eVダークマターの熱生成と実験的探索

TOKYO METROPOLITAN UNIVERSITY
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東京都立大
殷　文 (Wen Yin)

@熱場の量子論とその応用, 2024/9/9

Talk plan

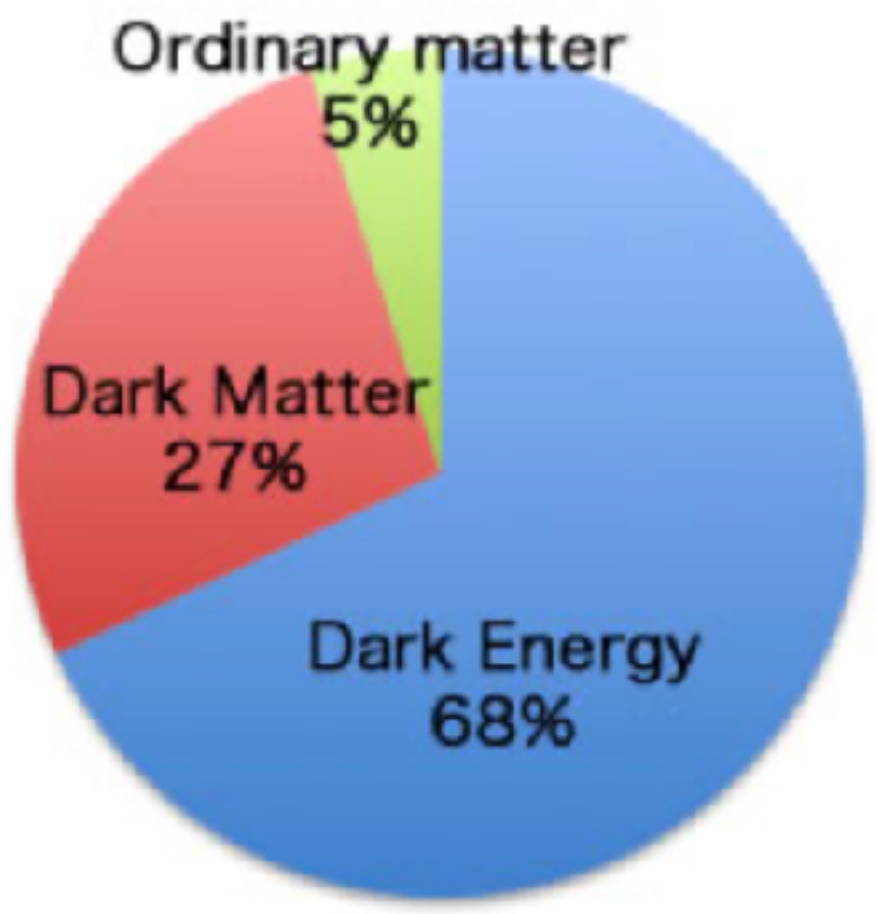
- 1. Introduction
- 2. Thermal production of eV dark matter, coldly
- 3. Experimental search of the eV dark matter
- 4. Future prospects
- 5. Conclusions

- 1. Introduction

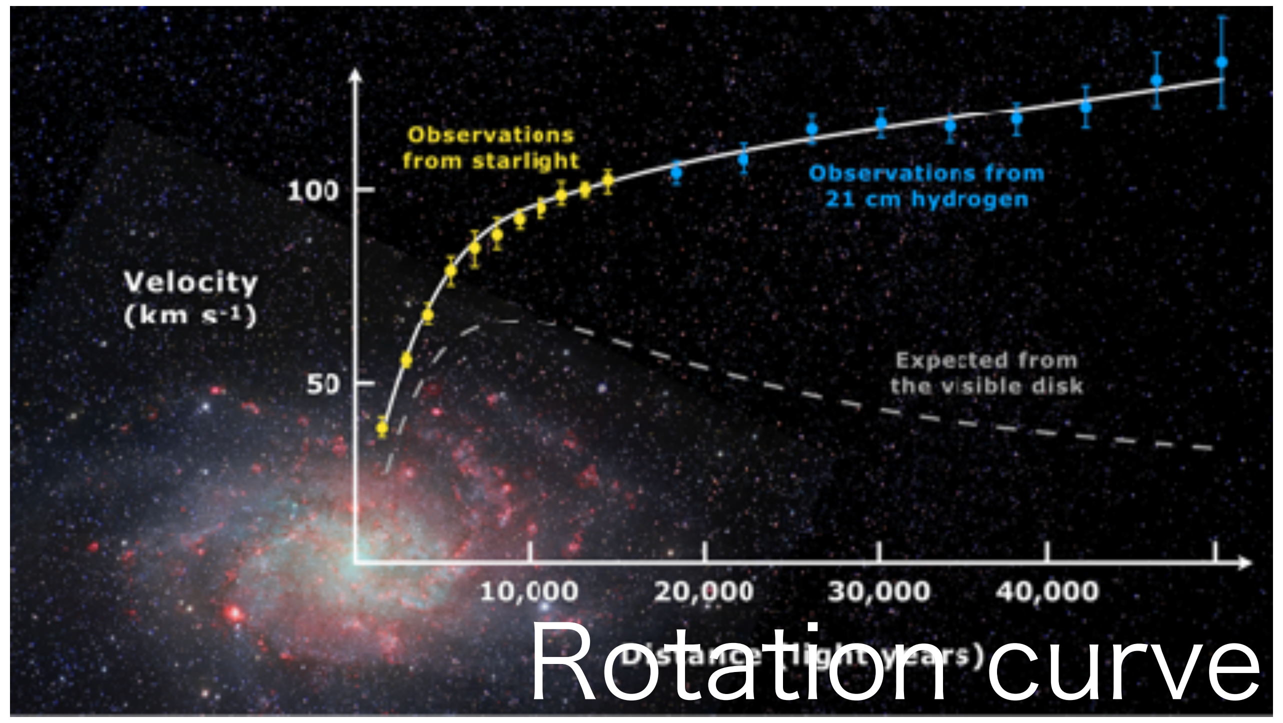
Dark matter (DM) and particle property

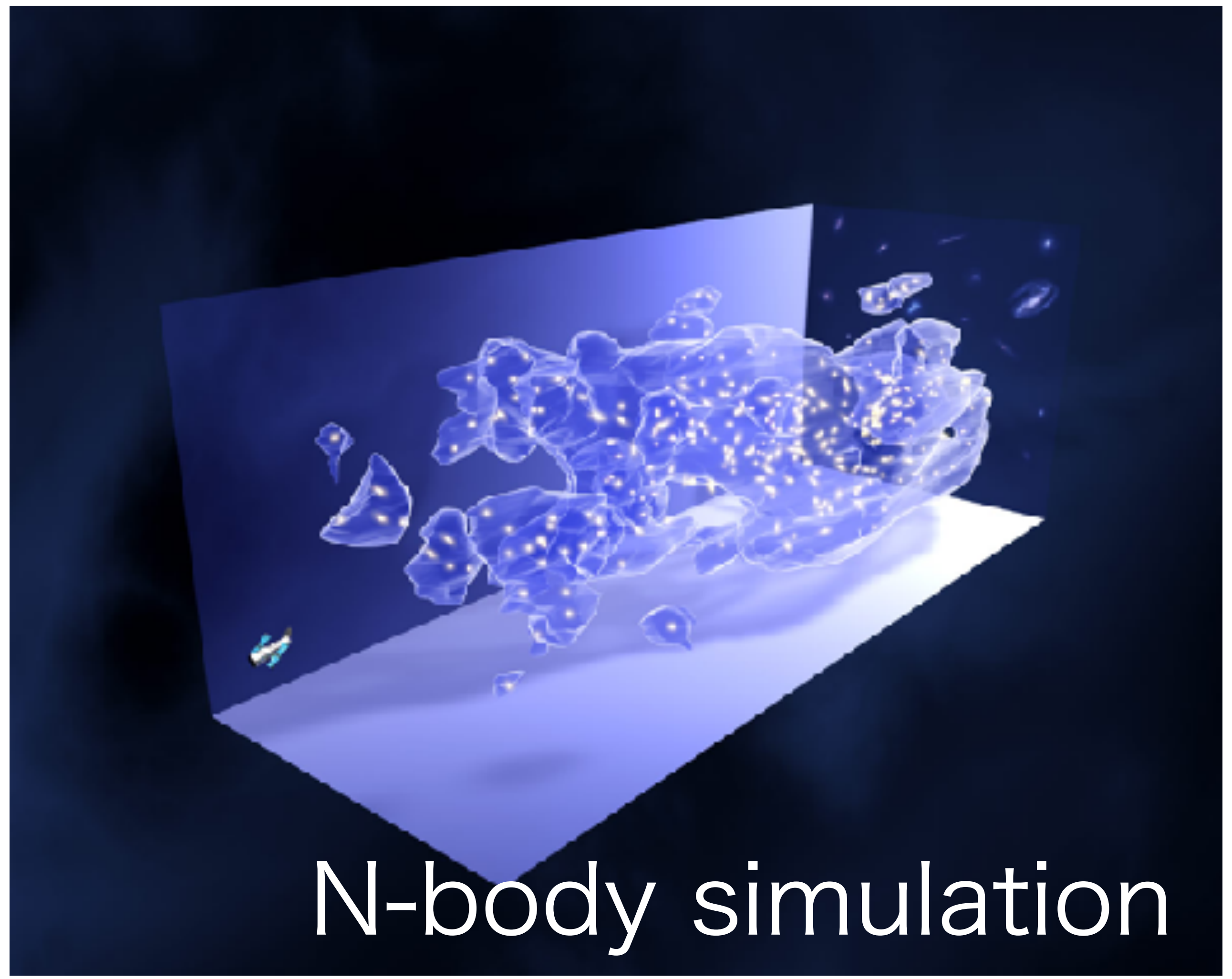
What is DM? Long lived, Neutral, Cold, $\rho_{\rm DM}/s \sim$ eV

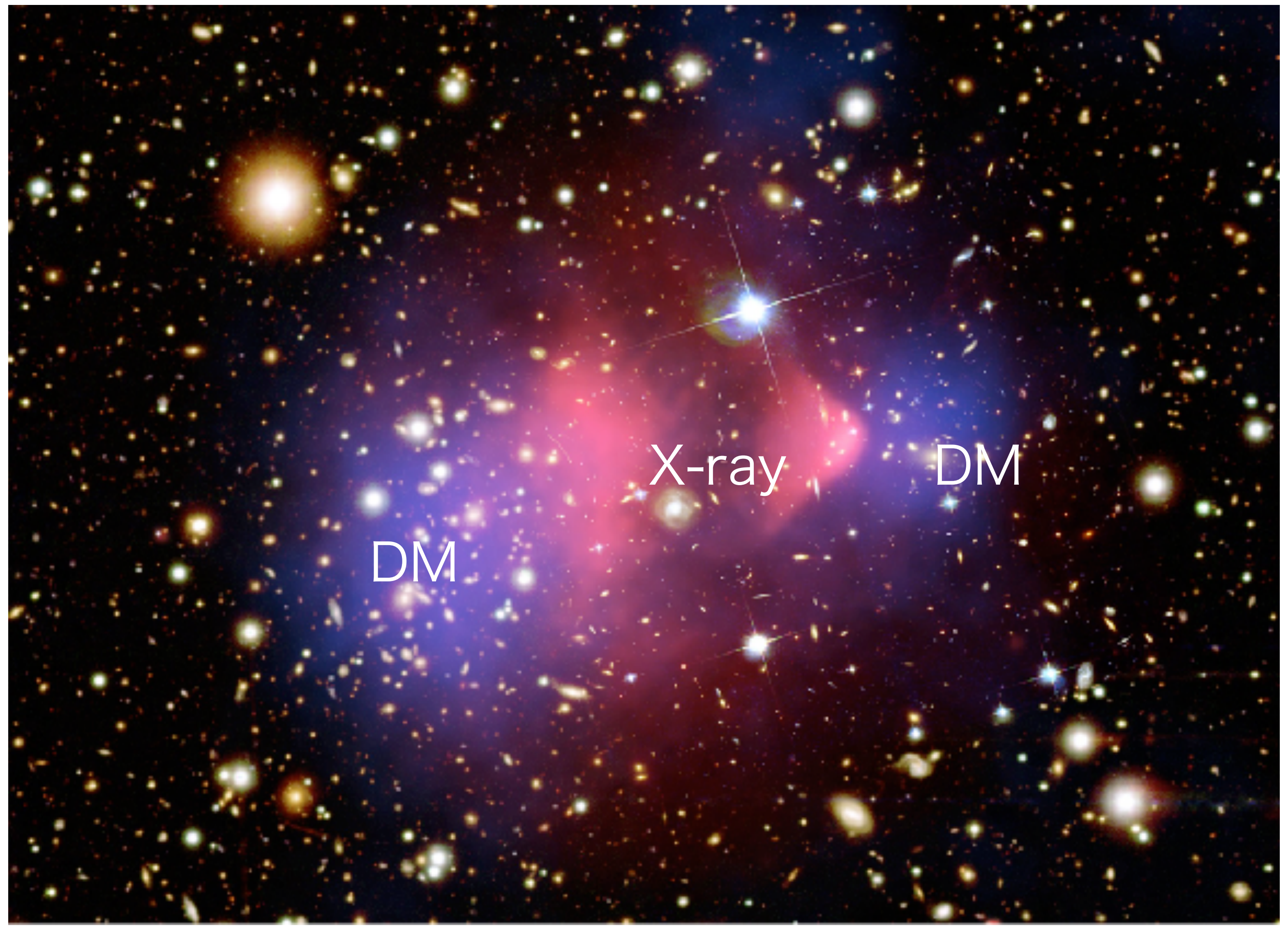
We do not know the particle property at all.



CMB data







Bullet cluster

Dark matter (DM) and particle property

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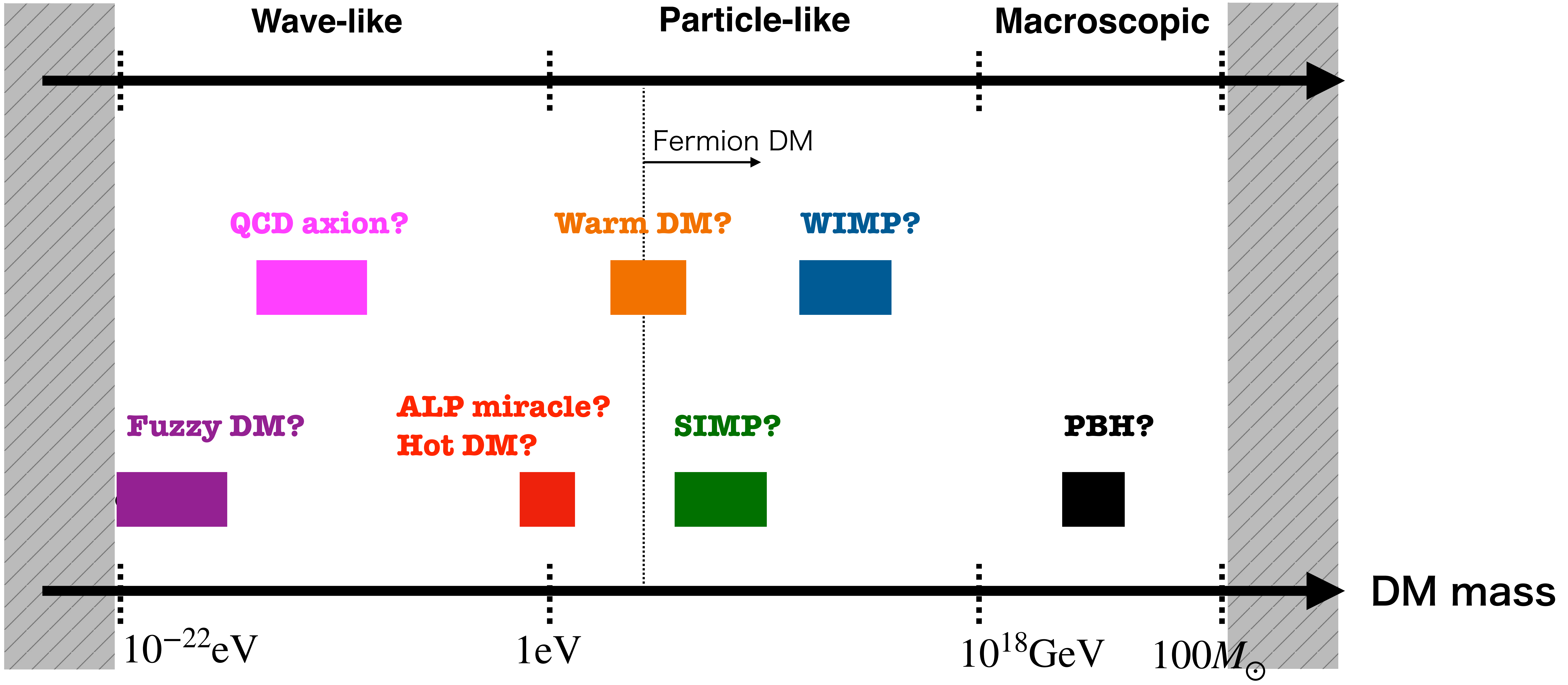

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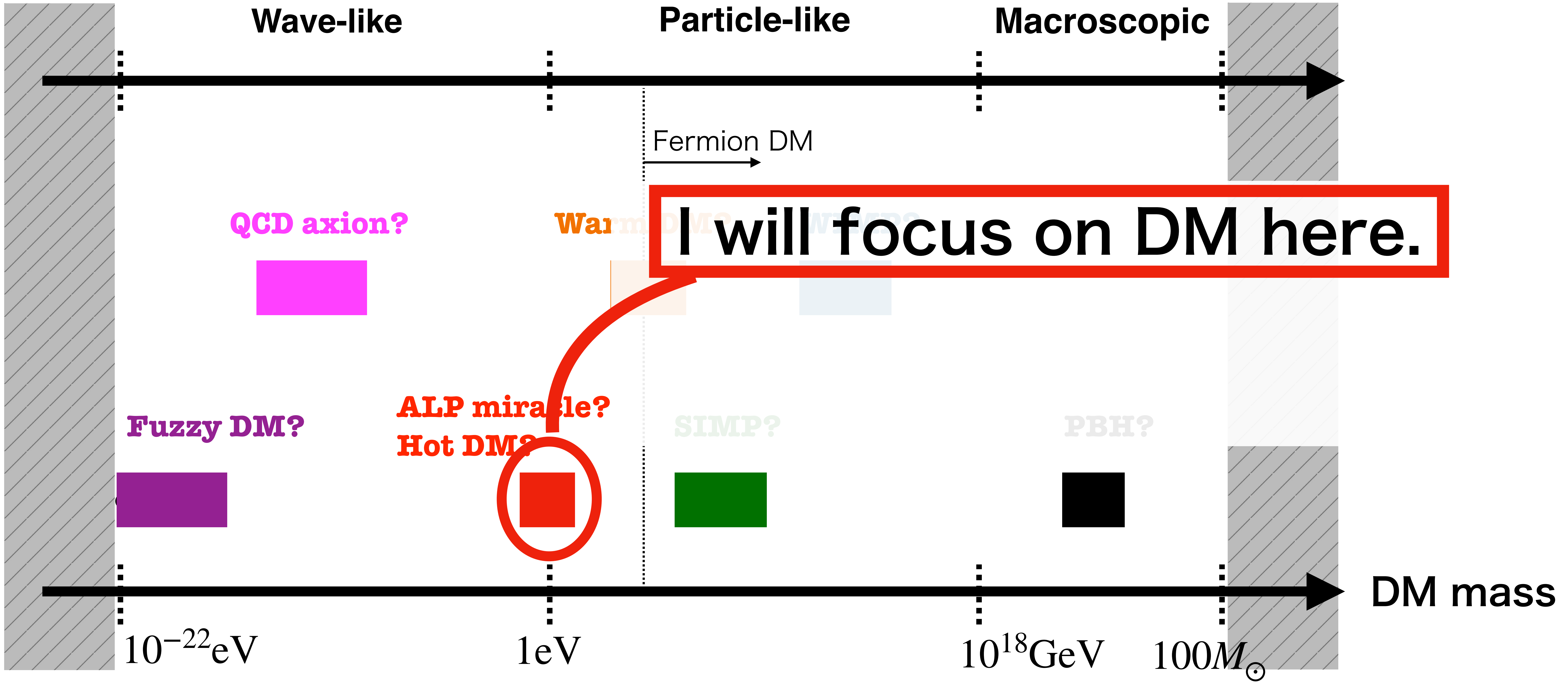


Hints for eV DM: Observations

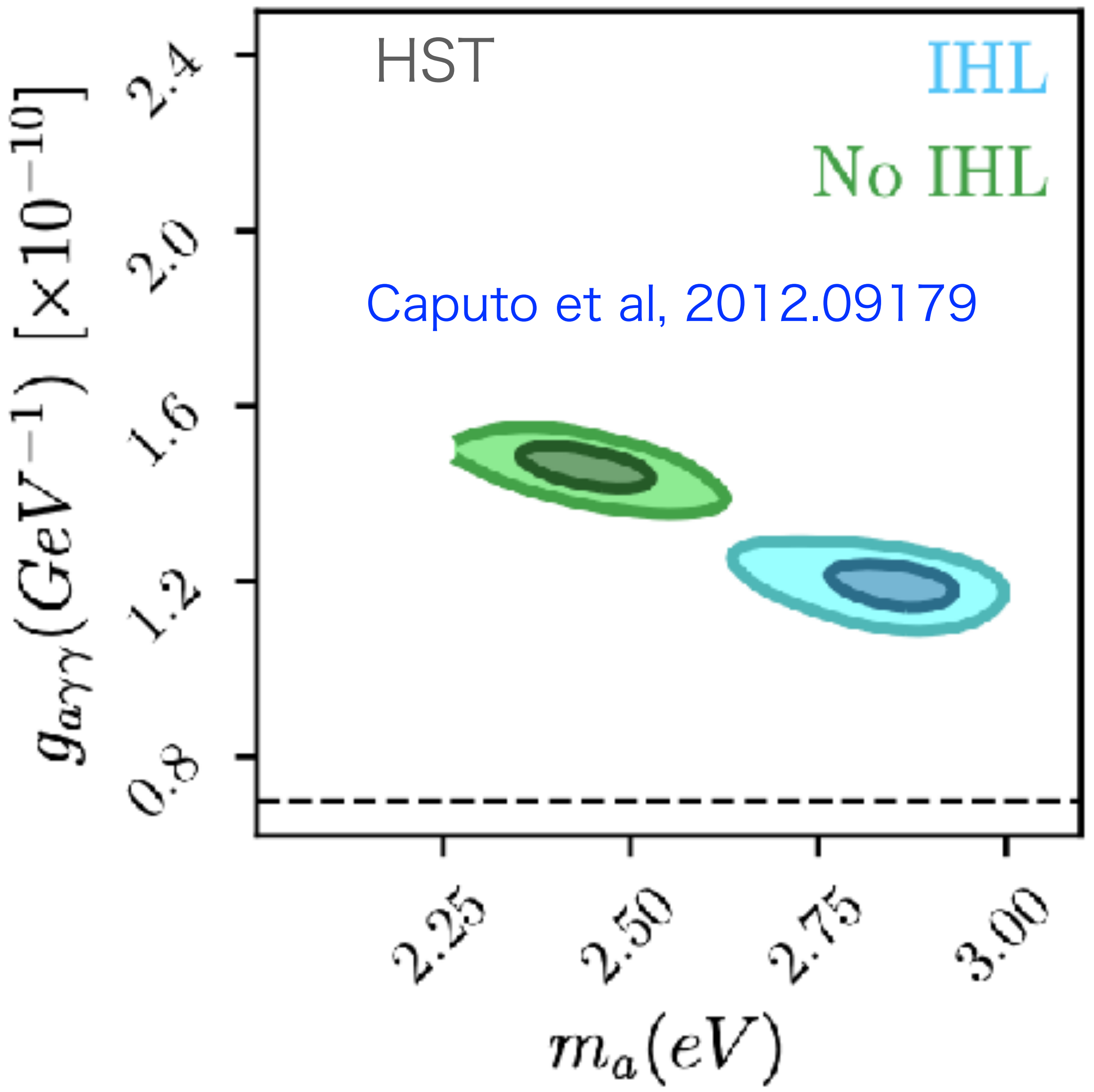
Interestingly, in the huge parameter region,

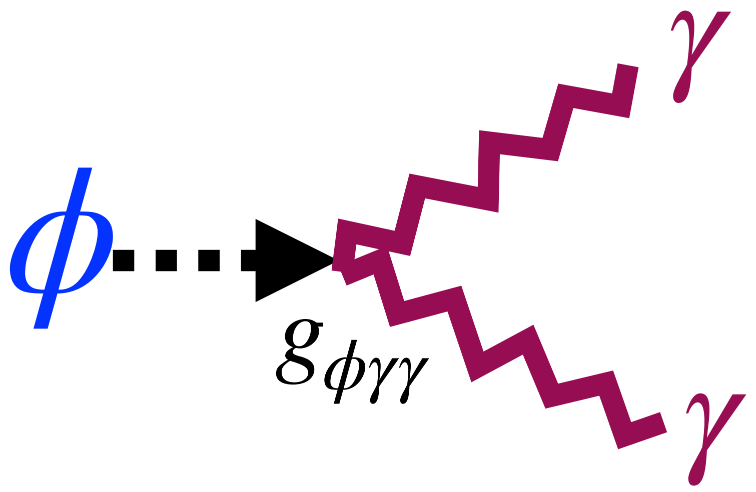
we have coincidences around eV.

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

$m_\phi \sim eV$, $g_{\phi\gamma\gamma} \sim 10^{-10}\mathrm{GeV}^{-1}$

Gong et al 1511.01577



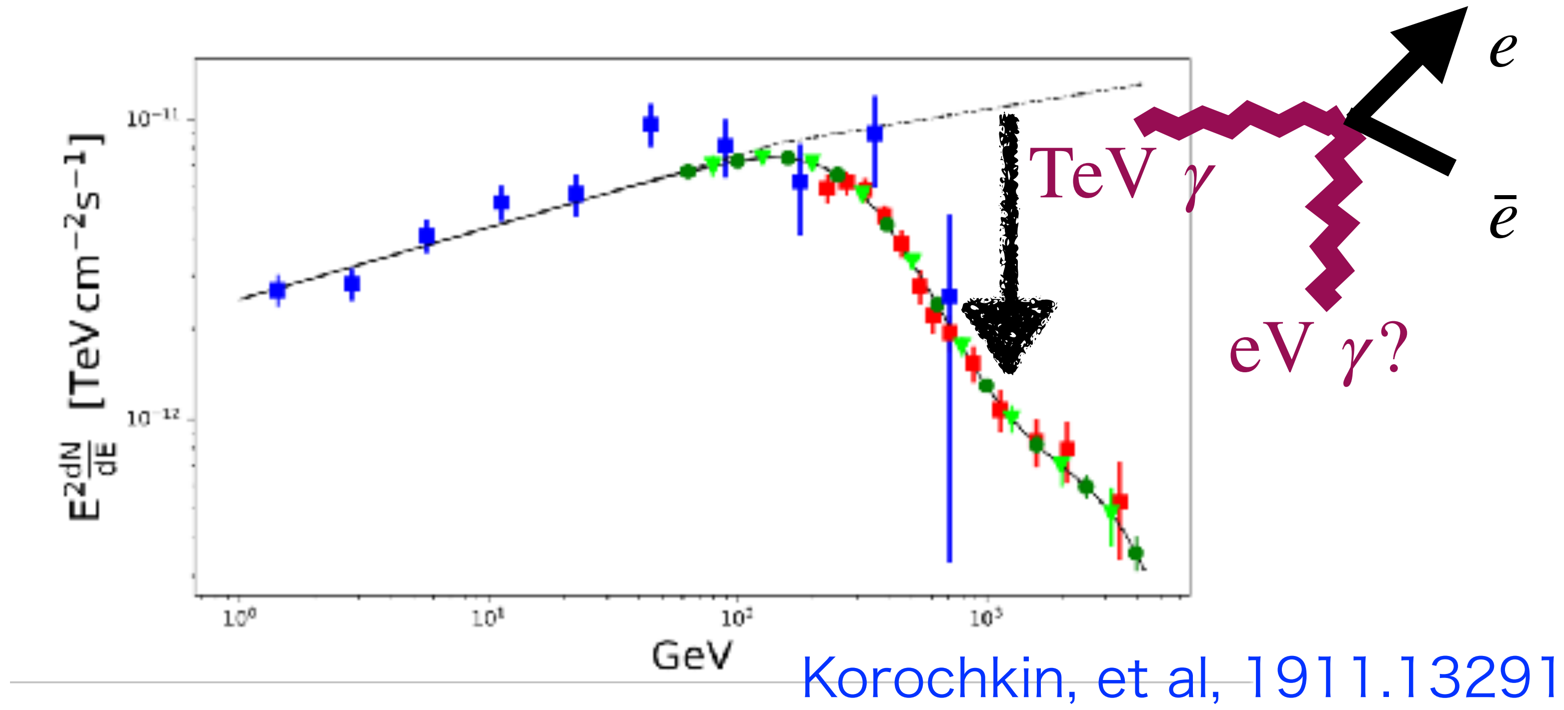


$$m_\phi \sim eV,$$

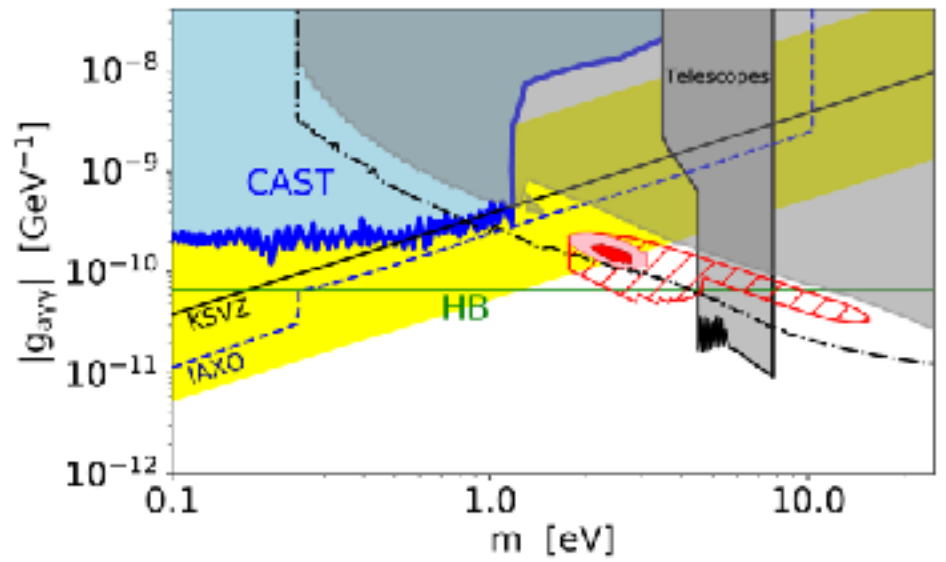
$$g_{\phi\gamma\gamma} \sim 10^{-10}\mathrm{GeV}^{-1}$$

spin=0

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



Korochkin, et al, 1911.13291
Bernal et al, 2208.13794



Hint for eV DM: ΛCDM

NASA / WMAP SCIENCE TEAM

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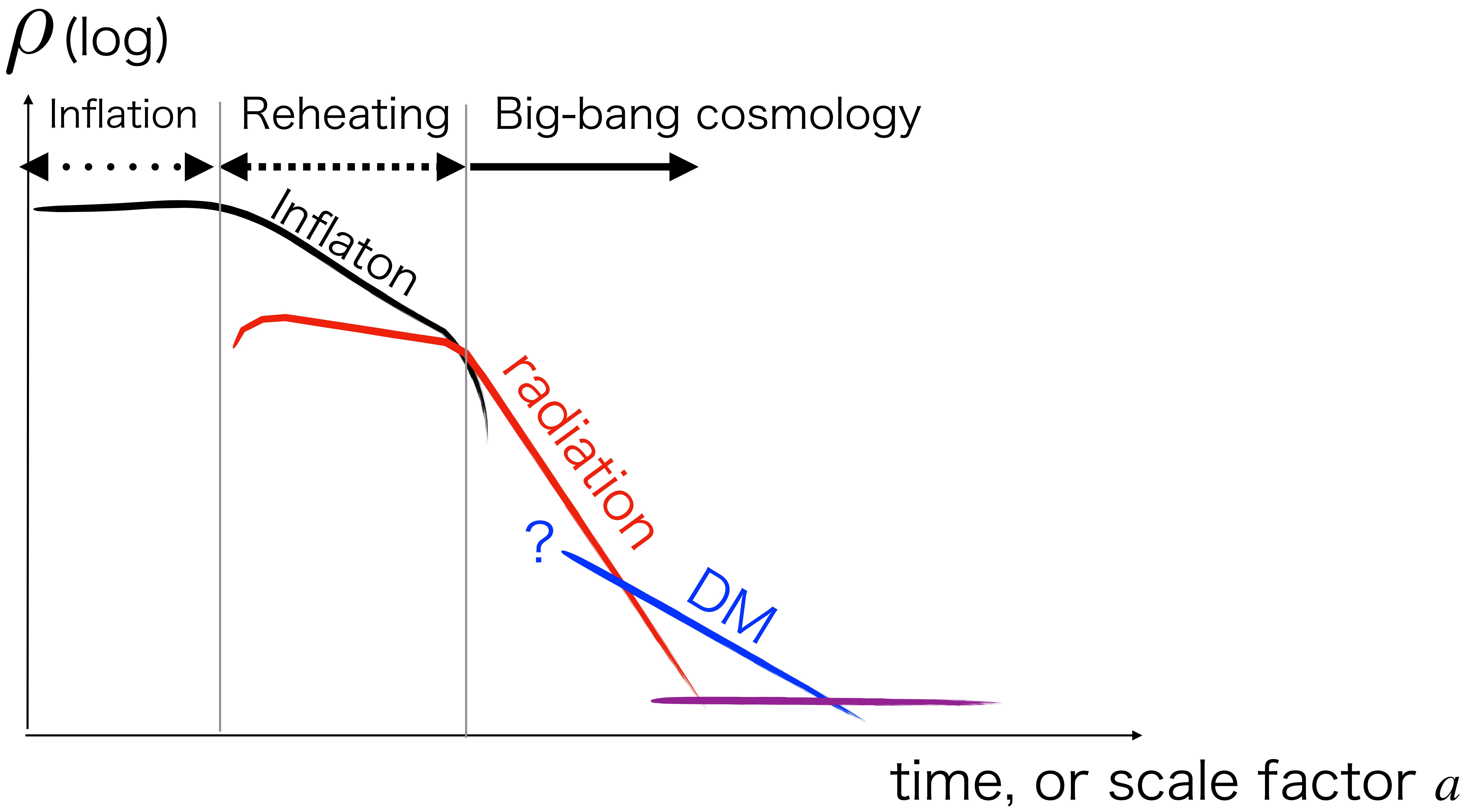

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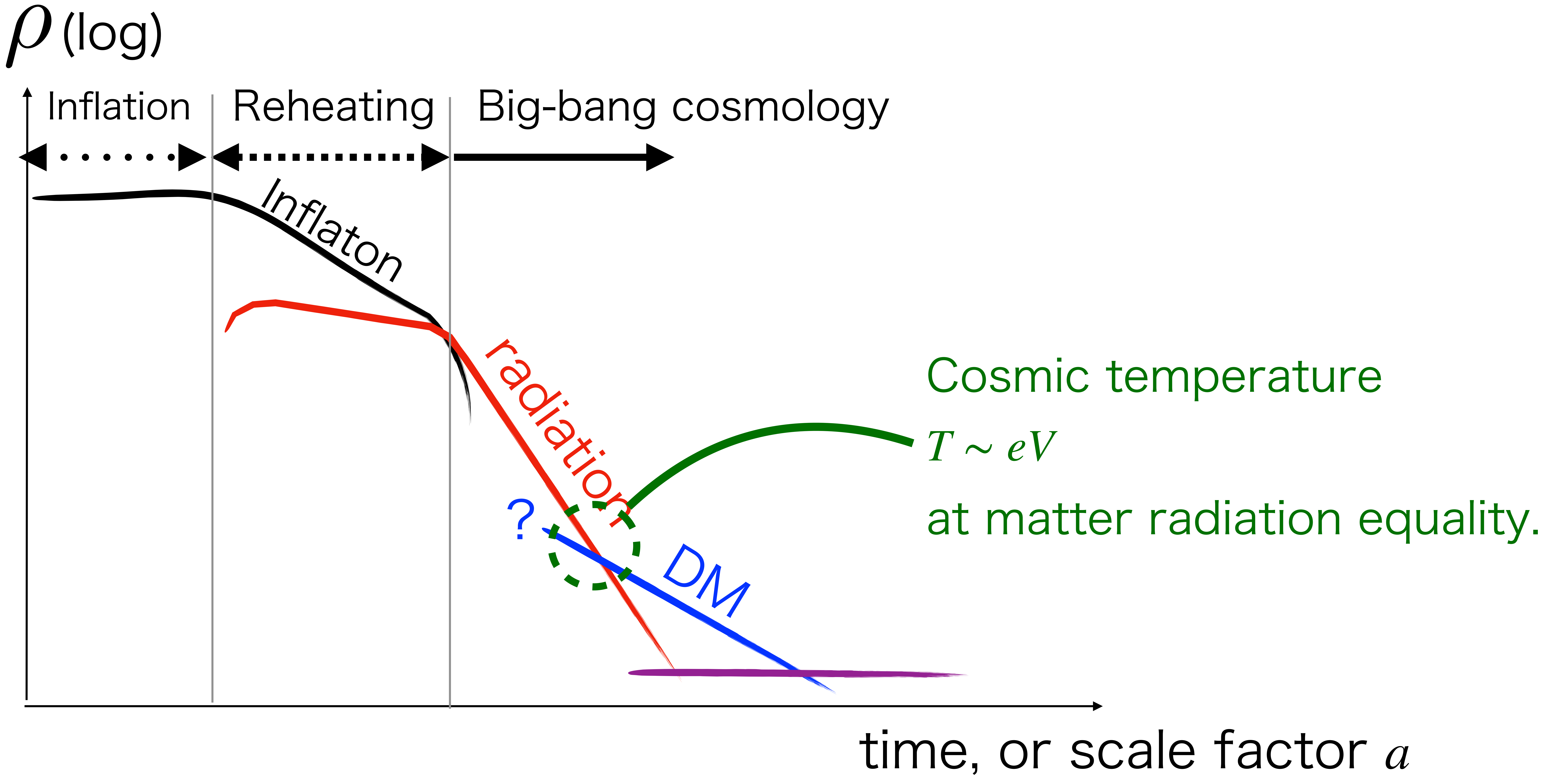
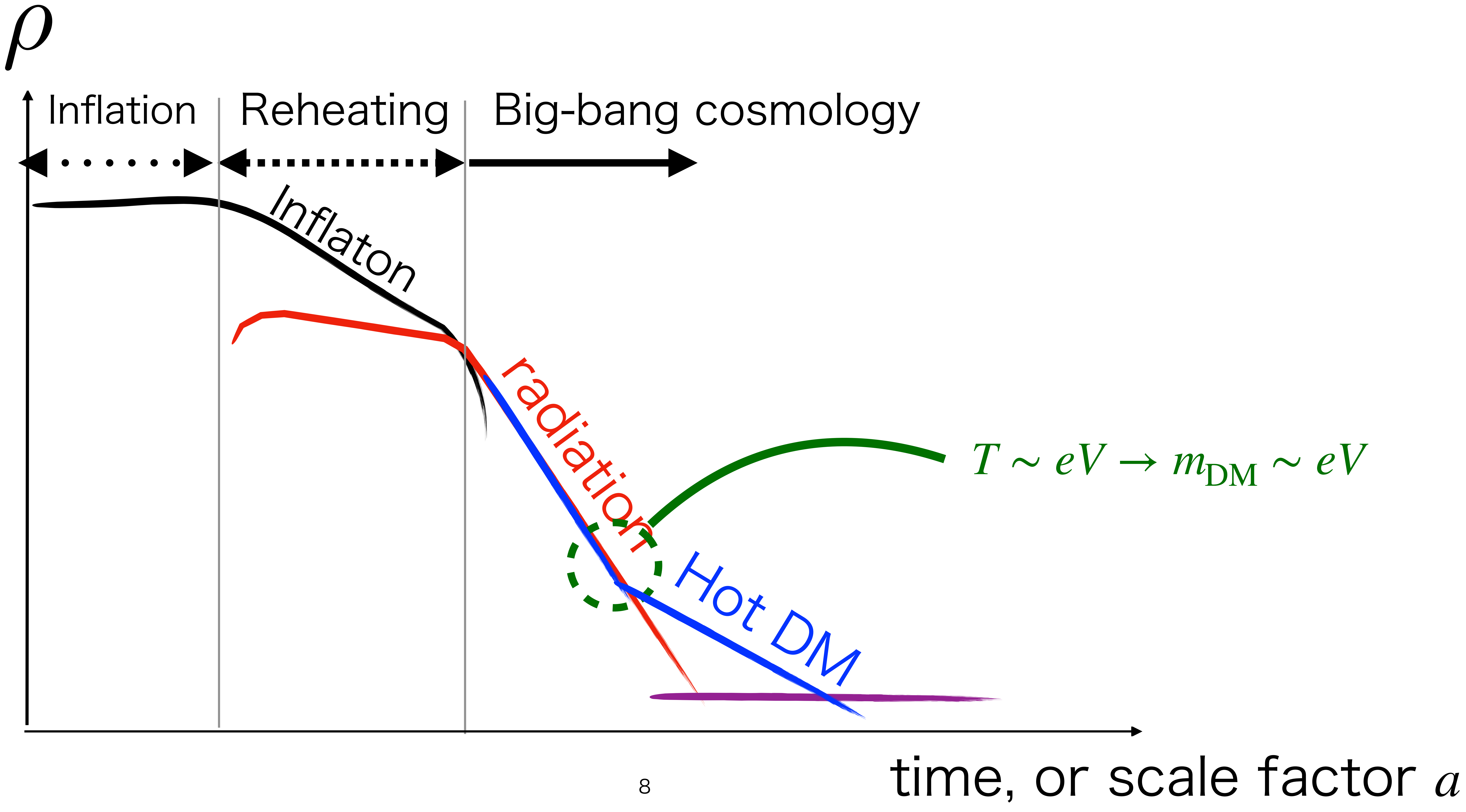


Hint for eV DM: Hot DM paradigm (-1984)



Hint for eV DM: 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.

$$\because n_{\rm DM} \sim T^3, \qquad \rho_{\rm DM}/s \sim m_{\rm DM} n_{\rm DM}/T^3 \sim \text{eV}$$

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

- Thermally produced eV DM is too hot.

$$\because P_{\rm DM} \sim T, v_{\rm DM}(T \sim eV) \sim 1$$

- ->Thermally produced eV DM is excluded.

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$$\because P_{\rm DM} \sim T, v_{\rm DM}(T \sim eV) \sim 1$$ **true?**

- ->Thermally produced eV DM is excluded.

- **2. Thermal production of eV dark matter, coldly**

WY, 2301.08735

$$n_{\rm DM} \sim \ T^3, \to m_{\rm DM} \sim {\rm eV}$$

$$P_{\rm DM} \ll T, \to v_{\rm DM}(T \sim eV) \ll 1$$

Keyword: bose enhancement

Setup:

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

WY 2301.08735

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

Equations:

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

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

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

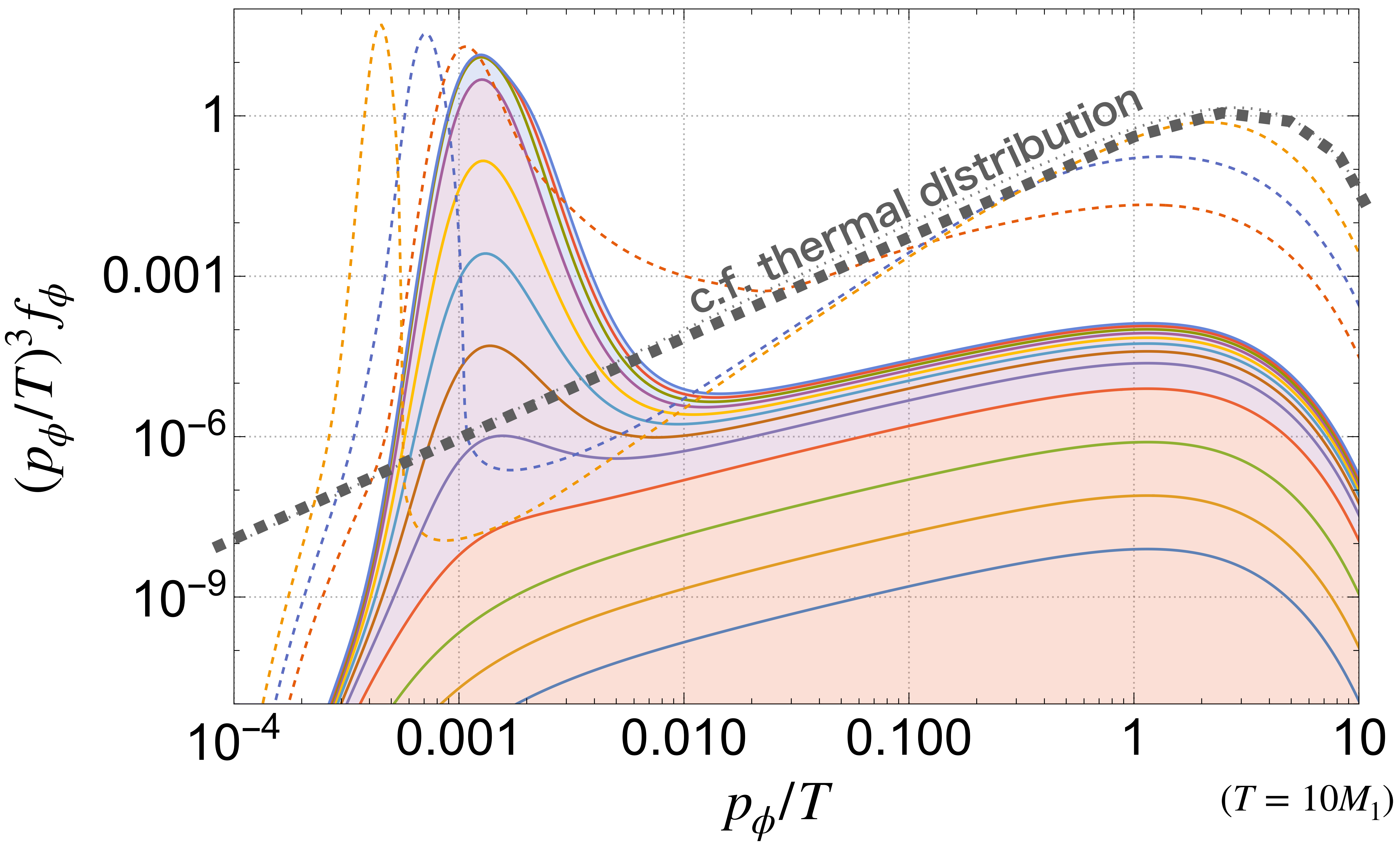
(Initial) conditions:

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

+ rotational invariance. $H=0$ for a while.

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

ϕ number density



Three stages of burst production:

1. Ignition
2. Burst
3. Saturation

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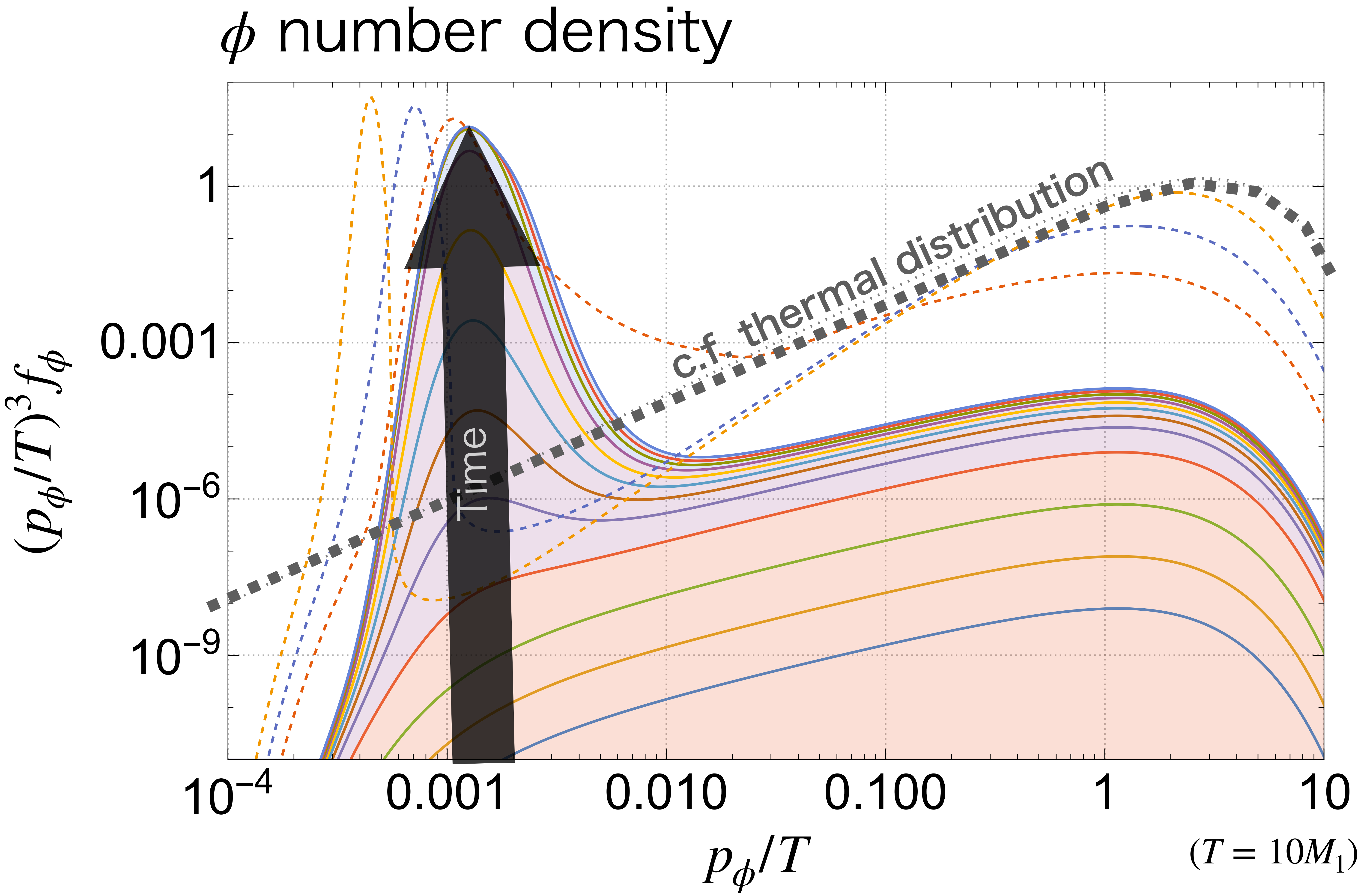

Three stages of burst production:

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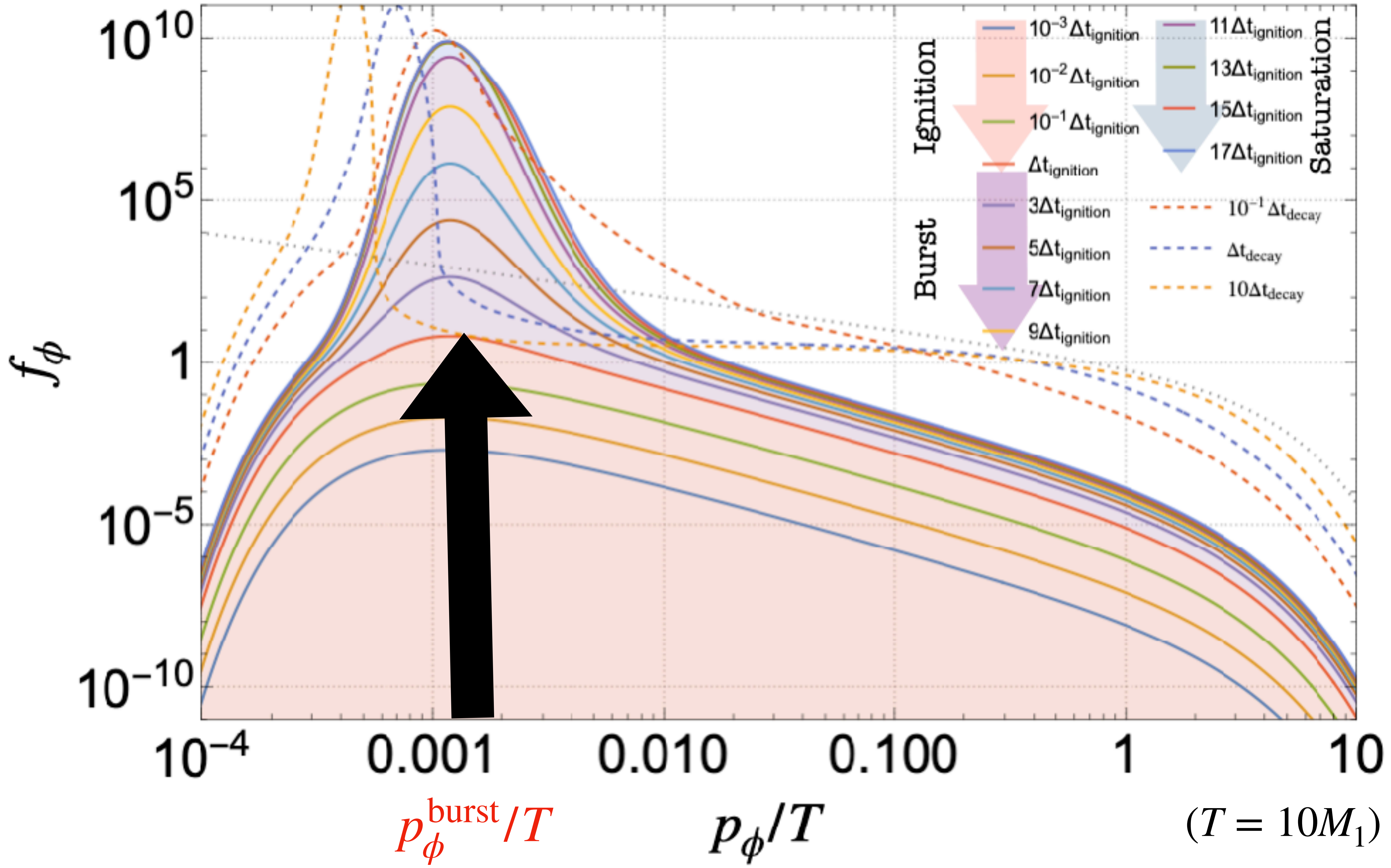
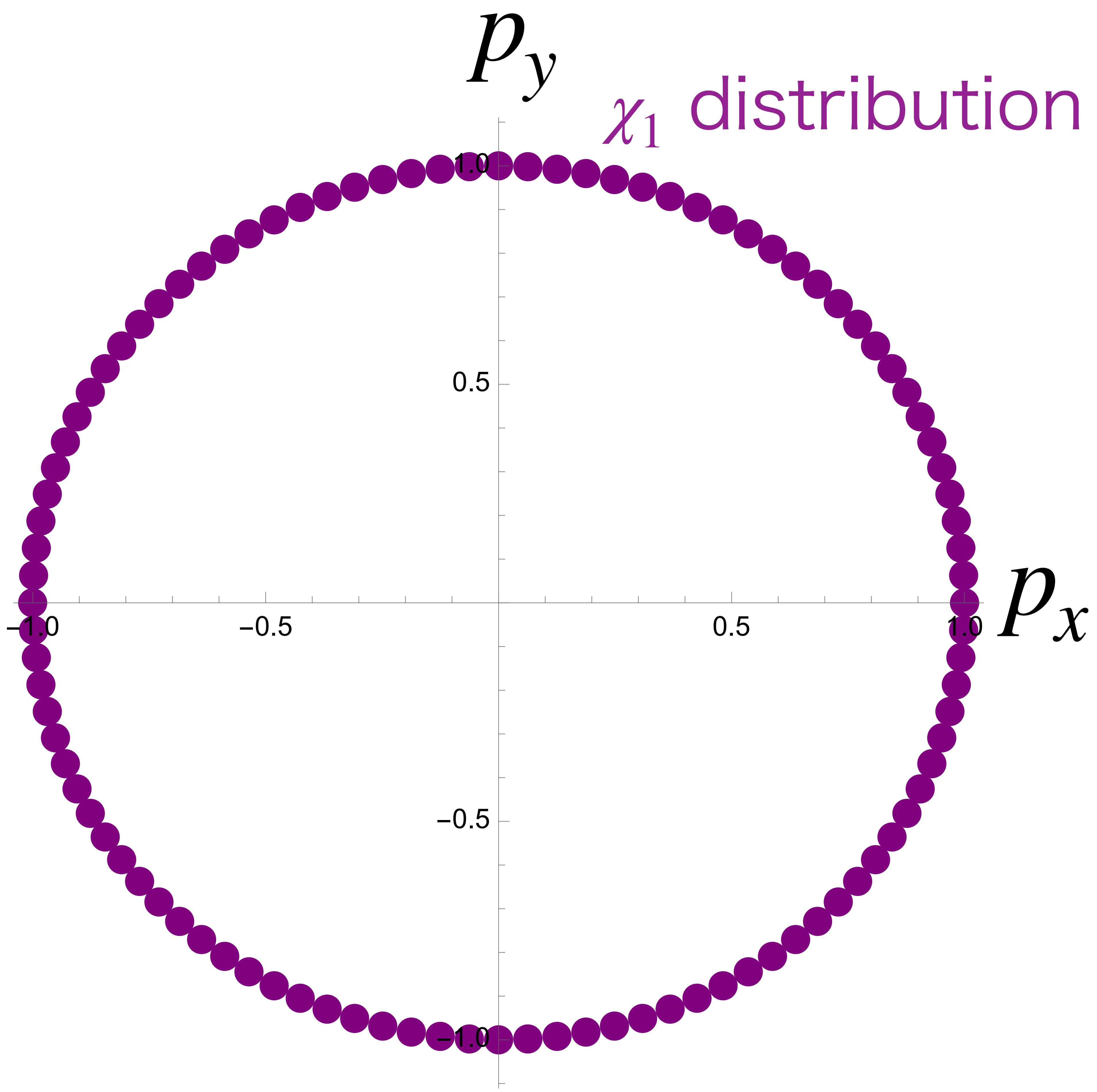
Stage 1: Ignition

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

Occupation number



Simplified model.



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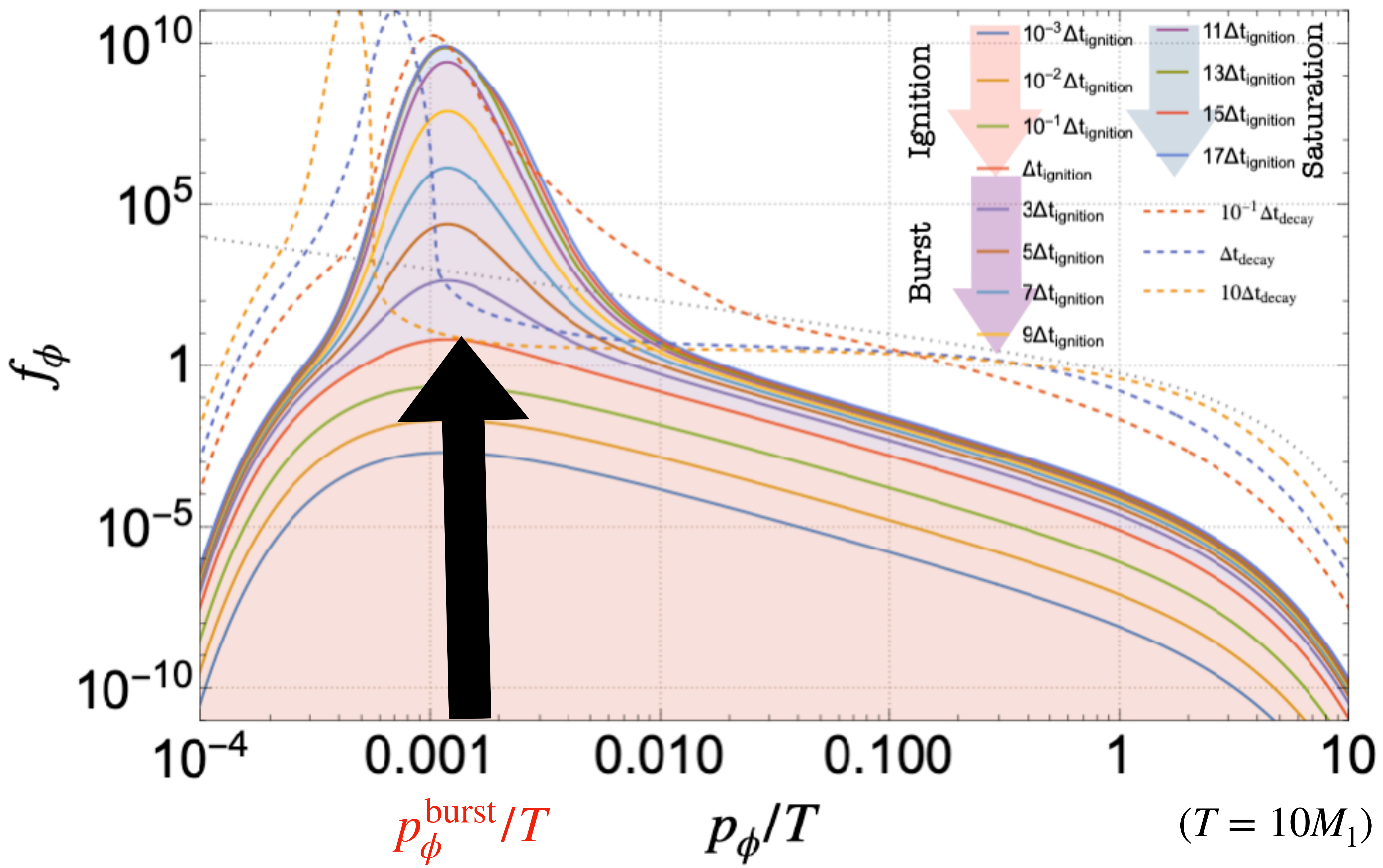

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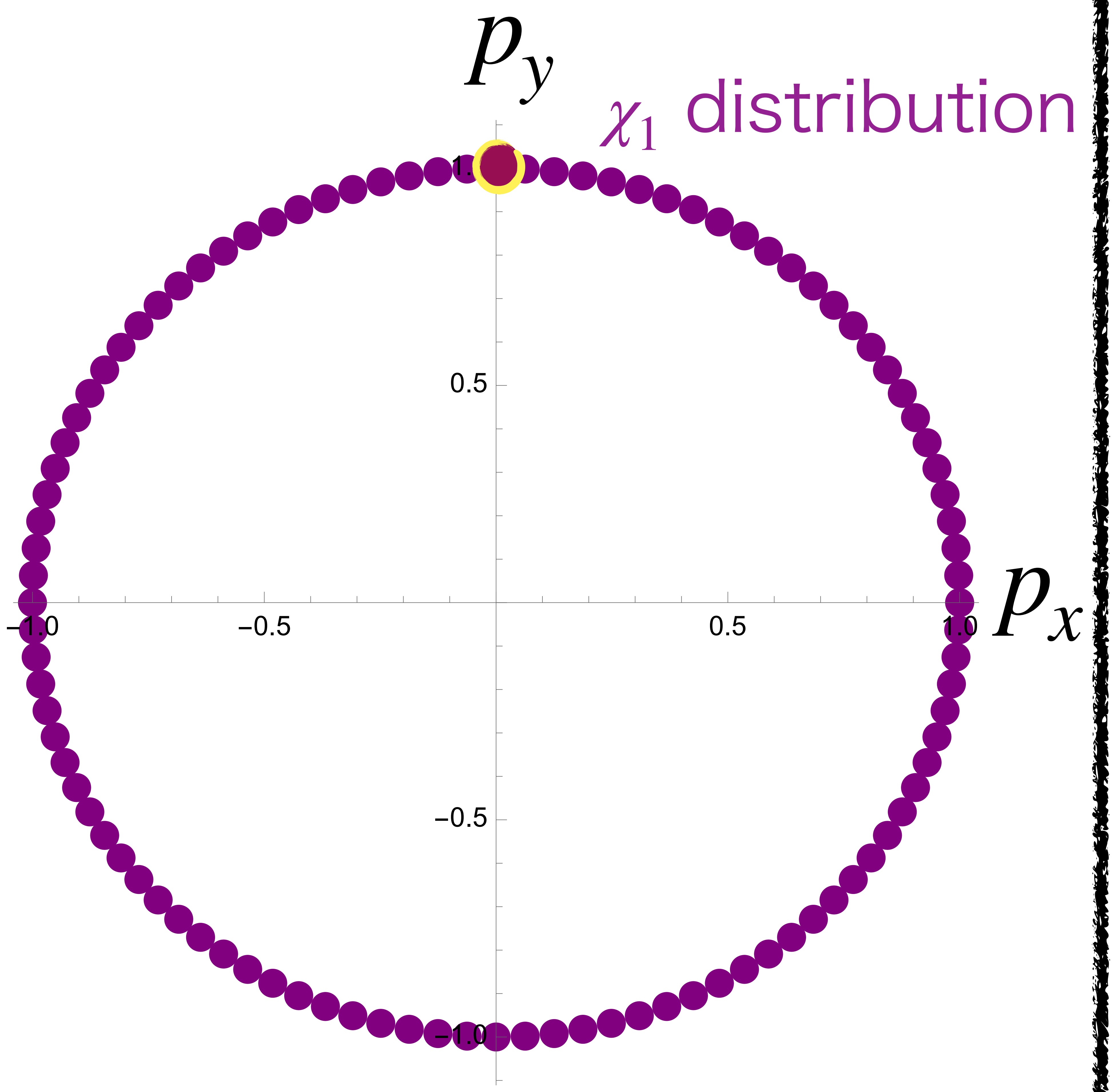

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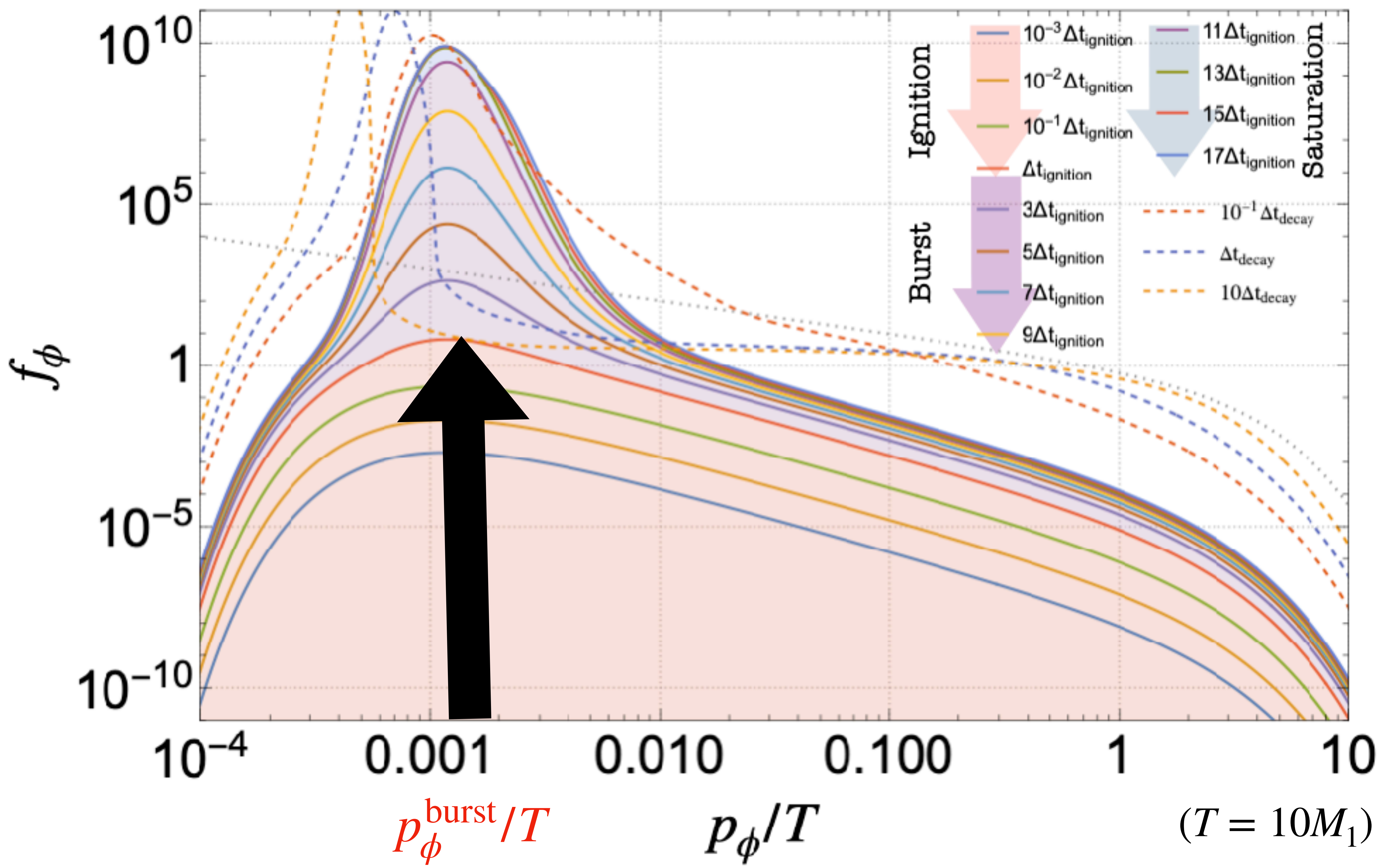

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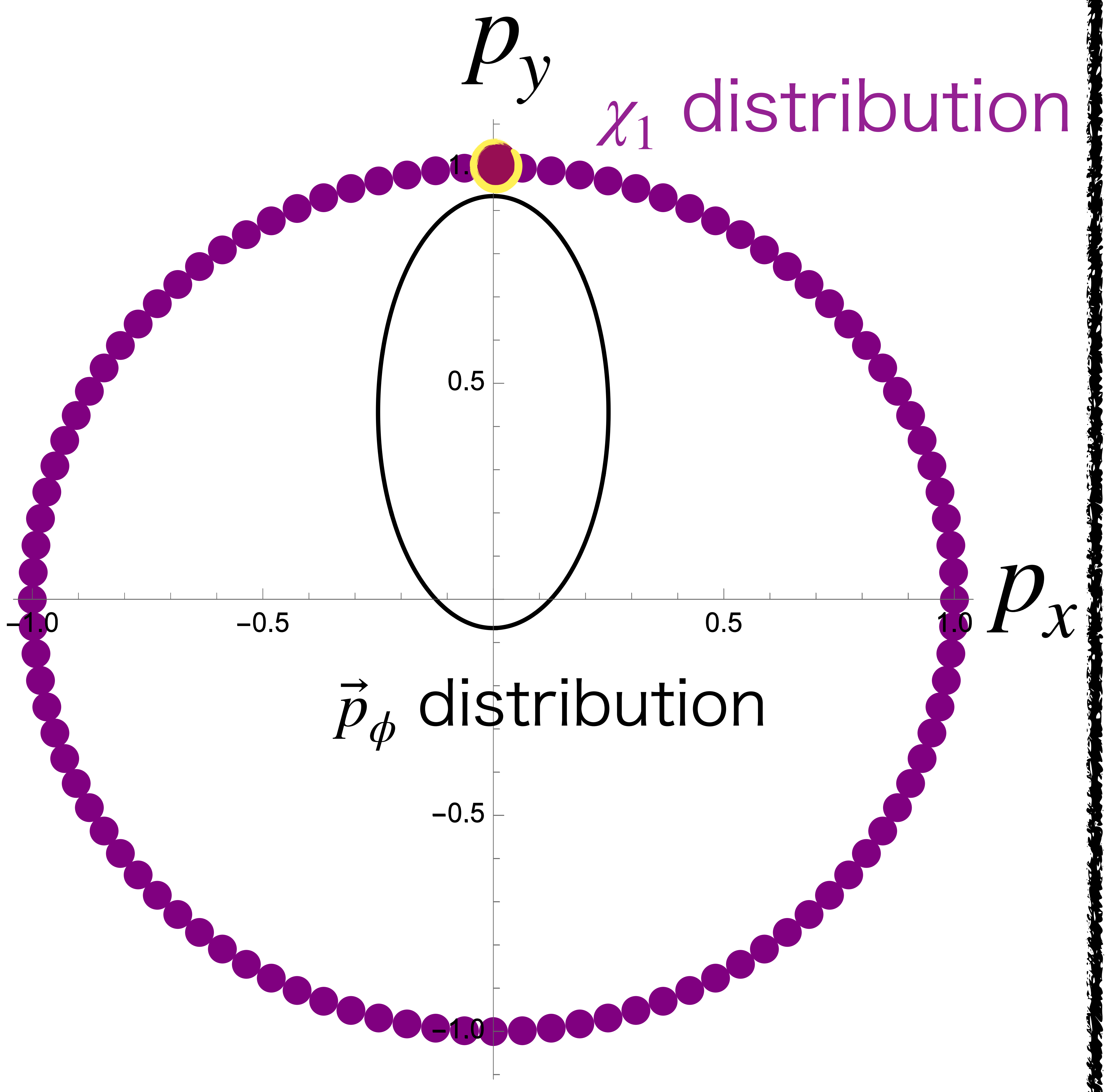

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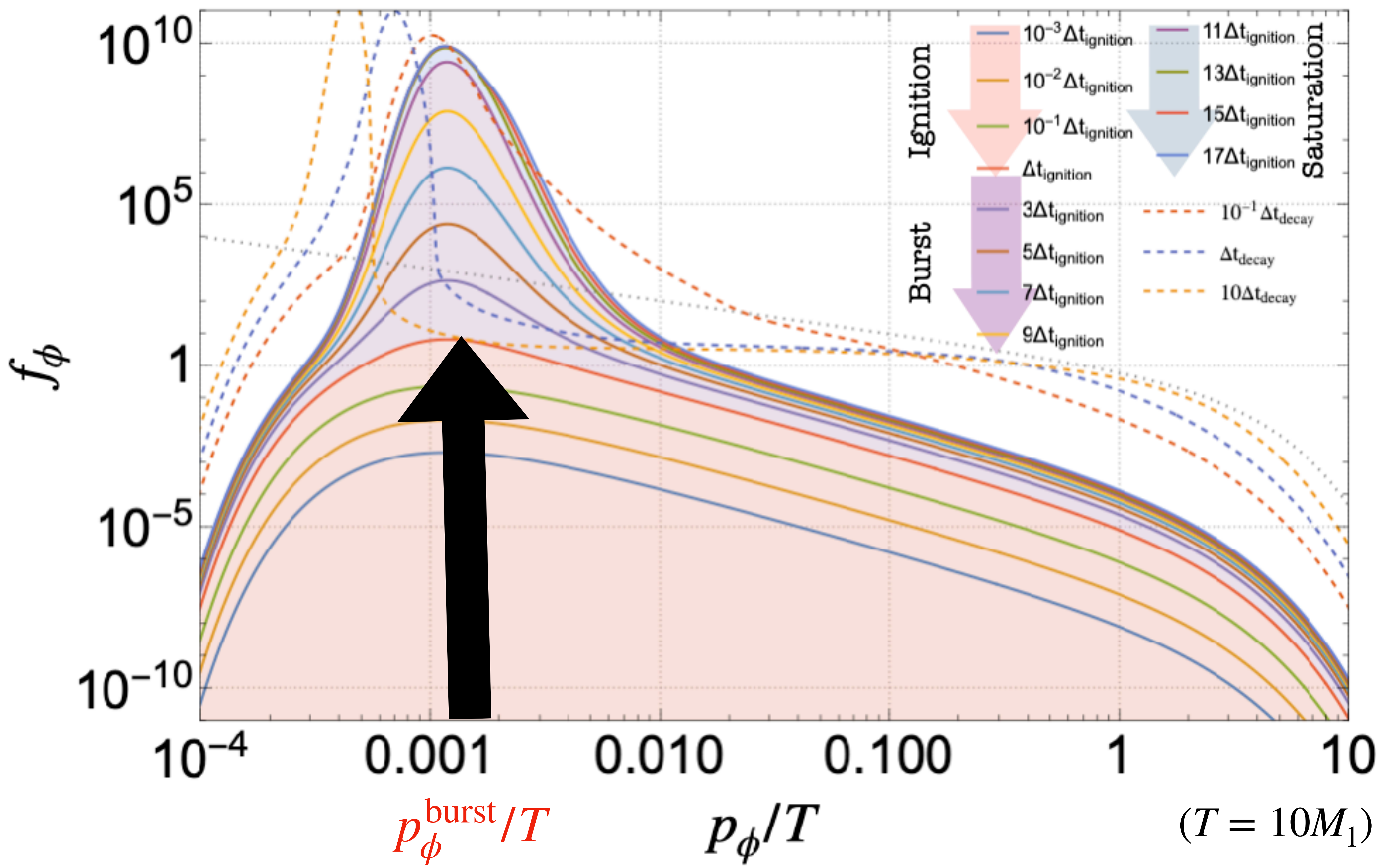

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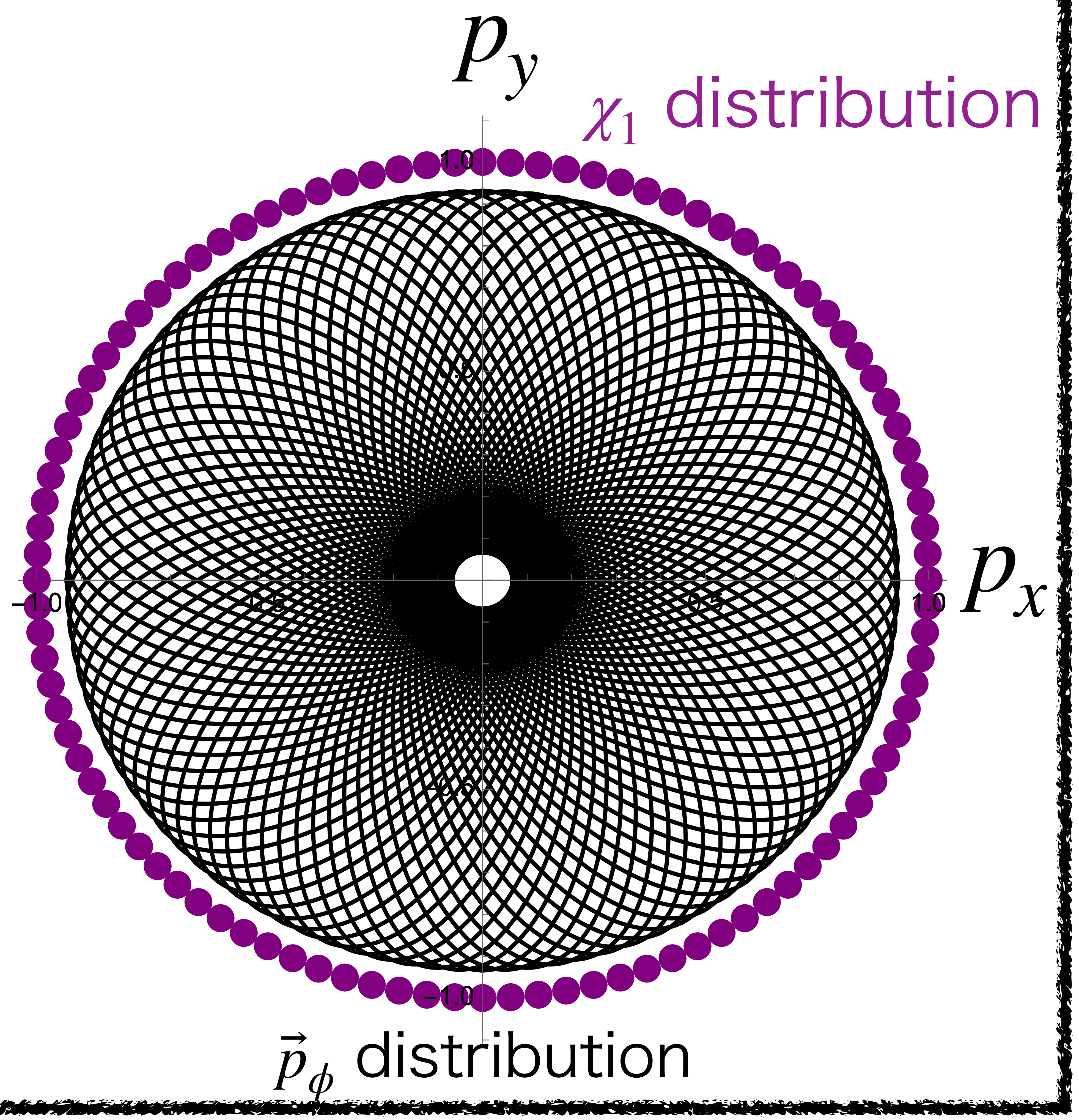

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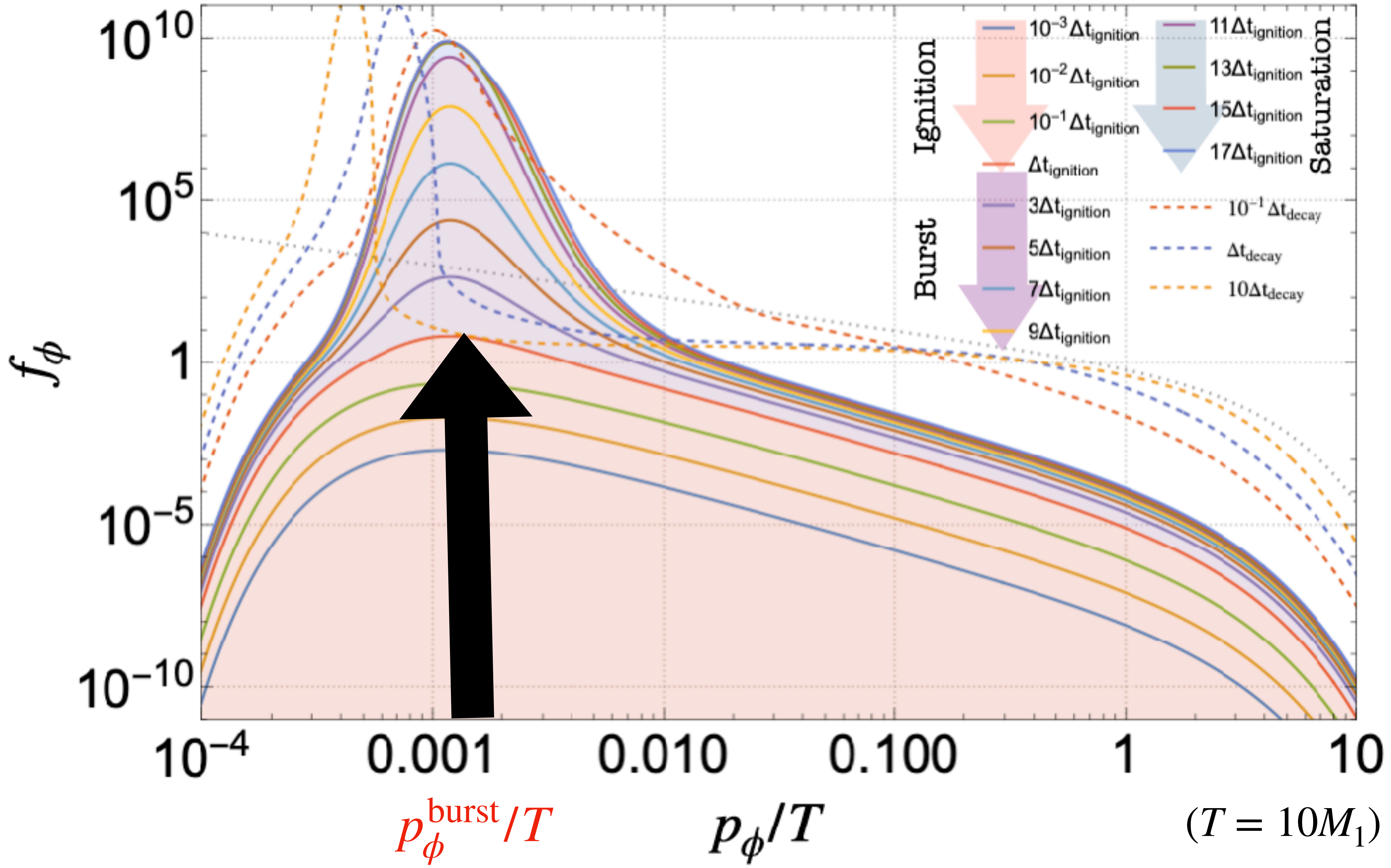

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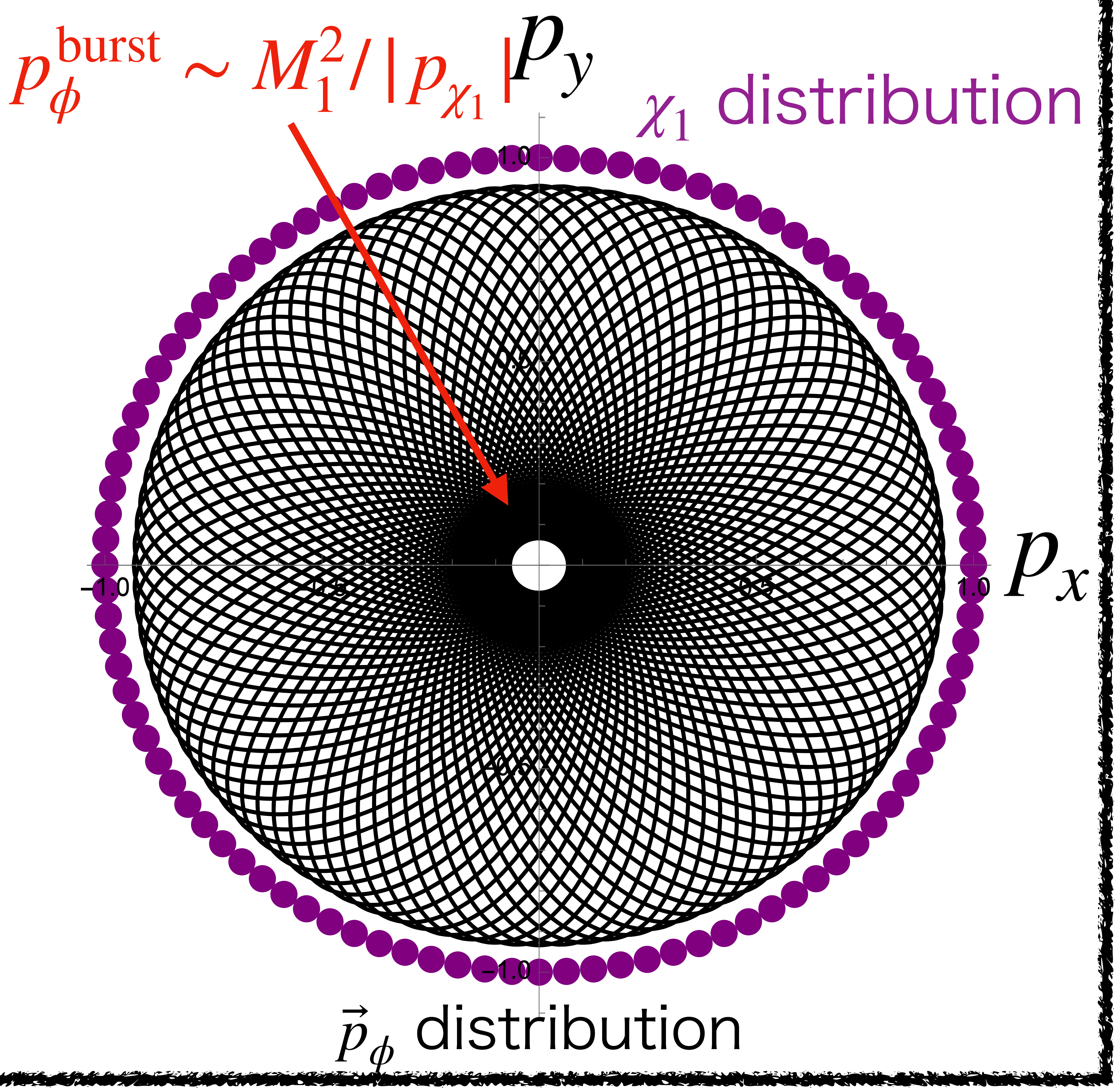
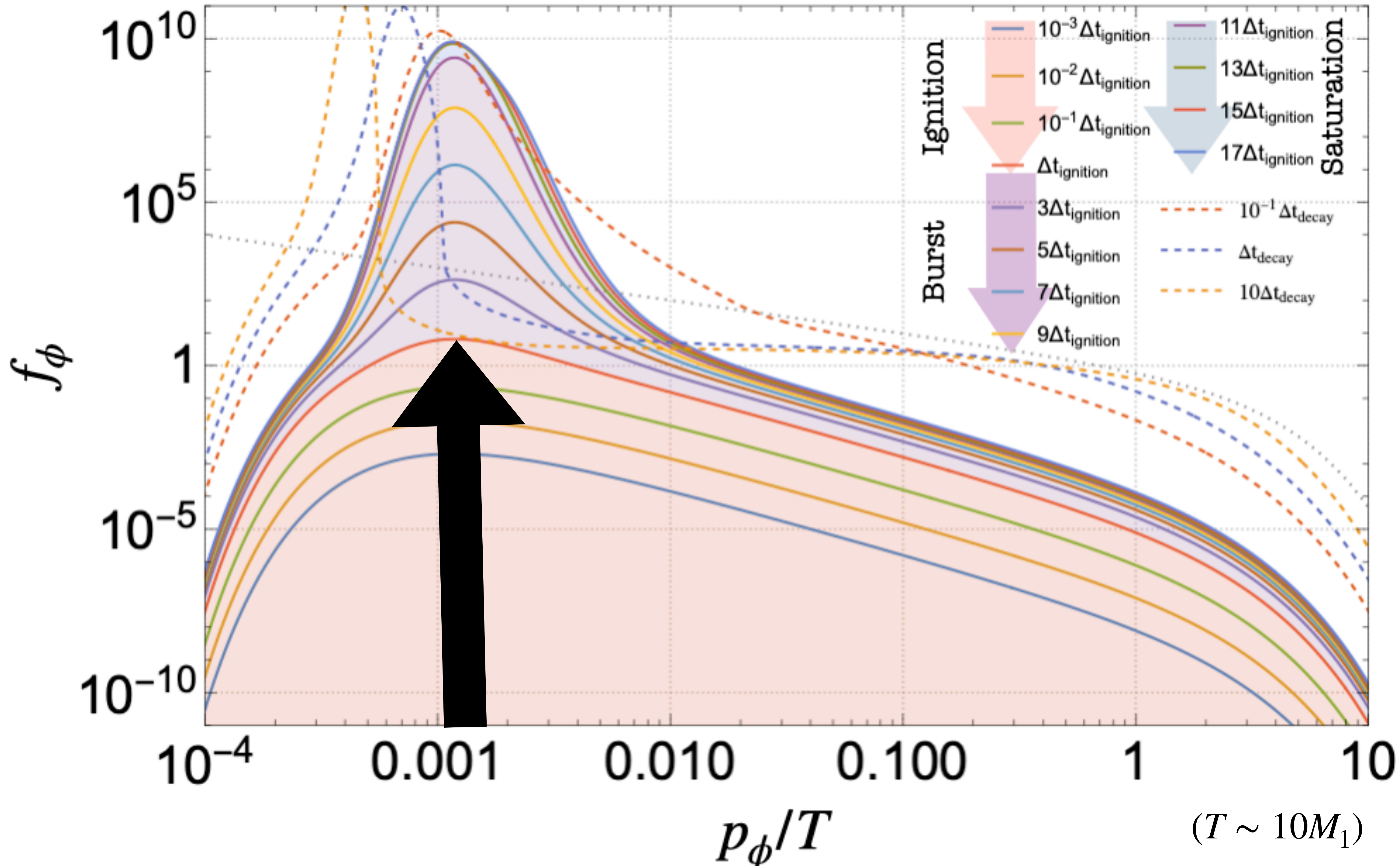


Stage 1: Ignition

The timescale, $\Delta t_{\text{iginition}}$, that the $p_\phi^{\text{burst}} \sim M_1^2/T$ occupation number reaches unity is :

$$\Delta t^{-1}_{\text{ignition}} \sim \underbrace{\frac{1}{(p_\phi^{\text{burst}})^3}}_{\text{Phase space volume}} \times \underbrace{T^3 \times \frac{p_\phi^{\text{burst}}}{T}\left(\frac{M_1}{T}\Gamma^{(\text{propoer})}_{\text{decay}}\right)}_{\text{Production rate of } p_\phi^{\text{burst}} \text{ number density}}$$



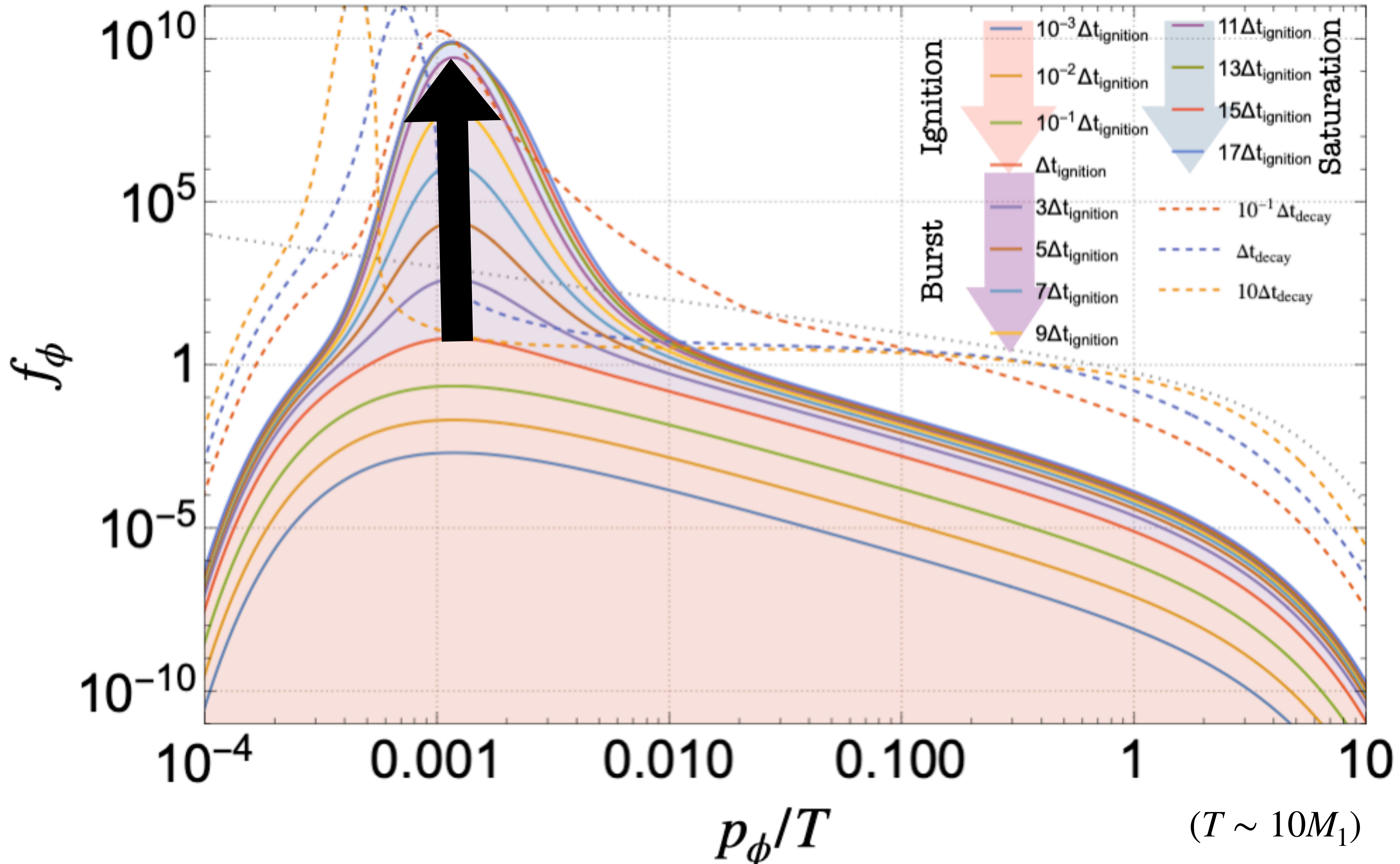
$(T \sim 10M_1)$

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

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

Stage 2: Burst

p_ϕ^{burst} modes grow exponentially in time.



$(T \sim 10M_1)$

Stage 2: Burst

$p_\phi^{\rm burst}$ modes grow exponentially due to Bose enhancement. $\chi_1[p_{\chi_1} \sim T] \to \chi_2[p_{\chi_2} \sim p_{\chi_1}] + \phi[p_\phi^{\rm burst} \ll p_{\chi_1}]$

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

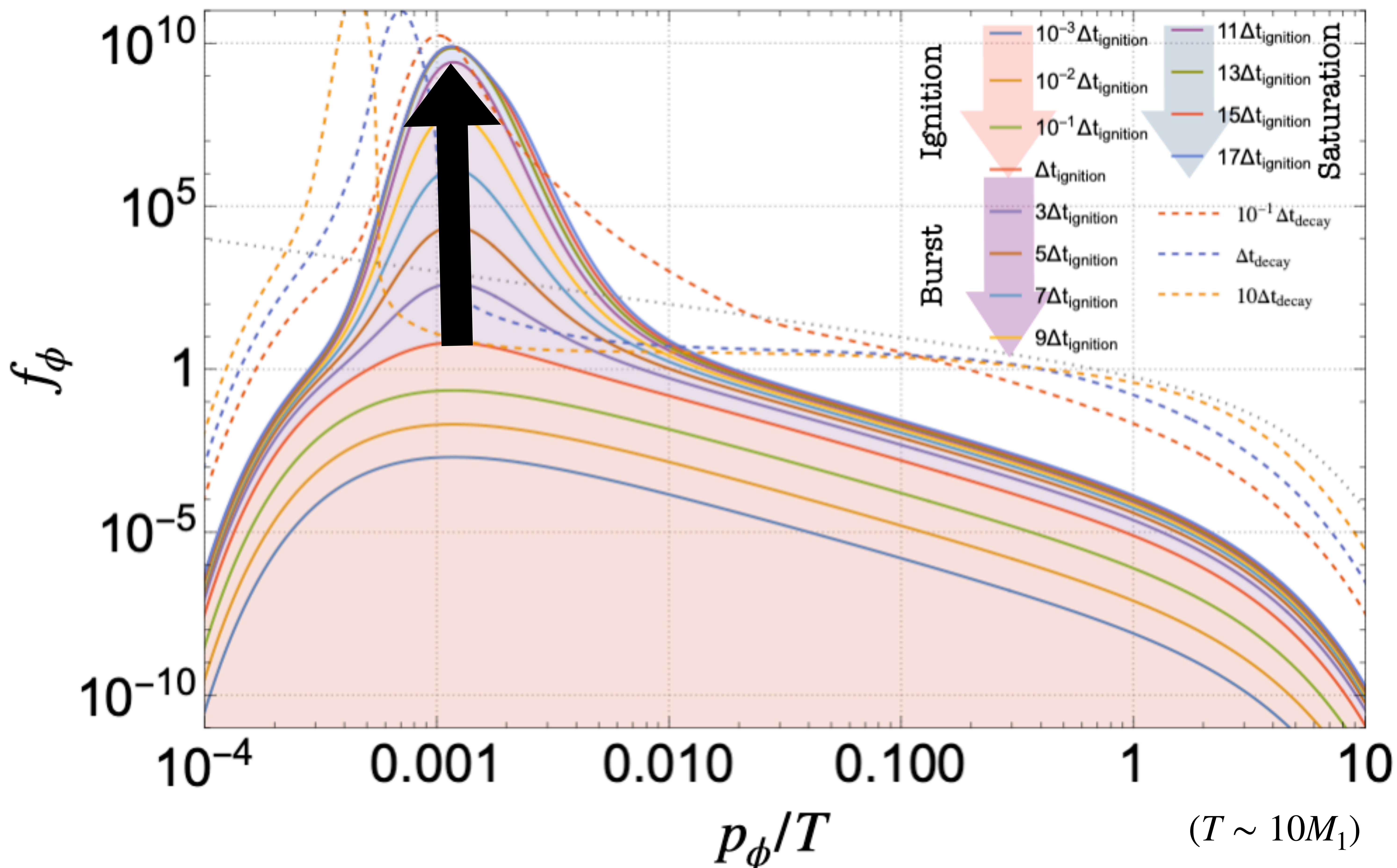
$$C^\phi = \frac{1}{2E_\phi g_\phi} \sum \int d\Pi_{\chi_1}\, d\Pi_{\chi_2}$$
$$(2\pi)^4 \delta^4(p_{\chi_1} - p_\phi - p_{\chi_2}) \times |\mathcal{M}_{\chi_1 \to \chi_2 \phi}|^2$$
$$\times S\left(f_{\chi_1}[p_{\chi_1}], f_{\chi_2}[p_{\chi_2}], f_\phi[p_\phi]\right)$$

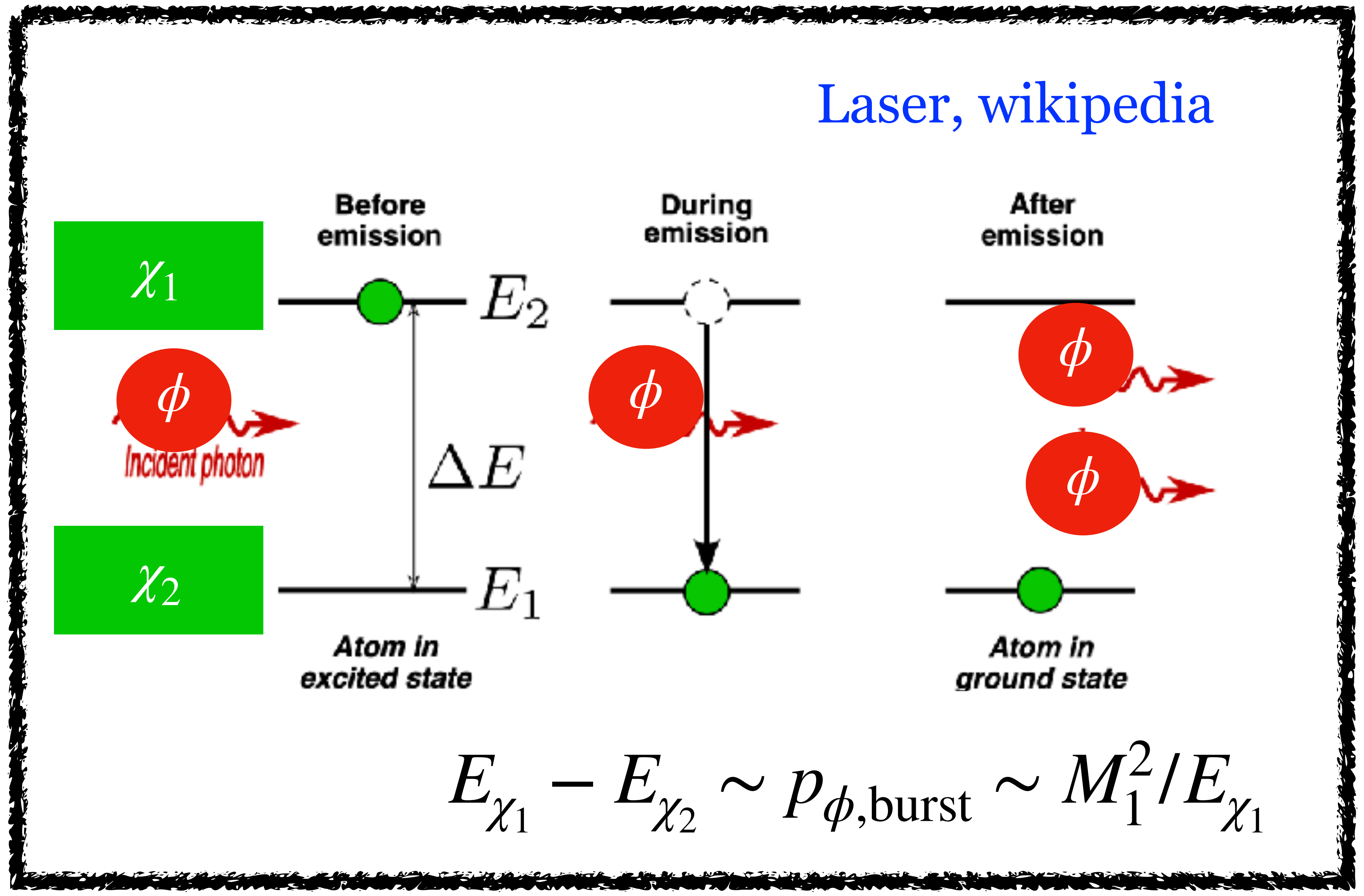
$$S \equiv f_{\chi_1}[p_{\chi_1} \sim T](1 \pm f_{\chi_2}[p_{\chi_2} \sim T])(1 + f_\phi[p_\phi \sim p_\phi^{\rm burst}]$$
$$-(1 \pm f_{\chi_1}[p_{\chi_1} \sim T])f_\phi[p_\phi \sim p_\phi^{\rm burst}]f_{\chi_2}[p_{\chi_2} \sim T]$$
$$\sim f_{\chi_1}[p_{\chi_1} \sim T](1 + f_\phi[p_\phi \sim p_\phi^{\rm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

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

Stage 2: Burst

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

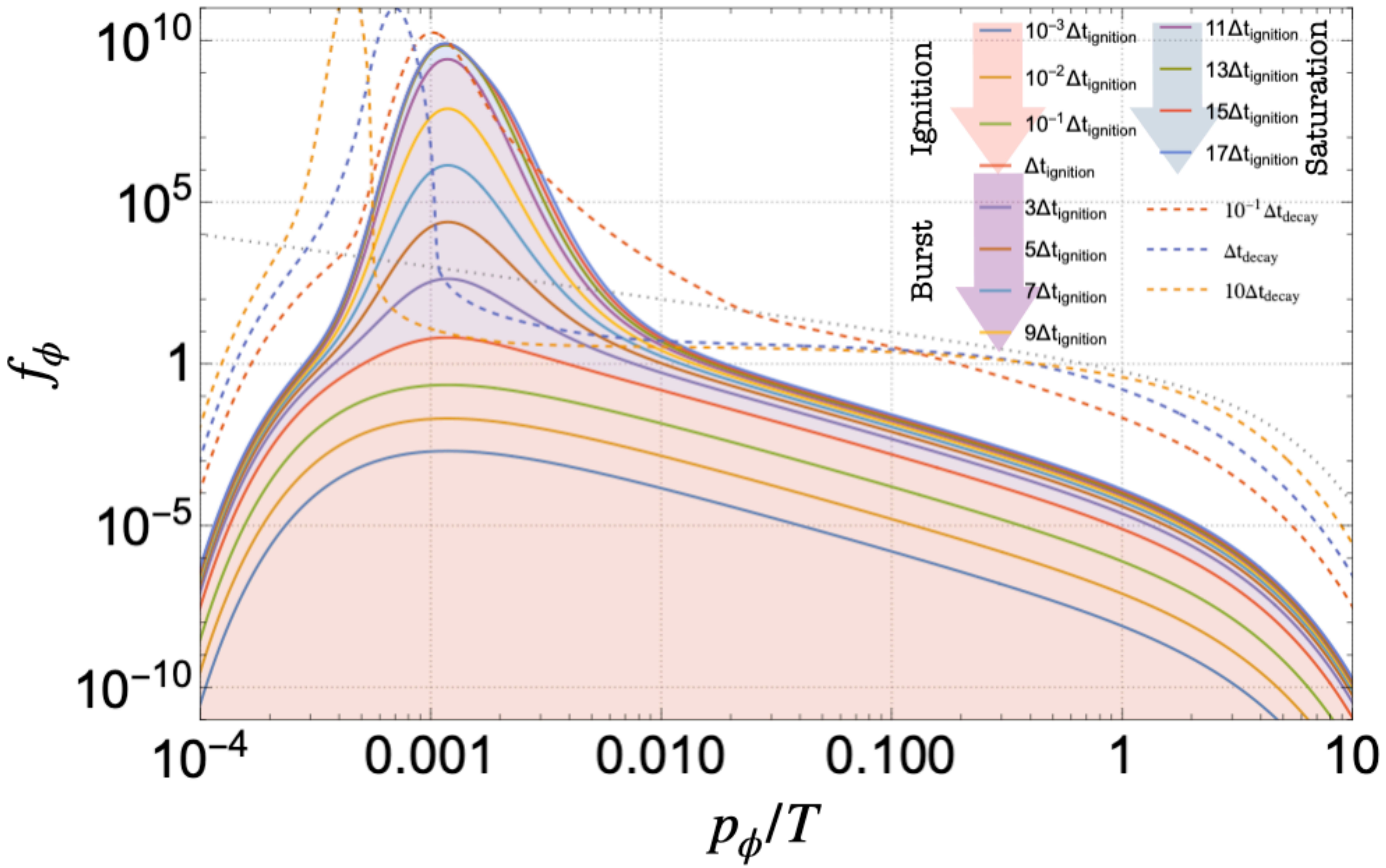




$$f_\phi[p_\phi \sim p_\phi^{\text{burst}}] \sim \exp[t/\Delta t_{\text{ignition}}]$$

Stage 3: Saturation (quasi-equilibrium)

The burst production stops and the spectrum is kept for a long time.



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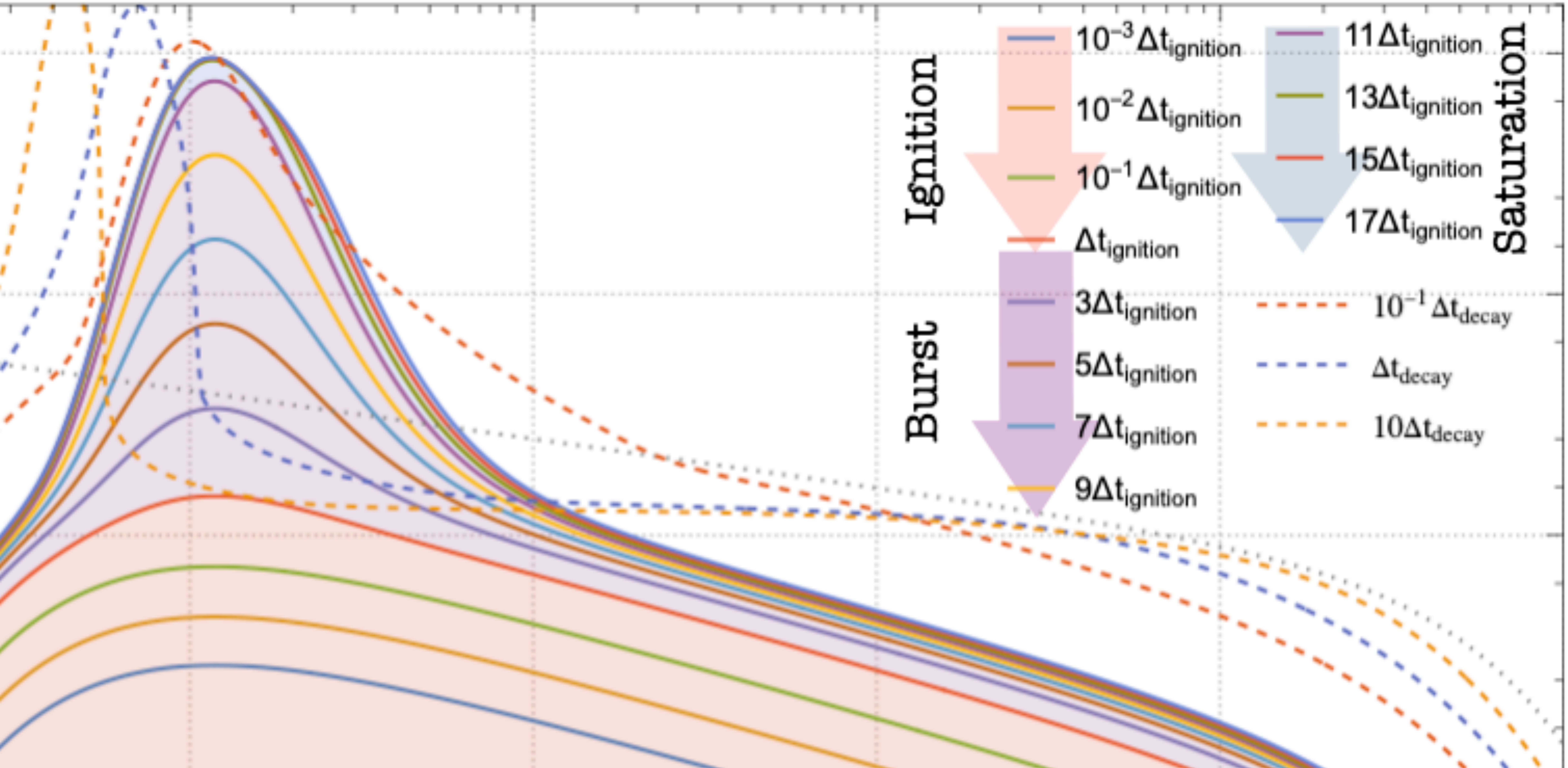

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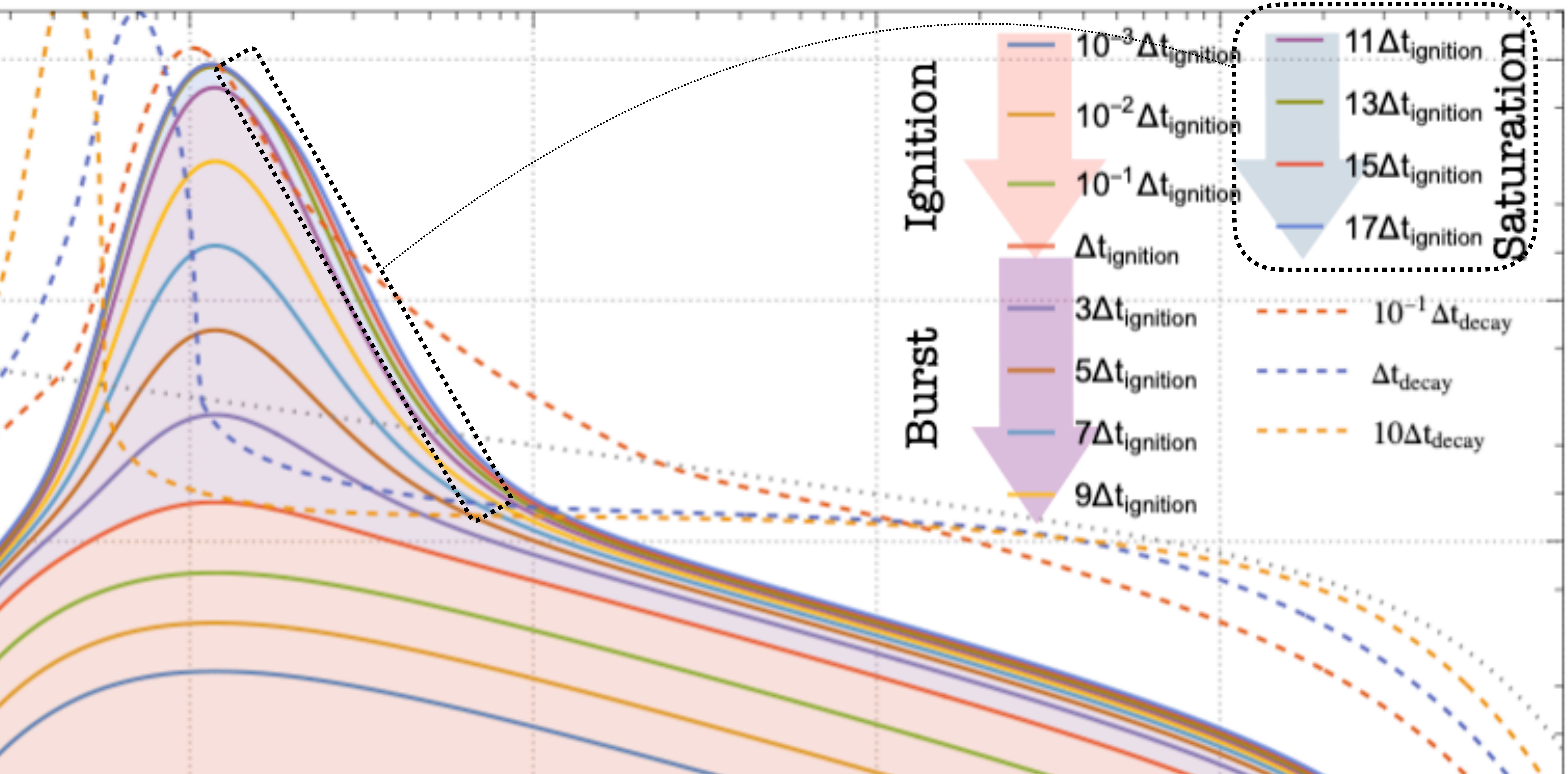
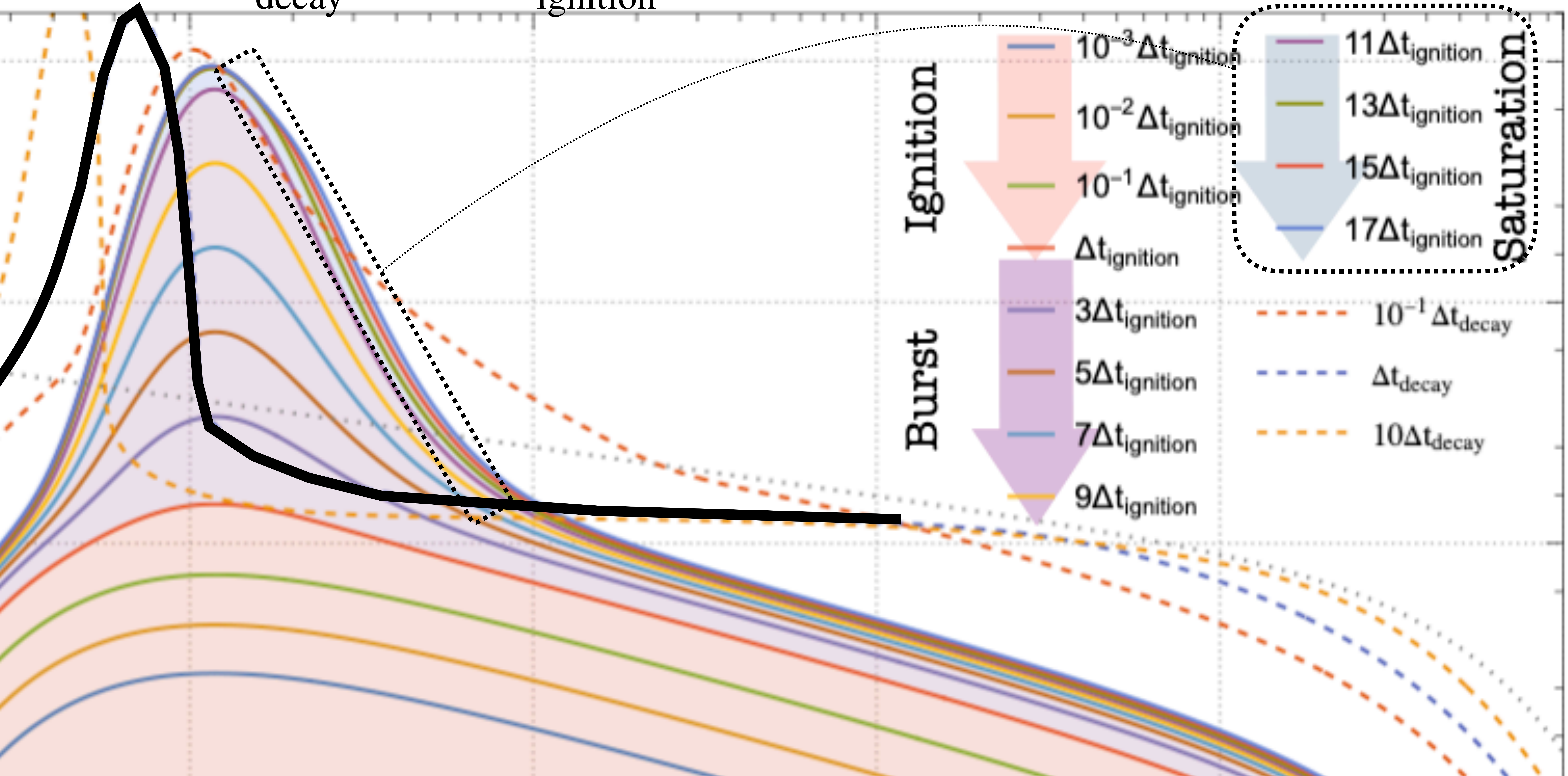


Stage 3: Saturation (quasi-equilibrium)

$t \sim \Delta t_{\mathrm{decay}} \sim 10^4 \Delta t_{\mathrm{ignition}}$



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

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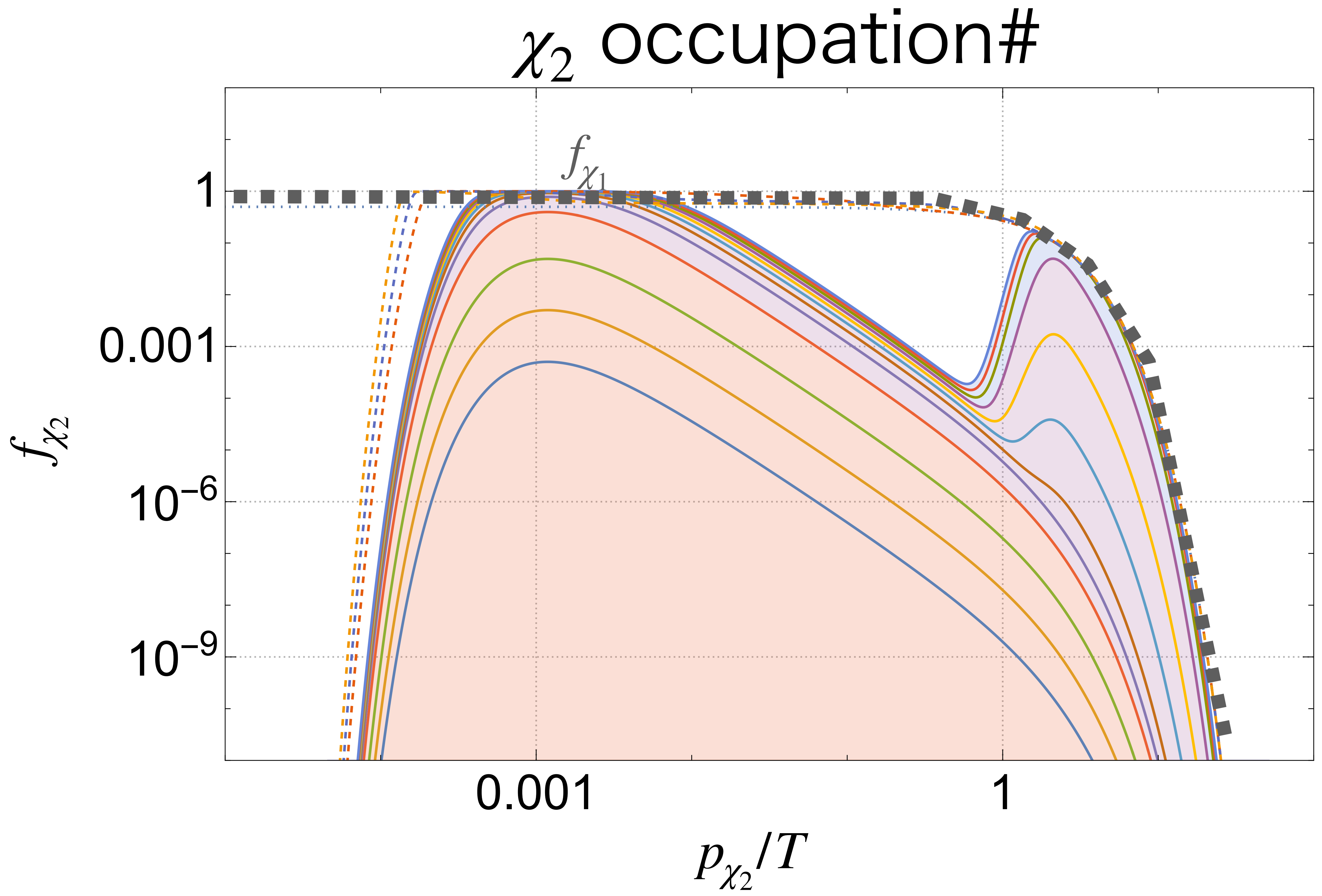
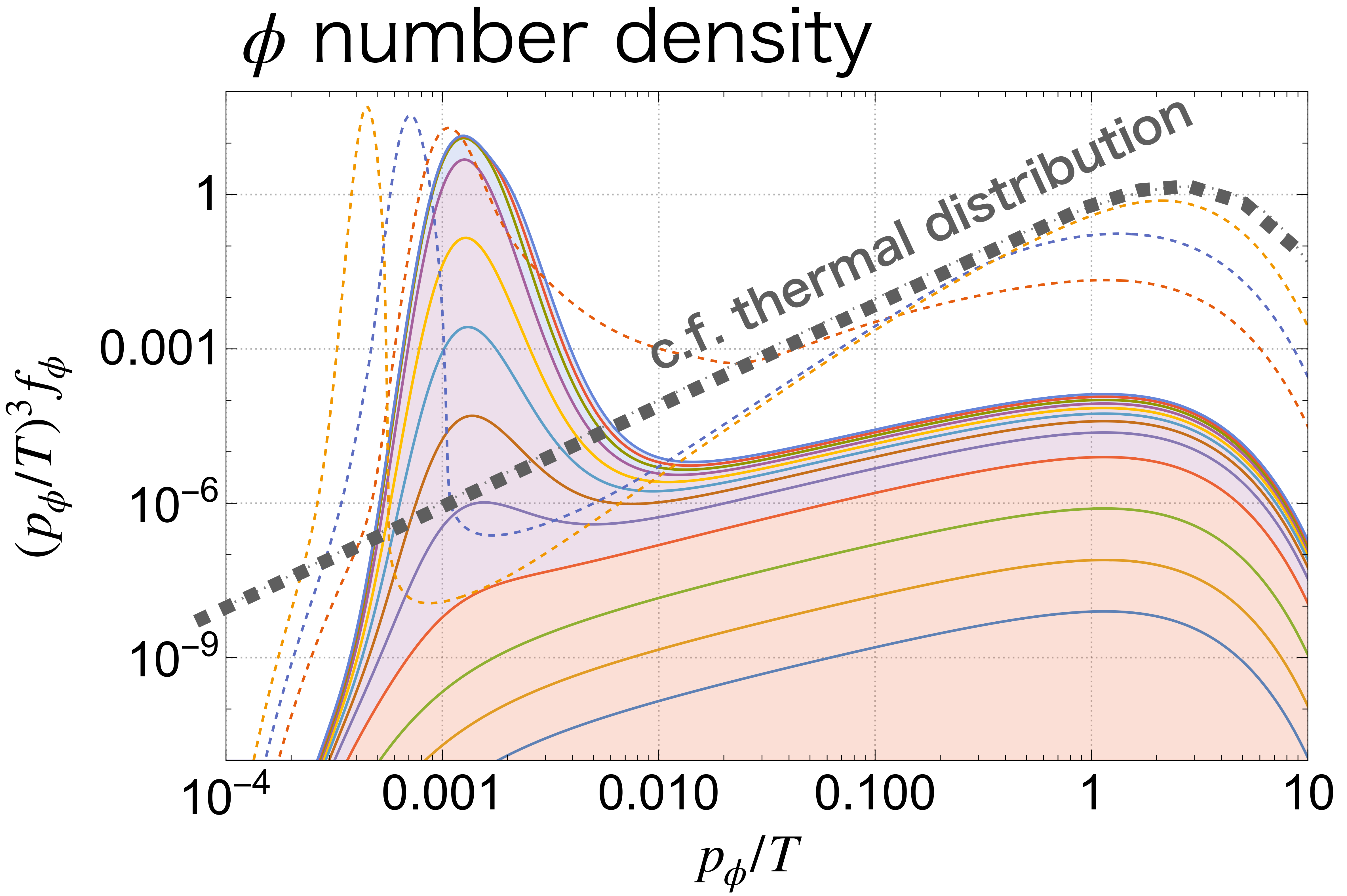
$$-(1 \pm f_{\chi_1}[p_{\chi_1} \sim T])f_\phi[p_\phi \sim p_\phi^{\rm burst}]f_{\chi_2}[p_{\chi_2} \sim T]$$
$$\sim (f_{\chi_1}[p_{\chi_1} \approx p_{\chi_2}] - f_{\chi_2}[p_{\chi_2} \sim T])f_\phi[p_\phi \sim p_\phi^{\rm burst}]$$

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

Stage 3: Saturation (quasi-equilibrium)

The number density of χ_2 at $p_{\chi_2} \sim T$ is $g_{\chi_2} T^3$. Since $\dot{n}_{\chi_2} = \dot{n}_\phi$ in $\chi_1 \leftrightarrow \chi_2 \phi$, we have $n_\phi = n_{\chi_2}$.





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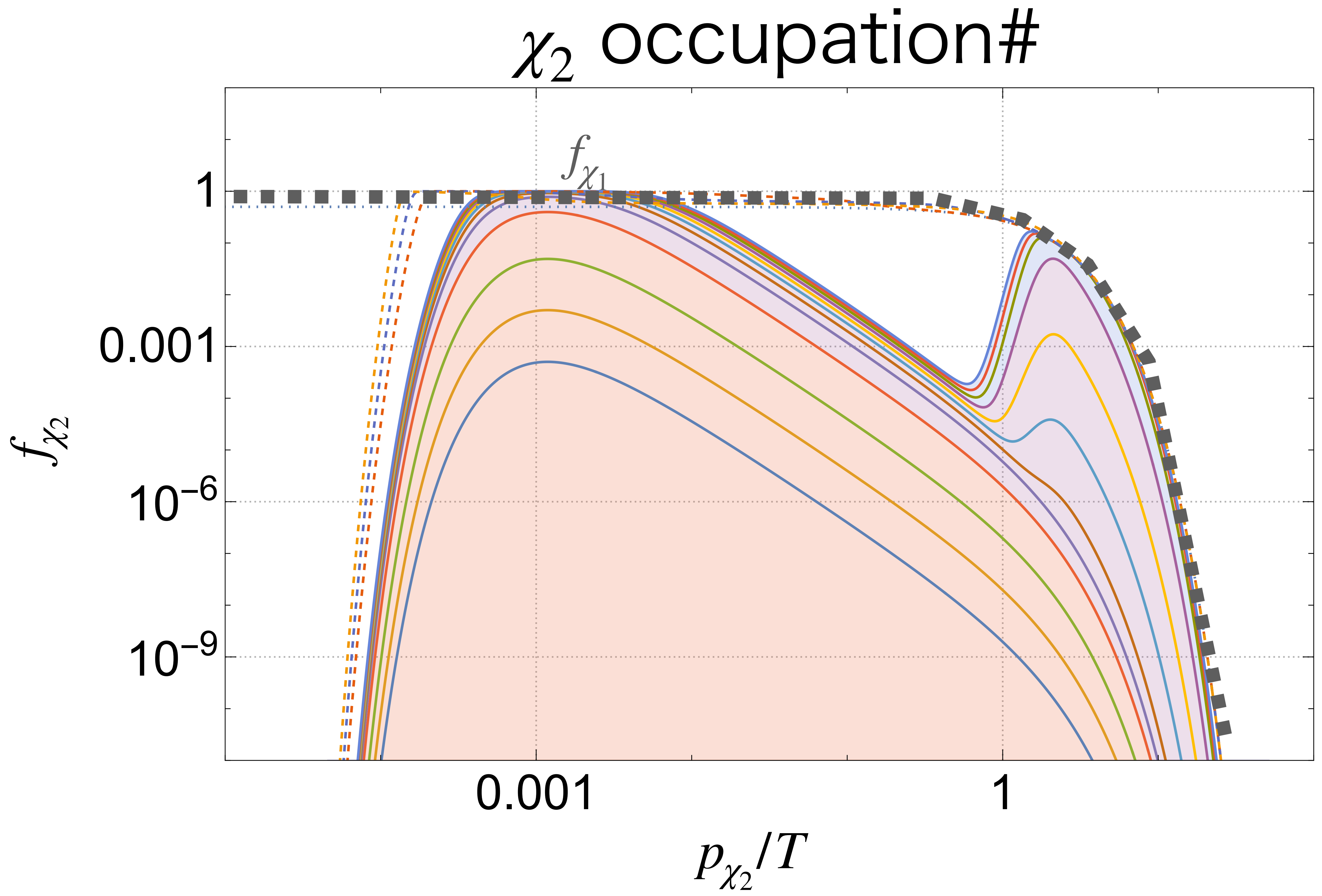
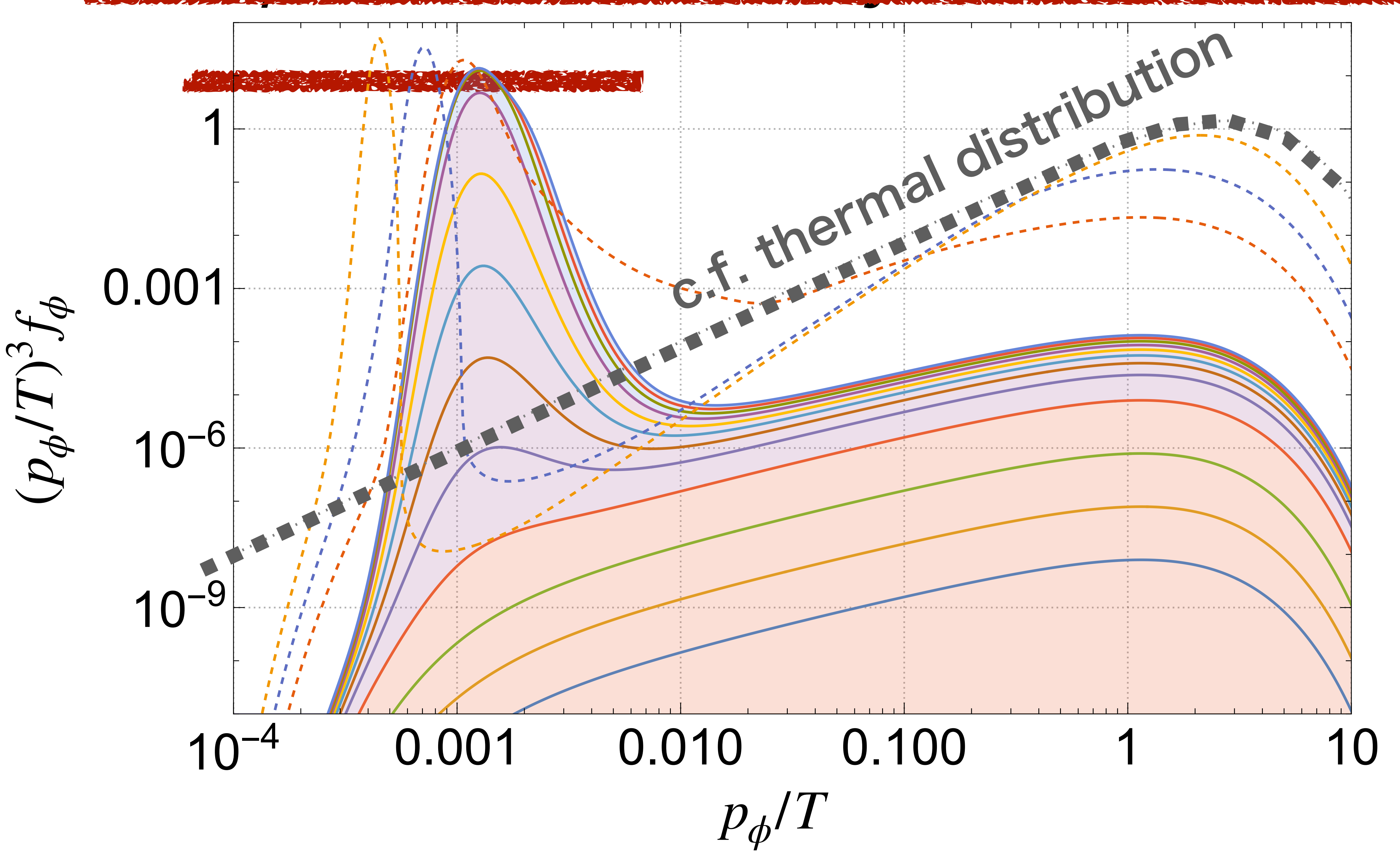
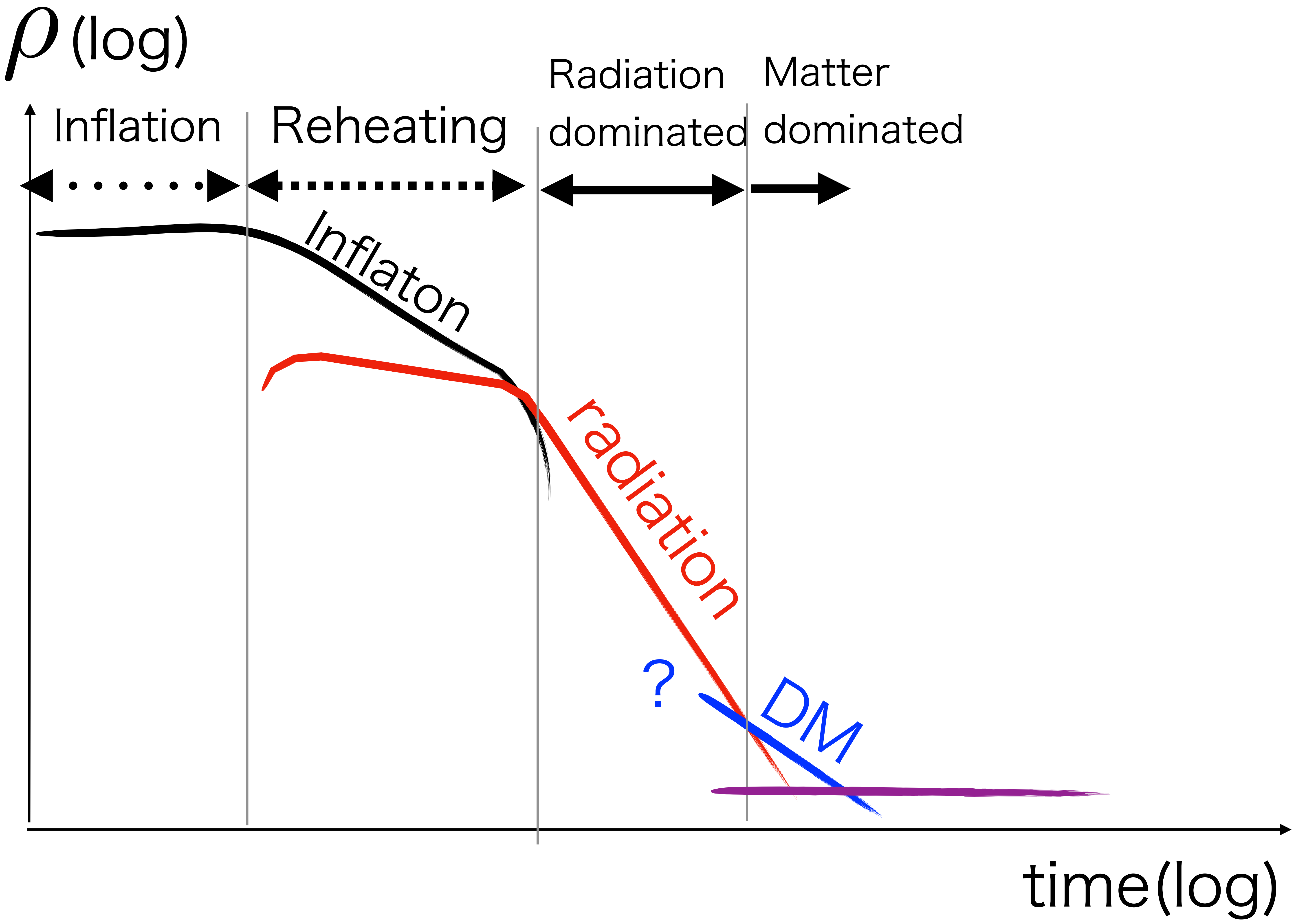
$n_\phi \sim g_{\chi_2} T^3, p_\phi \sim M_1^2/T,$ which is cold





Let’s introduce cosmological expansion



Burst production in expanding Universe

If there is a period, $T = T_{\rm prod}$, satisfying

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

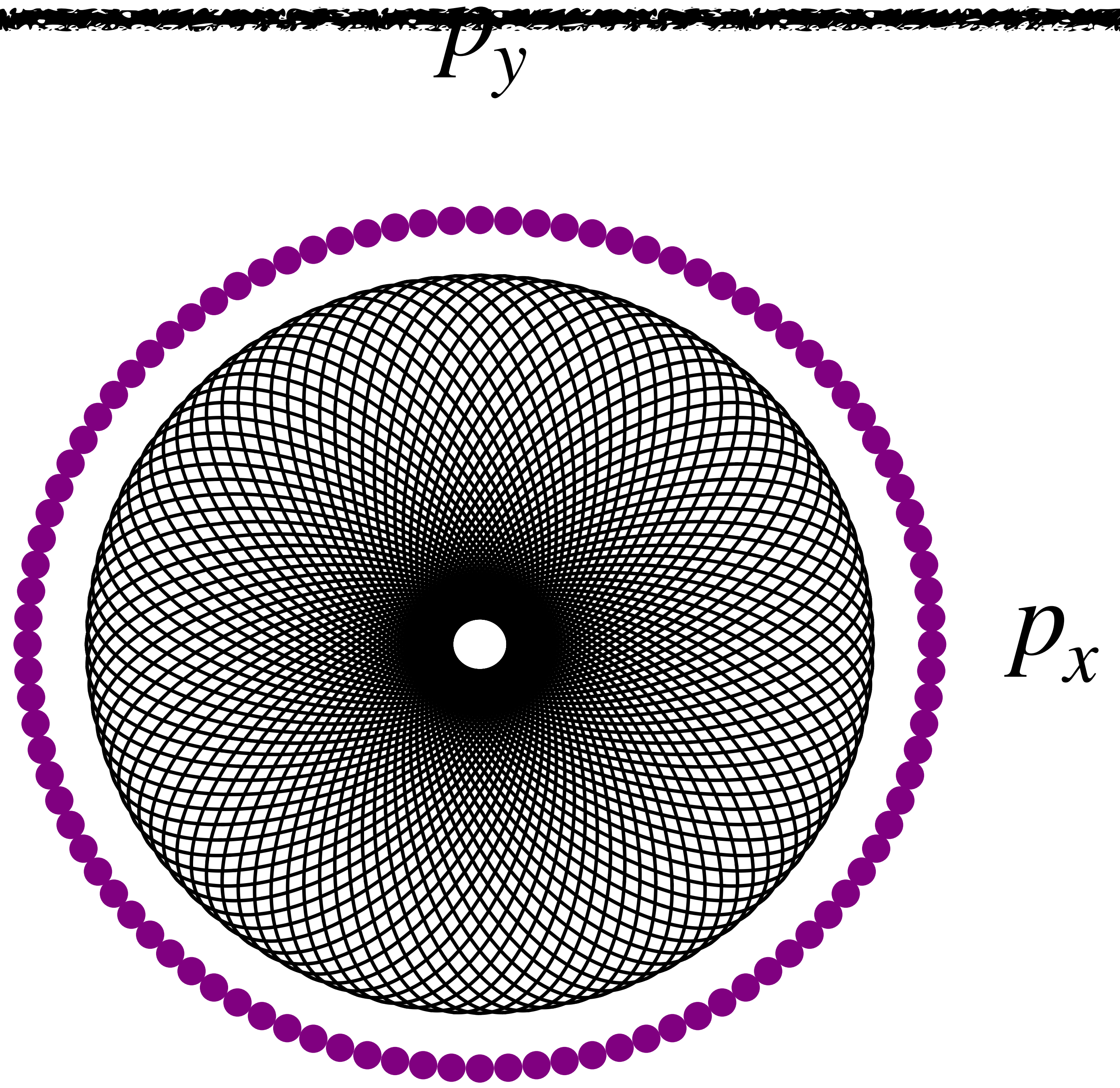
ϕ is burst produced. Later <u>the comoving number density is frozen</u> due to redshift and kinematics.

Simplified model.

$$T \propto a^{-1}$$

$$p_\phi^{\rm DM} \propto a^{-1}$$

$$p_\phi^{\rm burst} \sim M_1^2/T \propto a$$



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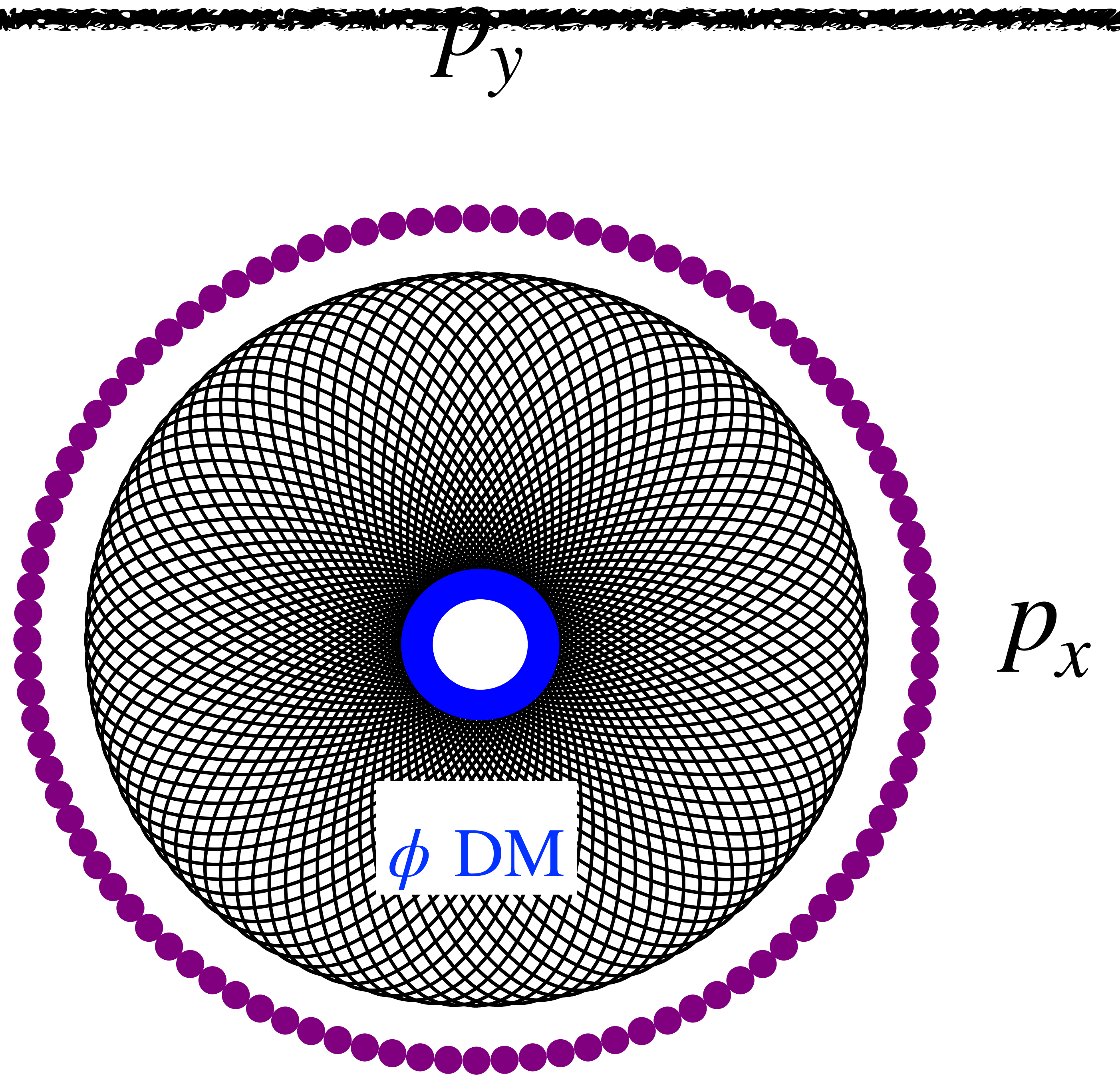

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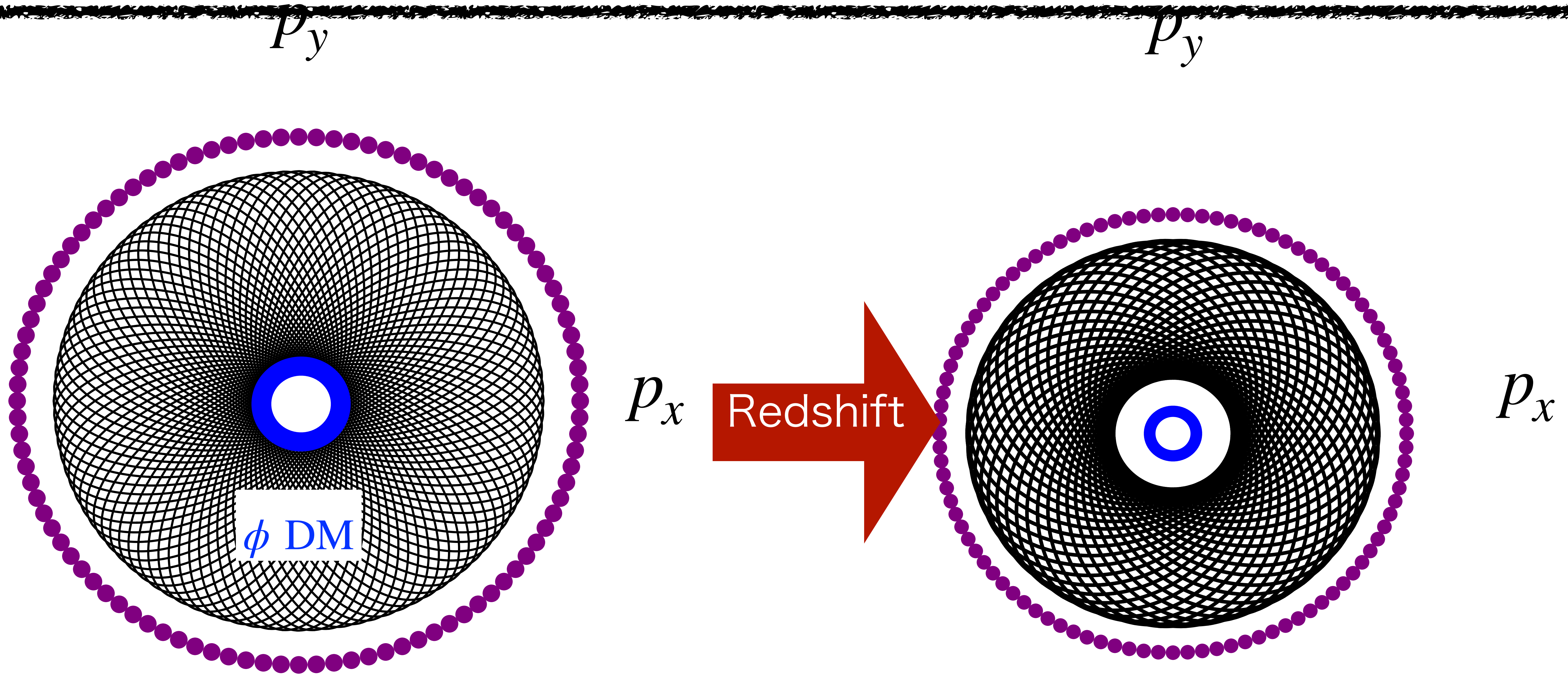
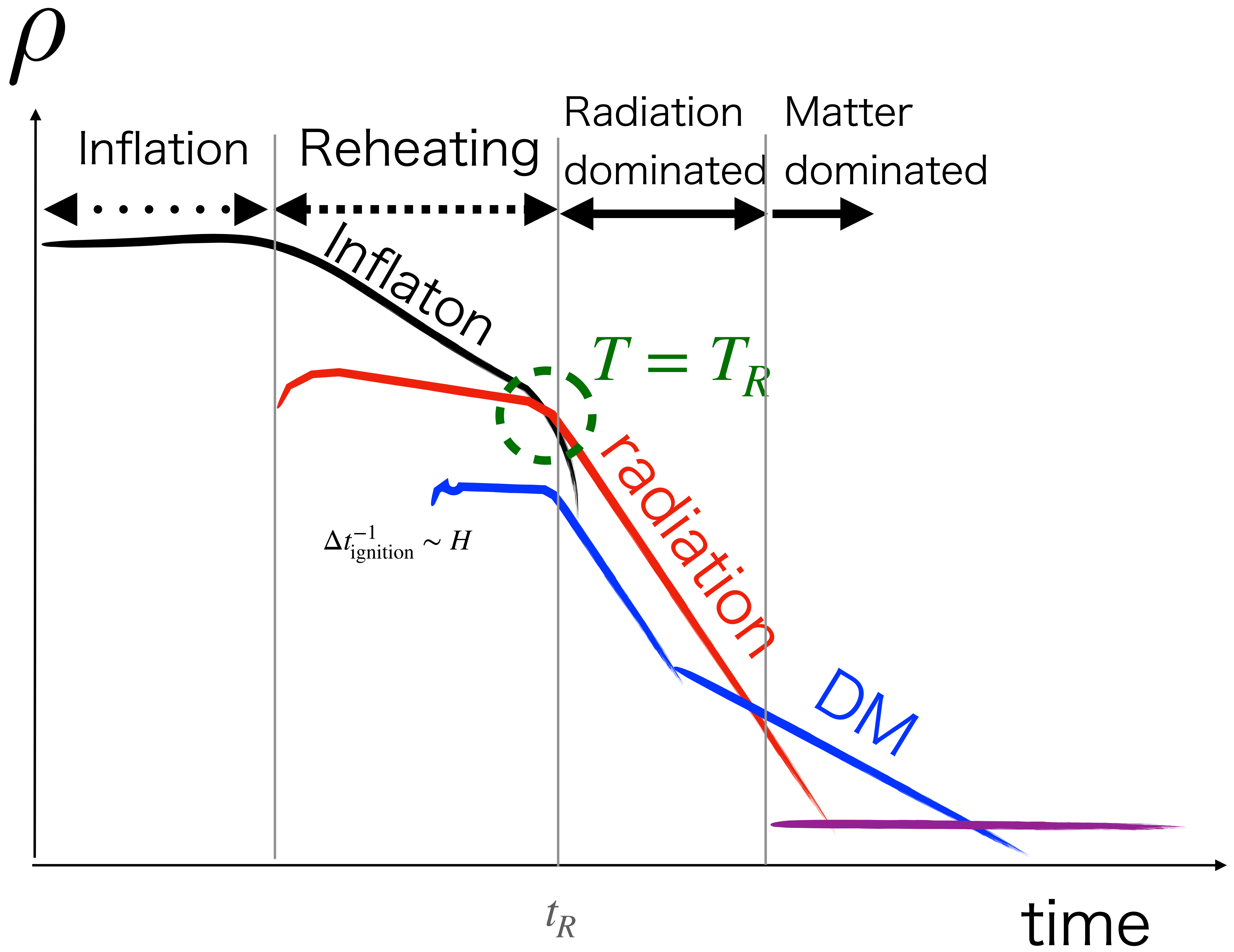


Burst Production during Reheating.

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



- Radiation dominated era:

$$\Delta t_{\rm ignition}^{-1} \propto a^{-3} \quad \text{v.s.} \quad H \propto a^{-2}$$

- Reheating era:

$$\Delta t_{\rm ignition}^{-1} \propto a^{-9/8} \quad \text{v.s.} \quad H \propto a^{-3/2}$$

- The stage 3, saturation, is reached at the end of reheating because $f_{\chi_2}(T)$ is no more diluted.

Alternatively, DM can be burst produced during χ_1 thermalization (i.e. χ_1 is not always thermalized).

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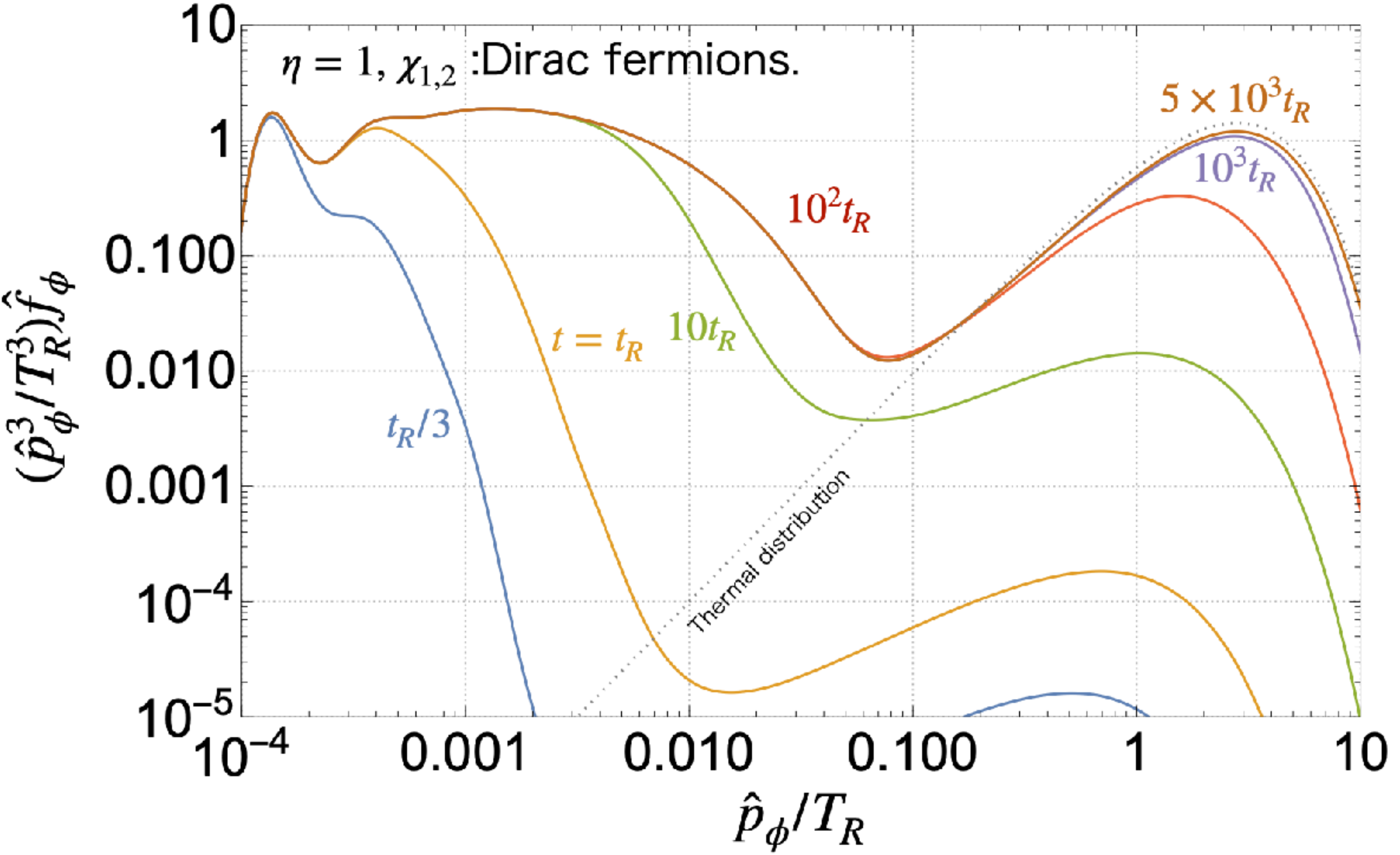

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ϕ is dominantly produced at the end of reheating

$$\because\ n_\phi \sim g_{\chi_2} T_R^3,\ p_\phi \sim M_1^2/T_{\rm R} \ @\ T = T_R$$

Explaining abundance of DM gives

$$m_\phi = 50{\rm eV}\,\frac{4}{g_{\chi_2}}\,\frac{g_{\star,s}[\ T_R\ ]}{100} = [1 - 100]eV$$

Coldness (Lyman α bound $L_{\rm FS} < 0.06{\rm Mpc}$) requires

$$\frac{M_1}{T_{\rm prod}} \lesssim 0.02 \left(\frac{g_{s\star}[T_{\rm prod}]}{100}\right)^{1/6} \sqrt{\frac{m_\phi}{\rm eV}}.$$

Comment: the difference between usual hot DM and burst production with $\chi_1 \leftrightarrow \phi\chi_2$

Usual Hot DM scenario

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

=> eV mass for DM abundance

- Comoving momentum is

$$p_{\rm comoving} \sim a_{\rm prod} T_{\rm prod}$$

=> hot

Burst production

- $\left(\frac{T}{M_1}\right)^3 \Gamma^{\rm (proper)}_{\chi_1\to\chi_2\phi} > H > \frac{M_1}{T}\Gamma^{\rm (proper)}_{\chi_1\to\chi_2\phi}$ at $T = T_R$
- $n_\phi \sim g_{\chi_2} T^3$ from **quasi-equilibrium** of bose-enhancement dynamics

=> eV mass for DM abundance

- Comoving momentum is

$$p_{\rm comoving} \sim a_{\rm prod} M_1^2 / T_{\rm prod}$$

=> cold

How about 2 to 2, e.g. $\chi\chi \to \phi\phi$?

Preliminary results from [Kodai Sakurai, WY, in preparation]

- Depending on the crosssection, Burst production happens: $\sigma \propto \dfrac{s^n}{E_{\chi_1} E_{\chi_2}}$

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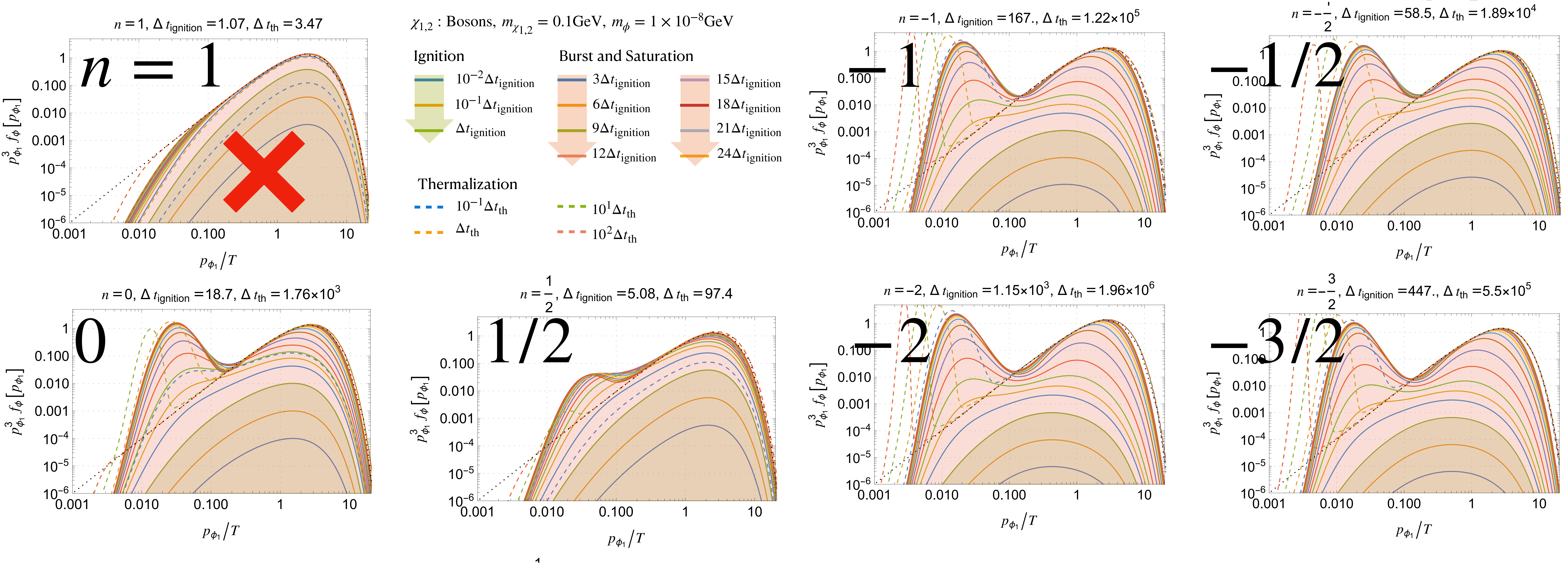

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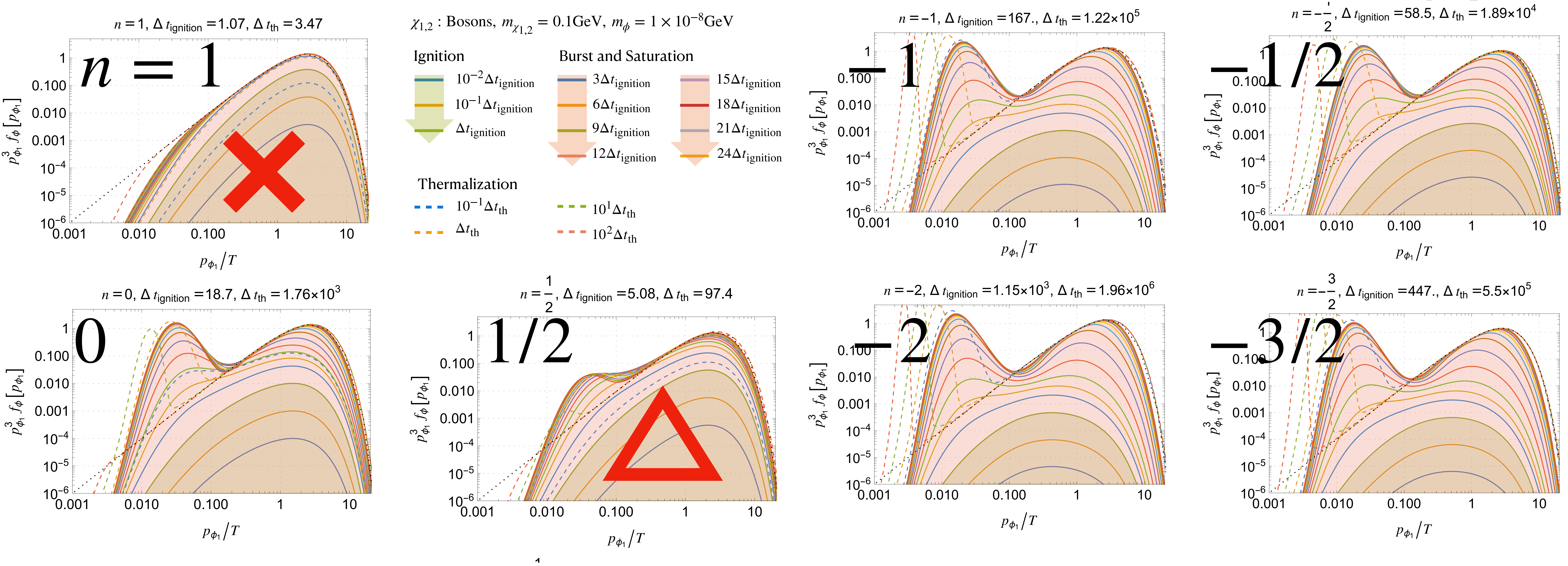

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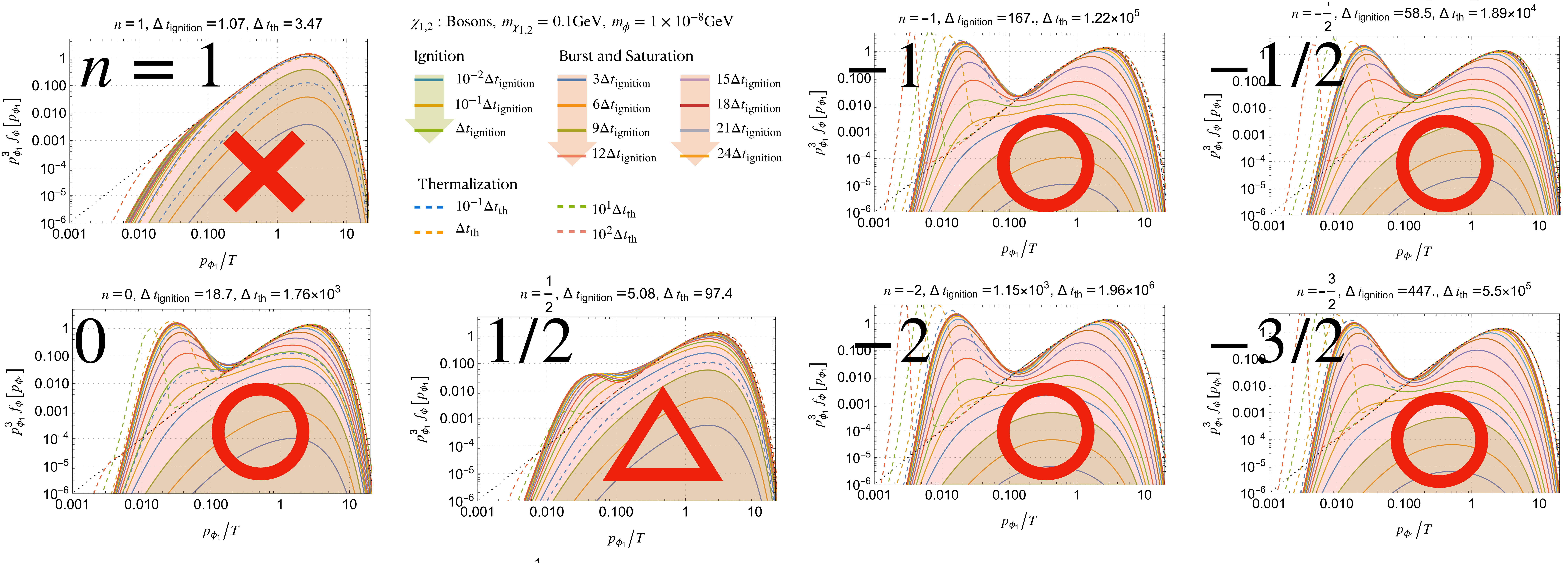


eV ダークマターはやはり特別だった！

3. eV ダークマターの実験的探索

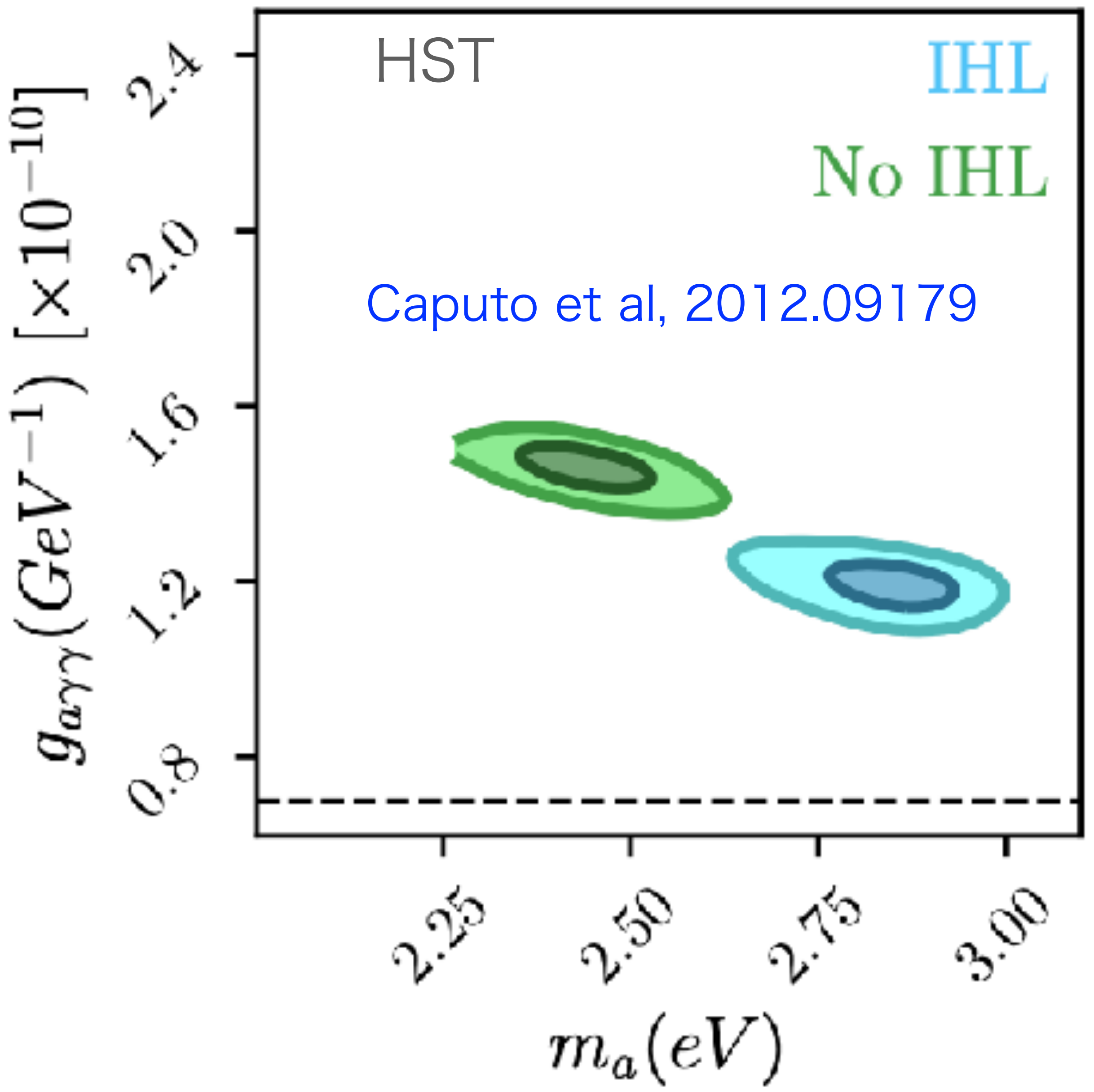
Hints for eV DM:

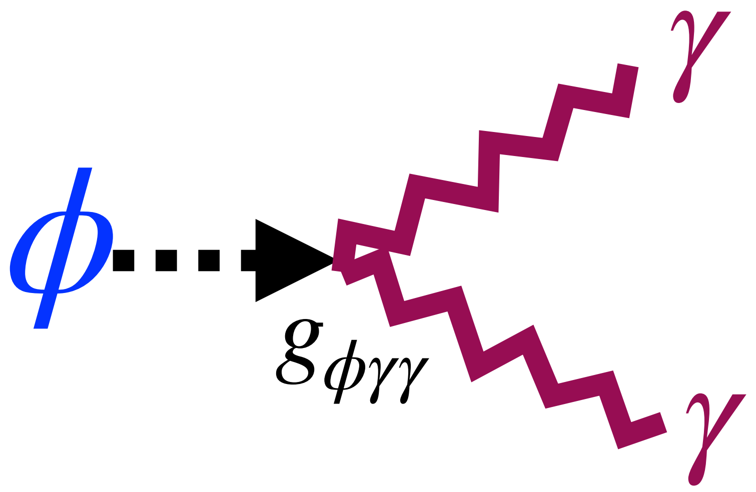
Interestingly, in the huge parameter region, we have coincidences around eV.

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

$m_\phi \sim eV$, lifetime $\sim 10^{16}$yrs

Gong et al 1511.01577



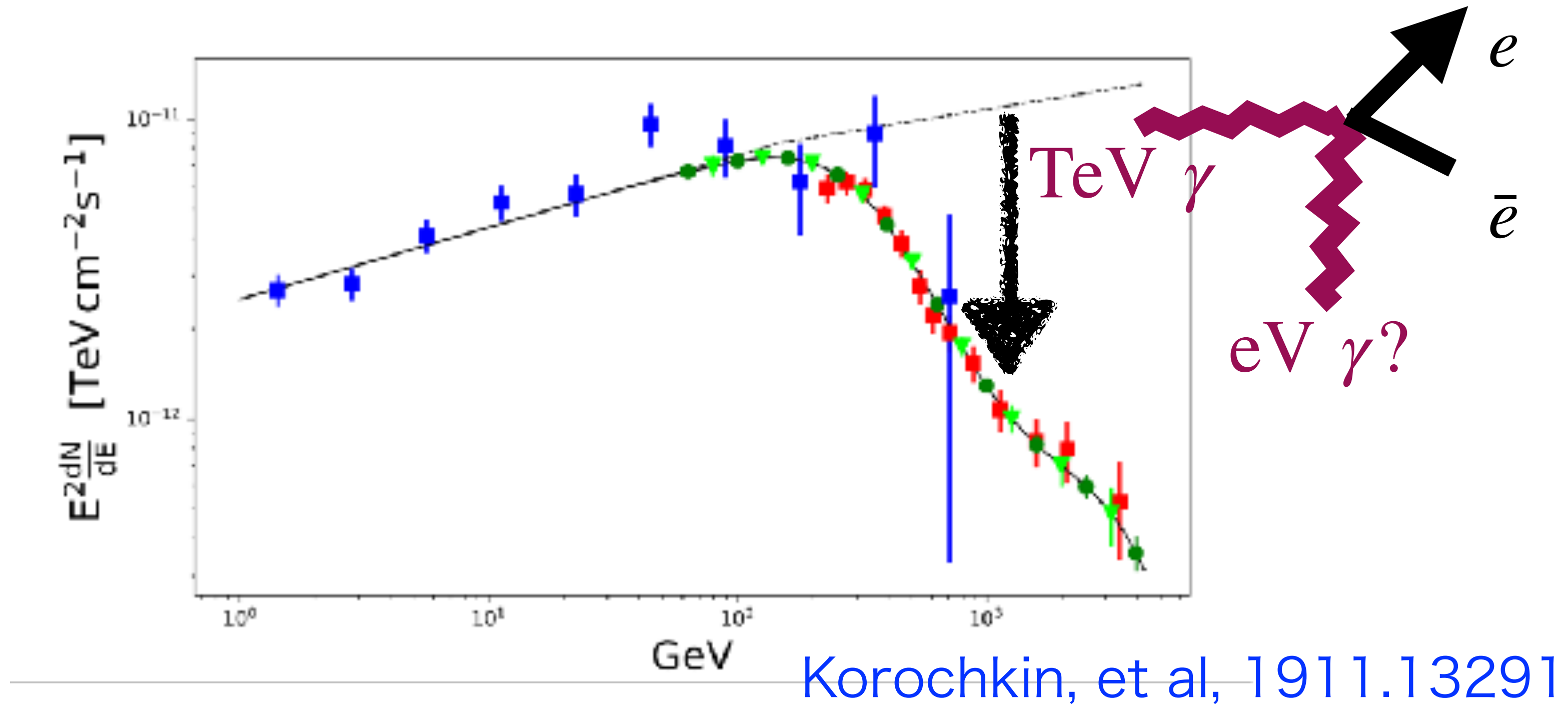


$m_\phi \sim eV$,

lifetime $\sim 10^{16}$yrs

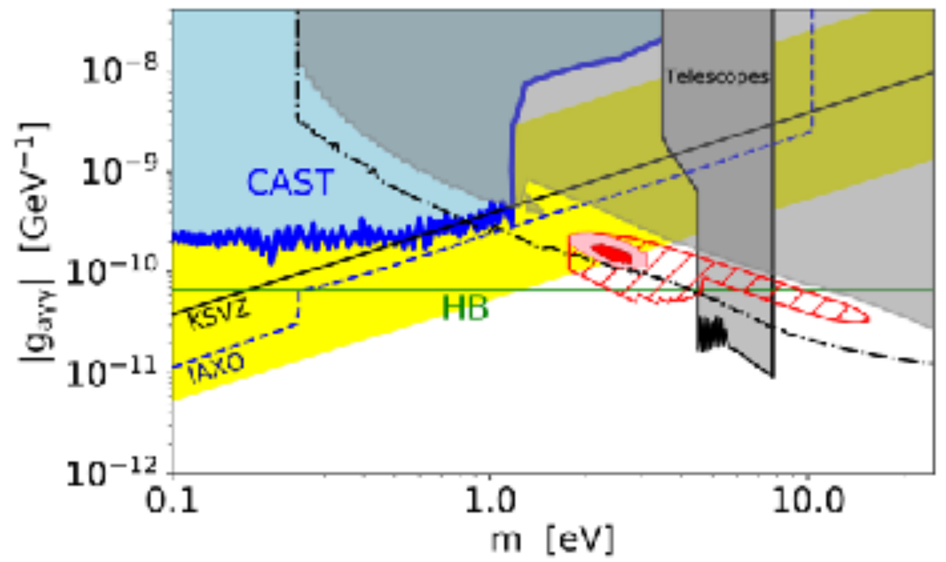
spin=0

The **TeV γ spectrum** gets a better fit by photons from ALP DM of $m_\phi \sim eV$, lifetime $\sim 10^{16}$yrs



Korochkin, et al, 1911.13291

Bernal et al, 2208.13794



Hints for eV DM:

Inte

we

+ Hot DM paradigm

The **anisotr**

background

a decaying

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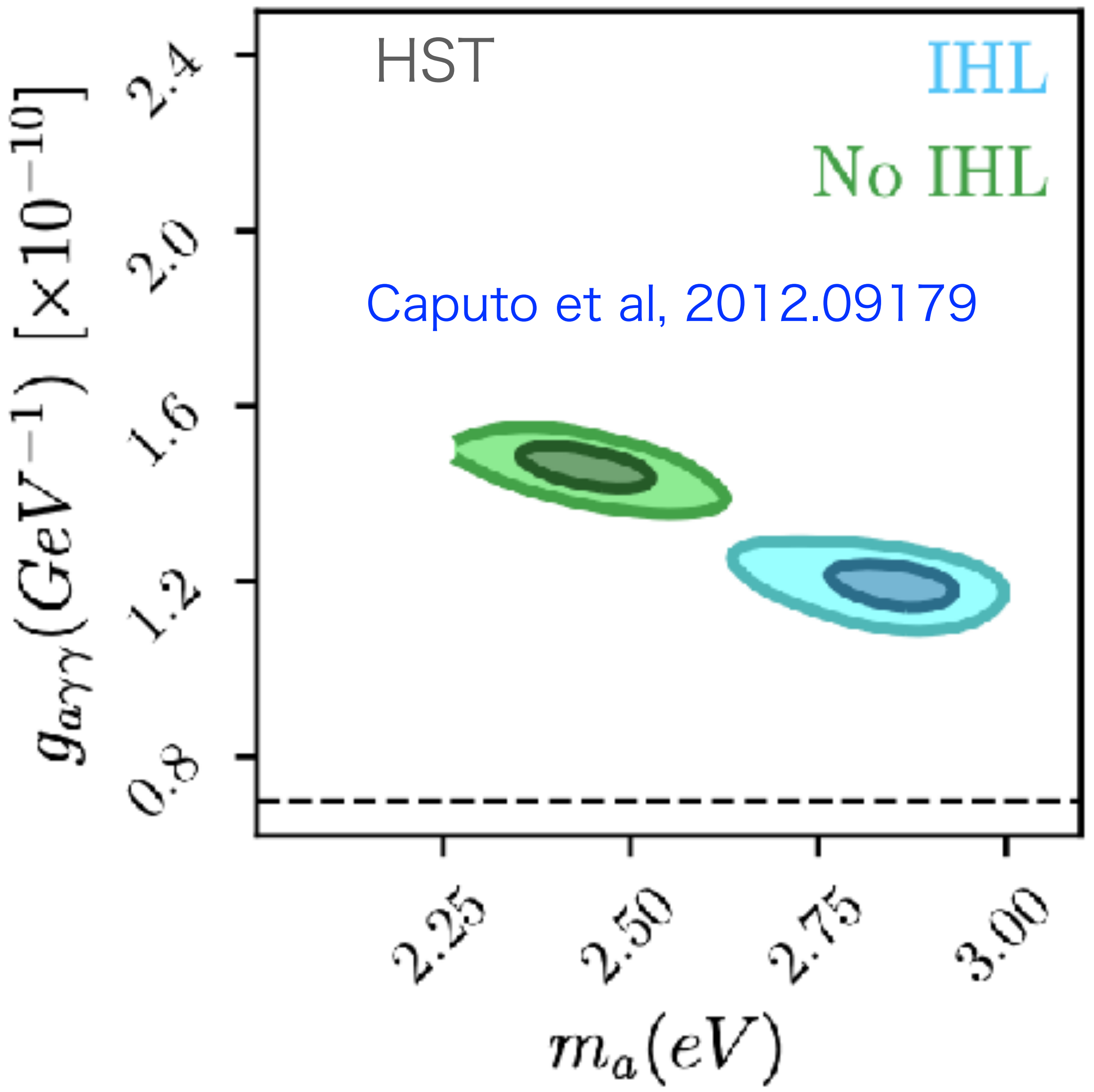

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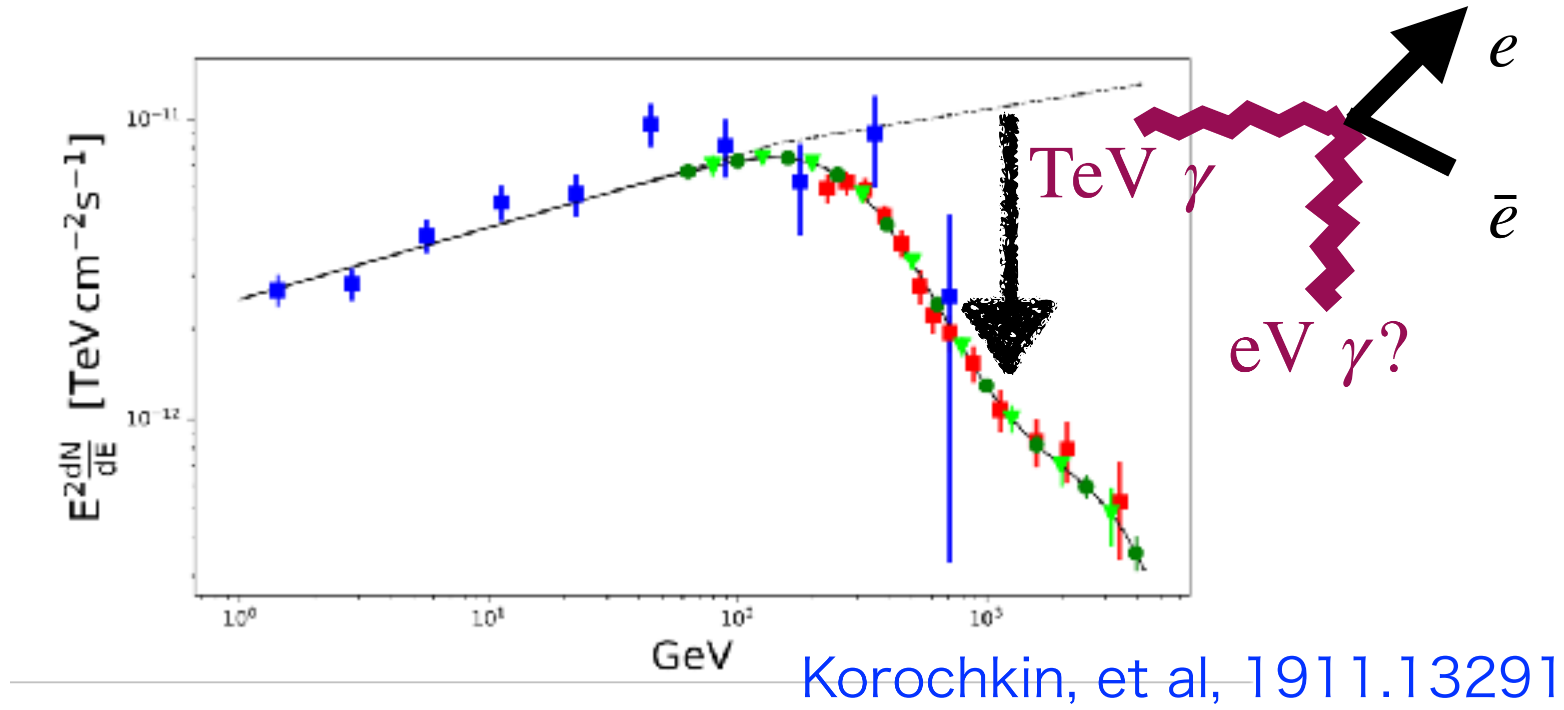

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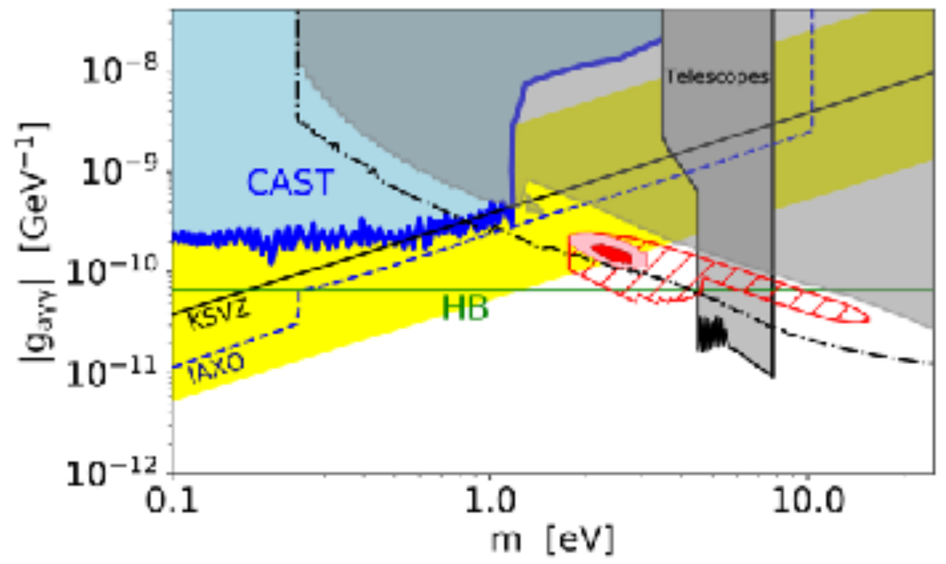


理論があって、観測ヒントもあって、

結構有望じゃね?

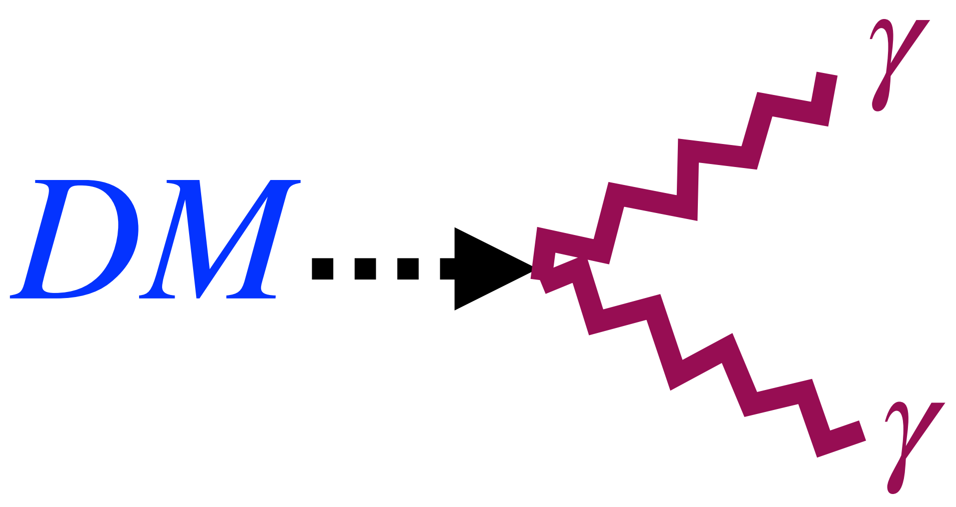
理論があって、観測ヒントもあって、

結構有望じゃね?

残念ながら、eVダークマター特化実験は

あまりない。😞

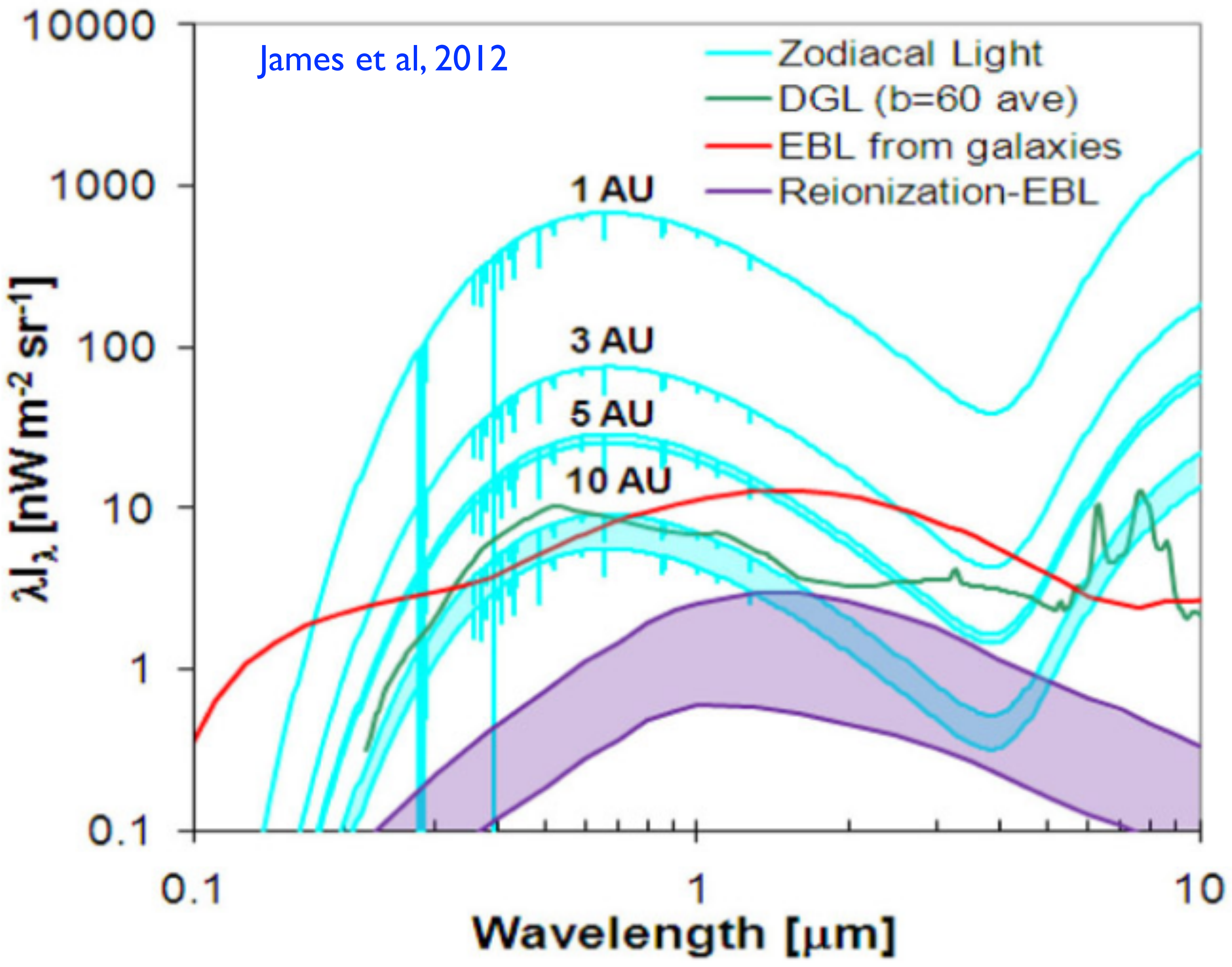
eV DMの間接探索の難しさ、バックグラウンドが多め。



$$E_\gamma \simeq m_{\rm DM}c^2/2 \sim eV \sim hc/\mu\text{m}:$$

(近)赤外線輝線

∵冷たい、銀河周りの存在量がわかっている。

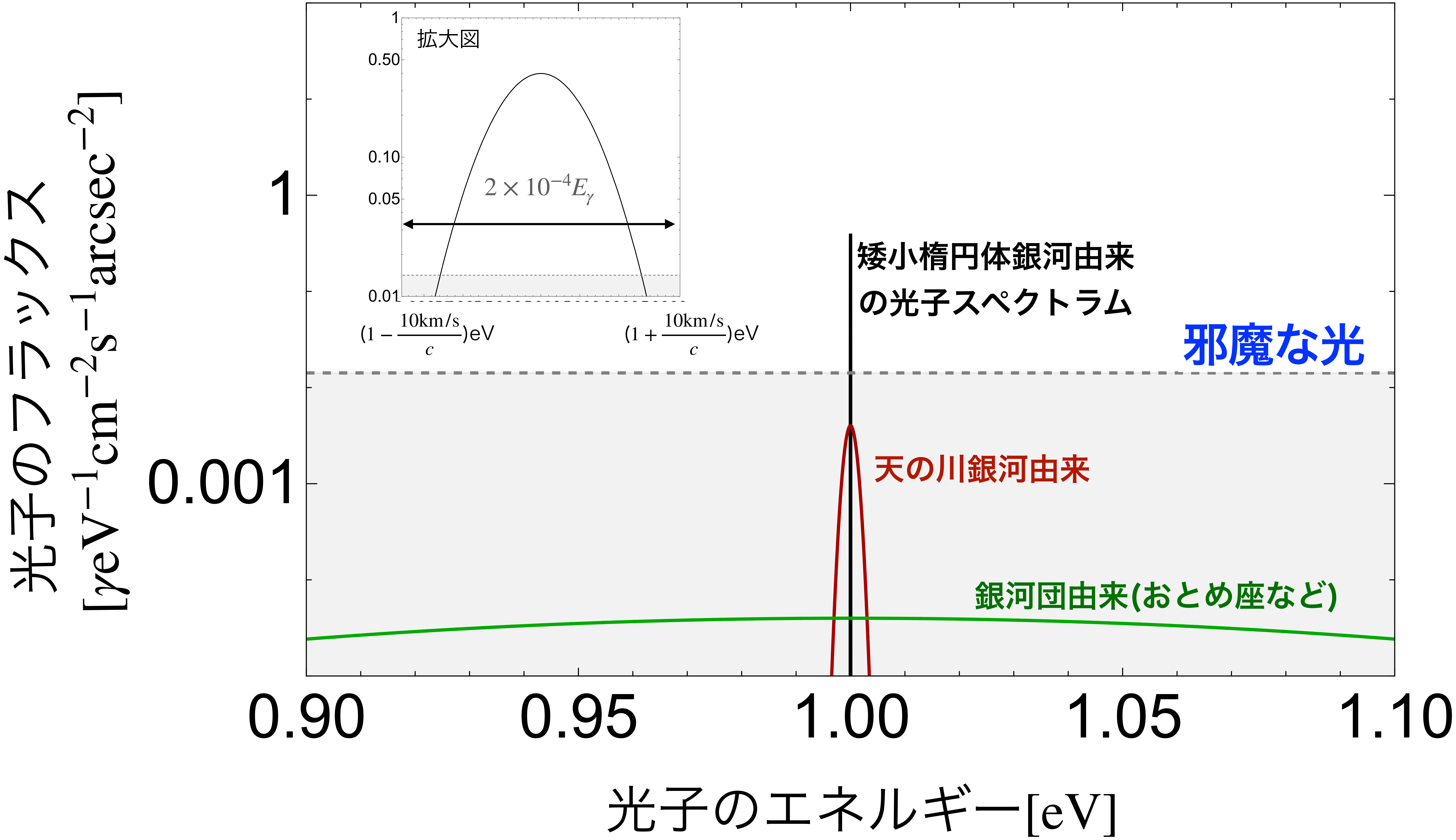


- 銀河まわりから**(近)赤外線狭線幅輝線**を探ることで発見可能。
- 従来では、黄道光、熱輻射などのバックグラウンドが著しいため、探索は困難。

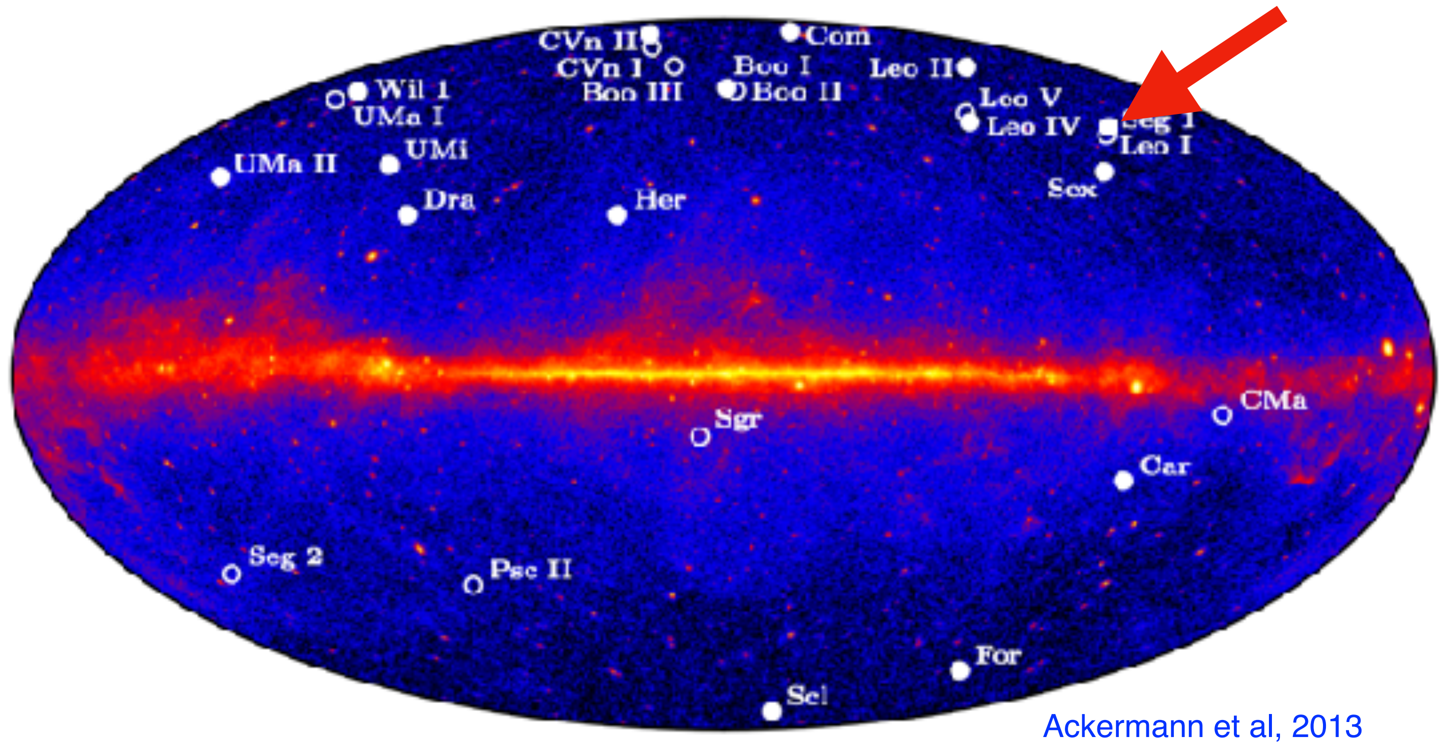
ダークマター由来の光は狭線幅輝線！超尖ってる。
十分な波長分解能があれば邪魔な光は無視できる。

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

暗黒物質の質量 = 2eV, 光子結合 = 10^{-10}GeV^{-1}



eV DM search with WINERED @ Magellan

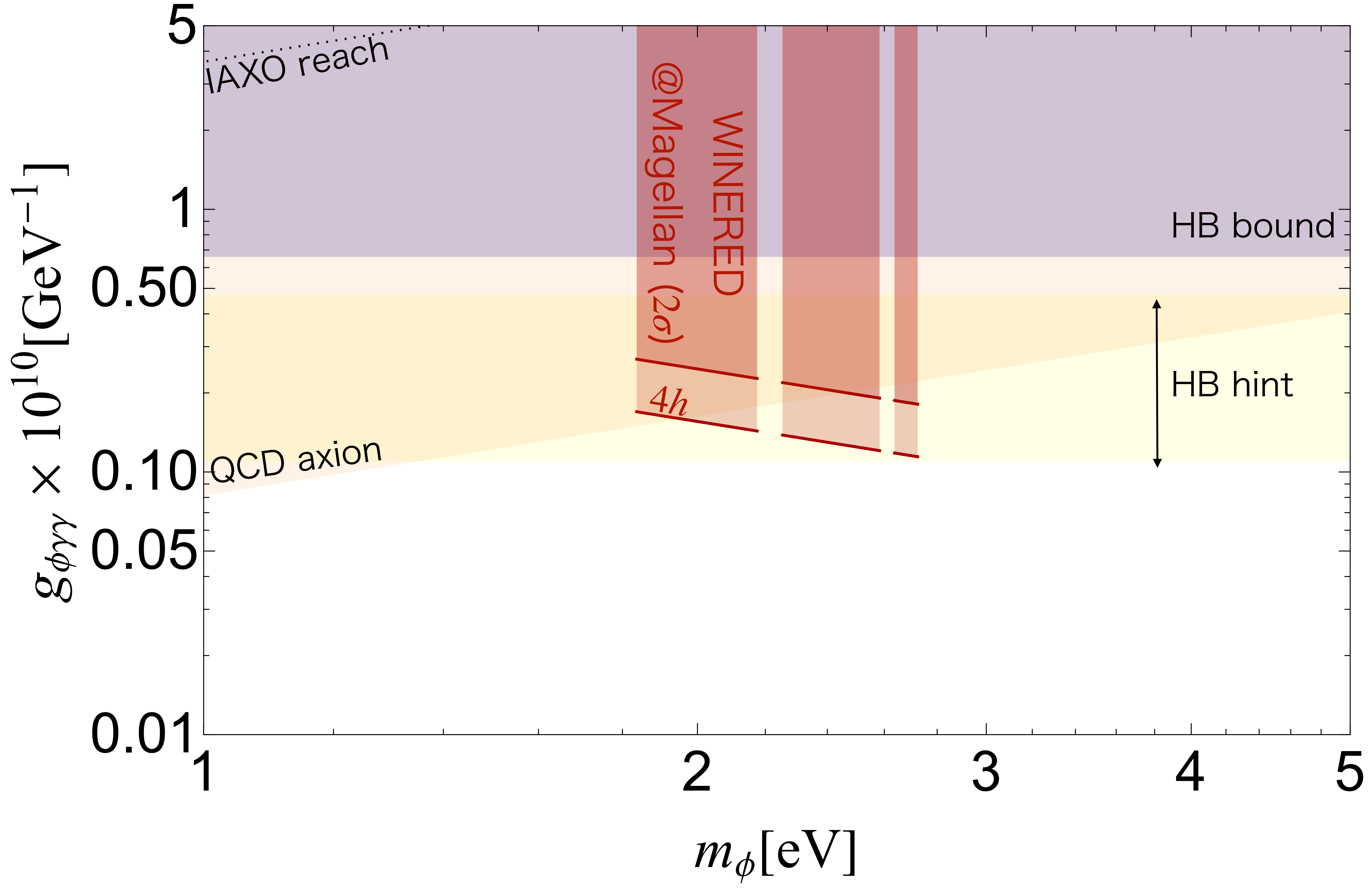


Ackermann et al, 2013

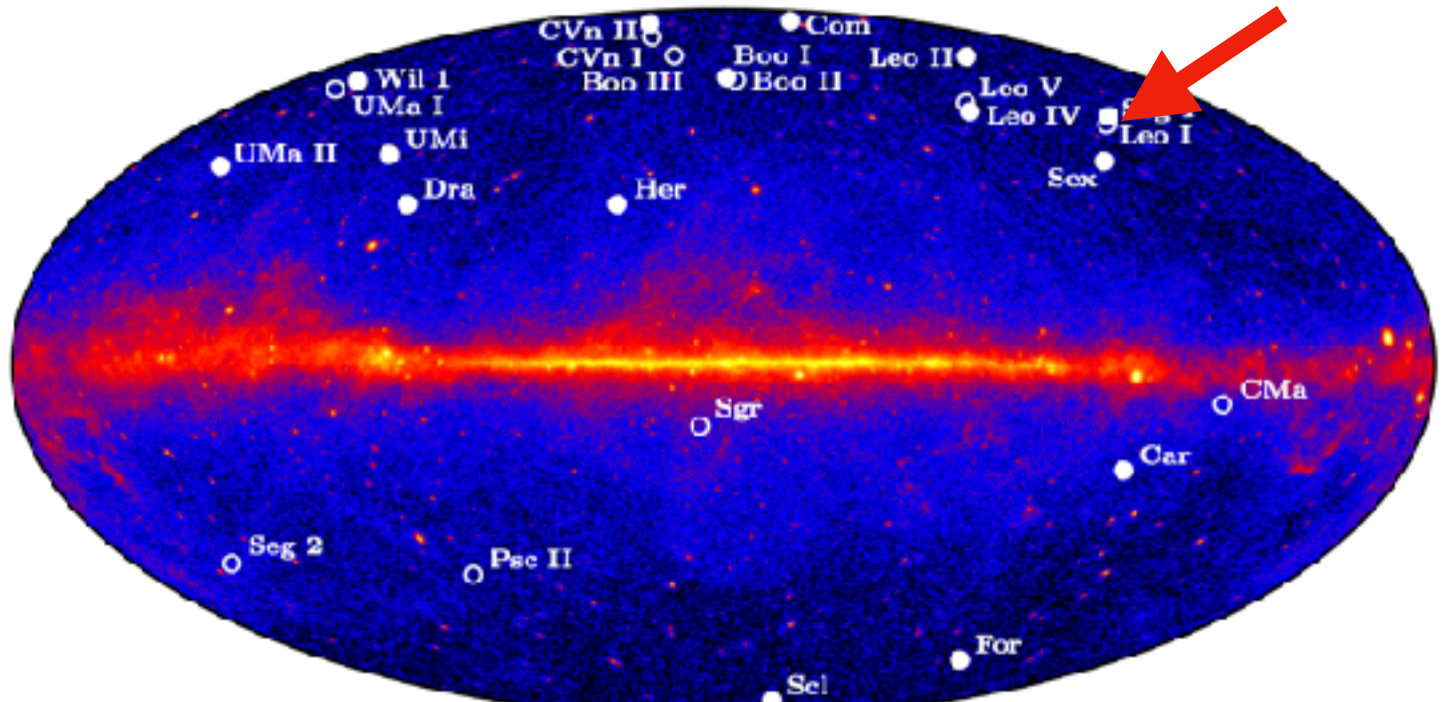
https://www.cfa.harvard.edu

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

$\lambda/\delta\lambda \sim 30000$ T. Bessho, Y. Ikeda, WY, 2208.05975



eV DM search with NIRSpec @ JWST

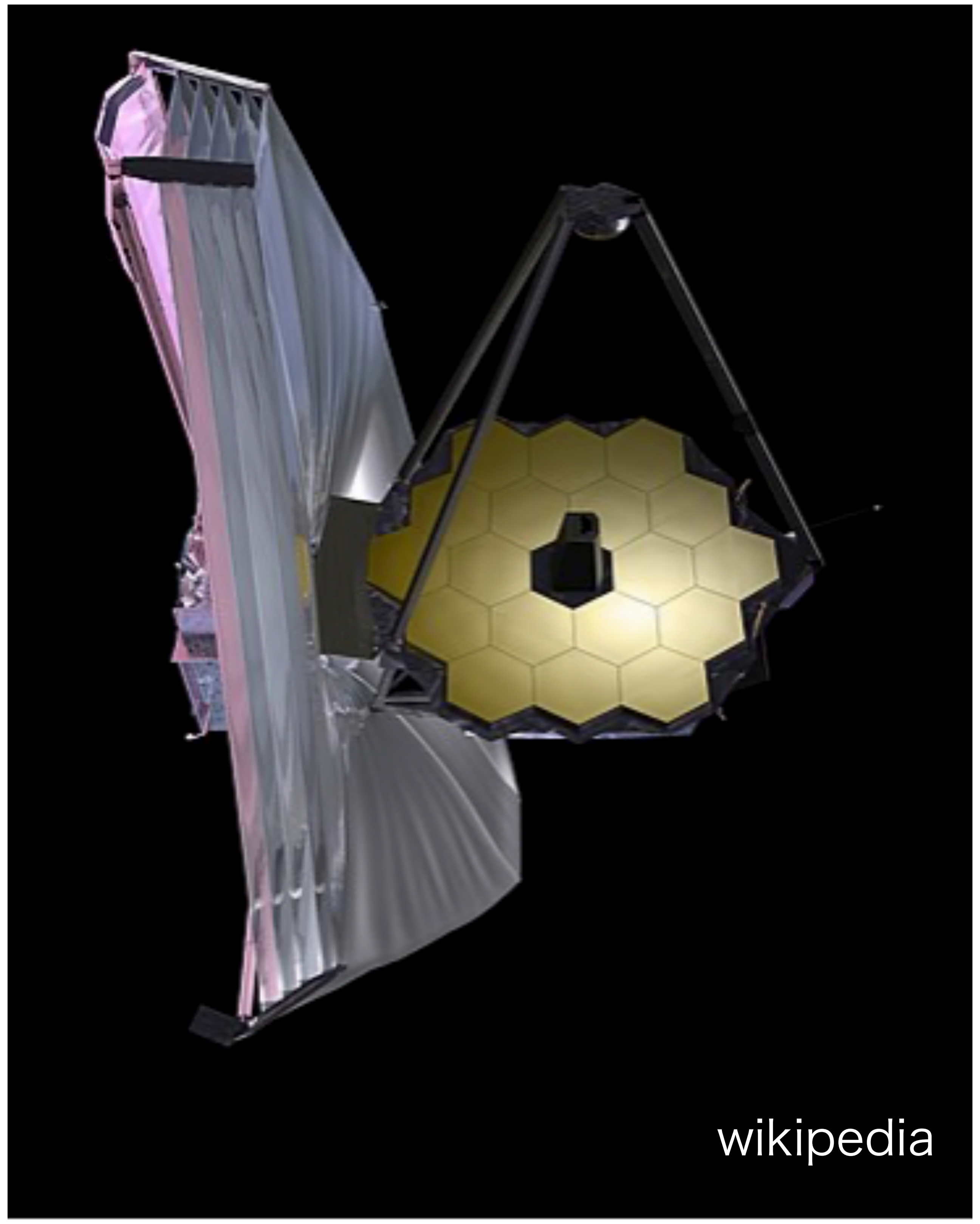


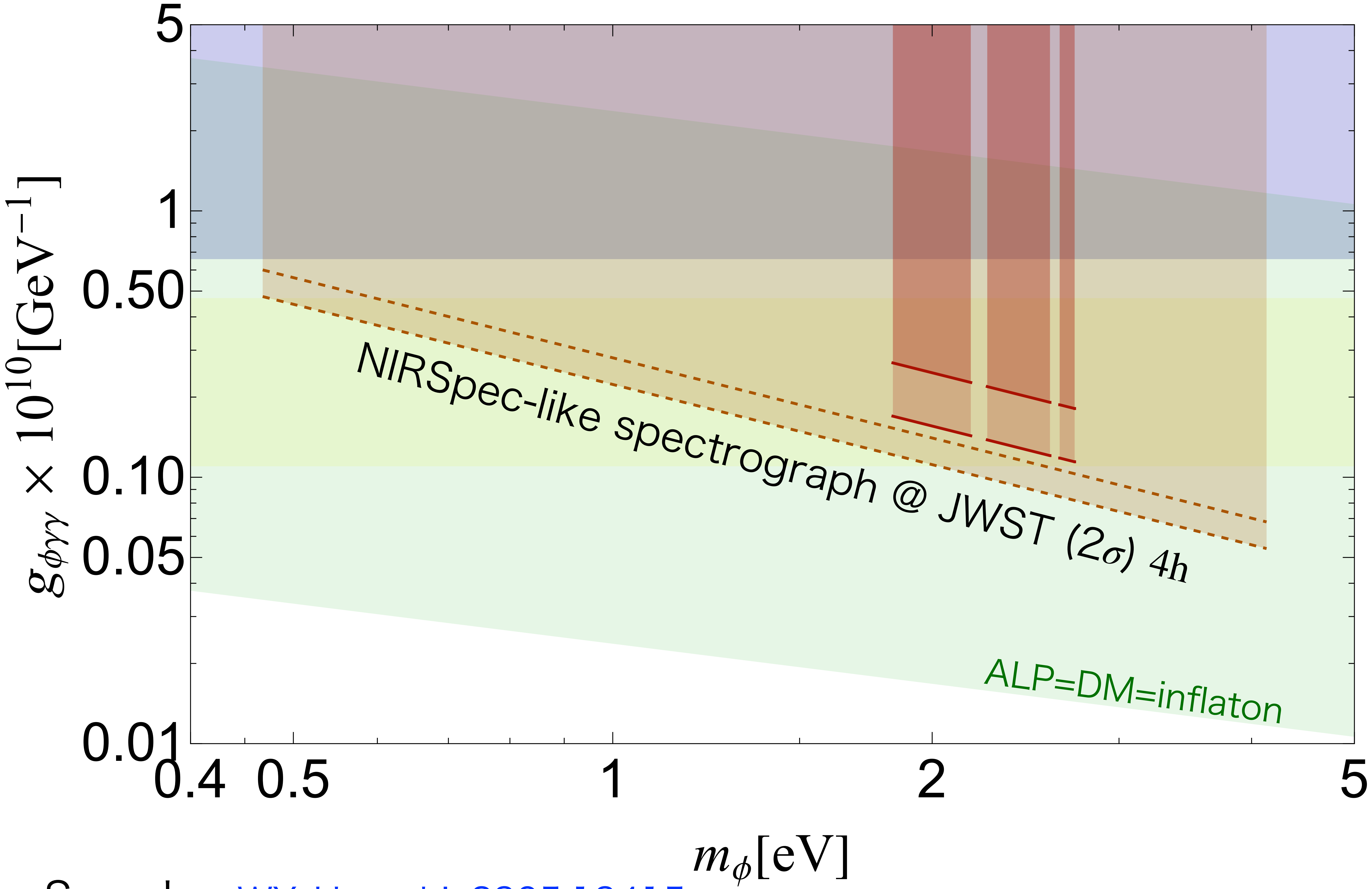
Ackermann et al, 2013

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

$\lambda/\delta\lambda \sim 3000$ T. Bessho, Y. Ikeda, WY, 2208.05975

See also Janish, Pinetti, 2310.15395, Roy et al, 2311.04987 with blank sky data,





See also WY, Hayashi, 2305.13415 for IRCS at Subaru

What we have observed

Based on proposals "eV-Dark Matter search with WINERED", Jun 2023, PI. WY Co-I. Ikeda, Bessho
"eV-Dark Matter search with WINERED", Nov 2023, PI. WY Co-I. Ikeda, Bessho

WY, Ikeda, Bessho, Kobayashi+WINERED team, 2402.07976

Table. I. Obervation logs. Here, Regions 1, 2, and 3 are for Leo V, Tucana II, and Tucana II, respectively.
resolution. T_I denotes the total integration time. Simbad, Inger et al 0002110

Object name	Object type	RA(J2000)	DEC(J2000)	Obs. date	J_m	R	T_I (sec)
Leo V	dSph	11:31:09.6	+02:13:12	2023.06.06	–	28,000	3600
Tucana II	dSph	22:51:55.1	-58:34:08	2023.11.02	–	28,000	4200
Sky region 1	–	11:31:56.97	+02:09:19	2023.06.06	–	28.000	1800
Sky region 2	–	22:51:06.5	-57:28:46	2023.11.02	–	28,000	1200
Sky region 3	–	22:38:08.1	-58:24:39	2023.11.02	–	28,000	1200
HD134936	A0V	15:14:41.4	-52:35:42	2023.06.06	9.44	28,000	90

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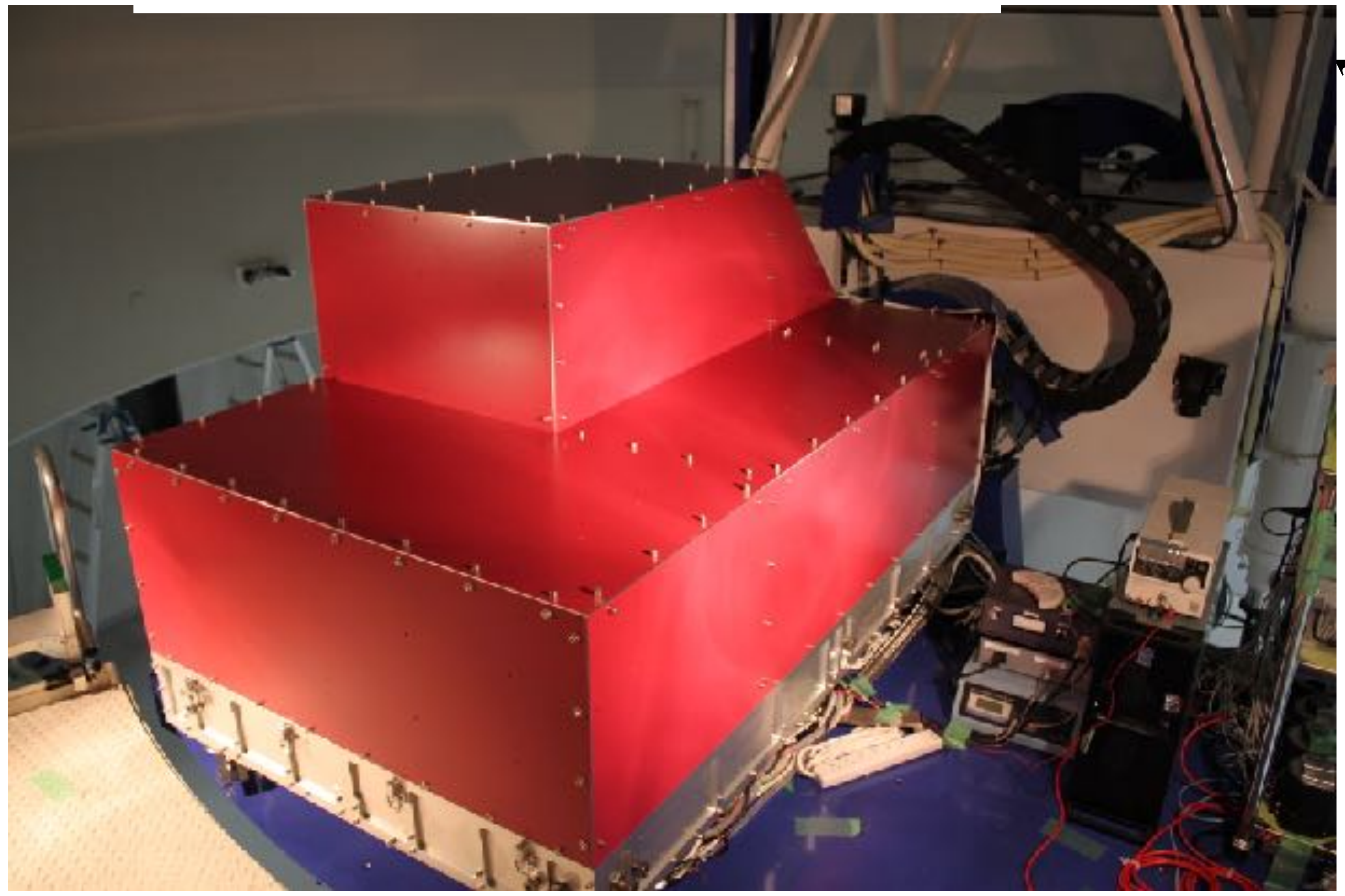
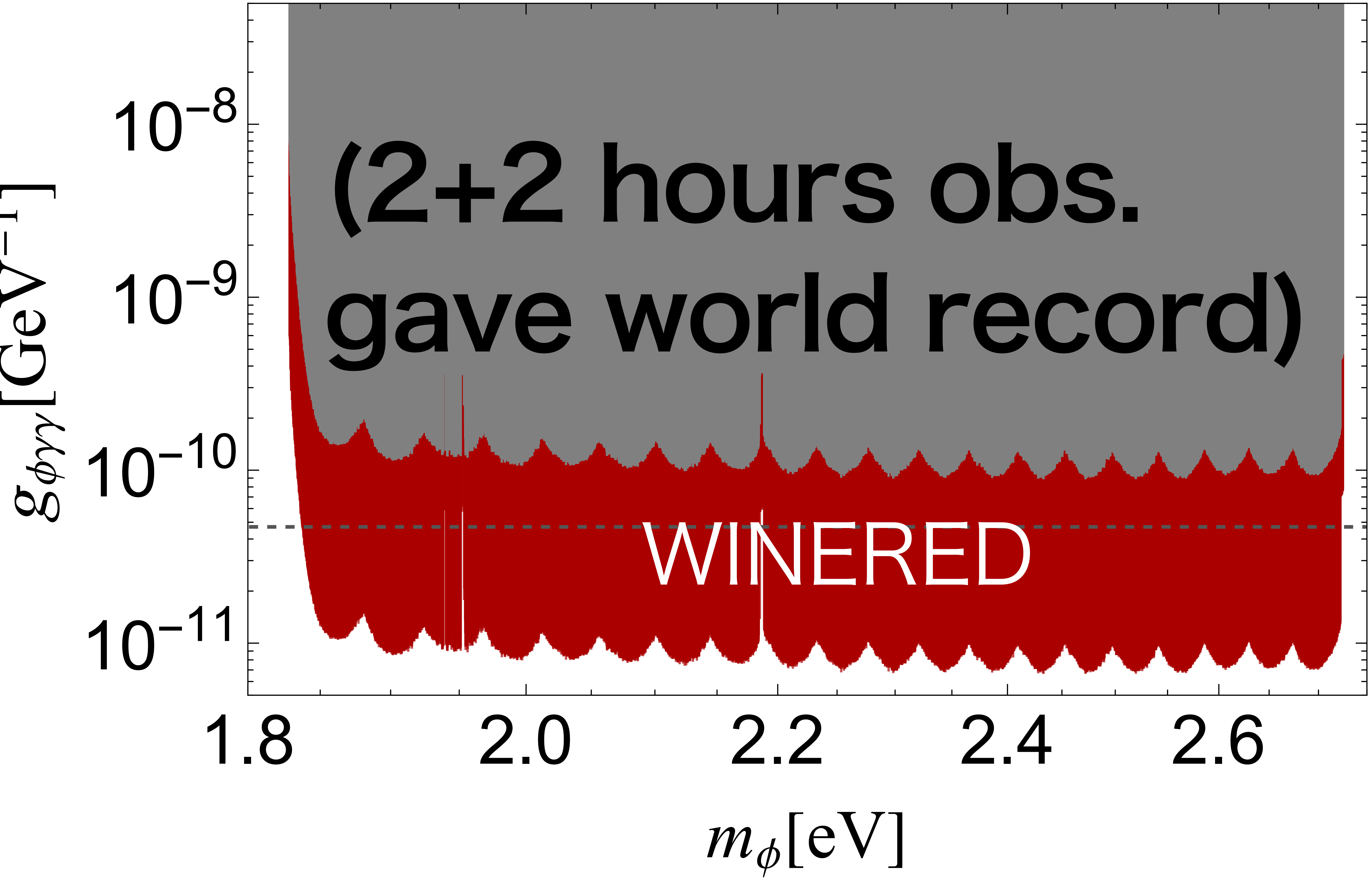
Result: subtracting continuous spectra (Only apply to line spectra)

WY, Ikeda, Bessho, Kobayashi+WINERED team, 2402.07976



Ikeda et al 2006



• 4. Future prospects

-超絶感度に向けて-

ダークマター高分散分光観測の弱点

- これ以上は結構むずい。競争率高い。
  時間制限がえぐい (c.f. 4時間の観測 v.s. WIMP search O(1)年)。

・“eV-Dark Matter search with WINERED”, May 2024, PI. WY Co-I. Ikeda, Bessho, Kobayashi は天候の都合によりキャンセル 😢…

- どうする？

赤外分光によるダークマター探索はまだ本気じゃない。

- 既存の高分散分光器（の望遠鏡）は恒星の物理が主要目的で、
  超高い**空間分解能**$O(0.1)$arcsecを持つように設計されている。

- ダークマターは銀河中に広がっているので、
  空間分解能いらない。

- 改良の余地がある。

DRAGON BALL Z, A. Toriyama

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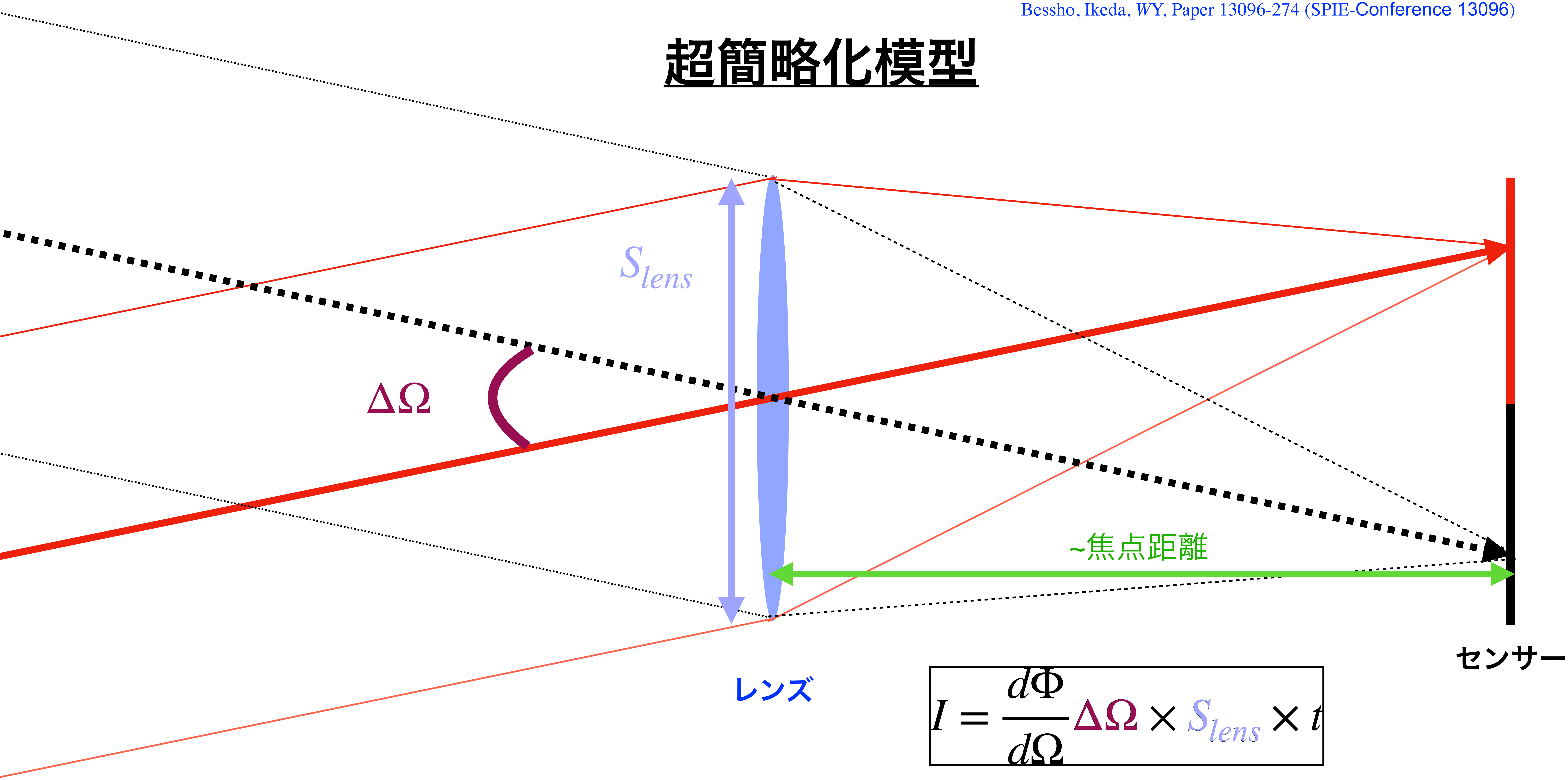
DRAGON BALL Z, A. Toriyama

eVダークマター特化分光器を開発しちゃえ!

・光学系の空間分解能と明るさと大きさ

Bessho, Ikeda, *WY*, Paper 13096-274 (SPIE-Conference 13096)

超簡略化模型

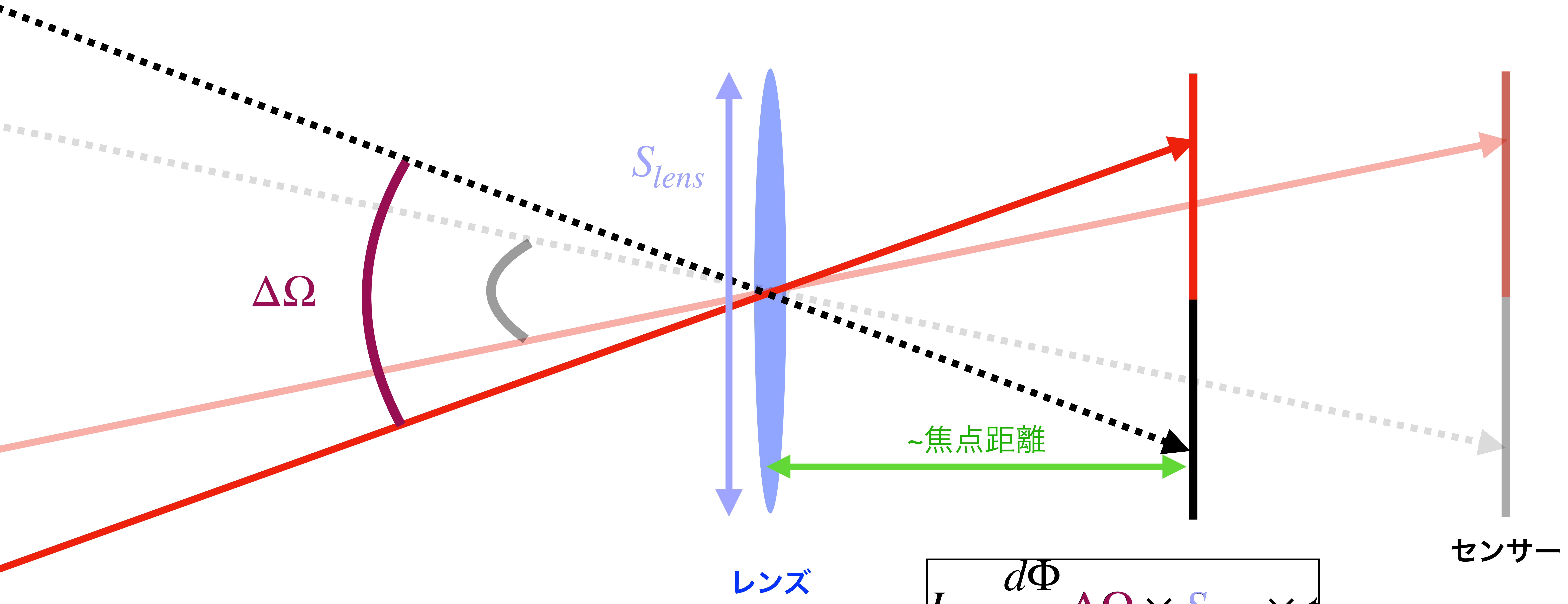


$$I = \frac{d\Phi}{d\Omega}\Delta\Omega \times S_{lens} \times t$$

•光学系の空間分解能と明るさと大きさ

Bessho, Ikeda, *WY*, Paper 13096-274 (SPIE-Conference 13096)

焦点距離↘空間分解能↘視野↗∴**明るさ**↗**(光源の角度依存性がない場合)**



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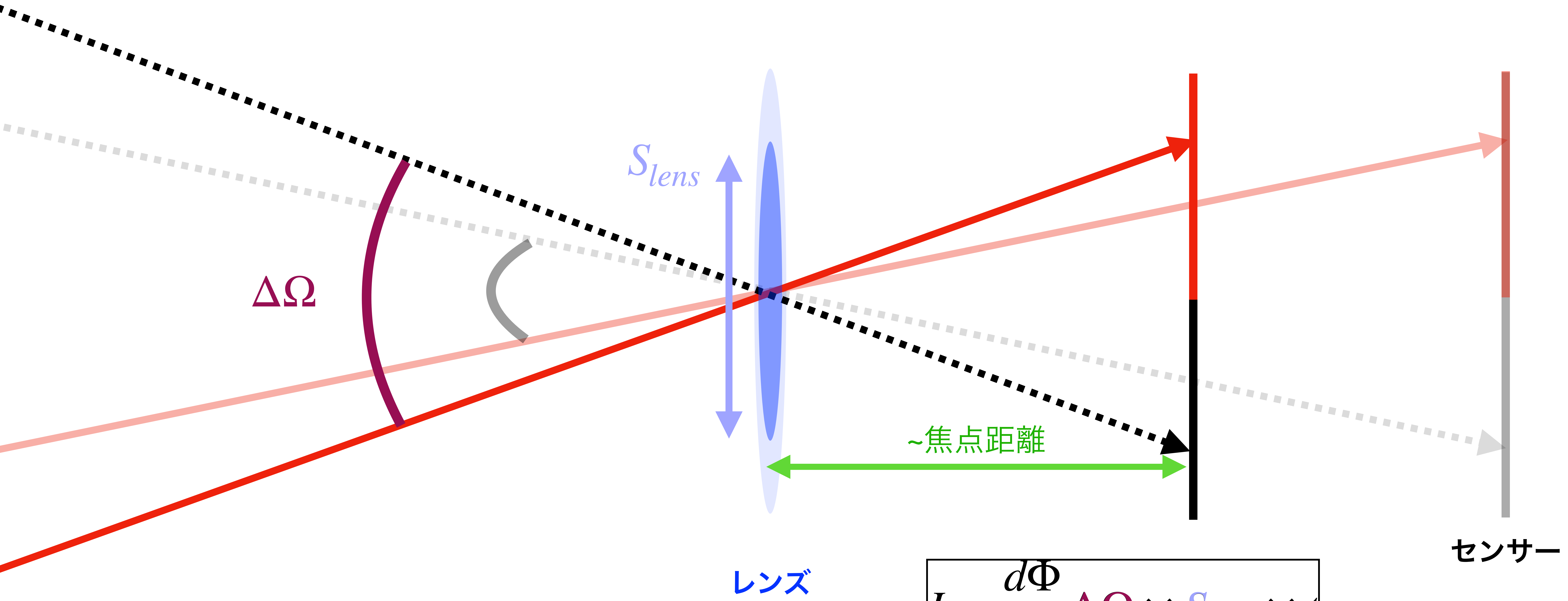

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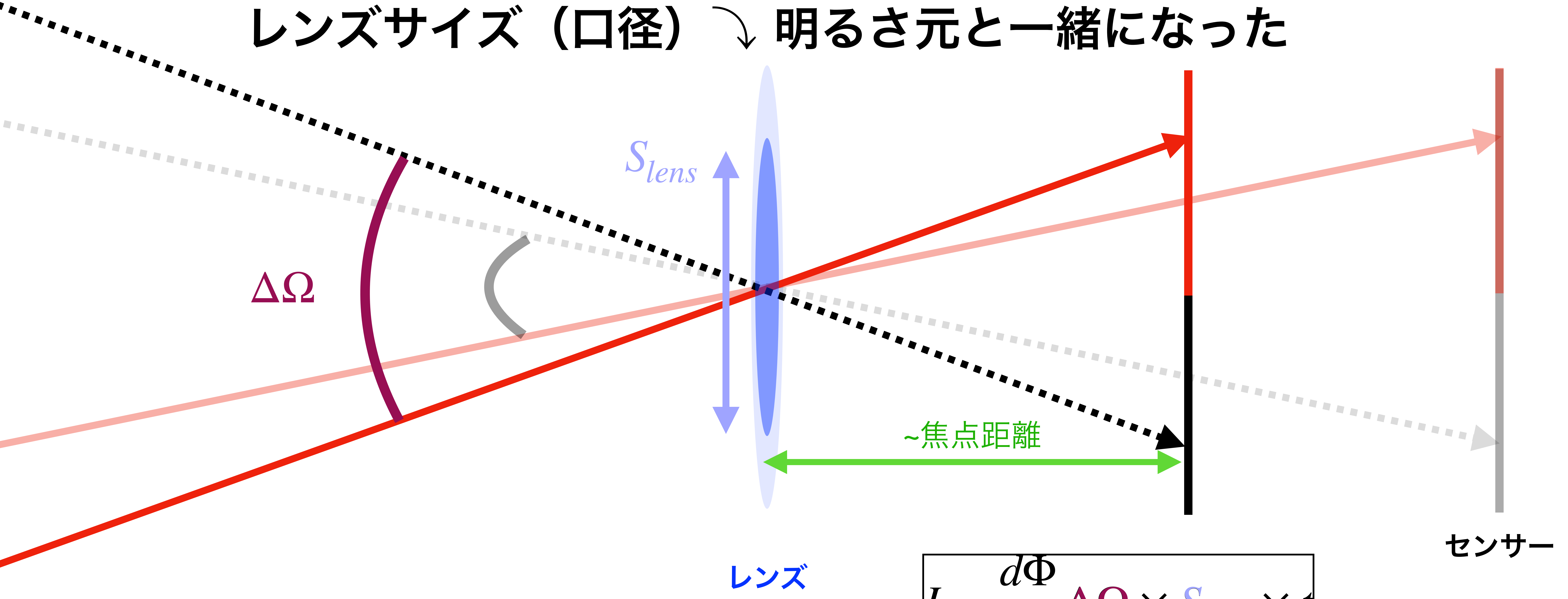
レンズサイズ（口径）↘ 明るさ元と一緒になった



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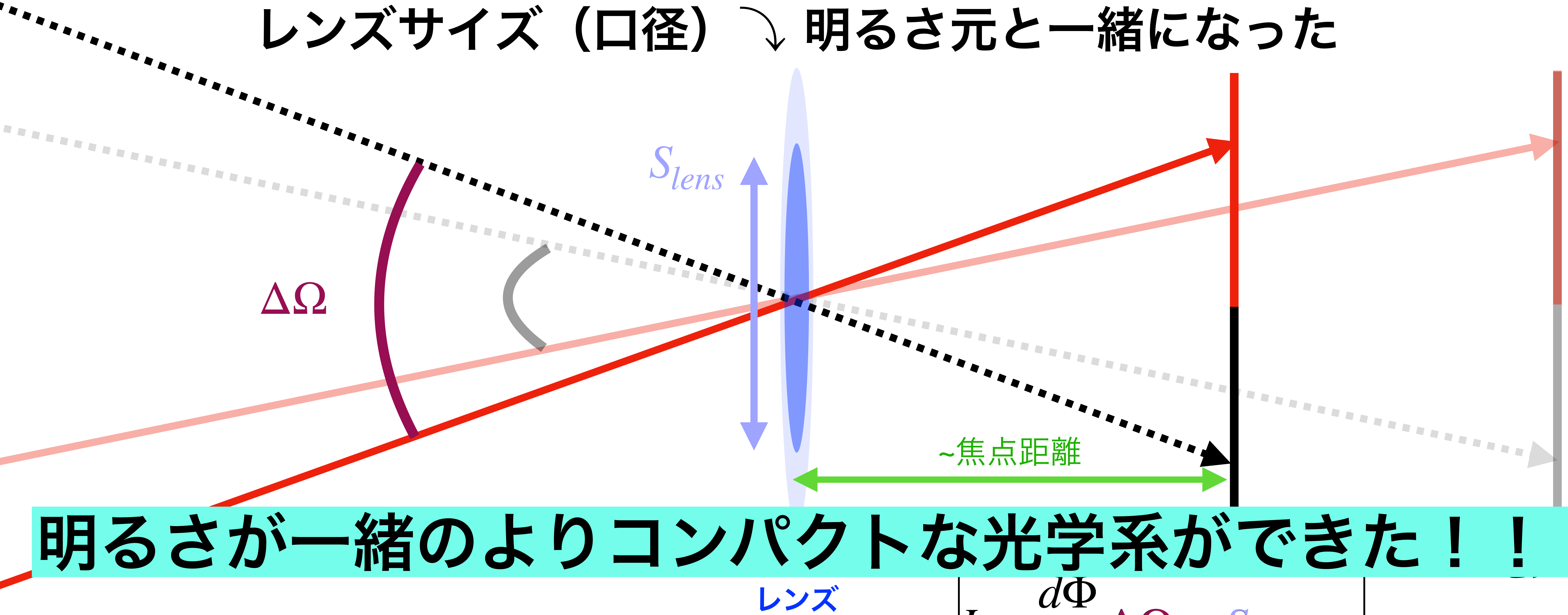

明るさが一緒のよりコンパクトな光学系ができた！！！

$$I = \frac{d\Phi}{d\Omega}\Delta\Omega \times S_{lens} \times t$$

Dark Matter Quest Spectrograph(DMQS)

Bessho, Ikeda, *WY*, Paper 13096-274 (SPIE-Conference 13096)

<1m 口径の望遠鏡に搭載可能なダークマター特化型高分散分光器の設計

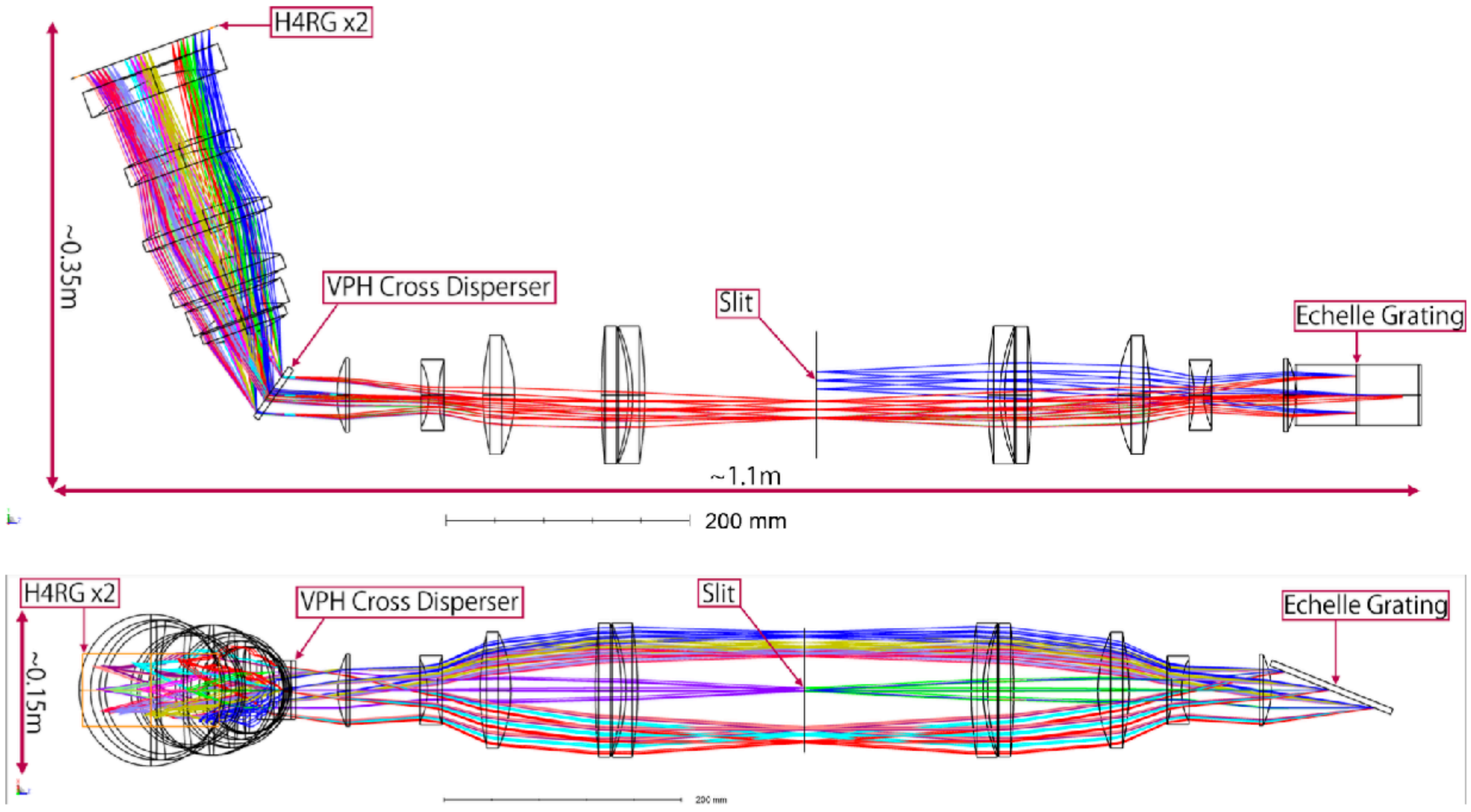

Figure 3. The top and front views of the optical layout of the high-resolution mode of the DMQS

C.f. 最先端天文望遠鏡
マゼラン6.5m口径
JWST6.5m口径
すばる8.3m口径
TMT30m口径（将来）

最先端ではなくなってしまったすべての小口径望遠鏡へ：ダークマター観測をするのだ！

Conclusions:

- 「熱生成によるDMの典型的運動量は温度くらい」は誤り。ボーズ統計の効果。
- ホットDMのような模型でeVを予言しつつ、冷たくする可能性がある。
- eV DMが輝線に崩壊する場合、その探索に、赤外線分光器は有効的！新探索結果と新技術に乞うご期待！