Light dark sector, quantum Zeno effect, and fuzzy Higgs boson

Mainly based on **Kodai** Sakurai (Tohoku -> Warszawa), WY 2204.01739

@25th May, IPMU seminar

Wen Yin (Tohoku University)

Contents

1. Introduction

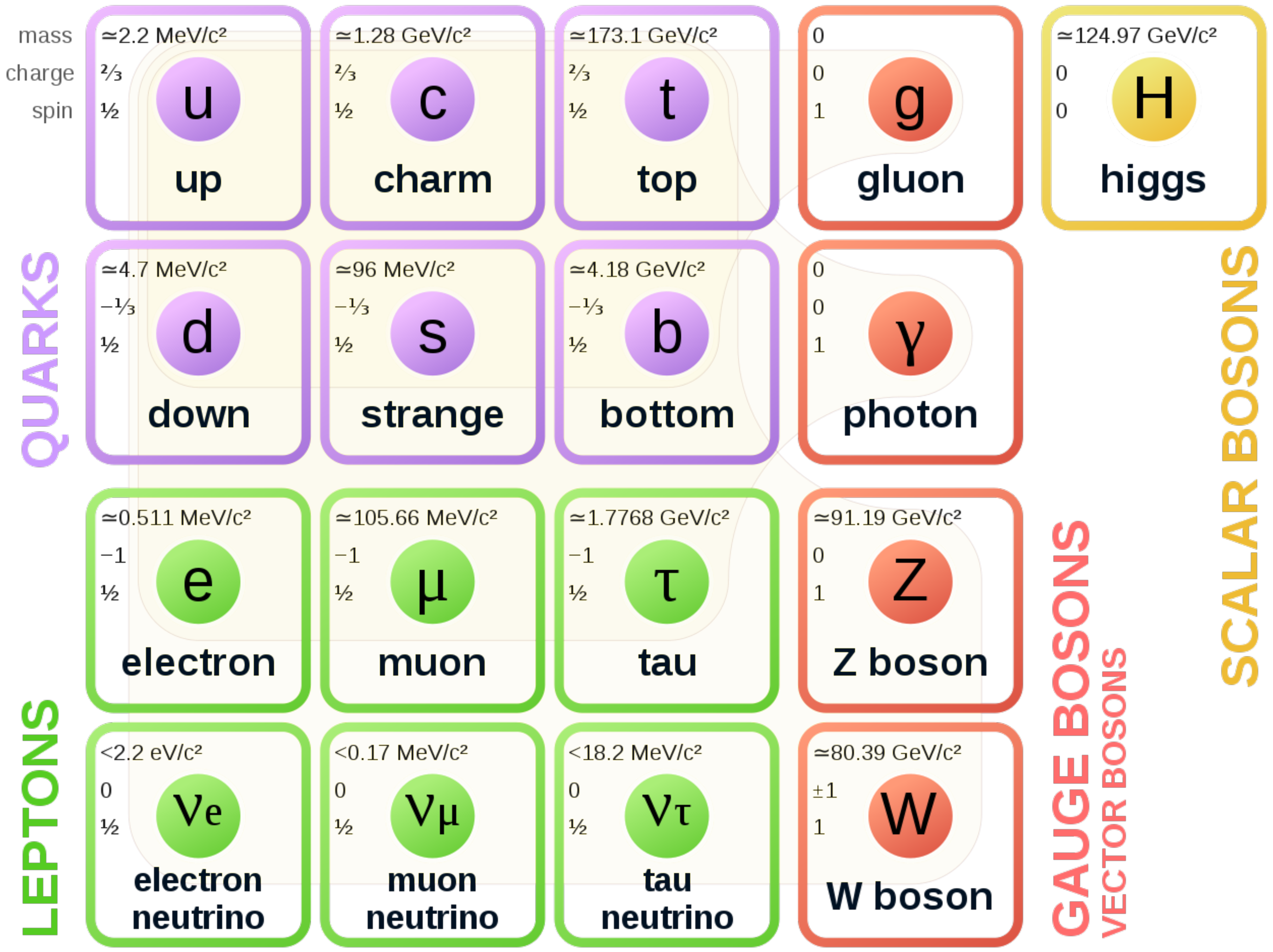
-Light dark sector is accidentally flavor and CP safe.

A few examples of the success of the SM

Standard Model

Renormalizability

+



Accidentally suppressed flavor violation!

Accidentally suppressed CP violation!

Accidental proton stability!

``Accidentally" means there is no extra assumption, e.g. symmetry. They are predicted from particle contents + renormalizability.

I would like to consider BSM that does not spoil this structure.

I do not talk about strong CP.

BSMs with similar properties.

Singlet scalar (dark sector) extensions

$$\delta V = V(|H|^2, s)$$

Silveira, 1985; Burgess et al 0011335

s can be thought to be CP-even if renormalizable, i.e. the potential is accidentally CP-conserving. Flavor violation, proton decay are suppressed as in the SM.

Massive dark gauge boson (SM is not charged) also belong to this category since we need a dark higgs.

This talk

Non-trivially charged particles

*Real adjoint Higgs boson

*Field with very large representation etc

Others

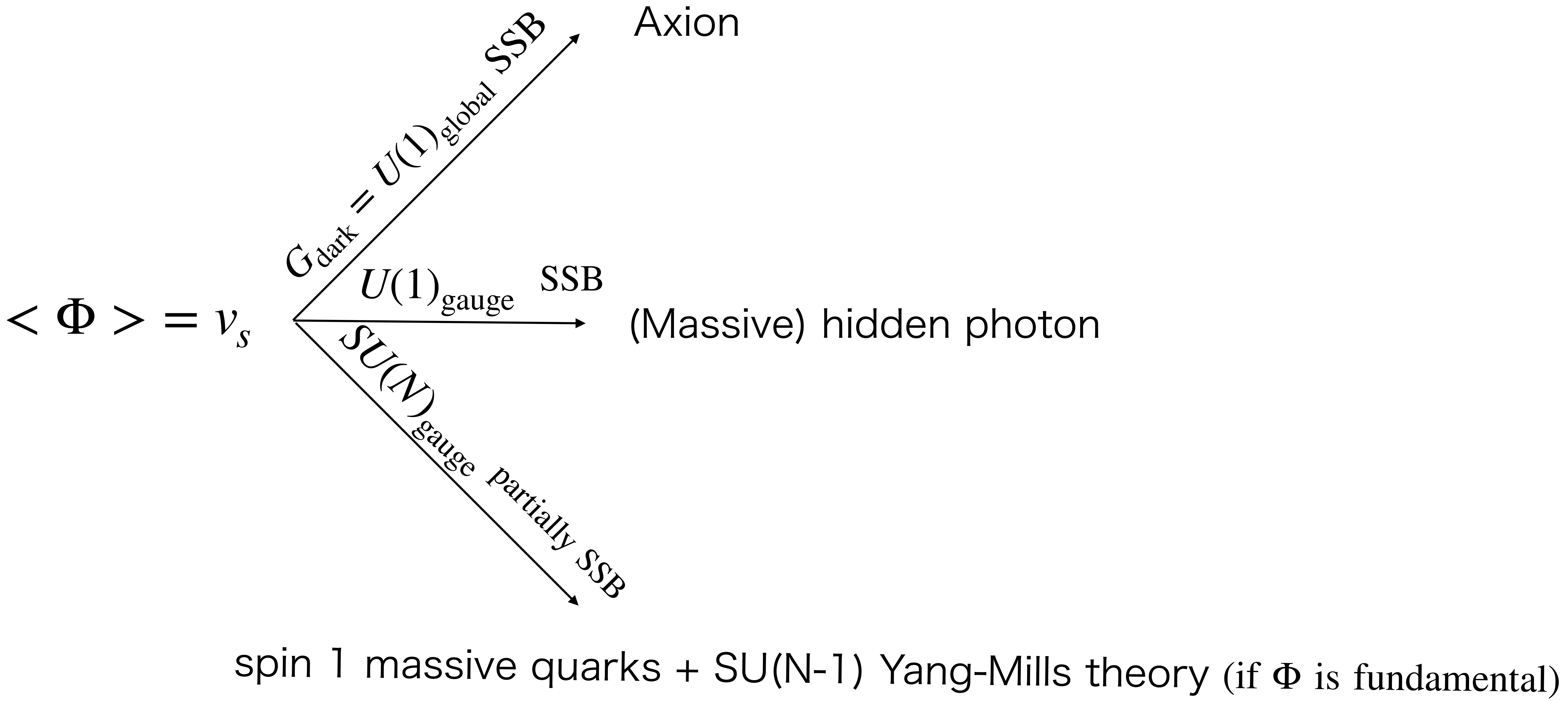
e.g. SUSY+R-parity (for DM stability)+gauge mediation, BSM are heavy.

Singlet scalar extensions can connect light dark sector:

$G_{\rm dark}$ symmetry extension. $\Phi \supset s$

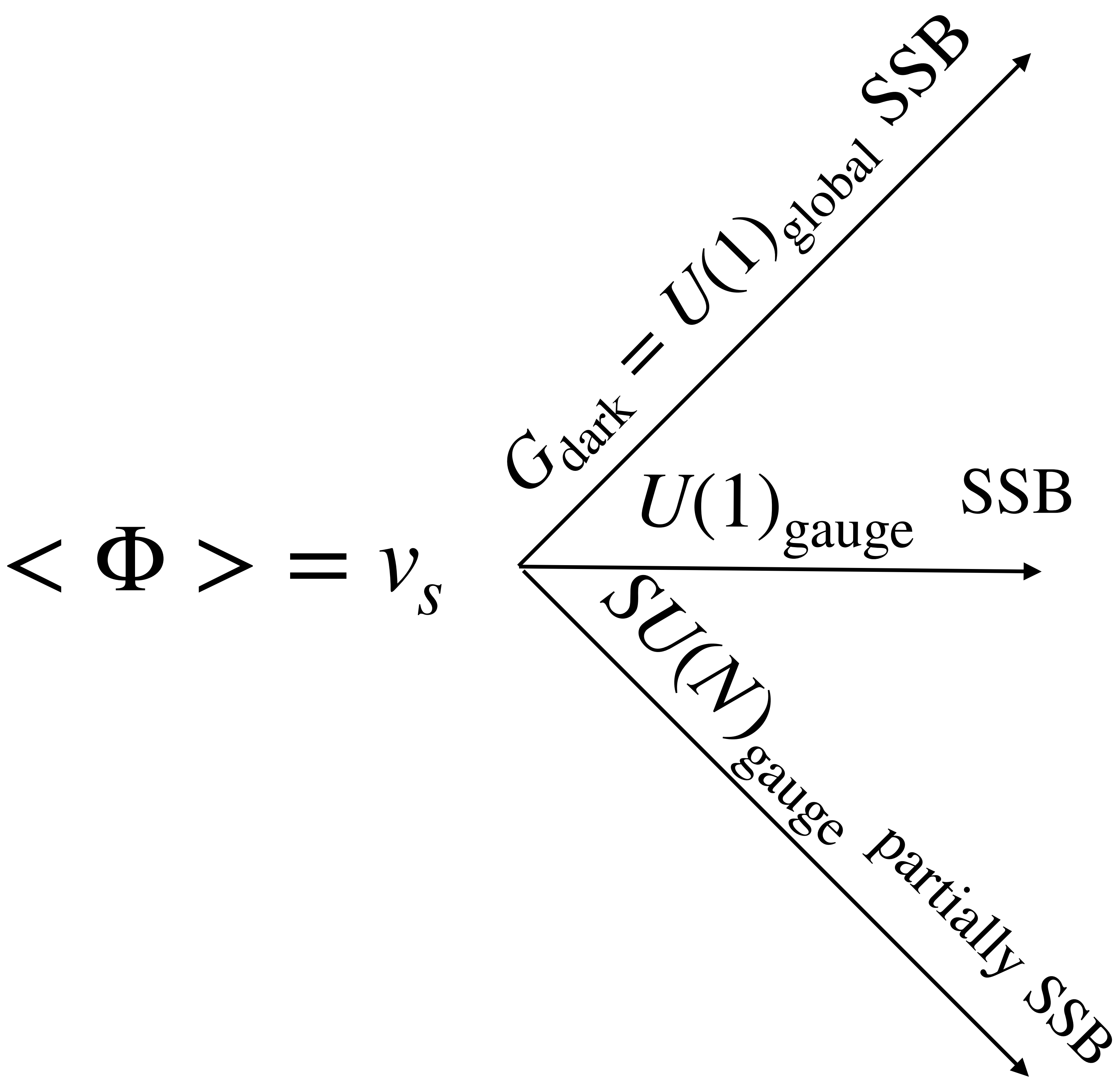
See CxSM Barger et al, 0811.0393

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



Light dark sector with Higgs portal coupling.

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



Axion

(Massive) hidden photon

spin 1 massive quarks + SU(N-1) Yang-Mills theory (if Φ is fundamental)

According to 't Hooft's naturalness $\lambda_P \sim 1$ should be written.

I will consider λ_P not very small in the talk.

(A loophole of the discussion: $\lambda_P \to 0$ Φ becomes a free particle.)

See also light axion/hidden photon dark matter production via PT with very small but non-zero λ_P, Nakayama WY 2105.14549

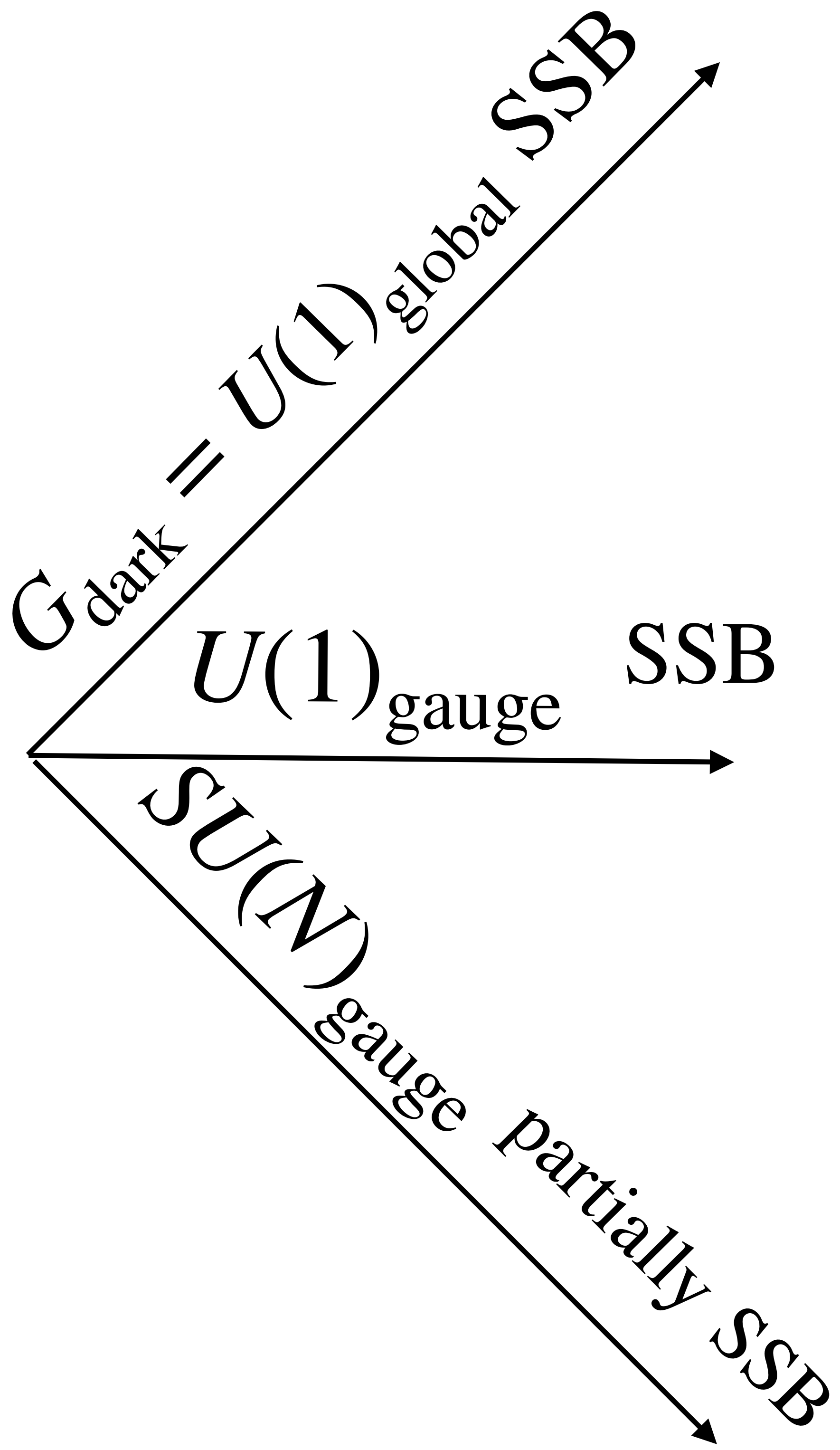
Light dark sector production via portal coupling in the early Universe.

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

Integrating-out Higgs fields: e.g.

$$-\frac{\sqrt{2}\lambda_P m_{\psi_{\rm SM}}}{(m_\Phi^2 - m_h^2)m_h^2}|\partial(\text{would-be})\text{NGB}|^2 \bar{\psi}_{\rm SM}\psi_{\rm SM} .$$

$<\Phi> = v_s$

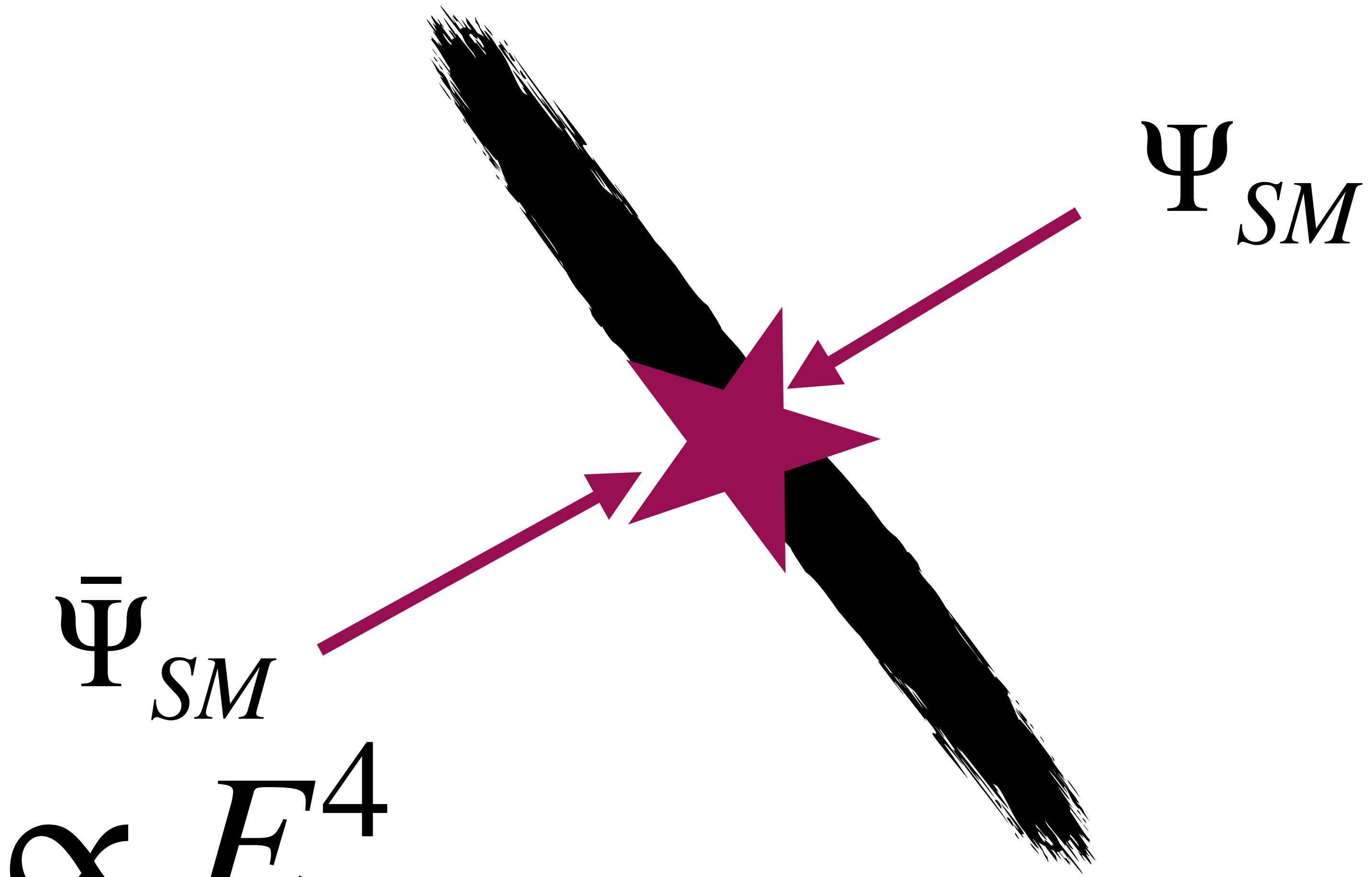


Axion

(Massive) hidden photon

spin 1 massive quarks + SU(N-1) Yang-Mills theory (if Φ is fundamental)

(would-be) NGB



$\sigma \propto E_{\rm cm}^4$

(would-be) NGB

Light dark sector production via portal coupling in the early Universe.

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

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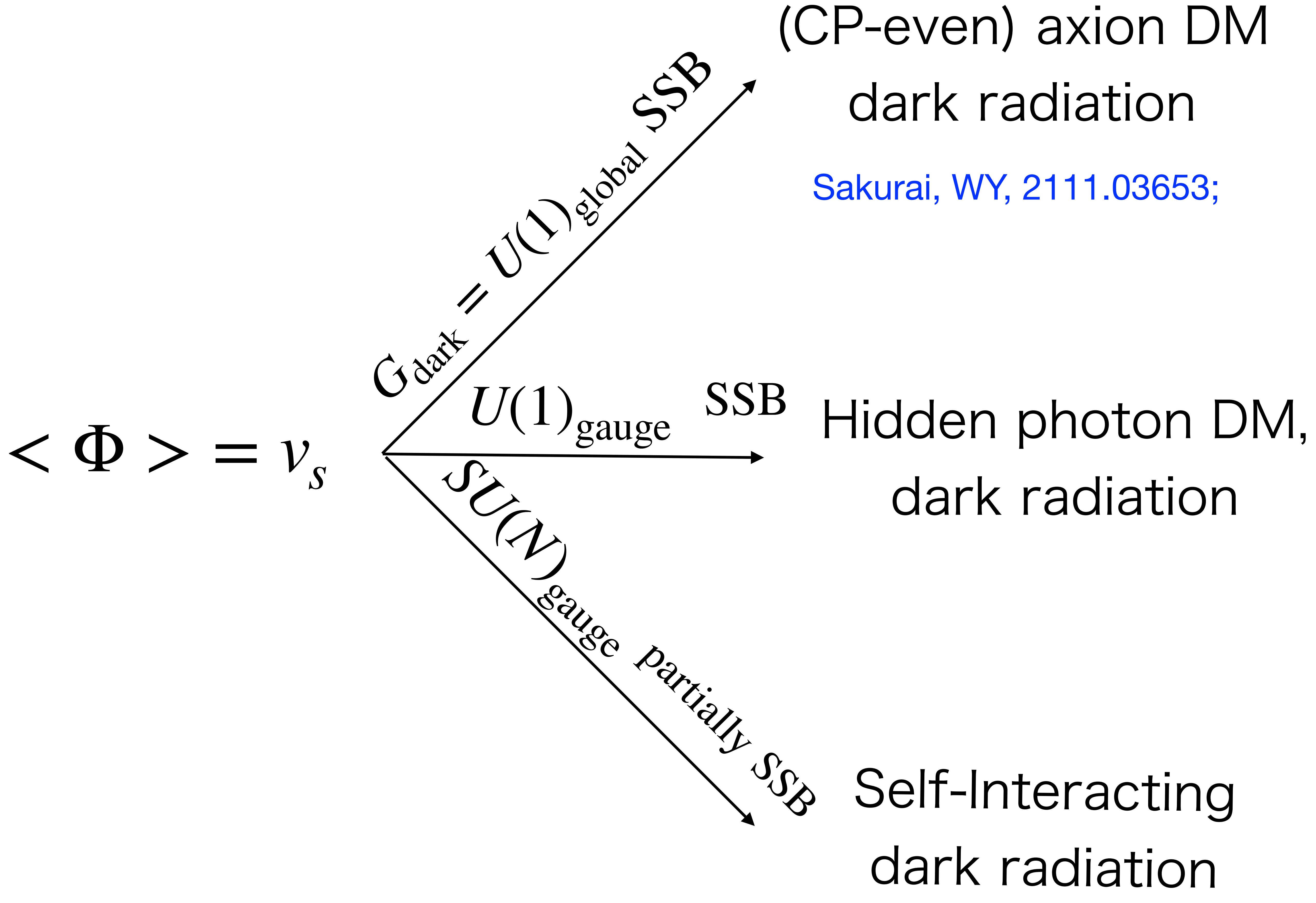
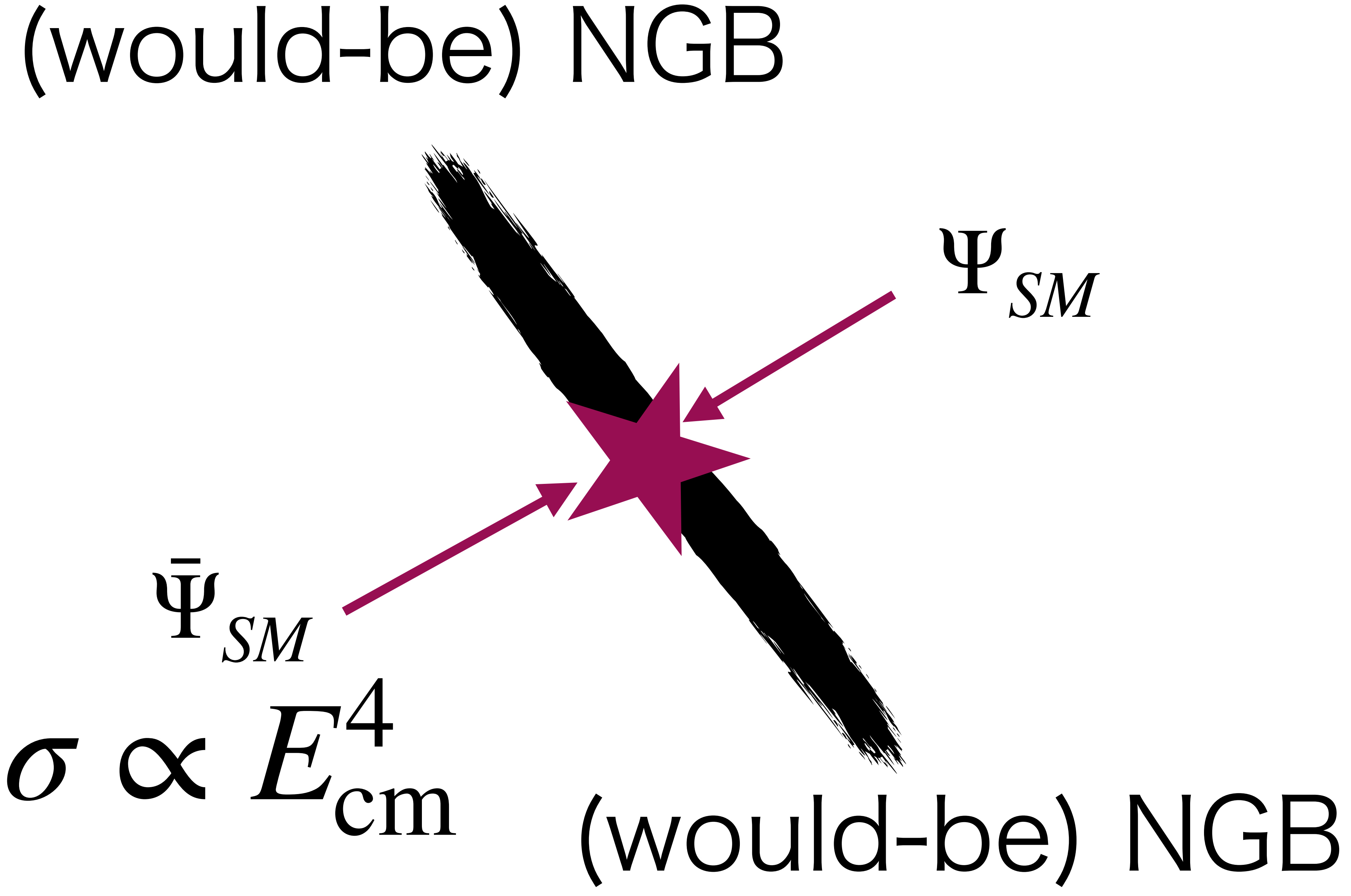
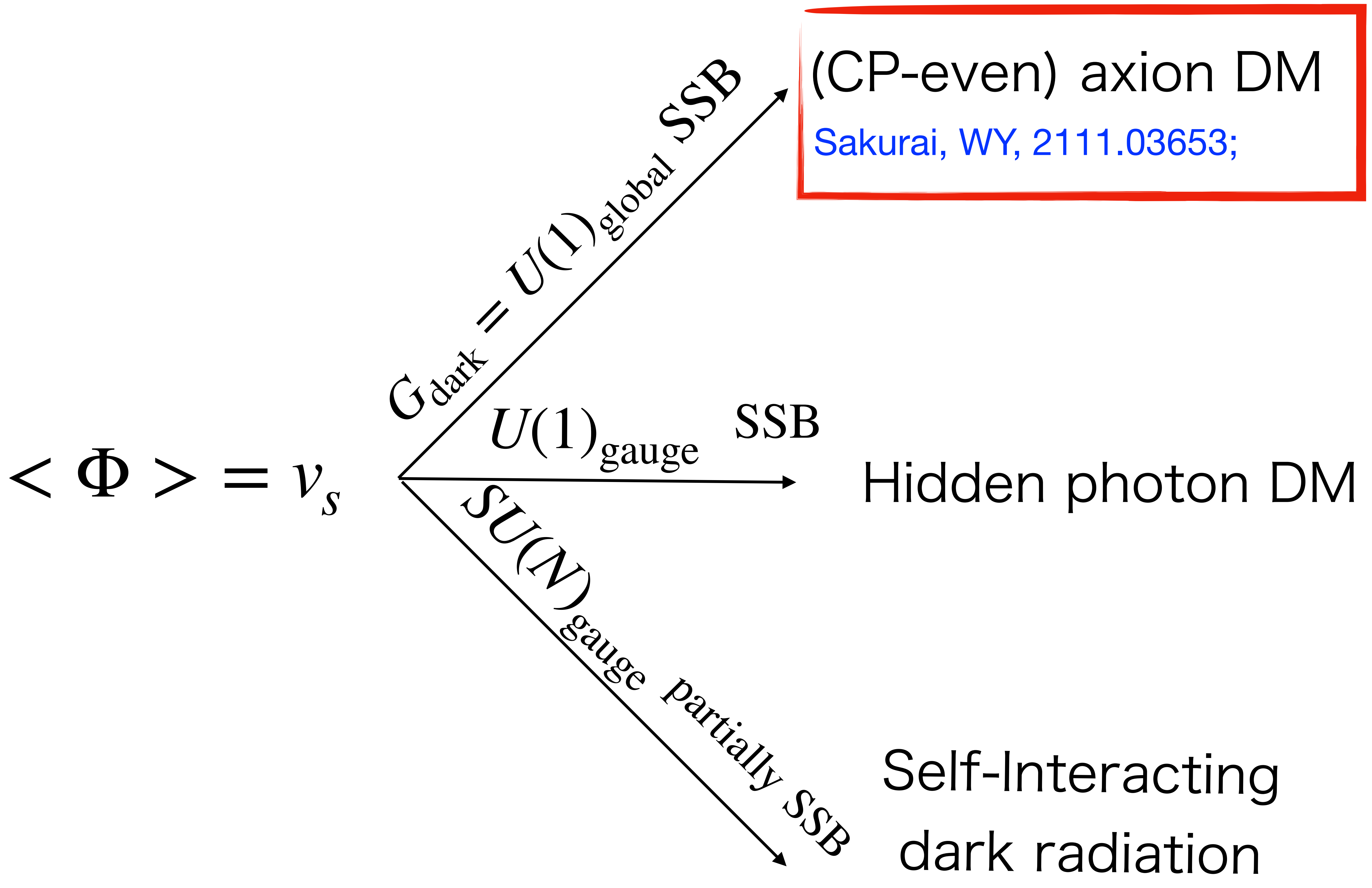




1. Introduction
-An example of light dark sector, CP-even axion DM



Takahashi, Sakurai, WY 2204.04770
see also Jeong, Takahashi, 1305.6521

Giving mass to the NG boson without a PQ fermion with generic explicit U(1) breaking terms predicts a CP-even axion.

Sakurai, WY, 2111.03653;

(Adding singlet PQ fermion preserving a $C_{\rm dark}$ symmetry will not change the conclusions.)

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

+generic explicit U(1) breaking with an order parameter κ, single BSM scale m_Φ

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

$$c_j, etc = O(1) + O(1)i$$

For simplicity of discussion,

$$\delta V^{\rm simp} = \kappa\left(|c_1|m_\Phi^2\cos[a/f_a + \theta_1] + |\tilde{c}_1^H|(v_{\rm EW}^2 + \sqrt{2}v_{\rm EW}h)m_\Phi\cos[a/f_a + \theta_2] + O(h^2, s)\right)$$

With field redefinition $\langle a\rangle = 0$ without loss of generality with generic θ_1, θ_2.

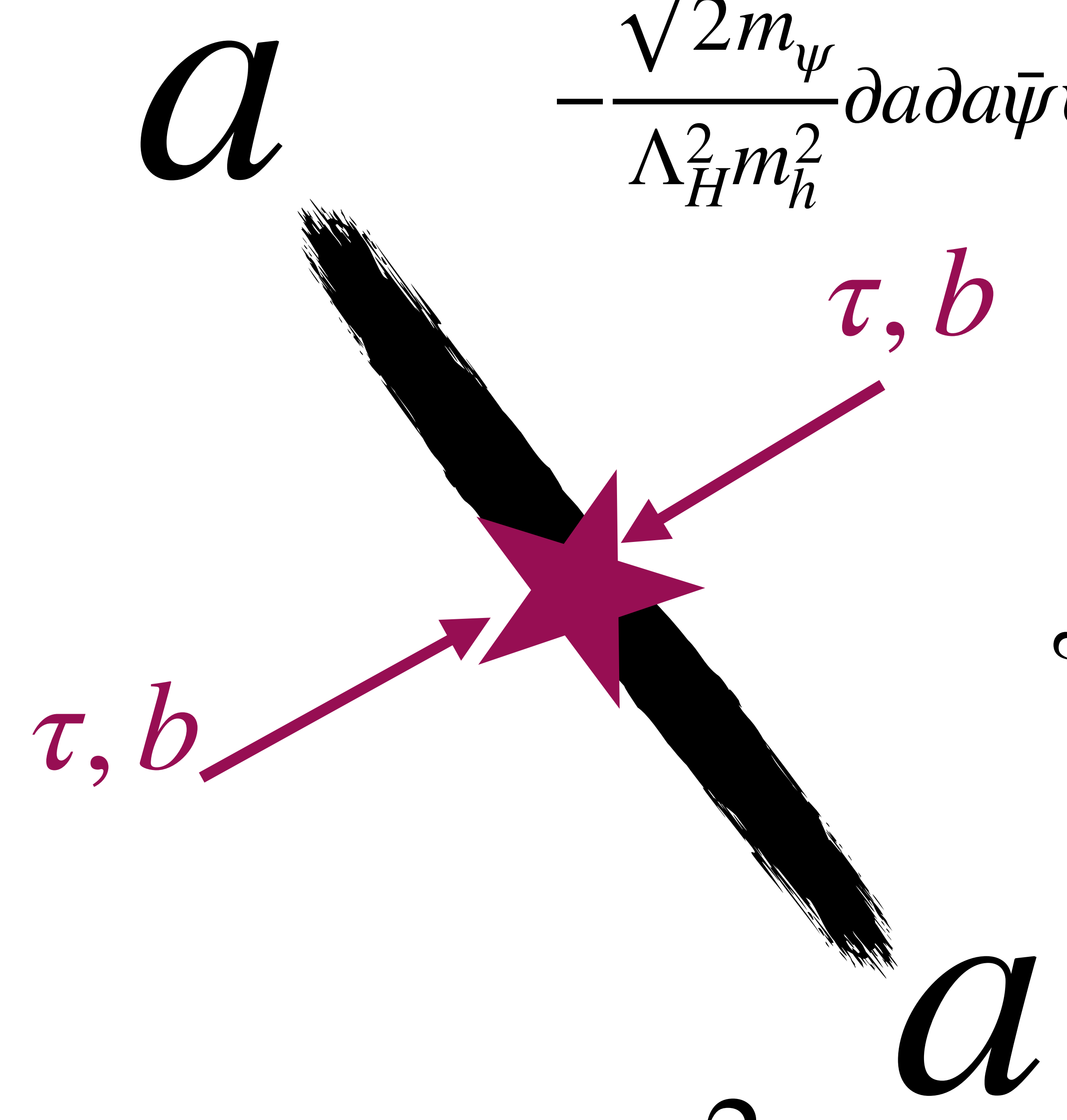
In general $_{(\theta_2 = O(1))}\langle\partial_h\partial_a\delta V^{\rm simp}\rangle \sim \kappa m_\Phi m_h \neq 0$, Axion is CP even !

c.f. singlet scalar extensions are accidentally CP-safe.

Thermally produced CP-even axion DM

CP-even axion is produced via λ_P in early Universe

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



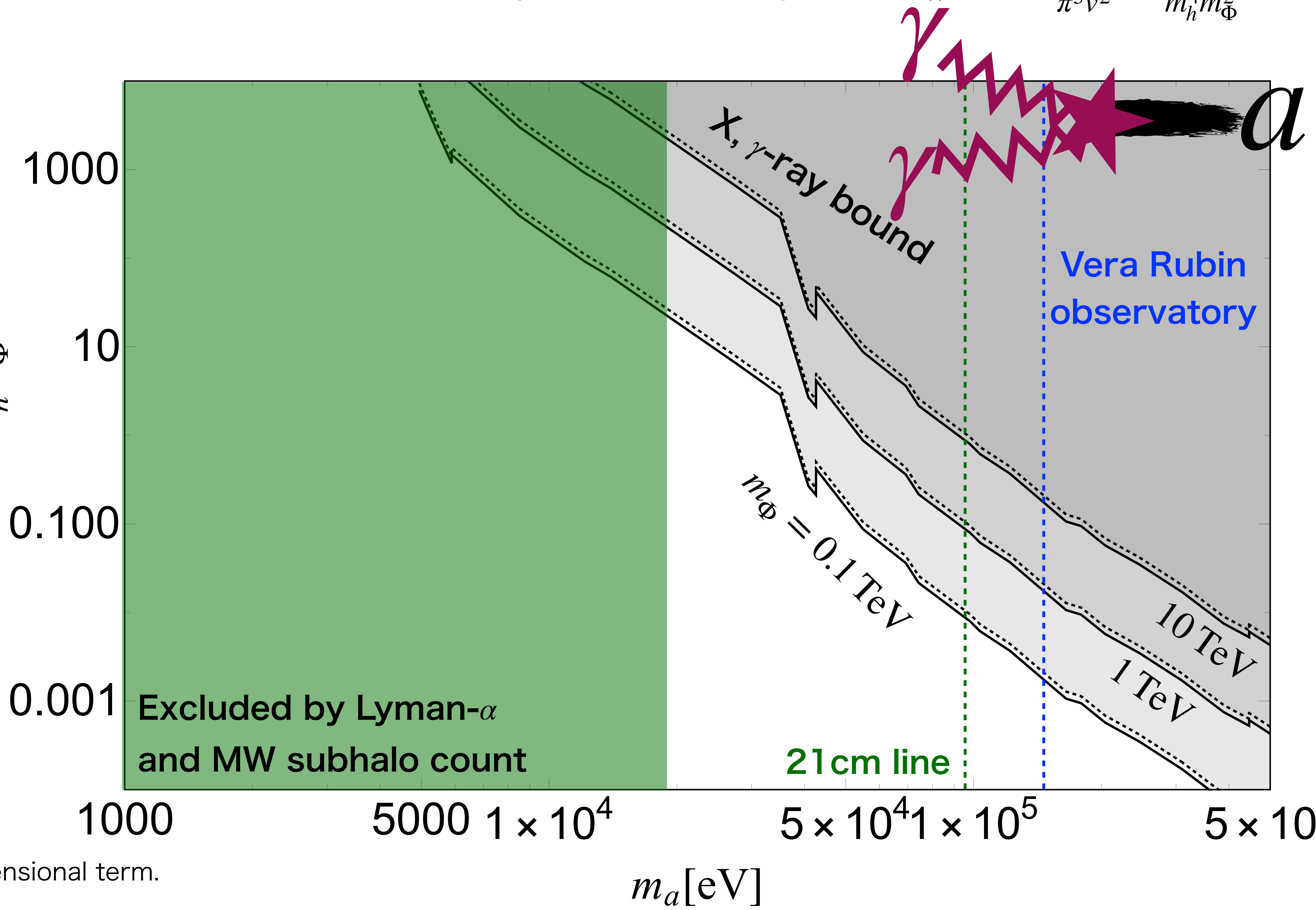
$$\sigma \propto s^2$$

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

$T_R > MeV$ is allowed thanks to the very higher-dimensional term.

It decays via a-h mixing

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



Early Universe with high enough reheating temperature populates dark sector particles.

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

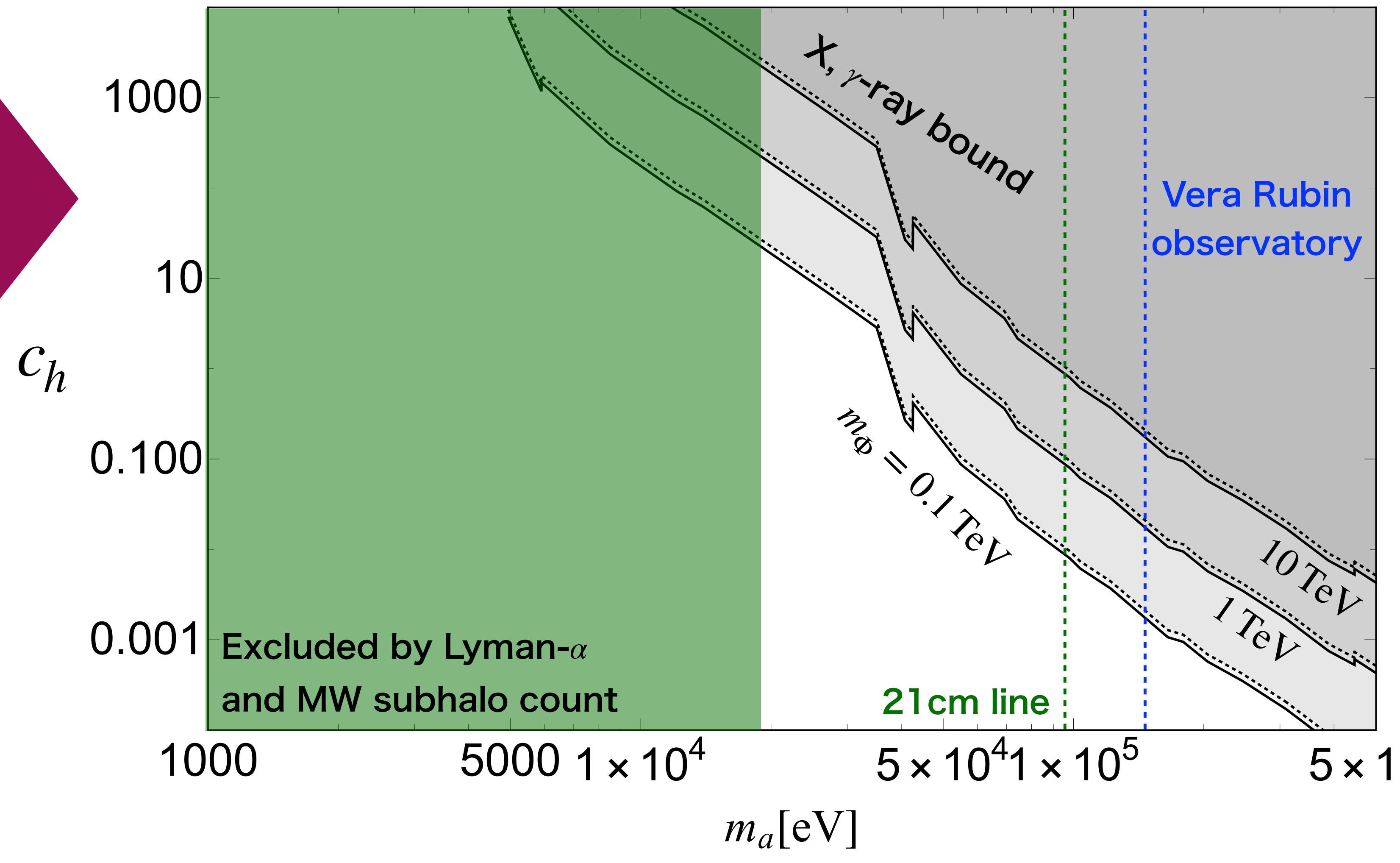
$< \Phi > = v_s$

- $G_{\rm dark} = U(1)_{\rm global}$ → (CP-even) axion DM
  Sakurai, WY, 2111.03653;
- $U(1)_{\rm gauge}$ → Hidden photon DM
  (kinetic mixing $\lesssim 10^{-14}$ by XENON exp and star cooling)
  e.g. Jaeckel, and Ringwald 1002.0329;
- $SU(N)_{\rm gauge}$ → Self-interacting dark radiation

10keV-MeV DM candidate

$T_{Reheating} = O(1-10)$GeV

CP-even axion DM



Takahashi, Sakurai, WY 2204.04770
see also Jeong, Takahashi, 1305.6521

Self-interacting dark radiation → $\Delta N_{\rm eff} \sim 0.4$ alleviates Hubble tension

It is a medalist🥉!

Schöneberg et al, 2107.10291

If Φ is a symmetric tensor of $G_{\rm dark} = SU(N)_{\rm gauge}$, an axion appears due to accidental symmetry.

Ardu et al, 2007.12663; WY 2007.13320;
(See also Lee, WY, 1811.04039)

Dark sector extension:

Accidentally suppressed FV!

Accidentally suppressed CPV!

Accidental proton stability!

+connected to mysteries in the early universe!

See also topics in similar models:

WIMP: Barger et al, 0811.0393, etc

PNGB WIMP: Ishiwata, Toma 1810.08139, etc

Electroweak baryogenesis: Barger et al, 0811.0393, Cho et al, 2105.11830, etc

Light mediator scenarios: Matsumoto, Tsai, Tseng, 1811.03292 etc

Light dark matter production via dark Higgs phase transition: Nakayama WY 2105.14549

1. Introduction
-Probing light dark sector with SM-like Higgs invisible decay in colliders.

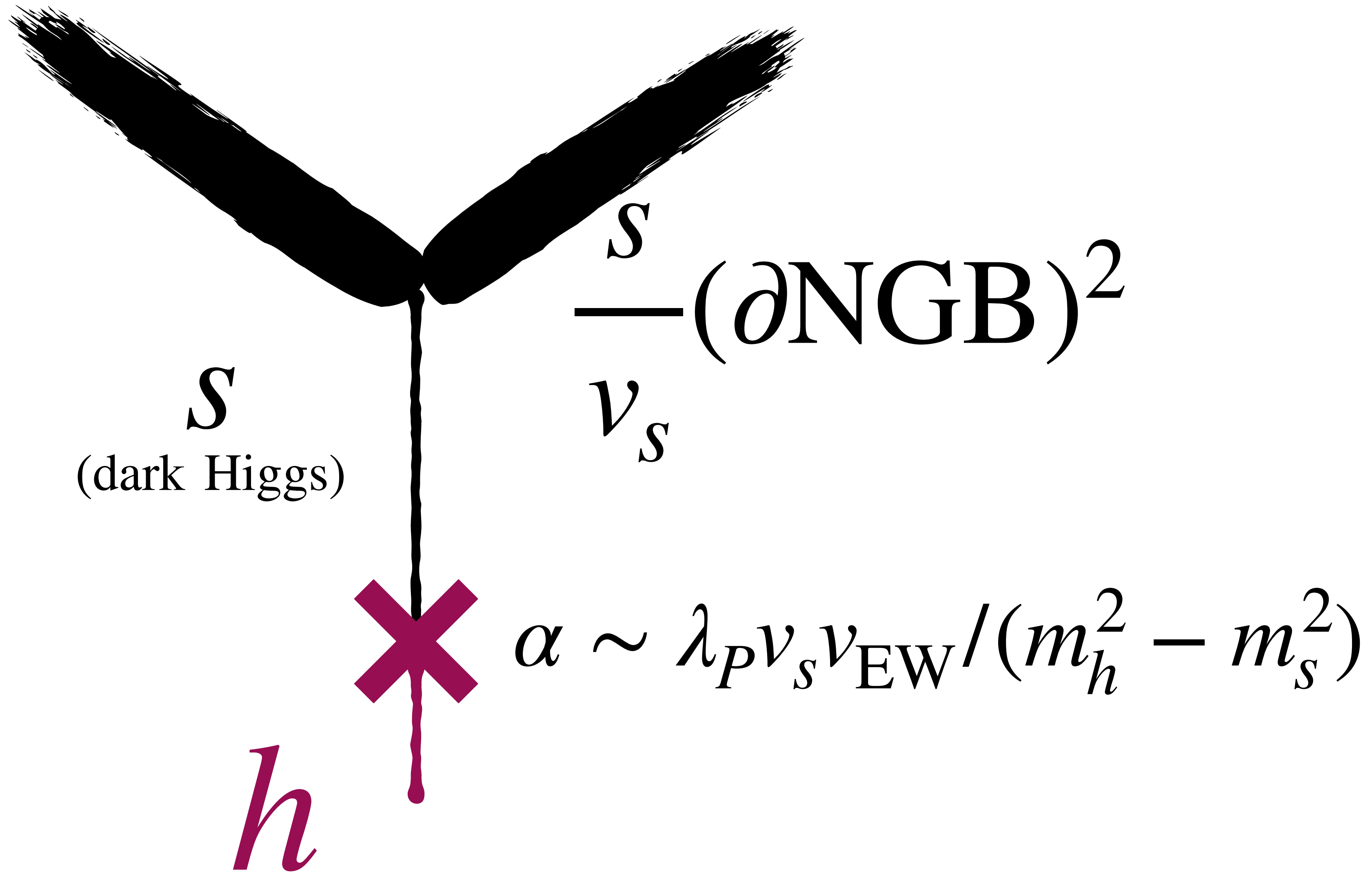
Sorry for the long way around.

A generic prediction is SM-like ***Higgs invisible decay.***

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

$$\supset \lambda_P v_s v_{\rm EW} s h$$

(would-be) NGB $\times 2$



Precisely studying Higgs invisible decay should be important to probe natural dark sectors.

*Theorertical understanding Today's talk

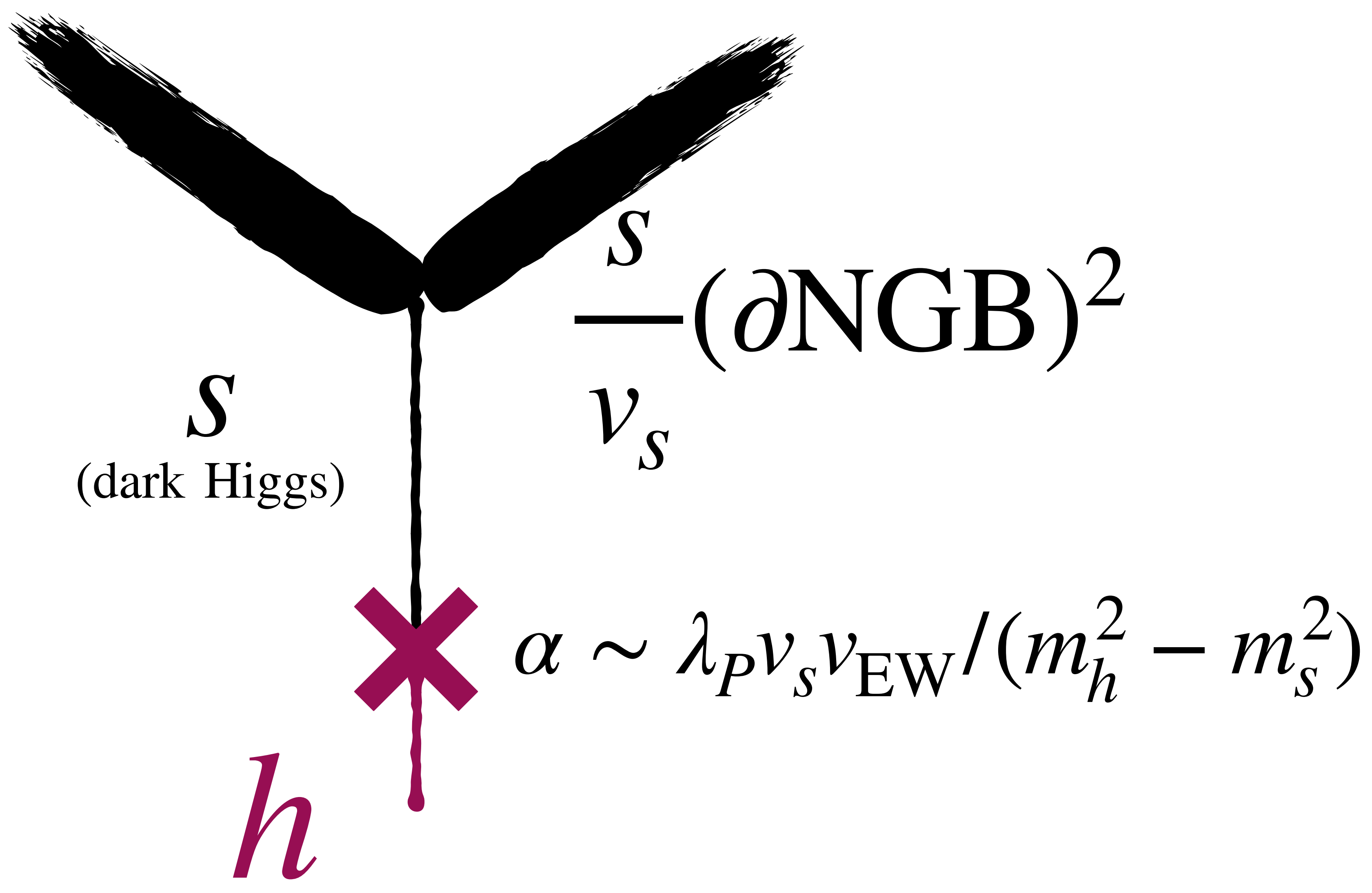
*Collider study Haghighat, Najafabadi, Sakurai, WY in progress

Naive estimate of the Higgs invisible decay

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

$$\supset \lambda_P v_s v_{\rm EW} s h$$

(would-be) NGB $\times 2$



Naively:

$$\Gamma_{h\to \rm darksector} \simeq \alpha^2 \Gamma_{s\to \rm darksector}$$

Naively:

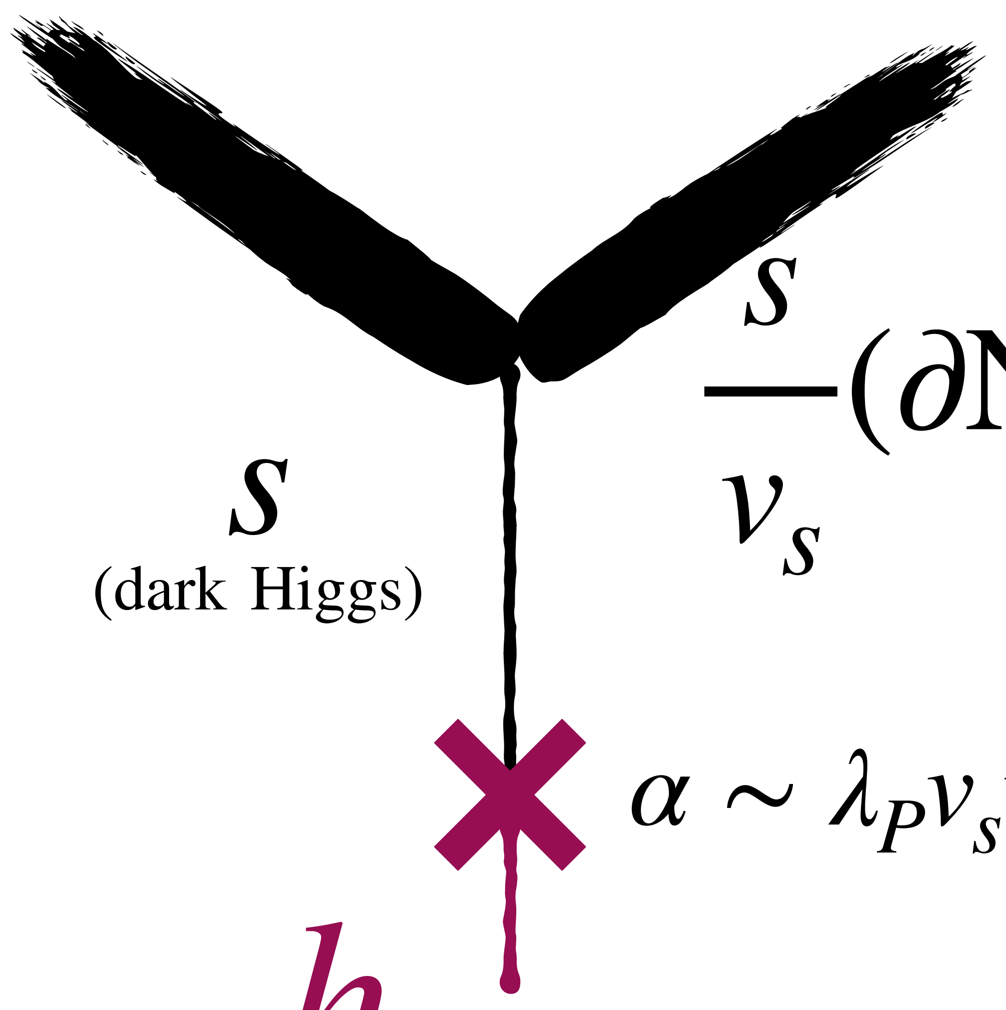
Signal strength $\kappa \simeq 1-\alpha^2$

Naive estimate of the Higgs invisible decay

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

$$\supset \lambda_P v_s v_{\rm EW} s h$$

(would-be) NGB $\times$ 2



s (dark Higgs)

$\dfrac{s}{v_s}(\partial \mathrm{NGB})^2$

$\alpha \sim \lambda_P v_s v_{\rm EW}/(m_h^2 - m_s^2)$

h

Naively:

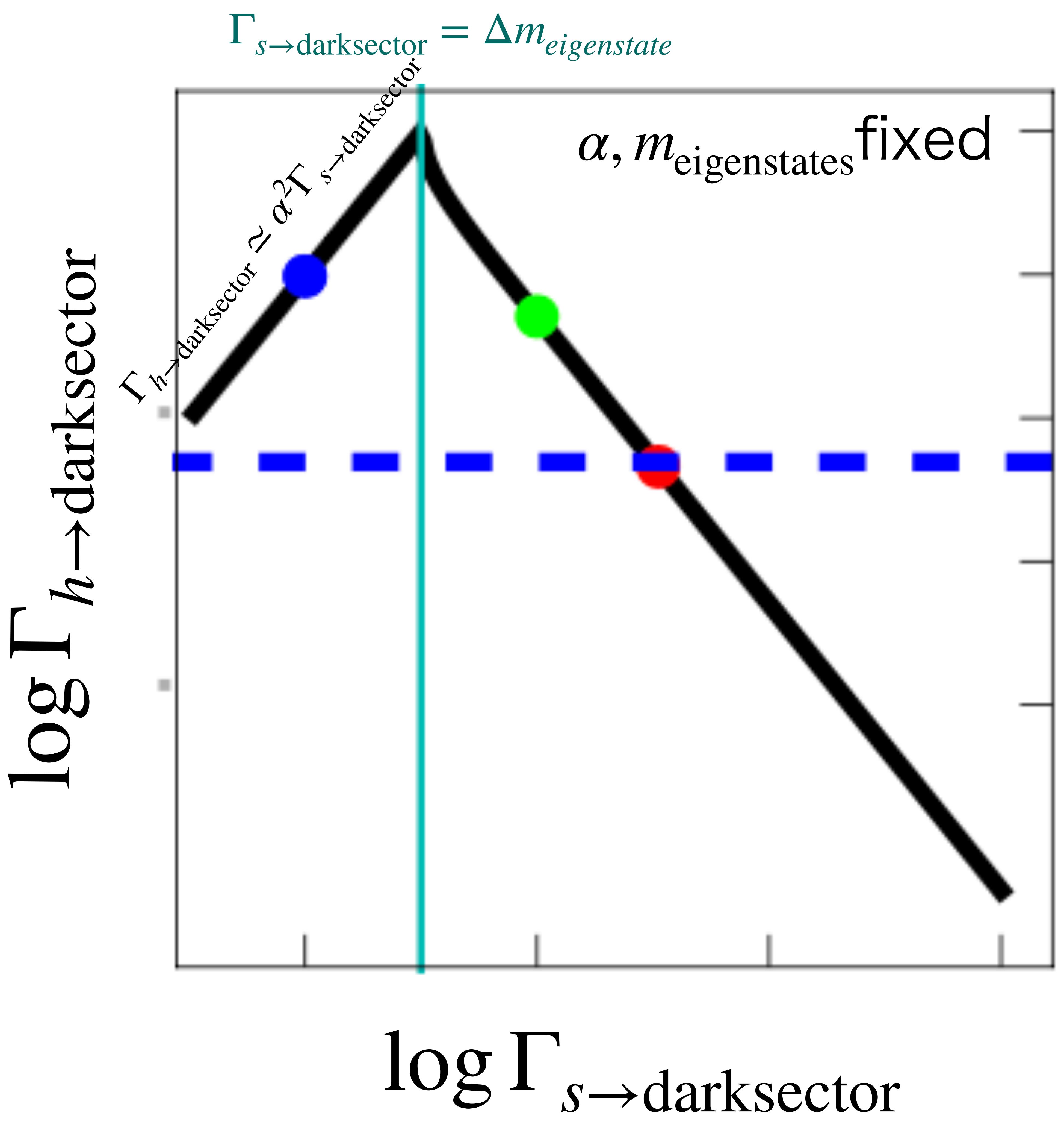
$\Gamma_{h\to \rm darksector} \simeq \ldots \Gamma_{s\to \rm darksector}$

Naively:

Signal strength $\kappa \ldots {}^2$

What I will talk about

Sakurai WY 2204.01739



★When $\Gamma_{s\to\mathrm{darksector}} > \Delta m_{eigenstate}$
the quantum Zeno effect is important.

★ On-shell Higgs boson
is not an eigenstate of the mass matrix but it is a superposition i.e. it is fuzzy.

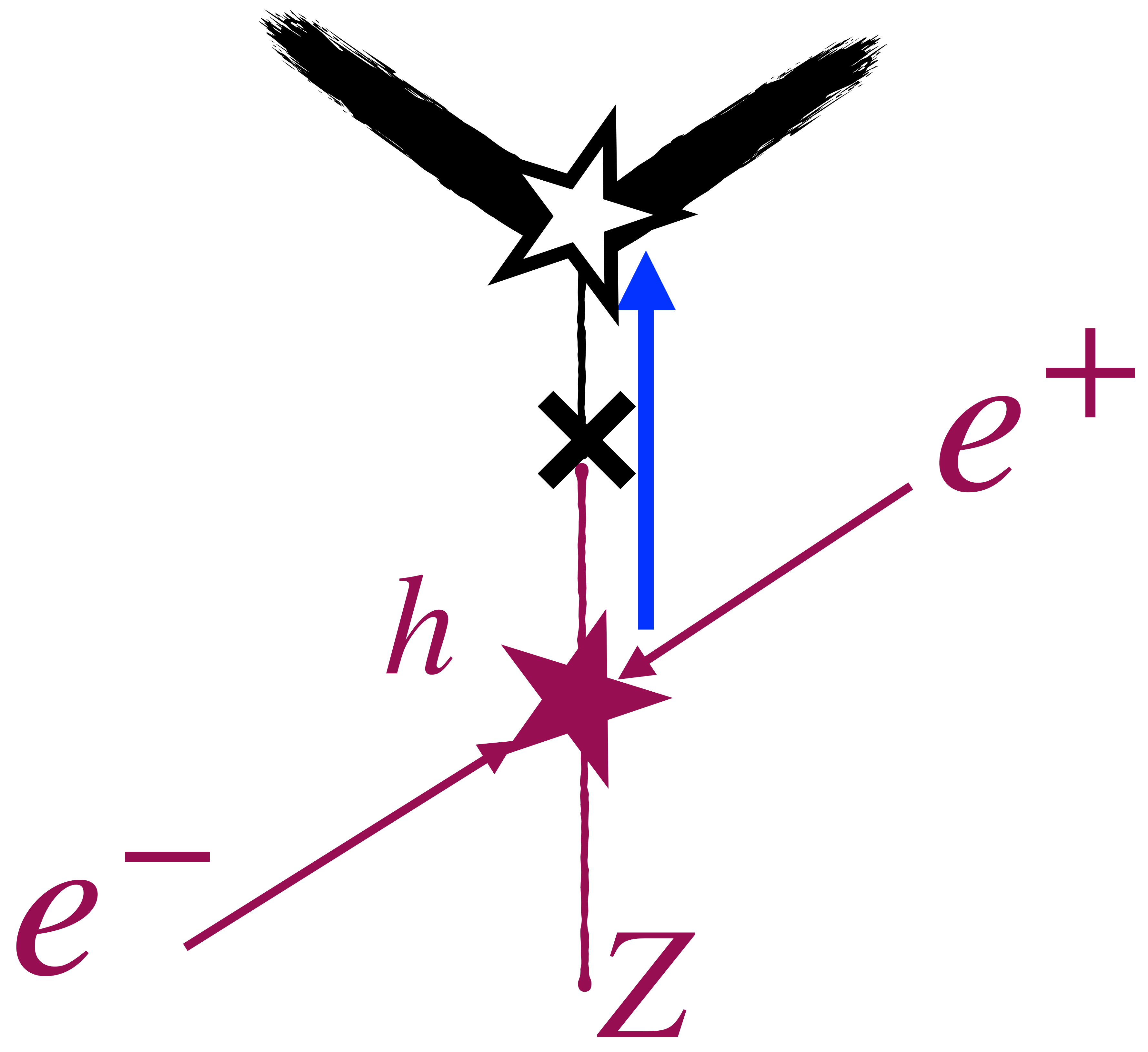
★The mixing effect is dynamically suppressed.
($\Gamma_{s\to darksector} \to \infty$, dark sector decouples)

2. Quantum mechanics of Higgs invisible decay

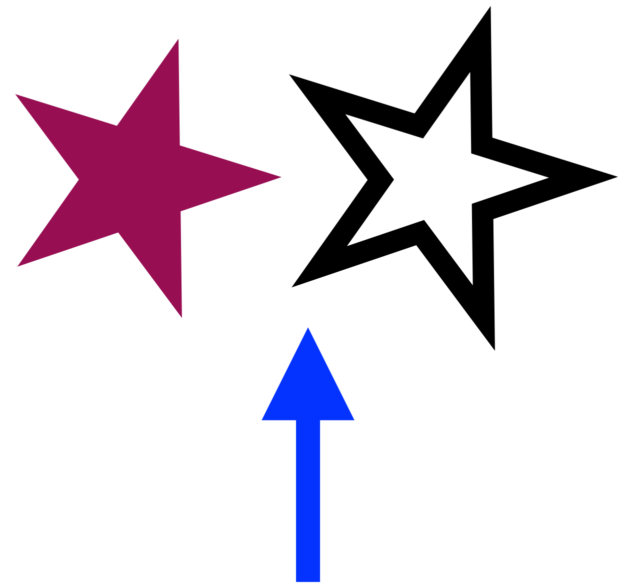
“Flavor” oscillation in Higgs invisible decay.

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

(would-be) NGB $\times 2$



In the production + decay process,
the interaction basis and mass basis are misaligned.

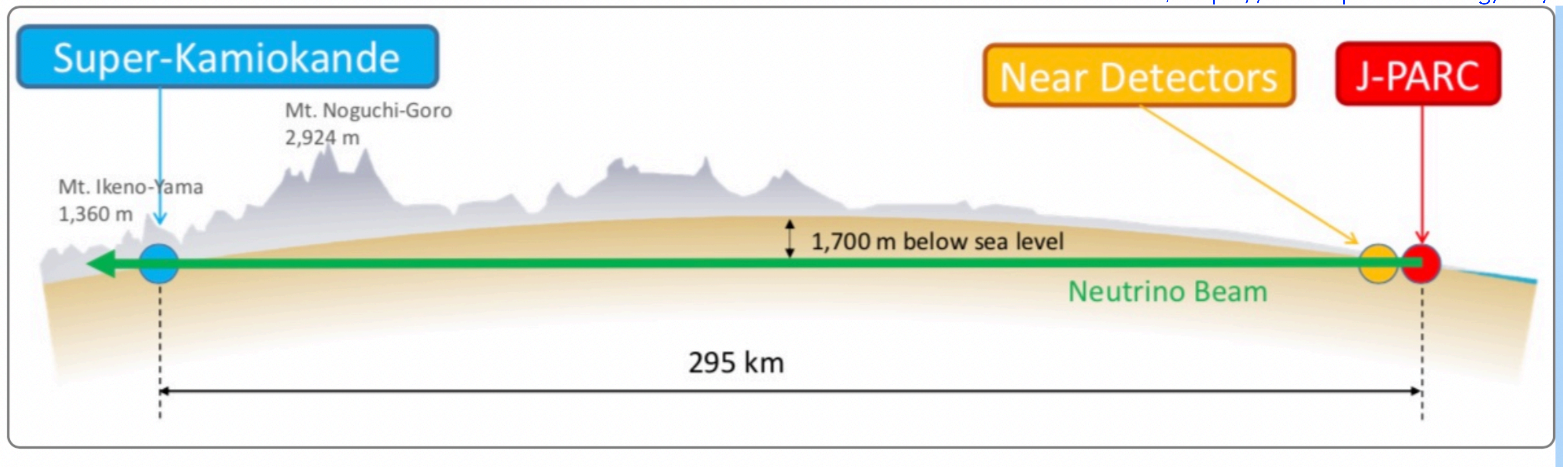


: Interaction basis, i.e. Interaction for doublet and singlet

: Mass basis

A similar setup is neutrino oscillation which is due to the misalignment of flavor basis and mass basis.

T2K collaboration, https://t2k-experiment.org/t2k/

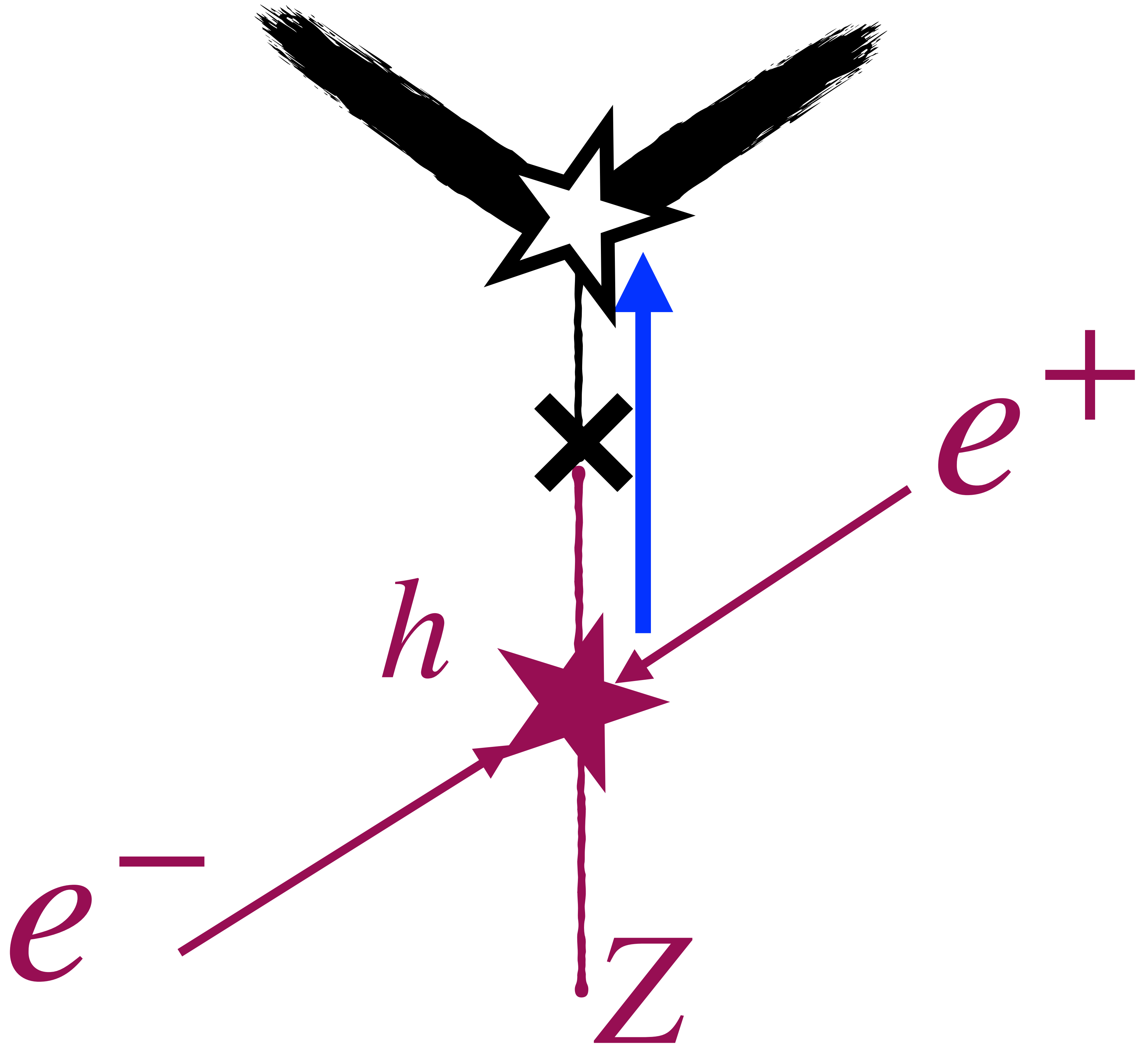


"Flavor" oscillation in Higgs invisible decay.

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

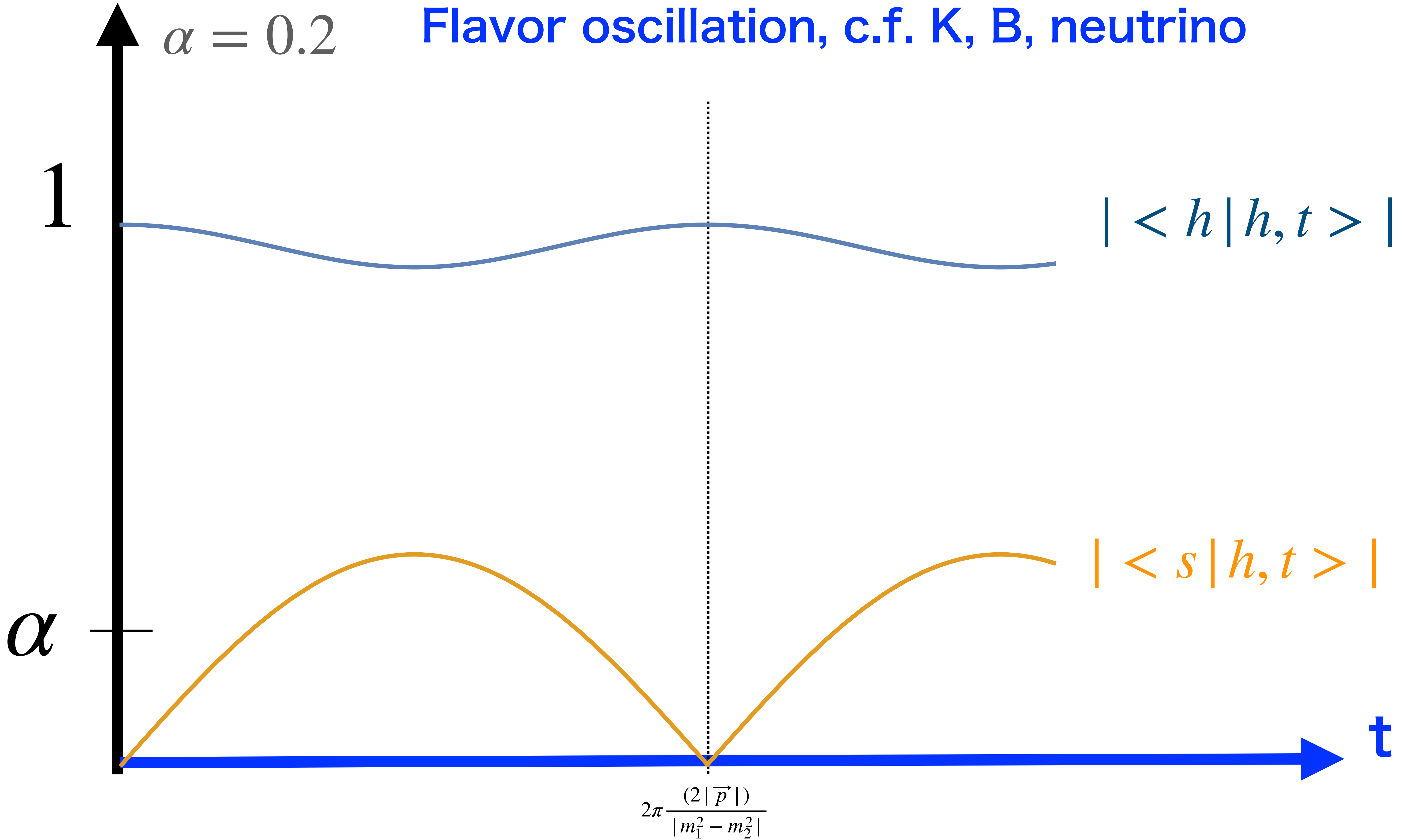
$$|h\rangle(= \cos\alpha|1\rangle + \sin\alpha|2\rangle)$$

(would-be) NGB $\times 2$



Solution of
schrodinger eq with free hamiltonian

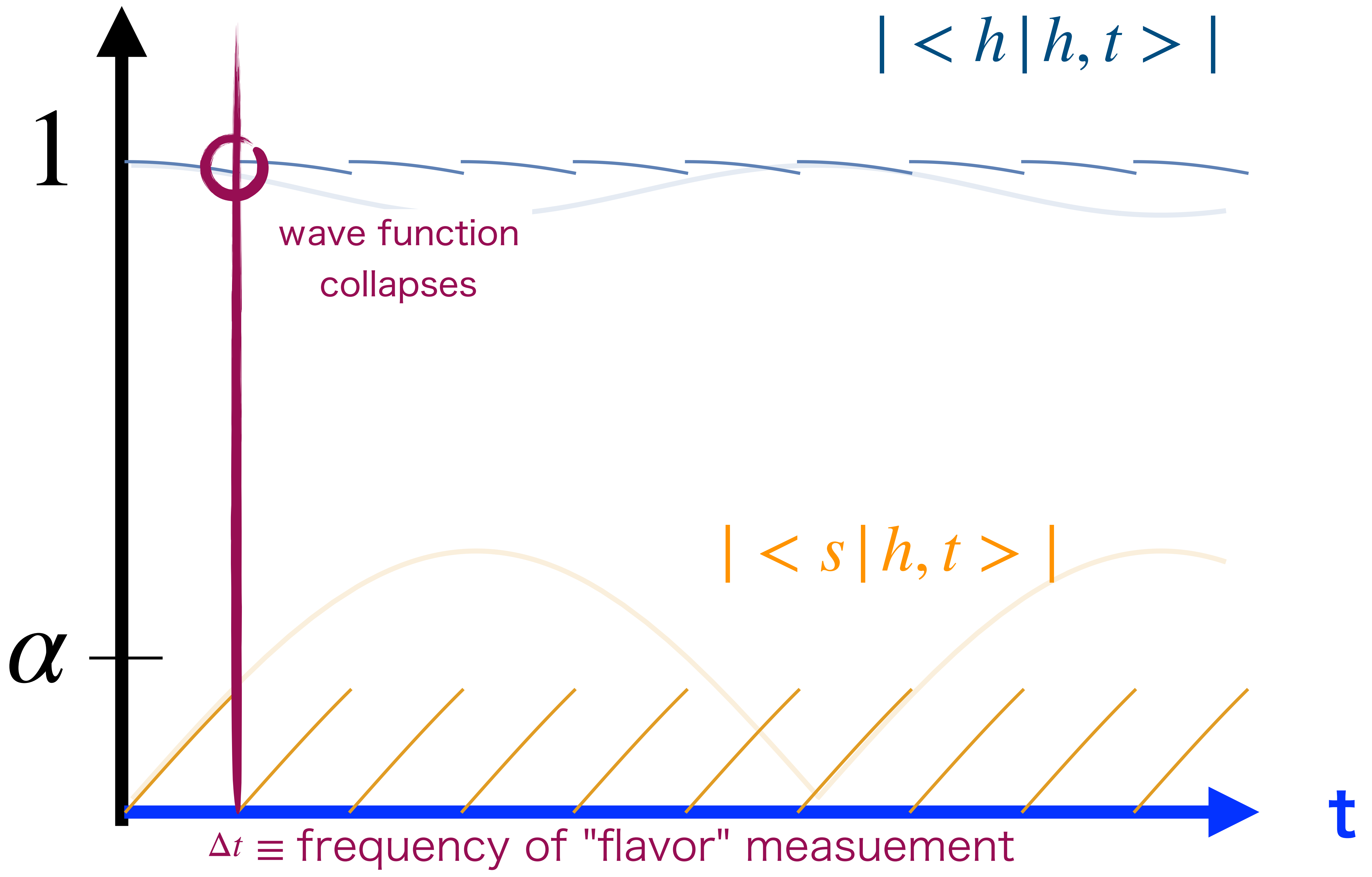
Flavor oscillation, c.f. K, B, neutrino



Quantum Zeno Effect with $\Gamma_{s\to dark} \gg |m_1 - m_2|$

e.g. Nakazato, Namiki, and Pascazio, quant-ph/9509016.

The quantum system with frequent measurements evolves in a subspace of the total Hilbert space.



(Sorry for very intuitive discussion)

Due to the s decay, the system decoheres at the timescale

$$t_{coh} \equiv \frac{|\vec{p}|}{\bar{m}}\frac{1}{\Gamma_s}.$$

In the vacuum, we may have $\Delta t \sim t_{\rm coh}$,

$$\Gamma_{h\to \rm dark} \propto \alpha^2 \frac{(m_1 - m_2)^2}{\Gamma^2_{s\to \rm dark}} \Gamma_{s\to \rm dark}.$$

The propagating mode

~``flavor" state, $|h\rangle (= \cos\alpha|1\rangle + \sin\alpha|2\rangle)$.

Thus, at $\Gamma_{s\to dark} \gg |m_1 - m_2|$, the produced Higgs is fuzzy i.e. propagating mode is a superposition of the mass states:

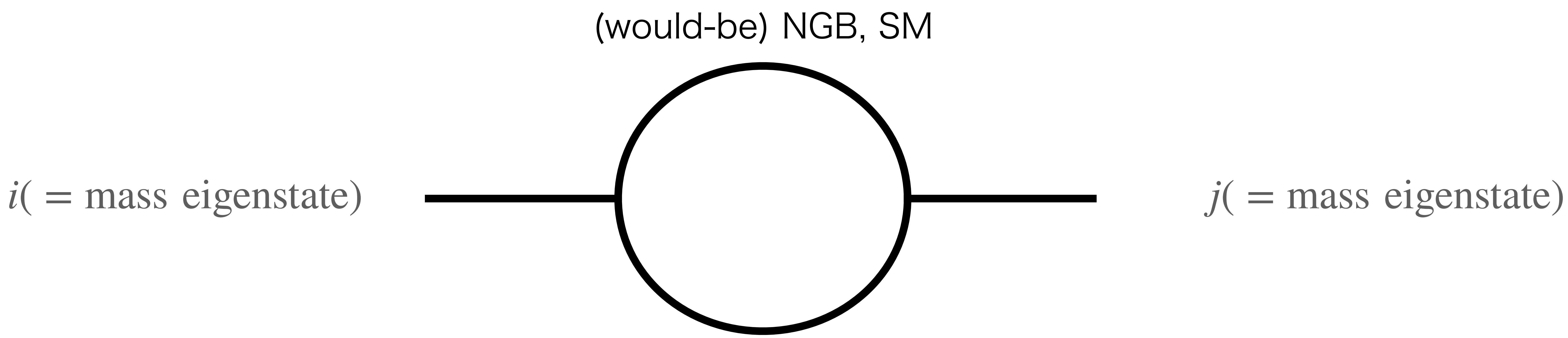
$$|h, \vec{p}\rangle = \cos\alpha\,|m_1, \vec{p}\rangle + \sin\alpha\,|m_2, \vec{p}\rangle$$

$$\bar{E}_h \simeq \langle h, \vec{p}\,|\hat{H}_{\rm free}|\,h, \vec{p}\rangle \simeq |\vec{p}\,| + \frac{m_1^2\cos^2\alpha + m_2^2\sin^2\alpha}{2|\vec{p}\,|}.$$

$$m_{h,\rm eff}^2 = m_1^2\cos\alpha^2 + m_2^2\sin\alpha^2$$

3. QFT justification and property of fuzzy higgs boson

In QFT, a resummation reproduces previous results.



$$\hat{\Pi}_{ij} \simeq \frac{i}{32\pi v_s^2}\begin{pmatrix} \sin^2(\alpha) m_1^4 & \sin\alpha\cos\alpha m_1^2 m_2^2 \\ \sin\alpha\cos\alpha m_1^2 m_2^2 & \cos^2(\alpha) m_2^4 \end{pmatrix}$$

Propagator in "flavor" basis ($\alpha, \beta = h, s$) is

Pilaftsis, 9702393, Arkani-Hamed, et al 9704205; Cacciapaglia, Deandrea, Curtis, 0906.3417;

$$\hat{\Delta}_{\alpha,\beta} = iR \cdot \begin{pmatrix} Q^2 - m_1^2 + \hat{\Pi}_{11} & \hat{\Pi}_{12} \\ \hat{\Pi}_{21} & Q^2 - m_2^2 + \hat{\Pi}_{22} \end{pmatrix}^{-1} \cdot R^T$$

Analytic check of $\hat{\Delta}_{hh}$.

Sakurai WY 2204.01739

$$\epsilon \equiv m_1^2 - m_2^2, m_{\rm eff} \equiv \sqrt{\cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2}$$

$$\Gamma_{s\to{\rm dark}} \sim \frac{m_{\rm heff}^3}{32\pi v_s^2}$$

By expanding $\frac{\epsilon}{m_{\rm heff}\Gamma_{s\to dark}}$ and assuming perturbativity, we obtain

$$\hat{\Delta}_{hh} \simeq \frac{i(Q^2 - m_{\rm heff}^2 + \epsilon\cos(2\alpha) + i\frac{m_{\rm heff}^4}{32\pi v_s^2}) + O(\frac{\epsilon^2}{\Gamma_s^2 m_{heff}^2})}{(Q^2 - m_{\rm heff}^2 + \epsilon\cos(2\alpha) + i\frac{m_{\rm heff}^4}{32\pi v_s^2})(Q^2 - m_{\rm heff}^2 + i\frac{8\pi\epsilon^2\sin^2(2\alpha)v_s^2}{m_{\rm heff}^4})}.$$

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By expanding $\frac{\epsilon}{m_{\text{heff}}\Gamma_{s\to dark}}$ and assuming perturbativity, we obtain

$$\hat{\Delta}_{hh} \simeq \frac{i(1-\sin^2(2\alpha)\frac{\epsilon^2}{4\Gamma_{s\to\text{dark}}[m_{\text{heff}}]^2 m_{\text{heff}}^2})}{Q^2 - m_{\text{heff}}^2 + i\frac{\epsilon^2\sin(2\alpha)^2}{4m_{\text{heff}}^2\Gamma_{s\to dark}[m_{\text{heff}}]}m_{\text{heff}}}$$

★ We get a single-pole propagator!

$$\hat{\Delta}_{hh} \simeq \frac{i\left(1 - \sin^2(2\alpha)\frac{\epsilon^2}{4\Gamma_{s\to\text{dark}}[m_{\text{heff}}]^2 m_{\text{heff}}^2}\right)}{Q^2 - m_{\text{heff}}^2 + i\frac{\epsilon^2 \sin(2\alpha)^2}{4m_{heff}^2 \Gamma_{s\to dark}[m_{heff}]} m_{heff}}$$

Fuzzy Higgs Property

Mass

$$m_{heff}^2 = \cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2$$

Invisible decay rate

$$\Gamma_{heff\to\text{dark}} \simeq \frac{\epsilon^2 \sin(2\alpha)^2}{4m_{heff}^2 \Gamma_{s\to\text{dark}}[m_{heff}]}$$

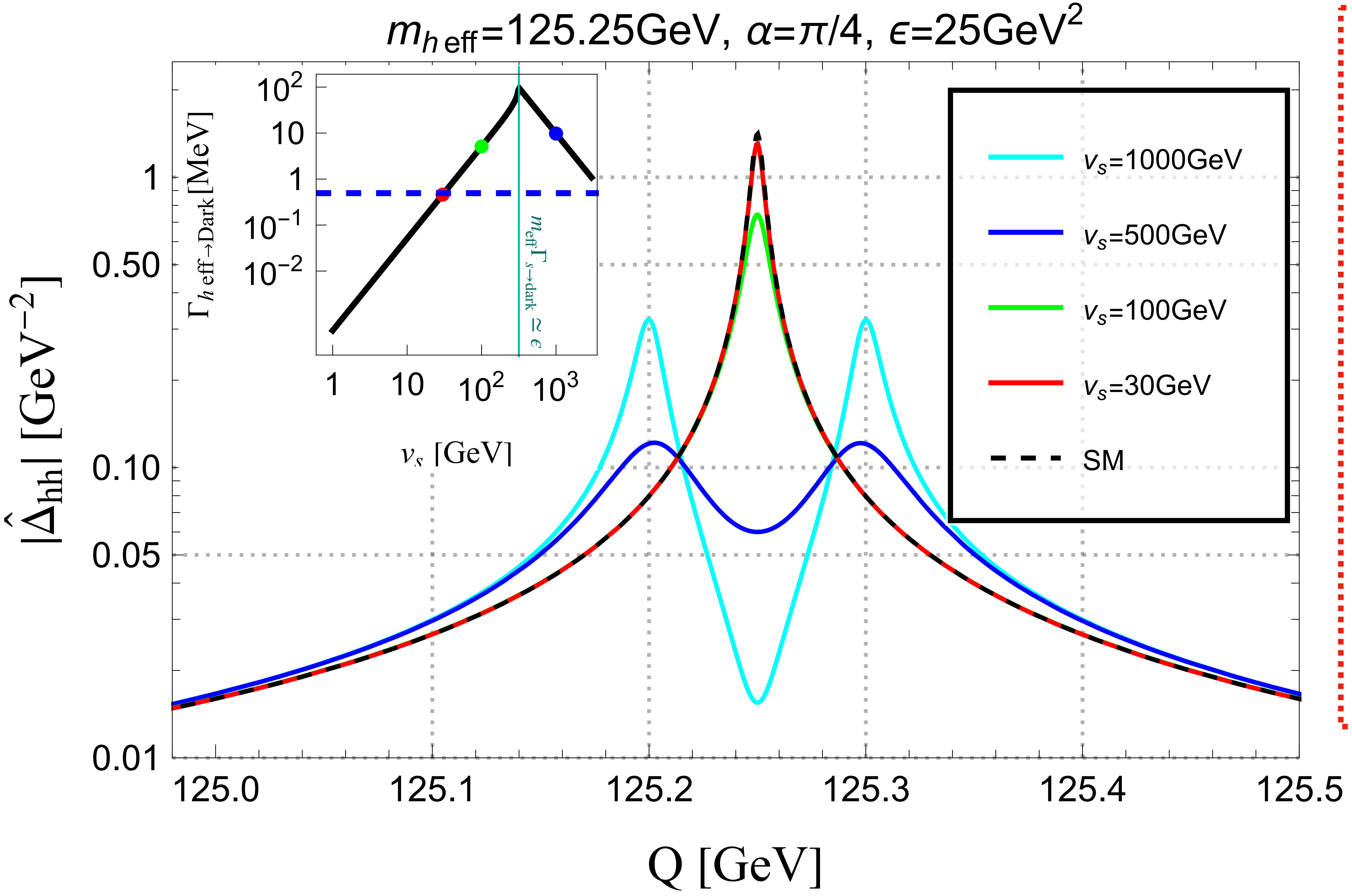
Mixing (deviation of Higgs coupling)

$$\sin[2\alpha_{\text{eff}}] \simeq \frac{\epsilon \sin(2\alpha)}{m_{heff}\Gamma_s[m_{heff}]}$$

Numerical check of $\hat{\Delta}_{hh}$.

$$\epsilon \equiv m_1^2 - m_2^2, m_{h\text{eff}} \equiv \sqrt{\cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2}$$

$$\Gamma_{s\to\text{dark}} \sim \frac{m_{h\text{eff}}^3}{32\pi v_s^2}$$



By increasing $\Gamma_{s\to\text{dark}}$,

1.

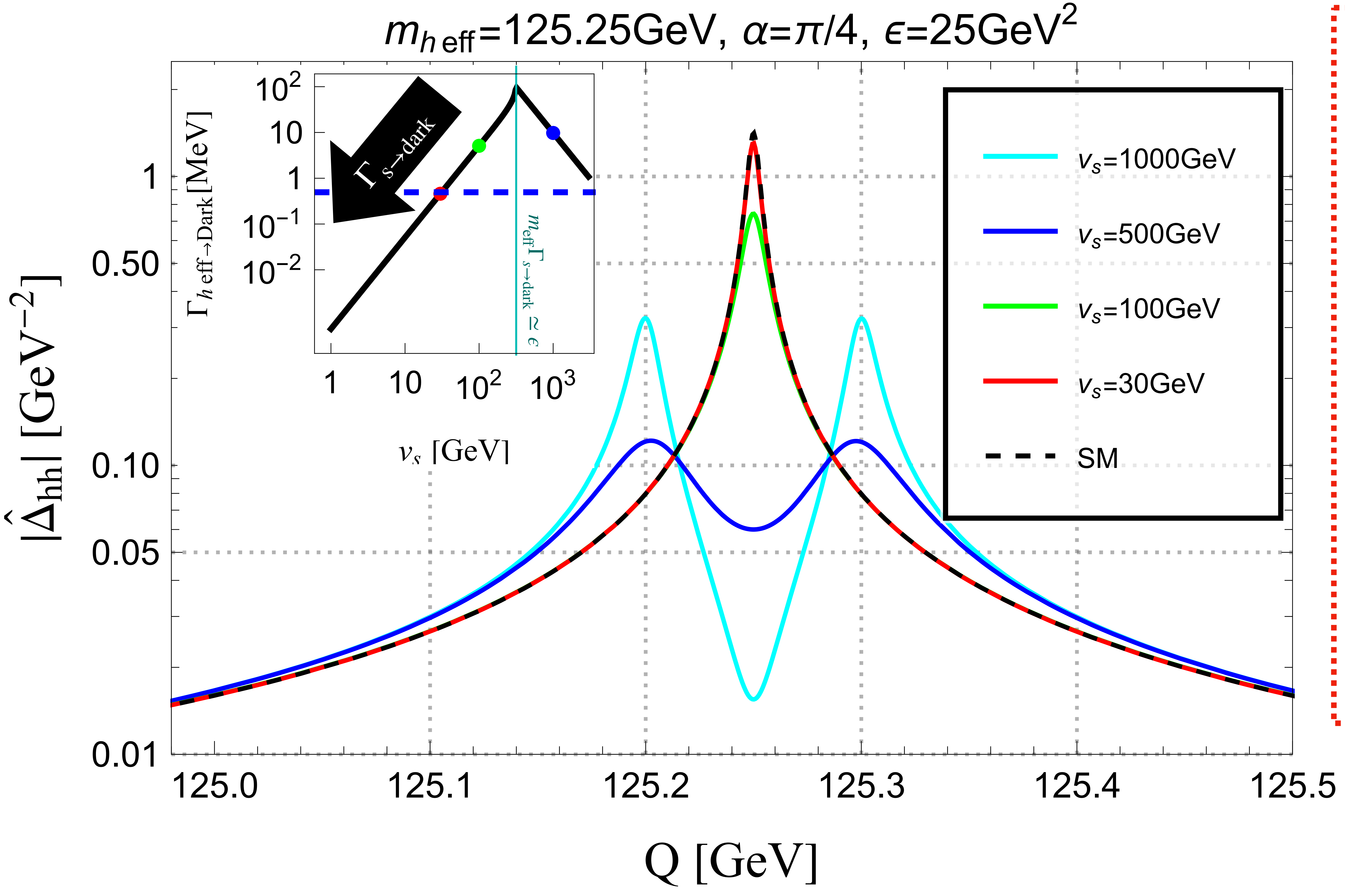
2.

3.

Numerical check of $\hat{\Delta}_{hh}$.

$\epsilon \equiv m_1^2 - m_2^2, m_{h\text{eff}} \equiv \sqrt{\cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2}$

$$\Gamma_{s\to\text{dark}} \sim \frac{m_{h\text{eff}}^3}{32\pi v_s^2}$$



By increasing $\Gamma_{s\to\text{dark}}$,

1. $\Gamma_{\text{h}\to\text{dark}}$ gets suppressed.

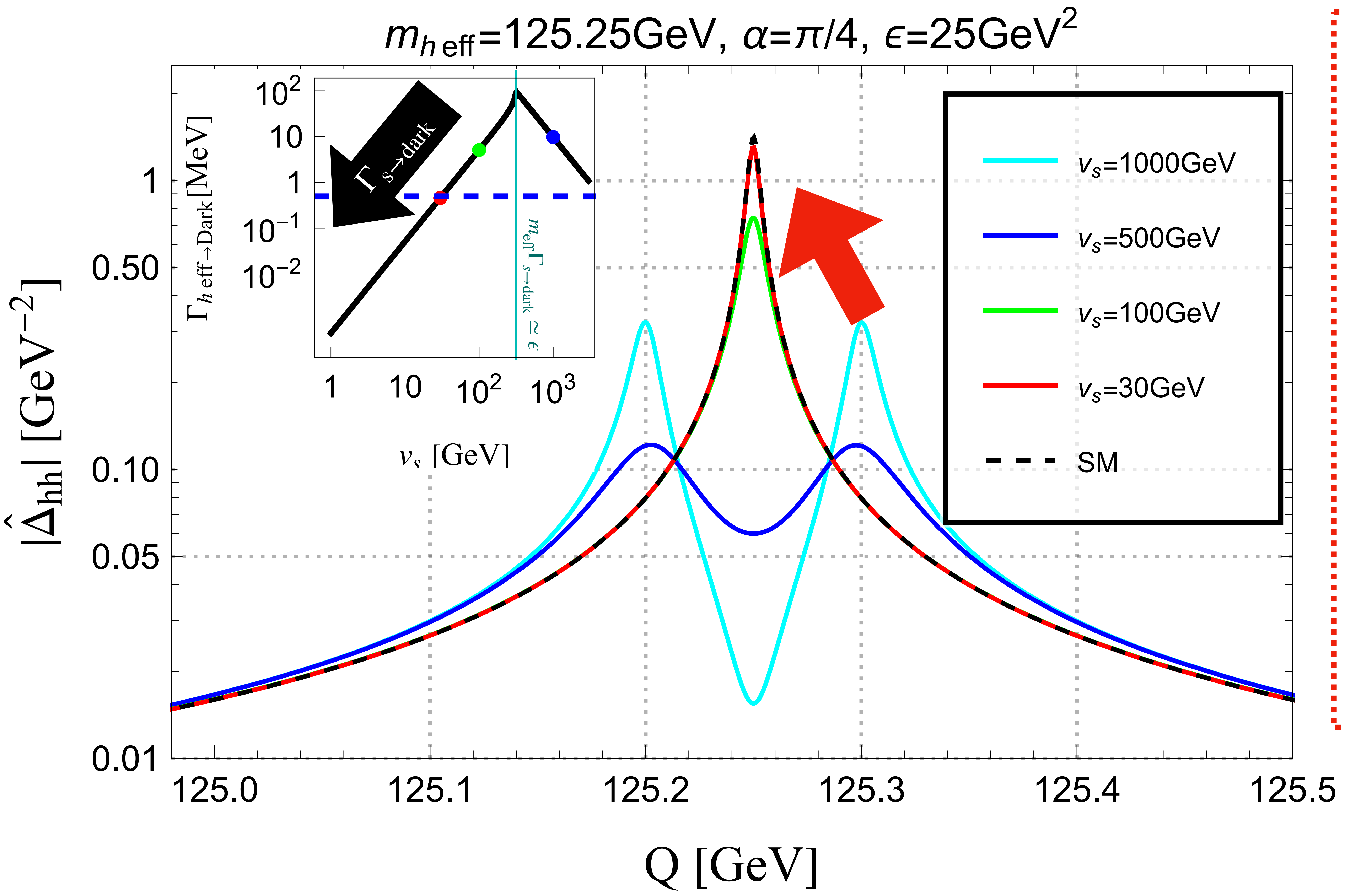
2.

3.

Numerical check of $\hat{\Delta}_{hh}$.

$$\epsilon \equiv m_1^2 - m_2^2, m_{h\text{eff}} \equiv \sqrt{\cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2}$$

$$\Gamma_{s\to\text{dark}} \sim \frac{m_{h\text{eff}}^3}{32\pi v_s^2}$$



By increasing $\Gamma_{s\to\text{dark}}$,

1. $\Gamma_{\text{h}\to\text{dark}}$ gets suppressed.
2. two poles approach to 1.
3.

Numerical check of $\hat{\Delta}_{hh}$.

$$\epsilon \equiv m_1^2 - m_2^2, m_{heff} \equiv \sqrt{\cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2}$$

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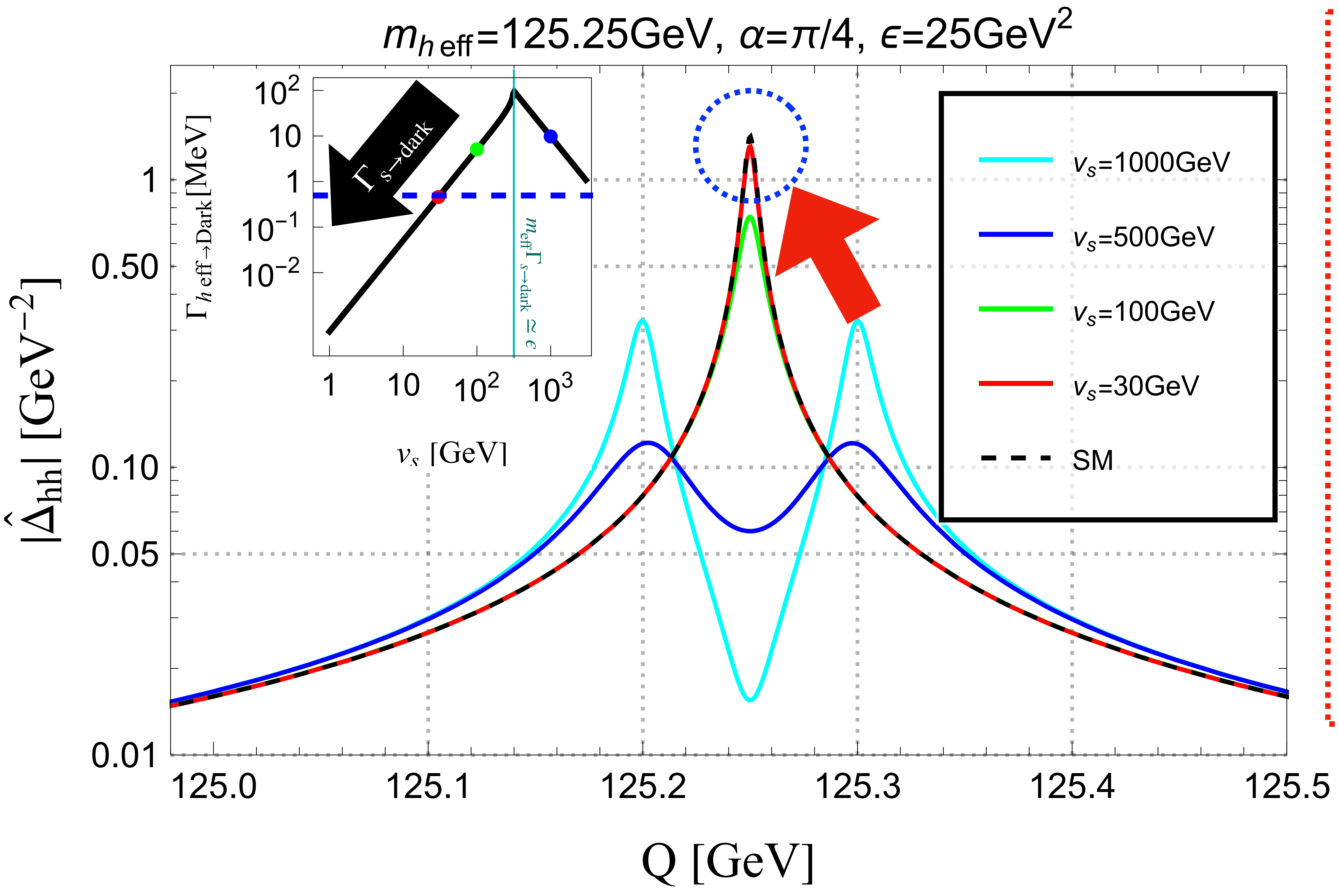
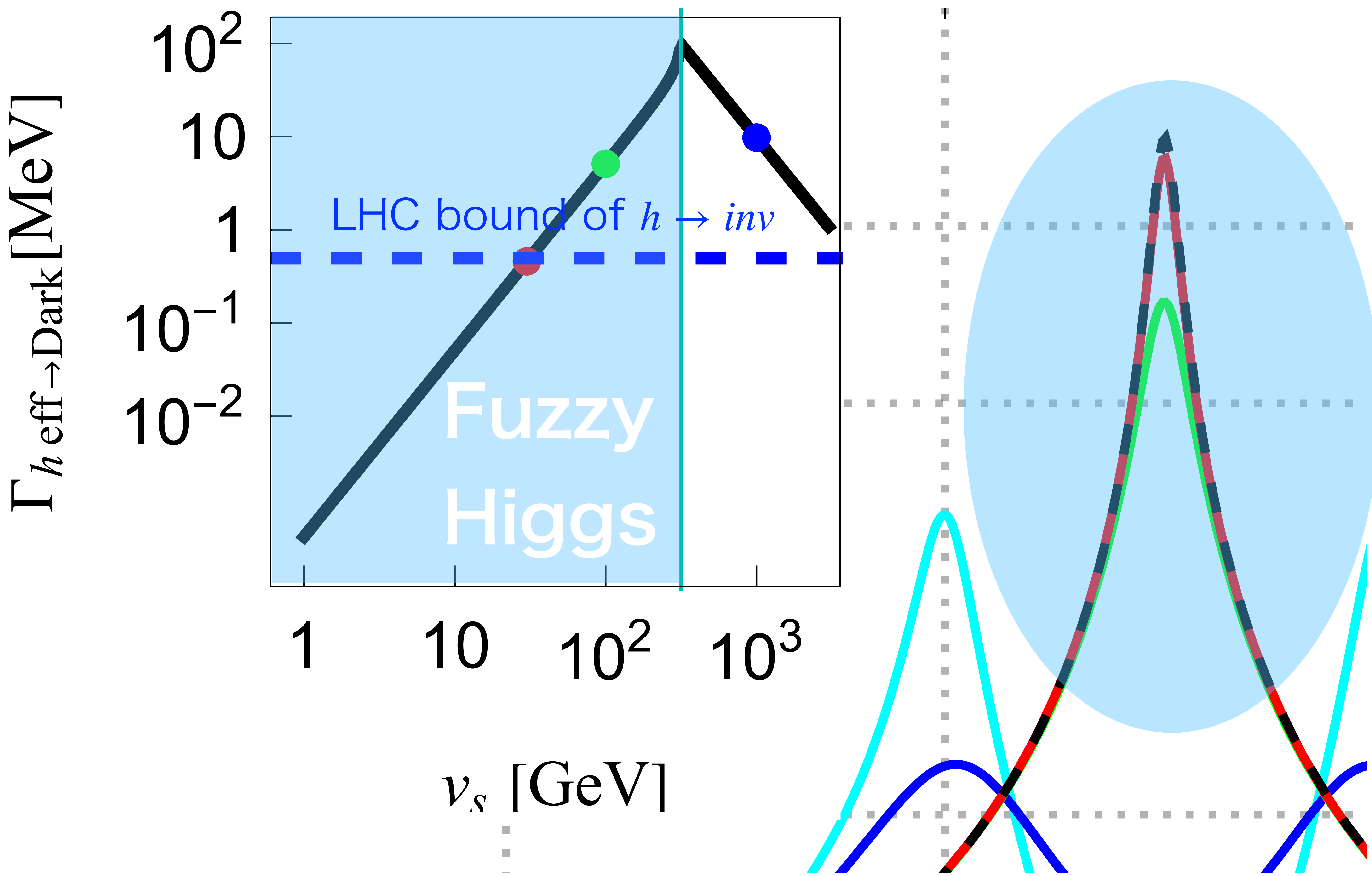


By increasing $\Gamma_{s\to\text{dark}}$,

1. $\Gamma_{h\to\text{dark}}$ gets suppressed.
2. two poles approach to 1.
3. $\hat{\Delta}_{hh}$ approaches to that of SM Higgs boson by taking $m_{heff} = 125.25\,GeV$.

Fuzzy Higgs Boson scenario ($\Gamma_{s\to dark} > |m_1 - m_2|$) is alive.

$$\epsilon \equiv m_1^2 - m_2^2, m_{heff} \equiv \sqrt{\cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2}$$



LHC bound for fuzzy higgs boson scenario

$$m_{heff} \simeq 125\, GeV$$

$$\Gamma_{heff\to dark} \simeq \frac{\epsilon^2 \sin(2\alpha)^2}{4m_{heff}^2 \Gamma_{s\to dark}[m_{heff}]} \lesssim MeV$$

$$\sin[2\alpha_{eff}] \simeq \frac{\epsilon \sin(2\alpha)}{m_{heff}\Gamma_s[m_{heff}]} \lesssim O(0.1)$$

Fuzzy higgs boson scenario is in the regime

$|m_1 - m_2| < O(0.1)(O(10))GeV$

for $\alpha = O(1), (O(0.001))$ by imposing perturbative unitarity.

The parameter region is larger for the strongly-coupled dark sector.

Conclusions:

Sakurai WY 2204.01739

Light dark sector extension, if natural, may be probed by Higgs invisible decay in the colliders model independently. Thus the precise study is important. We found

★ **When $\Gamma_{s\to\mathrm{darksector}} > \Delta m_{eigenstate}$ we should use the following properties to study the Higgs Boson rather than the usual naive estimate.**

Fuzzy Higgs Property

Mass

$$m_{heff}^2 = \cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2$$

Invisible decay rate

$$\Gamma_{heff\to\mathrm{dark}} \simeq \frac{\epsilon^2 \sin(2\alpha)^2}{4 m_{heff}^2 \Gamma_{s\to\mathrm{dark}}[m_{heff}]}$$

Mixing (deviation of Higgs coupling)

$$\sin[2\alpha_{\mathrm{eff}}] \simeq \frac{\epsilon \sin(2\alpha)}{m_{heff}\Gamma_s[m_{heff}]}$$

Fuzzy Englert and Higgs

Thank you very much!

Conclusions:

Sakurai WY 2204.01739

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Fuzzy Higgs Property

Mass

$$m_{\mathrm{heff}}^2 = \cos\alpha^2 m_1^2 + \sin\alpha^2 m_2^2$$

Invisible decay rate

$$\Gamma_{\mathrm{heff}\to\mathrm{dark}} \simeq \frac{\epsilon^2 \sin(2\alpha)^2}{4m_{\mathrm{heff}}^2 \Gamma_{s\to\mathrm{dark}}[m_{\mathrm{heff}}]}$$

Mixing (deviation of Higgs coupling)

$$\sin[2\alpha_{\mathrm{eff}}] \simeq \frac{\epsilon \sin(2\alpha)}{m_{\mathrm{heff}}\Gamma_s[m_{\mathrm{heff}}]}$$

backup

Possible applications.

Degenerate scalar scenario

When dark higgs masses are similar, some parameter space
for WIMP and EWPT will open.

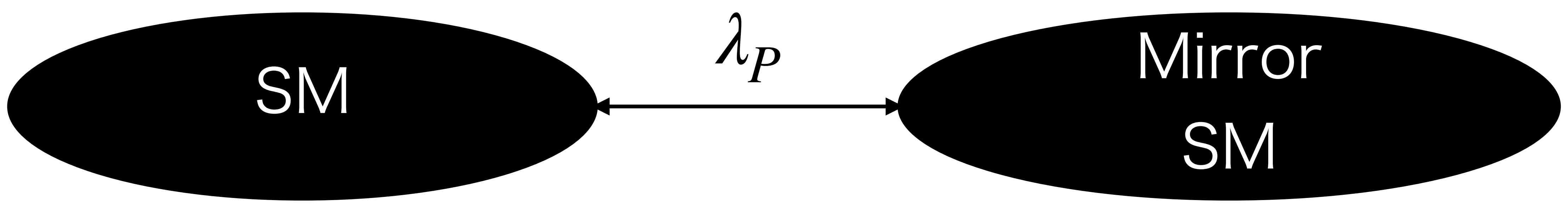
WIMP DM, Abe, Cho, Mawatari, 2101.04887
EWPT, Cho, Idegawa, Senaha 2105.11830

Degenerate scalars with $\Delta m \gtrsim 0.1\mathrm{GeV}$
can be distinguished at ILC Abe, Cho, Mawatari, 2101.04887

In the fuzzy Higgs region, the degenerate scalars cannot be distinguished. But it is probed by the Higgs invisible decay also at the ILC. Sakurai WY 2204.01739

Exact Z_2 mirror symmetry

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\mathrm{mirror\ SM}} - \lambda_P |H|^2 |H_{\mathrm{mirror}}|^2$$



Relevant to fine-tuning problems or lighter QCD axion. Hook 1802.10093

$\Gamma_h = \Gamma_{mirrorh} \sim 4\mathrm{MeV},\ m_h \simeq m_{mirrorh} = 125.25GeV, \alpha = \pi/4.$

In this case, the Higgs coupling deviation of $\kappa_X = \cos(2\alpha_{\mathrm{eff}})$
can be also probed together with invisible decay.

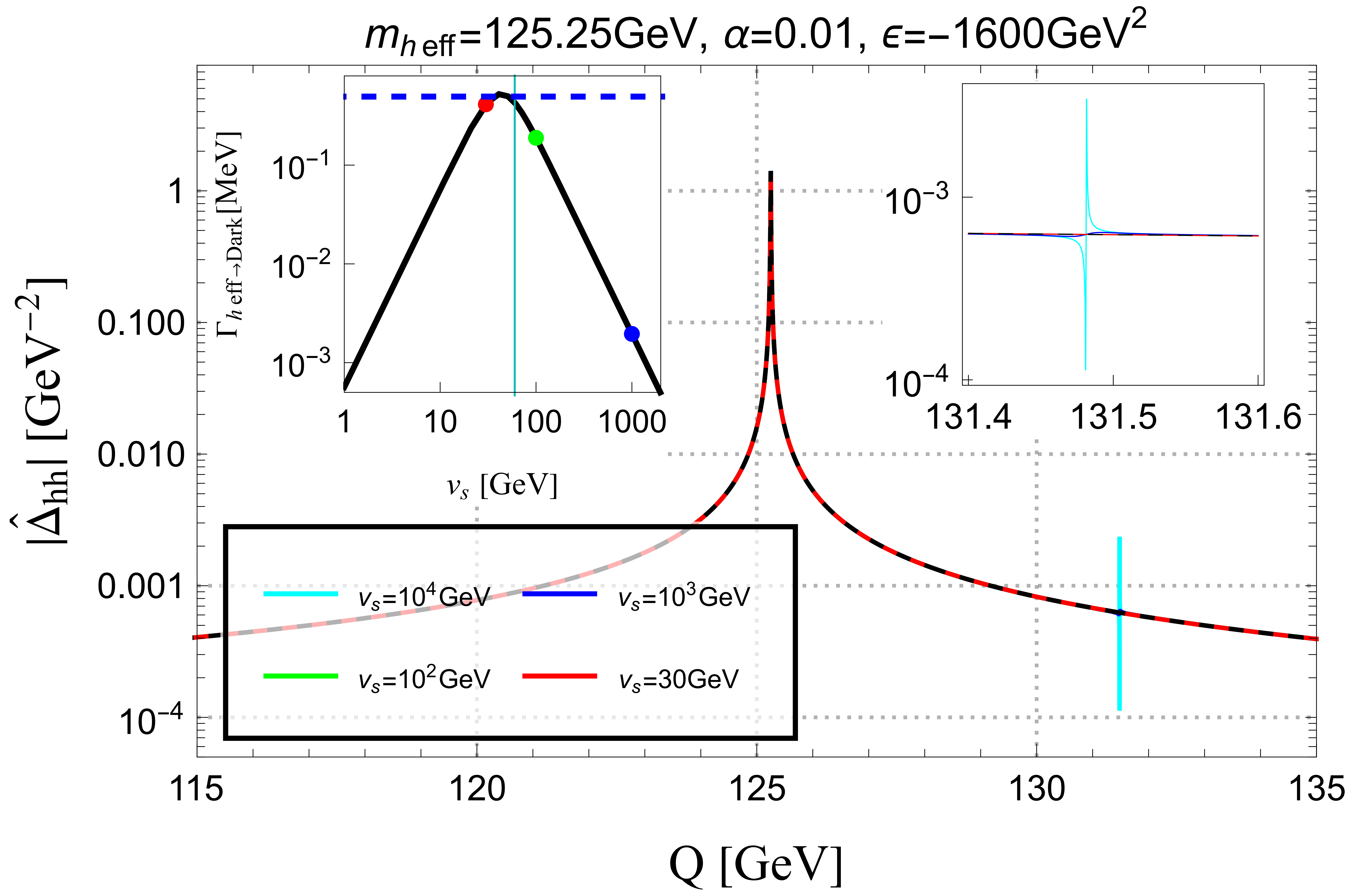
Sakurai WY 2204.01739

Strongly coupled dark sector

Go beyond perturbative unitarity. If $\Gamma_{s\to dark}$ can be arbitrarily large, fuzzy Higgs boson is realized with arbitrary $|m_1 - m_2|$
and thus generically realized.

Extention to dark scalar phenomena

Mixed axions with one component decay very fast has the other component stabilized.



$m_{h\,\mathrm{eff}}$=125.25GeV, α=0.01, ϵ=−1600GeV^2
$|\hat{\Delta}_{\mathrm{hh}}|$ [GeV^{-2}]
Q [GeV]
$\Gamma_{h\,\mathrm{eff}\to\mathrm{Dark}}$[MeV]
v_s [GeV]
v_s=10^{4}GeV
v_s=10^{3}GeV
v_s=10^{2}GeV
v_s=30GeV

Solution to kinetic equations.
(It is used in neutrino oscillations)

Sigl, Raffelt, 1993

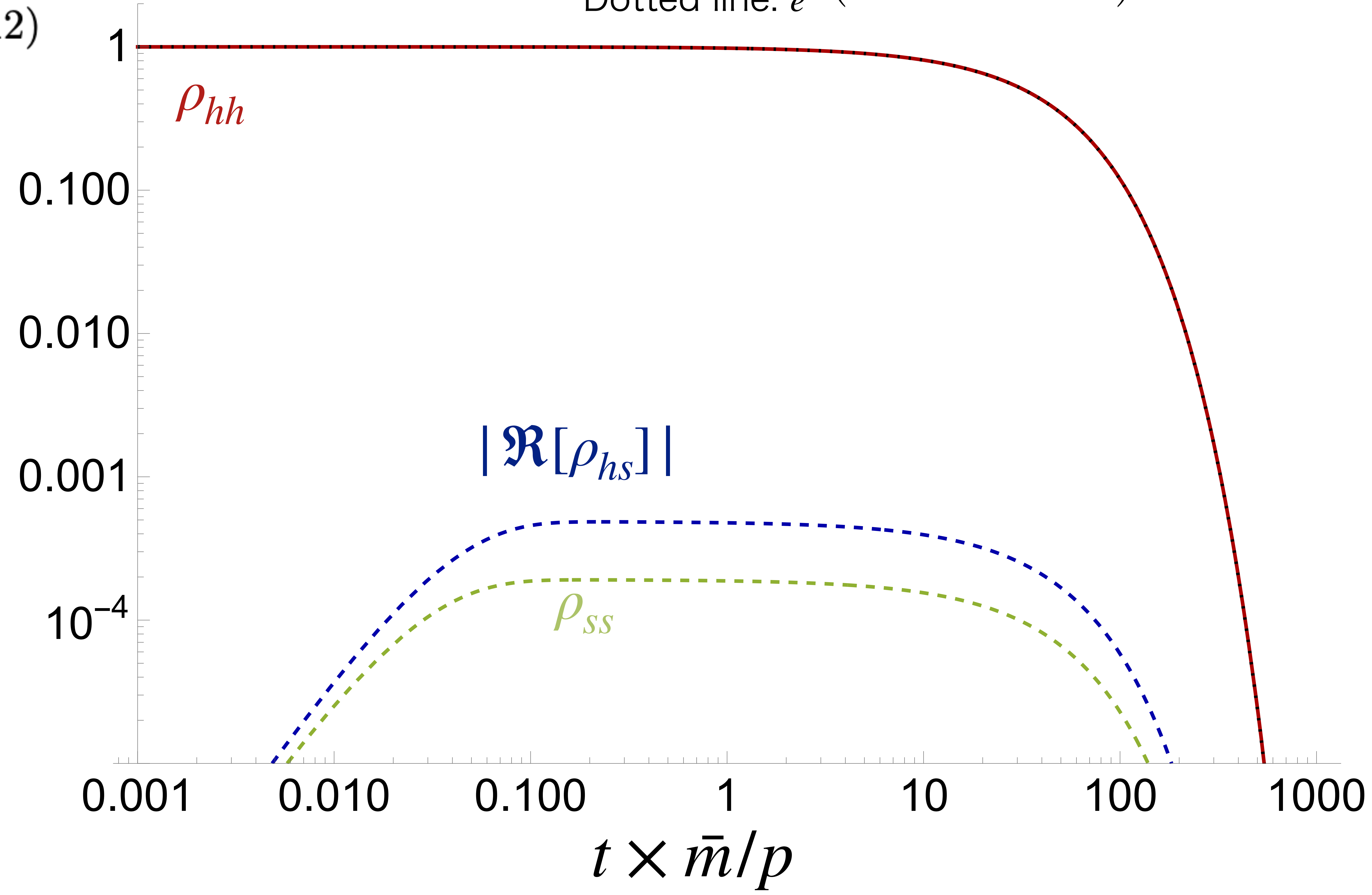
$$i\frac{d\rho}{dt} = [\Omega_{\vec{p}}, \rho] - \frac{i}{2}\{\Gamma^d_{\vec{p}}, \rho\}, \qquad (12)$$

Mass mixing   Decay

The second term is of the same form for neutrino oscillation scattering with the medium i.e. the measurement. Thus I define the decay as a measurement.

$\frac{m_2^2 - m_1^2}{\bar{m}\Gamma_s} \approx 0.05$

Dotted line: $e^{-\left(\sin(2\alpha)^2\left(\frac{m_1^2 - m_2^2}{2\Gamma_s \bar{m}}\right)^2 \Gamma_s + \Gamma_h\right)\frac{\bar{m}}{p}t}$

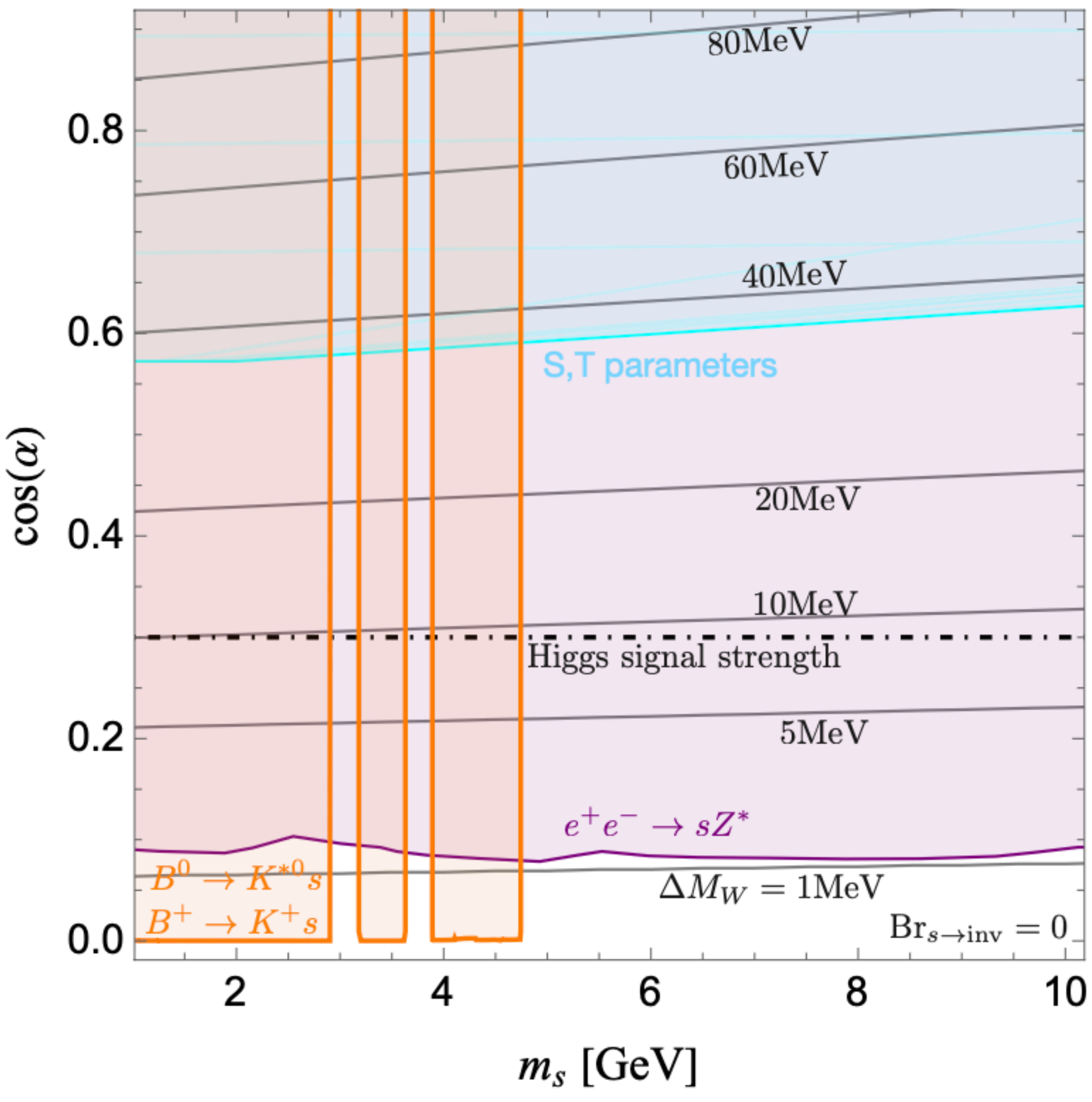


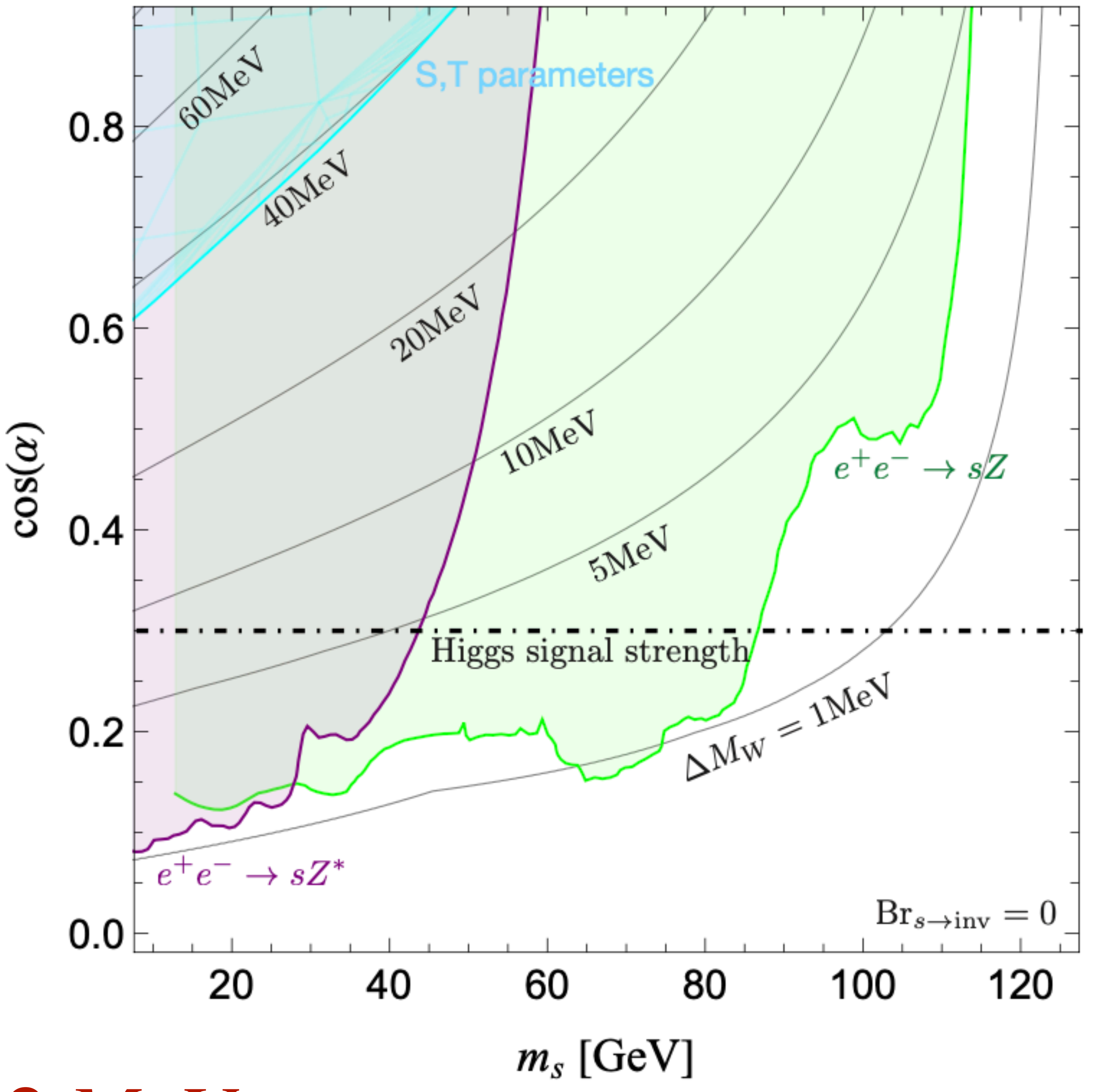
W-boson mass shift

Takahashi, Sakurai, WY 2204.04770

$s \to visible$ (No light dark sector)

Takahashi, Sakurai, WY 2204.04770

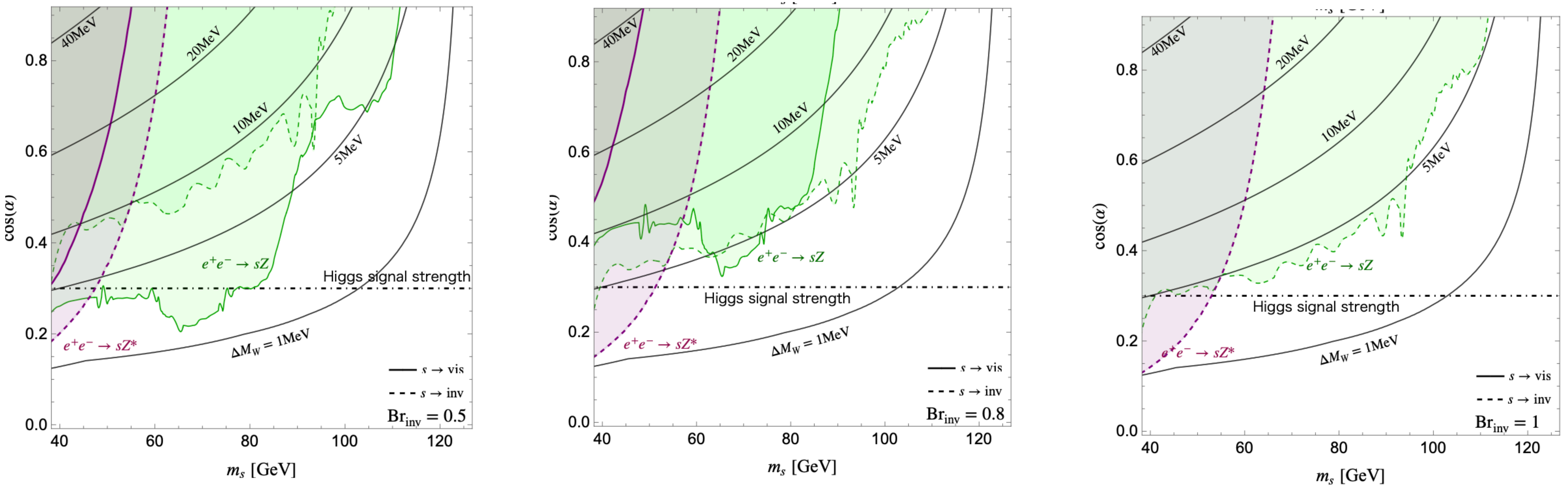




$\Delta M_W < 2\,MeV$

$s \to visible, invisible$

Takahashi, Sakurai, WY 2204.04770



$\Delta M_W < 4\,MeV$ ∴ CDF-II result cannot be explained.

It can relax the tension without CDF results.

Prediction: increasing the W-boson mass shift beyond 2MeV induces 125GeV Higgs Boson invisible decay via mixing.

3. CP-even ALP from generic CPV

Kodai Sakurai, WY 2111.03653

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Couplings of the CP-even ALP

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

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

- 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.

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

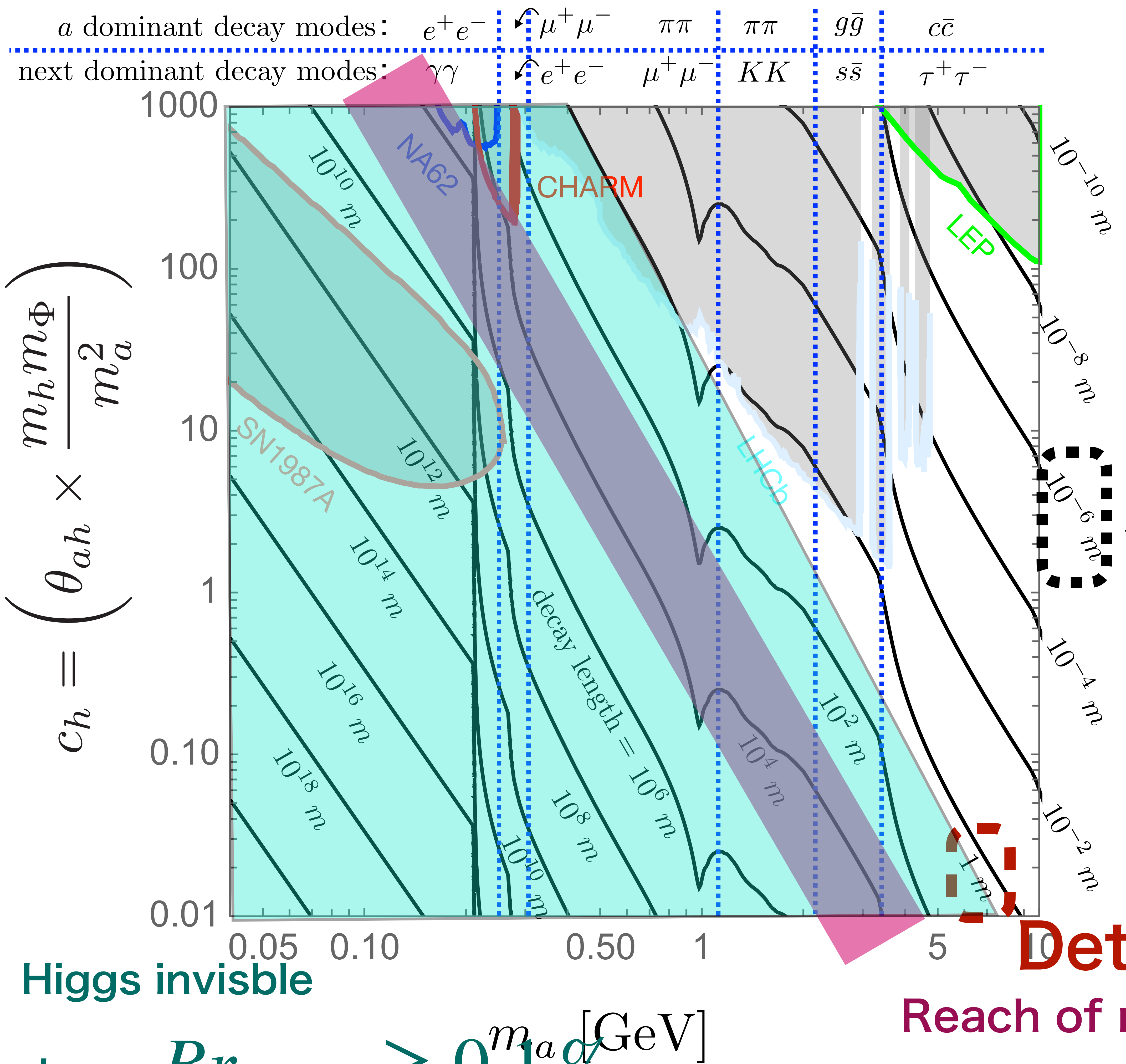
$$\mathscr{L}_{\rm eff} \sim \frac{m_a^2 m_h}{m_\Phi} ah, \theta_{ah} \sim \frac{m_a^2}{m_h m_\Phi}$$

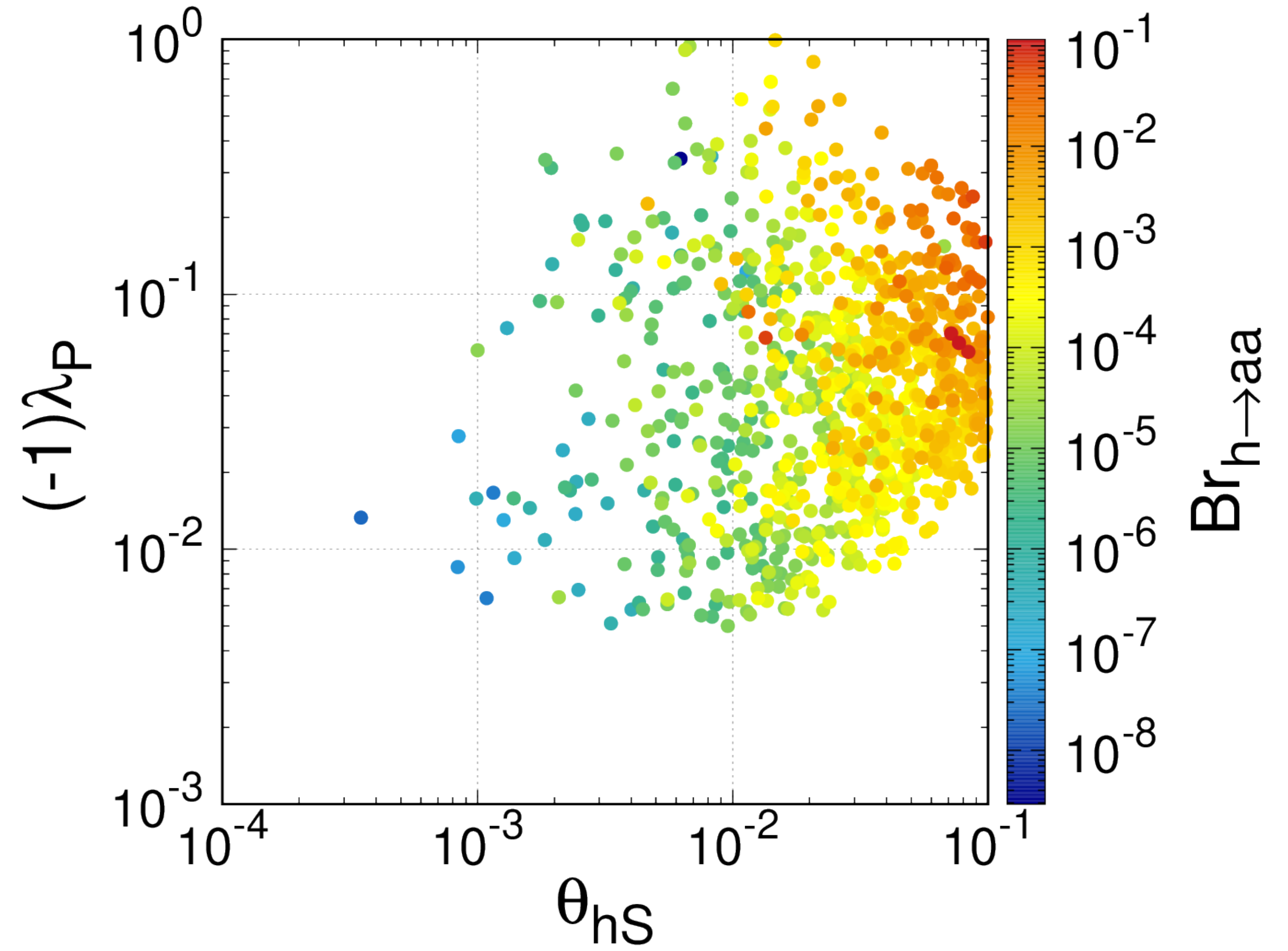
- Induced from U(1) breaking part.
- At $\kappa \to 0$,(i.e. $m_a^2 \to 0$), it vanishes, i.e. amplitude $\propto m_a^2$
- Renormalizable, dominant at low energy.

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





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

Liu et al, 1612.09284

Higgs exotic decay

Vertex resolution

Displaced vertex ×2

$Br_{h\to aa} \gtrsim 10^{-6}$, (2σCL, 3 ab^{-1})

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

Detector size (TPC)

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

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

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!

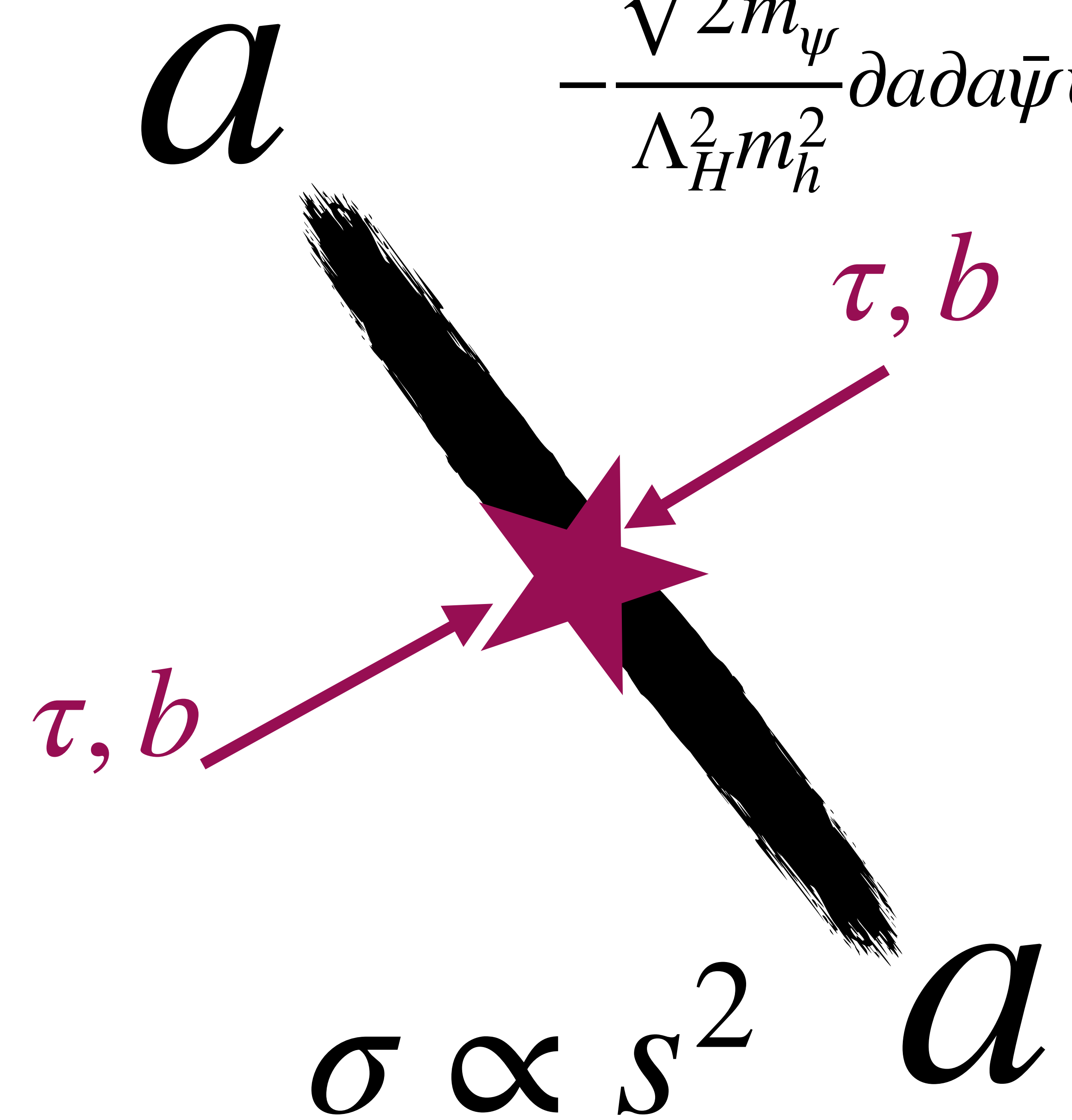
- **CP-even ALP DM.** This talk.

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

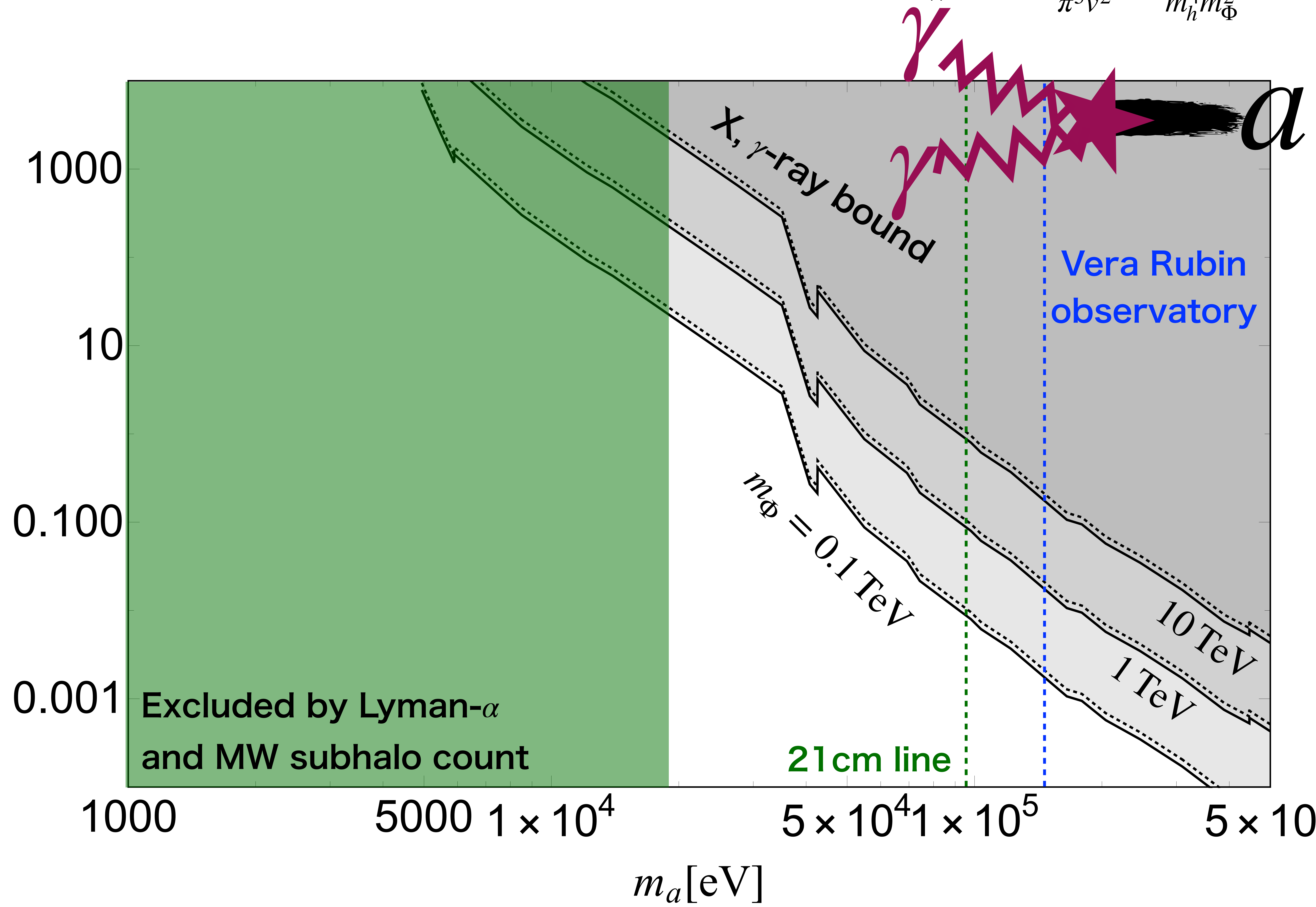
$$-\frac{\sqrt{2}m_\psi}{\Lambda_H^2 m_h^2}\partial a \partial a \bar{\psi}\psi .$$



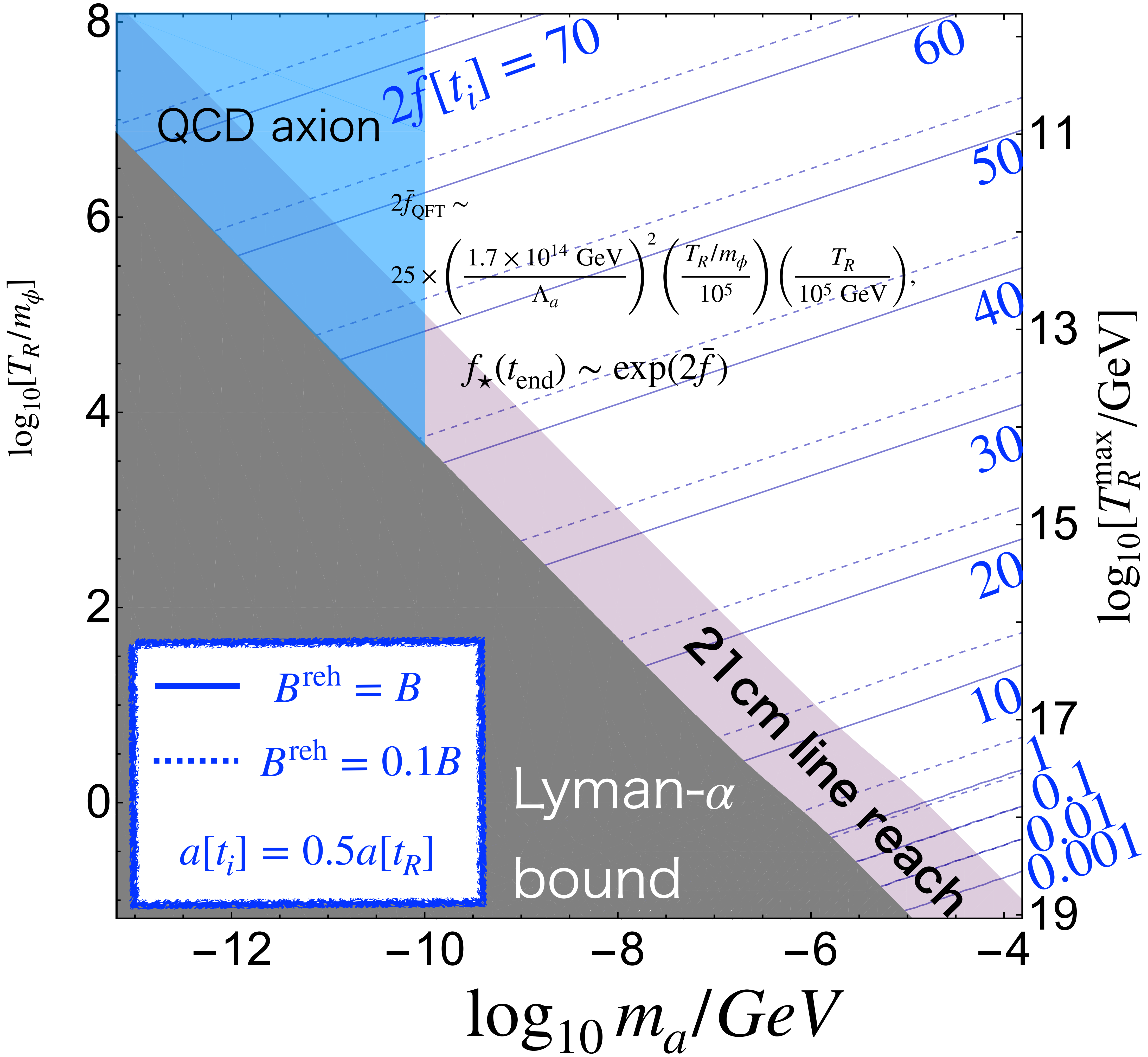
$$\sigma \propto s^2$$

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

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



Non-thermal production scenario: lighter mass range.



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

Moroi, WY, 2011.09475, 2011.12285

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

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.