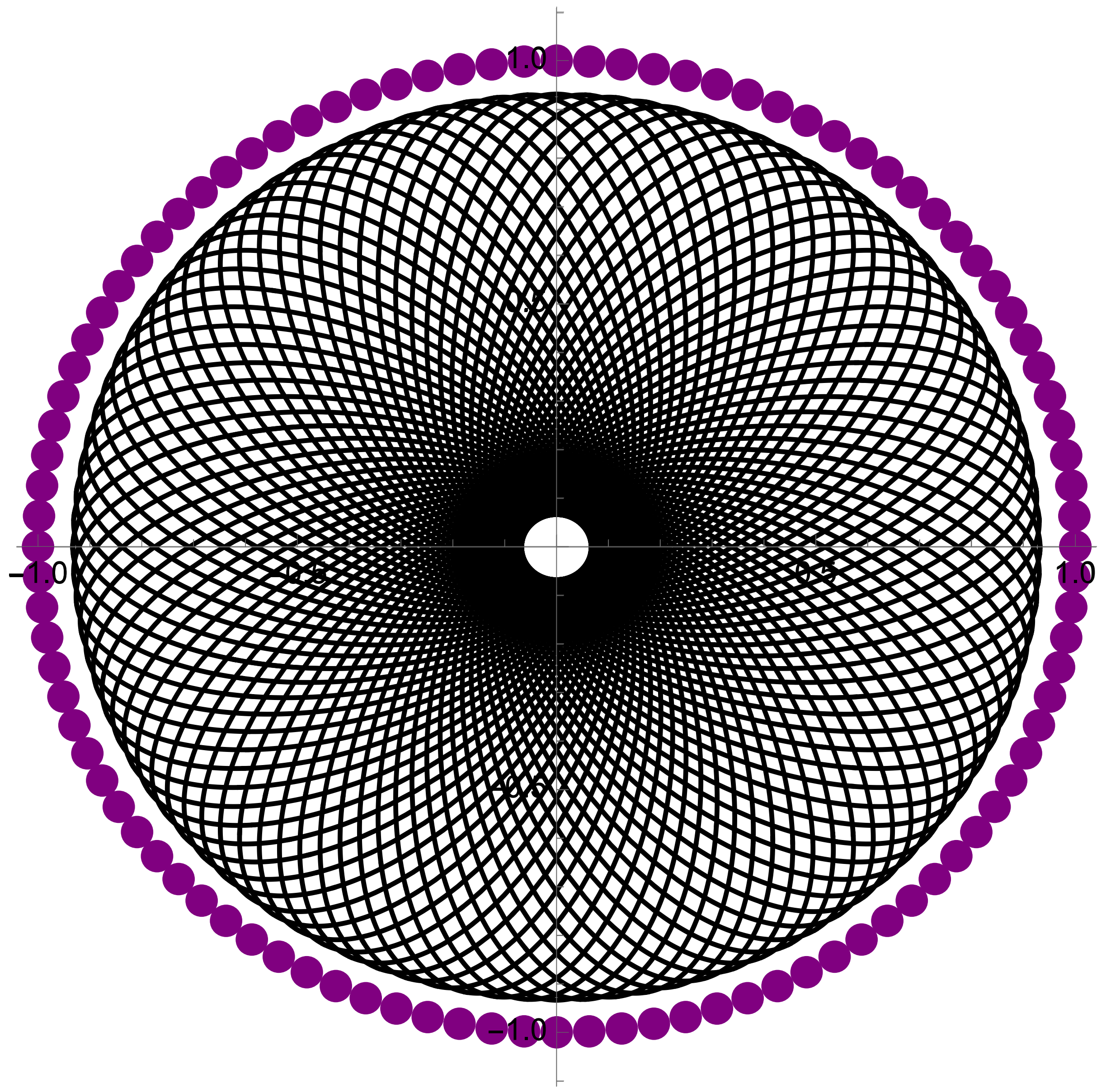
Thermal production of eV range light DM

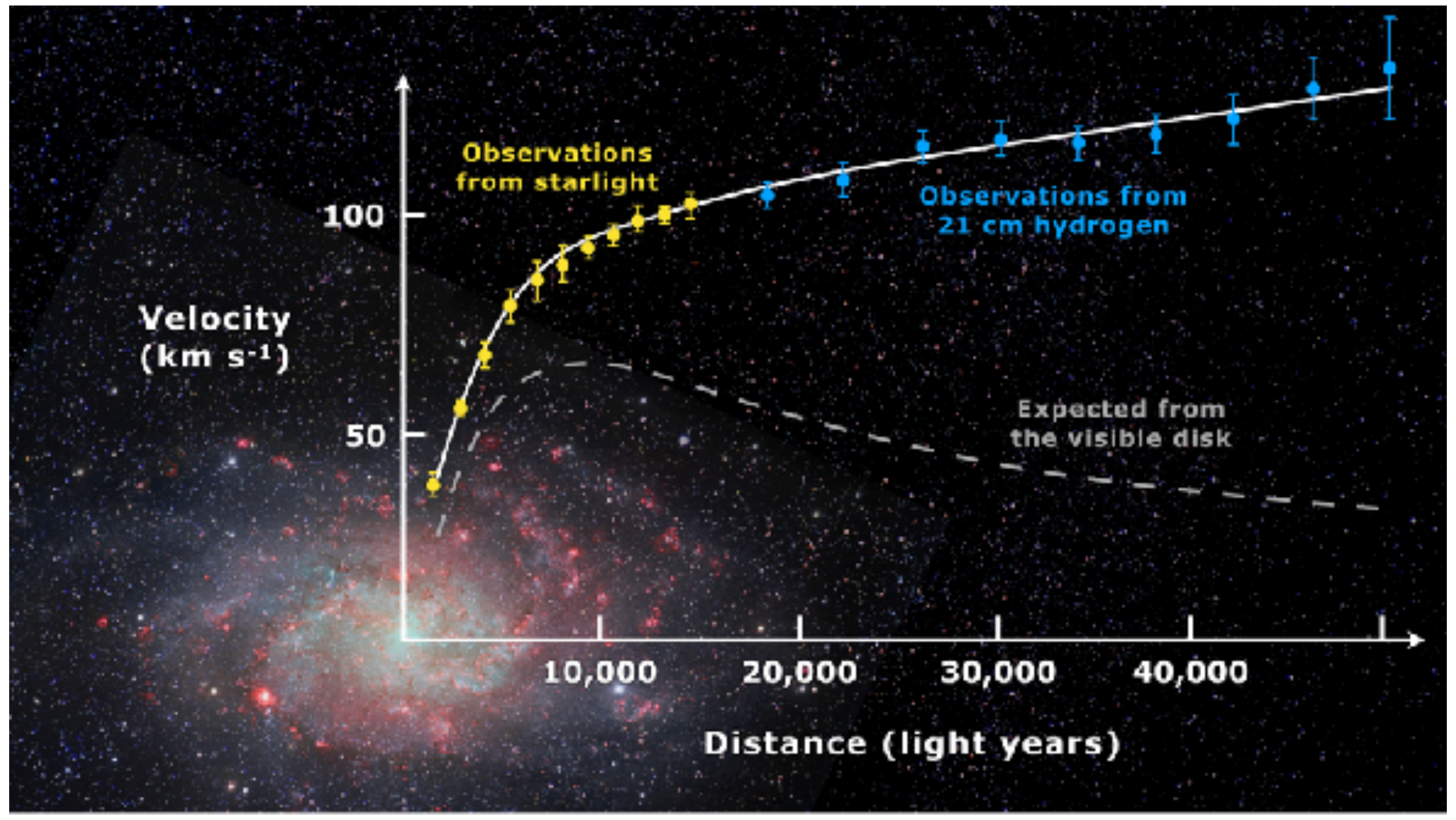


Tohoku U.
Wen Yin, 殷 文

Based on 2301.08735

@ IAS Program on High Energy Physics 2023/2/14

Dark matter



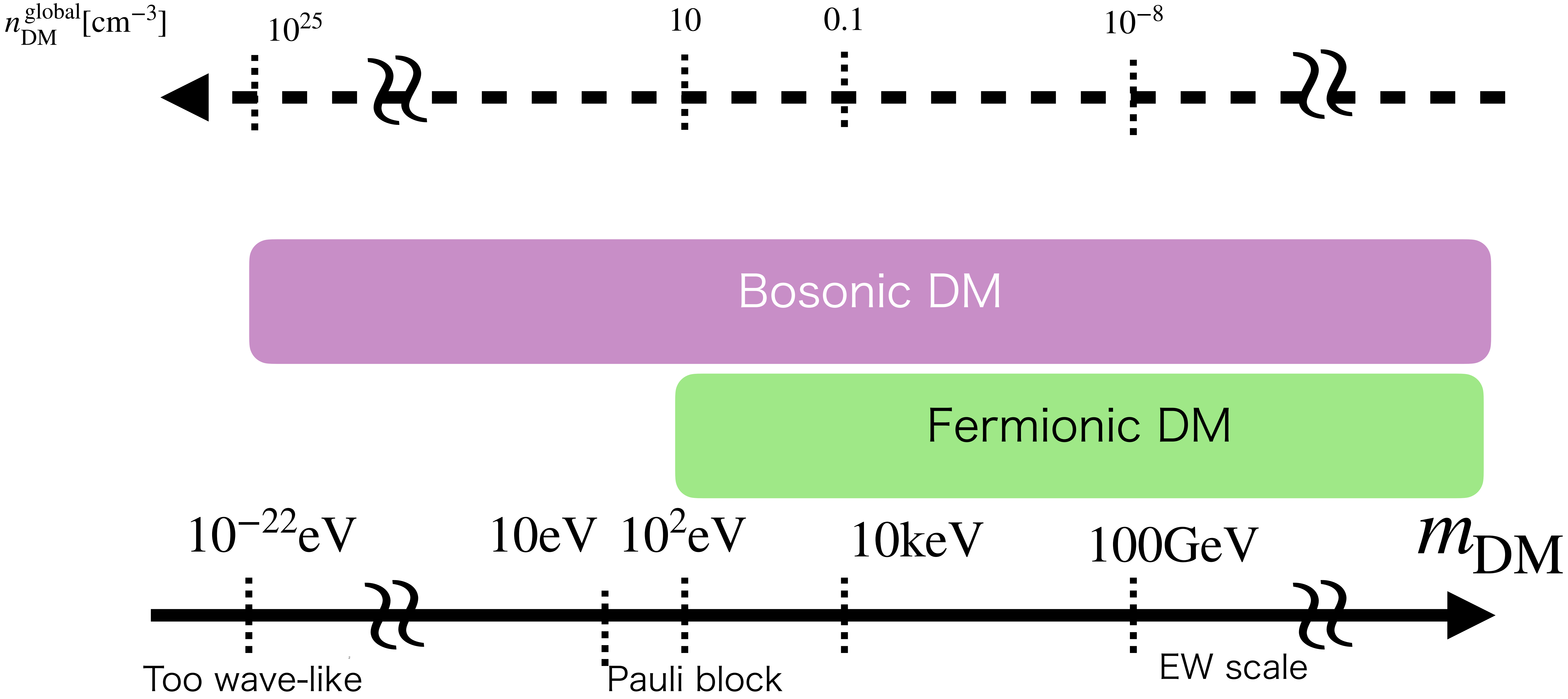
- **What is dark matter?**

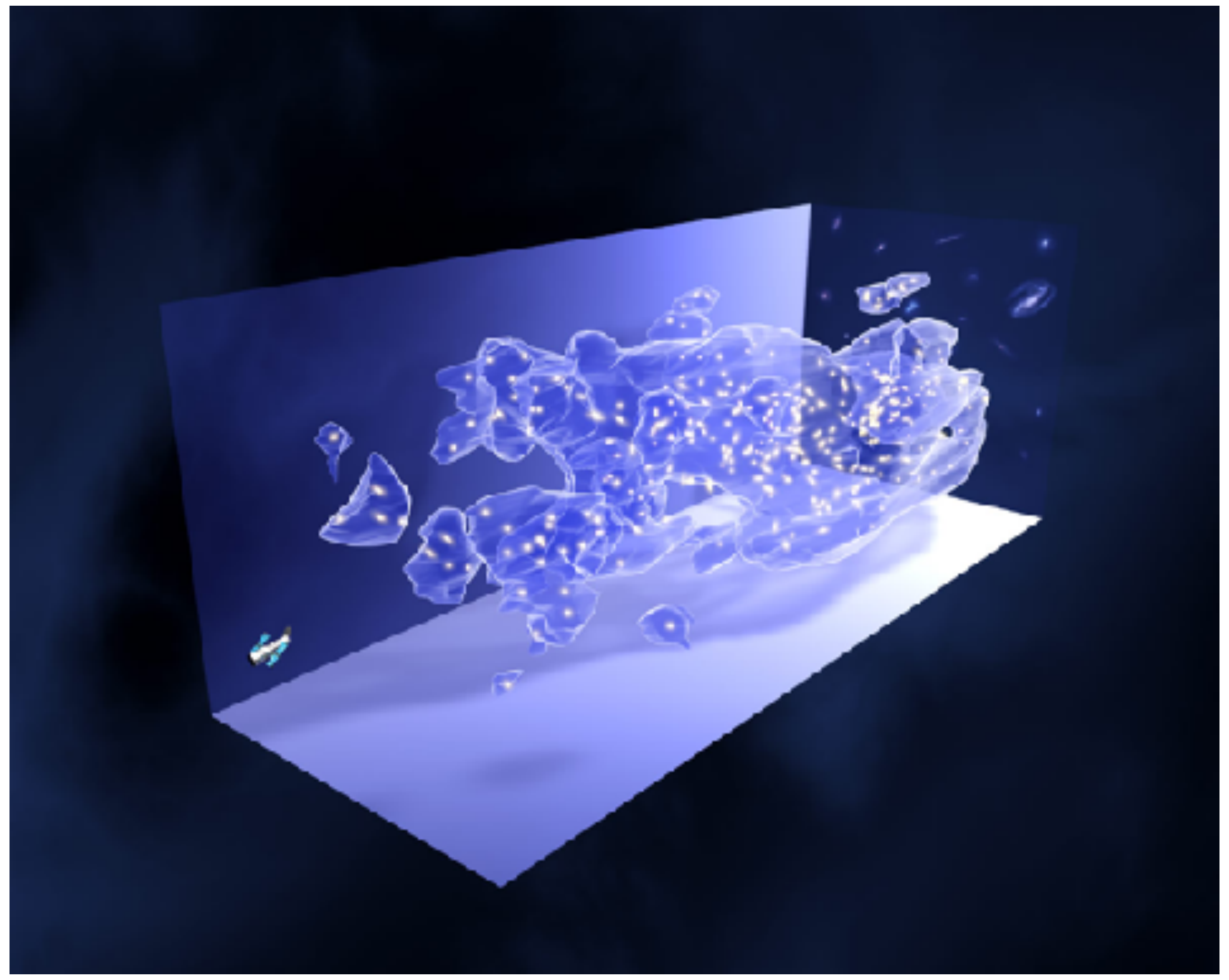
Very stable
Neutral
Cold

ρ_{DM} $\quad (= n_{\mathrm{DM}} m_{\mathrm{DM}})$

wikipedia

- **Generic mass range** **(for a single dominant component DM)**





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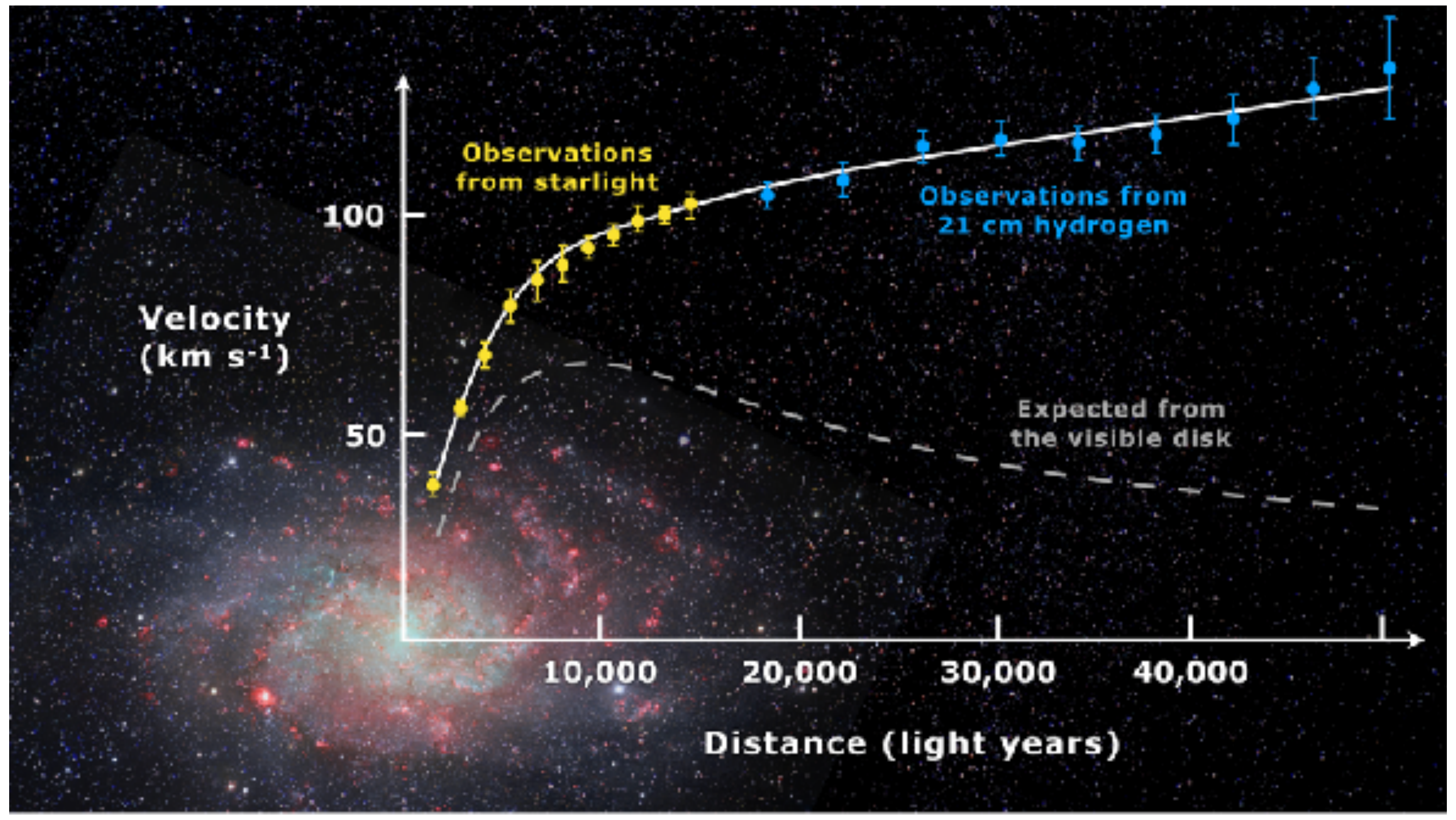

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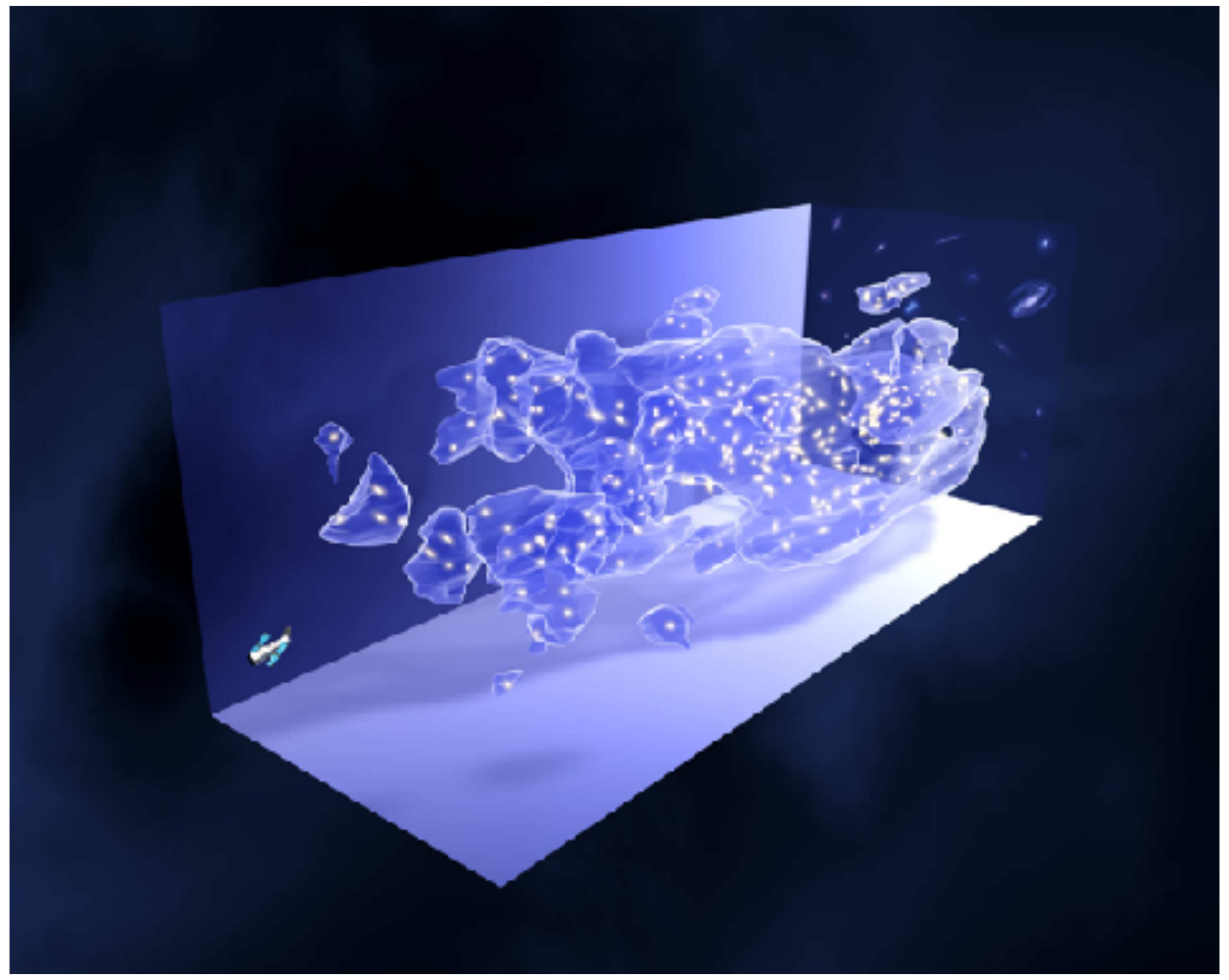

$\rho_{\rm DM}$ $(= n_{\rm DM} m_{\rm DM})$

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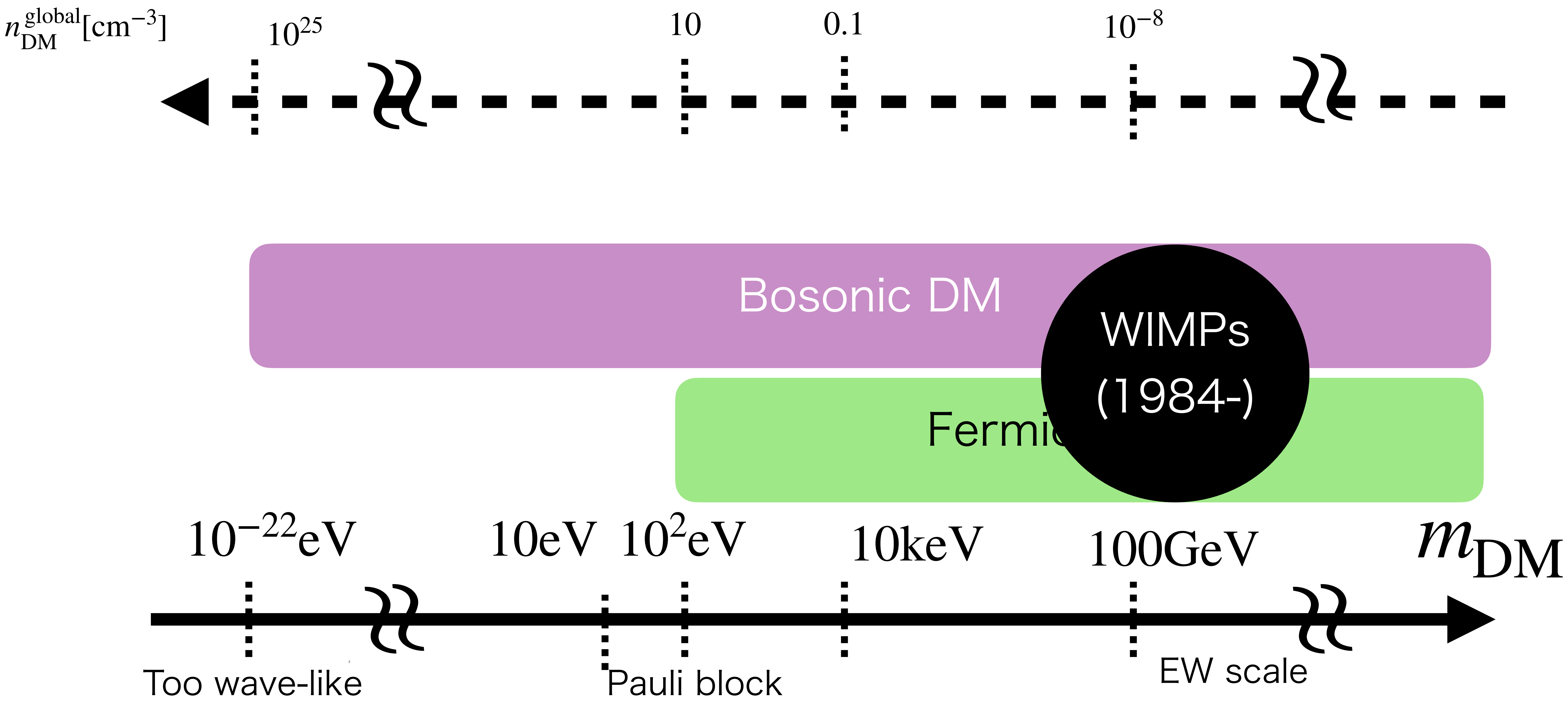

Light DM

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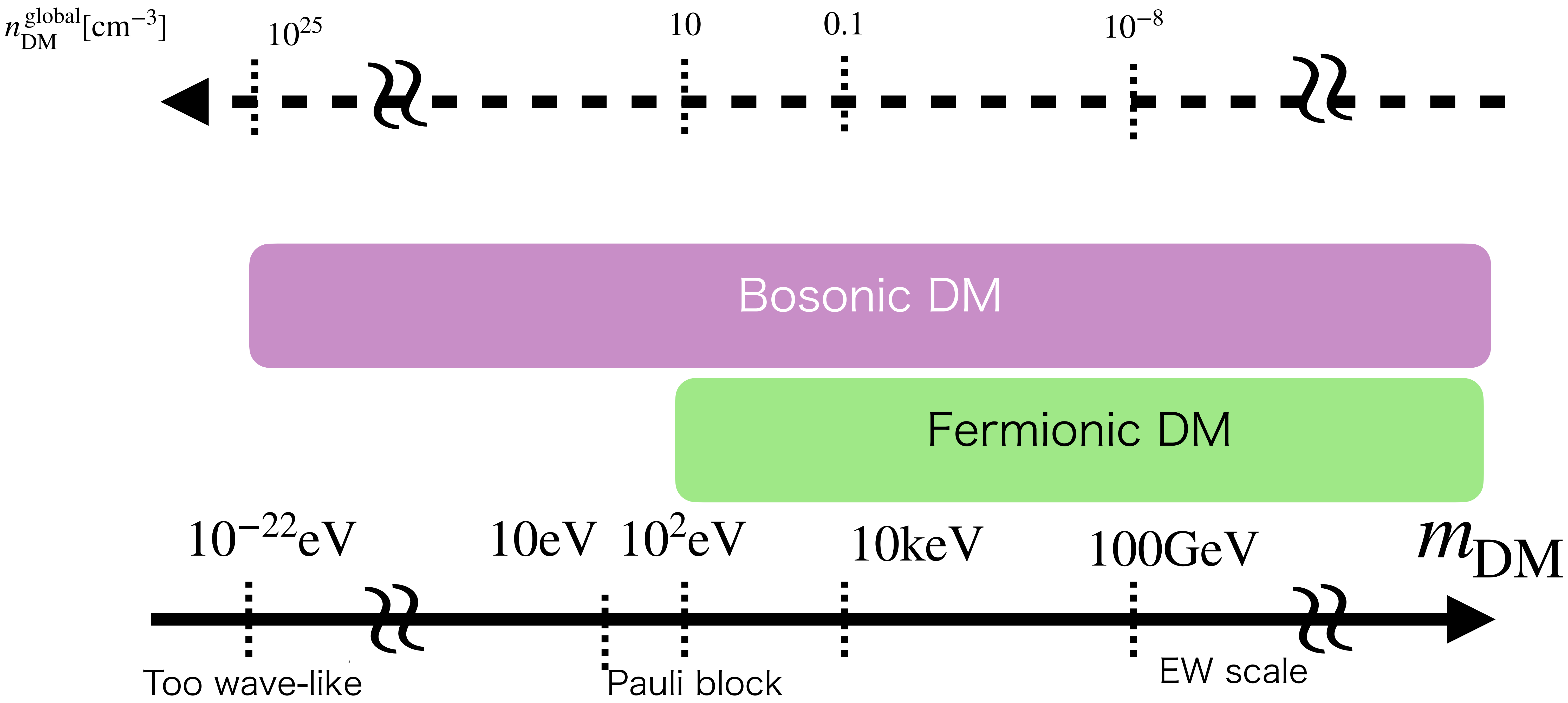

- **Questions for light DM**

Why is it light? (what is the origin?)
How to produce it? cold.
How to detect it?

- **Light DM candidates**

Boson: axion/ALP, hidden photon etc.

Fermion: chiral fermion
(sterile neutrino) etc

Light DM

- **What is dark matter?**

Very stable $\Gamma_{decay} \propto m_{\rm DM}^{\rm positive} \to$ Light DM?

Neutral

Cold

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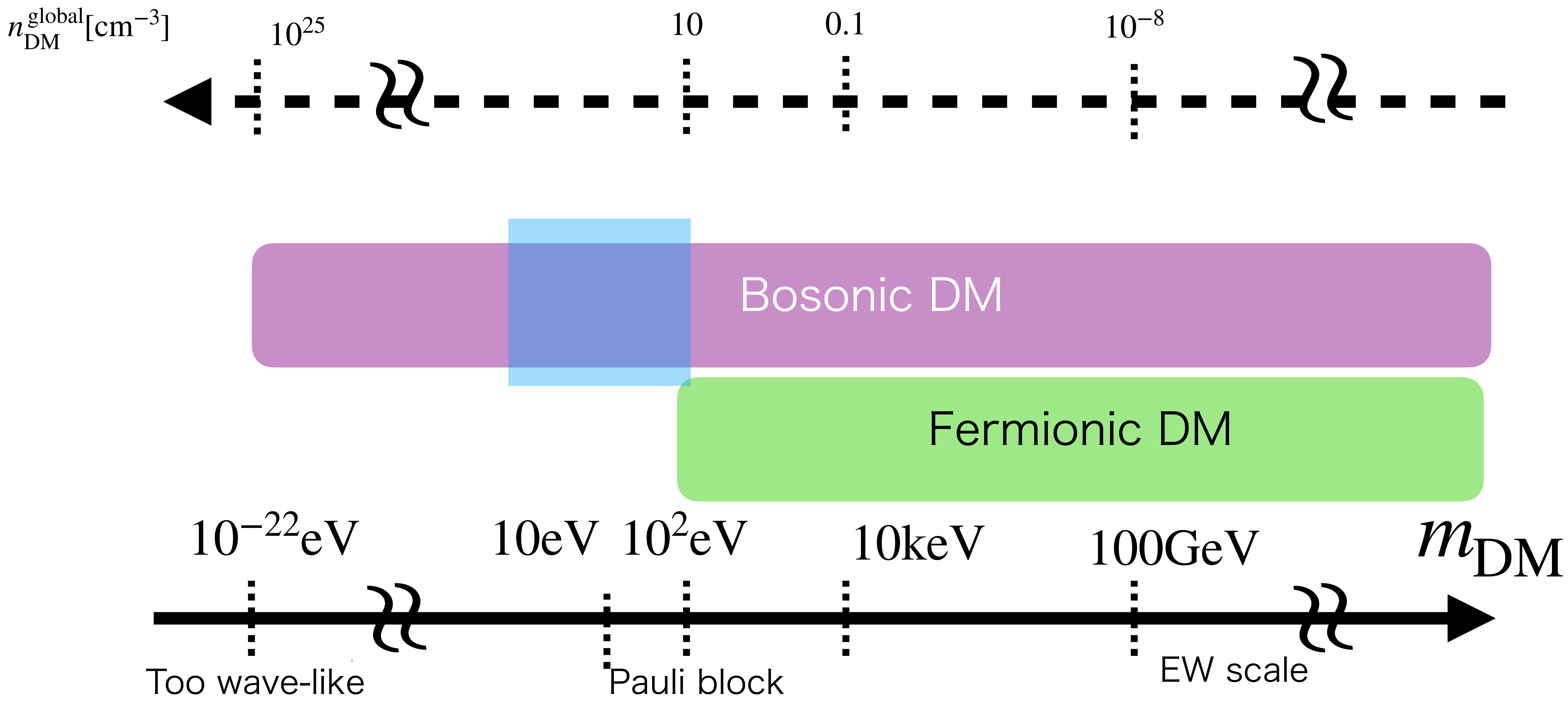

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Why is it light? (what is the origin?)

How to produce it? cold.

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Boson: axion/ALP, hidden photon etc.

Fermion: chiral fermion
(sterile neutrino) etc

How to detect it? Hints and prospects.

DM photon coupling

- 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

hints

- Direct detection by multilayer optical haloscopes Baryakhtar et al 1803.11455
  indirect detection by infrared spectrograph Bessho, Ikeda, WY, 2208.05975
  are proposed for eV-range DM.
- IAXO IAXO collaboration,1904.09155, photon collider Homma et al 2212.13012 , etc.

SSB model

- SM-like+dark Higgs bosons decaying into invisible DM, corresponding to $Br_{h\to\mathrm{inv}} \gtrsim 10^{-3}\,\%$, can be probed in CEPC, ILC, FCC-ee etc.
  Haghighat, Mohammadi Najafabadi, Sakurai, WY, 2209.07565

proposals

No-go theorem for thermal production

- **What is dark matter?**

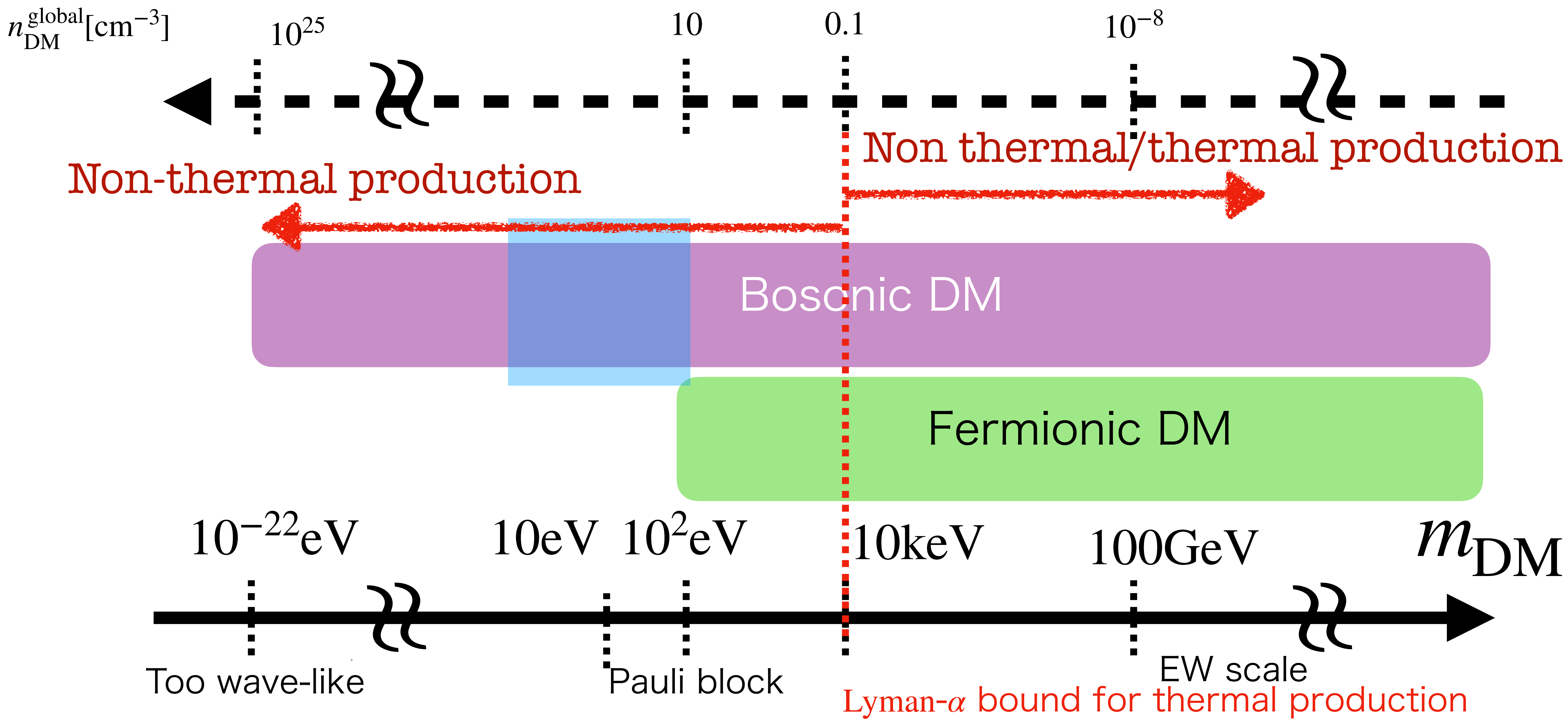
Very stable $\Gamma_{decay} \propto m_{\rm DM}^{\rm positive} \rightarrow$ Light DM?

Neutral

Cold

$\rho_{\rm DM}$ $(= n_{\rm DM} m_{\rm DM})$

- **Generic mass range** (for a single dominant component DM)



- **Questions for light DM**

Why is it light? (what is the origin?)

How to produce it? cold.

How to detect it?

Today's focus

- **Light DM candidates**

Boson: axion/ALP, hidden photon etc.

Fermion: chiral fermion (sterile neutrino) etc

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

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

Hot DM paradigm (-1984):

$$\begin{cases} \dfrac{\rho_{\rm DM}}{s} \sim eV \\ \rho_{\rm DM} \sim n_{\rm DM} m_{\rm DM} \\ s \sim T^3 \end{cases} \Rightarrow \begin{cases} \text{if} \quad n_{\rm DM} \sim T^3, \\ \boxed{m_{\rm DM} \sim eV} \end{cases}$$

- Hot DM production belongs to the thermal one.

$p_{\rm DM} \sim T$, e.g., $v_{\rm DM} \sim p_{\rm DM}/m_{\rm DM} \sim 1$ @recombination

and it is excluded. See the warm DM bound Viel et al, 0501562; Irsic et al,1702.01764.

- Is thermal production of eV range DM really no-go?

See also ALP miracle scenario, Daido, Takahashi, WY, 1702.03284,1710.11107, predicting eV range DM=ALP=inflaton.
Possible resolution of strong CP problem was pointed out: Takahashi WY, 2301.10757

What I will talk about

WY 2301.08735

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

Setup:

WY 2301.08735

$\chi_1 \to \chi_2 \phi$: Thermalized χ_1, χ_2, $\phi(=\text{bosonic DM})$ are absent initially

χ_1 mass : M_1 $\qquad$ χ_2, ϕ : massless

Equations:

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

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

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

We neither assume that χ_2 is a thermalized background field nor neglect Bose-enhancement/Pauli-blocking effect.

There is a burst production of DM before the usual thermalization.

$\chi_1 \to \chi_2 \phi$: Thermalized $\chi_1, \chi_2, \phi(= \text{bosonic DM})$ are absent initially

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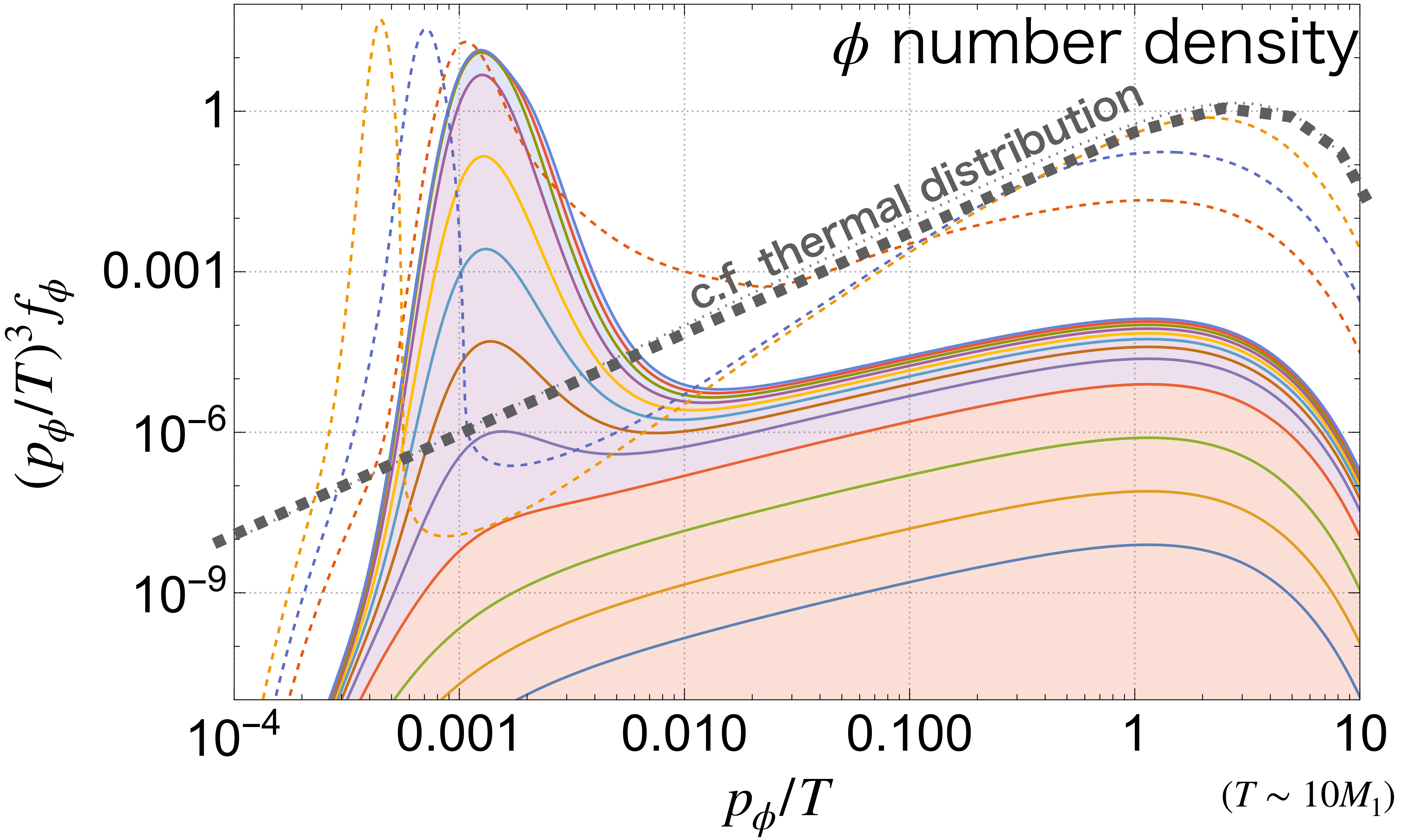

Three stages of burst production:

1. Ignition
2. Burst
3. Saturation

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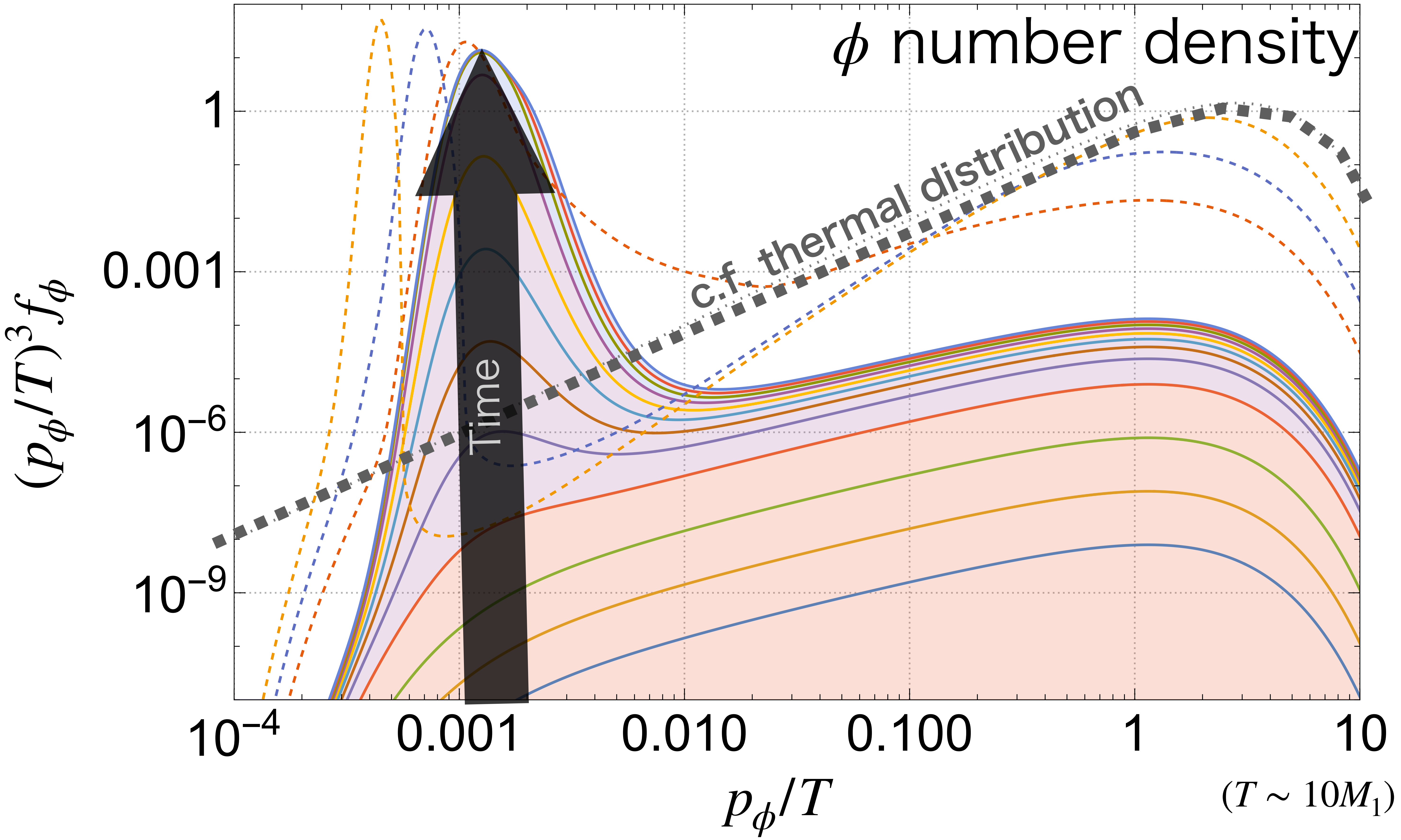

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Burst production of DM (in Minkowski space)
- Stage 1: Ignition

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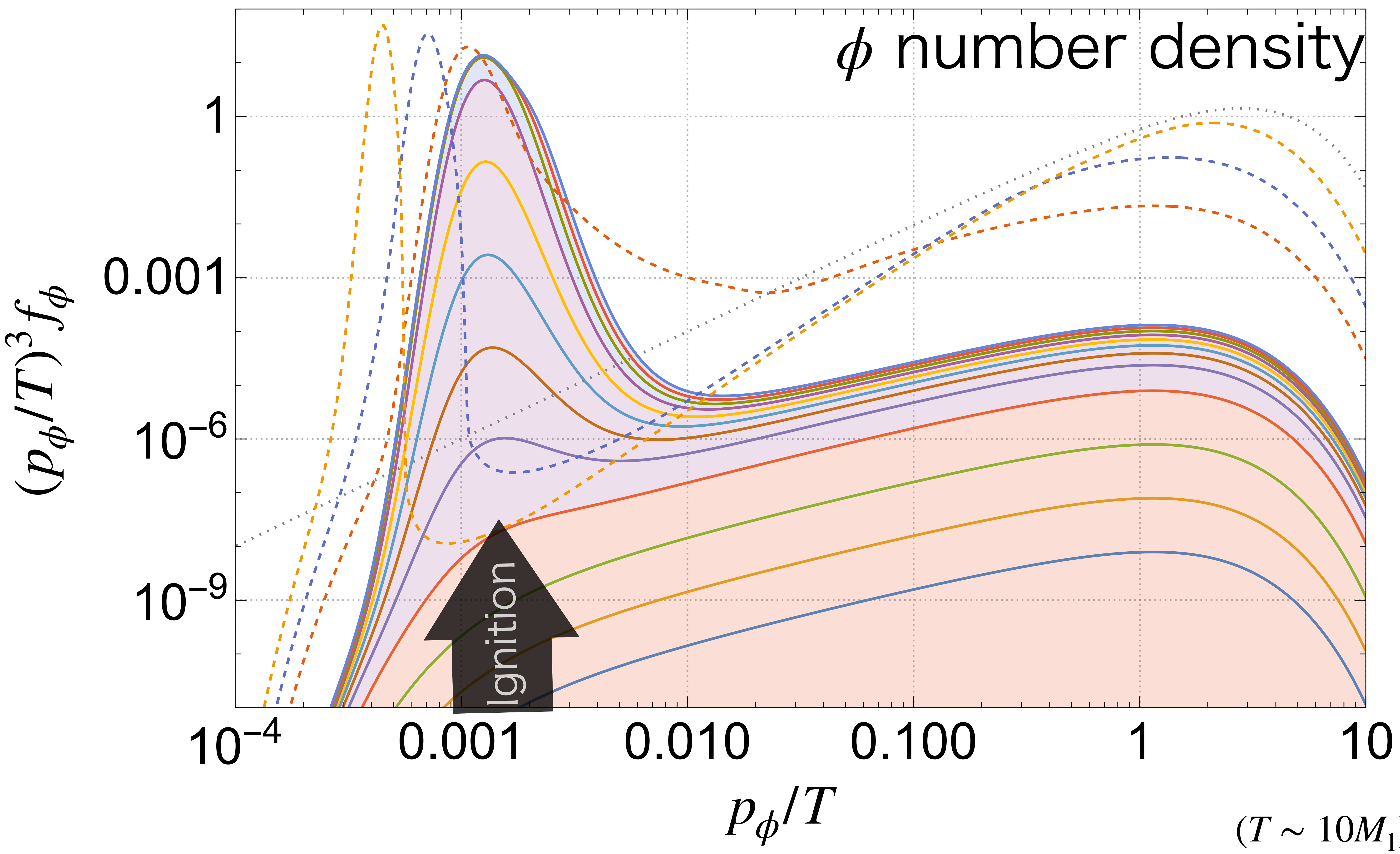


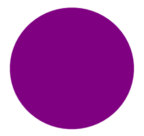
$(T \sim 10 M_1)$

I will explain the **three stages of burst production:**

1. <u>**Ignition**</u>
2. **Burst**
3. **Saturation**

Stage 1: Ignition

$\chi_1 \to \chi_2 \phi$



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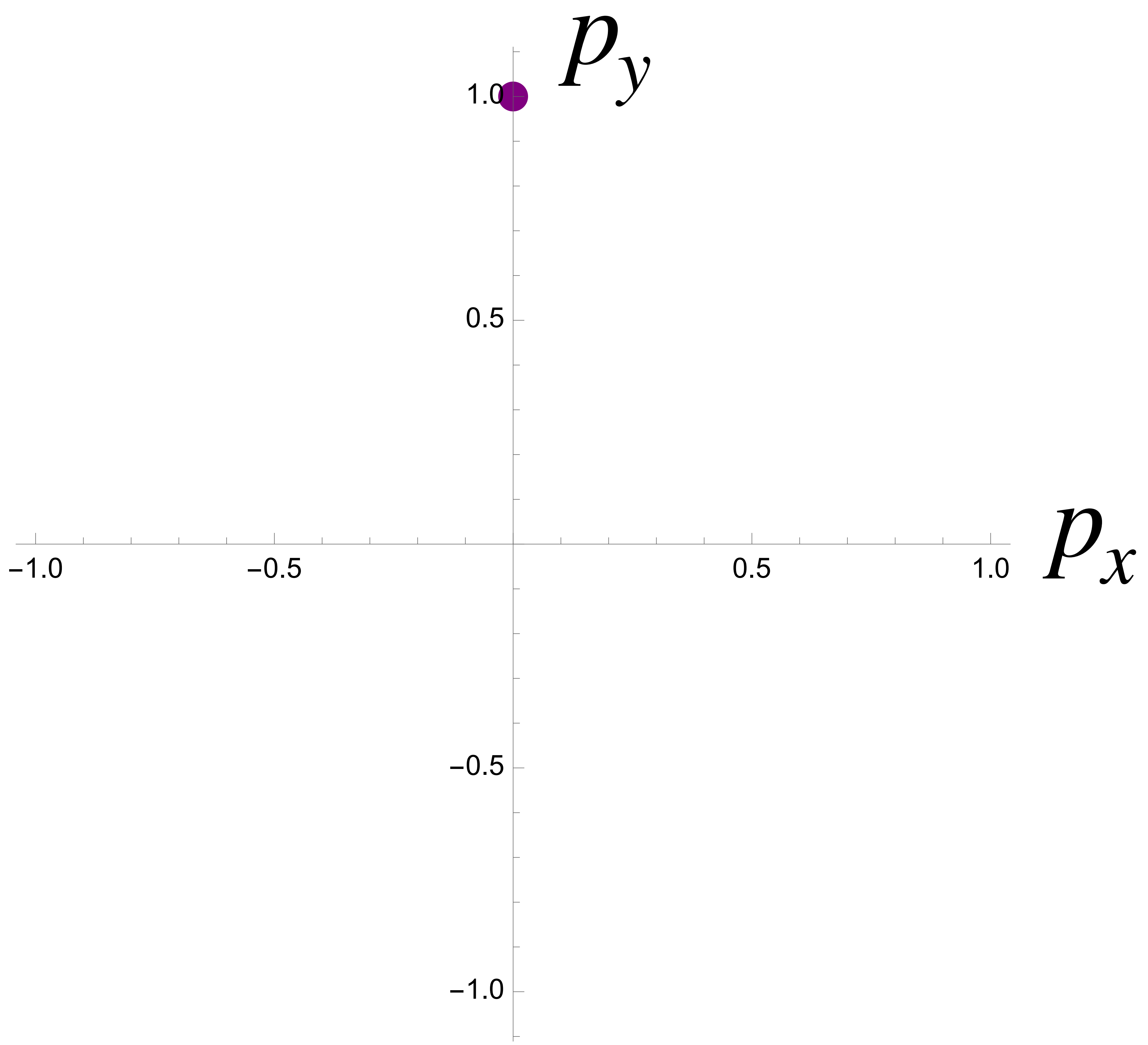

$(M_1 = 1/2, \gamma = 2)$

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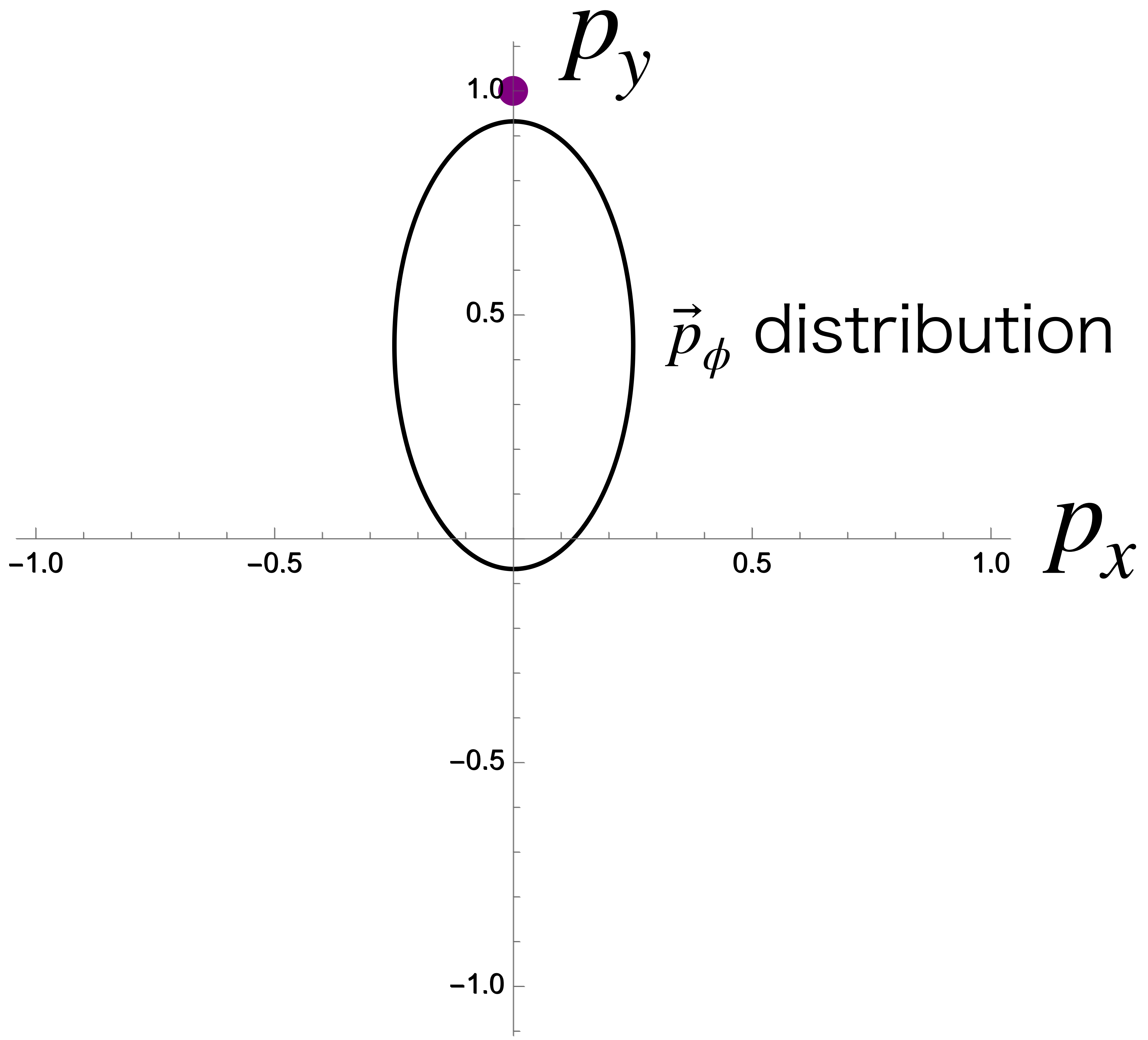

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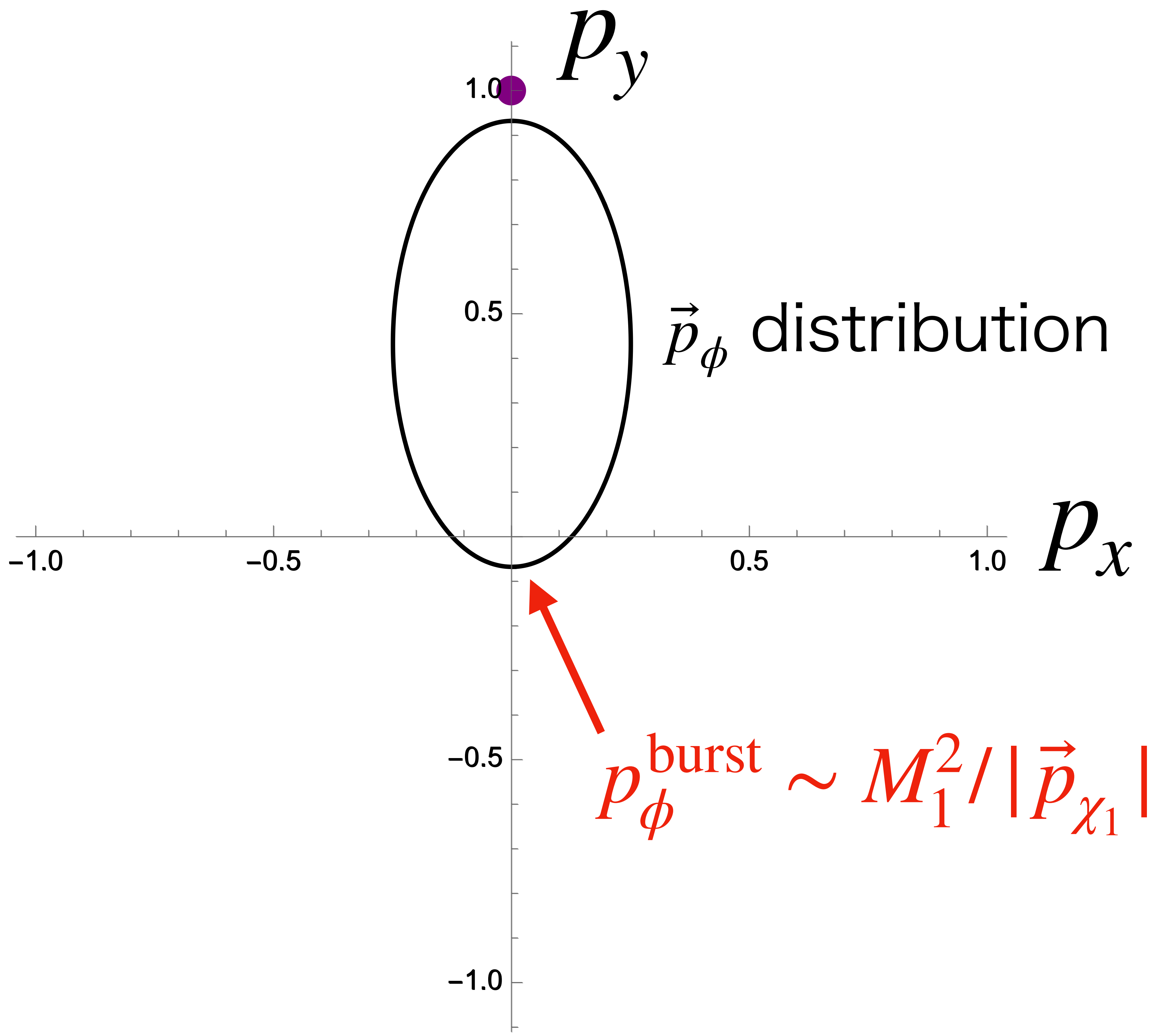

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Stage 1: Ignition

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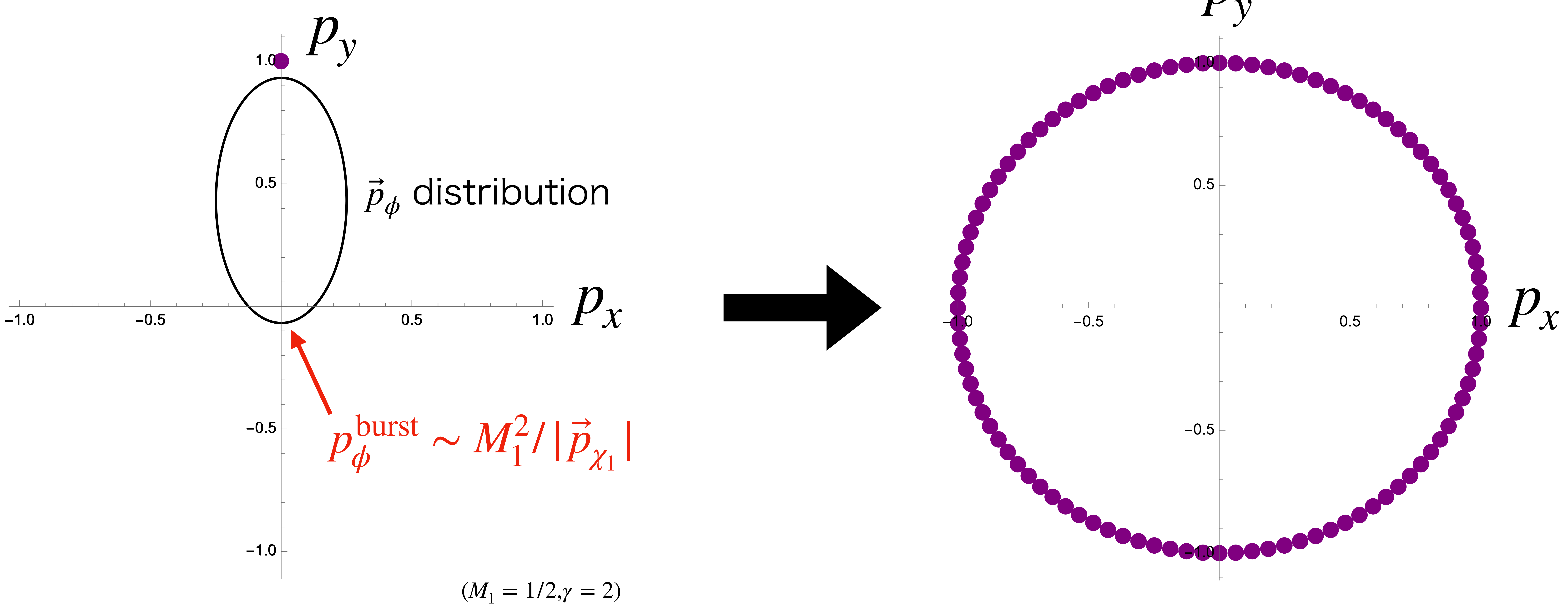
Second, let us consider the distribution of $\vec{p_\phi}$ from circular distribution χ_1 like in the thermal distribution, where $|\vec{p}_{\chi_1}| \sim T$.



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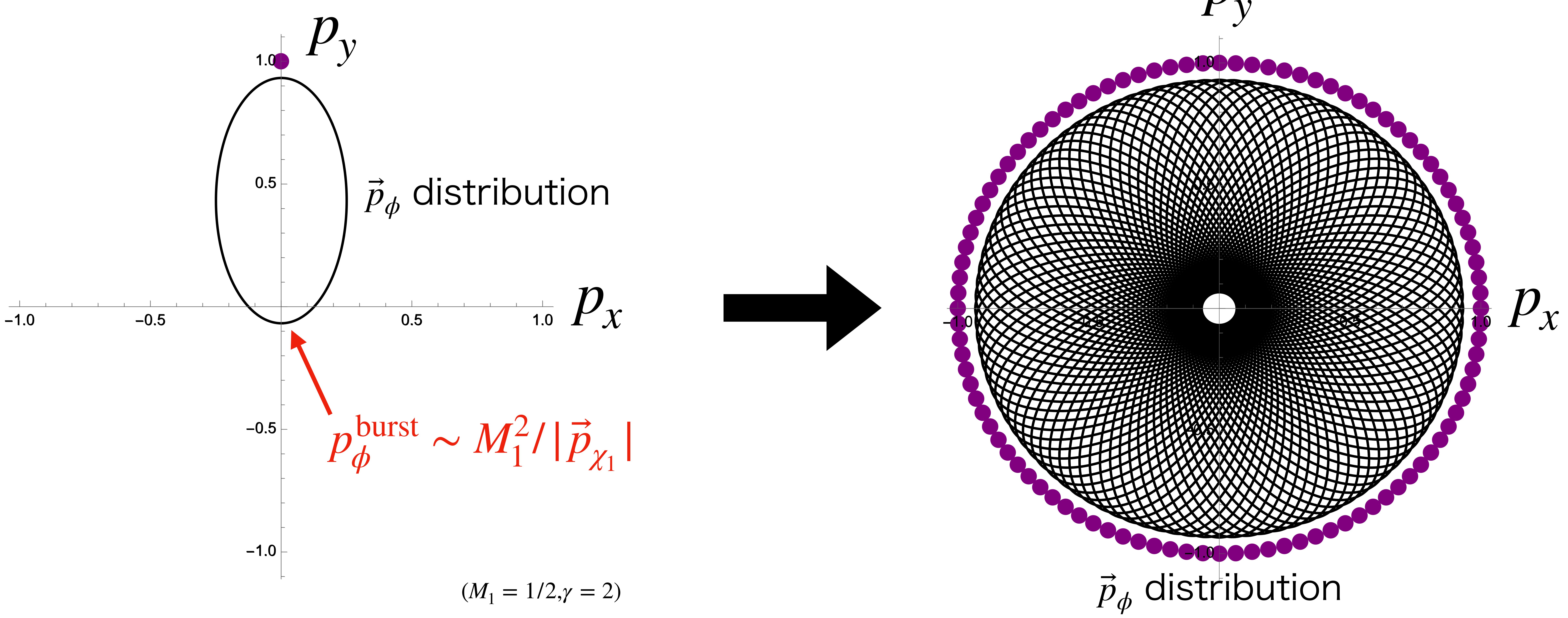

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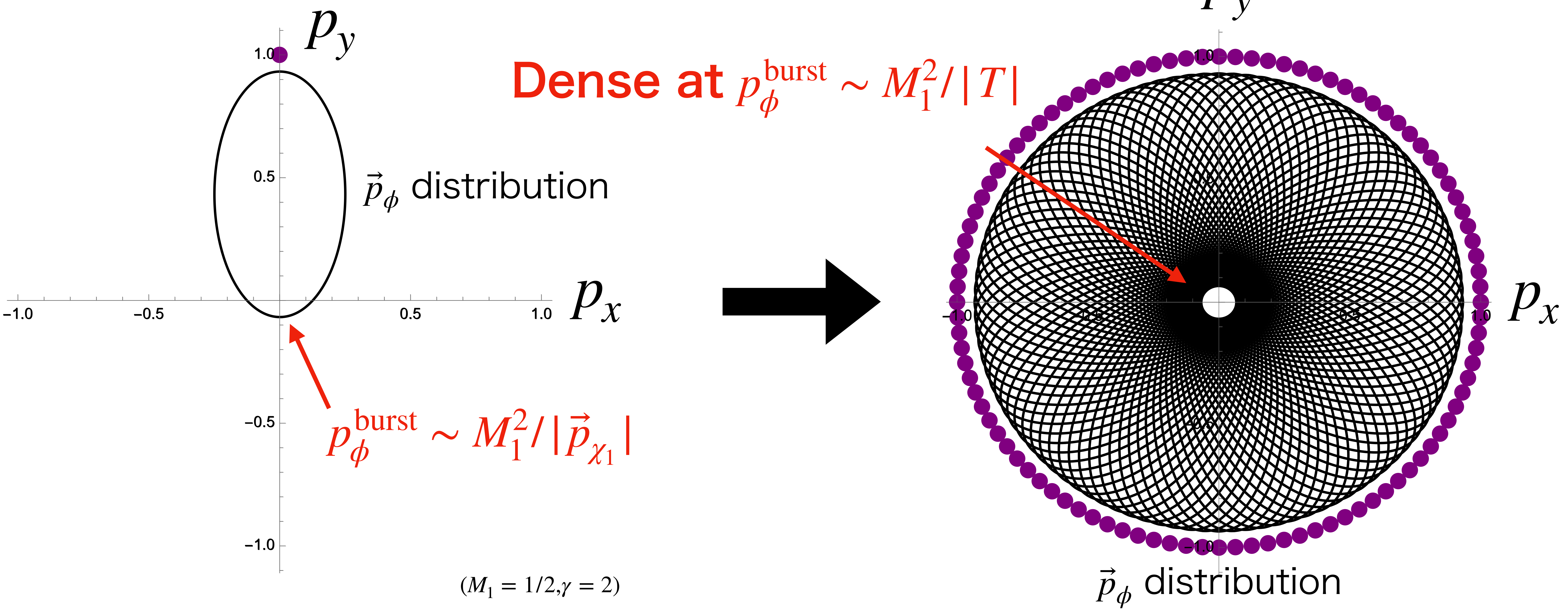
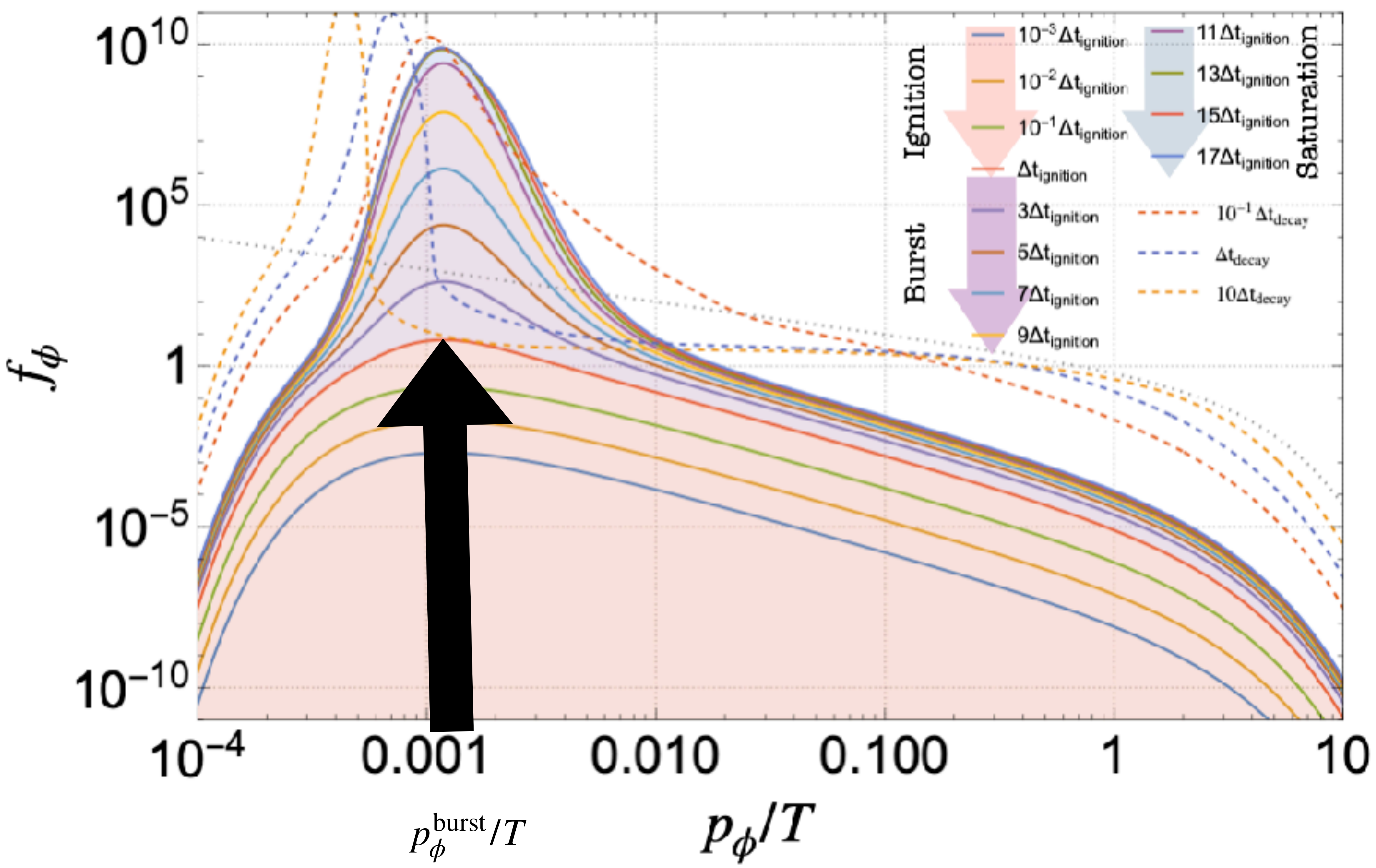
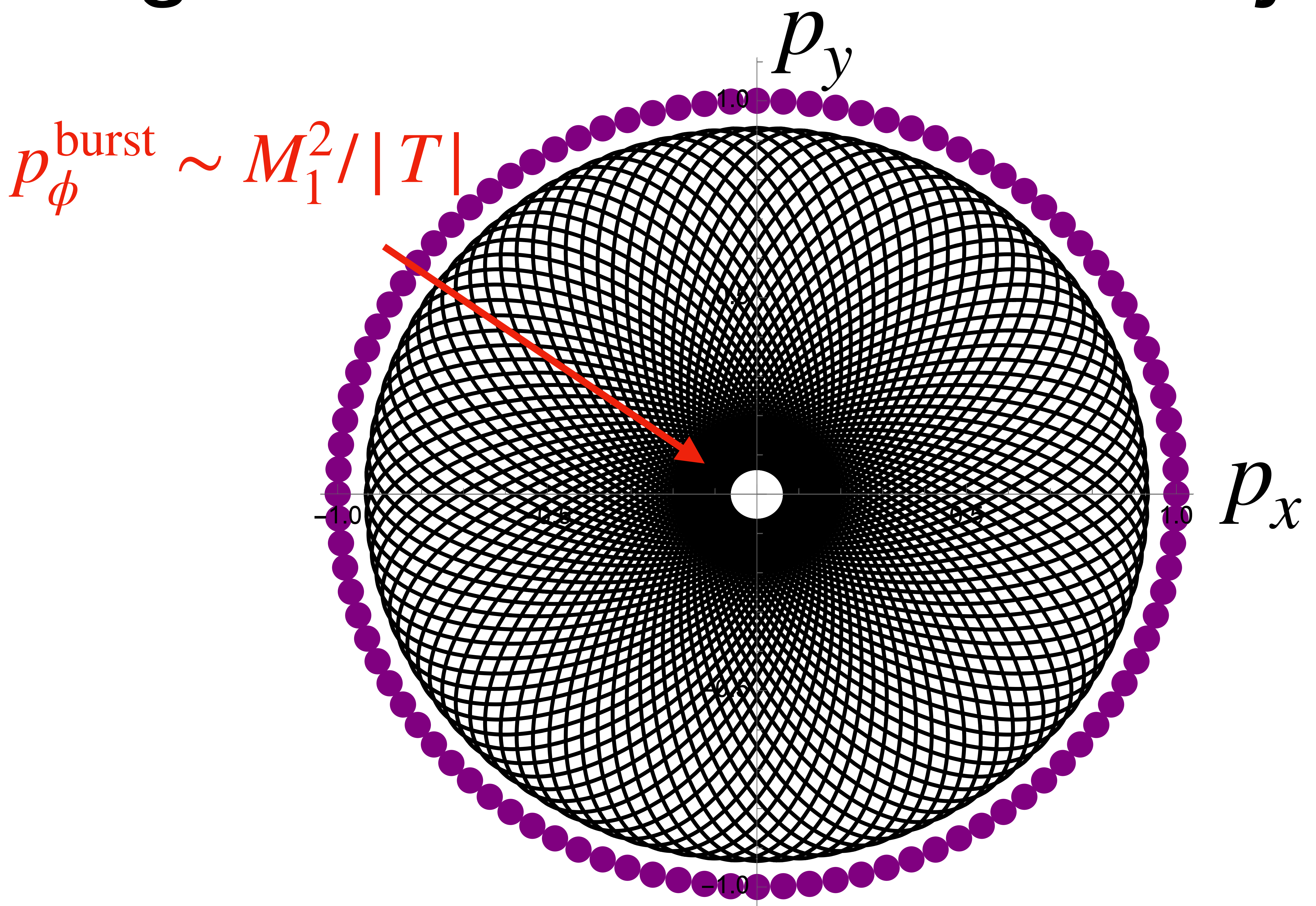


Stage 1: Ignition

In 3D realistic cases, the occupation number with $p_\phi \sim \; p_\phi^{\mathrm{burst}}$ increases rapidly. The ignition stage ends when it reaches unity.

Occupation number





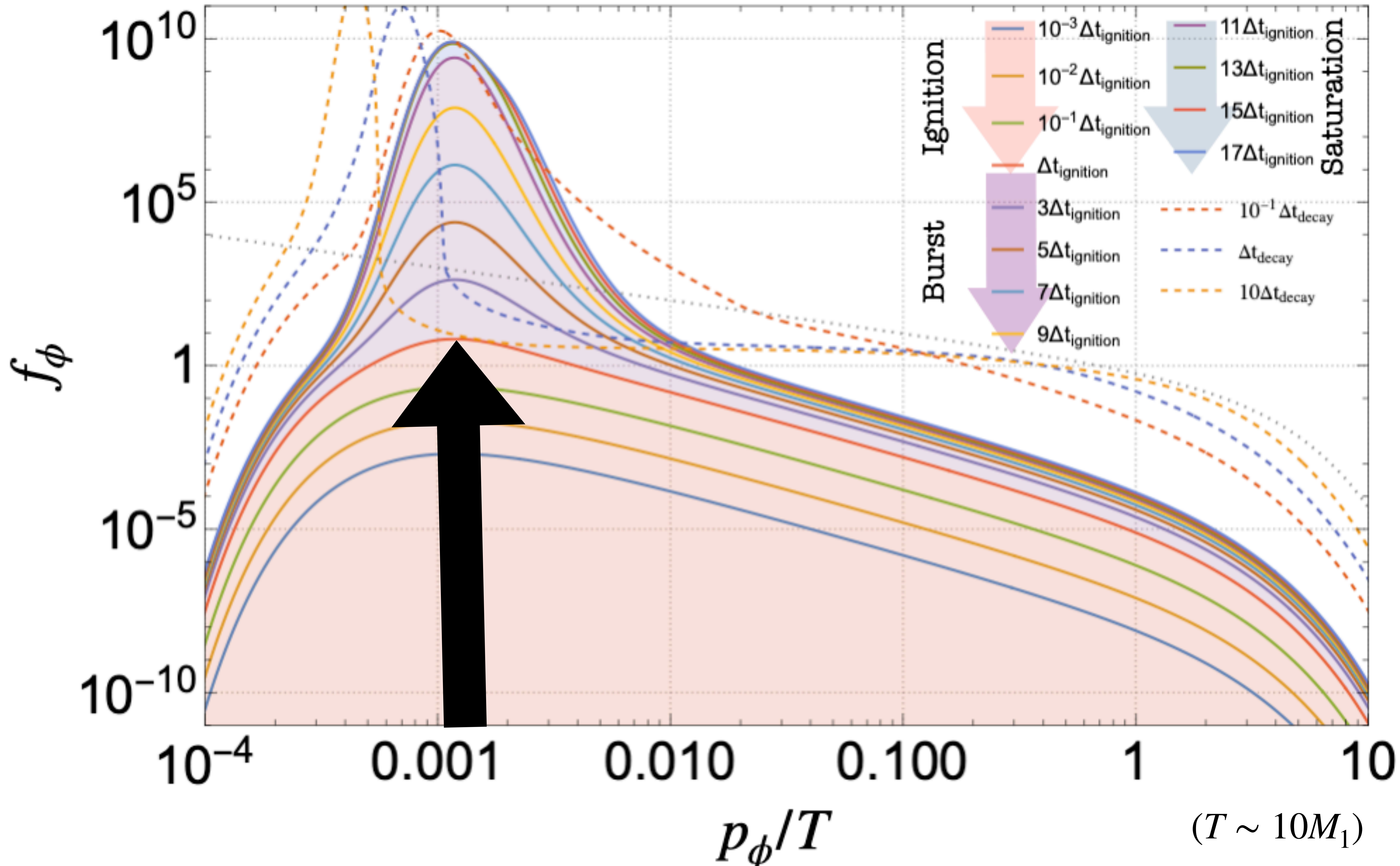
$\vec{p}_\phi$ distribution

Stage 1: Ignition

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

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

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

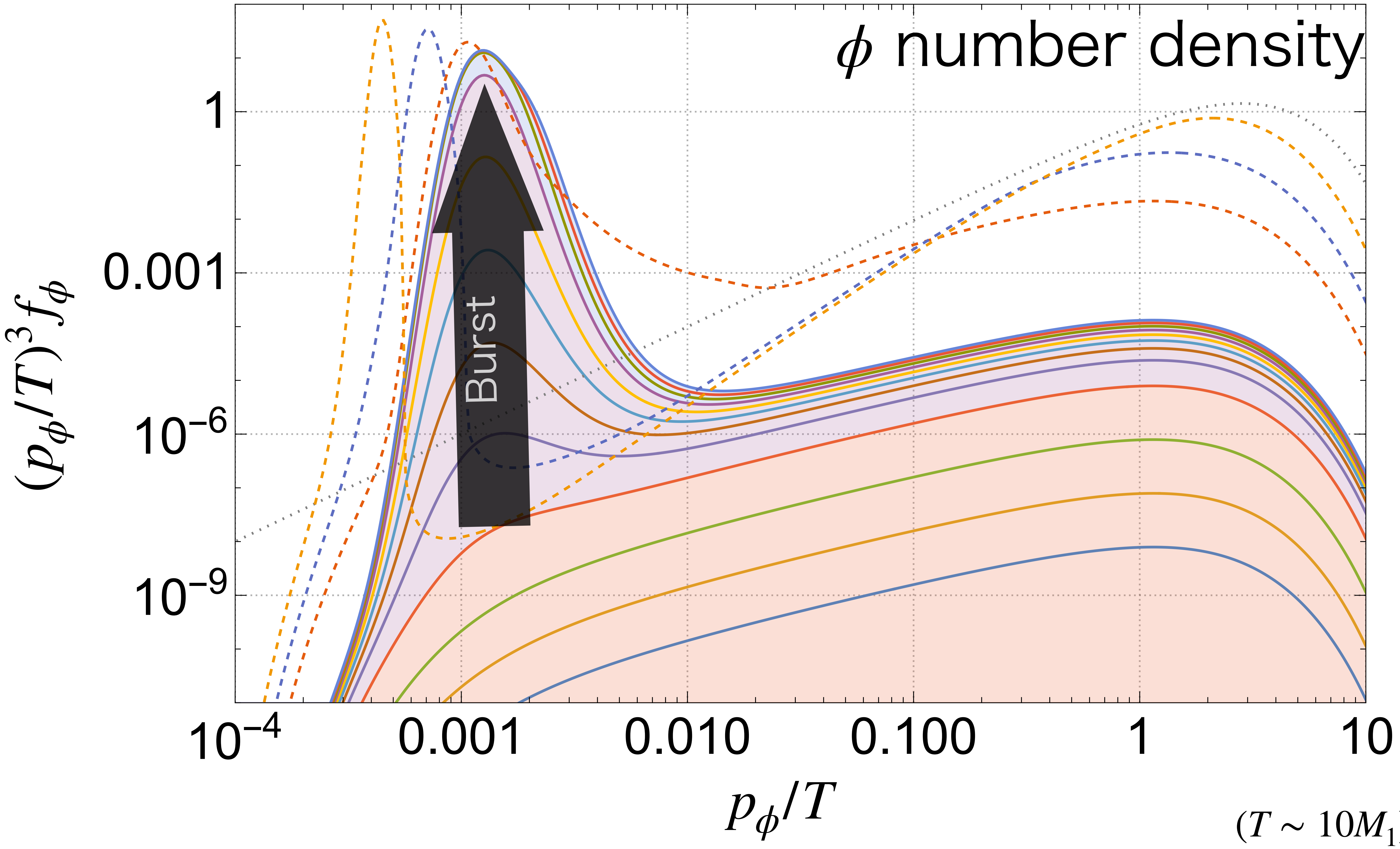


This is much faster than the ordinary thermalization rate by T^4/M_1^4.

Burst production of DM (in Minkowski space) - Stage 2: Burst

$\chi_1 \to \chi_2 \phi$: Thermalized $\chi_1, \chi_2, \phi(=\text{bosonic DM})$ are absent initially

χ_1 mass : M_1 χ_2, ϕ : massless



$(T \sim 10M_1)$

I will explain the **three stages of burst production:**

1. **Ignition**
2. **<u>Burst</u>**
3. **Saturation**

Stage 2: Burst

$p_\phi^{\rm burst}$ modes grow exponentially due to Bose enhancement. i.e. χ_1 has stimulated decays into ϕ IR mode and χ_2 with $p_{\chi_2} \sim T$. c.f. laser.

With $f_\phi[p \sim p_\phi^{\rm burst}] \gtrsim 1, f_{\chi_2} \ll 1$

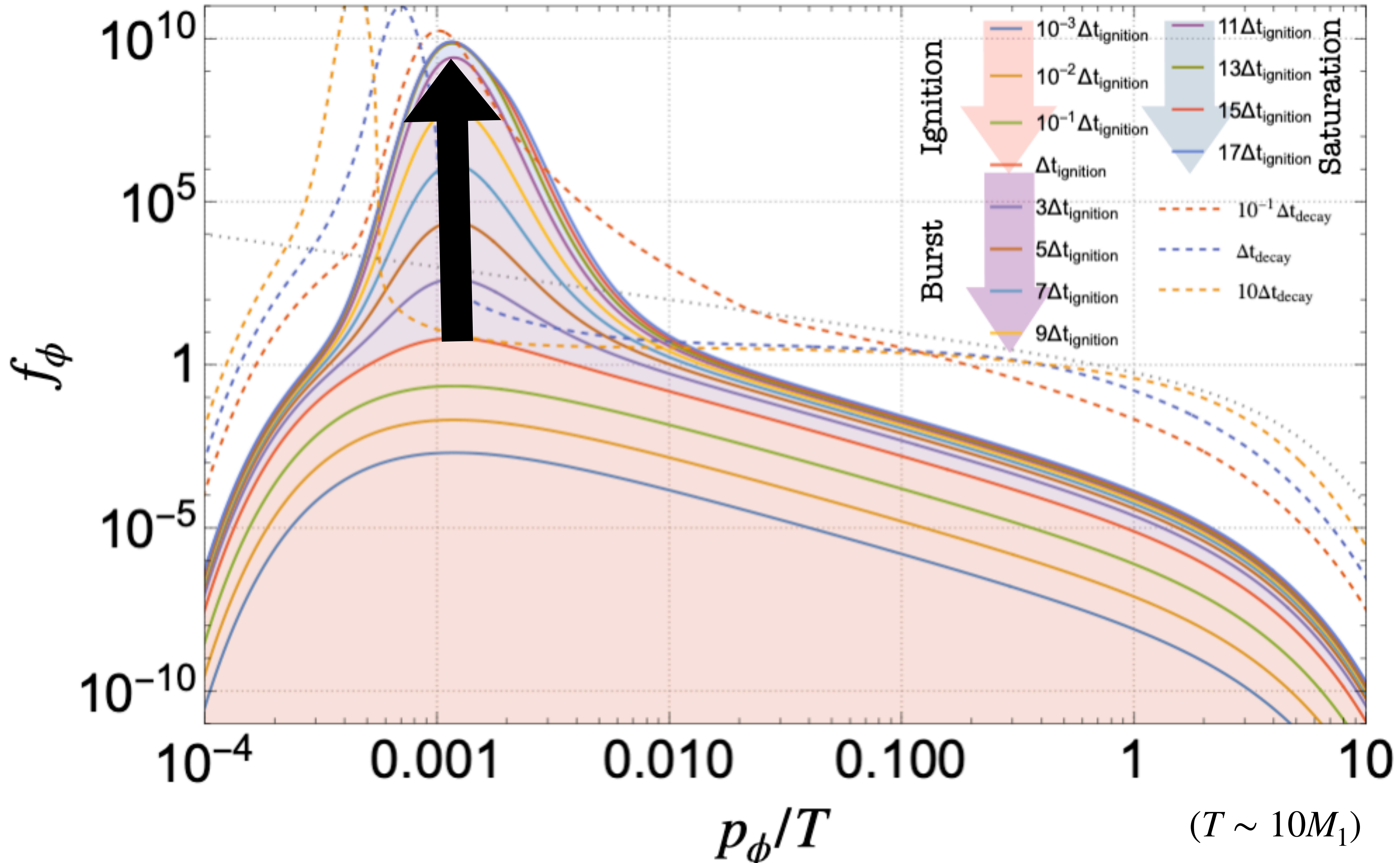
$$C^\phi = \frac{1}{2E_\phi g_\phi} \sum \int d\Pi_{\chi_1}\, d\Pi_{\chi_2}$$
$$(2\pi)^4 \delta^4(p_{\chi_1} - p_\phi - p_{\chi_2}) \times |\mathcal{M}_{\chi_1 \to \chi_2 \phi}|^2$$
$$\times S\left(f_{\chi_1}[p_{\chi_1}], f_{\chi_2}[p_{\chi_2}], f_\phi[p_\phi]\right)$$

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

$$\Rightarrow \quad \dot{f}_\phi[p_\phi \sim p_\phi^{\rm burst}] \sim \Delta t_{\rm iginition}^{-1} f_{\chi_1}(p_{\chi_1} \sim T)(1 + f_\phi[p_\phi \sim p_\phi^{\rm burst}])$$

Stage 2: Burst

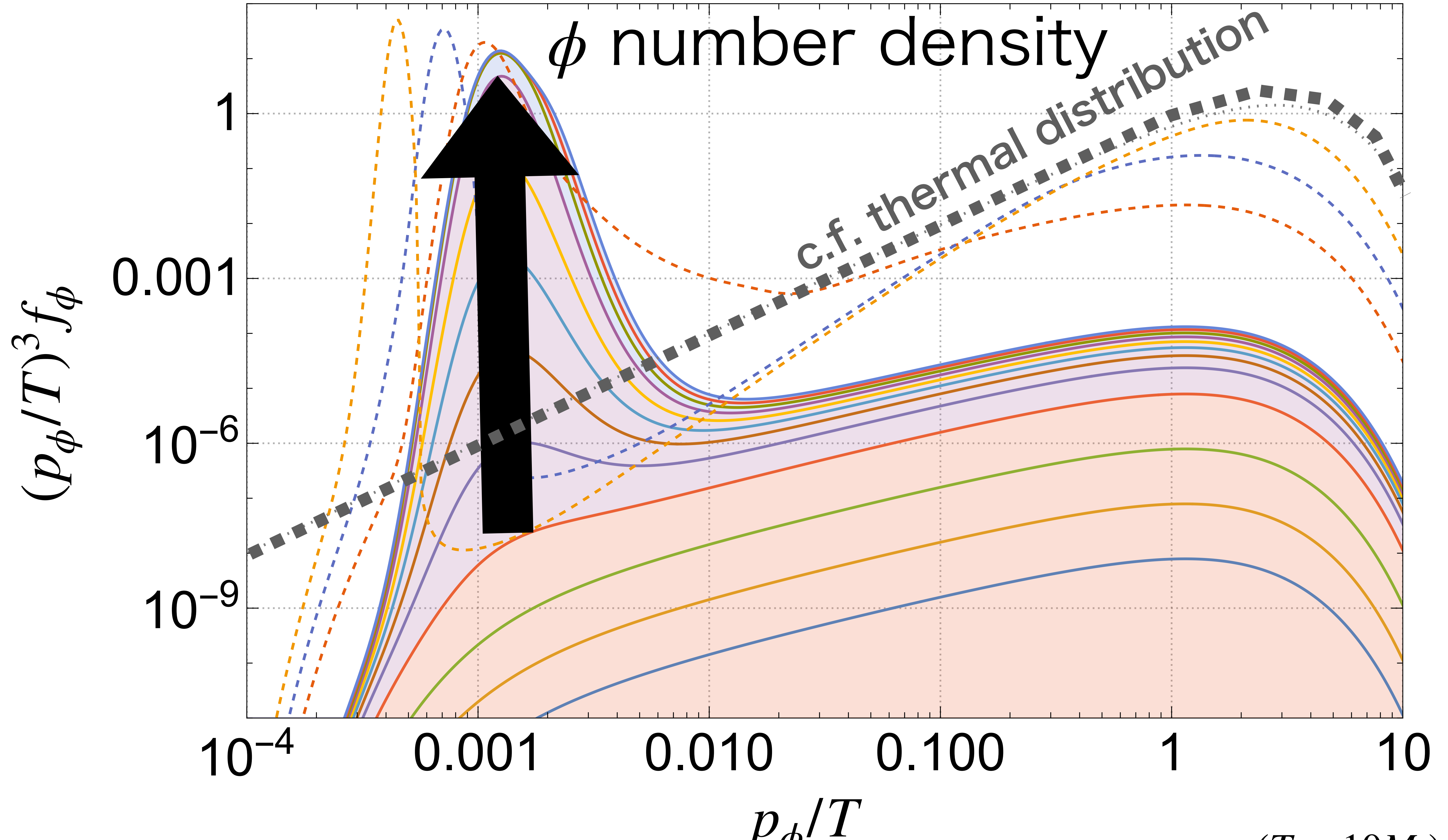
In a timescale of $t \sim \Delta t_{\text{iginition}}$, the IR modes with $p_\phi \sim p_\phi^{\text{burst}}$ are violently populated.



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

Stage 2: Burst

In a timescale of $t \sim \Delta t_{\rm iginition}$, the IR modes with $p_\phi \sim p_\phi^{\rm burst}$ is violently populated. So does the total ϕ number density.



$(T \sim 10 M_1)$

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

Burst production of DM (in Minkowski space)
- Stage3: Saturation (quasi-equilibrium)

$\chi_1 \to \chi_2\phi$: Thermalized χ_1, χ_2, $\phi(=$ bosonic DM) are absent initially

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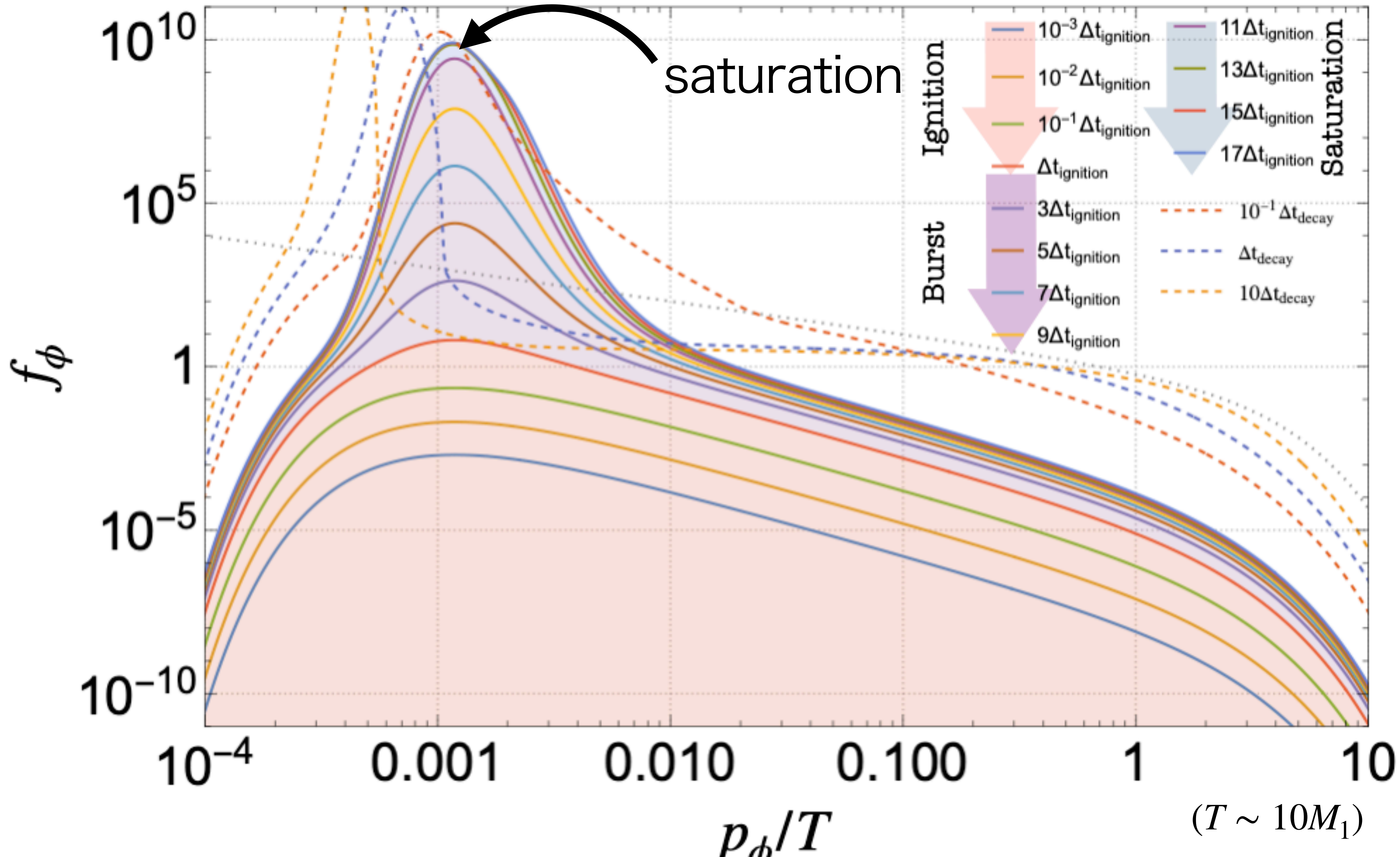

I will explain the **three stages of burst production:**

1. **Ignition**
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3. **<u>Saturation</u>**

Stage 3: Saturation (quasi-equilibrium)

The burst production stops due to the back reaction when $\chi_2[p_{\chi_2} \sim T]$ modes are also populated.

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

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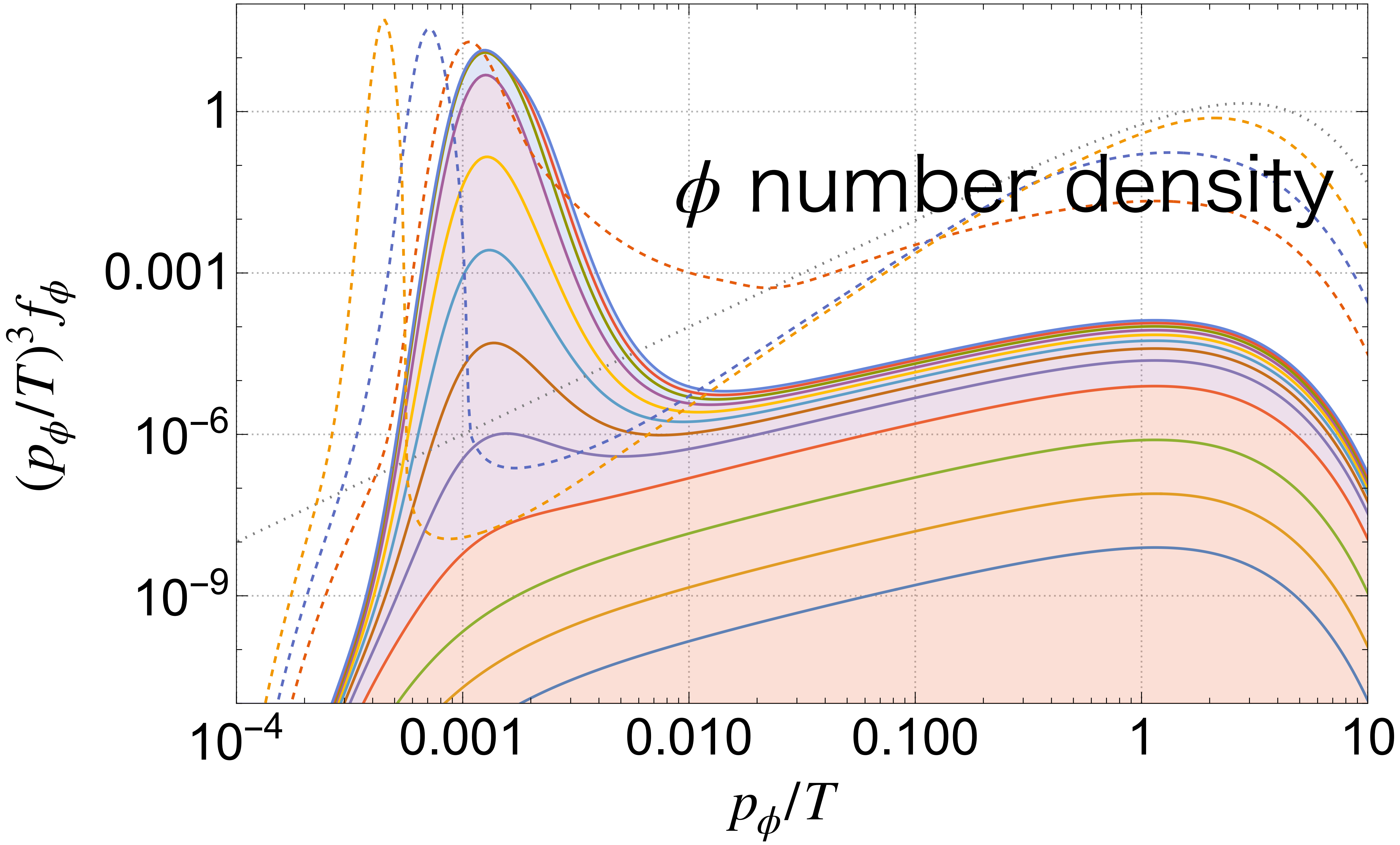
$$S \equiv f_{\chi_1}[p_{\chi_1} \sim T](1 \pm f_{\chi_2}[p_{\chi_2} \sim T])(\cancel{1} + f_\phi[p_\phi \sim p_\phi^{\rm burst}])$$
$$-(1 \pm f_{\chi_1}[p_{\chi_1} \sim T])f_\phi[p_\phi \sim p_\phi^{\rm burst}]f_{\chi_2}[p_{\chi_2} \sim T]$$
$$\sim (f_{\chi_1}[p_{\chi_1} \sim T] - f_{\chi_2}[p_{\chi_2}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

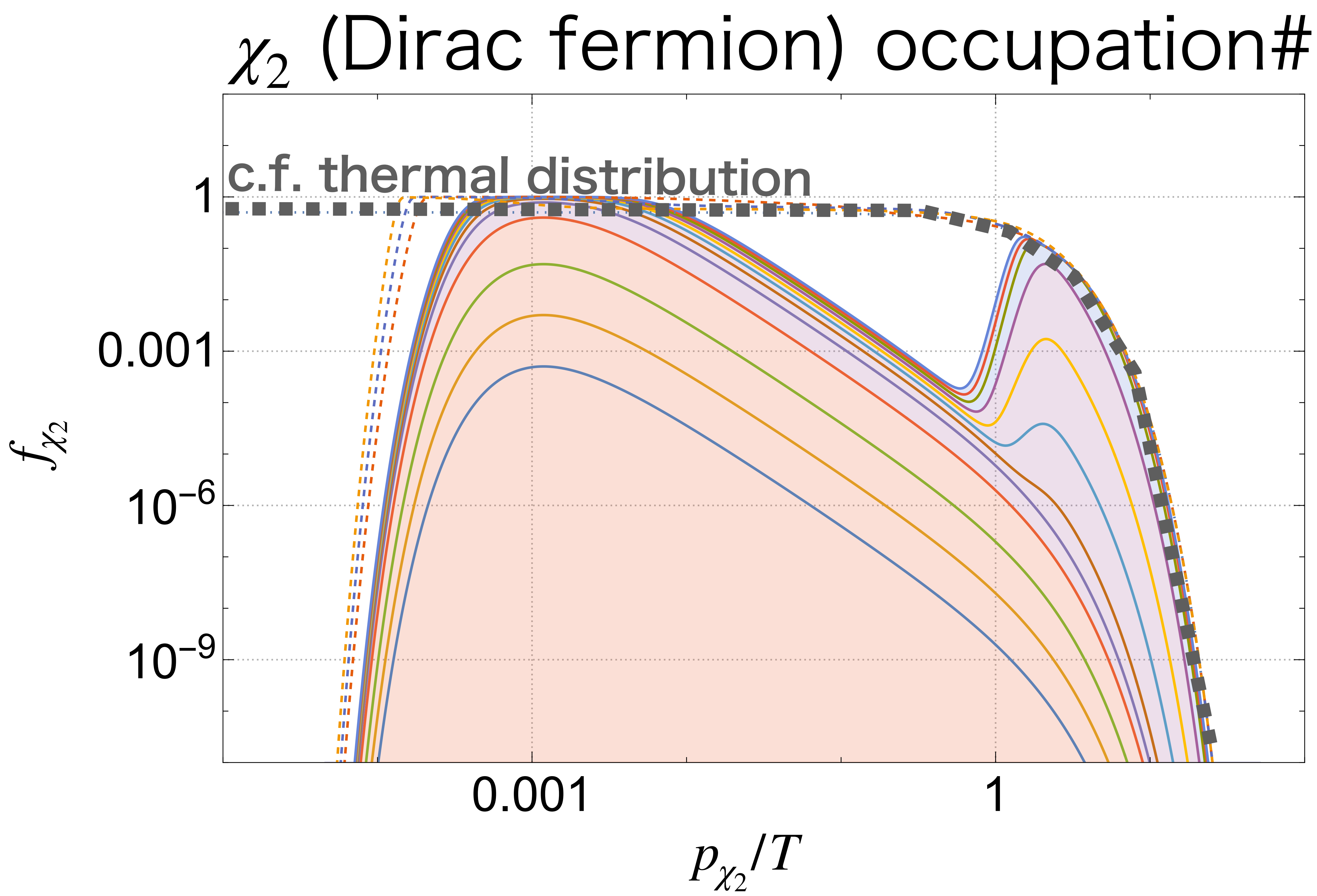
$$\Rightarrow \quad \dot{f}_\phi[p_\phi \sim p_\phi^{\rm burst}] \sim 0$$

Stage 3: Saturation (quasi-equilibrium)

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

$\dot{n}_{\chi_2} = \dot{n}_\phi$ during the whole $\chi_1 \leftrightarrow \chi_2\phi$ process,





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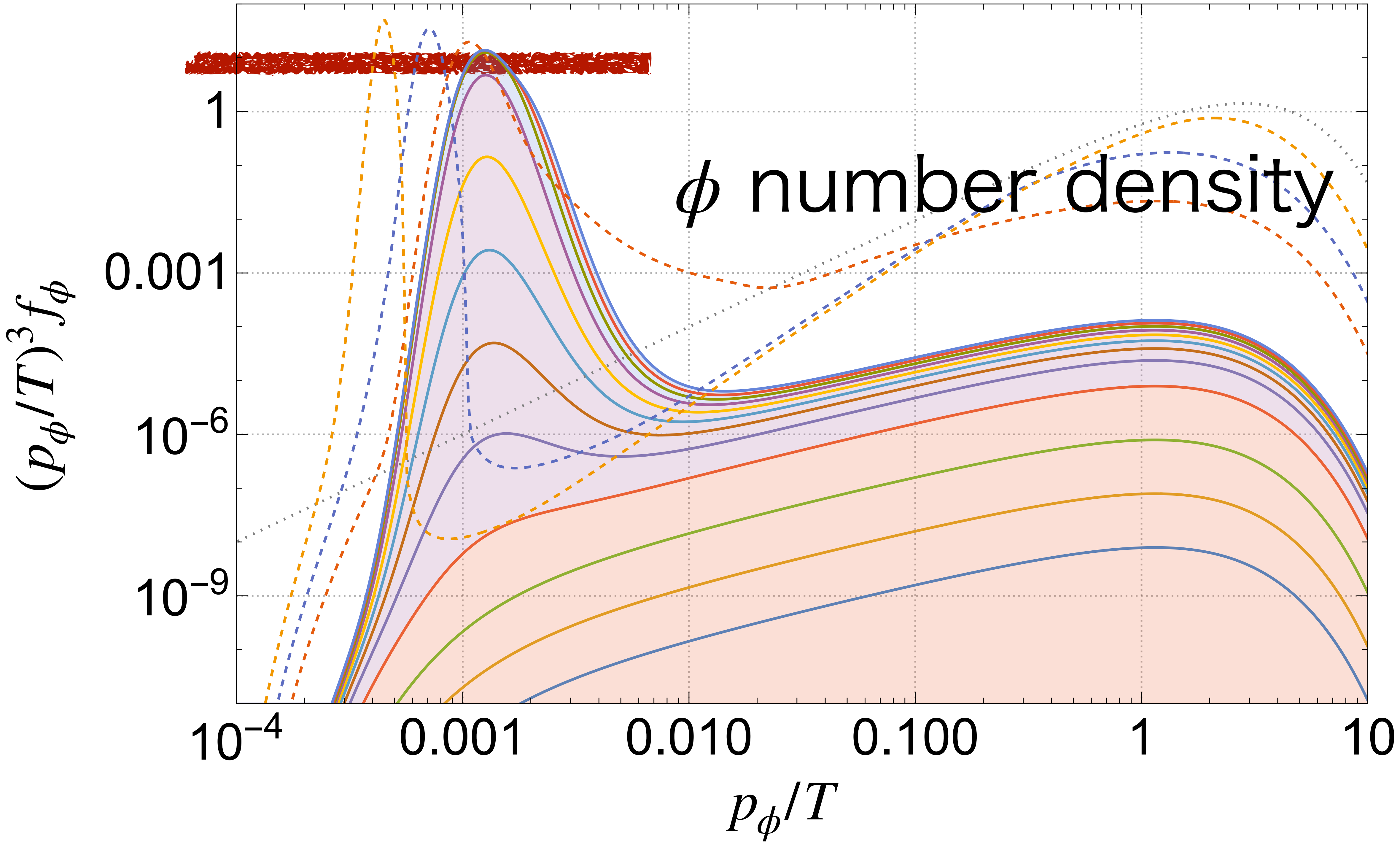
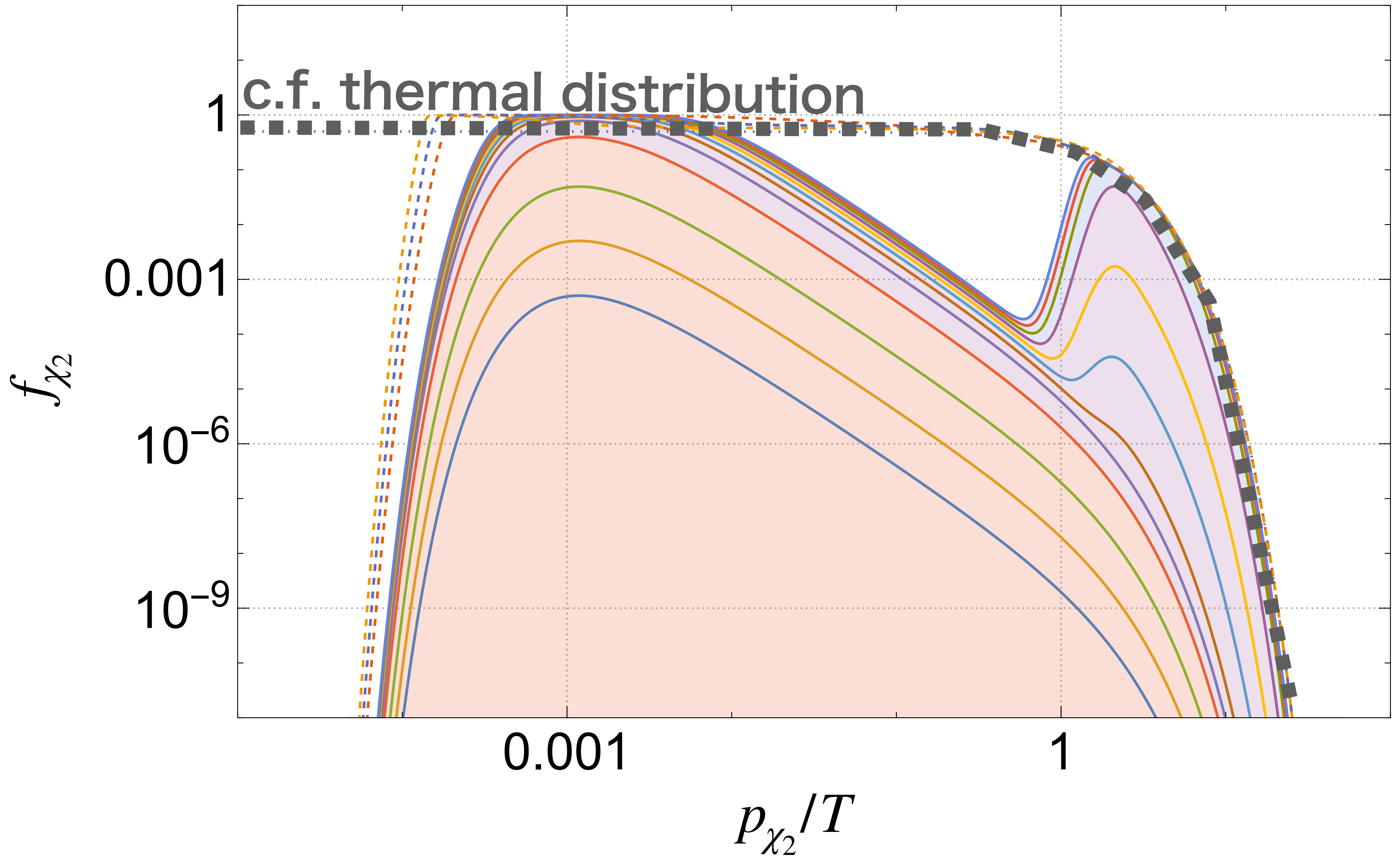
$n_\phi \sim T^3, p_\phi \sim M_1^2/T$, which is cold



χ_2 (Dirac fermion) occupation#



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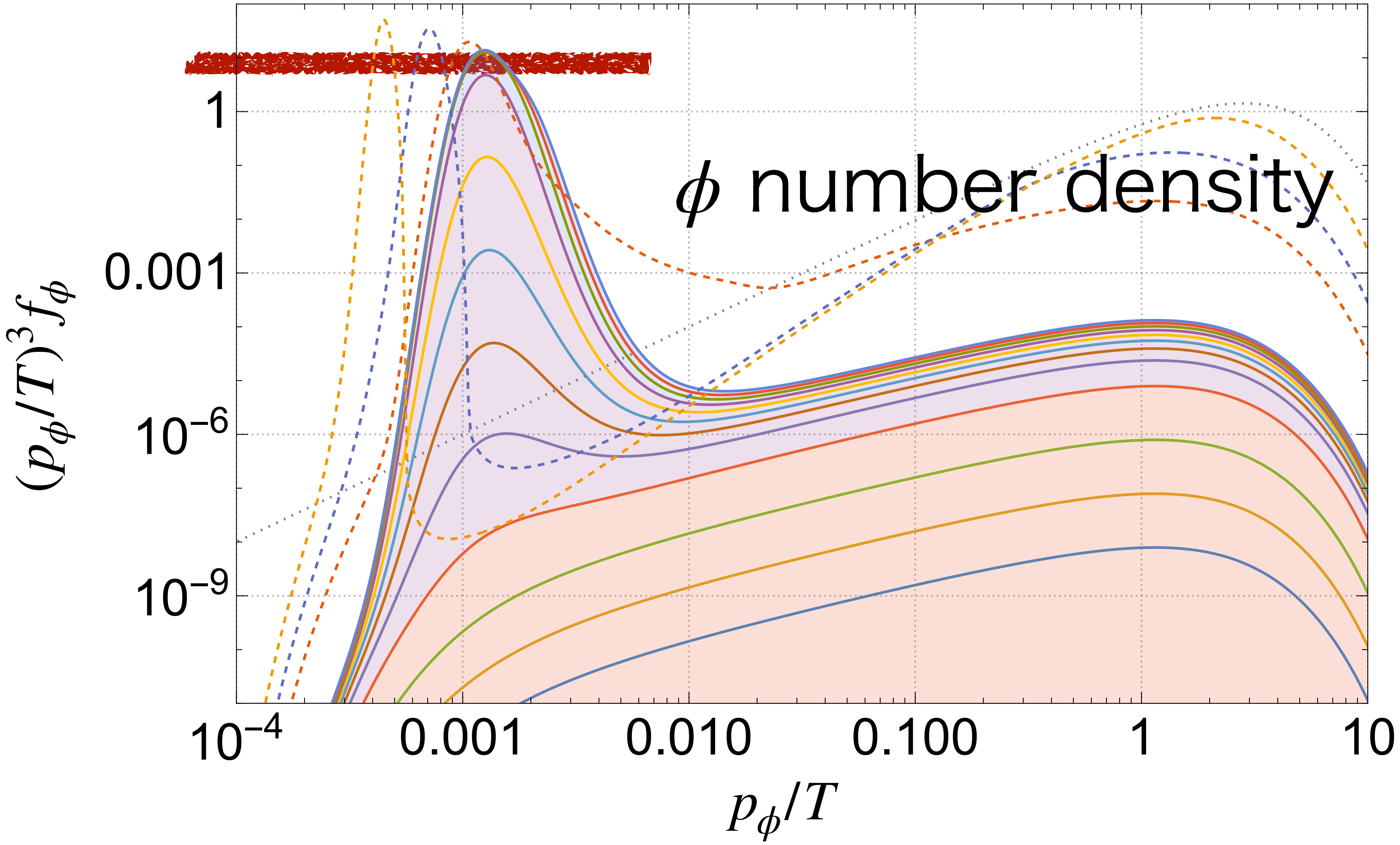


This is kept in very long time scale

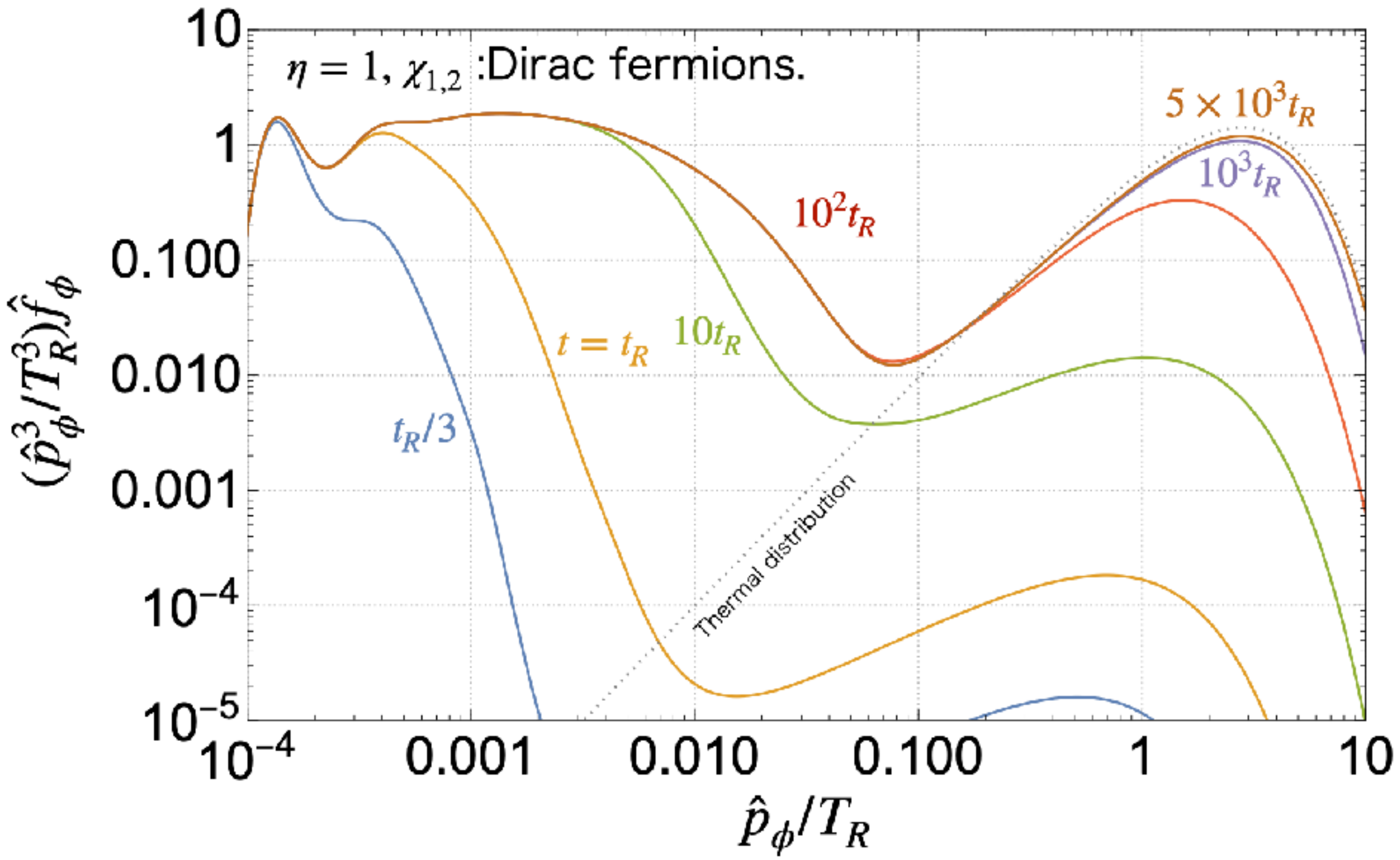
until $t \sim \Gamma_{\rm decay}^{-1} \dfrac{T}{M_1} \sim \left(\dfrac{T}{M_1}\right)^4 \Delta t_{\rm ignition}$.

Burst production in expanding Universe

If there is a period satisfying

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

the burst produced ϕ remains due to redshift and kinematics.



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

Prediction:

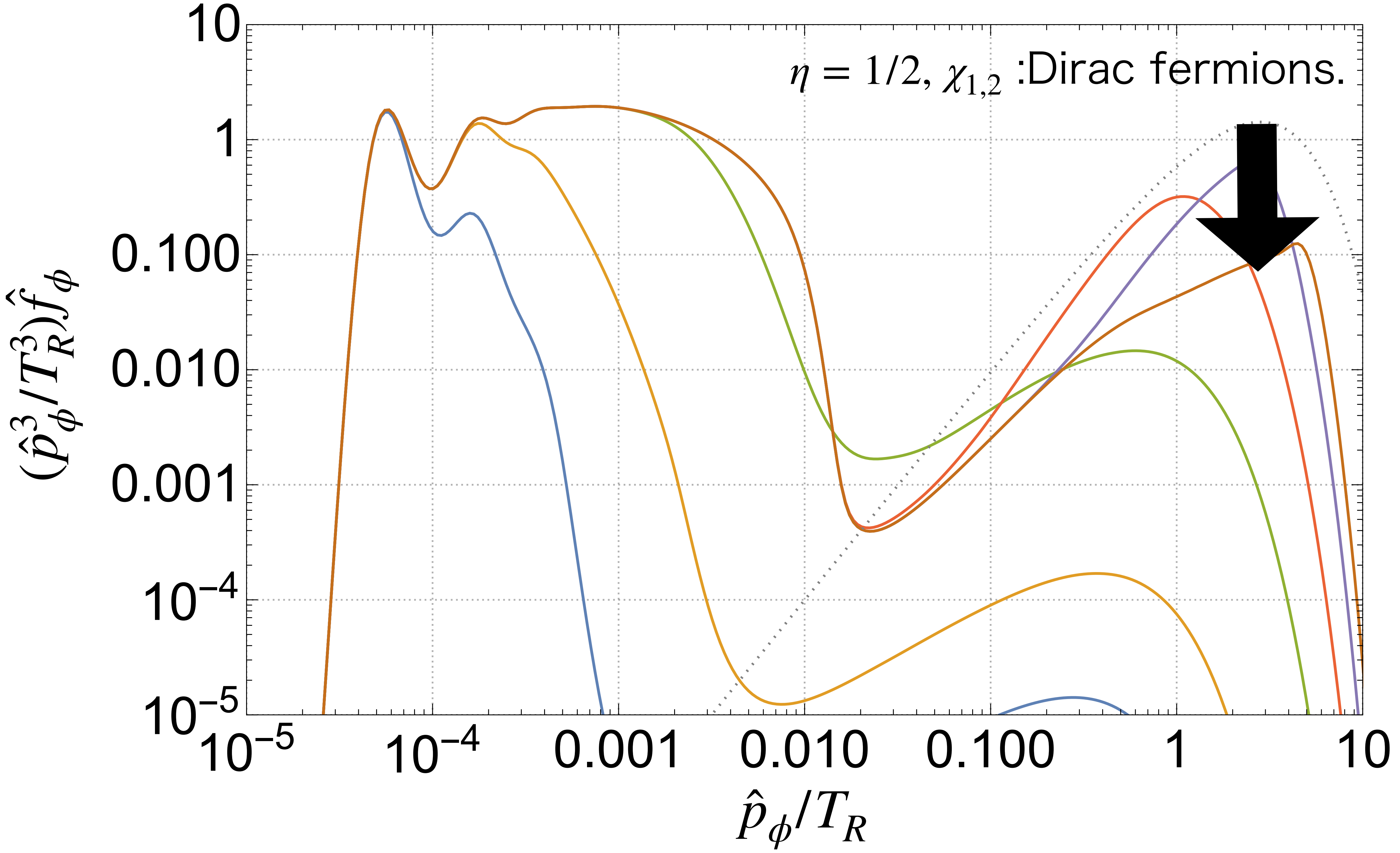
Cold DM with

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

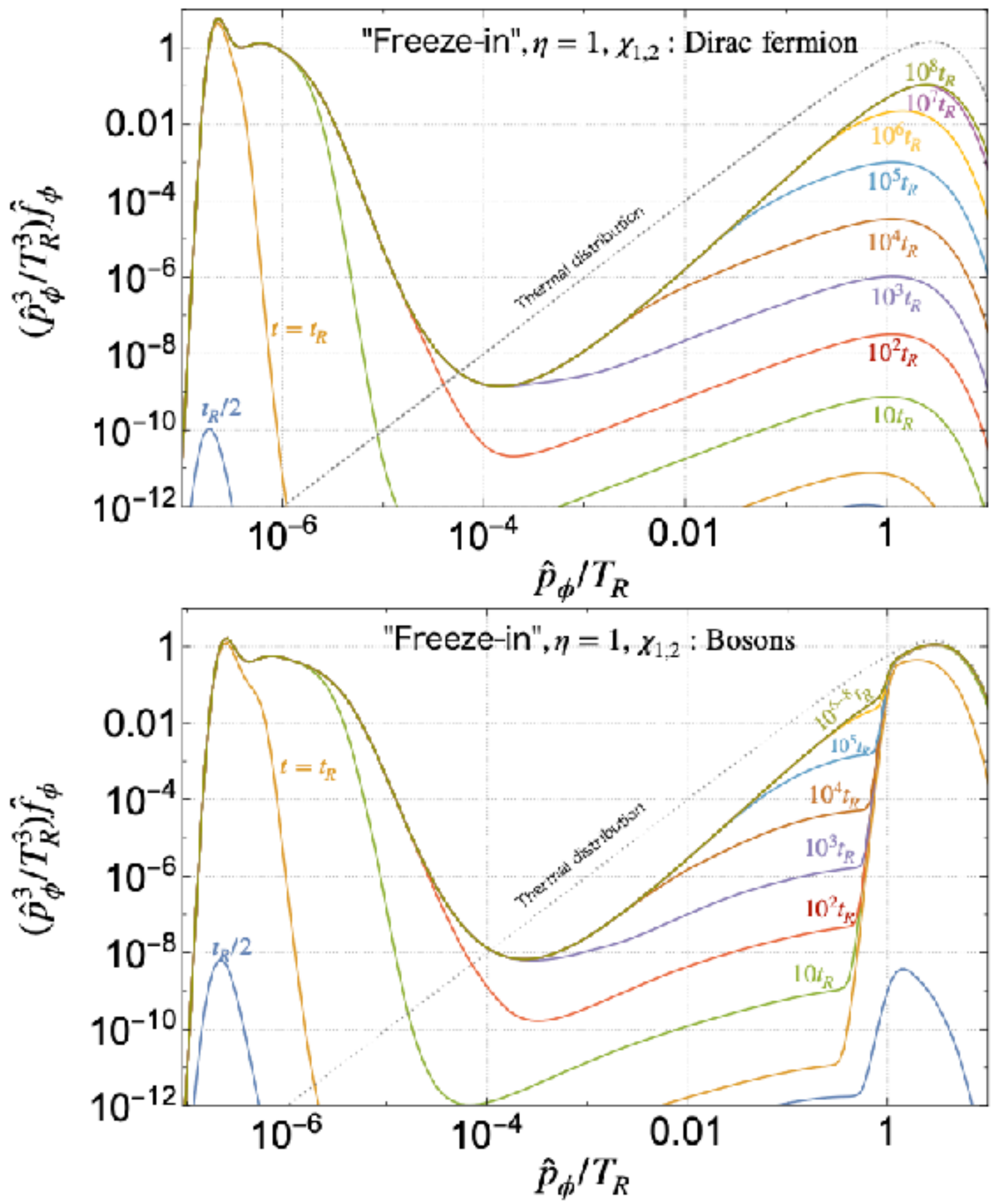
Non-trivial results in slightly different setups:

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.



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

WY 2301.08735

- eV-keV range cold DM can be produced thermally depending on reactions
- eV range DM is still special and theoretically well-motivated, a la hot DM paradigm.
- Predictions of freeze-in scenarios $\chi_1 \to \chi_2\phi$, $\chi_1 \to \phi\phi$, may be significantly altered by this effect.

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

What is the definition of an axion/ALP, a?

Scalar with an approximate shift symmetry, $a \to a + C$,

in a periodic field space satisfying $a \leftrightarrow a + 2\pi f_a$.

Axion features derivative couplings, small mass and periodic potential.

I will sometimes use ϕ.

Sorry in advance for confusion.

UV completions:

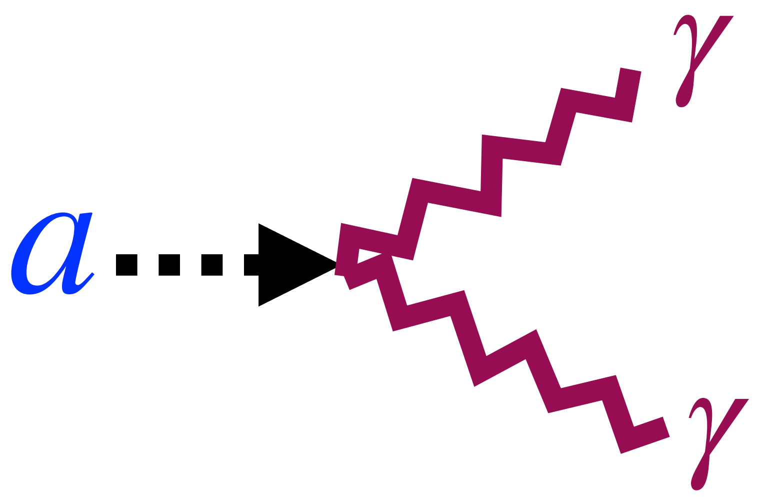
- String/M theory $(f_a \sim 10^{15-17}\,\mathrm{GeV}: \text{ string scale})$
- Pseudo Nambu-Goldstone boson $(f_a \sim \text{arbitrary}: \text{ SSB scale})$

Many kinds of axions:

- QCD axion (→part 1)
- Others (→part 2-5, axion/ALP)

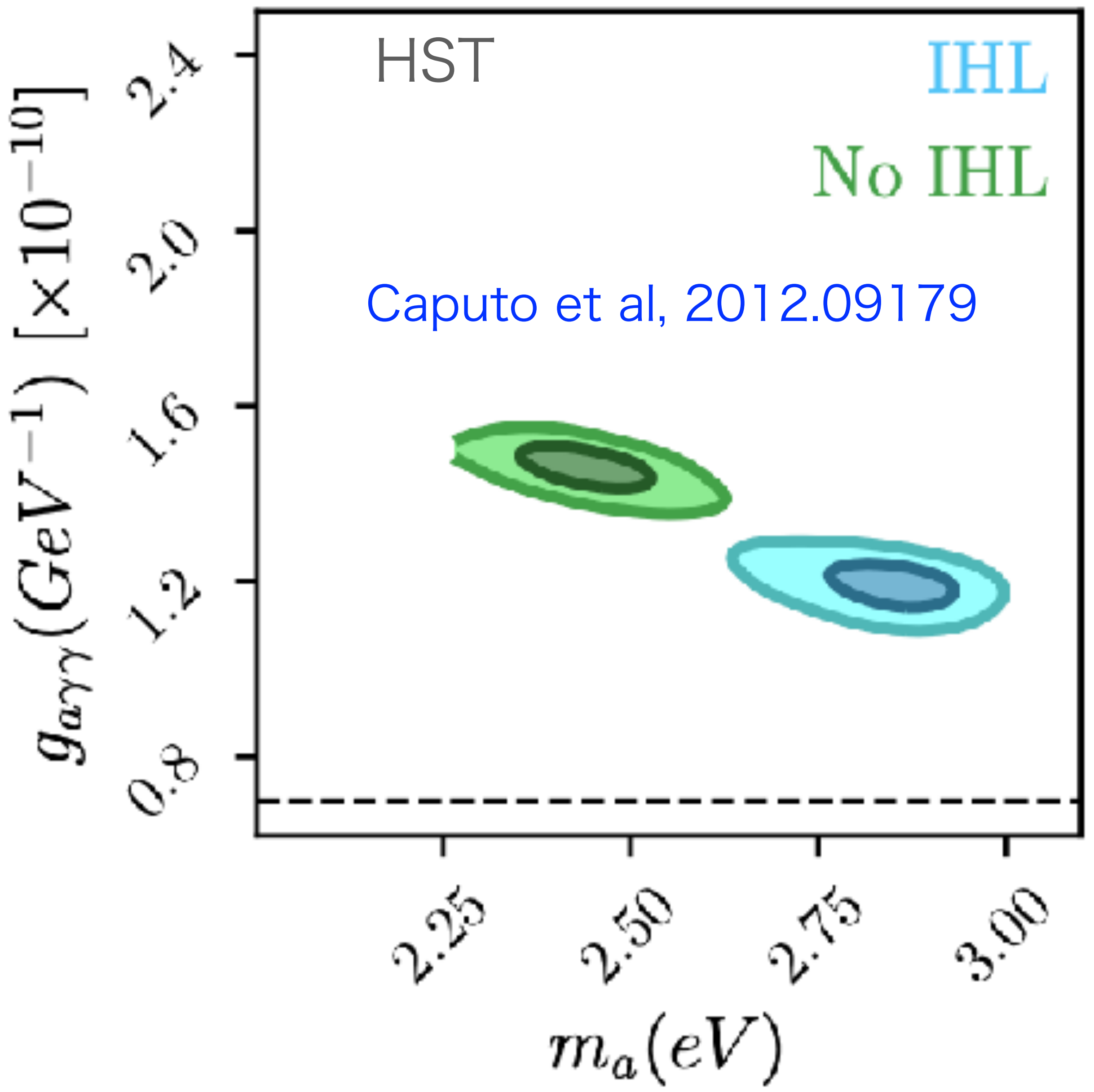
eV ALP hint from "Indirect detection"

Indirect detection of eV is with serious sky background (e.g. Zodiacal light)

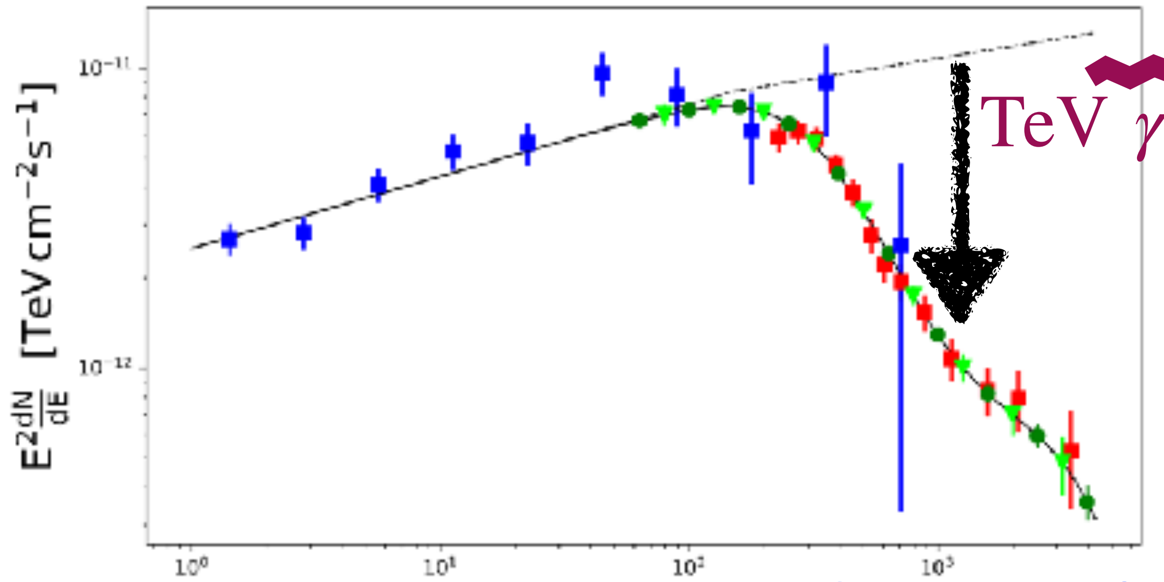


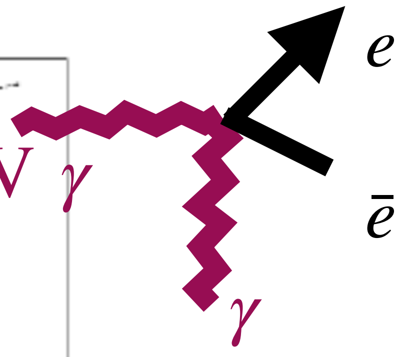
The **anisotropic cosmic infrared background (CIB)** data suggests a decaying DM with

$m_a \sim eV$, $g_{a\gamma\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$ Gong et al 1511.01577

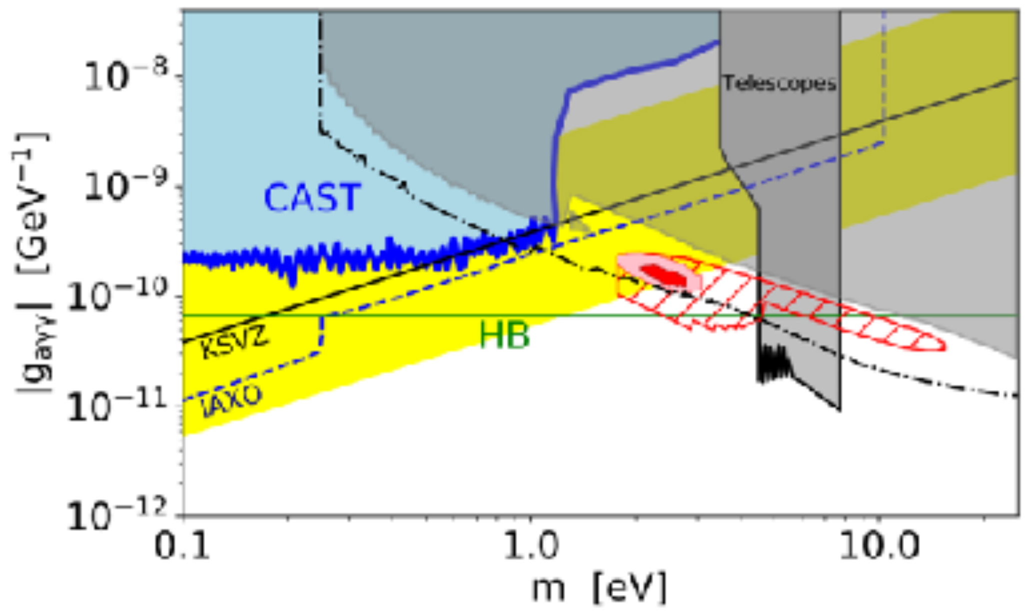


The **TeV γ spectrum** gets a better fit by photons from ALP DM of $m_a \sim eV$, $g_{a\gamma\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$





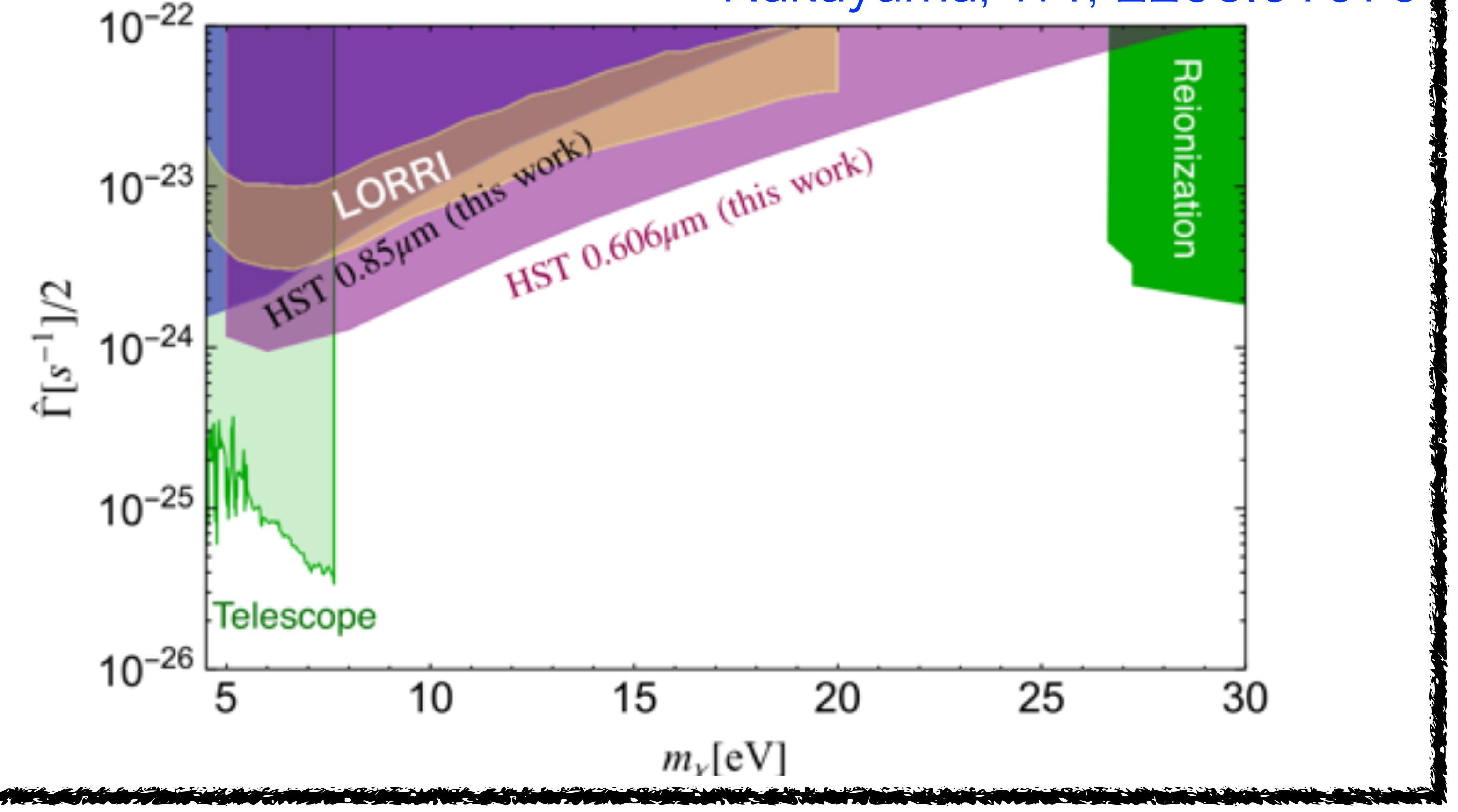
Korochkin, Neronov, and Semikoz, 1911.13291



c.f. excess in the isotropic cosmic optical background by New Horizons may suggest 5-20 eV ALP DM Lauer et al, Astrophys. J. Lett. 927, L8 (2022), Bernal et al, 2203.11236.

But it is in tension with the data from anisotropic CIB and TeV γ unless some extensions.

Nakayama, WY, 2205.01079



+
A cooling hint from horizontal branch star $g_{a\gamma\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$.

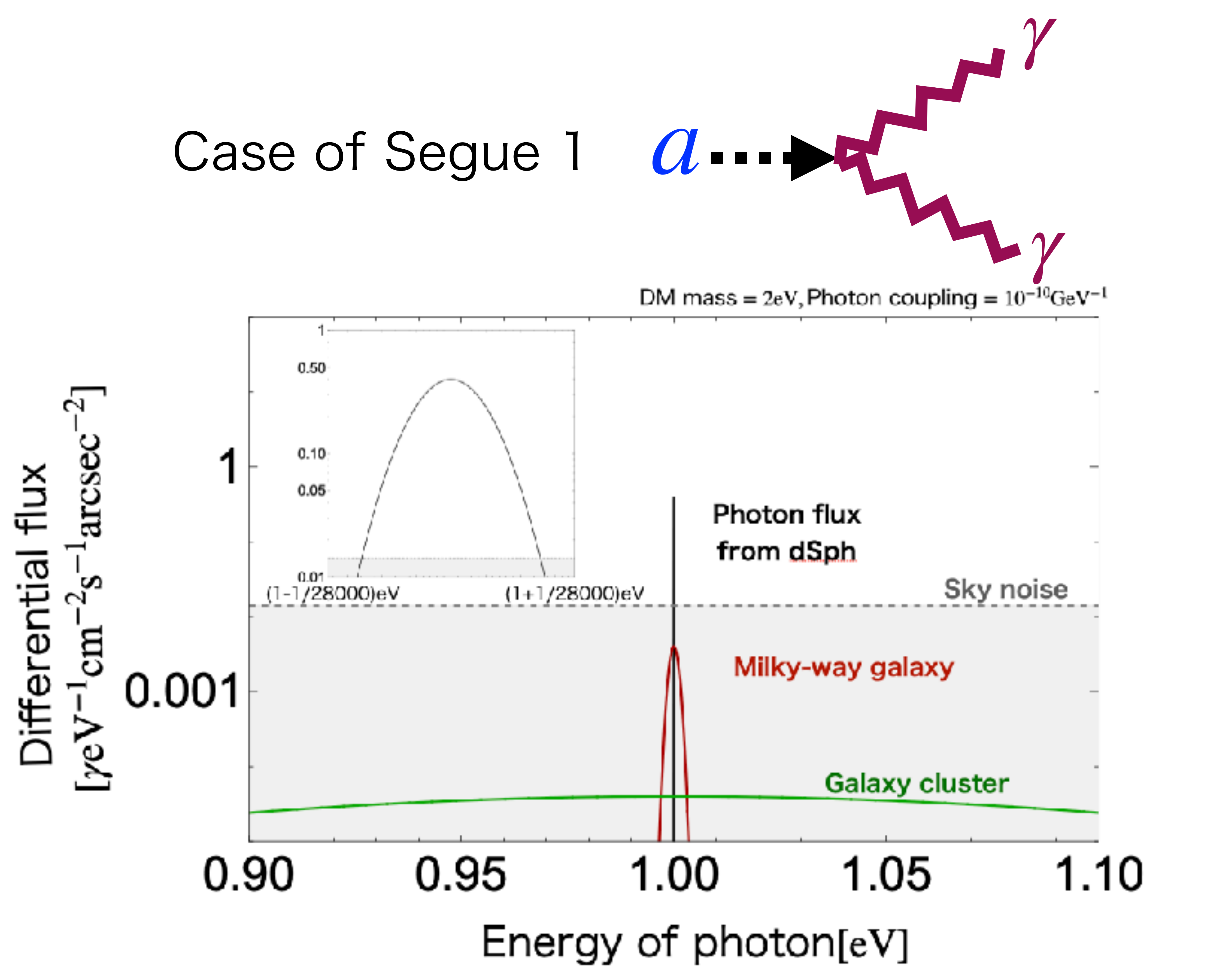
Ayala et al 1406.6053

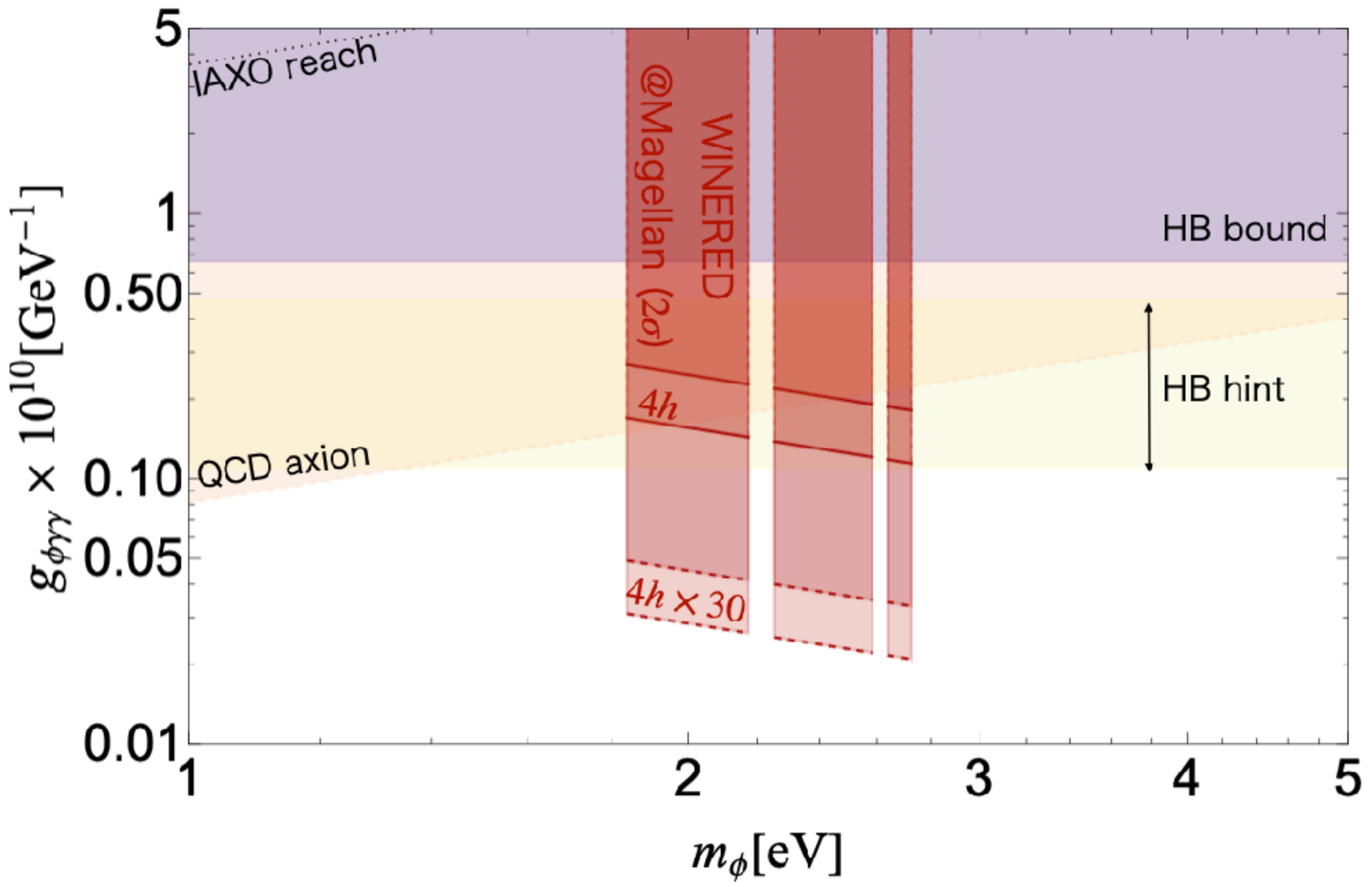
Indirect detection of ALP DM in infrared regime

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

Bessho, Ikeda, WY, 2208.05975

Case of Segue 1





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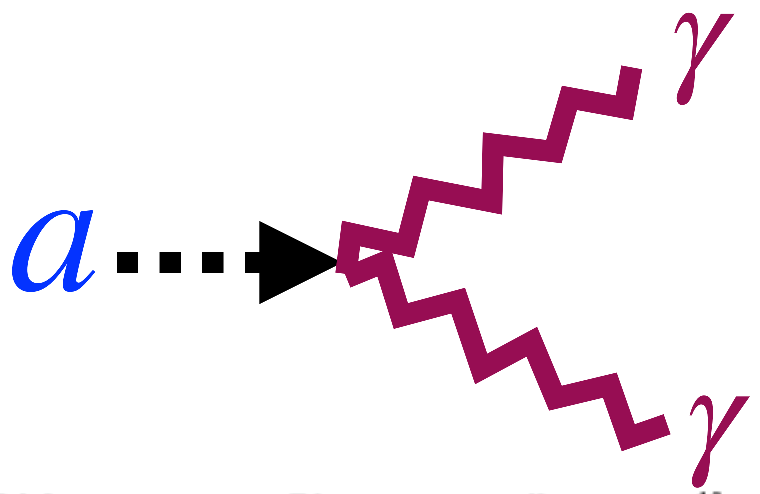
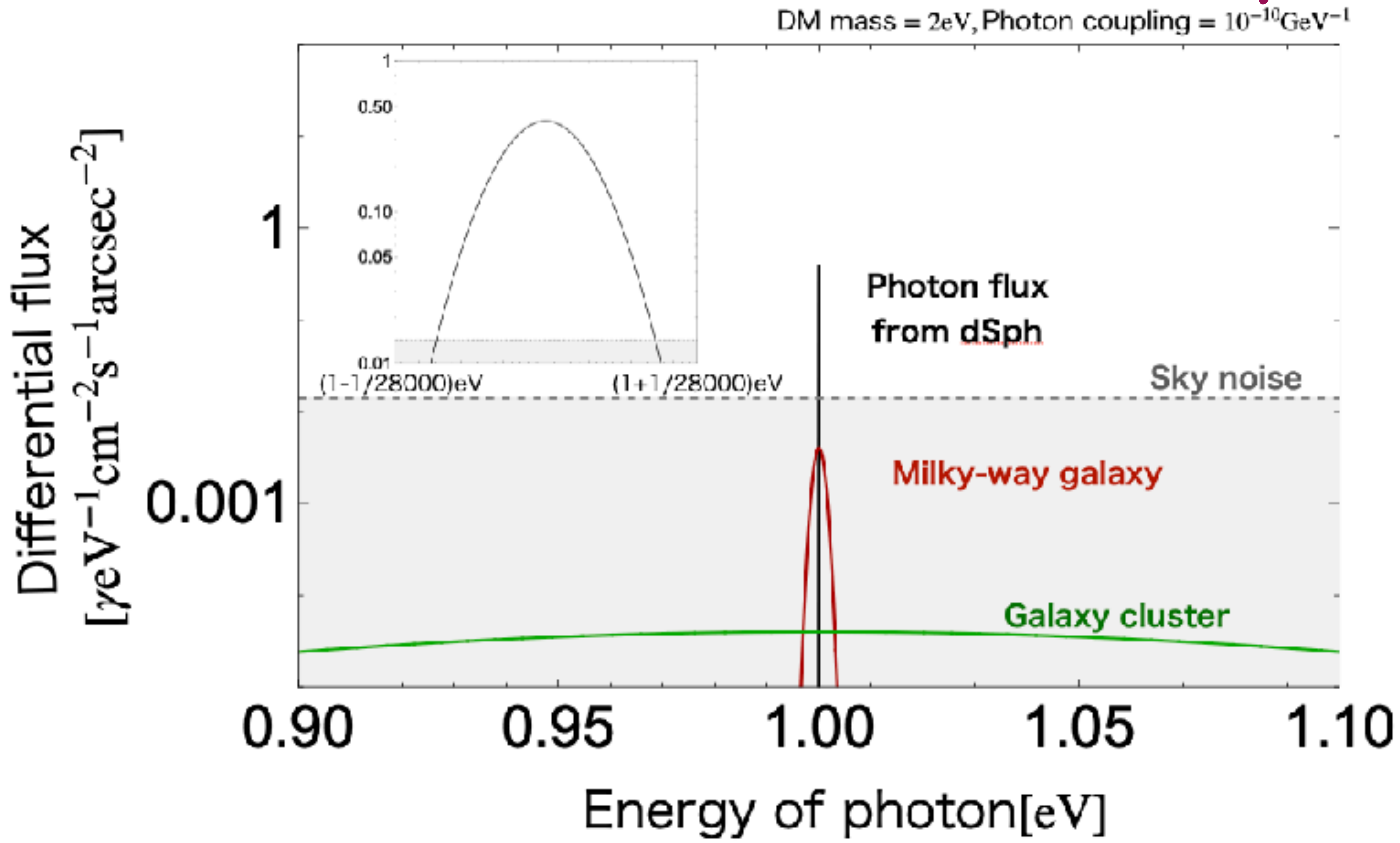
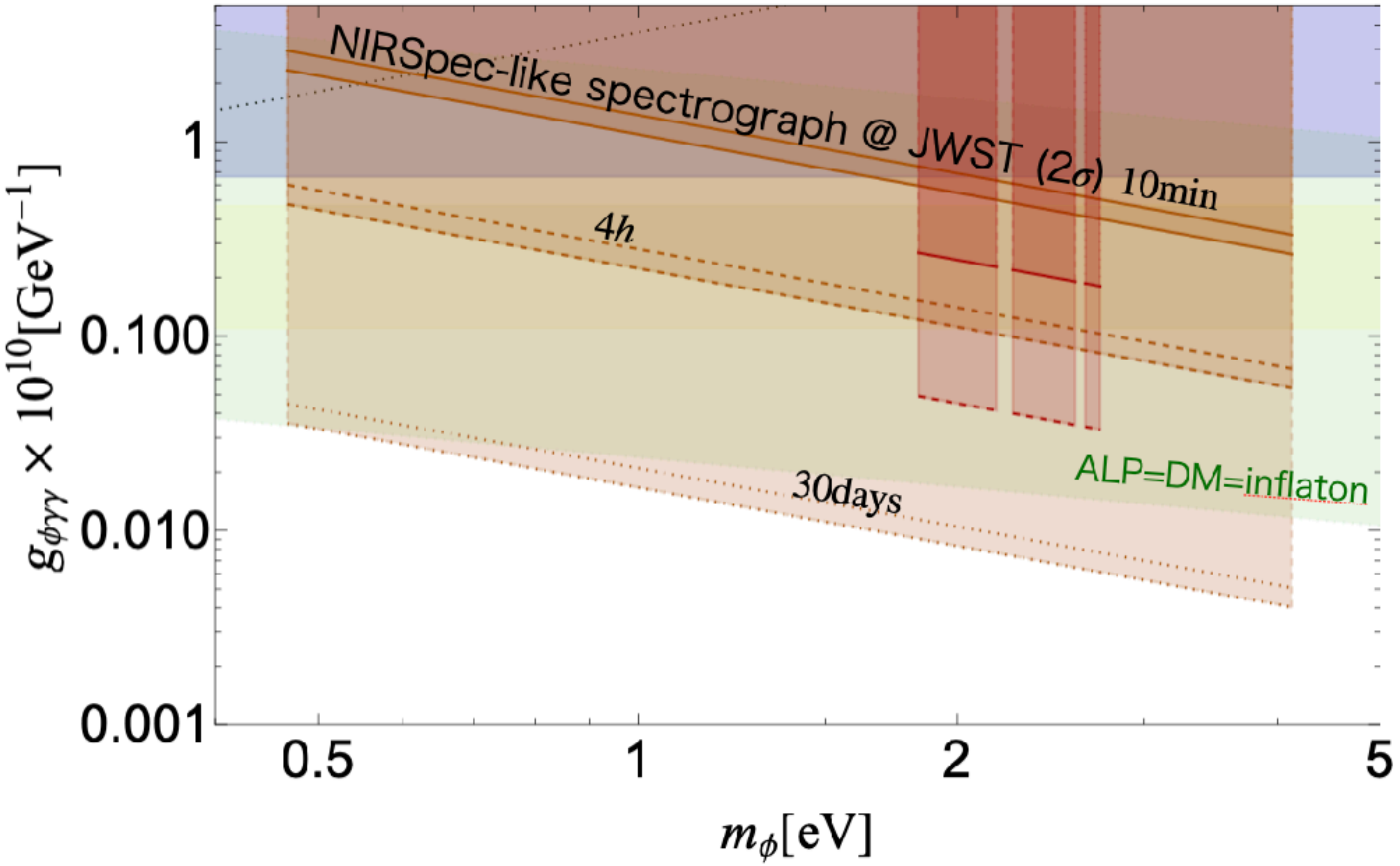
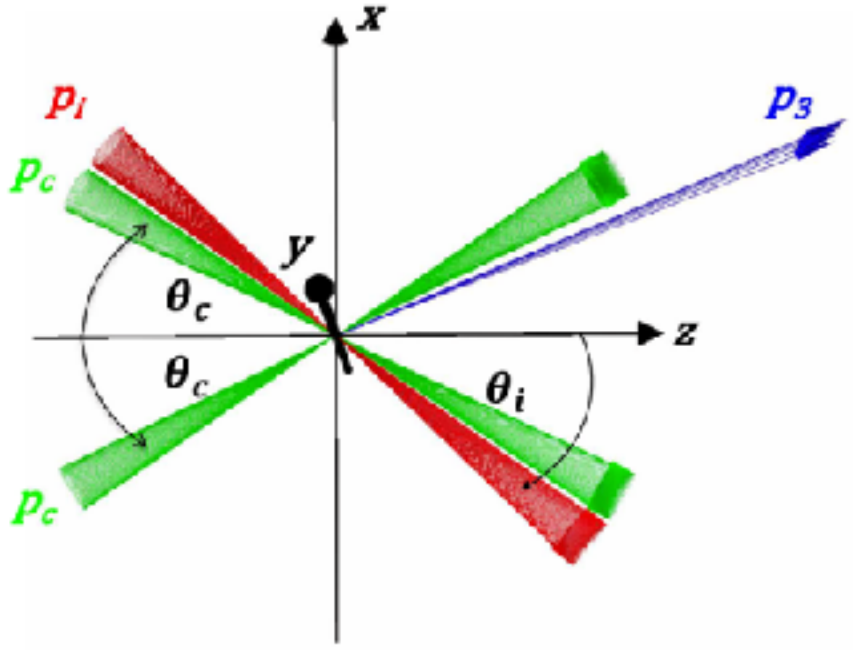
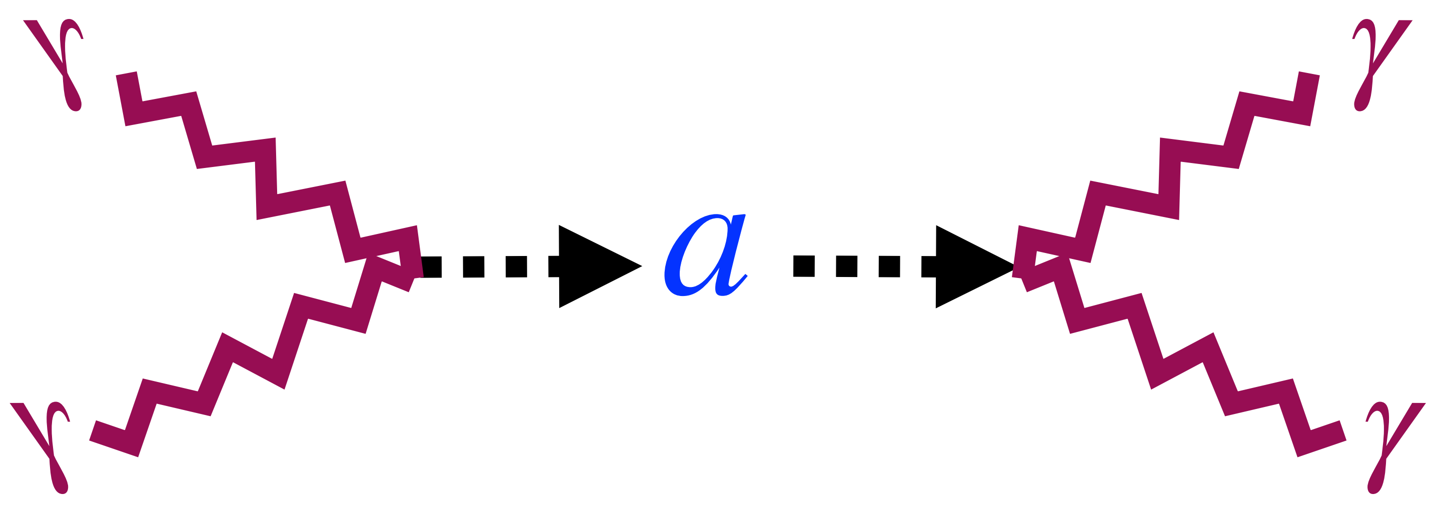






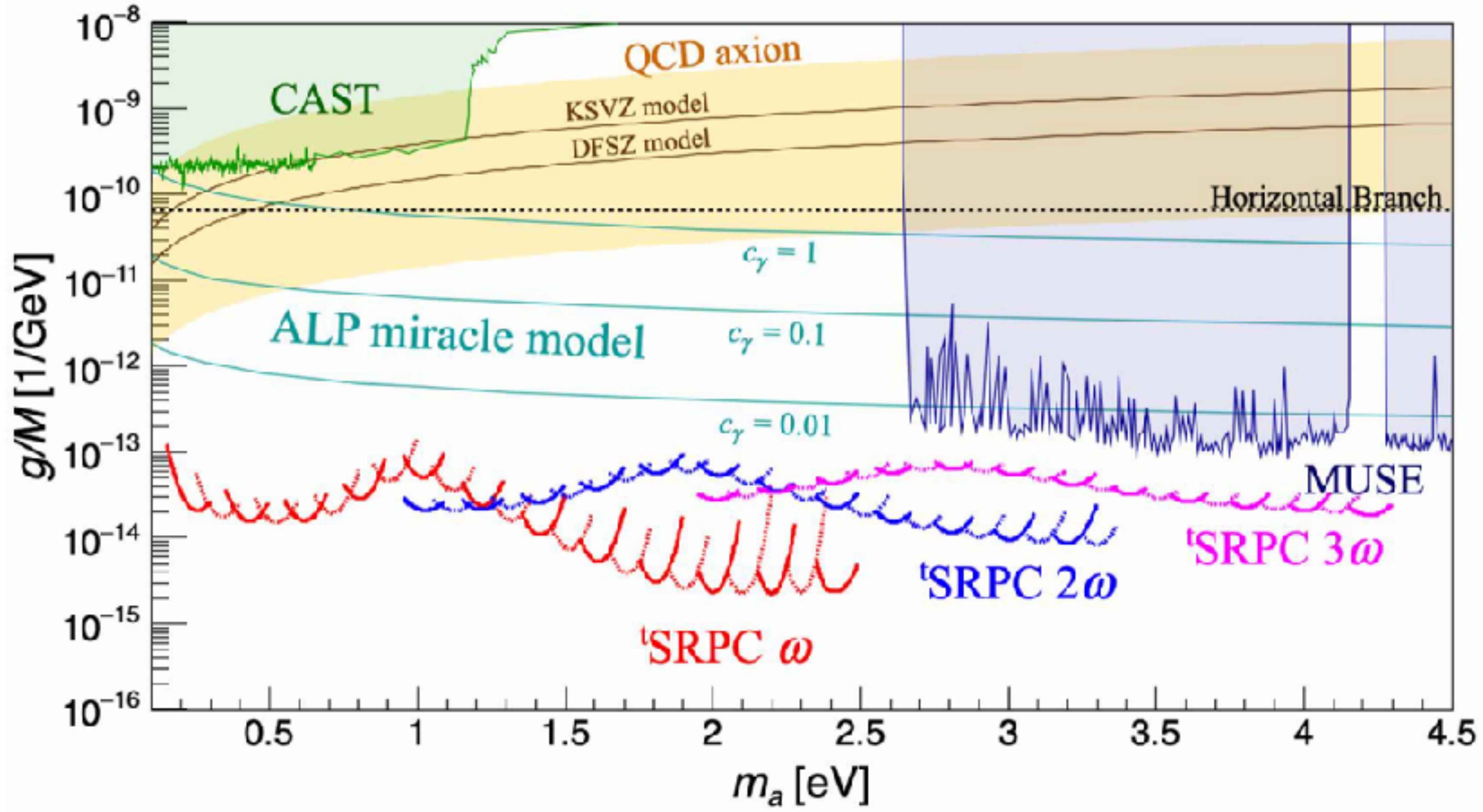
Probes it generic as interacting particles



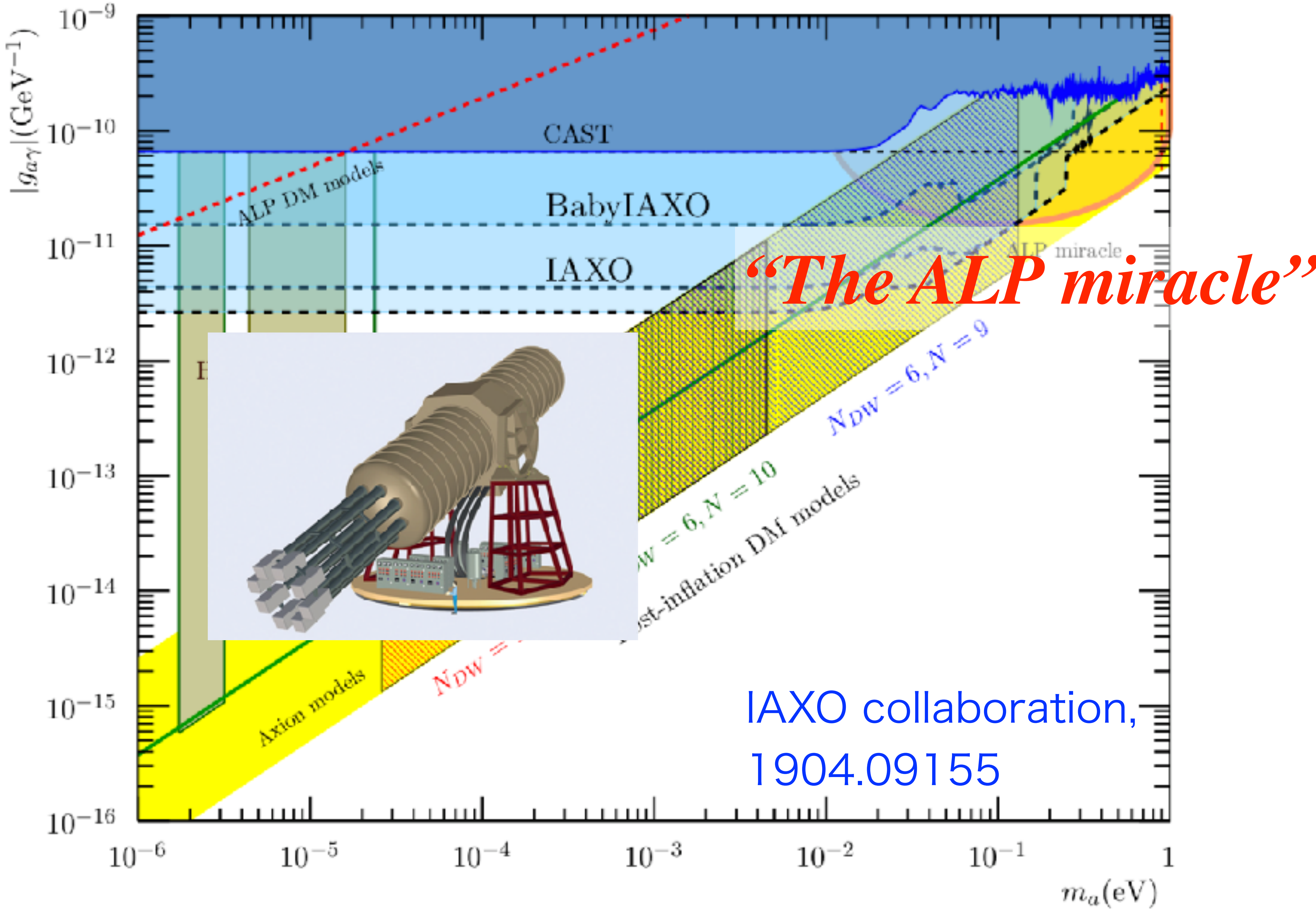


Probe ALP from laser collider.

Homma et al 2212.13012



Probe ALP from Sun



IAXO collaboration, 1904.09155

QCD axion and strong CP problem

Strong CP phase sources the nucleon EDM, the observation of which strictly constrains the strong CP phase $|\theta| < 10^{-10}$.

$$\mathscr{L} = \mathscr{L}_{\rm SM}|_{\theta_{\rm CP}=0} - \frac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon} - \frac{c_Y\theta g_Y^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}B_{\mu\nu}B_{\delta\epsilon} - \frac{c_2\theta g_2^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}W_{\mu\nu}W_{\delta\epsilon}$$

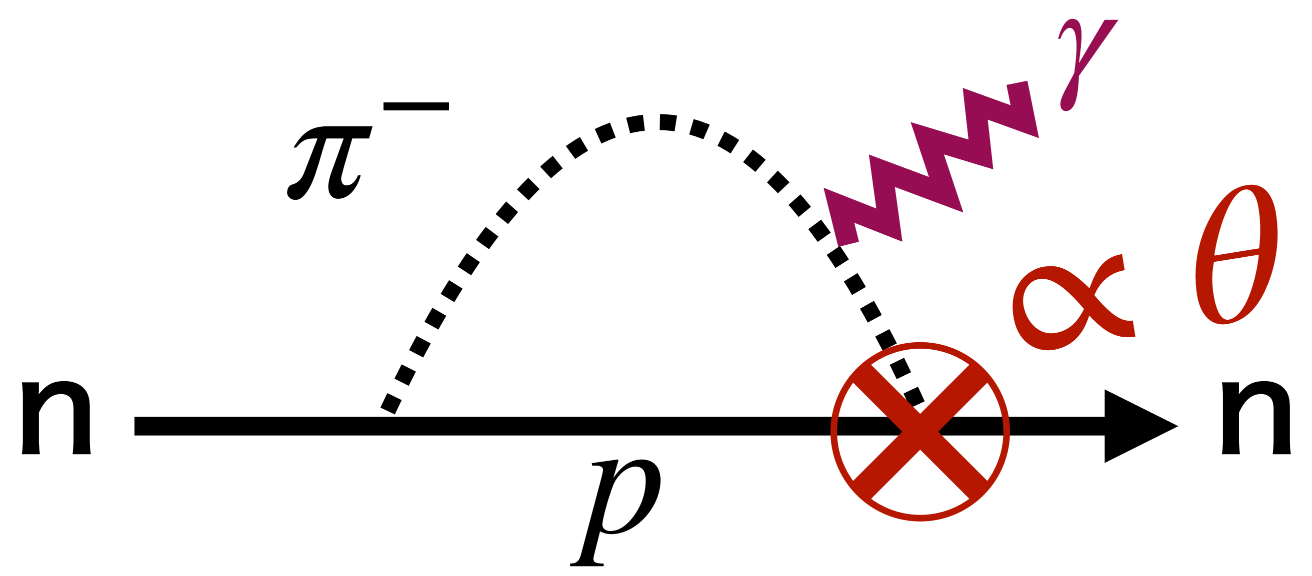
standard model

CPV: $\frac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon}$

θ changes QCD potential:

$$-\mathscr{L} \supset \frac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon} \leftrightarrow m_u\bar{u}e^{i\gamma_5\theta}u \rightarrow m_u\cos[\theta]\langle\bar{u}u\rangle$$

EDM:



Non-observation of neutron EDM

→Strong CP problem: $|\theta| \lesssim 10^{-10}$

QCD axion and strong CP problem

Strong CP phase sources the nucleon EDM, the observation of which strictly constrains the strong CP phase $|\theta| < 10^{-10}$.

$$
\begin{aligned}
\mathscr{L} = &\ \mathscr{L}_{\rm SM}|_{\theta_{\rm CP}=0} \\
&- \frac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon} \\
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&- \frac{c_2 \theta g_2^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}W_{\mu\nu}W_{\delta\epsilon} \\
&- \frac{f_a^2}{2}(\partial_\mu \theta)^2
\end{aligned}
$$

standard model

QCD Axion model

Axion: $a = \theta f_a$

θ changes QCD potential:

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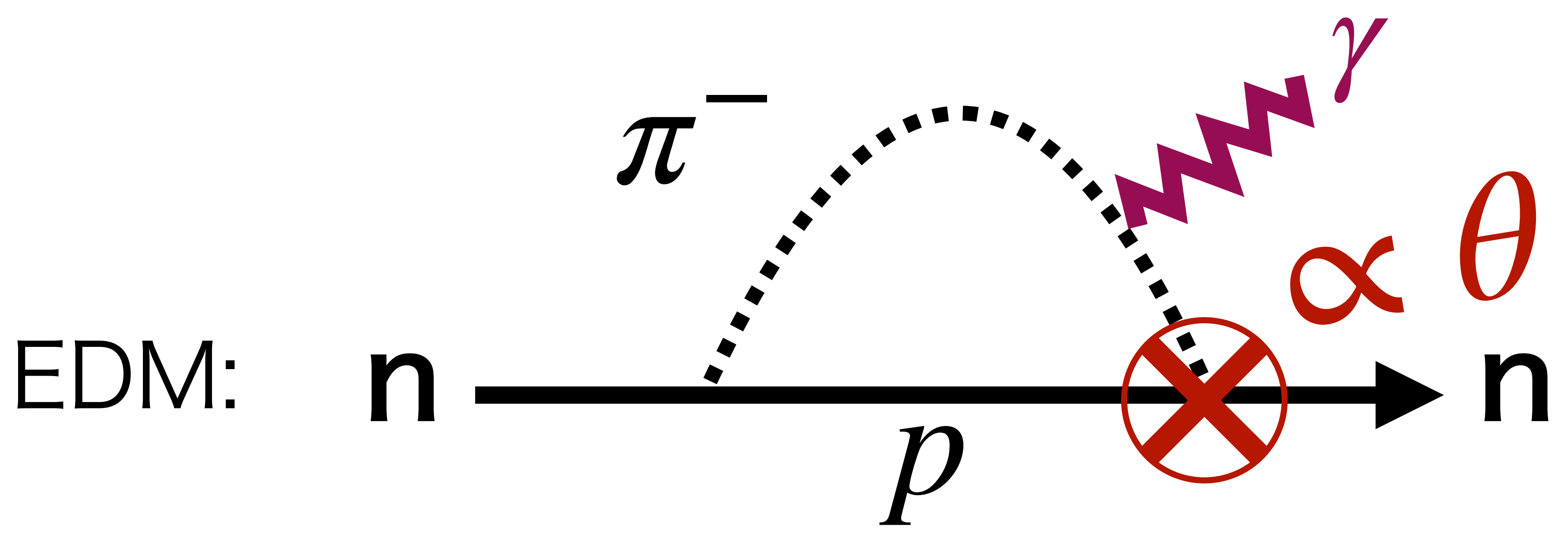
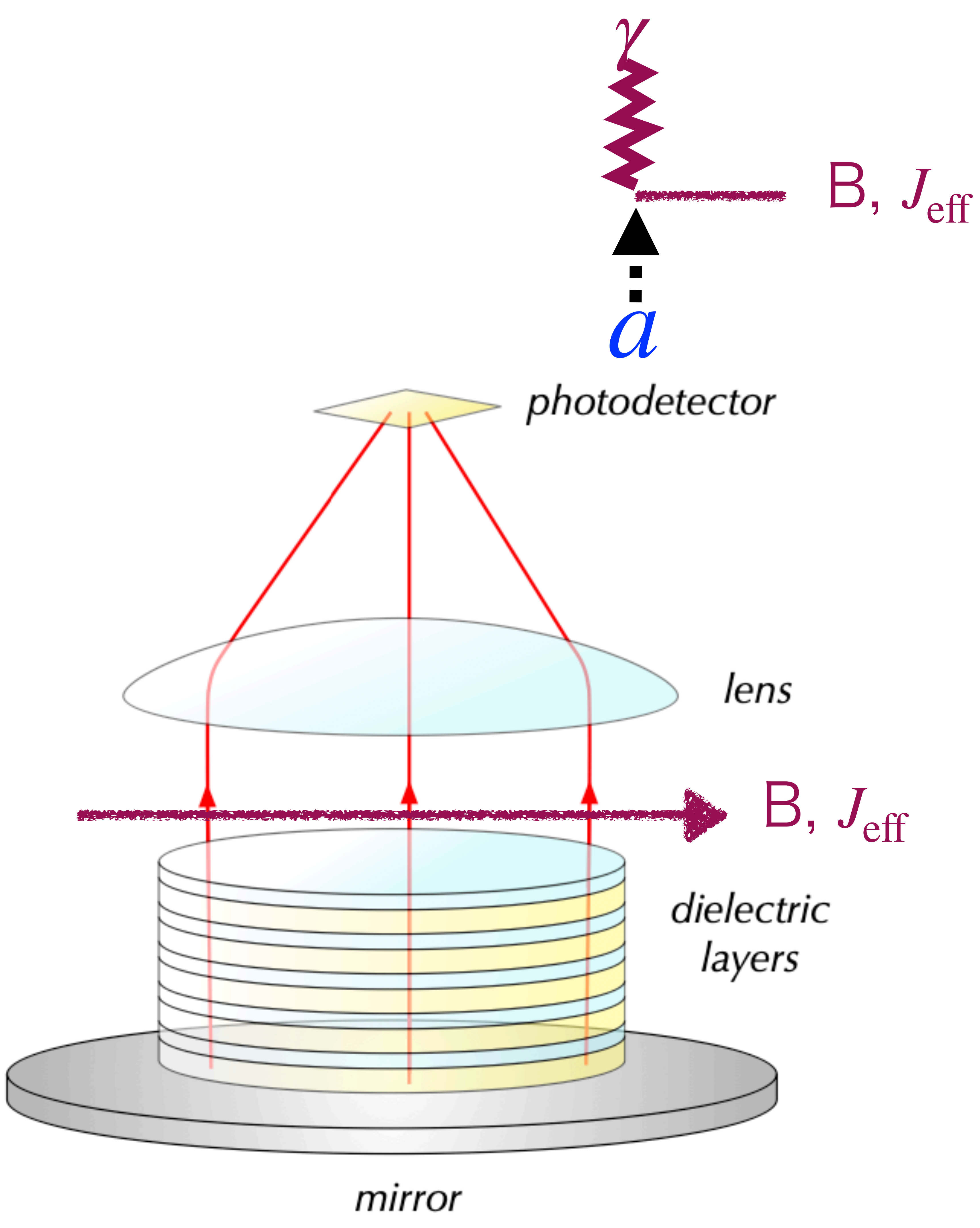


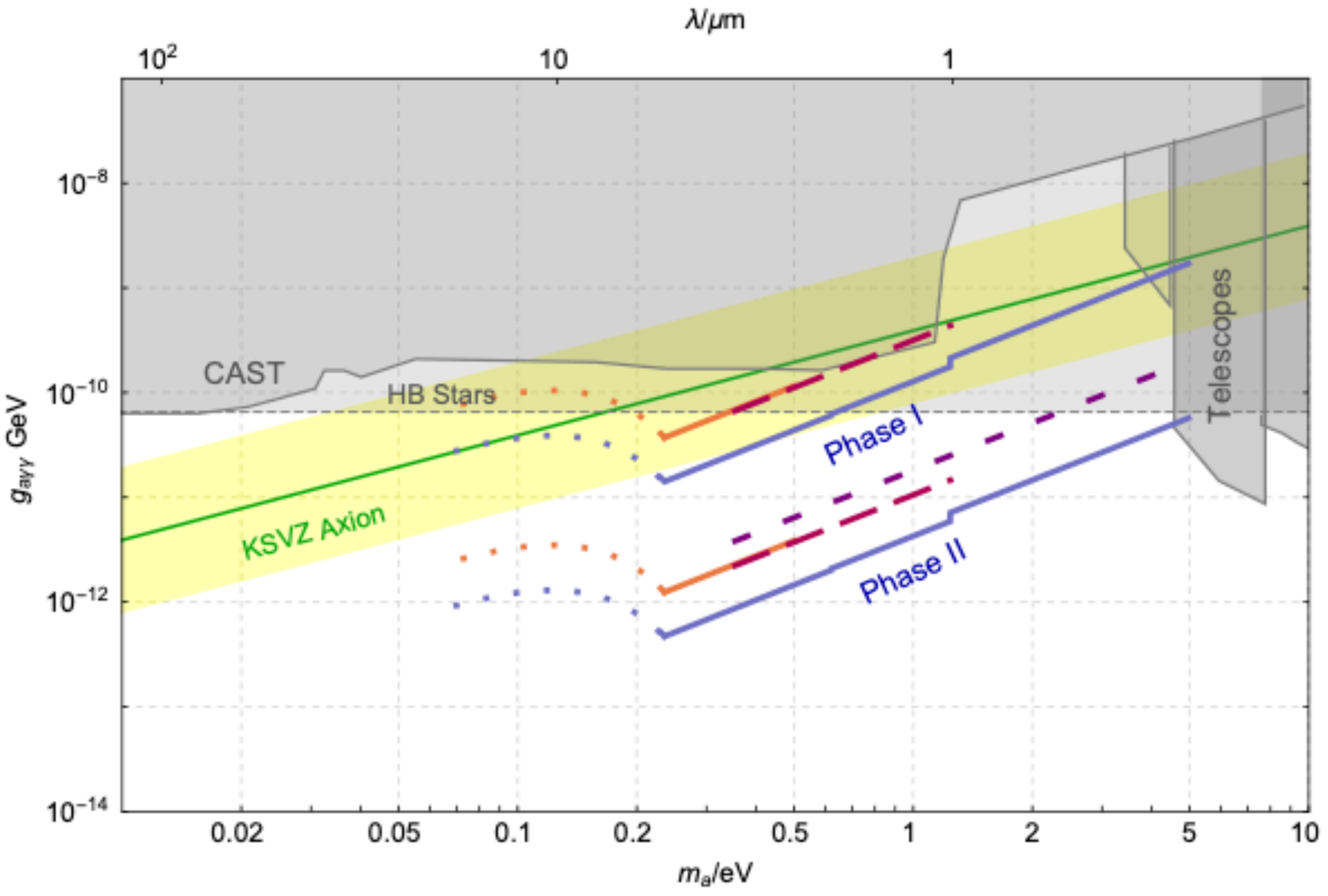
Non-observation of neutron EDM

→Strong CP problem: $|\theta| \lesssim 10^{-10}$

Probes it by "direct detection"

Baryakhtar et al 1803.11455





QCD axion and strong CP problem

Peccei, Quinn, 77; Weinberg, 78; Wilczek, 78;

QCD axion acquires its potential via the non-perturbative effect of QCD.
Minimizing the QCD potential solves the strong CP problem.

$$\mathscr{L} = \mathscr{L}_{\rm SM}|_{\theta_{\rm CP}=0} - \frac{\theta g_s^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}G_{\mu\nu}G_{\delta\epsilon} - \frac{c_Y\theta g_Y^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}B_{\mu\nu}B_{\delta\epsilon} - \frac{c_2\theta g_2^2}{32\pi^2}\epsilon^{\mu\nu\delta\epsilon}W_{\mu\nu}W_{\delta\epsilon} - \frac{f_a^2}{2}(\partial_\mu\theta)^2$$

standard model

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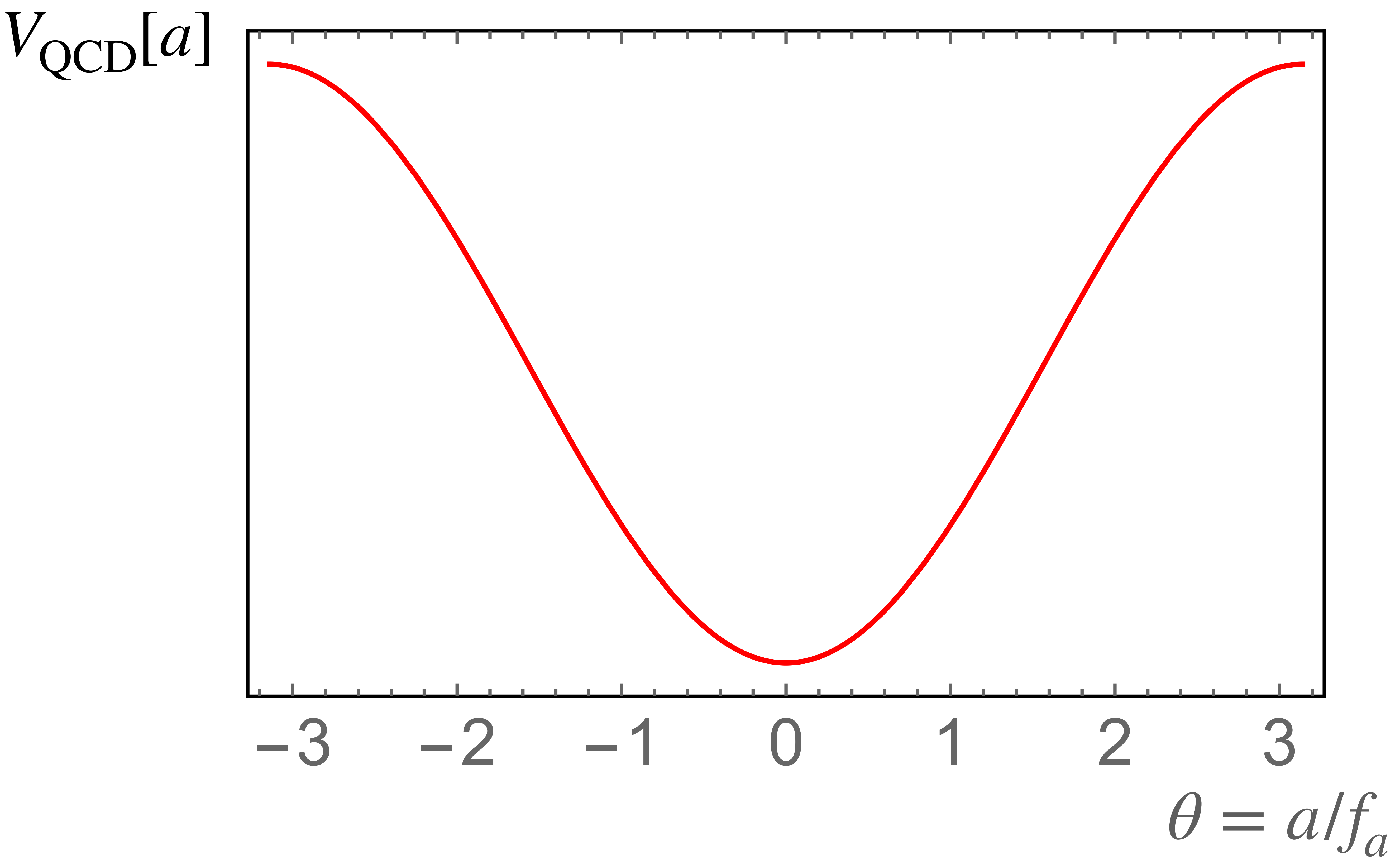

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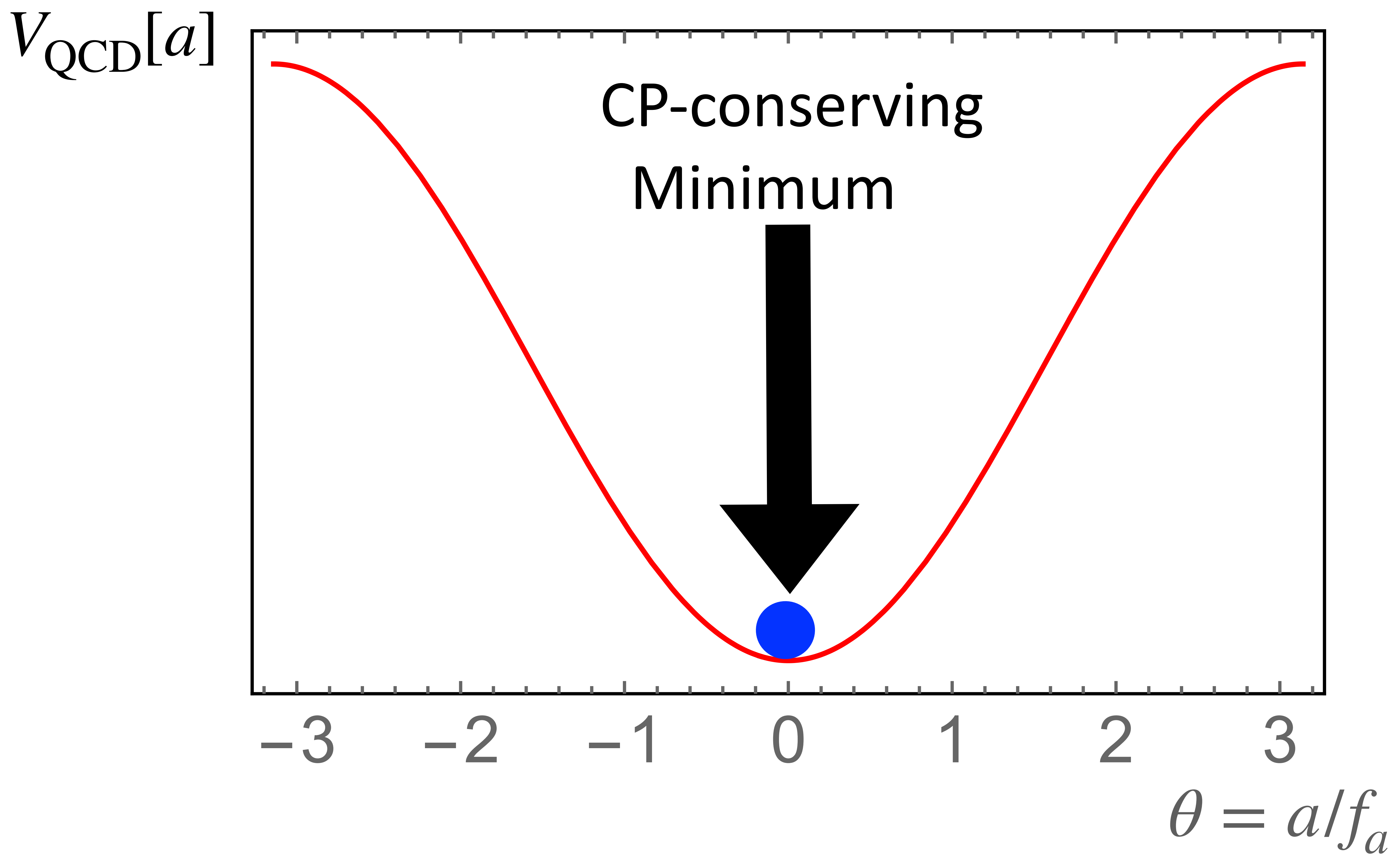
standard model

QCD Axion model

$$m_a \simeq \frac{(80{\rm MeV})^2}{f_a}$$



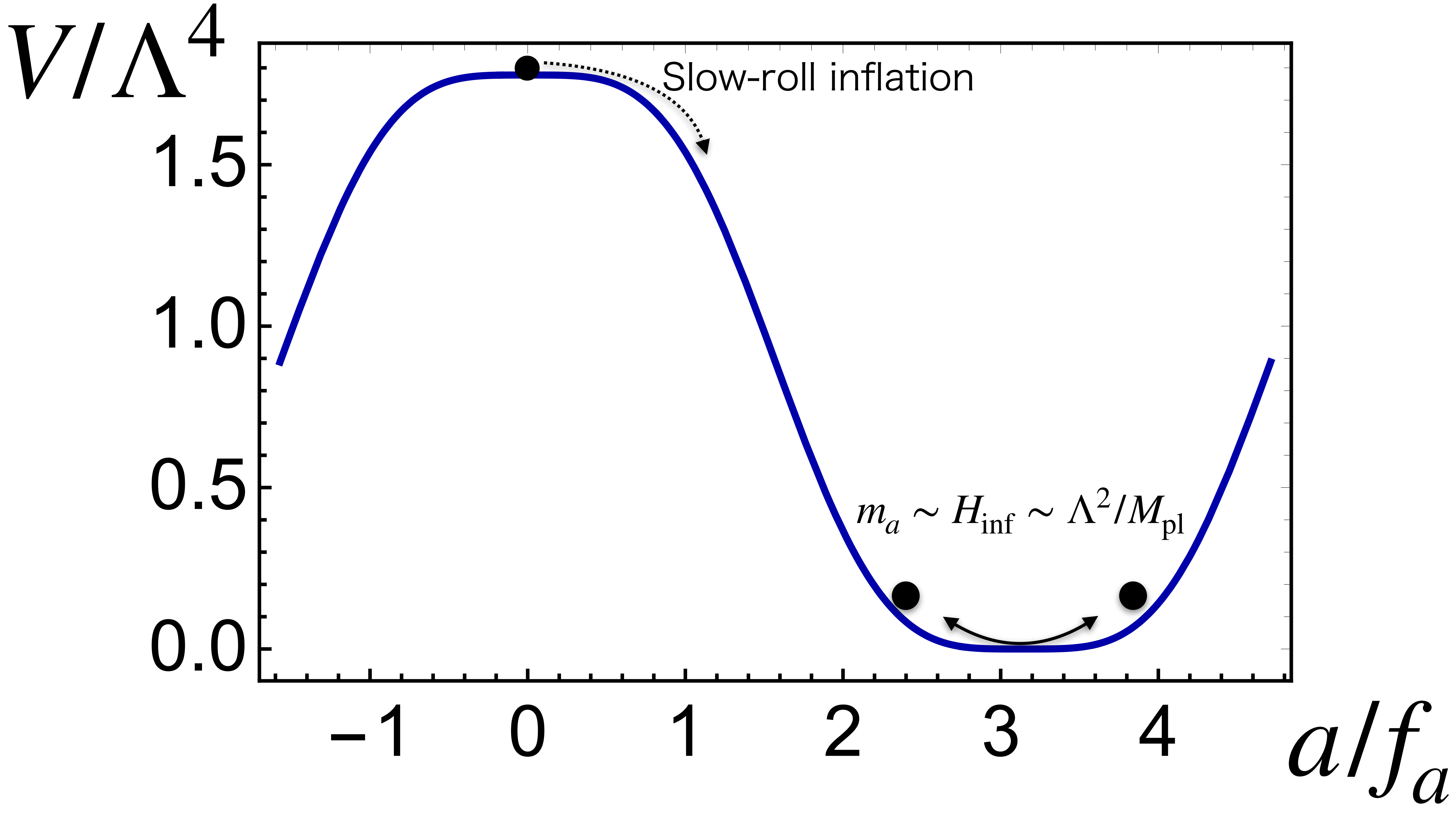
The ALP miracle scenario: Inflaton = DM = ALP

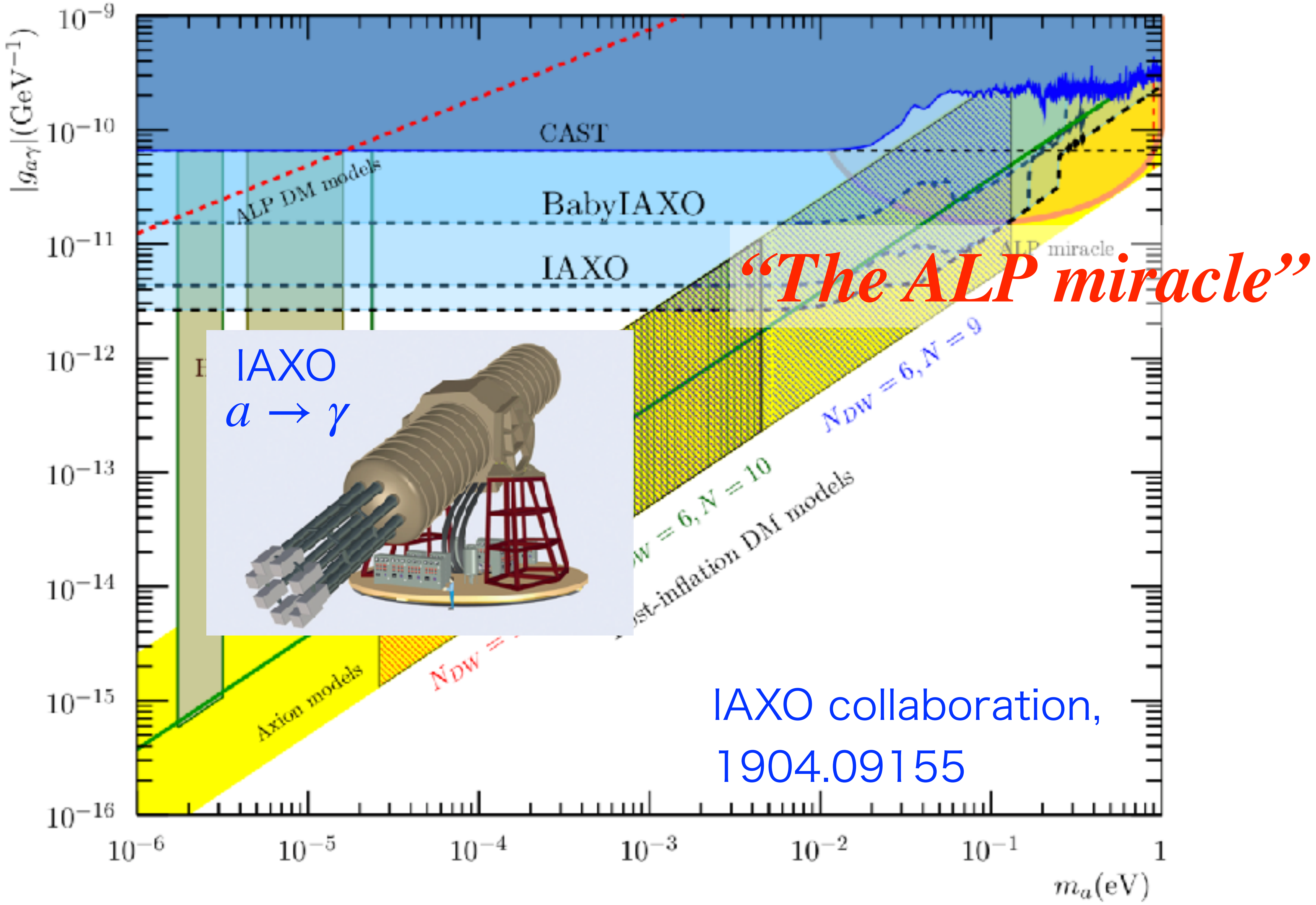
Daido, Takahashi, WY, 1702.03284, 1710.11107

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