Istituto Nazionale di Fisica Nucleare
Sezione di Padova

Collider and astrophysical signatures of light scalars with enhanced τ couplings

Discrete 2024, Ljubljana, 3 Dec 2024

Nudžeim Selimović
INFN Padova

Based on work with:

Jorge Alda, Gabriele Levati, Paride Paradisi, and Stefano Rigolin

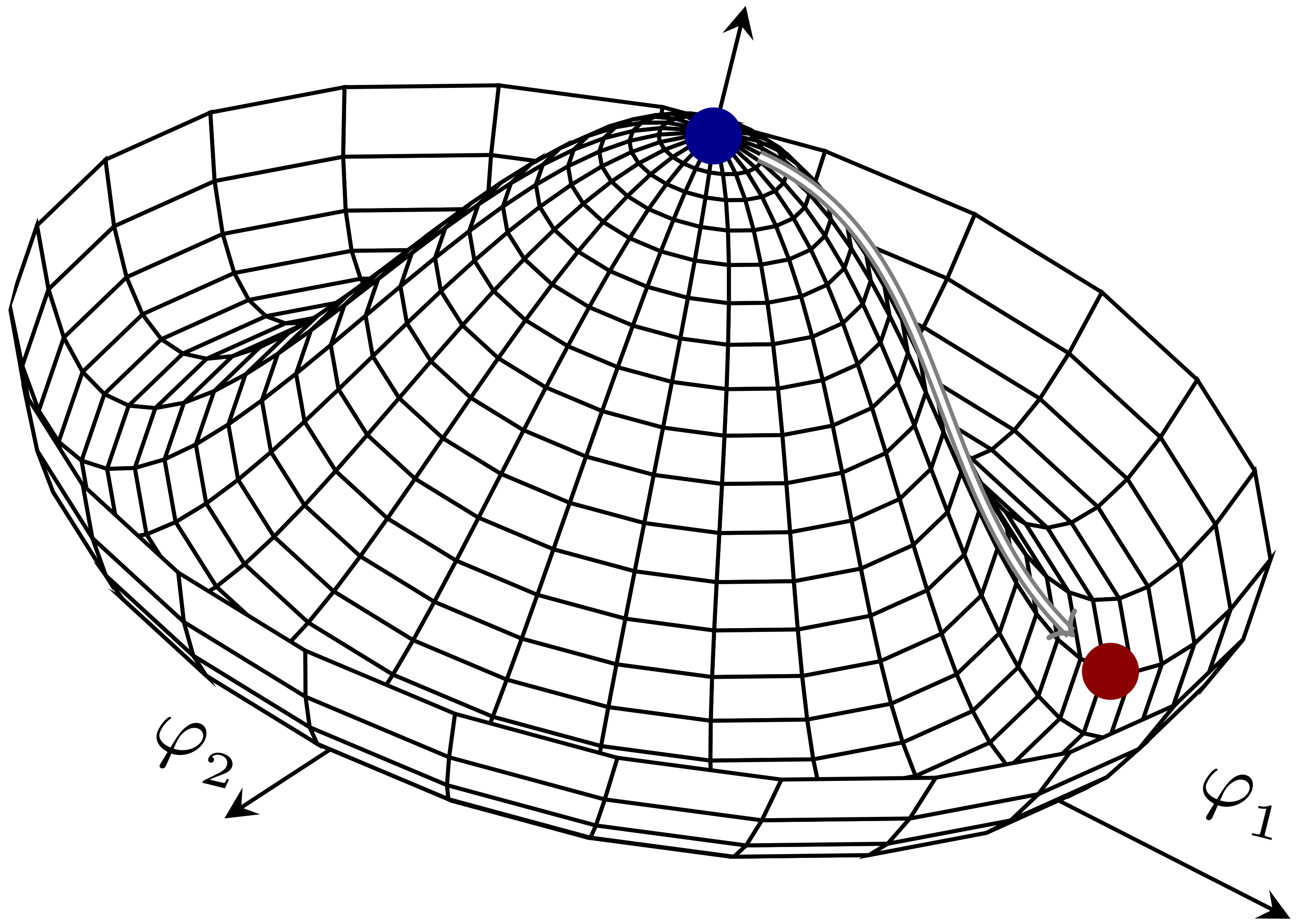
arXiv:2407.18296

Why light scalars?

- Well motivated theoretically:

  Strong CP problem
  Dark matter
  Flavour puzzle
  String theory constructions

  ⋮

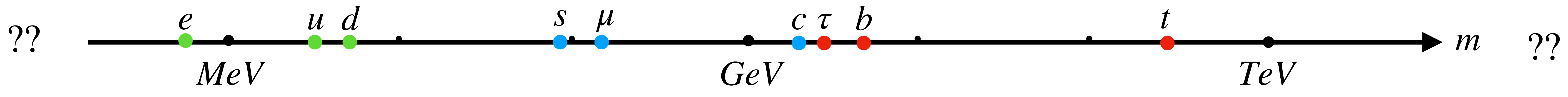


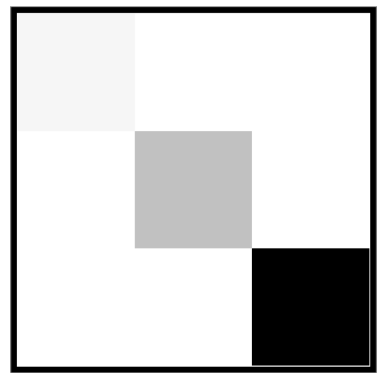
- Generally present in many Standard Model extensions:

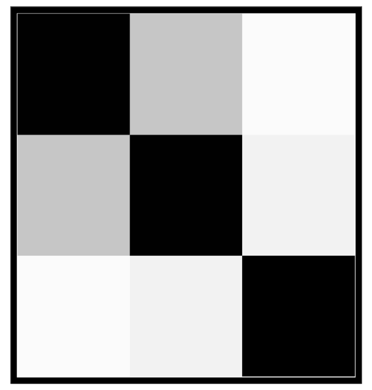
  pNGBs of spontaneously broken global symmetries

Why light scalars dominantly coupled to τ?

- Connection to the SM flavour puzzle



$M_{u,d,e} \sim$ 

$V_{\text{CKM}} \sim$ 

- $$\mathcal{L}_Y \supset Y\bar{\psi}_L H \psi_R \qquad Y \sim \begin{array}{cl} \begin{array}{cc} U(2)_{\psi_R} & \end{array} & \\ \begin{pmatrix} \Delta & V \\ 0 & 1 \end{pmatrix} & \begin{array}{l} U(2)_{\psi_L} \\ \end{array} \end{array}$$

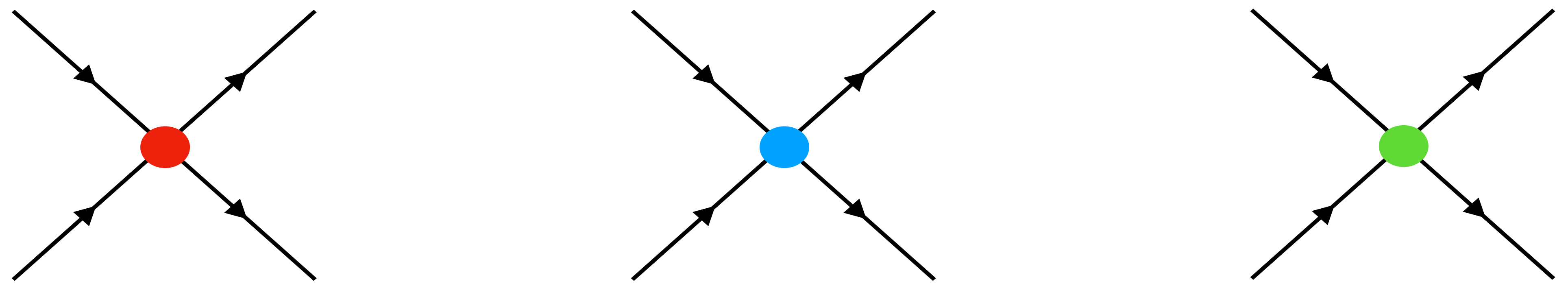
$U(2)^5 \equiv U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$

$|V_q| \sim V_{cb} \qquad |\Delta_u| \sim y_c$

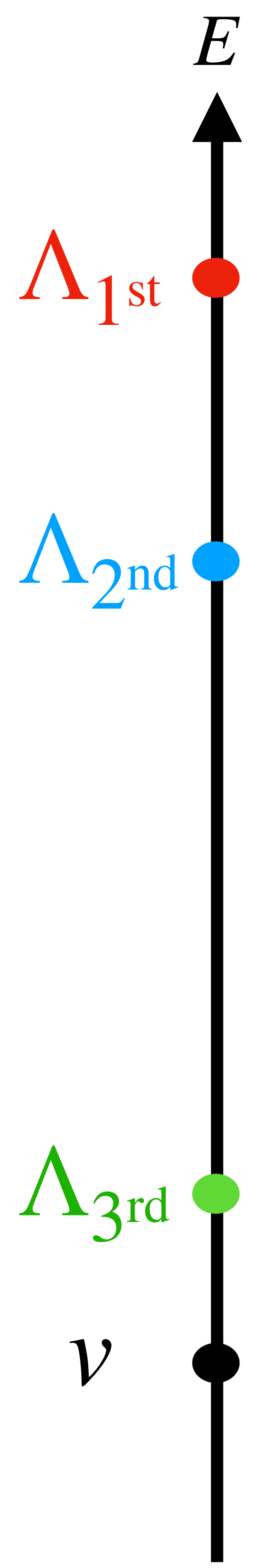
What is the origin of these symmetries?

Why light scalars dominantly coupled to τ?

- The SM Yukawas are very hierarchical because they originate from very different scales!
- NP dominantly coupled to third and to a lesser extent light families.
- $U(2)^5$ - like protection from flavour $\oplus$ high-p_T constraints, scale could be low (~ TeV).



$\sim \Lambda_{1\,\mathrm{st}}^{-2}\,(\overline{\psi}_1\psi_1)^2$ $\quad \sim \Lambda_{2\mathrm{nd}}^{-2}\,(\overline{\psi}_2\psi_2)^2$ $\quad \sim \Lambda_{3\mathrm{rd}}^{-2}\,(\overline{\psi}_3\psi_3)^2$

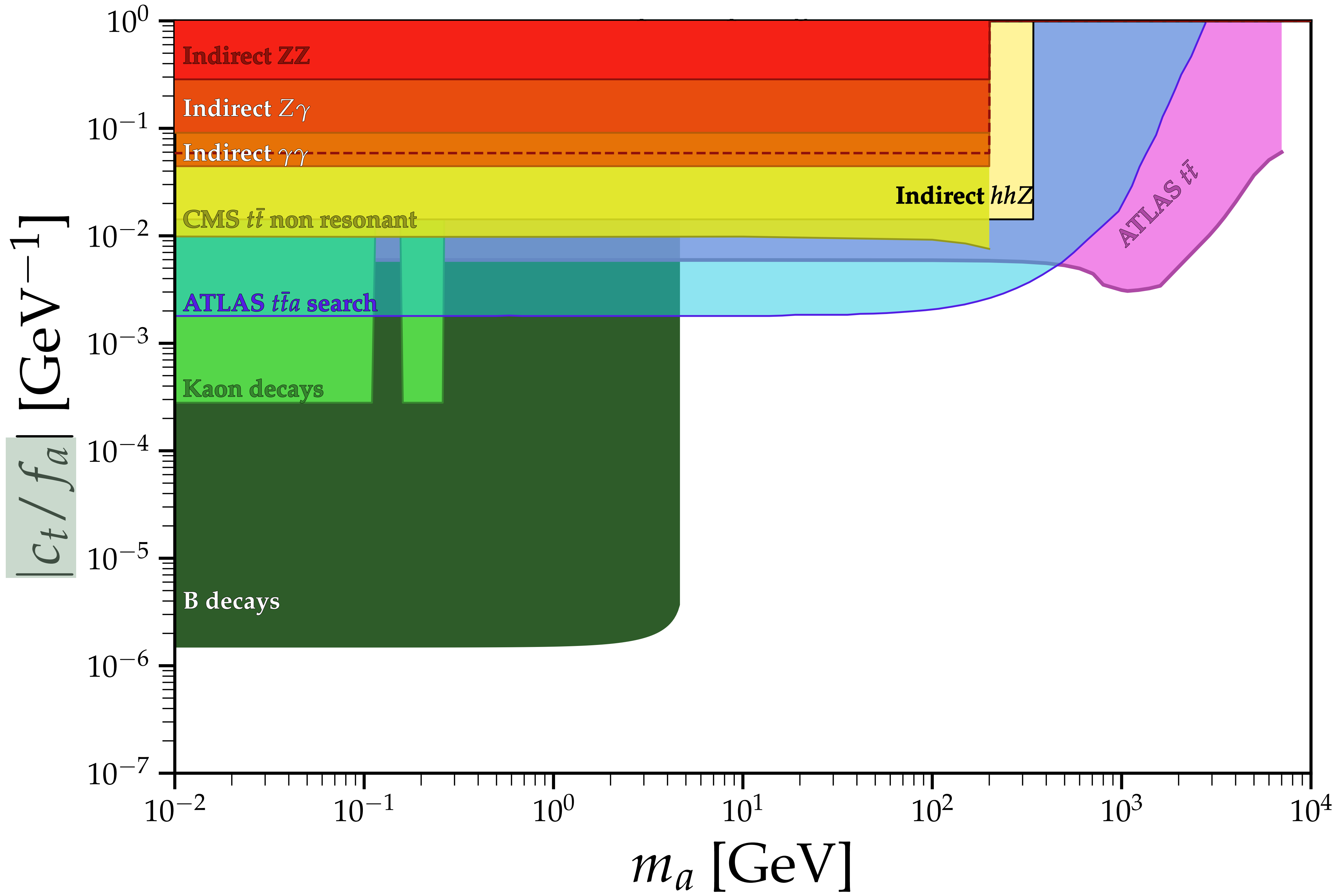


Global symmetries could follow the pattern, resulting in the third-family specific light scalars!

[G. Panico, A. Pomarol, 1603.06609]
[J. Fuentes-Martin, G. Isidori, J. Lizana, N. Selimovic, B. Stefanek 2203.01952]
[J. Davighi. G. Isidori 2303.01520]   [M.F. Navarro, S. King 2305.07690]   [...]

Current searches

- Top-axion-like particle (ALP)



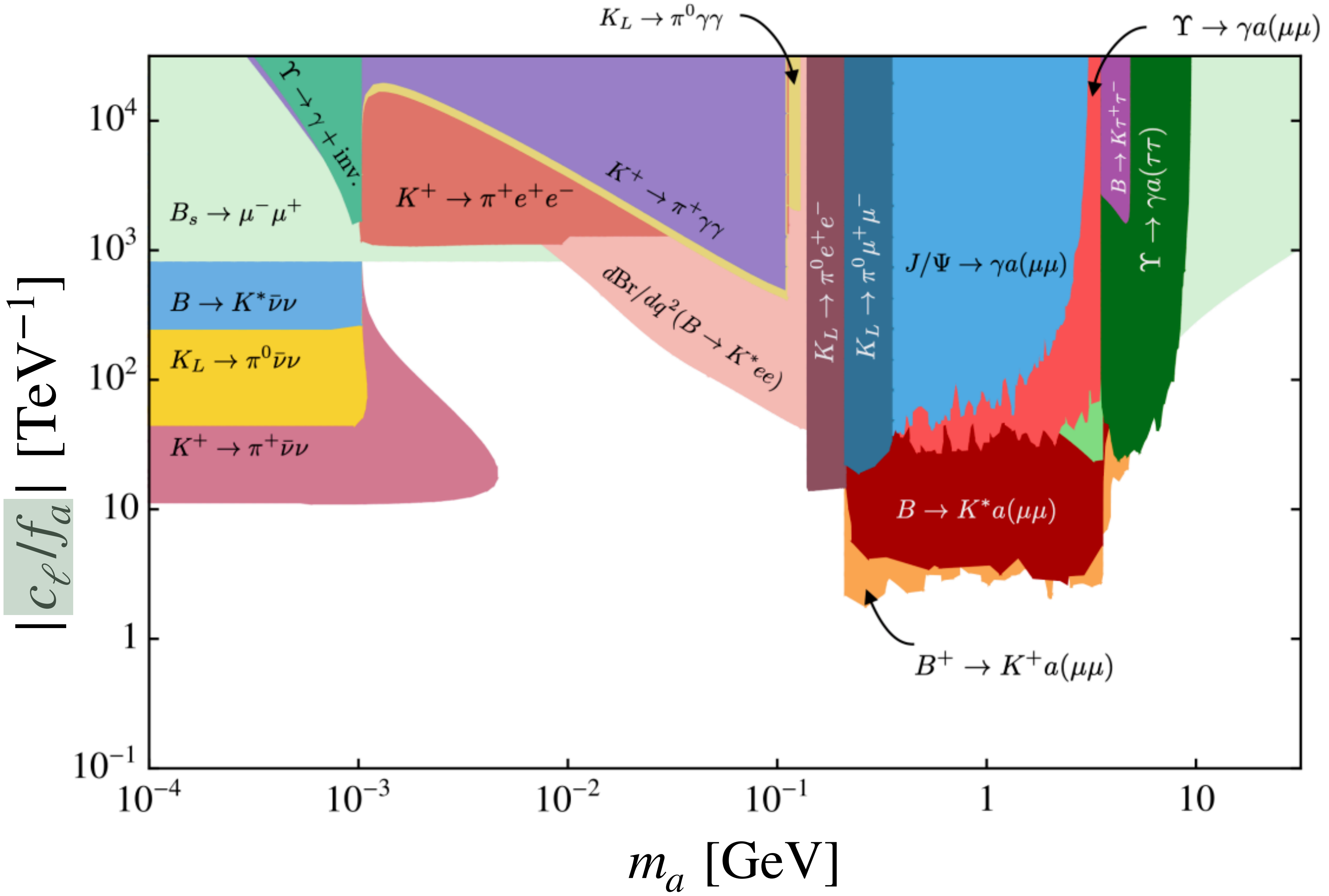
$$\mathscr{L} \supset -\frac{c_t}{2f_a}(\partial_\mu a)\,\bar{t}\gamma^\mu\gamma_5 t$$

[F. Esser, M. Madigan, V. Sanz, M. Ubiali 2303.17634]

- Nothing (yet) for the tau-axion-like particle

[M. Bauer, M. Neubert, S. Renner, M. Schnubel, A. Thamm 2110.10698]

- Results for lepton-ALP interactions



$$\mathscr{L} \supset -\frac{c_\ell}{2f_a}(\partial_\mu a)\,\bar{\ell}\gamma^\mu\gamma_5\ell \qquad c_\ell = c_\ell\, 1_{3\times 3}$$

- Lepton Flavour Universality hypothesis, limits dominated by electron processes

How do we describe a τ-specific ALP?

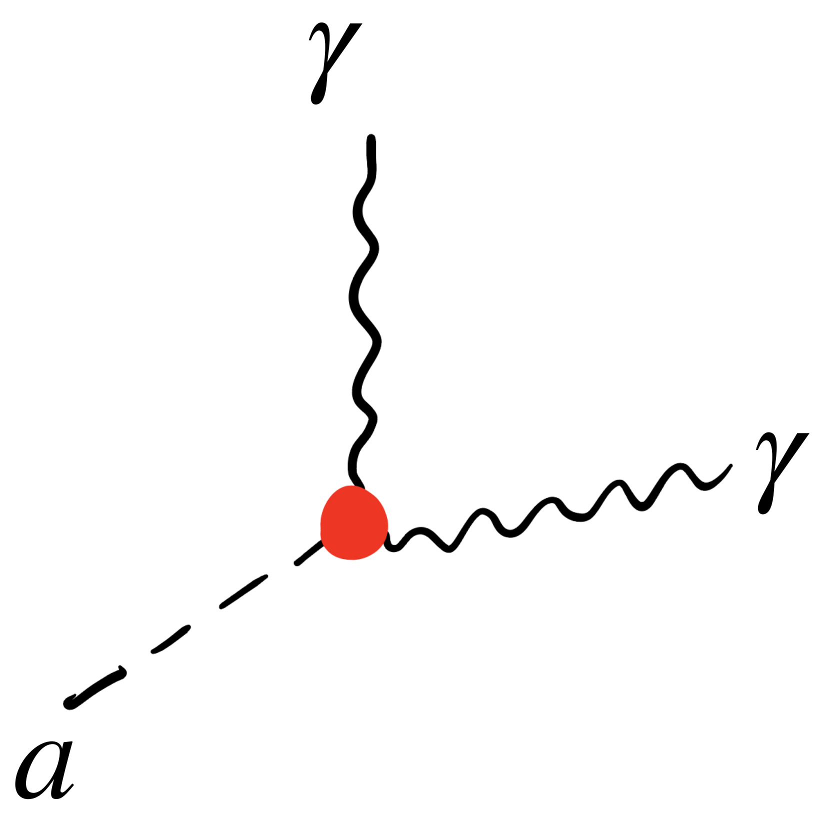
Theoretically:

→ Below the electroweak scale

$$\mathcal{L}^a_{d\leq 5} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2\, a^2 - \frac{\alpha_{\rm em}}{4\pi} c^0_{\gamma\gamma}\frac{a}{f_a}\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{c_\tau}{2f_a}(\partial_\mu a)\, \bar{\tau}\gamma^\mu\gamma_5\tau$$

$$\mathcal{L}^a_{\rm int} \supset i\, m_\tau \frac{c_\tau}{f_a}\, a\, \bar{\tau}\gamma_5\tau - \frac{\alpha_{\rm em}}{4\pi}\frac{c^0_{\gamma\gamma} + c_\tau}{f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

→ Phenomenology driven through interactions with tau leptons and photons



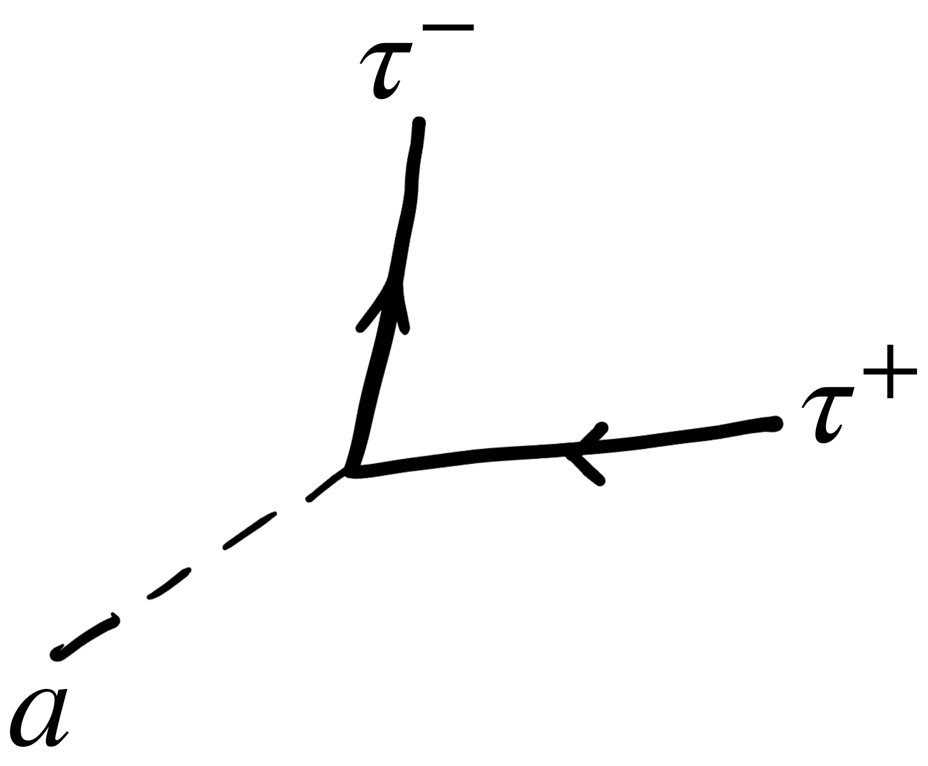
$m_a < 2m_\tau$

$$\Gamma(a \to \gamma\gamma) = \frac{\alpha_{\rm em}^2}{(4\pi)^3} m_a^3 \frac{|c^{{\rm eff},0}_{\gamma\gamma}|^2}{f_a^2}$$

$$c^{{\rm eff},0}_{\gamma\gamma} = c^0_{\gamma\gamma} + c_\tau\, B_1\left(\frac{4m_\tau^2}{m_a^2}\right)$$

$m_a > 2m_\tau$

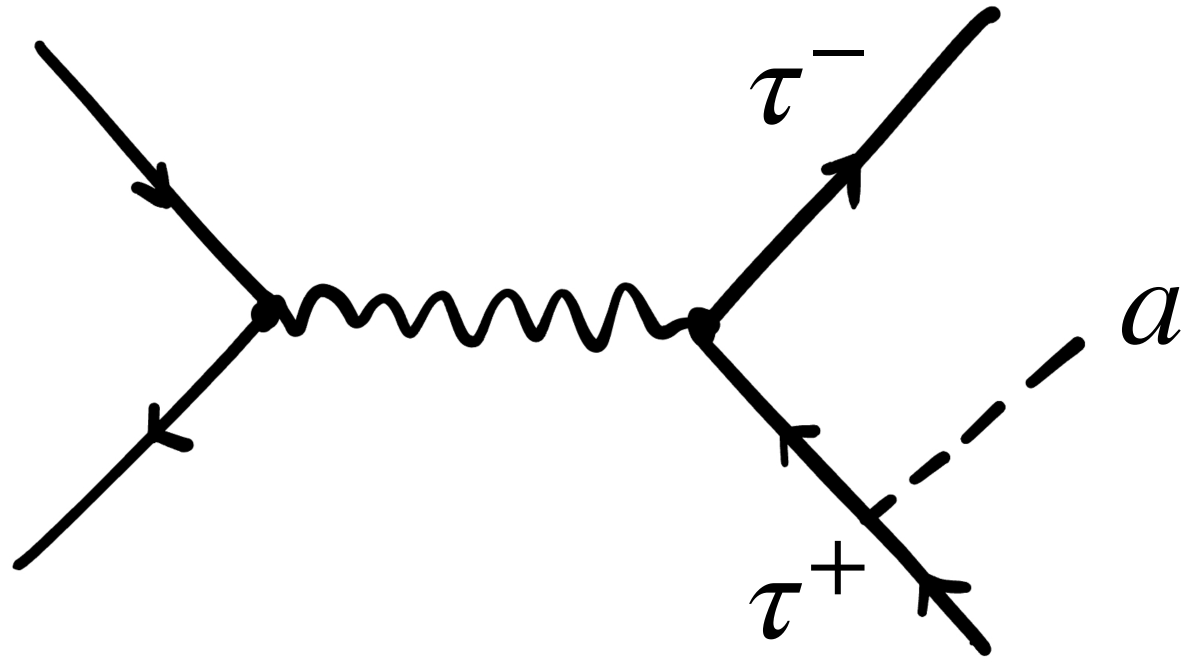
$$\Gamma(a \to \tau^+\tau^-) = \frac{m_a m_\tau^2}{8\pi f_a^2}|c_\tau|^2\sqrt{1 - \frac{4m_\tau^2}{m_a^2}}$$



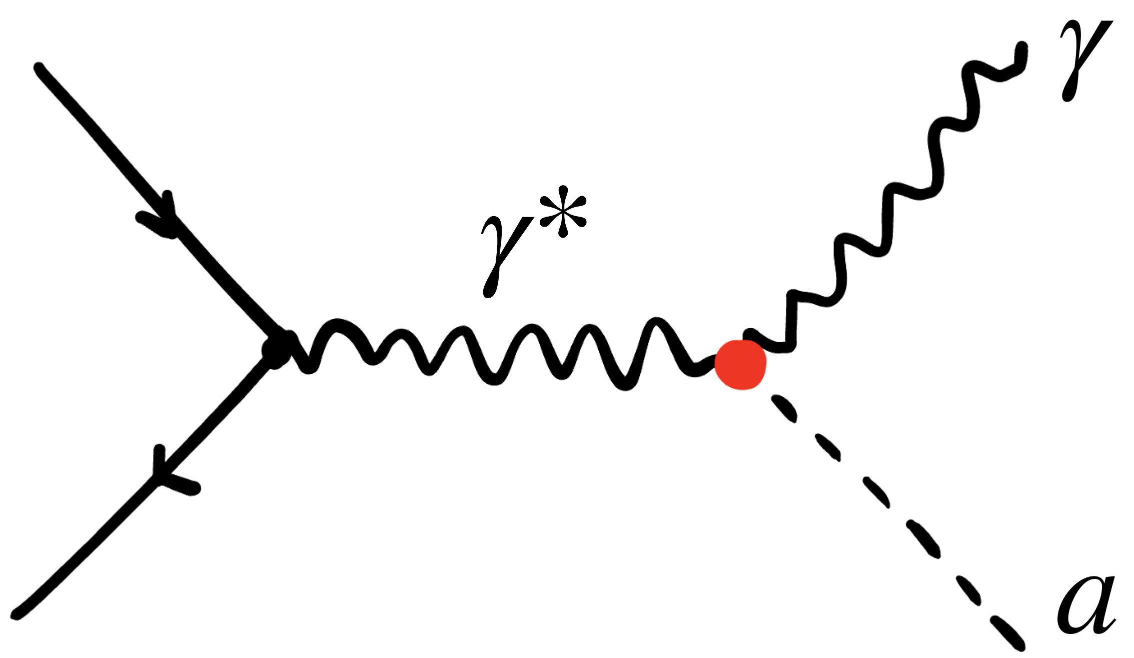
How do we describe a τ-specific ALP?

Experimentally:

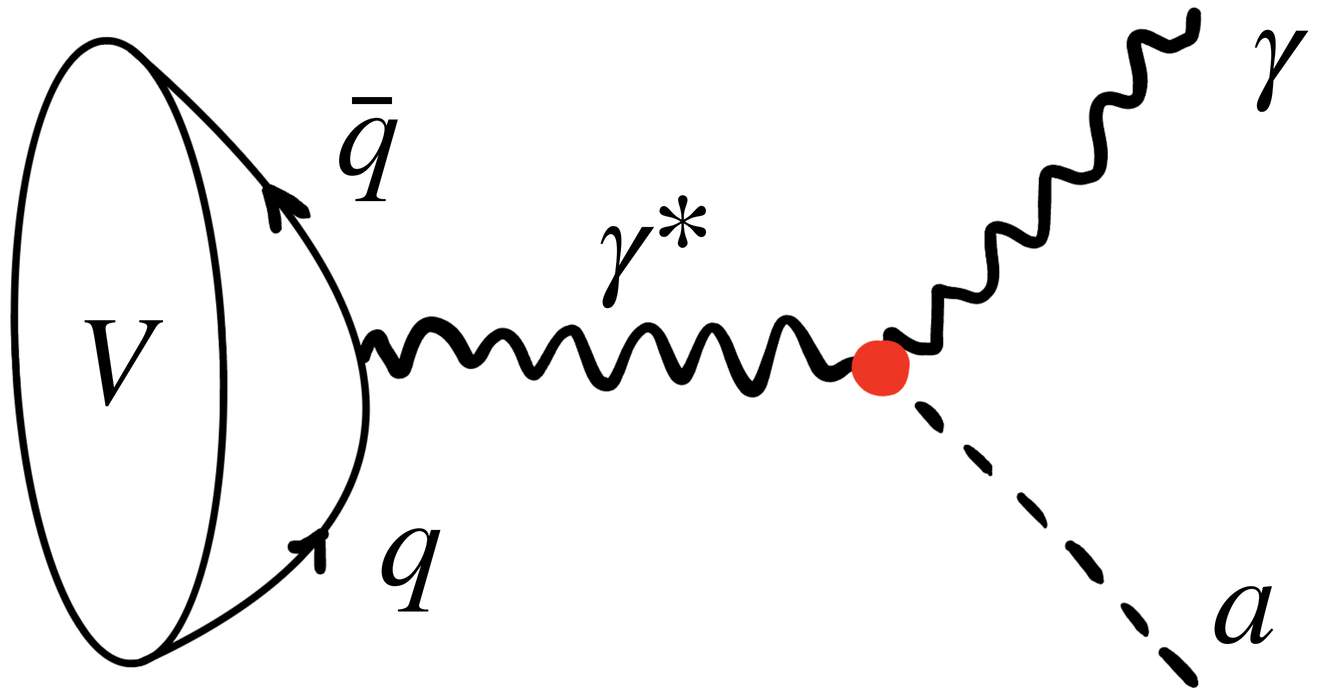
→ Different production channels at colliders



Radiation off the final state τ-lepton

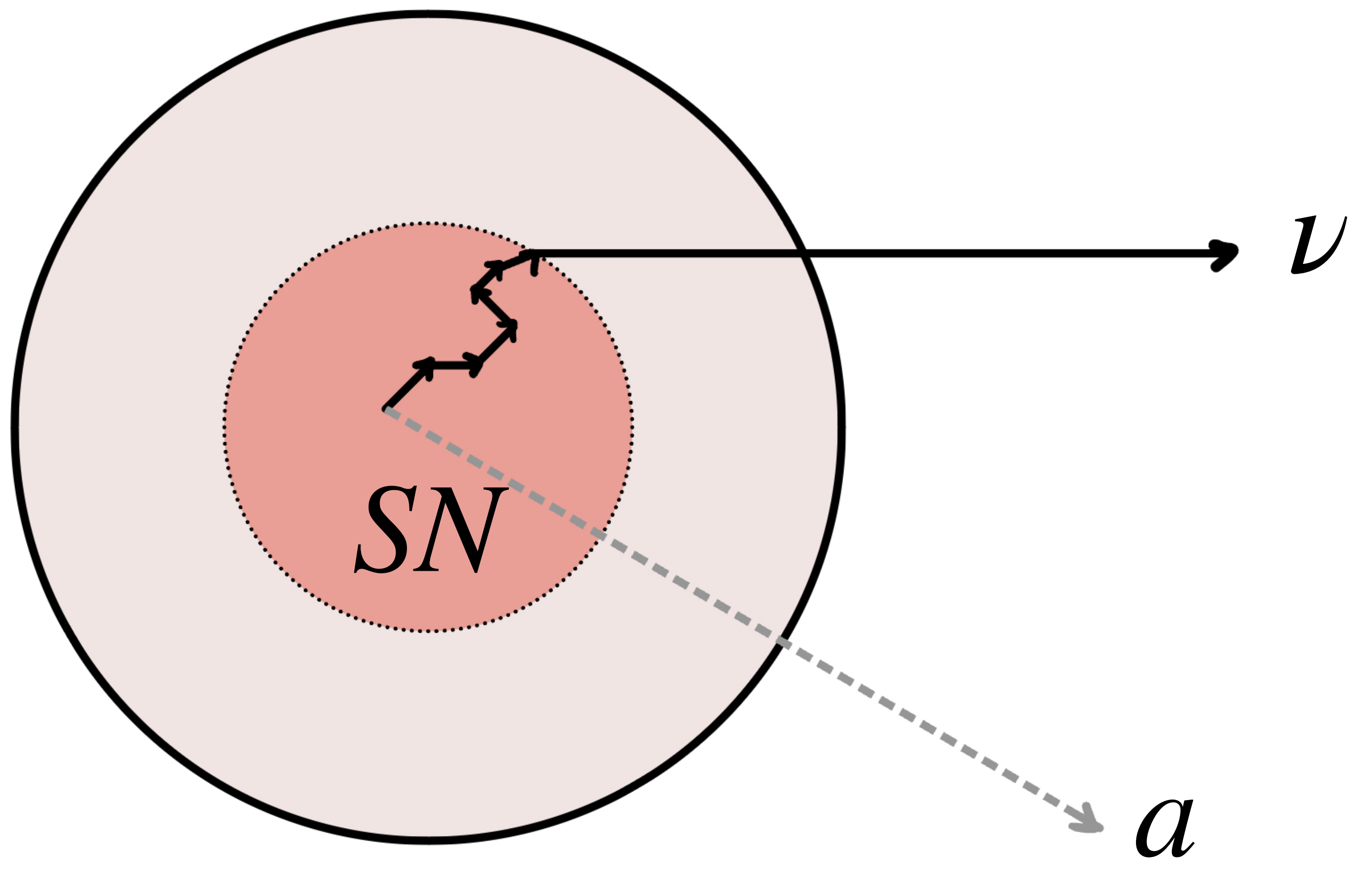


Through the off-shell photon

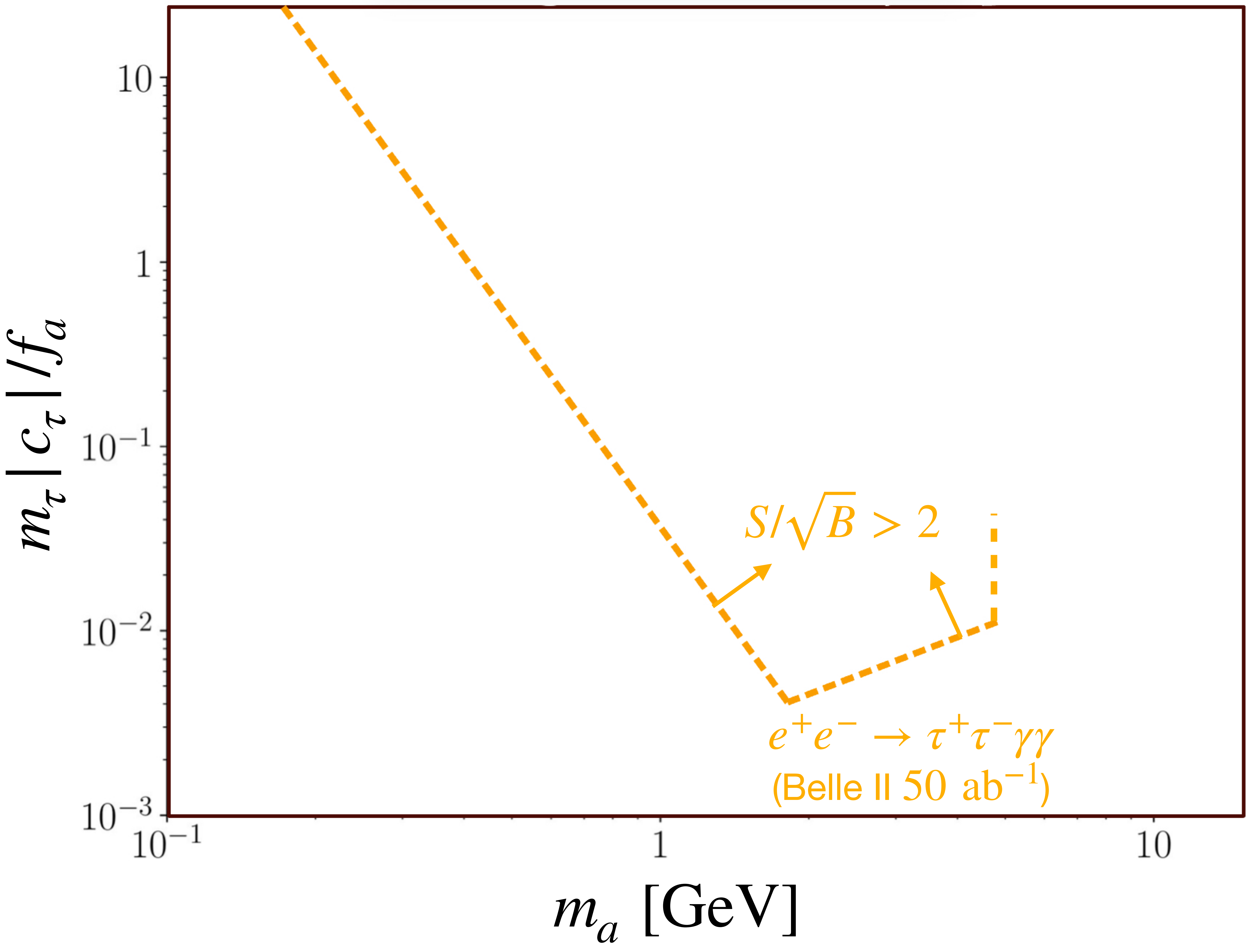


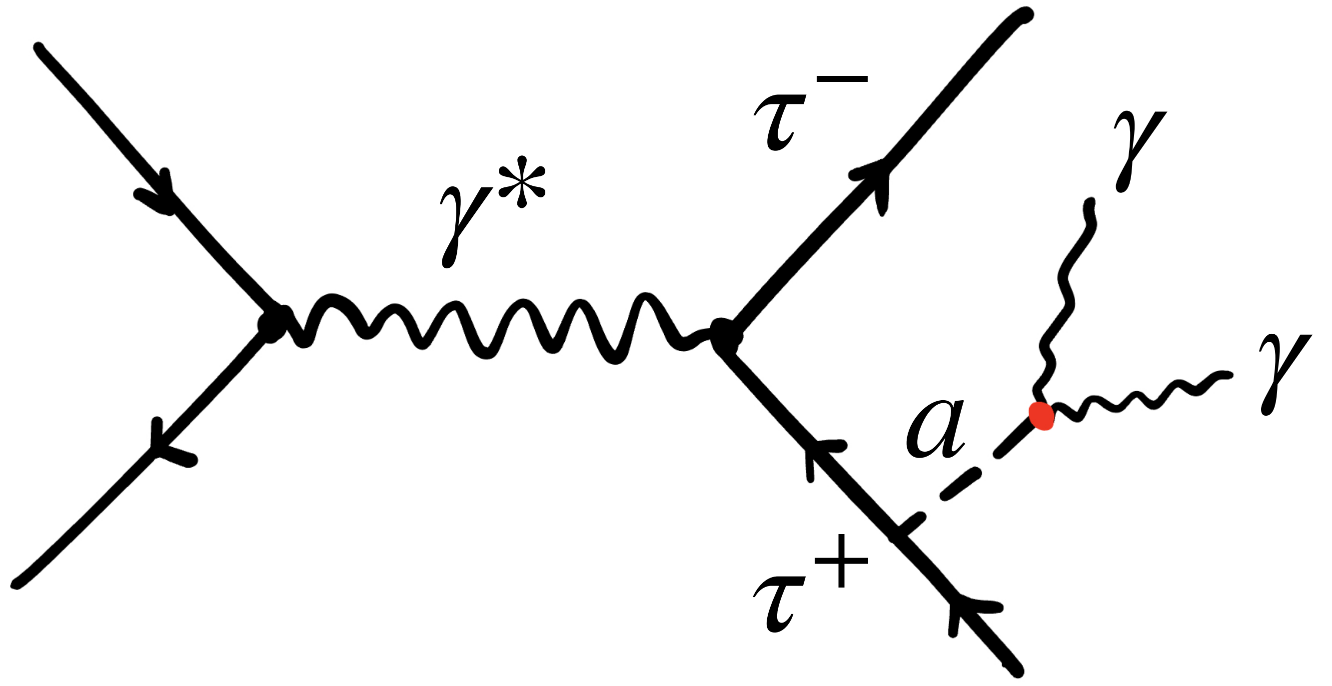
Decay of the meson resonance

→ Modify astrophysical events if present



$e^+e^- \to \tau^+\tau^-\gamma\gamma$ at Belle II





- FeynRules-Ufo-MadGraph5_aMC@NLO simulation chain for signal and background.
- Narrow peak in the $m^2_{\gamma\gamma}$ spectrum: same $m^2_{\gamma\gamma}$ resolution as in $e^+e^- \to 3\gamma$

[Belle-II collaboration, Search for Axion-Like Particles produced in e+e− collisions at Belle II, Phys. Rev. Lett. 125 (2020) 161806]

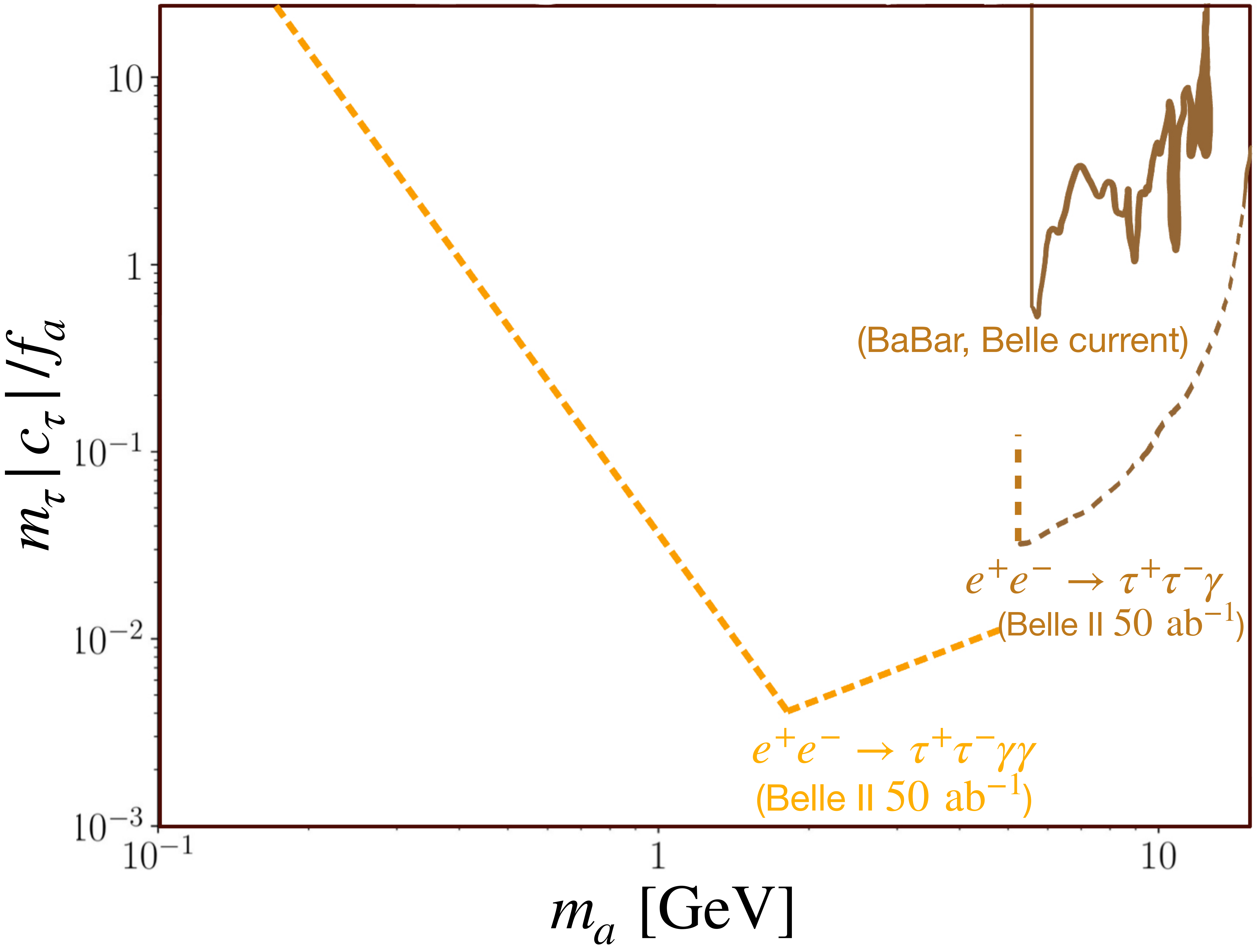
- $E_\gamma > 1$ GeV , $37.3^\circ < \theta < 123.7^\circ$ $\Delta\theta_{\gamma\gamma} > 0.014$ rad , $\Delta\phi_{\gamma\gamma} > 0.4$ rad (has the best energy resolution and and minimises beam background levels).

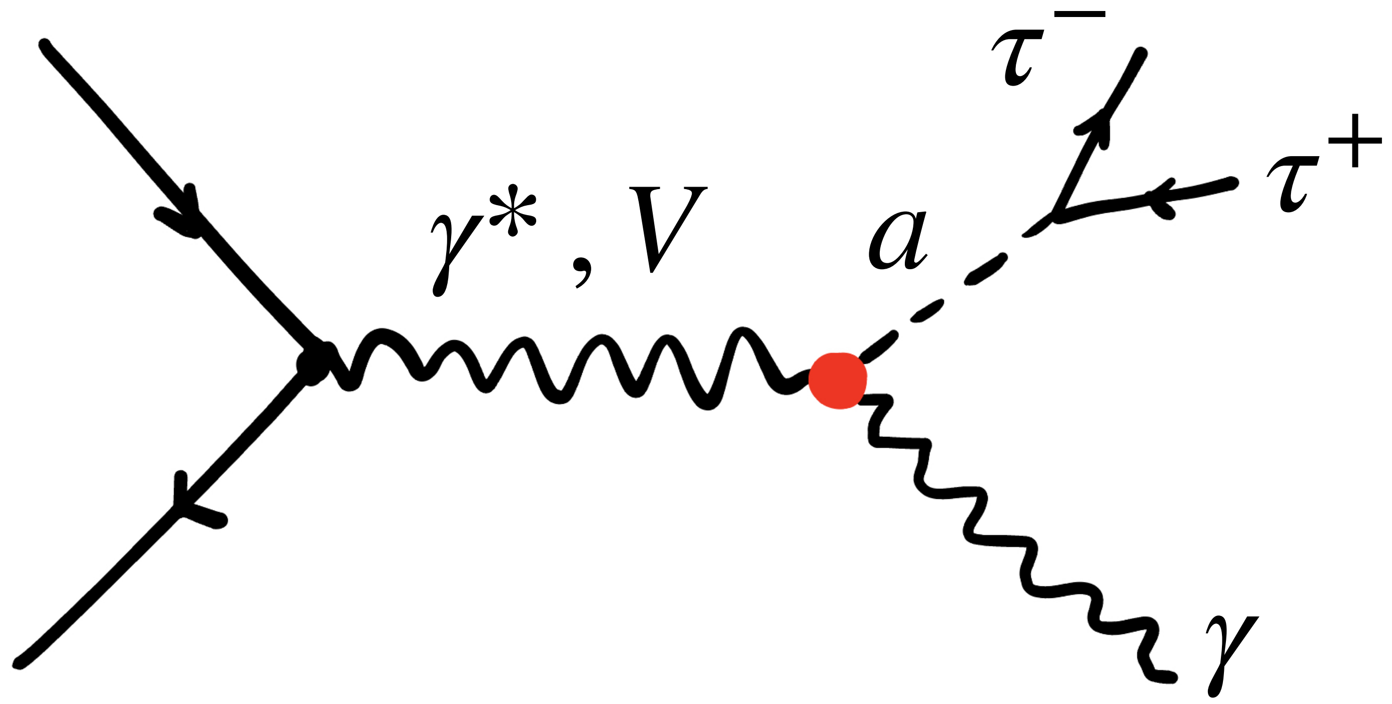
[Belle-II collaboration, The Belle II Physics Book, PTEP 2019 123C01]

- Sensitivity loss when $L_0 \simeq 25$ cm.

[Belle collaboration, Search for a dark leptophilic scalar produced in association with τ +τ - pair in e+e- annihilation at center-of-mass energies near 10.58 GeV, Phys. Rev. D 109 (2024) 032002]

$e^+e^- \to \tau^+\tau^-\gamma$ at Belle II





- BaBar ($e^+e^- \to \Upsilon(1S,3S) \to a\gamma \to \tau^+\tau^-\gamma$)
Belle ($e^+e^- \to \Upsilon(3S) \to a\gamma \to \tau^+\tau^-\gamma$)
set limits already.

[BaBar, Search for a low-mass Higgs boson in Y(3S) —> gamma A0, A0—> tau+ tau- at BABAR, Phys. Rev. Lett. 103 181801]

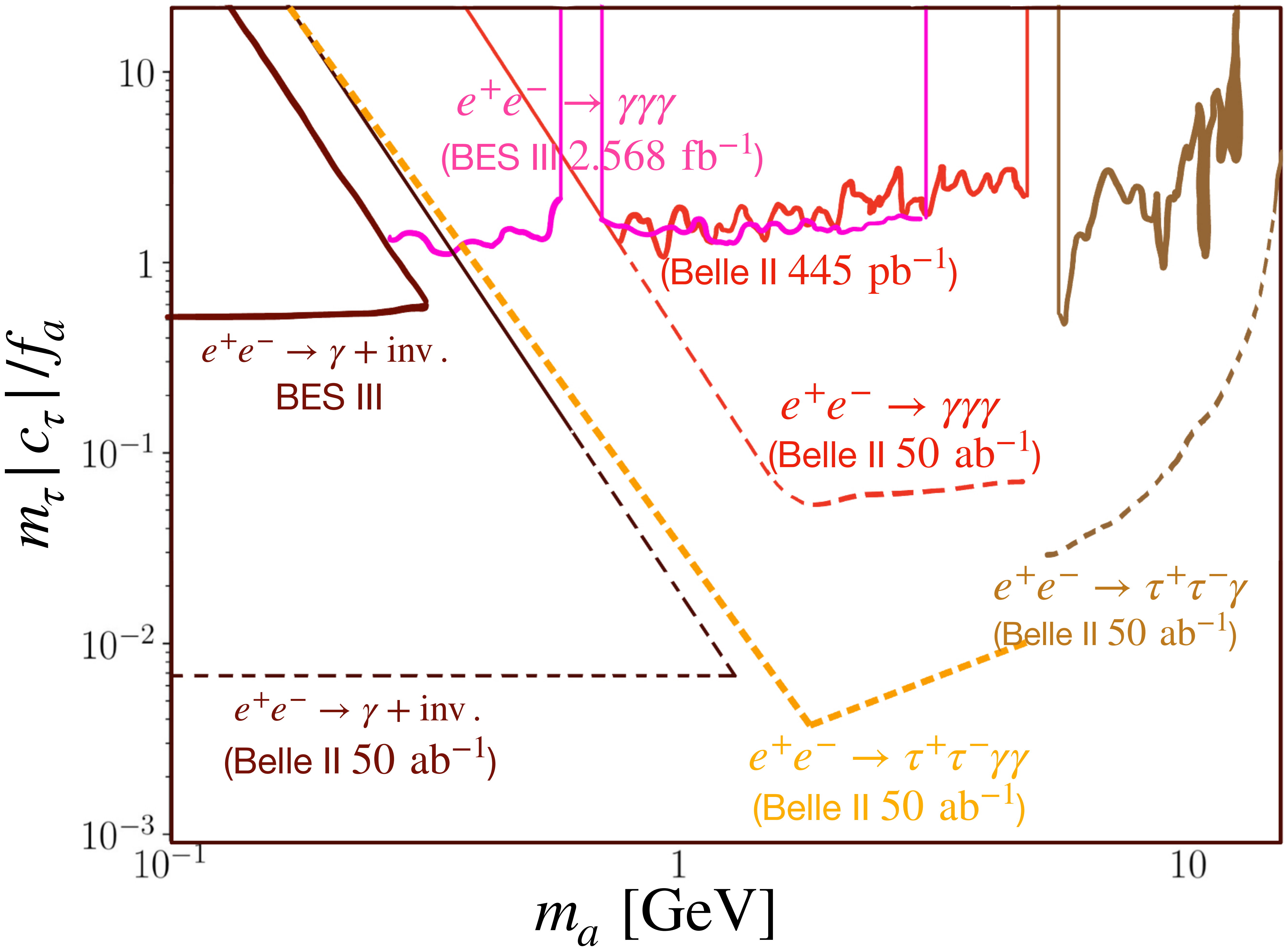
[Belle, Search for a light Higgs boson in single-photon decays of Y(1S) using Y(2S) → π+π−Y(1S) tagging method, Phys. Rev. Lett.128 081804]

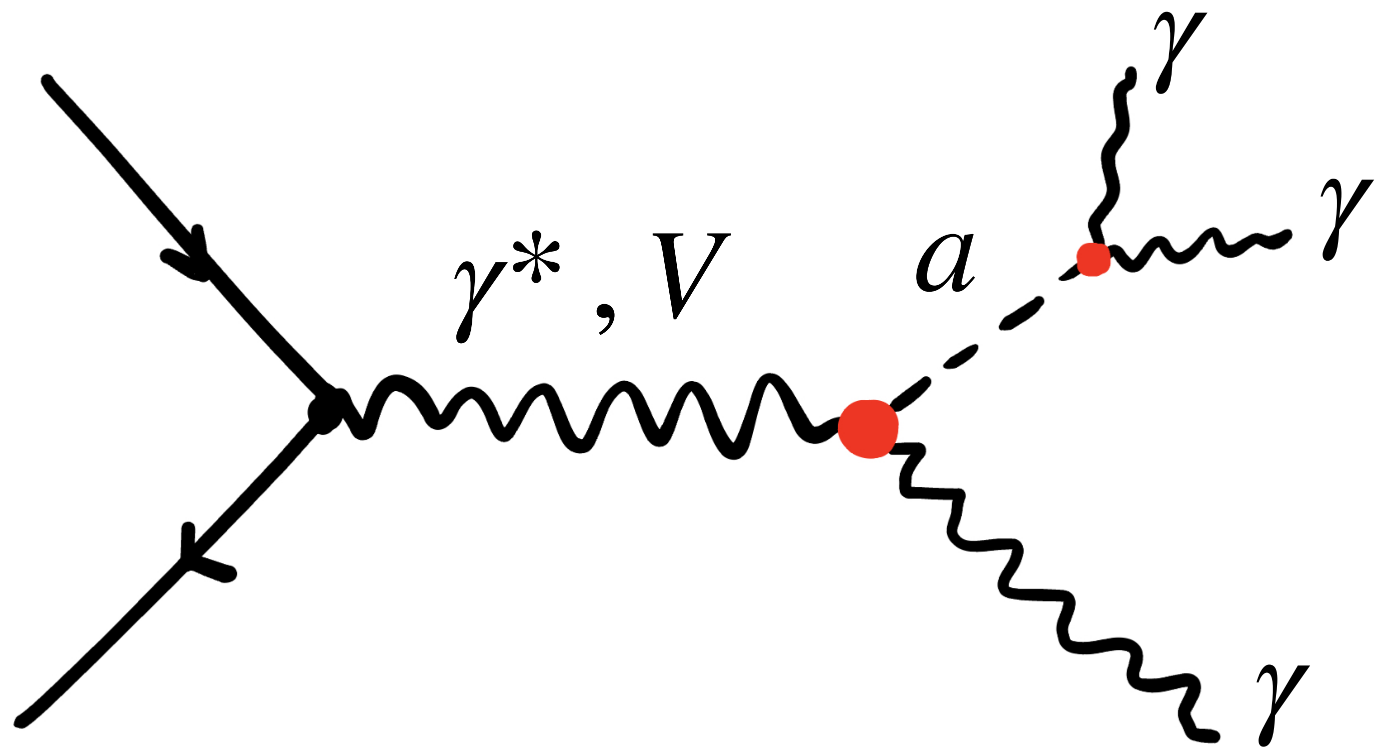
- At Belle II ($e^+e^- \to \Upsilon(4S) \to a\gamma \to \tau^+\tau^-\gamma$) suppressed compared to the non-resonant ($e^+e^- \to \gamma^* \to a\gamma \to \tau^+\tau^-\gamma$).

- Narrow peak in the $m_{\tau\tau}^2 = s - 2\sqrt{s}E_\gamma$ distribution: $E_\gamma > 0.1$ GeV and photon energy resolution in:

[Belle-II collaboration, The Belle II Physics Book, PTEP 2019 123C01]

$e^+e^- \to \gamma\gamma\gamma\ (\gamma + \text{inv.})$





- BES III ($e^+e^- \to J/\Psi \to a\gamma \to 3\gamma$)
  Belle II ($e^+e^- \to \Upsilon(4S) \to a\gamma \to 3\gamma$)
  set limits already.

[BESIII, Search for di-photon decays of an axion-like particle in radiative J/ψ decays, 2404.04640]

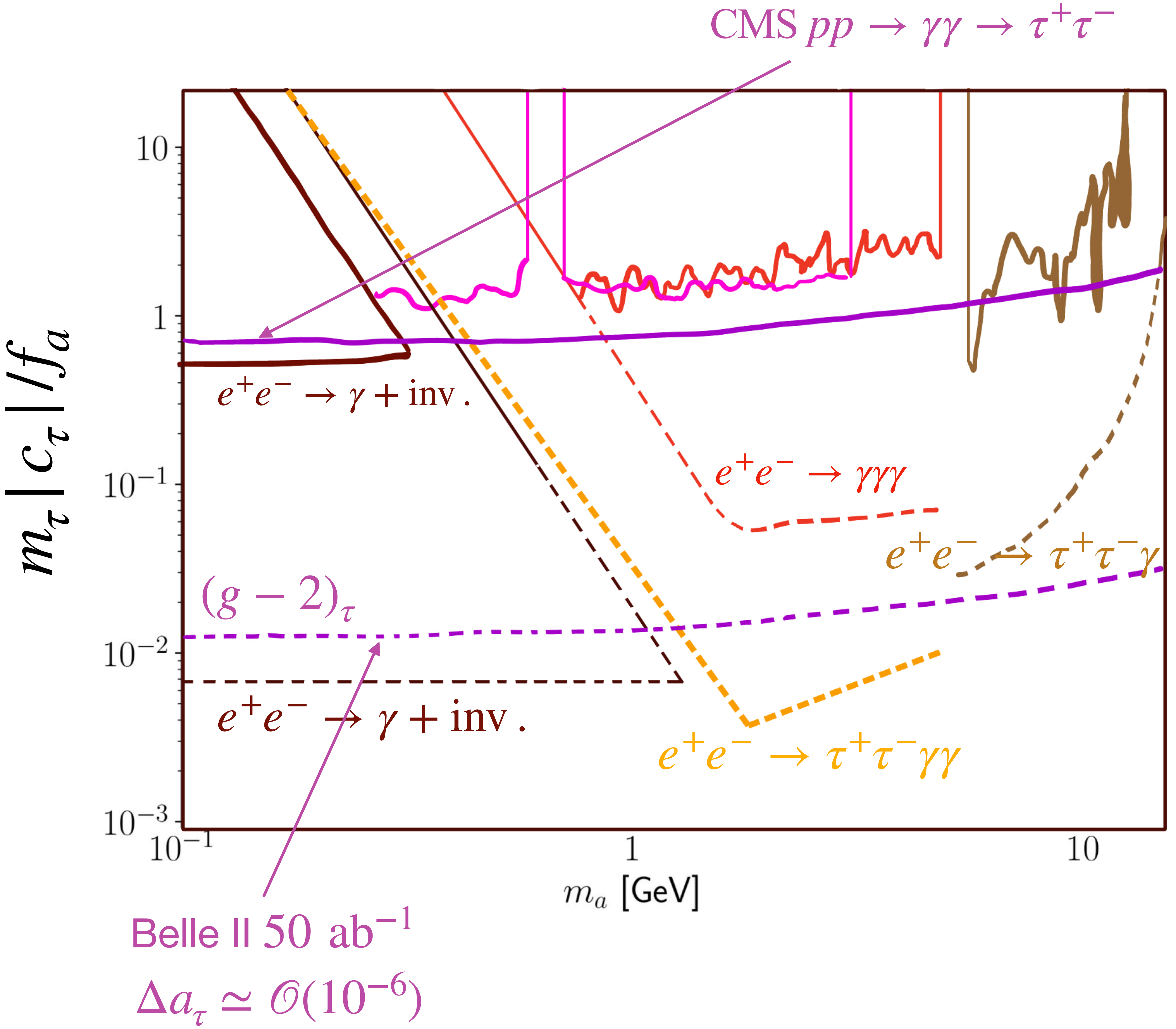
[Belle-II, Search for Axion-Like Particles produced in e+e− collisions at Belle II, Phys. Rev. Lett. 125 (2020) 161806]

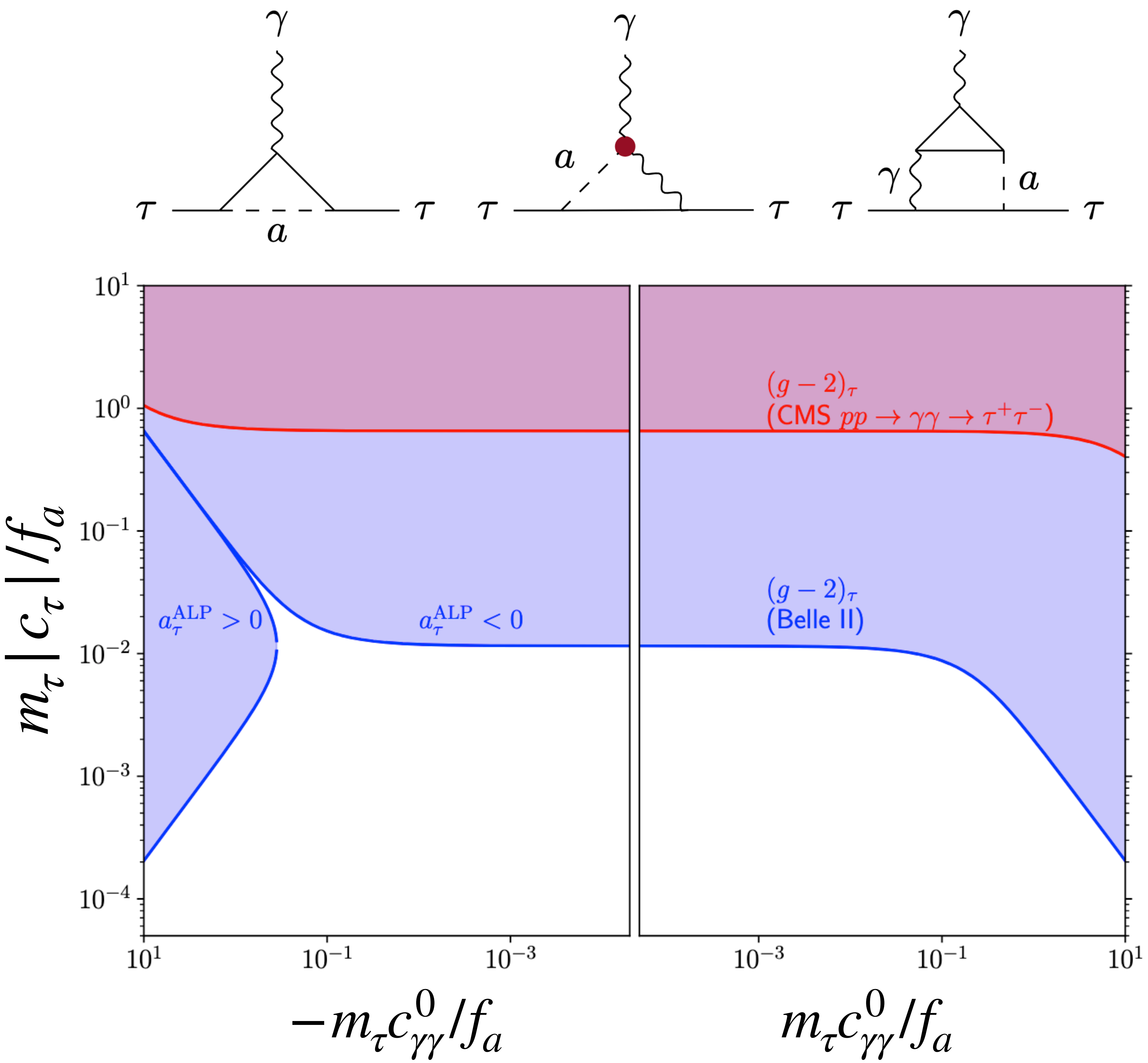
- Signature changes when $L_{\text{dec}} \simeq L_{\text{det}} \simeq 3$m.
- BES III also limits ($e^+e^- \to \gamma + \text{inv}.$)
  Belle II only projections based on:

  [Belle-II collaboration, The Belle II Physics Book, PTEP 2019 123C01]

- Sensitivity on $c^0_{\gamma\gamma}$

$(g-2)_\tau$

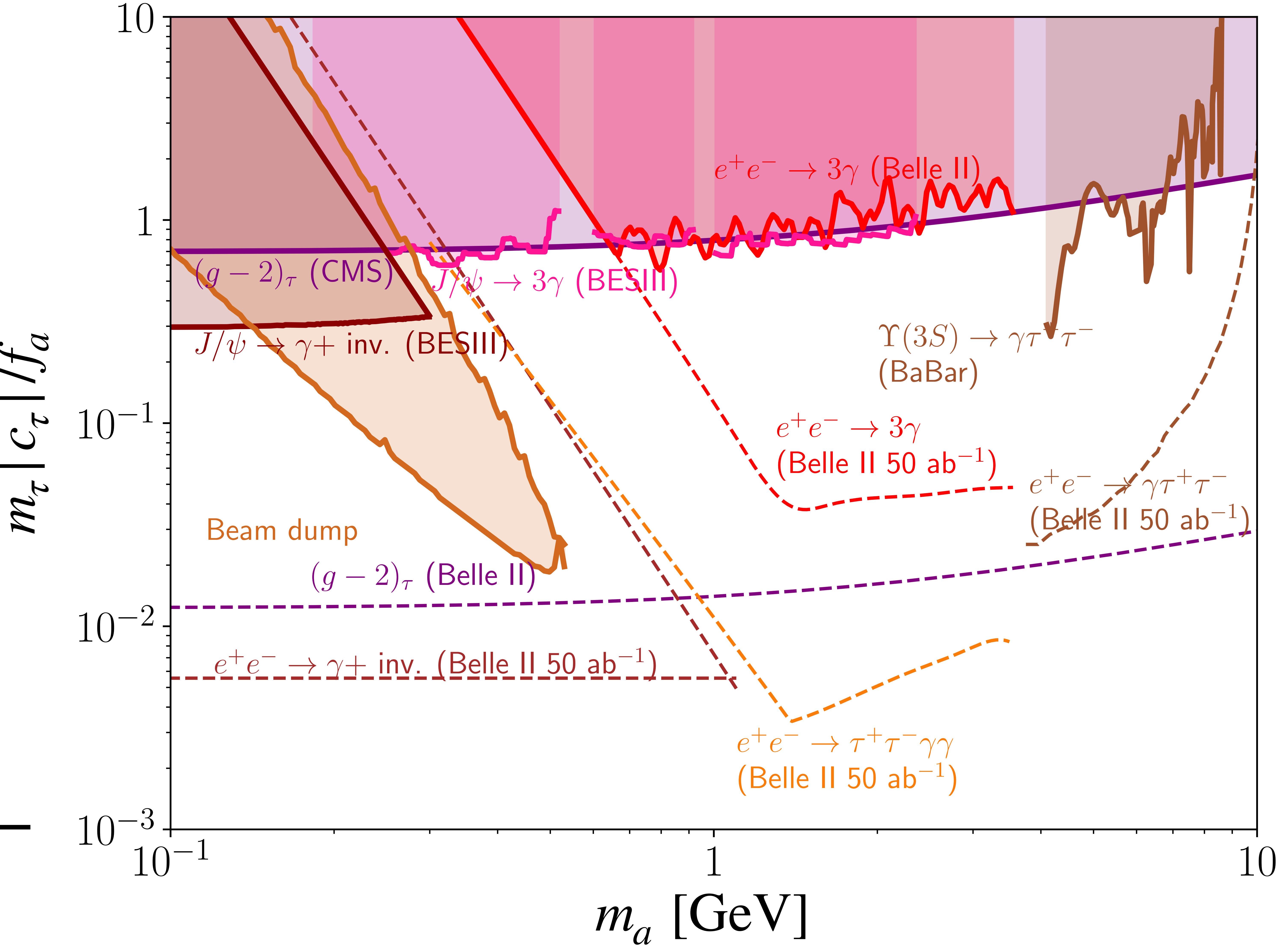




[CMS, Observation of $\gamma\gamma \to \tau\,\tau$ in proton-proton collisions and limits on the anomalous electromagnetic moments of the τ lepton, Rept. Prog. Phys. 87 (2024) 107801]

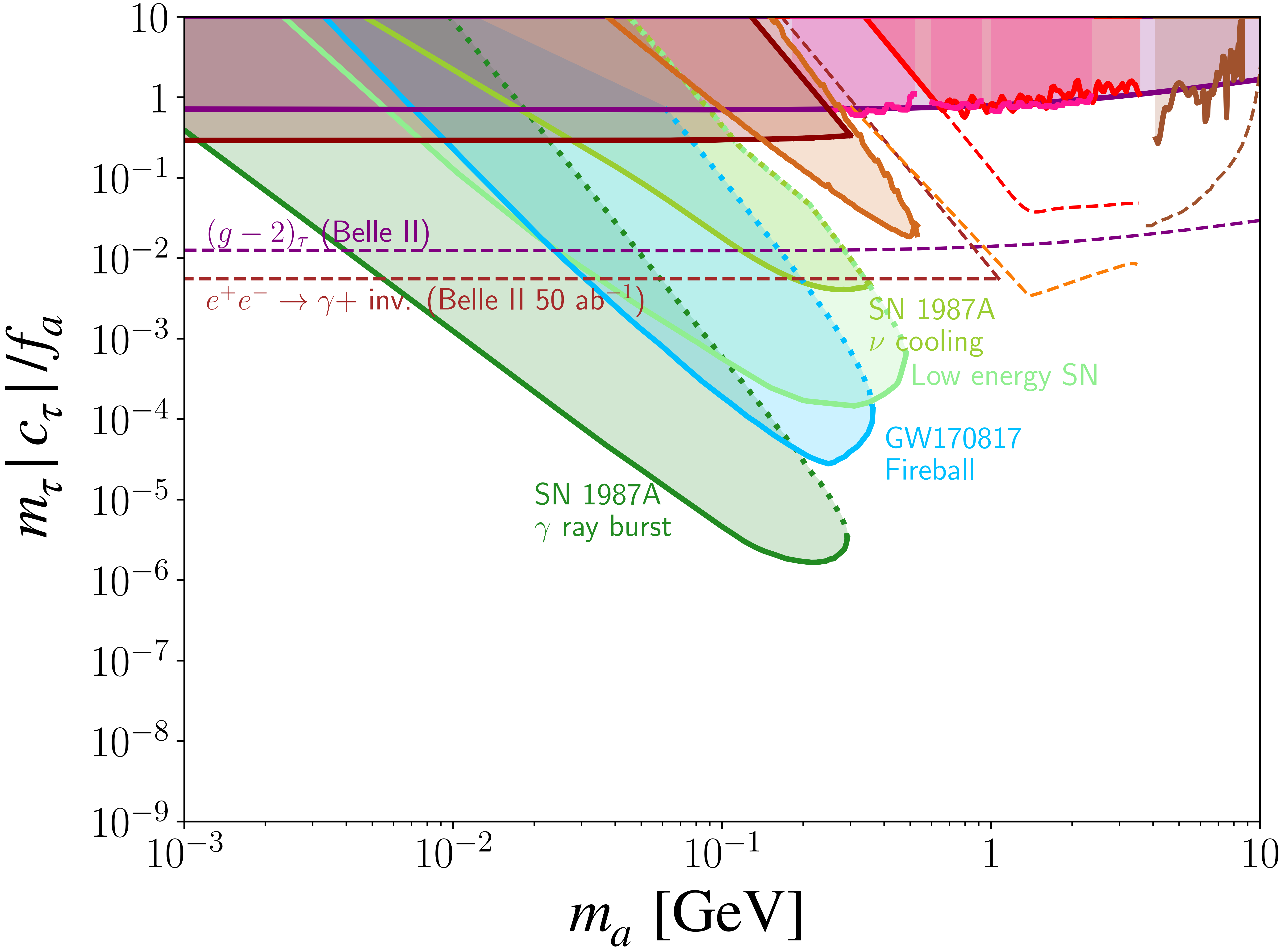
[A. Crivellin, M. Hoferichter and J. M. Roney, Toward testing the magnetic moment of the tau at one part per million, Phys. Rev. D 106 (2022) 093007]

Summary collider $m_a \in [0.1, 10]$ GeV



Astro ⟵ ⟶ LHC

Astrophysical bounds

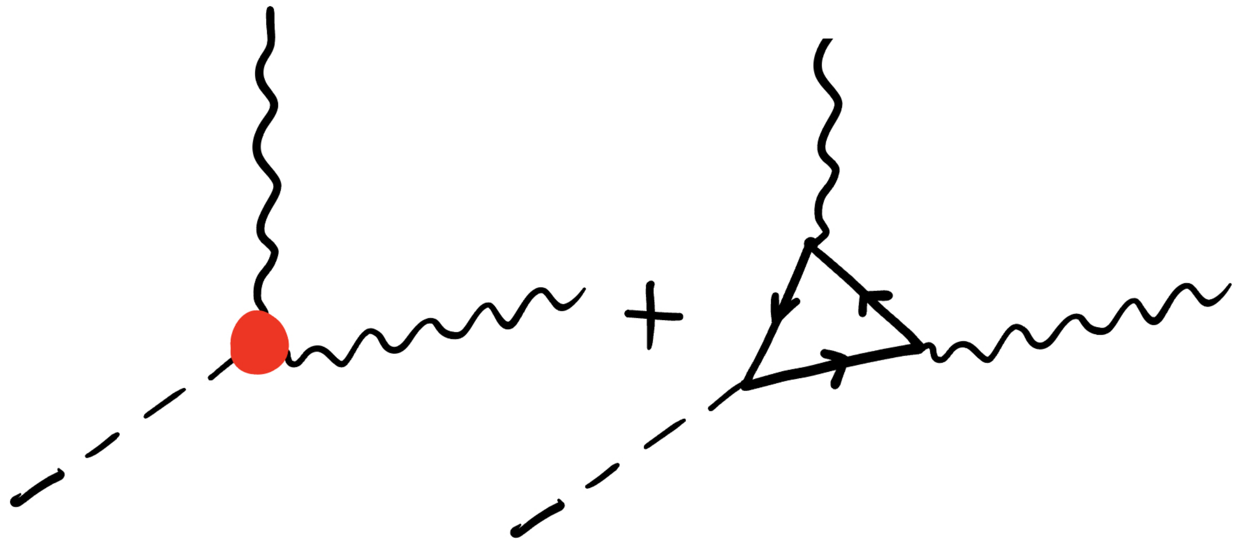


- τ-specific ALPs can be generated in astrophysical environments:
  $\rightarrow$ Primakoff effect ($\gamma + X \rightarrow a + X$)
  $\rightarrow$ coalescence ($\gamma + \gamma \rightarrow a$)
- Subsequent decays into photons:
  $\rightarrow$ change SN 1987A cooling rate
  $\rightarrow$ result in SN 1987A γ-ray burst
  $\rightarrow$ contribute to the explosion energy of SNe
  $\rightarrow$ result in X-rays from "fireballs"
- For small ALP masses, the $a - \gamma - \gamma$ loop functions suppresses the astro signals

$$c_{\gamma\gamma}^{\text{eff},0} = B_1\left(\frac{4m_\tau^2}{m_a^2}\right) \simeq -\frac{m_a^2}{12m_\tau^2}$$

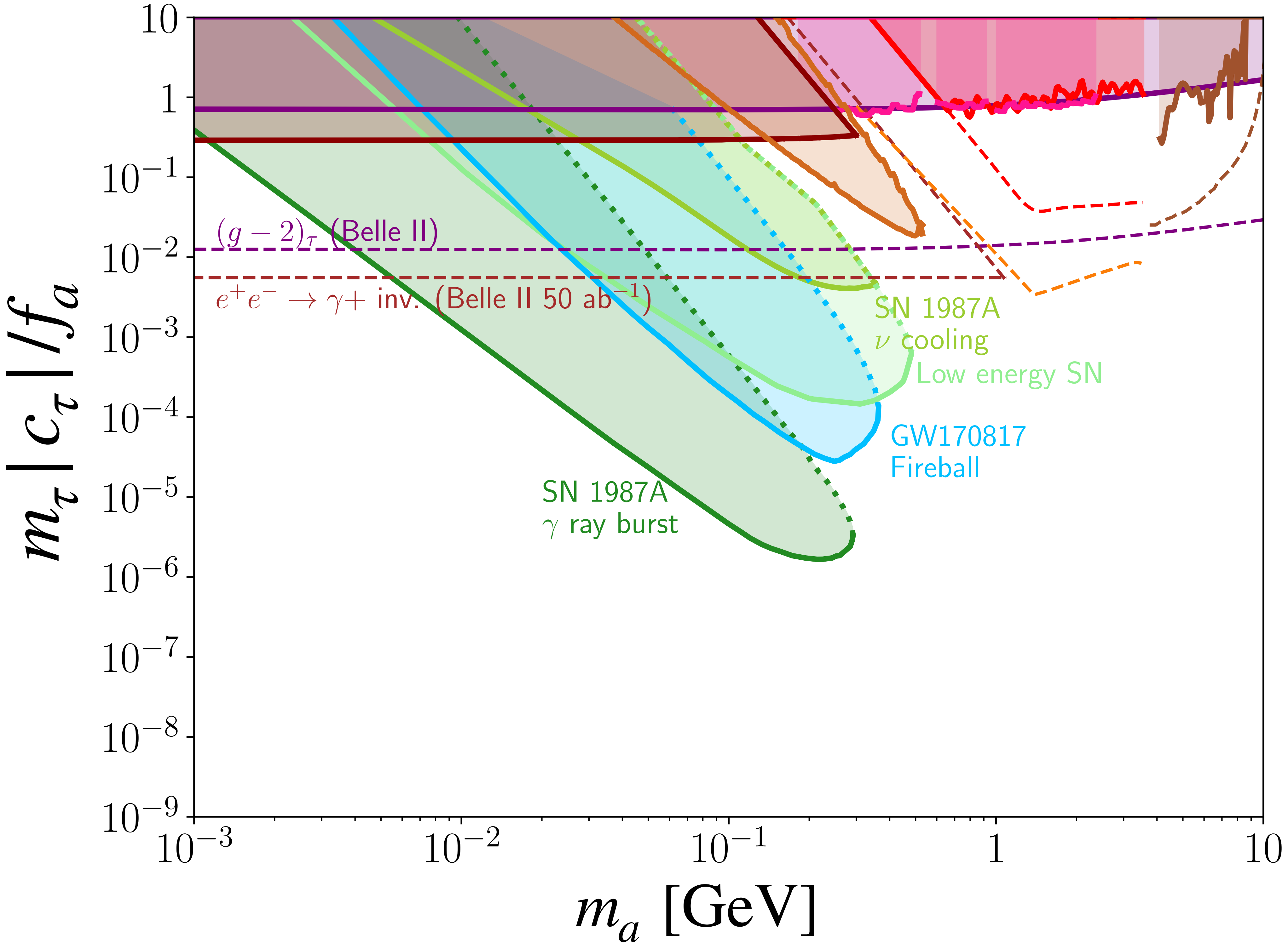
Comparison to other scalars

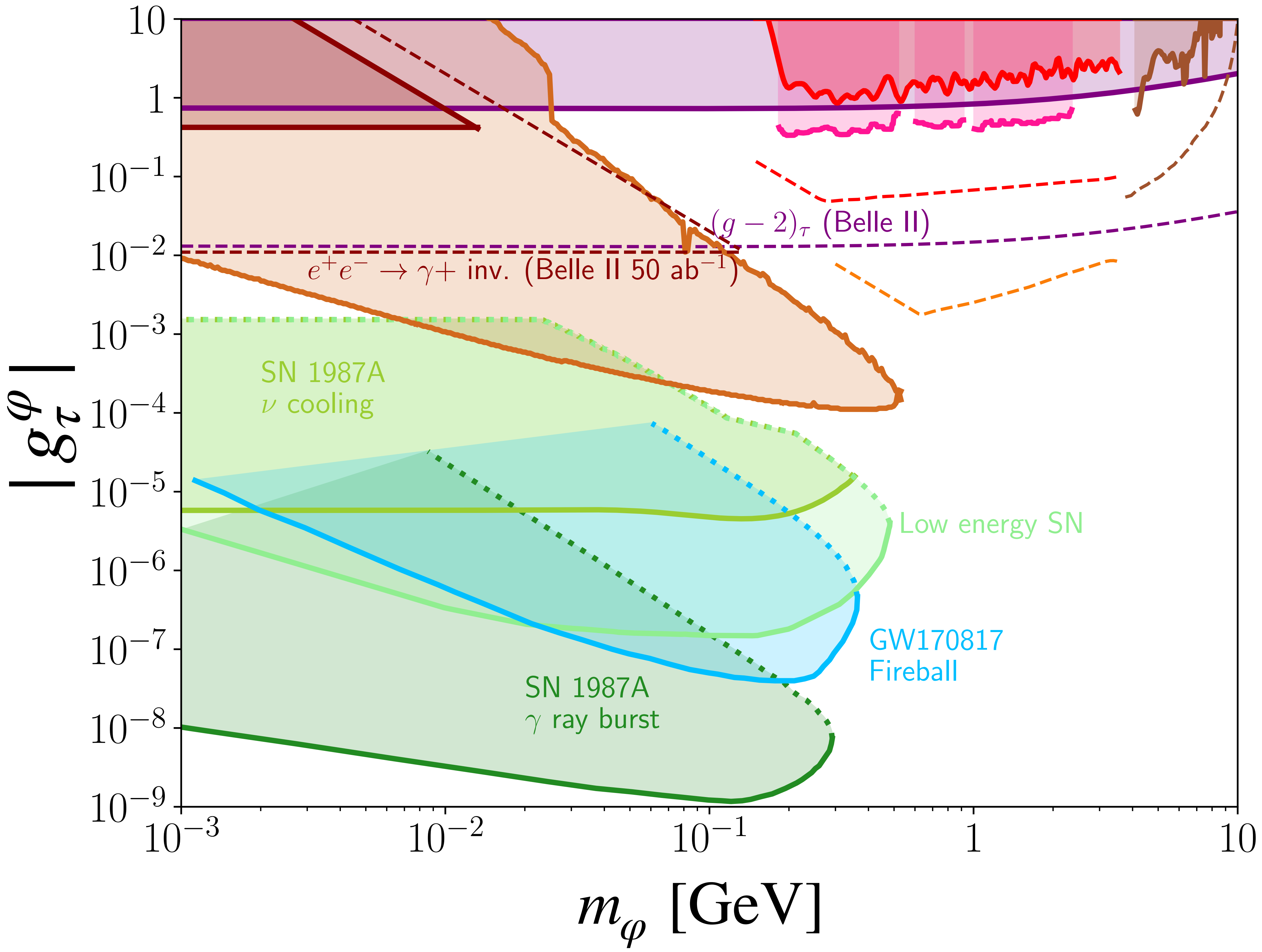
Loop function encoding $a-\gamma-\gamma$ interaction is vastly different for a non-derivatively coupled scalars.



$$\propto \begin{cases} 1 \\ 0 \end{cases} + f(s, m_\tau^2, m_a^2)$$

- 1 or 0 makes a huge difference for $m_a \ll m_\tau$ as $f \to -1$.
- Even for larger $m_a \simeq m_\tau$, at Belle II: $\sigma(e^+e^- \to \gamma a)/\sigma(e^+e^- \to \gamma\varphi) \simeq 4$.





Conclusions

1. The first study of light scalars with dominant couplings to the τ-lepton.
   (Multi-scale solutions to the flavour puzzle and the hierarchy problem motivate light scalars dominantly coupled to the third-generation fermions.)

2. Interplay of different observables is essential.
   (The correlated pattern could help us discover the underlying new physics dynamics.)

3. Belle II is running and could start probing the parameter space.
   (Making a more refined analysis should make the constraints better.)

4. Could we understand the CP and/or pNGB nature of the associated spin-0 particle?
   (Effective interactions with photons and various rates are different.)

Thank you!

$e^+e^- \to \tau^+\tau^-\gamma$ at Belle II

L. Merlo, F. Pobbe, S. Rigolin, O. Sumensari [1905.03259]

Resonant cross-section (through the vector meson resonance):

$$\sigma_{\mathrm{R}}(q^2) = \frac{\Gamma_V^2}{(q^2 - m_V^2)^2 + m_V^2\Gamma_V^2}\, 12\pi\, \mathrm{Br}(V \to e^+e^-)\, \mathrm{Br}(V \to \gamma a)$$

$$\langle \sigma_{\mathrm{R}}(s) \rangle = \int \frac{dq}{\sqrt{2\pi}\sigma_W} \sigma_{\mathrm{R}}(q^2) \exp\left[-\frac{(q - \sqrt{s})^2}{2\sigma_W^2} \right]$$

Non-resonant cross-section (through the off-shell photon):

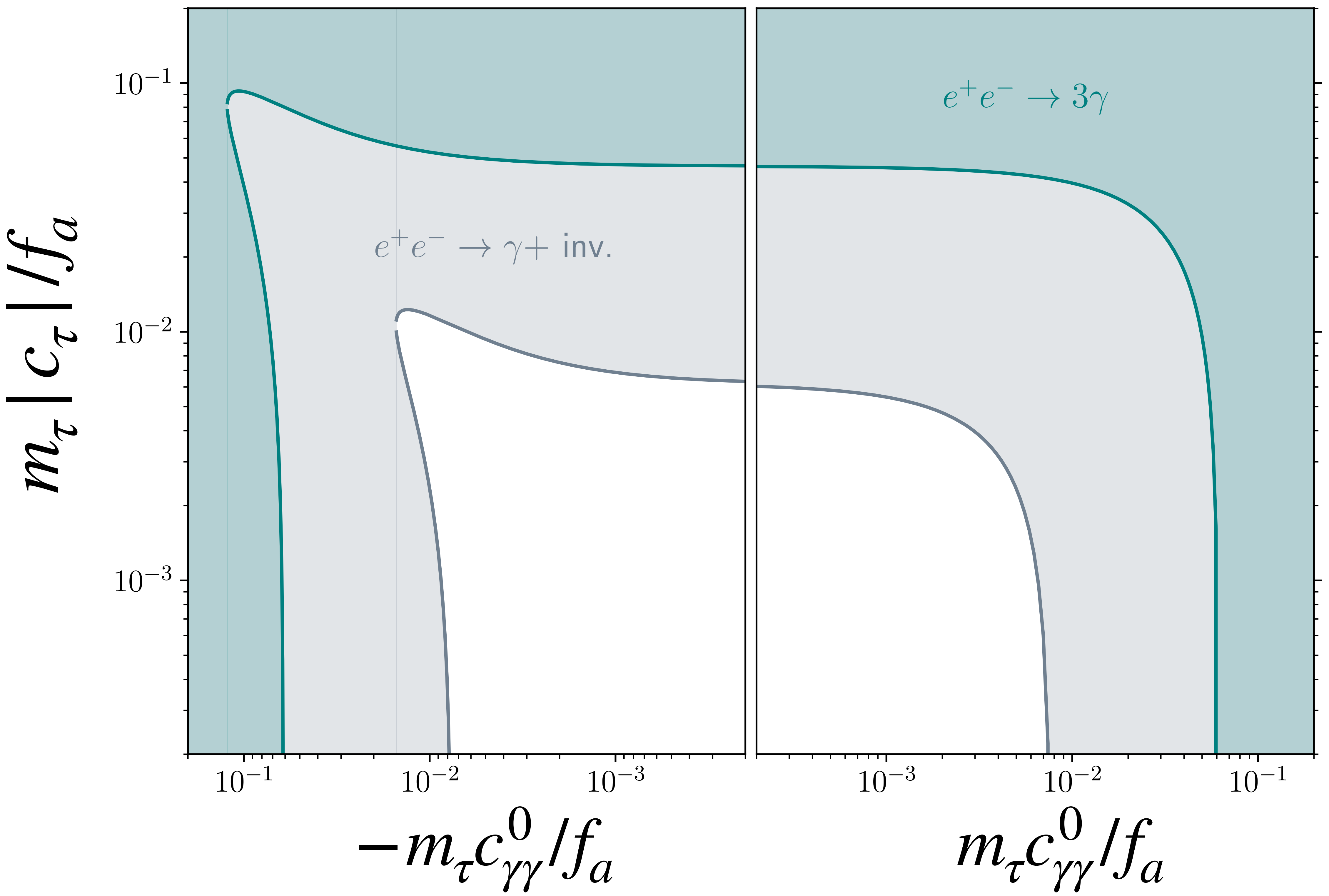
$$\sigma_{\mathrm{NR}}(e^+e^- \to \gamma a) = \frac{\alpha_{\mathrm{em}}^3}{24\pi^2} \frac{|c_{\gamma\gamma}^{\mathrm{eff},s}|^2}{f_a^2} \left(1 - \frac{m_a^2}{s}\right)^3$$

For Belle II (and the $\Upsilon(4S)$ resonance):

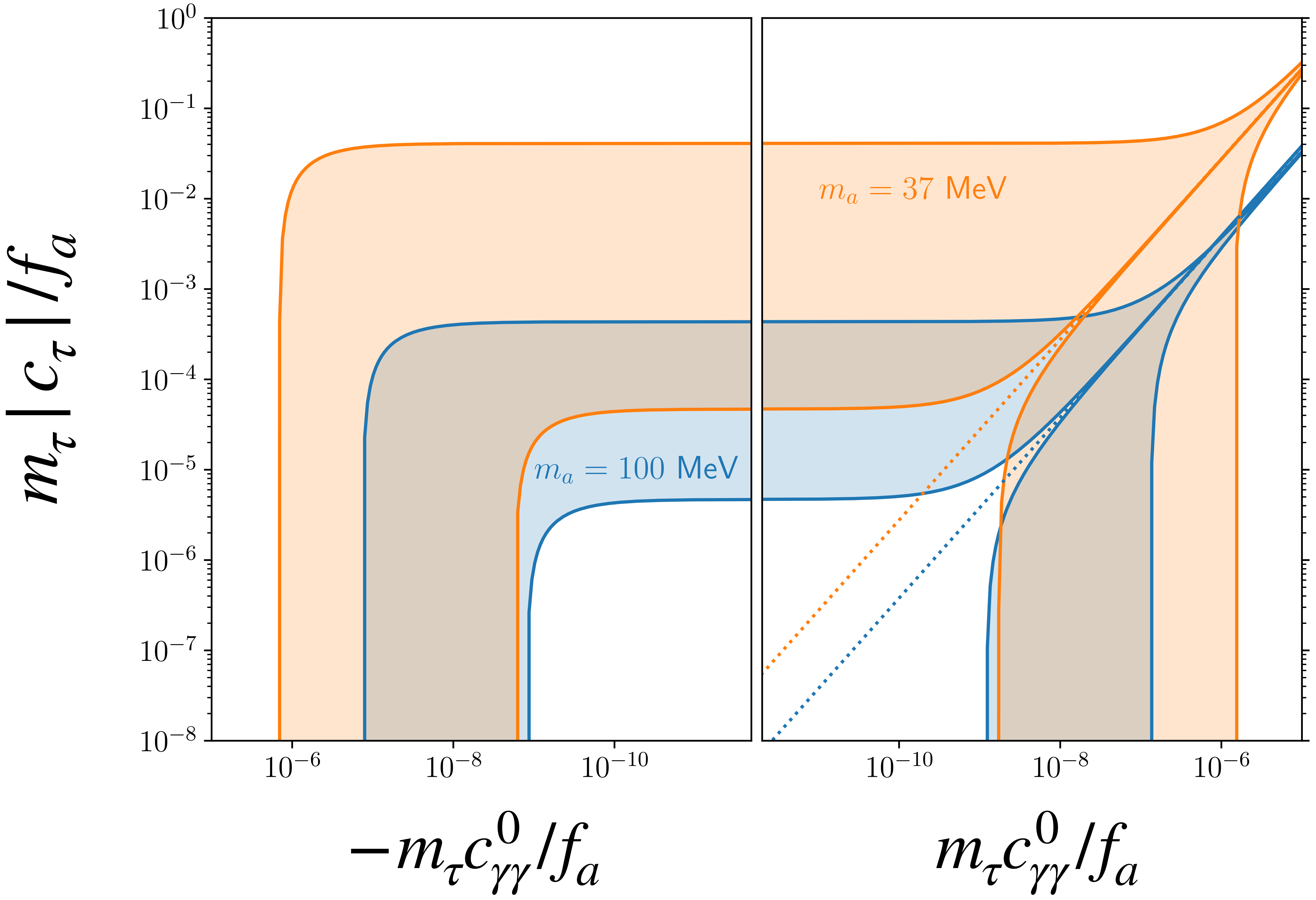
$$\langle \sigma_{\mathrm{R}}(s) \rangle / \sigma_{\mathrm{NR}} \simeq 3 \cdot 10^{-5}$$

Impact of $c^0_{\gamma\gamma}$

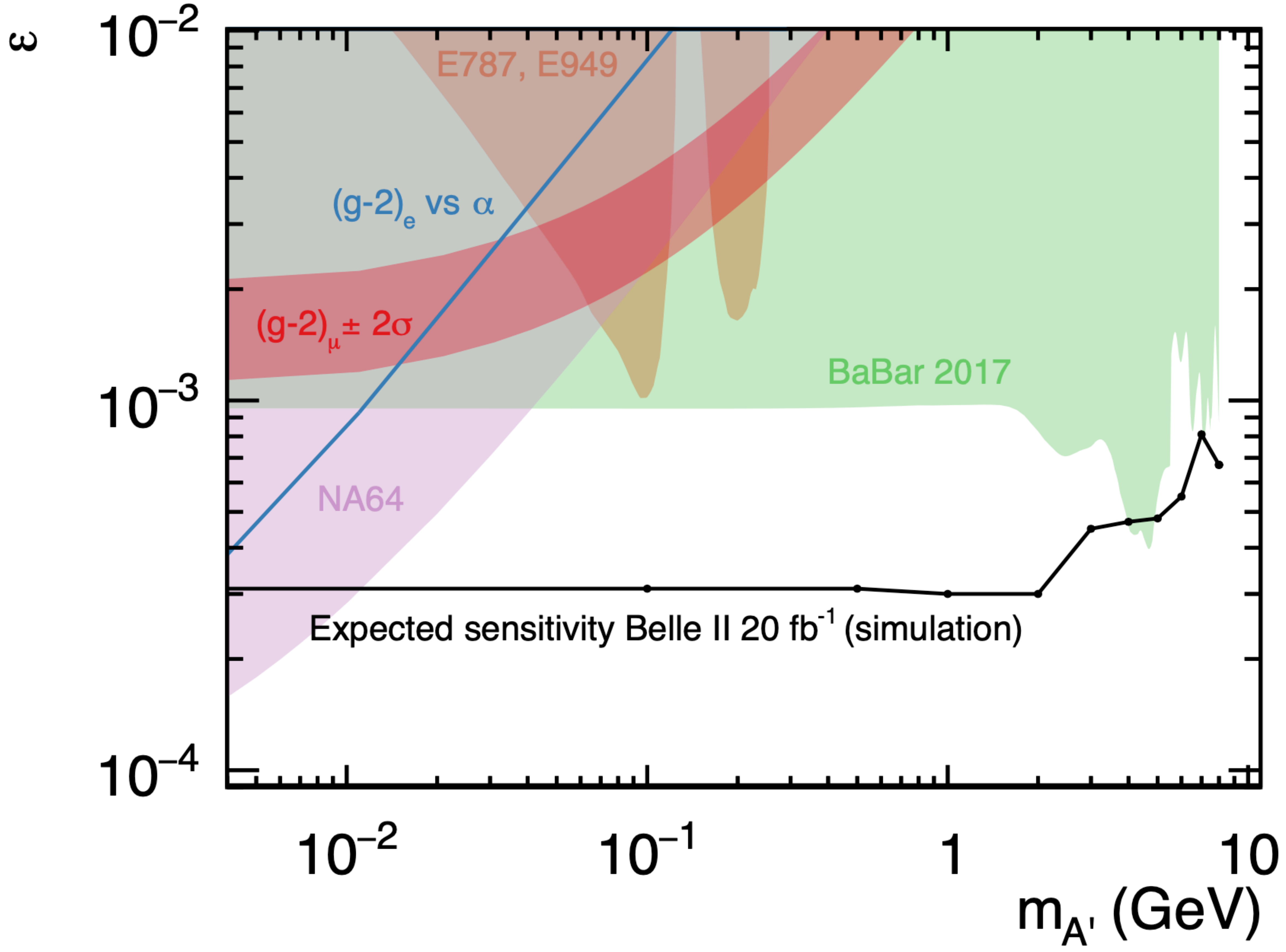
$e^+e^- \to \gamma\gamma\gamma$ (γ + inv.)



Astrophysics



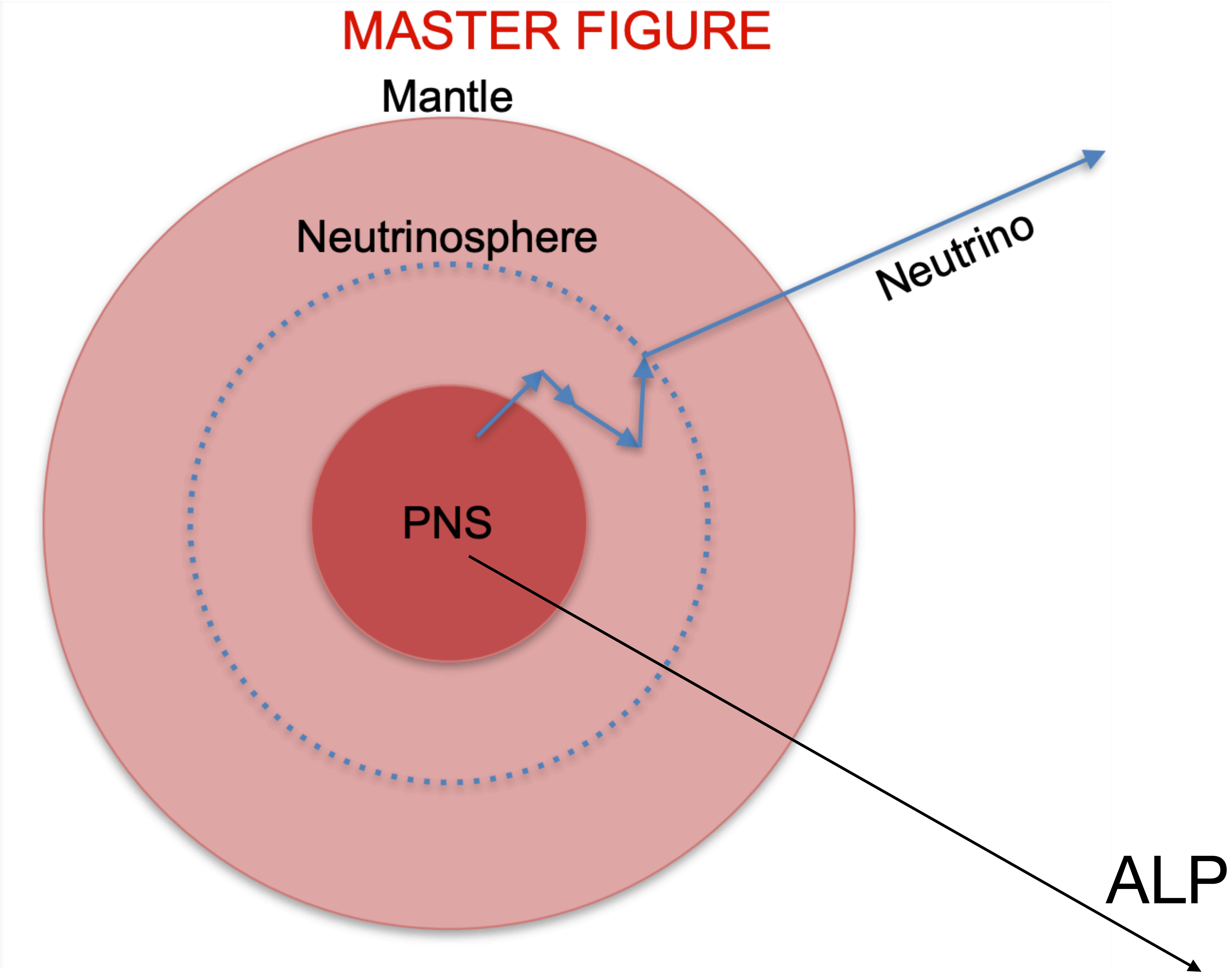
$e^+e^- \to \gamma + \text{inv.}$ at Belle II



Recast of a proposed mono-γ search at Belle II:

[Belle-II collaboration, The Belle II Physics Book, PTEP 2019 123C01]

Astrophysics



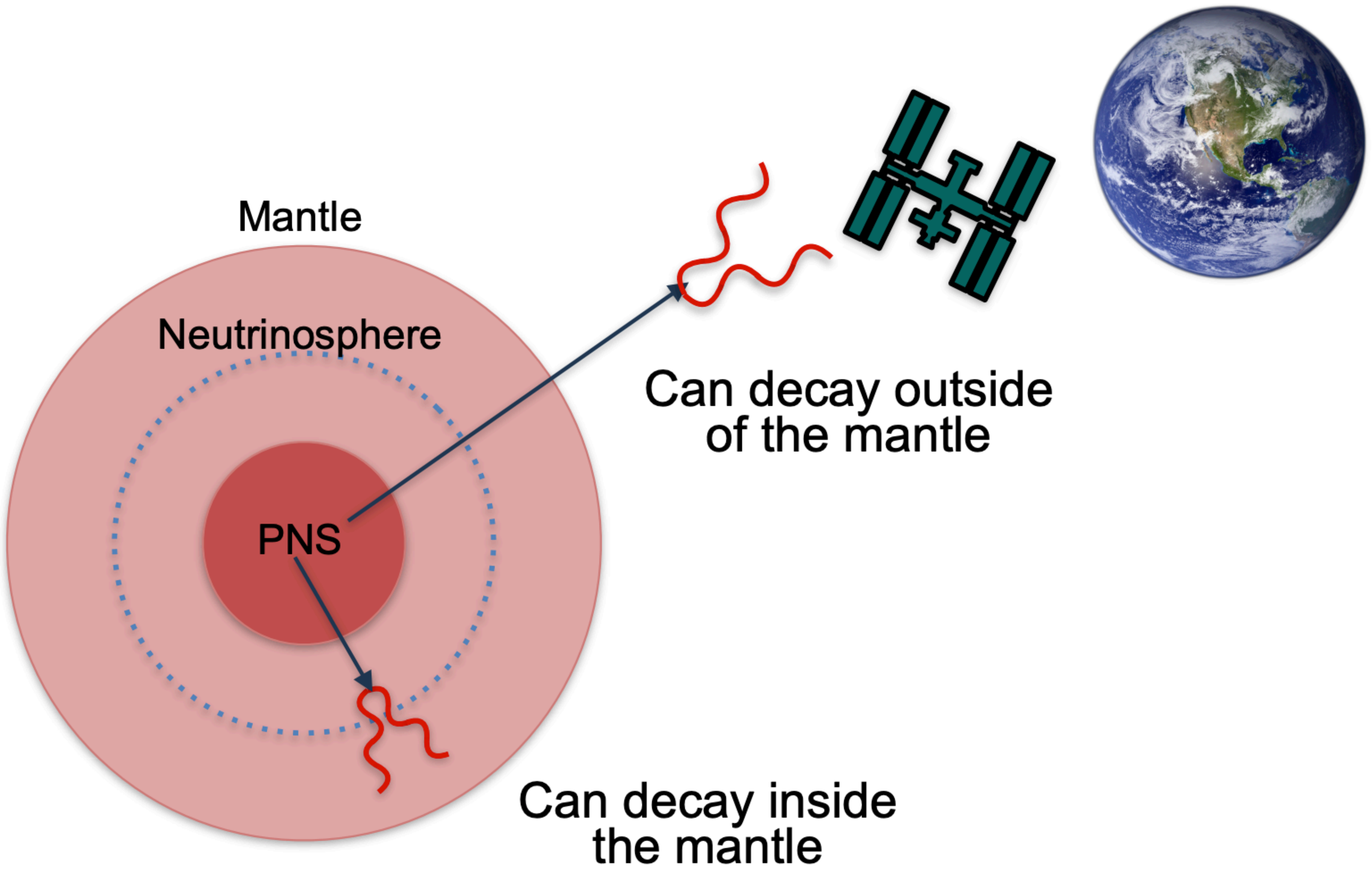
[Raffelt (1994)]

SN 1987A ν cooling:

ALPs carry away the energy

→ less energy available to neutrinos: shortening of the time of the event

Astrophysics

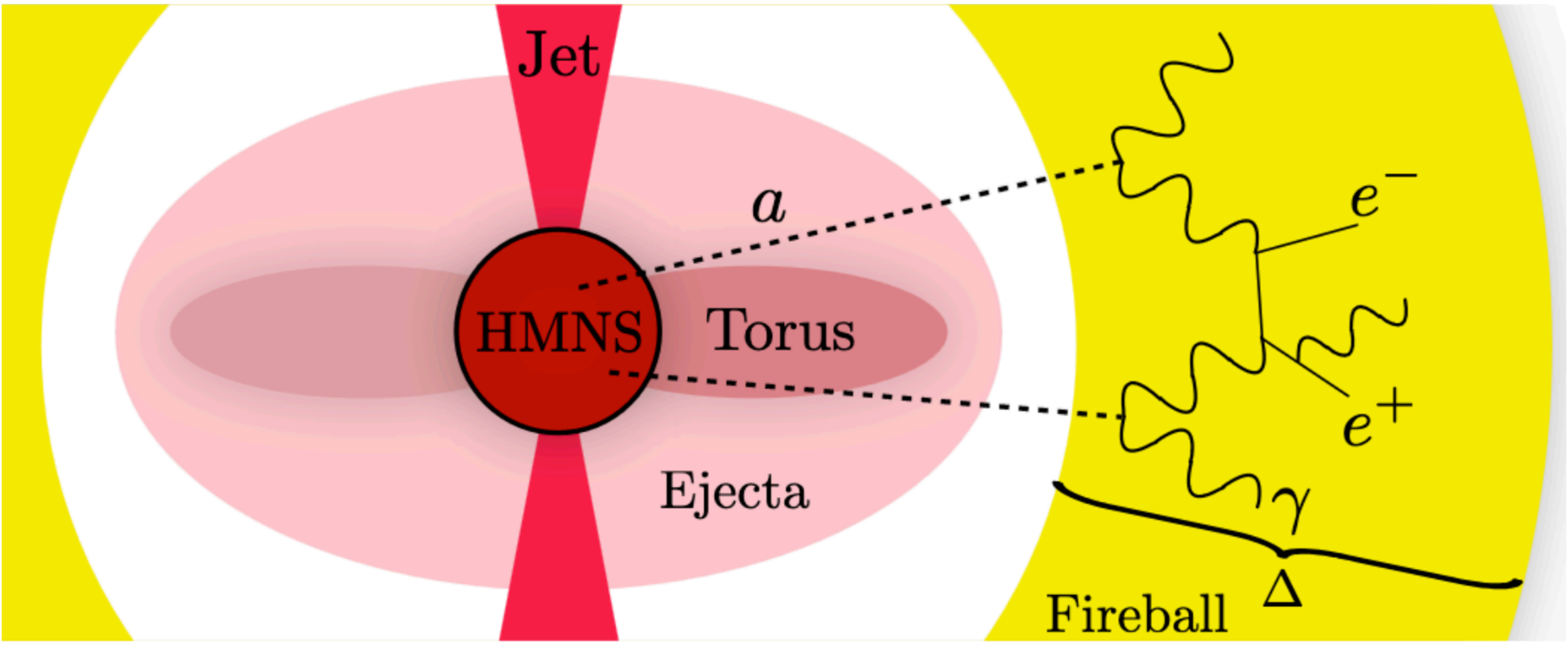


SN 1987A γ-ray burst:

Gamma-ray burst could have been observed by the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite that operated 02/1980–12/1989

[Oberauer et al. Astropart.Phys. 1 (1993) 377-386 Chupp et al. Phys.Rev.Lett. 62 (1989) 505-508 Jaeckel et al., Phys.Rev.D 98 (2018) 5, 055032 Caputo, Raffelt, Vitagliano, Phys.Rev.D 105 (2022) 3, 035022 Hoof and Schulz (2022)]

Astrophysics



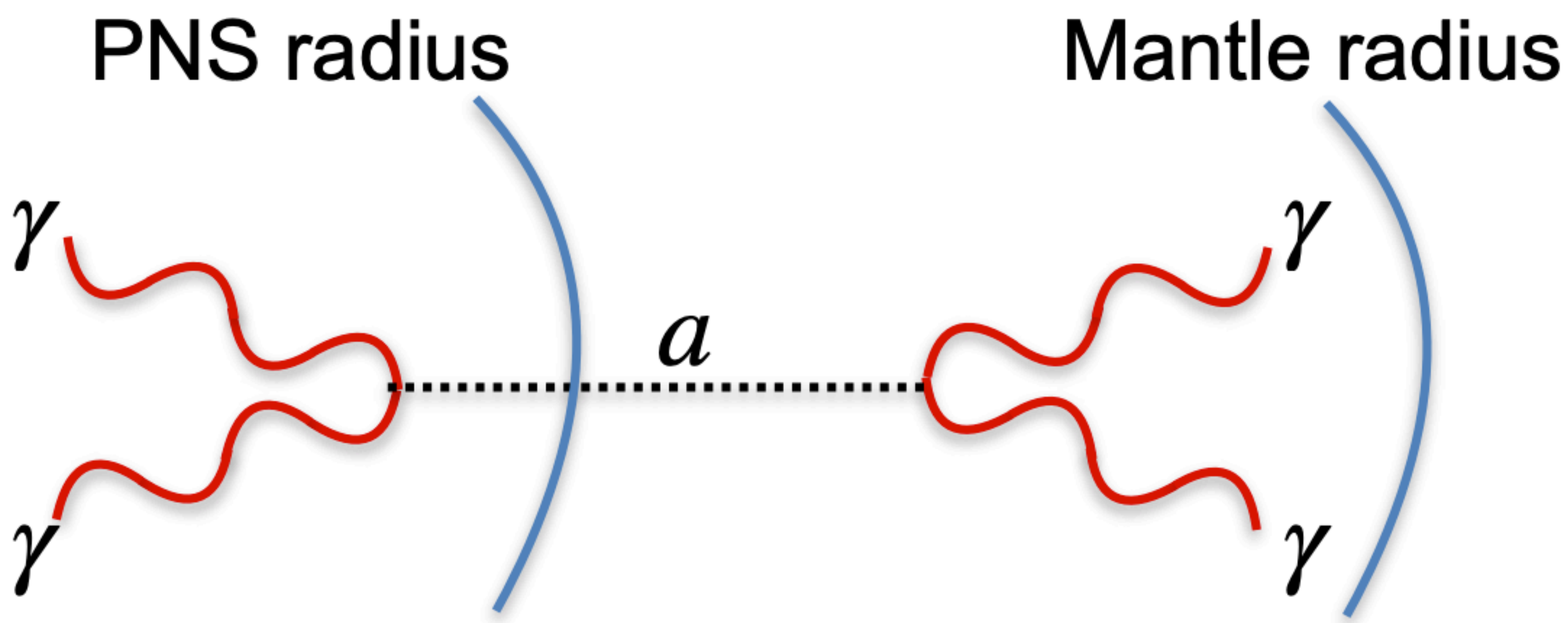
GW17081 Fireball:

The decay of the ALPs produced during a neutron star merger would produce a dense plasma of interacting photons: “fire-ball”.

Result in X-rays which could be detected by detectors of GW 170817.

[Diamond, Fiorillo, Marques-Tavares, Tamborra, Vitagliano, Phys.Rev.Lett. 132 (2024) 10, 10]

Astrophysics



Low-E SNe:

Some SNe have very small observed explosion energies < 0.1 B (Bethe) = 10^{50} erg.

If ALPs were short-lived, they would deposit their energy within the progenitor star, contributing to the explosion energy.

[Caputo, Raffelt, Janka, Vitagliano, Phys.Rev.Lett. 128 (2022) 22, 221103]