CP-violating light dark sector

Wen Yin (Tohoku University) 殷 文（東北大学）

Based on **2111.03653** with Kodai Sakurai and
Phys.Rev.D 104 (2021) 9, 095010 with
Dongok Kim, Younggeun Kim, Yannis K. Semertzidis, Yun Chang Shin,

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- 3. Phenomenology of CP even ALP
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2. Introduction

-light axion/ALP DM and CP-

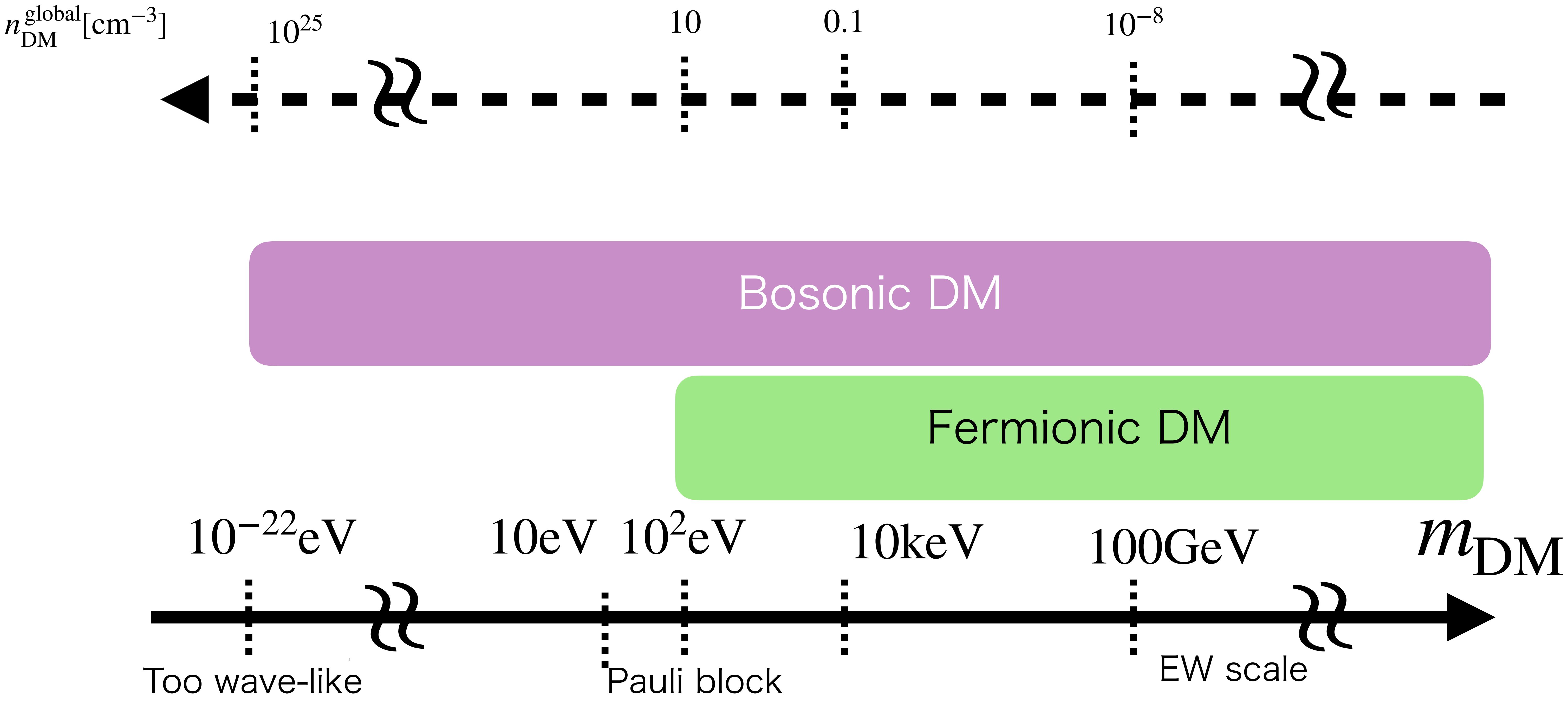
Light dark matter

- **What is dark matter?**

Very stable
Neutral
Cold

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

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



- **Questions for very light DM**

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

- **Light DM candidates**

Boson: axion/ALP, hidden photon etc.

Fermion: chiral fermion
(sterile neutrino) etc

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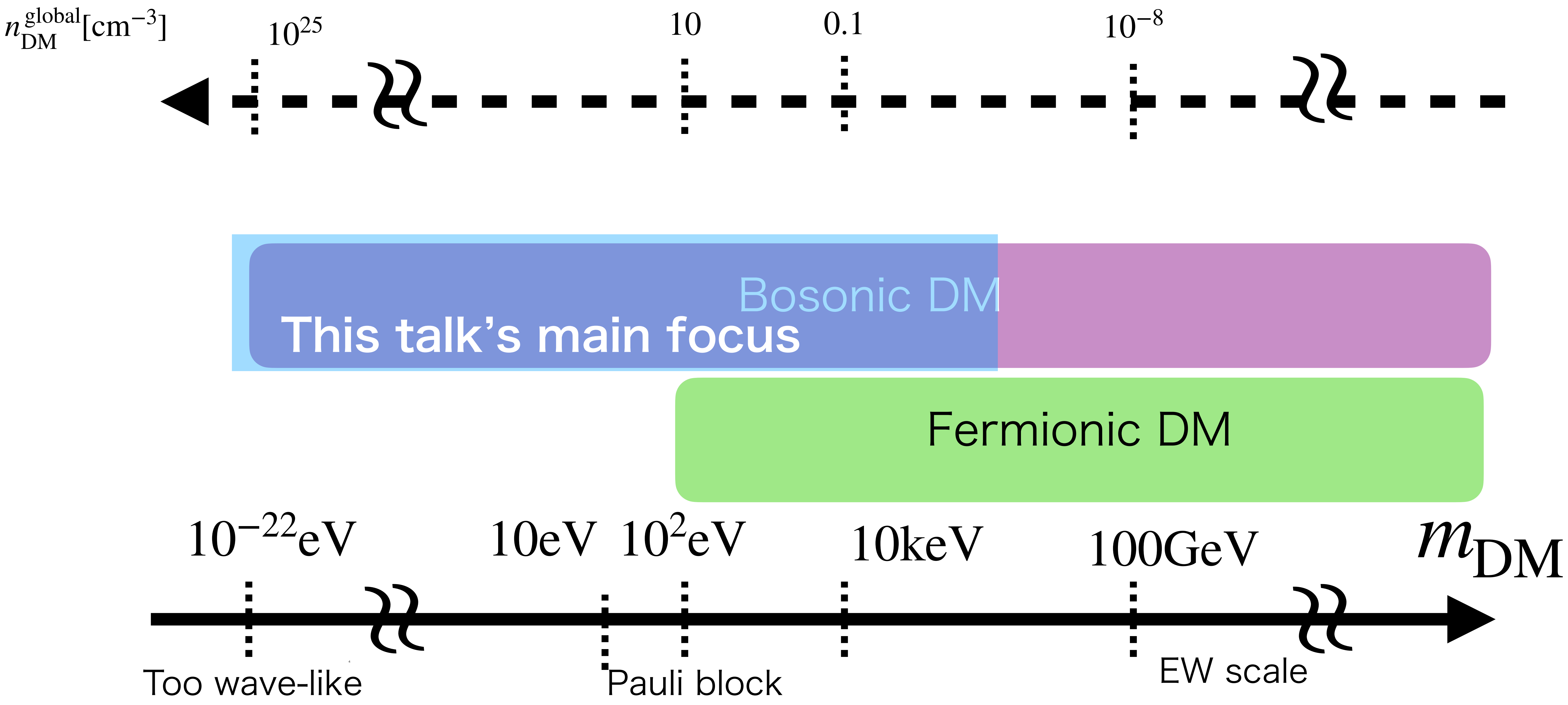

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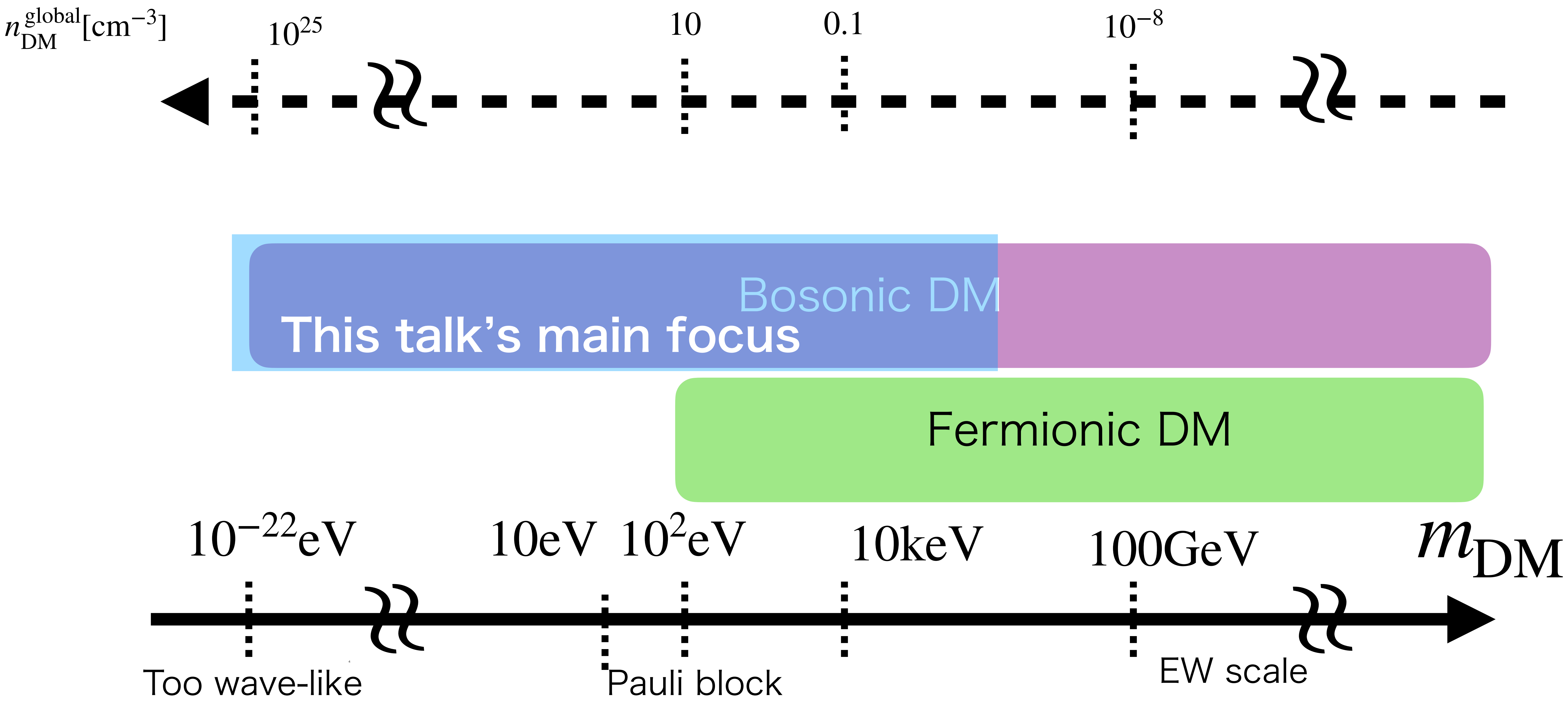

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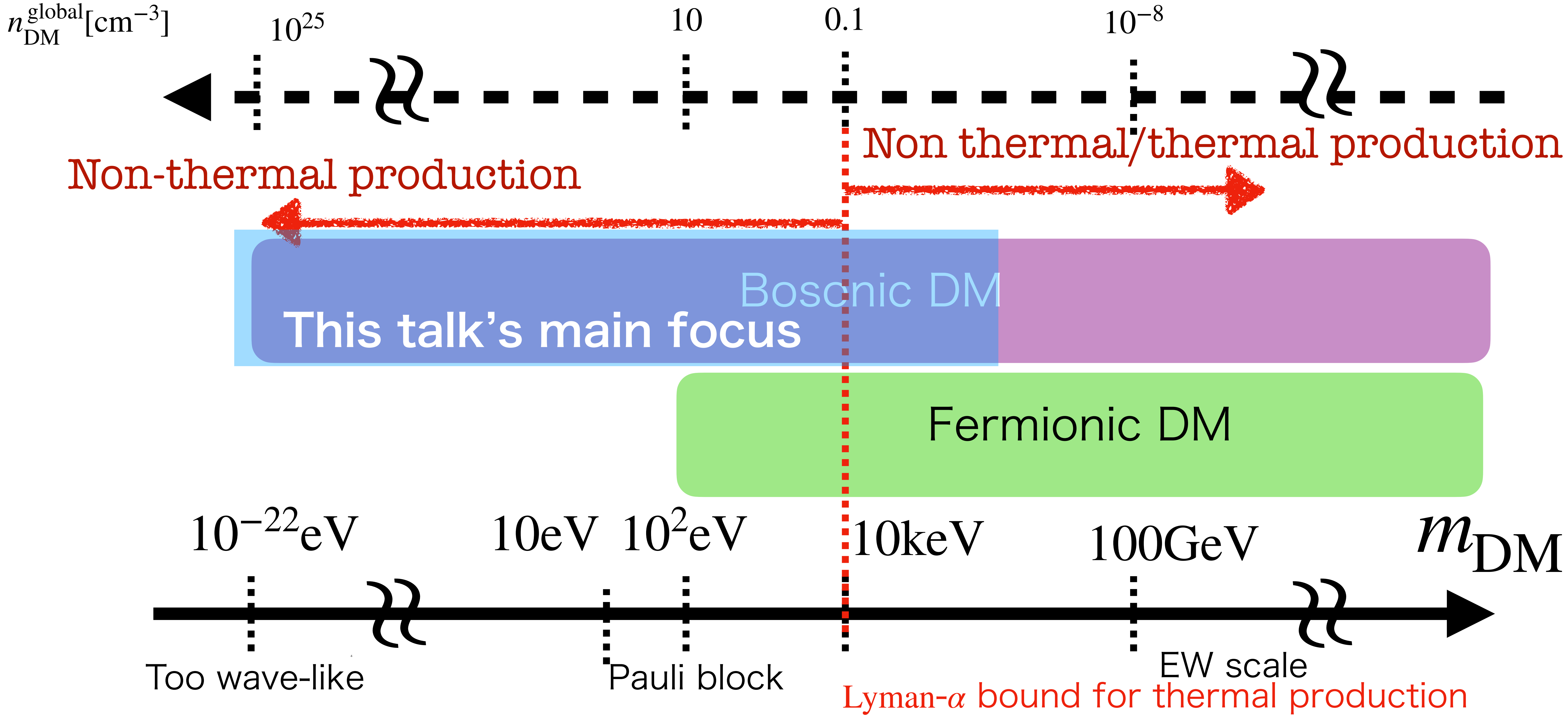

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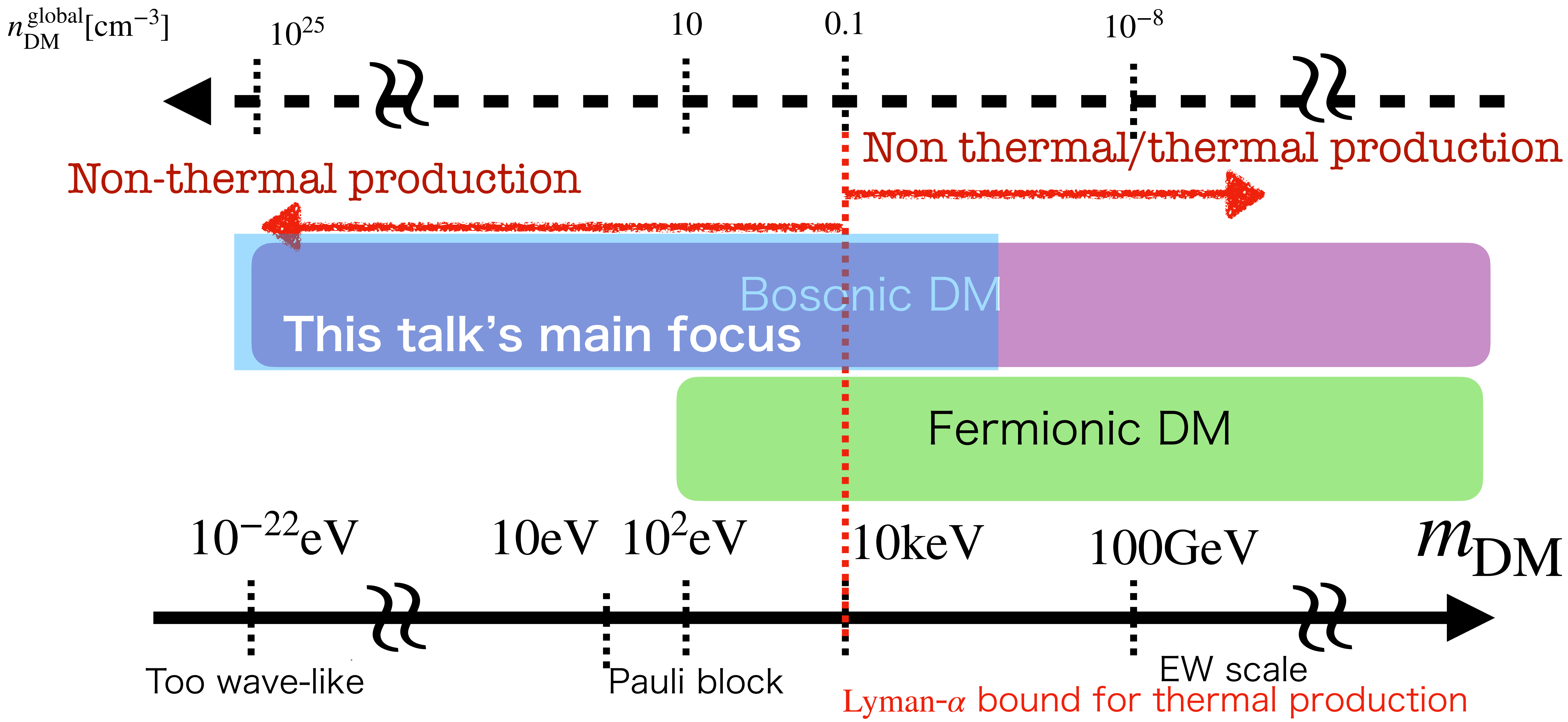

$n_{\rm DM}^{\rm global}[{\rm cm}^{-3}]$ 10^{25} 10 0.1 10^{-8}

Non-thermal production

Non thermal/thermal production

Bosonic DM

This talk's main focus

Fermionic DM

10^{-22}eV 10eV 10^2eV 10keV 100GeV $m_{\rm DM}$

Too wave-like

Pauli block

EW scale

Lyman-α bound for thermal production

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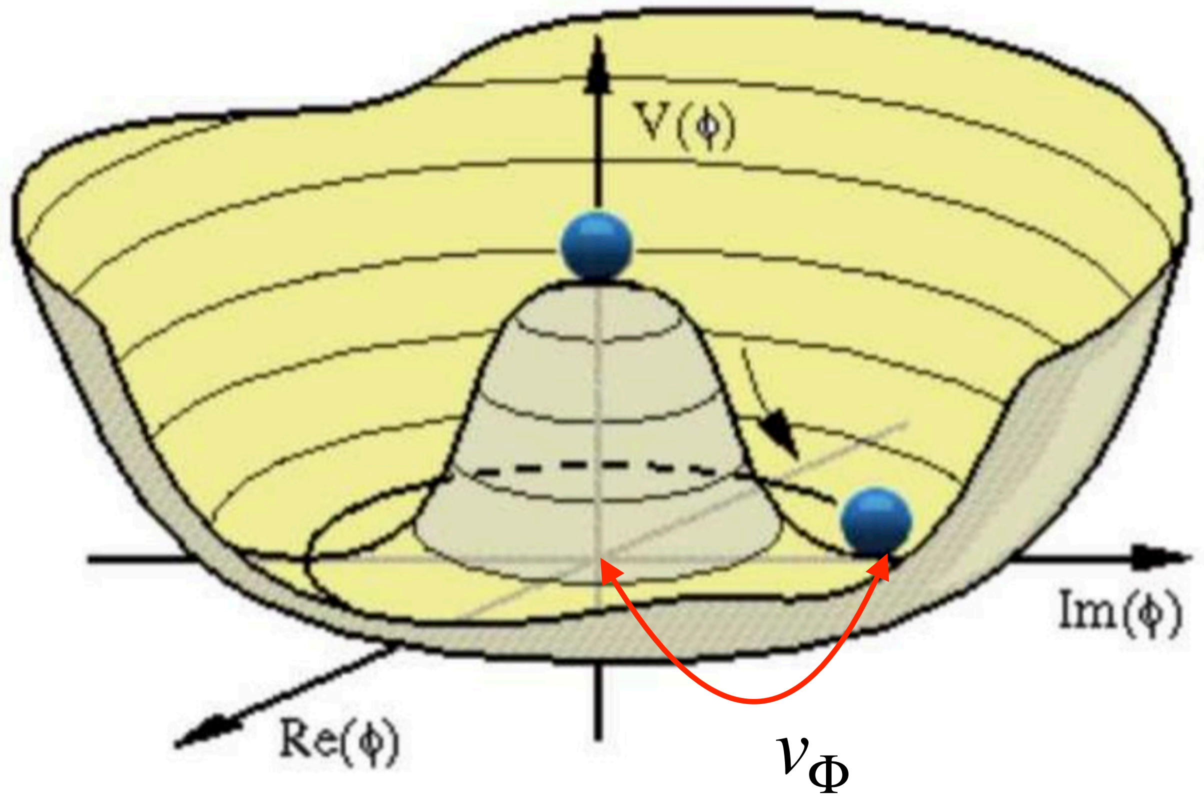
Review: model of ALP/axion

If a continuous global U(1) symmetry is *spontaneously* broken, there is a Nambu Goldstone Boson (NGB), a, which is massless.

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2.$$



https://physicsforme.com/2012/01/31/a-historical-profile-of-the-higgs-boson/

U(1) Higgs field: $\Phi \sim (v+s)\exp(i\frac{a}{\sqrt{2}v})$

$$U(1) \quad a \to a + \alpha$$

$$\tilde{V}(a) = \tilde{V}(a+\alpha)$$

The mass of the NGB is 0.

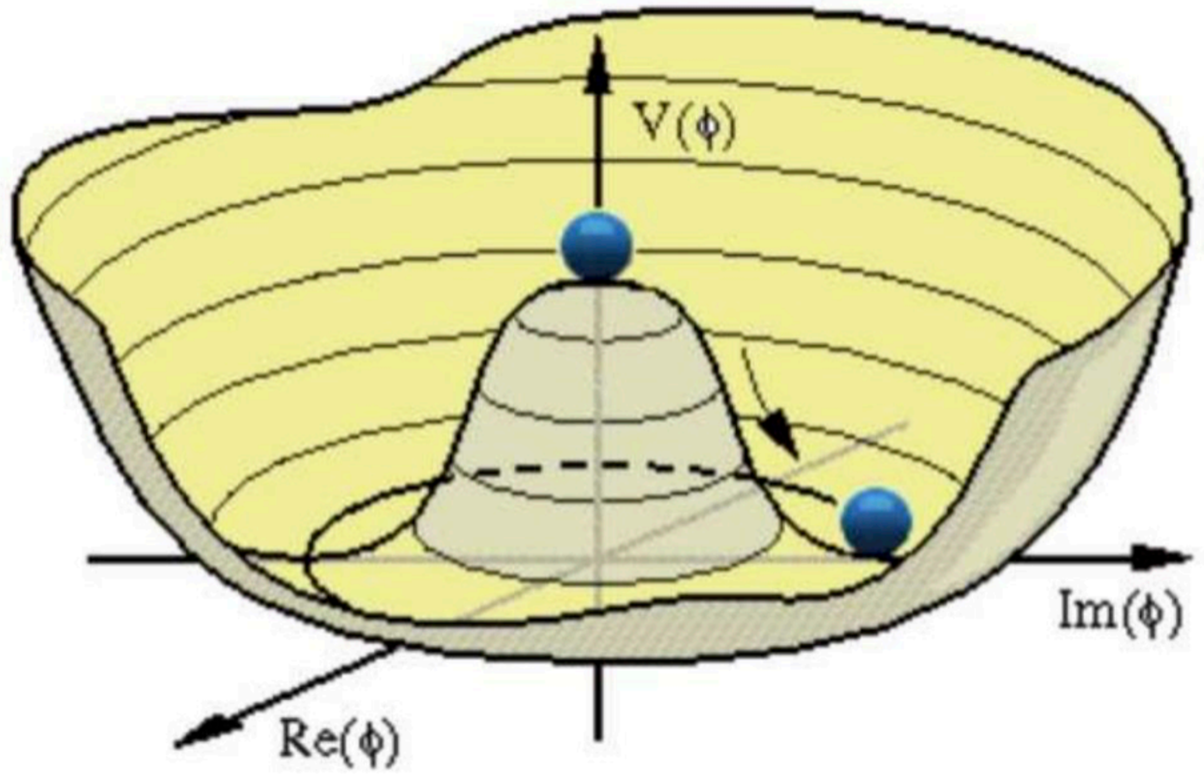
Review: model of ALP/axion

Axion obtains a small mass via explicit breaking of U(1)

$$V = - m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \lambda_P |H|^2 |\Phi|^2 + \lambda_H |H|^4 - \mu_H^2 |H|^2 .$$

$$\boxed{+\kappa m_\Phi^3 \Phi + \mathrm{h.c.}}$$

(or $\frac{g_s^2 a}{16\pi^2 f_a} G\tilde{G}$) QCD axion



$$\Phi \sim (v_\Phi + s)\exp(i\frac{a}{\sqrt{2}v})$$

$$\tilde{V} \sim \kappa v_\Phi^4 \cos[\frac{a}{f_a}]$$

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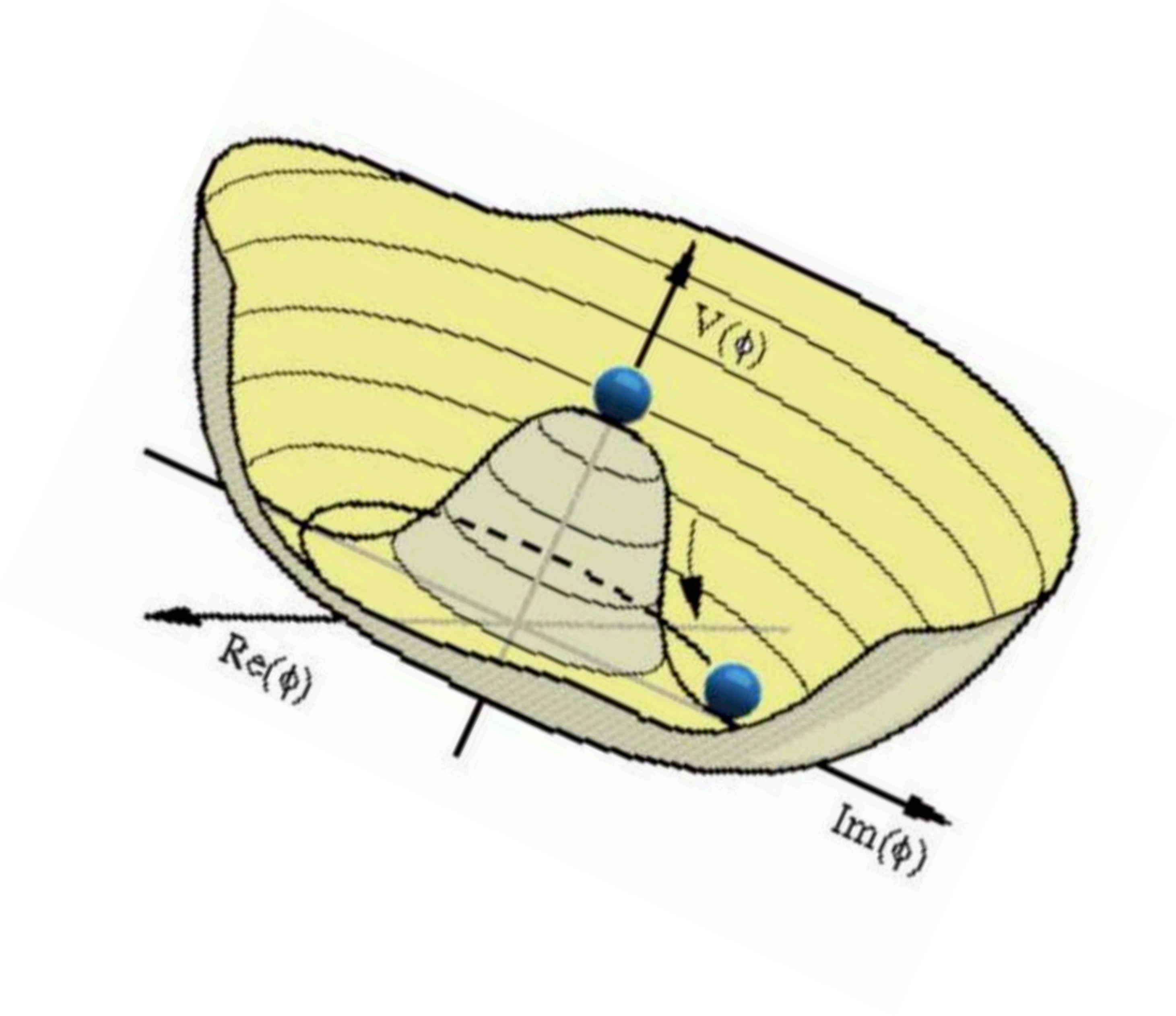

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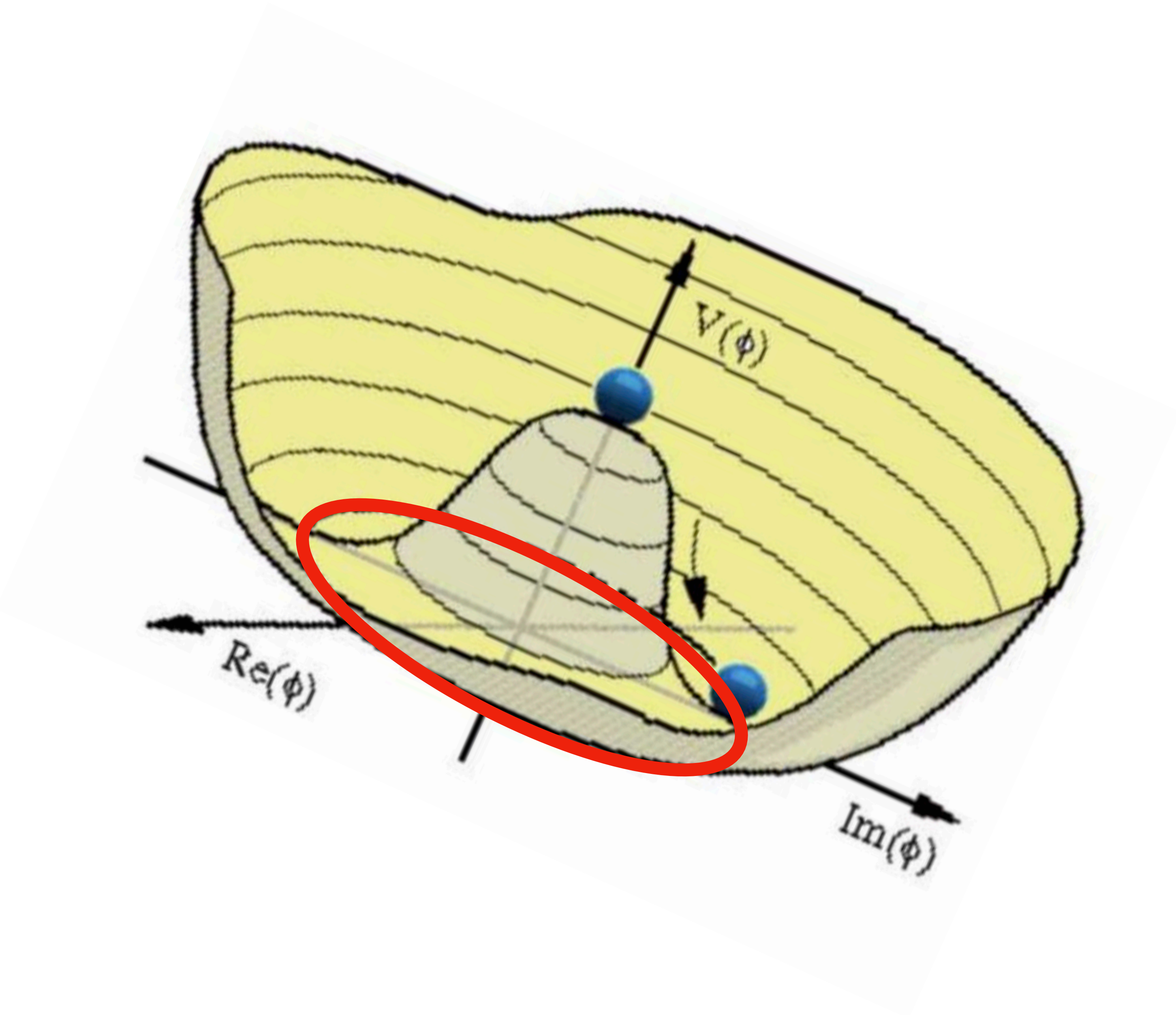

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*QCD axion explains the vanishingly small neutron EDM.

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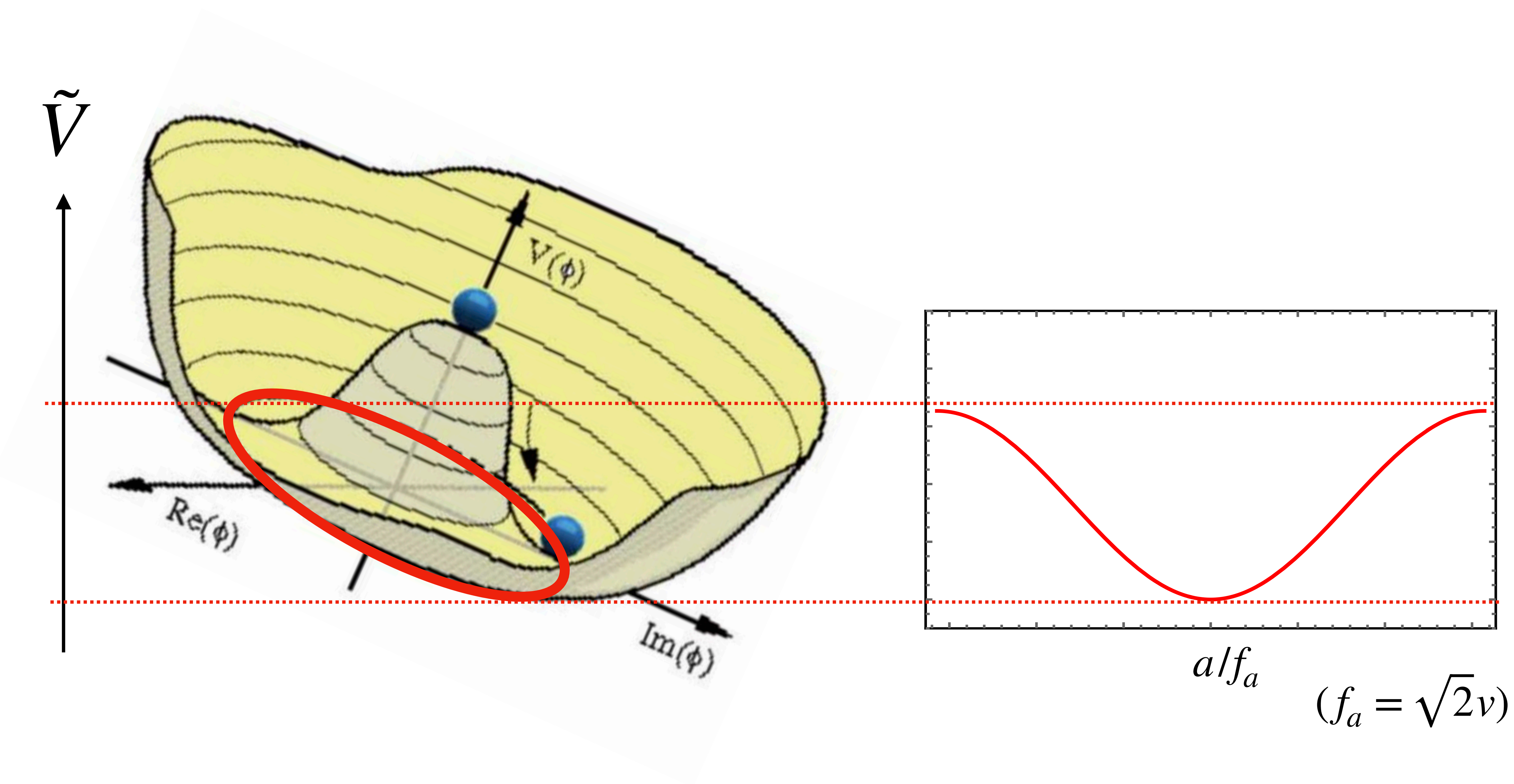

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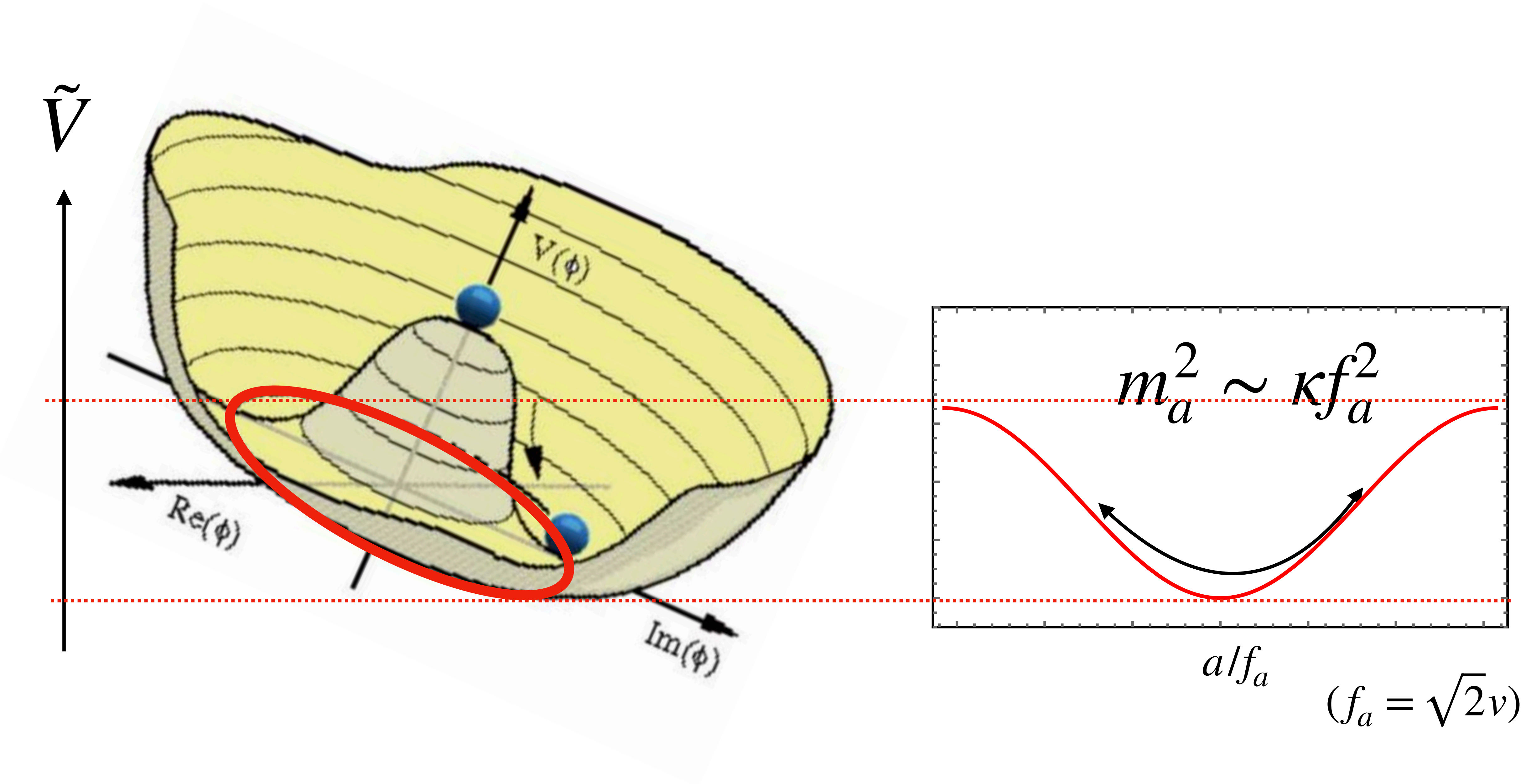

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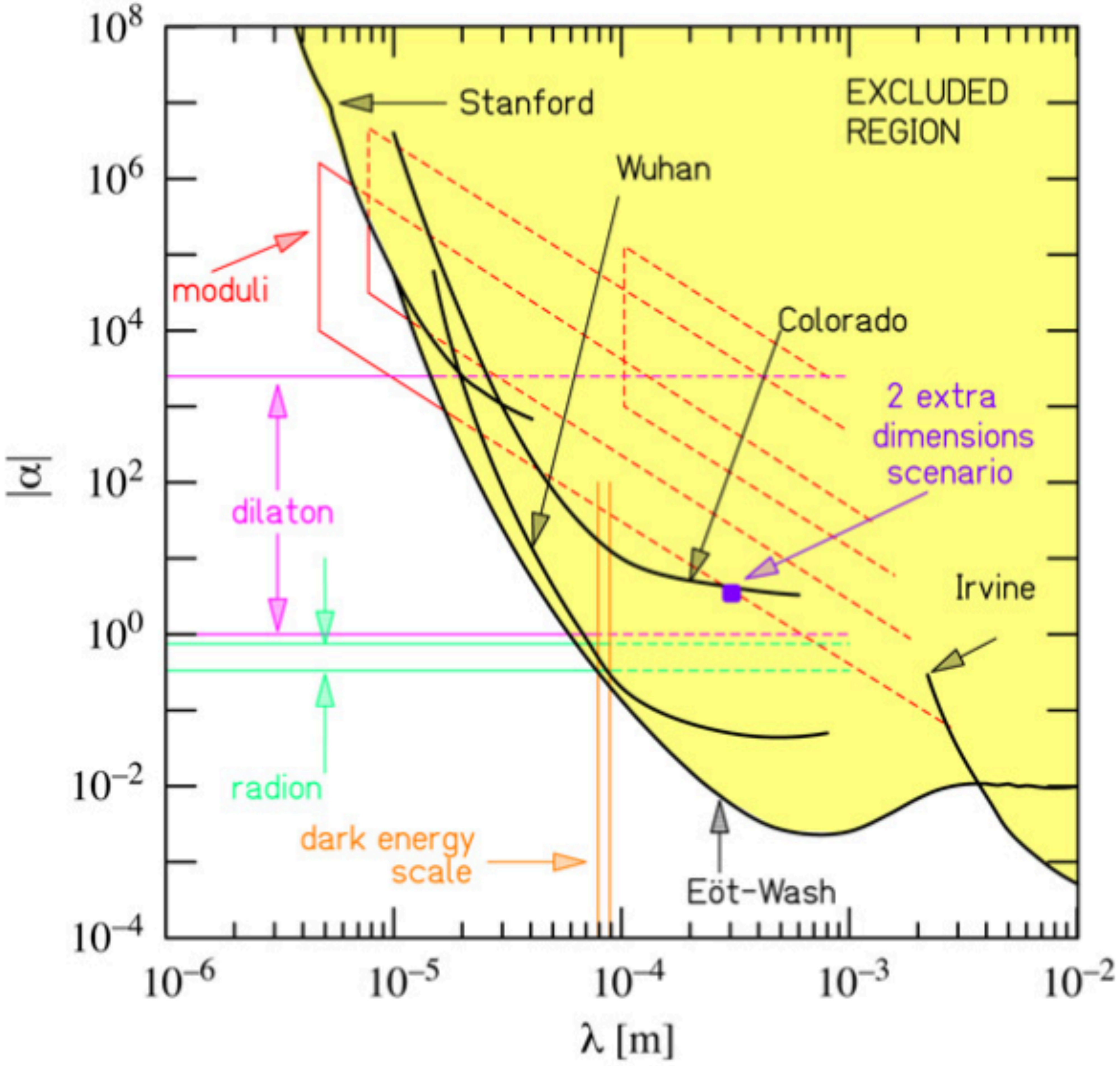
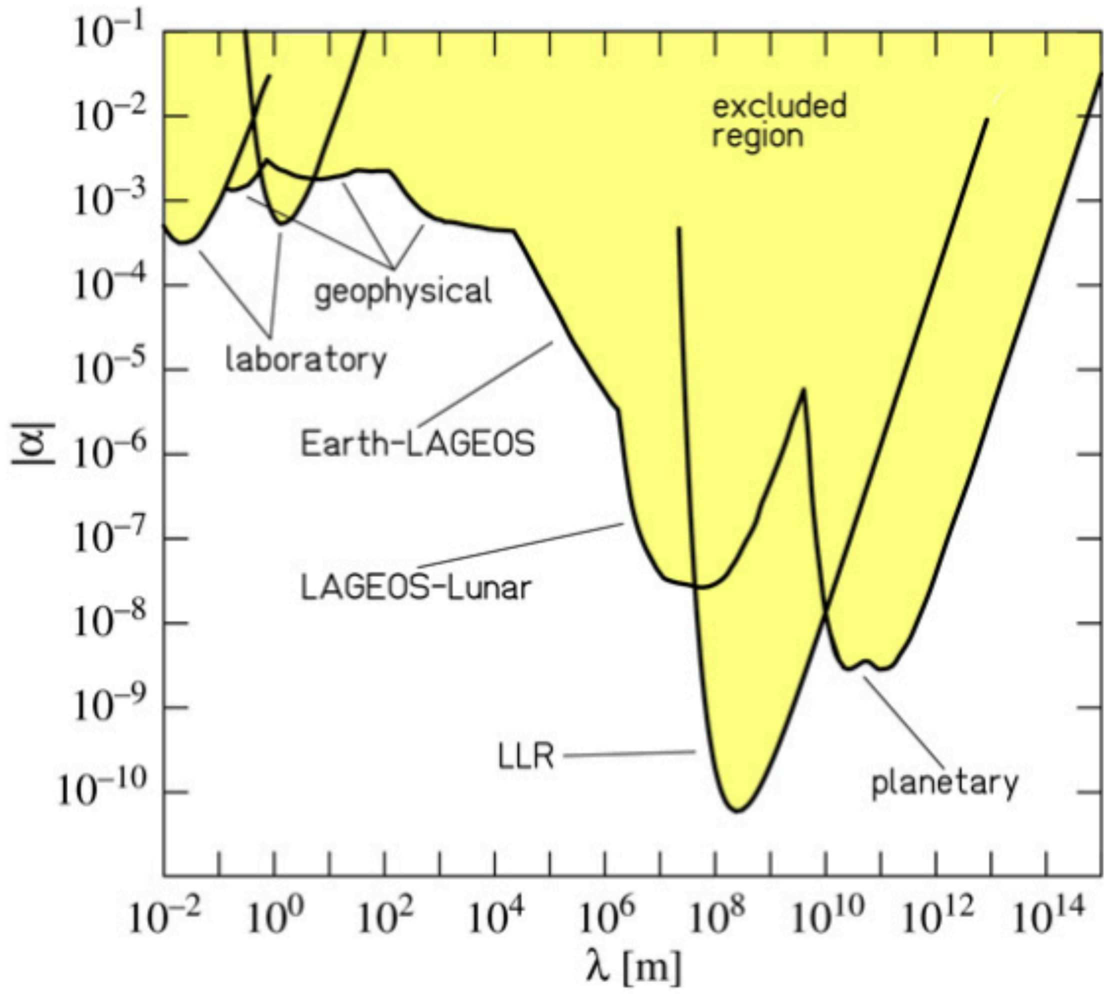
Why not a CP even scalar DM, e.g. modulus?

Fifth force search kills most models with CP even scalar mass $m_\phi < 10^{-3} eV$.



$$V = -G_N \frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$

$$\lambda \sim 2 \times 10^{-4}\text{m}\frac{10^{-3}eV}{m_\phi}$$



Why aren’t axion/ALP ruled out by the fifth force?

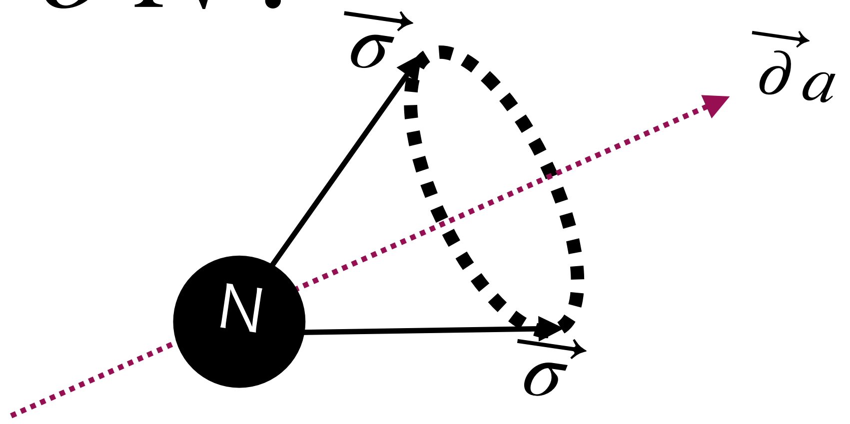
-> They are CP odd particles. Thus the mediated force is short range (dipole-dipole or spin-spin type force).

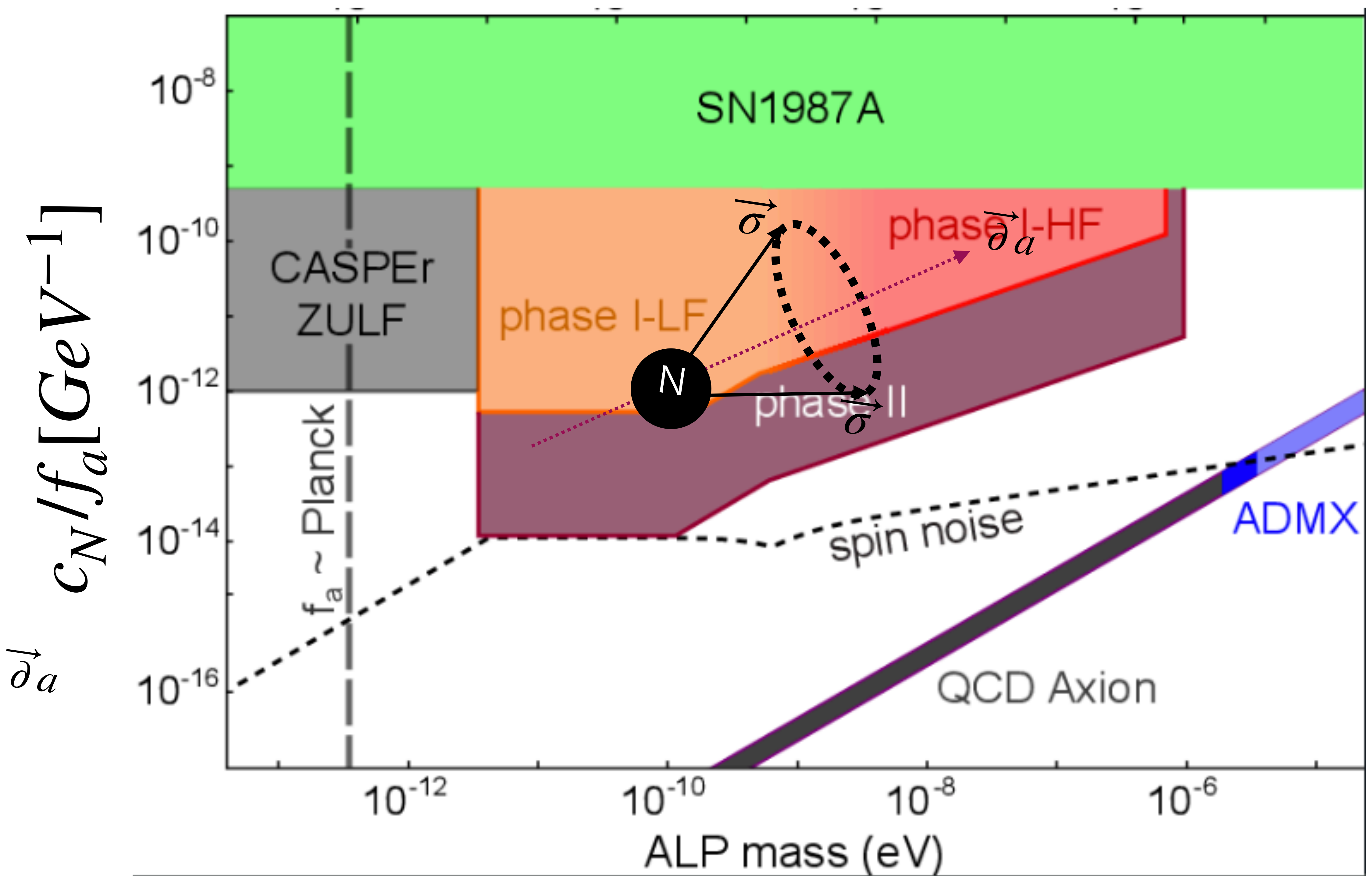
$$i\frac{c_N M_N}{f_a} a\bar{N}\gamma_5 N$$

It couples nucleon spin.

$$H_{\rm EFT}^{\rm nonrela} \simeq -\frac{c_N}{2f_a}\vec{\partial} a \cdot \bar{N}\vec{\sigma}N\,.$$

$$\vec{\partial} a \sim v_{\rm DM}\sqrt{\rho_{\rm DM}} \sim 10^{-3}\sqrt{\rho_{\rm DM}}$$





Jackson Kimball et al, 1711.08999

*It may or may not a QCD axion depending on whether there is gluon anomaly.

Why aren't axion/ALP ruled out by the fifth force?

-> They are CP odd particles. Thus the mediated force is short range (dipole-dipole or spin-spin type force).

CP symmetry is based on miracle and accident

Strong CP problem

$\frac{\alpha_s}{4\pi}\theta_{\rm CP} G\tilde{G}$ $\qquad \theta_{\rm CP} \lesssim 10^{-10}$

$$\mathscr{L} \supset g_{aNN}^{\rm CPV} a\bar{N}N \qquad g_{aNN}^{\rm CPV} \sim \frac{c_g \theta_{\rm CP}}{f_a}\frac{2m_u m_d}{(m_u+m_d)^2}\langle N|\sigma|N\rangle$$

Moody and Wilczek, 1984

$$V(r) \sim \frac{\theta_{\rm CP}^2 M_N^2}{4\pi f_a^2 r}\exp(-m_a r)$$

It is strong CP problem that allows us to have a light CP odd DM.

This problem is naturally solved if there is a QCD axion.
But I will not discuss about it.

Given the tuning, accidental CP symmetry

$$\theta_{\rm eff} \sim J G_F^2 \Lambda_{\rm QCD}^4$$

$$J \equiv Im V_{tb} V_{td}^* V_{cd} V_{cb}^* \sim 10^{-5}$$

$$V(r) \sim \frac{\theta_{\rm eff}^2 M_N^2}{4\pi f_a^2 r}\exp(-m_a r)$$

EW induced contribution is small by an accident.

Axion/ALP can be light DM without running afoul with 5th force bounds because of the fine-tuning + accidental CP symmetry. This is observational consequence which we have to admit, but

do we really need to impose CP symmetry in dark sector?

3. CP-even ALP from generic CPV

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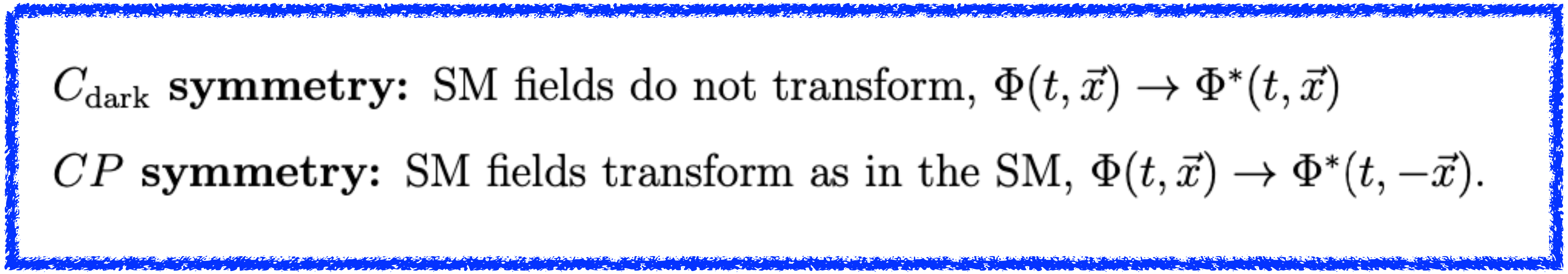
In the following I take for simplicity $\theta_{\rm CP} = \theta_{CKM} = 0$, which does not change our conclusions.

If we do not impose CP symmetry in the dark sector,

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 .$$

Accidental discrete symmetry in dark global U(1) symmetric limit:



$C_{\rm dark}$ **symmetry:** SM fields do not transform, $\Phi(t,\vec{x}) \to \Phi^*(t,\vec{x})$

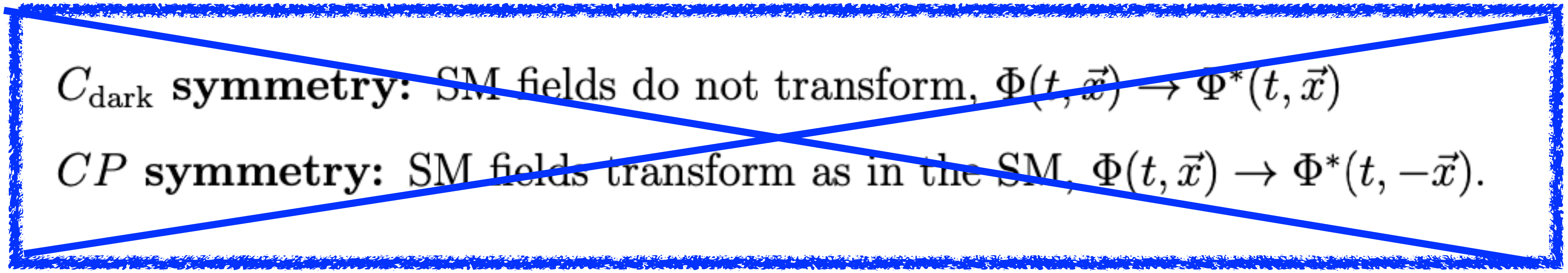
CP **symmetry:** SM fields transform as in the SM, $\Phi(t,\vec{x}) \to \Phi^*(t,-\vec{x})$.

If we do not impose CP symmetry in the dark sector,

Explicit breaking of dark $U(1)$ controlled by κ is

$$\delta V = \kappa \left(\sum_{j=1}^{4} c_j m_\Phi^{4-j} \Phi^j + \sum_{j=1}^{2} (\tilde{c}_j^H m_\Phi^{2-j} \Phi^j |H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j} \Phi^j |\Phi|^2) \right) + \mathrm{h.c.}$$

$$\arg c, \tilde{c} \neq 0$$



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$$\arg c, \tilde{c} \neq 0$$

But $C_{\text{dark}} \cdot CP$ remains: SM → CP SM,

$\Phi(t, \overrightarrow{x}) \to \Phi(t, -\overrightarrow{x})$ (a parity for dark Higgs).

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$C_{\mathrm{dark}} \cdot CP$: SM → CP SM

$\Phi(t, \vec{x}) \to \Phi(t, -\vec{x})$, thus $a[t, \vec{x}] (\equiv -i \arg \Phi) \to a[t, -\vec{x}]$

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$$\arg c, \tilde{c} \neq 0$$

$CP_{\mathrm{EFT}} \equiv \ C_{\mathrm{dark}} \cdot CP$: SM → CP SM, $a[t, \vec{x}] \to a[t, -\vec{x}]$

A simple UV completion of axion without imposing CP symmetry has accidental CP_{EFT} with **ALP being CP-even**.

Couplings of the CP-even ALP

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 .$$

- Induced from U(1) symmetric part, and thus $C_{\rm dark}\times CP$ symmetric.
- Non-renormalizable (dim 6 or 8).
i.e. very weak at low energy.

$$\mathscr{L}_{\rm eff} \sim \frac{\mathcal{O}_{SM}}{m_\Phi^{d_{\mathcal{O}_{\rm SM}}}}(\partial a)^2$$

$$\delta V = \kappa\left(\sum_{j=1}^{4} c_j m_\Phi^{4-j}\Phi^j + \sum_{j=1}^{2}(\tilde{c}_j^H m_\Phi^{2-j}\Phi^j|H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j}\Phi^j|\Phi|^2)\right) + \mathrm{h.c.}$$

$$\mathscr{L}_{\rm eff} \sim \frac{m_a^2 m_h}{m_\Phi}ah, \theta_{ah} \sim \frac{m_a^2}{m_h m_\Phi}$$

- Induced from U(1) breaking part.
- At $\kappa\to 0$,(i.e. $m_a^2\to 0$), it vanishes, i.e.
amplitude $\propto m_a^2$
- Renormalizable, dominant at low energy.

3. Phenomenology of CP-even ALP

- Probing CP-even ALP in Higgs factory
- CP-even ALP DM

Kodai Sakurai, WY 2111.03653

CP-even ALP can be naturally produced via Higgs boson decay

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|\Phi|^2|H|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 .$$

Higgs portal coupling

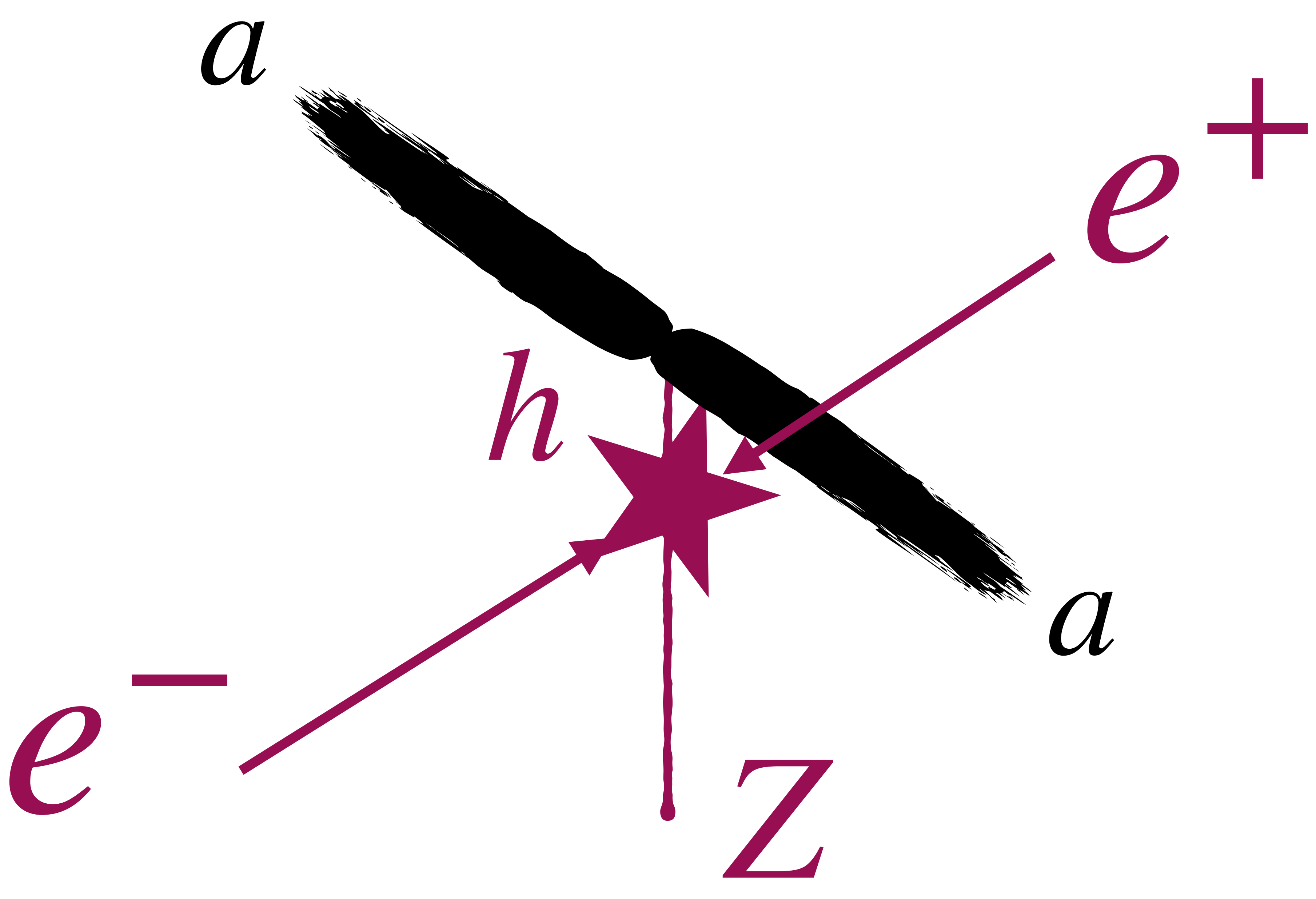
Φ: U(1) Higgs field

H :SM Higgs doublet

$$\mathscr{L}_{\rm eff} \sim \frac{\sqrt{2}v}{\Lambda_H^2} h(\partial a)^2 \qquad \frac{1}{\Lambda_H^2} \equiv -\frac{\lambda_P}{m_s^2 - m_h^2}.$$

$$\Gamma_{h\to aa} \simeq \frac{1}{16\pi}\frac{v^2 m_h^3}{\Lambda_H^4} .$$

$$\mathrm{Br}_{h\to aa} = 2\,\% \left(\frac{2\mathrm{TeV}}{\Lambda_H}\right)^4$$



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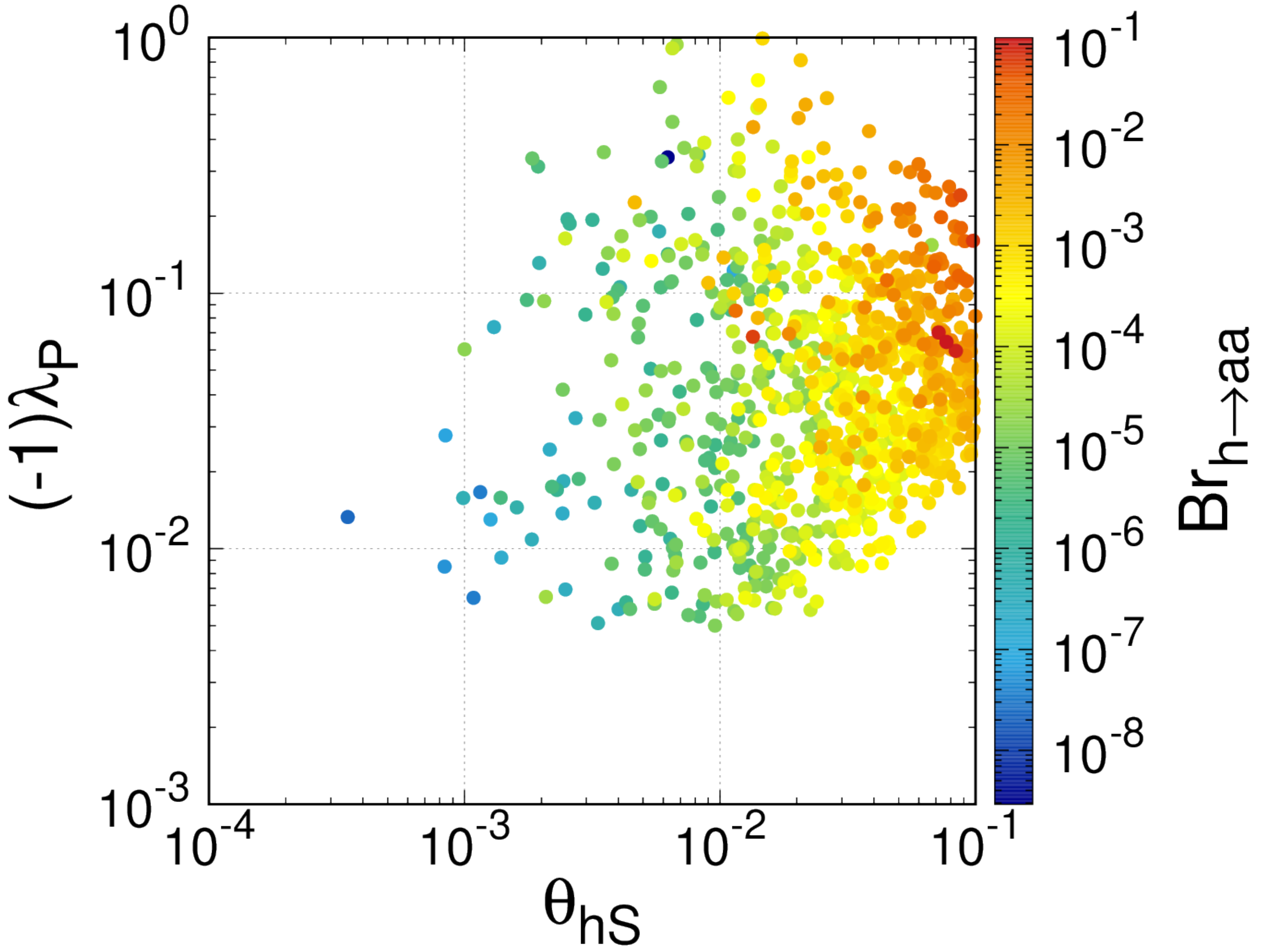
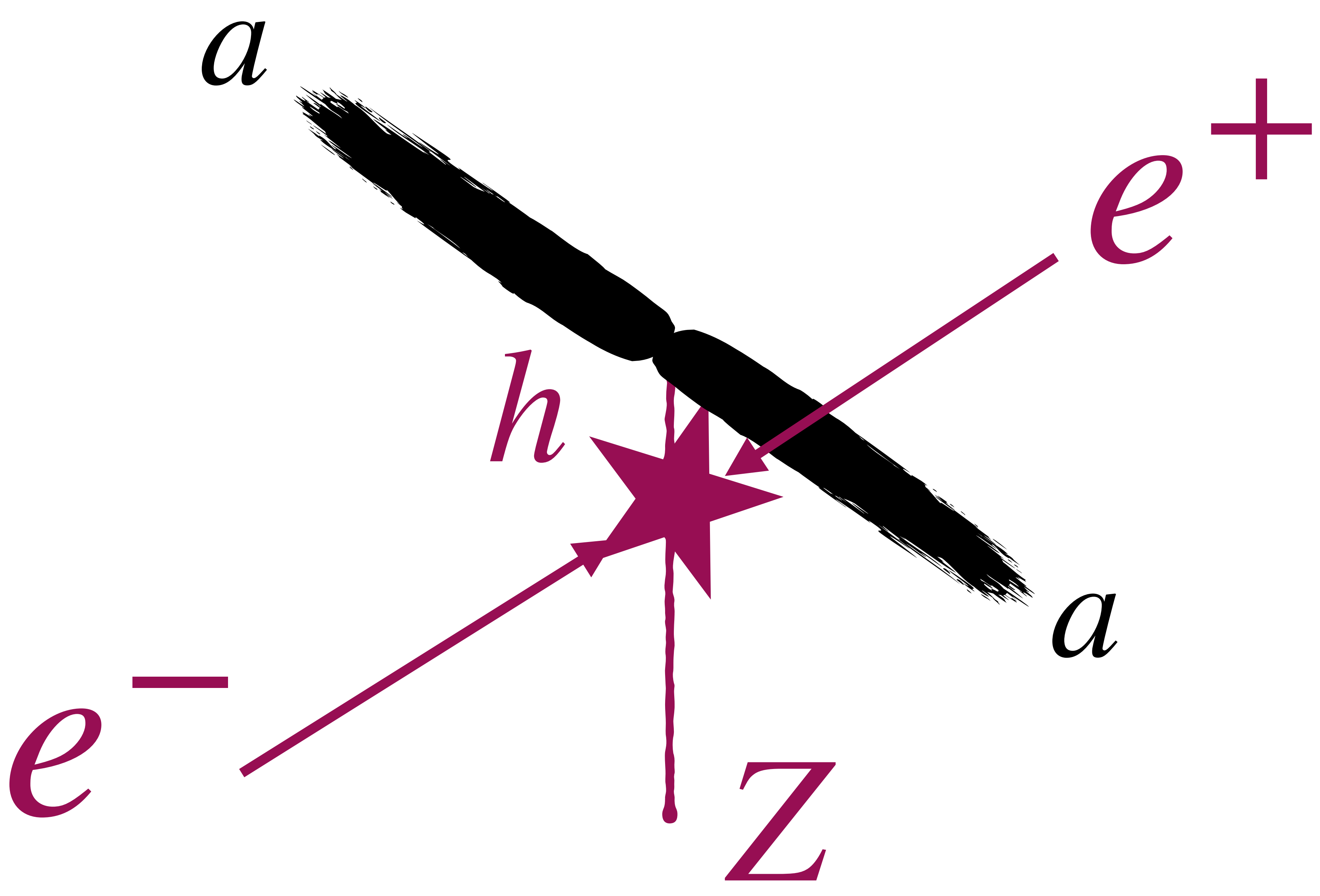
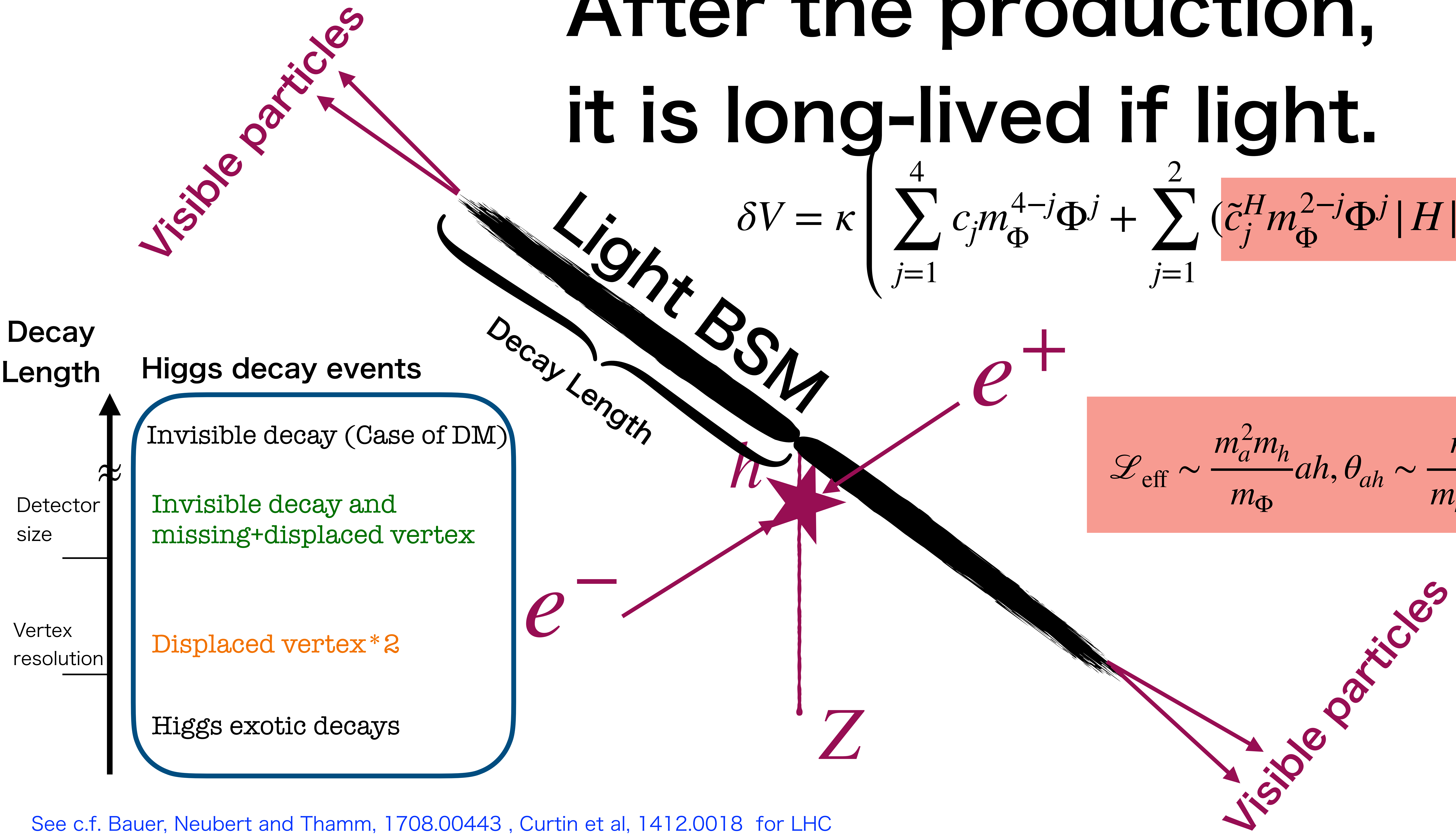
Production from Higgs decay





After the production, it is long-lived if light.

$$\delta V = \kappa \left(\sum_{j=1}^{4} c_j m_\Phi^{4-j} \Phi^j + \sum_{j=1}^{2} (\tilde{c}_j^H m_\Phi^{2-j} \Phi^j |H|^2 + \right.$$



Decay Length

Higgs decay events

Invisible decay (Case of DM)

$\approx$

Detector size

Invisible decay and missing+displaced vertex

Vertex resolution

Displaced vertex＊2

Higgs exotic decays

$$\mathscr{L}_{\rm eff} \sim \frac{m_a^2 m_h}{m_\Phi} a h, \theta_{ah} \sim \frac{m_a^2}{m_h m_\Phi}$$

See c.f. Bauer, Neubert and Thamm, 1708.00443 , Curtin et al, 1412.0018 for LHC

Probing CP-even ALP at e.g. ILC 250GeV

Decay length and product of a from Higgs decay and signature at ILC

Kodai Sakurai, WY 2111.03653

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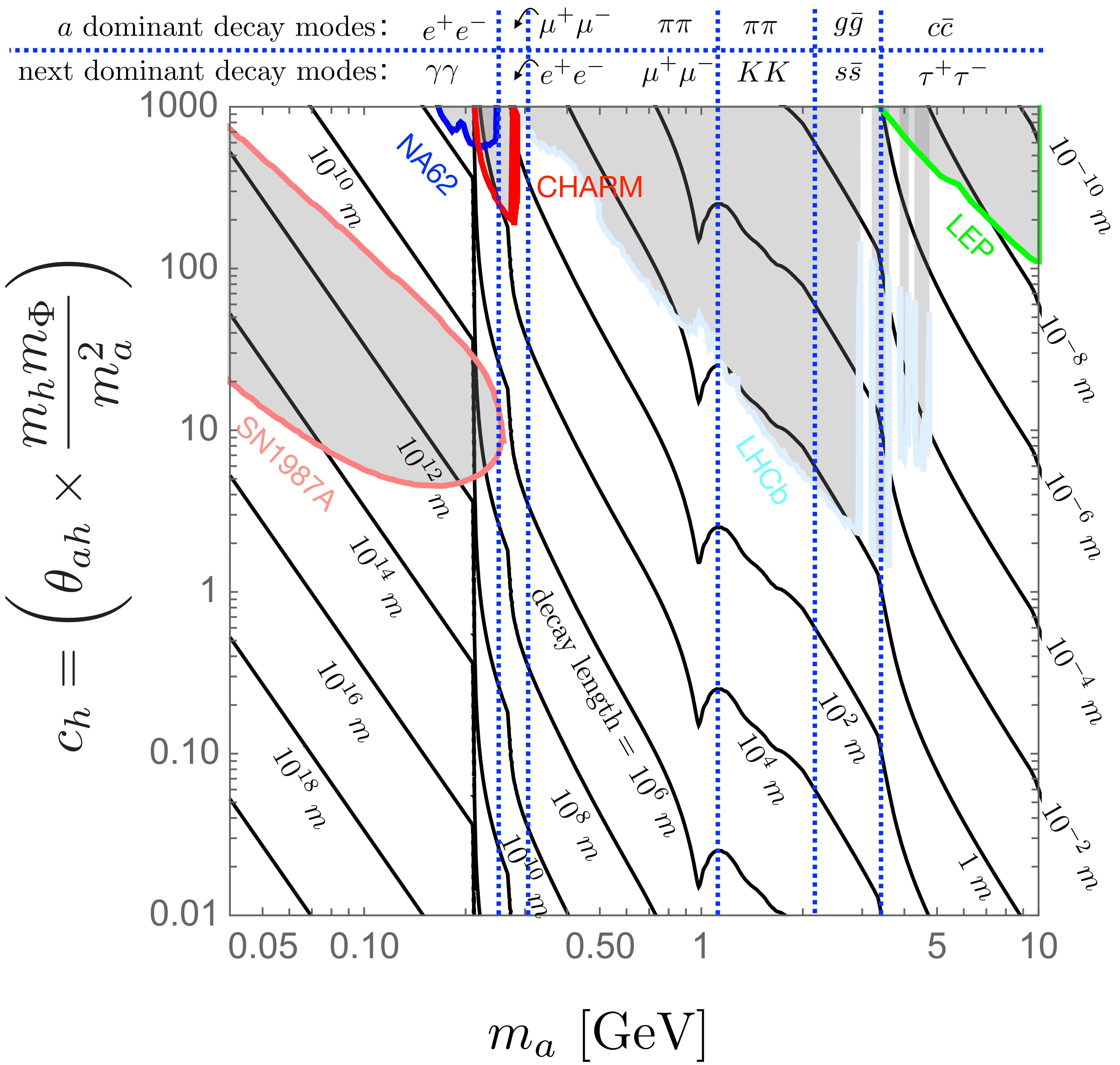

See also Bhattacherjee et al 2111.02437 for hadron collider reach of CP-even light mediator

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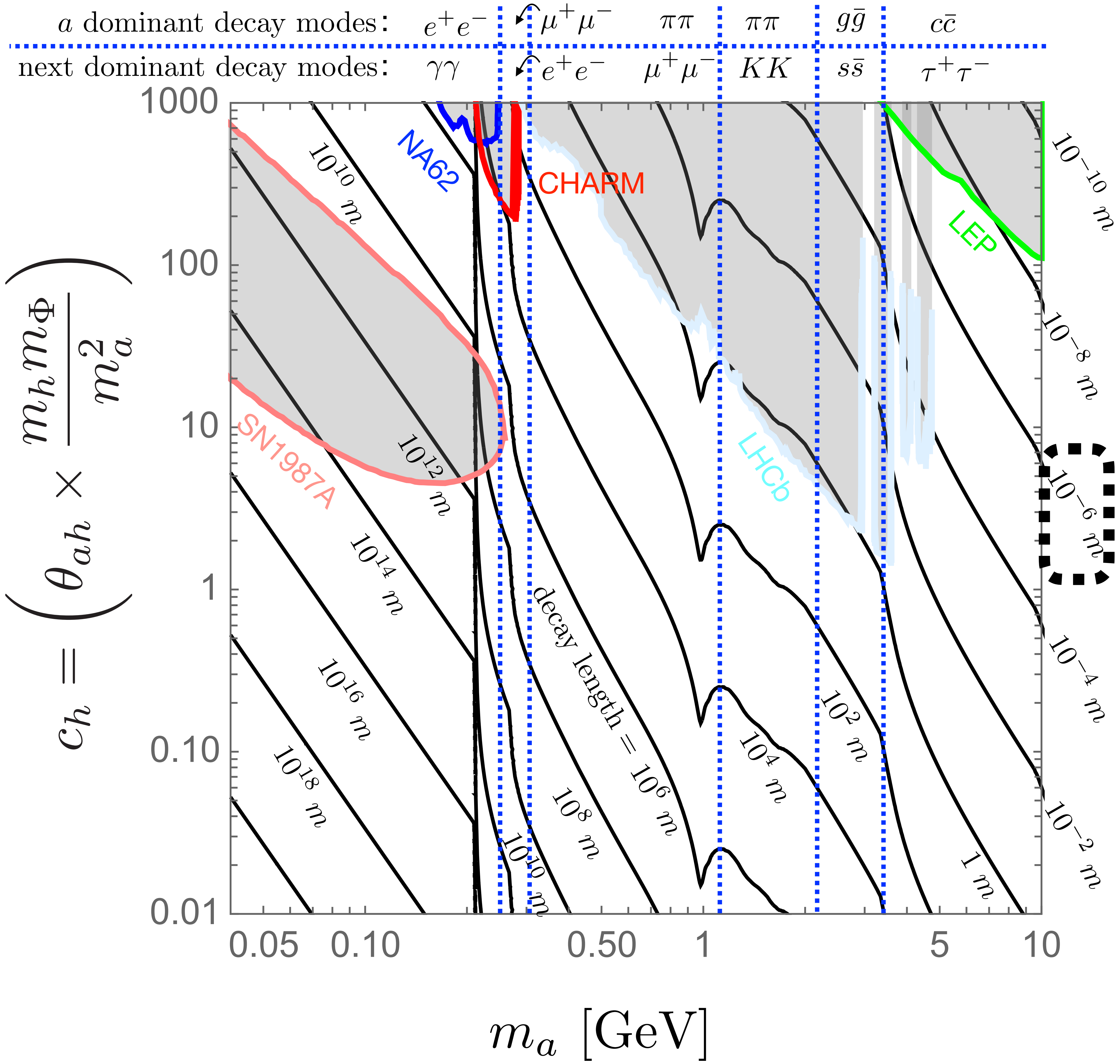

Vertex resolution

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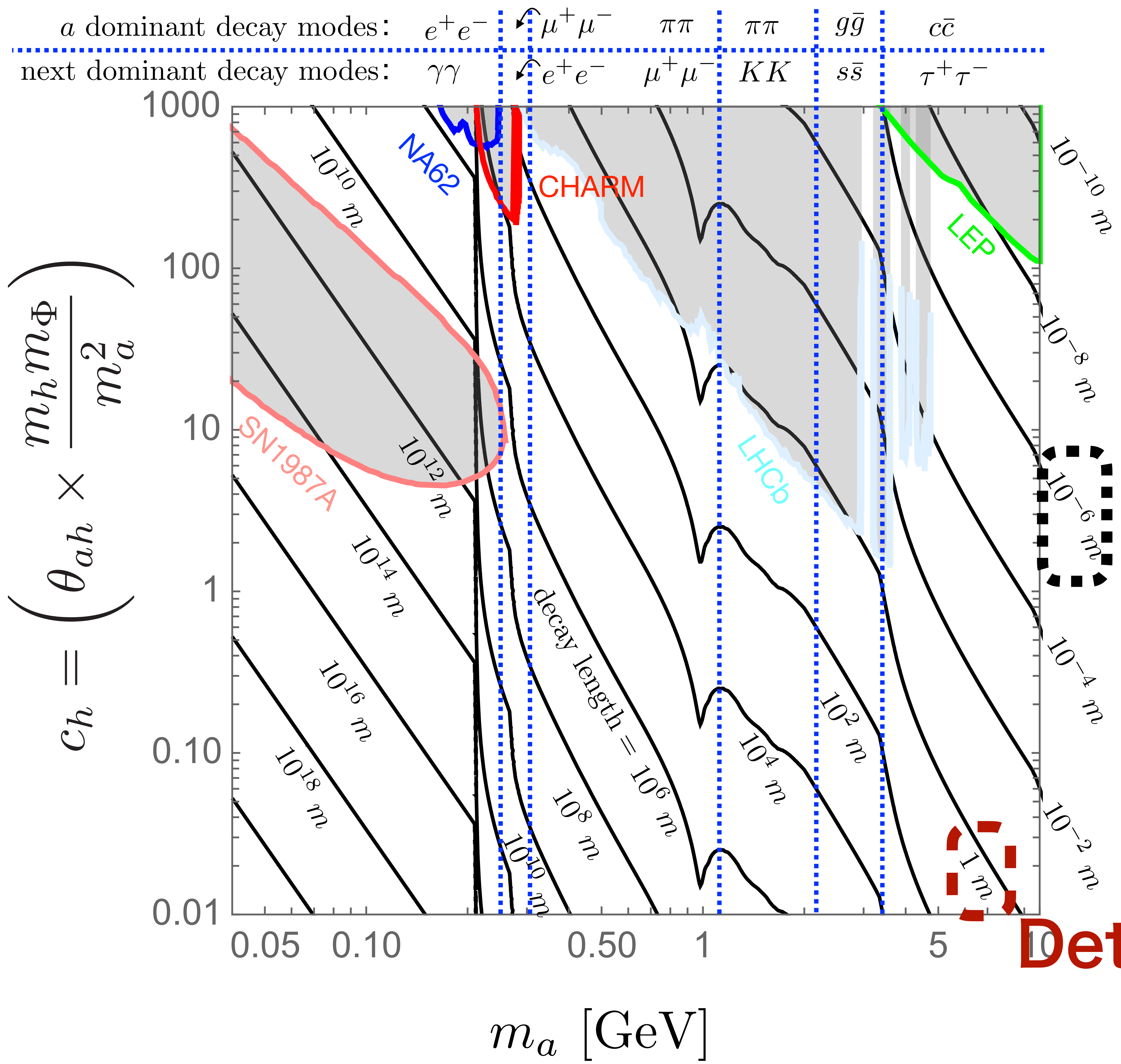

Vertex resolution

Detector size (TPC)

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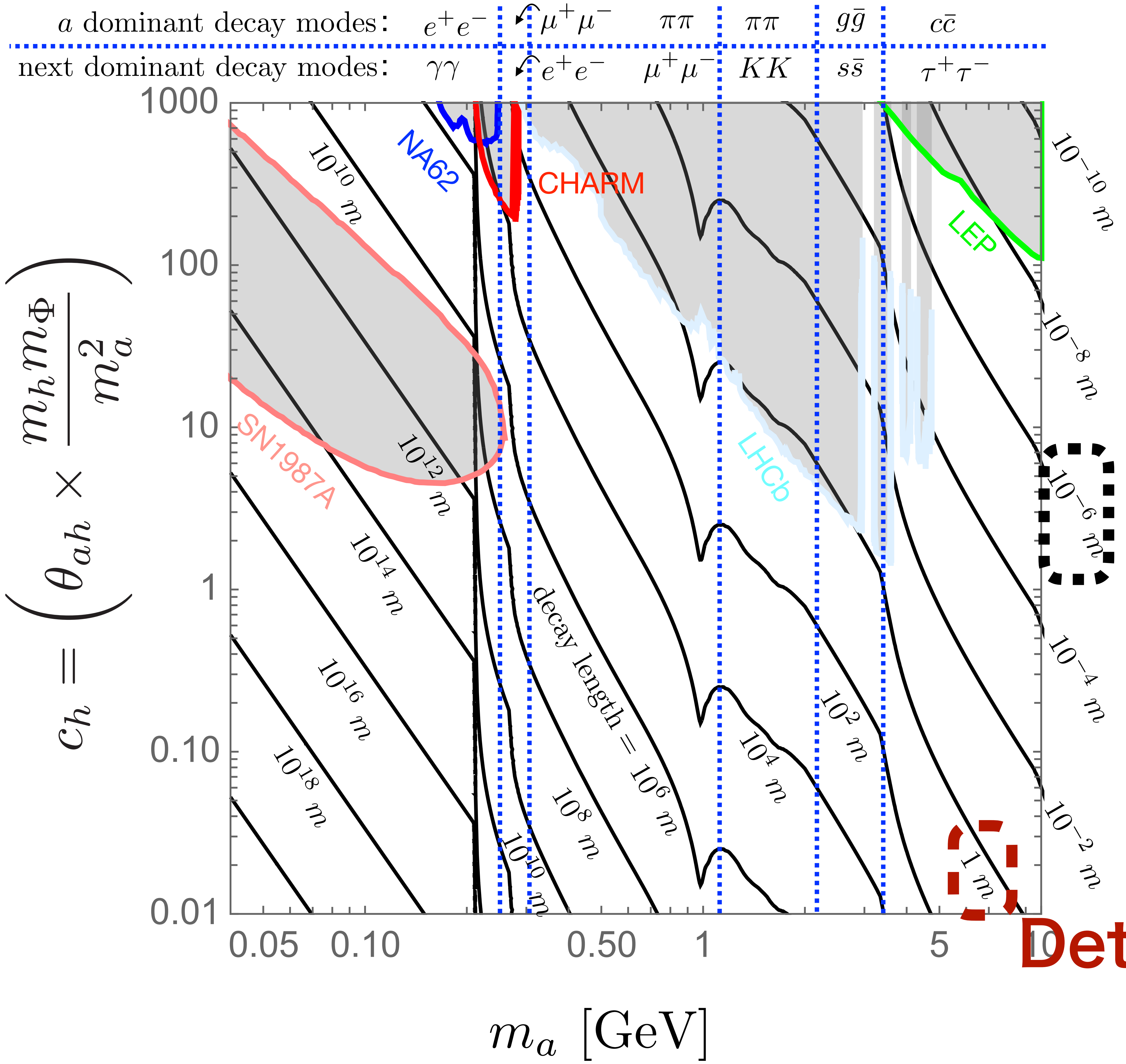
Kodai Sakurai, WY 2111.03653

$$\mathscr{L}_{\rm eff} \sim \frac{m_a^2 m_h}{m_\Phi} a h, \theta_{ah} \sim \frac{m_a^2}{m_h m_\Phi}$$



Higgs
exotic
decay

$$Br_{h\to aa(\to c\bar c c\bar c)} \gtrsim 10^{-3}\ (2\sigma\text{CL},2\ \text{ab}^{-1})$$

Liu et al, 1612.09284

Vertex resolution

Detector size (TPC)

See also Bhattacherjee et al
2111.02437
for hadron collider reach
of CP-even light mediator

Probing CP-even ALP at e.g. ILC 250GeV

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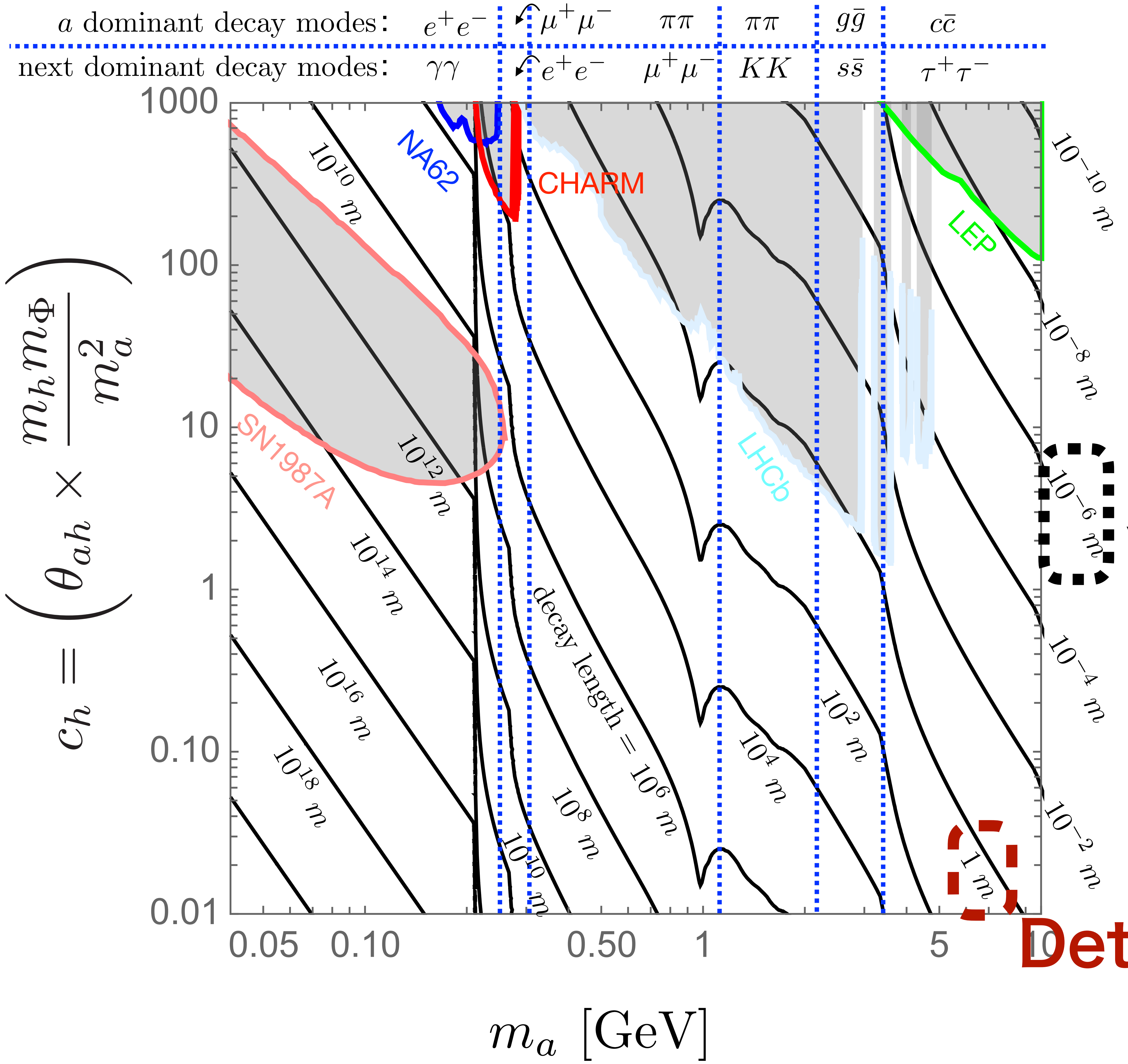

Higgs exotic decay

Vertex resolution

Displaced vertex ×2

Detector size (TPC)

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$$Br_{h\to aa} > 10^{-6},$$
$$(2\sigma\text{CL}, 3\ \text{ab}^{-1})$$

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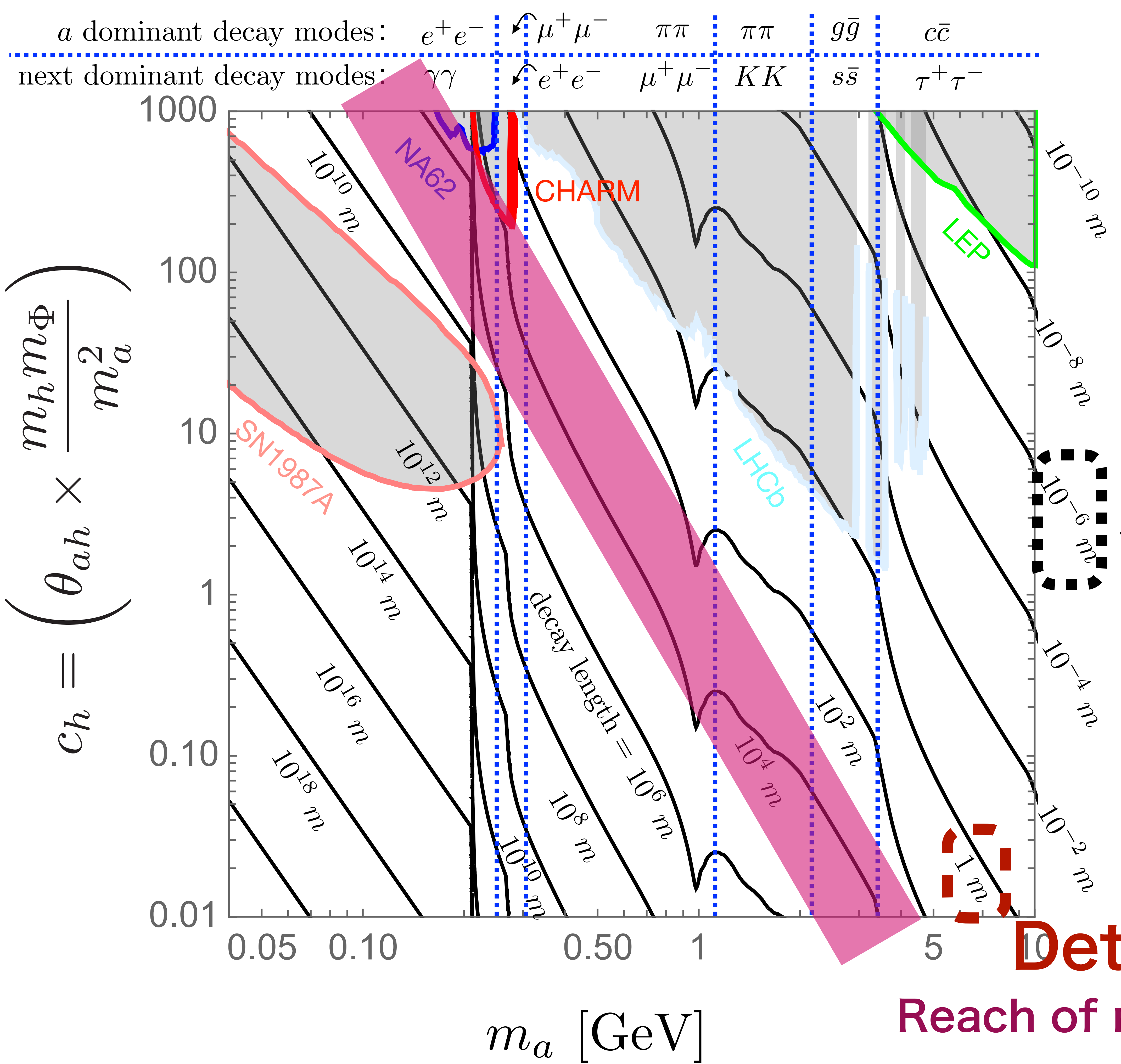

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Reach of rare displaced vertex
($Br_{h\to aa} \sim 1\,\%$, 3ab^(-1))

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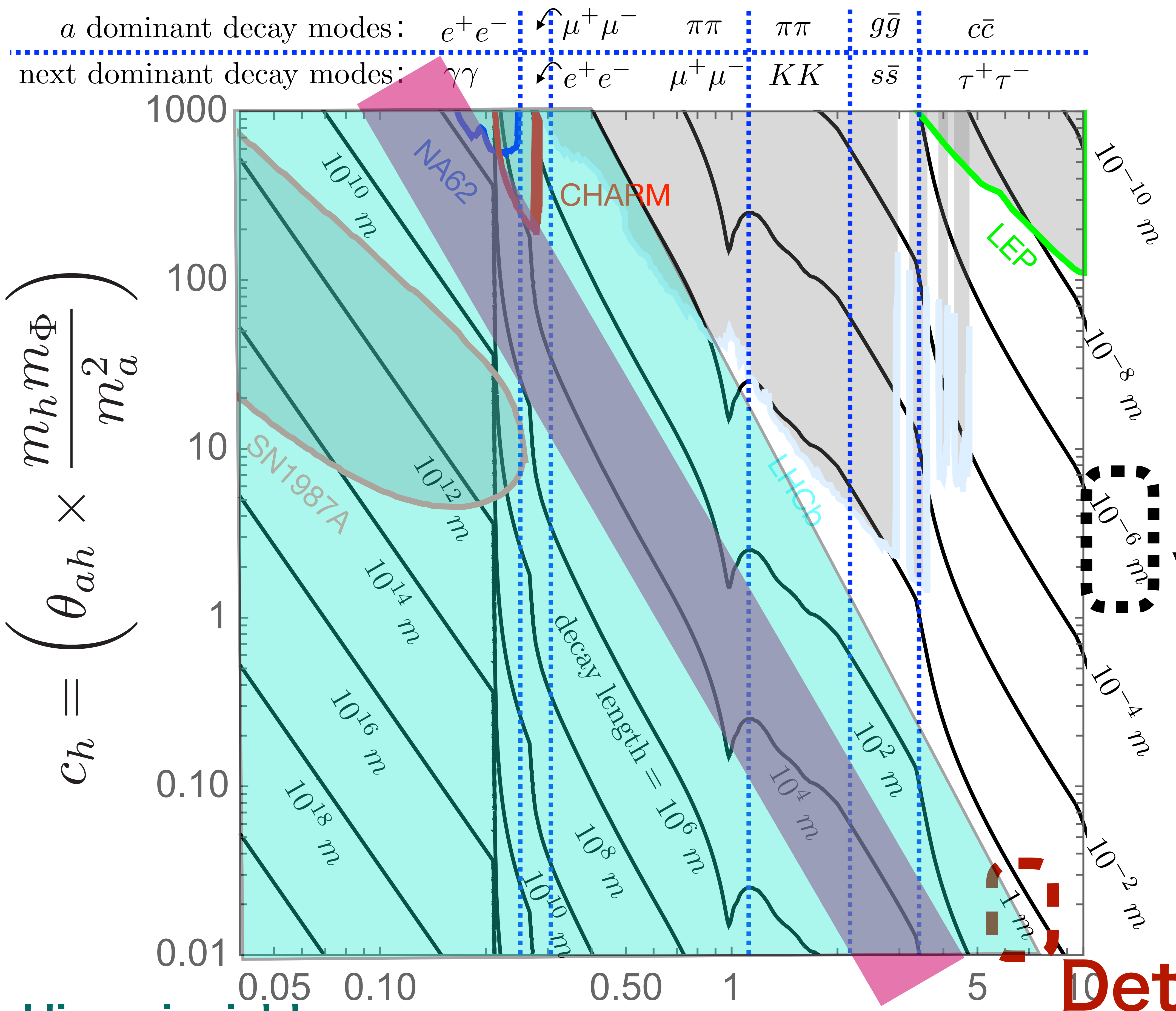

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Liu et al, 1612.09284

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See also Bhattacharjee et al 2111.02437 for hadron collider reach of CP-even light mediator

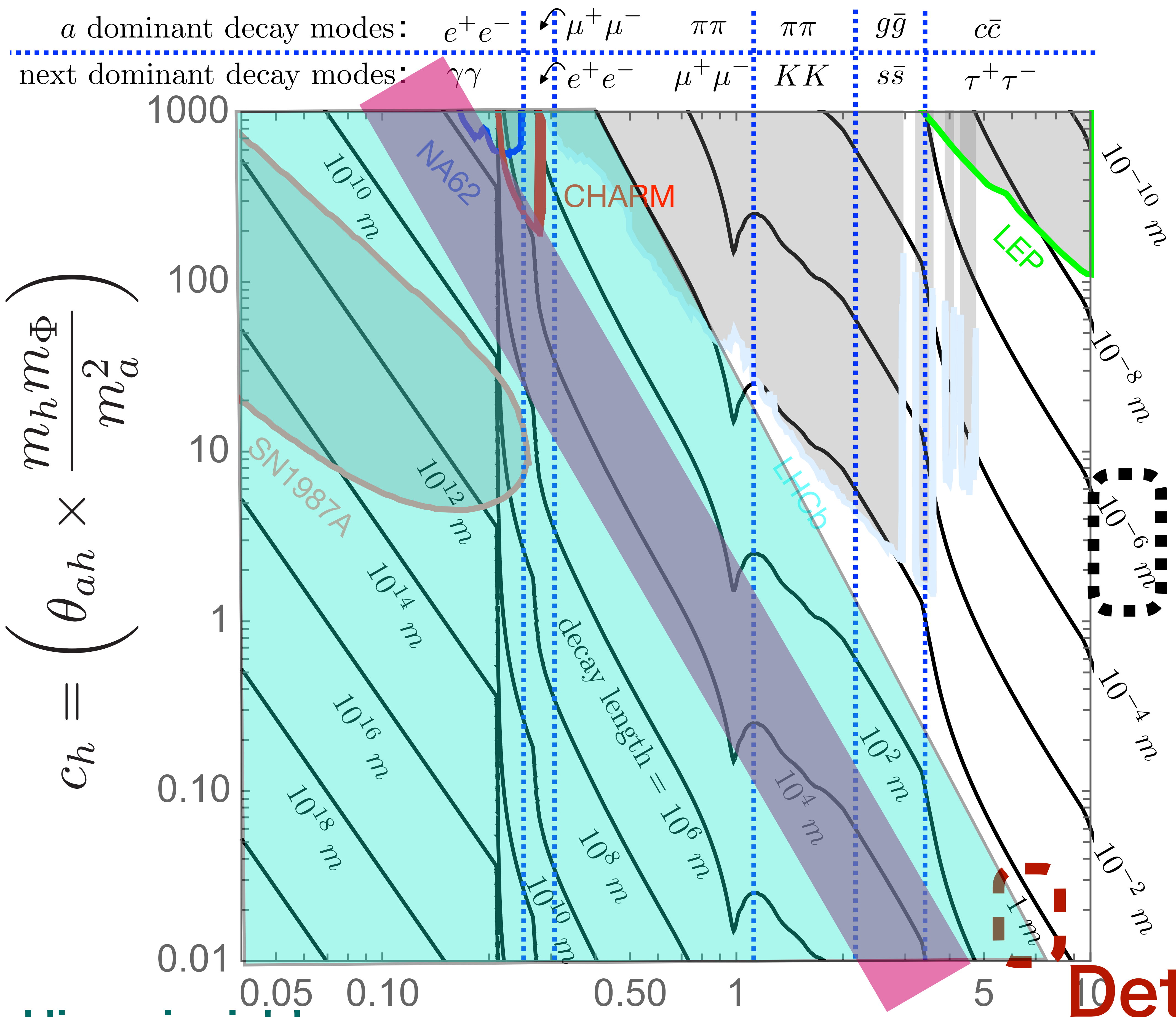
Higgs invisible decay $Br_{h\to aa} \gtrsim 0.1\,\%$ ILC whitepaper

Detector size (TPC)

Reach of rare displaced vertex ($Br_{h\to aa} \sim 1\,\%$, 3ab^(-1))

Probing CP-even ALP at e.g. ILC 250GeV

Decay length and product of a from Higgs decay and signature at ILC



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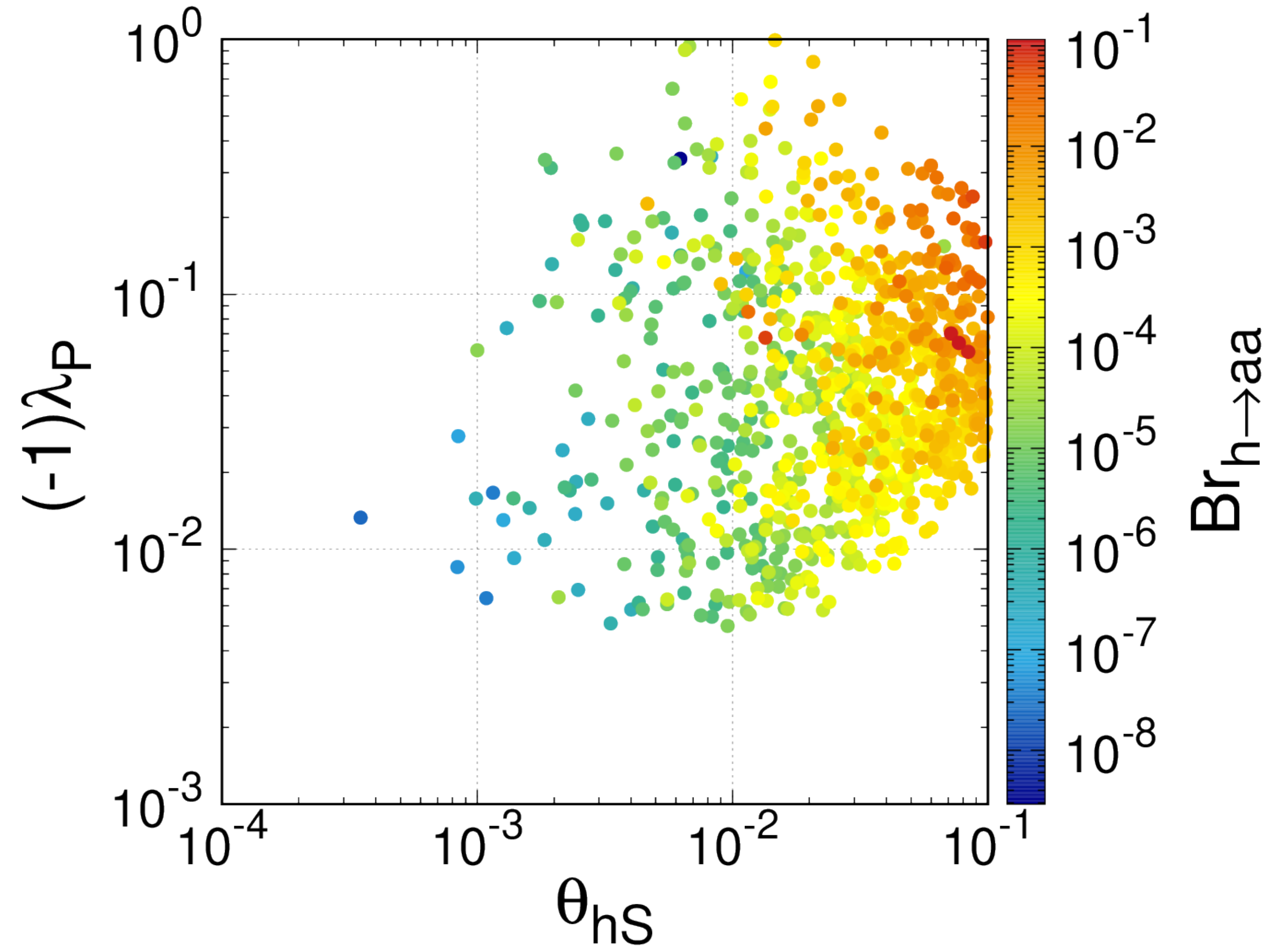

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2111.02437
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of CP-even light mediator

What roles does CP-even ALP play in the early Universe?

- Light mediator to DM with $\mathscr{L} \supset \Phi \bar{\Psi}^c_{\rm DM} \Psi_{\rm DM}$.

ALP couples SM fermion weakly but strongly with DM, which is the desired property of a light mediator.

Please study it with WIMP, which should be an interesting topic!

- **CP-even ALP DM.** This talk.

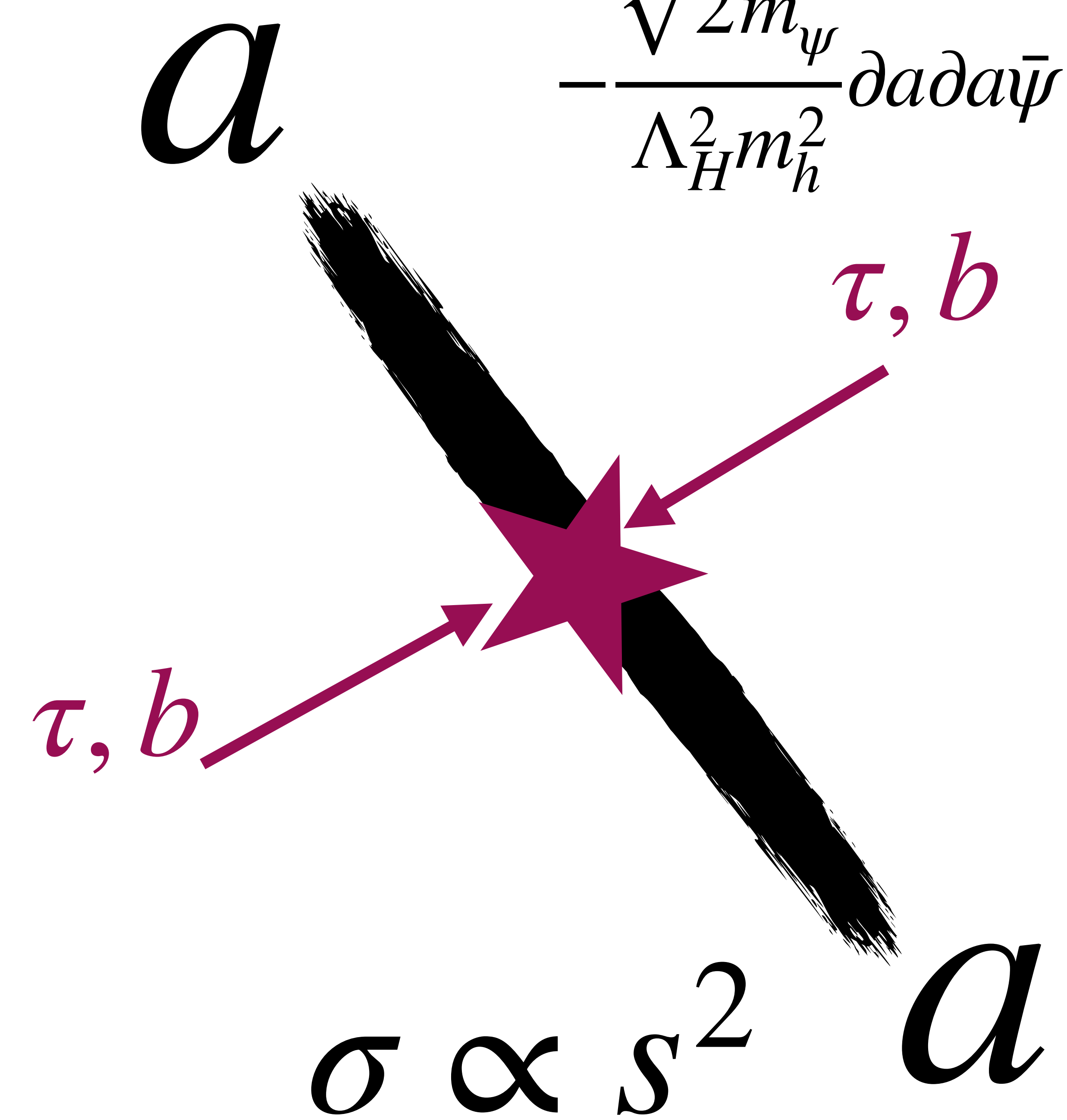
CP-even ALP is a good DM candidate if it is lighter than MeV.

$$\Gamma_{a\to\gamma\gamma} \sim 10^{-4}\frac{m_a^3\theta_{ah}^2}{\pi^5 v^2} \propto \frac{m_a^7}{m_h^4 m_\Phi^2}$$

Thermally produced CP-even ALP DM

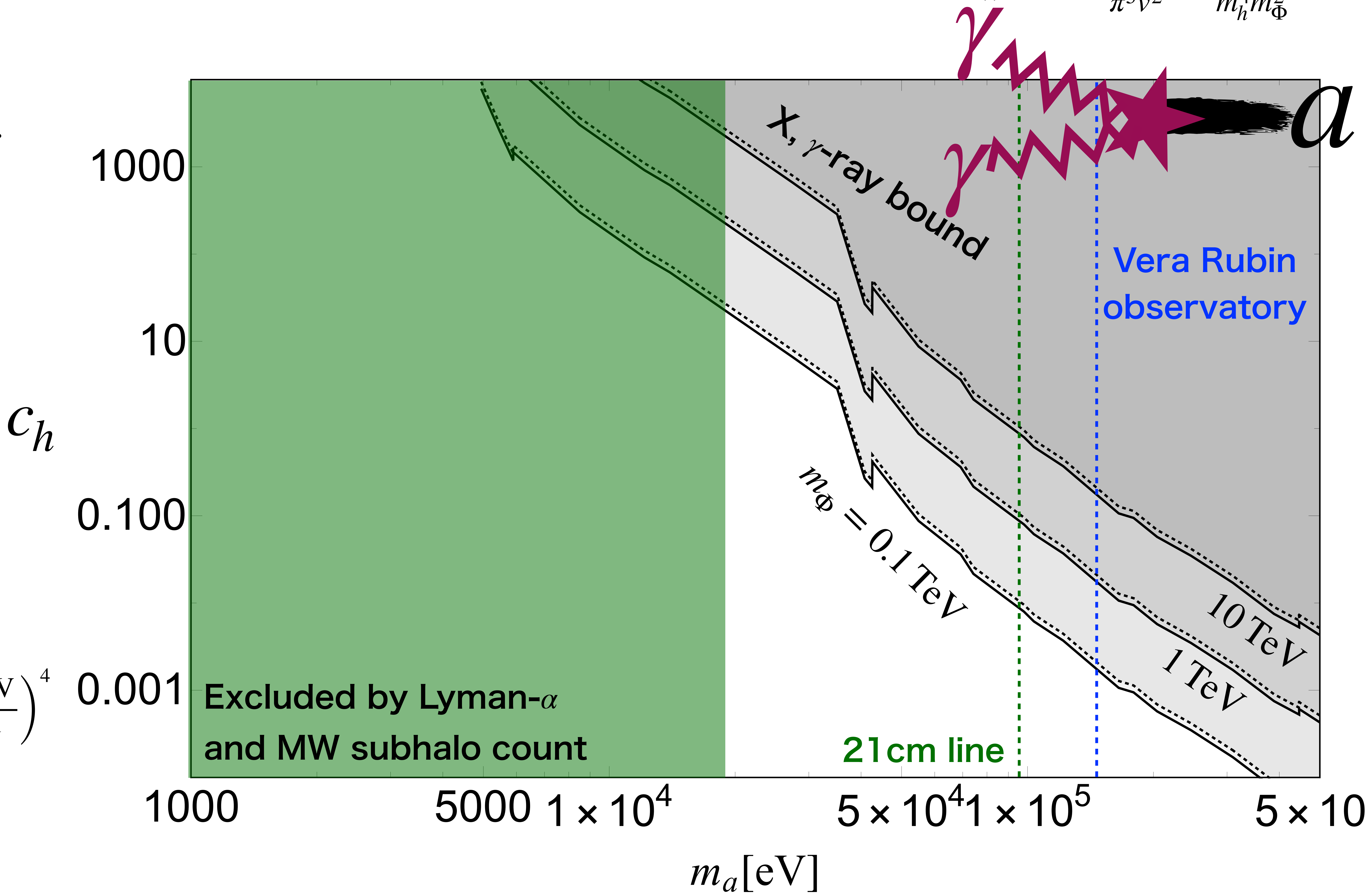
$$\Gamma_{a\to\gamma\gamma} \sim 10^{-4}\frac{m_a^3\theta_{ah}^2}{\pi^5 v^2} \propto \frac{m_a^7}{m_h^4 m_\Phi^2}$$

$$-\frac{\sqrt{2}m_\psi}{\Lambda_H^2 m_h^2}\partial a\partial a\bar{\psi}\psi.$$

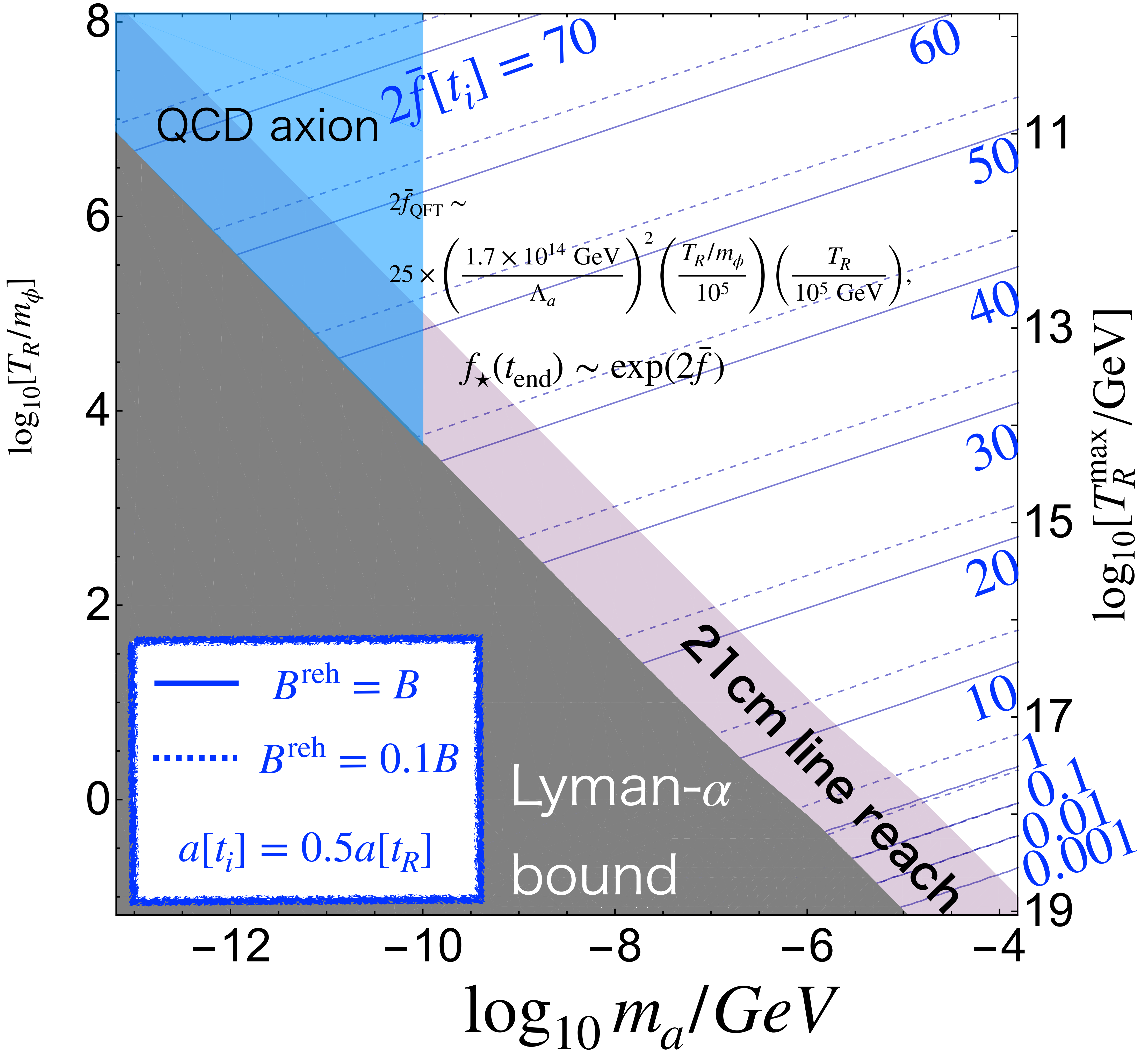


$$\sigma \propto s^2$$

$$\Omega_a \sim 0.35\frac{m_a}{20\mathrm{keV}}\left(\frac{m_\psi}{\mathrm{GeV}}\right)^2\left(\frac{T_R}{2\mathrm{GeV}}\right)^5\left(\frac{3\mathrm{TeV}}{\Lambda_H}\right)^4$$



Non-thermal production scenario: lighter mass range.



Light bosonic DM can be produced during reheating if $T_R > m_{inflaton}$ as laser.

Moroi, WY, 2011.09475, 2011.12285

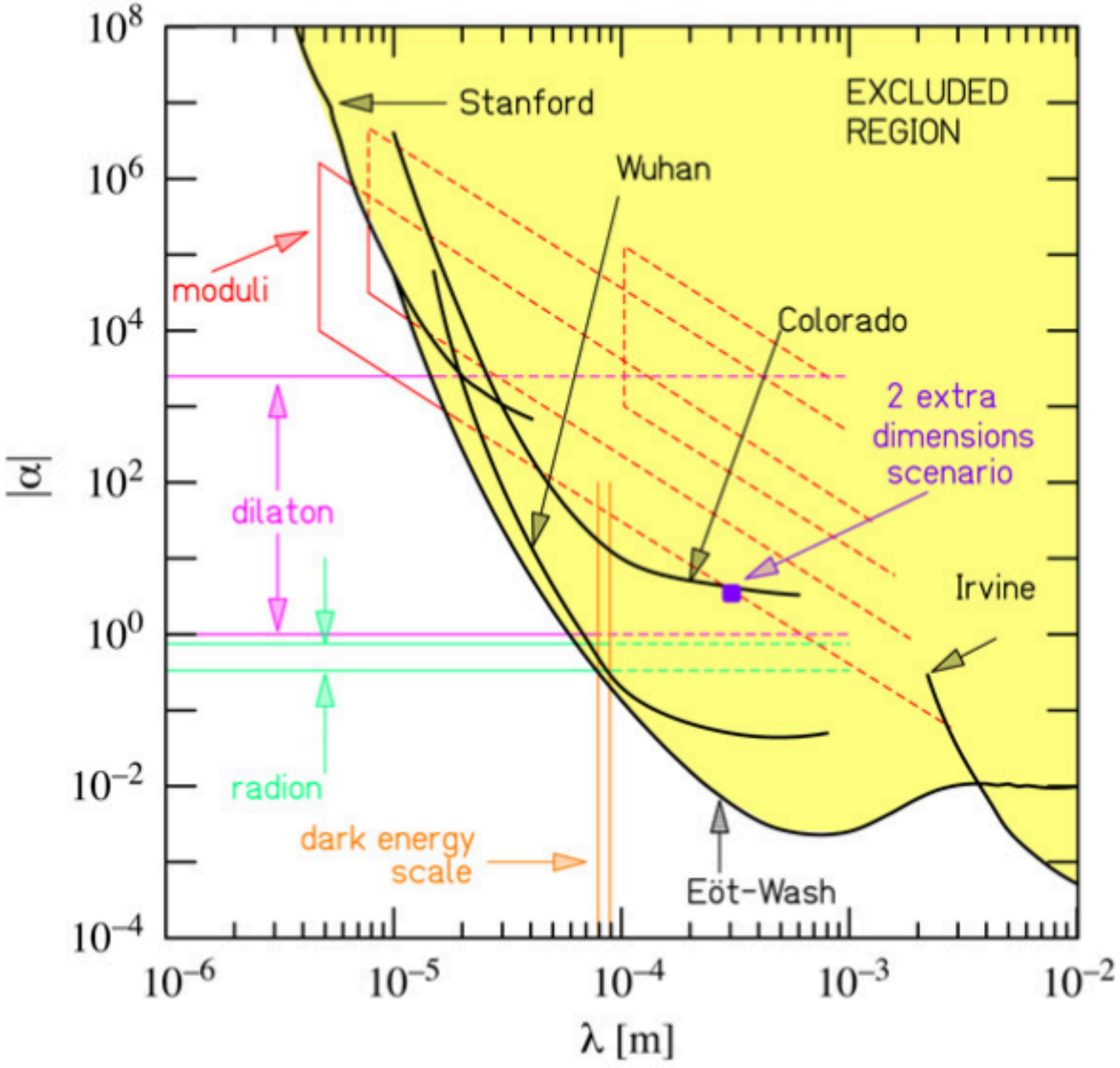
$$\mathscr{L}_{\rm int} = \frac{\phi}{\Lambda_a}\partial_\mu a \partial^\mu a + \frac{\phi}{\Lambda_G} G^{(a)}_{\mu\nu} G^{(a)\mu\nu}$$

For CP-even ALP, we need $T_R \ll m_\Phi$ for the produced ALP not to be thermalized.

Probed by inflaton search, 21cm line.

Does fifth force search kills the CP even ALP DM with $m_a < 10^{-3} eV$?

$$\alpha \sim \theta_{ah}^2 \frac{M_{\rm pl}^2}{v^2} \sim 10^{-27} (\frac{3\text{TeV}}{m_\Phi})^2 (\frac{m_a}{10^{-3}\text{eV}})^4$$



$$V = -G_N \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda})$$

$$\lambda \sim 2 \times 10^{-4} \text{m} \frac{10^{-3} eV}{m_\phi}$$

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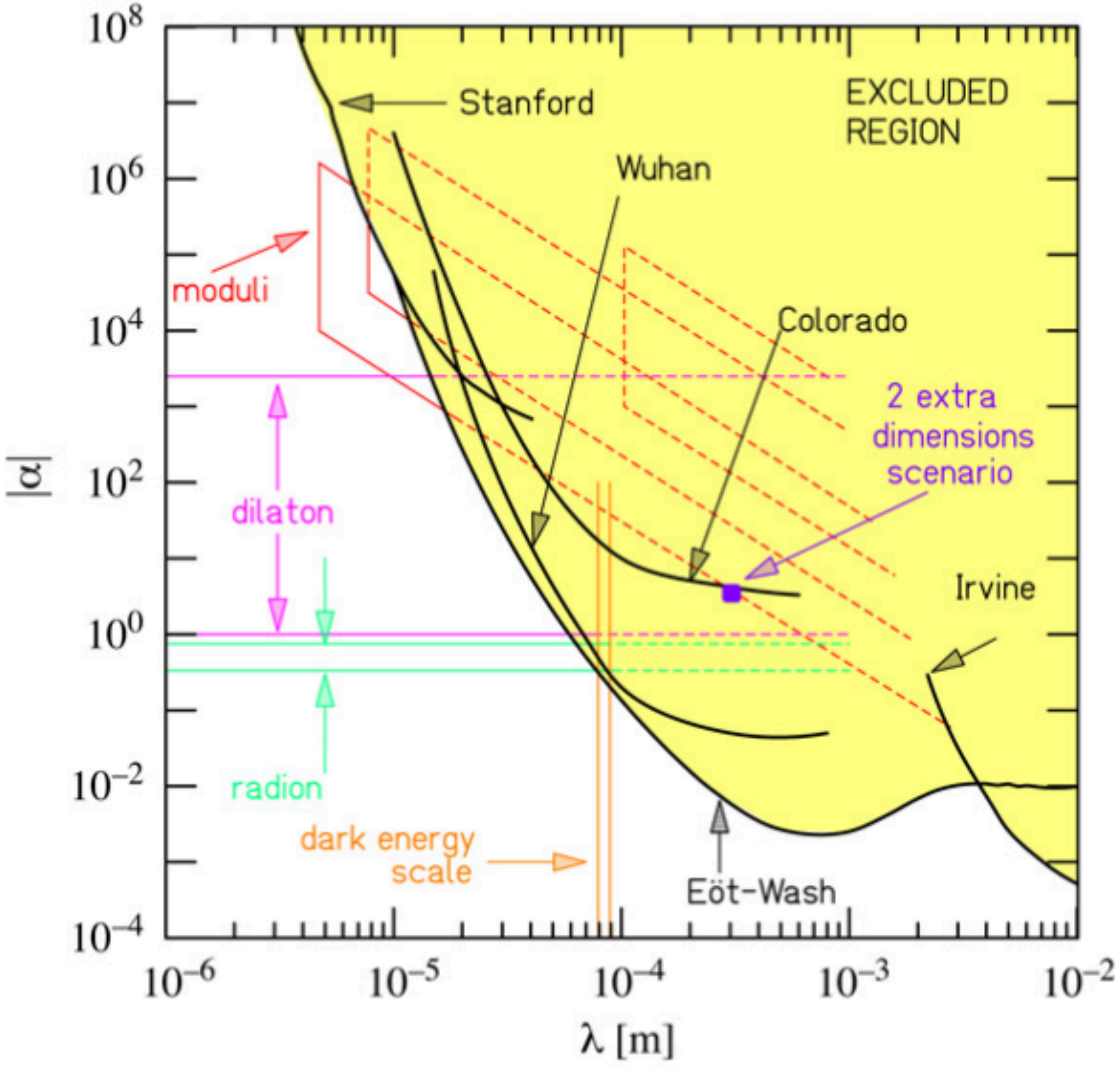
No, totally safe.

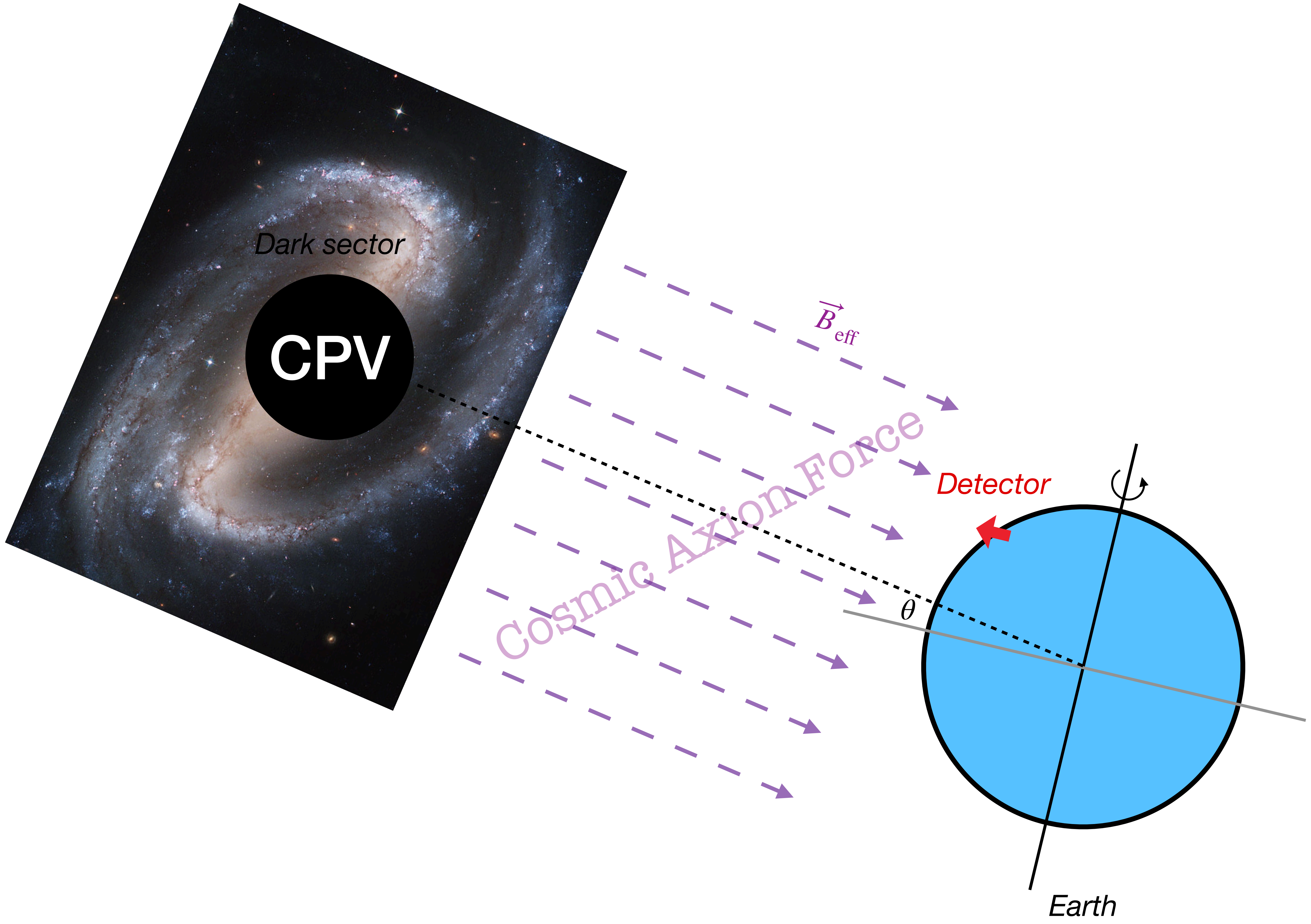


$$V = -G_N \frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$

$$\lambda \sim 2 \times 10^{-4}\mathrm{m} \frac{10^{-3}eV}{m_\phi}$$

Difficult to test it at low energy,
but it is probed by the Higgs invisible decay!

4. Cosmic axion force from ultra-light ALP



Dongok Kim, Younggeun Kim, Yannis K. Semertzidis, Yun Chang Shin, WY, Phys.Rev.D 104 (2021) 9, 095010

Motivation for ultra-light ALP

- Axiverse Witten 1984, Arvanitaki et al 0905.4720, see also Kitano, and WY 2103.08598 for a simplified QCD axion model.

  e.g. if SUSY scale is high, an M-theory compactification predicts axion coupled to photons with mass Acharya, et al 1004.5138, see also Marsh WY, 1912.08188;

$$m_\phi^2 f_\phi^2 \sim M_{\rm pl}^4 \exp(-2\pi/\alpha_{Y,2}) \sim e^{-O(1000)}{\rm GeV}^4$$

- Axionic relaxation of cosmological constant
  - Relaxing CC around today, Abbott 1985; Banks 1984, but predicts empty Universe.
  - Possibility of reheating the Universe after a bounce Graham et al 1902.06793,
  - Relaxation during inflation with a peculiar inflaton potential WY, 2108.04246

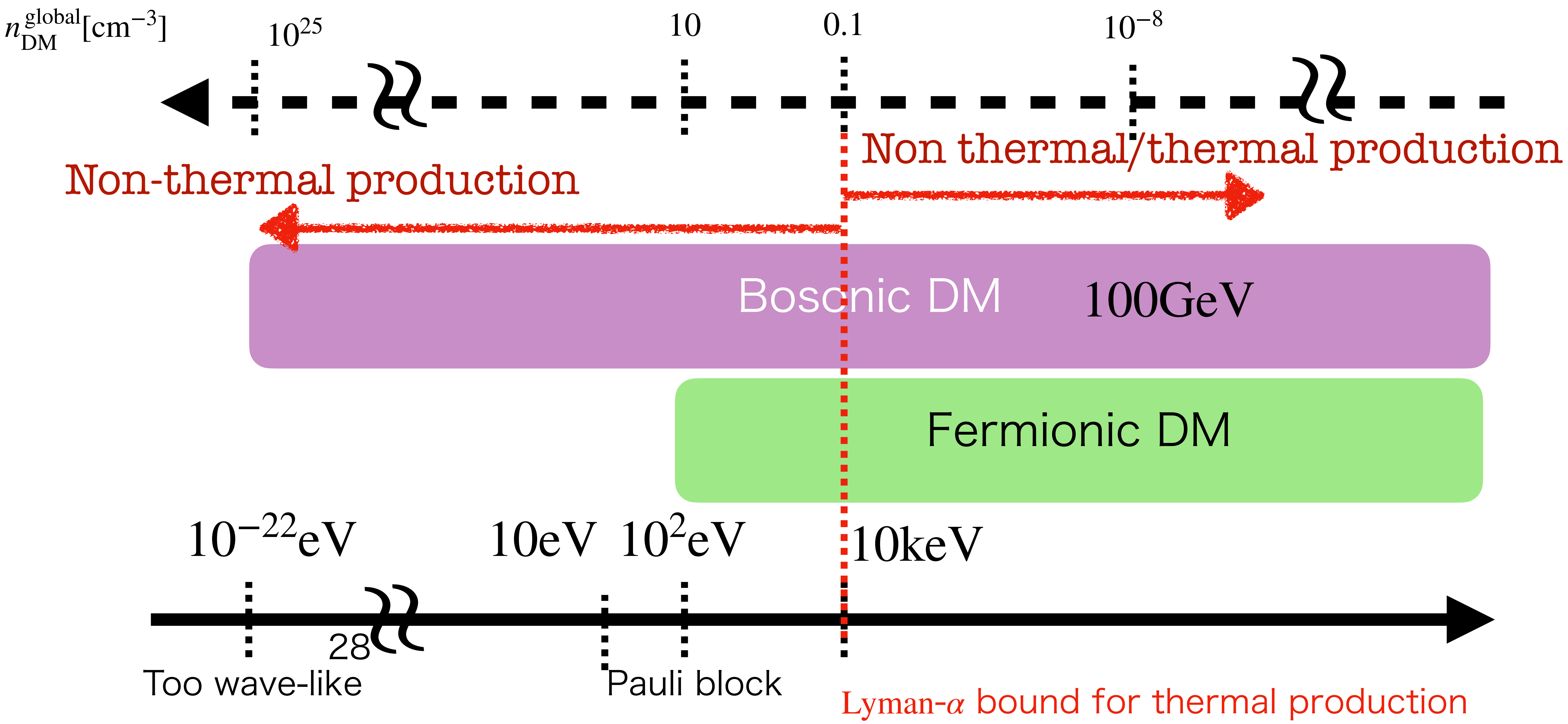
In any case

$$m_\phi \lesssim H_0 \sim 10^{-42}\,{\rm GeV}$$

- Cosmic birefringence
  - Parity violation of CMB photon propagation, Minami and Komatsu, 2011.11254; See also Clark et al, 2105.00120 for discussion on dust.
  - Time-varying ALP explanation Minami and Komatsu, 2011.11254, Fujita et al, 2011.11894, (CB and H_0 tension) etc $m_\phi \lesssim 10^{-27}{\rm eV}$
  - Spatially varying ALP explanation, ALP domain wall Takahashi, WY, 2012.11576 $m_\phi \lesssim 10^{-17}{\rm eV}$

—> Ultra-light ALP+SM+DM

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



$n_{\rm DM}^{\rm global}$[cm^{-3}]
10^{25}
10
0.1
10^{-8}

Non-thermal production

Non thermal/thermal production

Bosonic DM
100GeV

Fermionic DM

10^{-22}eV
10eV
10^2eV
10keV
28

Too wave-like

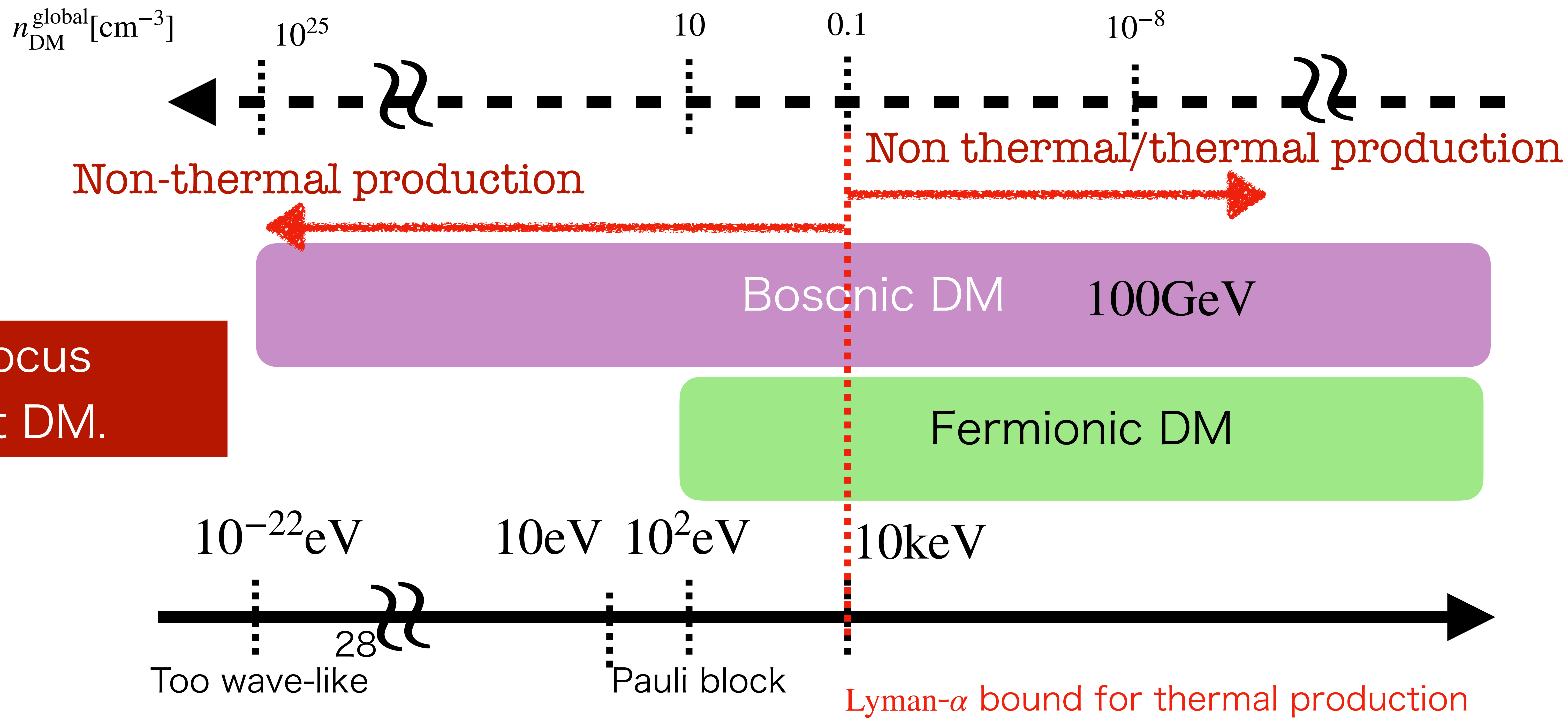
Pauli block

Lyman-α bound for thermal production

Ultra-light ALP may couple to DM.

—> Ultra-light ALP+SM+DM

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



$n_{\rm DM}^{\rm global}[{\rm cm}^{-3}]$

10^{25} 10 0.1 10^{-8}

Non thermal/thermal production

Non-thermal production

Bosonic DM 100GeV

Fermionic DM

10^{-22}eV 10eV 10^{2}eV 10keV

28

Too wave-like

Pauli block

Lyman-α bound for thermal production

Ultra-light ALP which is our focus
which cannot be the dominant DM.

Ultra-light ALP may couple to DM.

DM-ALP interaction is easily CPV.

ALP DM a + ultralight ALP ϕ

$$V = -\Lambda^4 \left(\kappa_1 \cos(n_a \frac{a}{f_a}) + \kappa_2 \cos(\frac{\phi}{f_\phi} + \frac{a}{f_a}) + \kappa_3 \cos(n_\phi \frac{\phi}{f_\phi}) \right) \tag{34}$$

with $\kappa_1 \gtrsim \kappa_2, \kappa_3, n_a > 1$ then we can integrate out a who has local minima $\langle a \rangle / f_a \approx 0, 2\pi/n_a, 4\pi/n_a \cdots (n_a - 1)2\pi/n_a$. The mass of a is

$$m_a^2 \sim \kappa_1 \frac{n_a^2 \Lambda^4}{f_a^2} \tag{35}$$

$$V_{\text{eff}} \simeq -\Lambda^4 \left(\kappa_2 \cos(\theta + \frac{\phi}{f_\phi}) + \kappa_3 \cos(n \frac{\phi}{f_\phi}) \right) \qquad \theta = \langle a/f_a \rangle$$

$$V \supset \frac{A_a}{2} \delta a^2 \delta\phi$$

$$A_a \simeq \theta \frac{\kappa_2 \kappa_3 n^2}{\kappa_2 + \kappa_3 n^2} \frac{\Lambda^4}{f_a^2 f_\phi} + \mathcal{O}(\theta^3) \equiv \epsilon_a \frac{m_a^2}{f_\phi}.$$

Dark nucleon DM+ ultralight ALP ϕ

$$\mathscr{L} \supset g^{\text{CPV}}_{\phi N' N'} \phi \bar{N}' N'$$

$$g^{\text{CPV}}_{\phi N' N'} \sim \frac{\theta_{\text{darkCP}}}{f_\phi} \frac{2 m_{u'} m_{d'}}{(m_{u'} + m_{d'})^2} \langle N' | \sigma | N' \rangle$$

$$\equiv \epsilon_{\text{CPV}} \frac{m_{N'}}{f_\phi}$$

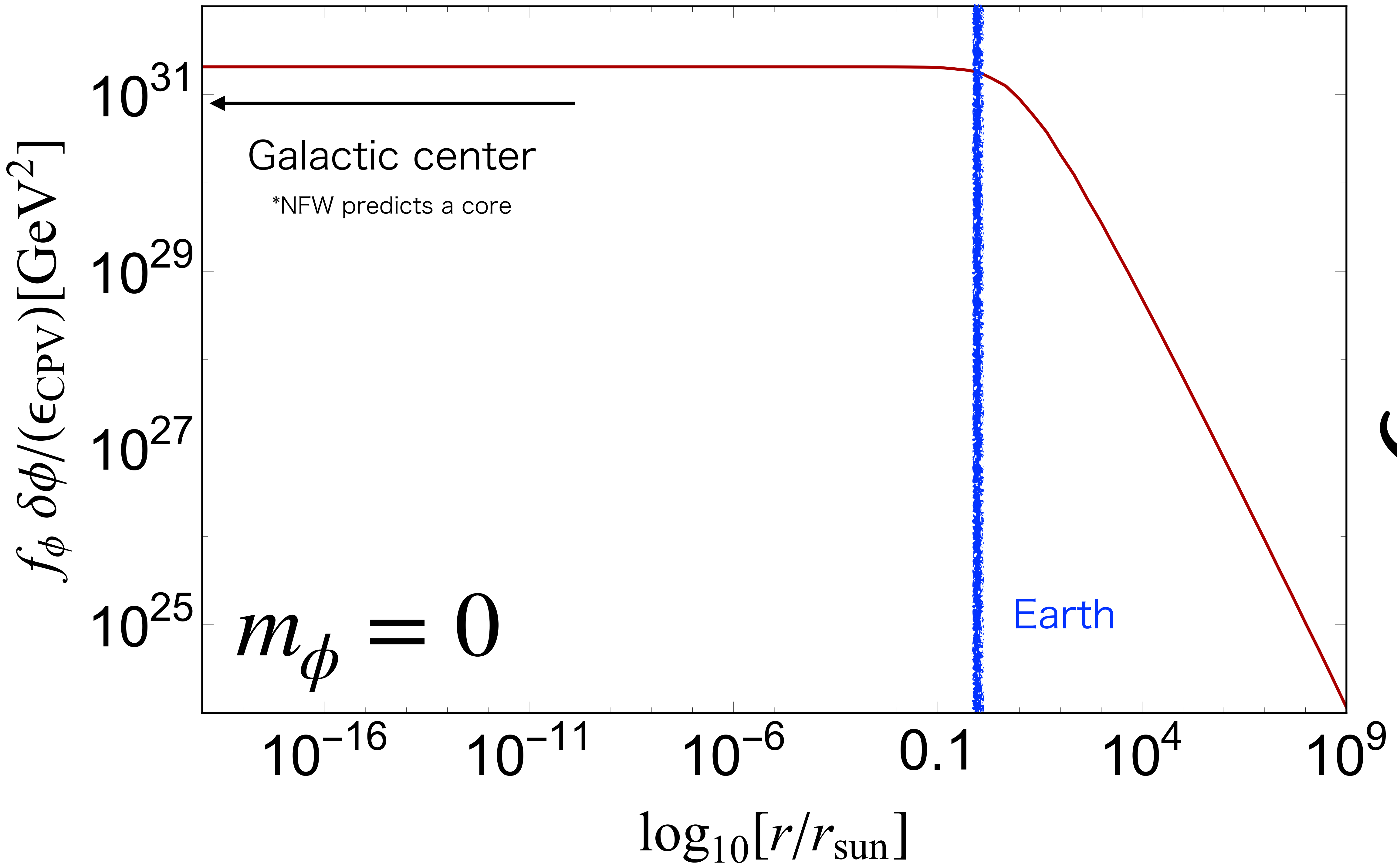
If dark QCD does not have the strong CP problem, $\theta_{\text{darkCP}} = O(1)$ and $\epsilon_{\text{CPV}} = O(1)$.

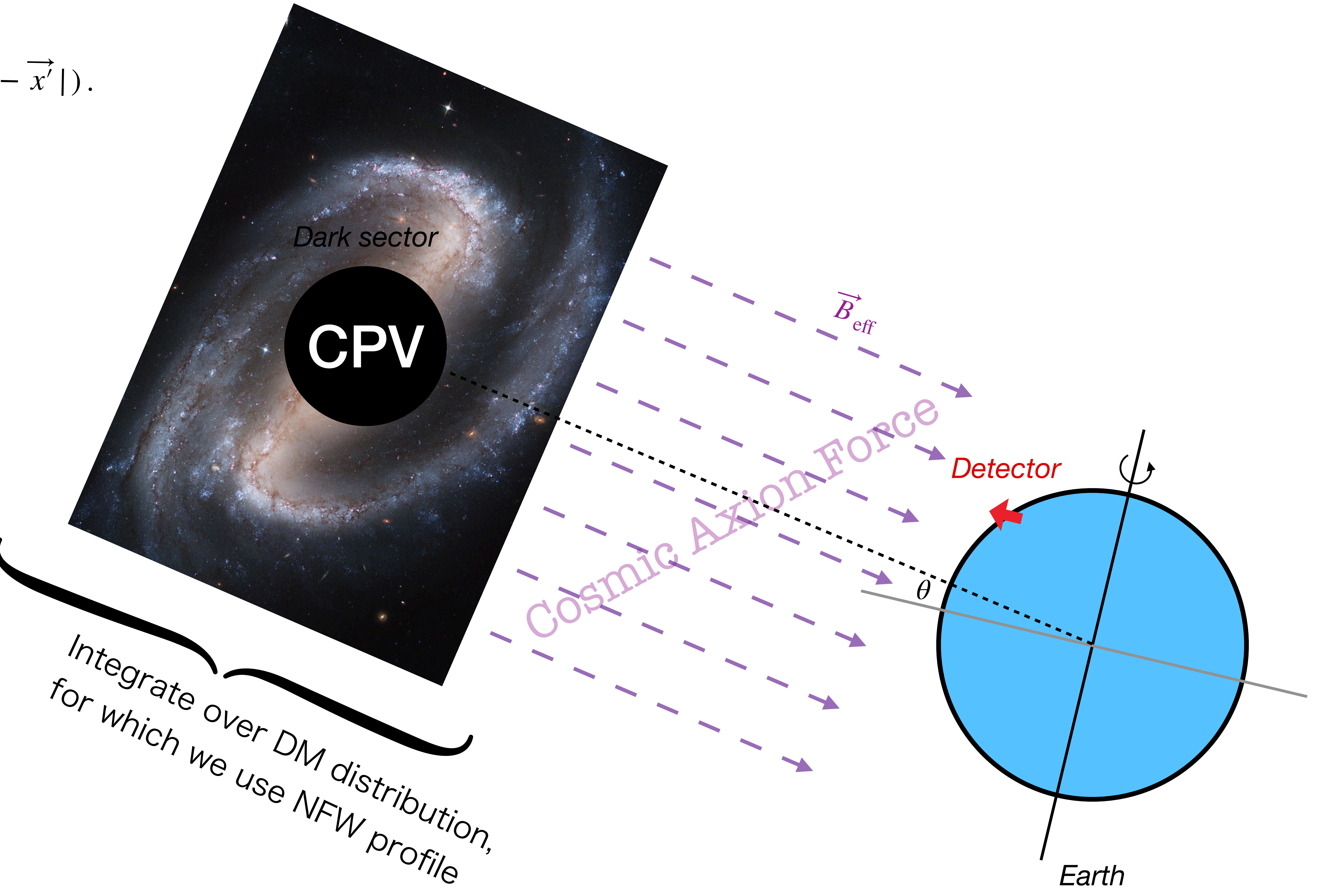
Ultra-light ALP mediates long range force from DM!

Cosmic axion force from DM

From $$(\partial_t^2 - \nabla^2)\delta\phi(t,\vec{x}) = -m_\phi^2\delta\phi(t,\vec{x}) - J(t,\vec{x}),$$

$$\delta\phi^{\rm ps} \sim \epsilon_{\rm CPV}\frac{m_{\rm DM}}{4\pi f_\phi r}\exp(-m_\phi r) \qquad \delta\phi(t,\vec{x}) \approx \int d^3\vec{x}' n_{\rm DM}(x')\delta\phi^{\rm ps}(t,|\vec{x}-\vec{x}'|).$$

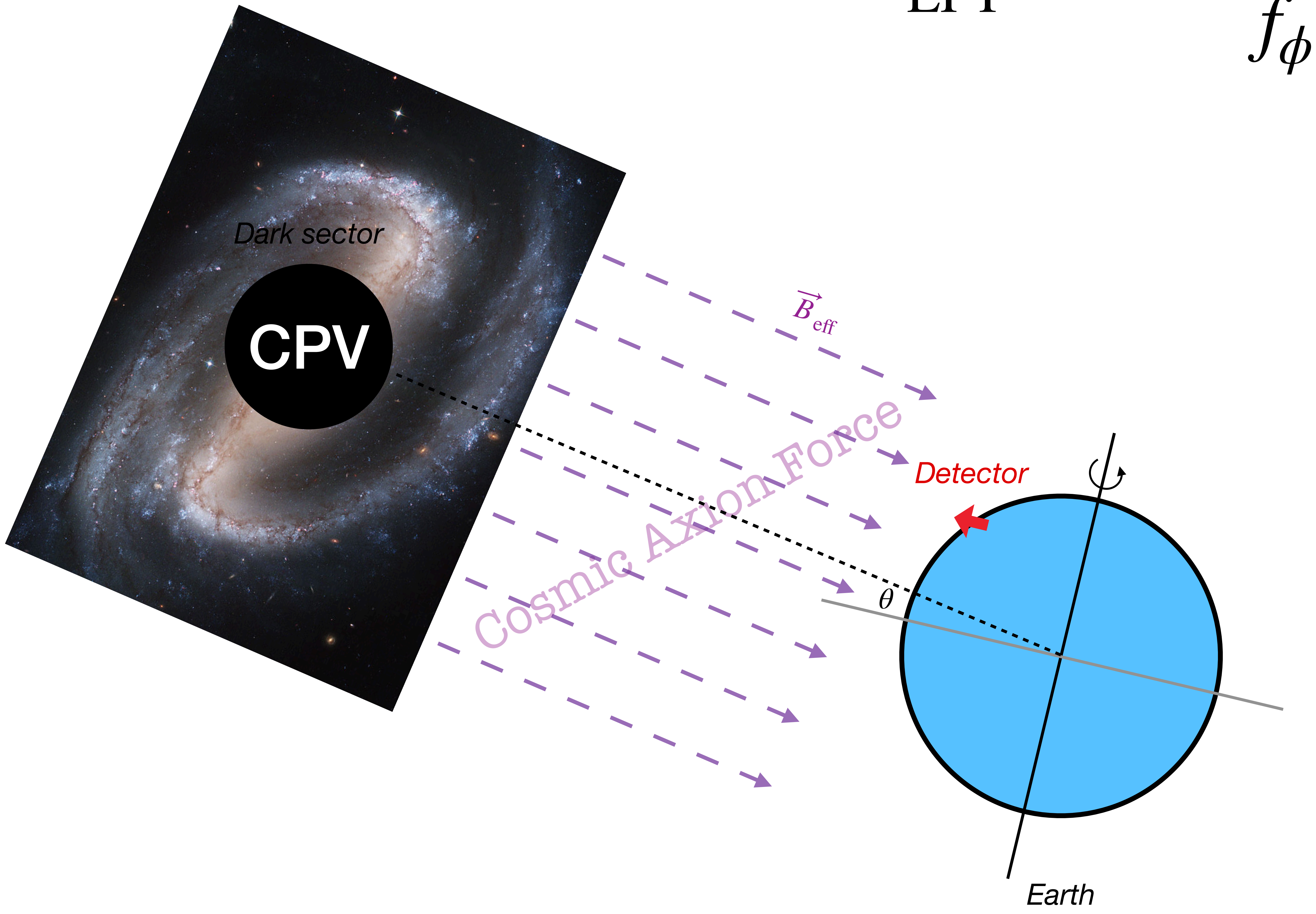




Integrate over DM distribution, for which we use NFW profile

Spin precession towards galactic center everywhere on Earth!

$$H_{\rm EFT}^{\rm nonrela} \simeq -\frac{c_N}{f_\phi}\overrightarrow{\partial}\phi \cdot \bar{N}\overrightarrow{\sigma}N\,.$$



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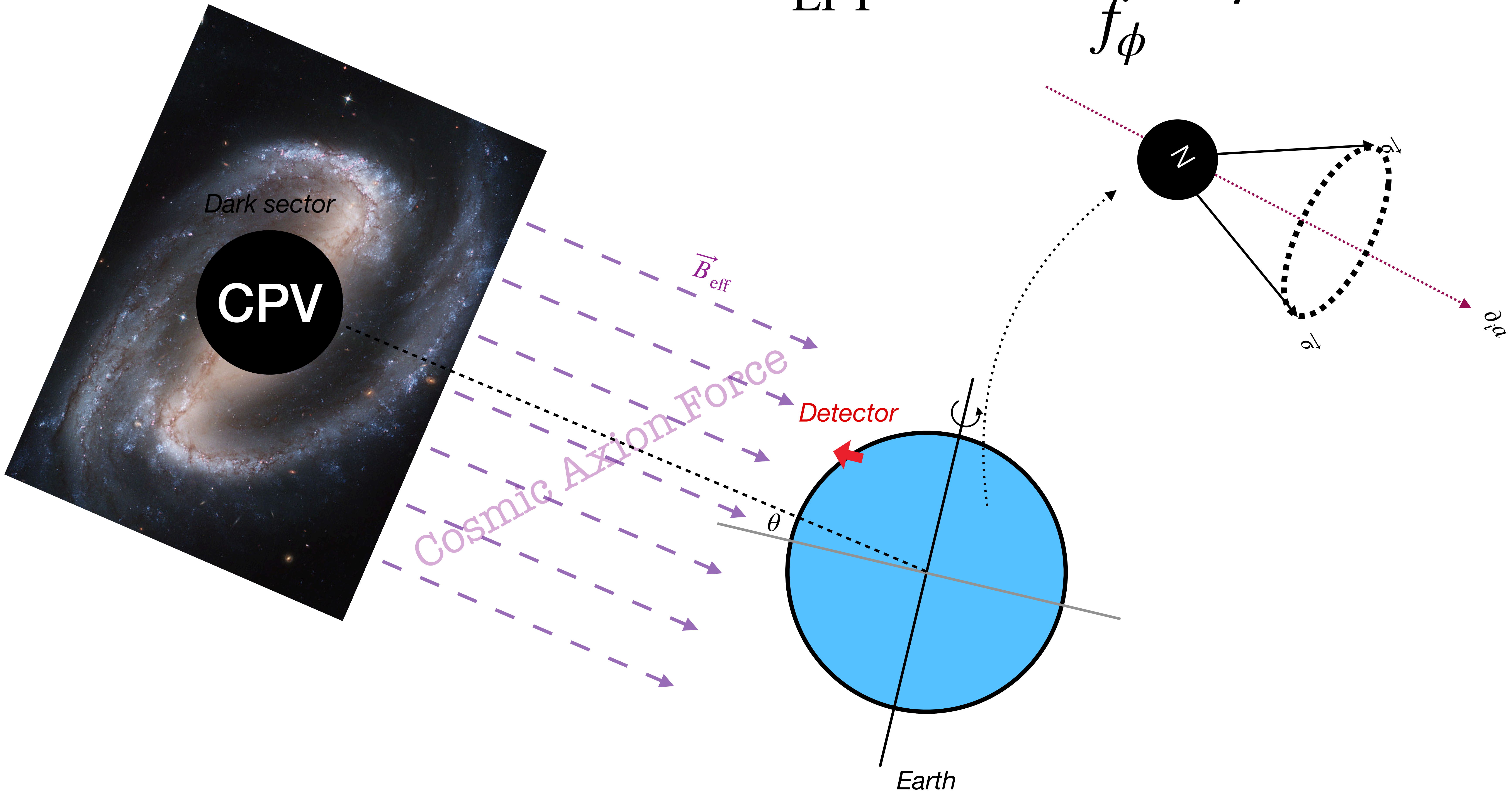

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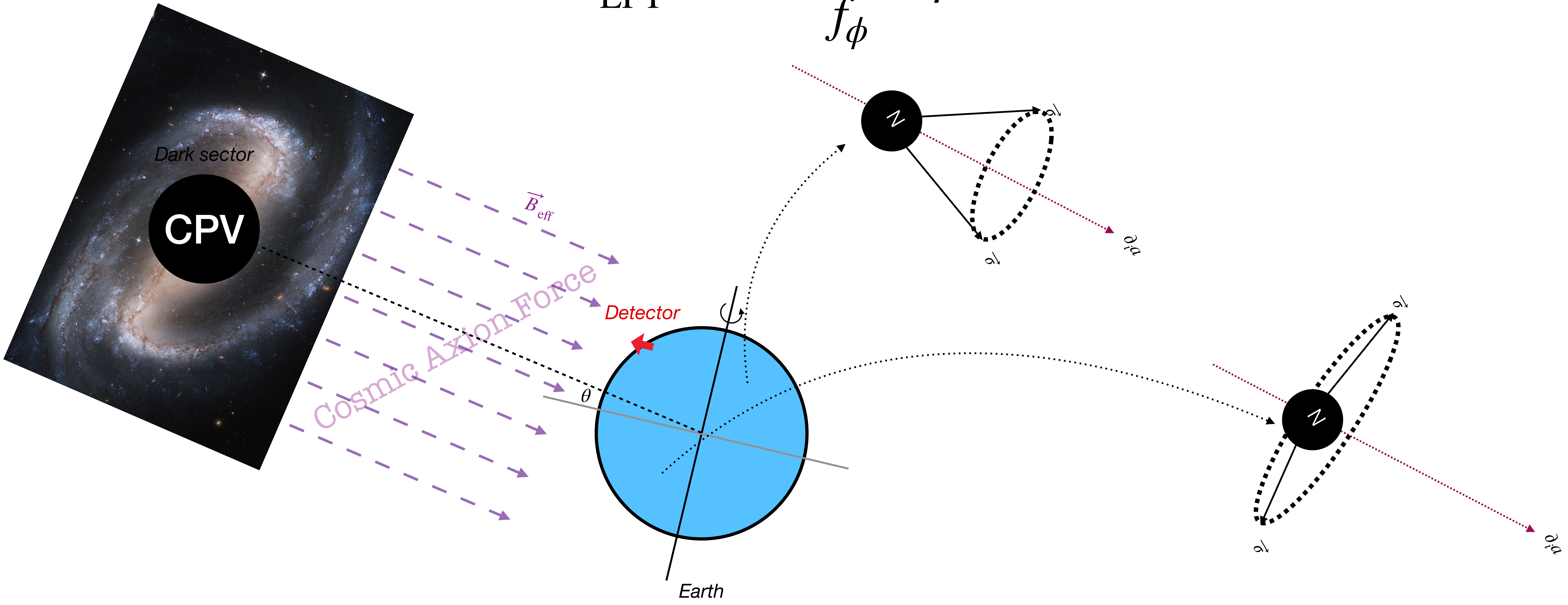

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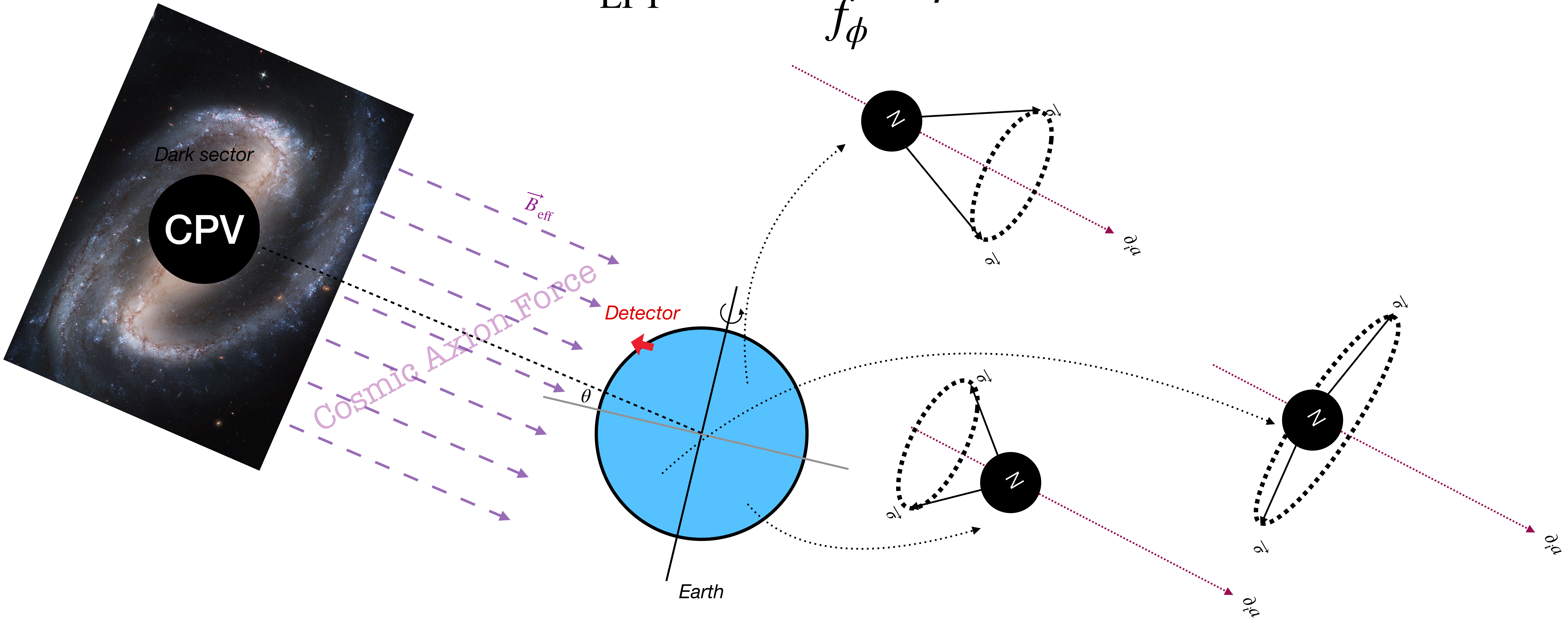
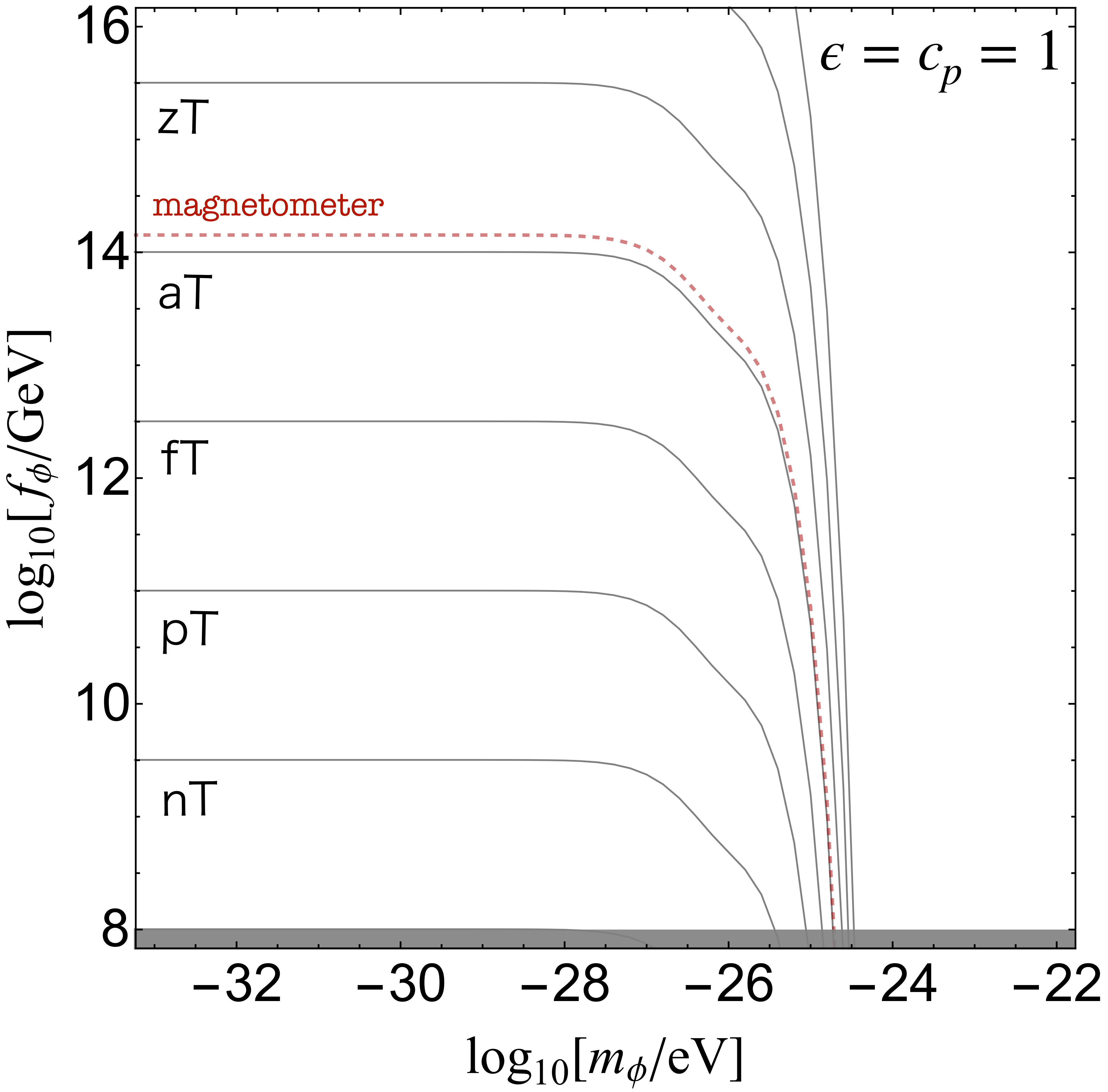
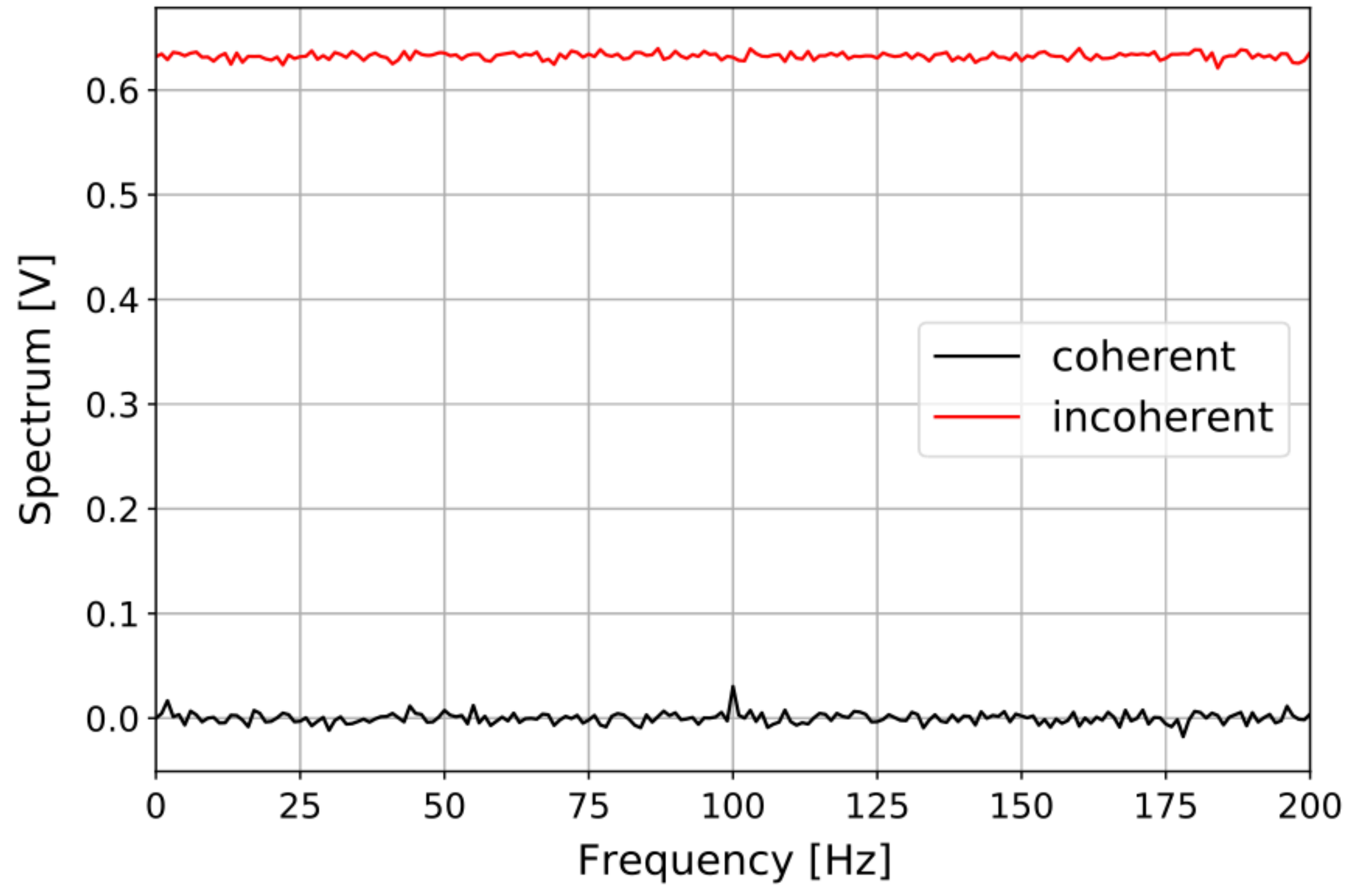


Sensitivity reach from magnetometer



- Detector has directional sensitivity
  -> galactic center.
- A calibration erases a constant effective magnetic field.
  -> Daily modulation
- Known periodicity
  -> Coherent averaging
  is efficient.

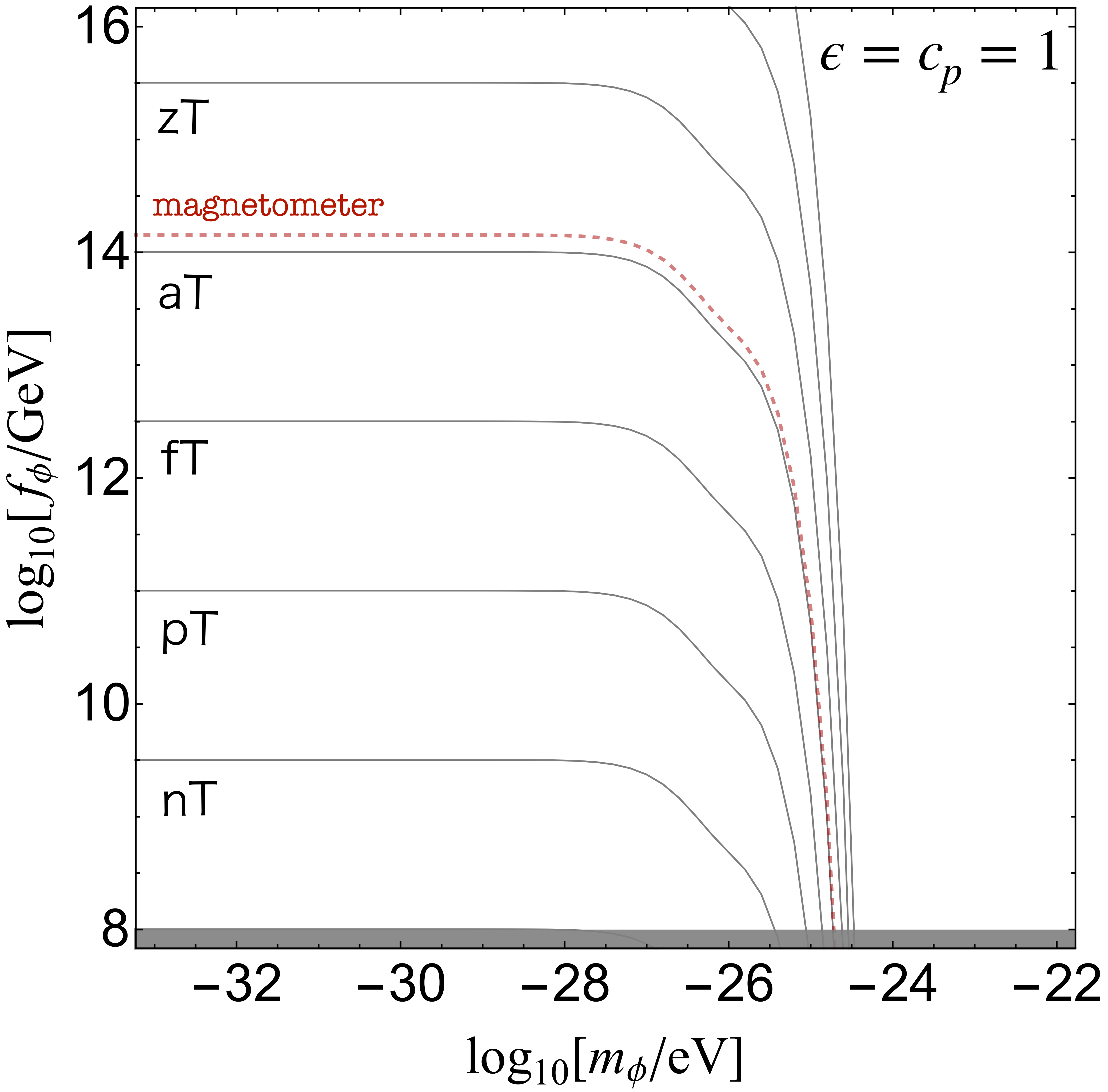


Case of nucleon-electron co-magnetometer with coherent averaging.

$$B_{\mathrm{sig}} \approx 0.67\,\mathrm{aT}\left[\frac{\mathrm{SNR}}{5}\right]\left[\frac{300}{N}\right]^{0.5}\left[\frac{\delta B_n}{1\,\mathrm{fT}/\sqrt{\mathrm{Hz}}}\right]\left[\frac{b}{20\,\mu\mathrm{Hz}}\right]^{0.5}\frac{1}{\sqrt{2}}\,.$$

We can probe ultra-light axion with decay constant close to the string scale!

Sensitivity reach from magnetometer



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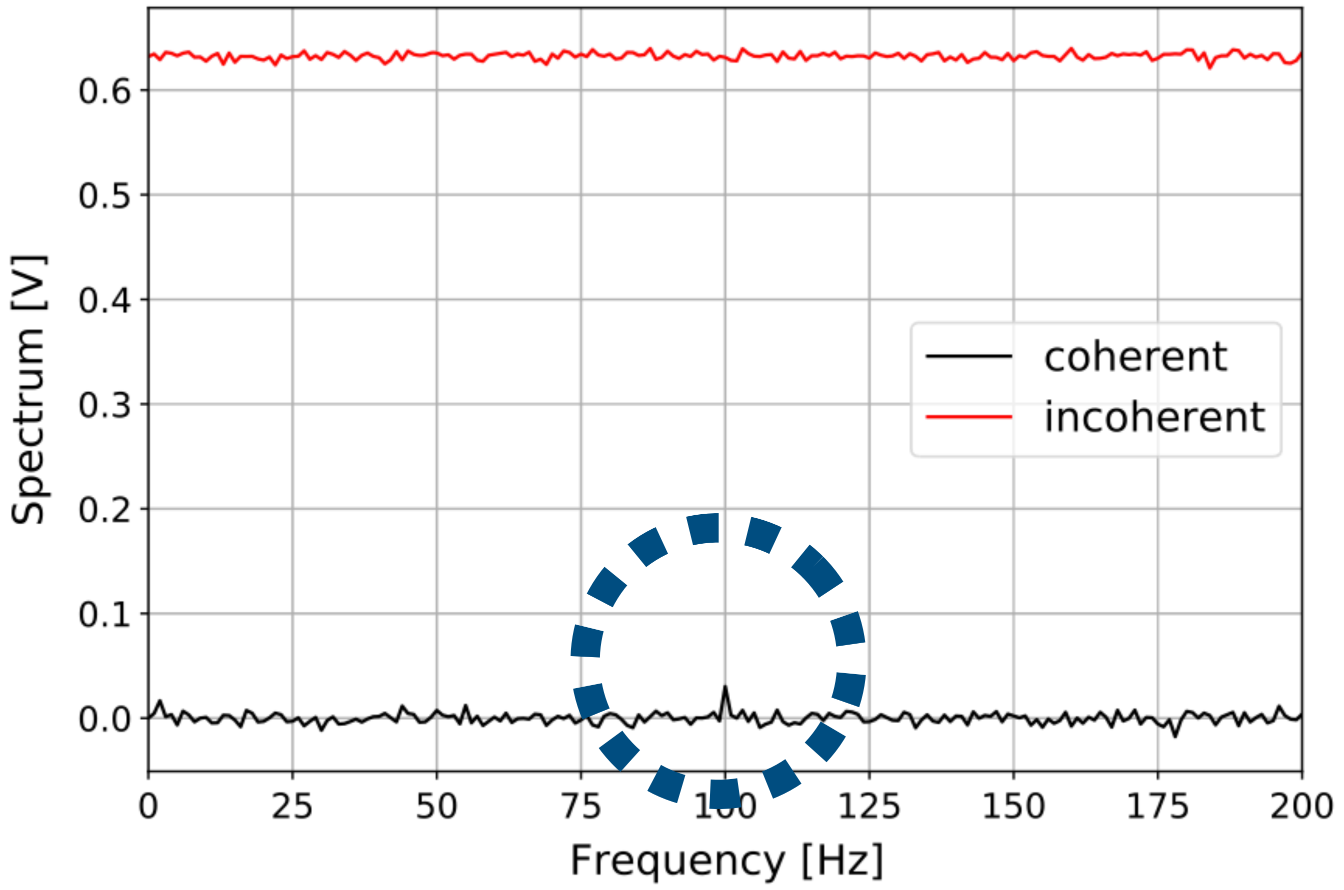

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Conclusions

Light ALPs are motivated and not excluded by 5th force because the miraculous and accidental CP-conserving nature in the SM. On the other hand, if we do not impose the miracle in the dark sector,

Kodai Sakurai, WY 2111.03653

- A simple, or perhaps the simplest, ALP model predicts **CP-even ALP**.
- It may be probed via displaced vertex followed by Higgs boson decay.
- It is a good DM candidate if $m_a < MeV$.

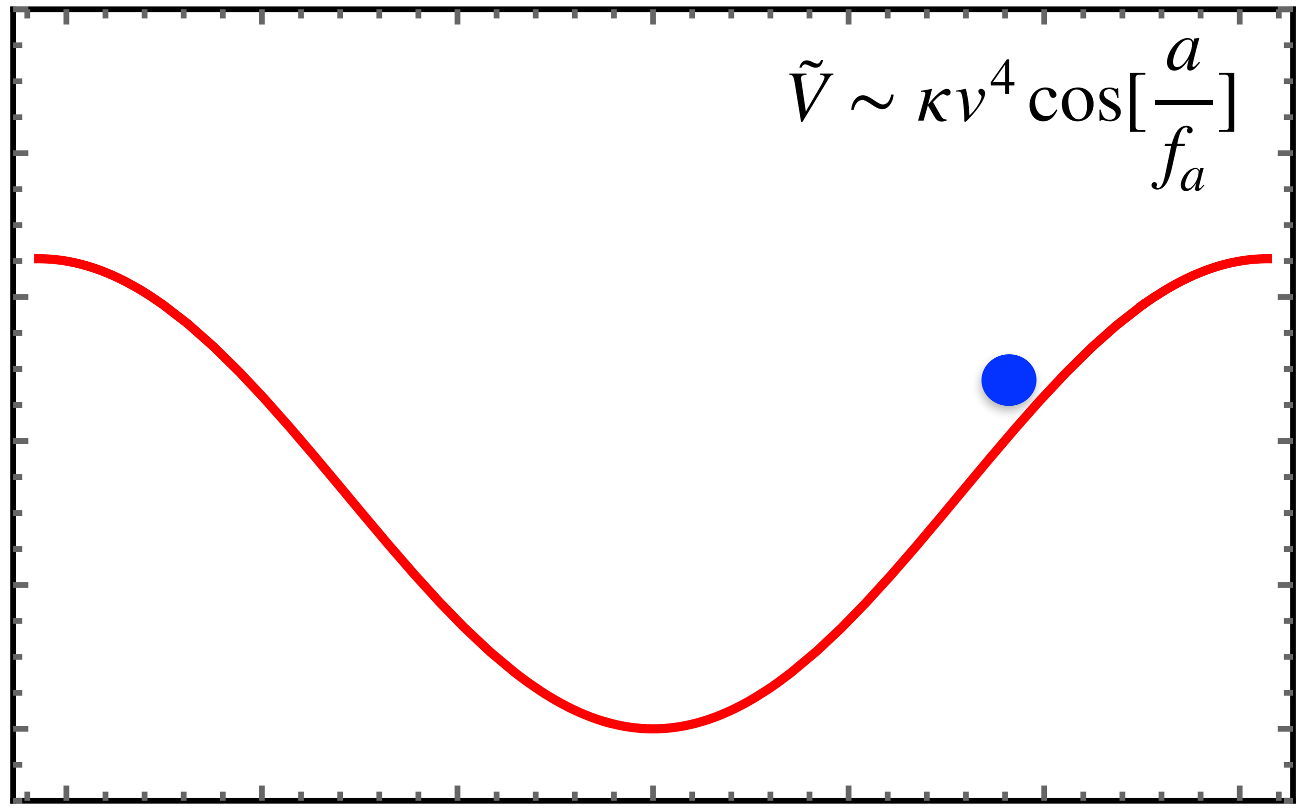
Dongok Kim, Younggeun Kim, Yannis K. Semertzidis, Yun Chang Shin, WY, Phys.Rev.D 104 (2021) 9, 095010

- Very light ALP coupled to DM with CPV induces a **cosmic axion force** towards galactic center.
- A decay constant around string scale can be probed via the spin precession of SM fermion.

Backup

Axion DM production in early Universe

Misalignment mechanism



Preskill et al, 1983;
Abbott, Sikivie, 1983;
Dine, Fishler, 1983;

Energy density of coherent oscillation contributes to DM.

*Misalignment mechanism with low-scale inflation

Graham, Scherlis, 1805.07362;
Takahashi, WY, and Guth 1805.08763 etc

⋮

Others (with interactions)

*Inflaton decay to axion particles

Moroi WY, 2011.09475;

*Broad parametric resonance

Mazumdar, Qutub, 1508.04136;Co et al, 1711.10486

*U(1) phase transition

Nakayama, WY, 2105.14549 (See also Harigaya, Leedom 1910.04163)

⋮

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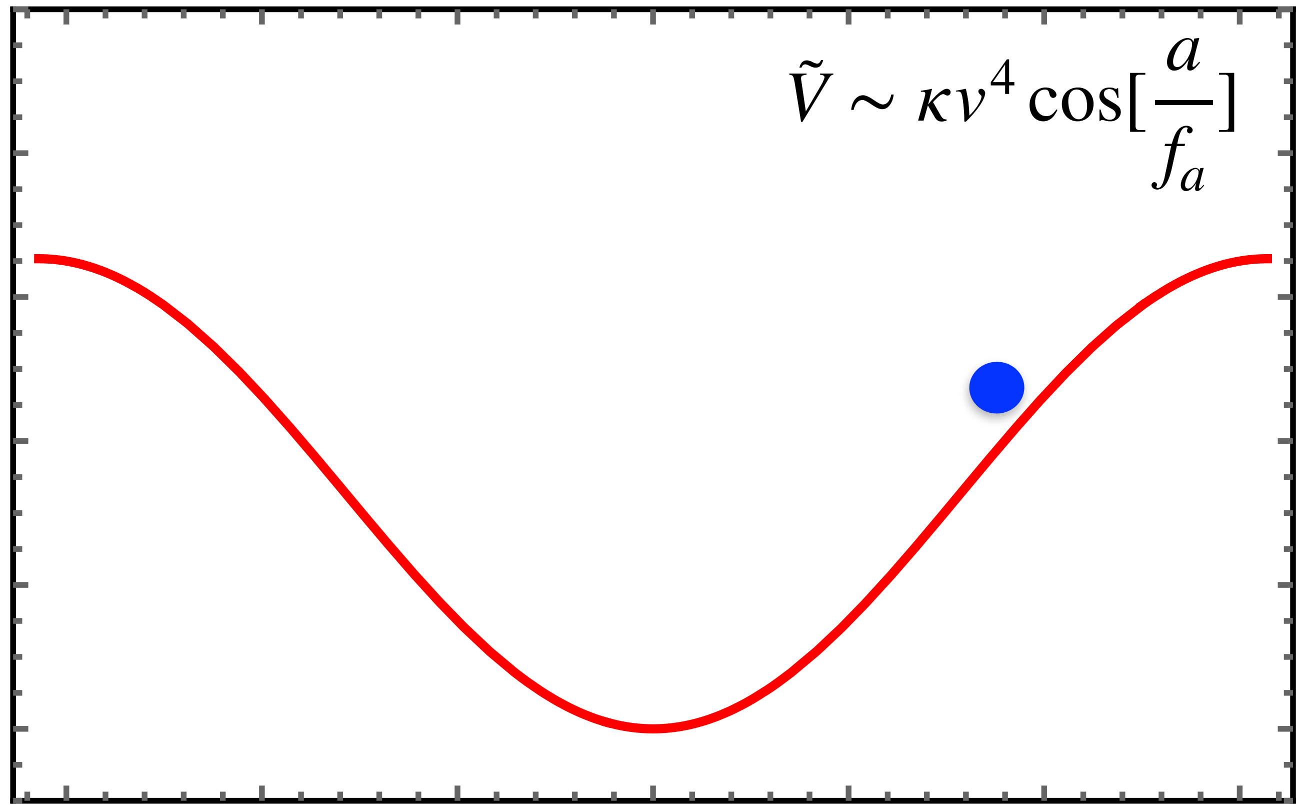

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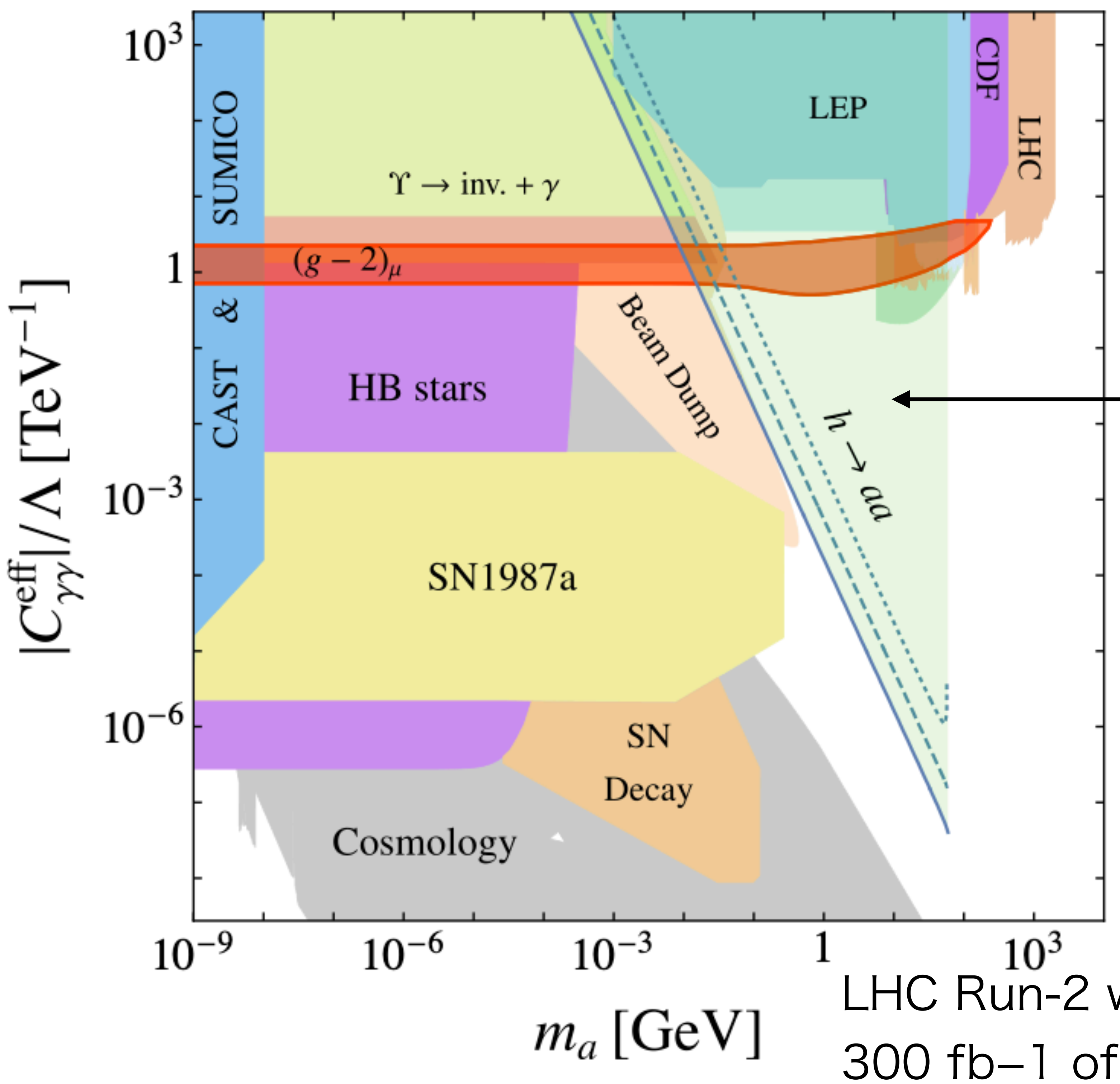
⋮

LHC (future-)search which reaches smaller couplings. This is the case if the event can be identified.

ALP	Hidden photon mixed with photon

Bauer, Neubert and Thamm, 1708.00443

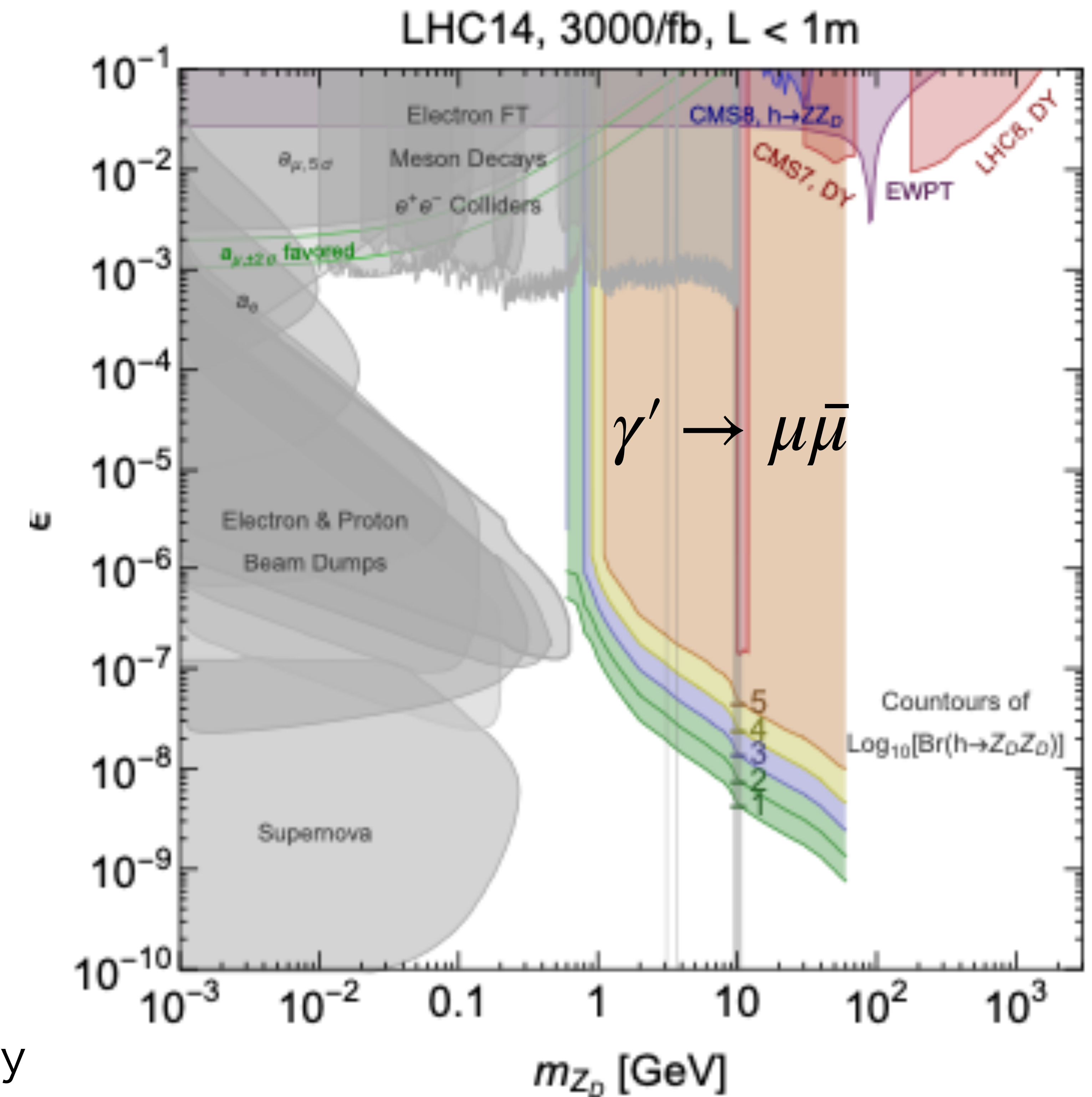


>100event

$\Lambda_H \sim (1-10) TeV$

LHC Run-2 with
300 fb−1 of integrated luminosity

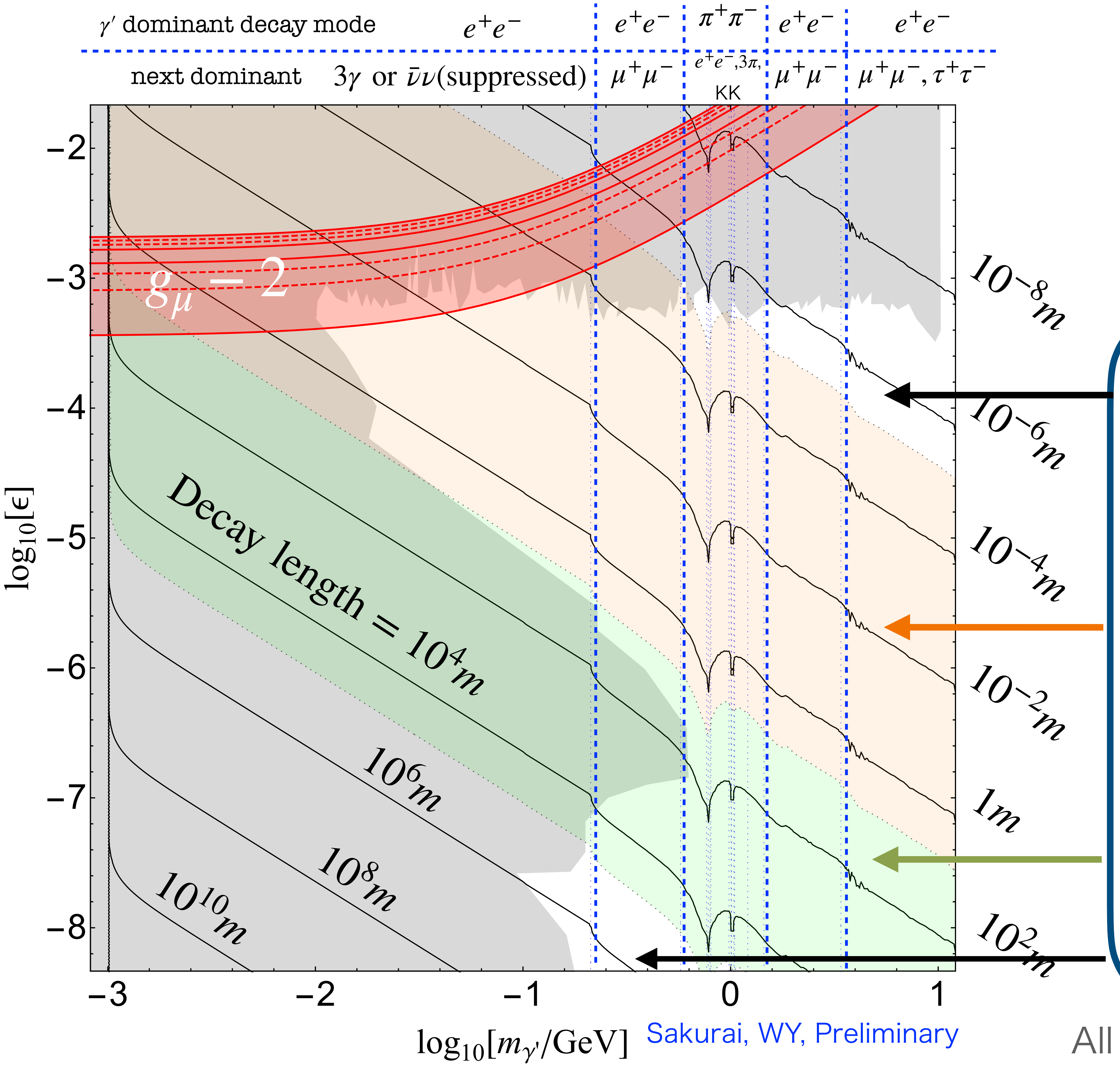
Curtin et al, 1412.0018



*di-electron reconstruction at low $m_{\gamma'}$ is challenging.

MeV range is open.

Case of **hidden photon** at ILC 250GeV $h \to \gamma'\gamma', \gamma' \to \mathrm{SMs}$



Sakurai, WY, Preliminary

Higgs decay events

Exotic decay

Displaced vertex＊2

Invisible decay and missing+displaced vertex

Invisible decay (Case of DM)

All testable? $m_{\gamma'}$ reconstruction can discriminates models?

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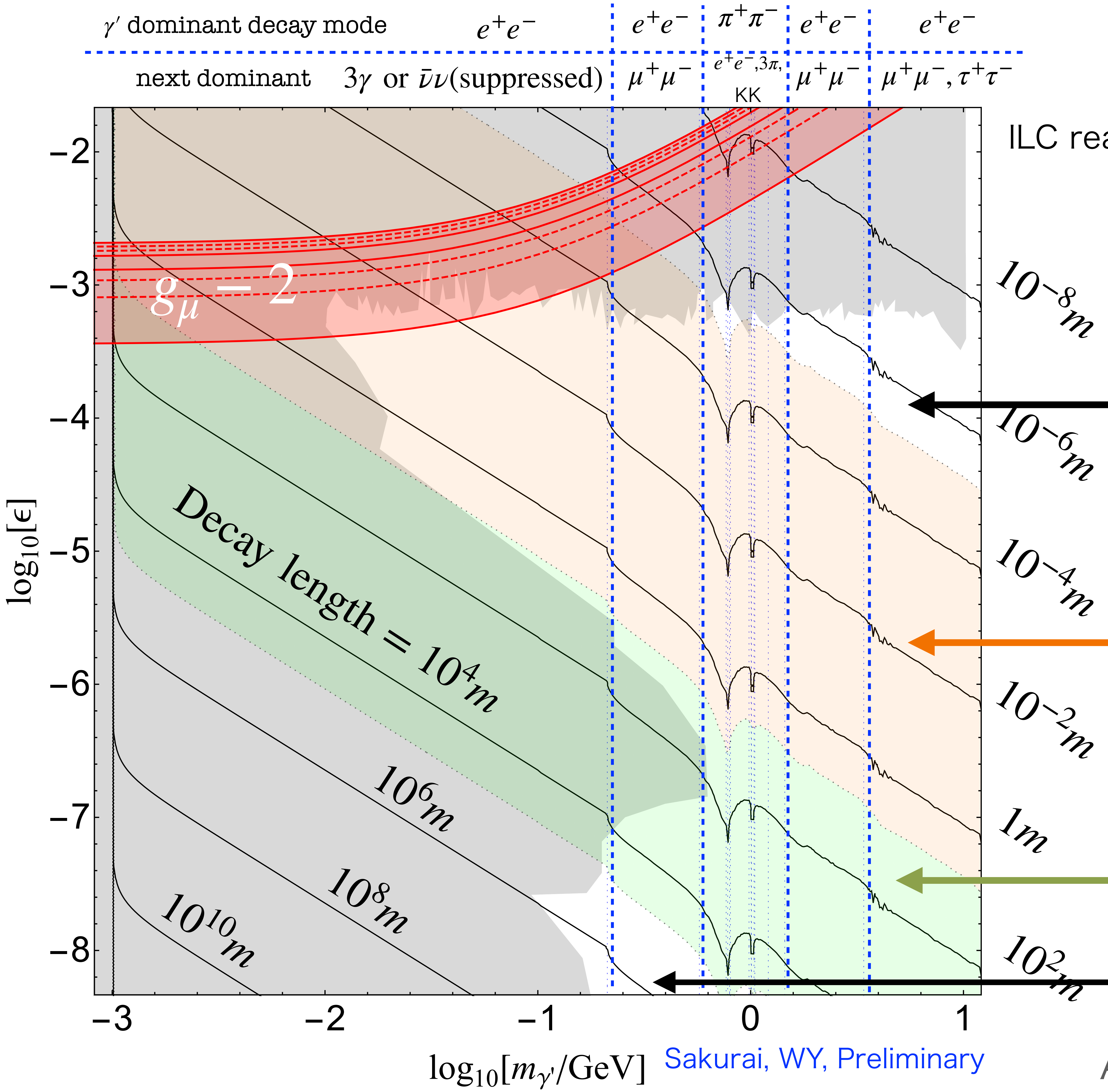

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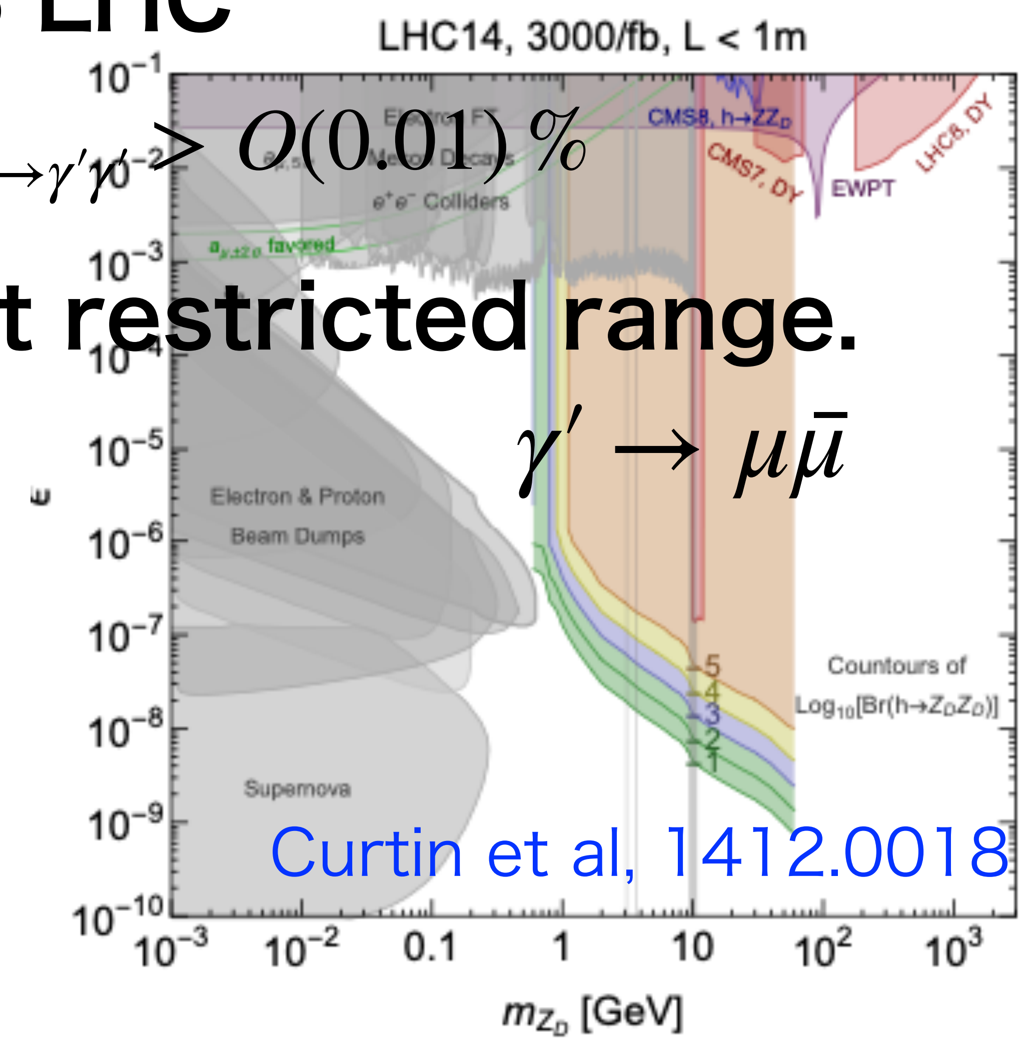

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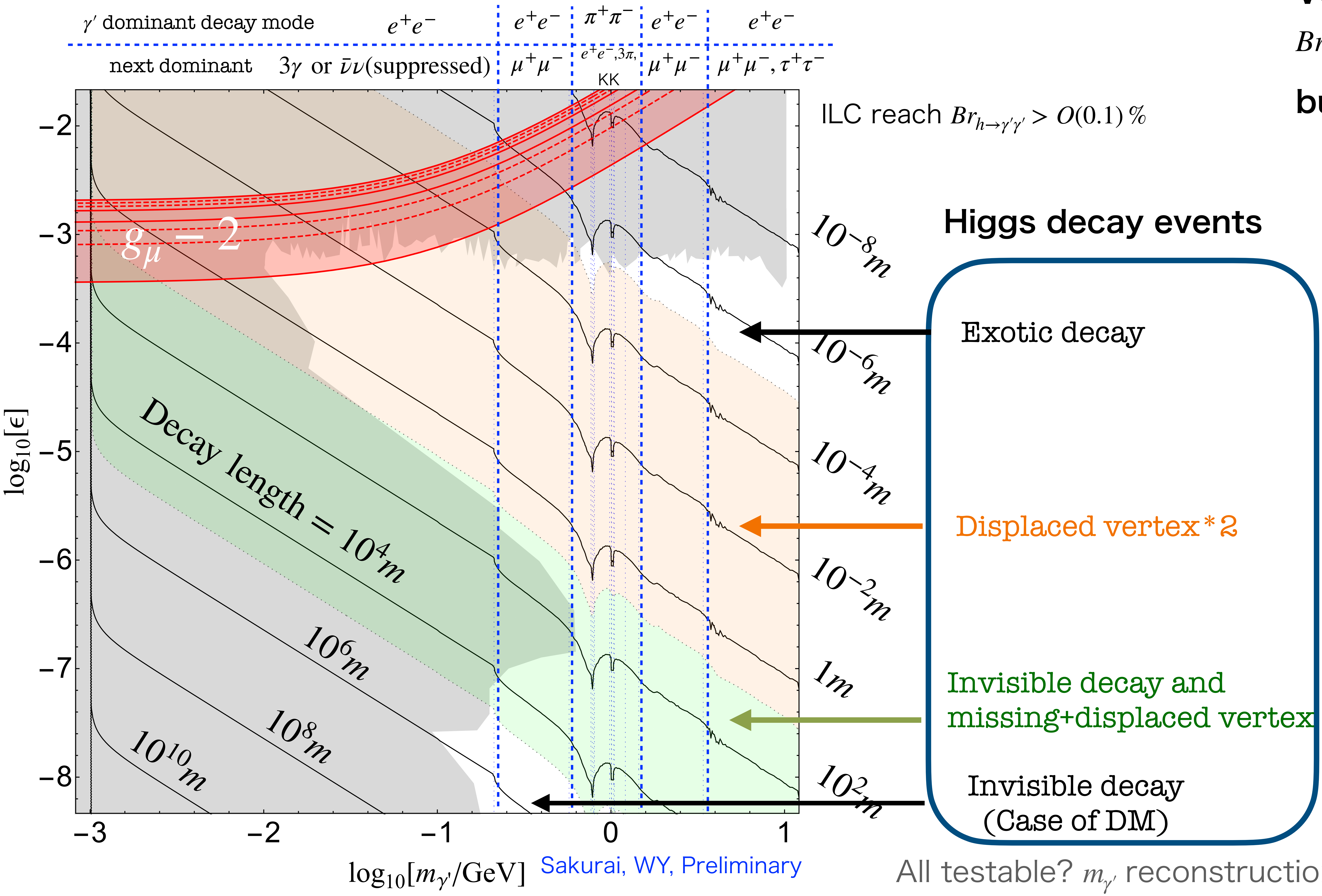

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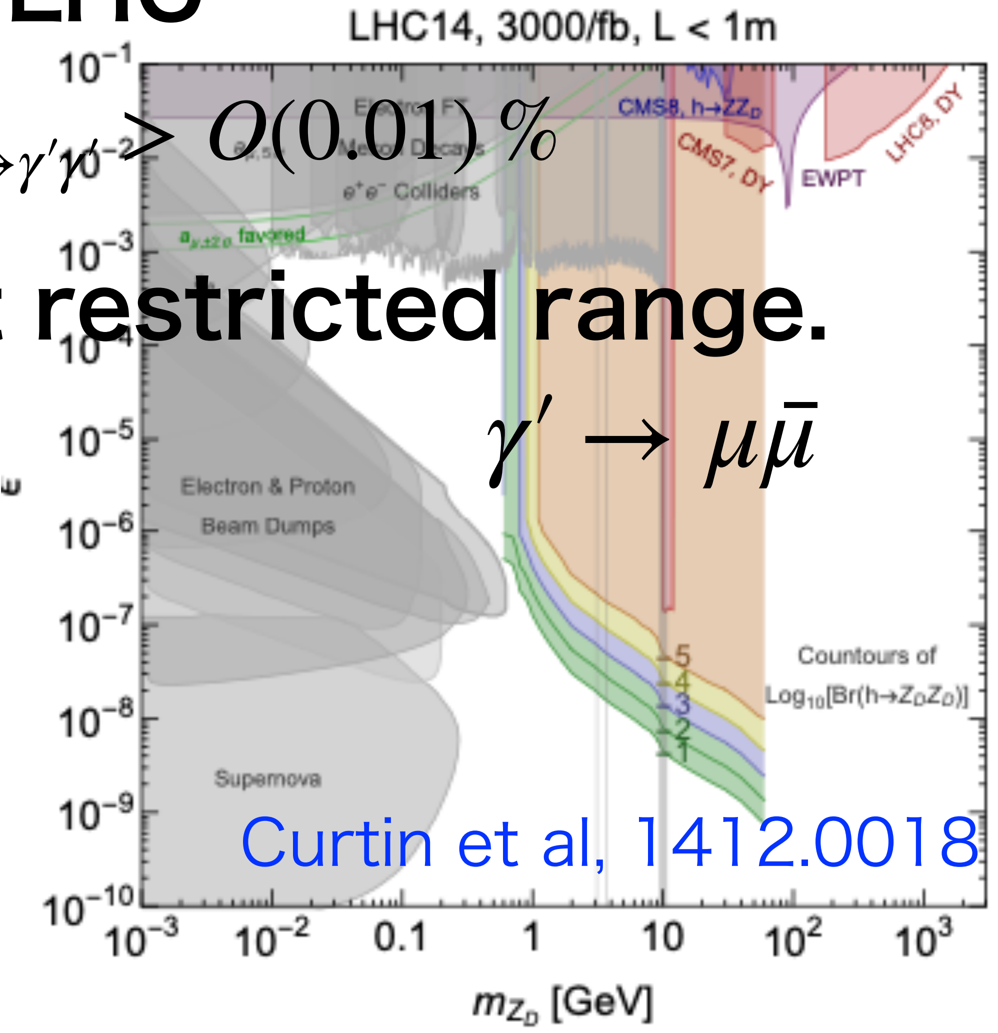

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Decay lenght $\sim \Delta L_{\mathrm{measured}}$

Decay lenght $\sim L_{\mathrm{detector}} \dfrac{Br_{\mathrm{h\to vis+missing}}}{Br_{\mathrm{h\to inv}}}$

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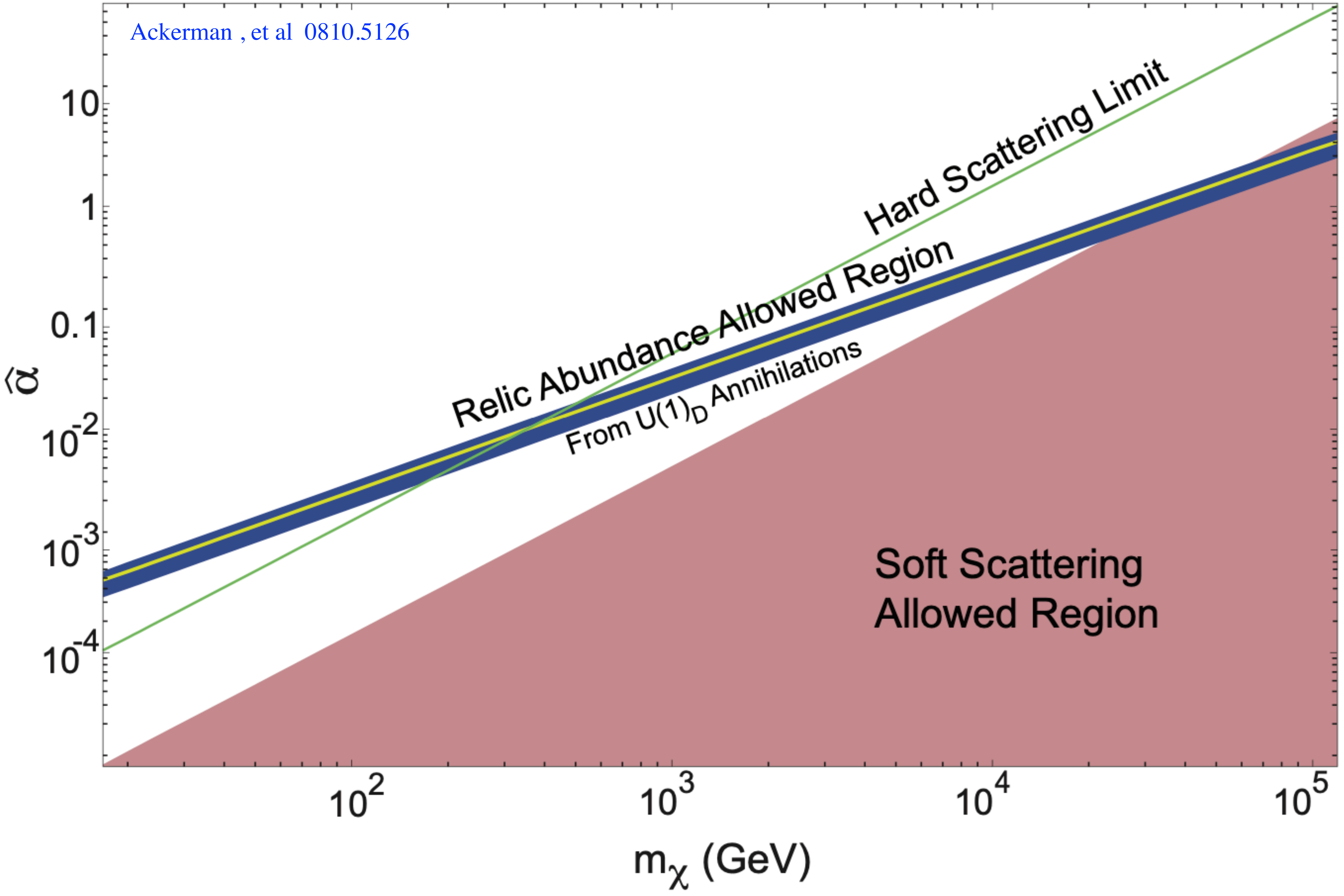
Constraint on DM self-interaction. (U(1)_dark gauge symmetry)

- $\hat{\alpha}$: dark fine-structure constant

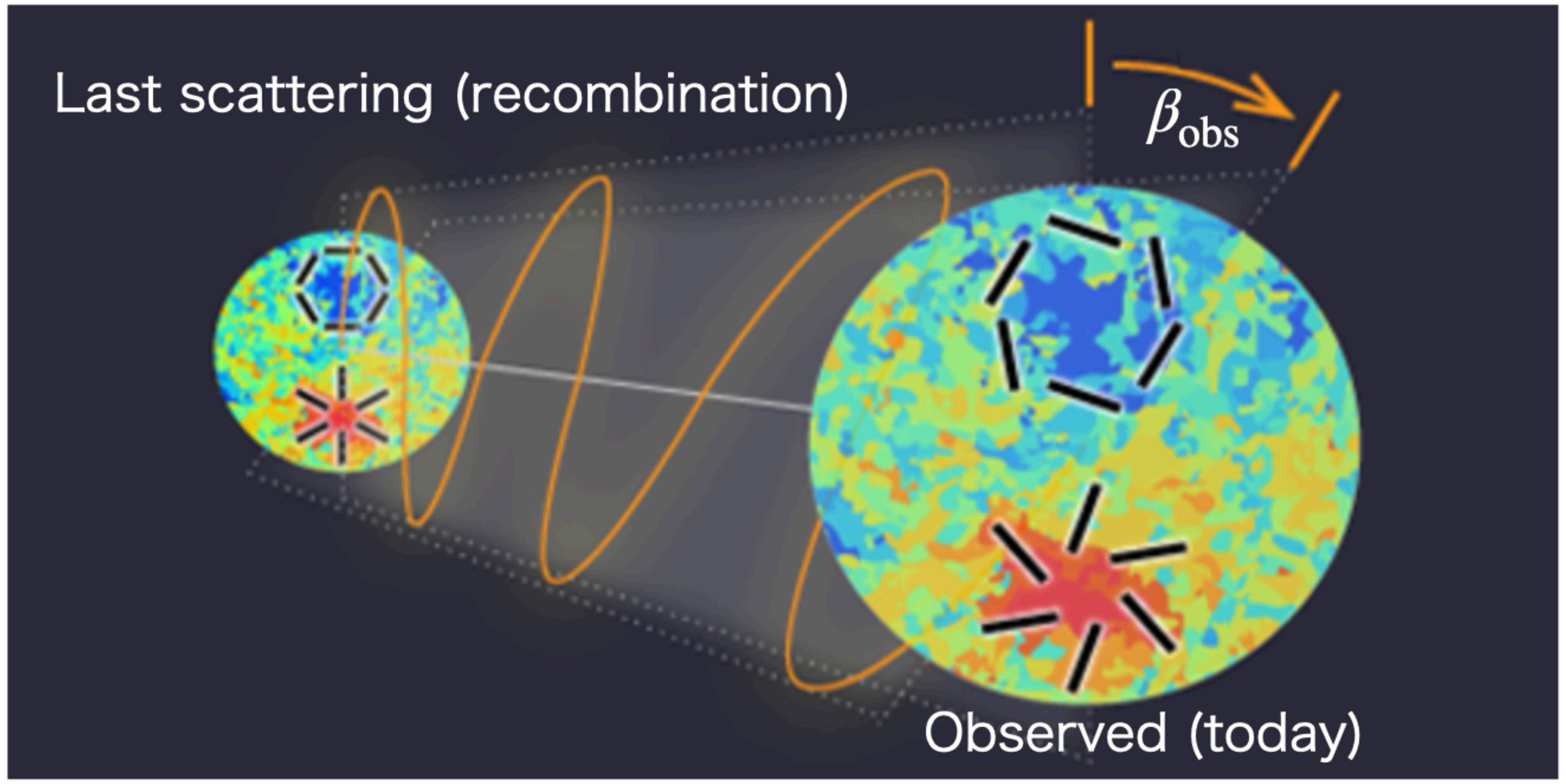
- Screening is taken account
  (I am not sure if there is study without screening. Anyway $m_\phi \gtrsim 10^{-30} eV \sim 1/Mpc$ should have a similar effect for screening.)



Light axion for CMB polarization?

A new analysis is recently performed to get a parity-violating isotropic cosmic birefringence (CB) from Planck2018 data.

$$\mathscr{L} \supset \frac{g_{\phi\gamma\gamma}}{4}\phi F\tilde{F}$$



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$\beta_{\rm obs} = 0.35 \pm 0.14$ deg, (2.4 σ)

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See also Clark et al, 2105.00120 for discussion.

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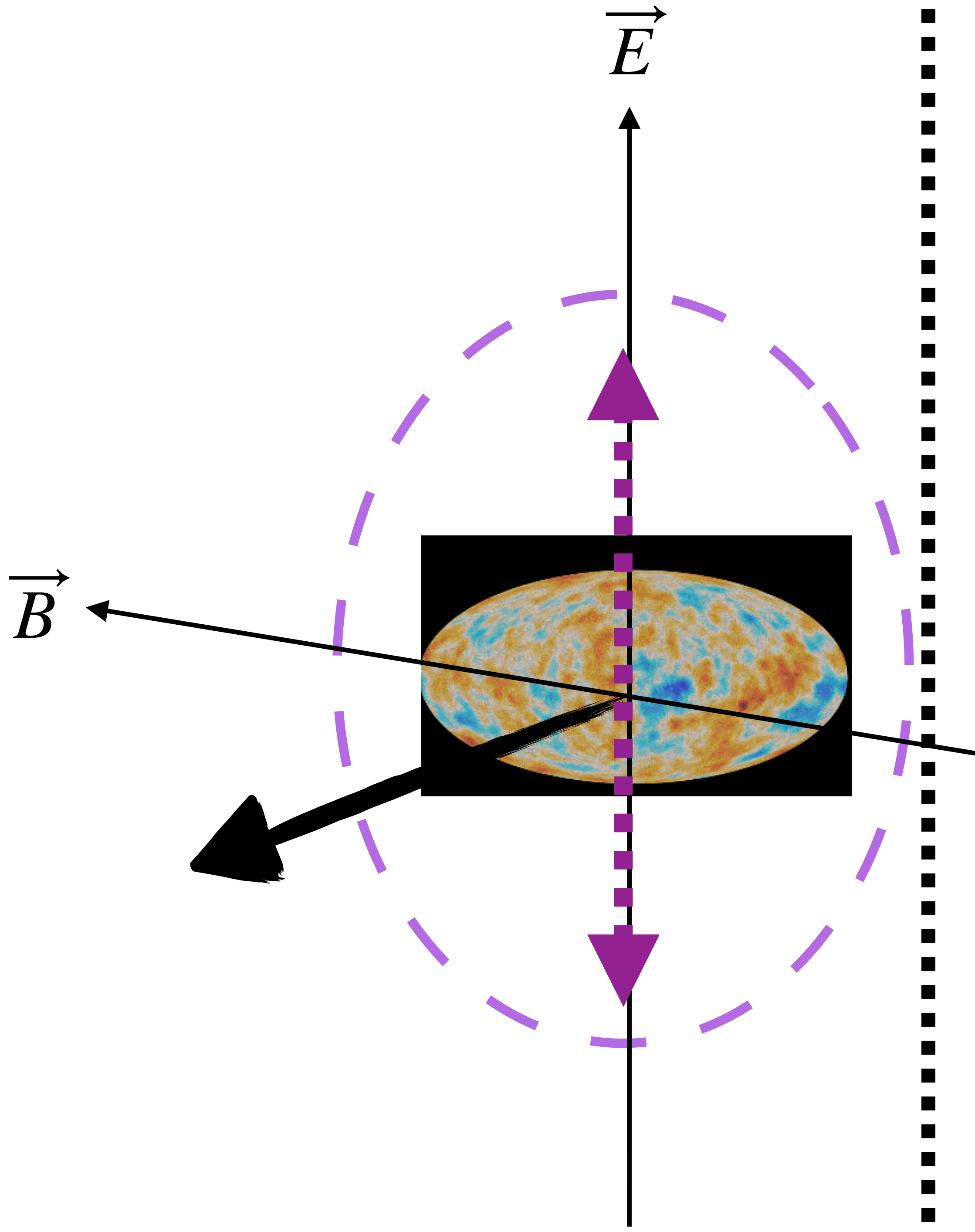

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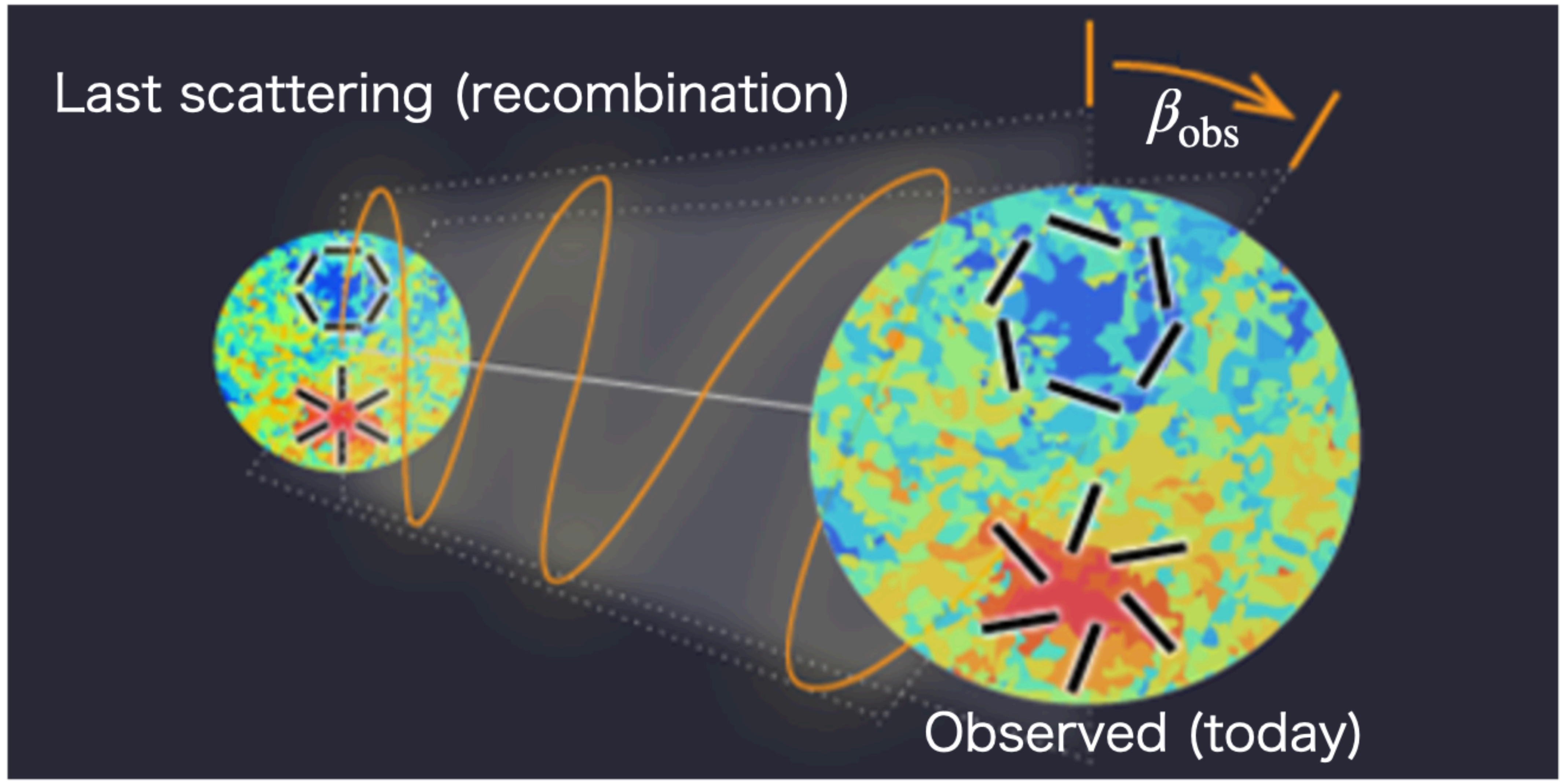

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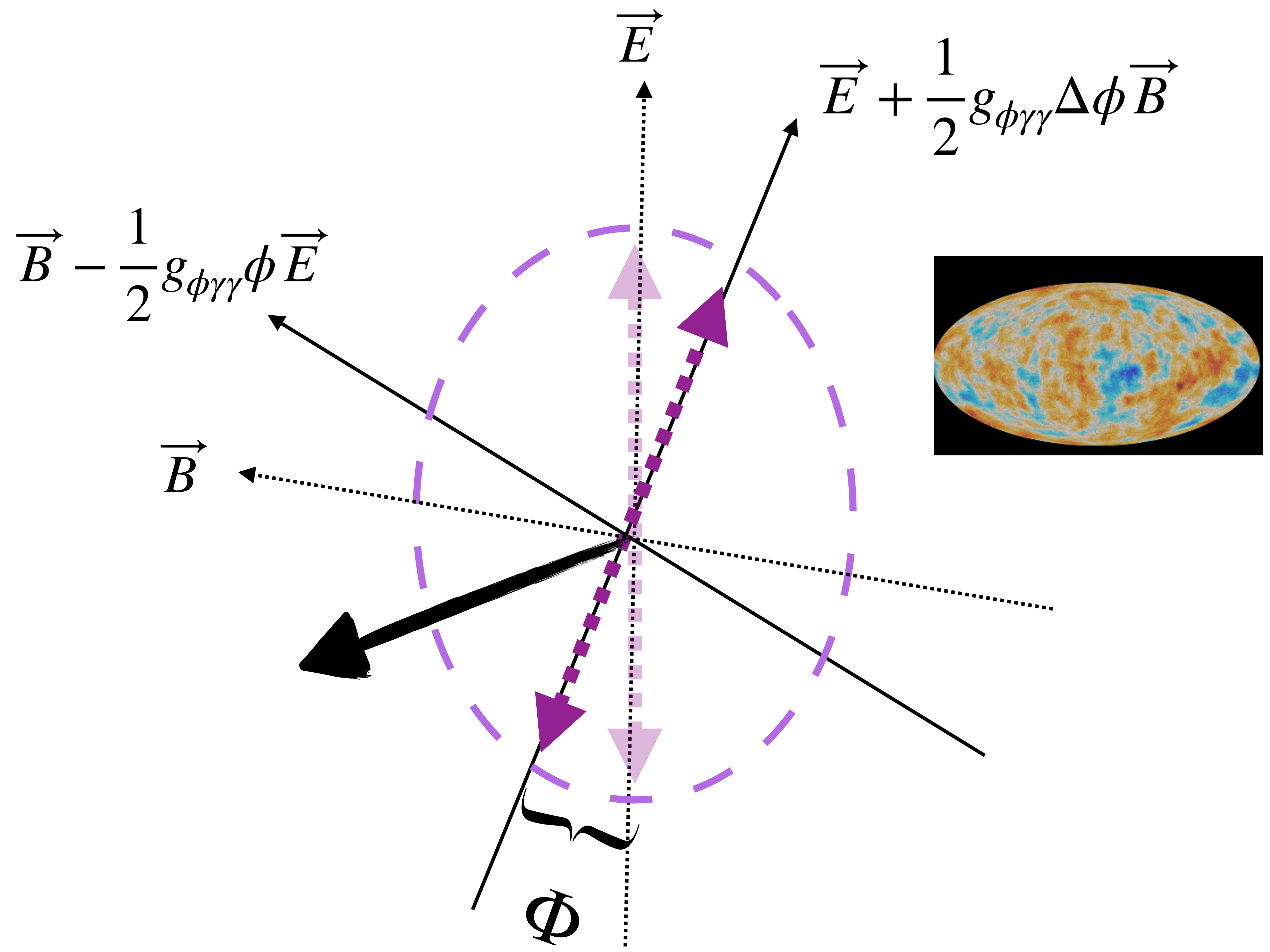

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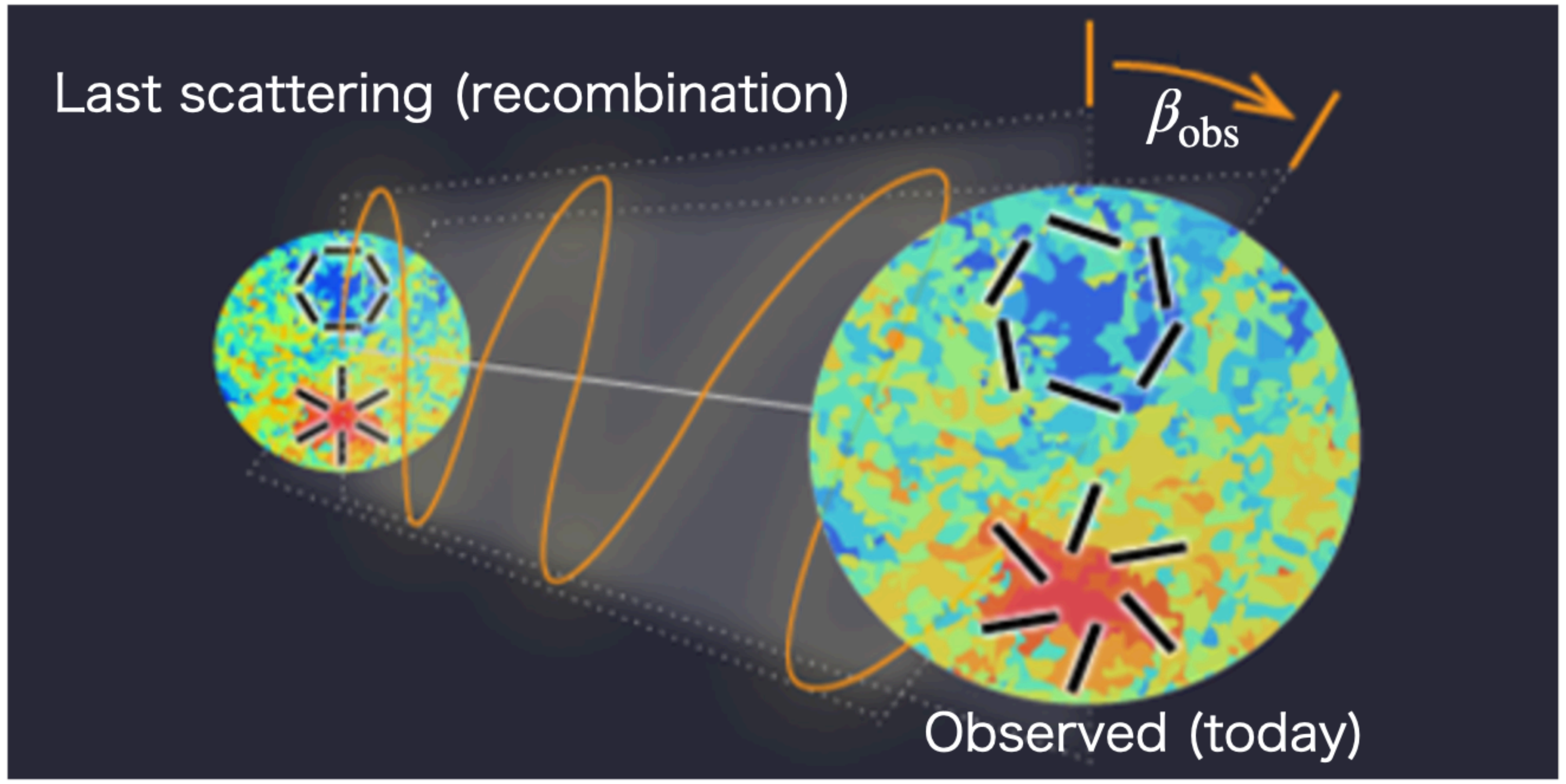

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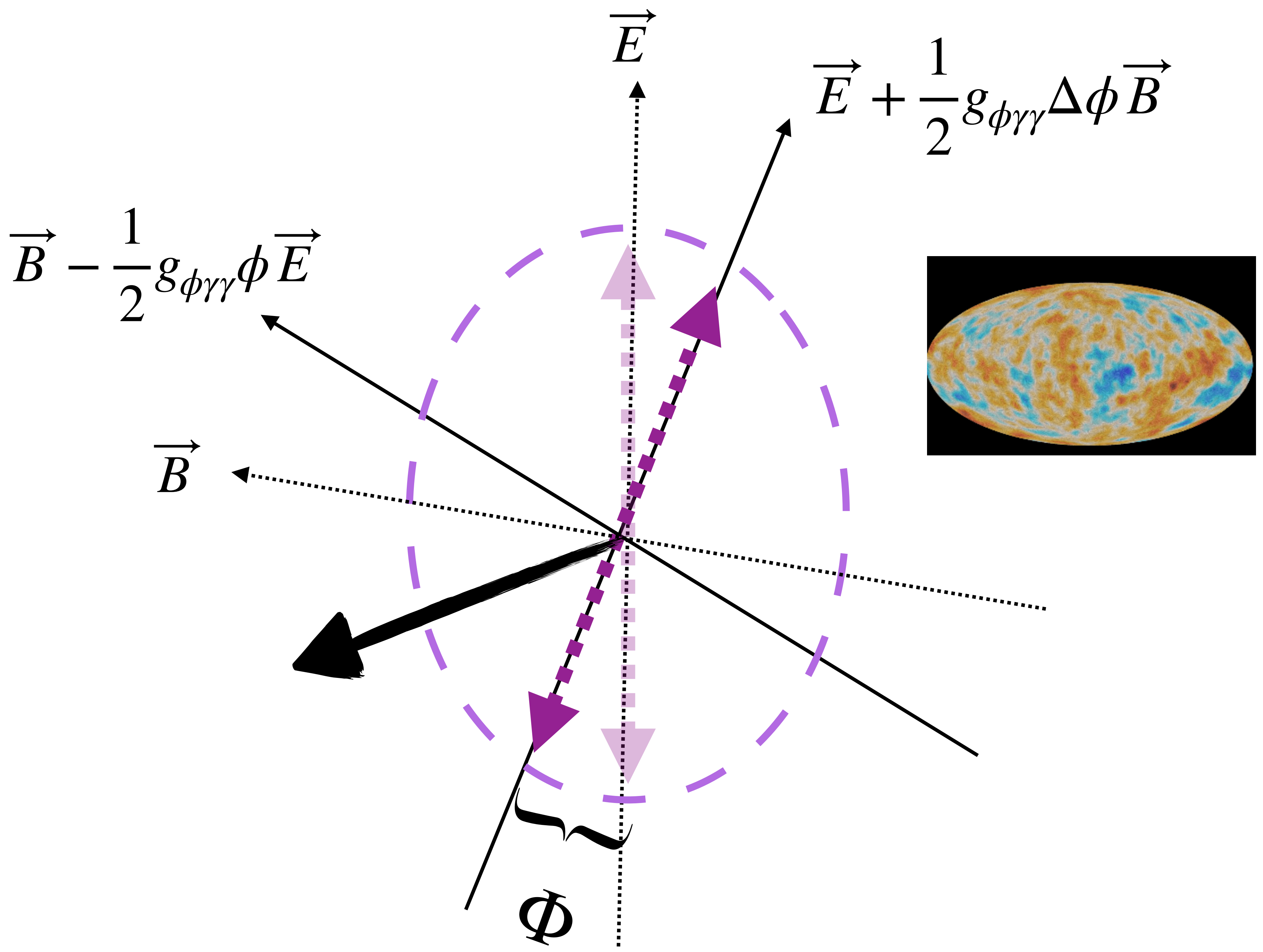

Explanation:

- Isotropic CB by $\dot{\phi} \neq 0$: Slow-rolling axion

  Minami and Komatsu, 2011.11254, Fujita et al, 2011.11894, (CB and H_0 tension)

  Mehta et al, 2103.06812, (Many ALPs); Nakagawa et al, 2103.08153, (Very light ALP); etc

- Isotropic CB by $|\partial_{\vec{x}}\phi| \neq 0$: axion domain walls

  Takahashi, WY, 2012.11576