# eV Dark Matter and Experimental Searches



TOKYO METROPOLITAN UNIVERSITY
東京都立大学

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@The 12th KIAS Workshop on Particle Physics and Cosmology, 20 Nov. 2024

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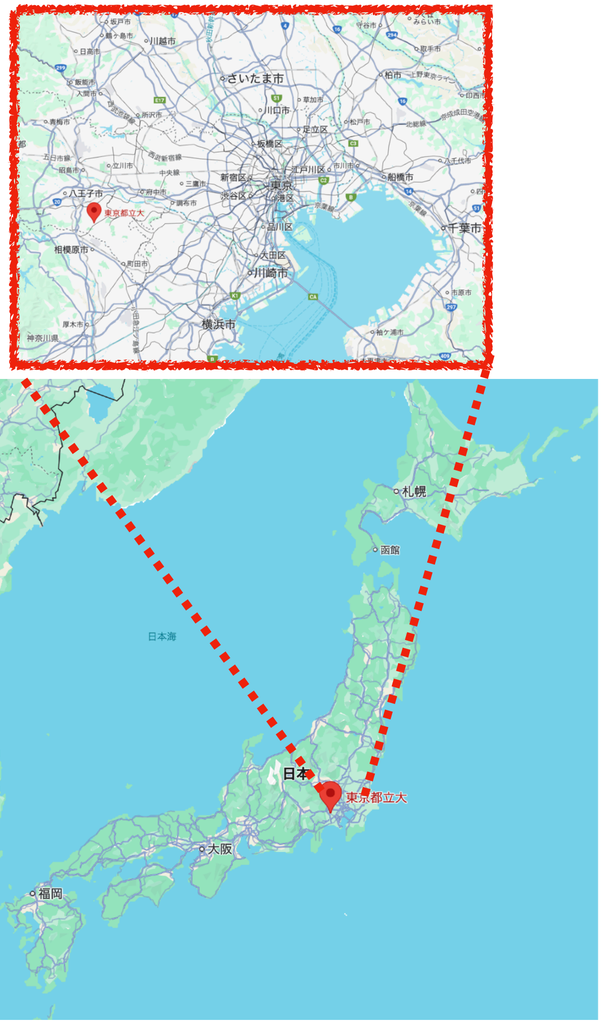
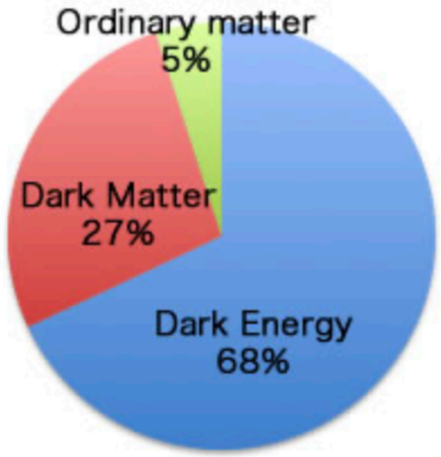


# • 1. Introduction

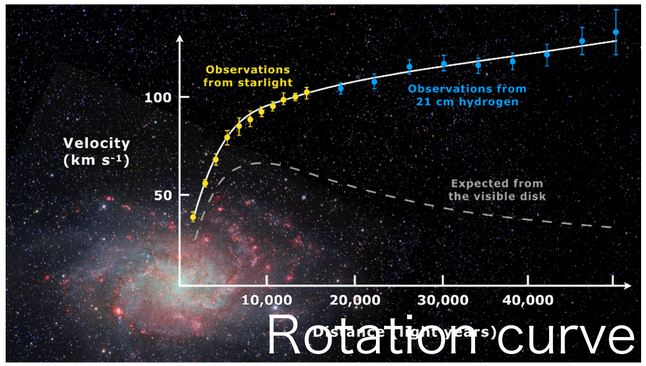
# Dark matter (DM) and particle property

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

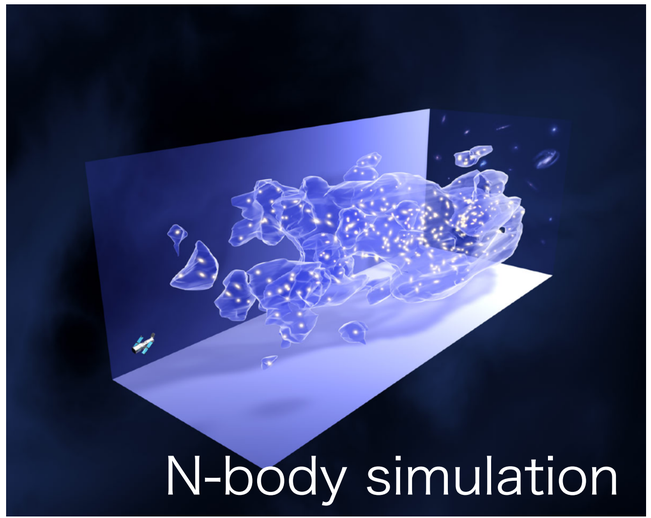
We do not know the particle property at all.



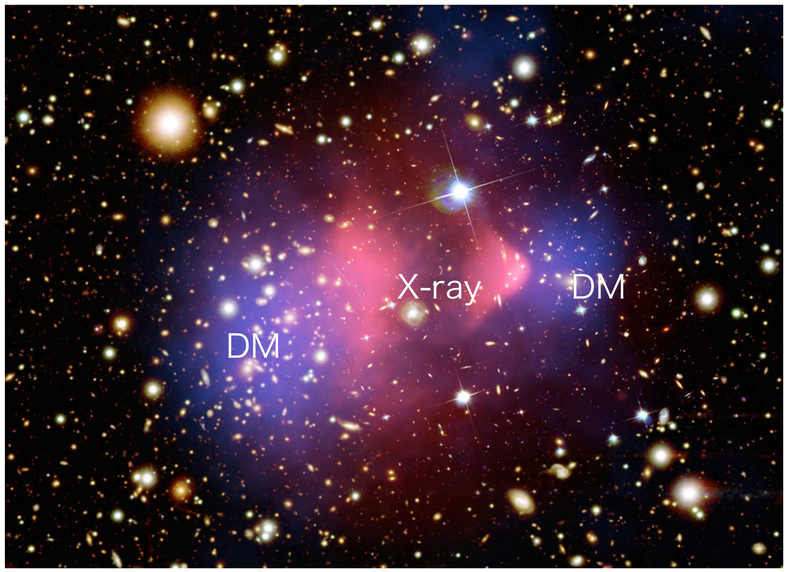

CMB data




Rotation curve



N-body simulation




Bullet cluster

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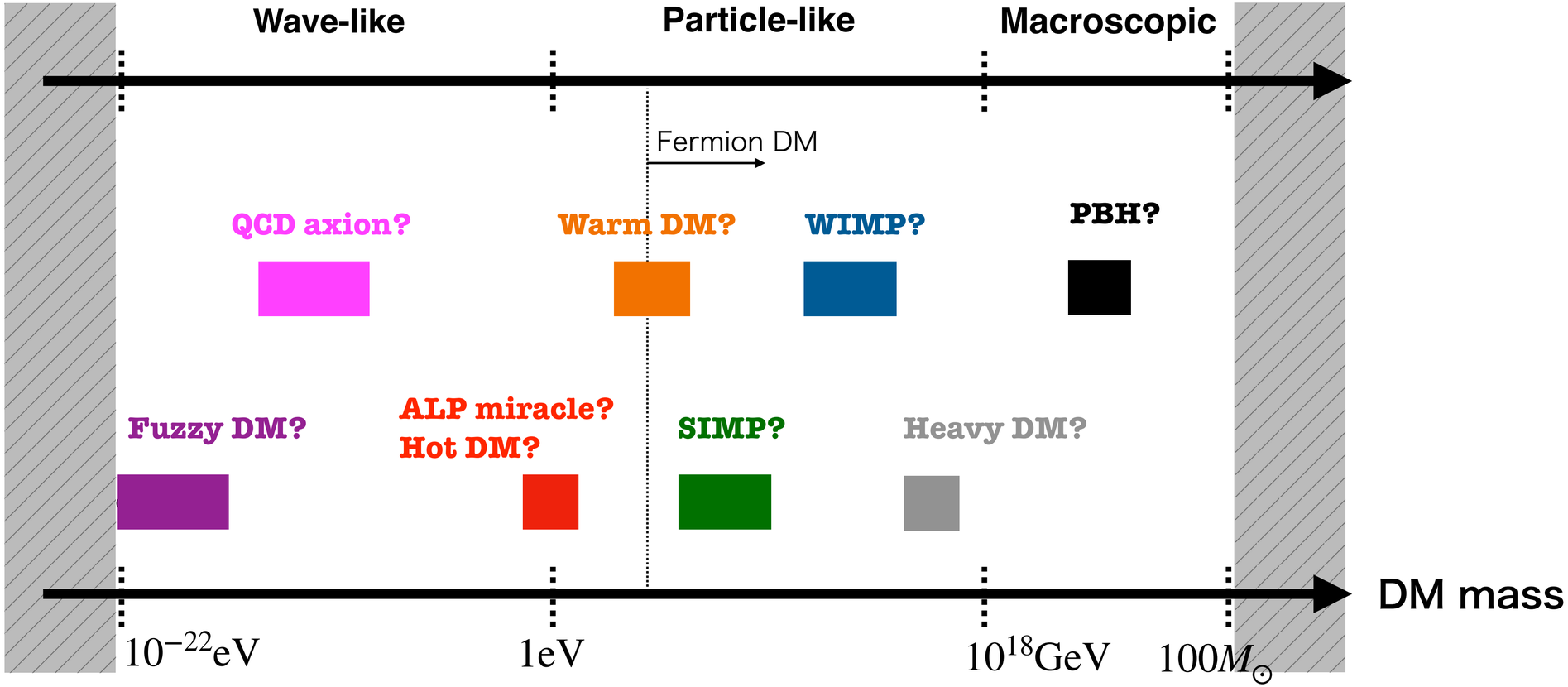

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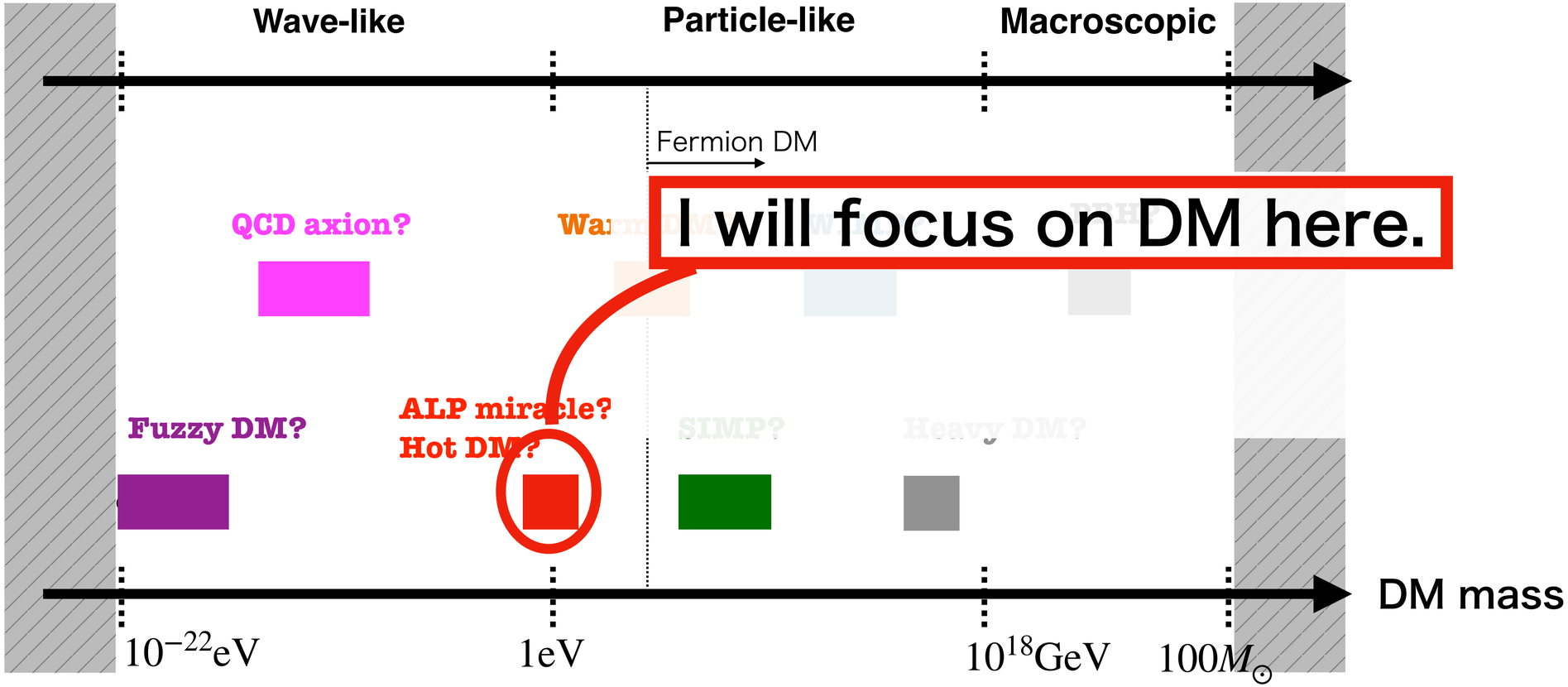


# Hints for eV DM: Observations

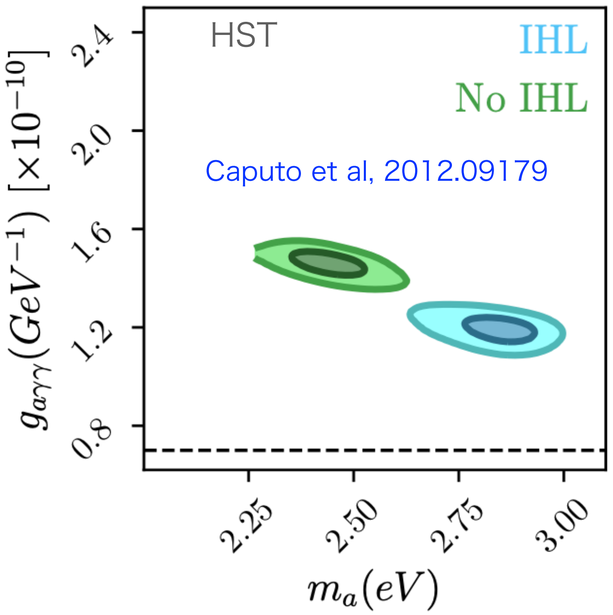
Interestingly, in the huge parameter region,

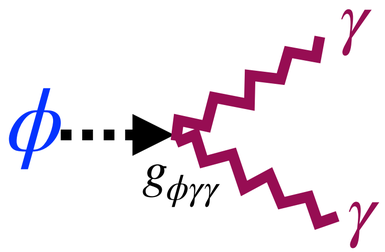
we have coincidences around eV.

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



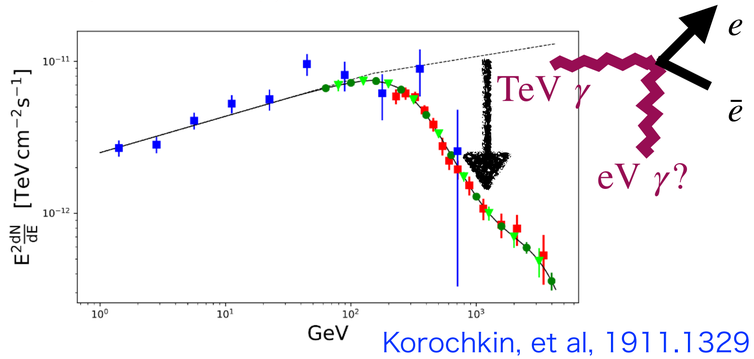




$m_\phi \sim eV$,

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

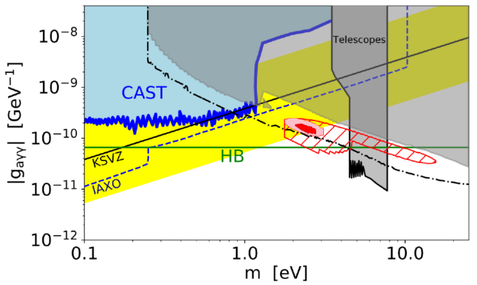
**spin=0**

The **TeV $\gamma$ 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: 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.

$\because n_{\rm DM} \sim T^3$, $\rho_{\rm DM}/s \sim m_{\rm DM} n_{\rm DM}/T^3 \sim$ 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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- Thermally produced eV DM is too hot.

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

- ->Thermally produced eV DM is excluded.

- **2. ‘Hot dark matter’ can be cool.**

WY, 2301.08735

Sakurai, WY, 2410.18968

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

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

Keyword: bose enhancement

# Setup:

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

WY 2301.08735

$\chi_1$ mass : $M_1(\ll T)$ $\qquad$ $\chi_2, \phi$ : massless

# Equations:

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

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

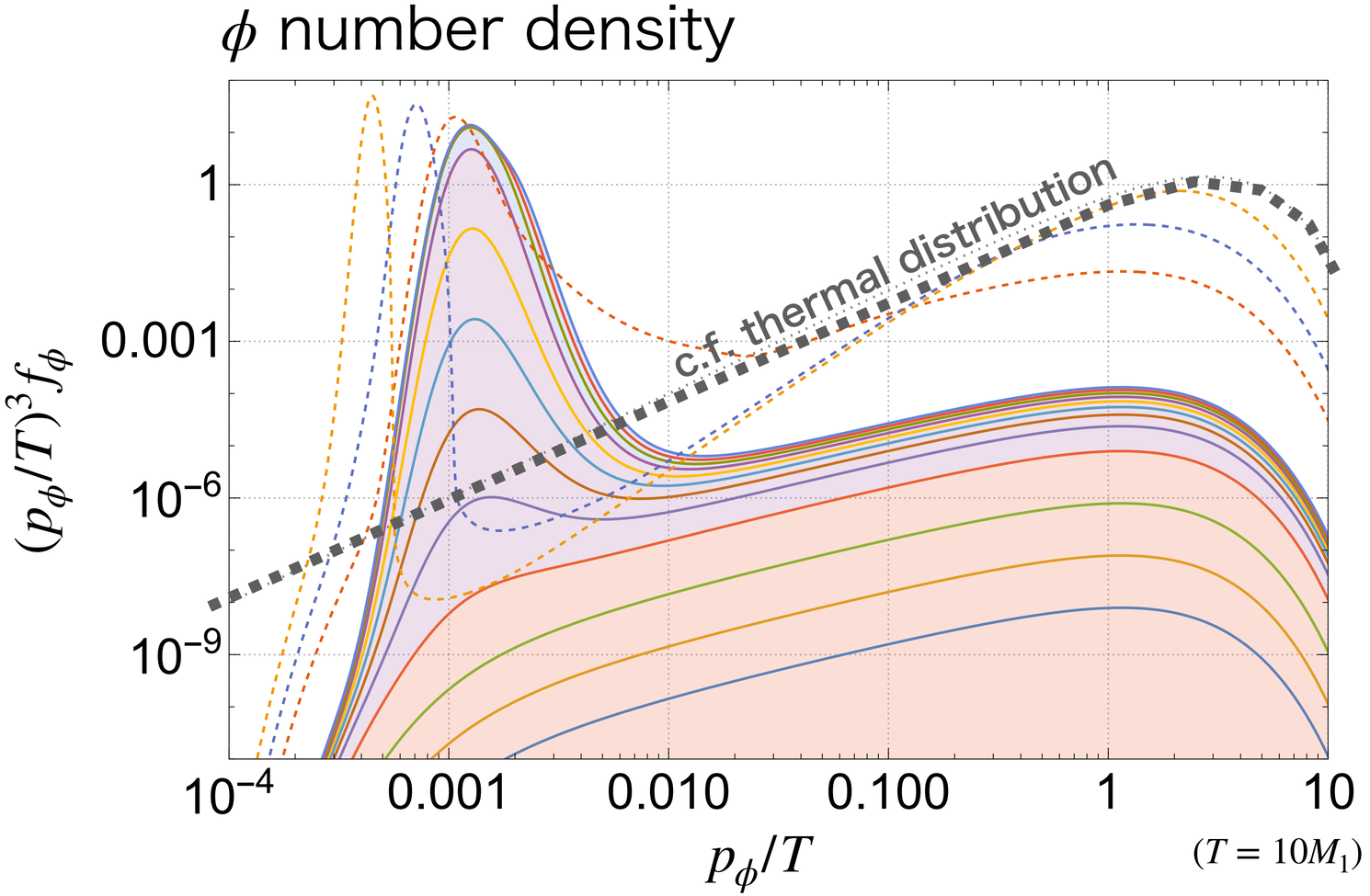
$$S \equiv f_{\chi_1}[p_{\chi_1}](1 \pm f_{\chi_2}[p_{\chi_2}])(1 + f_\phi[p_\phi]) - (1 \pm f_{\chi_1}[p_{\chi_1}])f_\phi[p_\phi]f_{\chi_2}[p_{\chi_2}]$$

# (Initial) conditions:

$\chi_1$ is always thermalized, while $\chi_2$ and $\phi$ are absent initially,

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

# Burst production of DM $\phi$ turns out thanks to bose enhancement.




Three stages of burst production:

1. Ignition
2. Burst
3. Saturation

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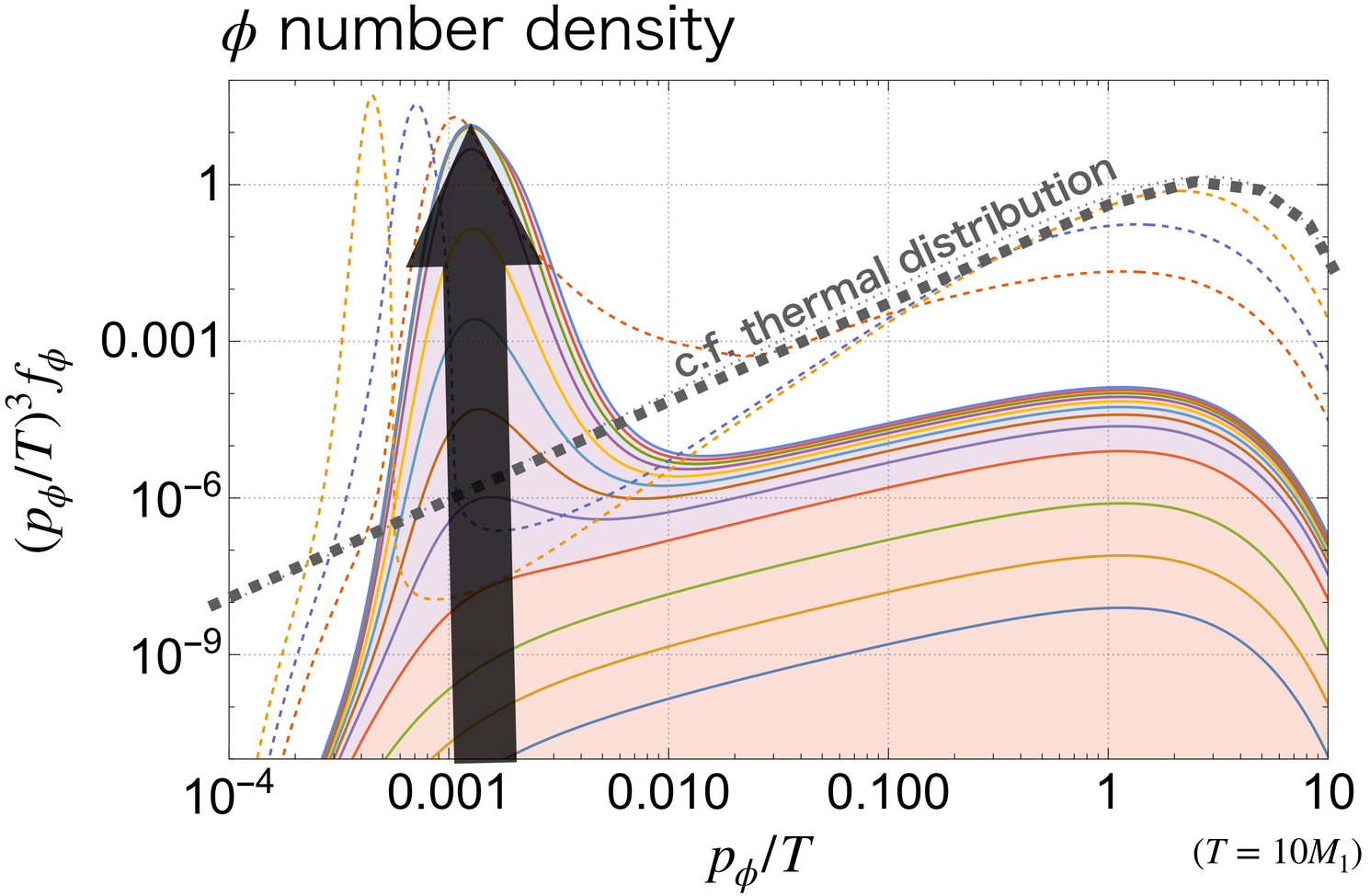


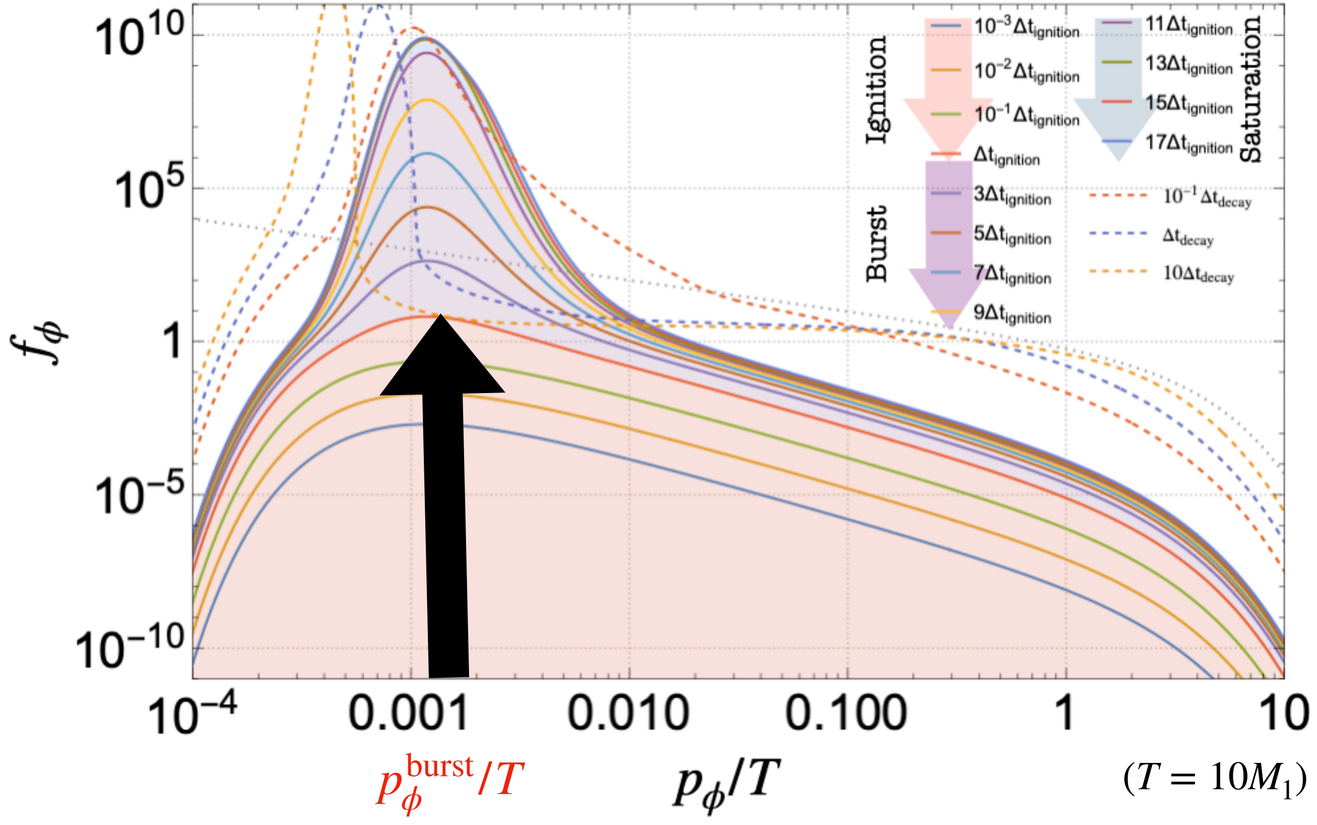

Three stages of burst production:

1. Ignition
2. Burst
3. Saturation

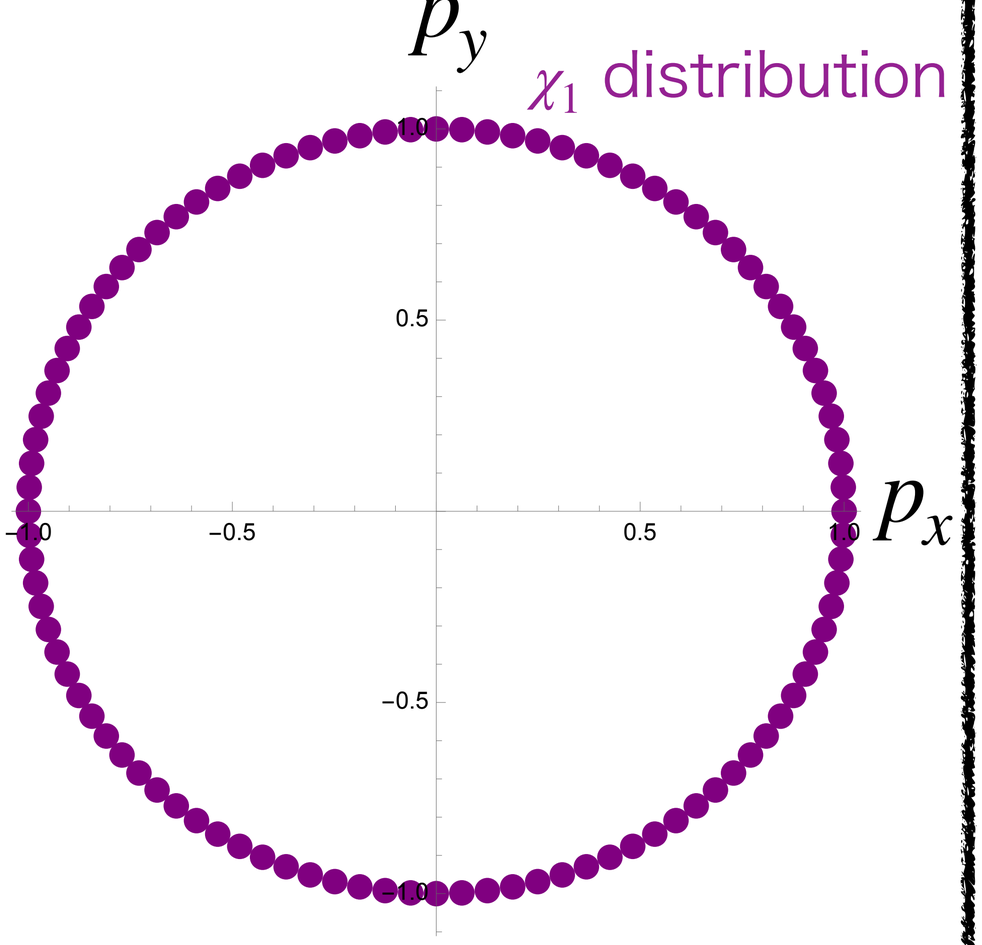
# Stage 1: Ignition

-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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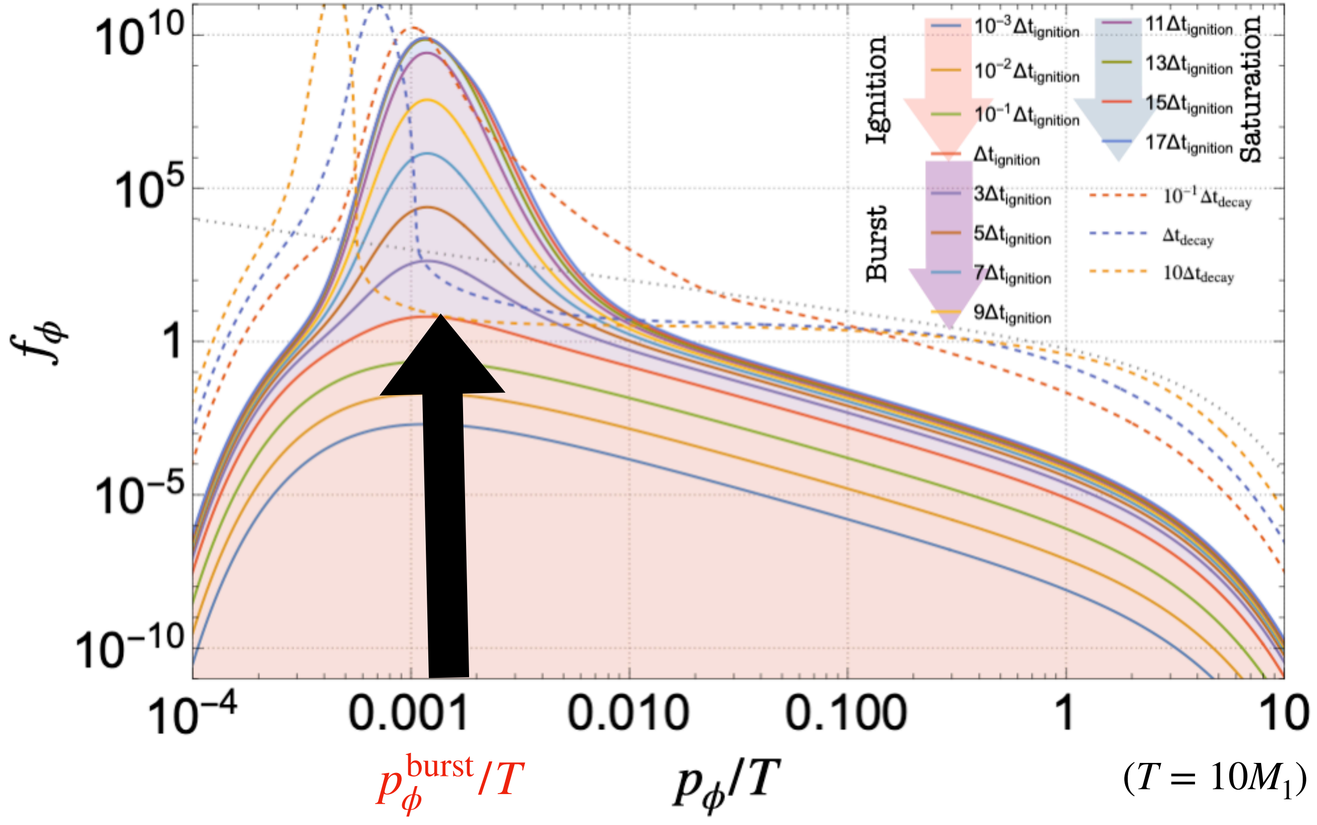


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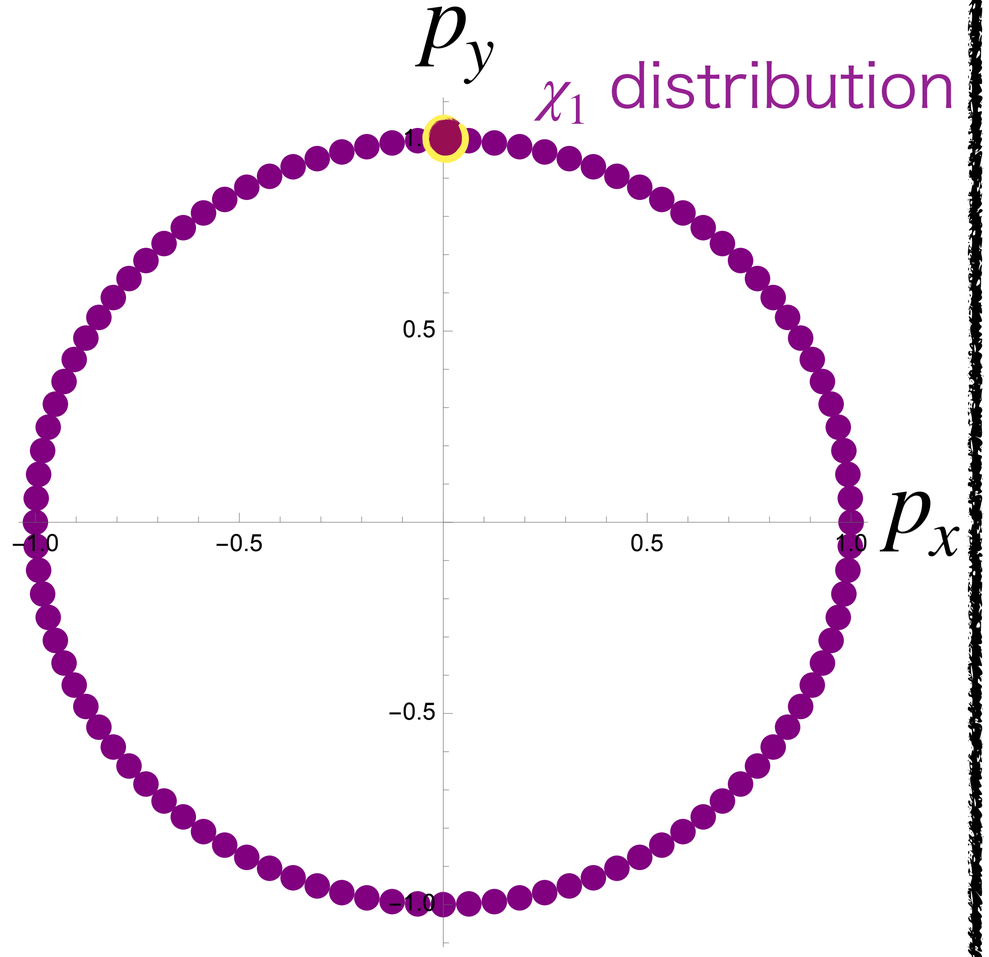

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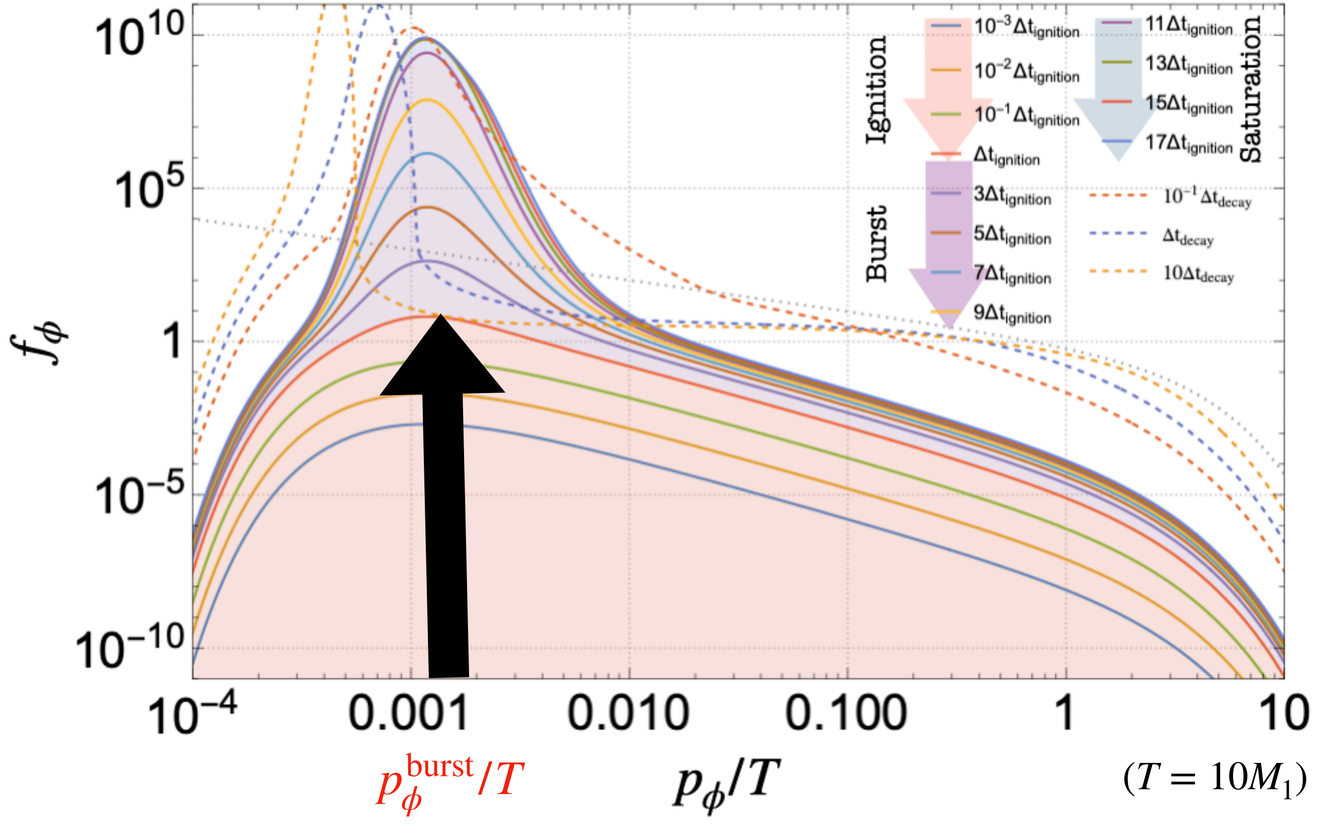


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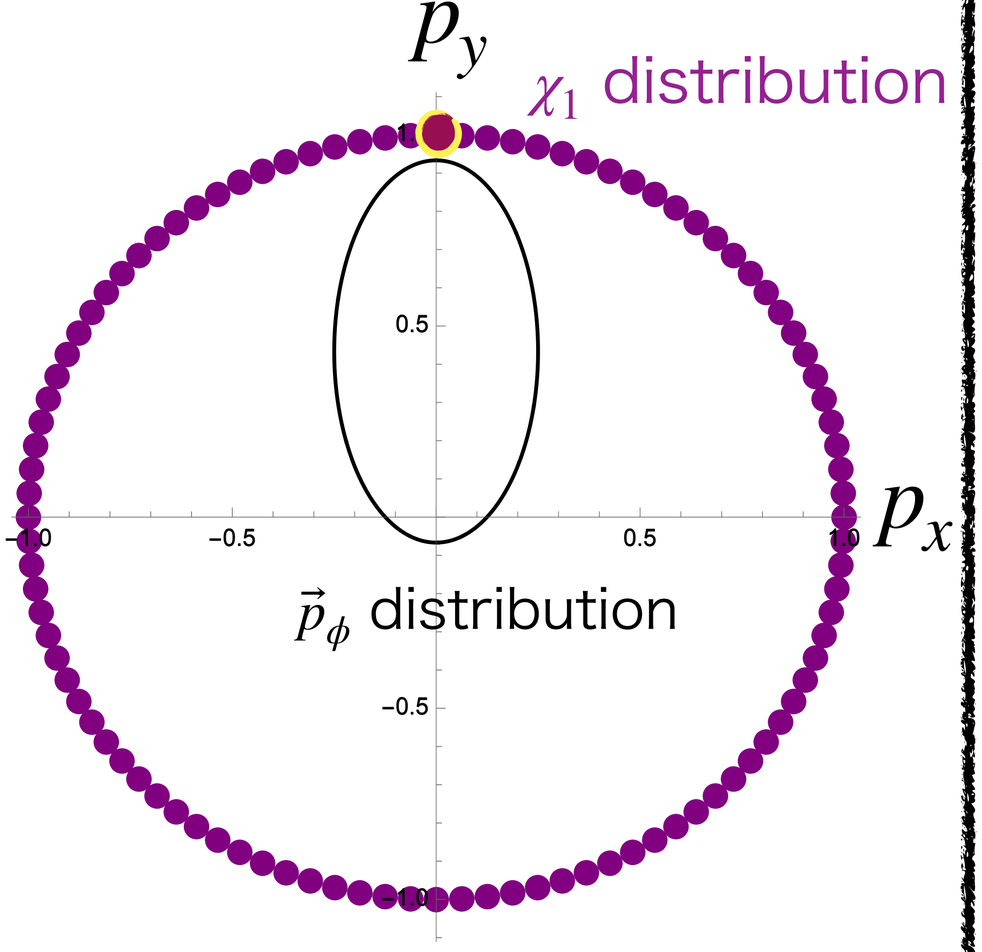

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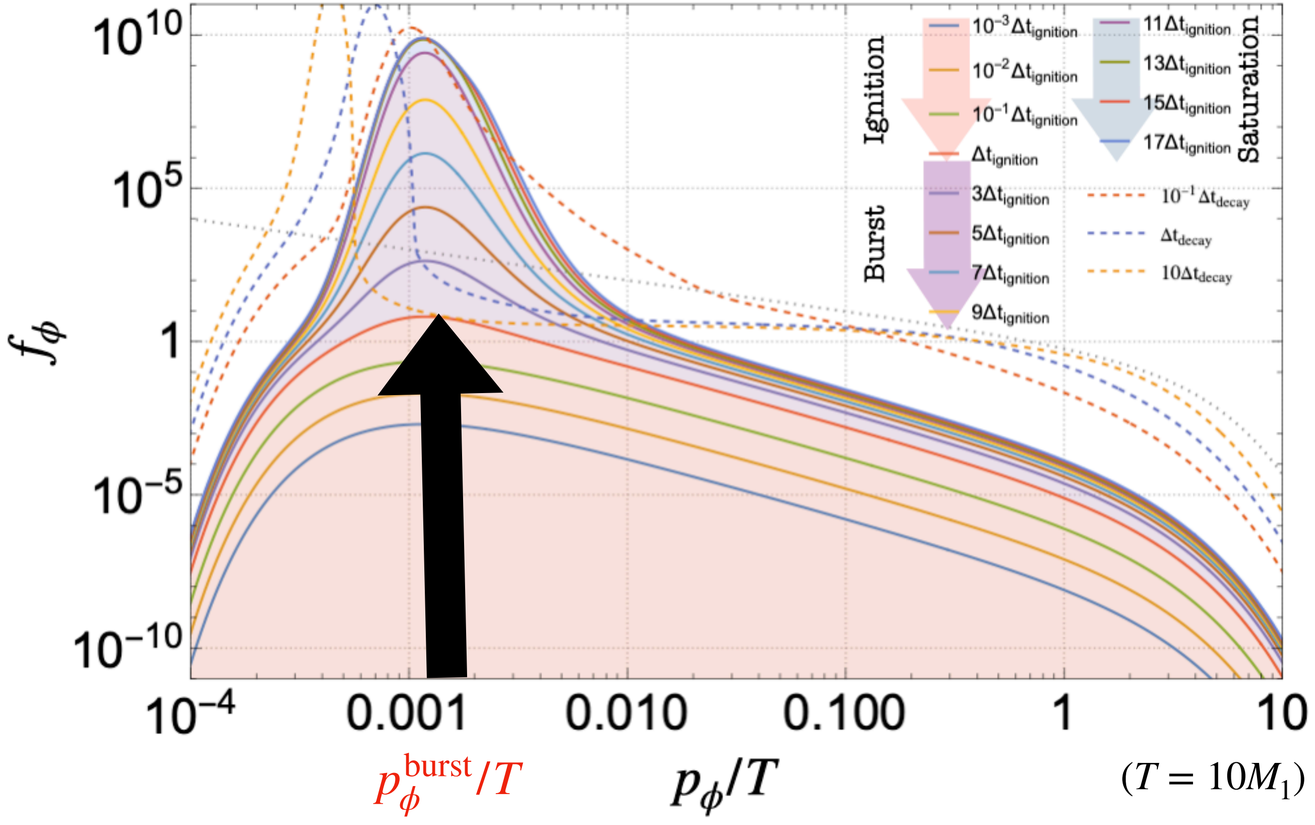


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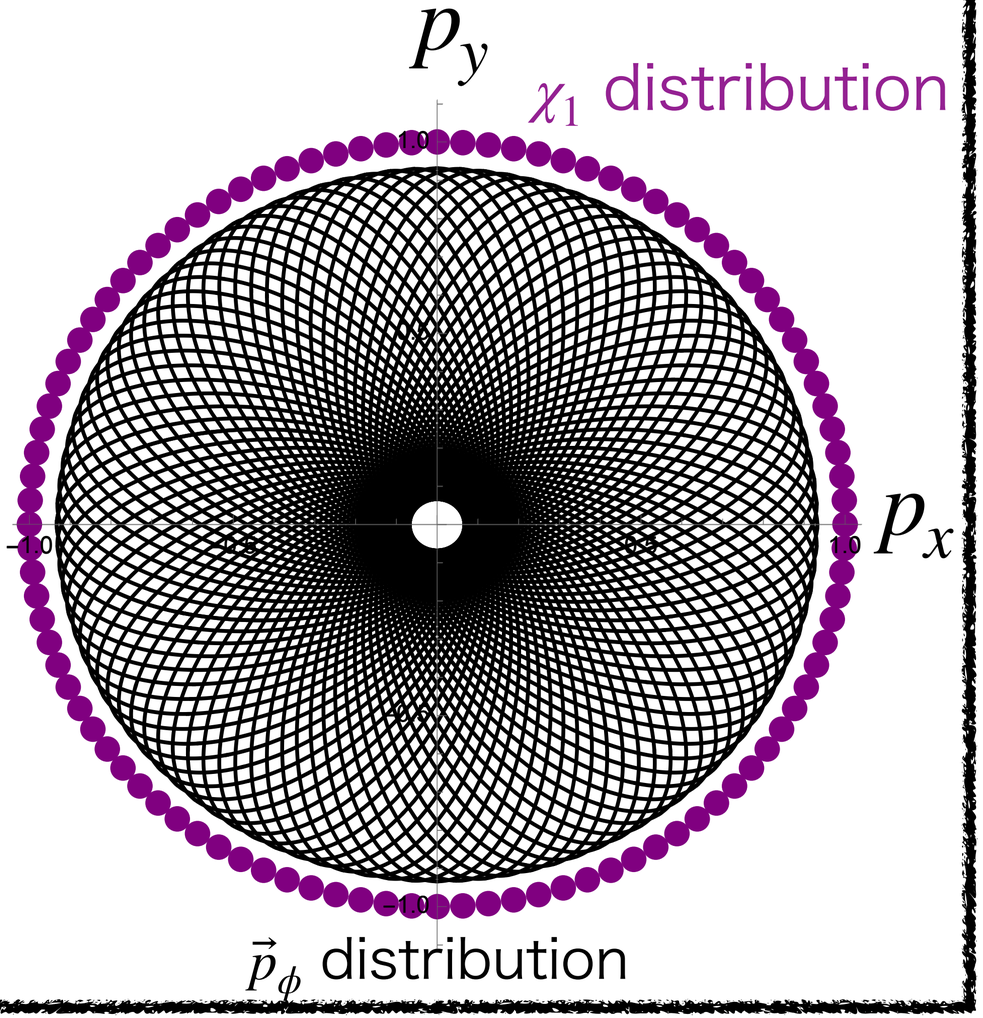

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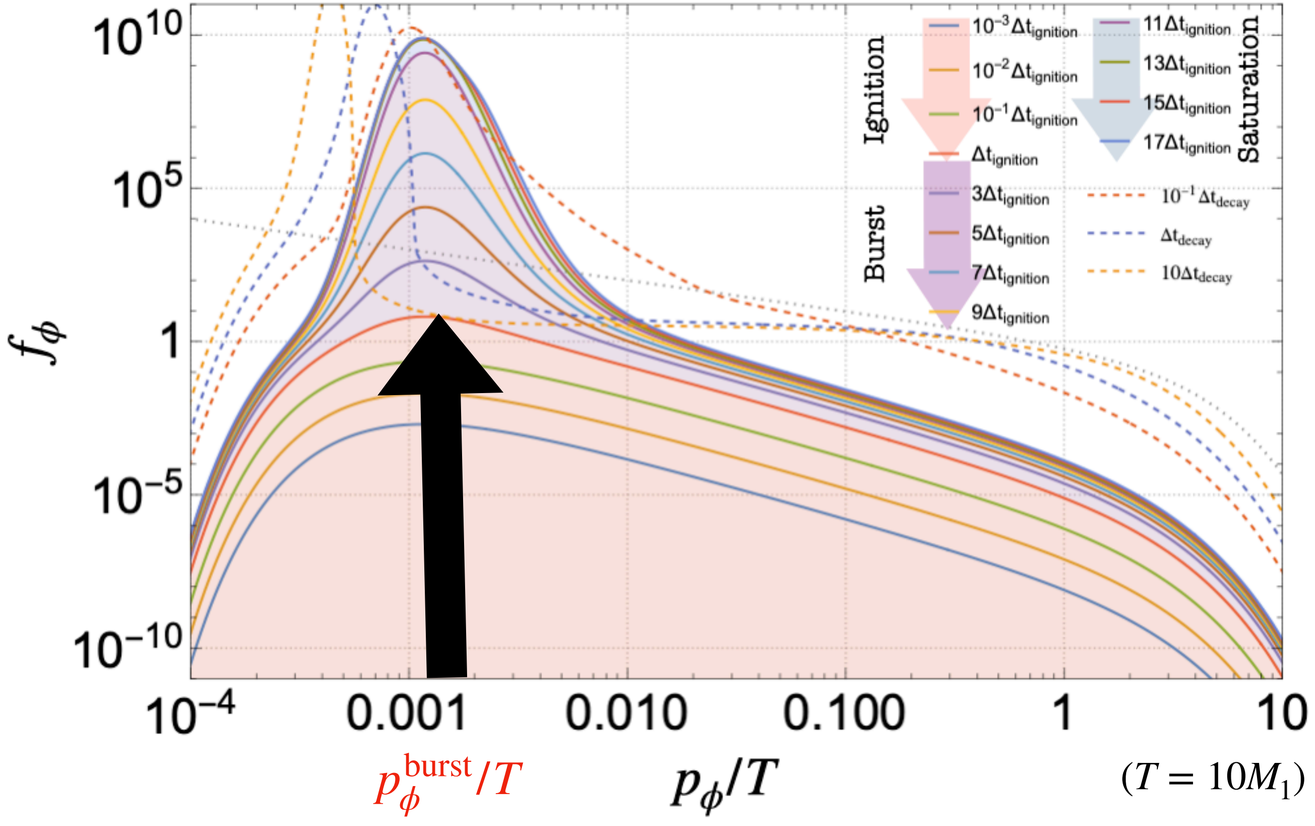


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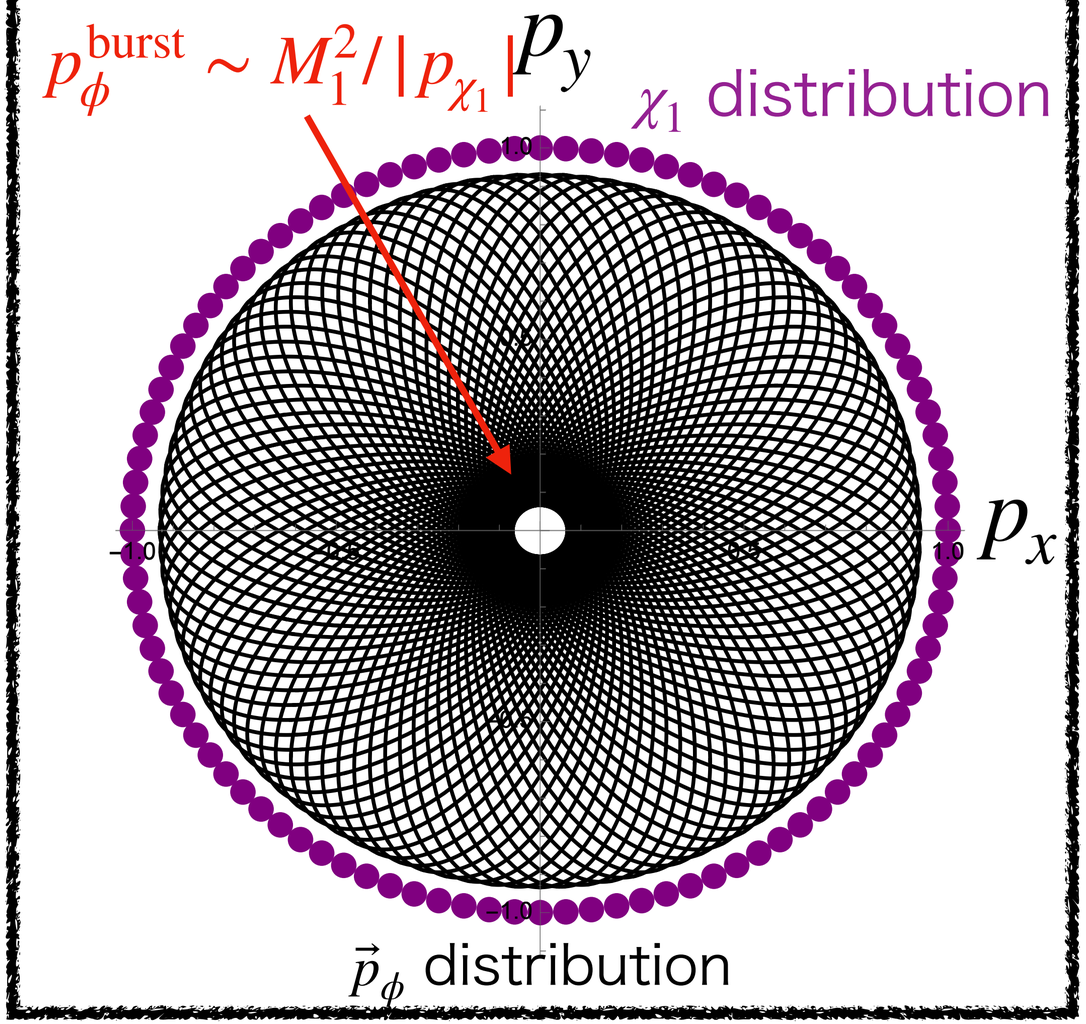
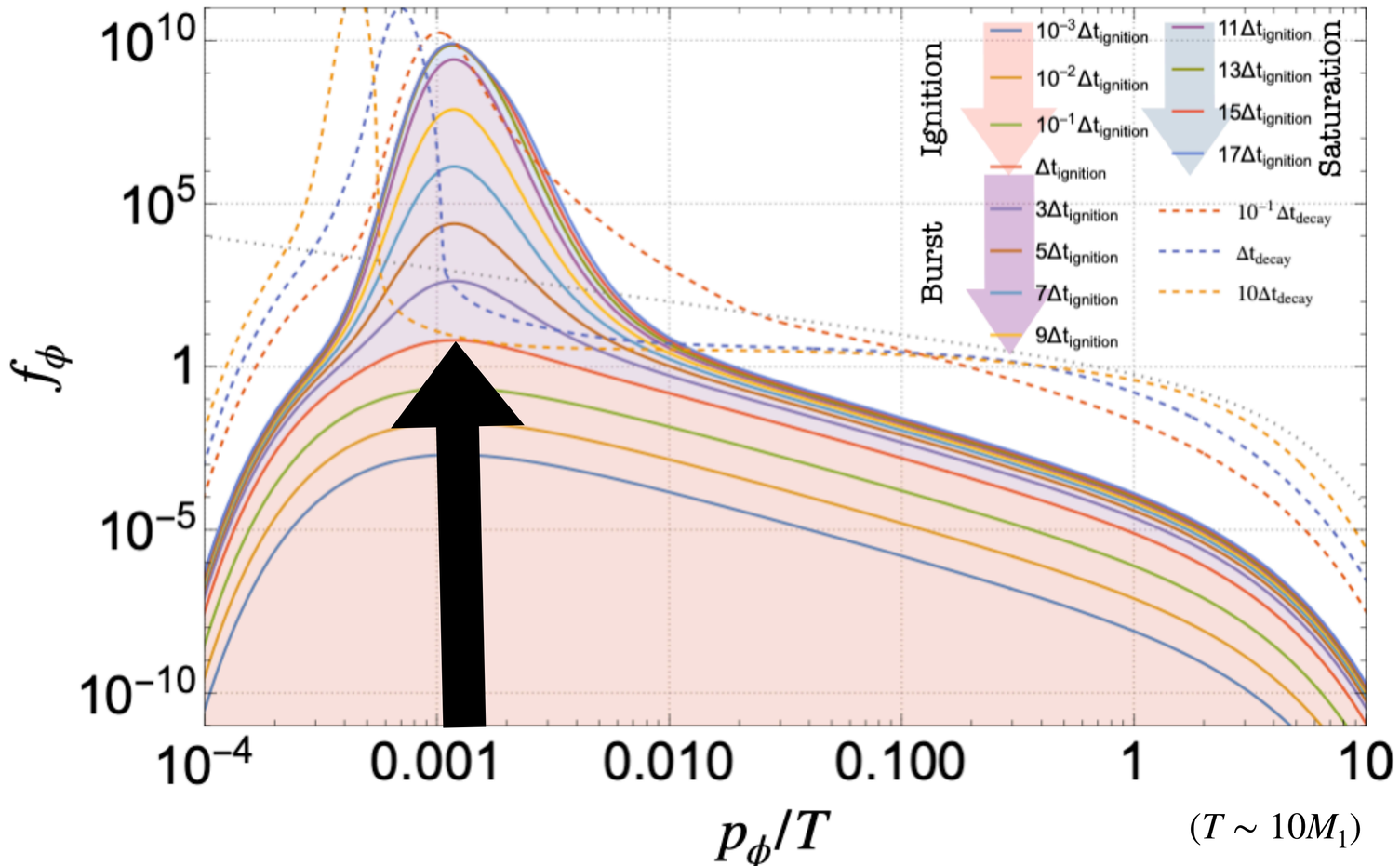


# Stage 1: Ignition

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

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



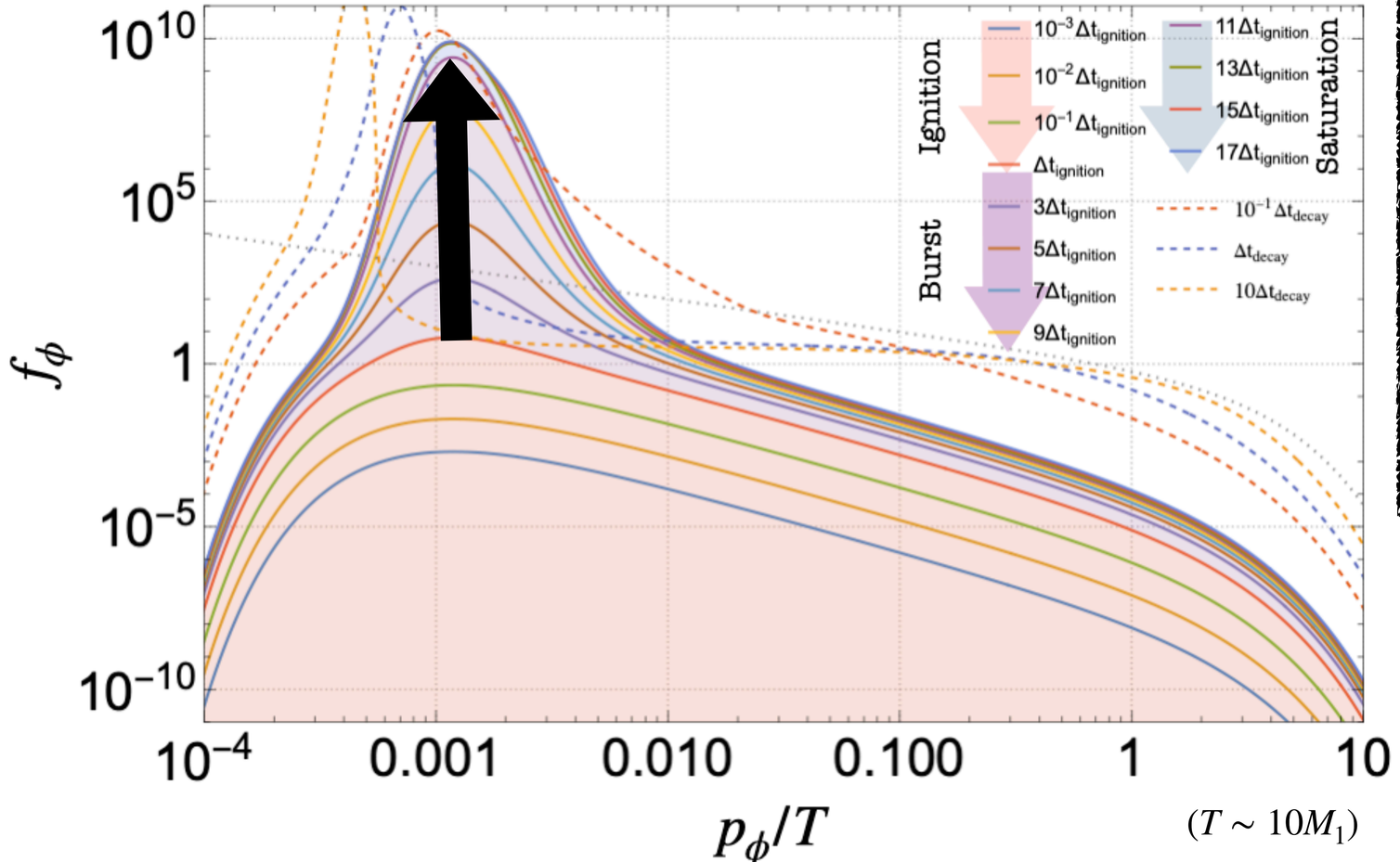

$(T \sim 10 M_1)$

$$\sim \frac{T^4}{M_1^4} \times \left(\frac{M_1}{T}\Gamma_{\rm decay}^{\rm (proper)}\right) \propto T^3$$

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

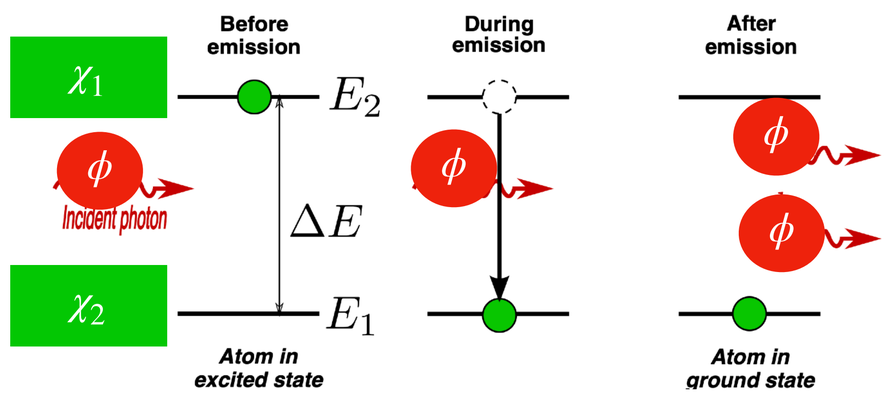
# Stage 2: Burst

$p_\phi^{\rm burst}$ modes grow exponentially due to Bose enhancement. c.f. laser.




$(T \sim 10M_1)$

Laser, wikipedia

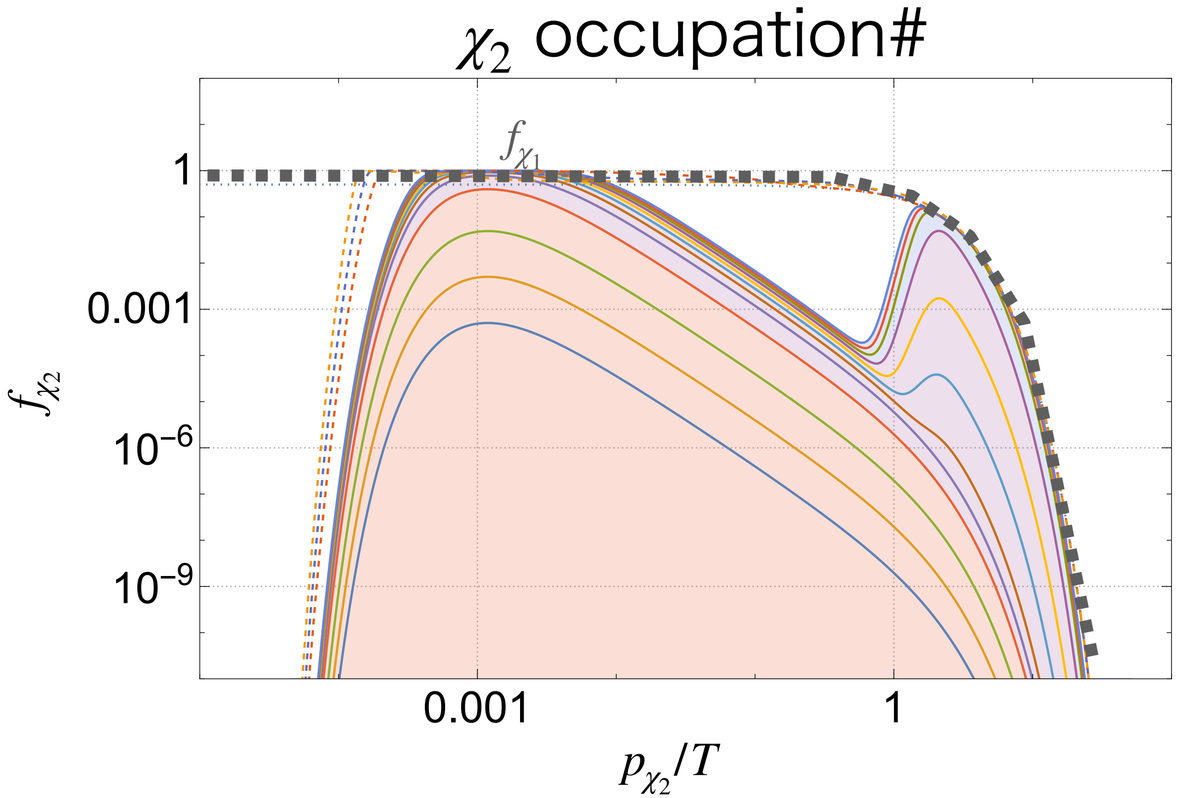


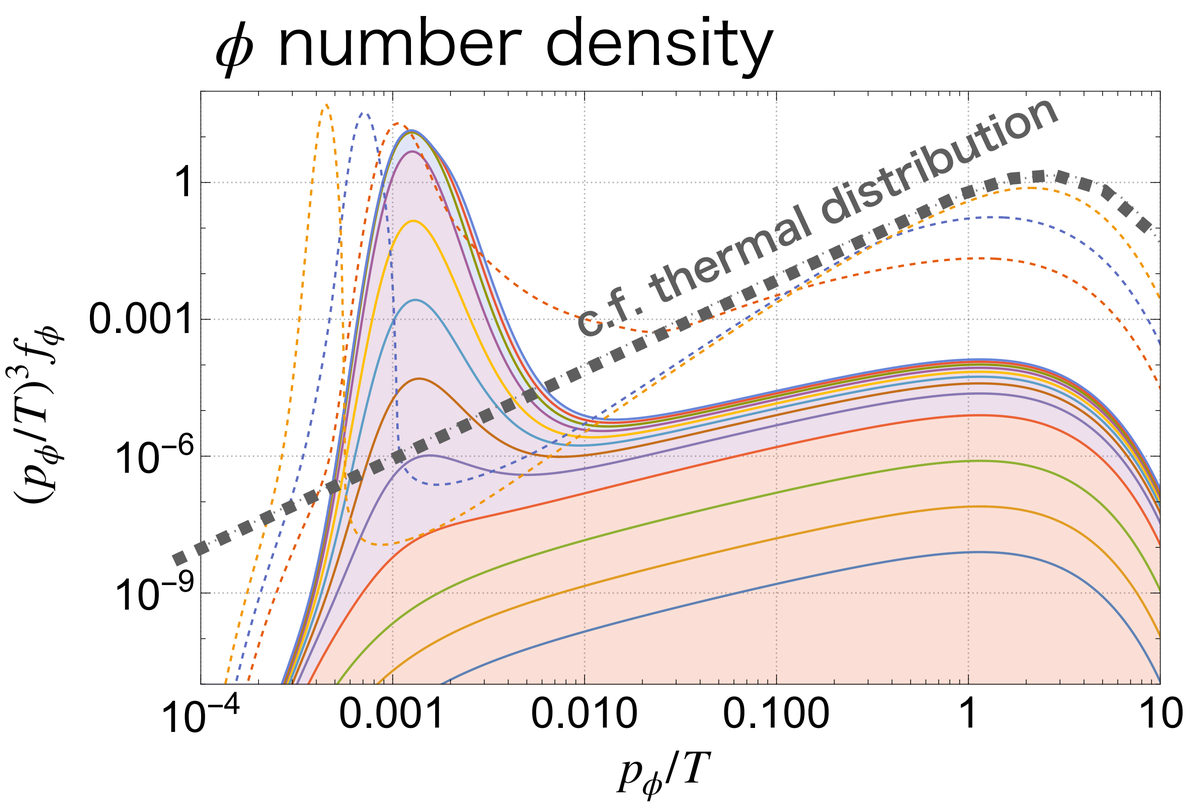

$$E_{\chi_1} - E_{\chi_2} \sim p_{\phi,\rm burst} \sim M_1^2/E_{\chi_1}$$

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

# Stage 3: Saturation (quasi-equilibrium)

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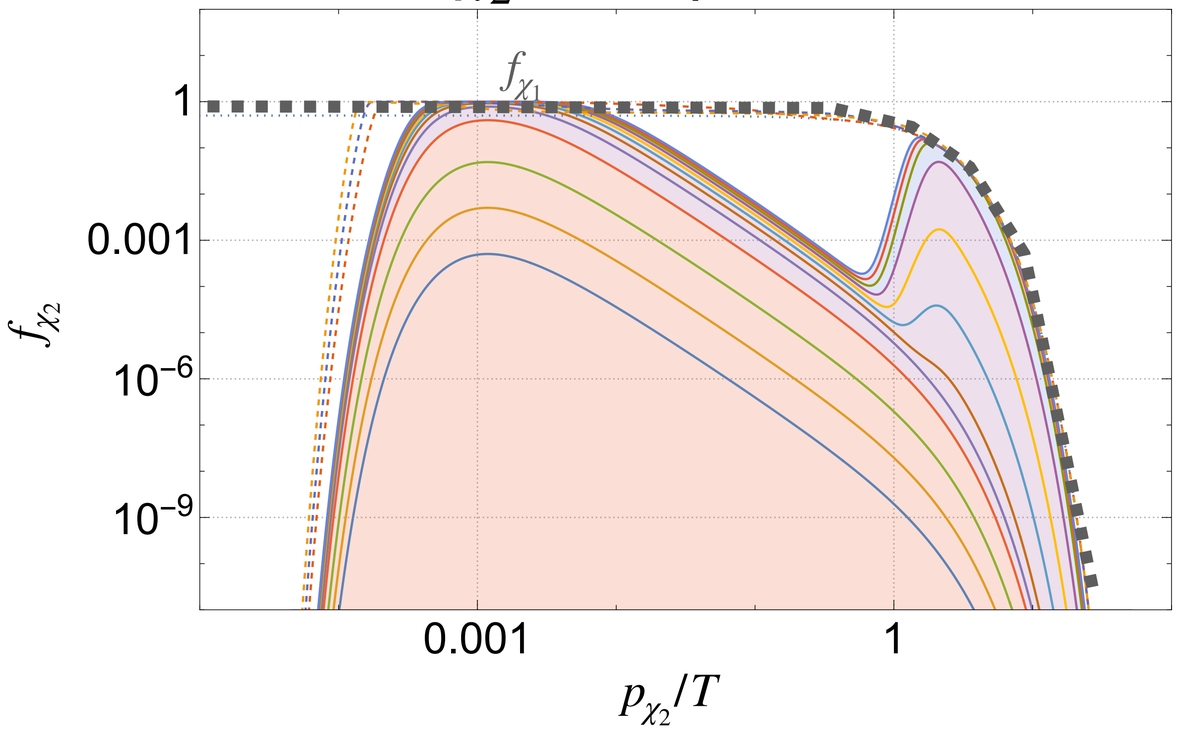
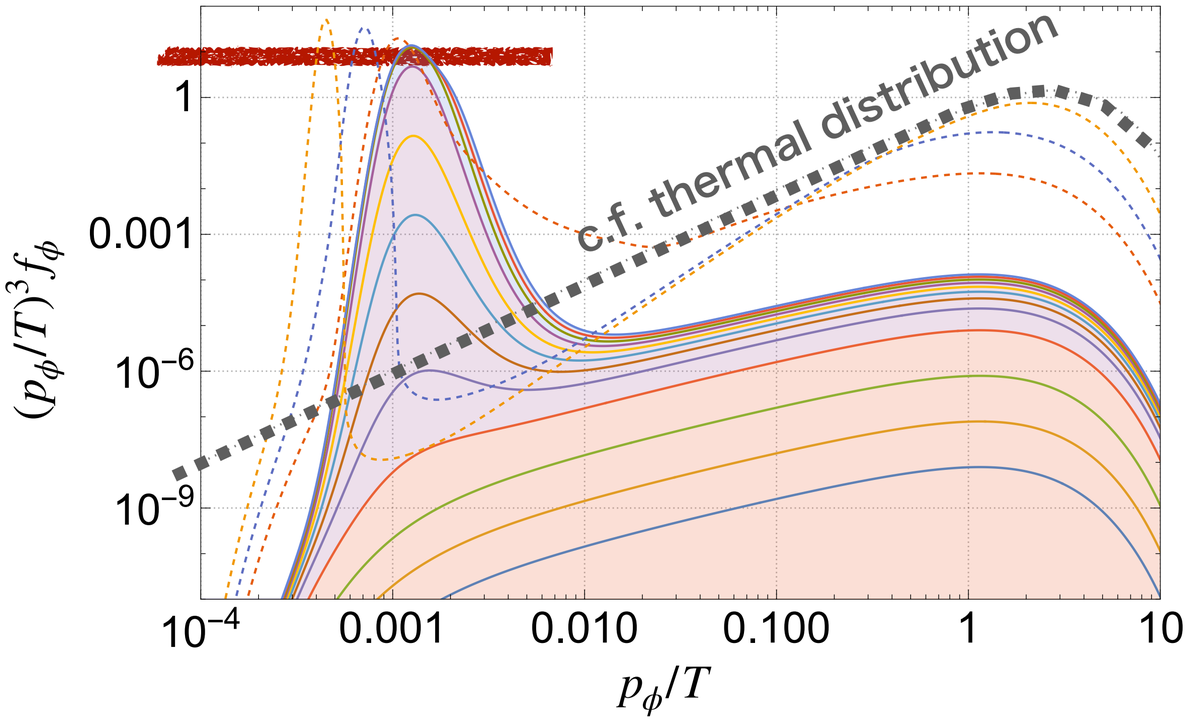
$n_\phi \sim g_{\chi_2} T^3, p_\phi \sim M_1^2/T$, which is cold



WY, 2301.08735

Explaining abundance of DM gives

$$m_\phi = 50\mathrm{eV}\,\frac{4}{g_{\chi 2}}\,\frac{g_{\star,s}[\ T_R\ ]}{100} = [1-100]eV$$

Coldness (Lyman $\alpha$ bound $L_{\mathrm{FS}} < 0.06\mathrm{Mpc}$ ) requires

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

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

## Usual Hot DM scenario

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

=> eV mass for DM abundance

- Comoving momentum is

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

=> hot

## Burst production

- $\left(\frac{T}{M_1}\right)^3 \Gamma^{(\mathrm{proper})}_{\chi_1\to\chi_2\phi} > H > \frac{M_1}{T}\Gamma^{(\mathrm{proper})}_{\chi_1\to\chi_2\phi}$ 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

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

=> cold

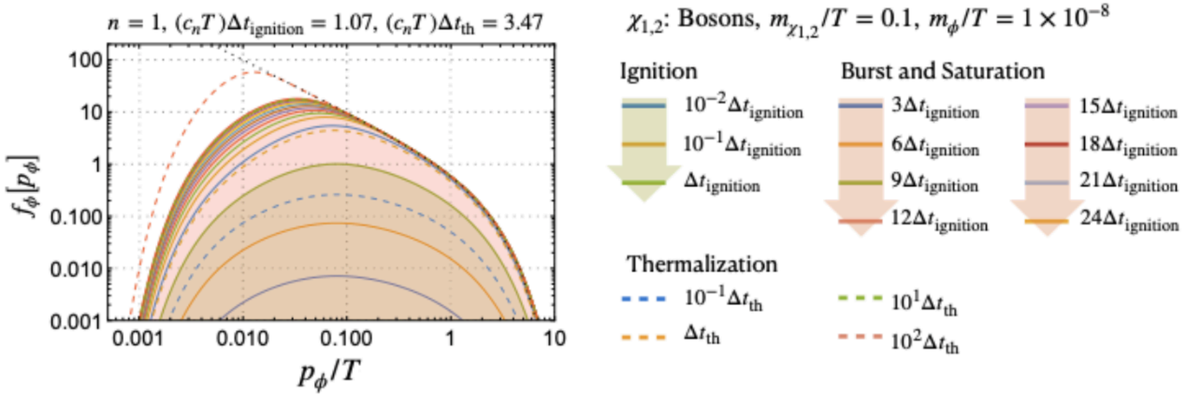
# How about 2 to 2, e.g. $\chi\chi \to \phi\phi$?

$$\sigma \sim \frac{c_n s^n}{(m_{\chi_1} m_{\chi_2})^n E_{\chi_1} E_{\chi_2}}$$

Sakurai, WY, 2410.18968

- Depending on the crosssection, Burst production happens:

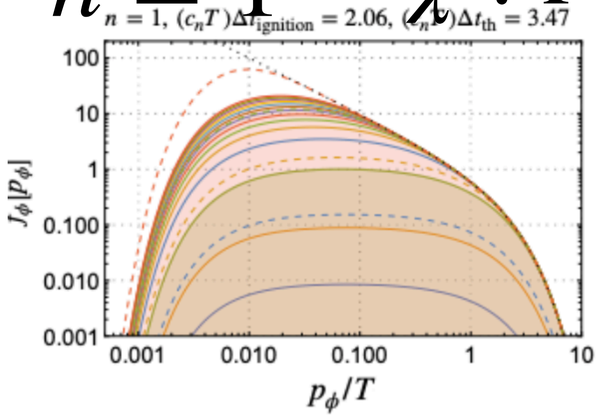
$n = 1$ $\chi$ : *Boson*

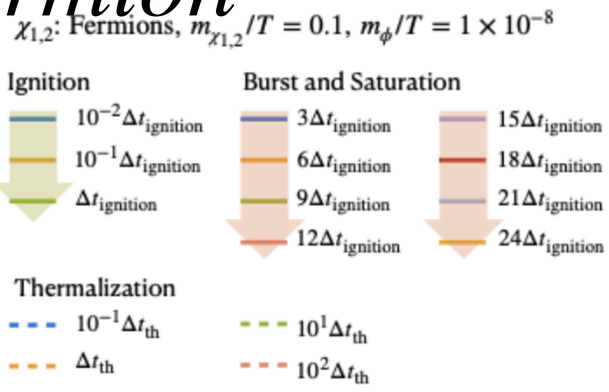


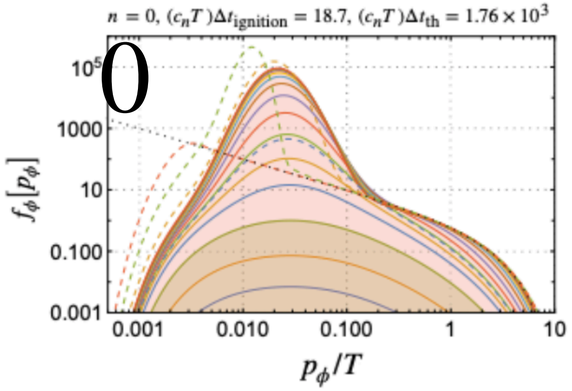


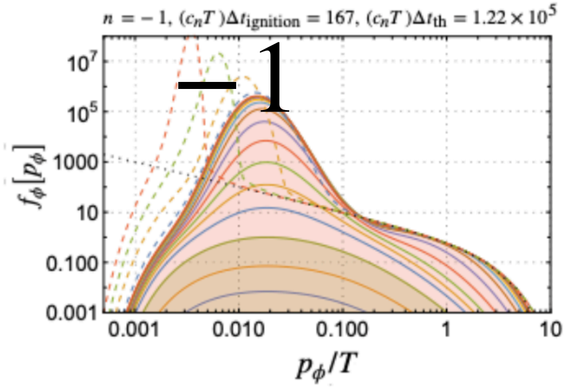


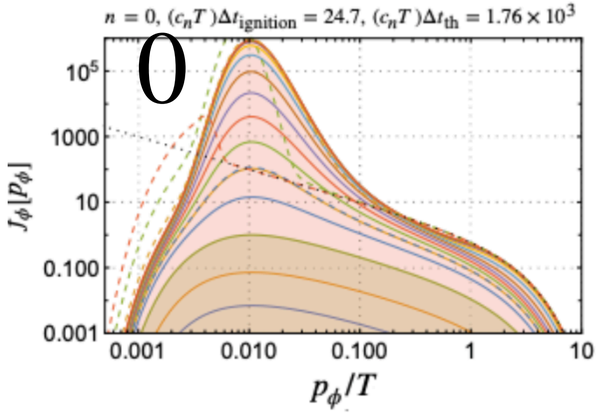
$n = 1$ $\chi$ : *Fermion*

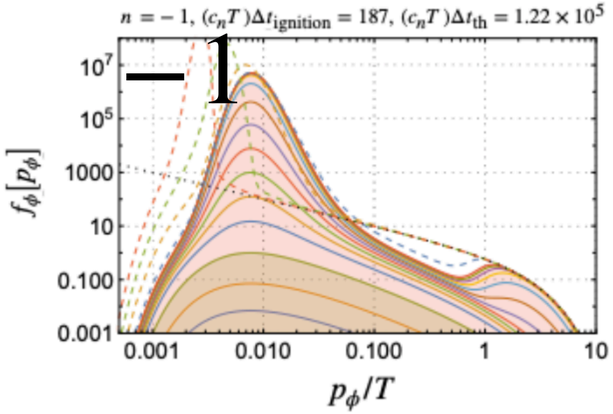


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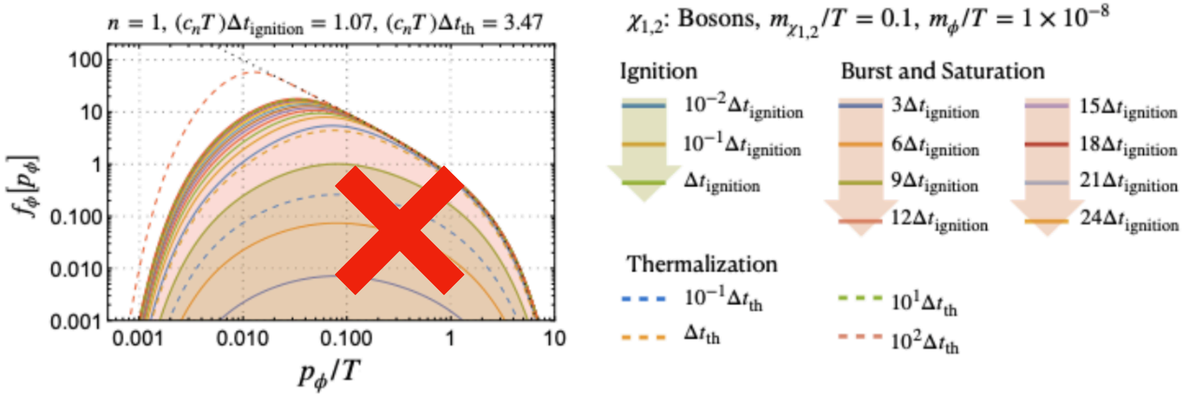
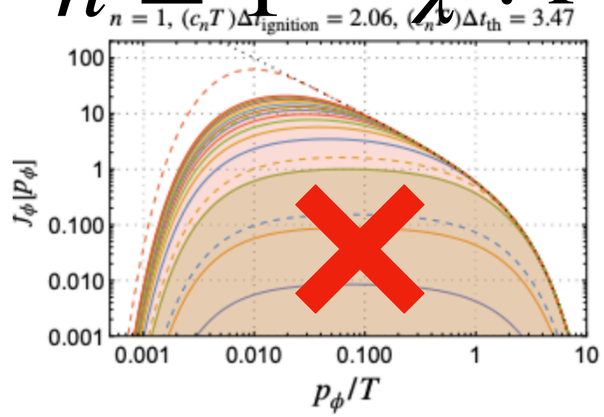
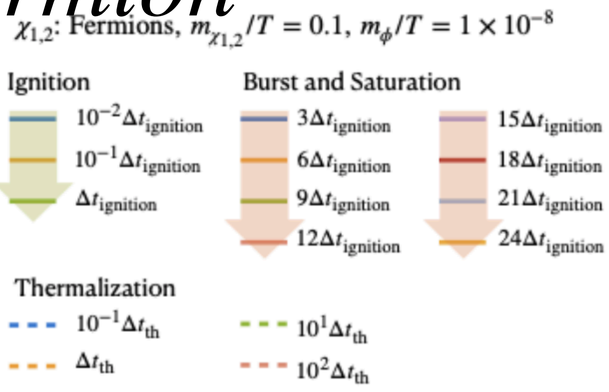


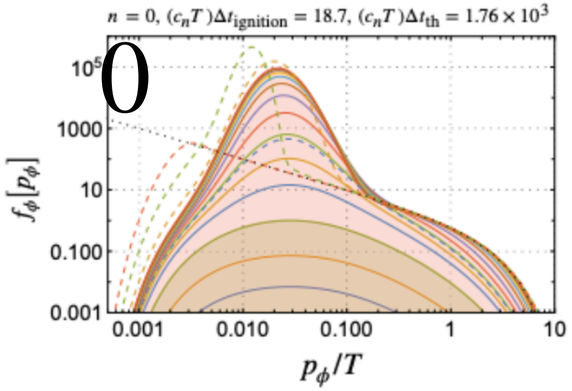


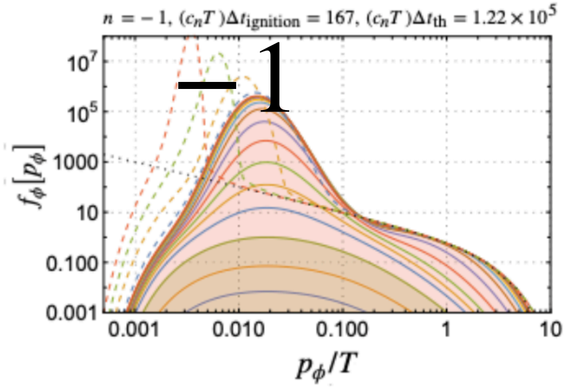


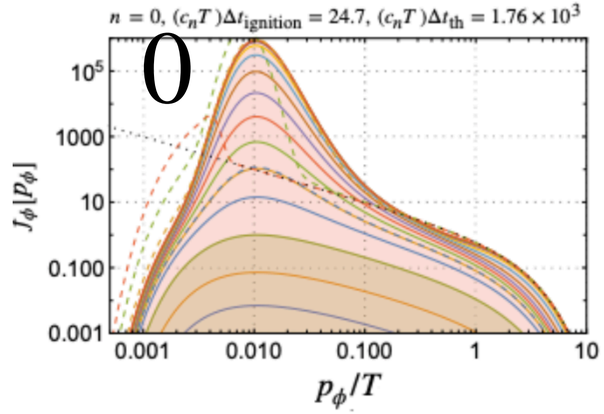
$n = 1$ $\chi$ : *Fermion*

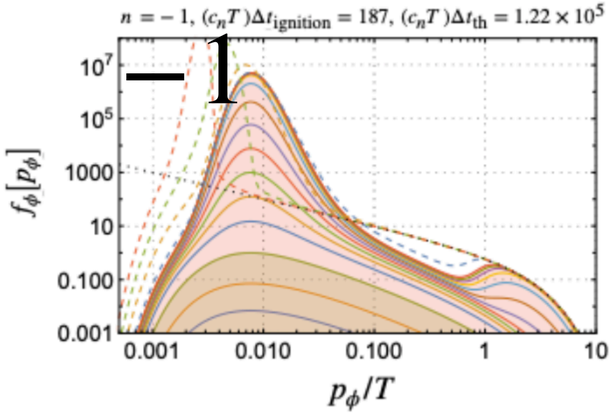


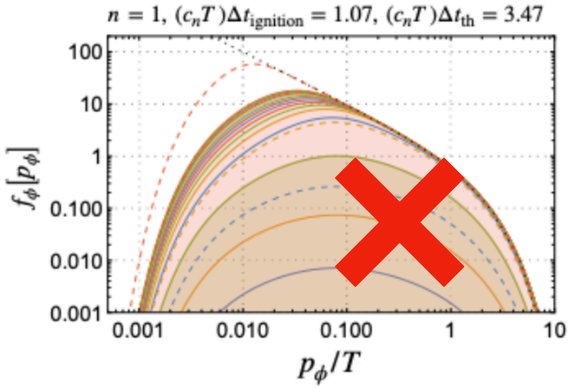
# How about 2 to 2, e.g. $\chi\chi \to \phi\phi$?

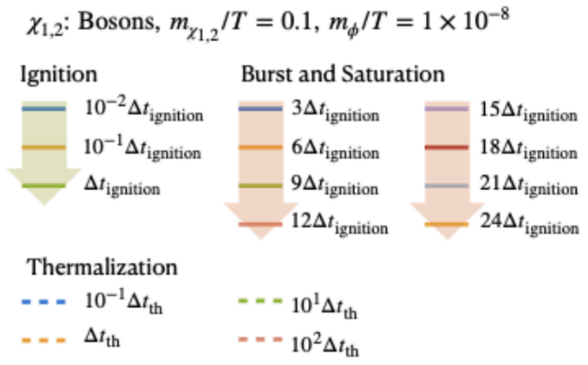
$$\sigma \sim \frac{c_n s^n}{(m_{\chi_1} m_{\chi_2})^n E_{\chi_1} E_{\chi_2}}$$

Sakurai, WY, 2410.18968

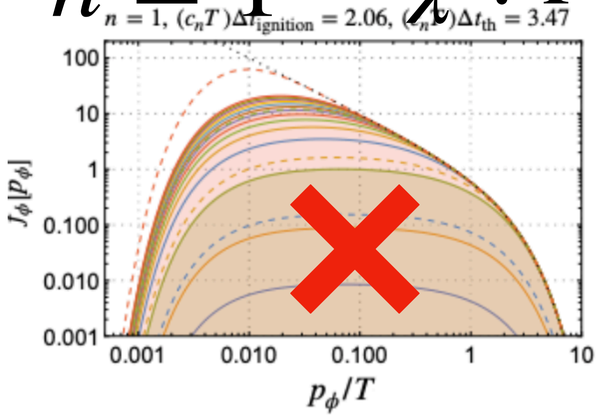
- Depending on the crosssection, Burst production happens:

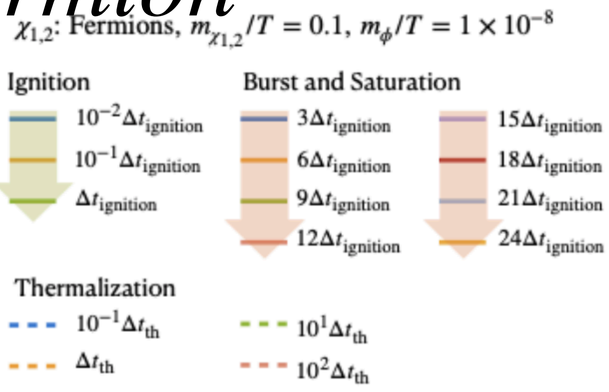
$n = 1$ $\chi$ : *Boson*

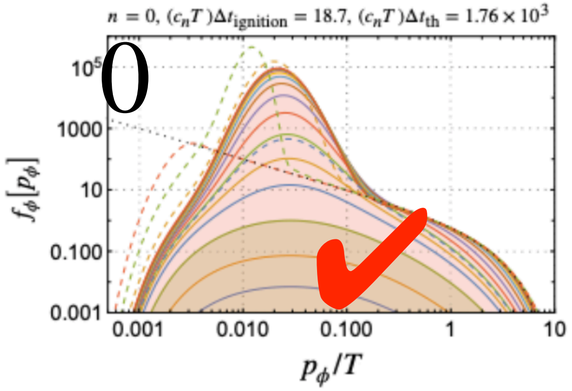


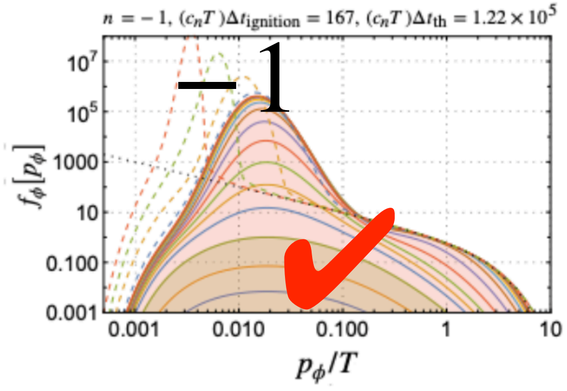



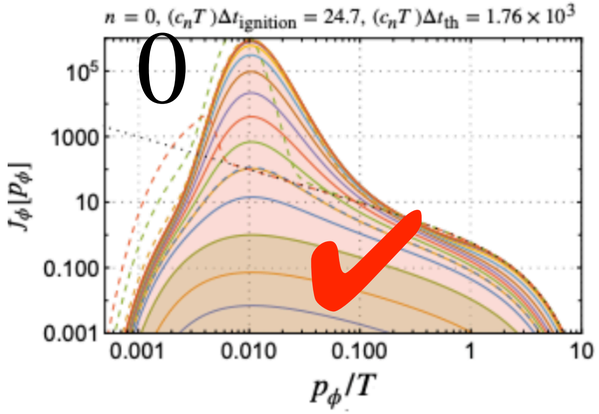

$n = 1$ $\chi$ : *Fermion*

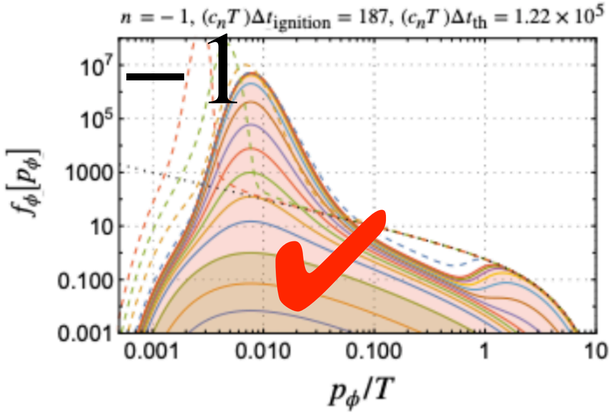


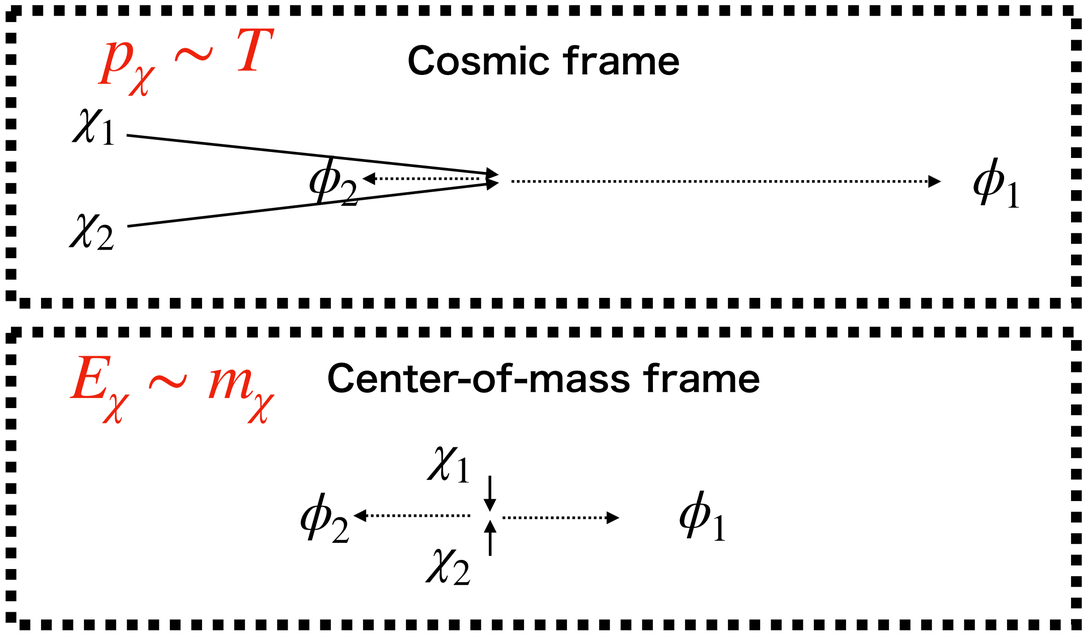



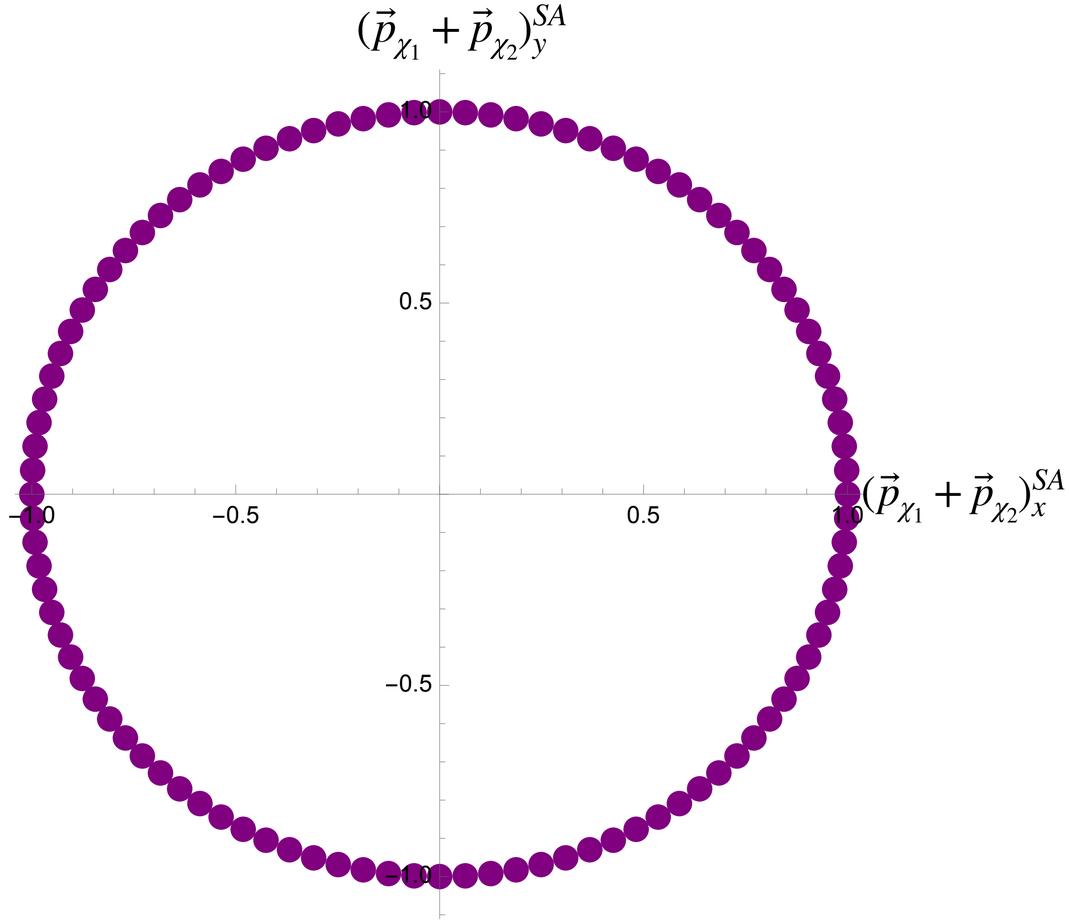



# 2 to 2, burst production mechanism: small angle scattering



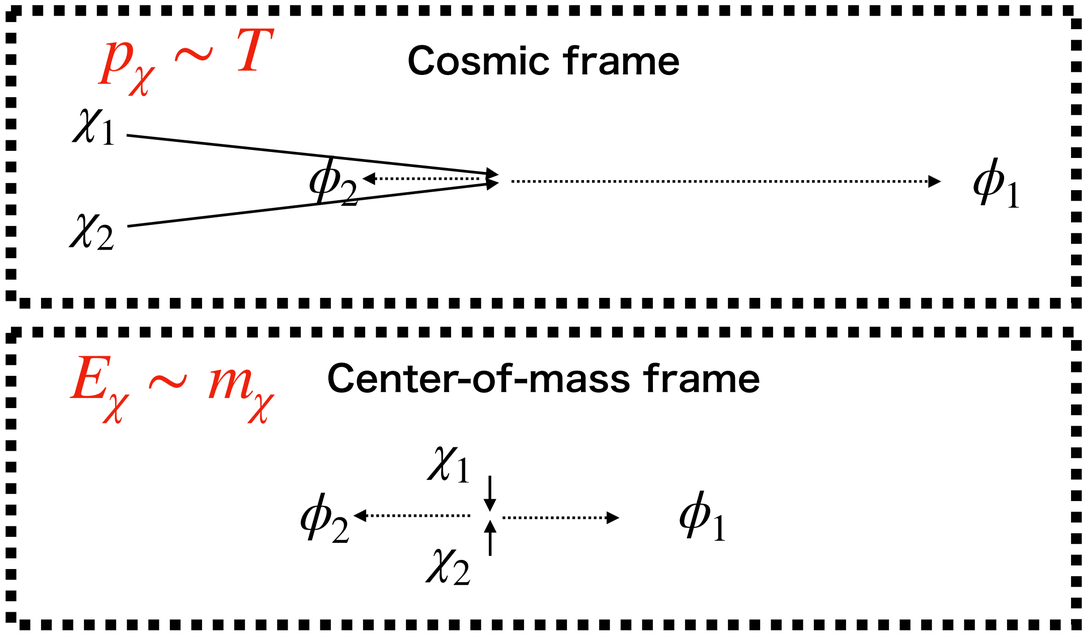

$$t_{\text{ignition}}^{-1} \sim c_n T^3/(m_\chi^2)$$

## Simplified model.




- When $n$<1 ignition rate>thermalization rate
  =>Burst production
- Ignition rate $\propto T^3$ similar to $1 \to 2$ case independent of n.

# 2 to 2, burst production mechanism: small angle scattering

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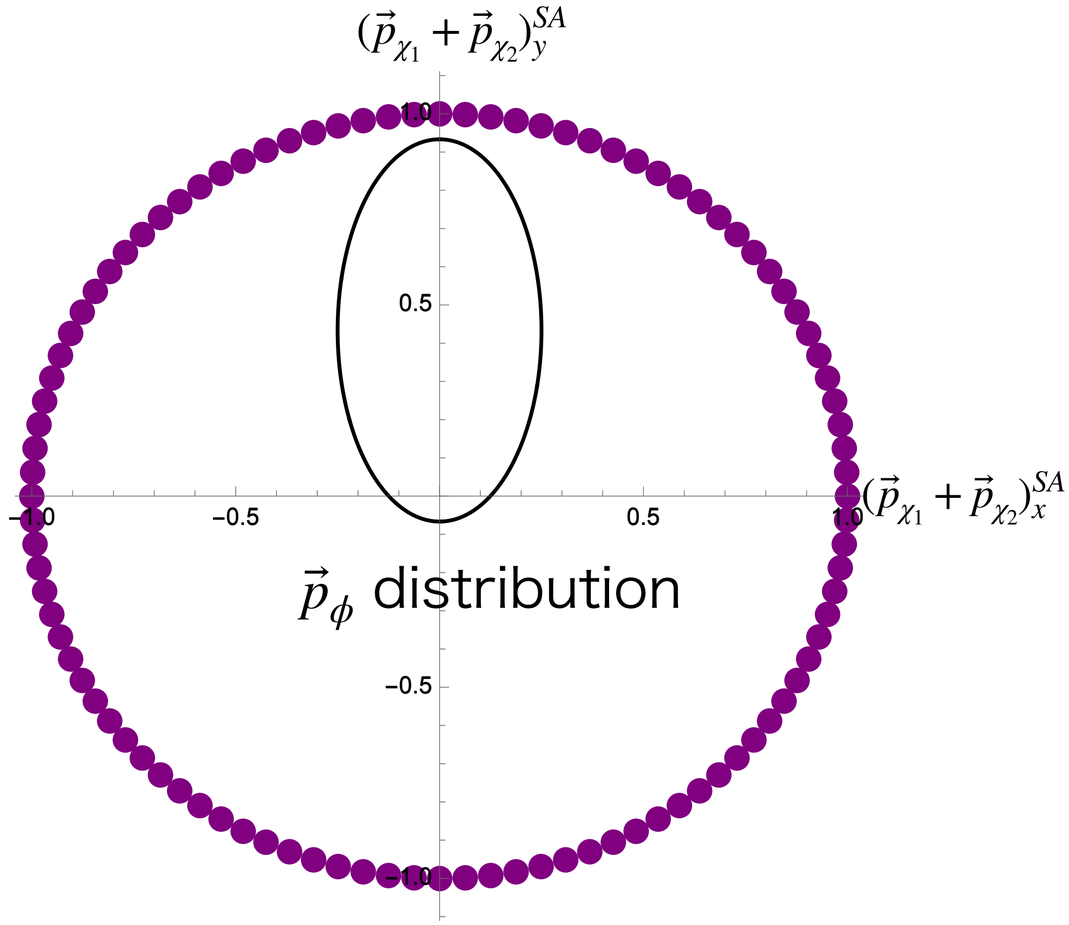


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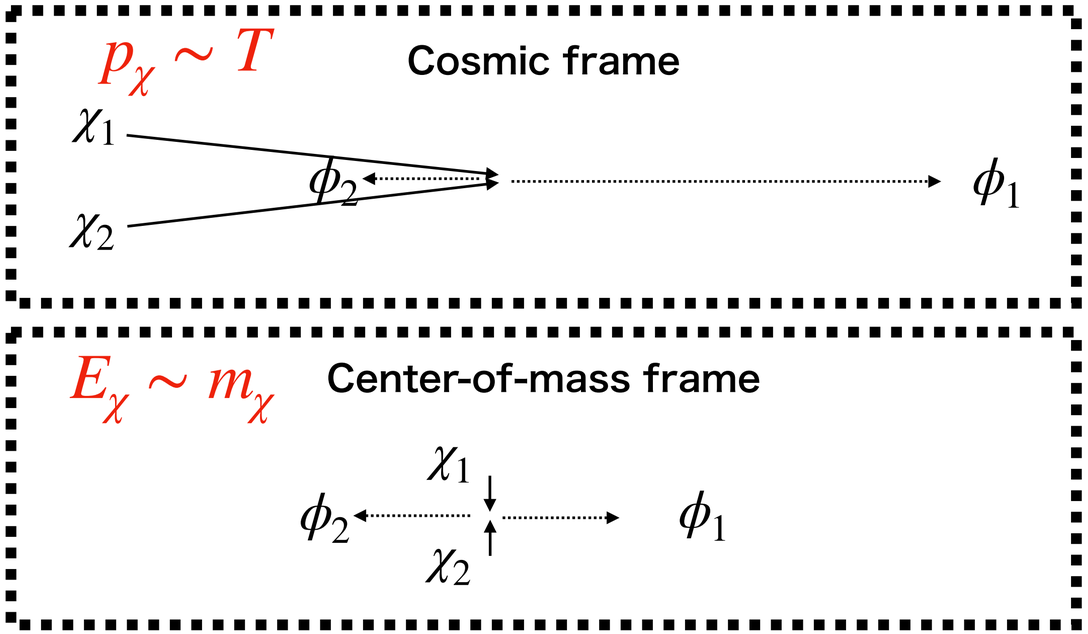
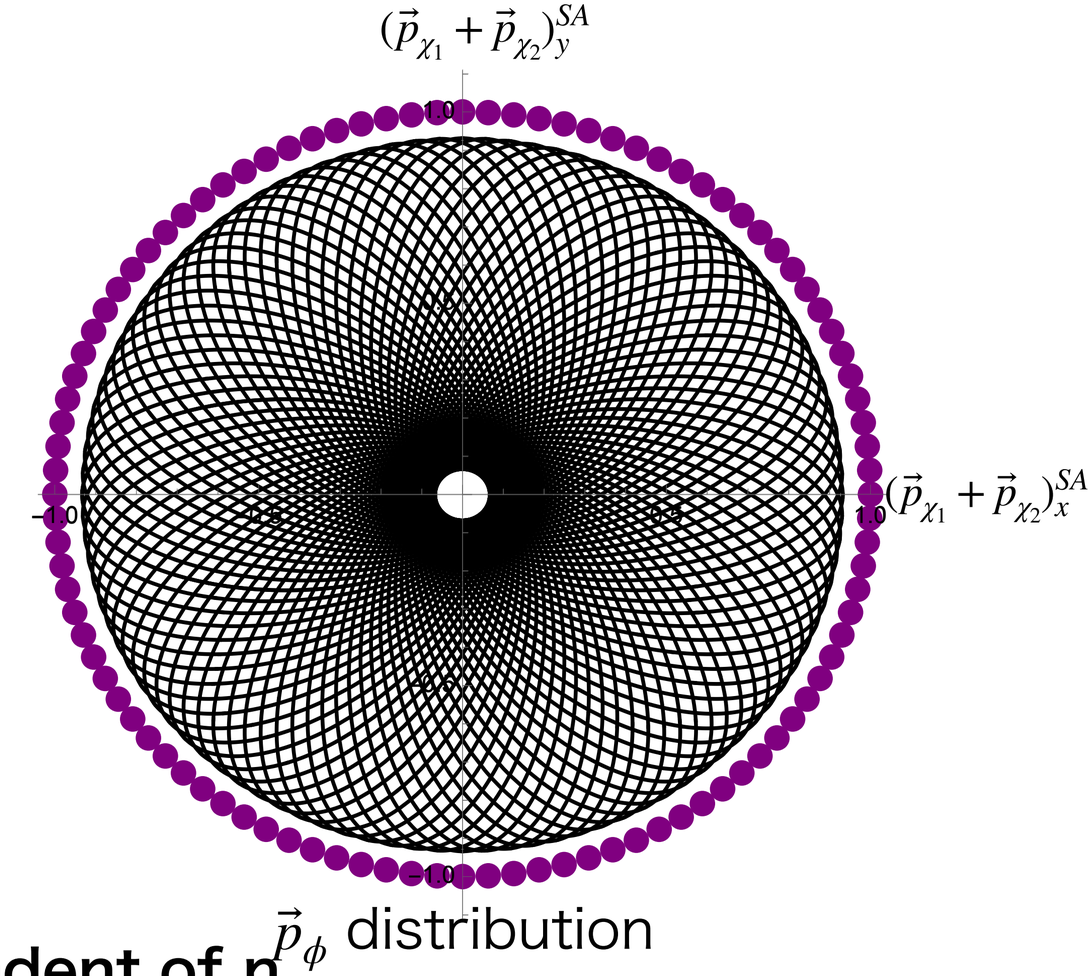



## Simplified model.




$\vec{p}_\phi$ distribution

$$t_{\text{ignition}}^{-1} \sim c_n T^3/(m_\chi^2)$$

- When $n$<1 ignition rate>thermalization rate
  =>Burst production
- Ignition rate $\propto T^3$ similar to $1 \to 2$ case independent of n.

# Messages: Both $1 \to 2, 2 \to 2$ has burst production

WY, 2301.08735; Sakurai, WY, 2410.18968

- Stimulated emission may **generically** occur in thermal production of bosonic particles.
- **Caveats in freeze-in** production. We need to avoid iginition to justify the usual estimate of the freeze-in.
- eV dark matter can be thermally produced with suppressed free-streaming length!
  **"Hot DM" Revives!?**

# eV dark matter is special!

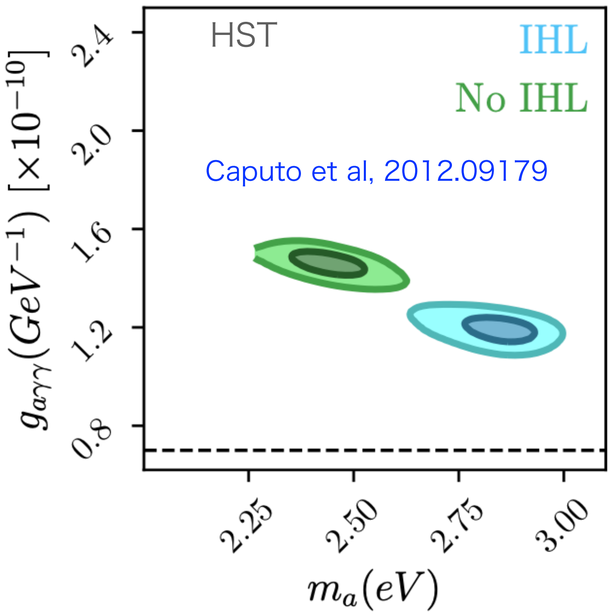
Interestingly, in the huge parameter region,

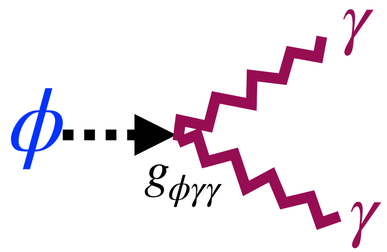
we have coincidences around eV.

**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



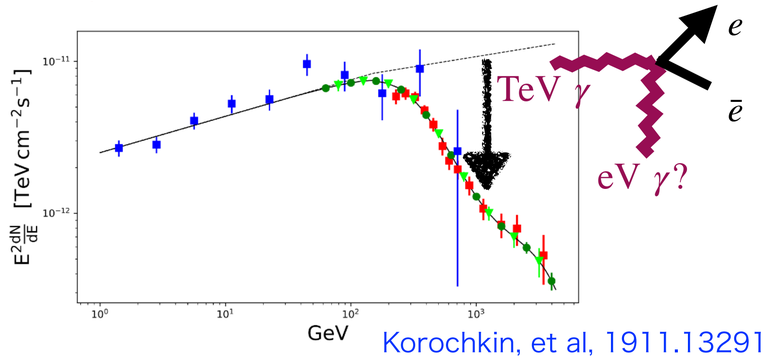




$m_\phi \sim eV$,

lifetime $\sim 10^{16}$yrs

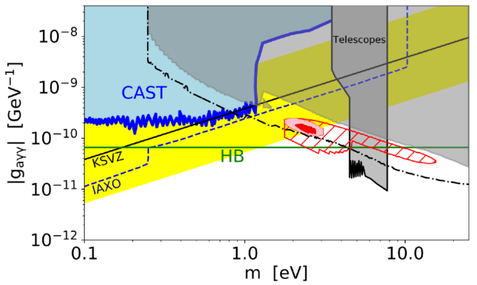
**spin=0**

**The TeV $\gamma$ 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



# eV dark matter is special!

Inte

we

**+ Hot DM paradigm**

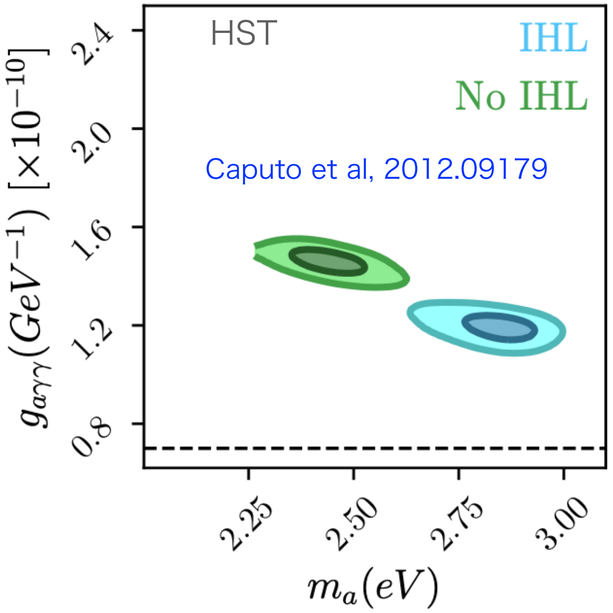
The **anisotr** **ets a better**

**backgroun** **ALP DM**

a decaying

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

Gong et al 1511.01577



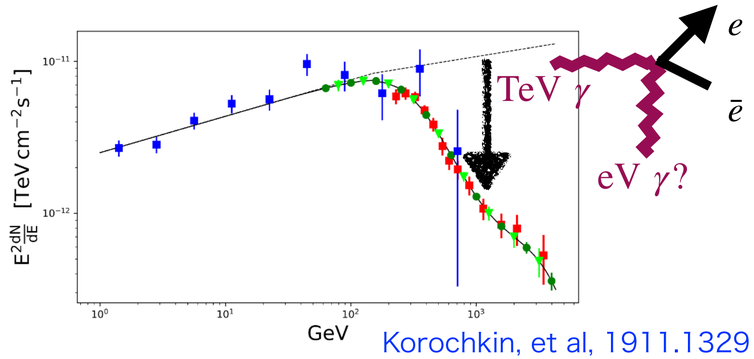

$\phi\phi \to \gamma\gamma$

$m_\phi \sim eV$,

lifetime $\sim 10^{16}$yrs

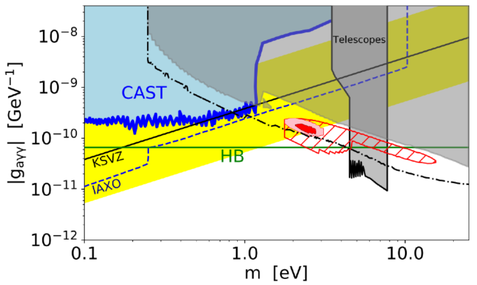
**spin=0**

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




Korochkin, et al, 1911.13291

Bernal et al, 2208.13794



# 3. Experimental search for eV Dark Matter

- Indirect detection
  with infrared spectrograph

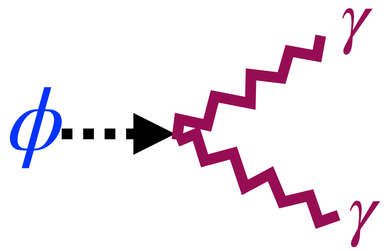
T. Bessho, Y. Ikeda, WY, 2208.05975
WY, Hayashi 2305.13415
WY et al, 2402.07976
Bessho, Ikeda, *WY*, Paper 13096-274 (SPIE-Conference 13096)

# Difficulties of eV DM indirect detection

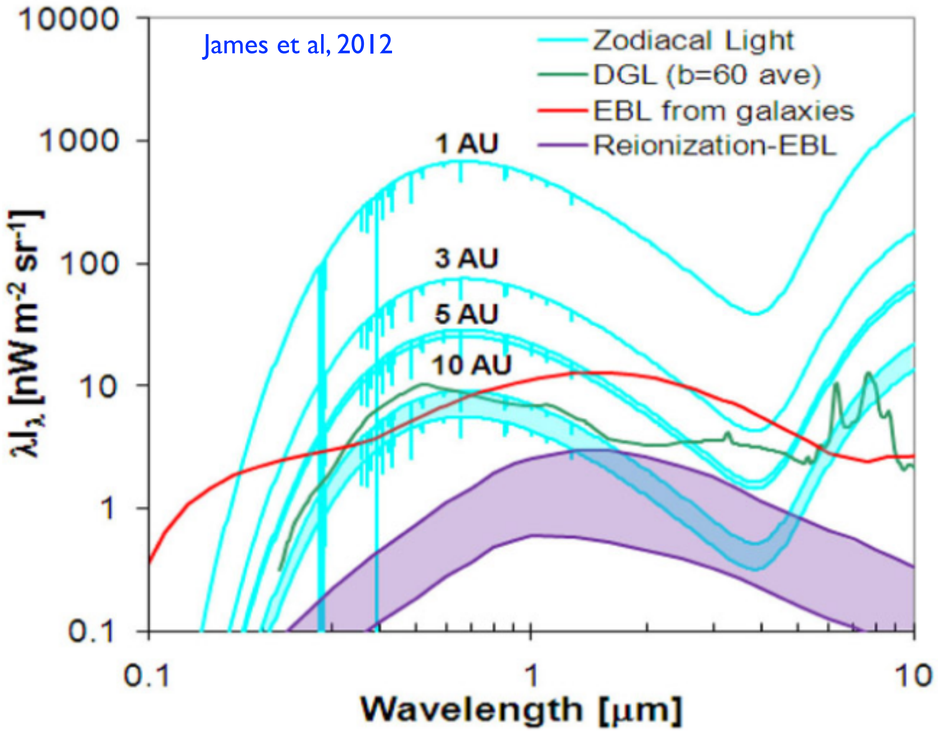
## Significant background:

- Thermal radiation
- Zodiacal light: sun light scattered by dusts
- Star light
- Cosmic infrared background






$$\lambda_\gamma \sim 1\mu m \frac{2\mathrm{eV}}{\mathrm{m}_\phi}$$

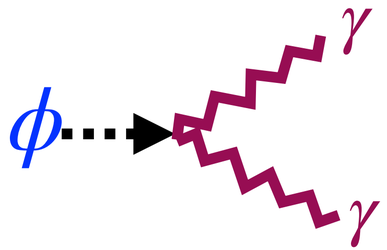


# Difficulties of eV DM indirect detection

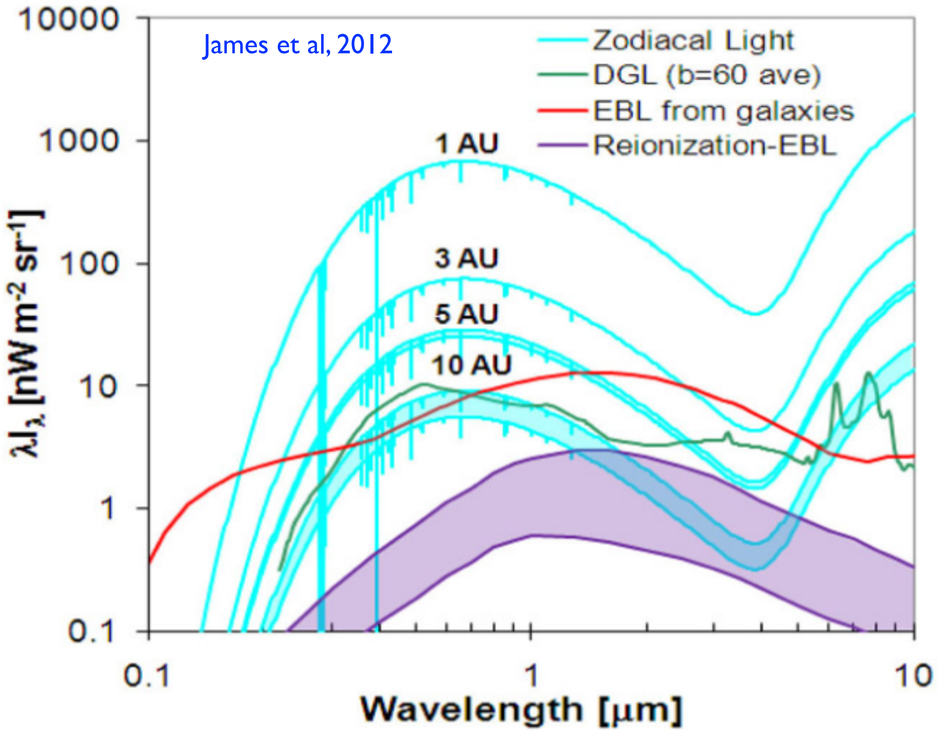
## Significant background: continuous spectra

- Thermal radiation
- Zodiacal light: sun light scattered by dusts
- Star light
- Cosmic infrared background

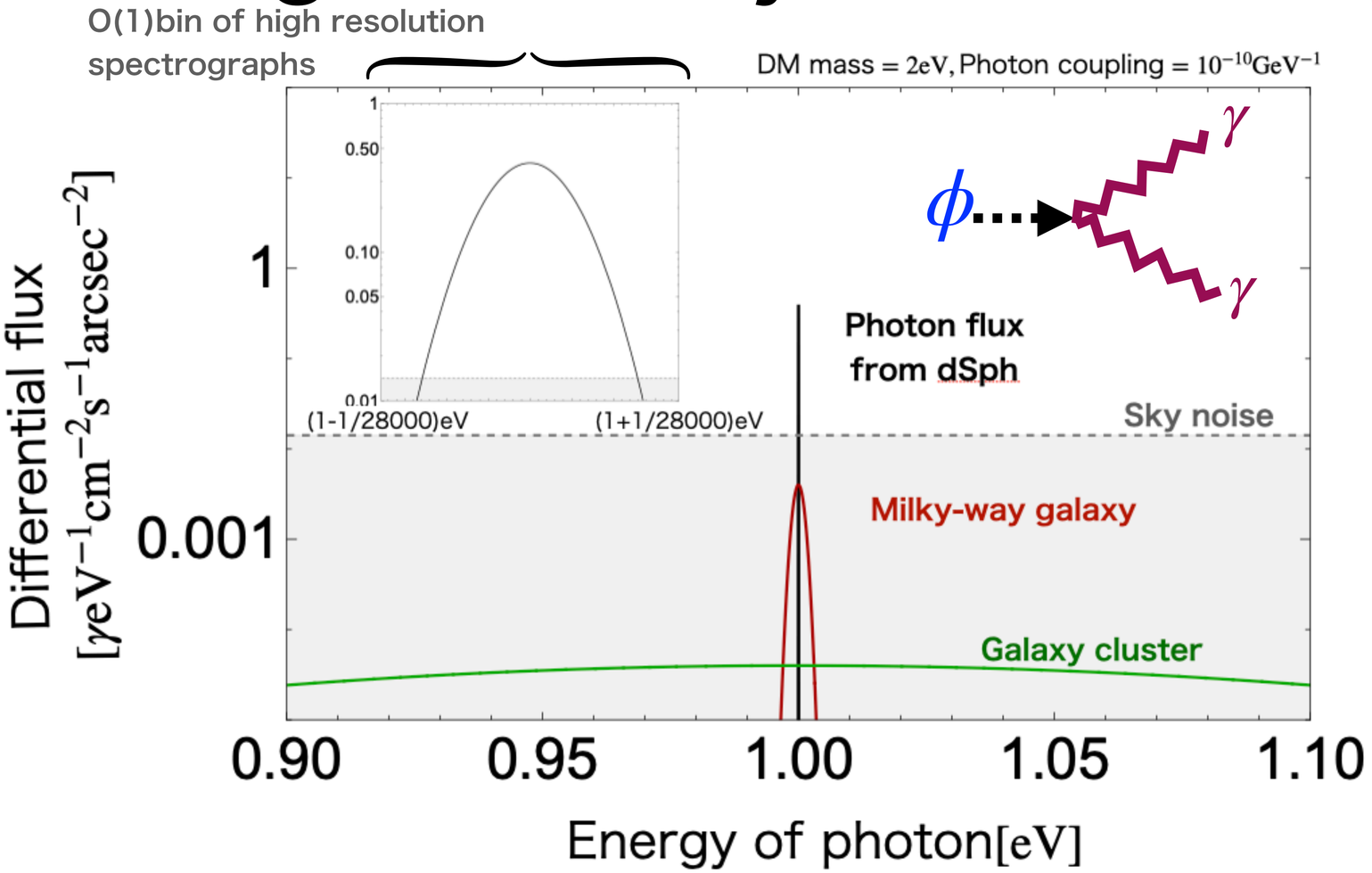





$$\lambda_\gamma \sim 1\mu m \frac{2\mathrm{eV}}{\mathrm{m}_\phi}$$



# **DM line-like spectrum** and **background continuous spectrum** can be distinguished by **infrared spectrographs.**




T. Bessho, Y. Ikeda, WY, 2208.05975

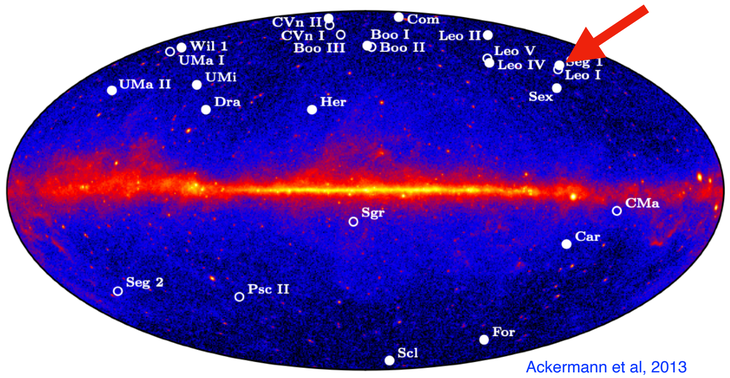
-DM signals from some dwarfs are **sky background free** for existing **high energy resolution** infrared spectrographs.

T. Bessho, Y. Ikeda, WY, 2208.05975

-With **high angular resolution** one can avoid seeing visible stars, while “see” the DM distribution from the decay photon in dwarfs.

WY, Hayashi, 2305.13415

# eV DM search with WINERED @ Magellan



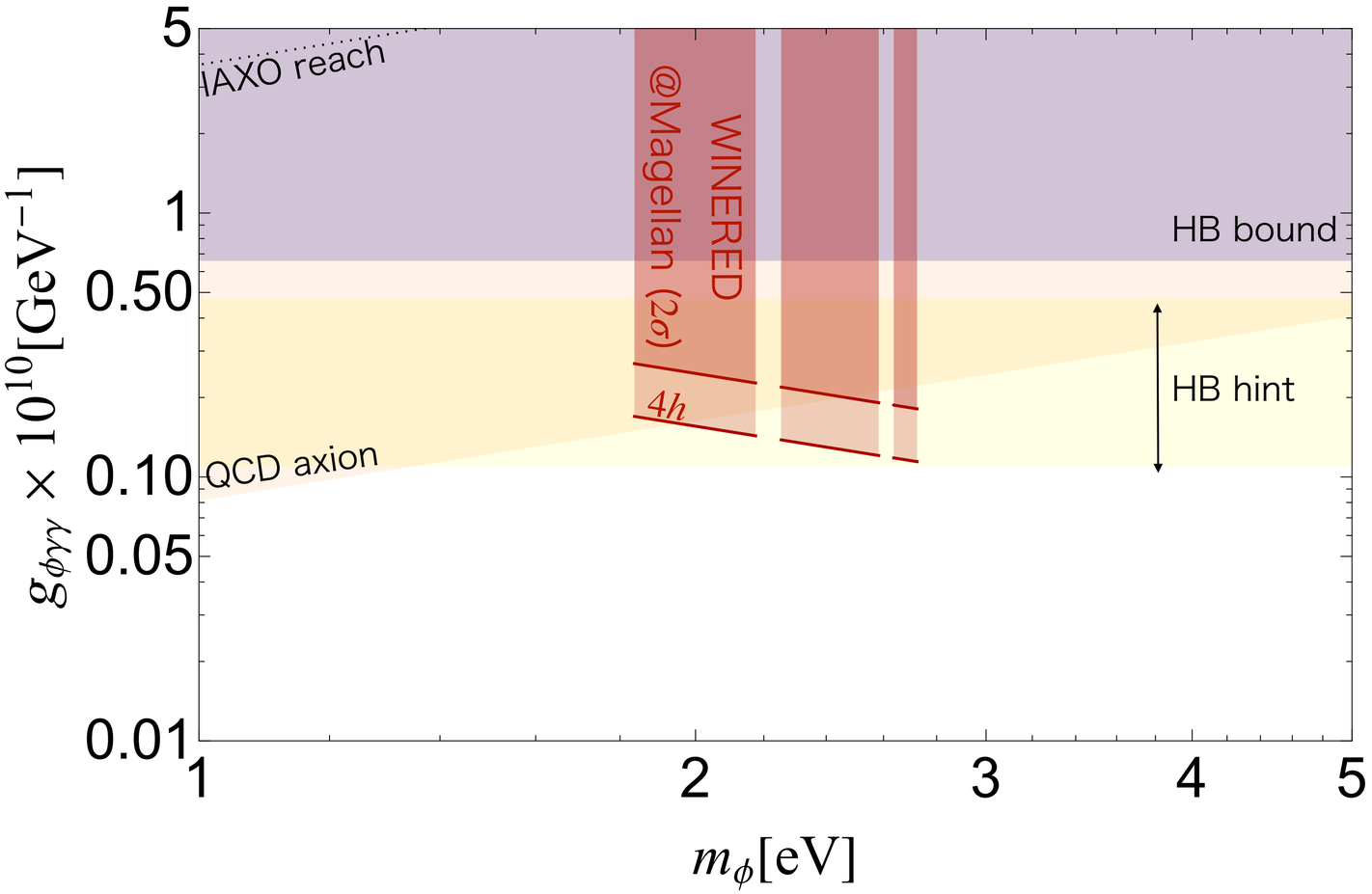

Ackermann et al, 2013



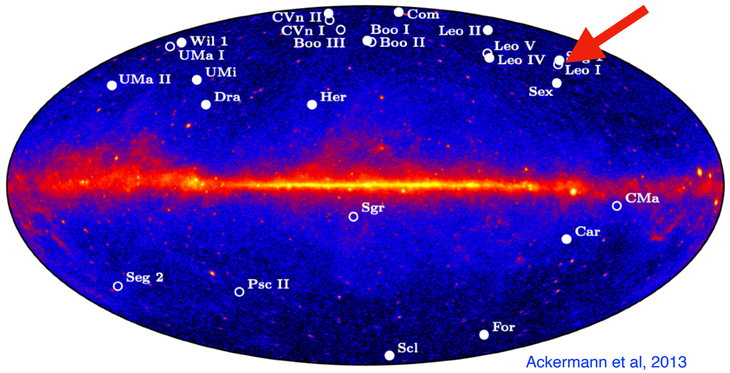
https://www.cfa.harvard.edu

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

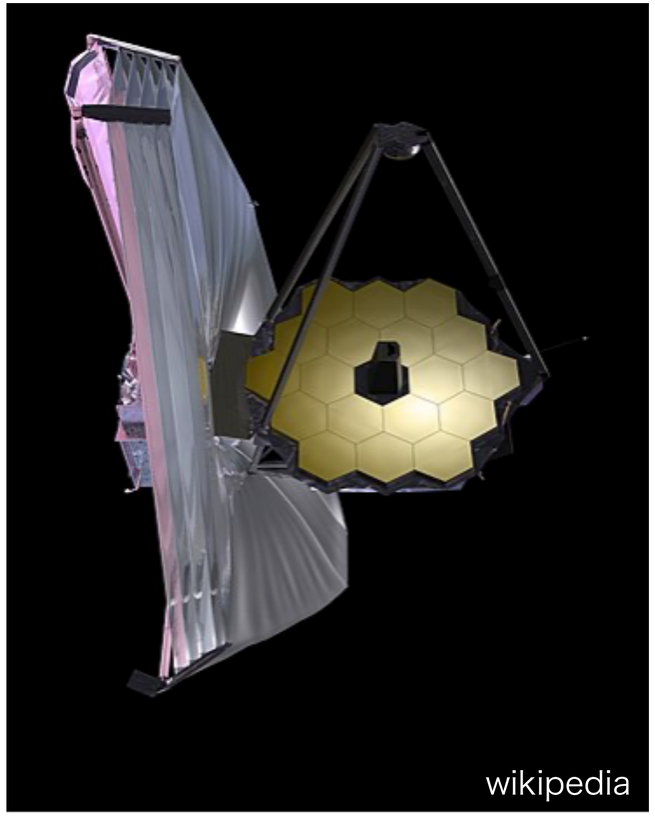
$\lambda/\delta\lambda \sim 30000$ T. Bessho, Y. Ikeda, WY, 2208.05975



# eV DM search with NIRSpec @ JWST



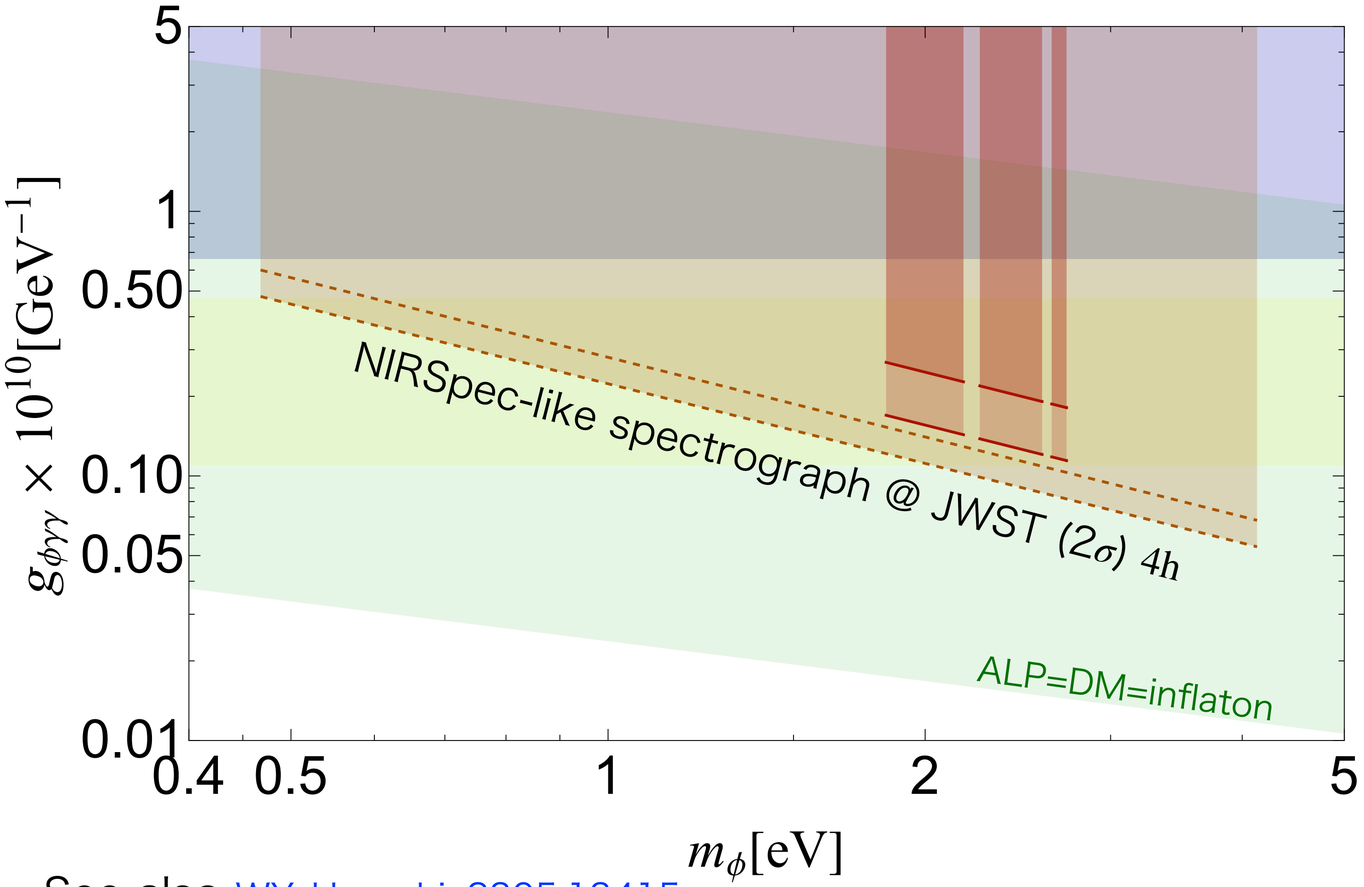

Ackermann et al, 2013




**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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Target dSphs

| Object name | Object type | RA(J2000) | DEC(J2000) | Obs. date | $J_m$ | $R$ | $T_I$ (sec) |
|---|---|---|---|---|---|---|---|
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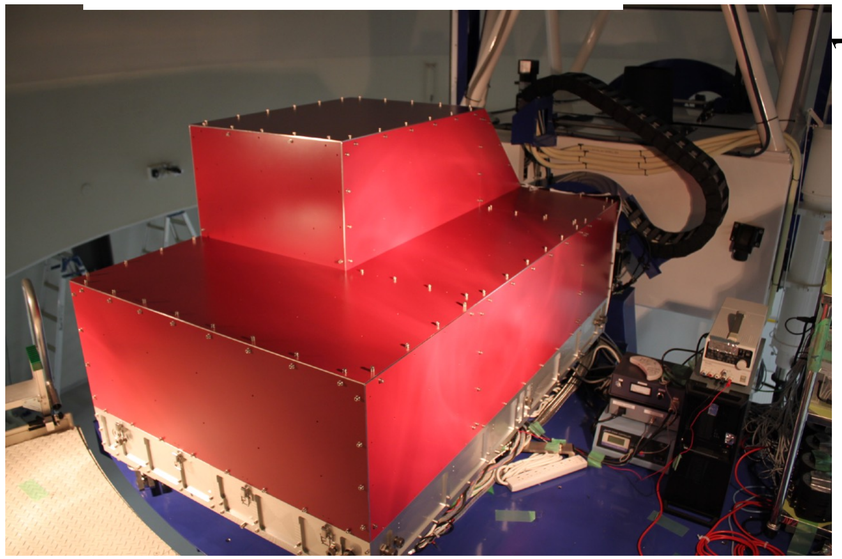
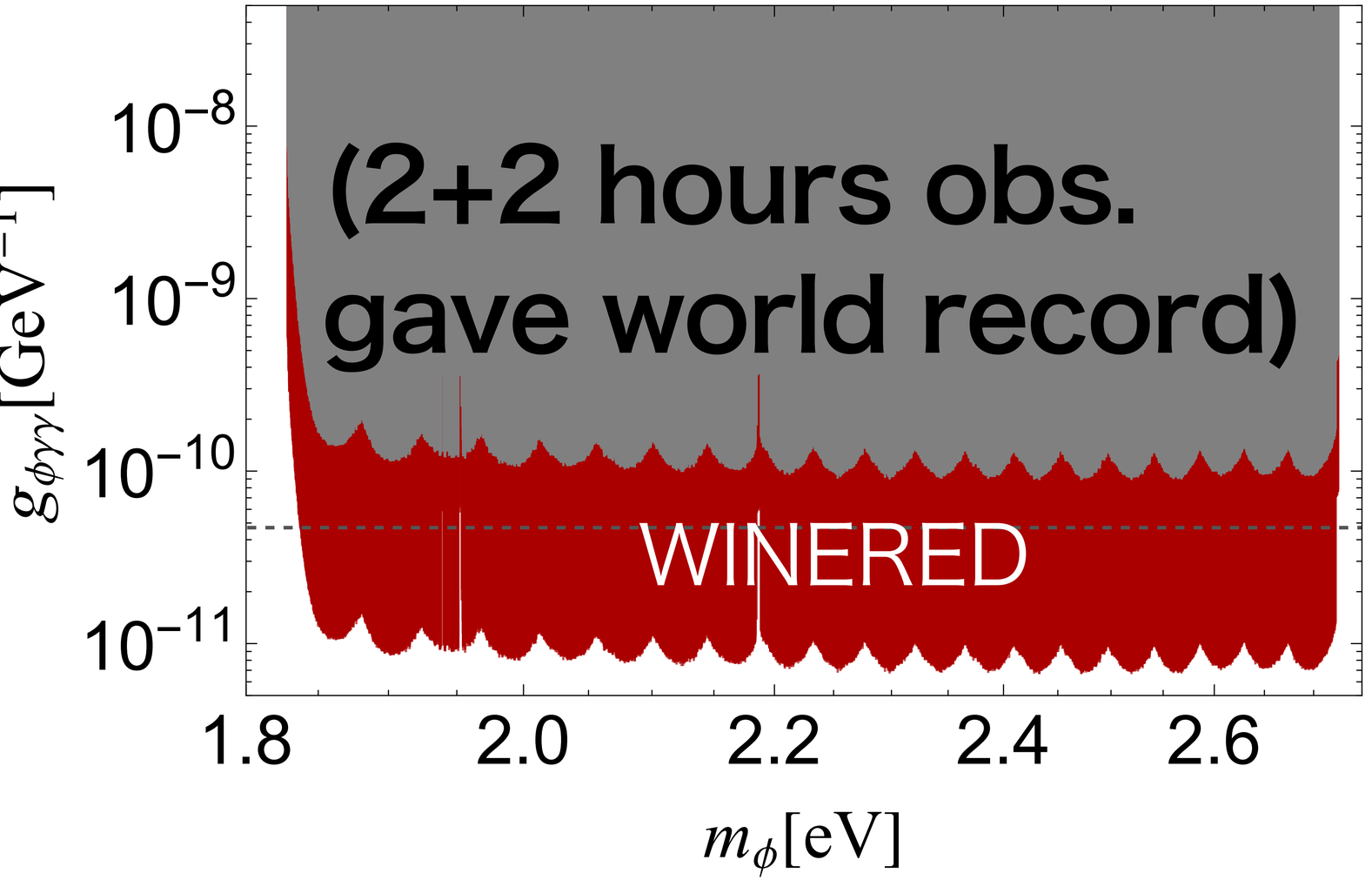
# Result: (continuous spectra subtracted)

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



Ikeda et al 2006



# ·4. Future Prospect

- **A future direction for eV dark matter search with infrared spectrograph**

  - Observation with state-of-the-art observatories is super competitive.

  - Is there a less competitive approach?

# Dark Matter Quest Spectrograph(DMQS)

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

**We proposed the design of an infrared spectrograph with the same senstivy for DM as WINERED but installable on a sub-meter aperture telescope!**

**The price to pay is the angular(spatial) resolution.**

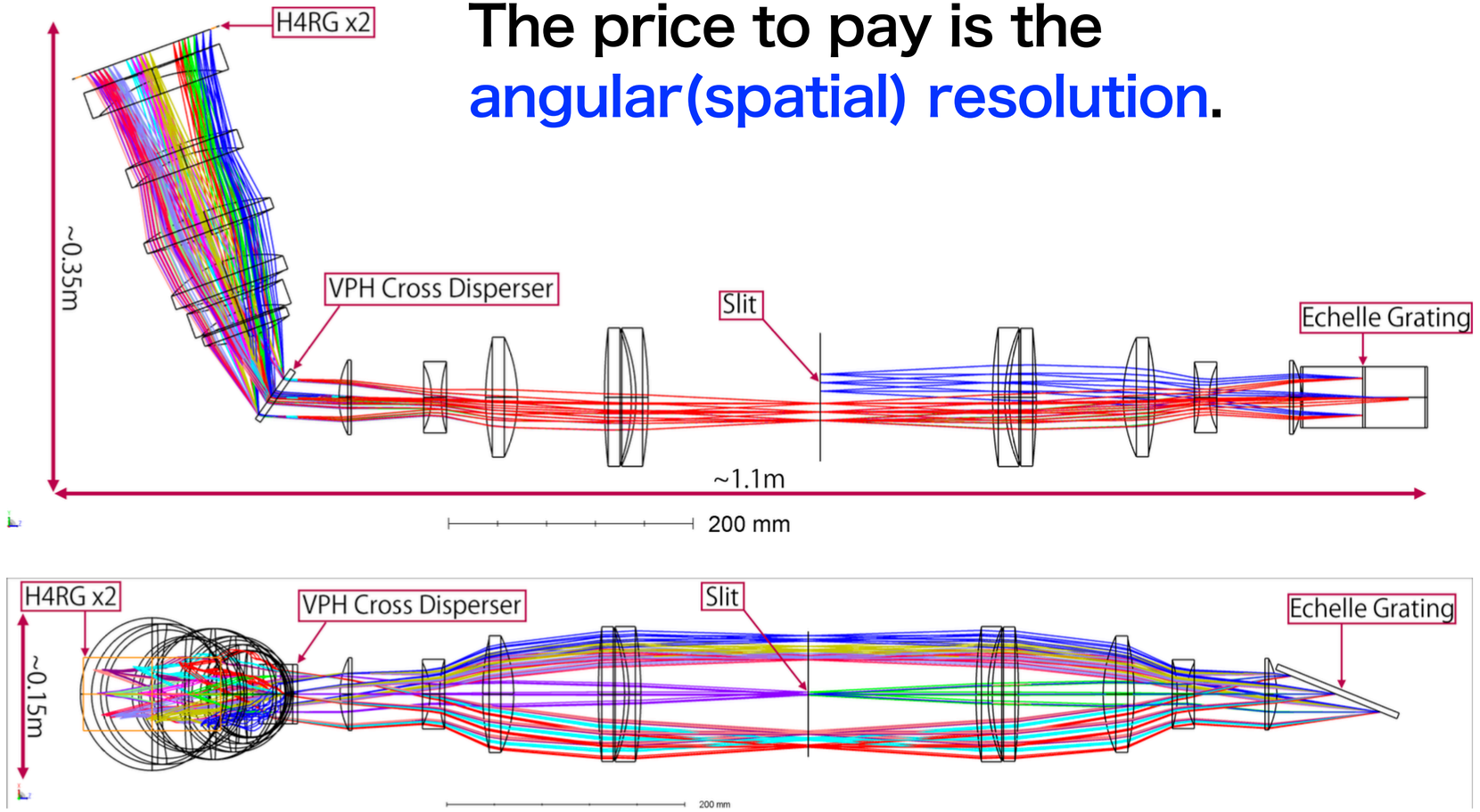



Figure 3. The top and front views of the optical layout of the high-resolution mode of the DMQS

C.f. state-of-the-art telescopes

Magellan:6.5m

JWST:6.5m

Subaru:8.3m

TMT(future):30m

**Our strategy:**

**Install DMQS on less competitive small telescopes and wait!**

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https://www.rentio.jp/matome/2021/01/dslr-smartphone-compare/

https://www.n-pri.jp/print/tips/tips17/

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

**We proposed the design of an infrared spectrograph with the same senstivy for DM as WINERED but installable on a sub-meter aperture telescope!**

**The price to pay is the angular(spatial) resolution.**













https://www.rentio.jp/matome/2021/01/dslr-s

https://www.n-pri.jp/print/tips/t

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

C.f. state-of-the-art telescopes

agellan:6.5m

VST:6.5m

ubaru:8.3m

MT(future):30m

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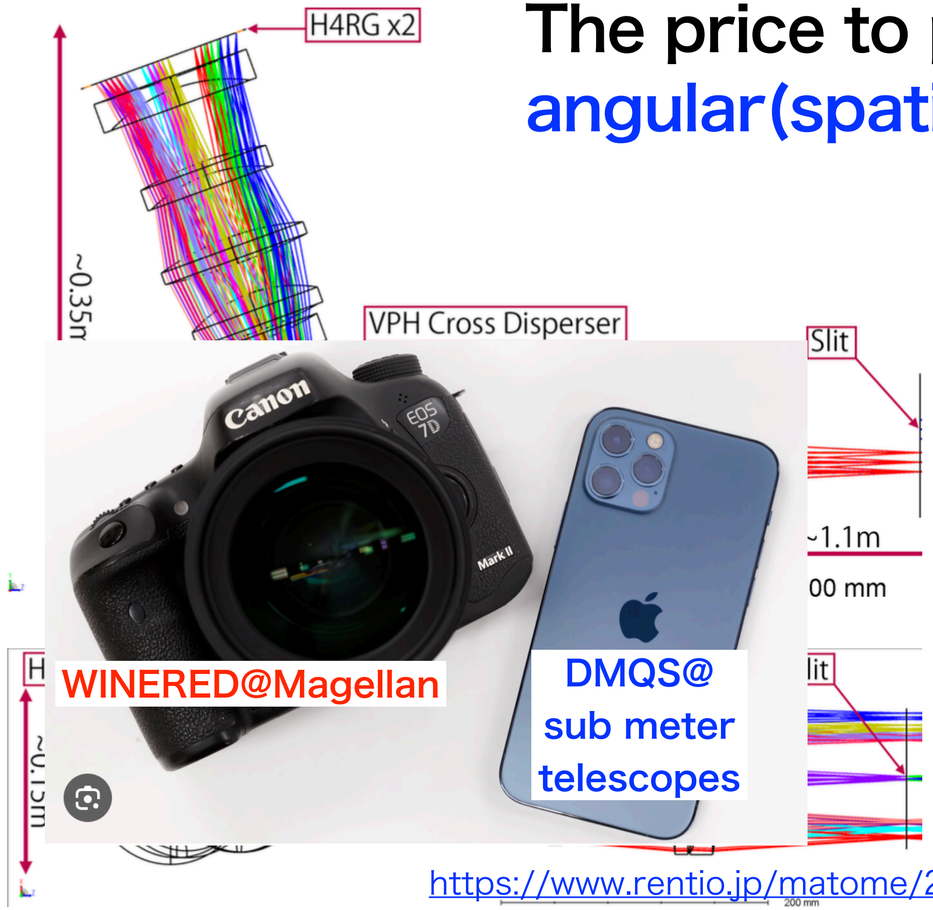








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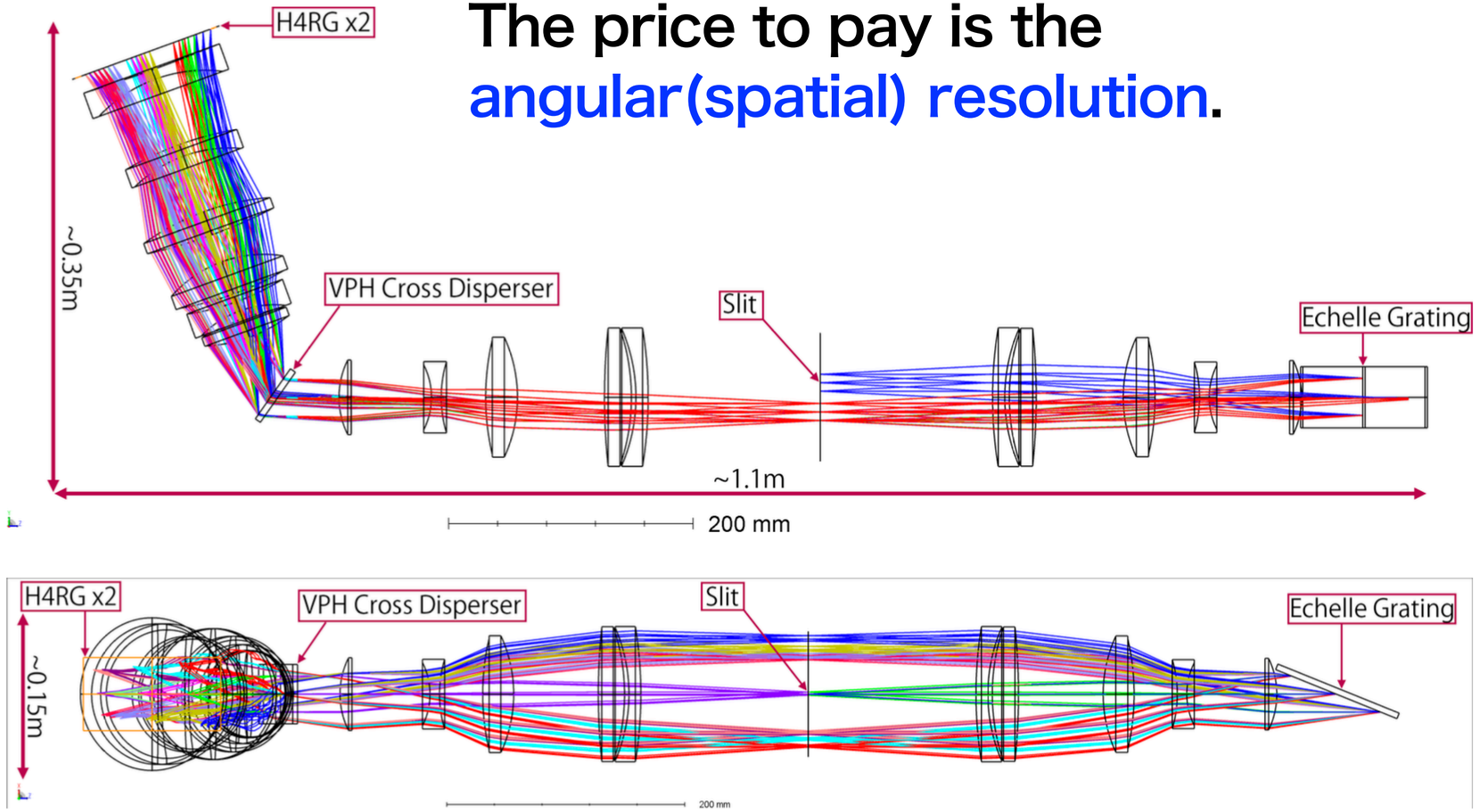


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# Conclusions:

- Typical momentum of thermally produced DM may be much lower than $T$ when stimulated emission is significant.
- 'hot DM' can be cold DM!
  **eV dark matter is special.**
- **Infrared spectrographs are powerful detectors for eV DM searches**. Stay tuned—new results and technologies are on the way!

# Back up slides