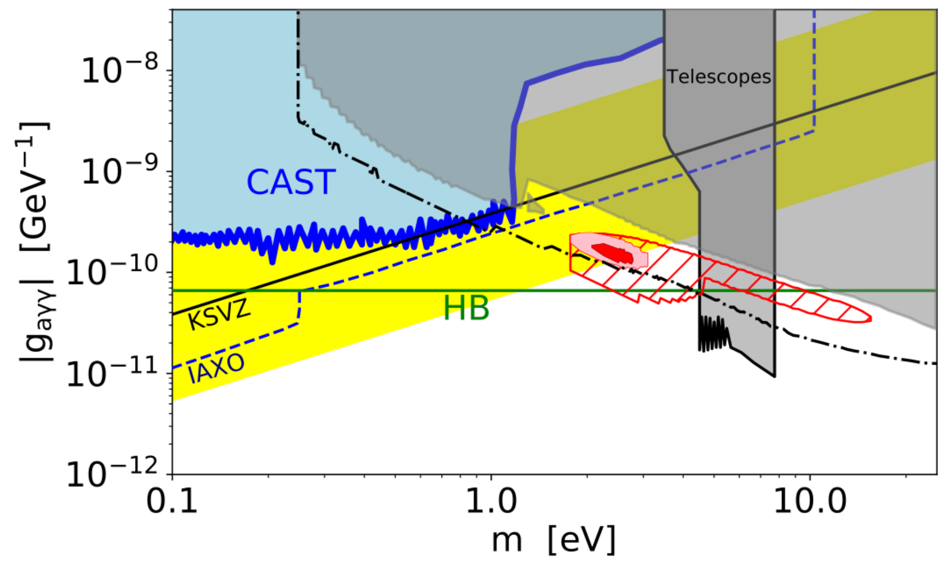
spin=0

The **TeV γ spectrum** gets a better fit by photons from ALP DM of $m_a \sim eV$, $g_{a\gamma\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$



Korochkin, et al, 1911.13291

Bernal et al, 2208.13794



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 the WIMP paradigm.

$$\because n_{\rm DM} \sim T^3, T_{\text{matter-radiation equality}} \sim eV$$

$$m_{\rm DM} \sim eV$$

- However, it is too hot.

- See also ALP miracle scenario, Daido, Takahashi, WY, 1702.03284,1710.11107, where DM=inflaton predicts eV axion.

What I will talk about

WY 2301.08735

- **Thermal production** of eV bosonic **cold** DM, a la hot DM, is **available.**
- eV range DM is still special and theoretically well-motivated.

Setup:

WY 2301.08735

$\chi_1(\text{fermion}) \to \chi_2(\text{fermion})\phi(\text{DM})\,.$

χ_1 mass : $M_1(\ll T)$

χ_2, ϕ : massless

Equations:

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

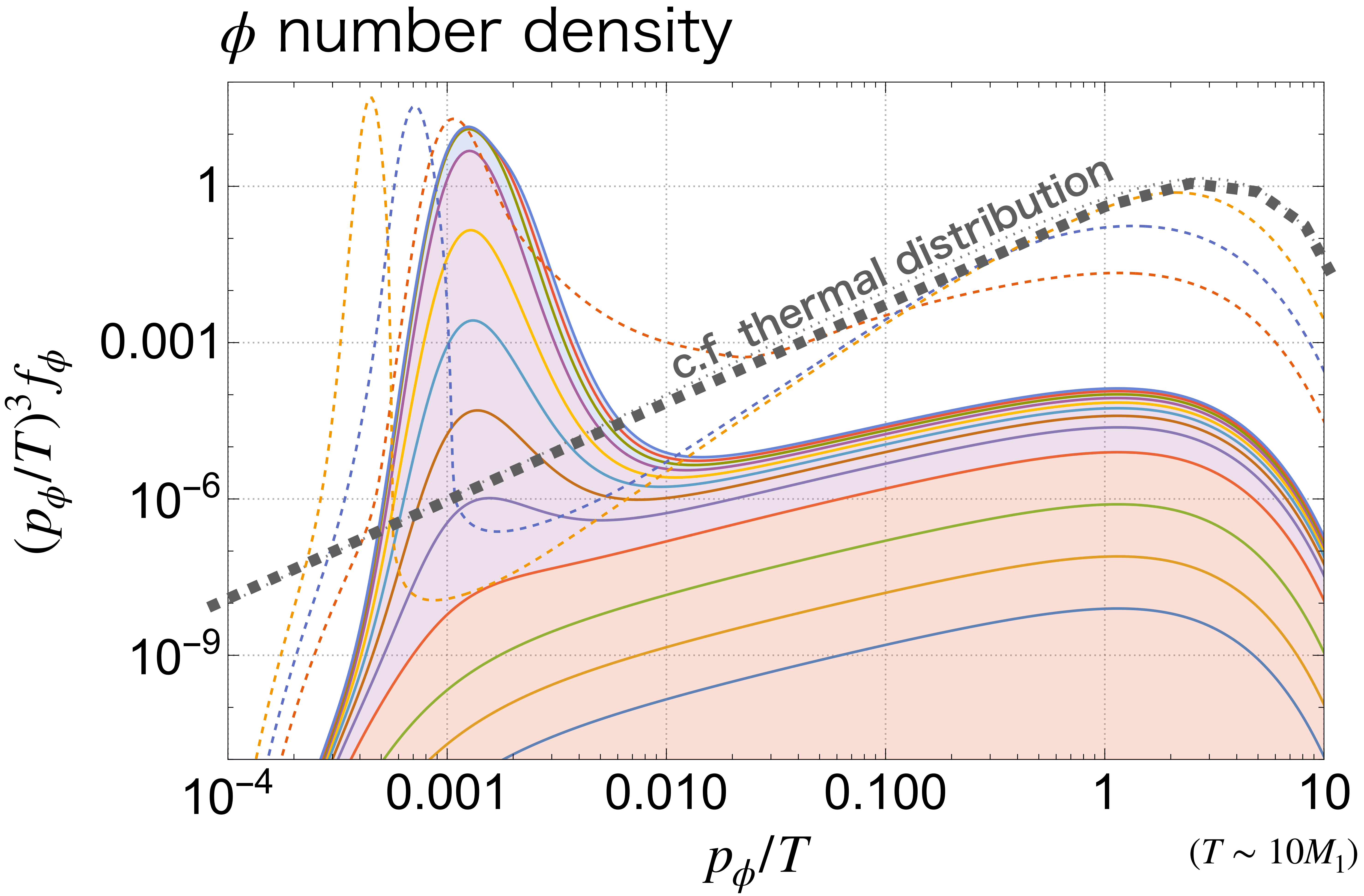
$$C^\phi = \frac{1}{2E_\phi g_\phi}\sum\int d\Pi_{\chi_1}\, d\Pi_{\chi_2}$$
$$(2\pi)^4\delta^4(p_{\chi_1} - p_\phi - p_{\chi_2}) \times |\mathcal{M}_{\chi_1\to\chi_2\phi}|^2$$
$$\times S\left(f_{\chi_1}[p_{\chi_1}], f_{\chi_2}[p_{\chi_2}], f_\phi[p_\phi]\right)$$

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

(Initial) conditions:

χ_1 is always thermalized, while χ_2 and ϕ are absent initially .

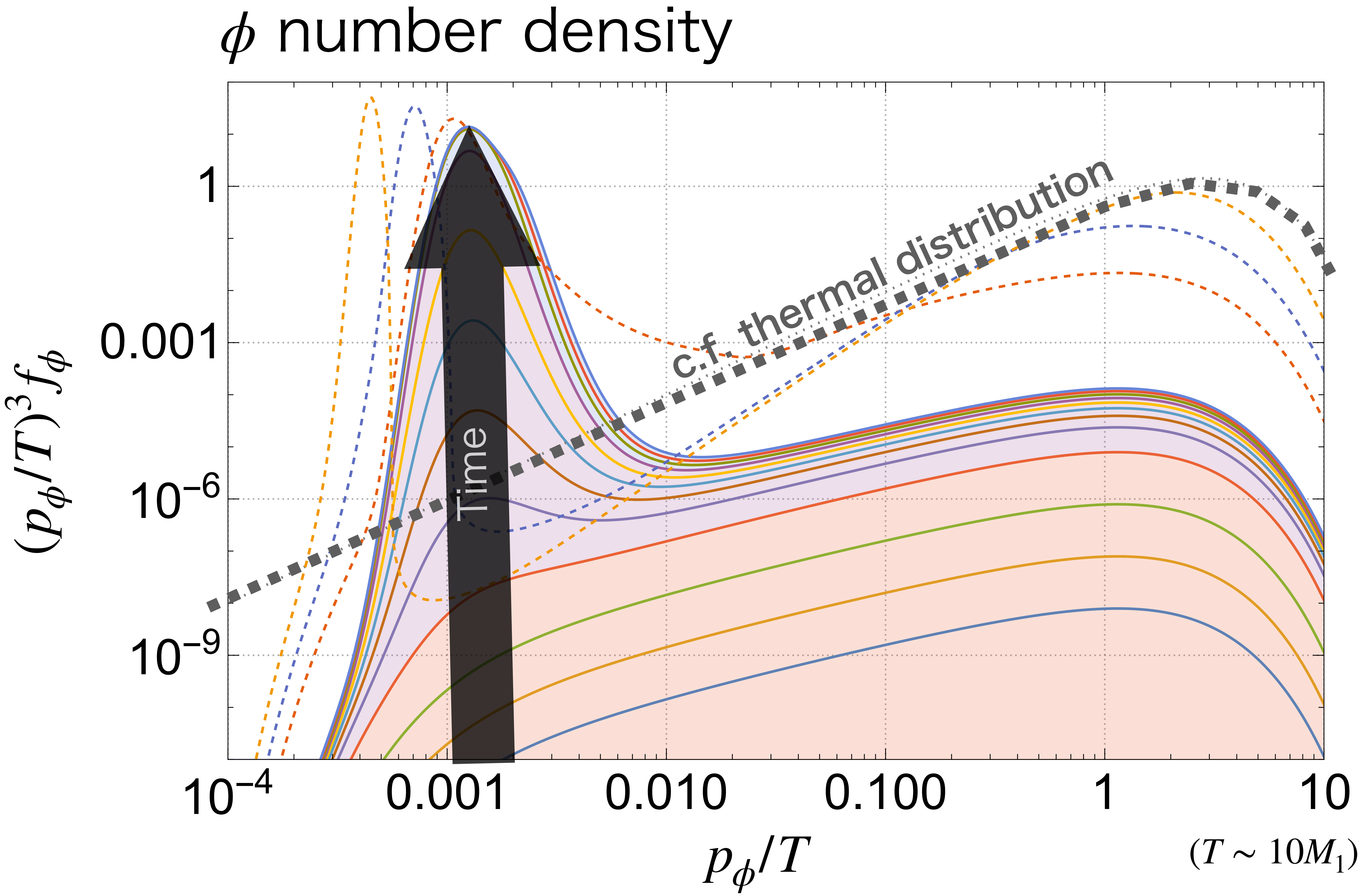
Burst production of DM ϕ turns out thanks to bose enhancement.



Three stages of burst production:

1. Ignition
2. Burst
3. Saturation

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



Three stages of burst production:

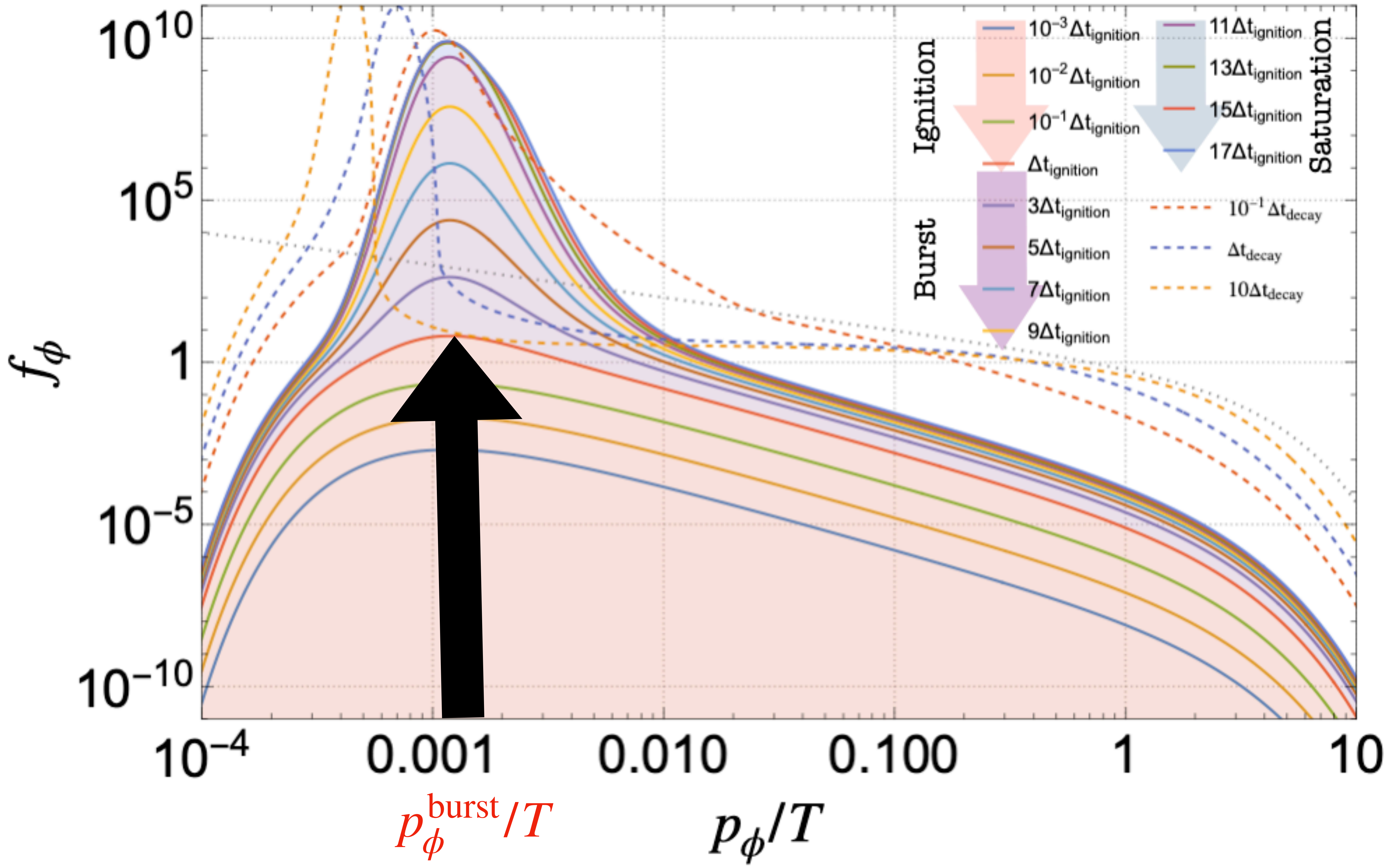
1. Ignition
2. Burst
3. Saturation

Stage 1: Ignition (occupation number ~1)

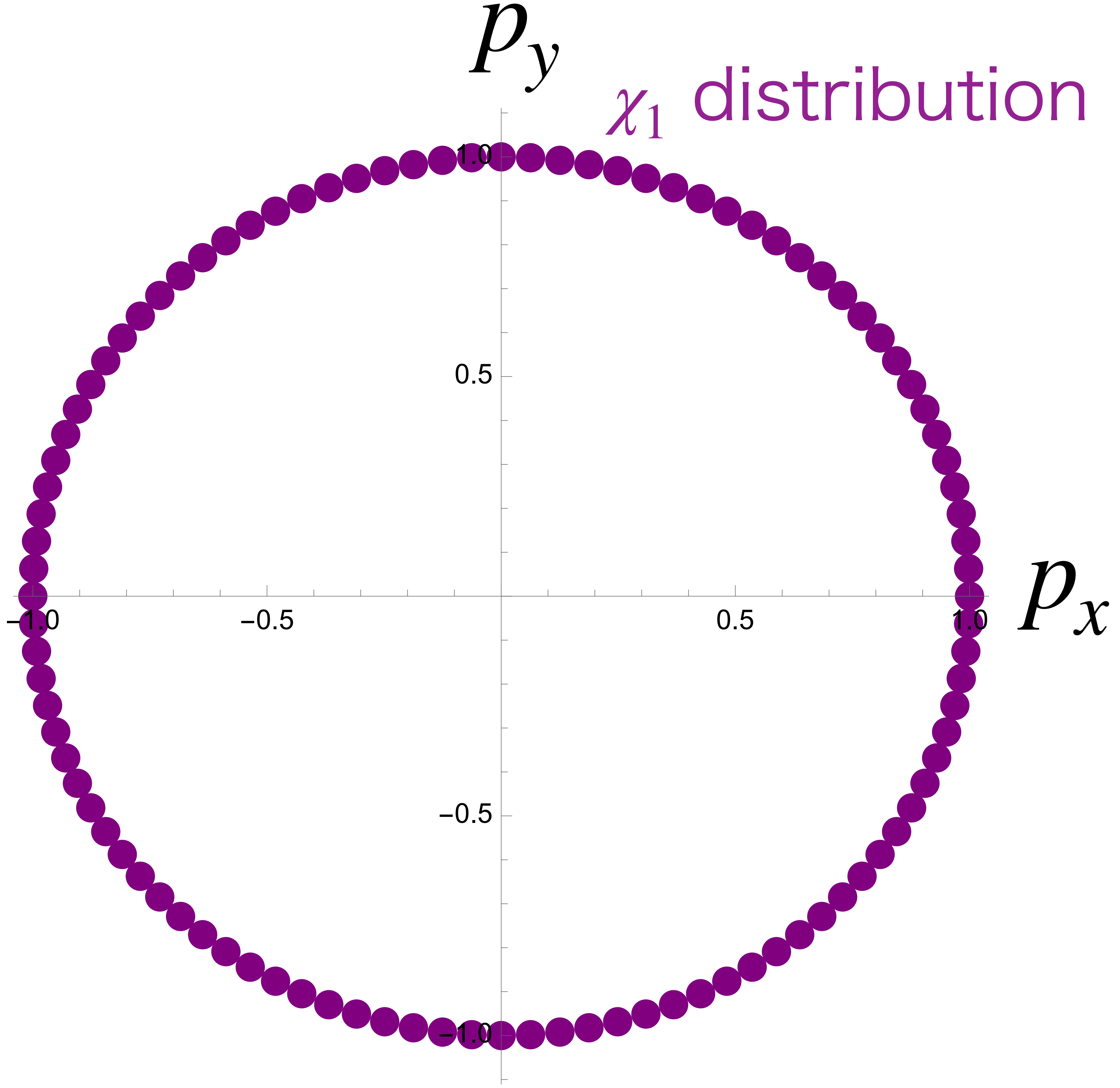
-Occupation number at $p_\phi \sim\ p_\phi^{\rm burst} \sim M_1^2/T$ increases fastest.

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

Occupation number



Simplified model.

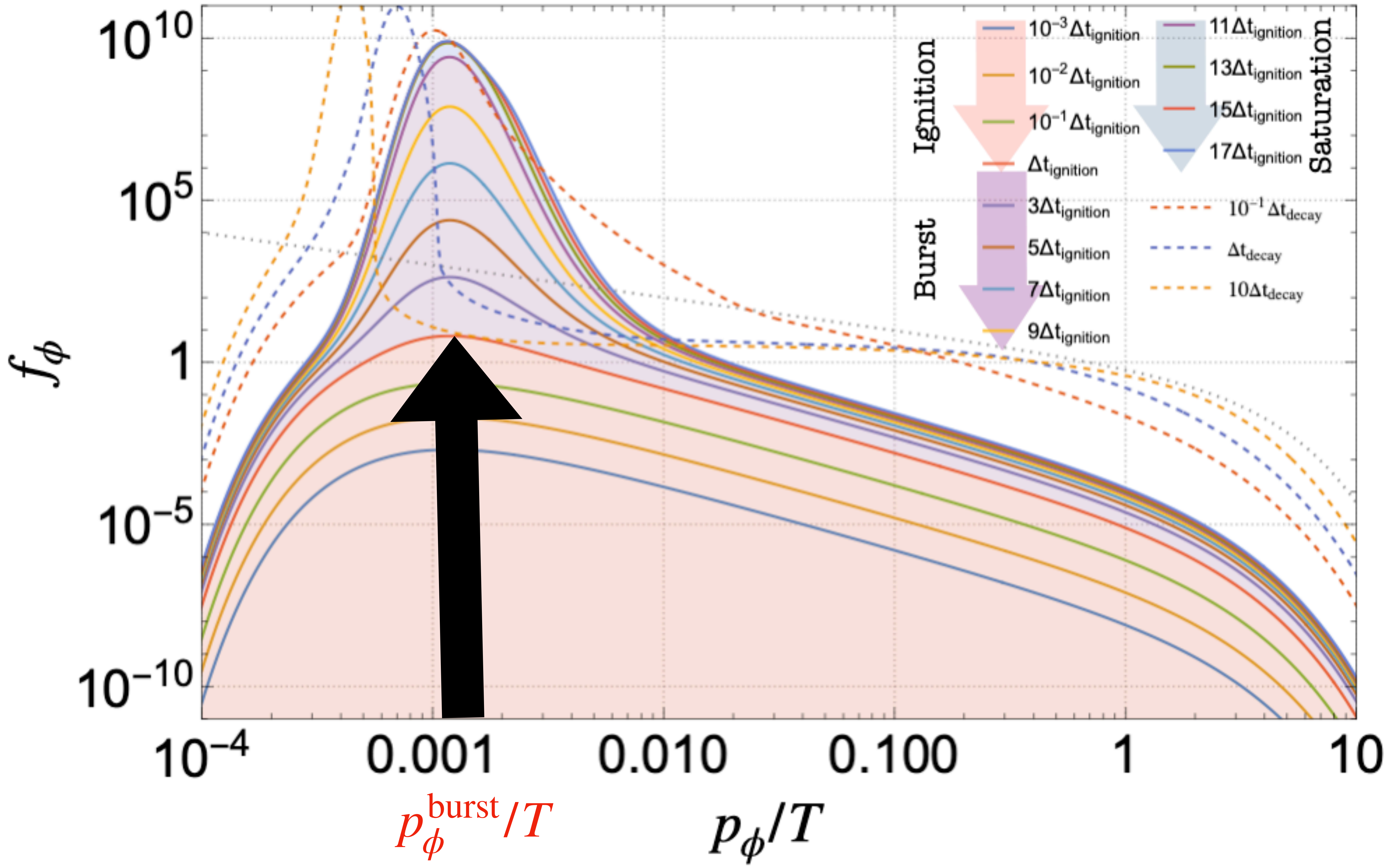


Stage 1: Ignition (occupation number ~1)

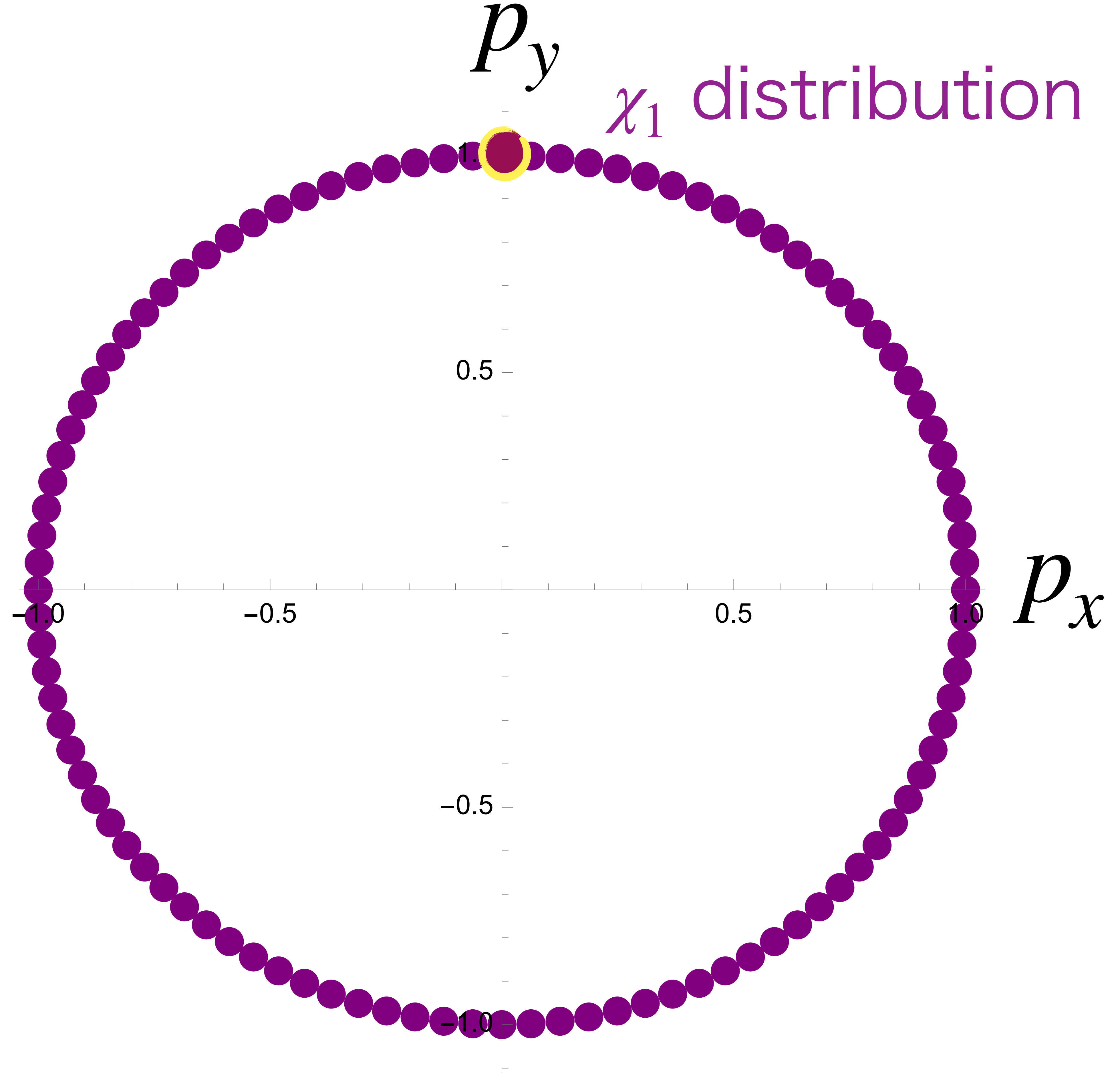
-Occupation number at $p_\phi \sim\ p_\phi^{\mathrm{burst}} \sim M_1^2/T$ increases fastest.

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

Occupation number



Simplified model.

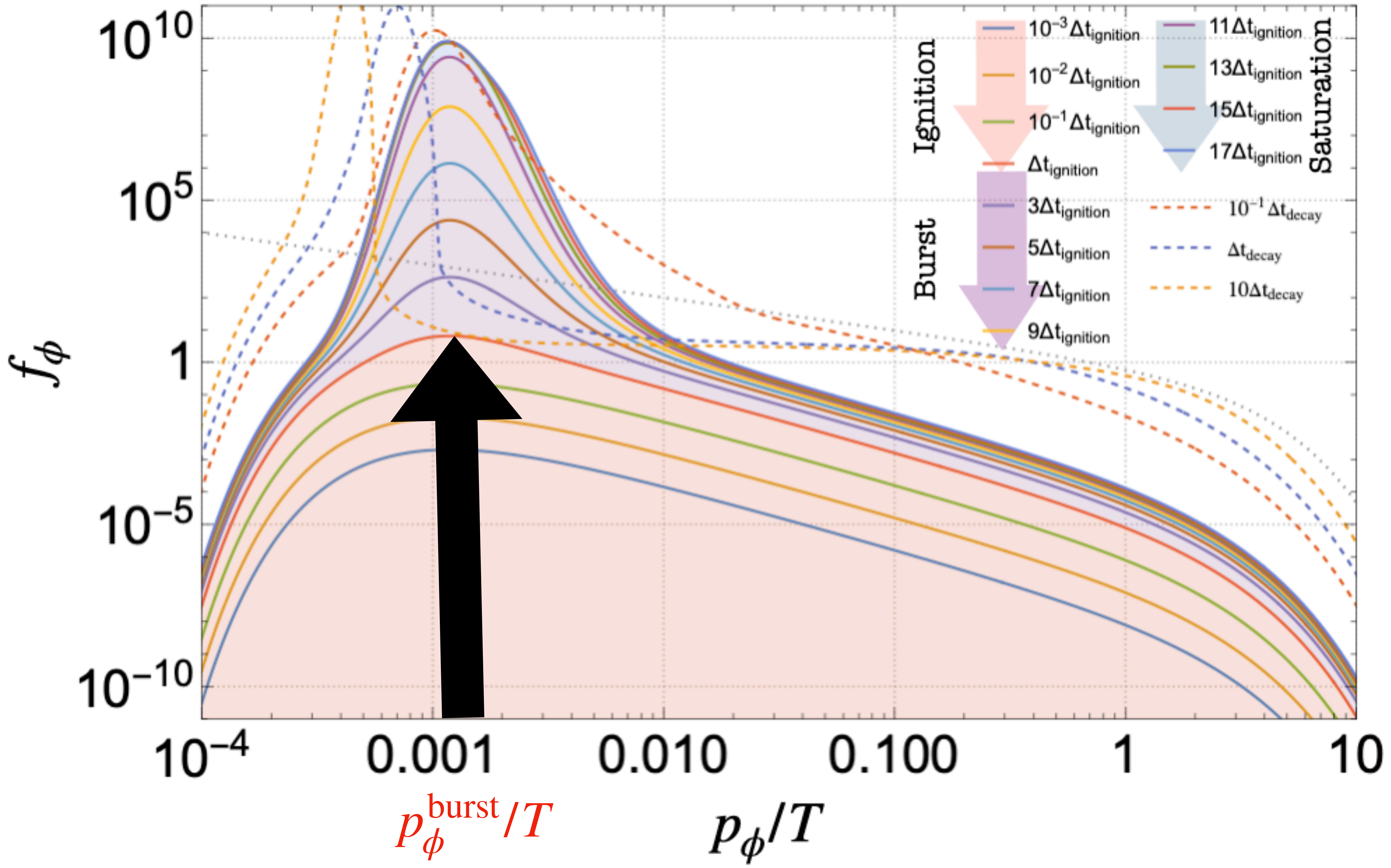


Stage 1: Ignition (occupation number ~1)

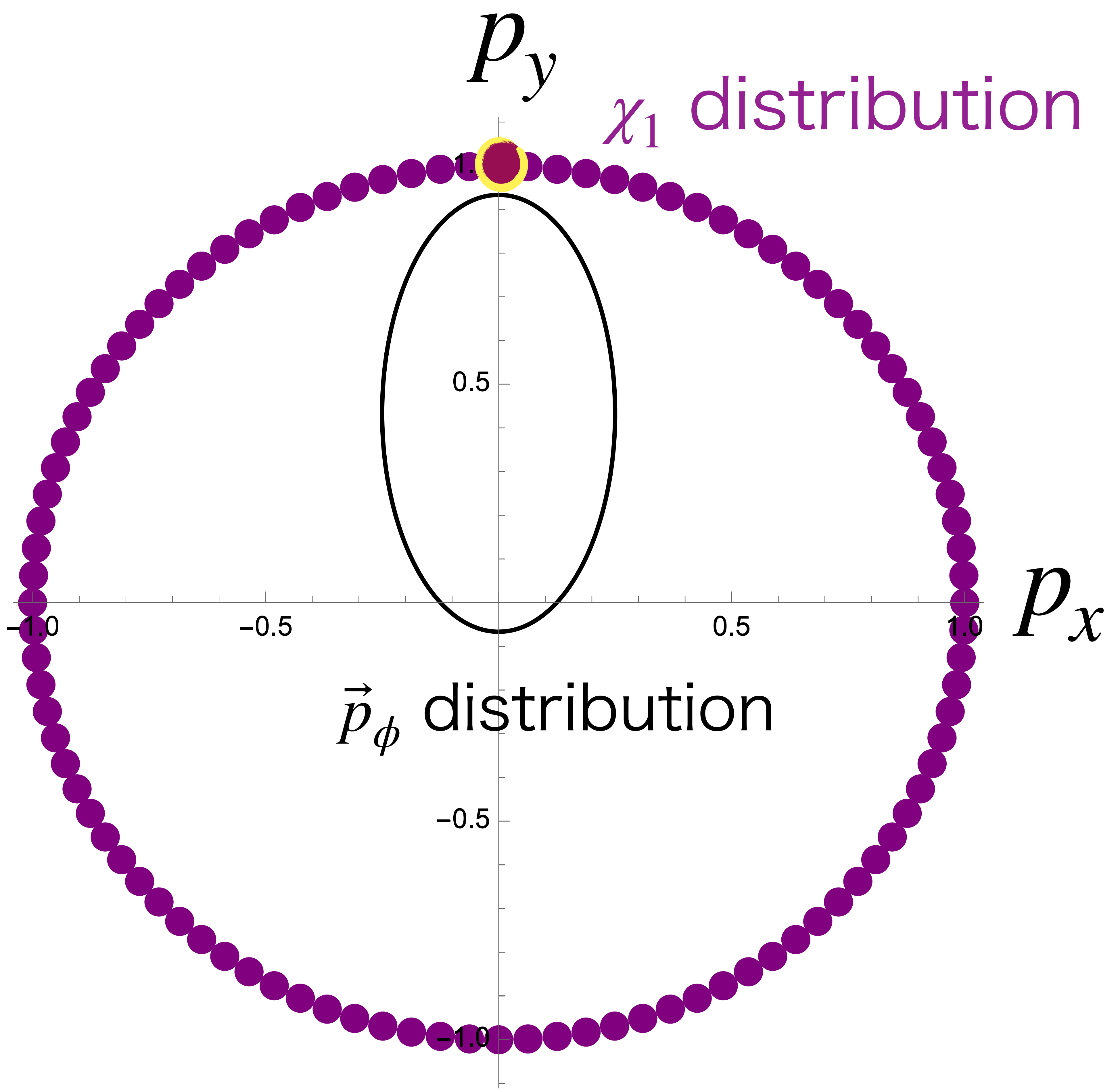
-Occupation number at $p_\phi \sim p_\phi^{\rm burst} \sim M_1^2/T$ increases fastest.

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

Occupation number



Simplified model.

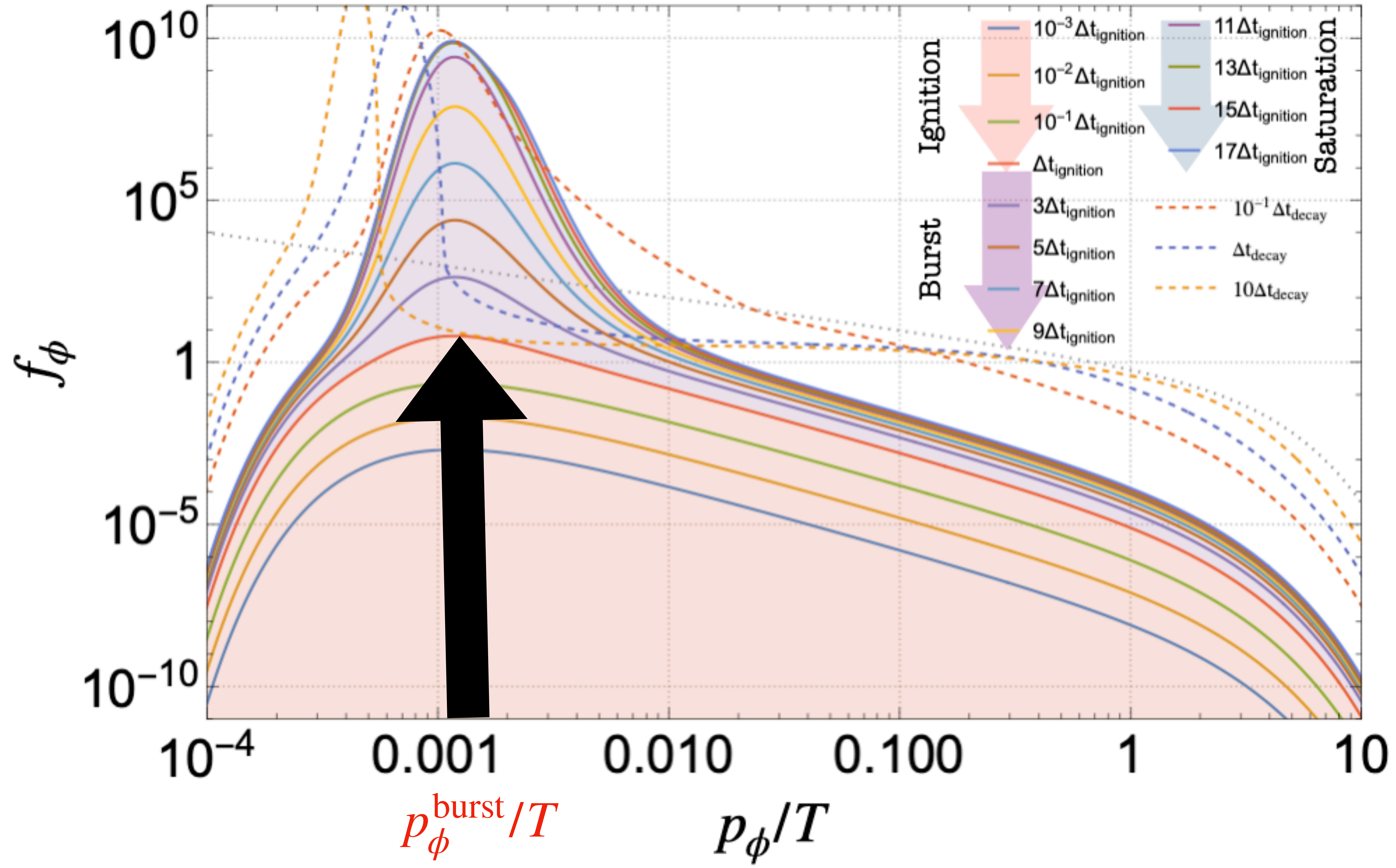


Stage 1: Ignition (occupation number ~1)

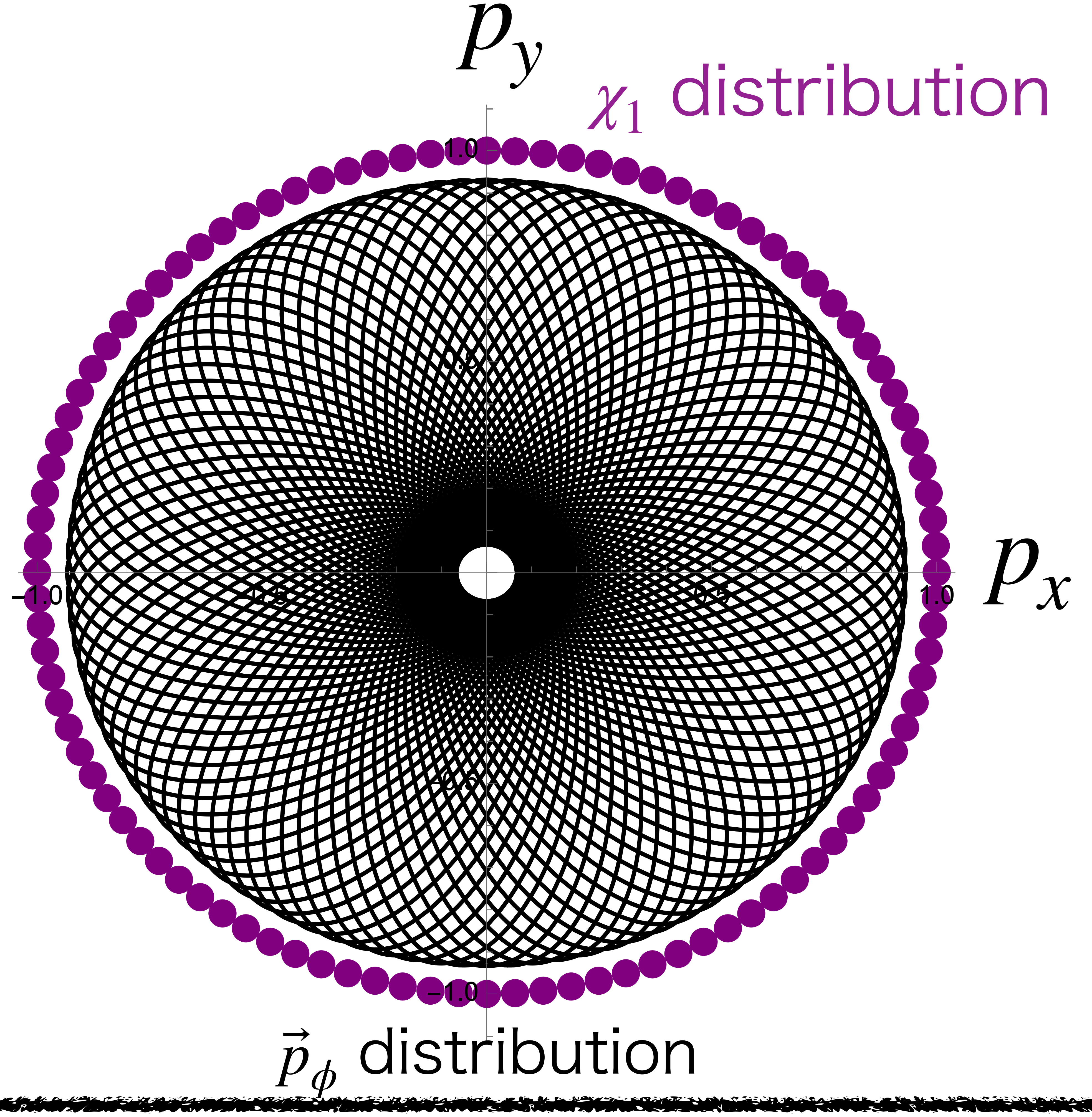
-Occupation number at $p_\phi \sim \ p_\phi^{\rm burst} \sim M_1^2/T$ increases fastest.

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

Occupation number



Simplified model.

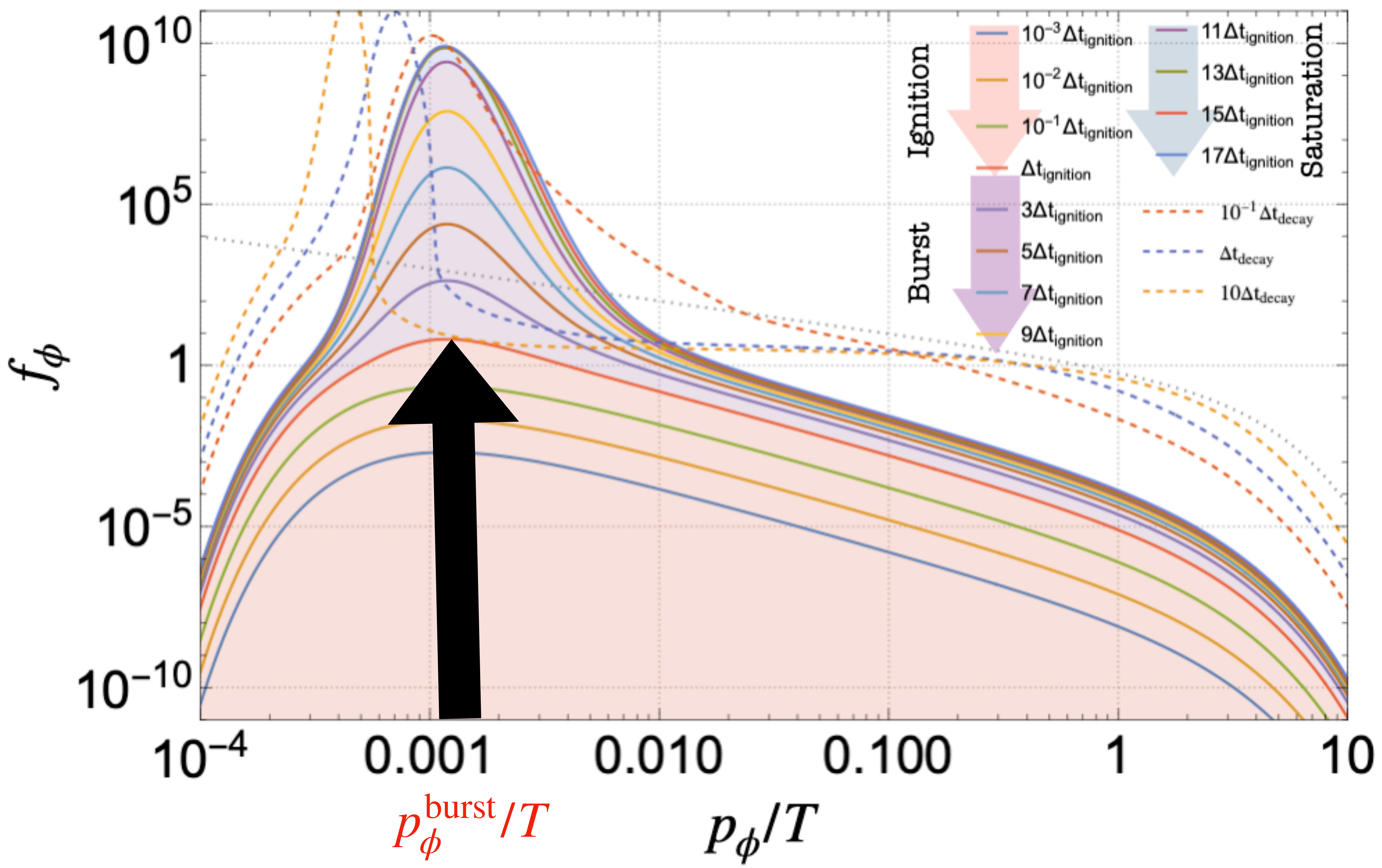


Stage 1: Ignition (occupation number ~1)

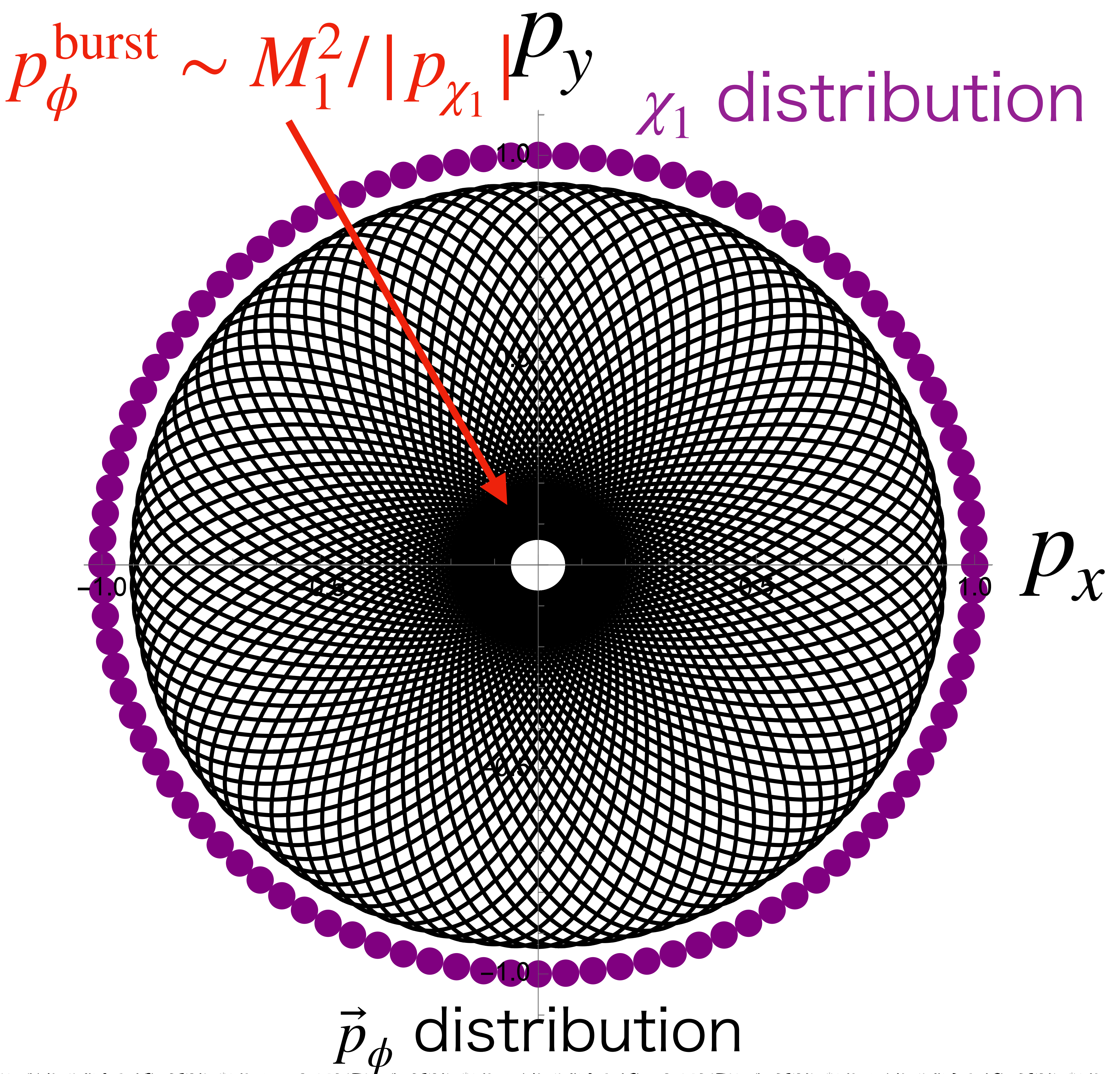
-Occupation number at $p_\phi \sim\ p_\phi^{\rm burst} \sim M_1^2/T$ increases fastest.

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

Occupation number

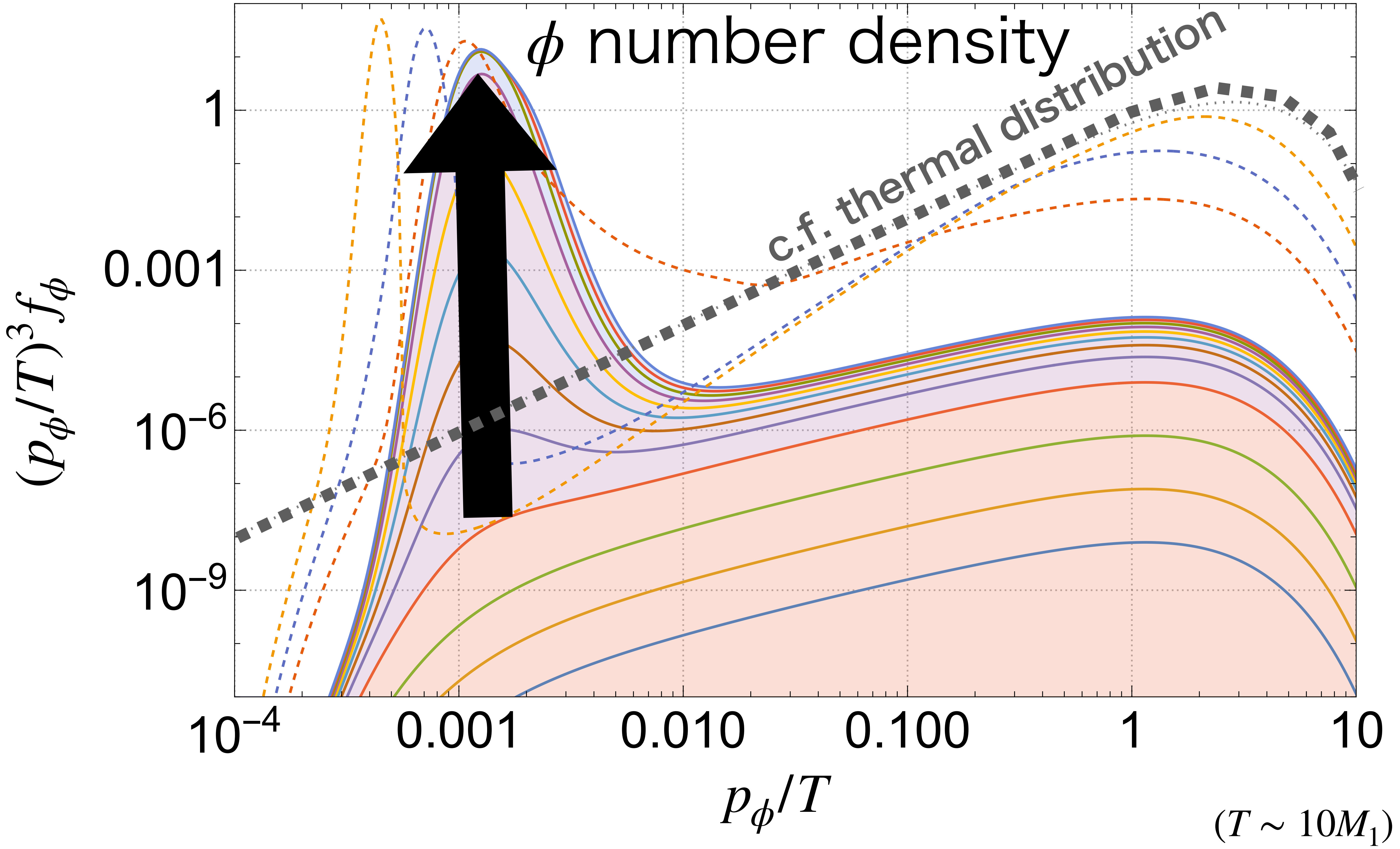


Simplified model.



Stage 2: Burst (Bose-enhanced production)

$p_\phi^{\rm burst}$ modes grow exponentially due to Bose enhancement. So does ϕ number density.



$(T \sim 10 M_1)$

$$(p_\phi^{\rm burst})^3 f_\phi[p_\phi \sim p_\phi^{\rm burst}]$$

$$\sim (p_\phi^{\rm burst})^3 \exp[t/\Delta t_{\rm ignition}]$$

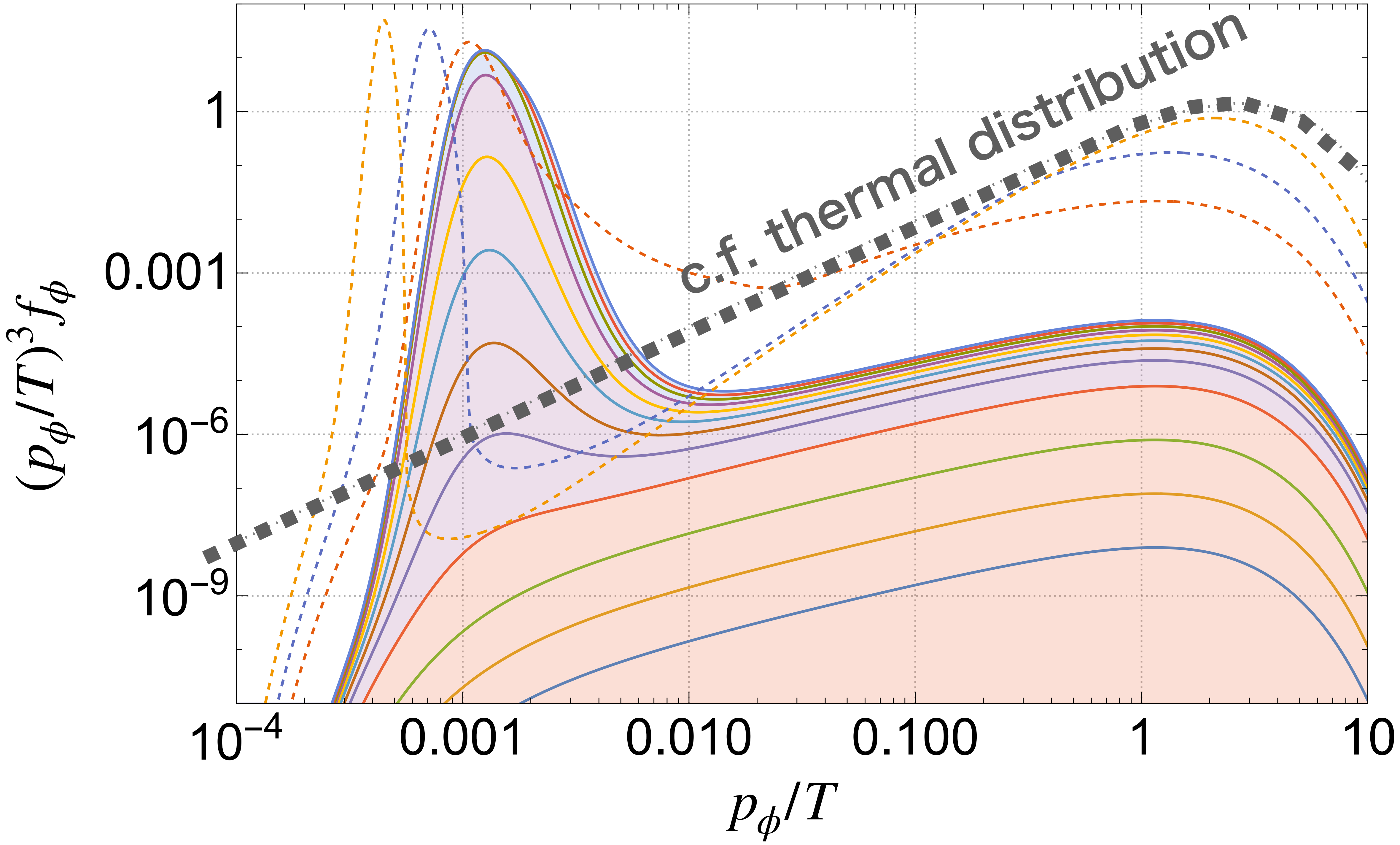
$$\sim n_\phi[t]$$

Stage 3: Saturation (quasi-equilibrium)

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

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

ϕ number density



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

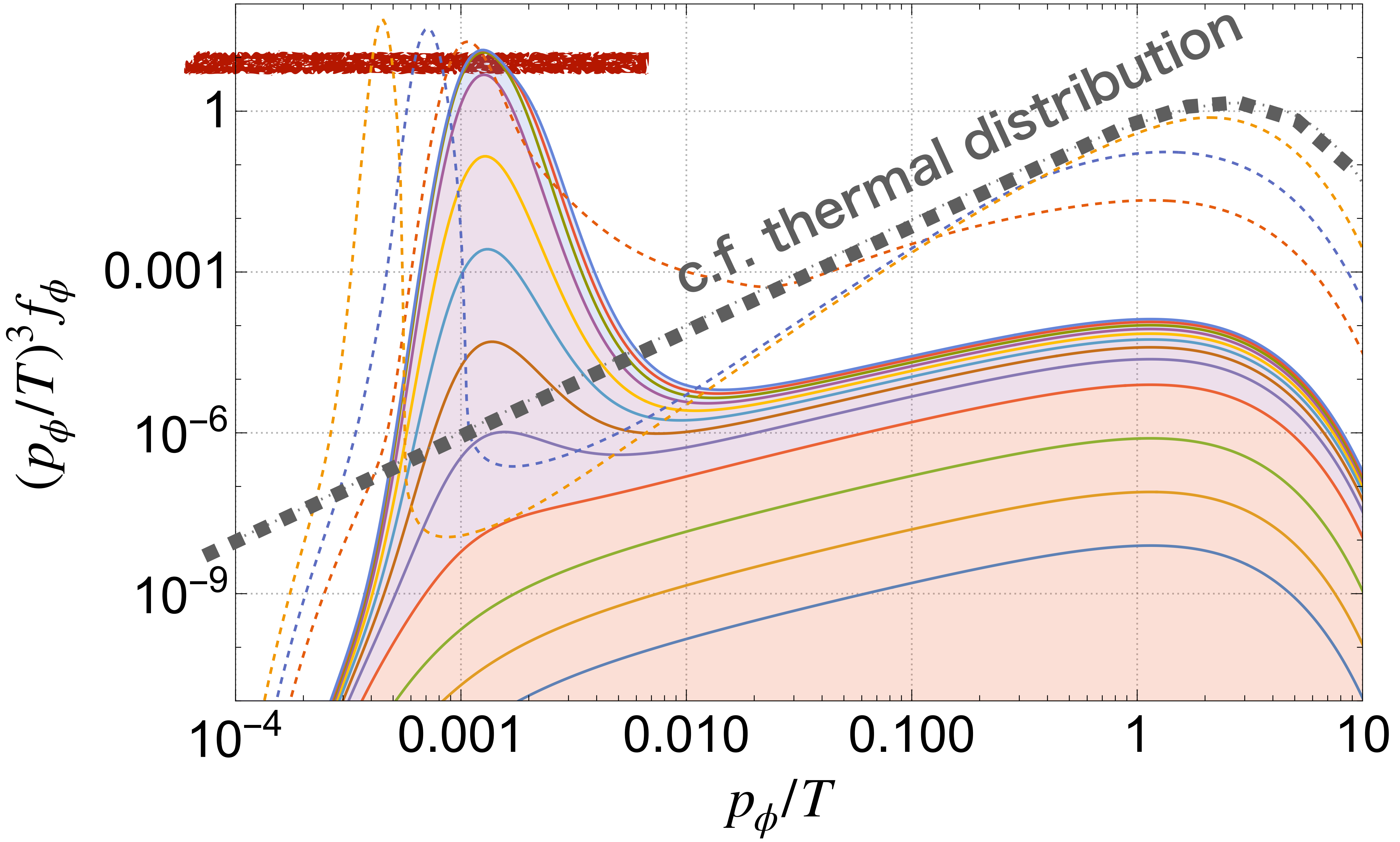
$$t \sim \left(\Gamma_{\rm decay}^{\rm (proper)}\right)^{-1} \frac{T}{M_1} \sim \left(\frac{T}{M_1}\right)^4 \Delta t_{\rm ignition}.$$

Stage 3: Saturation (quasi-equilibrium)

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

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

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



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

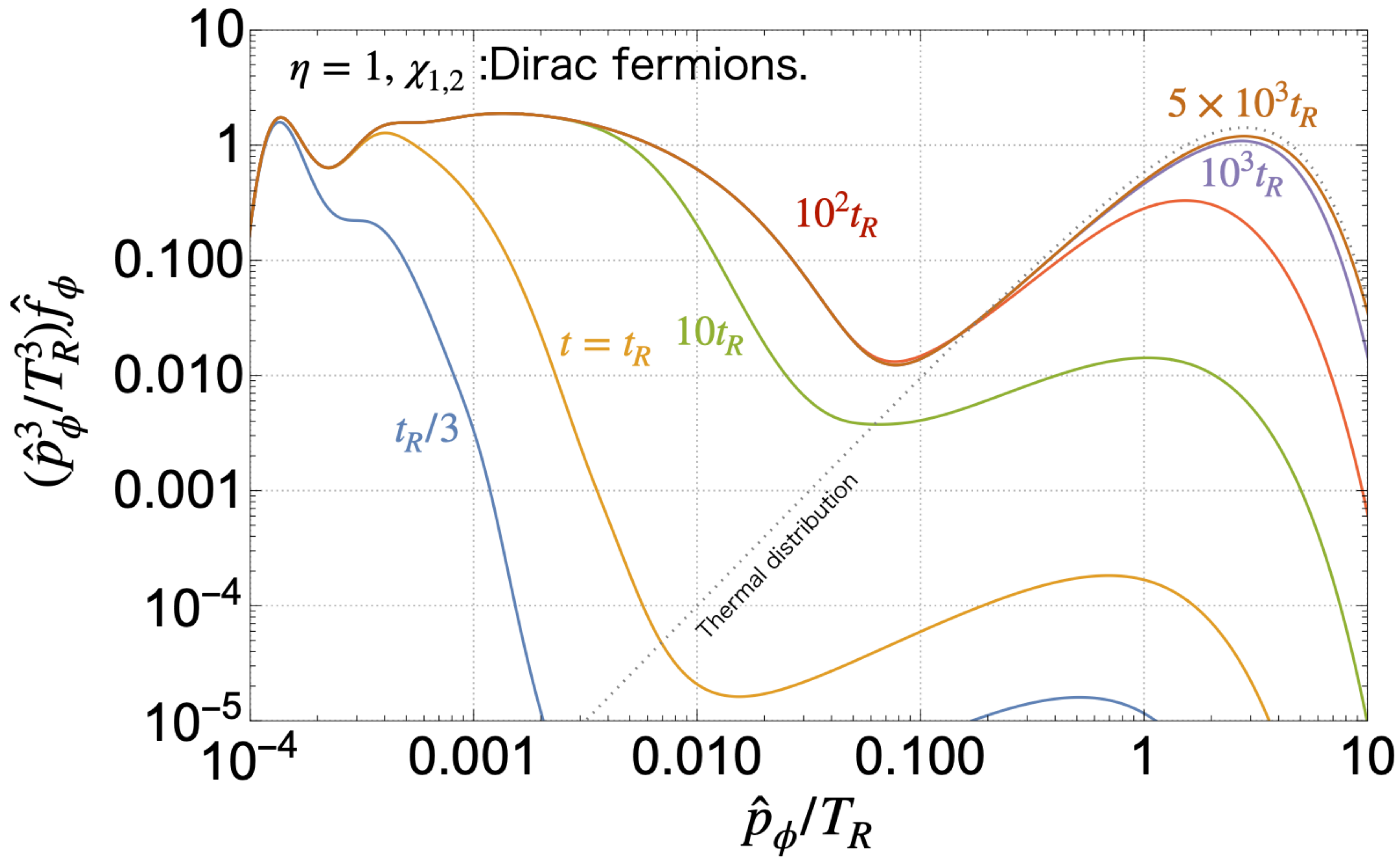
$$t \sim \left(\Gamma_{\rm decay}^{\rm (proper)}\right)^{-1} \frac{T}{M_1} \sim \left(\frac{T}{M_1}\right)^4 \Delta t_{\rm ignition}.$$

Burst production in expanding Universe

If there is a period satisfying

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

the burst produced ϕ remains due to redshift and kinematics.



$\because n_\phi \sim T^3, p_\phi \sim M_1^2/T_{\text{burst}} \times T/T_{\text{burst}}$

Prediction:

Cold DM

with

$m_{\text{DM}} = [1\text{-}100] eV$

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

WY 2301.08735

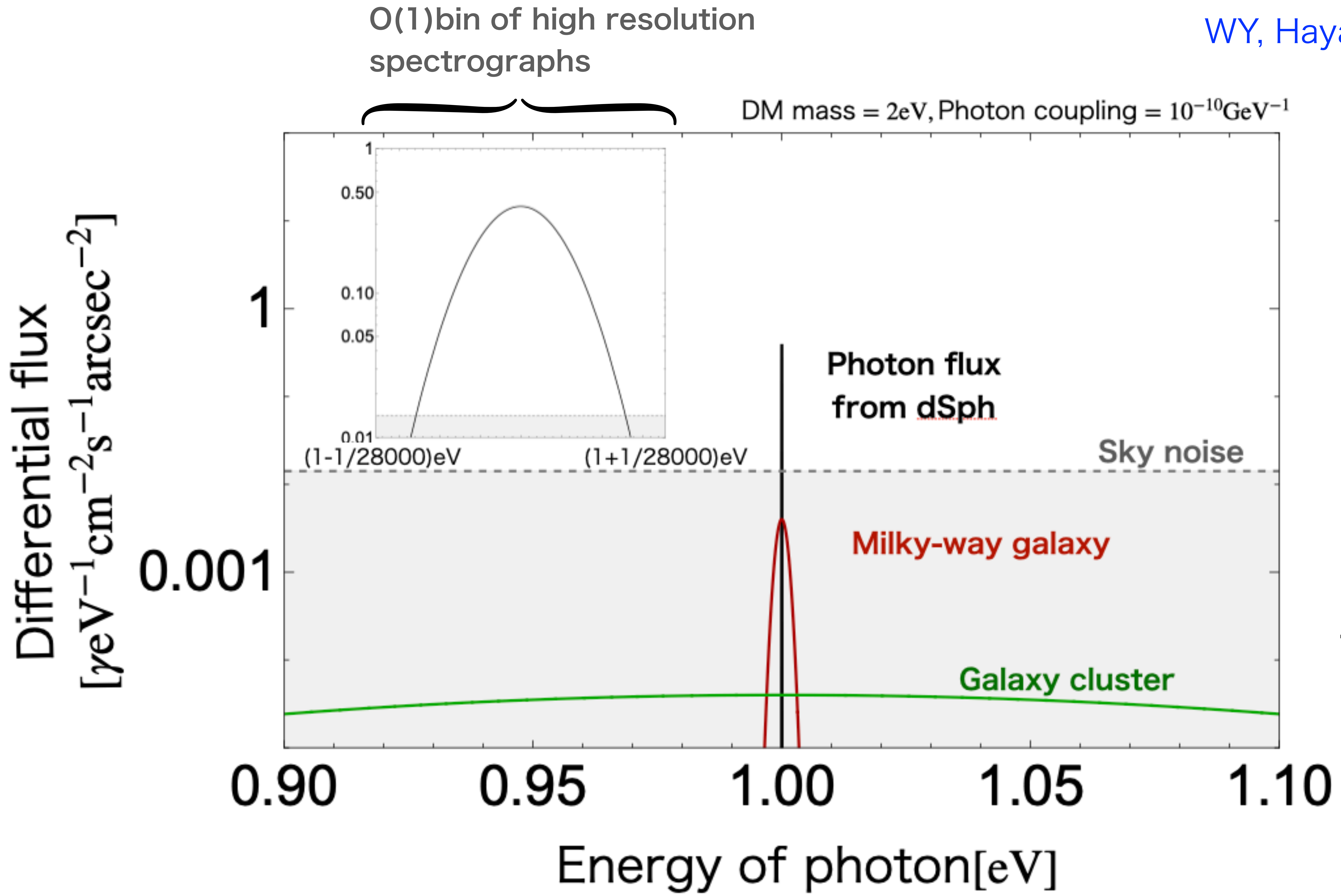
- eV range DM is still special and theoretically well-motivated, a la hot DM paradigm. The cosmic-infrared background and γ-ray hints may be interesting.

- Predictions of freeze-in scenarios $\chi_1 \to \chi_2 \phi$, $\Phi_1 \to \phi\phi$, may be significantly altered by this effect.

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

One can confirm the hints by using infrared spectrographs

T. Bessho, Y. Ikeda, WY, Phys.Rev.D 106 (2022) 9, 095025,
WY, Hayashi, 2305.13415

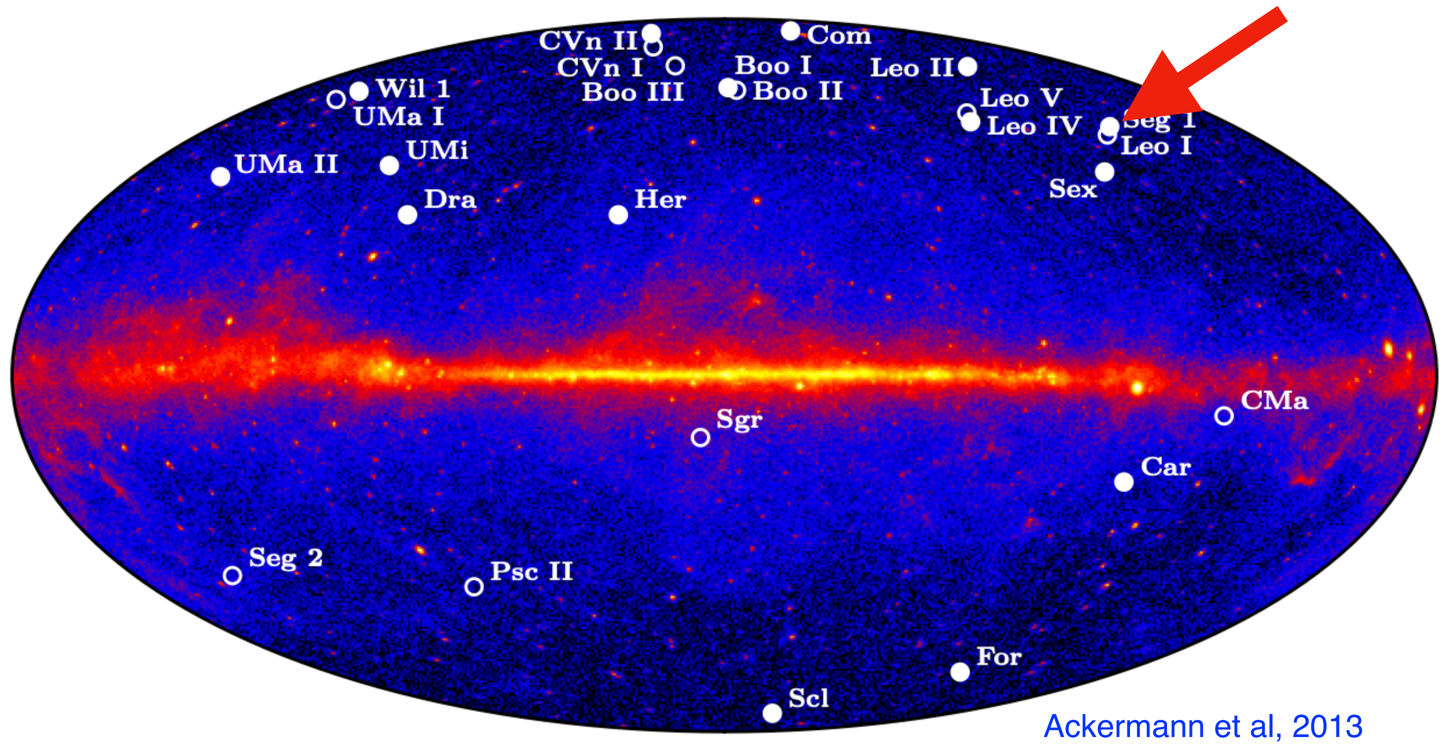


-DM signals from Dwarfs are **sky background free** for existing high energy resolution infrared spectrographs.

-With high angular resolution one can “see” the DM distribution from the decay photon in dwarfs.

WY, Hayashi, 2305.13415

eV DM search with WINERED @ Magellan

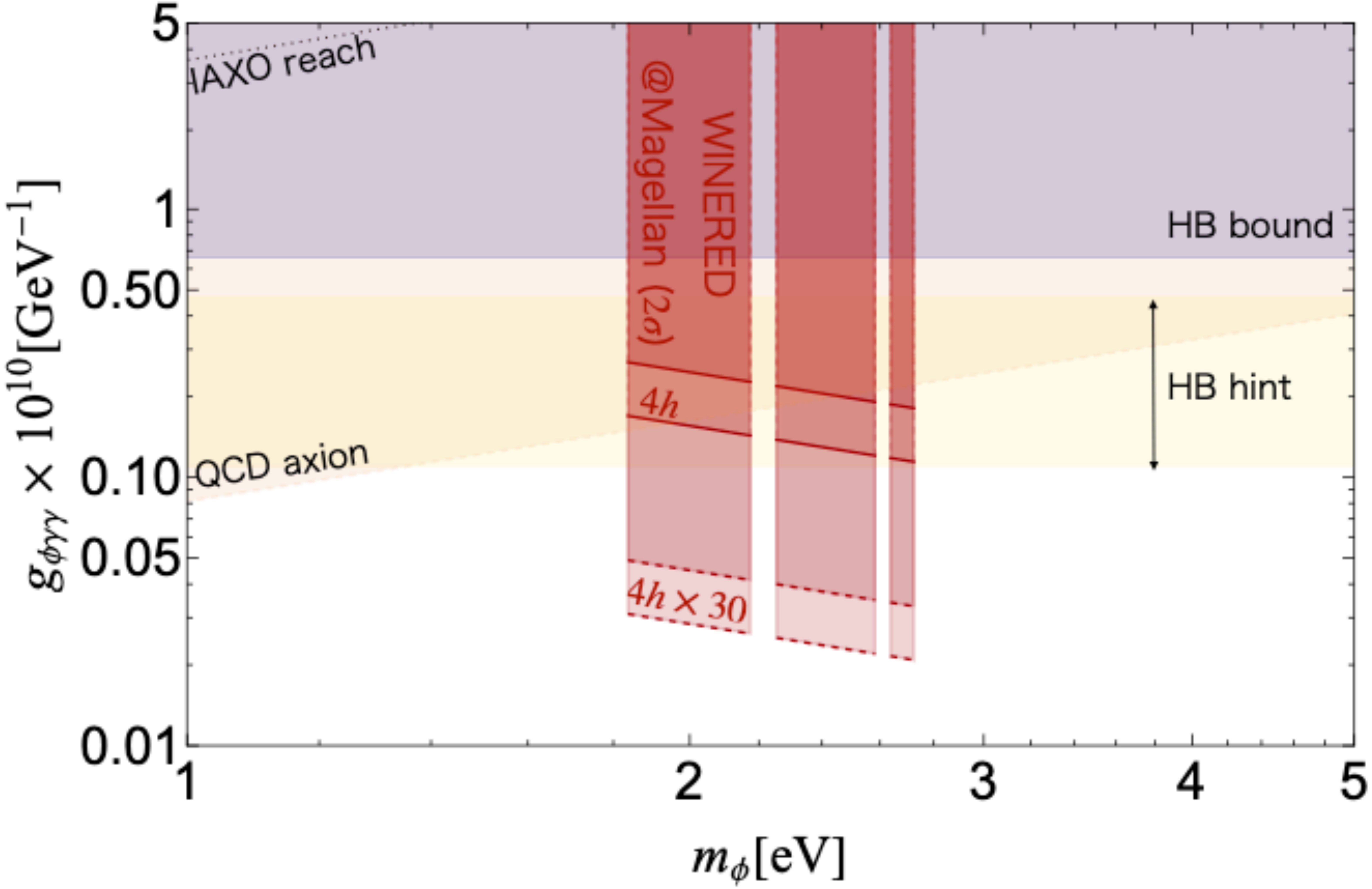


Ackermann et al, 2013

https://www.cfa.harvard.edu

A high-resolution infrared spectrograph is one of the most efficient DM detectors.

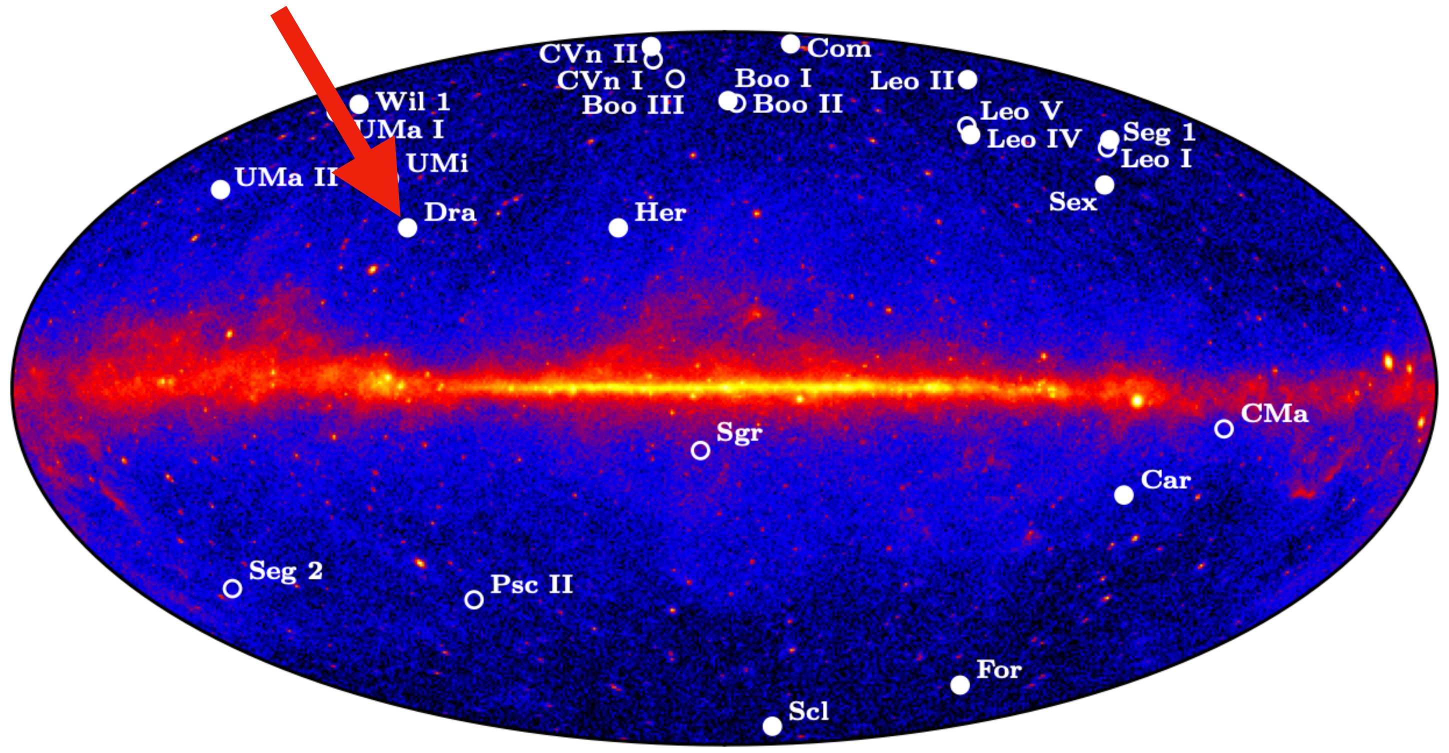
T. Bessho, Y. Ikeda, WY, Phys.Rev.D 106 (2022) 9, 095025,

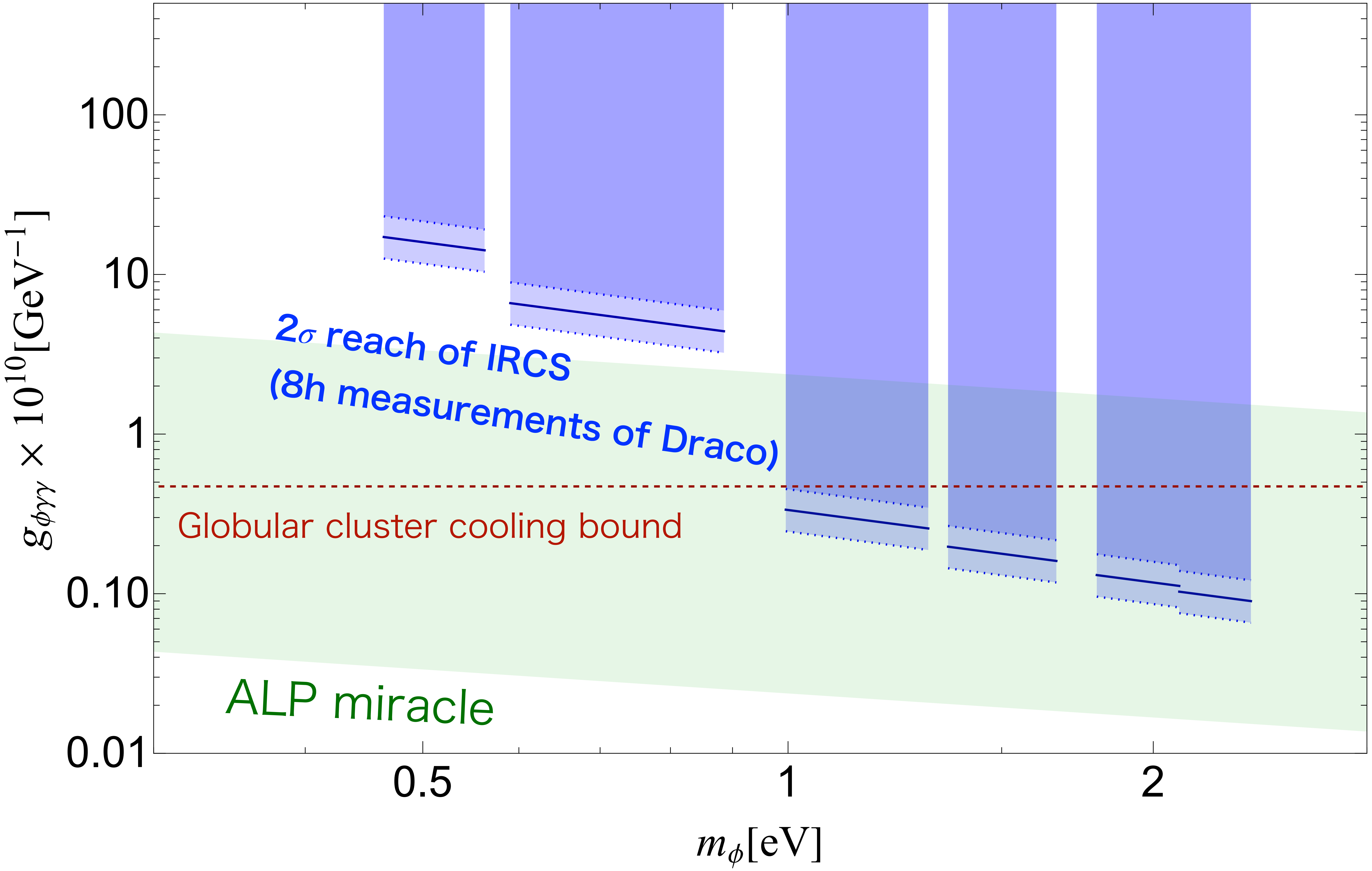


eV DM search with IRCS @ Subaru

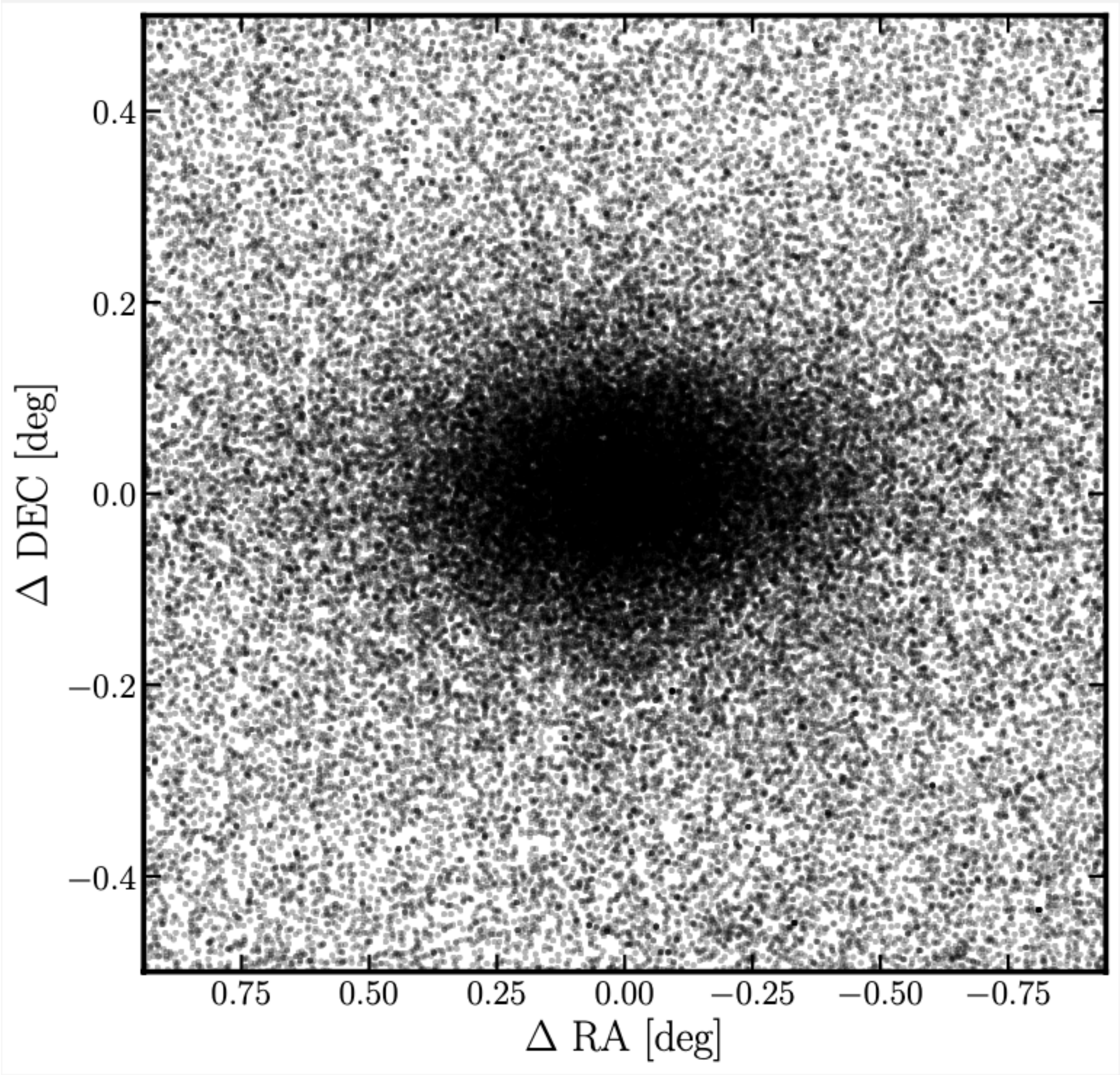
The high angular resolution requires a different estimation of DM signals. We estimated the DM (star) distributions around the centers of 35 (34) dSphs and show typical O(10) enhancement in signal rate.

WY, Hayashi 2305.13415



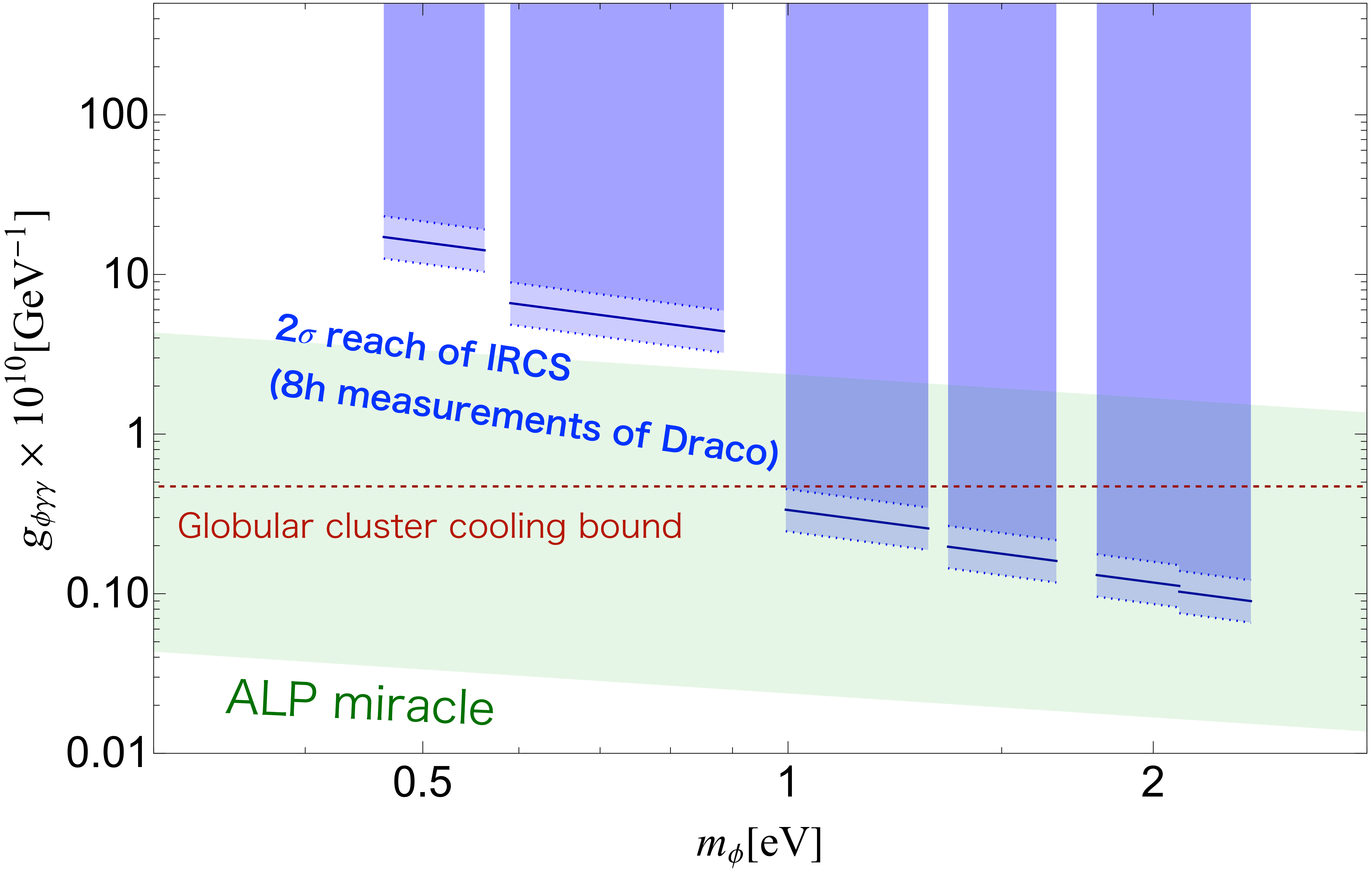


eV DM search with IRCS @ Subaru

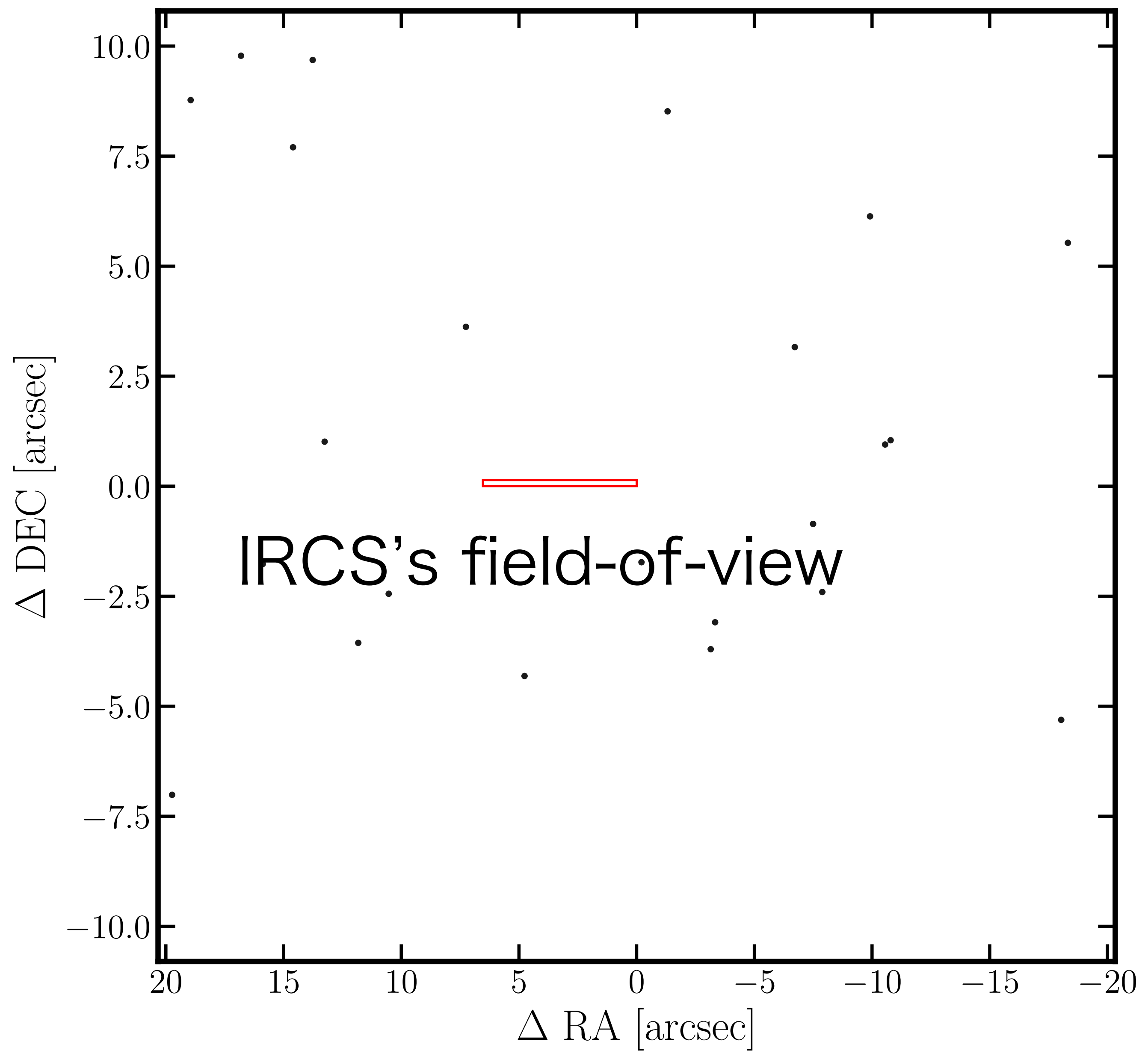


The high angular resolution requires a different estimation of DM signals. We estimated the DM (star) distributions around the centers of 35 (34) dSphs and show typical O(10) enhancement in signal rate.

WY, Hayashi 2305.13415

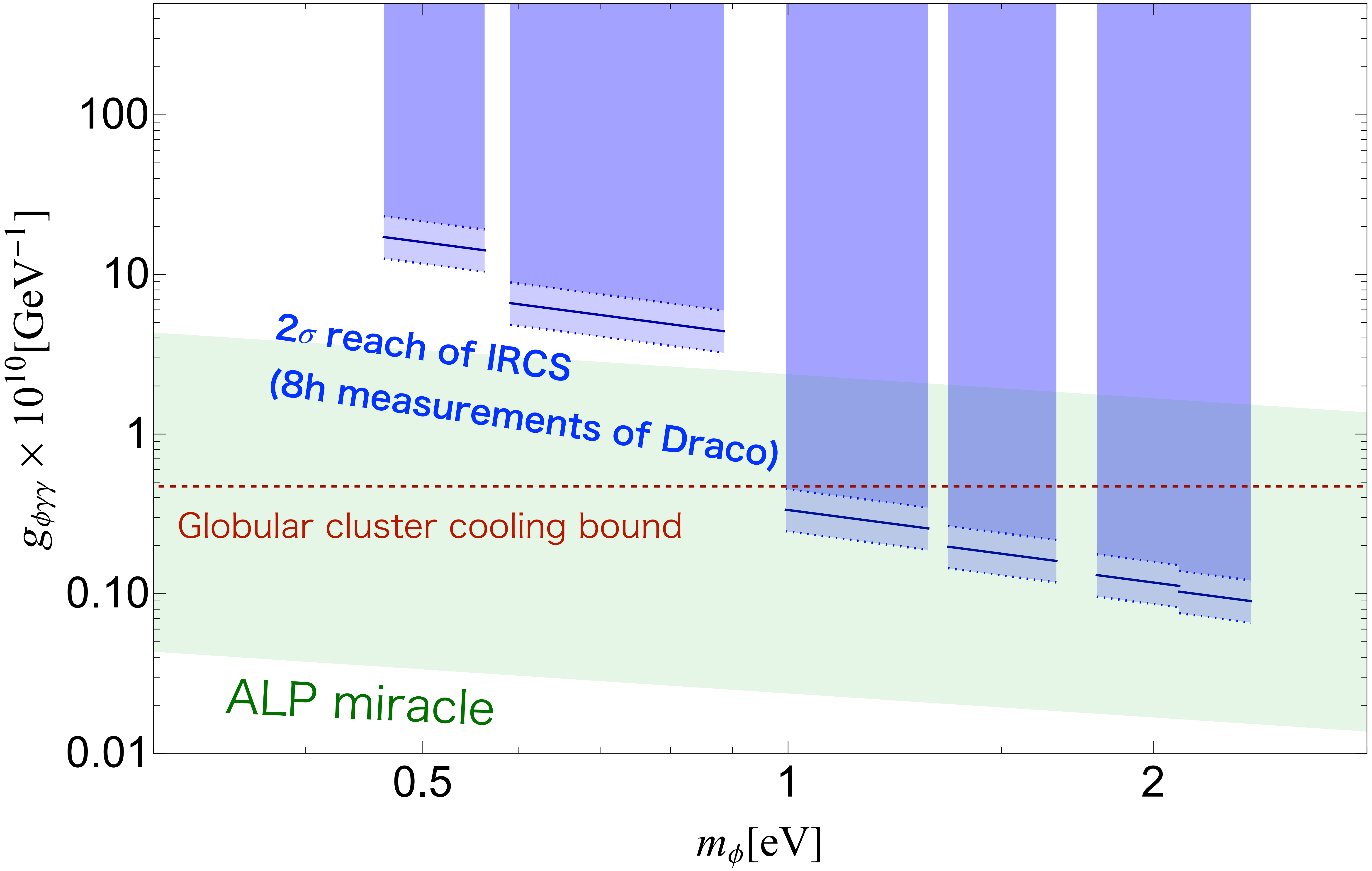


eV DM search with IRCS @ Subaru

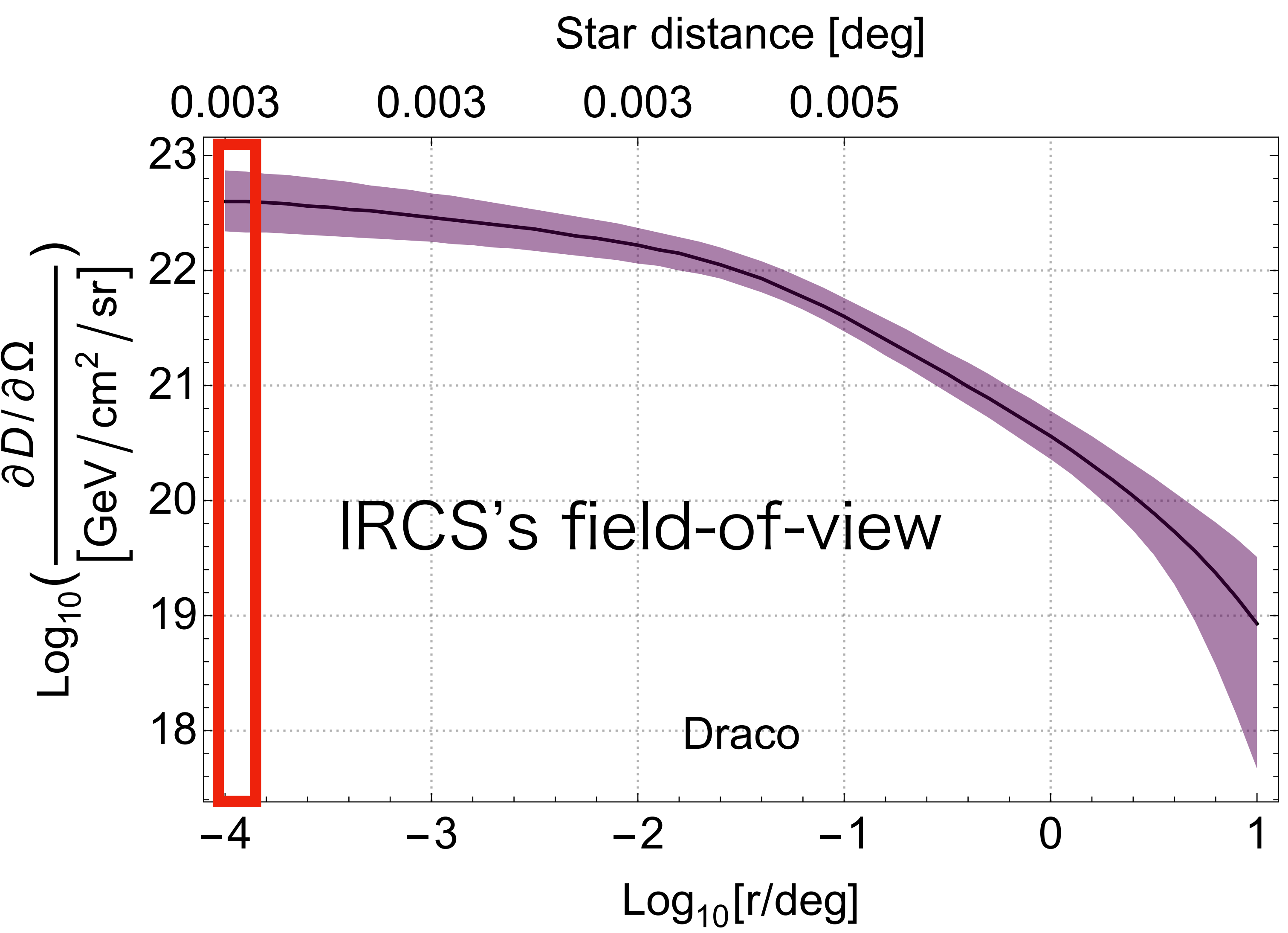


The high angular resolution requires a different estimation of DM signals. We estimated the DM (star) distributions around the centers of 35 (34) dSphs and show typical O(10) enhancement in signal rate.

WY, Hayashi 2305.13415

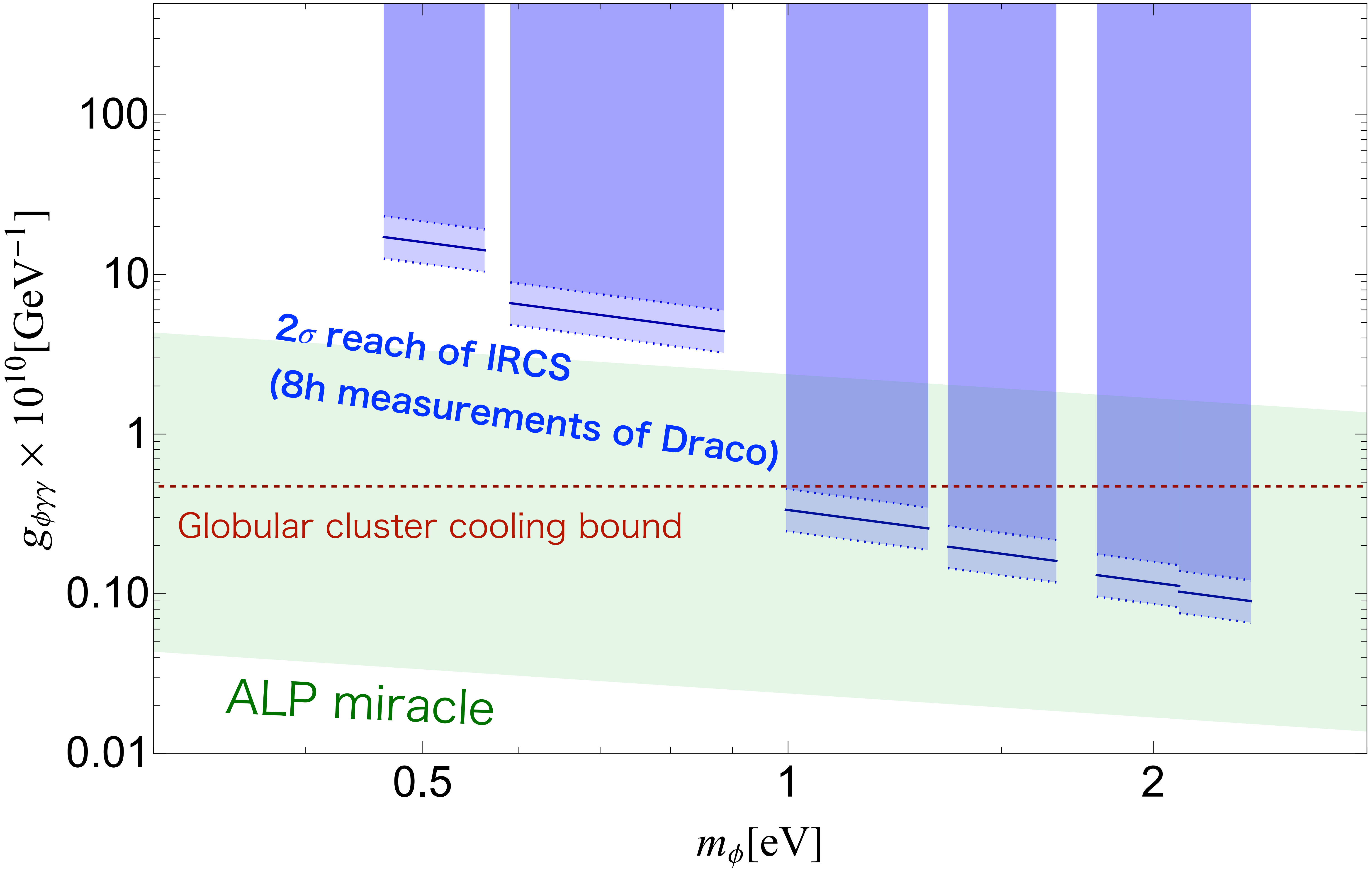


eV DM search with IRCS @ Subaru



The high angular resolution requires a different estimation of DM signals. We estimated the DM (star) distributions around the centers of 35 (34) dSphs and show typical O(10) enhancement in signal rate.

WY, Hayashi 2305.13415



Conclusions: eV DM!

- Observational hints coincide in the eV DM range.
- eV range DM is still special and theoretically well-motivated, a la hot DM paradigm. WY 2301.08735
- The hinted mass range can be checked by infrared spectrographs, and stay tuned!

T. Bessho, Y. Ikeda, WY, Phys.Rev.D 106 (2022) 9, 095025,
WY, Hayashi 2305.13415

Back up

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

$$C^\phi = \frac{1}{2E_\phi g_\phi} \sum \int d\Pi_{\chi_1}\, d\Pi_{\chi_2}$$
$$(2\pi)^4 \delta^4(p_{\chi_1} - p_\phi - p_{\chi_2}) \times |\mathcal{M}_{\chi_1 \to \chi_2 \phi}|^2$$
$$\times S\left(f_{\chi_1}[p_{\chi_1}], f_{\chi_2}[p_{\chi_2}], f_\phi[p_\phi]\right)$$

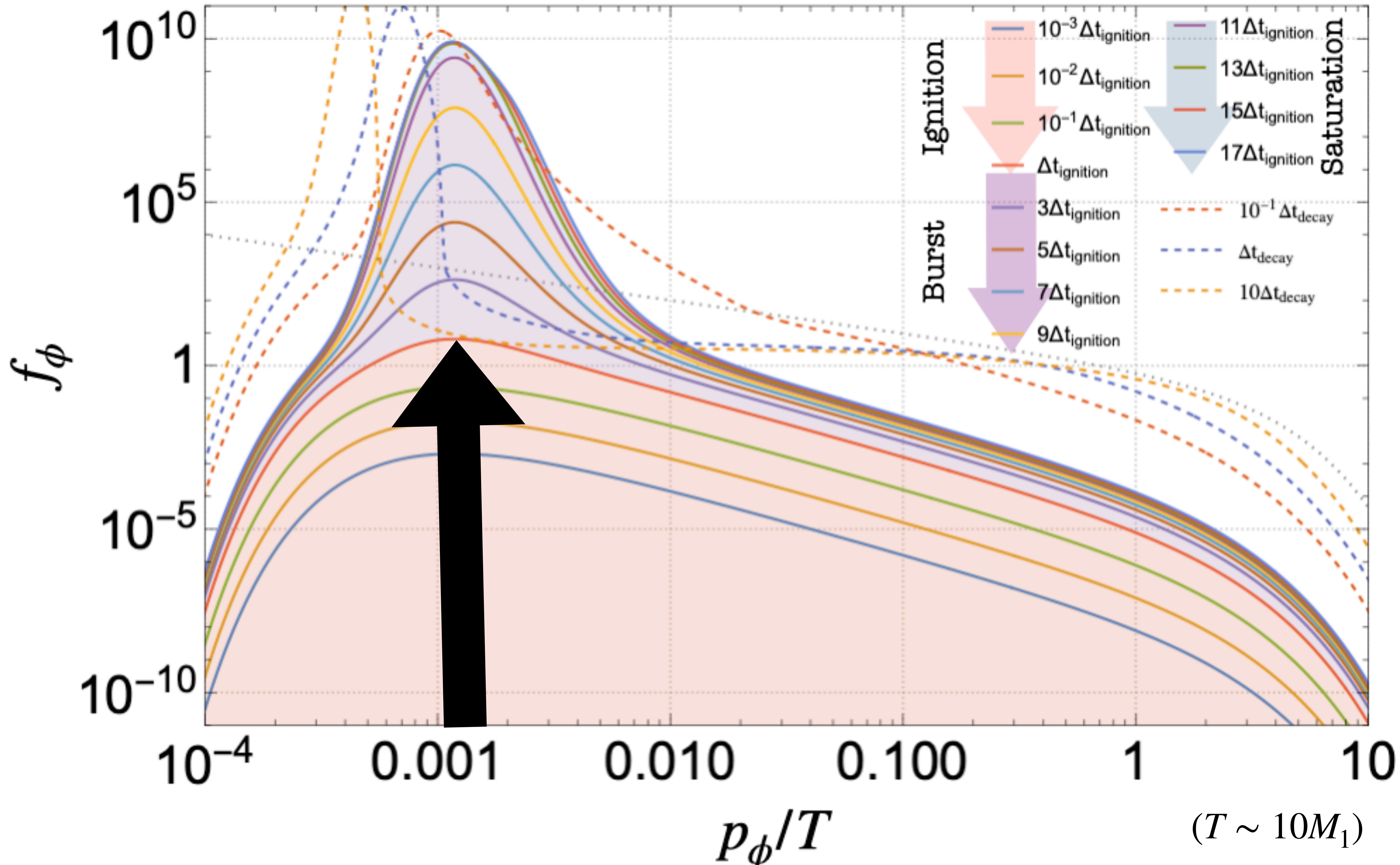
$$S \equiv f_{\chi_1}[p_{\chi_1} \sim T](1 \pm f_{\chi_2}[p_{\chi_2} \sim T])(\cancel{1 \pm} f_\phi[p_\phi \sim p_\phi^{\mathrm{burst}}])$$
$$-(1 \pm f_{\chi_1}[p_{\chi_1} \sim T]) f_\phi[p_\phi \sim p_\phi^{\mathrm{burst}}] f_{\chi_2}[p_{\chi_2} \sim T]$$
$$\sim (f_{\chi_1}[p_{\chi_1} \sim T] - f_{\chi_2}[p_{\chi_2} \sim T]) f_\phi[p_\phi \sim p_\phi^{\mathrm{burst}}]$$

$$\Rightarrow \quad \dot{f}_\phi[p_\phi \sim p_\phi^{\mathrm{burst}}] \sim 0$$

Stage 1: Ignition

Let the timescale that the occupation number of ϕ around $p_\phi^{\rm burst} \sim M_1^2/T$ reaches unity $\Delta t_{\rm iginition}$:

$$\Delta t_{\rm ignition}^{-1} \sim \underbrace{\frac{1}{(p_\phi^{\rm burst})^3}}_{\text{Phase space volume of } p_\phi^{\rm burst} \text{ modes}} \times \underbrace{T^3}_{\chi_1 \text{ number density}} \times \underbrace{\frac{p_\phi^{\rm burst}}{T}}_{\text{Branching fraction to } p_\phi^{\rm burst} \text{ modes.}} \underbrace{\left(\frac{M_1}{T}\Gamma_{\rm decay}\right)}_{\text{(boosted) } \chi_1 \text{ decay rate}}$$



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

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

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

WY 2301.08735

Hot DM paradigm (-1984):

- $\left(\frac{T}{M_1}\right)^3 \Gamma^{(\mathrm{proper})}_{\chi_1\to\chi_2\phi} > \frac{M_1}{T}\Gamma^{(\mathrm{proper})}_{\chi_1\to\chi_2\phi} > H$ for $T > M_1$
- $n_\phi \sim T^3$ from **thermal equilibrium**

=> eV mass for DM abundance

- Comoving momentum is

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

=> hot

Burst production of DM

- $\left(\frac{T}{M_1}\right)^3 \Gamma^{(\mathrm{proper})}_{\chi_1\to\chi_2\phi} > H > \frac{M_1}{T}\Gamma^{(\mathrm{proper})}_{\chi_1\to\chi_2\phi}$ @ a period
- $n_\phi \sim T^3$ from **quasi-equilibrium** of bose-enhancement dynamics

=> eV mass for DM abundance

- Comoving momentum is

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

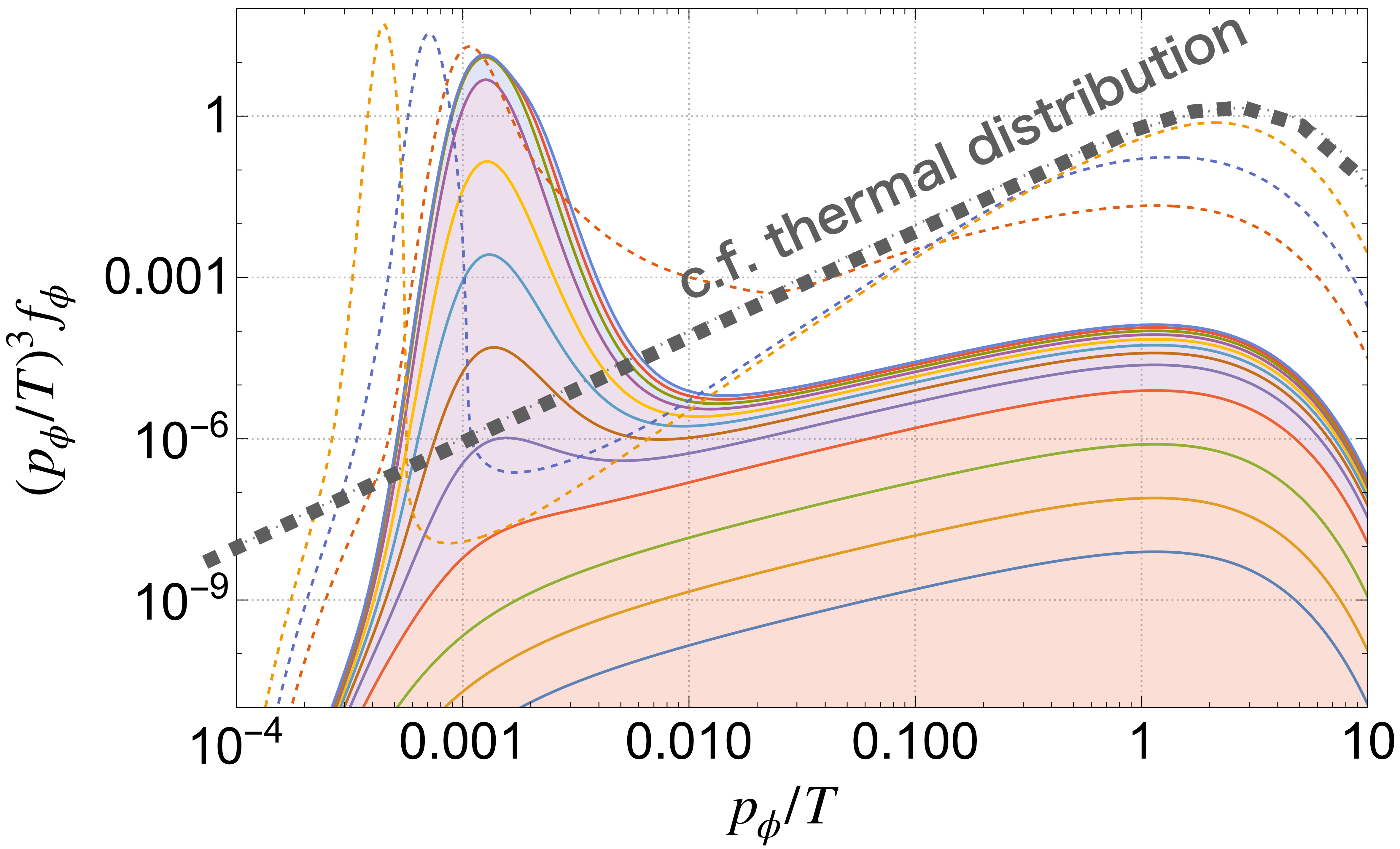
=> cold

Stage 3: Saturation (quasi-equilibrium)

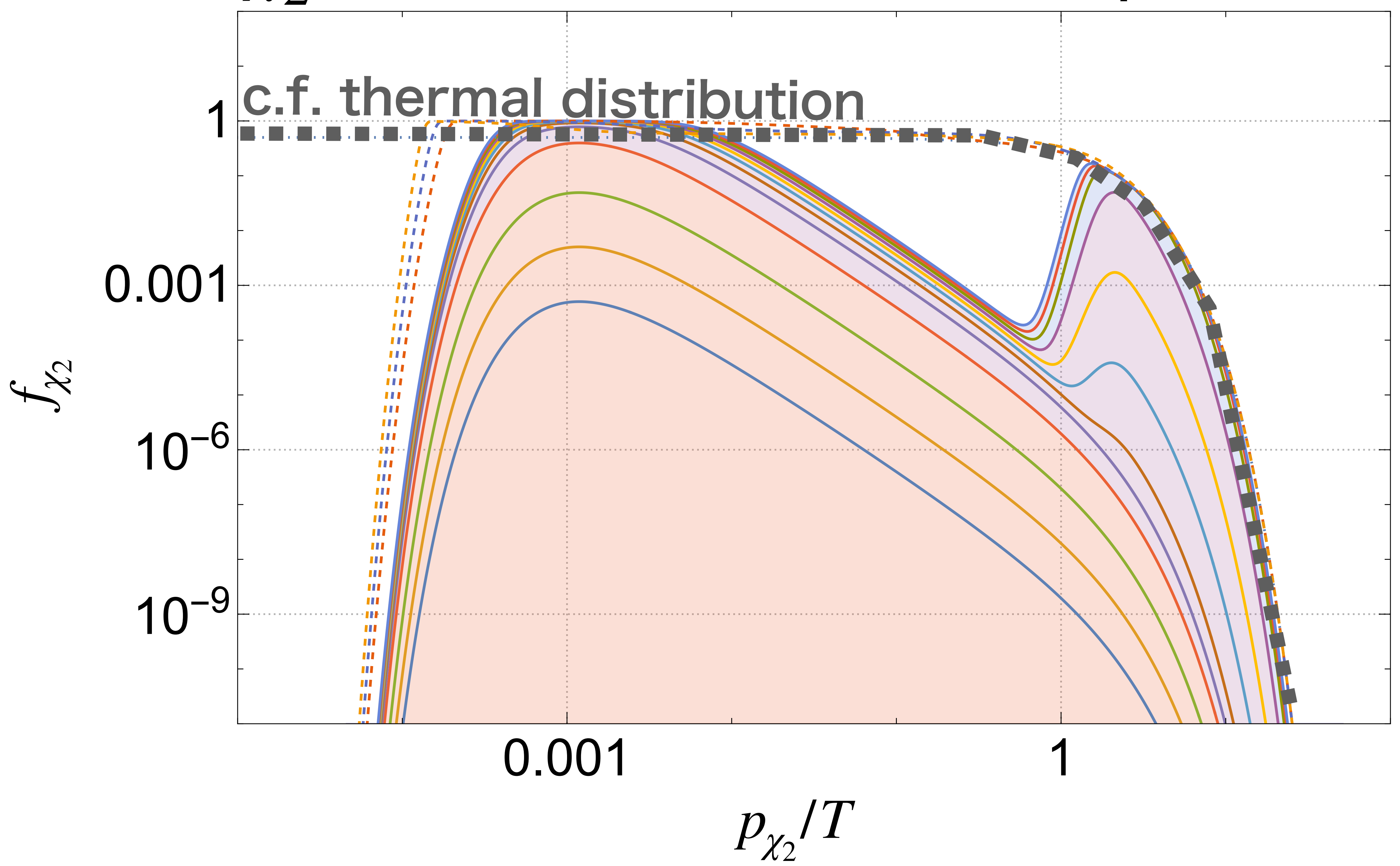
The number density of χ_2 at $p_{\chi_2} \sim T$ is T^3. Since

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

ϕ number density



χ_2 (Dirac fermion) occupation#

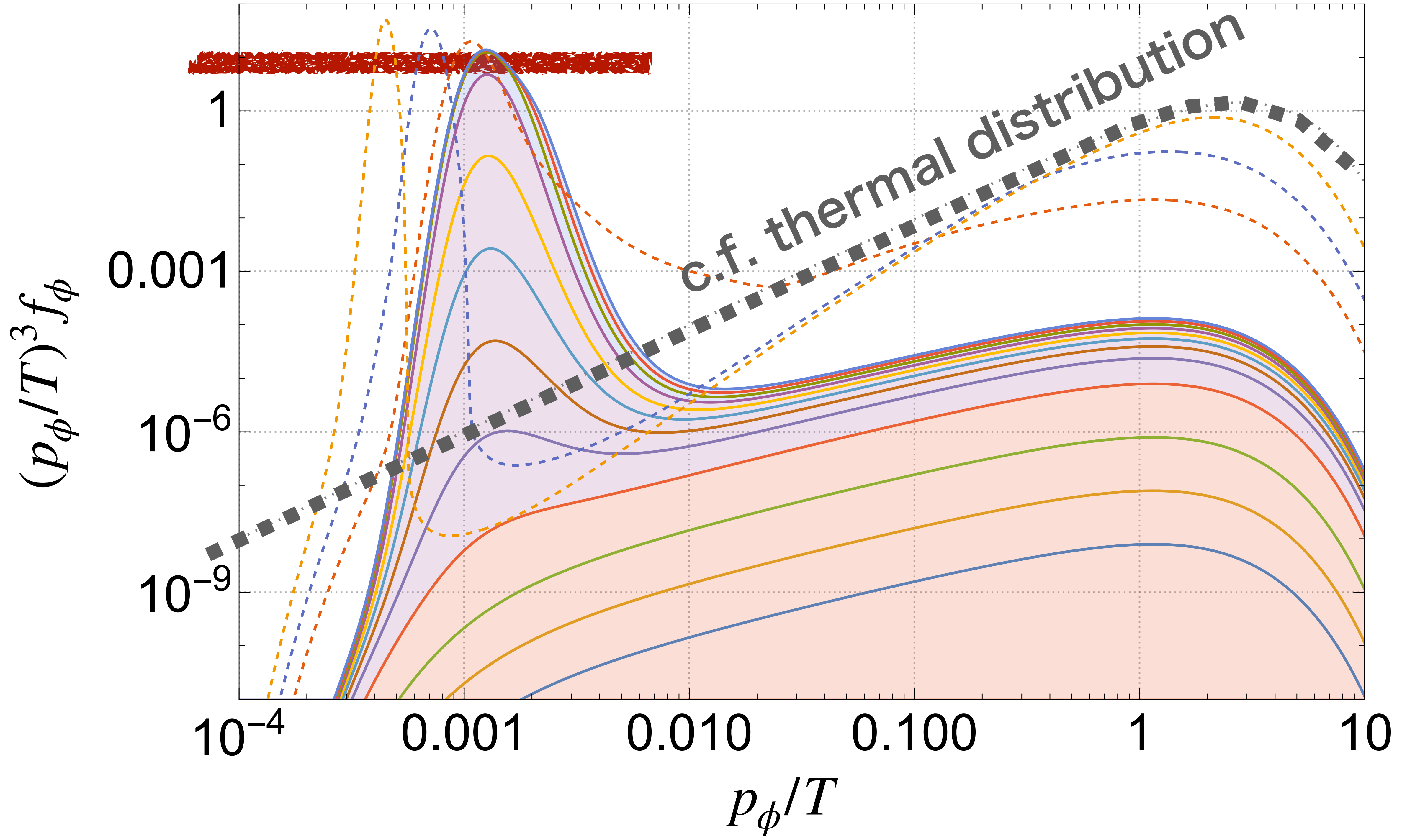


Stage 3: Saturation (quasi-equilibrium)

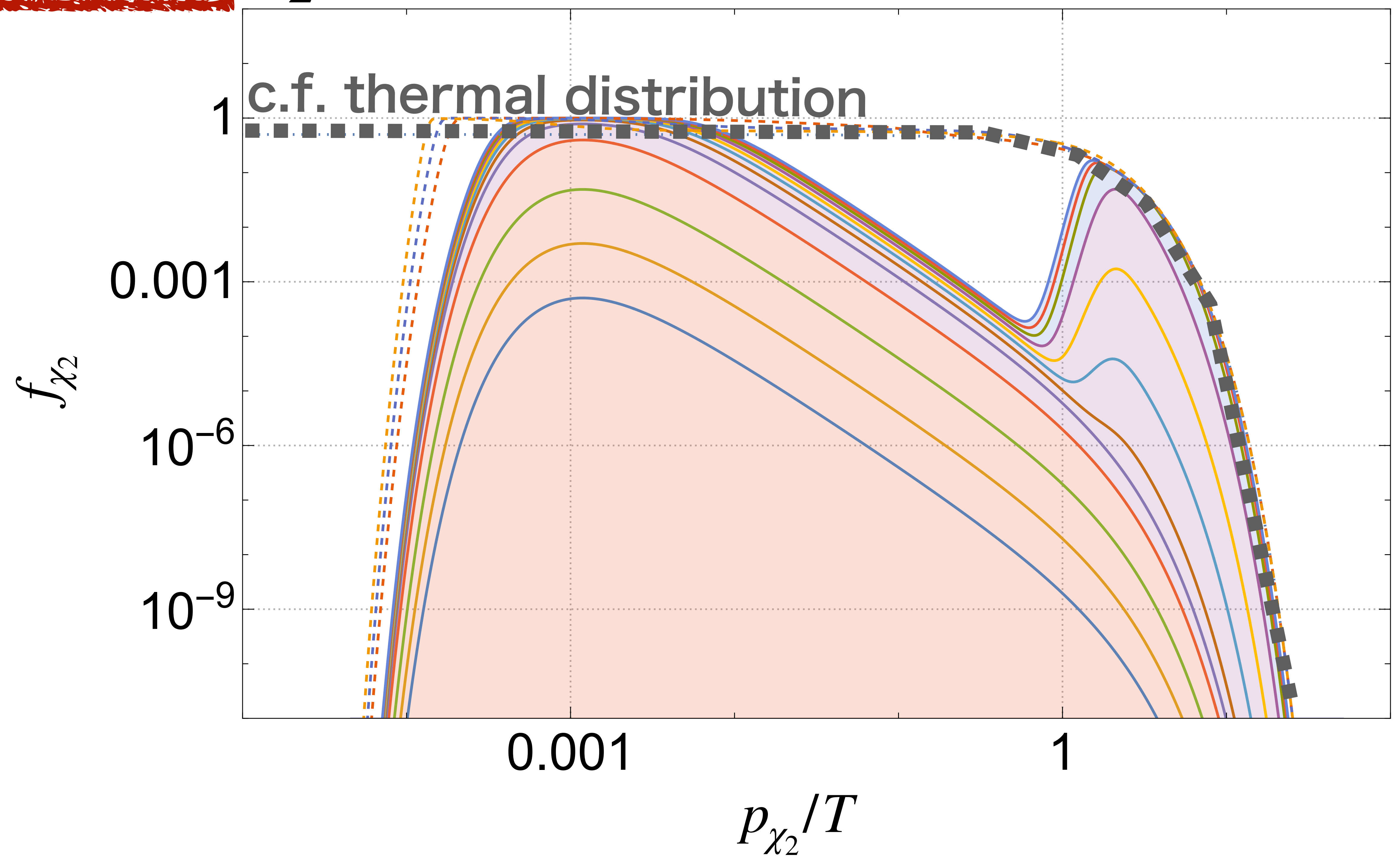
The number density of χ_2 at $p_{\chi_2} \sim T$ is T^3. Since

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

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



χ_2 (Dirac fermion) occupation#

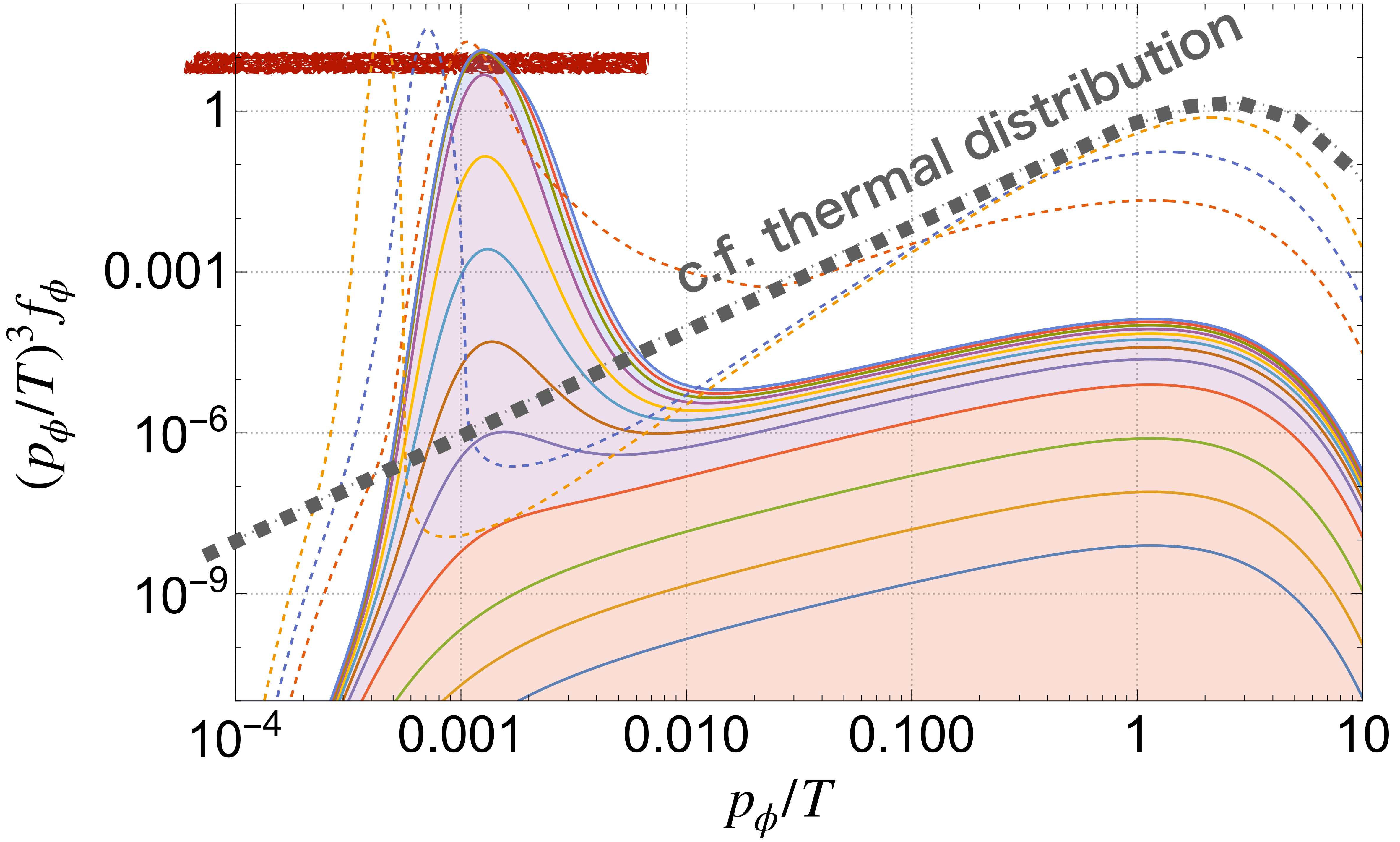


Stage 3: Saturation (quasi-equilibrium)

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

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

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



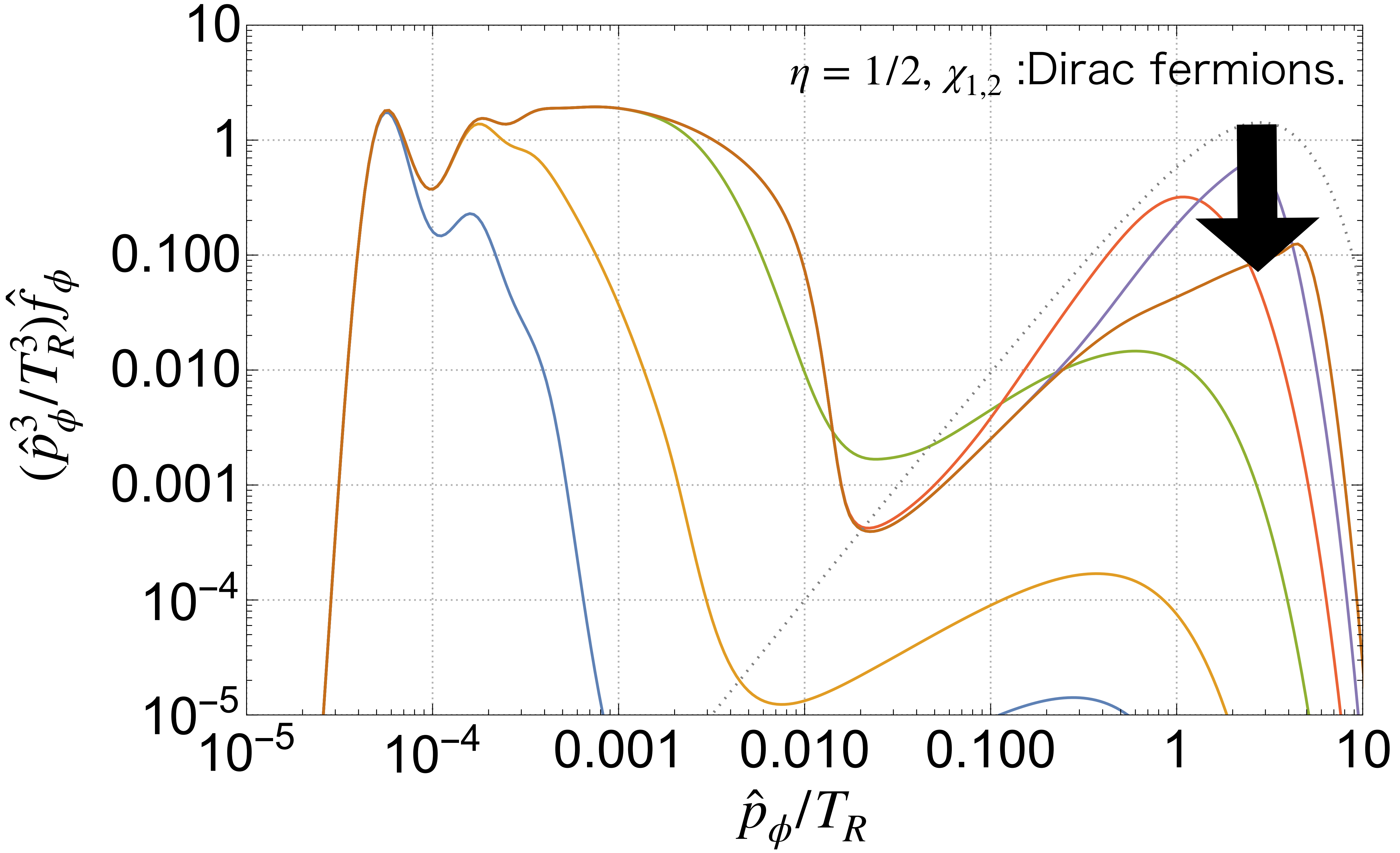
The quasi-equilibrium is kept on a very long time scale until

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

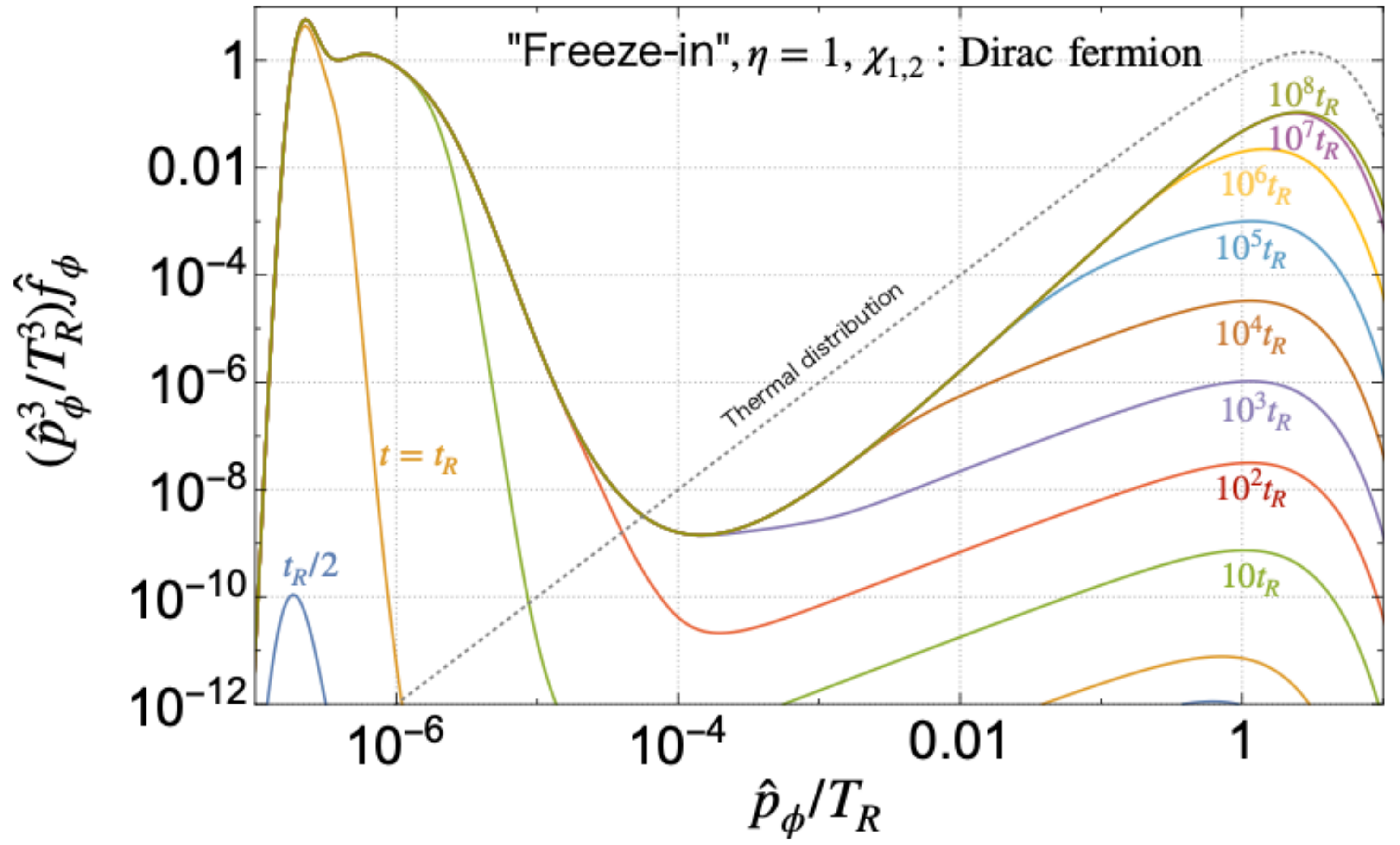
Non-trivial results in slightly different setups:

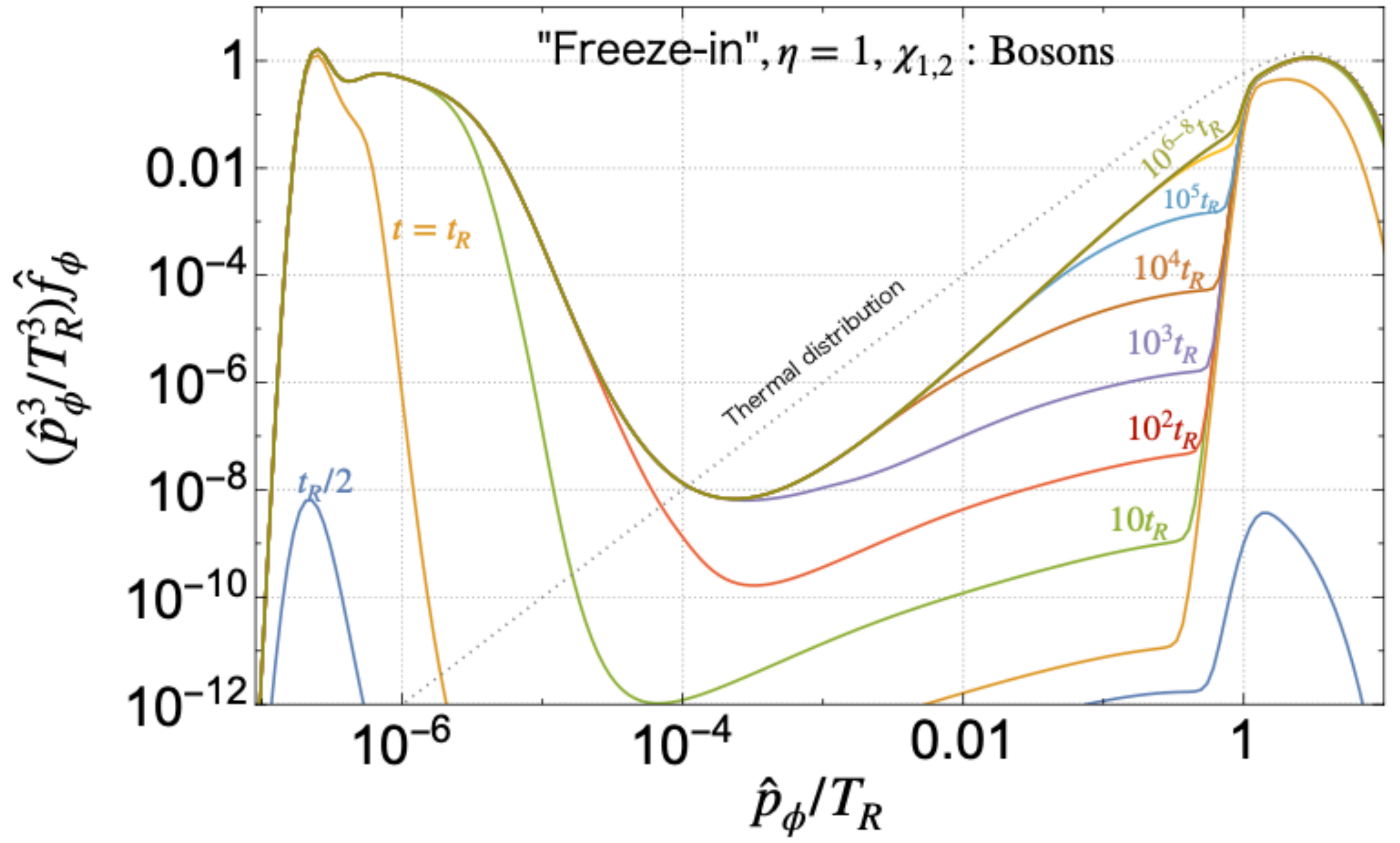
WY 2301.08735

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.





Narrow parametric resonance ≈ Boltzmann equation including Bose enhancement/Pauli-block factor. Moroi, WY, 2011.12285

(See also “Physical Foundations of Cosmology” Mukhanov)

-Analytical solution for DM distribution from condensate decays Moroi, WY, 2011.09475, 2011.12285

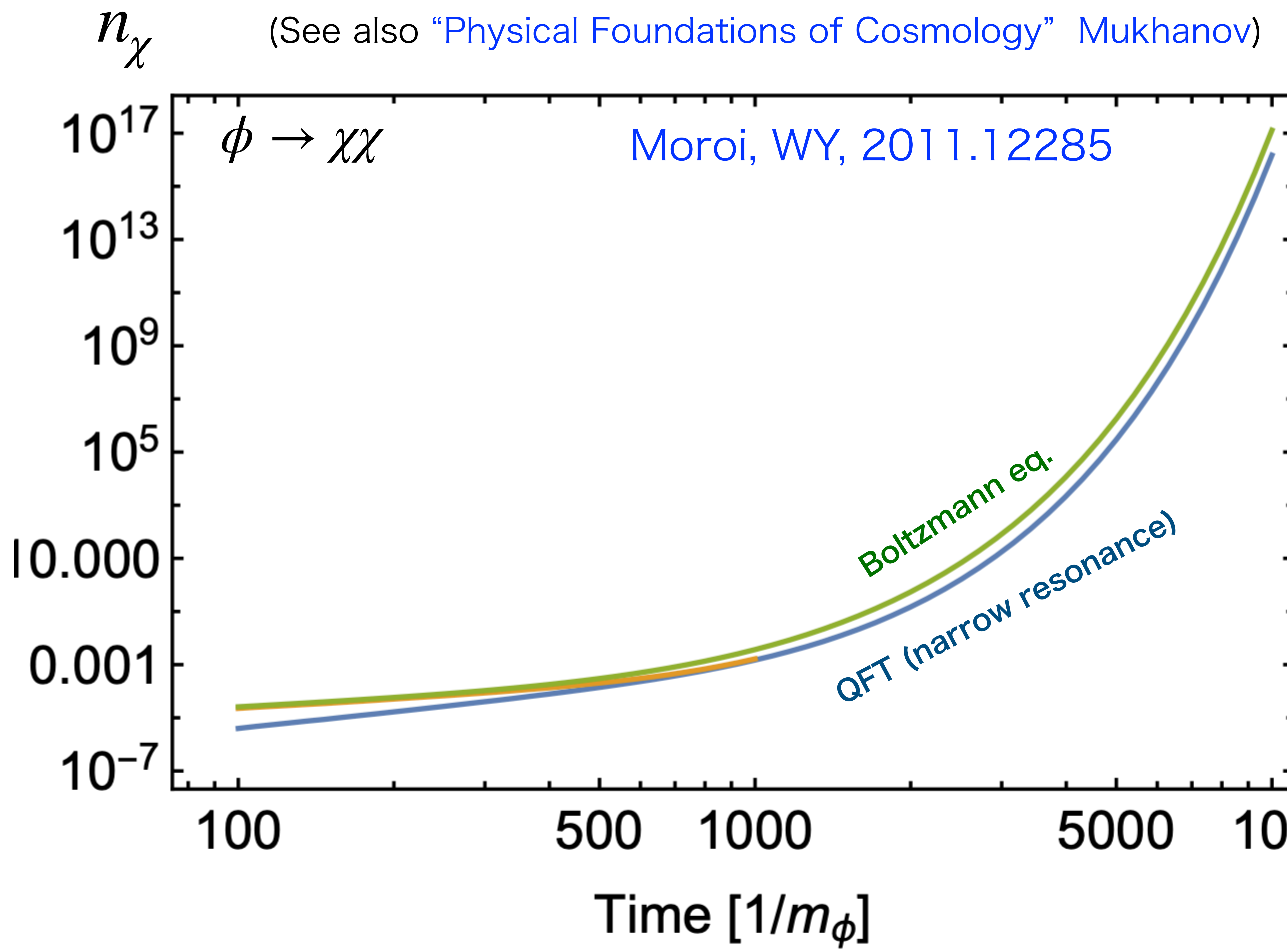
$$f_k(t\to\infty) = \pm\frac{1}{2}\left(e^{\pm 2\bar{f}(t_k)} - 1\right)\theta(p_\chi - k),$$

$$\bar{f}(t_k) \equiv \left.\frac{4\pi^2\Gamma^{(0)}_{\phi\to\chi\chi} n_\phi}{H p_\chi^3}\right|_{t=t_{\hat{k}}}$$

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

-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



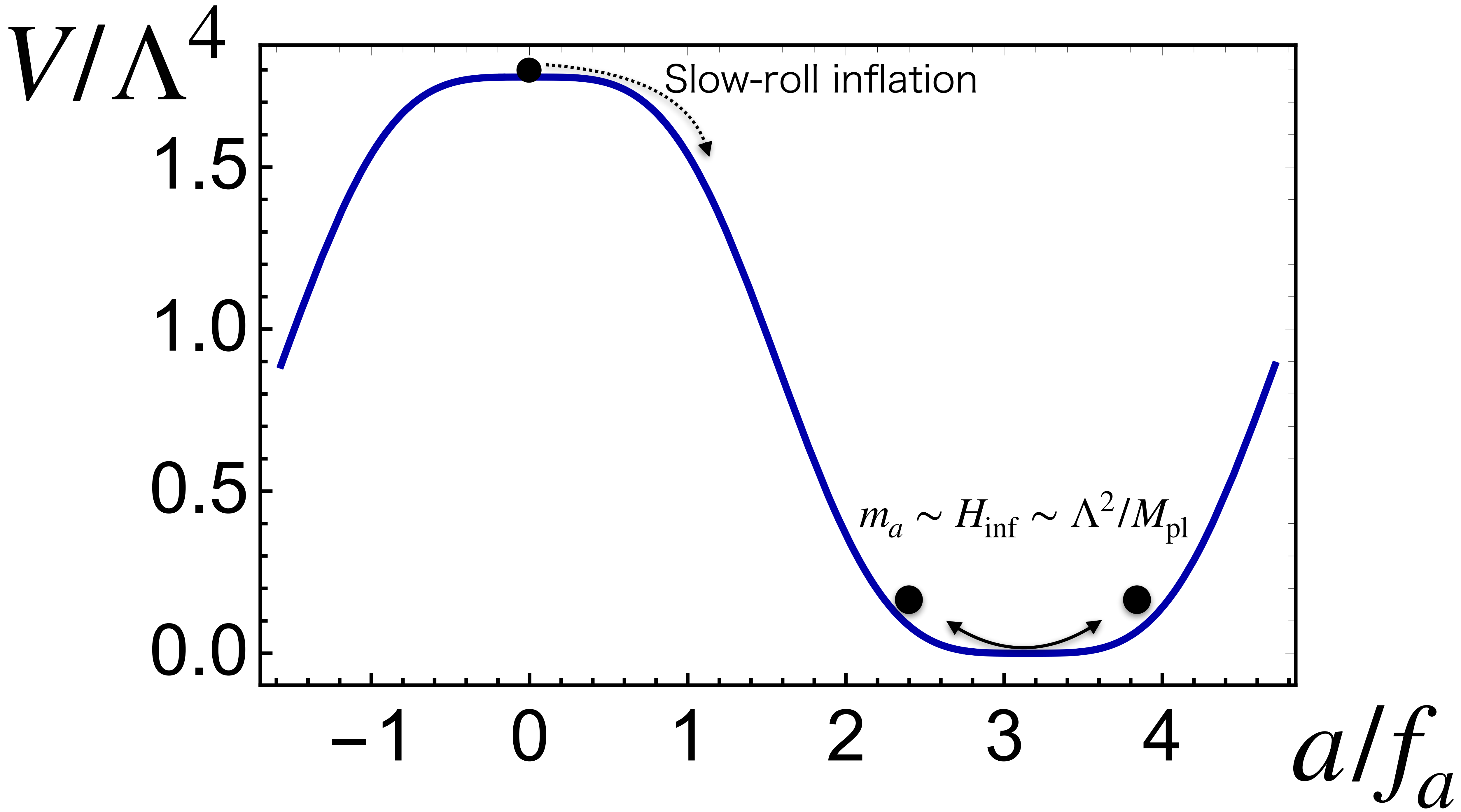
The ALP miracle scenario: Inflaton = DM = ALP

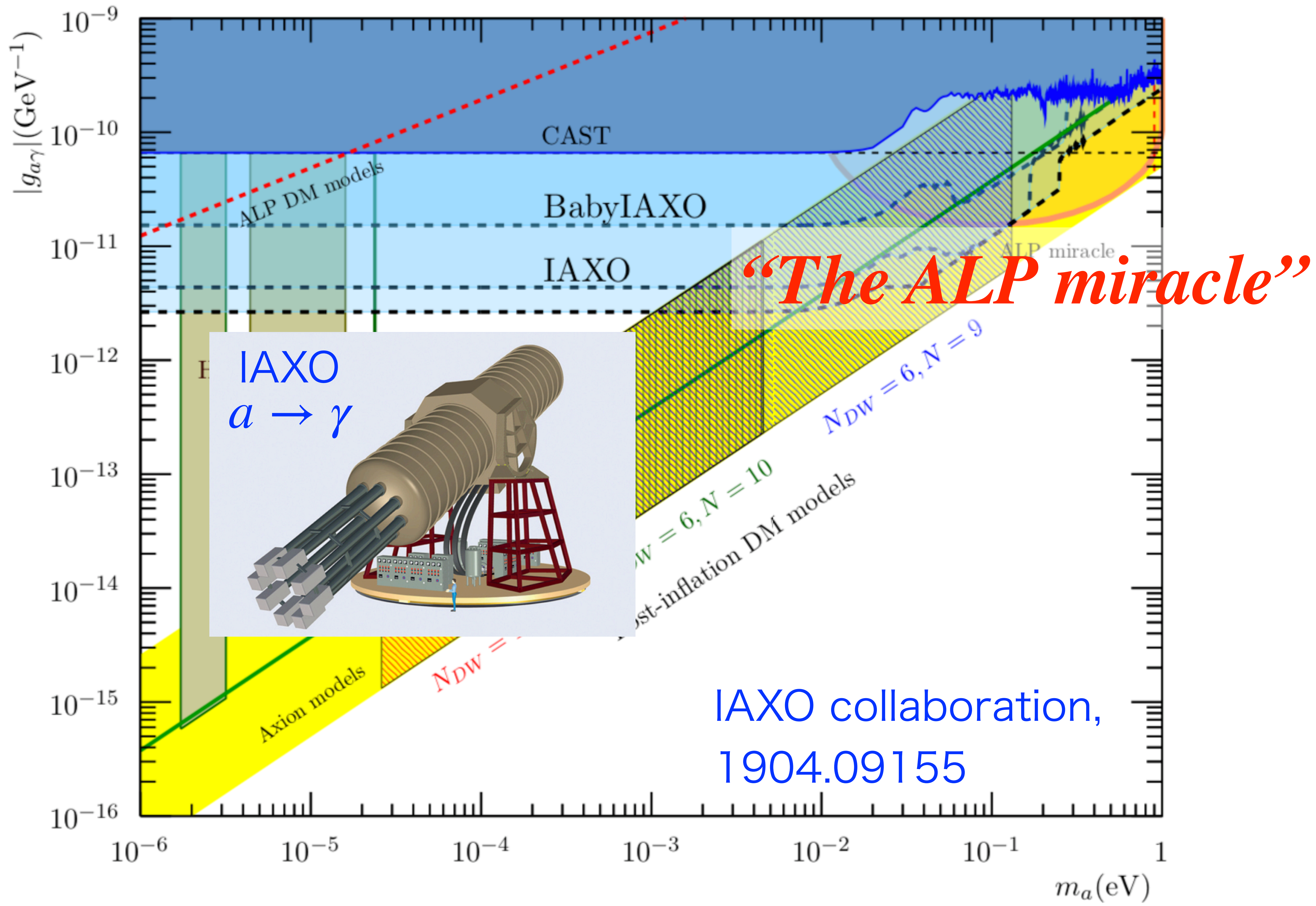
Daido, Takahashi, WY, 1702.03284, 1710.11107

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).

How to test the ALP?

The same ALP from sun, photon collider.
$\Delta N_{\rm eff} \approx 0.03$. "indirect/direct detection",
Next part