Current status of eV axion dark matter search

@FY2023 "What is dark matter? - Comprehensive study of the huge discovery space in dark matter" March 7, 2023, Kyoto University

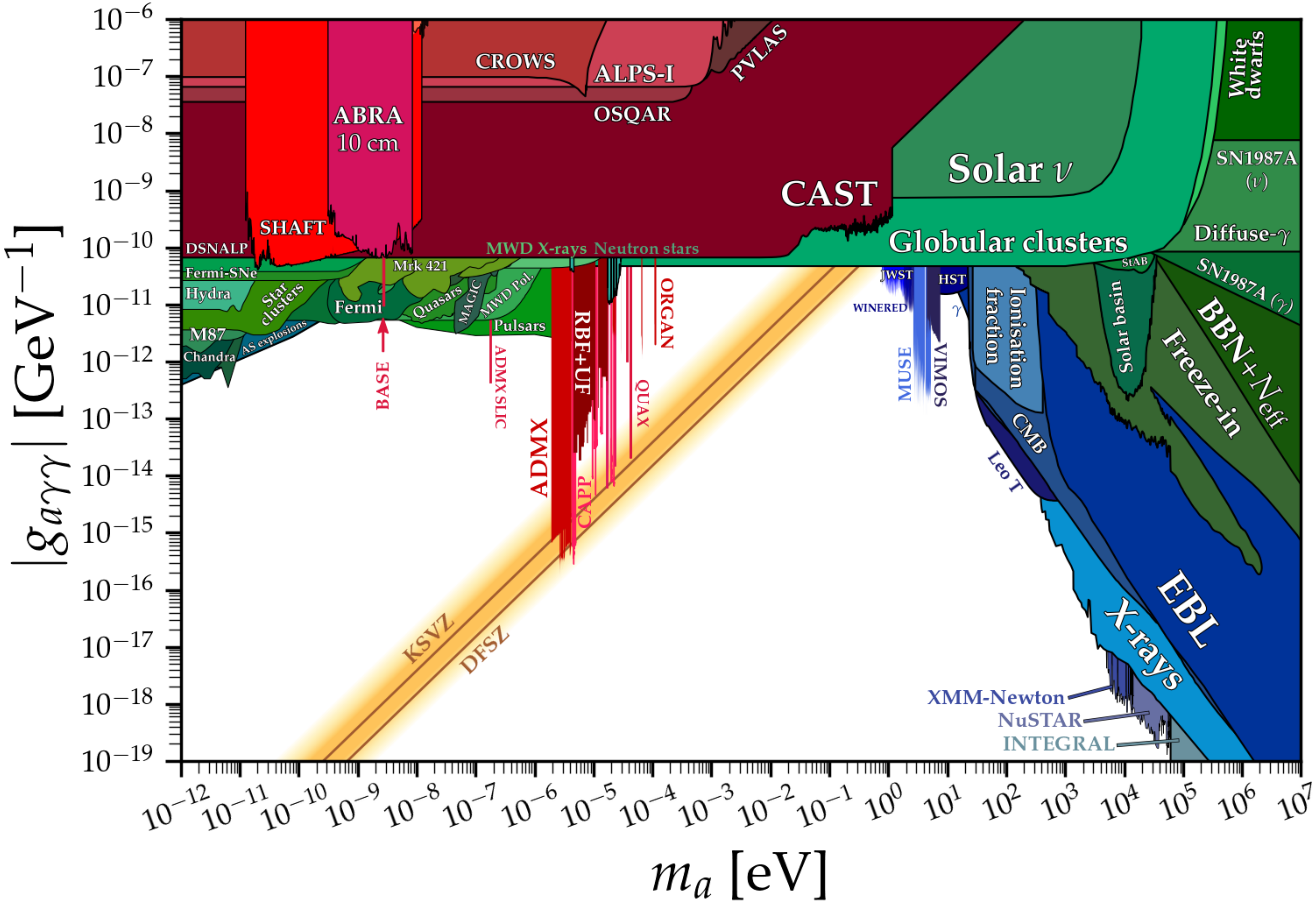
Tohoku U.-> Tokyo Metropolitan U.

Wen Yin

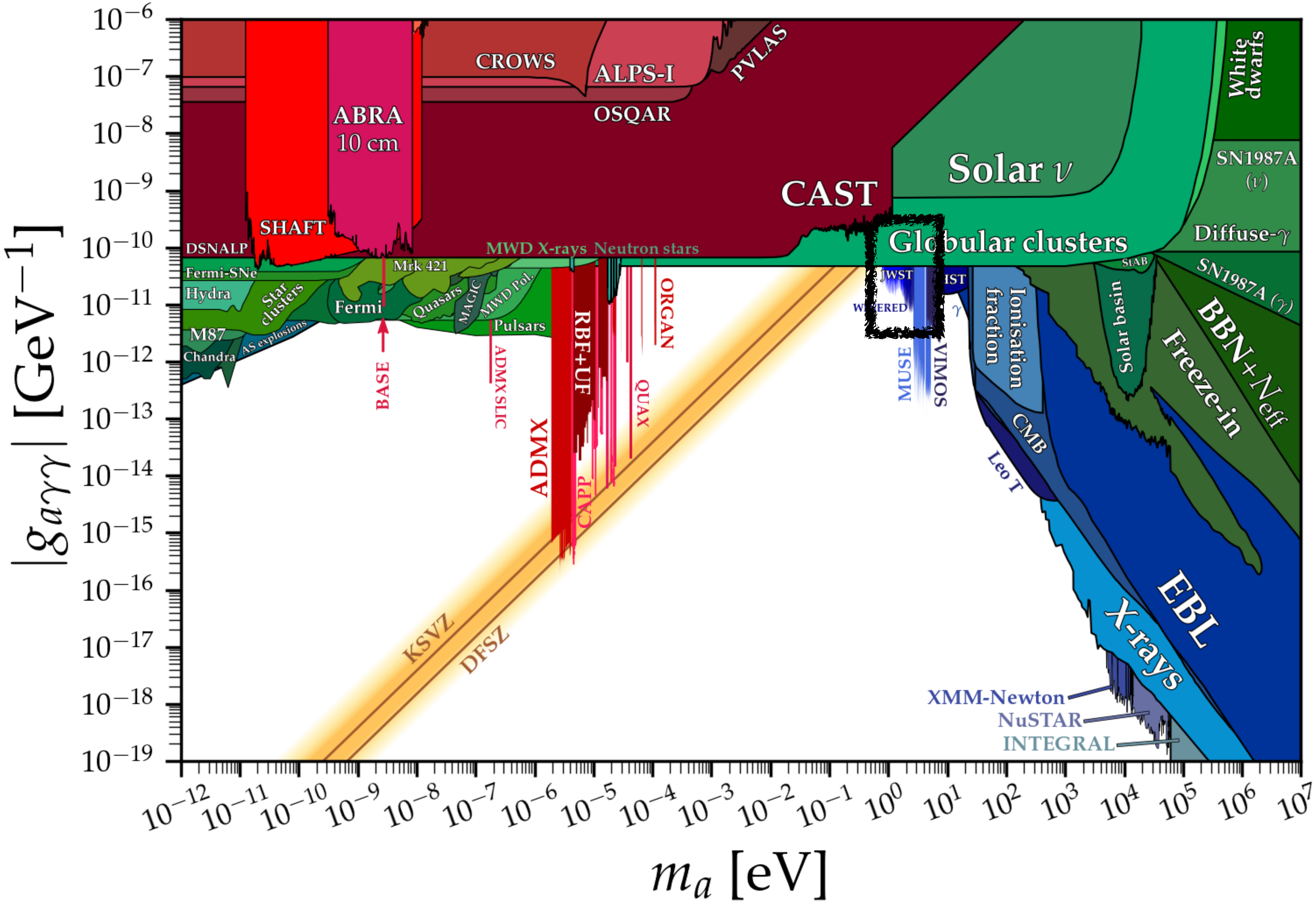
Based on Bessho, Ikeda, WY, 2208.05975
WY, Hayashi, 2305.13415,
WY, Ikeda, Bessho, Kobayashi+WINERED team, 2402.07976

- 1. Introduction

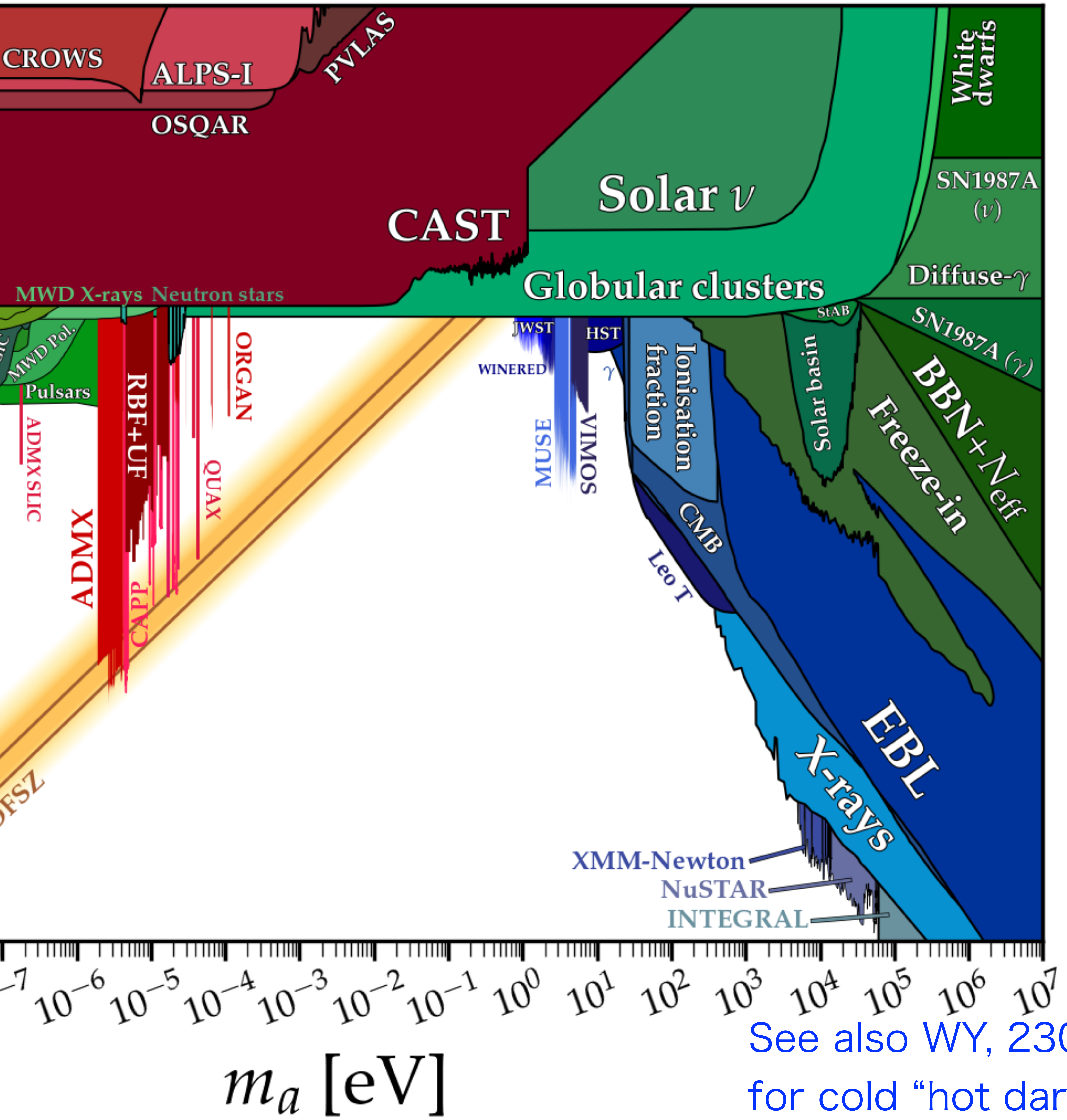
Axion Dark Matter



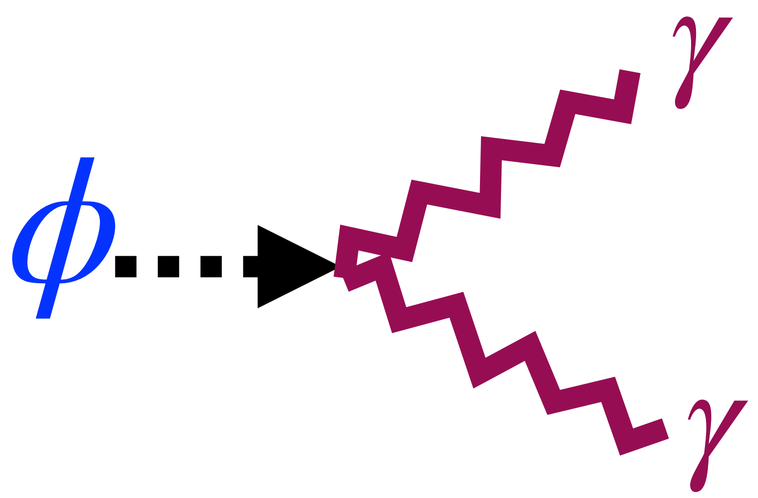
Axion Dark Matter



Why eV axion dark matter?



See also WY, 2301.08735
for cold “hot dark matter”



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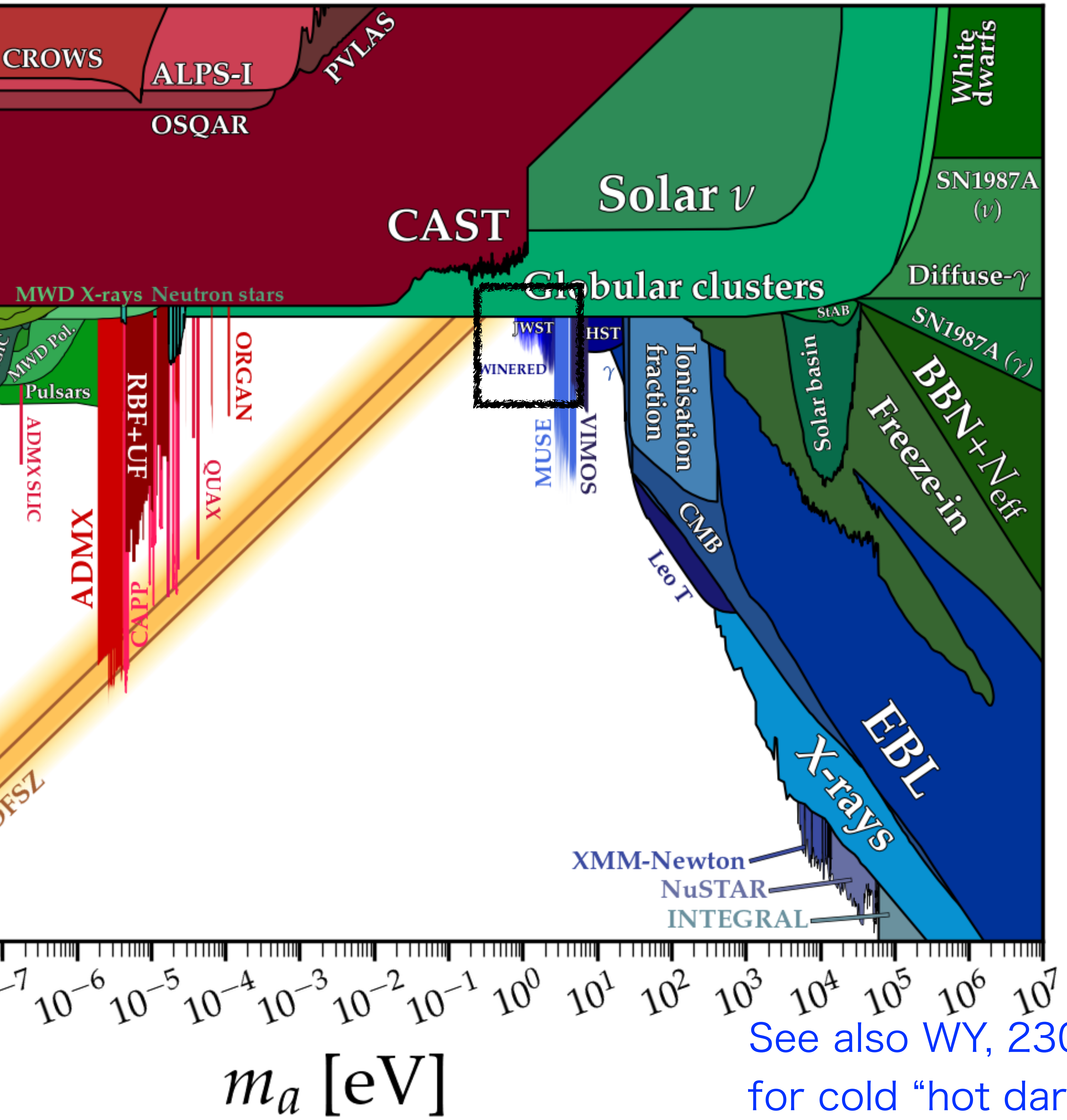
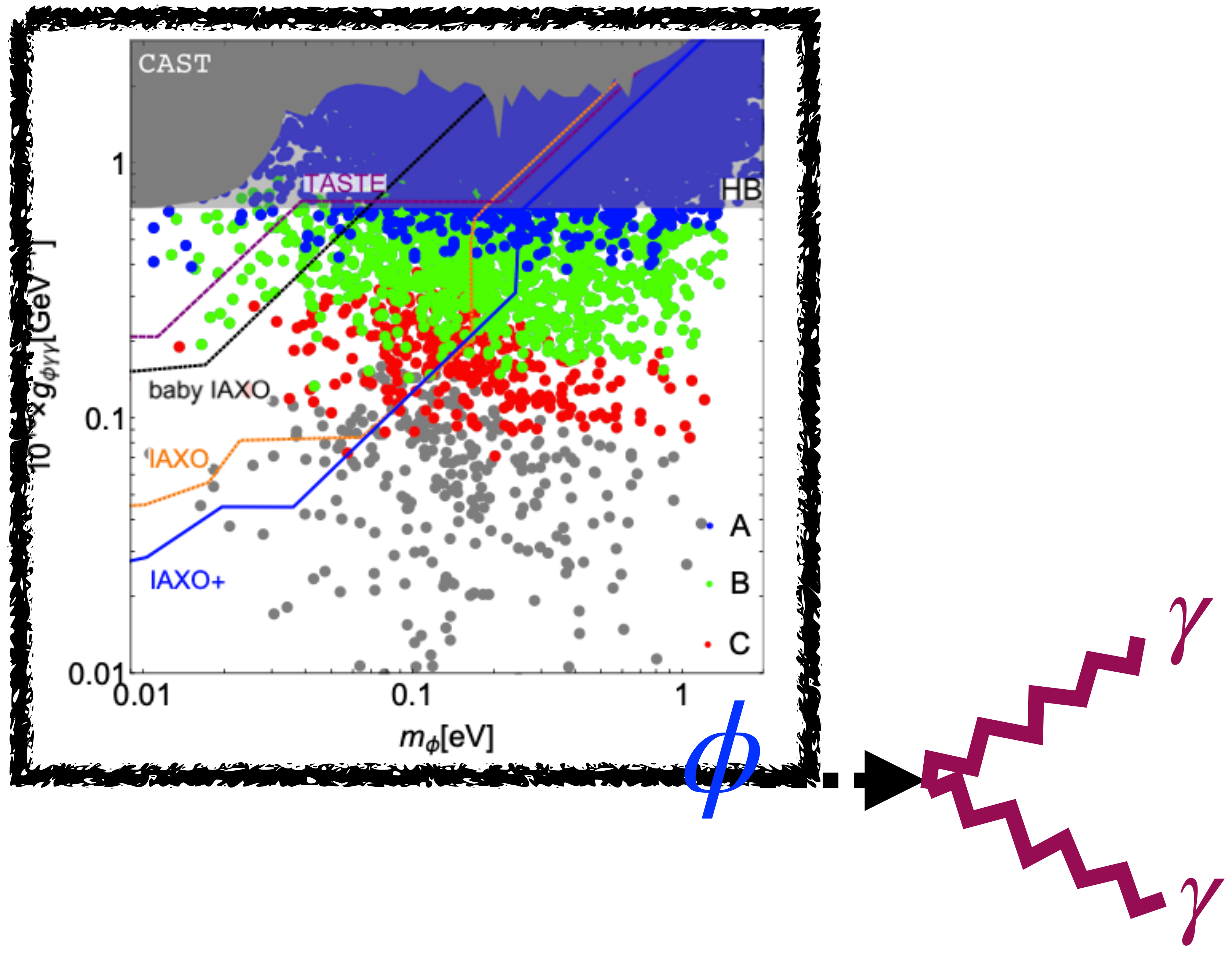


ALP miracle scenario:

Axion=Dark Matter=Inflaton

Daido, Takahashi, WY, 1702.03284,1710.11107



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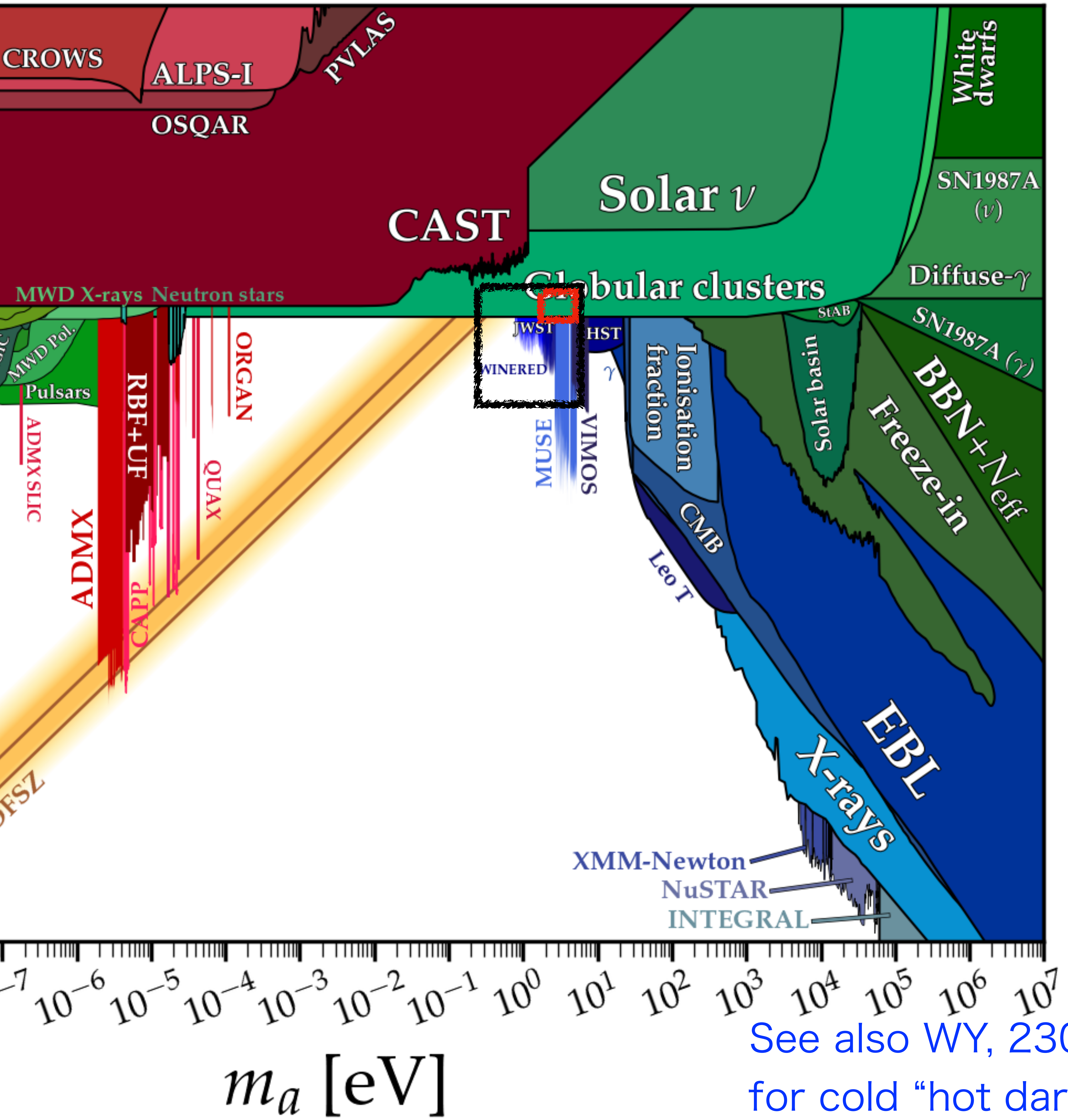

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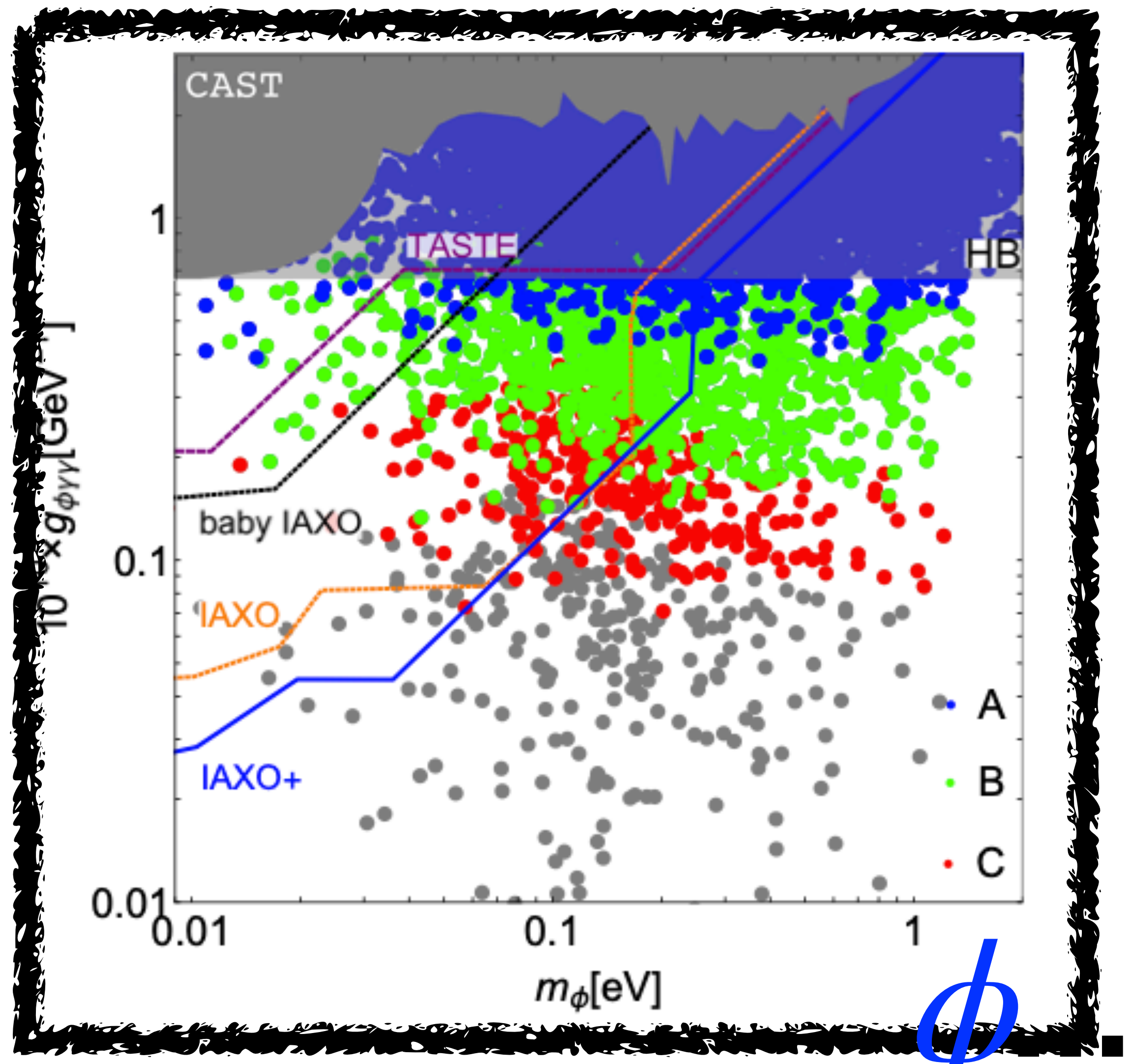
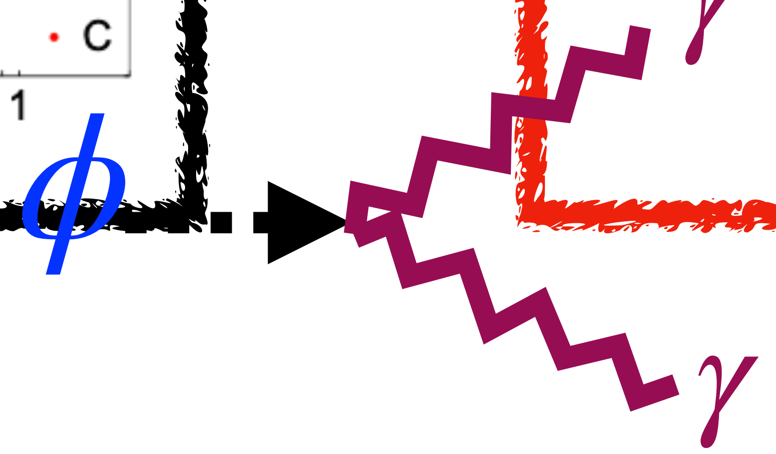
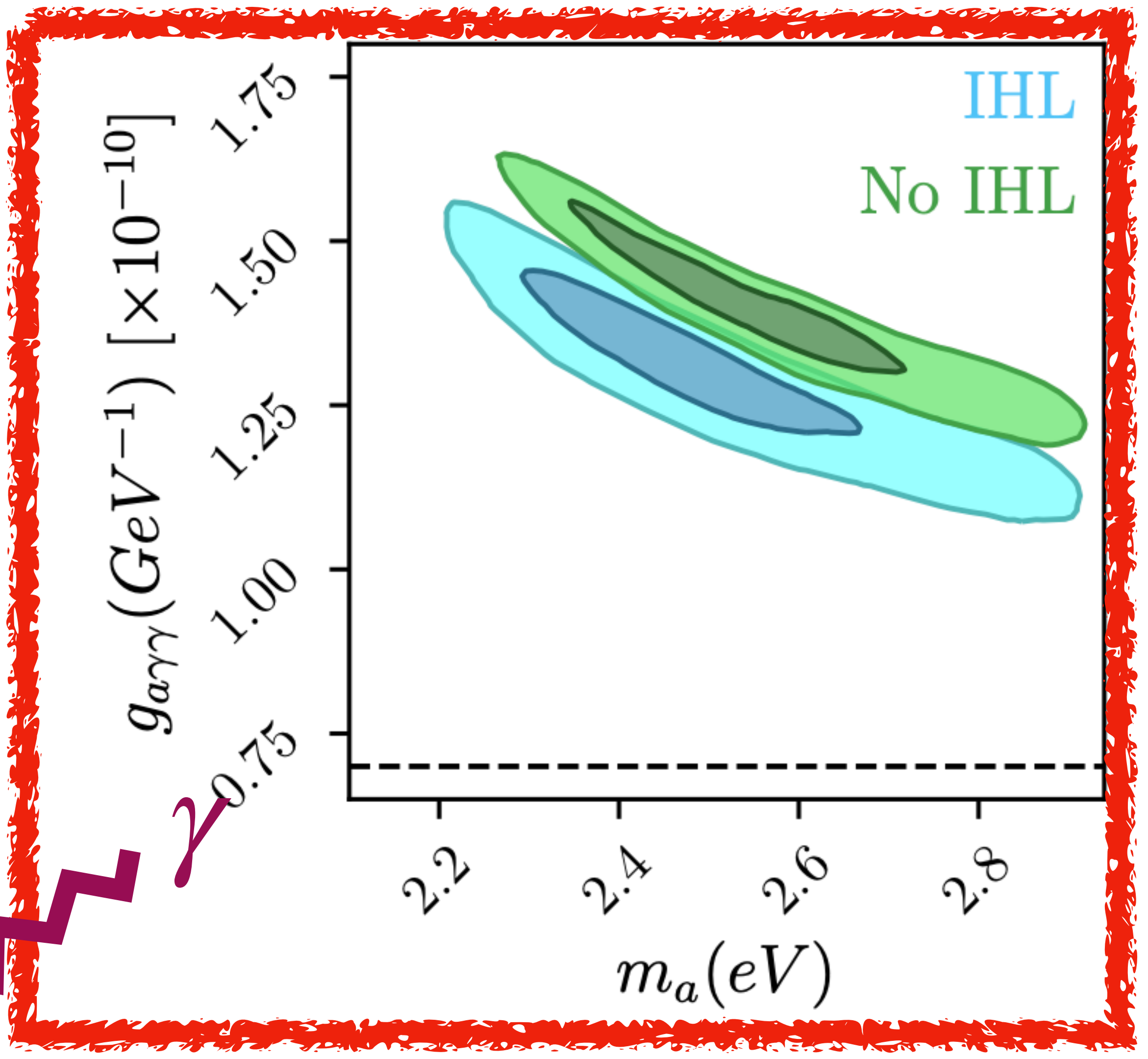




Anisotropic cosmic infrared background Gong et al 1511.01577, Caputo et al, 2012.09179



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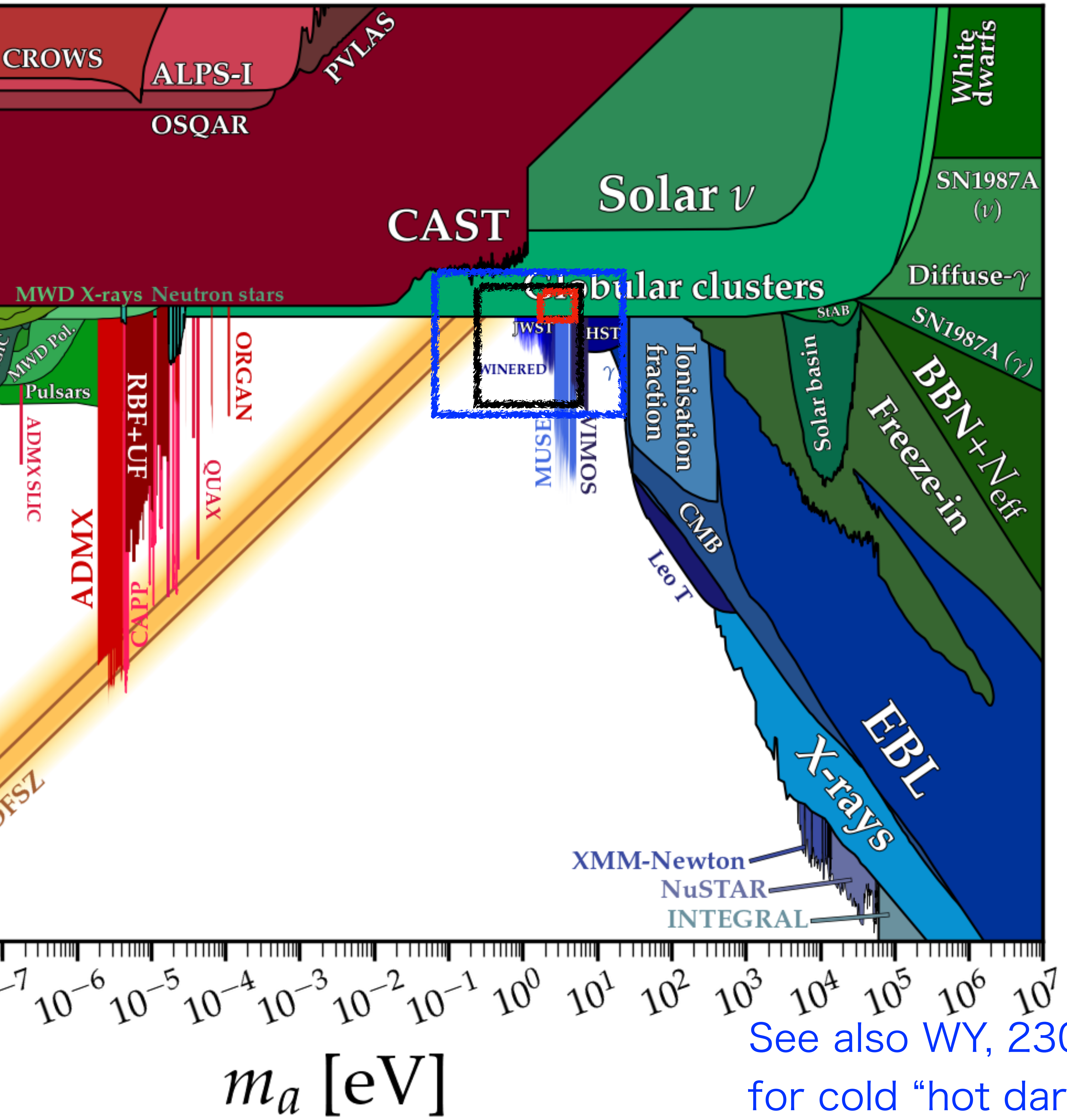

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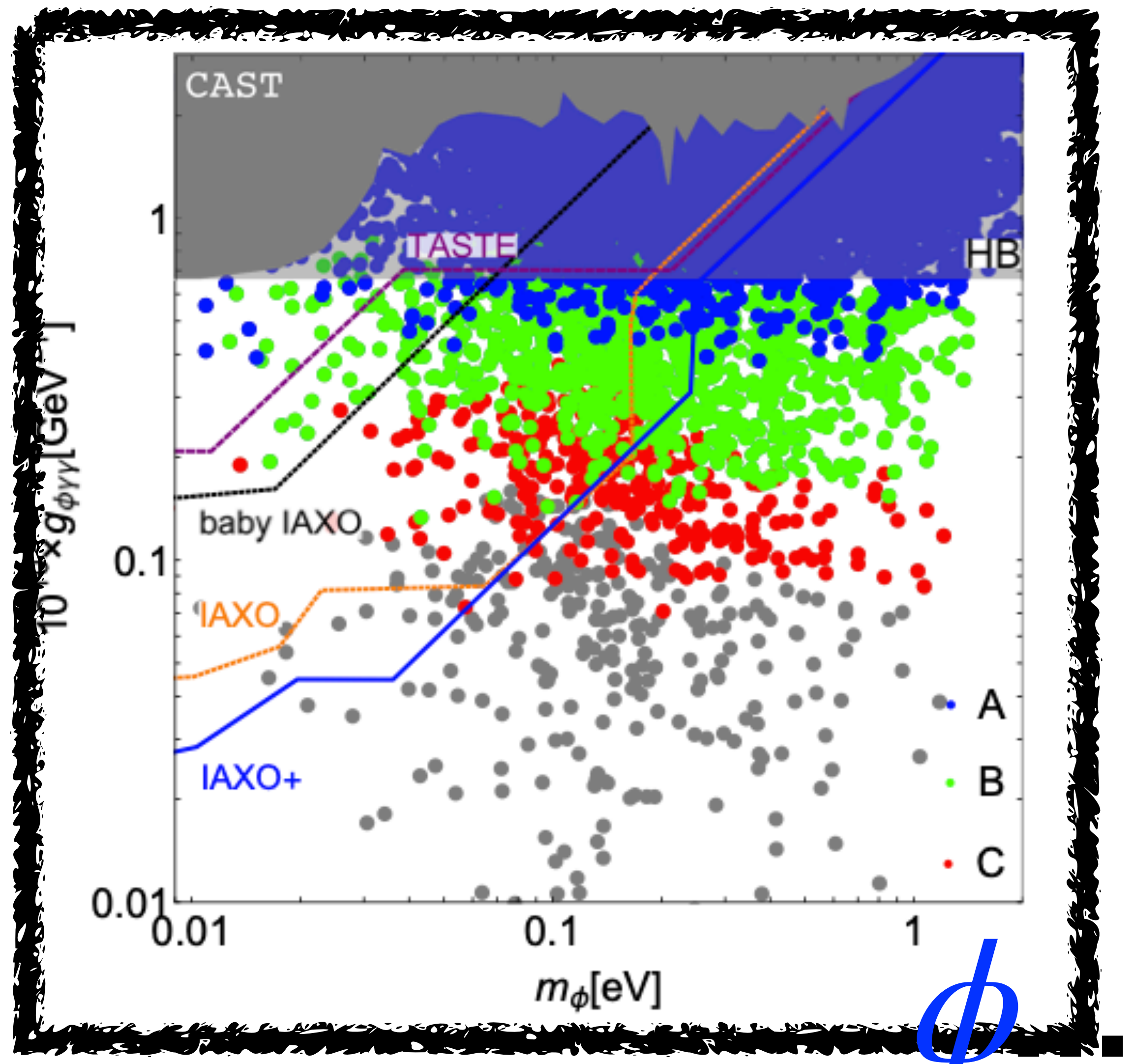

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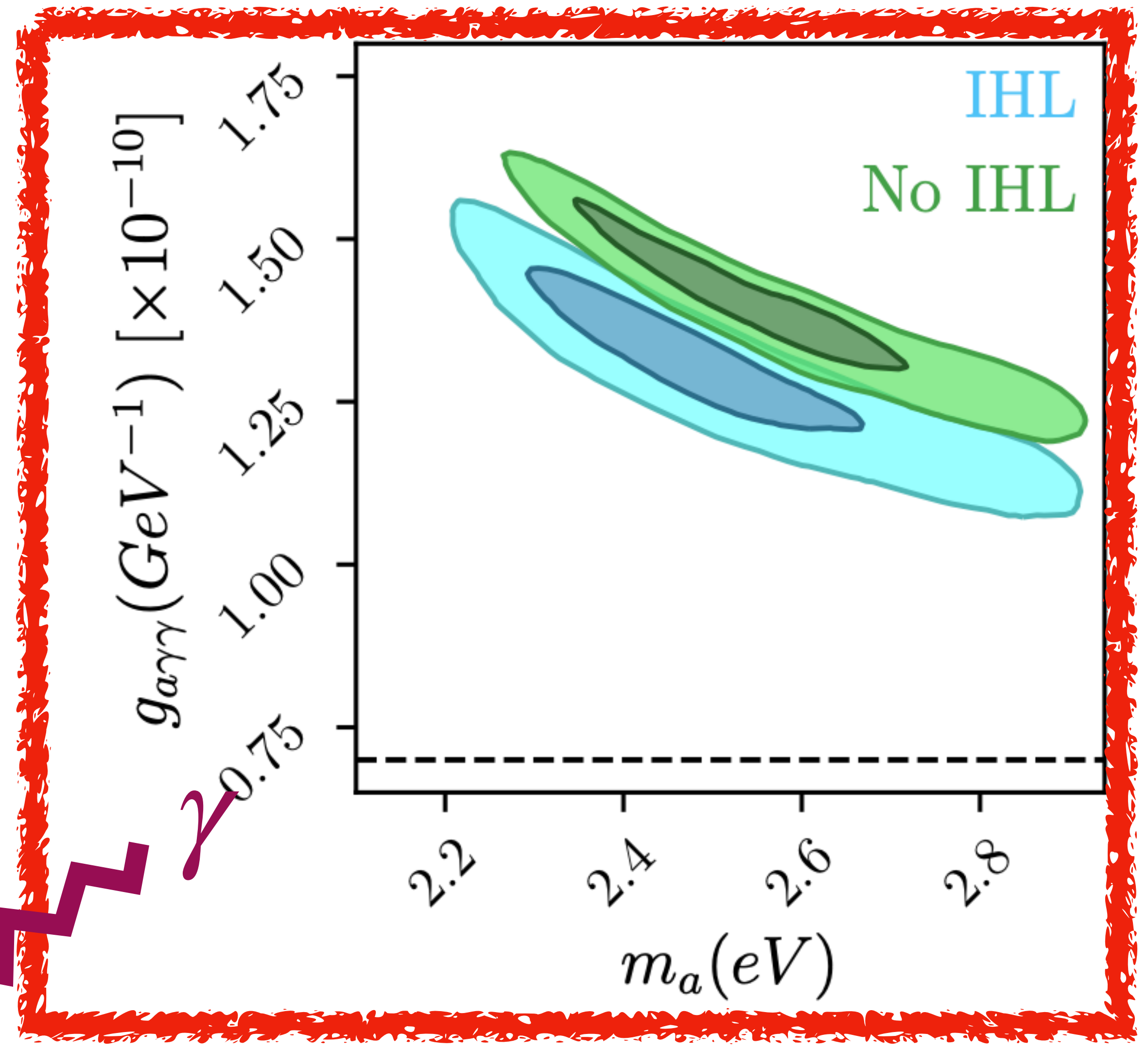

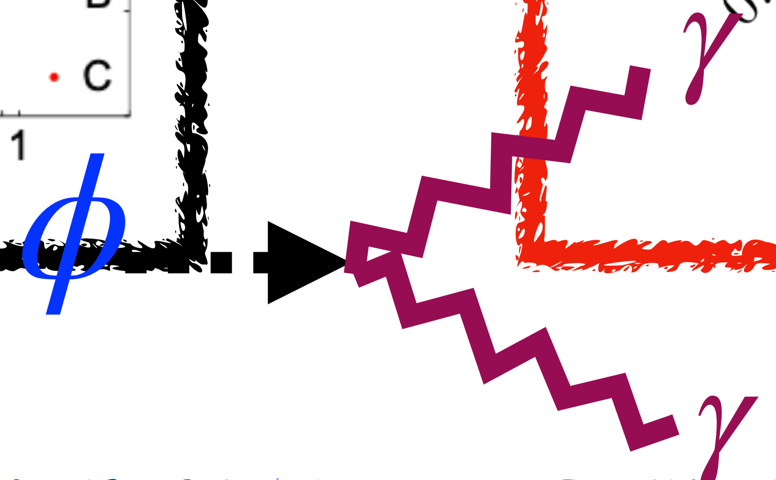

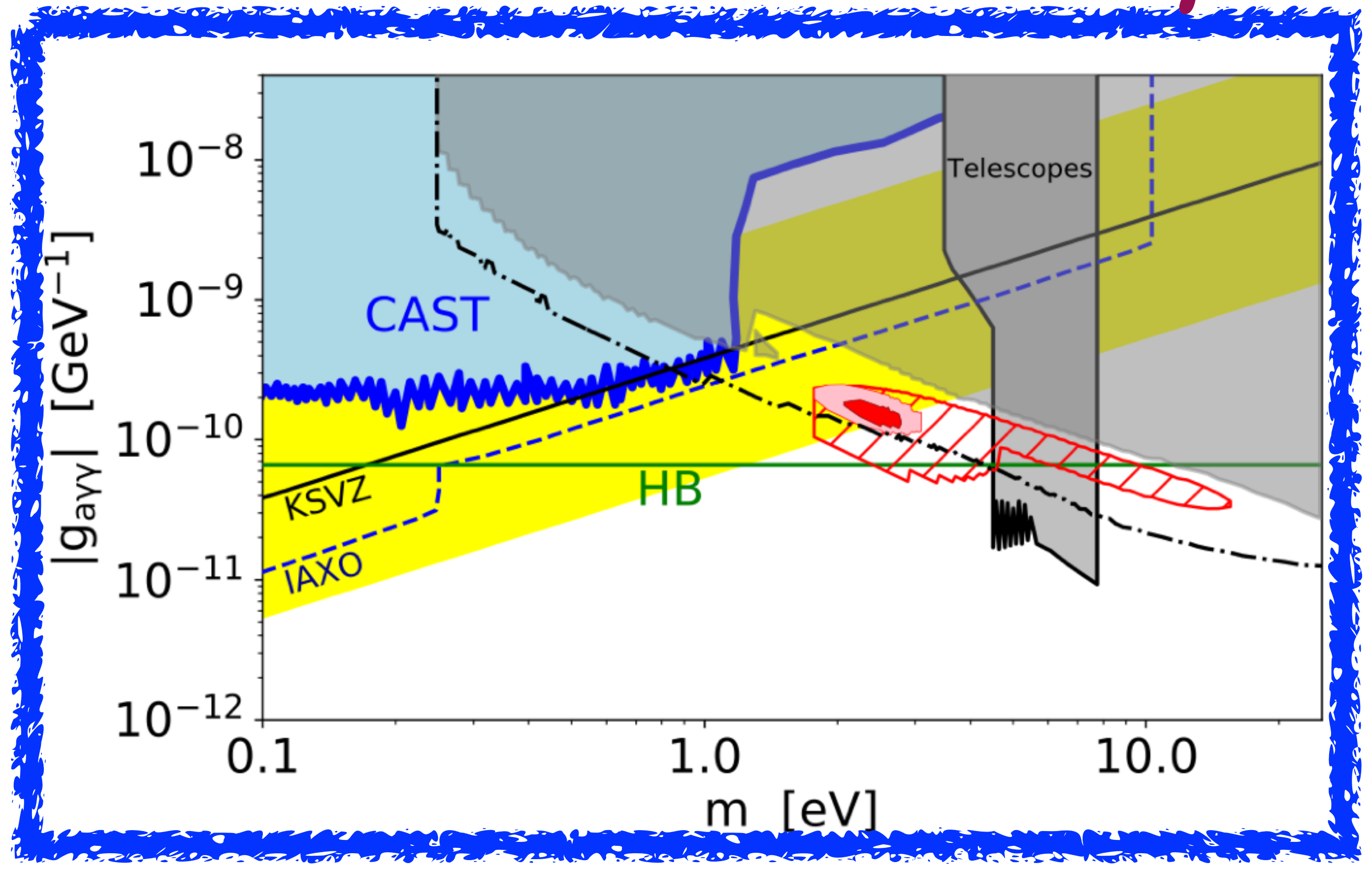

Gamma-ray attenuation

Korochkin, Neronov, and Semikoz, 1911.13291

See also WY, 2301.08735 for cold "hot dark matter"

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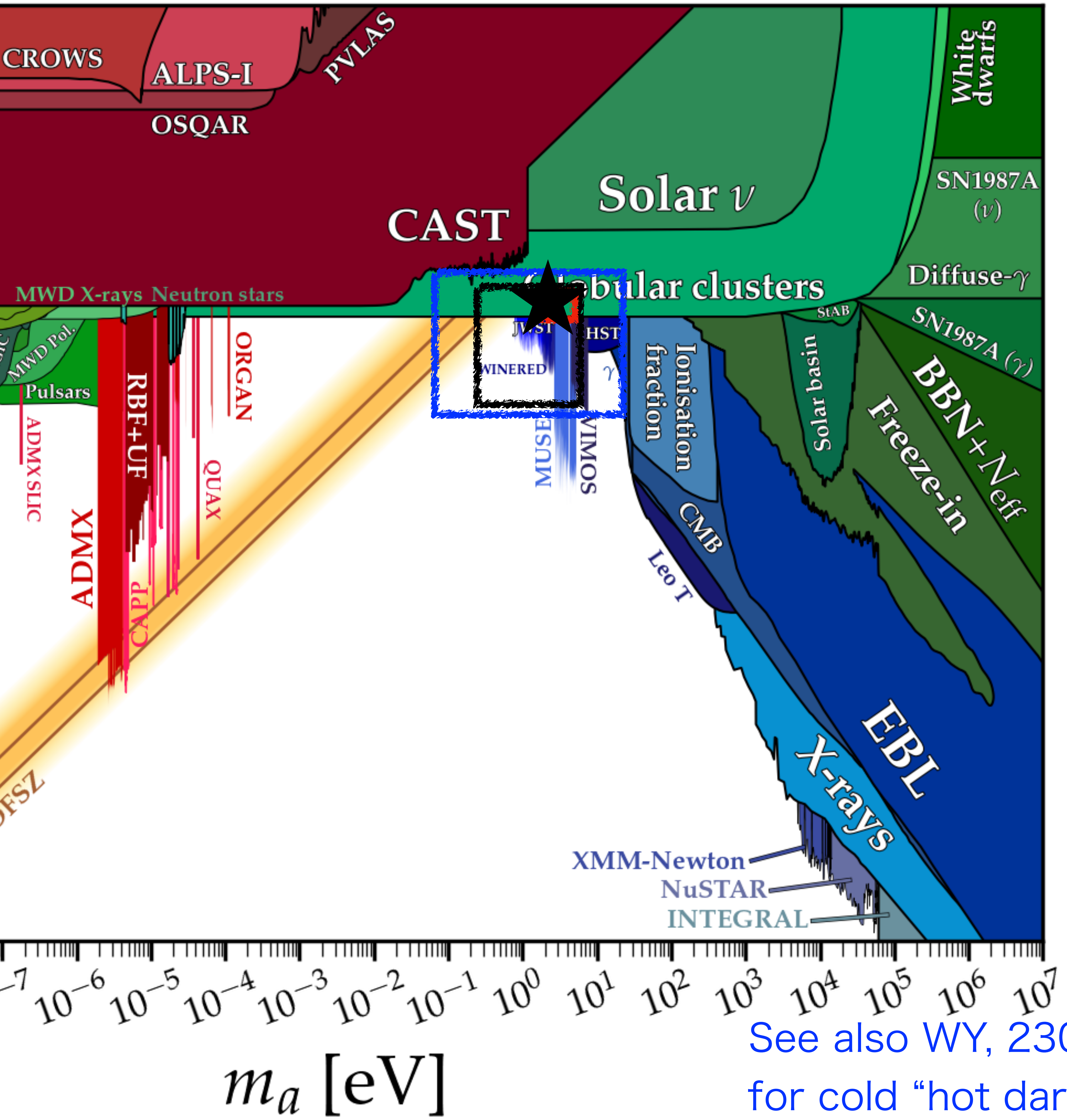

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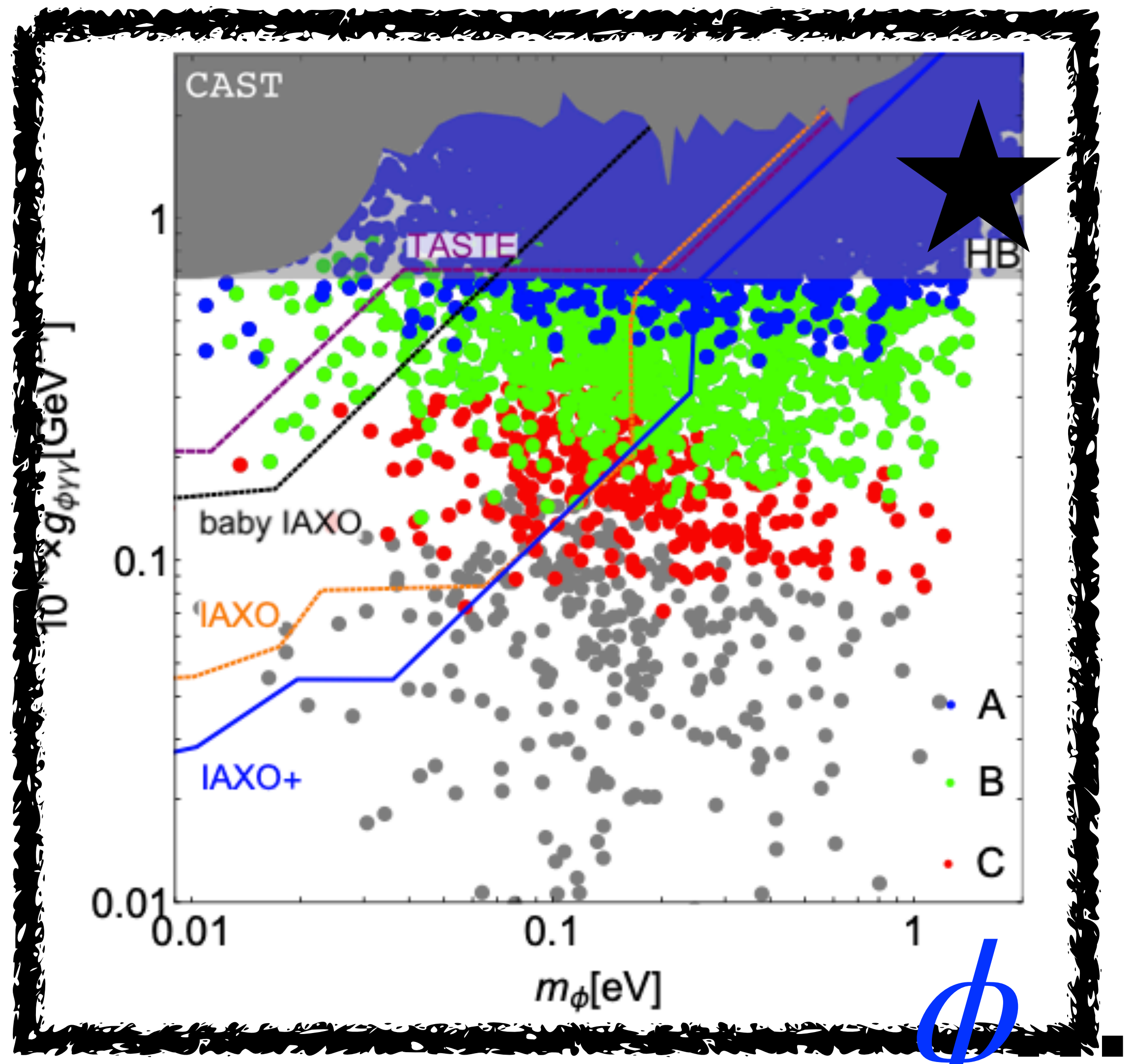

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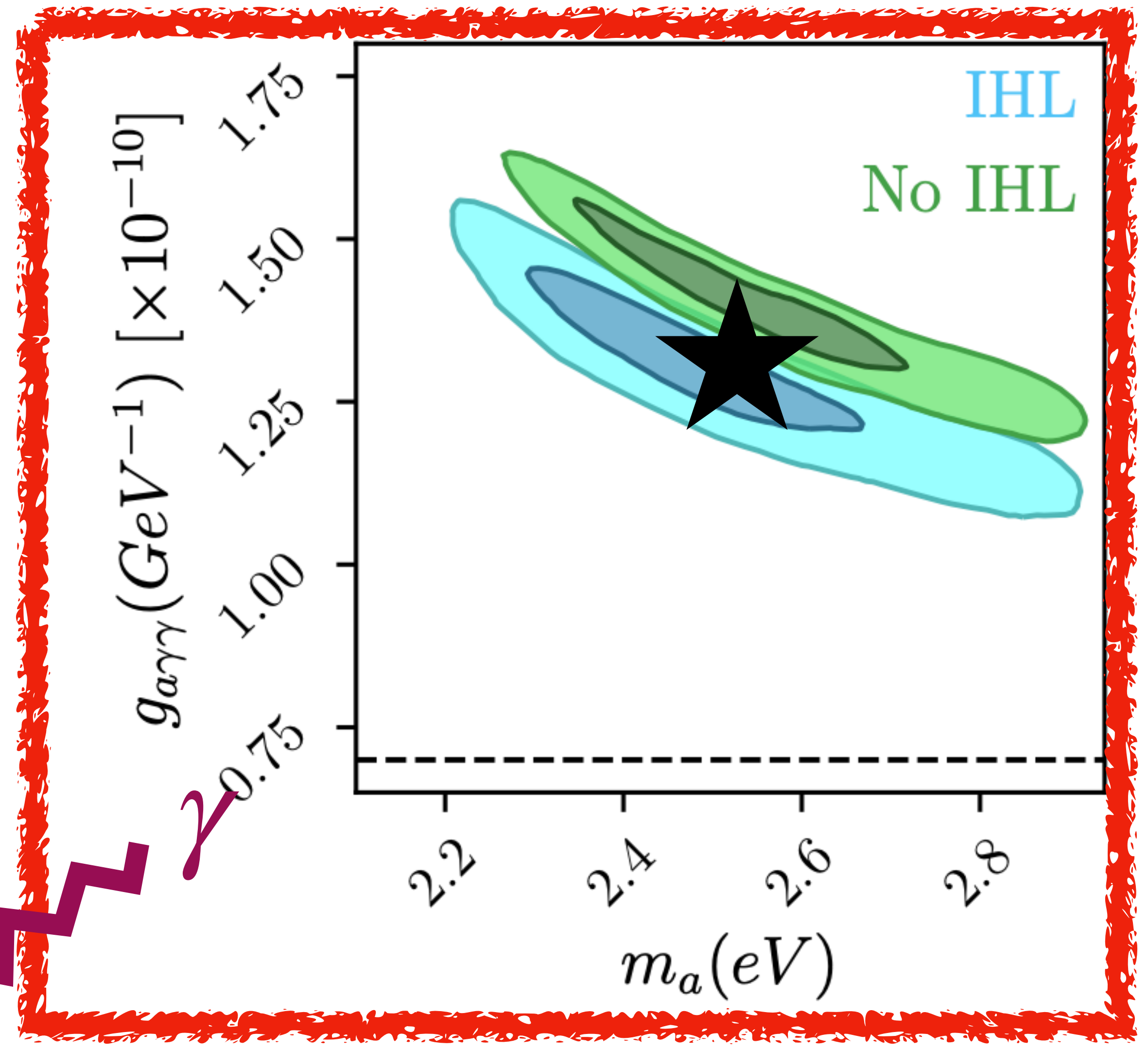

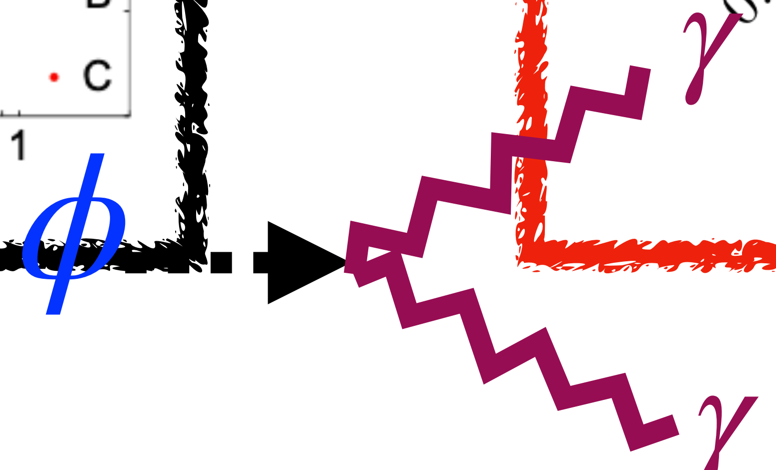

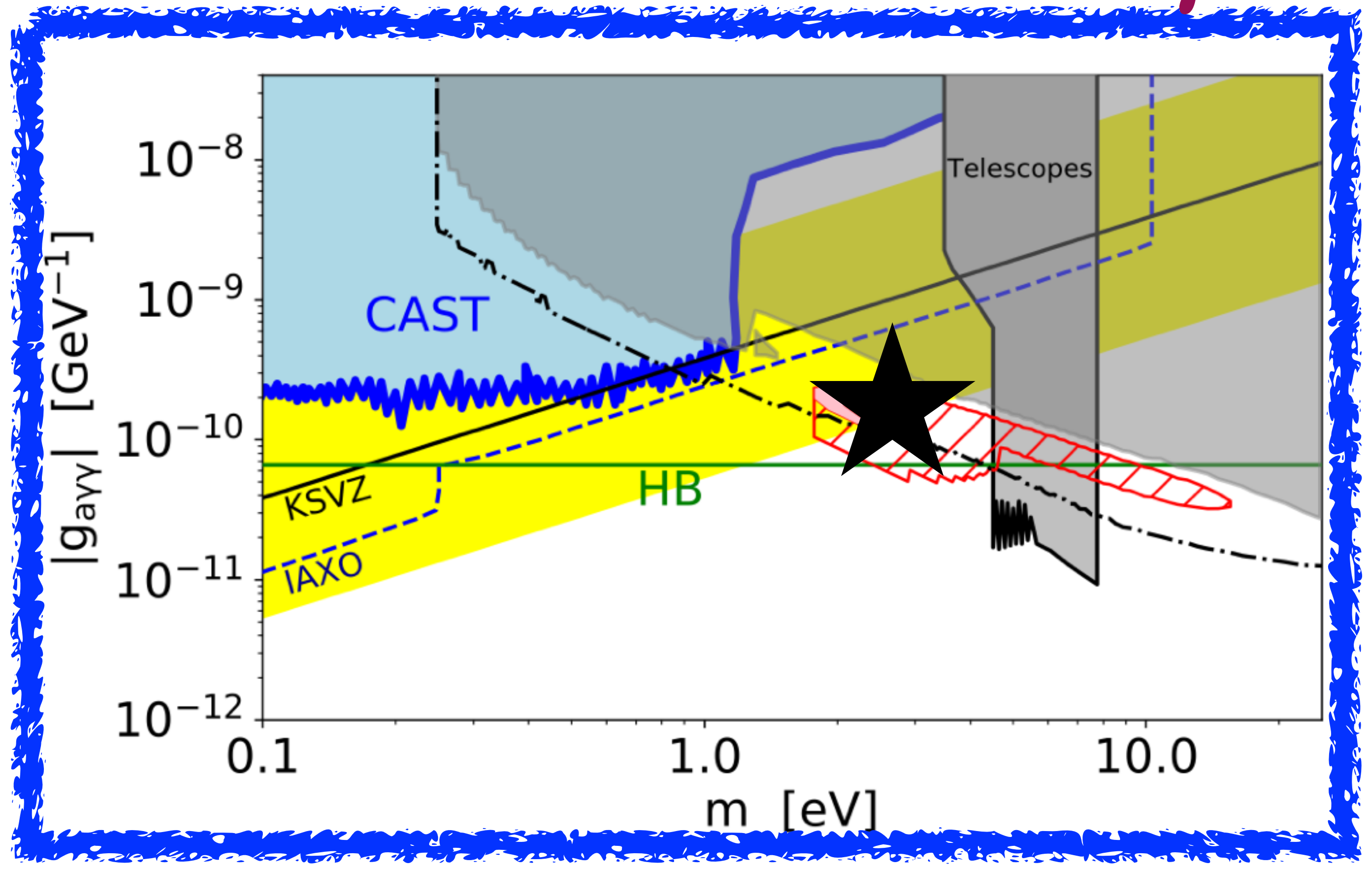

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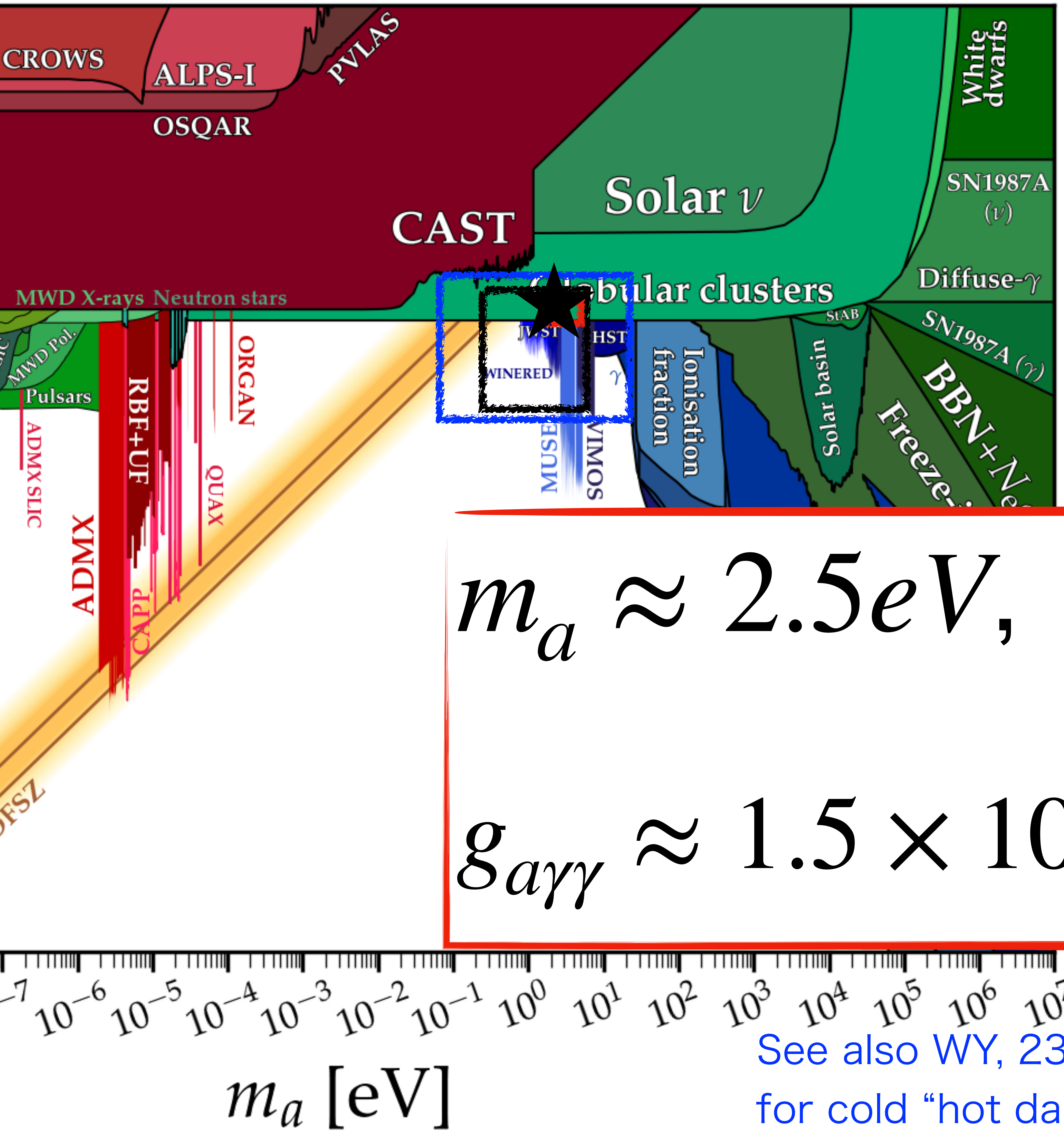

$$m_a \approx 2.5eV,$$

$$g_{a\gamma\gamma} \approx 1.5 \times 10^{-10}\mathrm{GeV}^{-1}$$

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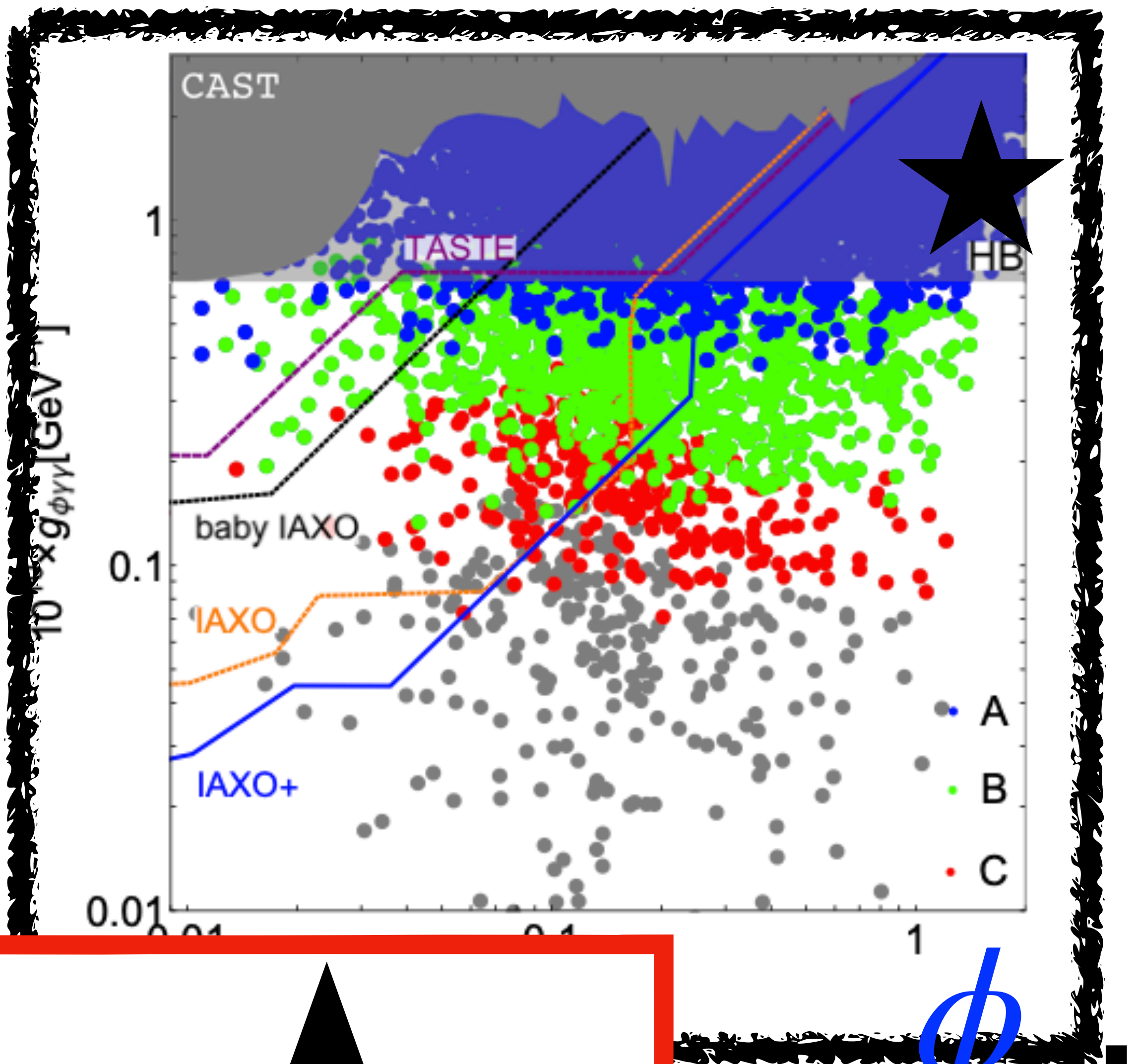

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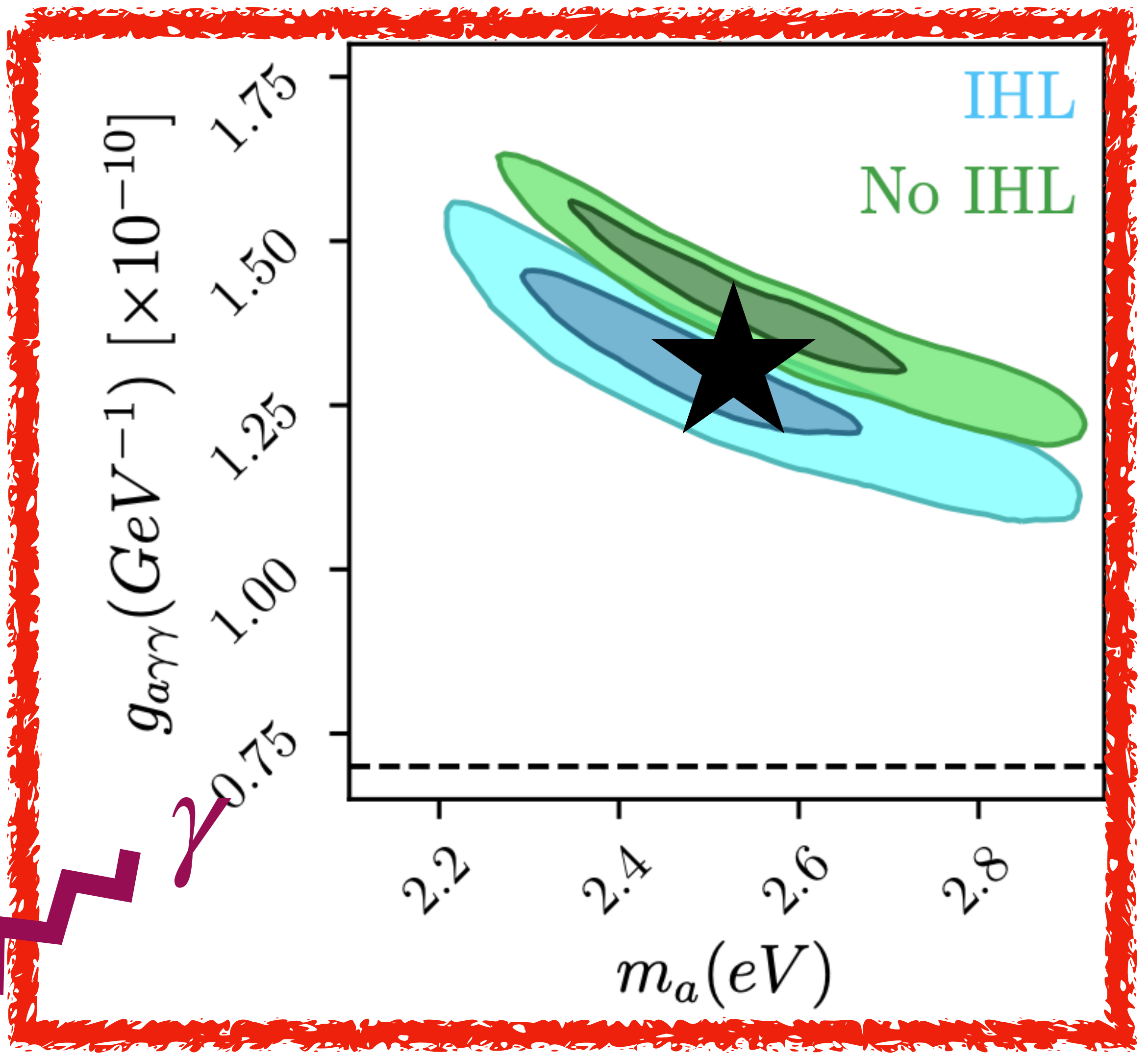

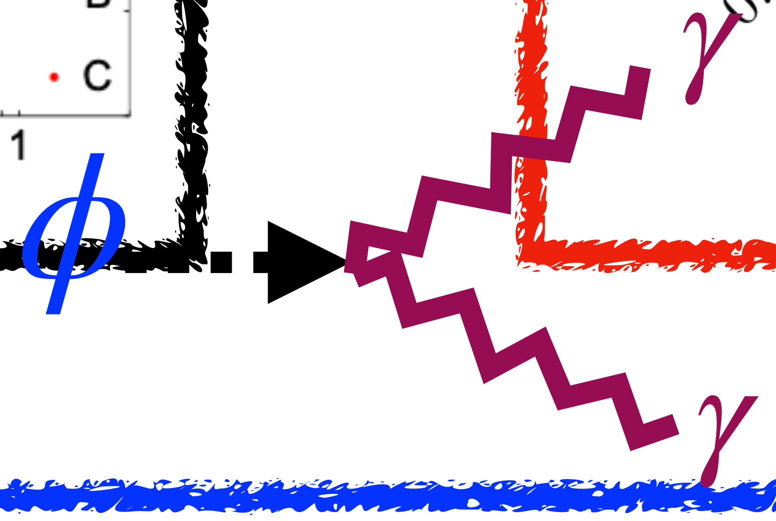

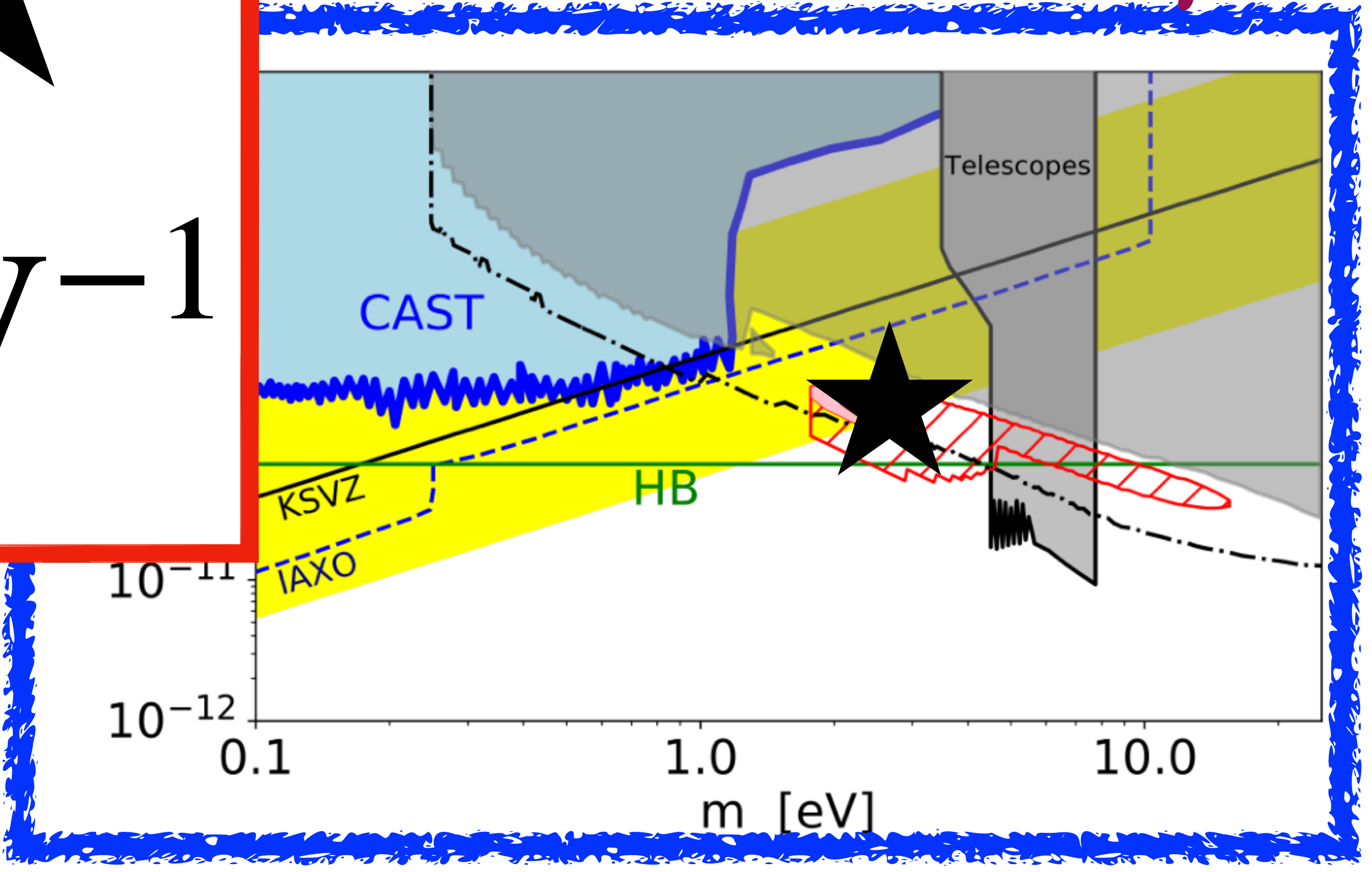

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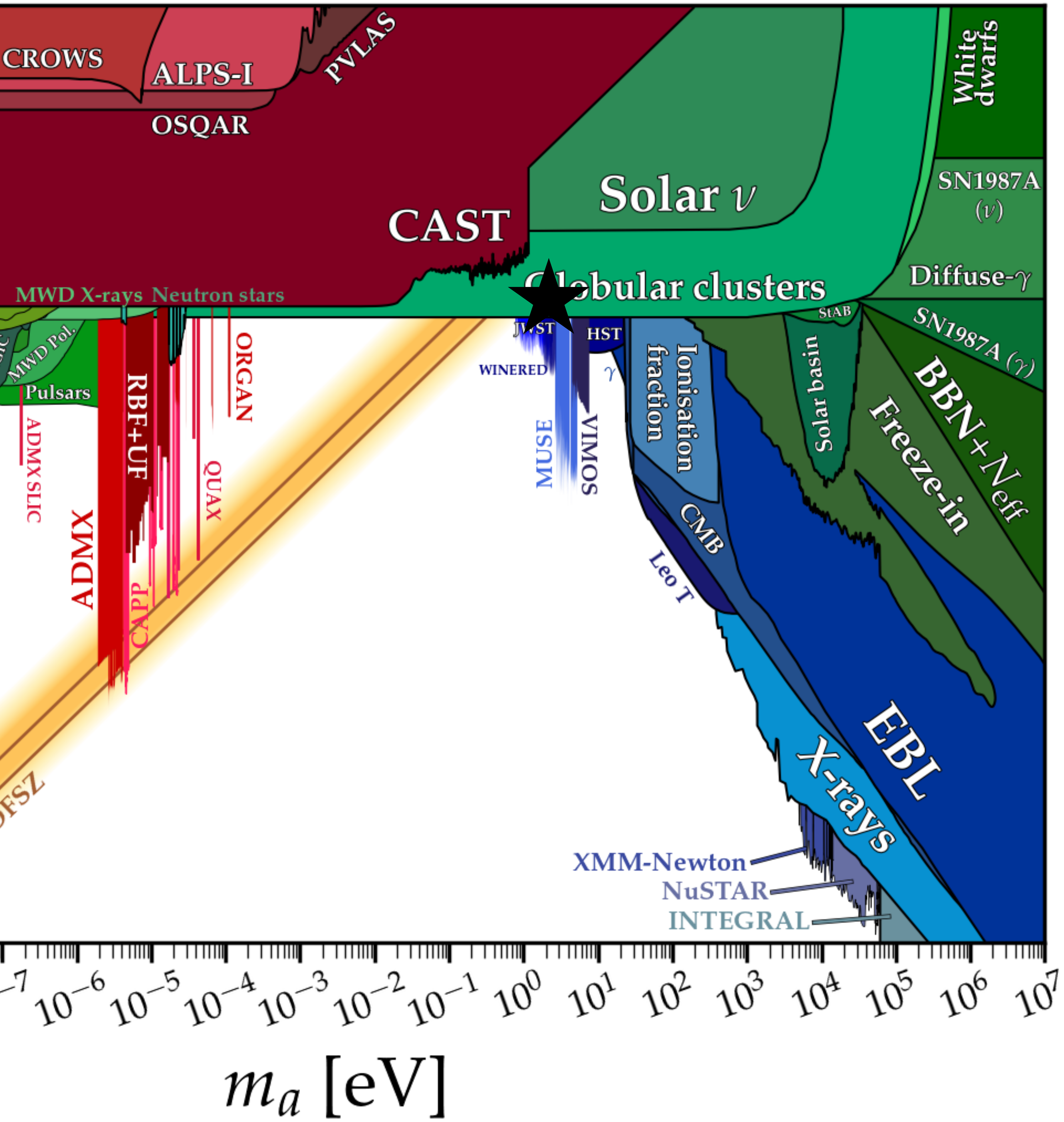
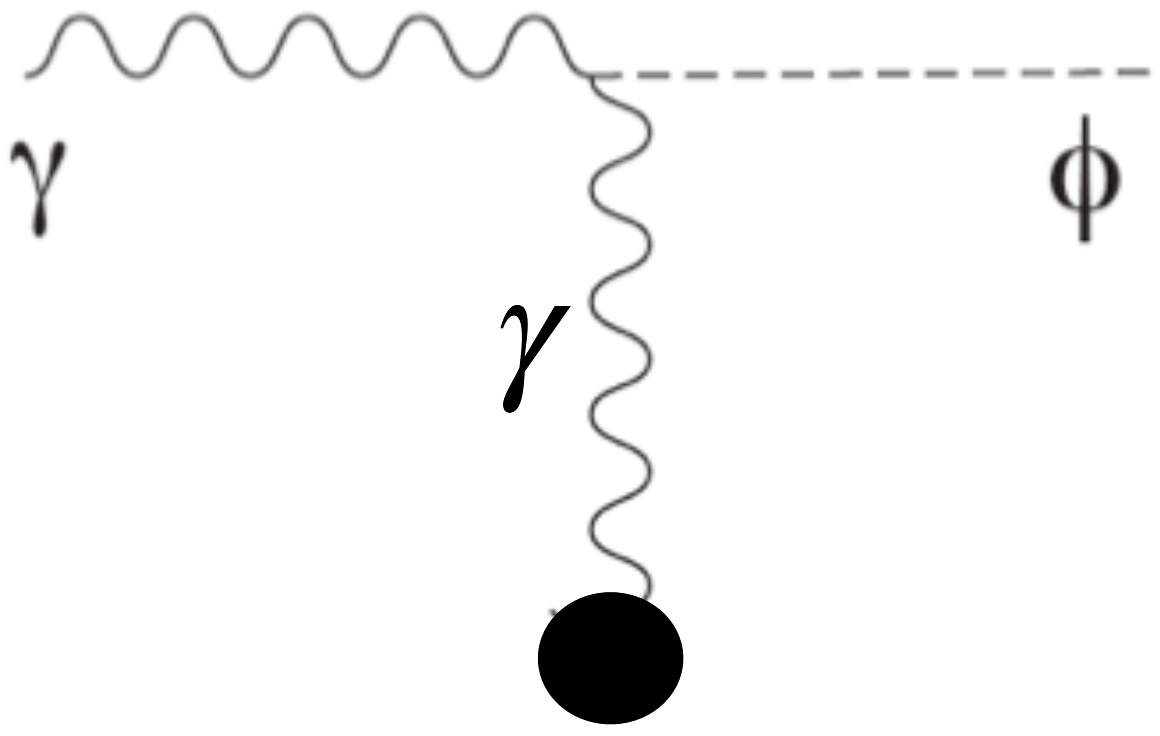
A comment on star cooling bound.



Axion coupling contributes to star cooling.



See e.g. Kaneta Lee Yun [1611.01466](1611.01466),
Kohri, Moroi, Nakayama, 1706.04921, Nakayama, WY [2205.01079](2205.01079)

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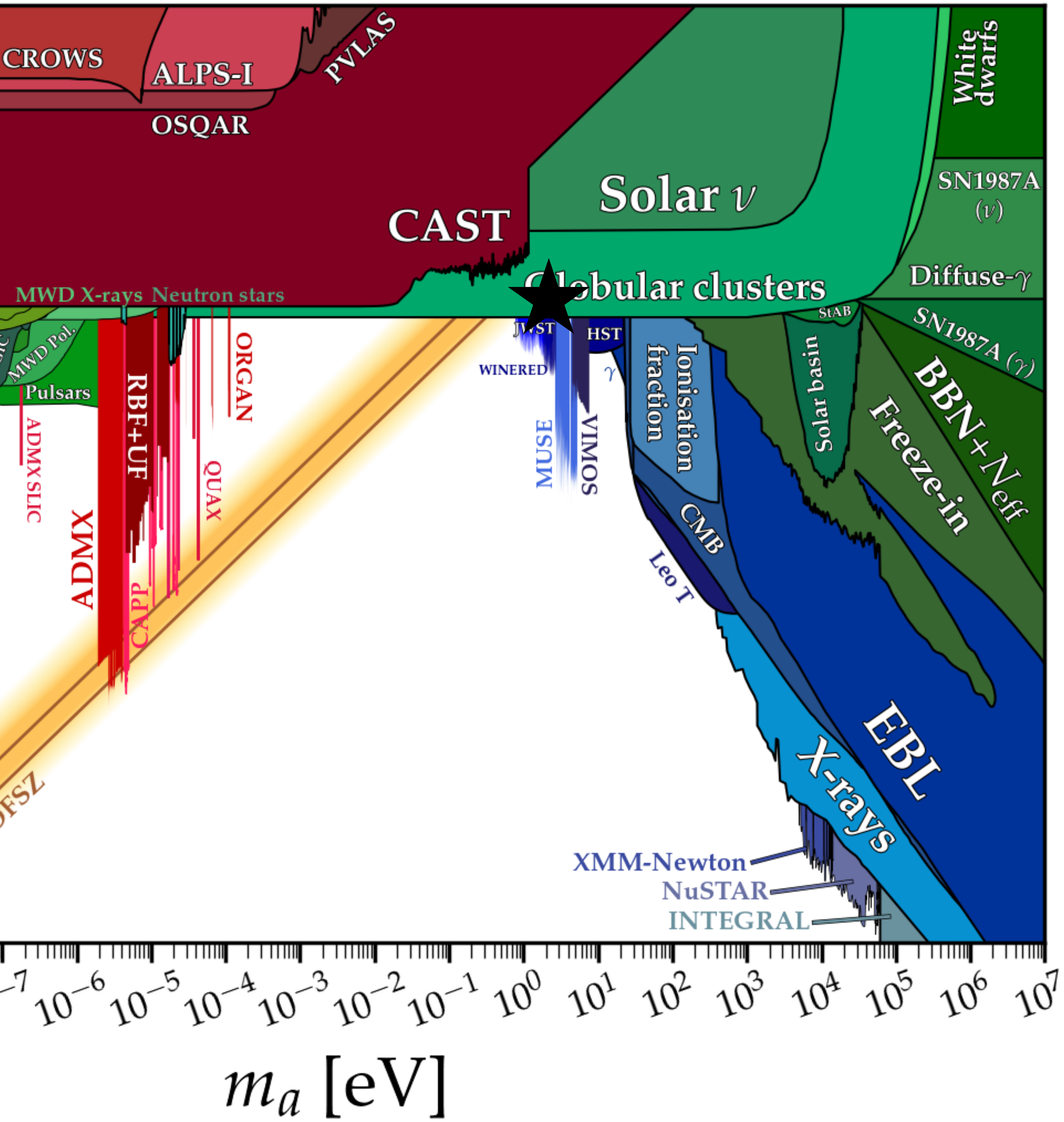

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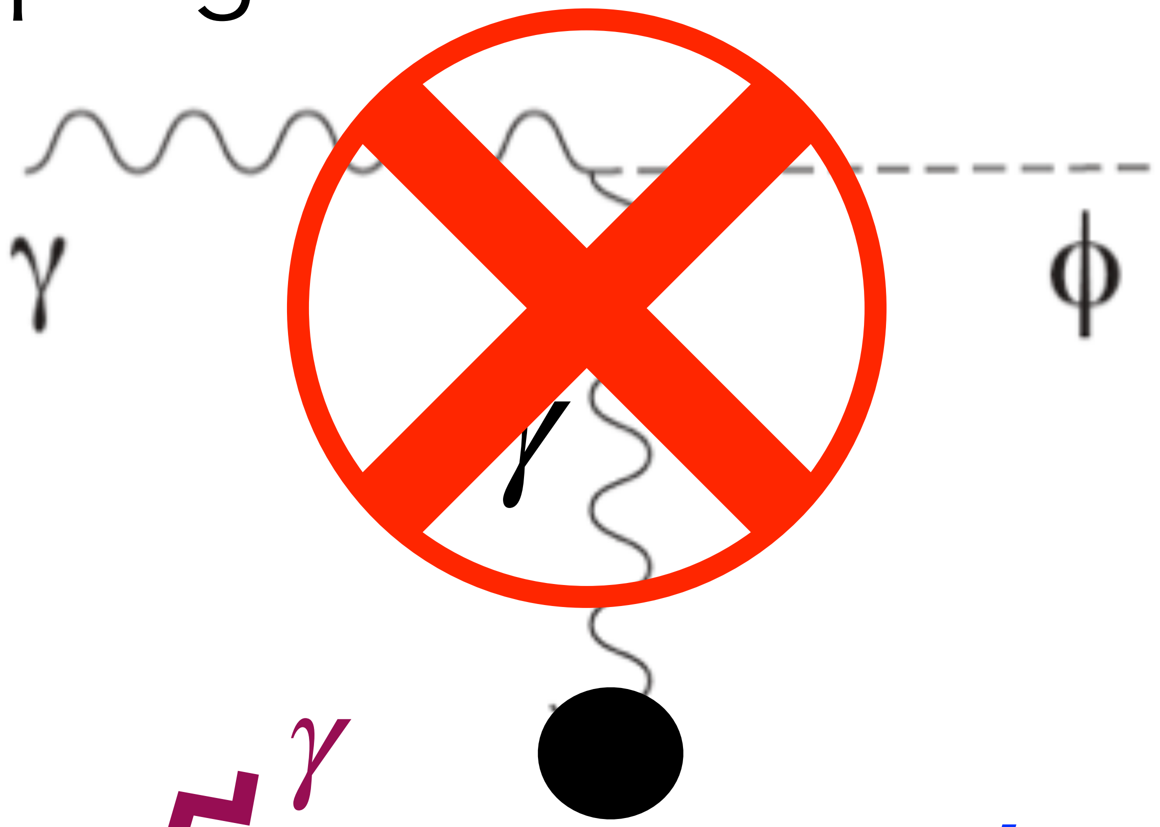
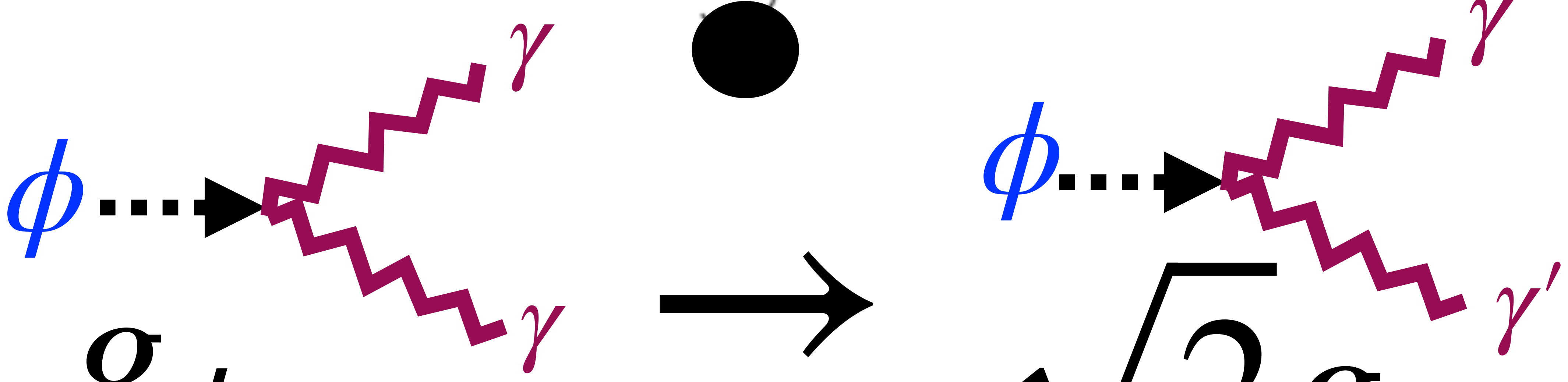




$$g_{\phi\gamma\gamma} \to \sqrt{2}\, g_{\phi\gamma\gamma'}$$

See e.g. Kaneta Lee Yun 1611.01466,
Kohri, Moroi, Nakayama, 1706.04921, Nakayama, WY 2205.01079

The coincidence holds.

(ALP miracle gives new prediction $\Delta N_{\rm eff} \sim 0.1$

compared with the original one $\Delta N_{\rm eff} \sim 0.03$.)

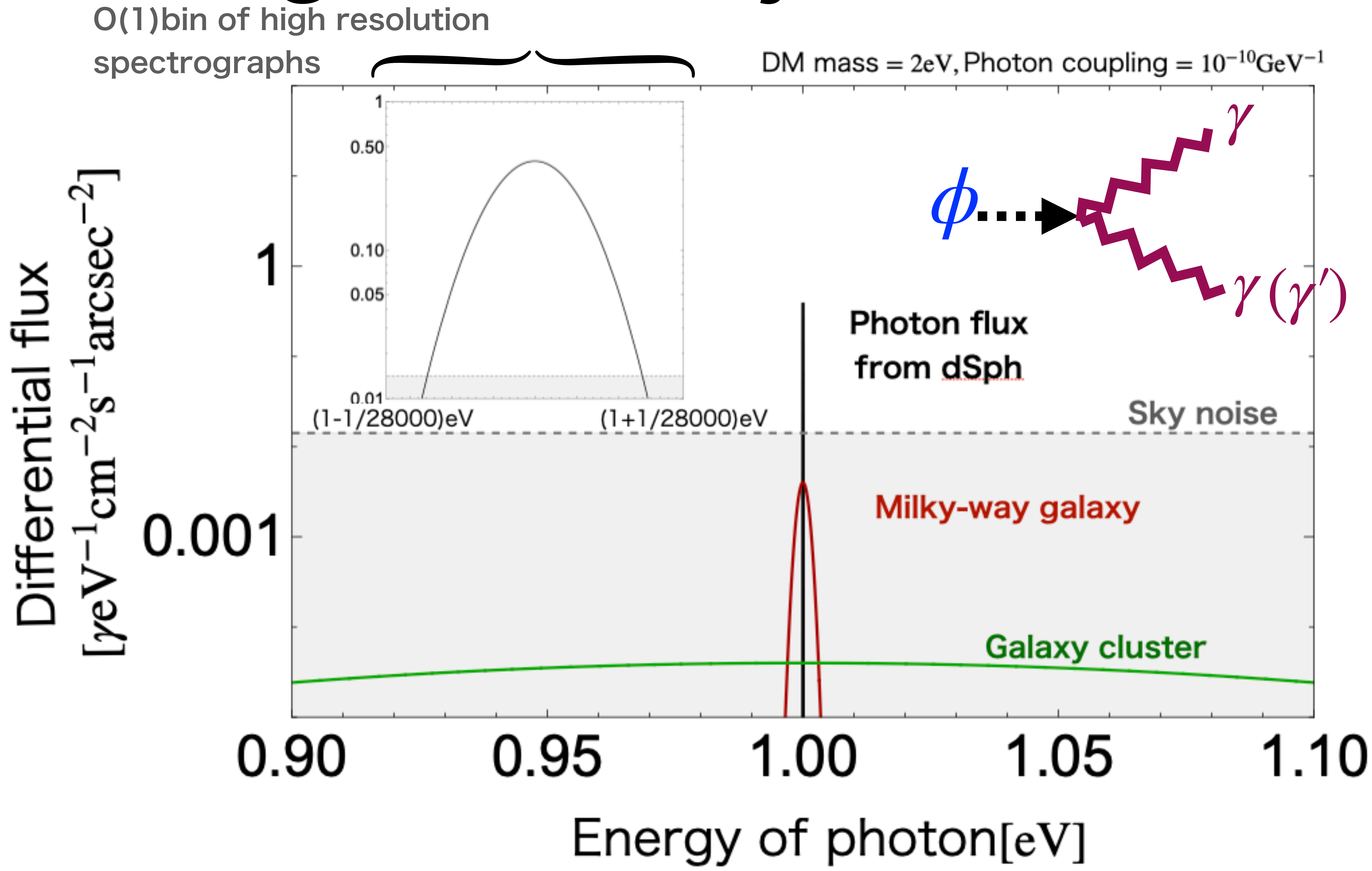
eV dark matter may be interesting.

- 2. Indirect detection with infrared spectrograph

T. Bessho, Y. Ikeda, WY, 2208.05975

WY, Hayashi 2305.13415

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



T. Bessho, Y. Ikeda, WY, 2208.05975

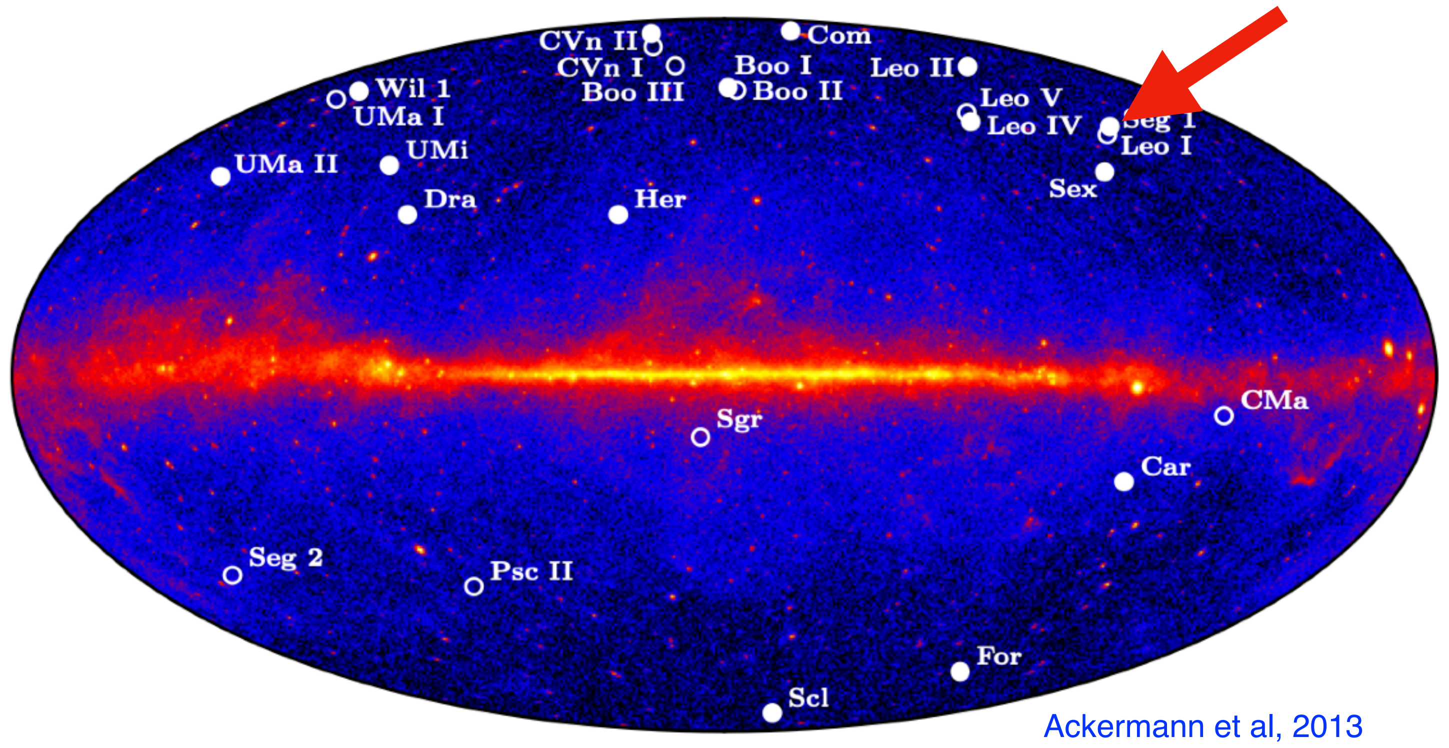
-DM signals from some dwarfs are **sky background free** for existing **high energy resolution** infrared spectrographs.

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

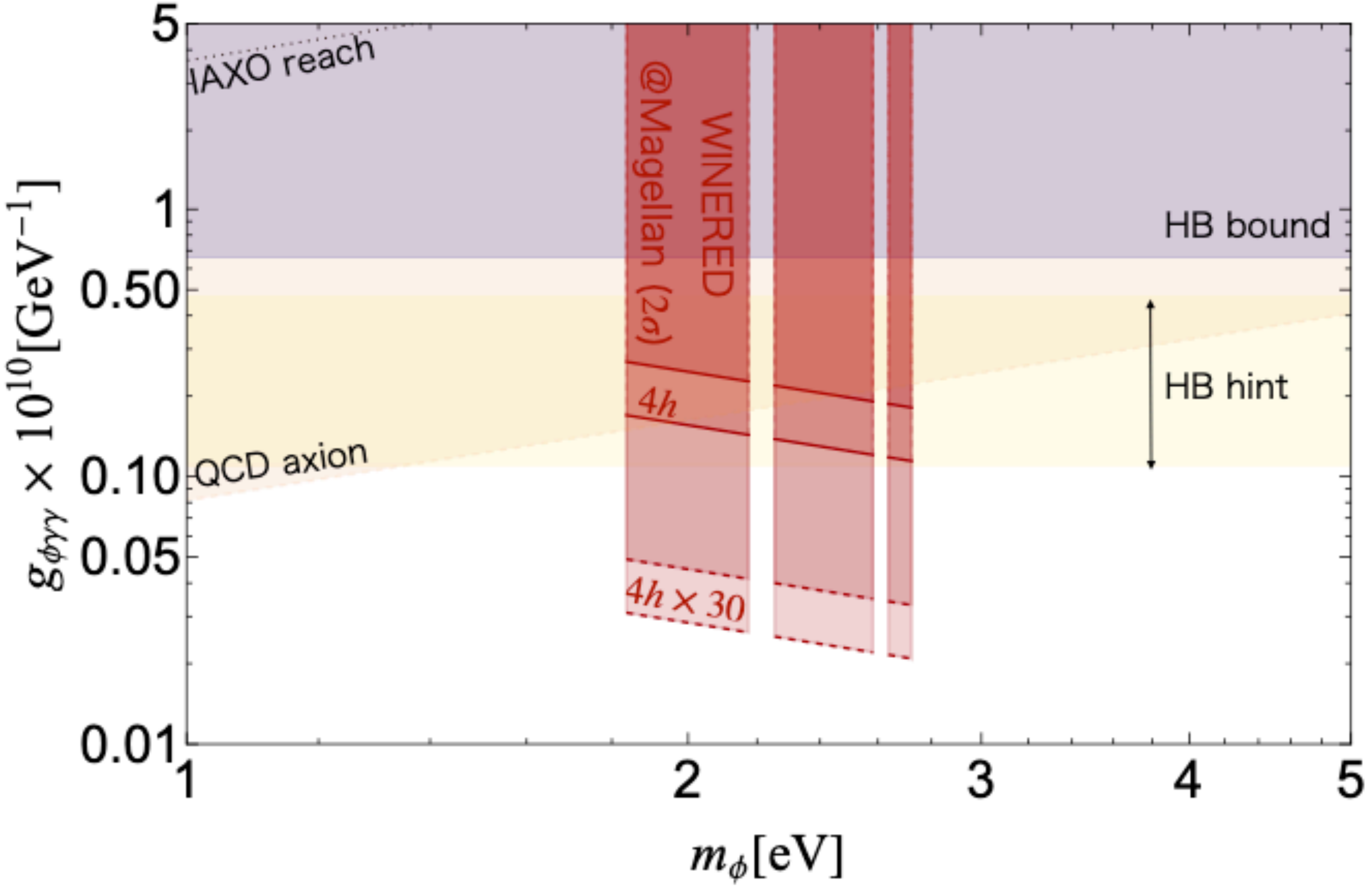


Ackermann et al, 2013

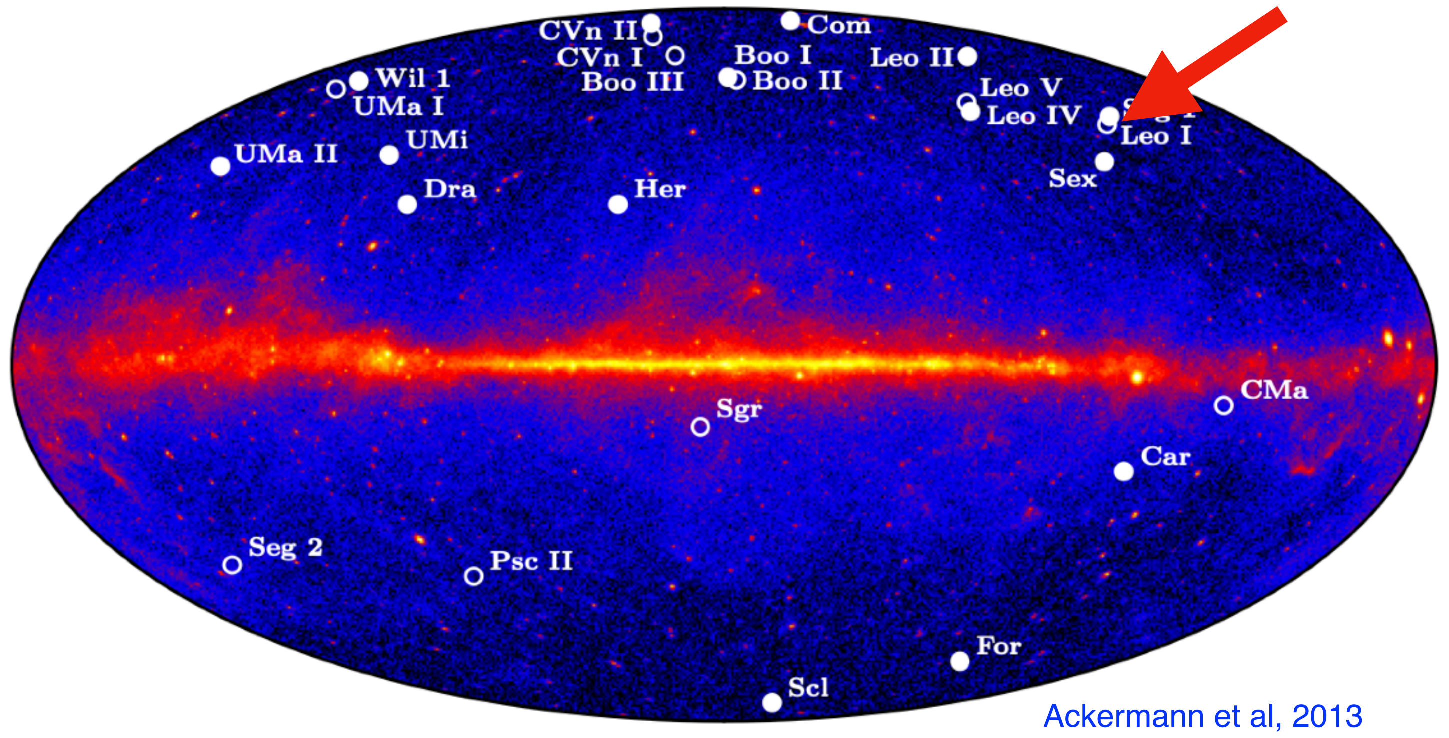
https://www.cfa.harvard.edu

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

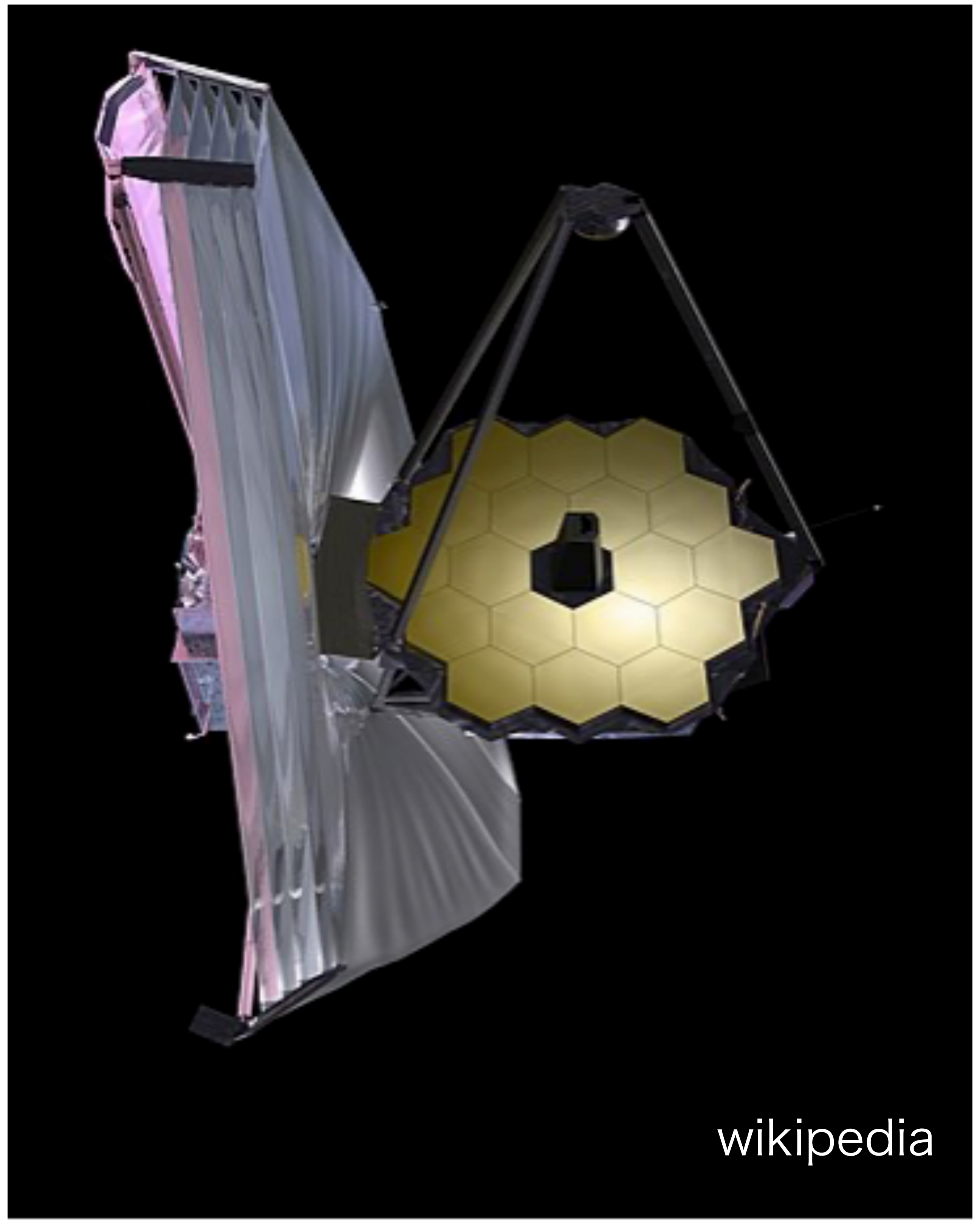


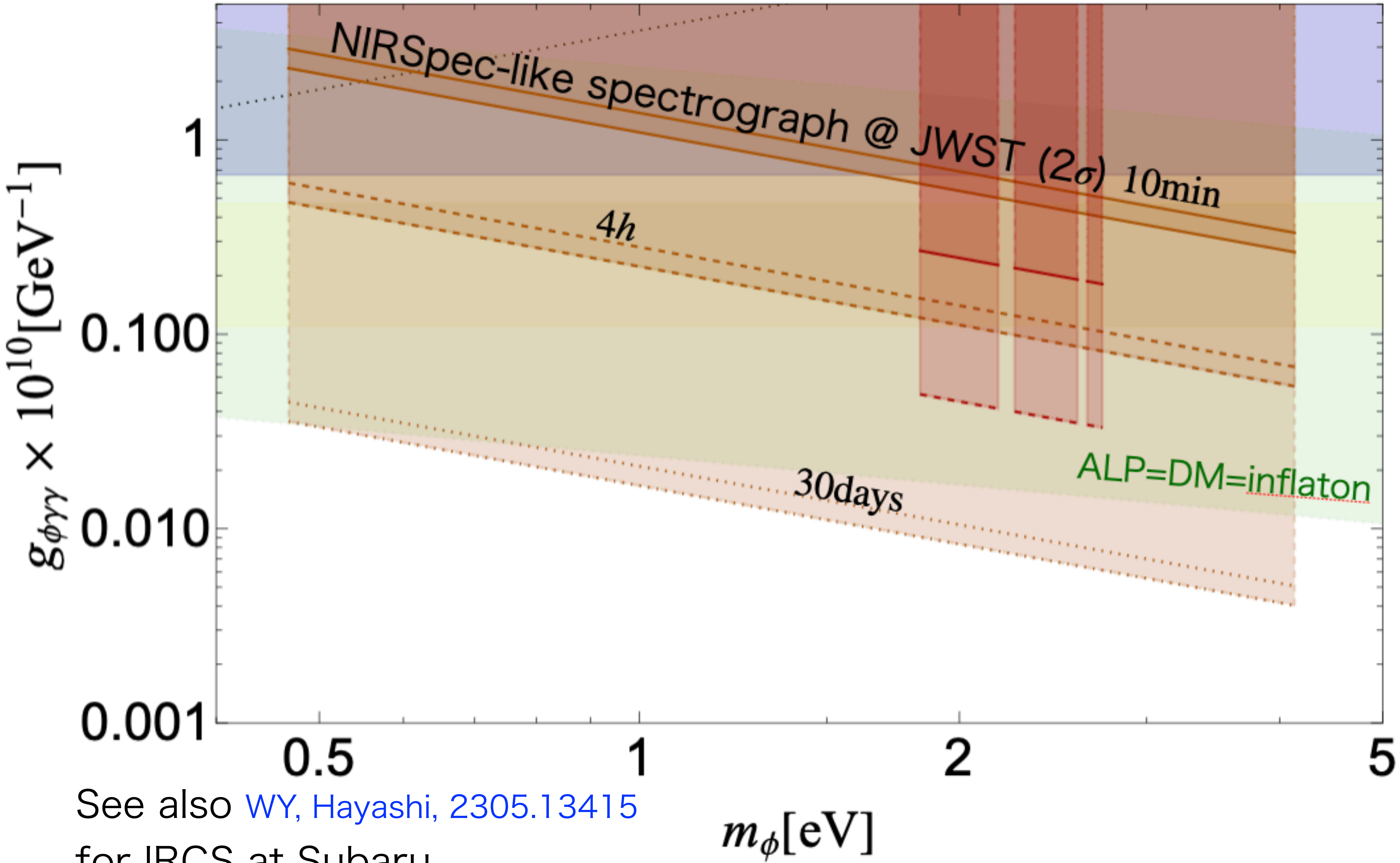
Ackermann et al, 2013

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

- # 3. Observations and results

$$\underline{\frac{\partial^2 \Phi_{\gamma,i}}{\partial\Omega\partial E}} \simeq \underline{\frac{\partial_\Omega D[s,\Omega]}{4\pi}} \frac{\Gamma_\phi}{m_\phi} \times 2\delta(\underline{E} - \frac{m_\phi}{2}(1 - v_i)) \times \underline{\eta}$$

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

Estimated in
WY, Hayashi
2305.13415

Measured in
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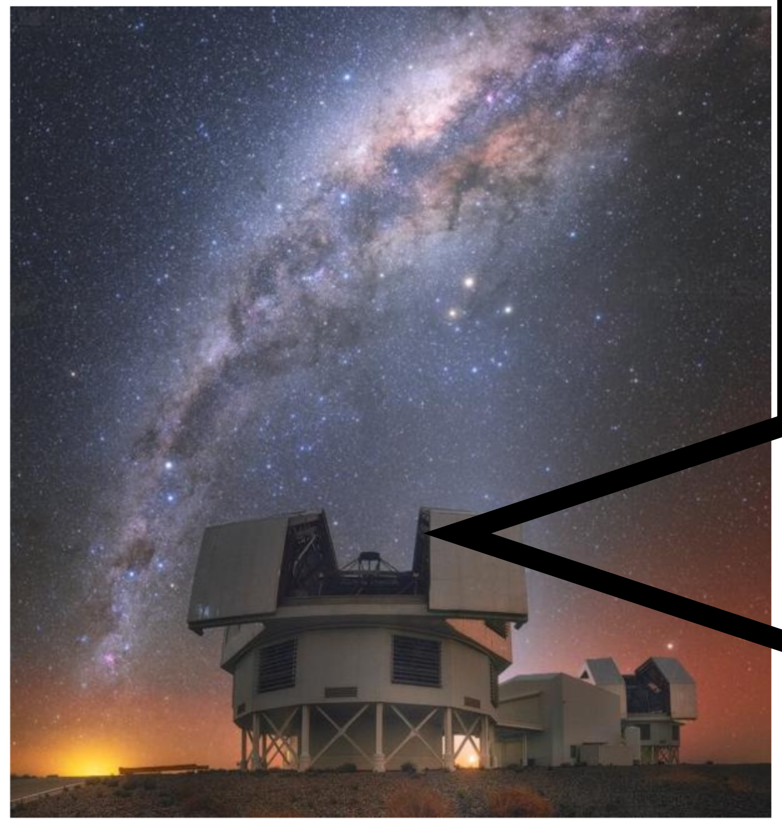
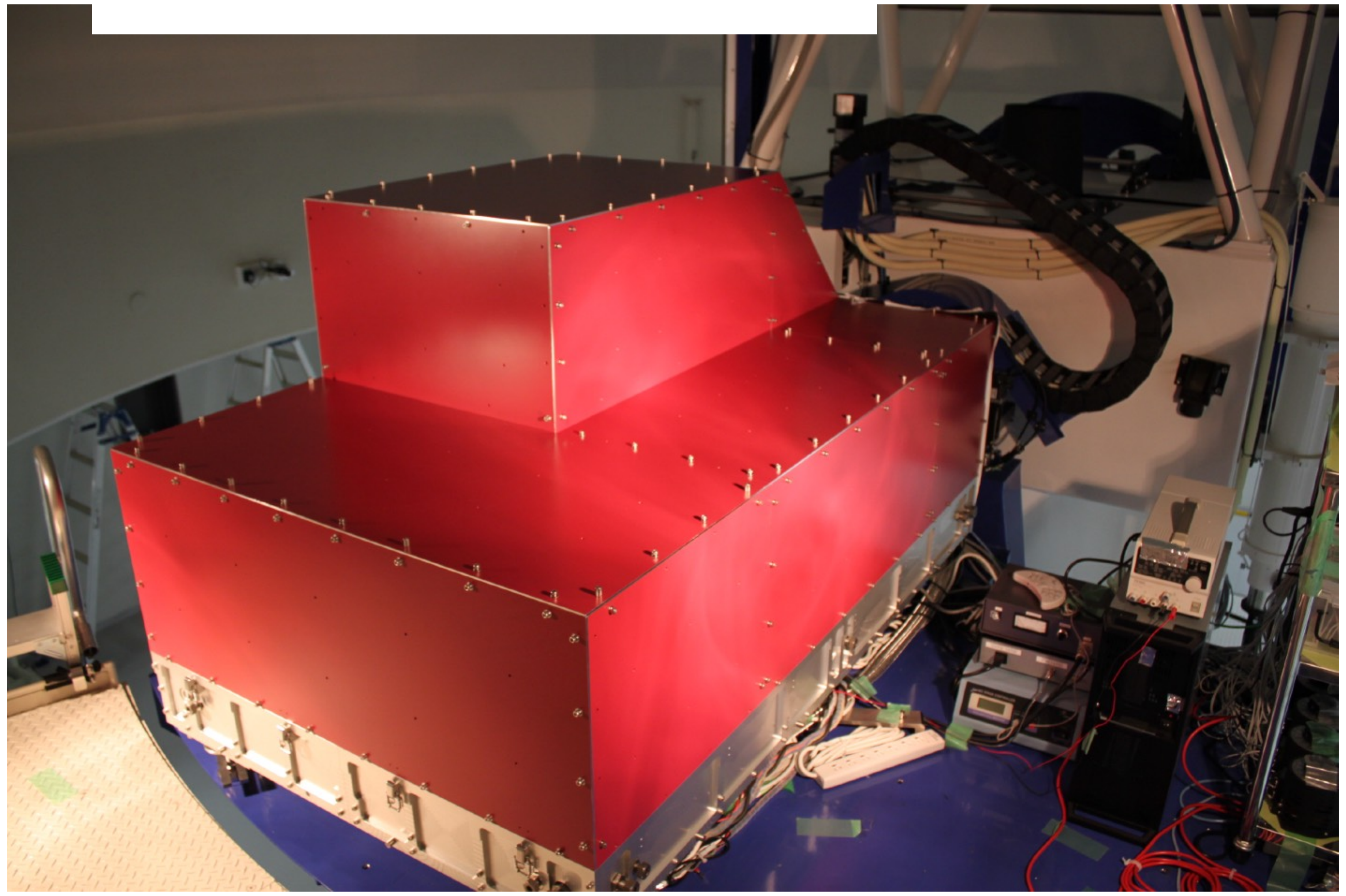
→ Bound on decay rate Γ_ϕ and thus $g_{a\gamma\gamma}$(or$\sqrt{2}g_{a\gamma\gamma'}$)

What we use: WINERED@ Magellan

Magellan



Ikeda et al 2006



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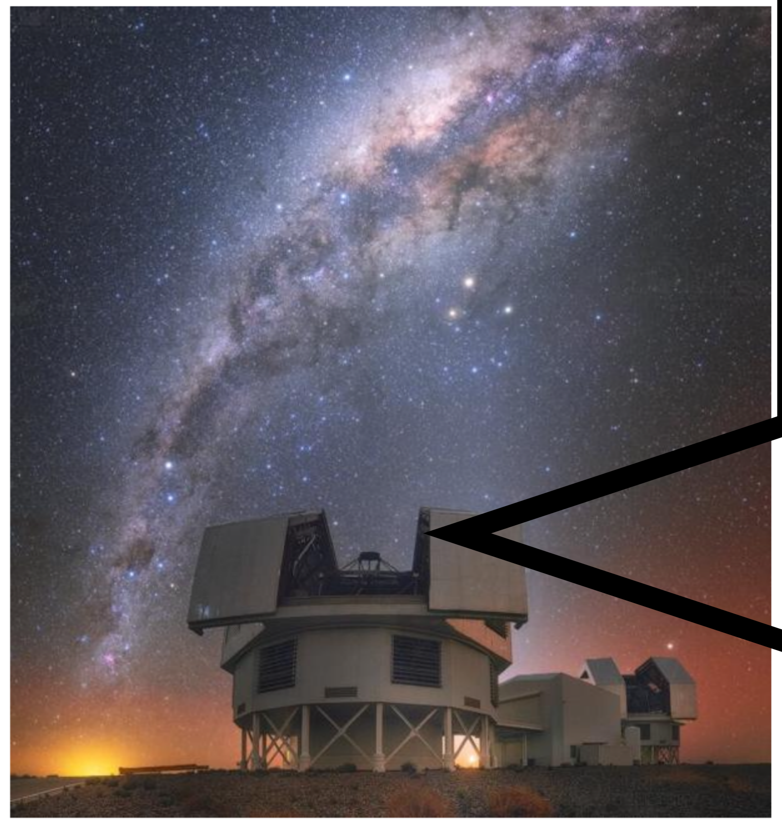

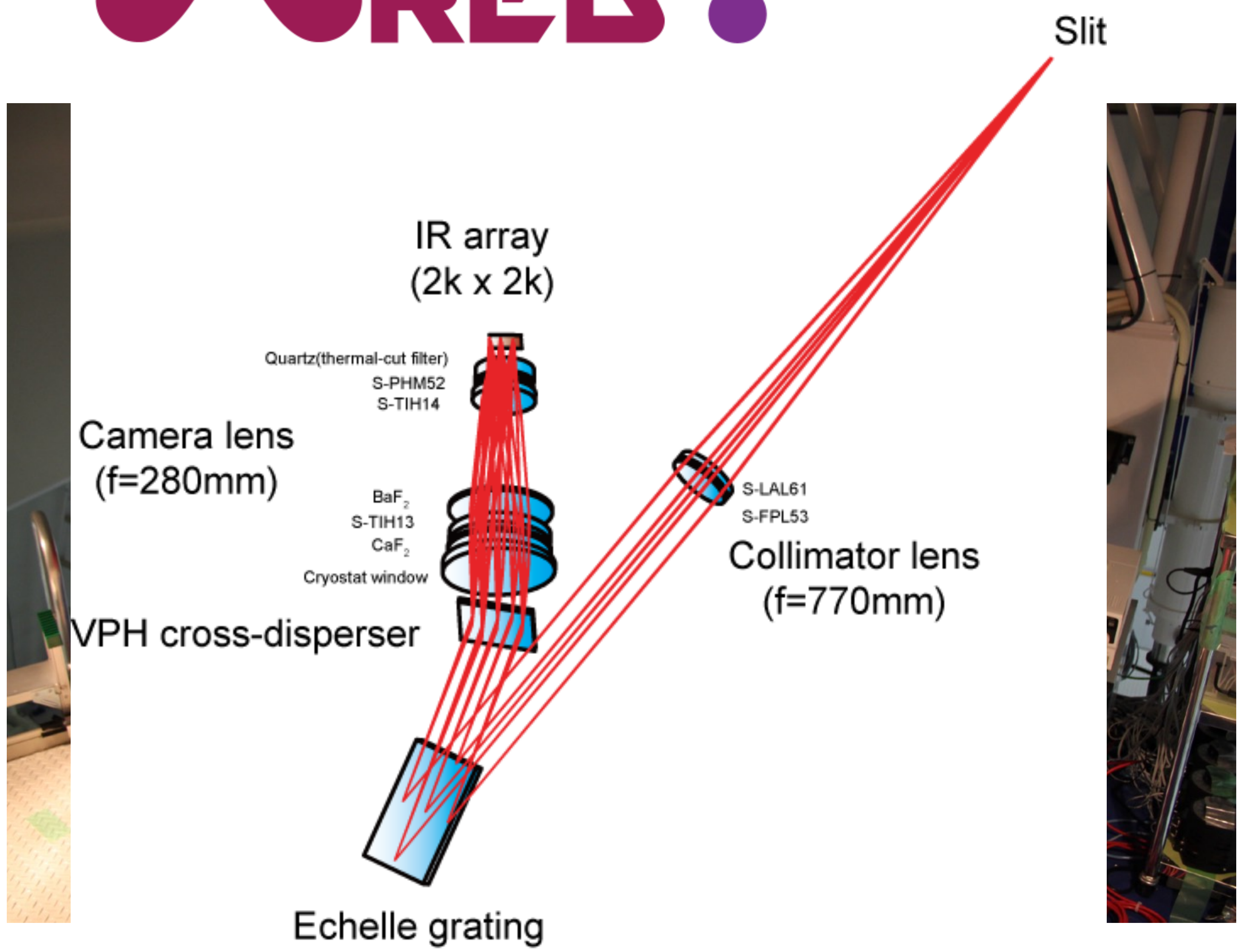

Ikeda et al 2006

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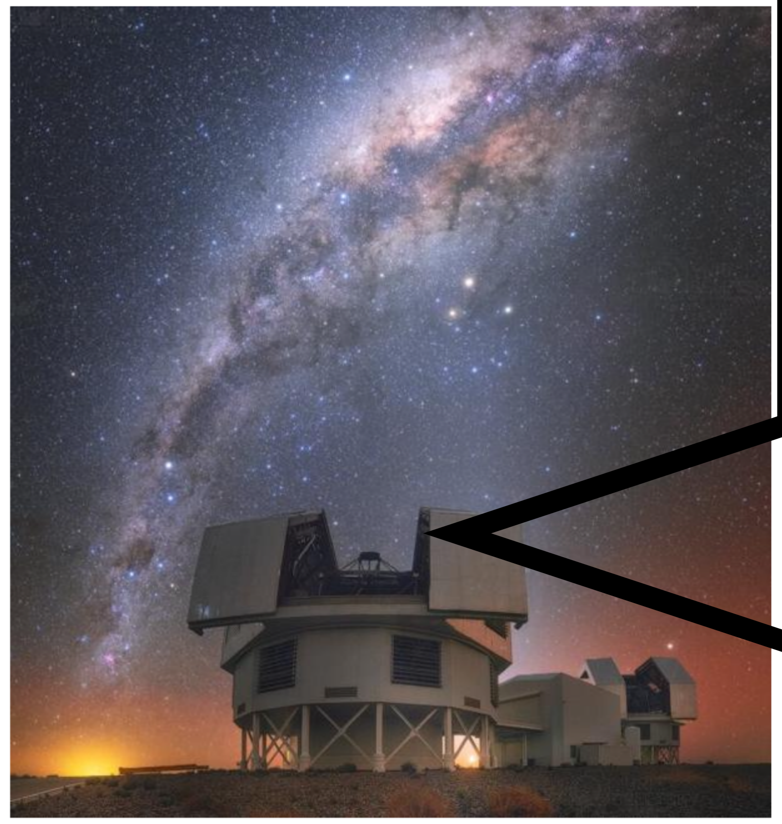

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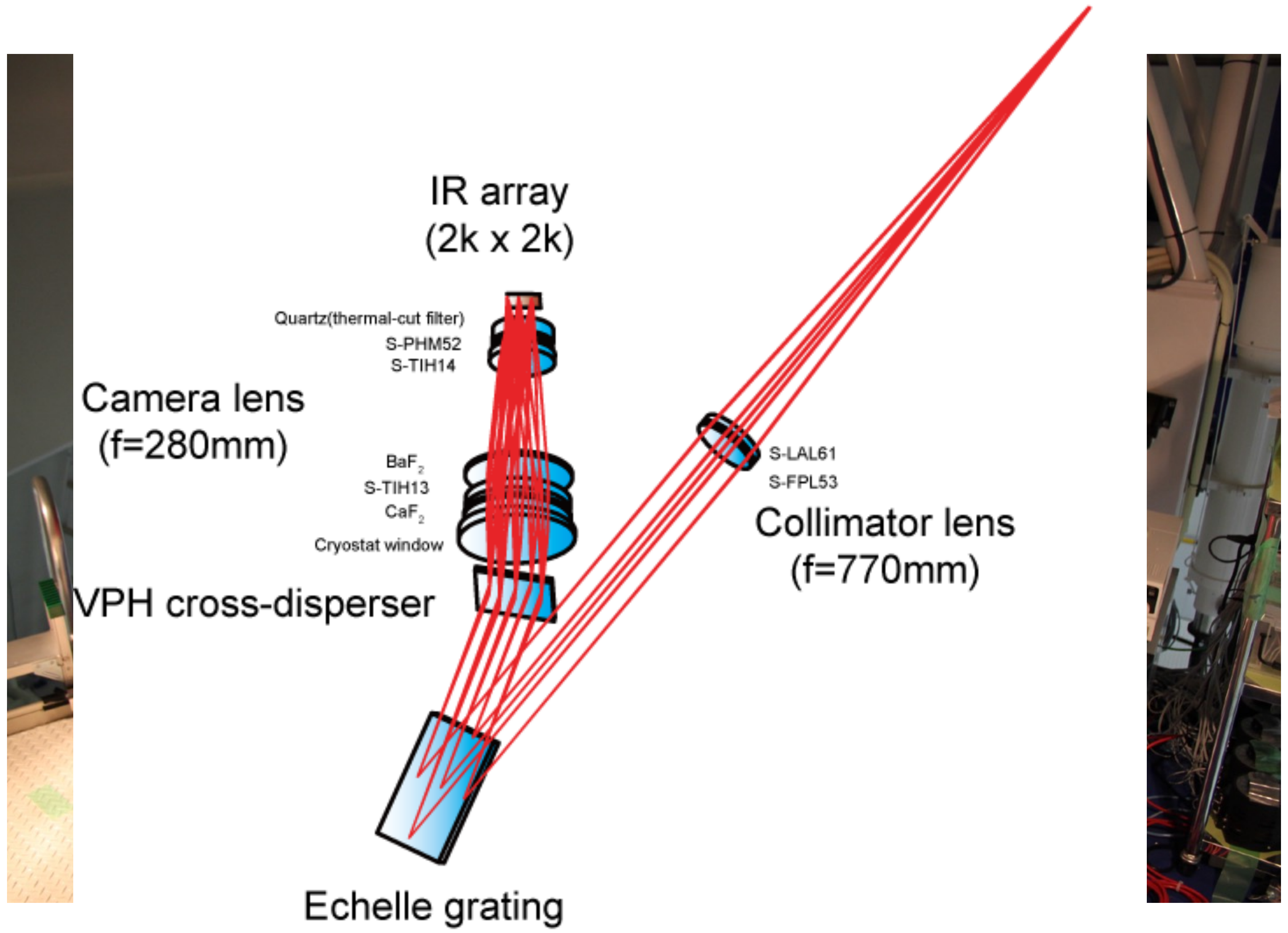
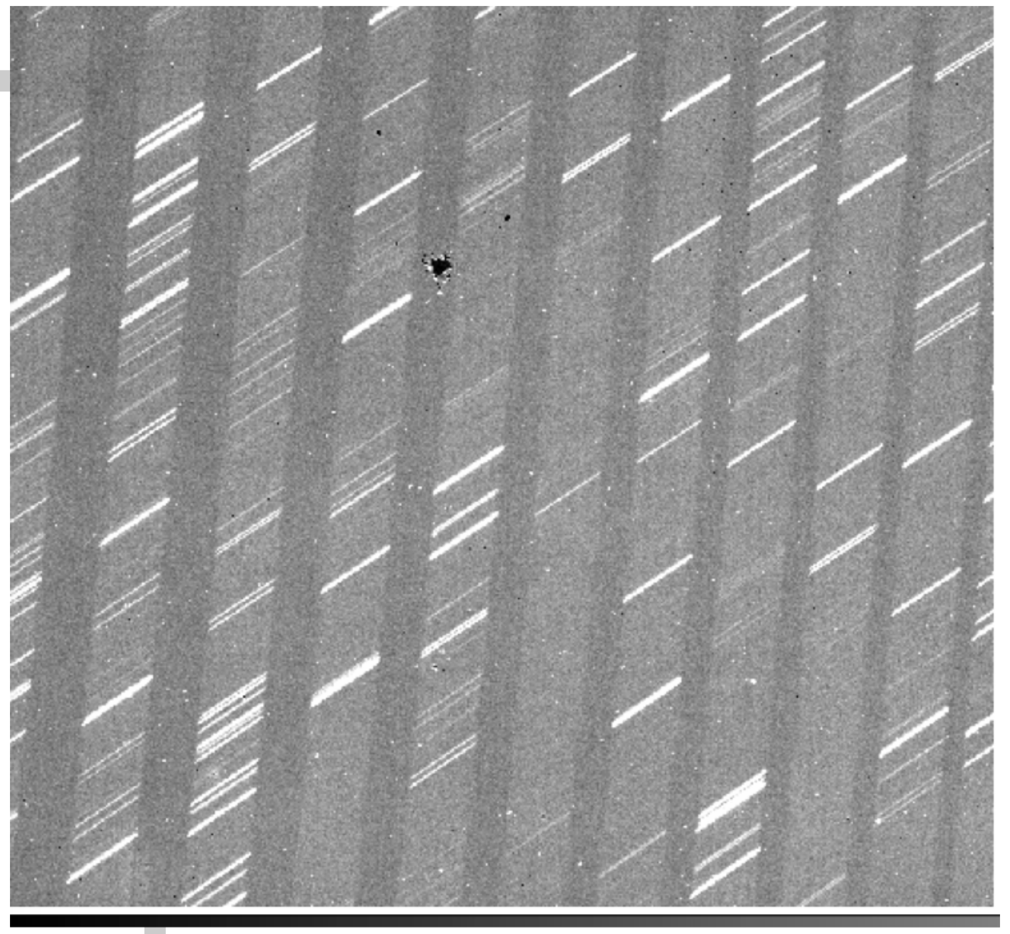


What we will obtain



What we use: WINERED@ Magellan

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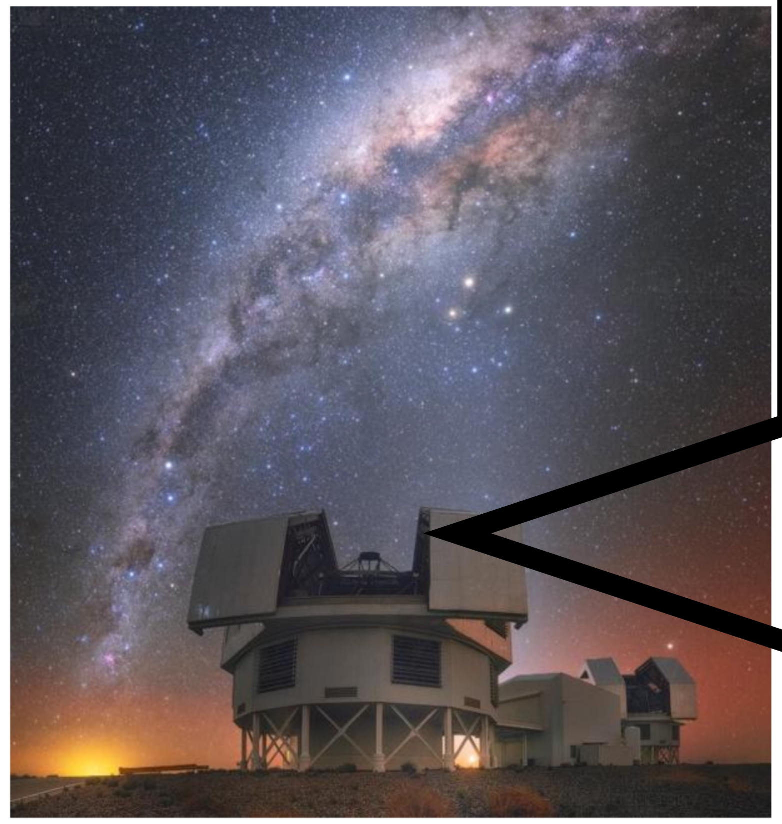

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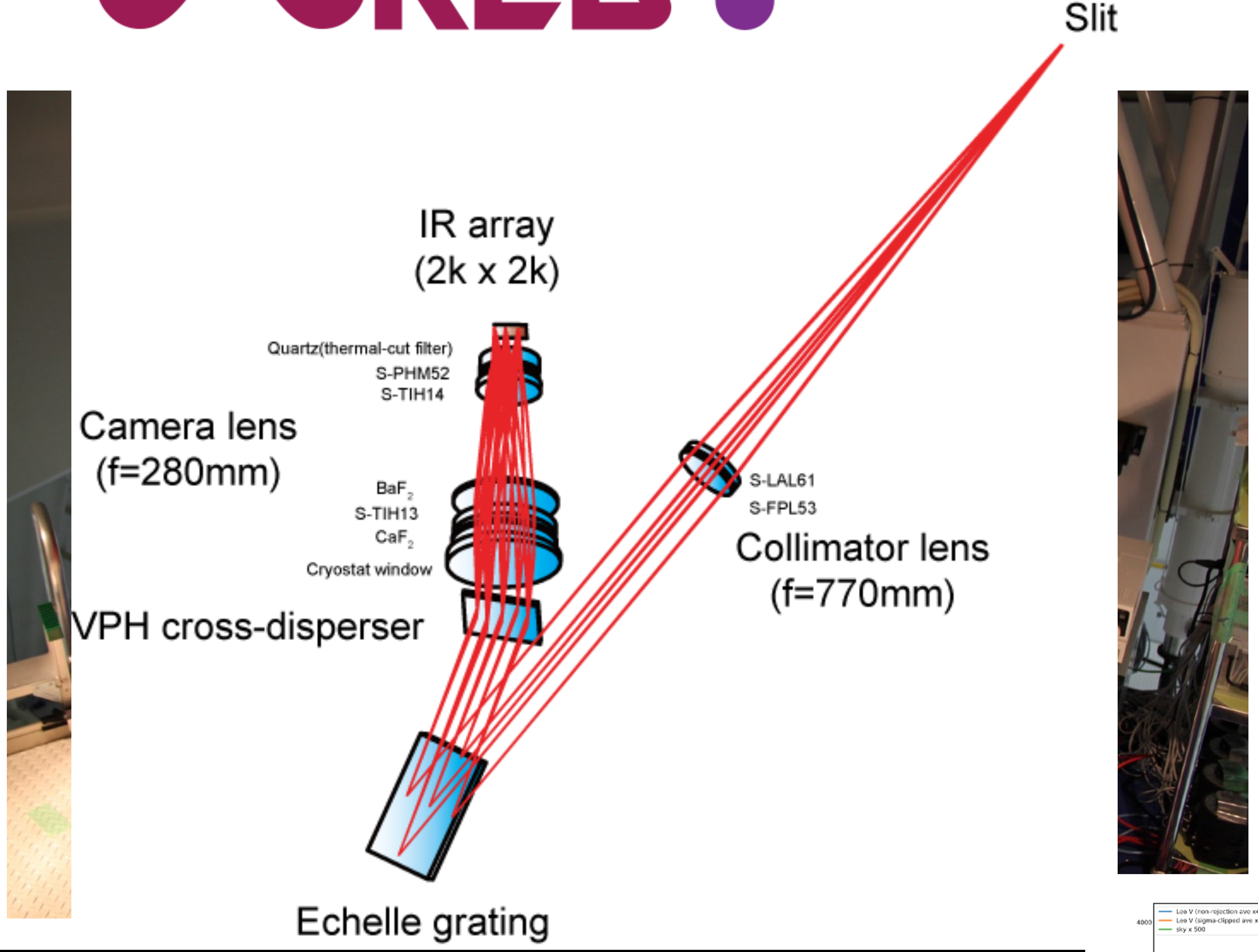
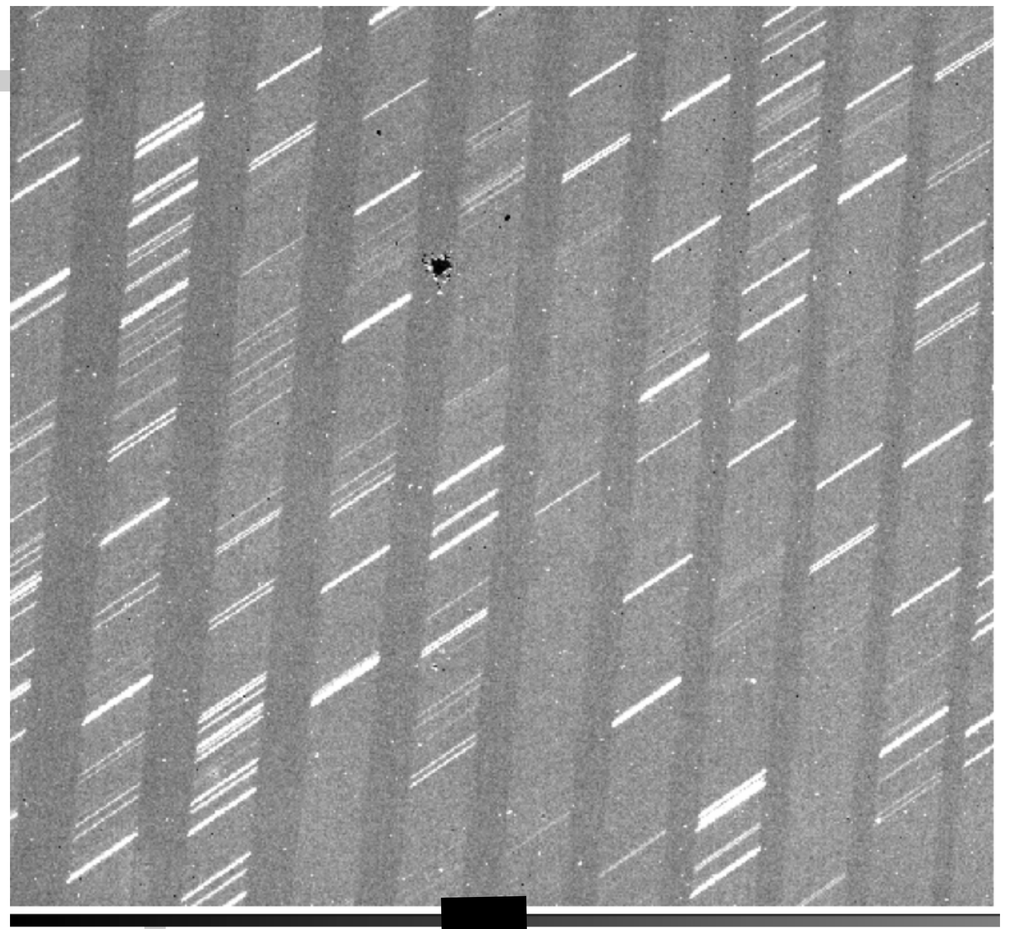


What we will obtain

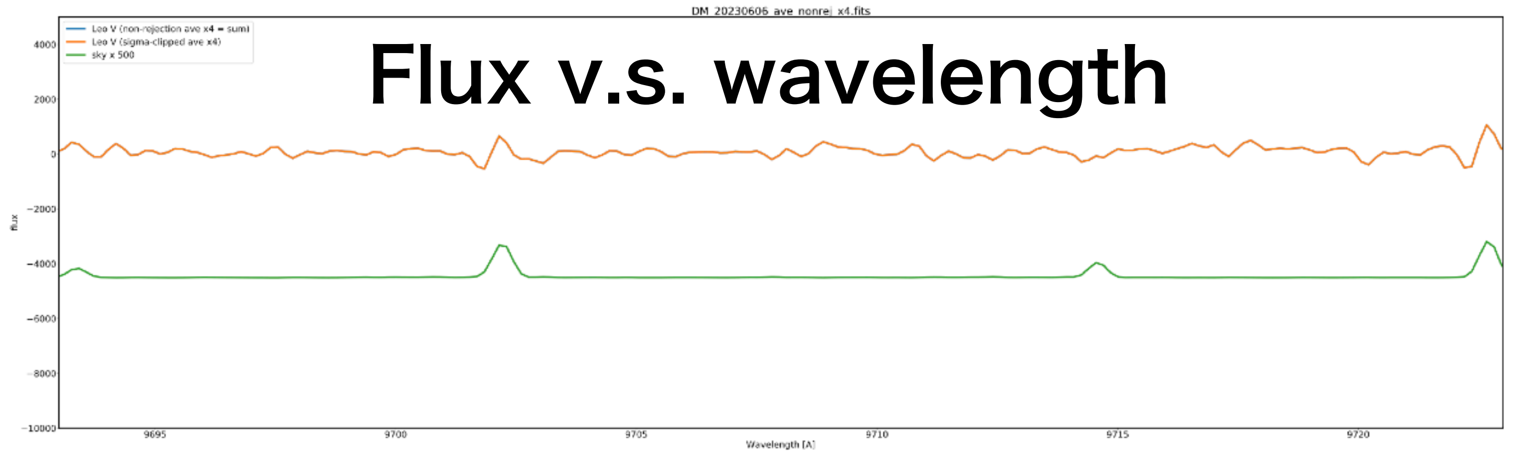
1st diffraction



2nd d fraction

WARP

Hamano et al, 2024



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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For background subtraction.

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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

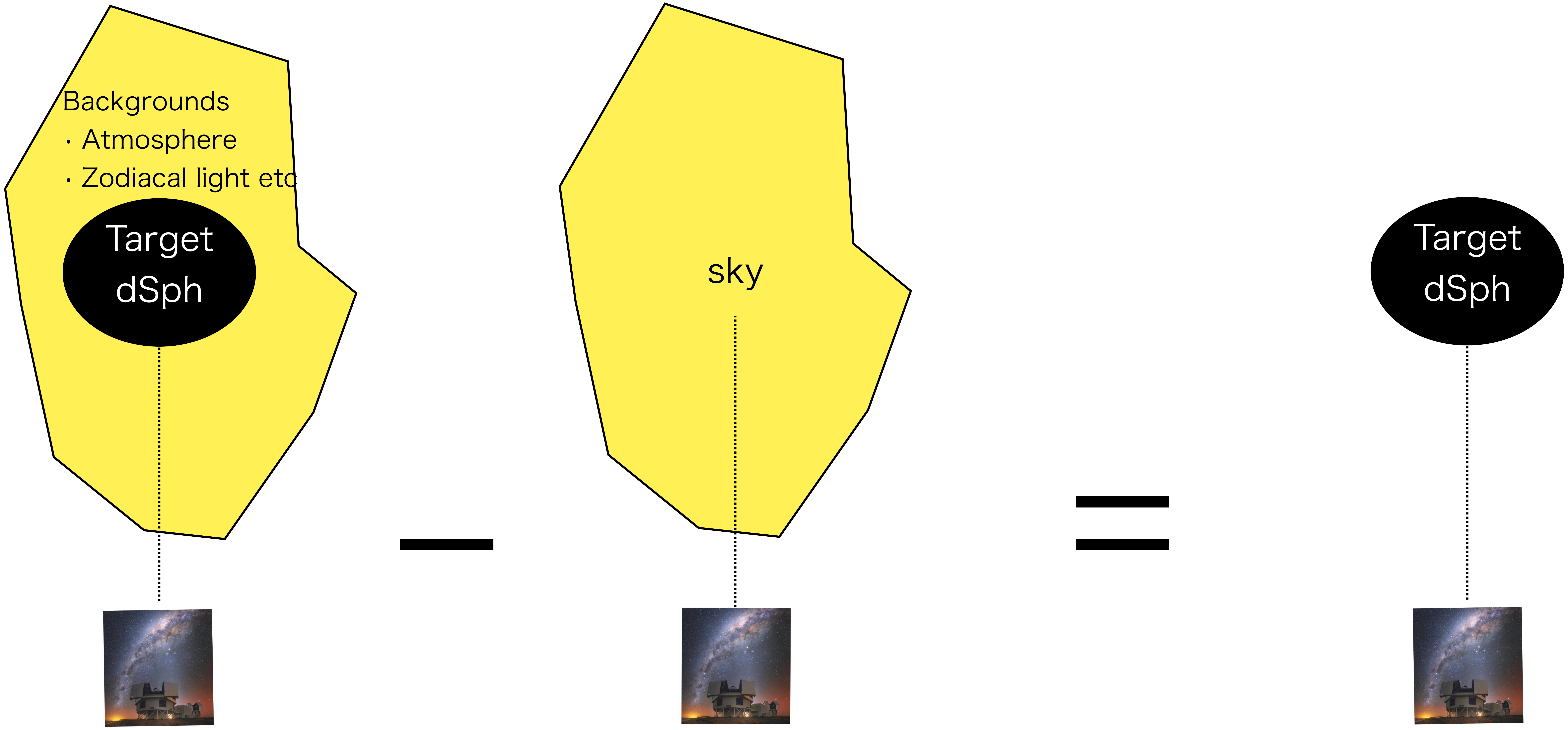
Target dSphs

For background subtraction.

For flux calibration and measuring atmospheric transmittance.

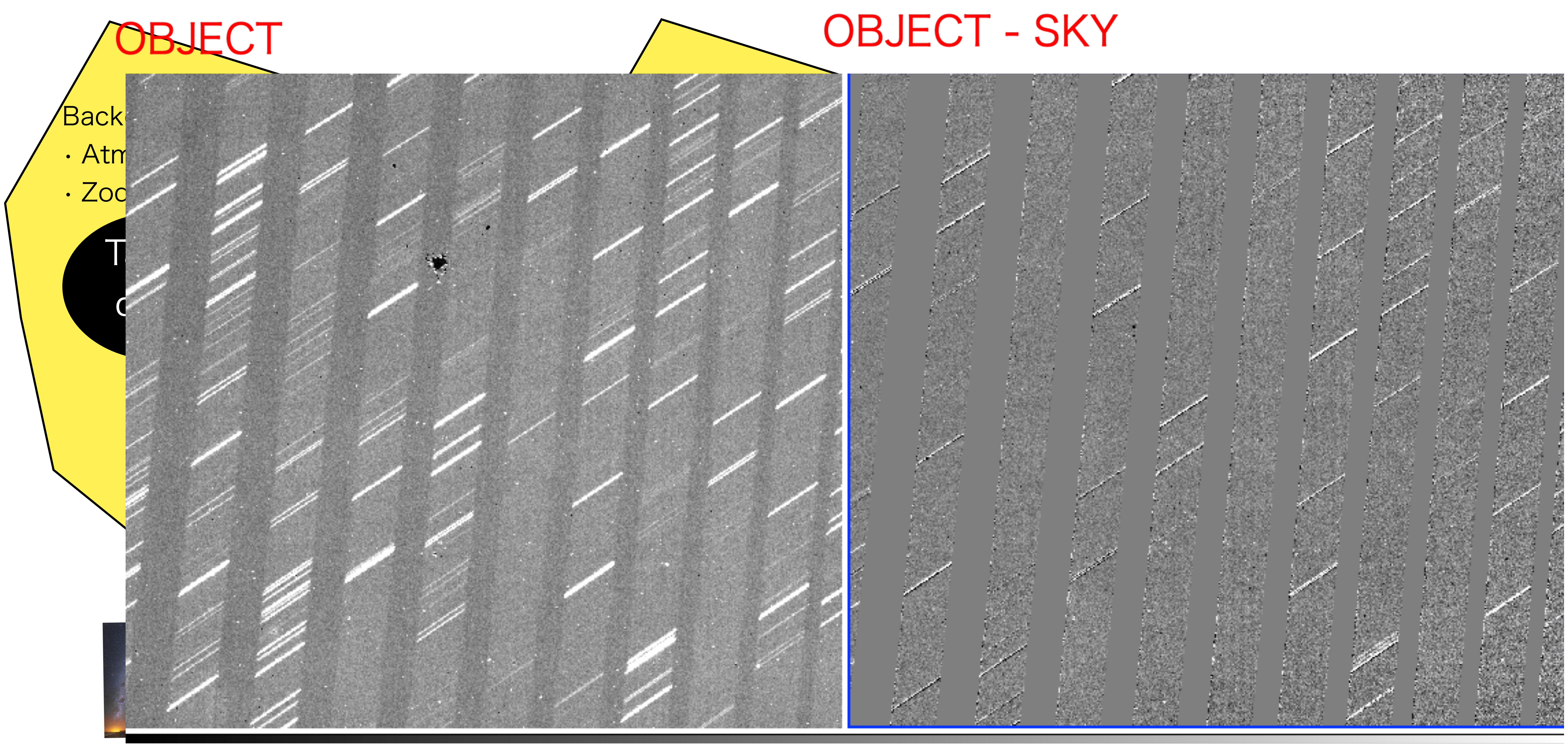
Object-Sky-Object Nodding Observation

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



Object-Sky-Object Nodding Observation

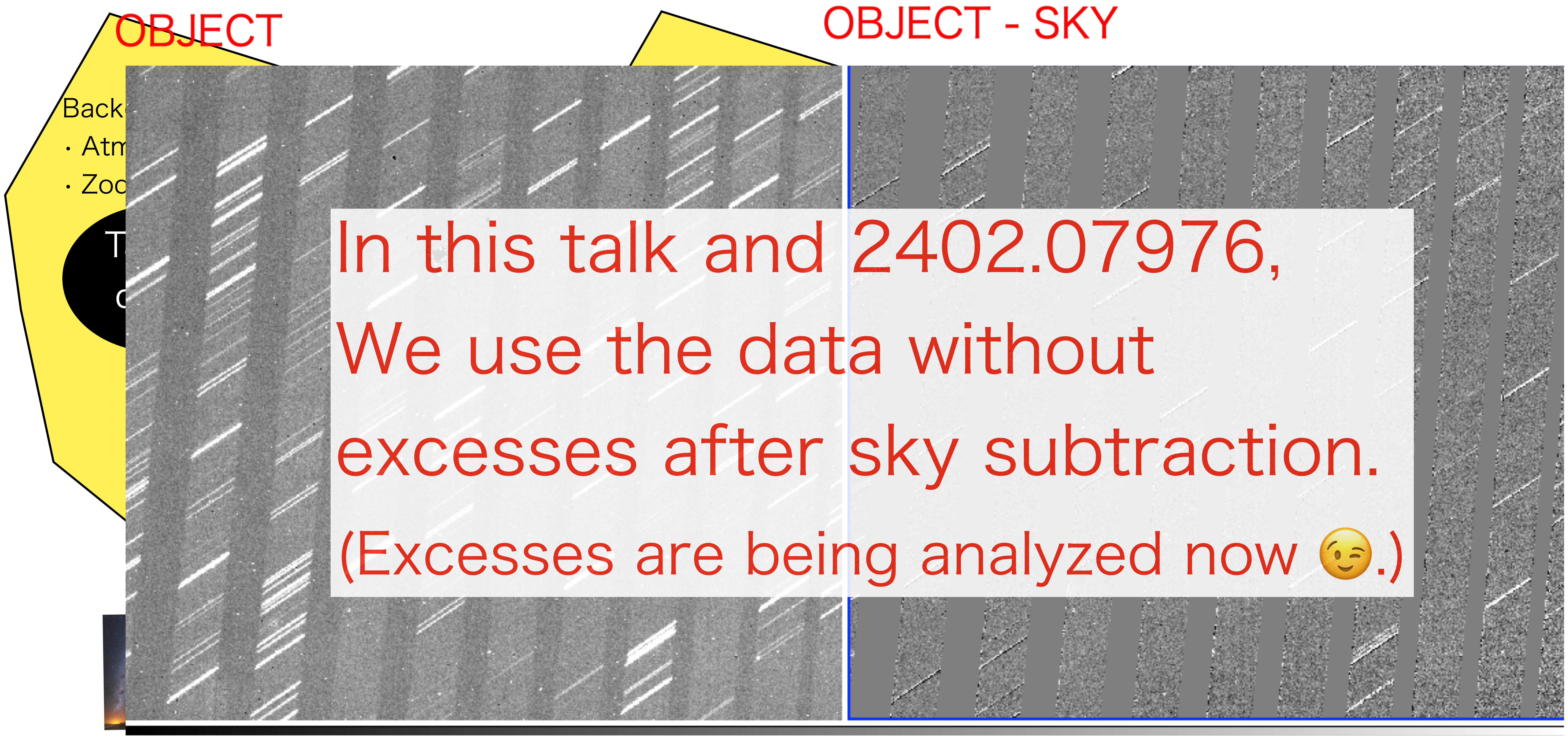
WY, Ikeda, Bessho, Kobayashi+WINERED team, 2402.07976



A tiny wavelength shift was found when we performed the first observation. We take this effect into account in the data analysis.
In the second observation, we reduced each exposure time to suppress this effect.

Object-Sky-Object Nodding Observation

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



In this talk and 2402.07976,
We use the data without
excesses after sky subtraction.
(Excesses are being analyzed now 😉.)

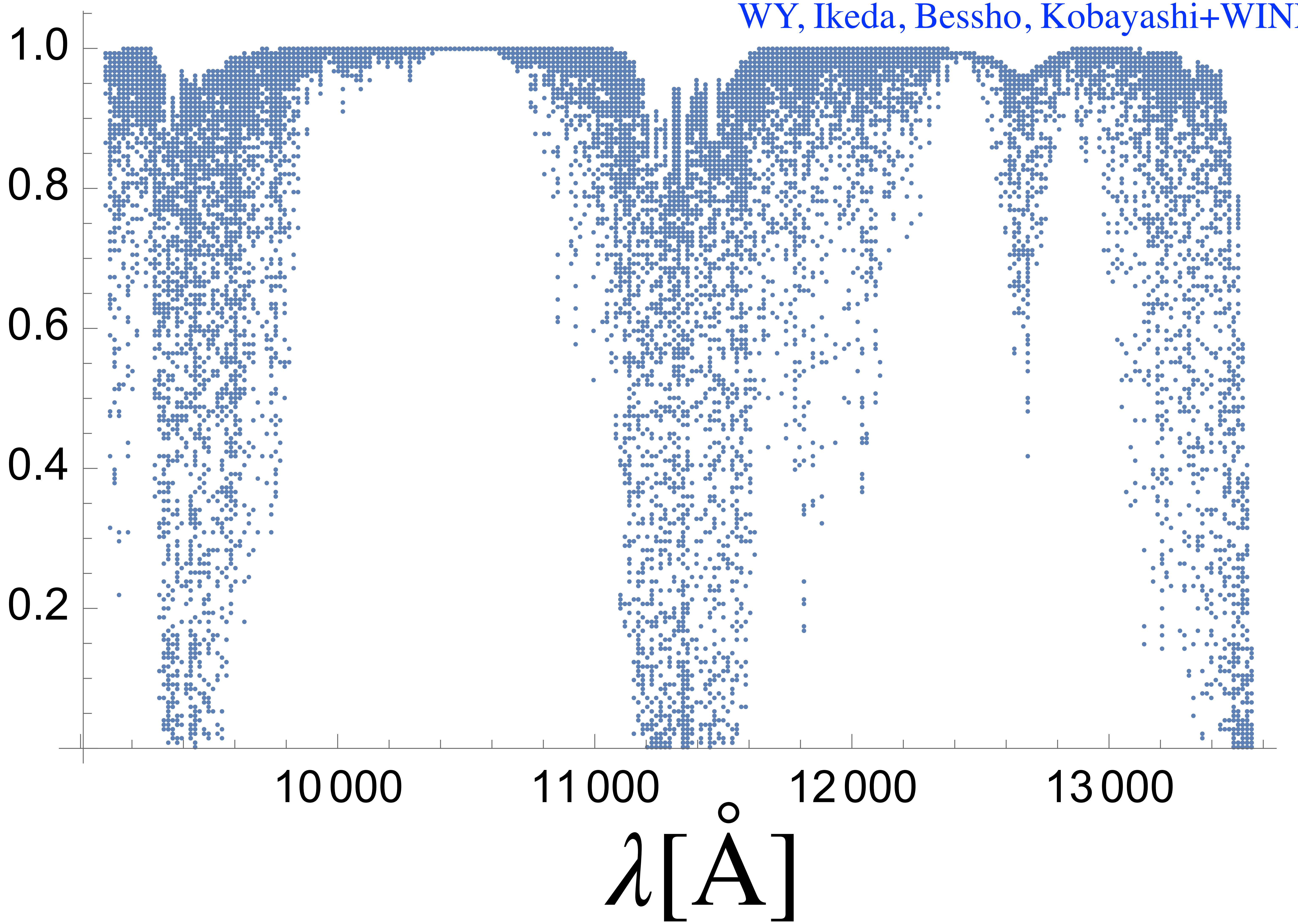
A tiny wavelength shift was found when we performed the first observation. We take this effect into account in the data analysis.
In the second observation, we reduced each exposure time to suppress this effect.

Atmospheric transmittance, η, measured from standard star.

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

η

Probability of transmitting the atmosphere



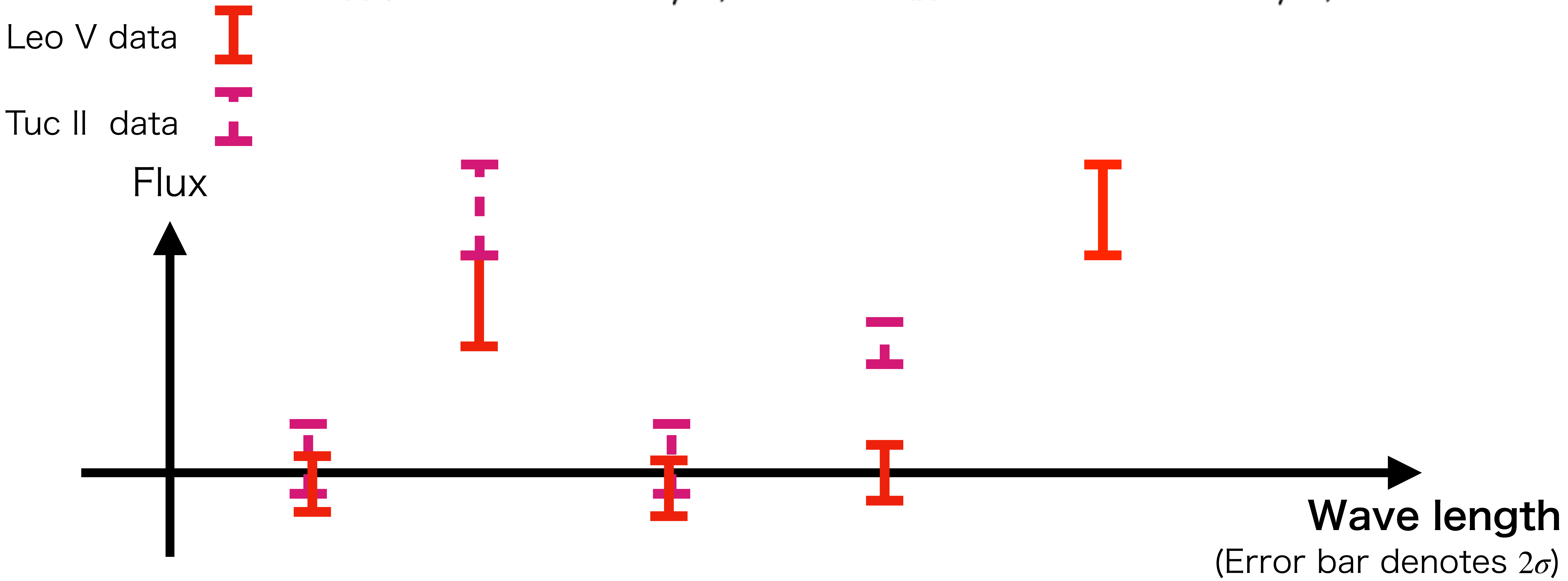
Analysis with Doppler Shift: Earth frame

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

Radial velocities of the dSphs are much larger than the resolution of WINERED

Simbad, Inger et al 0002110

$$v_{\rm LeoV} \approx 173.3\,{\rm km/s}, \;\; \text{and} \;\; v_{\rm TucII} \approx -129.1\,{\rm km/s},$$



We move to dSphs' frames for DM limit.

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

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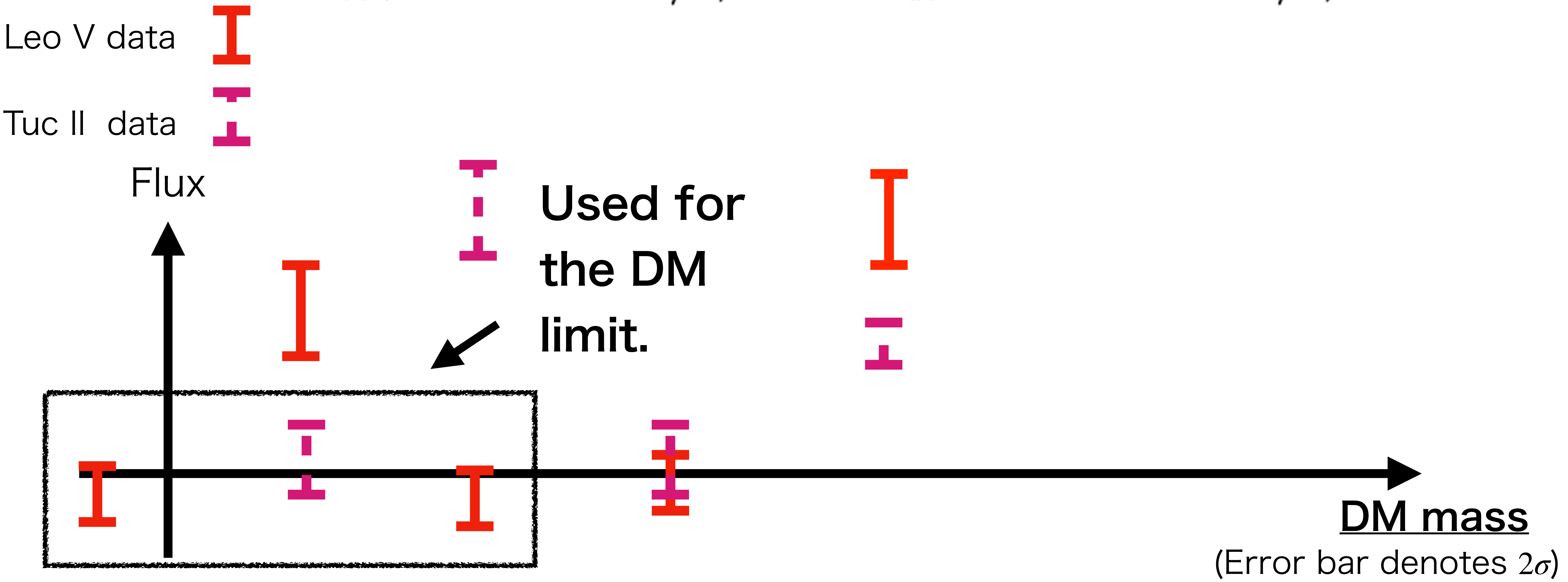

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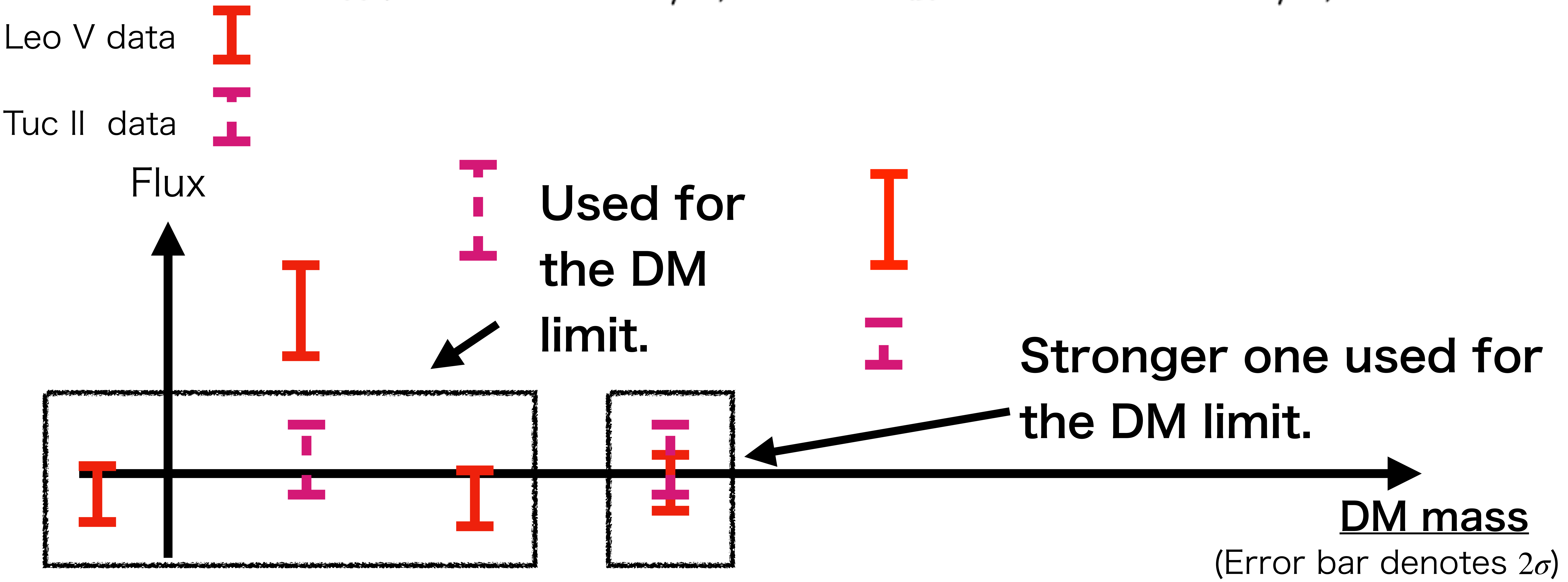

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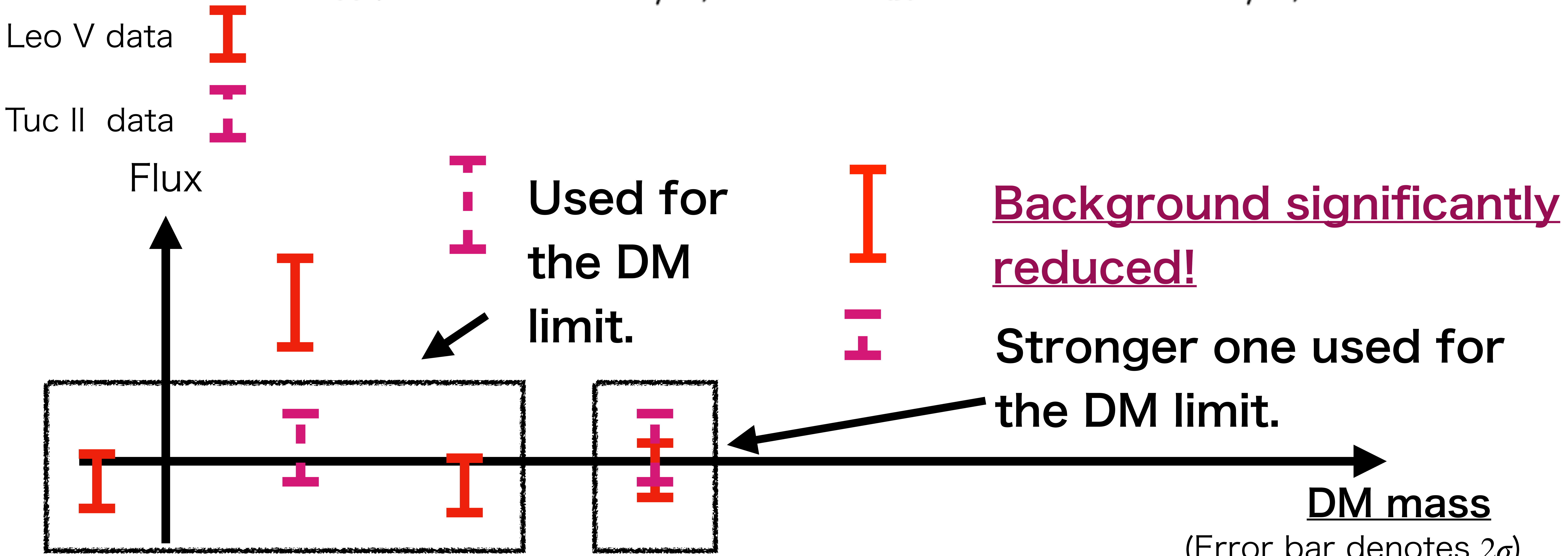

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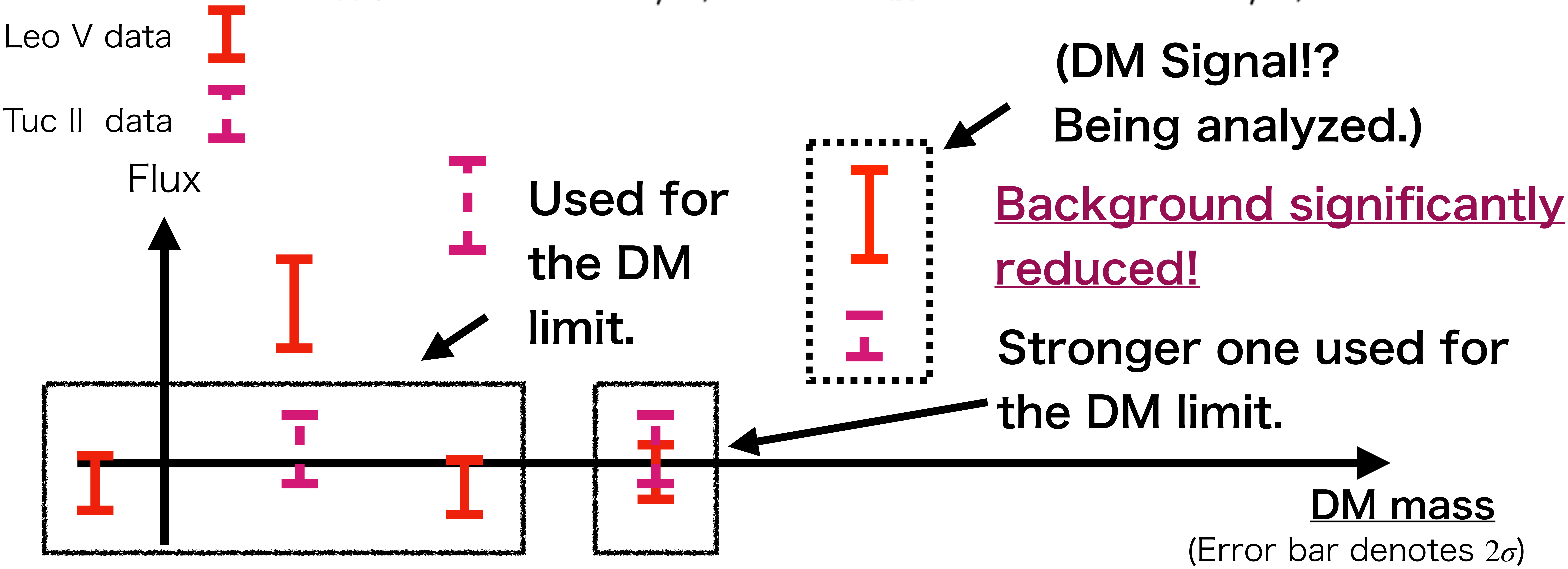

We use differential D-factor of dSphs at around the center

This gives O(10) enhancement of flux compared with using typical value

WY, Hayashi, 2305.13415
(See also Hayashi et al 2007.13780, 2206.02821)

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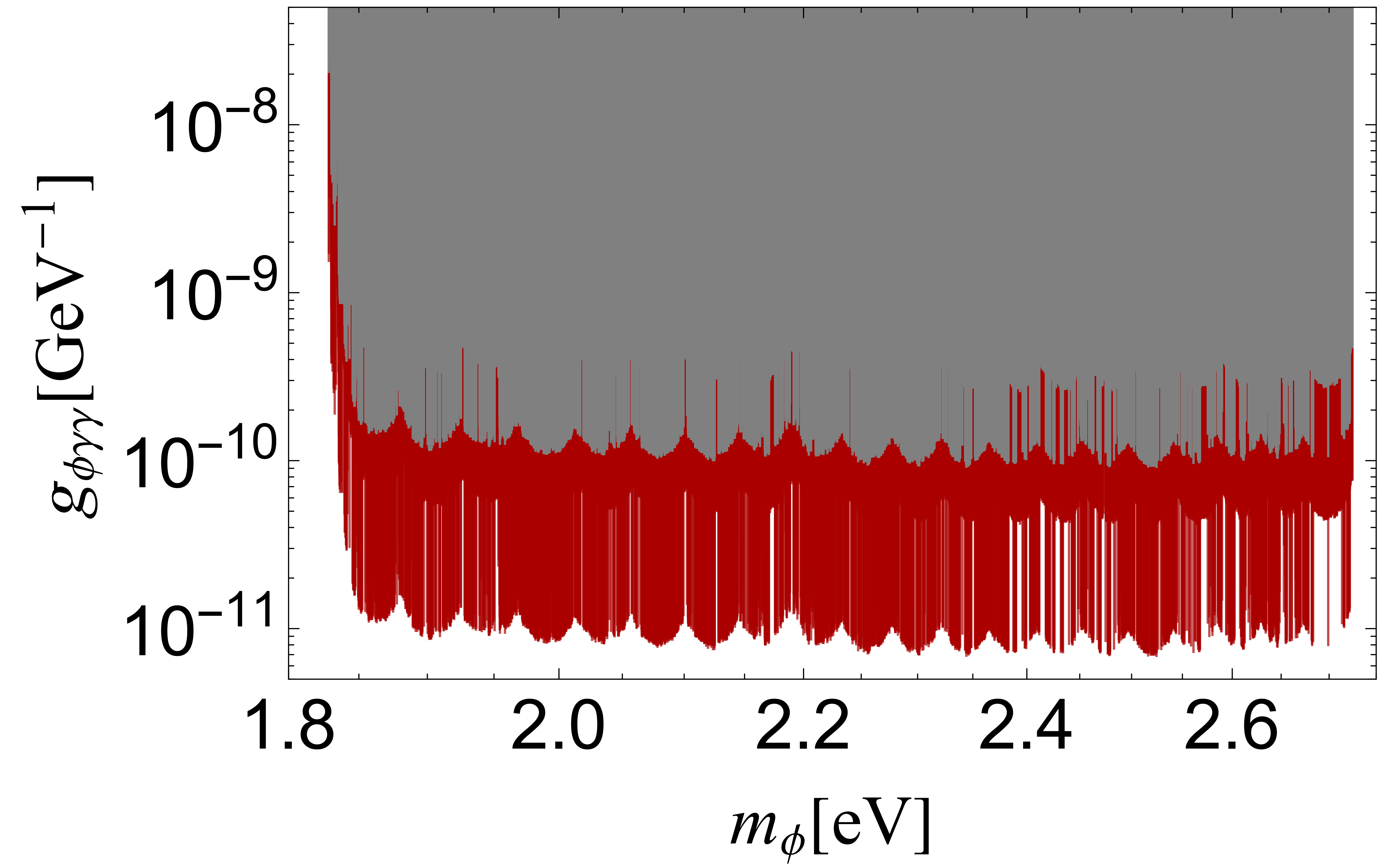
WY, Hayashi, 2305.13415
(See also Hayashi et al 2007.13780, 2206.02821)

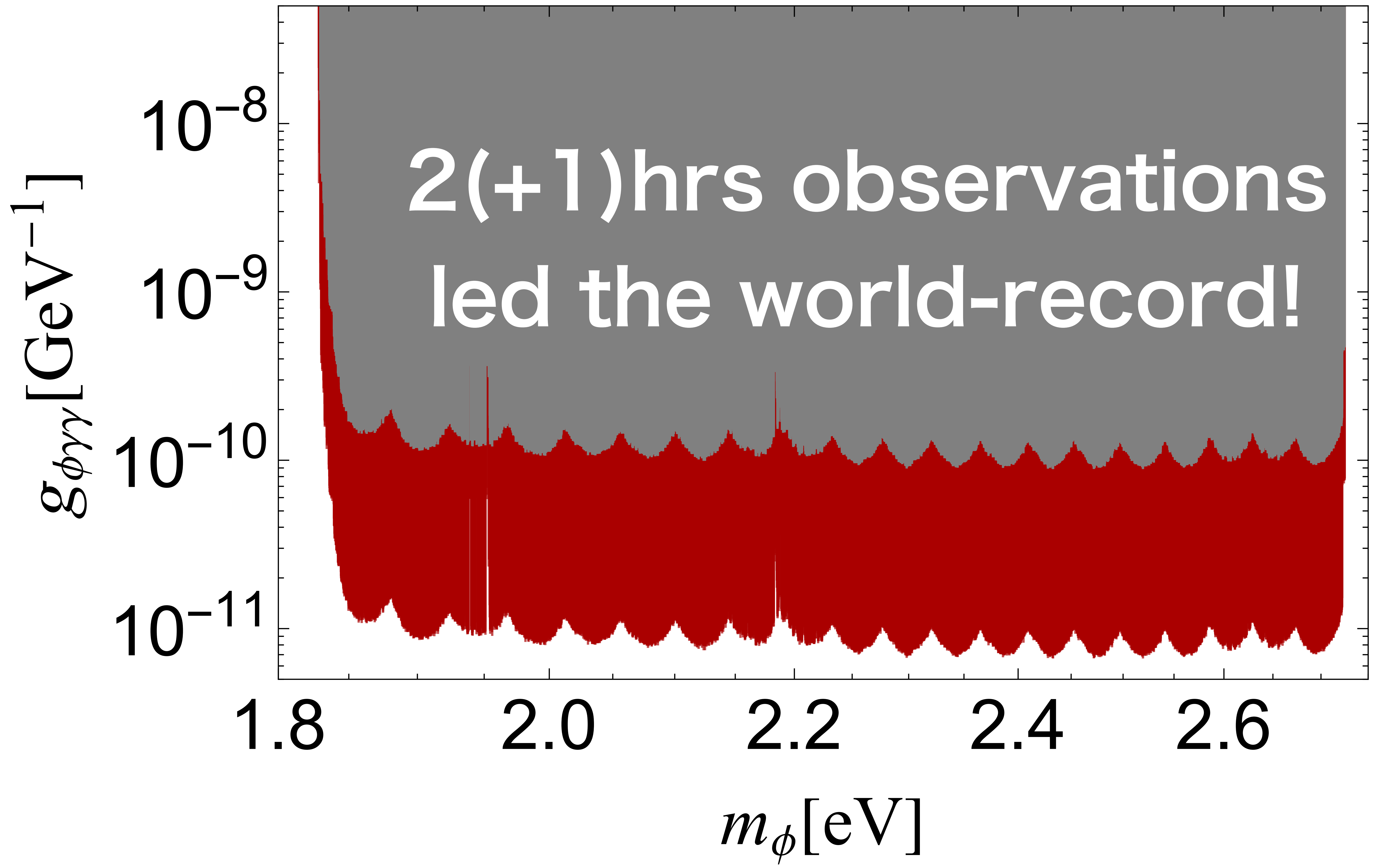
Result: before further data analysis (can be recast to generic spectra)

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



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

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



Conclusions: eV axion DM

- eV dark matter may be interesting because various hints coincide.
- It can be very efficiently searched for by using state-of-the-art infrared spectrographs.

Bessho, Ikeda, WY, 2208.05975

WY, Hayashi 2305.13415

- Performing just 2(+1)hours observations we set one of the strongest bounds in the world.

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

- Some excesses coincide after Doppler analysis. Further analysis/observation is planed.

stay tuned!

Back up slides

DM profiles

Hayashi et al 2020, 2022

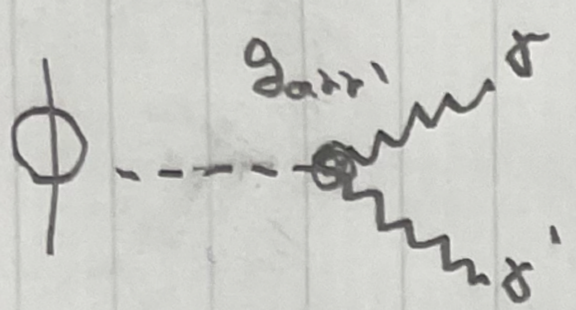
Einasto, and Burkert profiles. The generalized Hernquist profile in the cylindrical coordinates is expressed as

$$\rho_{\rm DM}(m) = \rho_0 \left(\frac{m}{b_{\rm halo}}\right)^{-\gamma} \left[1 + \left(\frac{m}{b_{\rm halo}}\right)^{\alpha}\right]^{-\frac{\beta-\gamma}{\alpha}},$$
$$m^2 = R^2 + z^2/Q^2, \qquad (7)$$

where ρ_0 and $b_{\rm halo}$ are the scale density and radius, respectively; α is the sharpness parameter of the transition from the inner slope γ to the outer slope β; and Q is a constant axial ratio of a DM halo. These (Q, ρ_0, $b_{\rm halo}$, α, β, γ) are the

Reheating for $g_{a\gamma\gamma'}$

Decay



$f_{\gamma'} \propto e^{\frac{8\pi^2 \Gamma_\phi n_\phi}{H P_{\gamma'}^3}}$

$\boxed{\text{bose enhancement}}$

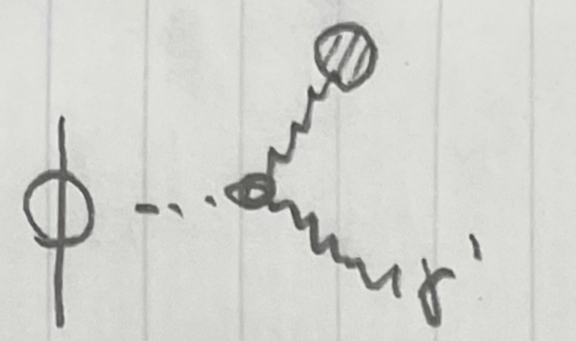
$P_{\gamma'} \simeq \frac{m_\phi}{2} - \frac{m_{th}^2}{2m_\phi}$

[Moroi, WY, 2011.09475]

$m_{th} \uparrow$ $P_{\gamma'} \downarrow$ $\log f_{\gamma'} \uparrow$

- Significant Production of γ'
- Even if $m_\phi < m_{th}$ stimulated decay is expected to proceed due to dissipation effect,

Equilibration



$\dot{f}_\phi \propto -f_{th}[f_\phi - f_{\gamma'}]$

$, f_{th}^{(1)} f_{th}^{(2)} [f_\phi - f_{\gamma'}]$

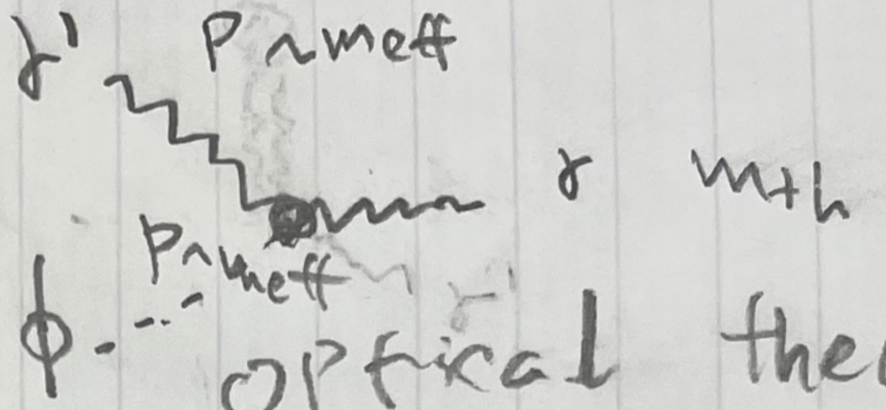
$\left(\because P_\phi \sim P_{\gamma'} \sim m_{eff} \ll T, \; f_{th}^{(1)} \sim f_{th}^{(2)} \right)$

$\Rightarrow f_\phi \sim f_{\gamma'}$

$\Rightarrow n_\phi \sim n_{\gamma'}$

[e.g. W.Y. 2301.08735]

Annihilation



optical theorem

$\sigma \sim \frac{1}{E_{cm} P_{cm}} \mathrm{Im}[\mathcal{M}_{\gamma'\phi \to \gamma'\phi}]$

$\sim \frac{1}{P^2} \mathrm{Im}\left[\frac{g_{\phi\gamma\gamma'}^2 P^4}{P^2 - m_{th}^2 + i m_{th} \Gamma} \right]$

Breit-Wigner

$m_{th} \mathrm{Im}[(P^2 - m_{th}^2 + i m_{th} \Gamma)^{-1}]$

Energy conservation violation.

$\Gamma \sim Y_t^2 g_\gamma^2 T$

[mean freepath of photon in plasma

$\Rightarrow \sigma \overset{P \to 0}{\sim} g_{\phi\gamma\gamma'}^2 \frac{\Gamma}{m_{th}} \sim g_\gamma g_{a\gamma\gamma'}^2$

Axion abundance

Things will not change if axion is produced from misalignment. In both cases, we have $m_\phi \sim H$.

Axion abundance

Annihilation stops when

$$n_\phi \sigma \sim H \quad \cdots ①$$

later comoving number conserves

$$\frac{n_\phi}{s} m_\phi \sim 0.1\,\mathrm{eV}.$$

for DM

$$\boxed{\begin{gathered} m_\phi \sim H_{inf} \underset{\text{(instant reheating)}}{\sim} H \\ s \sim T^3 \sim m_\phi^{\frac{3}{2}} M_{pl}^{\frac{3}{2}} \end{gathered}} \quad \cdots ②$$

$\Rightarrow$ ①②

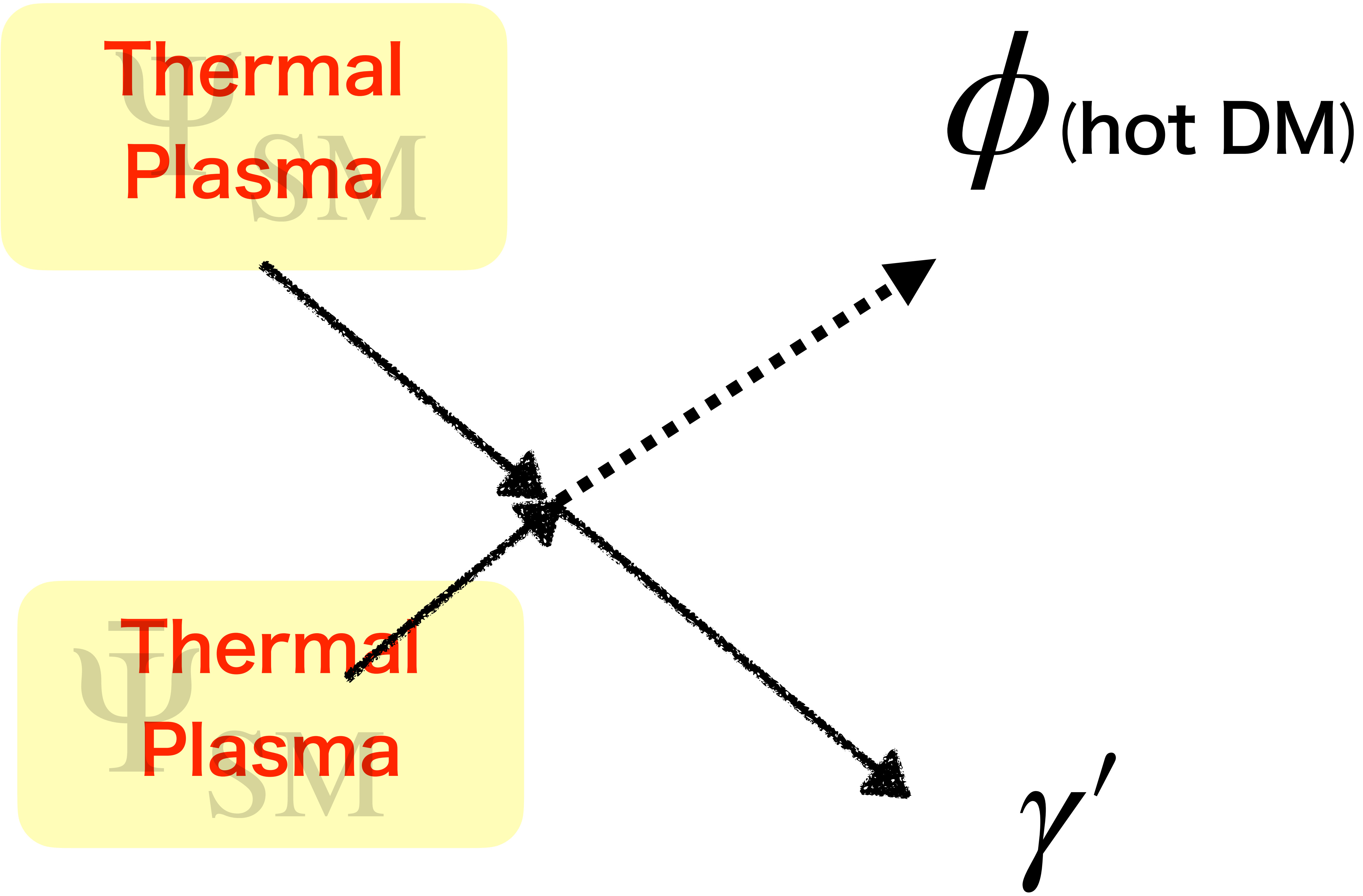
$$\frac{n_\phi m_\phi}{s} \sim \frac{m_\phi^{\frac{1}{2}}}{\sigma M_{pl}^{3/2}} \sim 0.1\,\mathrm{eV}\left(\frac{g_{\phi\gamma\gamma'}}{10^{-10}\,\mathrm{GeV}}\right)^{-2}\left[\frac{m_\phi}{\mathrm{eV}}\right]^{\frac{1}{2}}$$

- many $O(1)$ factors
- $\sigma \equiv \frac{C\, g_{\phi\gamma\gamma'}^2\, g_\gamma}{(4\pi)^3}$, using realistic parameters

$$\Omega_\phi = \frac{0.2}{C}\left(\frac{m_\phi}{2.5\,\mathrm{eV}}\right)^{1/2}\left(\frac{g_{\phi\gamma\gamma'}}{\sqrt{2}\times 1.5\times 10^{-10}\,\mathrm{GeV}}\right)^{-2}$$

Prediction

Thermal production of hot DM/dark radiation



$$\Delta g_{\text{eff}} = 3$$

$$\Delta N_{\text{eff}} \sim 3 \times 0.03 \sim 0.1$$

2. DM=inflaton=ALP

Axion inflation

The slow-roll flat direction is stable under radiative corrections if ϕ is an axion featuring a discrete shift symmetry:

$$\phi \to \phi + 2\pi f_\phi$$

$$\longrightarrow \quad V_{\rm inf}(\phi) = V_{\rm inf}(\phi + 2\pi f_\phi)$$

<u>Realization of axion inflation:</u>

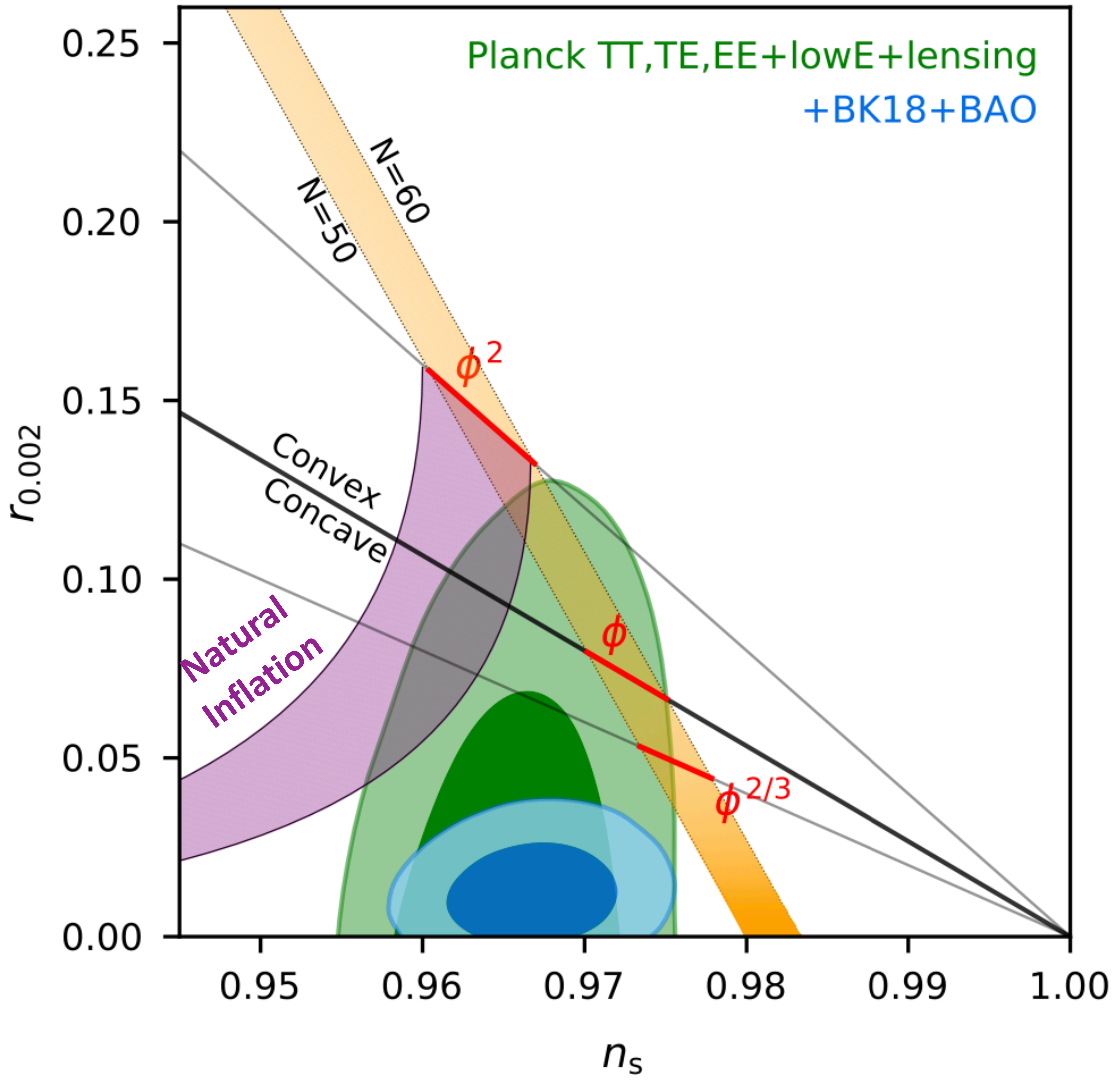
Natural inflation: single cosine

Freese, Frieman, Olinto `90

$$V_{\rm inf} = \Lambda^4(1 - \cos(\phi/f_\phi))$$

$f_\phi > M_{\rm pl}$ and excluded due to too high scale for inflation⋯

BICEP and Keck Collaborations, 2110.00483



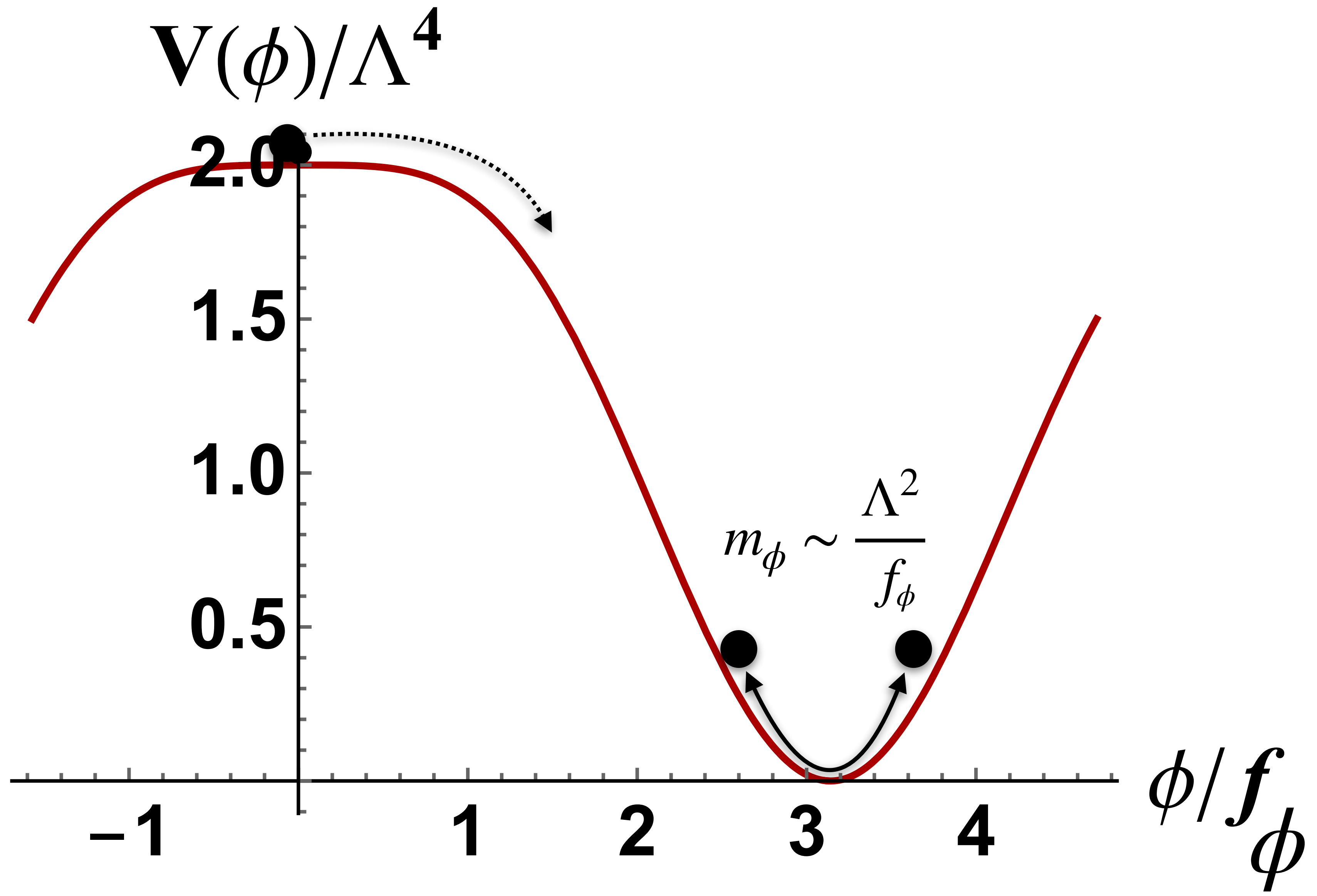
Multi-natural inflation: $V_{\rm inf}$ from 2 or more cos terms

Czerny, Takahashi 1401.5212; Czerny, Higaki, Takahashi 1403.0410, 1403.5883; Daido, Takahashi, and WY 1702.03284; 1710.11107; Takahashi and WY, 1903.00462;

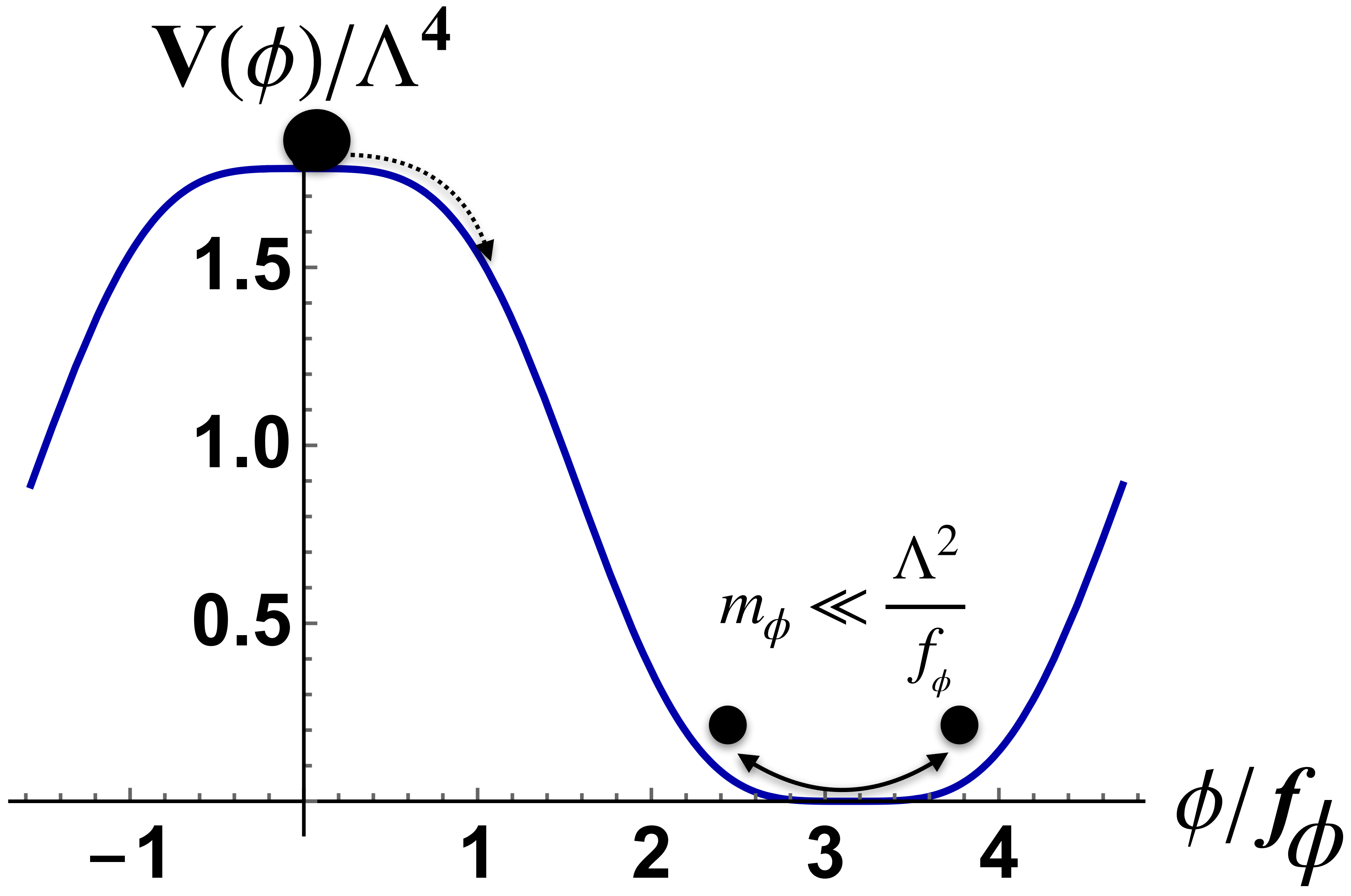
In multi-natural inflation, CMB data can be well explained with $f_\phi \ll M_{\rm pl}$.

$$V_{\rm inf}(\phi) = \Lambda^4 \left(\cos\left(\frac{\phi}{f_\phi} + \theta\right) - \frac{\kappa}{n^2} \cos\left(\frac{n\phi}{f_\phi}\right) \right) + {\rm const}$$

The inflaton masses depend on the parity of n.



Even n



Odd n

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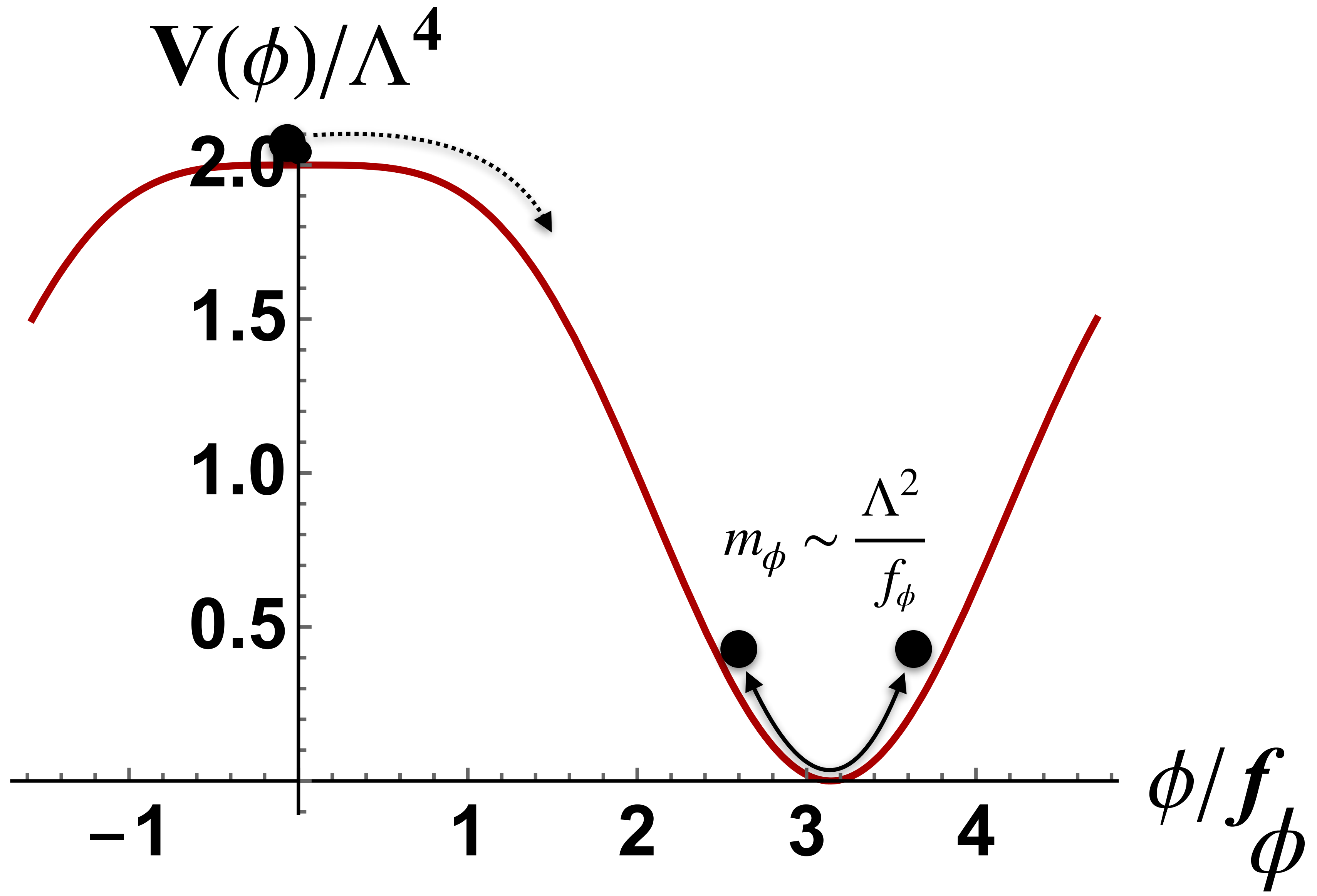

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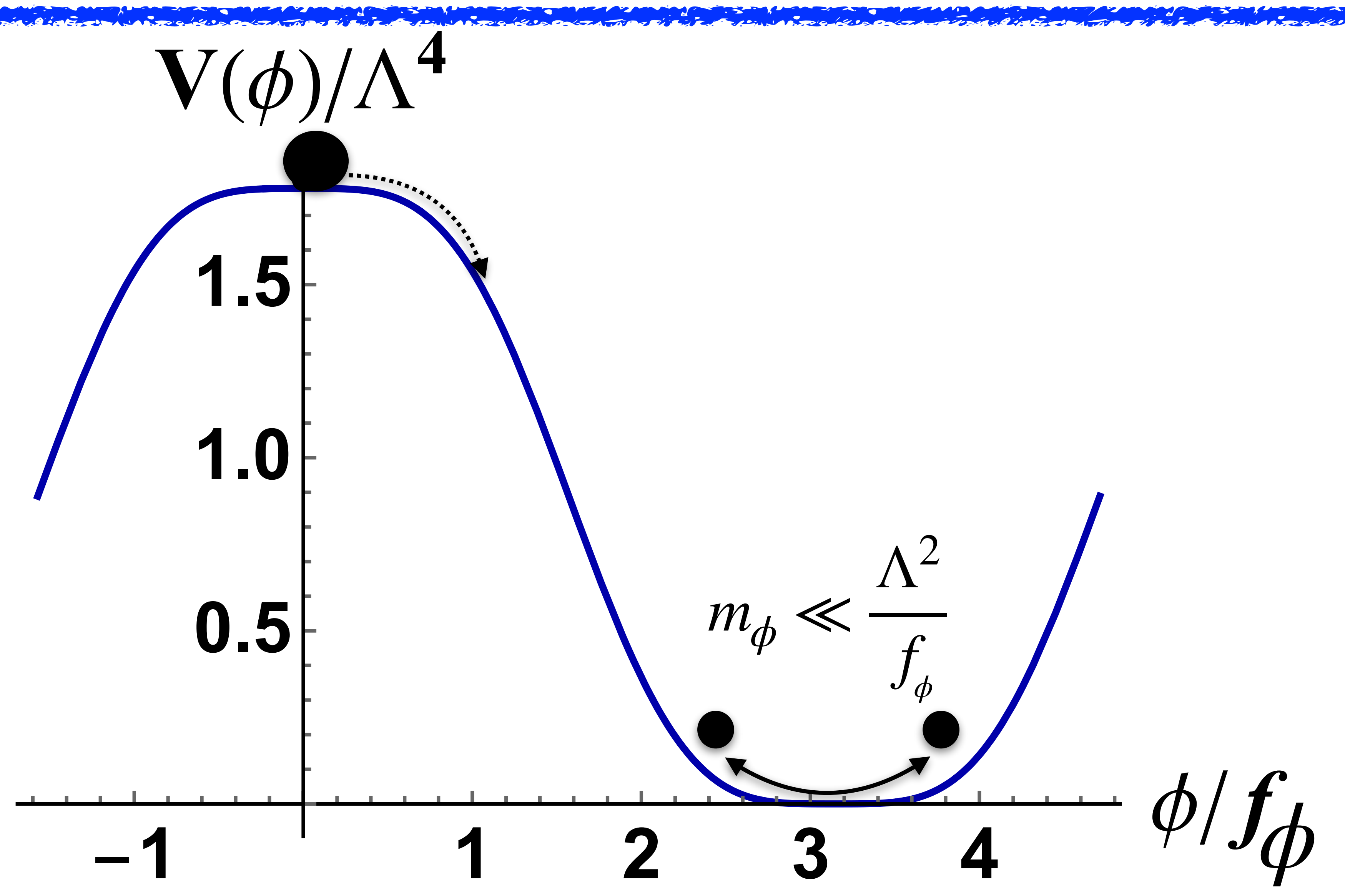

Odd n

Axion Hilltop inflation

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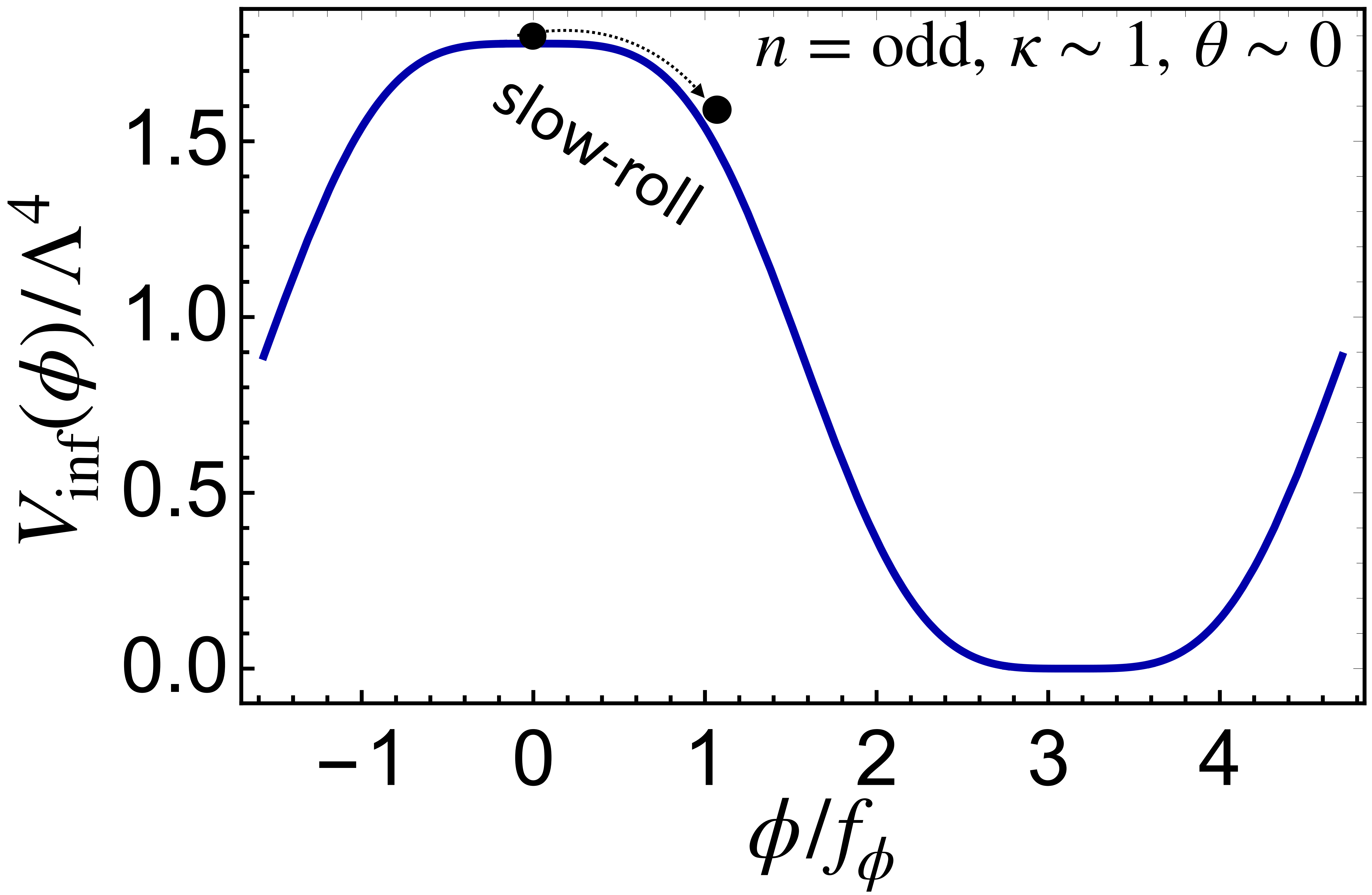
$$\simeq V_0 - \lambda\phi^4 - \Lambda^4\theta\frac{\phi}{f_\phi} + \cdots .$$



- Almost quartic hilltop inflation.
- n_s corrected from non-vanishing θ
- Upside-down symmetry when $n = \text{odd}$

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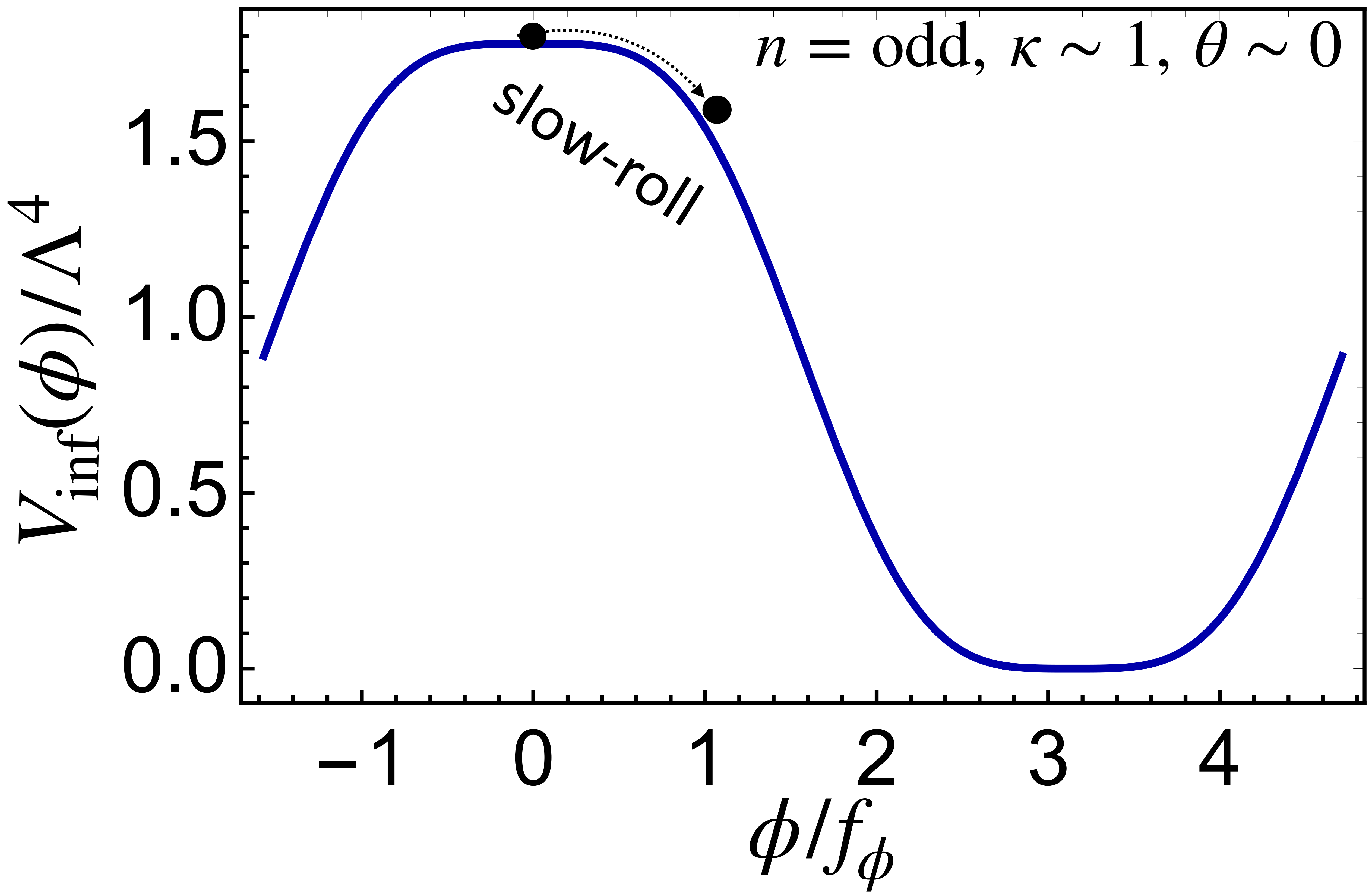

- Almost quartic hilltop inflation.

  CMB normalization:
  $$\lambda \sim \Lambda^4/f_\phi^4 \sim 10^{-12}$$

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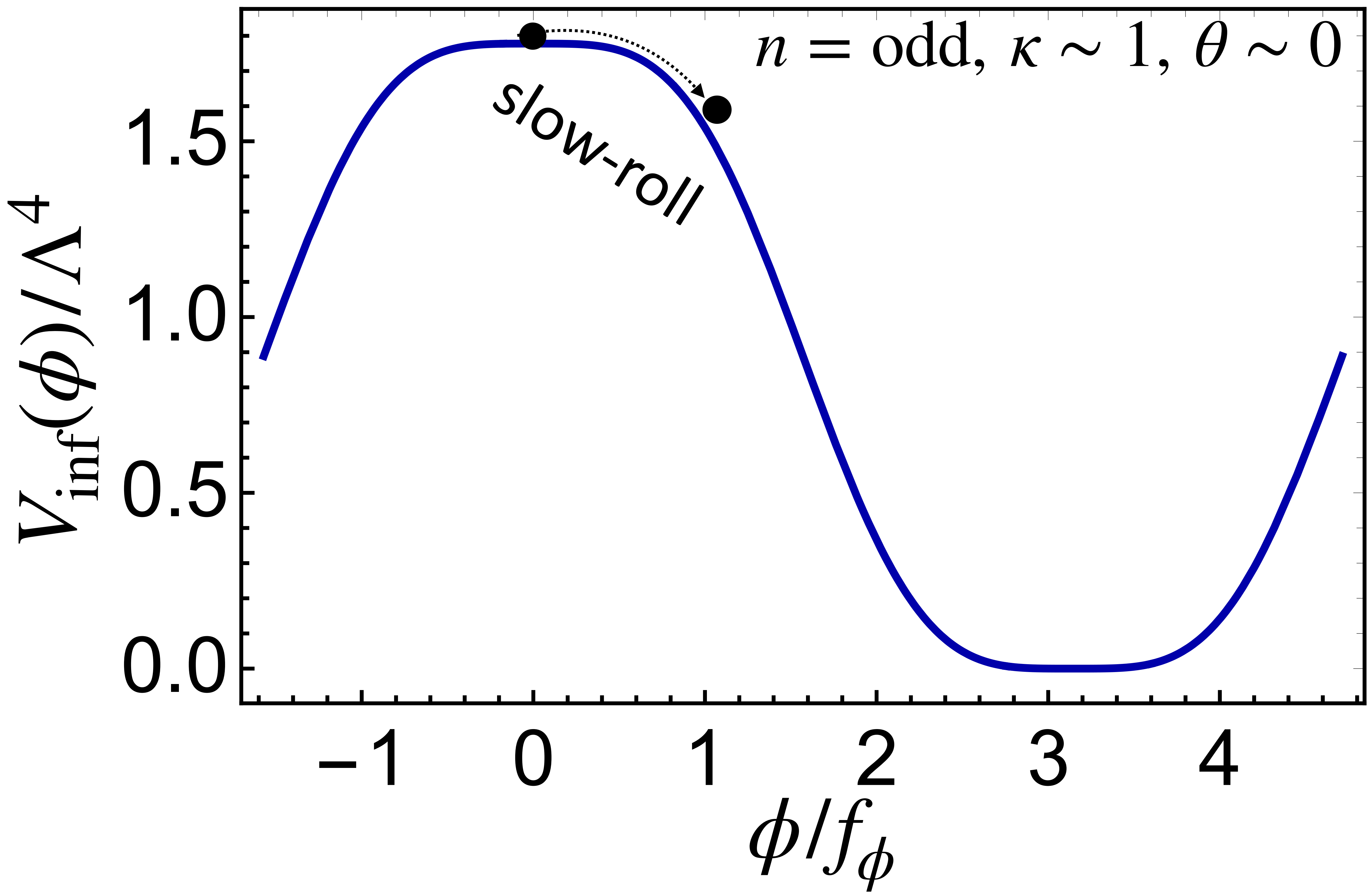
A linear term can give better fit of n_s.

Takahashi,1308.4212



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  $$n_s \approx 1 + 2V''_{\rm inf}/3H^2_{\rm inf} \approx 0.97$$

  $$V''_{\rm inf}|_{\rm hilltop} \approx -O(0.1-1)H^2_{\rm inf}$$

- Upside-down symmetry when $n = {\rm odd}$

Upside-down symmetry in axion hilltop inflation

Daido, Takahashi, WY 1702.03284, 1710.11107; Takahashi and WY,1903.00462;
UV model for hilltop condition: e.g. Croon and Sanz 1411.7809; Higaki, Takahashi 1501.02354;

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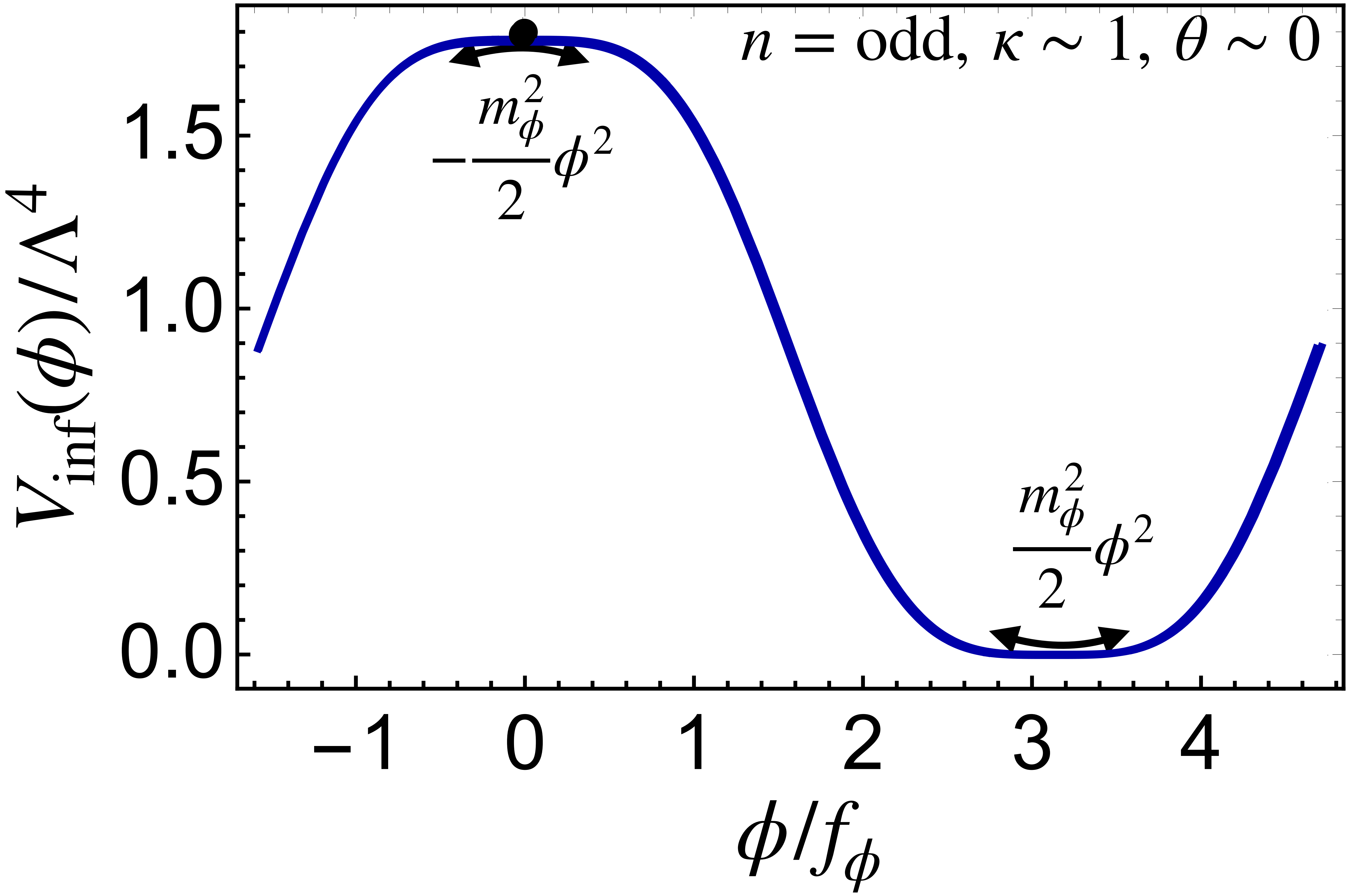

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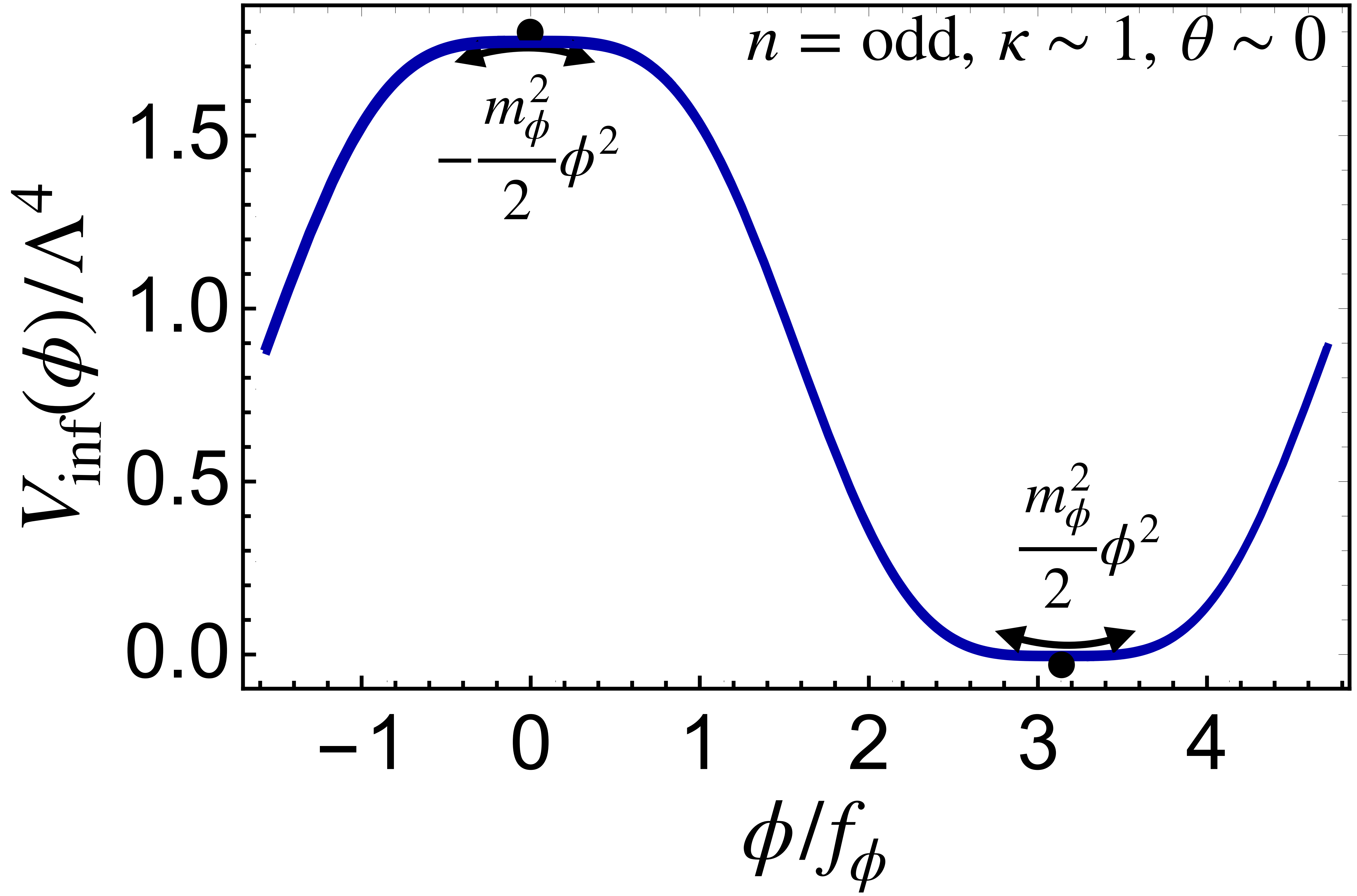

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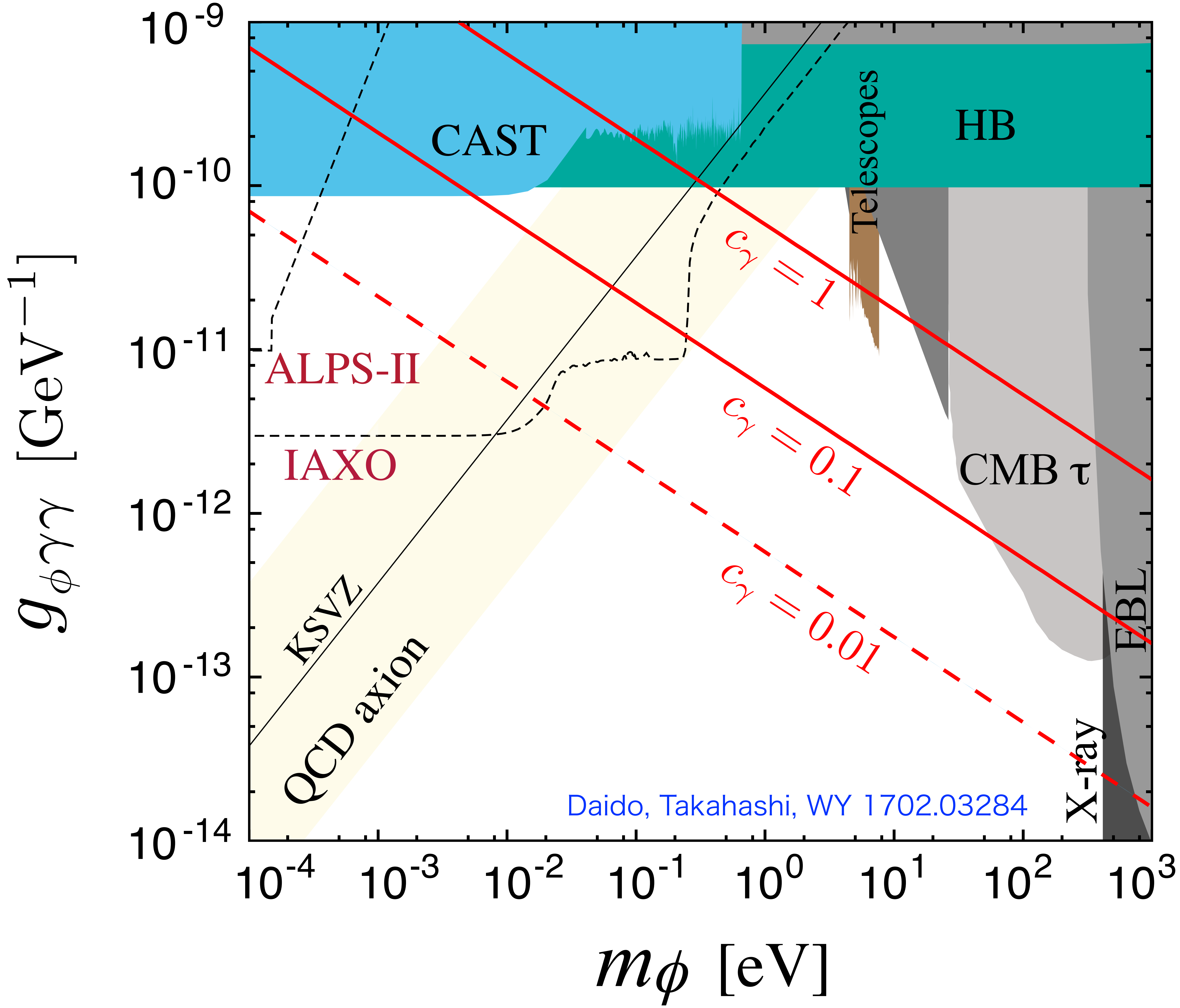
- Upside-down symmetry when $n = {\rm odd}$

$$\boxed{\begin{aligned}&\lambda(\text{self-coupling}) \sim 10^{-12}\\ &m_\phi = O(0.1-1)H_{\rm inf} \sim 10^{-6}\frac{f_\phi^2}{M_{\rm pl}}\end{aligned}}$$

(Note $H_{\rm inf} \sim \Lambda^2/M_{\rm pl}$)

ALP(axion coupled to photon)=inflaton

$$\mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad g_{\phi\gamma\gamma} = \frac{c_\gamma \alpha}{\pi f}$$



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—> sub-eV or eV-scale ALP DM candidate.

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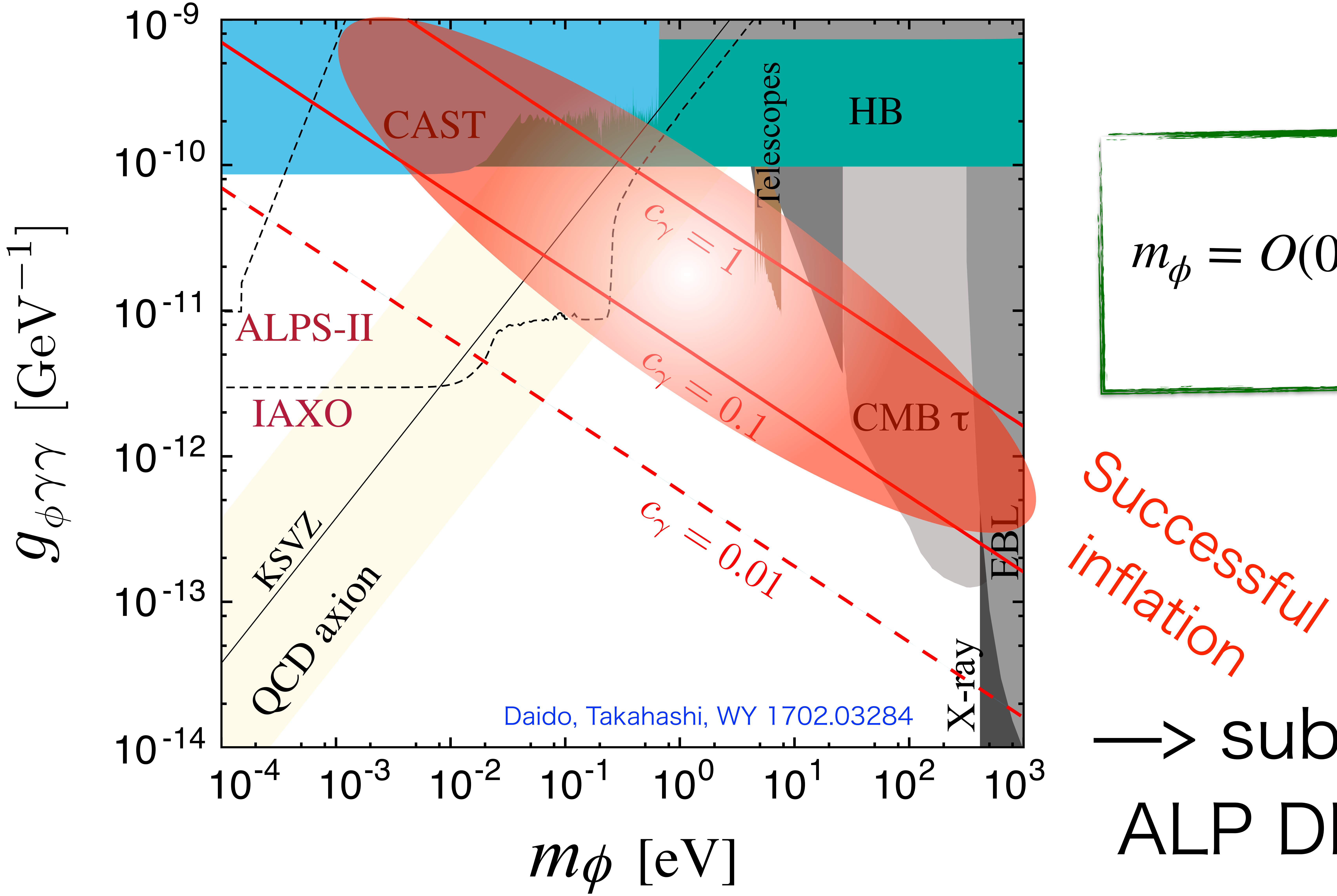

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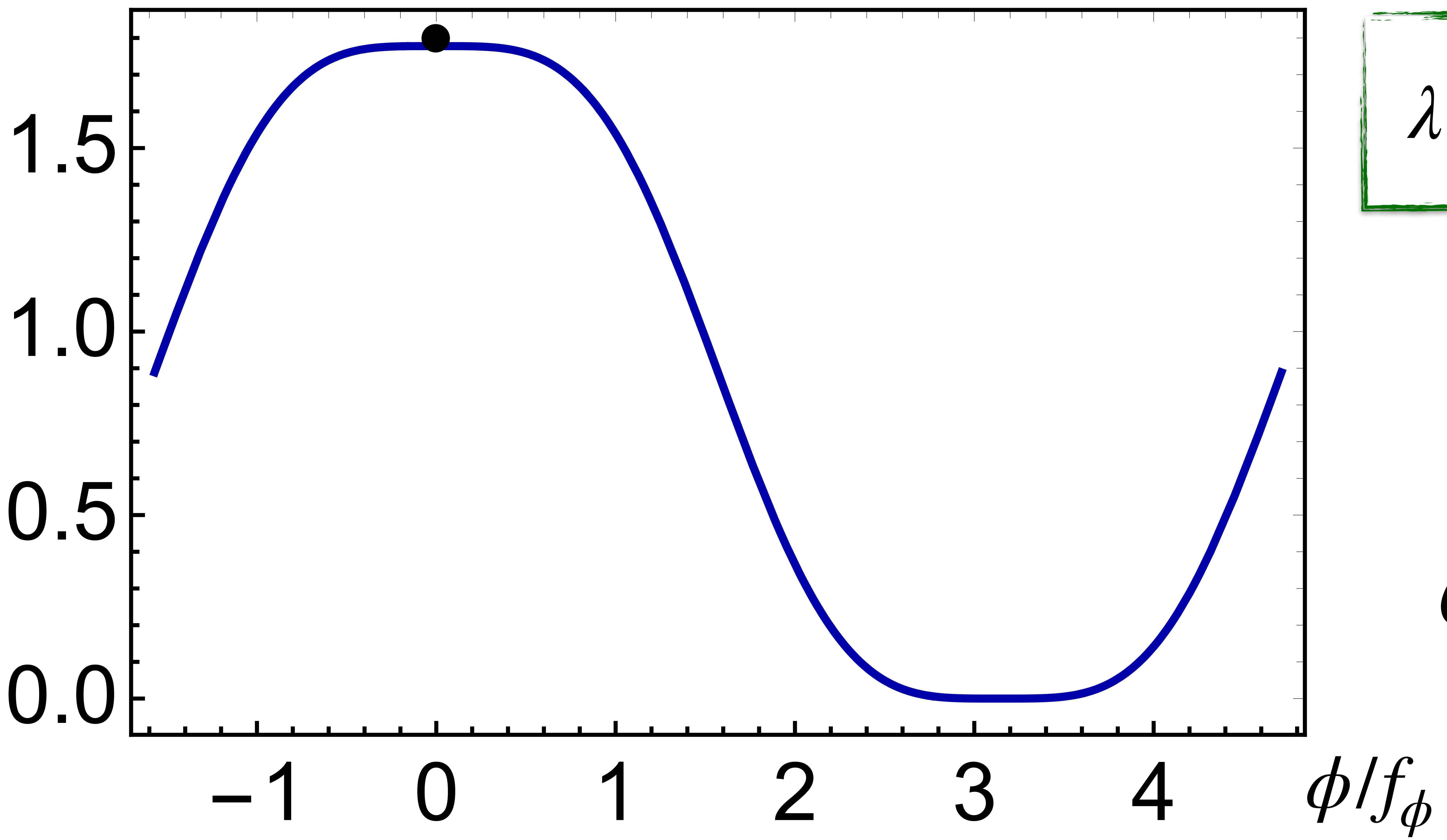
—> sub-eV or eV-scale ALP DM candidate.

Inflaton decays due to large effective mass

Just after inflation, ϕ acquires an effective mass

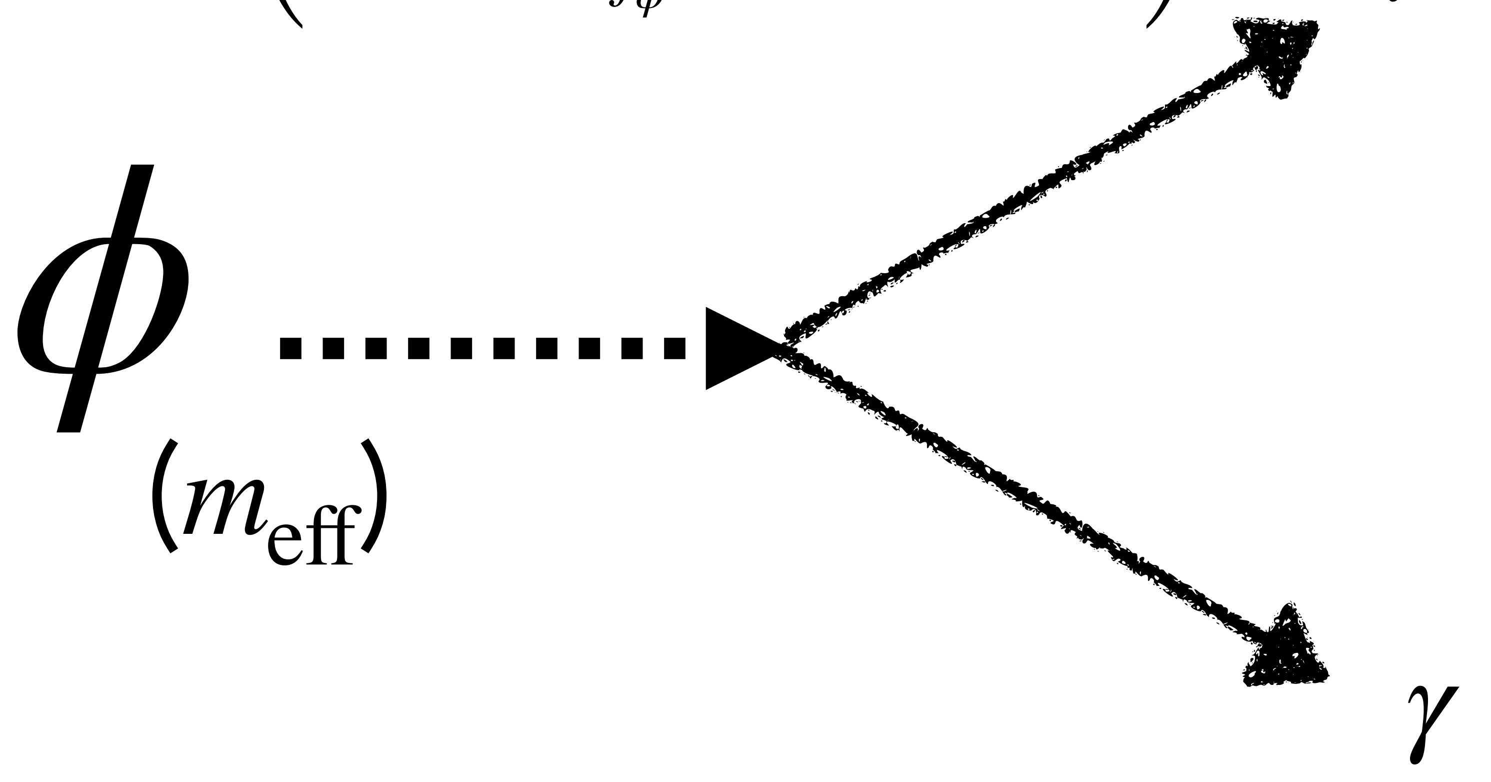
$$m_{\rm eff} \sim \sqrt{\lambda}\phi_{\rm amp} \sim 10{\rm GeV}\left(\frac{\phi_{\rm amp}}{10^7\,{\rm GeV}}\right).$$



$$\boxed{\lambda(\text{self-coupling}) \sim 10^{-12}}$$

$\Gamma_{\phi\to\gamma\gamma}|_{\rm reheating}$

$$\left(\sim 10^{33}\left(\frac{10^7 GeV}{f_\phi}\right)^3 \Gamma_{\phi\to\gamma\gamma}|_{\rm vacuum}\right)$$



Inflaton decays due to large effective mass

Just after inflation, ϕ acquires an effective mass

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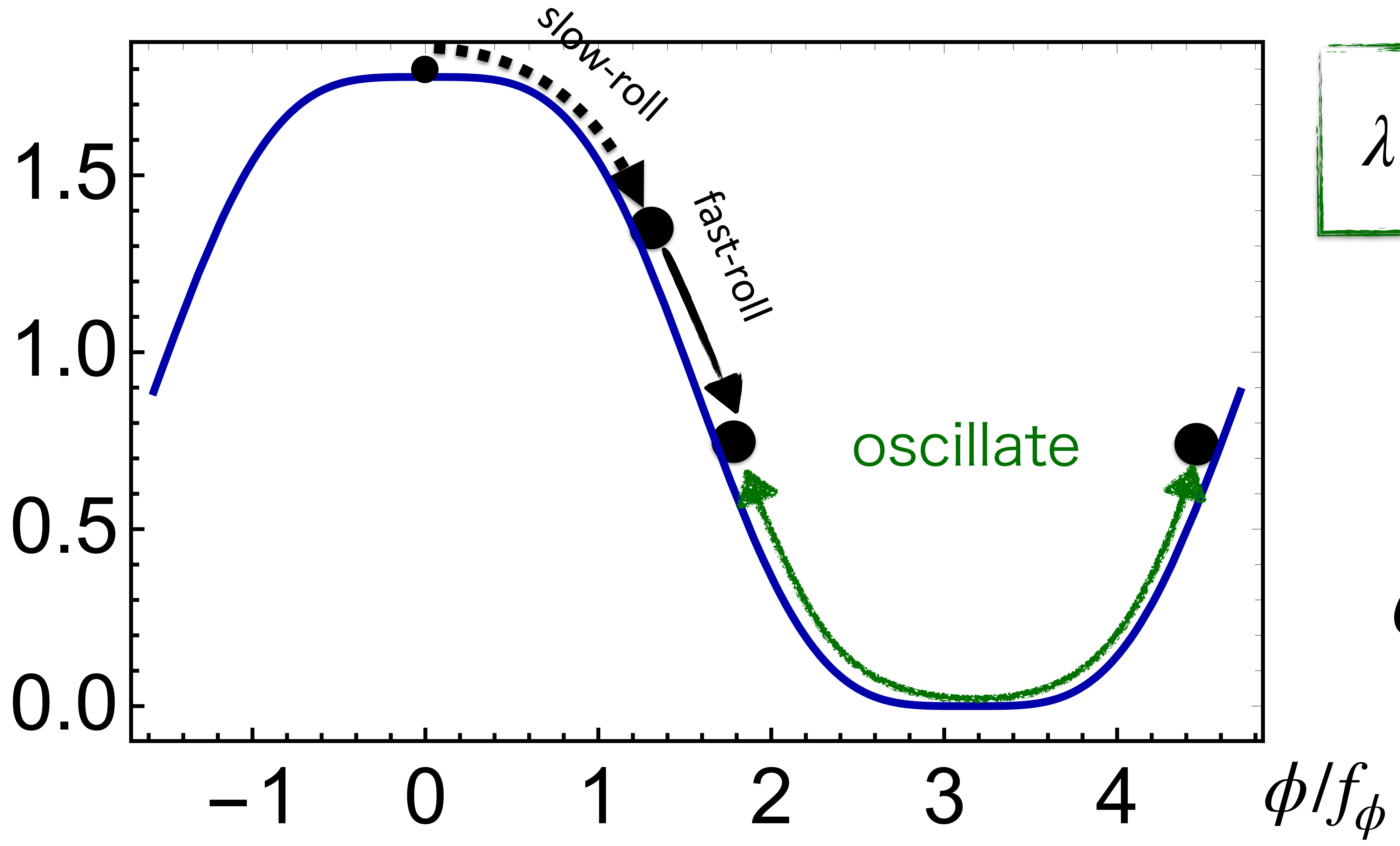

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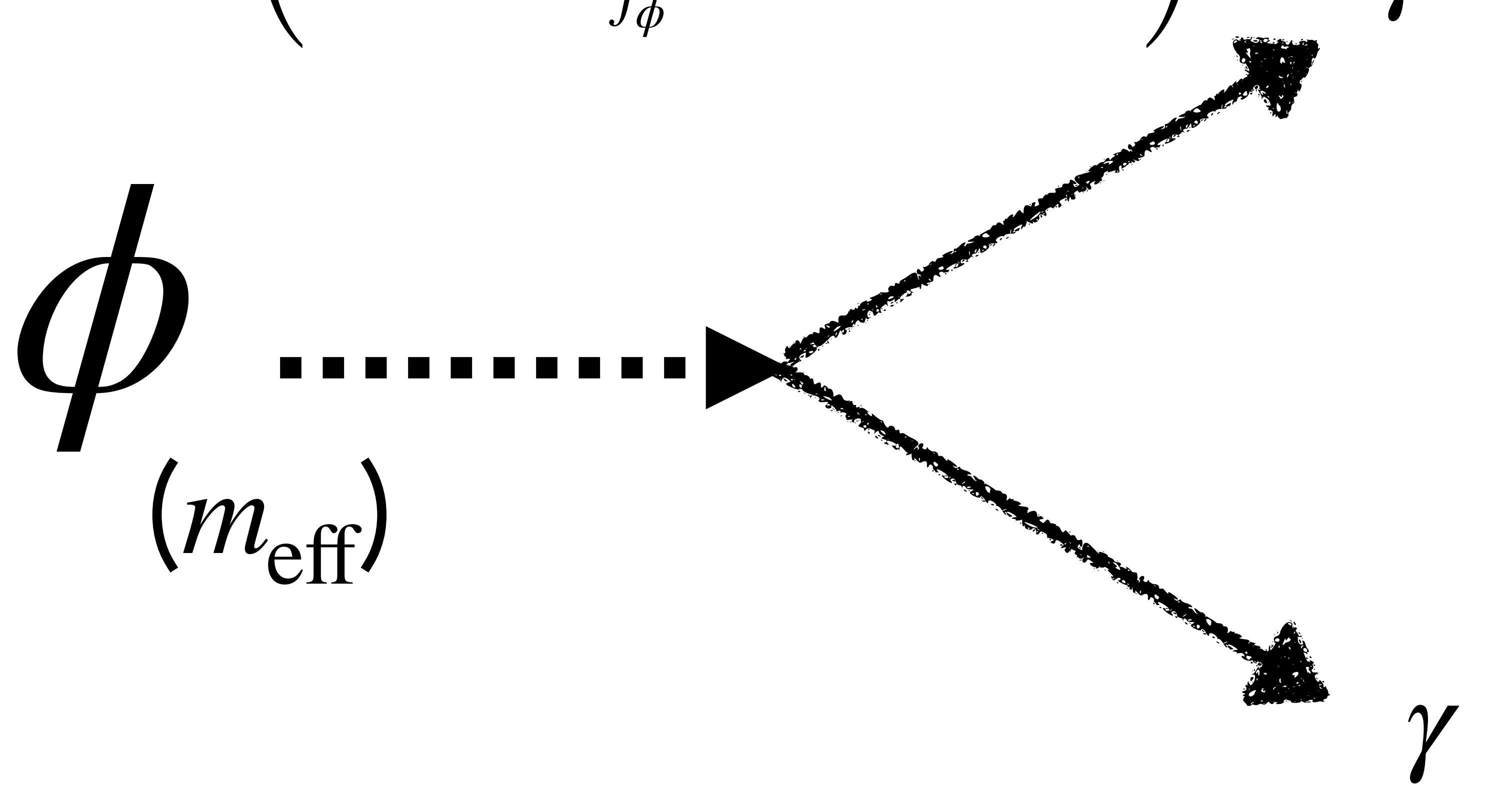
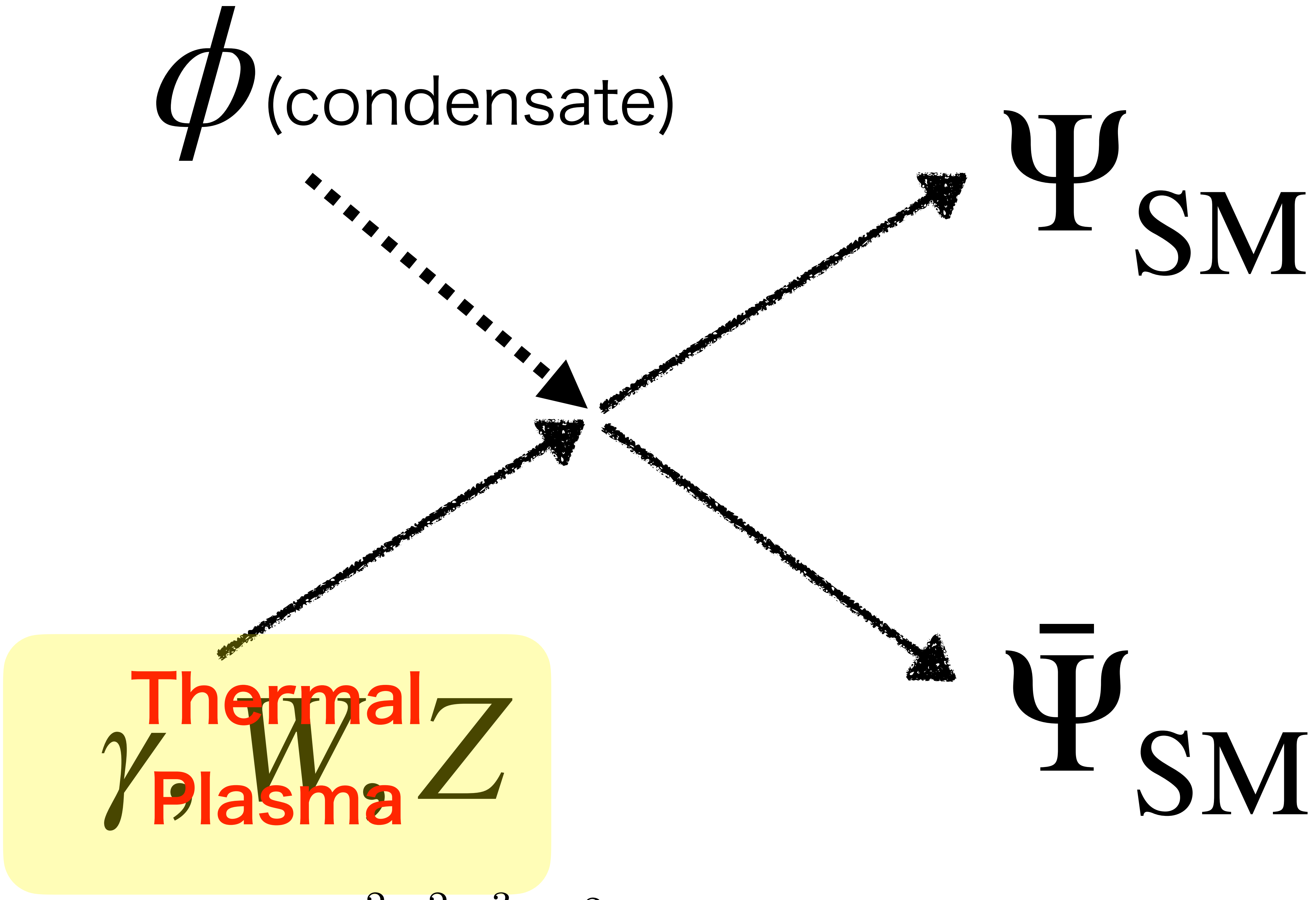


Cold ALP DM from incomplete reheating.

Reheating proceeds due to thermal scattering when $eT \gtrsim m_{\rm eff}$.

Dissipation effect for reheating

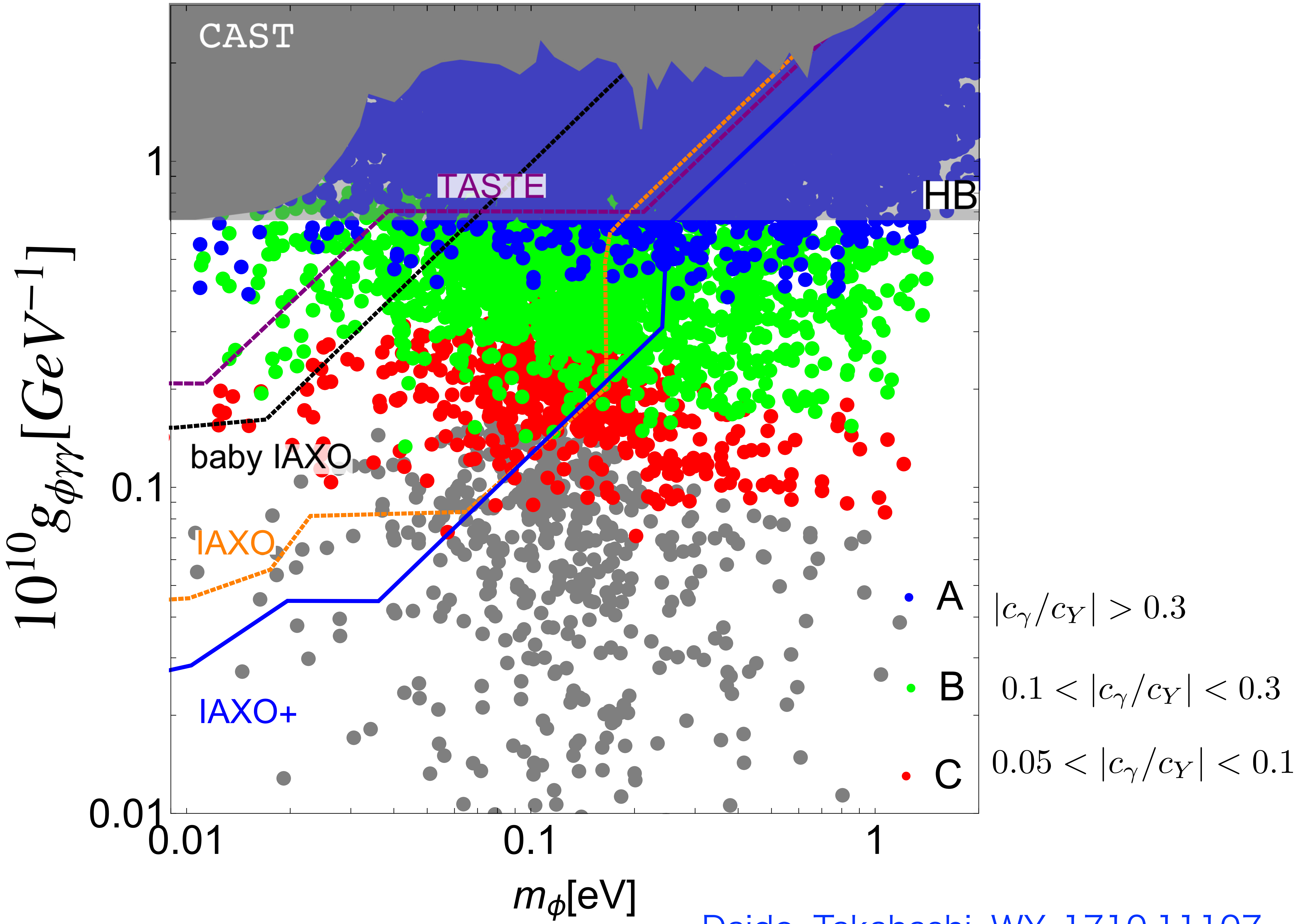


$$\Gamma_{\mathrm{dis},\gamma} = C\frac{c_\gamma^2\alpha^2T^3}{8\pi^2 f^2}\frac{m_{\rm eff}^2}{e^4T^2}$$

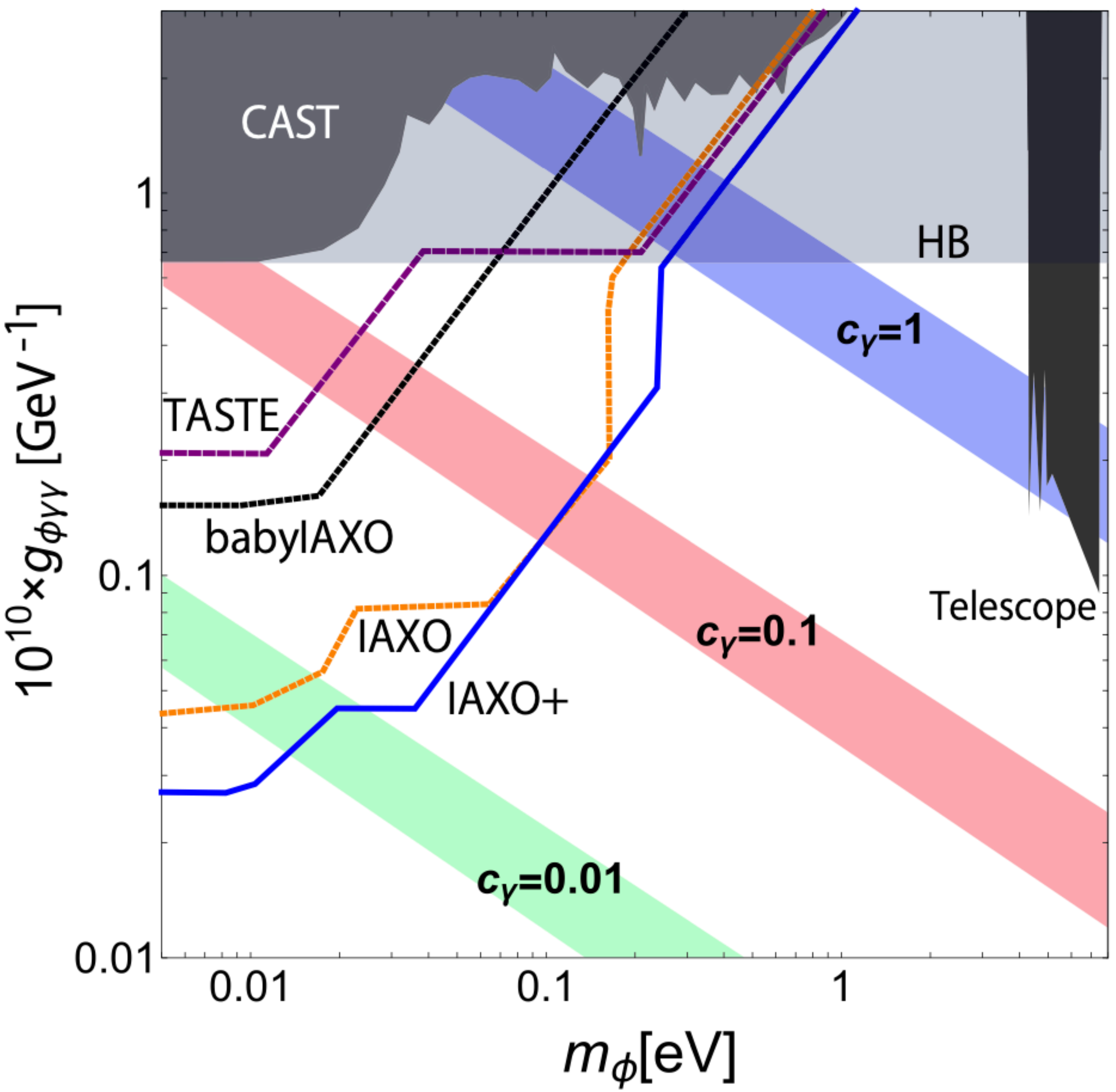
Moroi, Mukaida, Nakayama and Takimoto,1407.7465;

C=O(10) to take account of self-resonance, Lozanov, and Amin, 1710.06851;

Imposing $\Omega_\phi^{(\rm remnant)}h^2 \sim \Omega_{DM}h^2$ we obtain

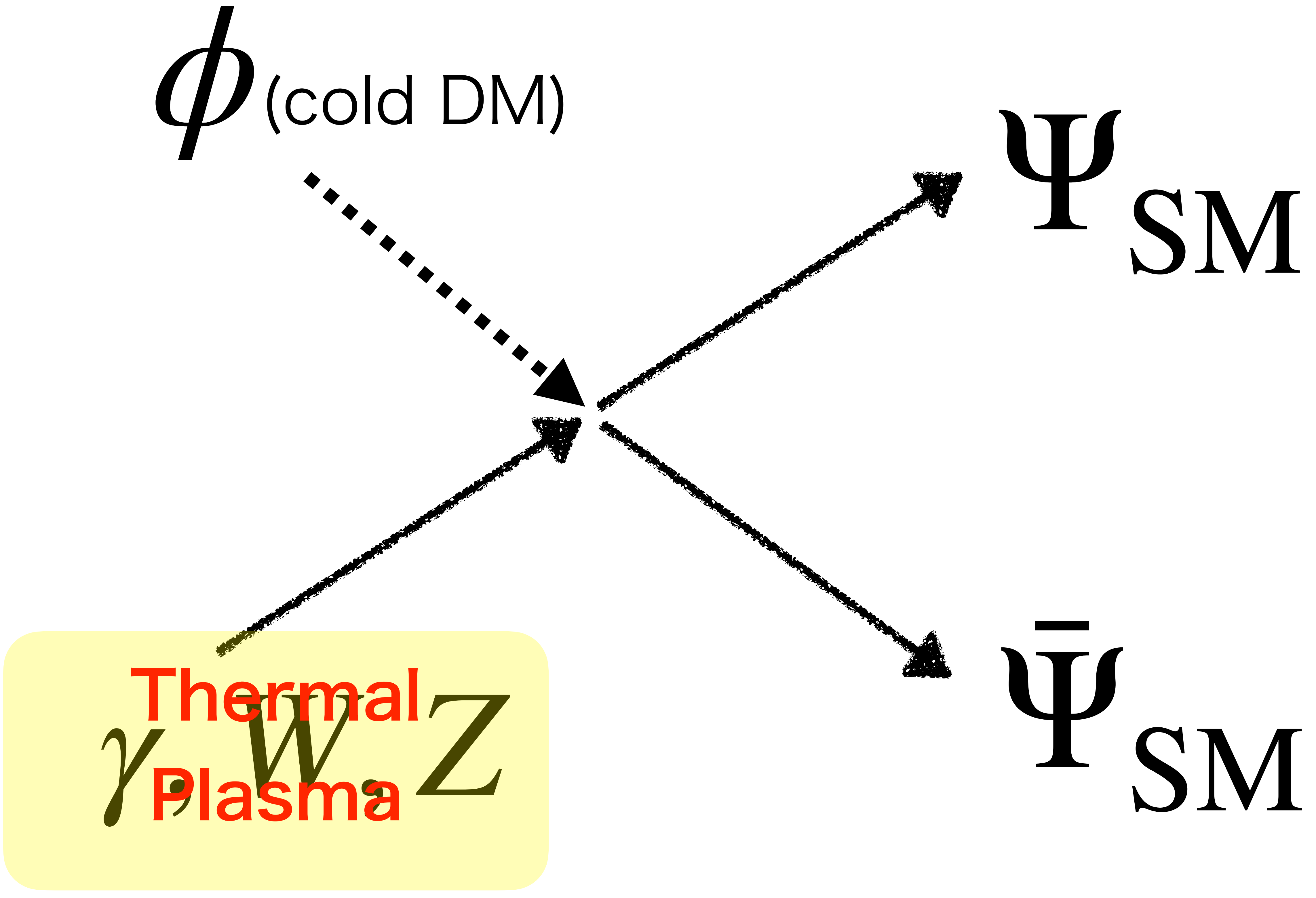


Daido, Takahashi, WY, 1710.11107

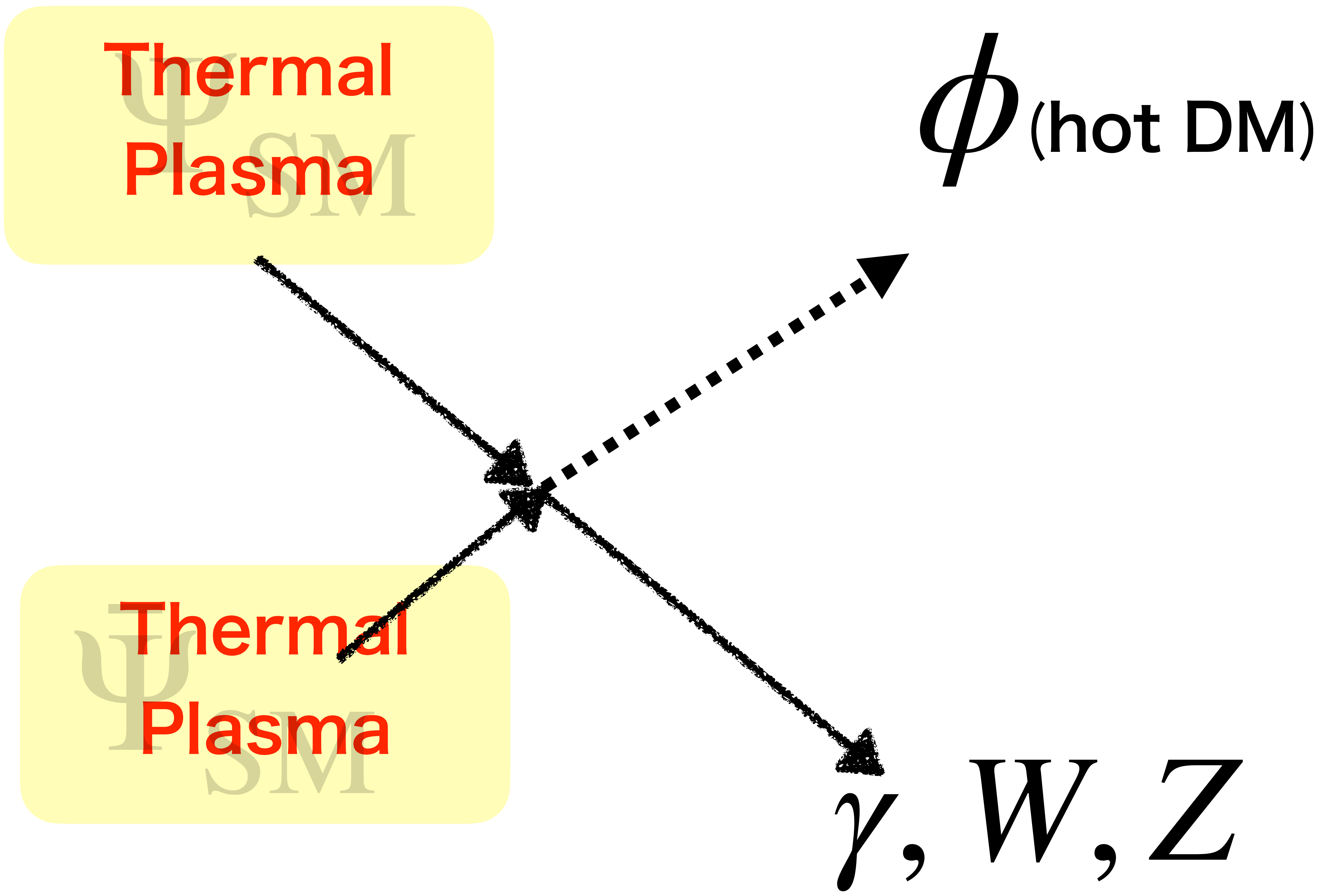

CAST
HB
TASTE
babyIAXO
IAXO
IAXO+
Telescope
c_γ=1
c_γ=0.1
c_γ=0.01
$10^{10}\times g_{\phi\gamma\gamma}$ [GeV^{-1}]
m_ϕ[eV]
1
0.1
0.01
0.01
0.1
1

Successful reheating means two typical momenta of DM.

Dissipation effect for reheating

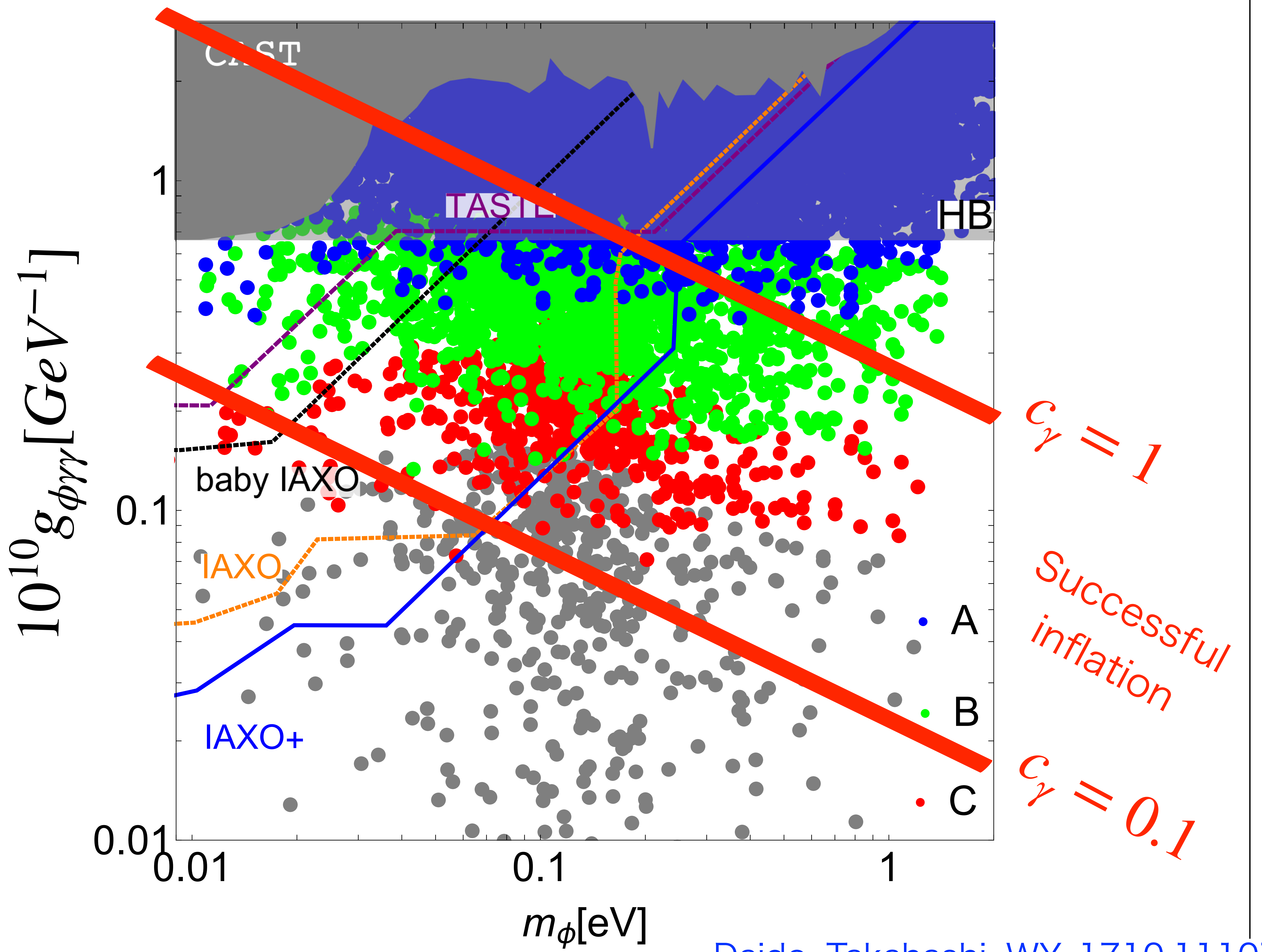


Thermal production of hot DM



DM components: Cold ALP condensate + hot ALP with $\Delta N_{\mathrm{eff}} \sim 0.03$

Hot DM bound: $m_\phi \lesssim 1\,\mathrm{eV}$



Daido, Takahashi, WY, 1710.11107

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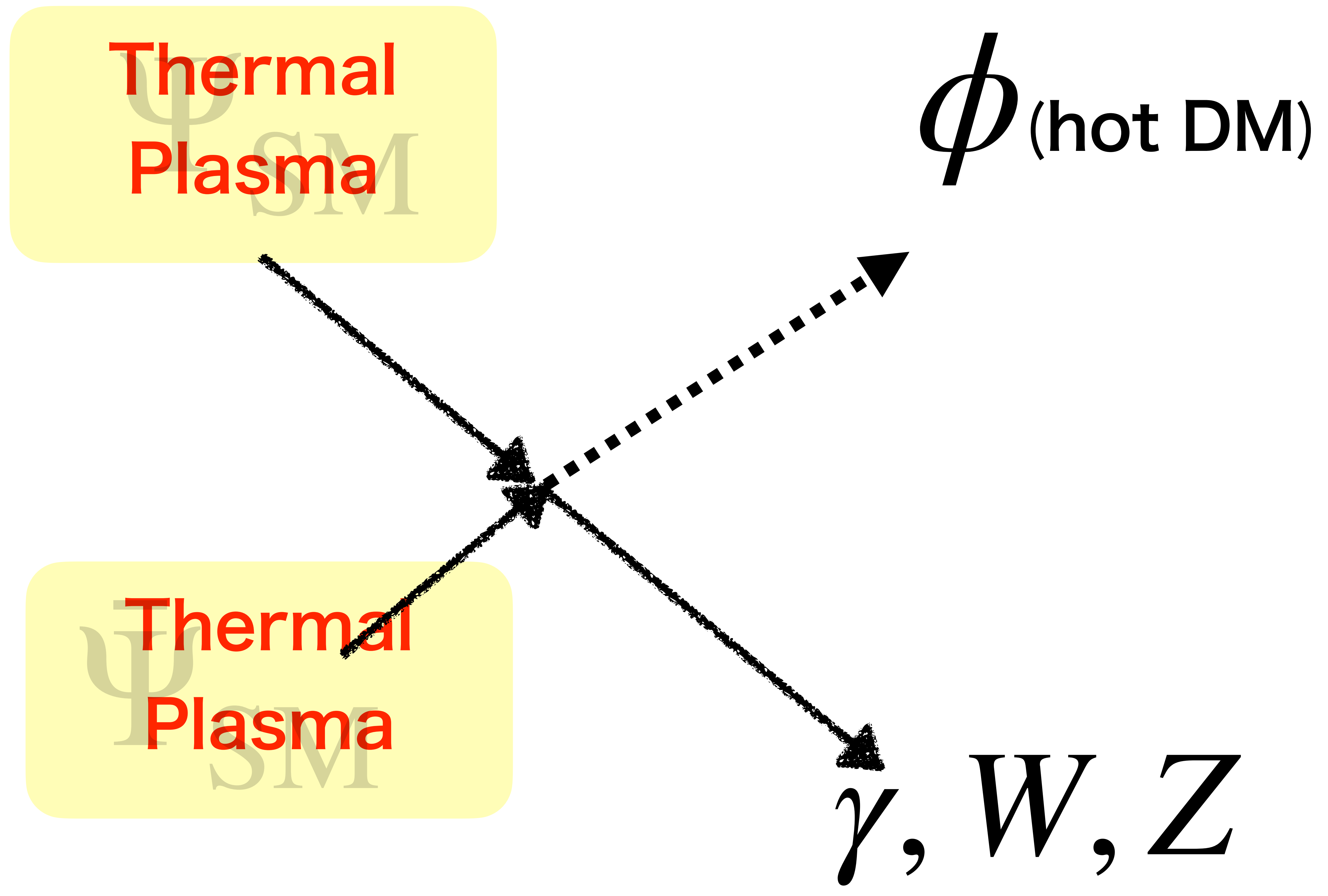

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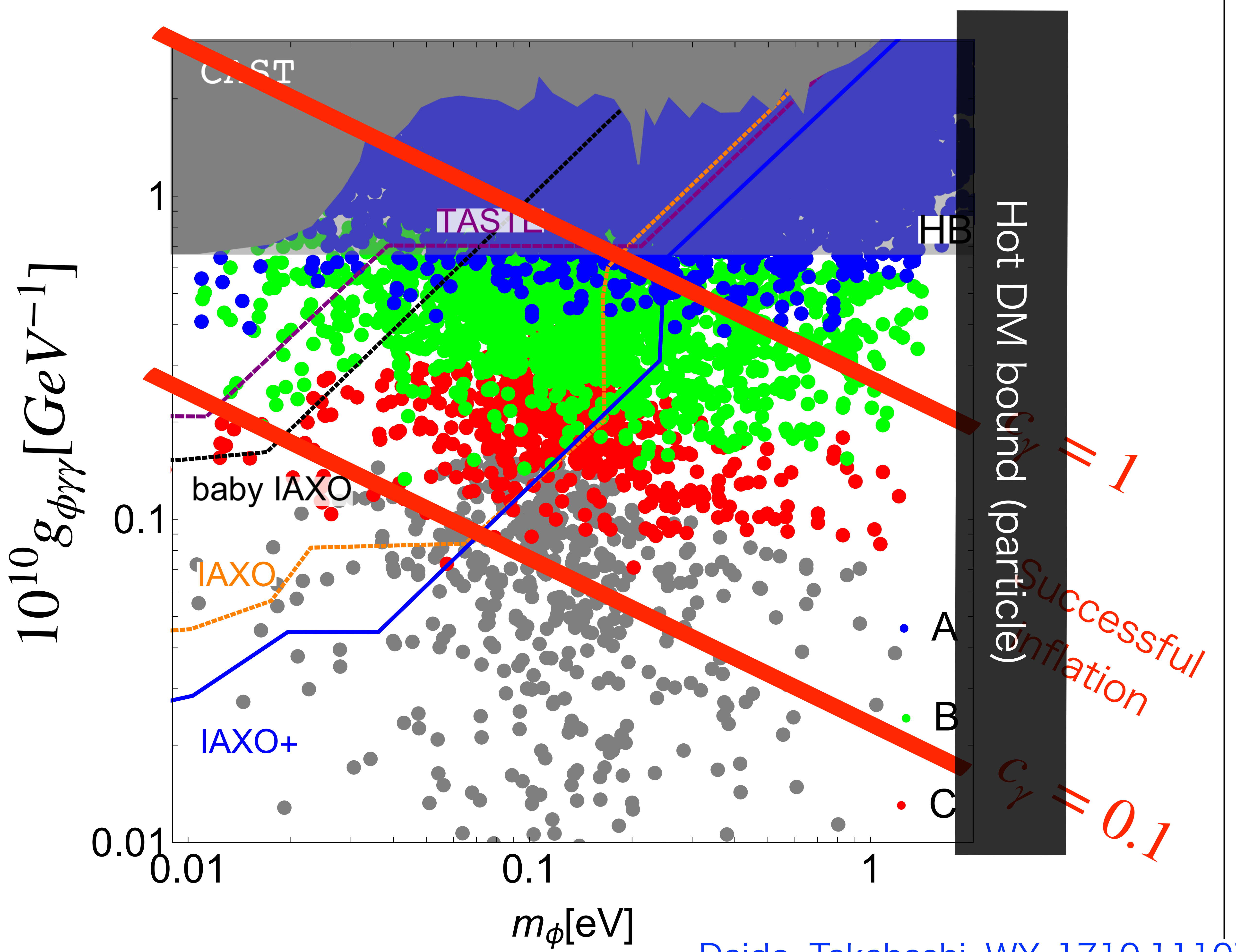

Daido, Takahashi, WY, 1710.11107

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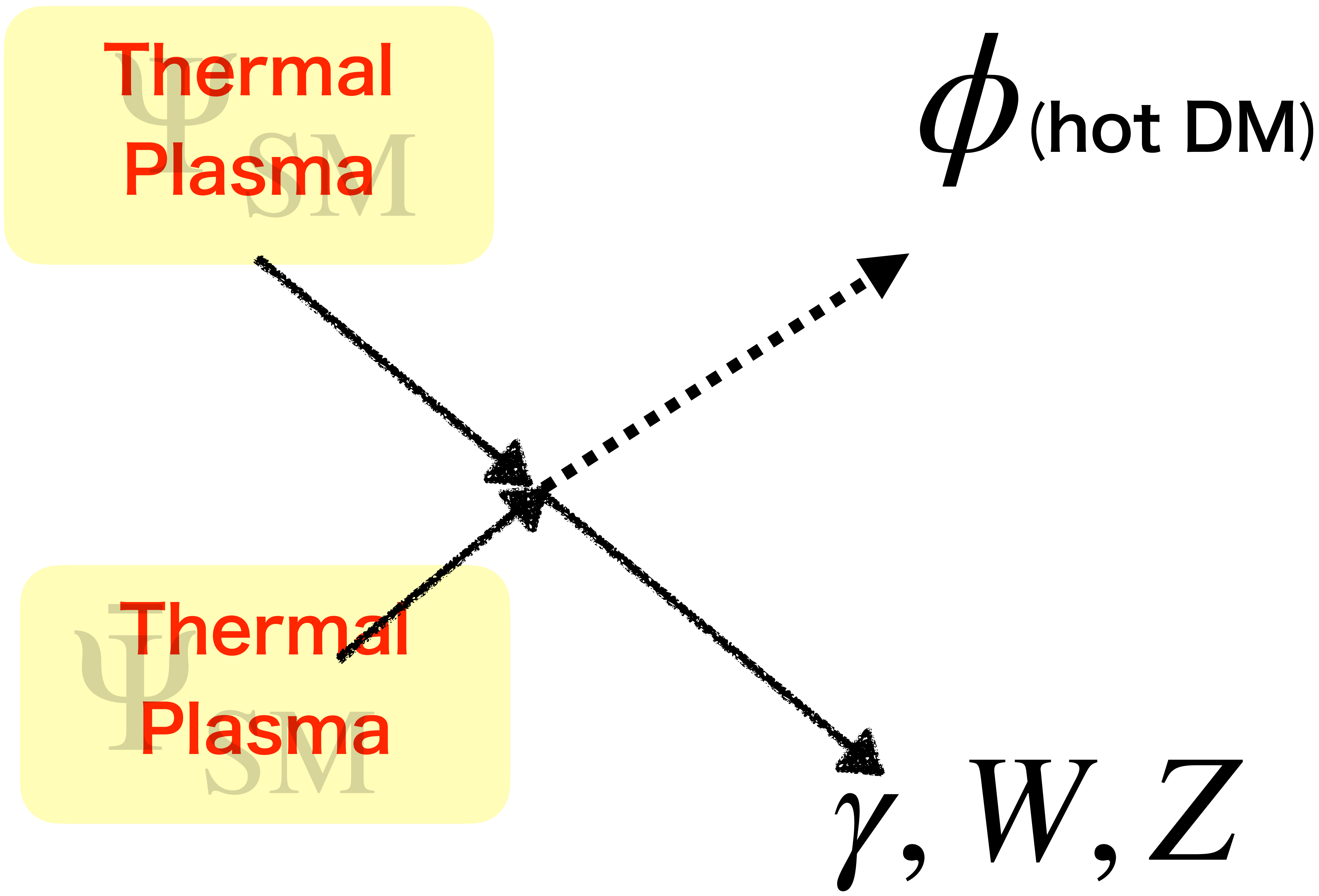

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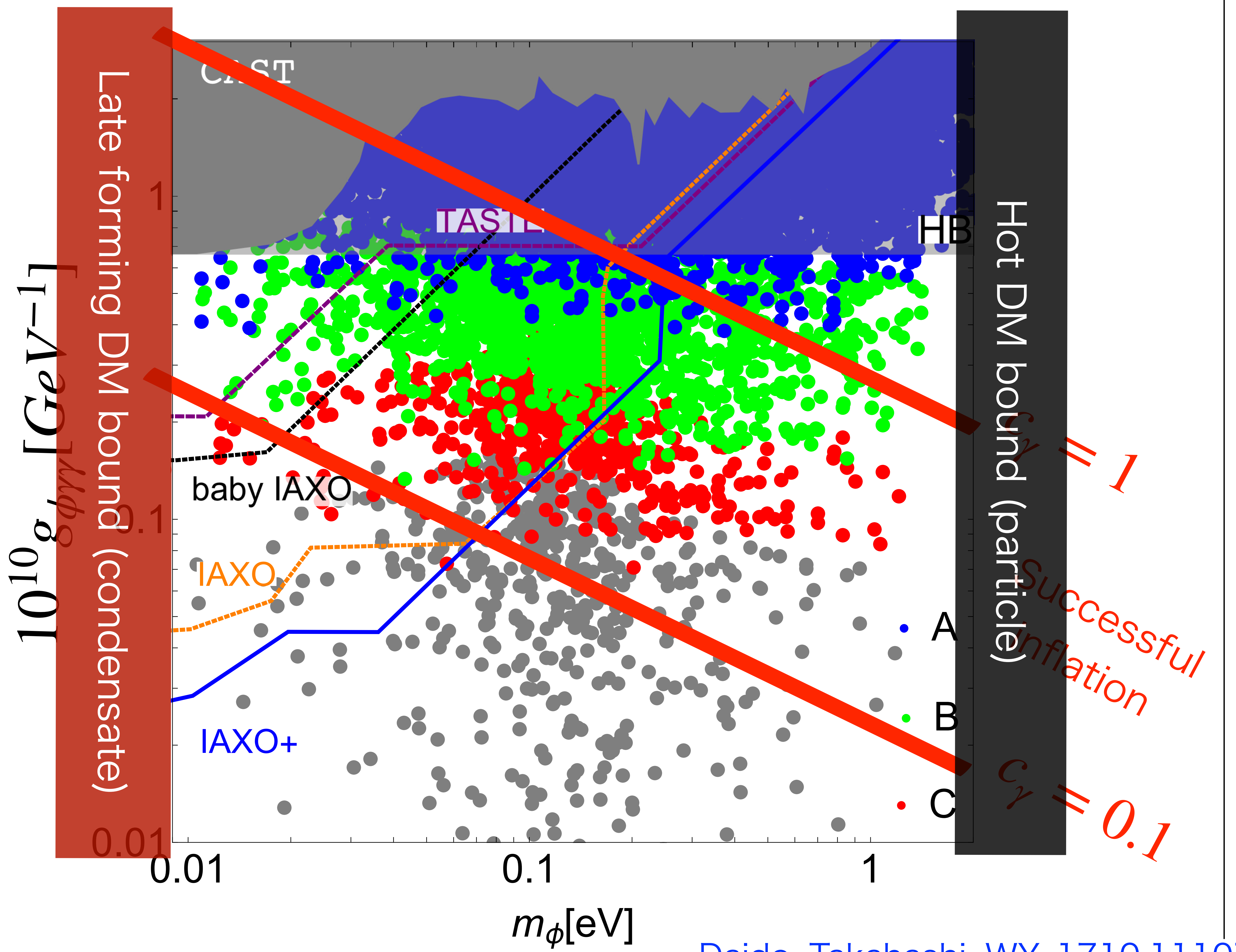
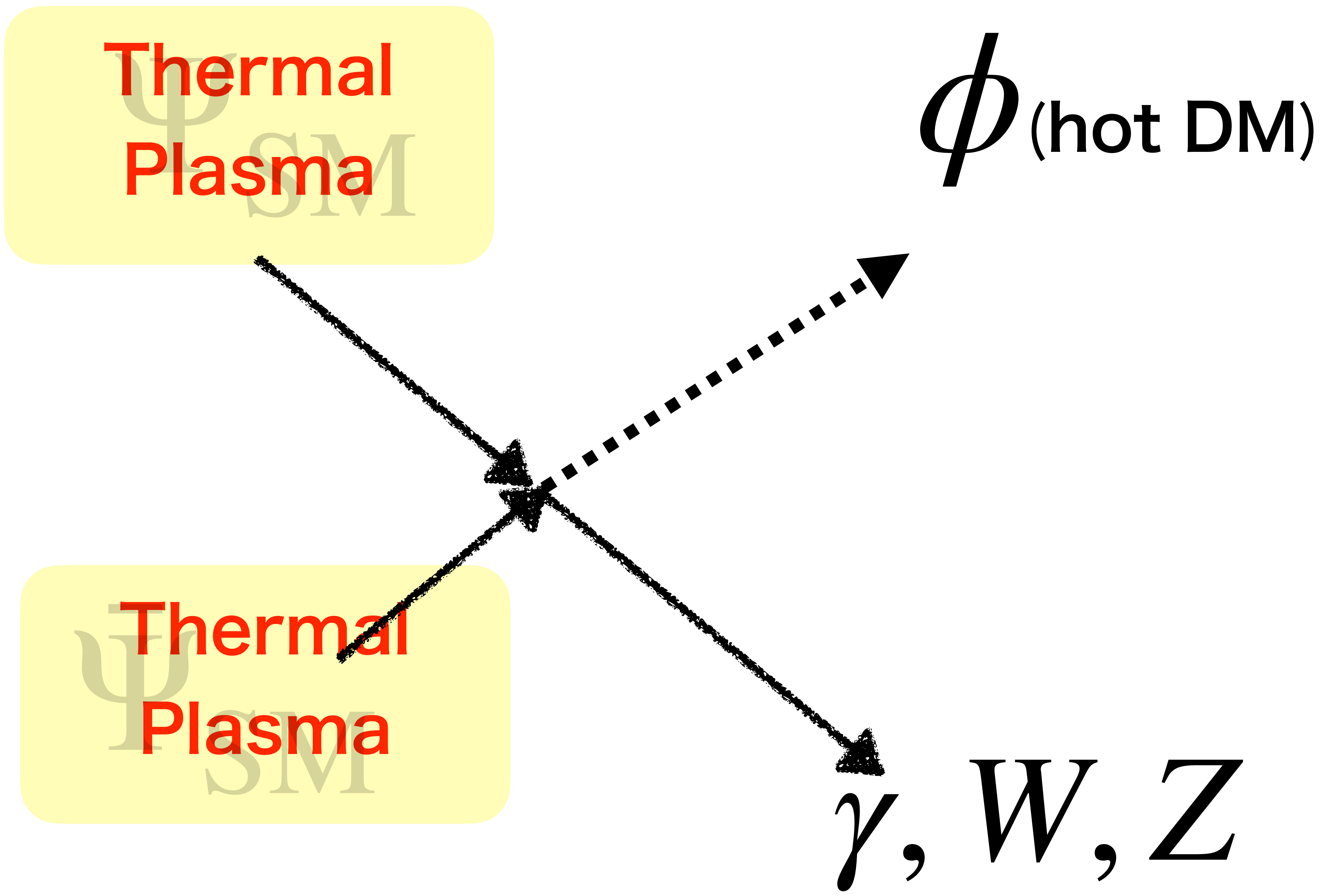


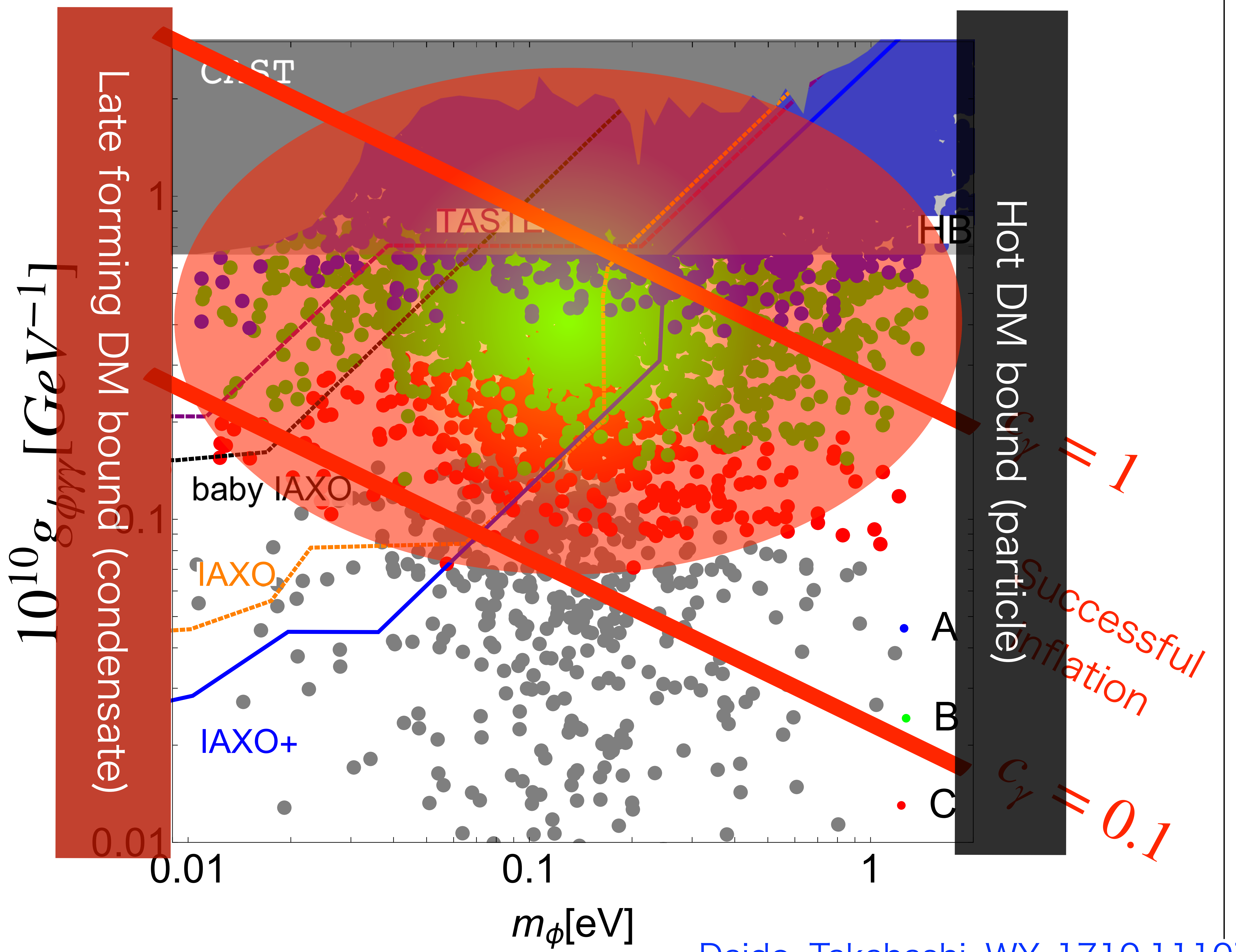
Daido, Takahashi, WY, 1710.11107

Thermal production of hot DM

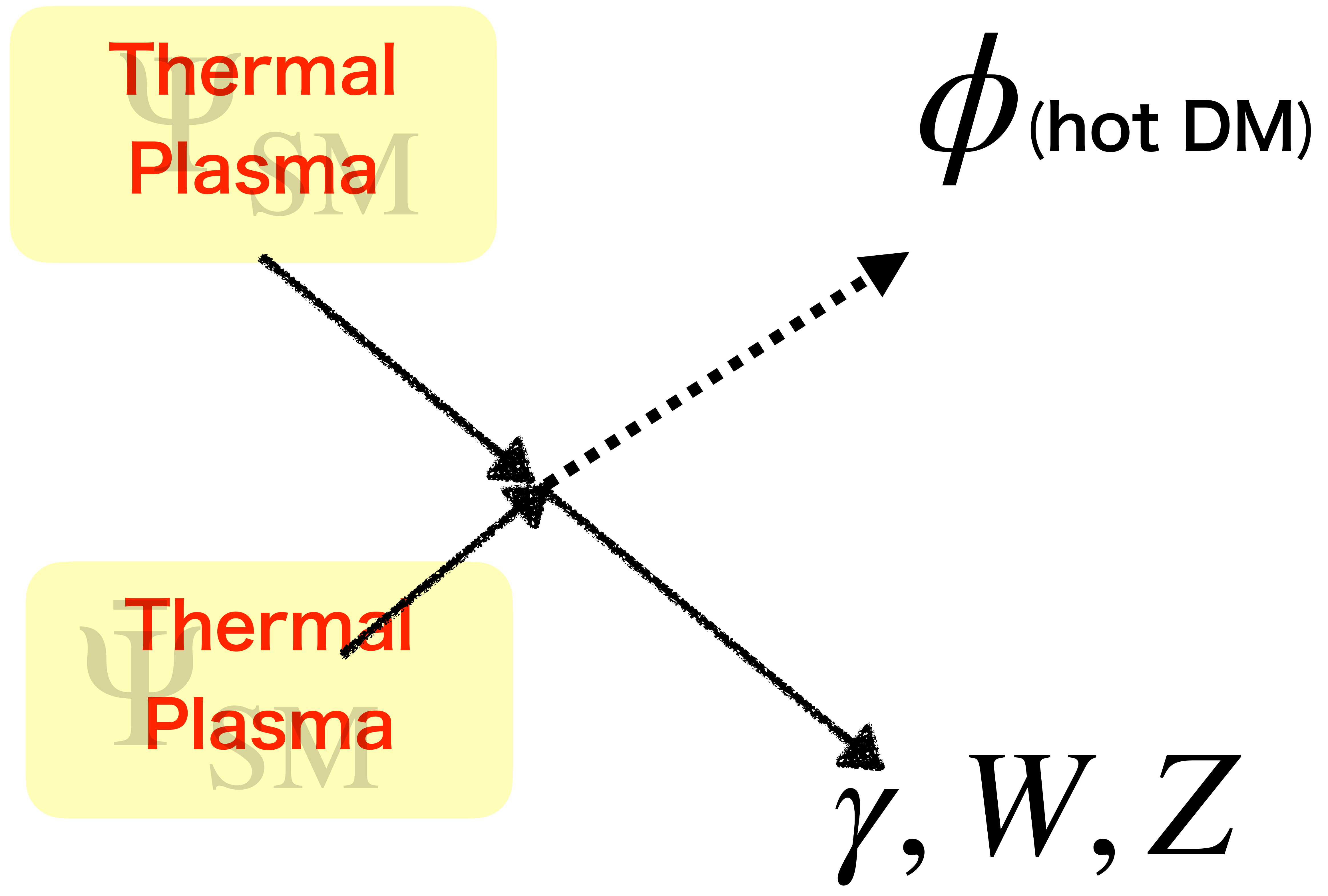


Hot DM bound: $m_\phi \lesssim 1\,\mathrm{eV}$

Several independent conditions point to the region!



Daido, Takahashi, WY, 1710.11107



“The ALP miracle”.

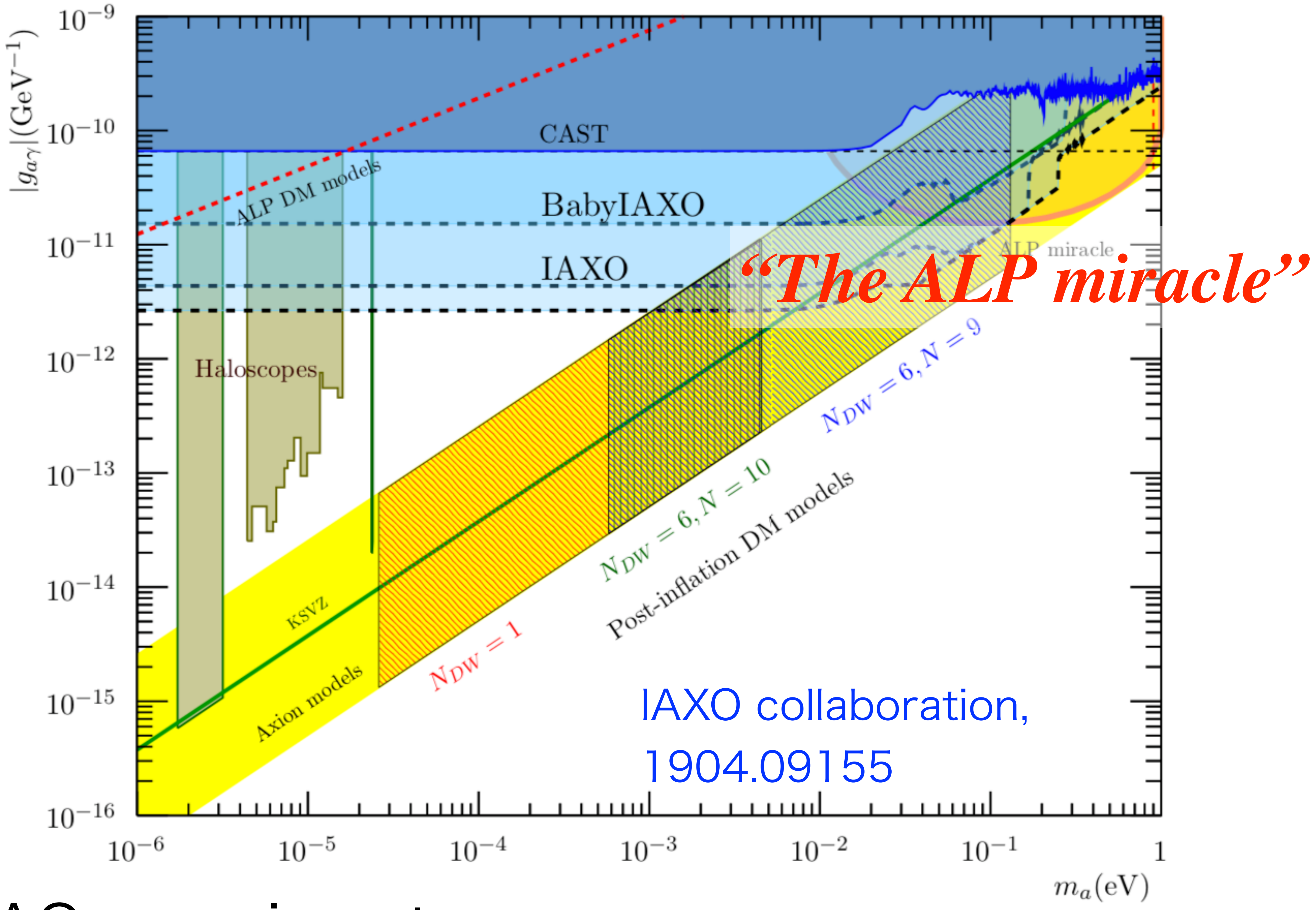
Daido, Takahashi, WY 1702.03284,1710.11107

Inflaton = DM = ALP

$$0.01\,\mathrm{eV} \lesssim m_\phi \lesssim 1\,\mathrm{eV}$$

$$g_{\phi\gamma\gamma} \gtrsim 10^{-11}\mathrm{GeV}^{-1}$$

significantly overlapping with future reach of axion helioscopes, IAXO/TASTE.



- $\Delta N_{\rm eff} \approx 0.03$ probed in the future CMB and BAO experiments.
- Overlapping with cooling hint of HB stars.

Ayala, Dominguez, Giannotti, Mirizzi and Straniero, 1406.6053, DESY- PROC-2015-02

- O(1) eV ALP with $g_{\phi\gamma\gamma} \sim 10^{-10}\mathrm{GeV}^{-1}$ is hinted by EBL analysis

Korochkin et al,1911.13291

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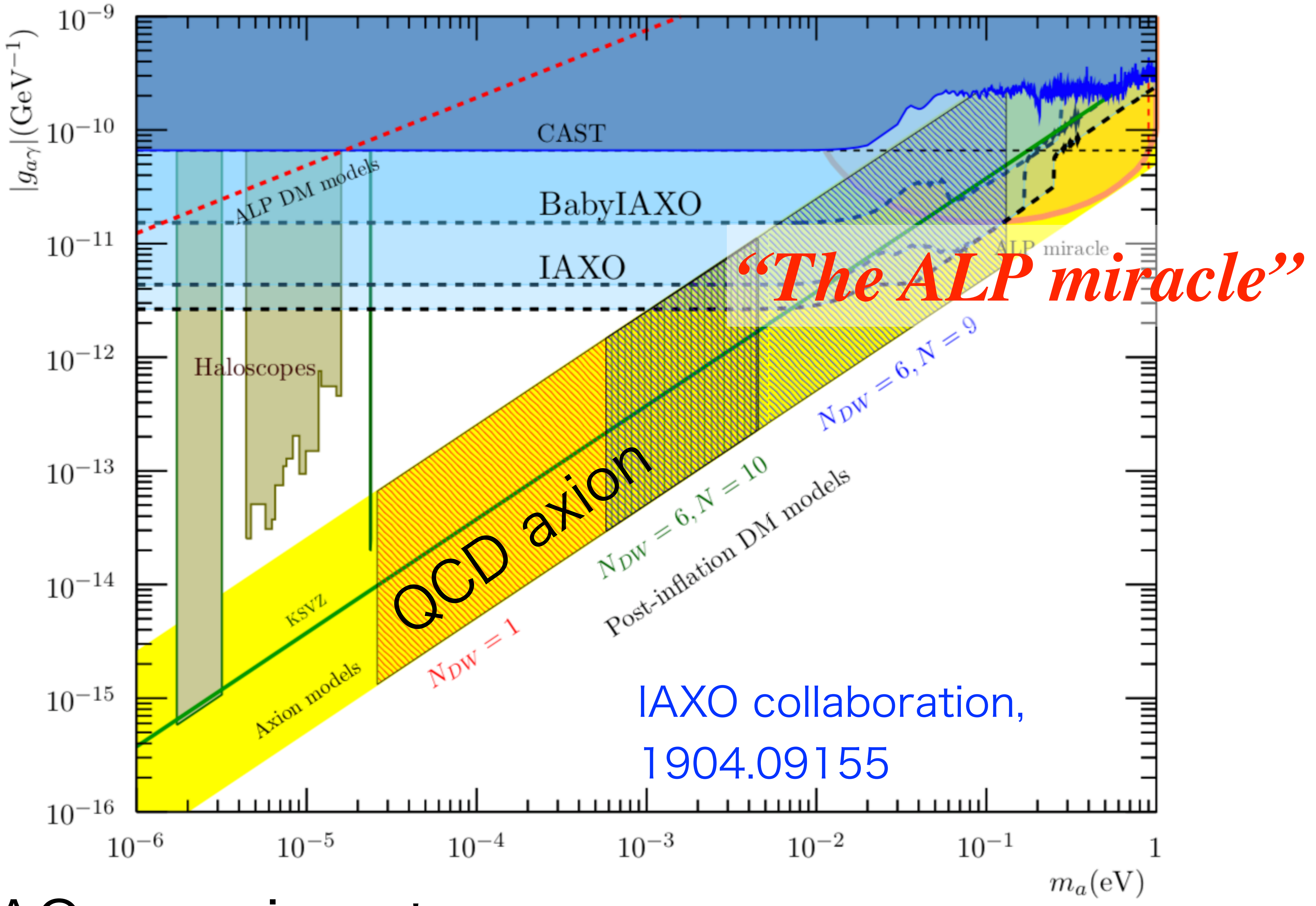

IAXO collaboration, 1904.09155

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★ Is the ALP relevant to the strong CP problem?

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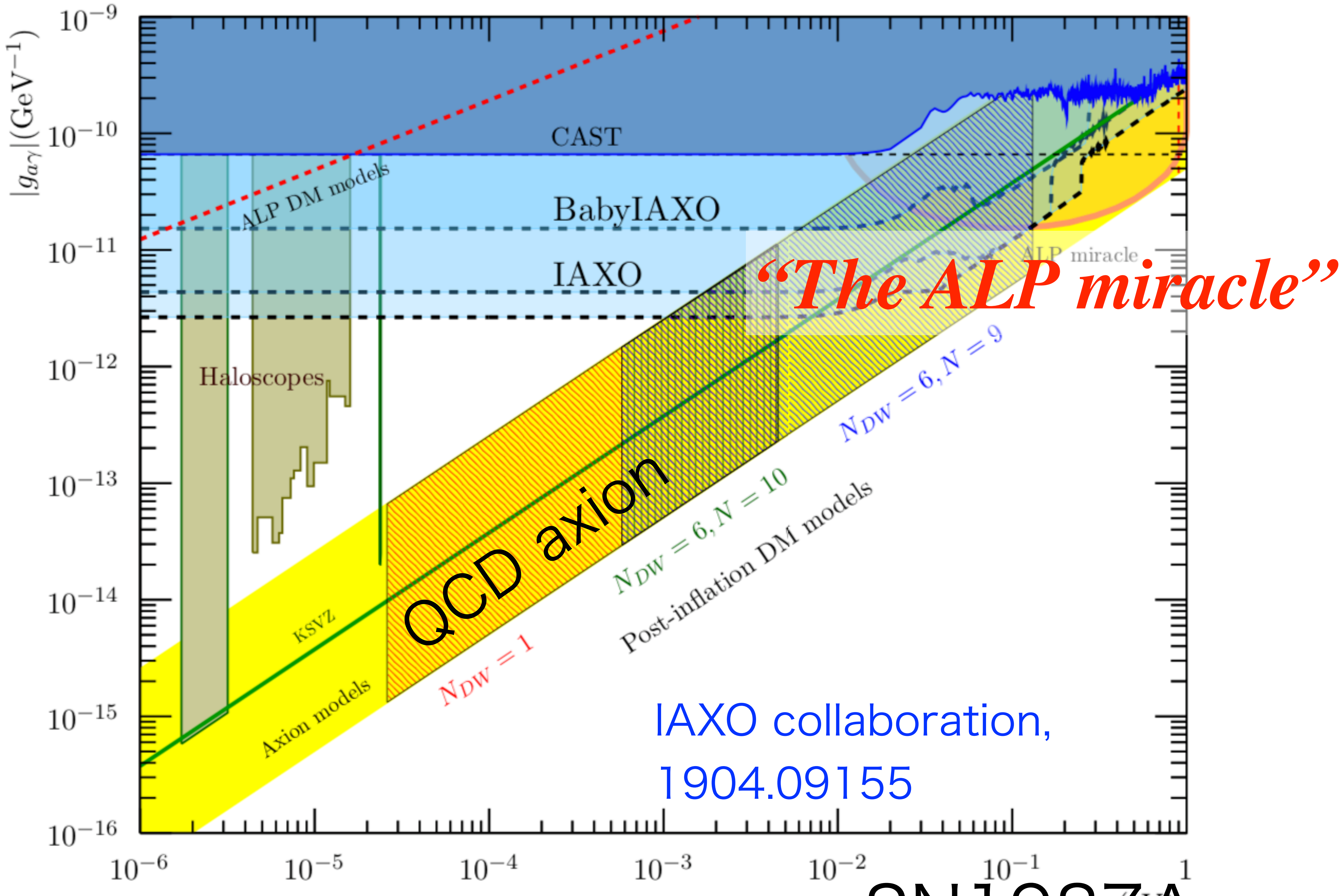

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SN1987A, NS bounds:

$f_\phi > 10^{8-9}\mathrm{GeV}$

ALP miracle:

$f_\phi \sim 10^{7}\mathrm{GeV}$

★ Is the ALP relevant to the strong CP problem?

Comparison of usual hot DM 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 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 $f_\phi[p \sim p_\phi^{\rm burst}] \gg 1, f_{\chi_2}[p_{\chi_2} \sim T] \sim 1$

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

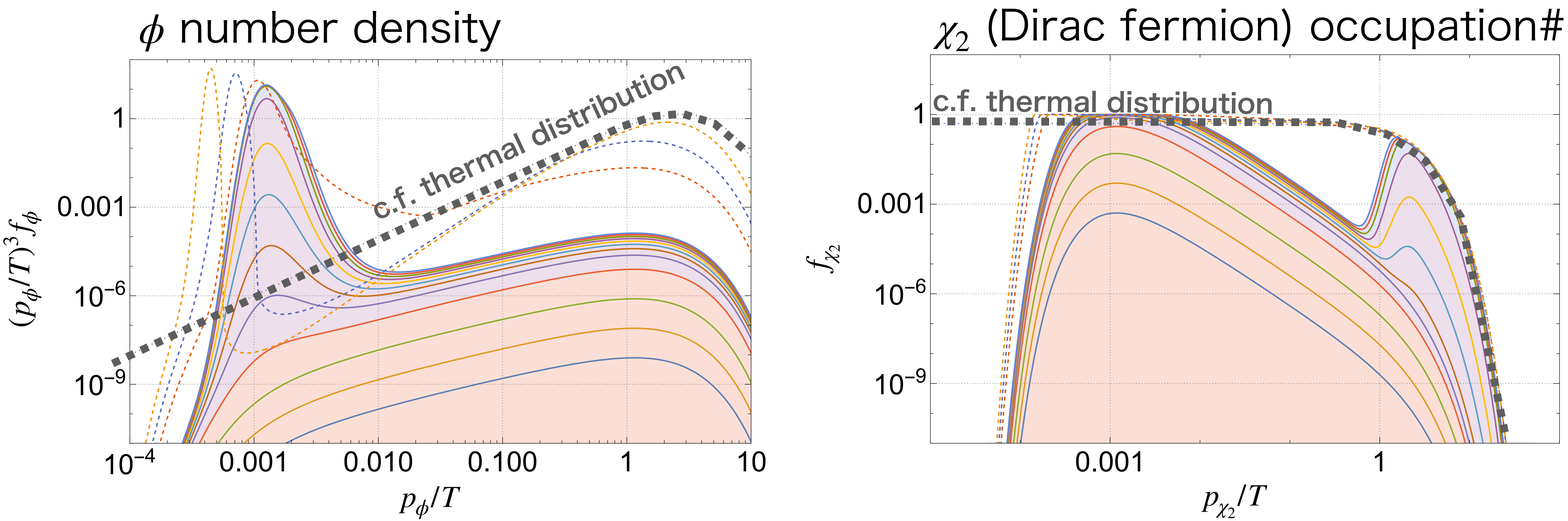
$$S \equiv f_{\chi_1}[p_{\chi_1} \sim T](1 \pm f_{\chi_2}[p_{\chi_2} \sim T])(\cancel{1+} f_\phi[p_\phi \sim p_\phi^{\rm burst}])$$
$$-(1 \pm f_{\chi_1}[p_{\chi_1} \sim T]) f_\phi[p_\phi \sim p_\phi^{\rm burst}] f_{\chi_2}[p_{\chi_2} \sim T]$$
$$\sim \boxed{(f_{\chi_1}[p_{\chi_1} \sim T] - f_{\chi_2}[p_{\chi_2}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

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

Stage 3: Saturation (quasi-equilibrium)

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

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



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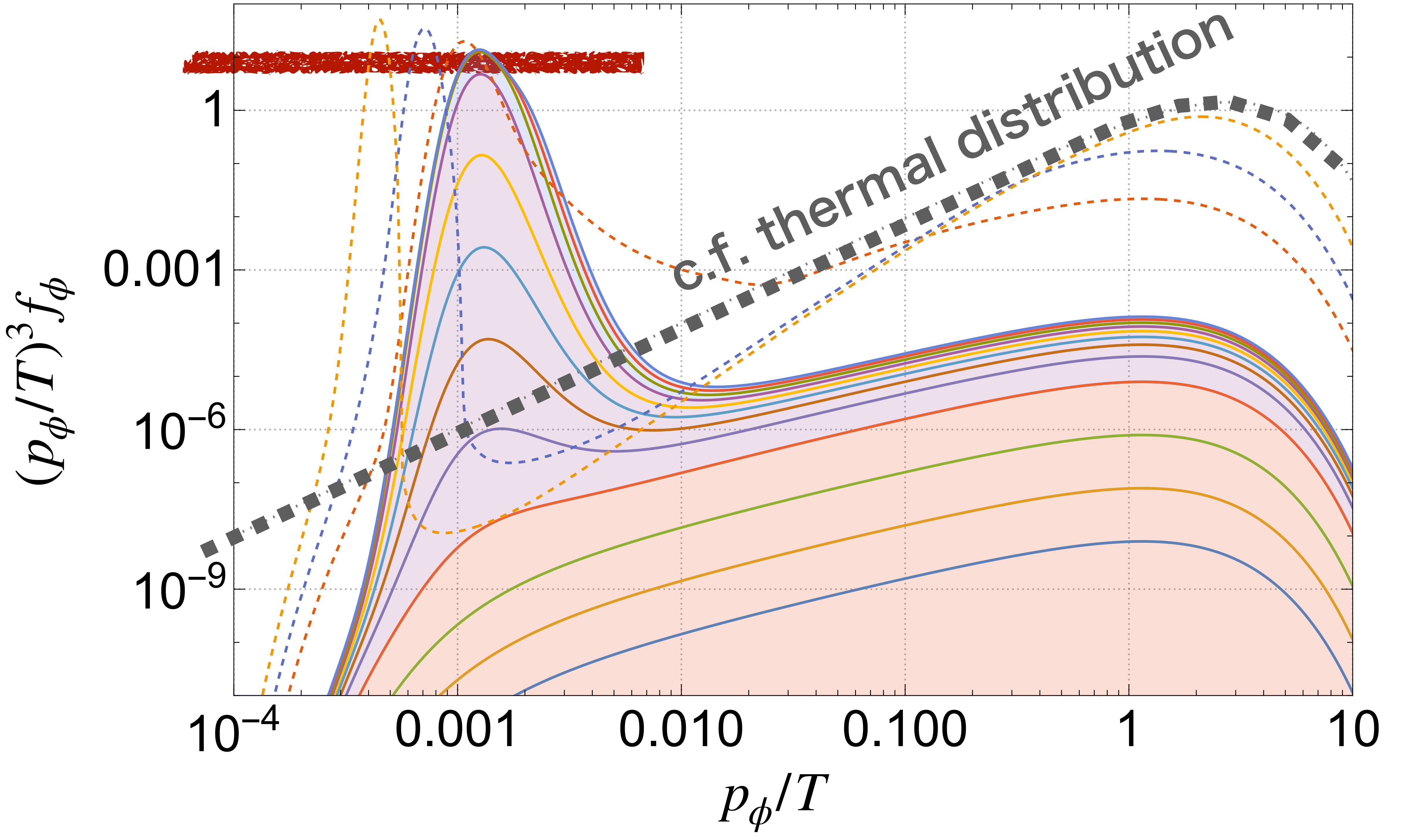
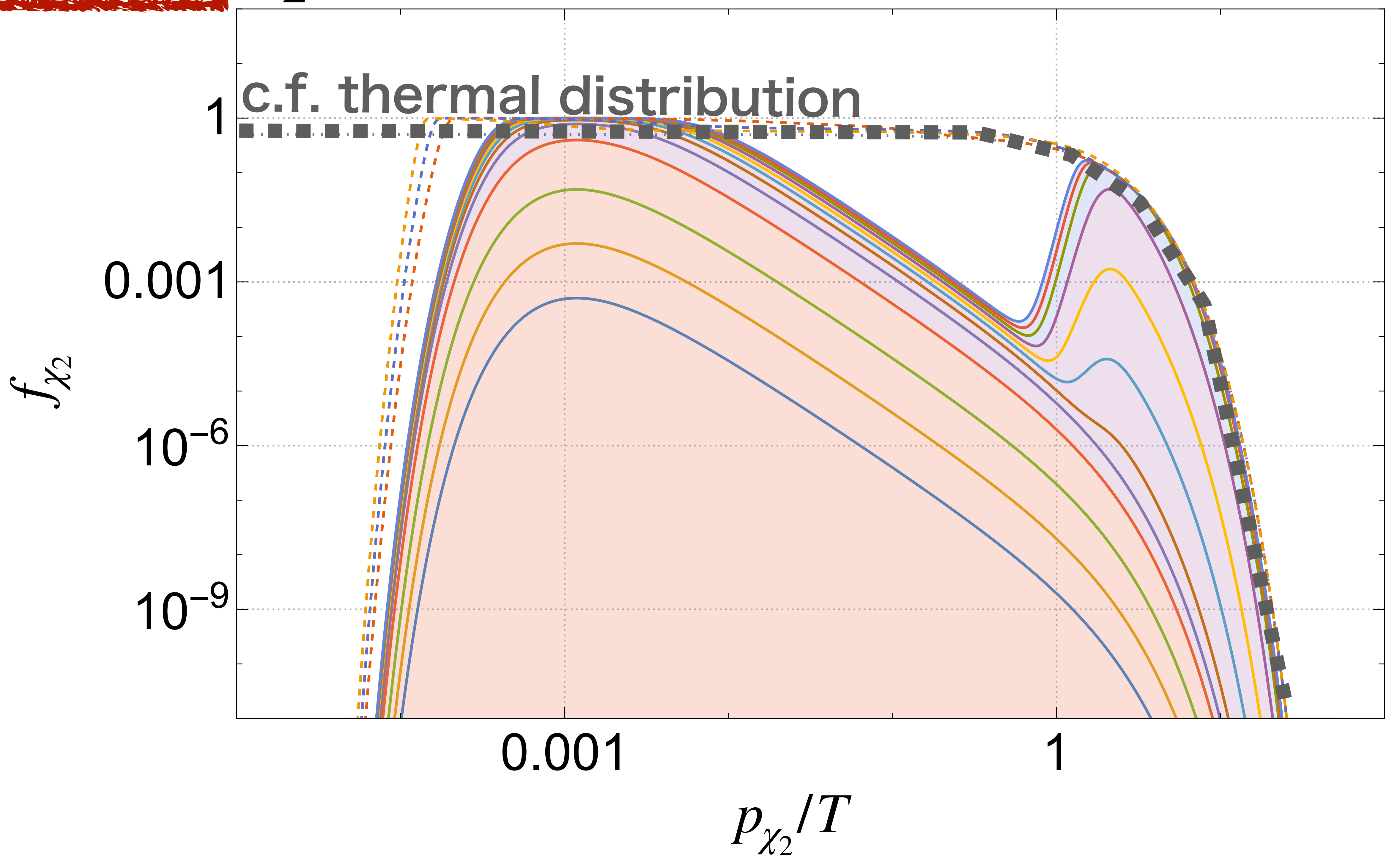
$$\boxed{n_\phi \sim T^3, p_\phi \sim M_1^2/T, \text{which is cold}}$$



χ_2 (Dirac fermion) occupation#



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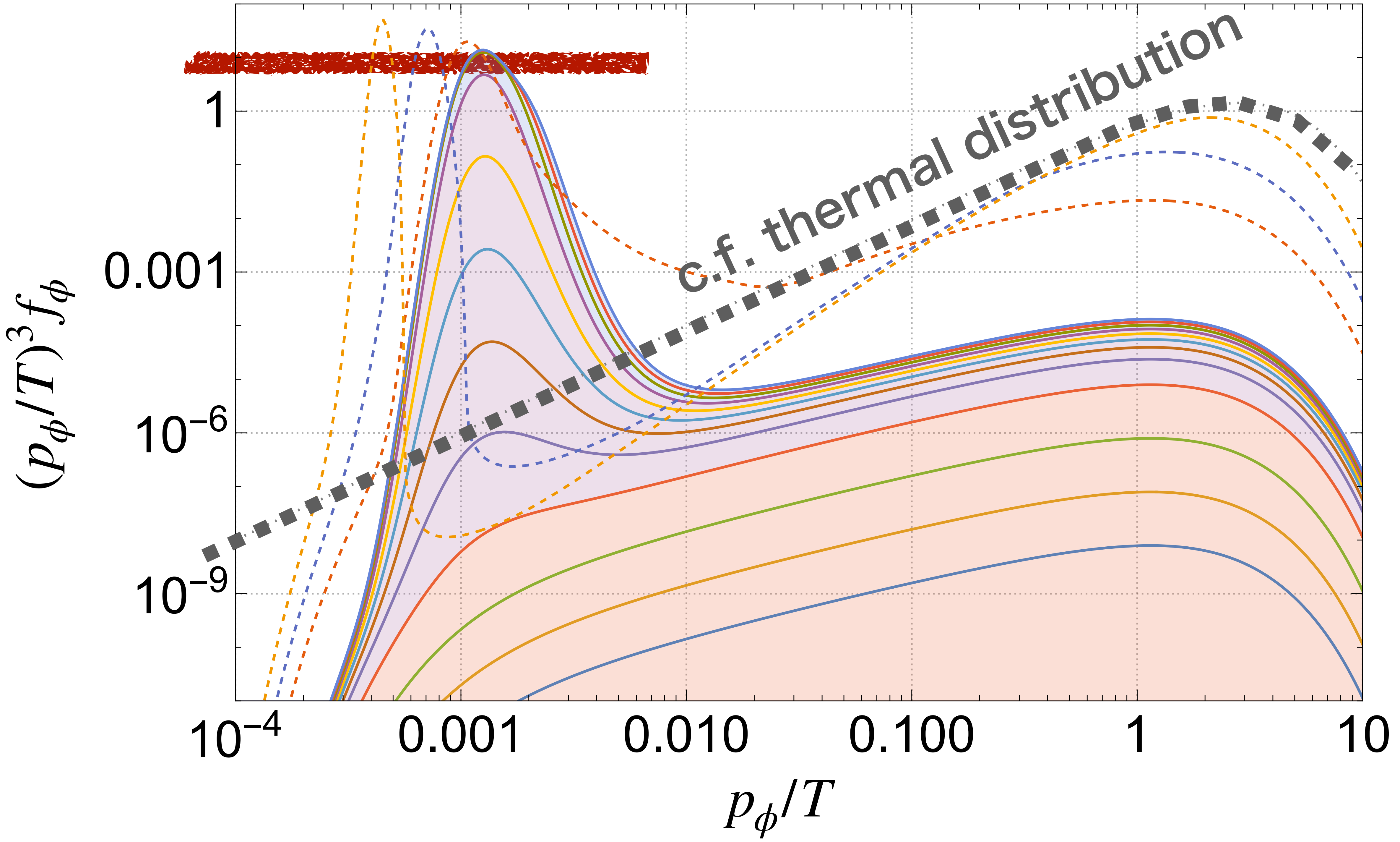
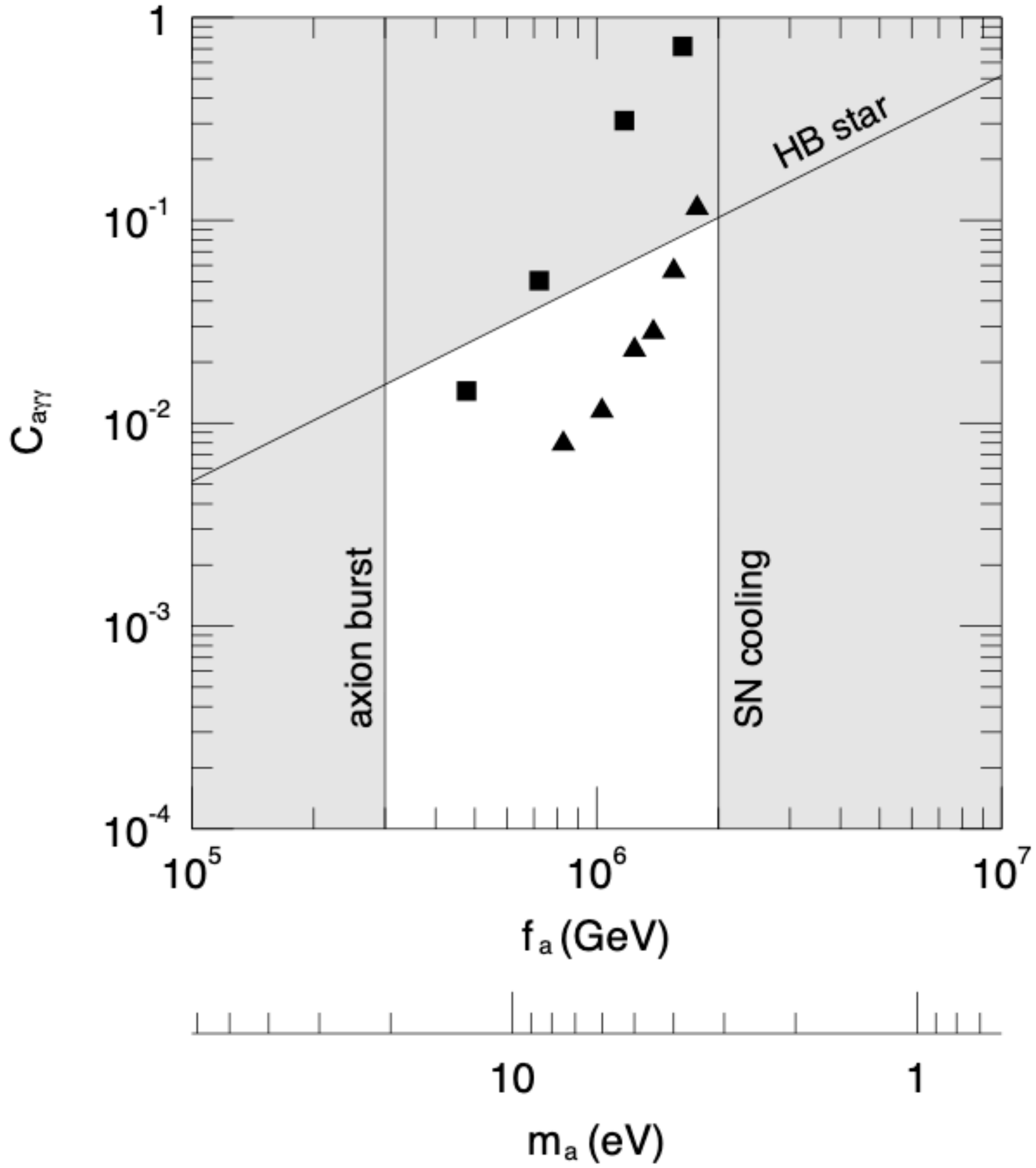


The quasi-equilibrium is kept on a very long time scale until

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

1. Hadronic QCD axion window



Chang:1993gm, Moroi:1998qs

QCD axion, coupled with hadrons, may change the measured duration of the neutrino burst from SN1987A.

Only relatively strong ($f_a < 10^6\, GeV$) or very weak ($f_a > 10^8 GeV$) interaction is allowed.

The former has a window around eV.

- Hot DM bound?
  ->model-building can evade it.
- Updates of SN1987A bound close the window? ($f_a < 10^4 GeV$? Chang:2018rso)
  ->SN1987A bound to axion may be wrong…
  Bar:2019ifz
- Neutron star cooling bound?
  Is there any study on the trapping regime?