Axion-like Particle

At Higgs Factories and at Super-K

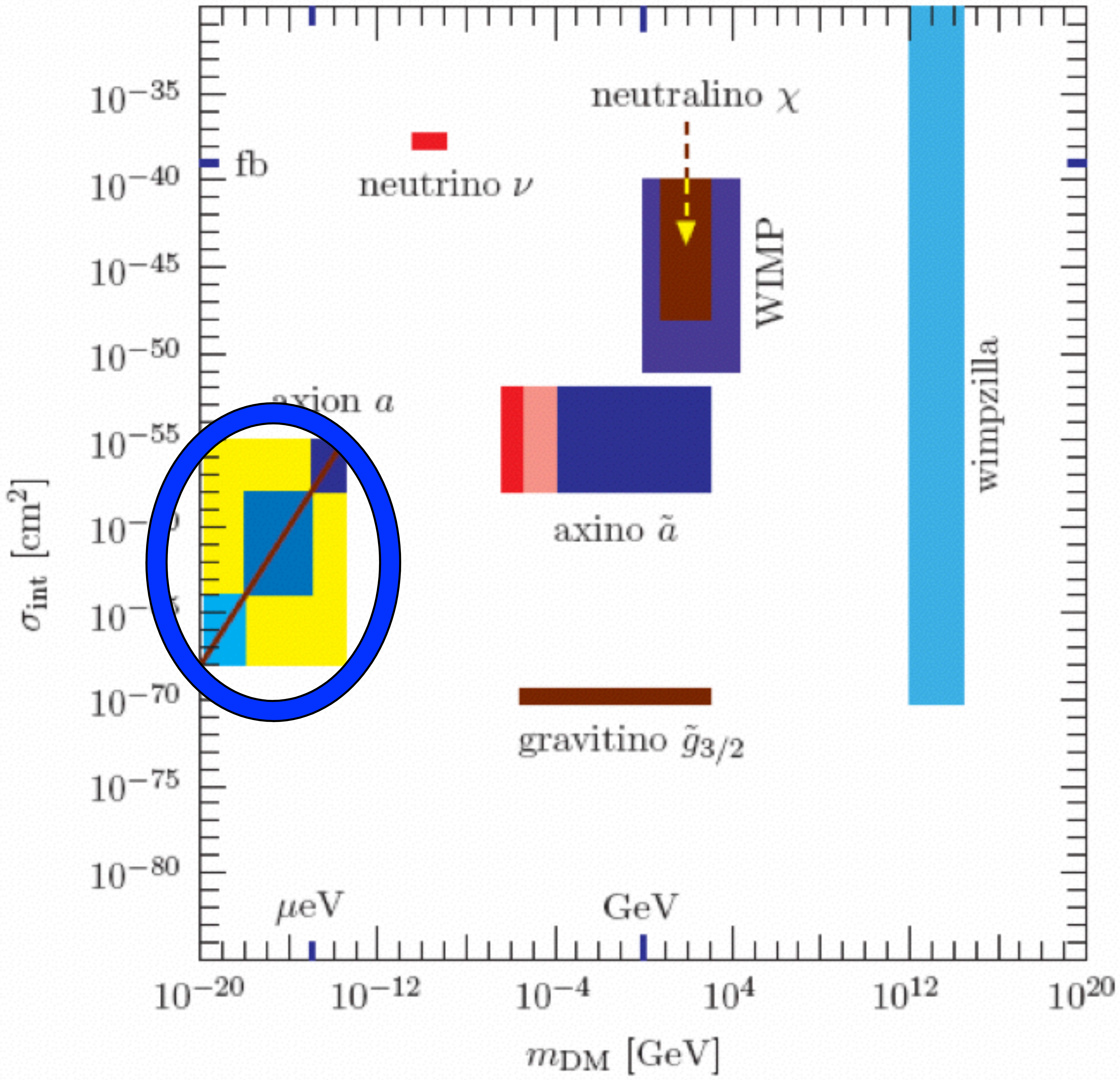
Kingman Cheung, IAS Program on High Energy Physics (HEP 2024)

Contents

- Motivations for axions
- Summary of current limits on axion or axion-like particle (ALP)
- Search for ALP at the Higgs factories (2303.16514)
- Atmospheric ALP at Super-K (2208.05111)

Axion is a strong case of Physics Beyond the SM

- Solve the strong QCD problem
- A potential dark matter candidate
- Unlike SUSY, it does not solve the hierarchy problem.



Strong QCD Problem: the θ term in QCD

- QCD Lagrangian: here $-\pi \leq \bar{\theta} \leq \pi$

$$\mathscr{L} = \bar{q}(i\gamma_\mu D^\mu - M_q)q - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s}{8\pi} \bar{\theta} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

- This θ term violates T and P, thus CP.
- Most sensitive probe of T and P violation in flavor-conserving process:

EDM of neutron

$$d_n(\bar{\theta}) = 2.4 \times 10^{-16}\, \bar{\theta} \;\; e\mathrm{cm}$$

- Experiment: current best limit:

$$|d_n| = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26} \;\; e\mathrm{cm}$$

[Abel etal 2020]

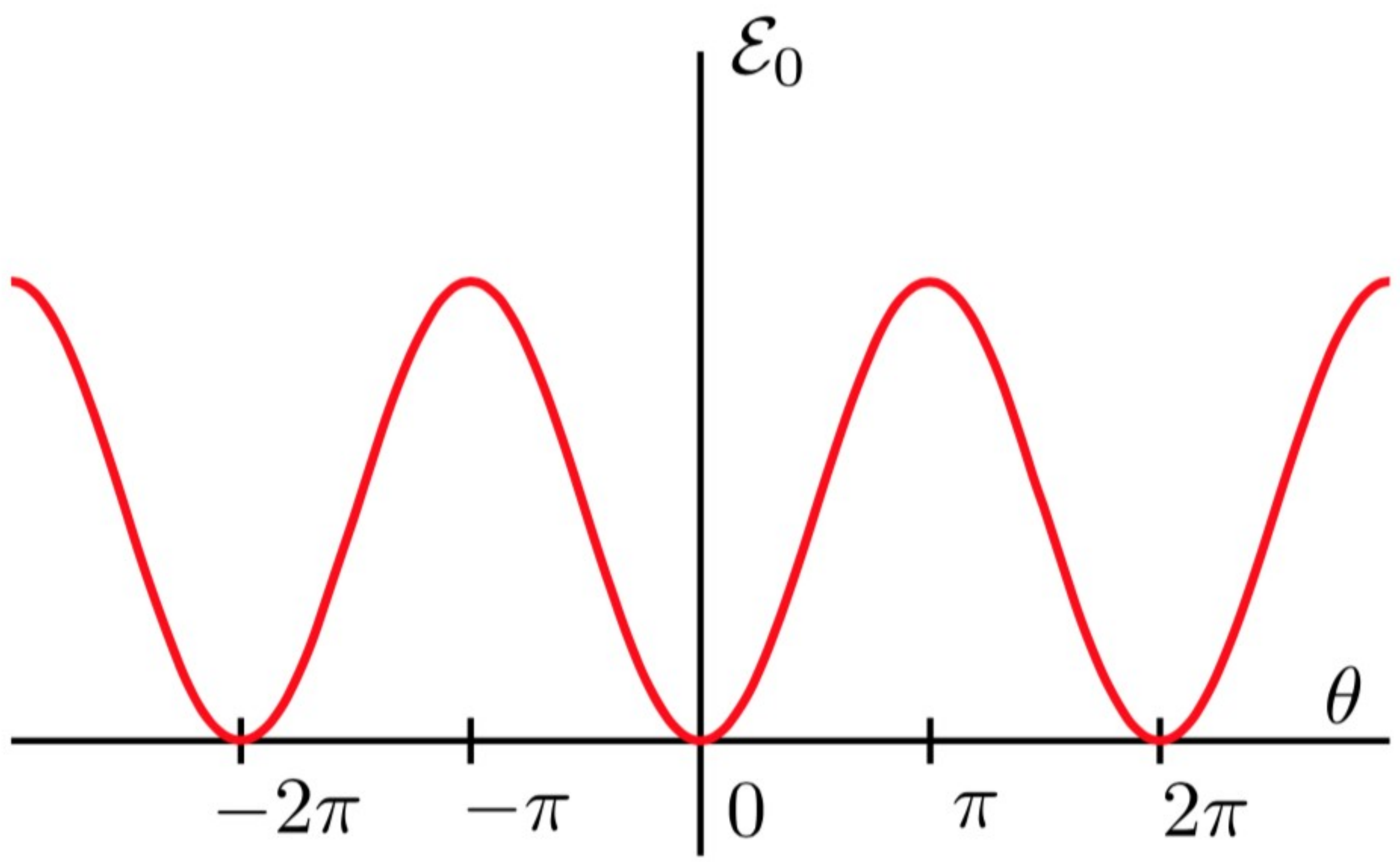
- It implies

$$|\bar{\theta}| < 10^{-10}$$

Strong CP problem: why $\bar{\theta}$ is so small.

A Dynamical solution: axion field

- Dynamical solution of strong CP problem based on observation that the vacuum energy in QCD has minimum at $\bar{\theta} = 0$



$$\epsilon_0(\bar{\theta}) \simeq \Sigma\,(m_u + m_d)\left(1 - \frac{\sqrt{m_u^2 + m_d^2 + 2 m_u m_d \cos\bar{\theta}}}{m_u + m_d}\right)$$

$$\Sigma = -\langle \bar{u}u \rangle = -\langle dd \rangle$$

[Di Vecchia,Veneziano `80; Leutwyler,Smilga 92]

- If $\bar{\theta}$ is a dynamical field, $\bar{\theta}(x) = a(x)/f_a$. Its VEV would be zero (to solve the strong CP)
- The particle excitation is called the axion.
- The mass: $m_a \simeq \frac{\sqrt{\Sigma}}{f_a}\sqrt{\frac{m_u m_d}{m_u + m_d}} \simeq \frac{m_\pi f_\pi}{f_a}\frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\mathrm{meV}\left(\frac{10^9\,\mathrm{GeV}}{f_a}\right)$. Note if it is not the QCD axion, this mass relation does not hold.

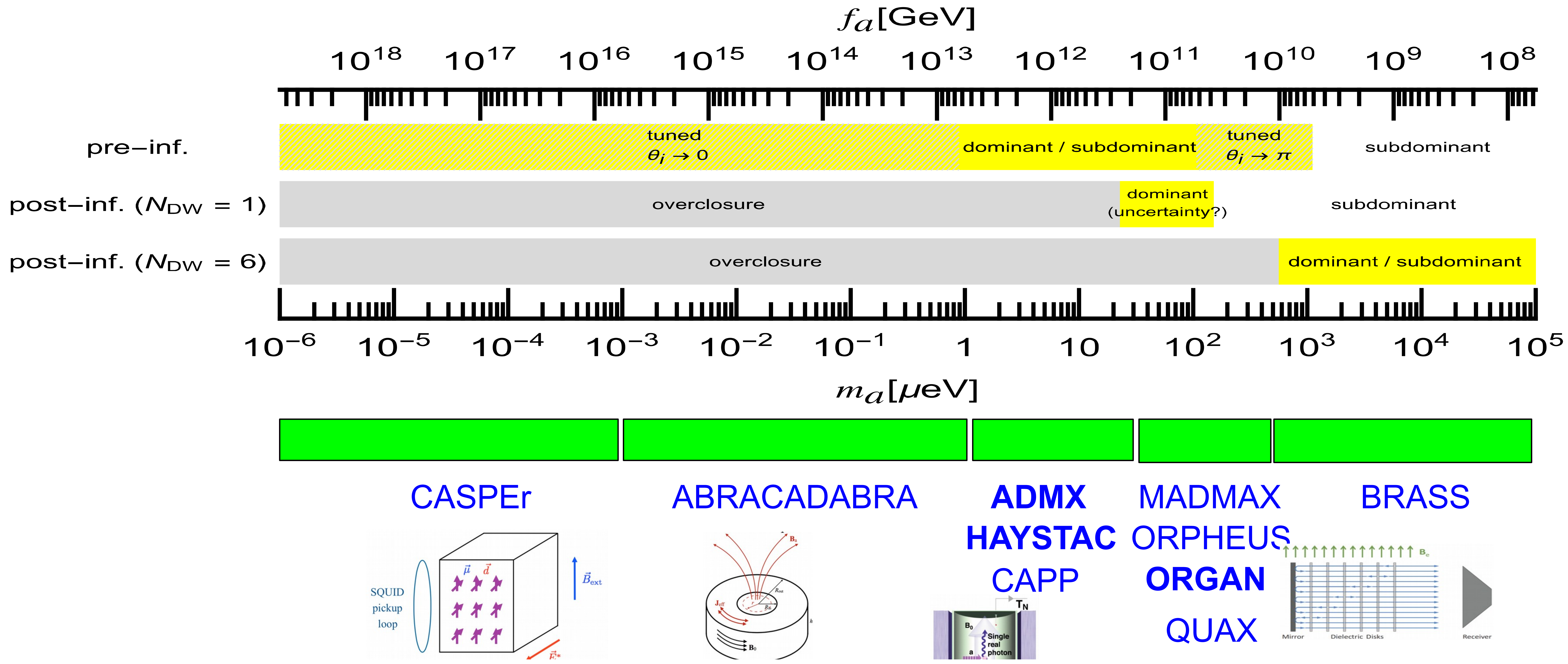
Axion Dark Matter

- DM prediction: $\Omega_a h^2 \simeq \left(\frac{f_a}{9\times 10^{11}\ \mathrm{GeV}}\right)^{1.165} \theta_i^2 \simeq 0.12 \left(\frac{6\mu\mathrm{eV}}{m_a}\right)^{1.165} \theta_i^2$
- For $f_a > 10^9$ GeV, axion DM can be substantial and even 100%.
- A lot of experiments searching for axion DM:

Axion Dark Matter

Experimental hunt

- Strong motivation for current und upcoming axion DM experiments:



ALP couples to photon pairs and fermions

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_{gg} + \mathcal{L}_{BB} + \mathcal{L}_{WW}$$

$$\mathcal{L}_f = \sum_f \frac{\partial_\mu a}{f_a} \bar{f}\gamma^\mu(1+\gamma^5)f = \sum_f -i\frac{2m_f}{f_a} a\bar{f}\gamma^5 f$$

$$\mathcal{L}_g = -C_g \frac{a}{f_a} G^A_{\mu\nu}\tilde{G}^{\mu\nu,A}$$

$$\mathcal{L}_{BB} = -C_{BB}\frac{a}{f_a} B_{\mu\nu}\tilde{B}^{\mu\nu}$$

$$\mathcal{L}_{WW} = -C_{WW}\frac{a}{f_a} W^i_{\mu\nu}\tilde{W}^{\mu\nu,i}$$

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} c_w & s_w \\ -s_w & c_w \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}.$$

$$\mathcal{L}_{gauge} = \sum_f -i\frac{2m_f}{f_a} a\bar{f}\gamma^5 f - C_g \frac{a}{f_a} G^A_{\mu\nu}\tilde{G}^{\mu\nu,A}$$
$$- \frac{a}{f_a}\Big[(C_{BB}c_w^2 + C_{WW}s_w^2)F_{\mu\nu}\tilde{F}^{\mu\nu} + (C_{BB}s_w^2 + C_{WW}c_w^2)Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$
$$+ 2(C_{WW} - C_{BB})c_w s_w F_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{WW}W^+_{\mu\nu}W^{-\mu\nu}\Big]$$

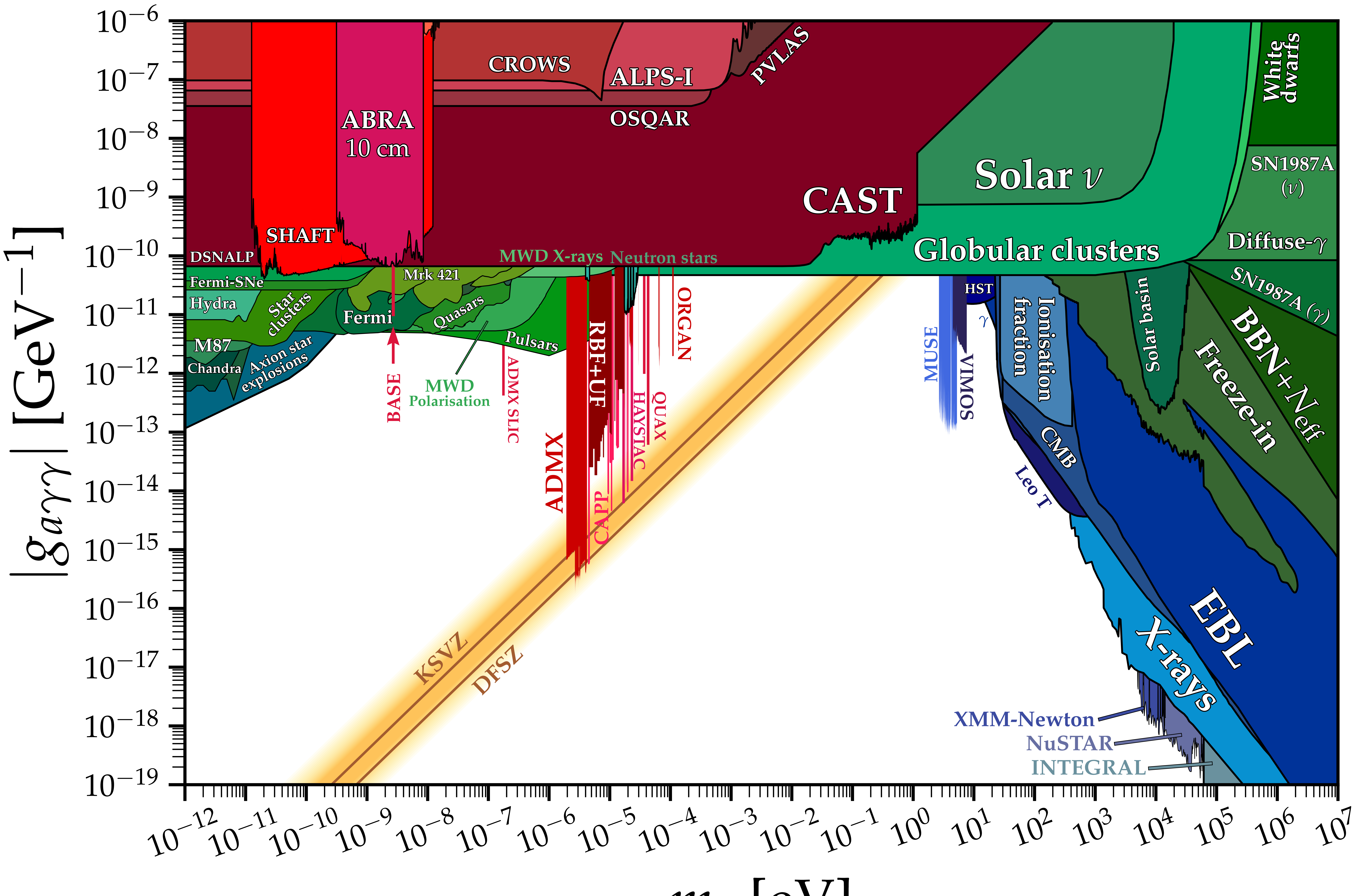
In terms of the conventional $g_{a\gamma\gamma}$, etc : $\mathscr{L} = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}g_{aZZ}aZ_{\mu\nu}\tilde{Z}^{\mu\nu} + \ldots$

$$g_{a\gamma\gamma} = \frac{4}{f_a}(C_{BB}c_w^2 + C_{WW}s_w^2),$$

$$g_{aWW} = \frac{4}{f_a}C_{WW},$$

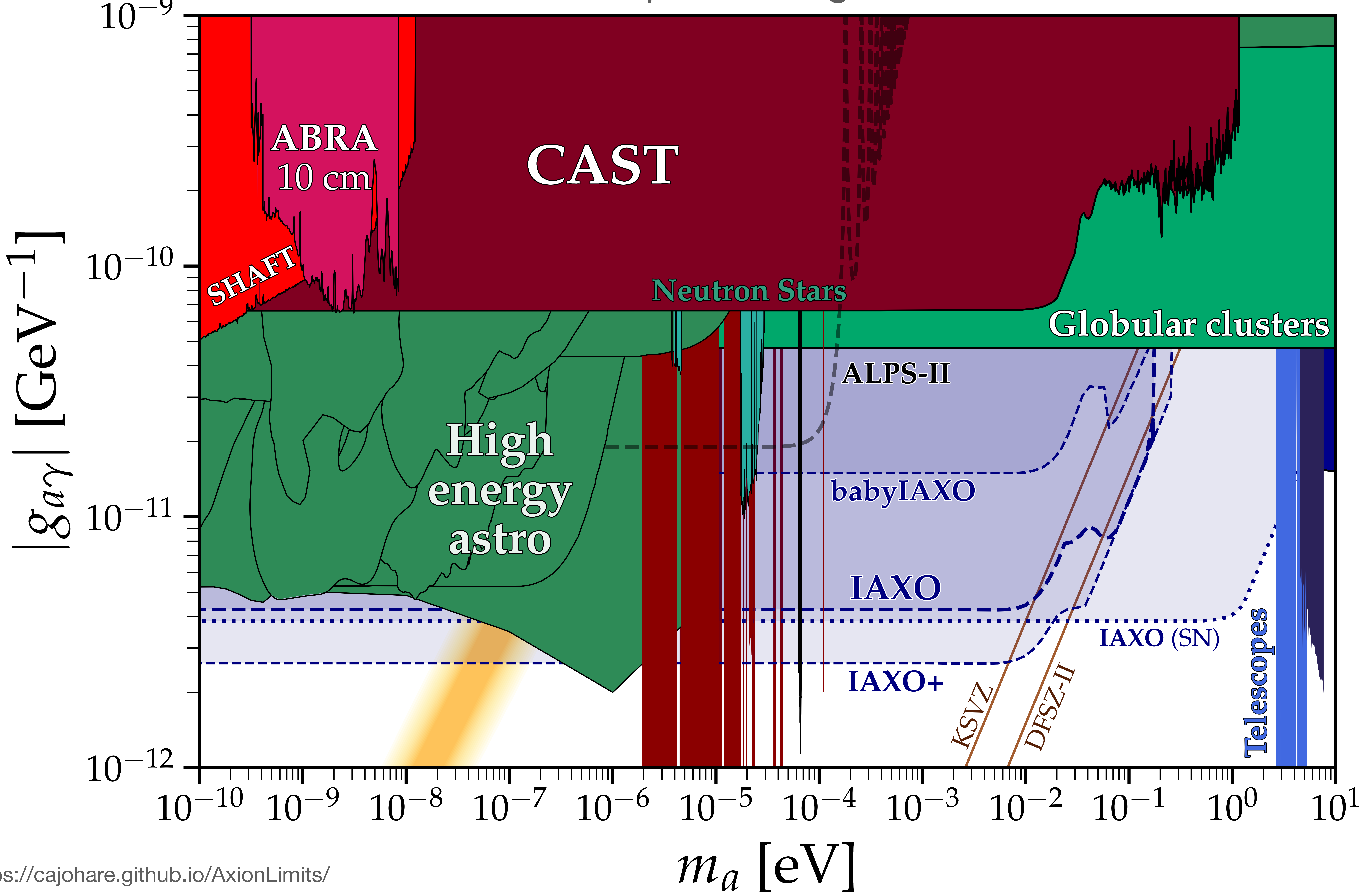
$$g_{aZZ} = \frac{4}{f_a}(C_{BB}s_w^2 + C_{WW}c_w^2),$$

$$g_{aZ\gamma} = \frac{8}{f_a}s_w c_w(C_{WW} - C_{BB})\,.$$



https://cajohare.github.io/AxionLimits/

Helioscope coverage



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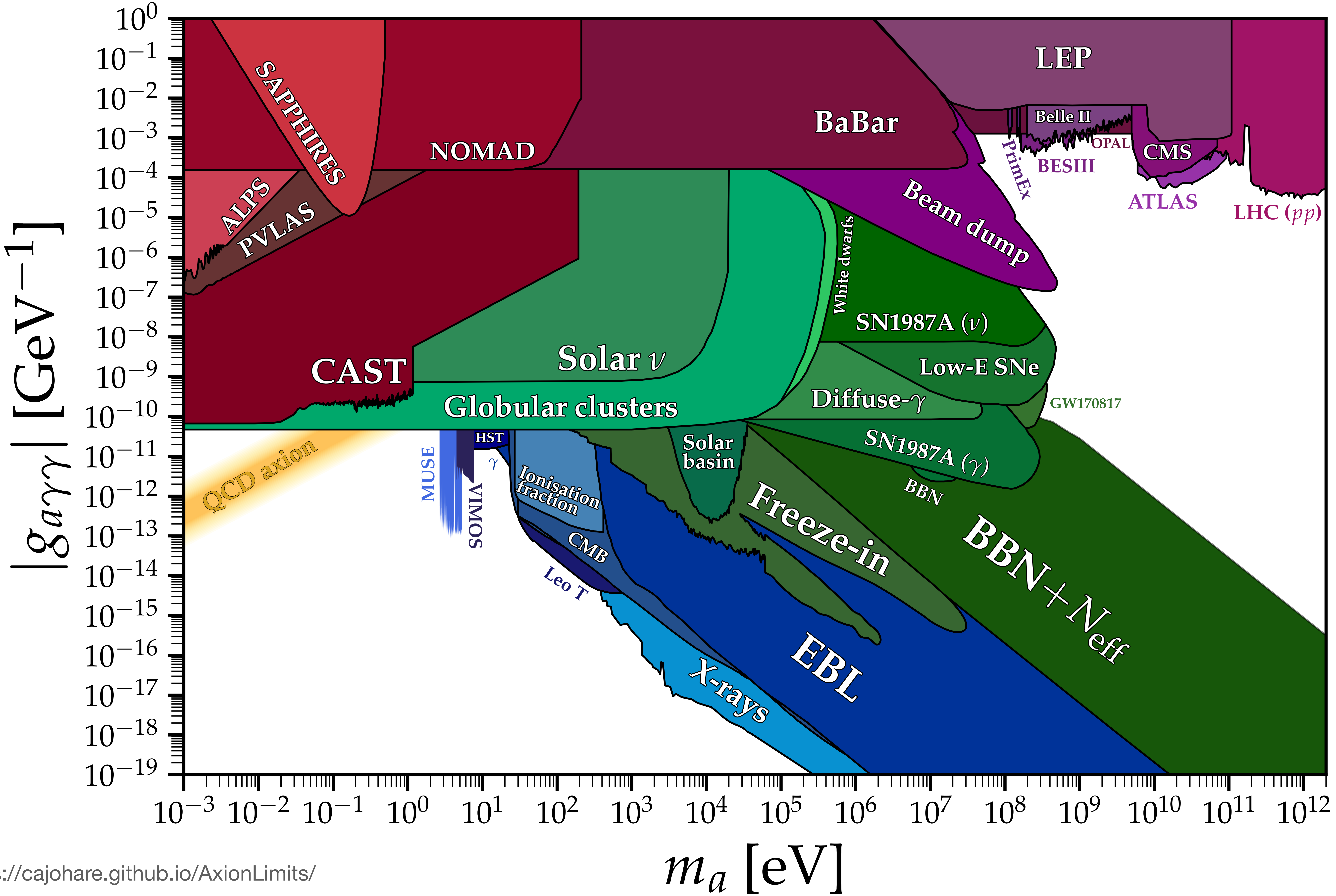
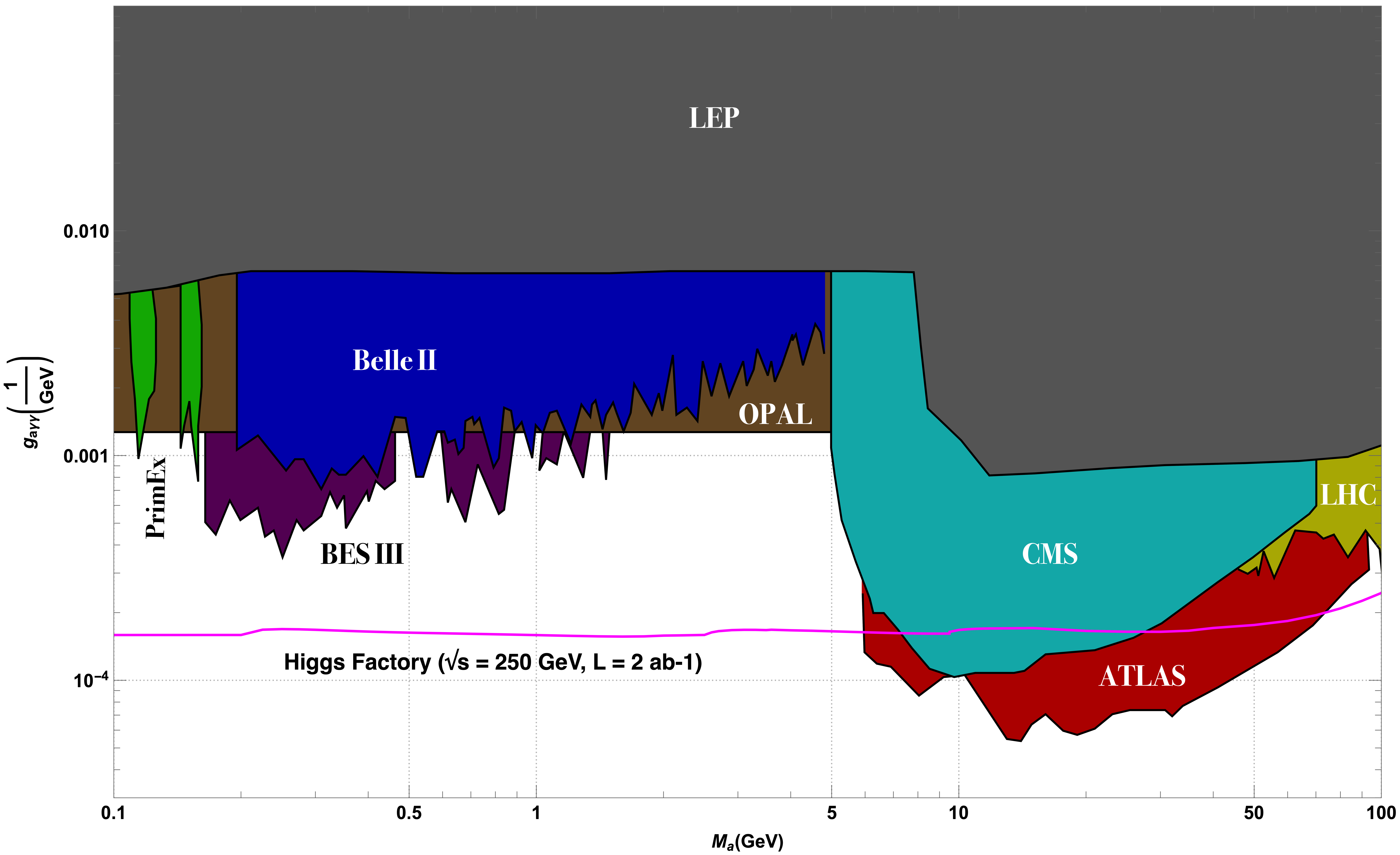
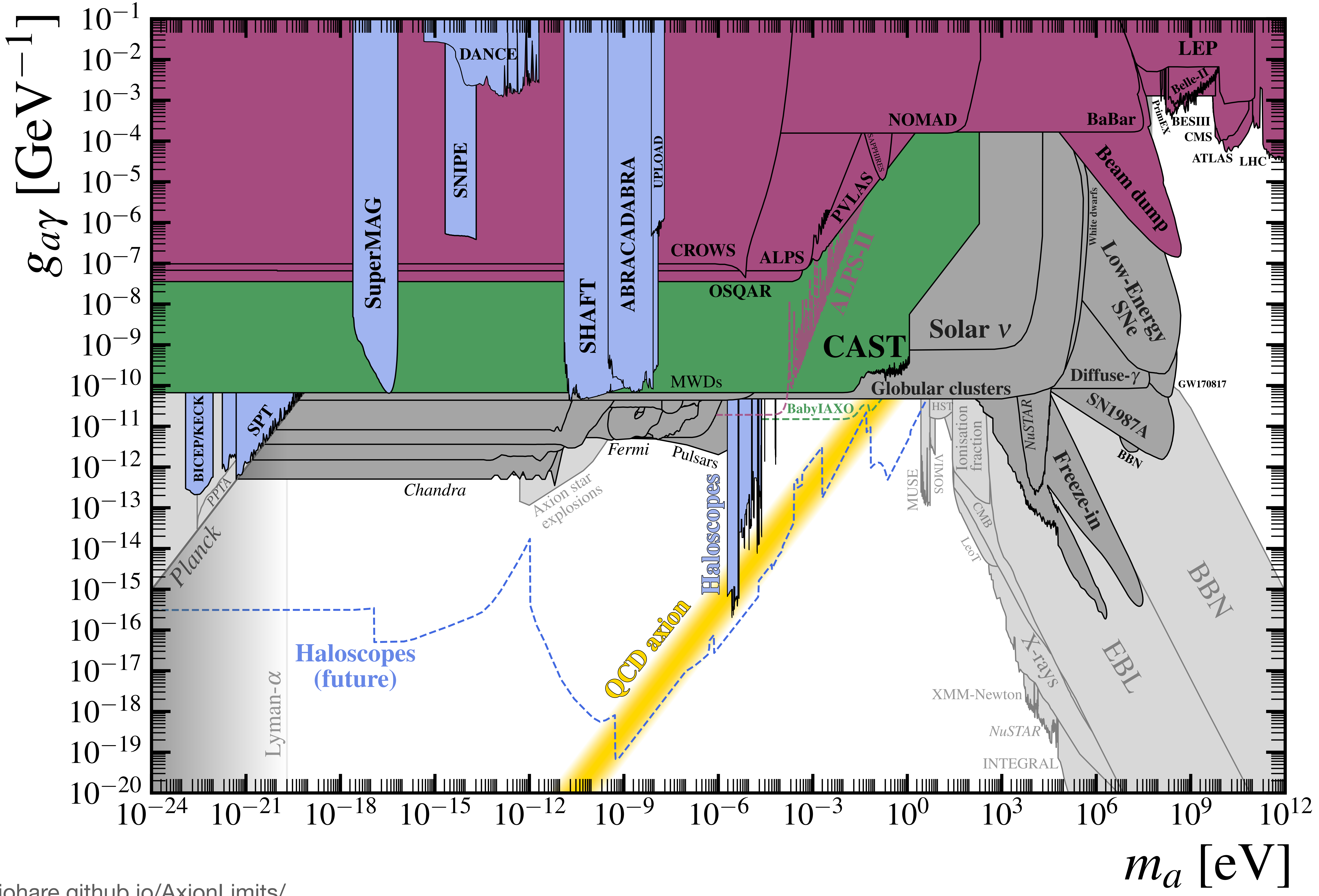


https://cajohare.github.io/AxionLimits/

$\sqrt{s} = 250$ GeV with an integrated luminosity 2 ab^{-1},



FIPs White Paper



https://cajohare.github.io/AxionLimits/

Axion Like Particle Search at Higgs Factories

K.C, Ouseph 2303.1651, PRD

e^+e^- Collider	$\sqrt{s}$ (GeV)	Integrated Luminosity (fb^{-1})
ILC	250	2000
CEPC	240	5600
FCC-ee	250	5000

TABLE I: A few proposals of e^+e^- colliders running as a Higgs factory, at which the center-of-mass energy and integrated luminosity are shown.

$$\mathcal{L}_{gauge} = \sum_f -i\frac{2m_f}{f_a} a\bar{f}\gamma^5 f - C_g \frac{a}{f_a} G^A_{\mu\nu}\tilde{G}^{\mu\nu,A}$$

$$- \frac{a}{f_a}\Big[(C_{BB}c_w^2 + C_{WW}s_w^2)F_{\mu\nu}\tilde{F}^{\mu\nu} + (C_{BB}s_w^2 + C_{WW}c_w^2)Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$+ 2(C_{WW} - C_{BB})c_w s_w F_{\mu\nu}\tilde{Z}^{\mu\nu} + C_{WW}W^+_{\mu\nu}W^{-\mu\nu}\Big]$$

In terms of the conventional $g_{a\gamma\gamma}$, etc : $\mathscr{L} = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{1}{4}g_{aZZ}aZ_{\mu\nu}\tilde{Z}^{\mu\nu} + \ldots$

$$g_{a\gamma\gamma} = \frac{4}{f_a}(C_{BB}c_w^2 + C_{WW}s_w^2),$$

$$g_{aWW} = \frac{4}{f_a}C_{WW},$$

$$g_{aZZ} = \frac{4}{f_a}(C_{BB}s_w^2 + C_{WW}c_w^2),$$

$$g_{aZ\gamma} = \frac{8}{f_a}s_w c_w(C_{WW} - C_{BB}).$$

We consider 3 channels:

$$e^-e^+ \to e^-e^+a;\ a \to \gamma\gamma$$
$$e^-e^+ \to \mu^-\mu^+a;\ a \to \gamma\gamma$$
$$e^-e^+ \to \nu\bar{\nu}a;\ a \to \gamma\gamma$$

Production Feynman Diagrams

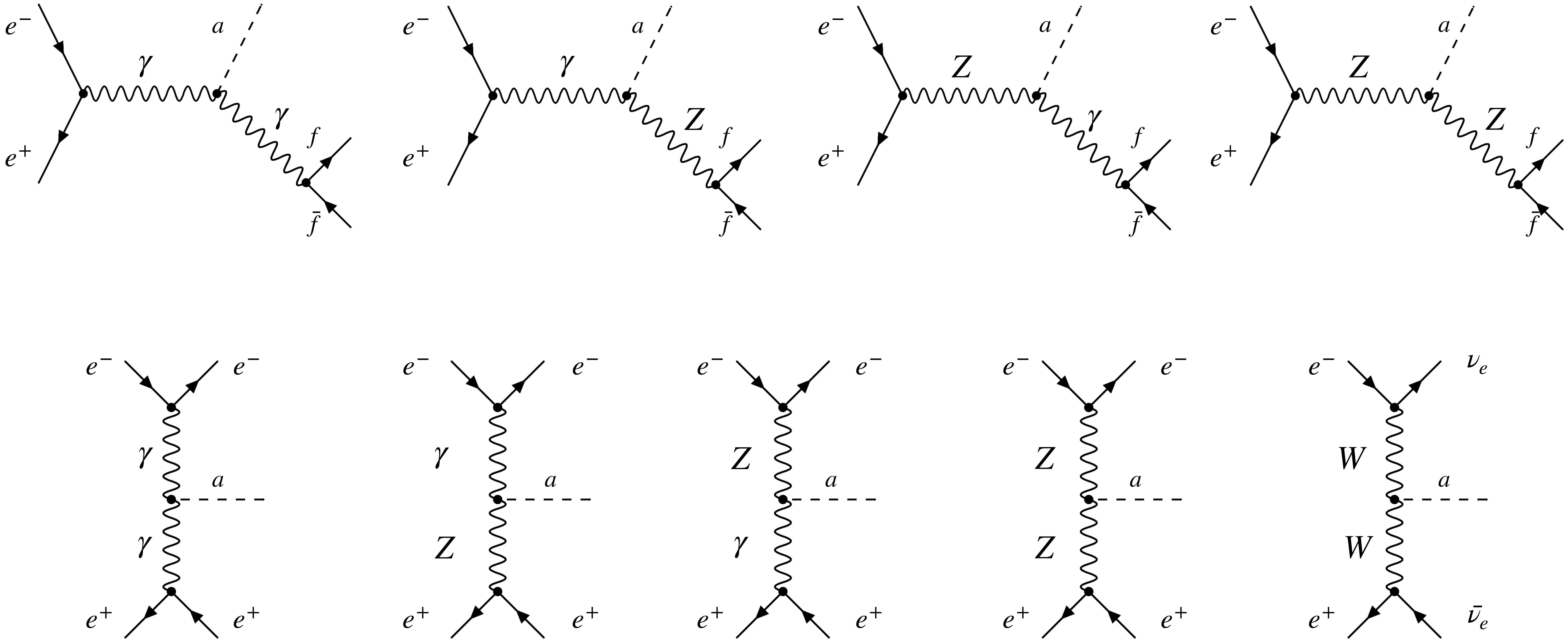
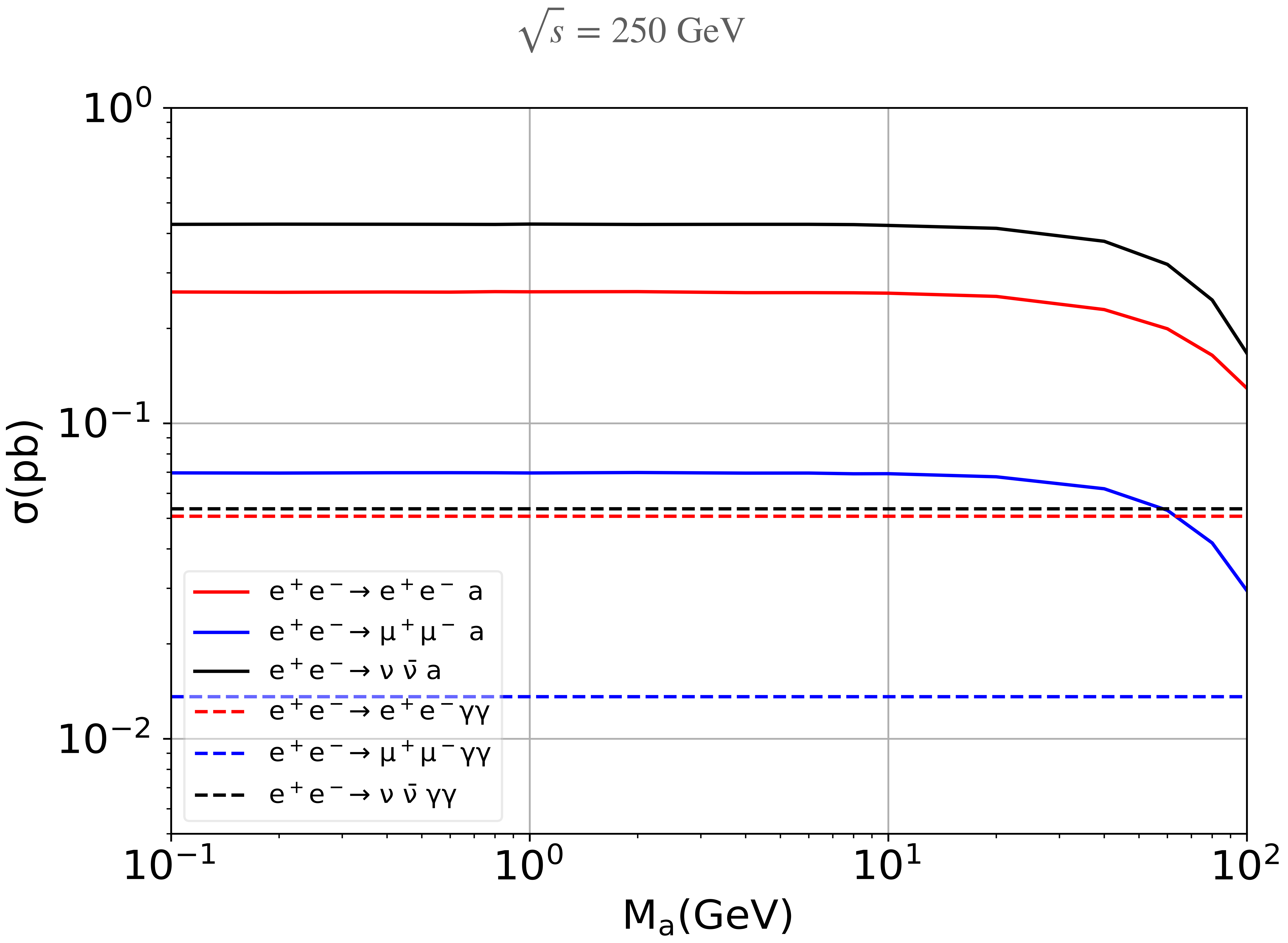


TABLE II: The ALP coupling strengths $g_{a\gamma\gamma}$, $g_{aZ\gamma}$, g_{aZZ}. and g_{aWW} with $C_{WW} = 2,\ C_{BB} = 1,\ f_a = 10^3$ GeV using Eqs. (4) – (7).

ALP couplings	Numerical Value (GeV^{-1})
$g_{a\gamma\gamma}$	4.88×10^{-3}
$g_{aZ\gamma}$	1.38×10^{-3}
g_{aZZ}	7.11×10^{-3}
g_{aWW}	8×10^{-3}



$\sqrt{s} = 250$ GeV
10^0
10^{-1}
10^{-2}
σ(pb)
$e^+e^- \to e^+e^-$ a
$e^+e^- \to \mu^+\mu^-$ a
$e^+e^- \to \nu\,\bar{\nu}$ a
$e^+e^- \to e^+e^-\gamma\gamma$
$e^+e^- \to \mu^+\mu^-\gamma\gamma$
$e^+e^- \to \nu\,\bar{\nu}\,\gamma\gamma$
10^{-1}
10^0
10^1
10^2
M_a(GeV)

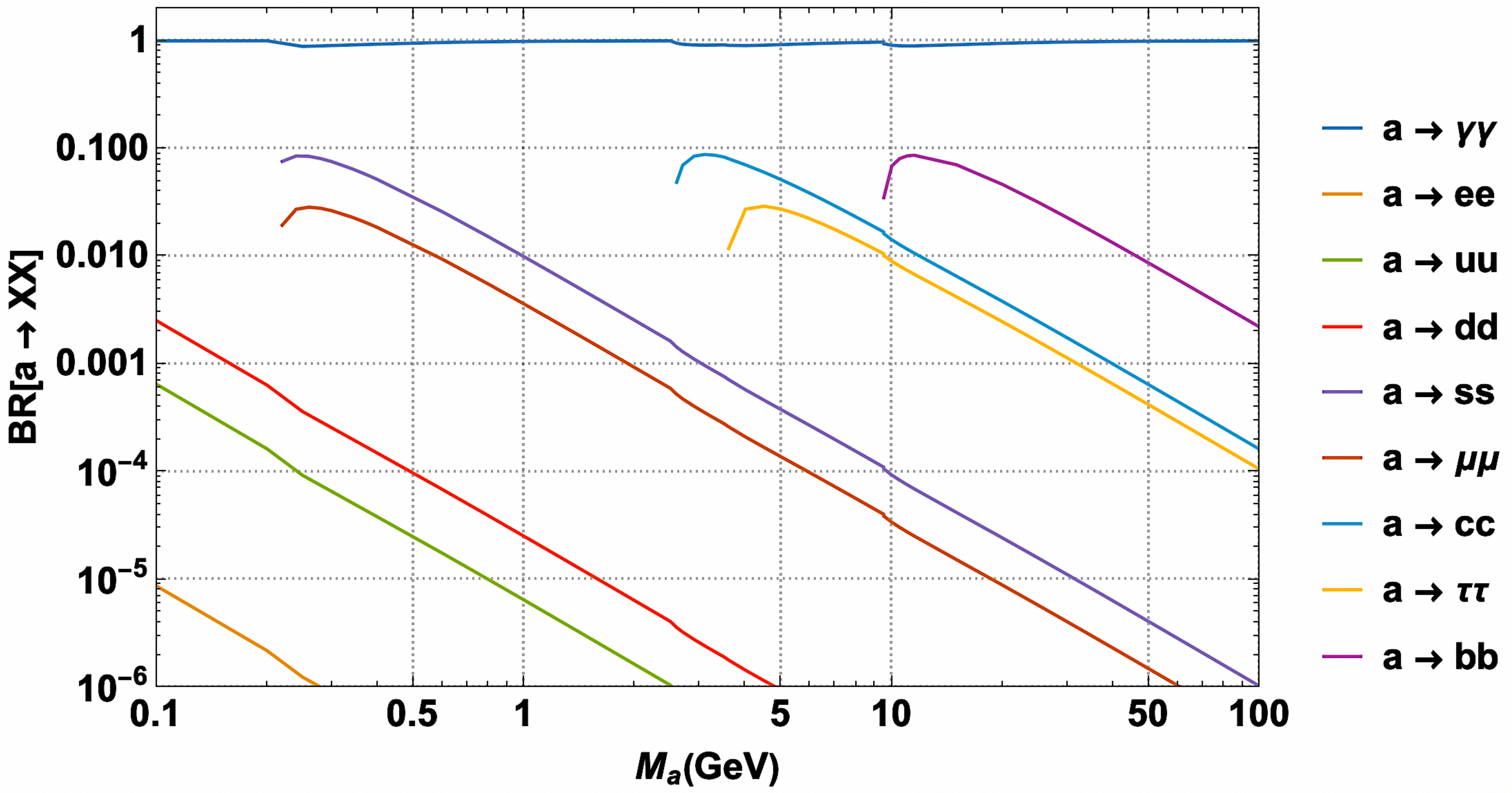


FIG. 8: Branching ratios of the ALP with $C_{WW} = 2$, $C_{BB} = 1$, and $f_a = 1$ TeV.

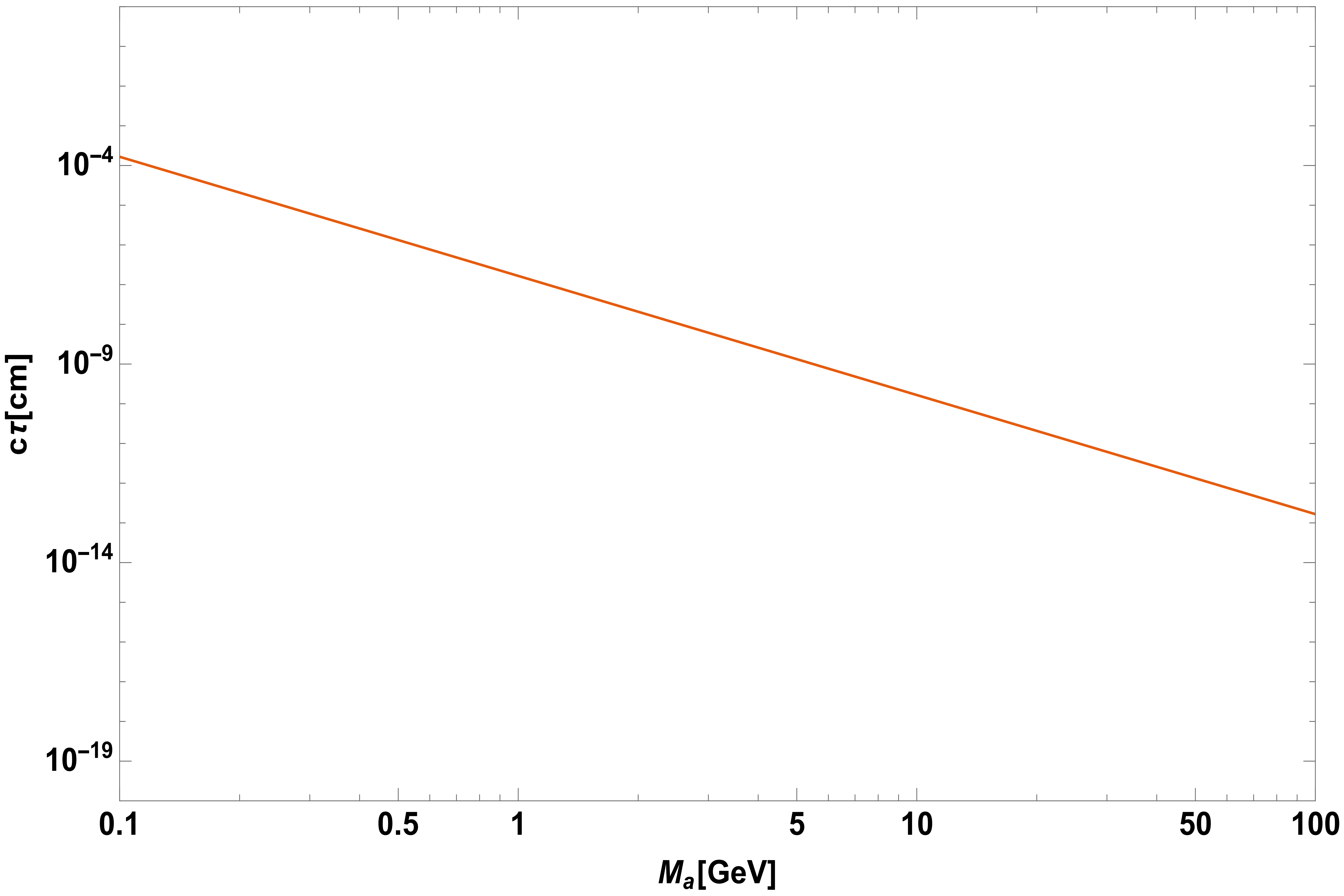
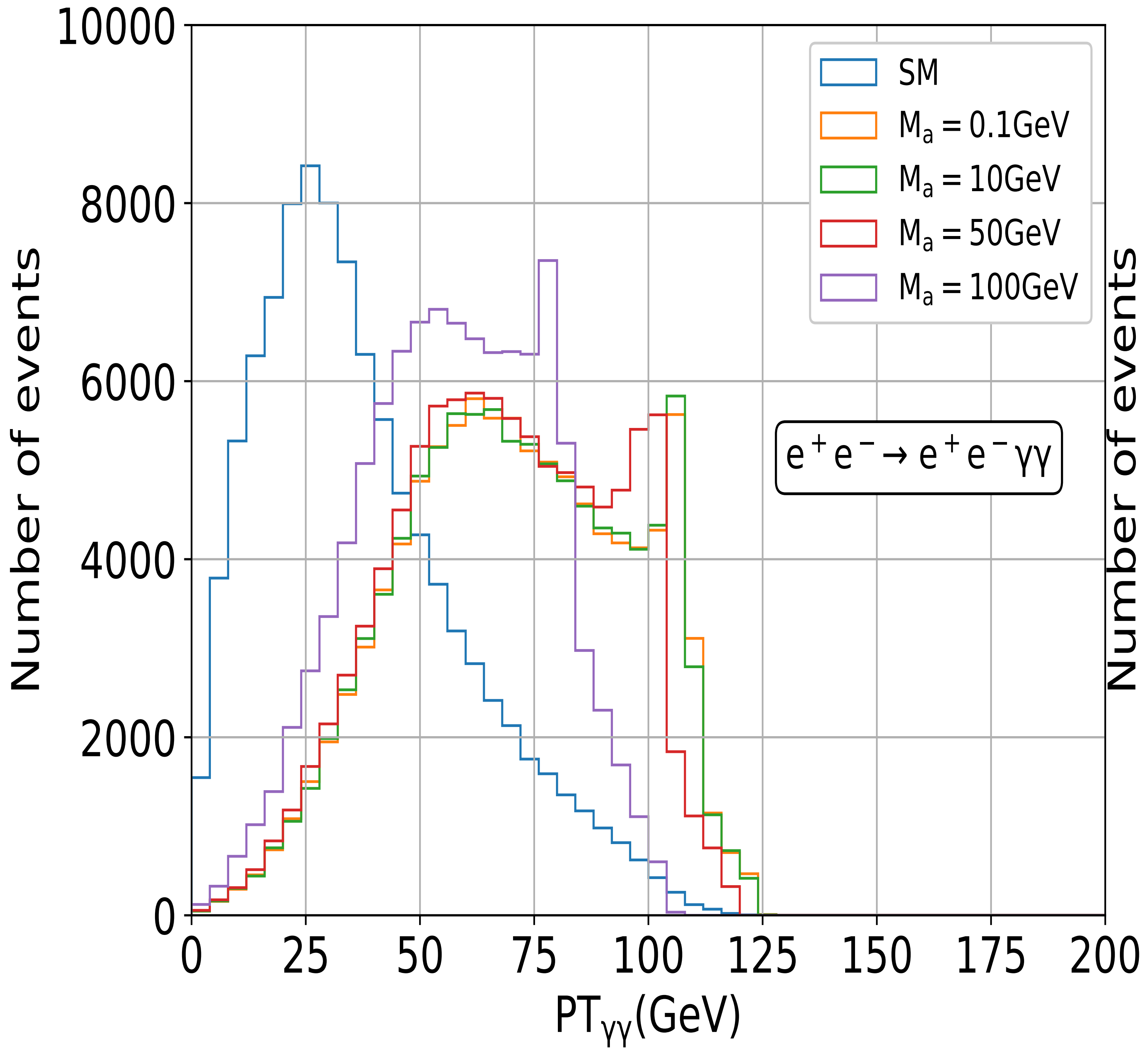
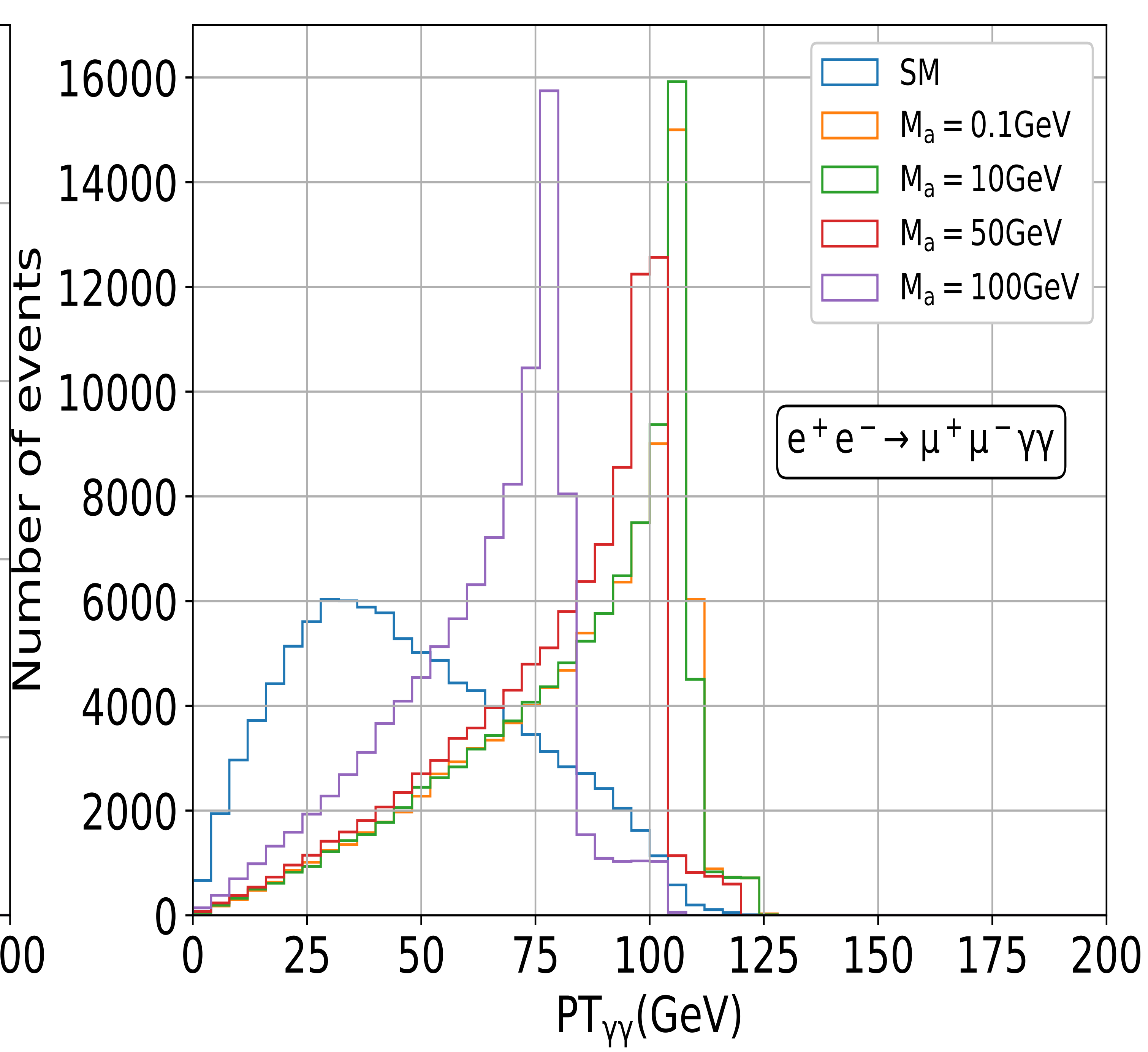
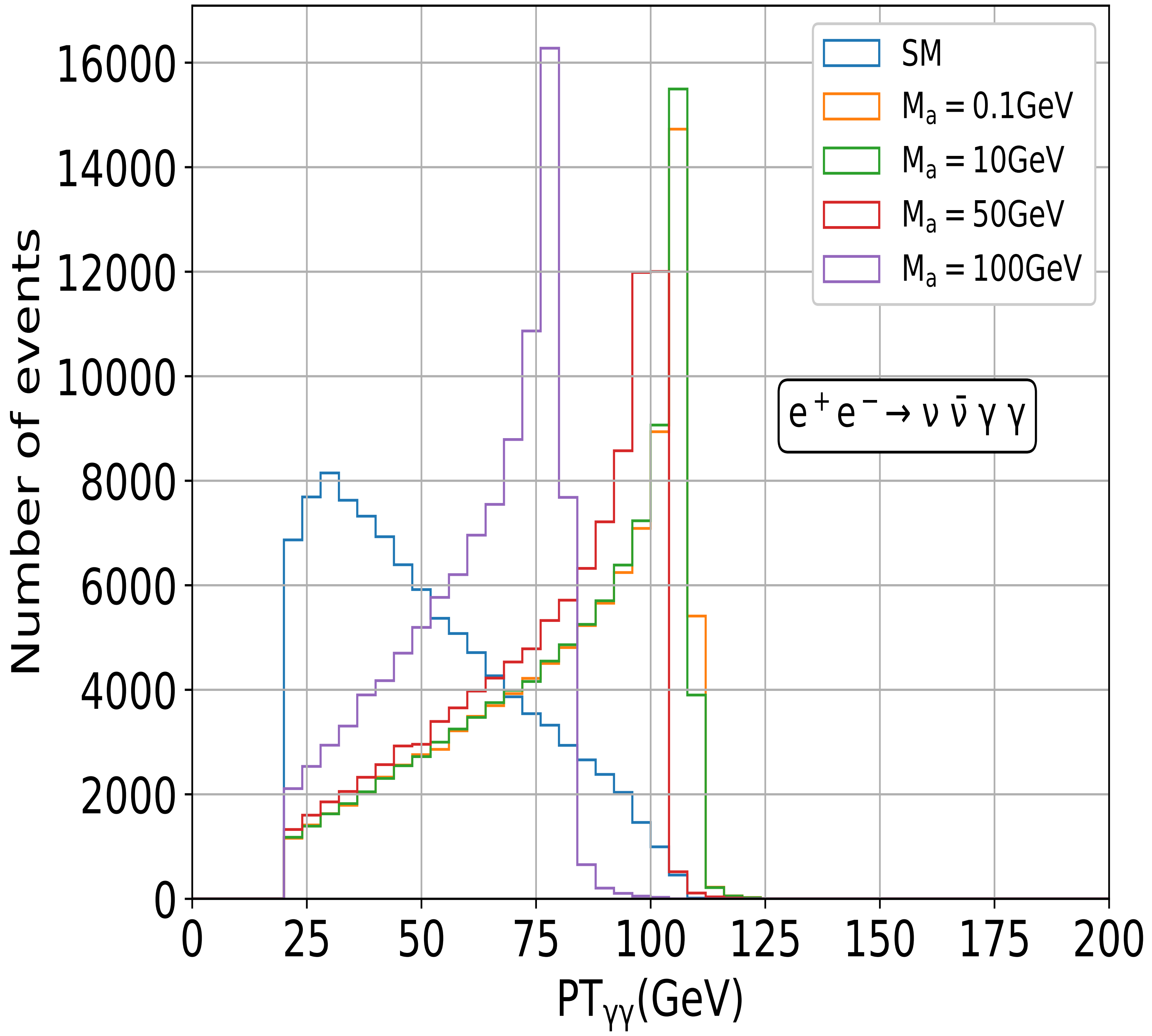


FIG. 8: Decay length of ALP with $g_{a\gamma\gamma} = 4.88 \times 10^{-3}\,\text{GeV}^{-1}$ ($C_{WW} = 2$, $C_{BB} = 1$, and $f_a = 1$ TeV).







Selection cuts:

$$p_T^{e,\mu} > 10 \text{ GeV}, \ \ |\cos\theta_{e,\mu}| < 0.95$$
$$p_T^{\gamma} > 10 \text{ GeV}, \ \ |\eta_\gamma| < 2.5$$
$$E_T^{\text{miss}} > 20 \text{ GeV}$$

Impose a further cut of $p_{T_{\gamma\gamma}} > 50\,\text{GeV}$

Estimating the Sensitivities

The number of signal events N_T at e^+e^- colliders with $\sqrt{s} = 250$ GeV is estimated as

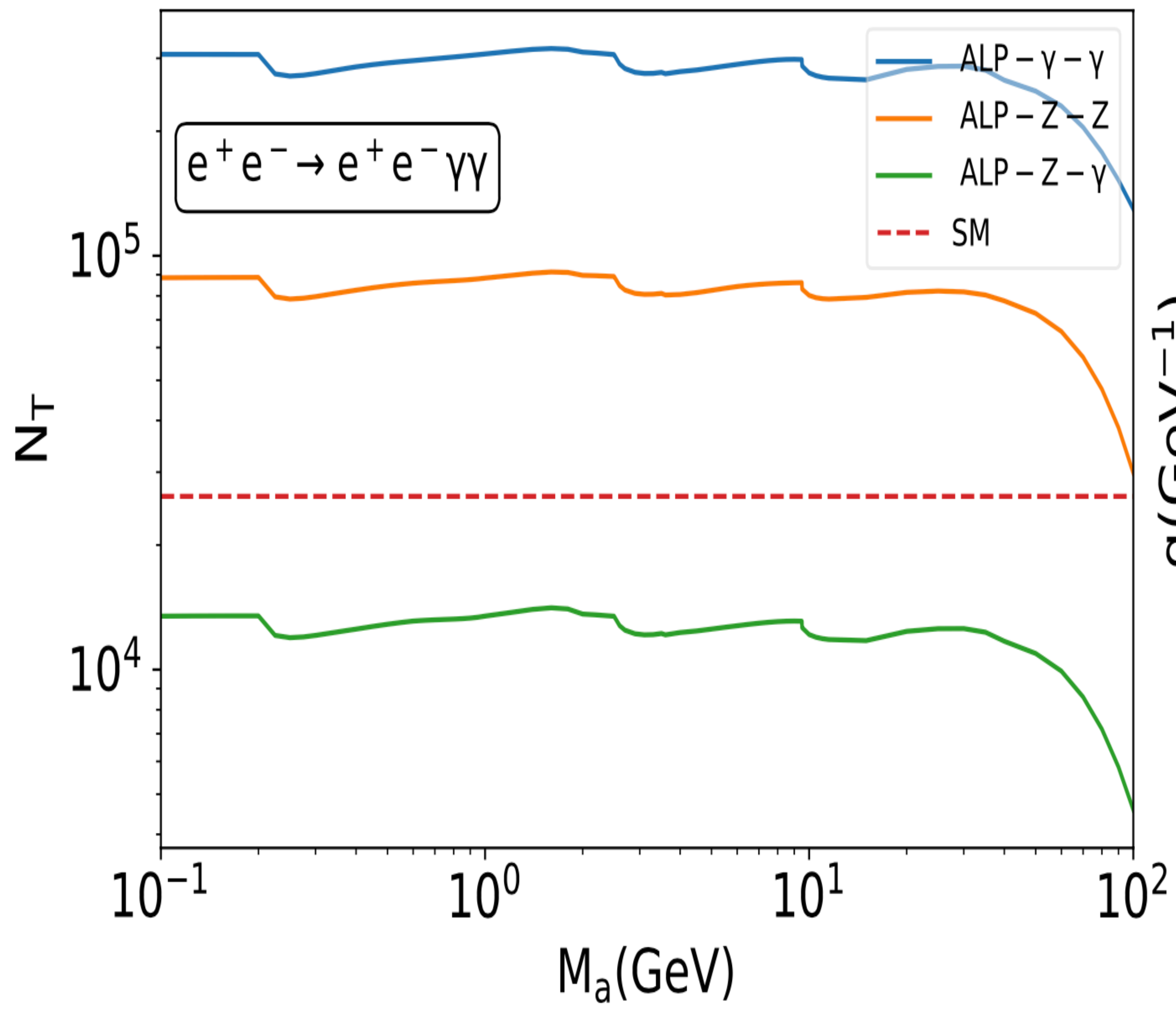
$$N_T = \sigma(e^+e^- \to \ f\bar{f}\ a) \times B(a \to \ \gamma\gamma) \times \frac{N(p_{T_{\gamma\gamma}} > 50 \text{ GeV})}{N_{\text{sim}}} \times \mathcal{L} \ ,$$

$$N_T^{\text{SM}} = \sigma(e^+e^- \to \ f\bar{f}\ \gamma\gamma) \times \frac{N(p_{T_{\gamma\gamma}} > 50 \text{ GeV})}{N_{sim}} \times \mathcal{L} \ .$$

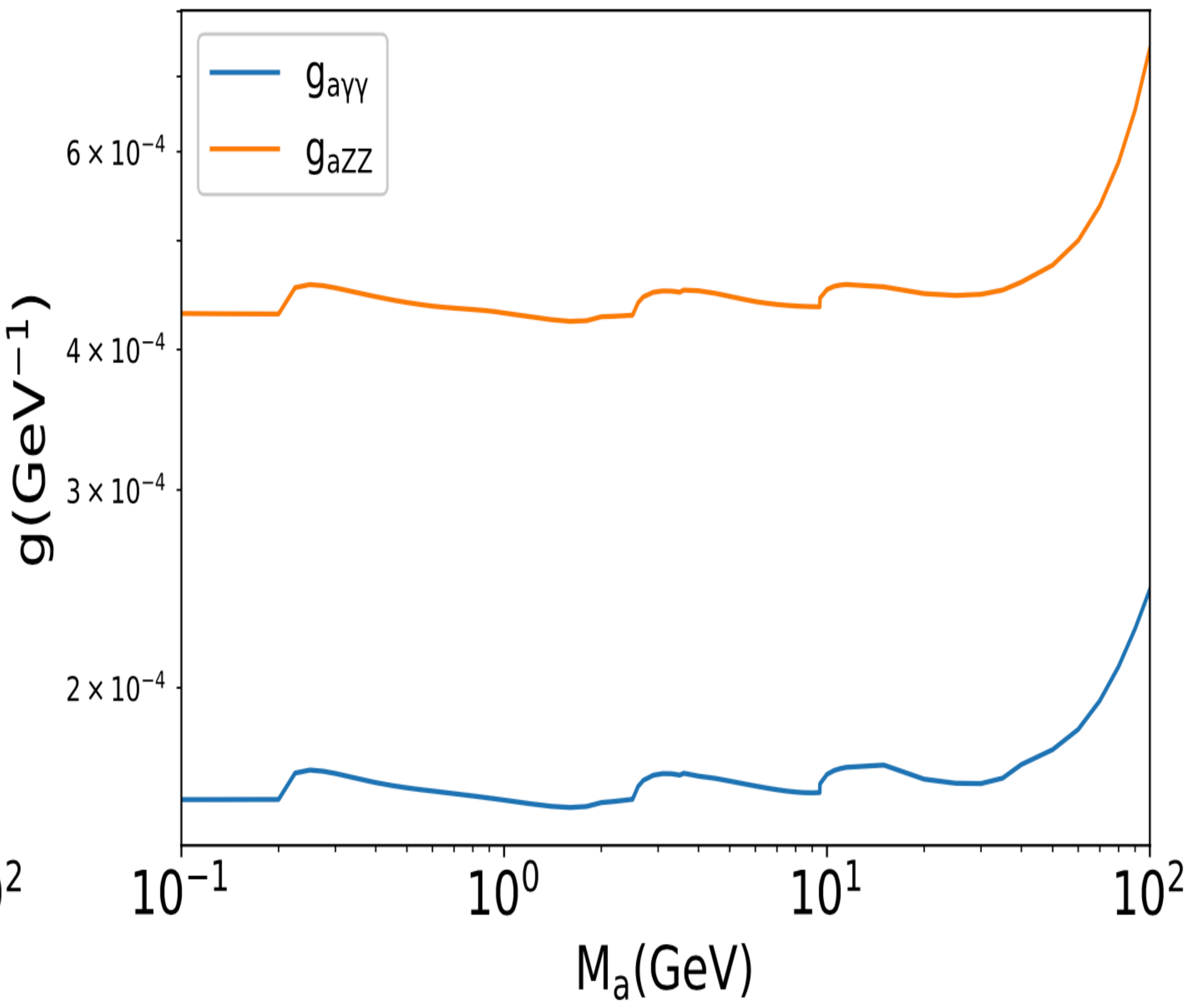
$$Z = \sqrt{2 \ . \Big[(s+b)\ \ln\Big(\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}\Big) - \frac{b^2}{\sigma_b^2}\, ln\Big(1+\frac{\sigma_b^2 s}{b(b+\sigma_b^2)}\Big)\Big]}\ ,$$

We use $L = 2\, ab^{-1}, \quad Z > 2$ to estimate the 95% sensitivities.

$$e^+e^- \to e^+e^-a,\ \ a \to \gamma\gamma$$

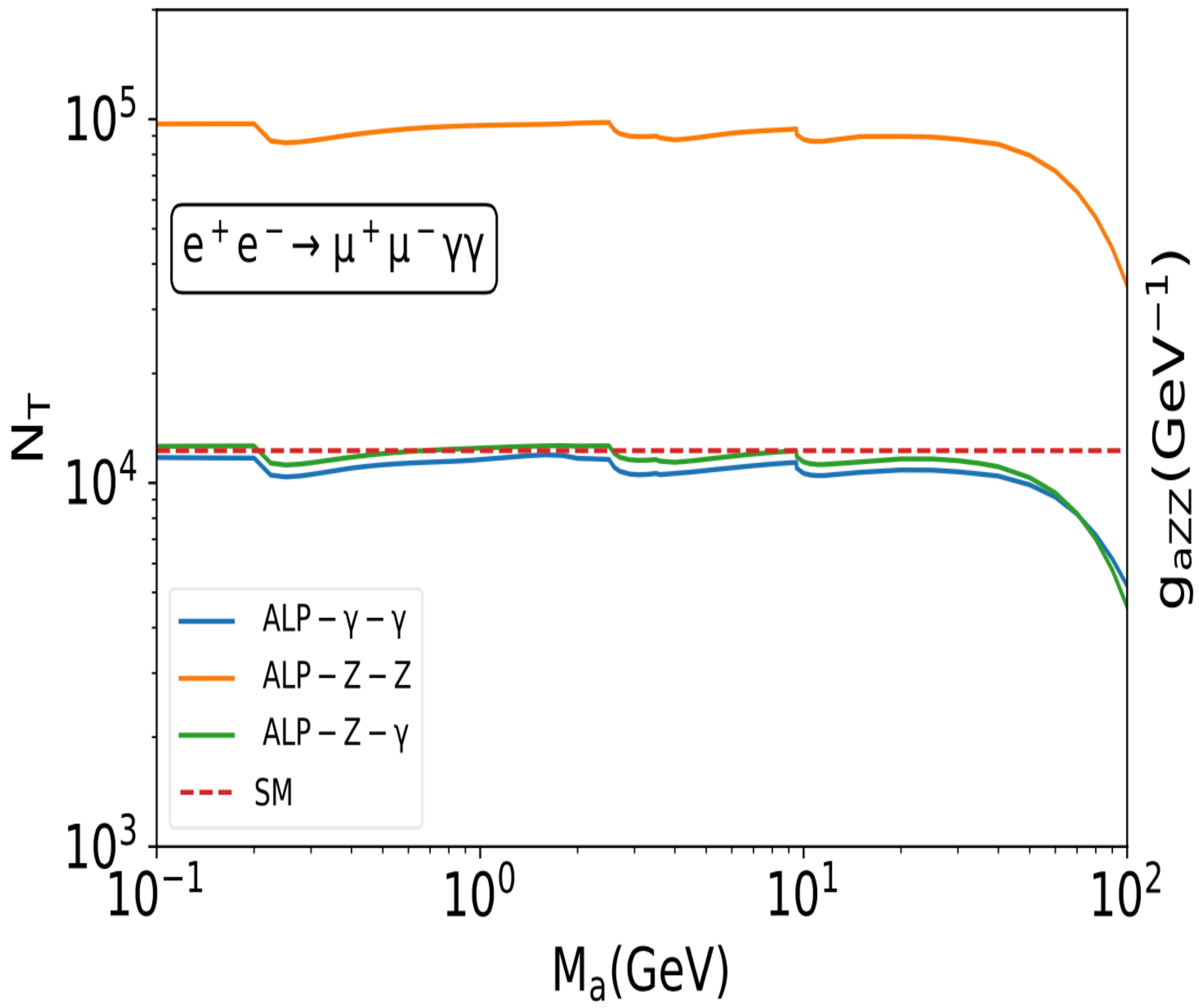


Number of events after cuts

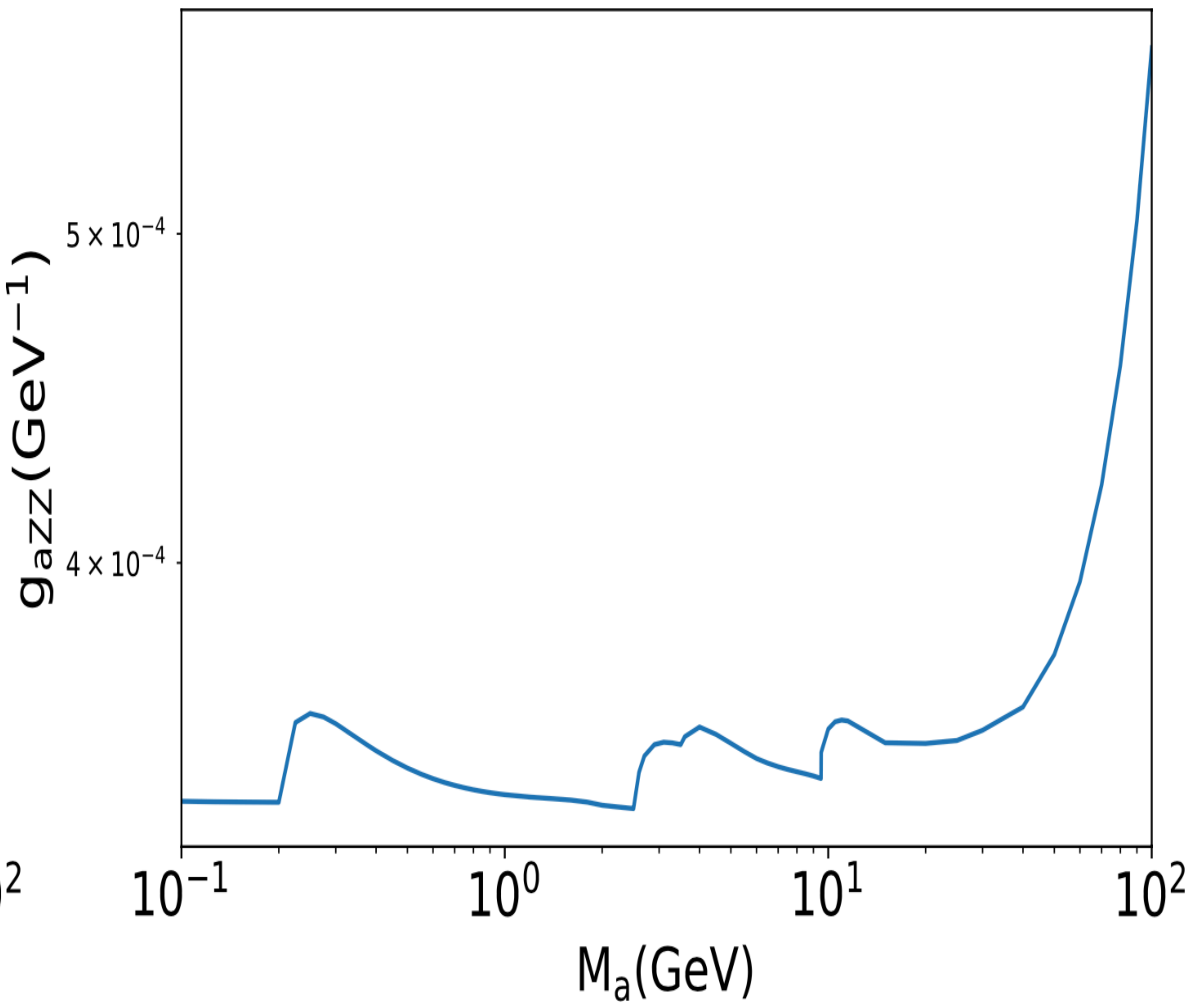


95% C.L. sensitivity

$e^+e^- \to \mu^+\mu^- a,\ a \to \gamma\gamma$

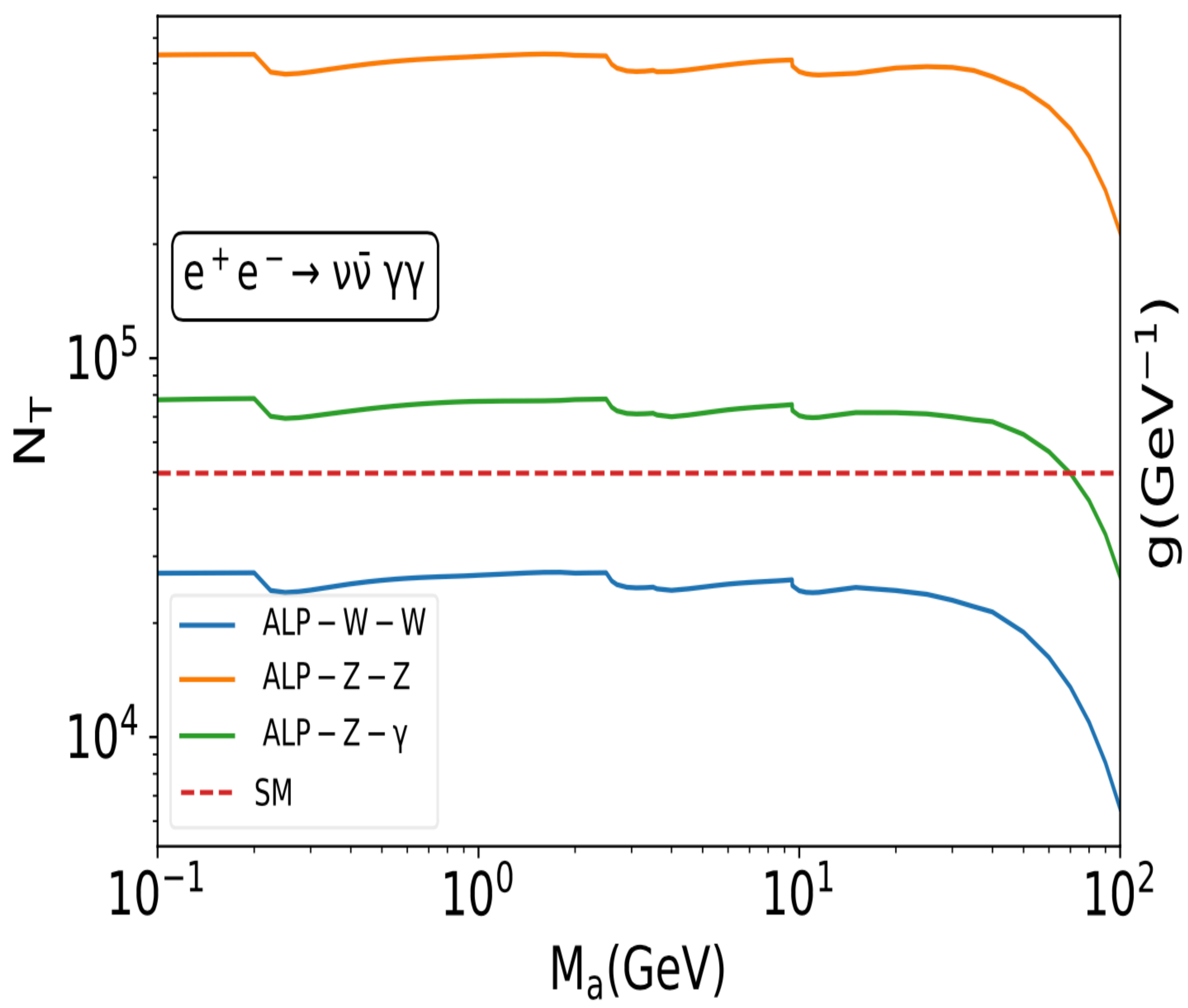


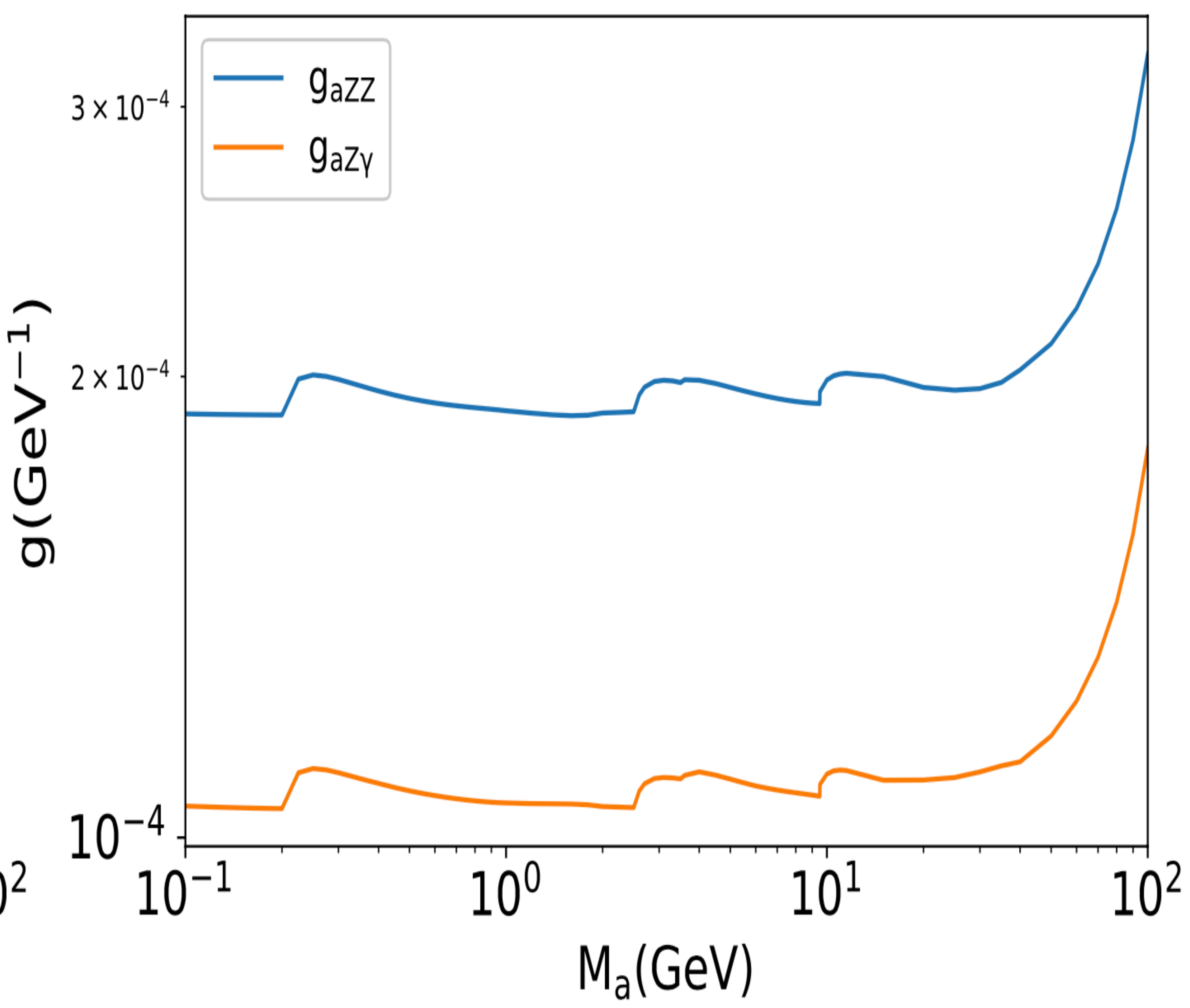
Number of events after cuts



95% C.L. sensitivity on g_{aZZ}

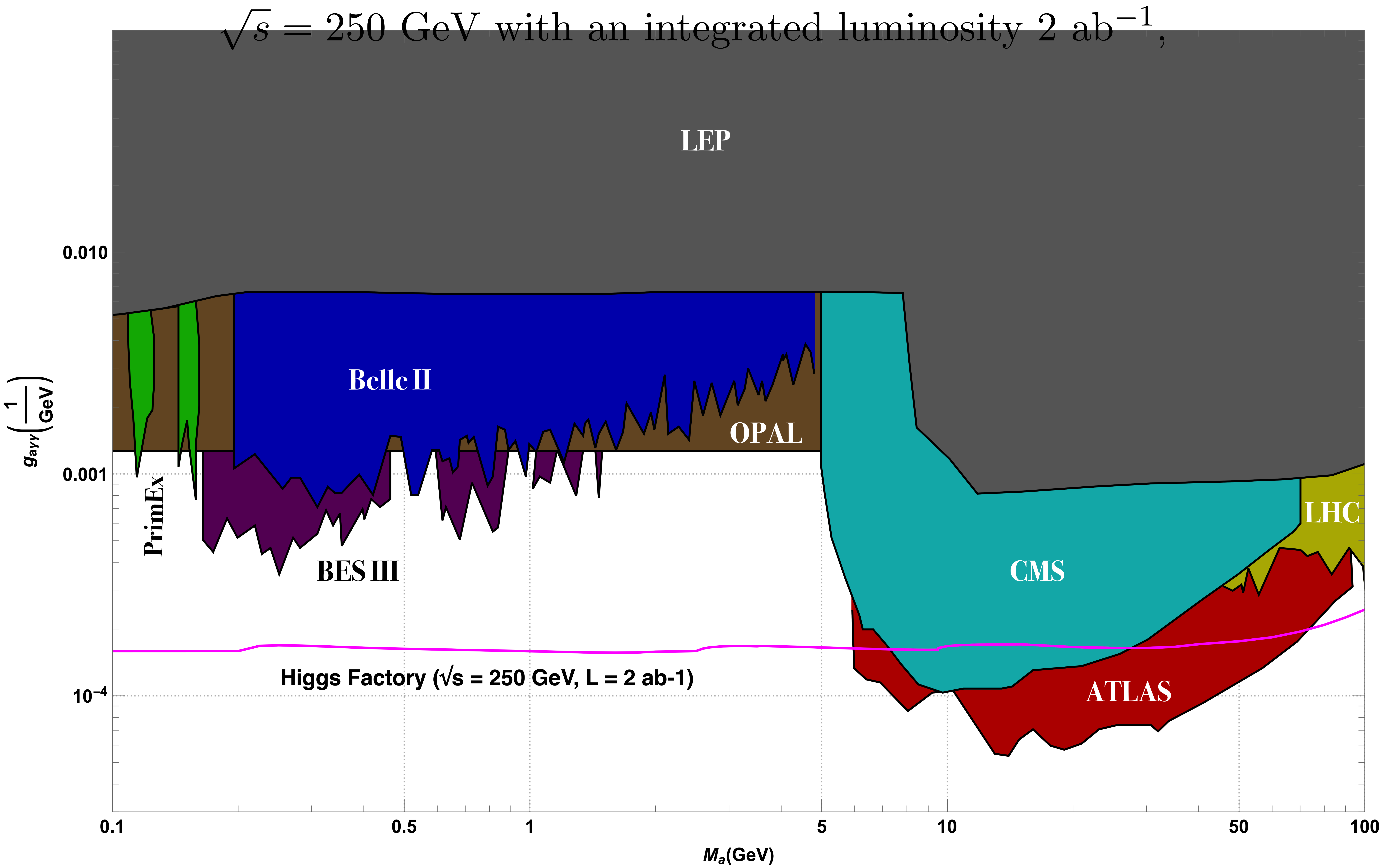
$$e^+e^- \to \nu\bar{\nu}a,\ \ a \to \gamma\gamma$$





Number of events after cuts

95% C.L. sensitivity


$\sqrt{s} = 250$ GeV with an integrated luminosity 2 ab^{-1},
LEP
Belle II
OPAL
PrimEx
BES III
CMS
LHC
ATLAS
Higgs Factory (√s = 250 GeV, L = 2 ab-1)
$g_{a\gamma\gamma}\left(\frac{1}{\text{GeV}}\right)$
0.010
0.001
10^{-4}
0.1
0.5
1
5
10
50
100
M_a(GeV)

Atmospheric axion-like particles at Super-Kamiokande

K.C., Jui-Lin Kuo, Po-Yan Tseng, Zeren Simon Wang   2208.05111 (PRD)

Motivation

Large numbers of mesons including charged pions are produced in the atmospheric air showers resulting from cosmic rays. Once ALPs are produced from these charged-pion decays, if long-lived, they can travel tens of kilometers downwards to the Earth's surface thanks to the large Lorentz boost, and decay in large-volume neutrino experiments such as Super-Kamiokande (SK), leading to Cherenkov signal events.

ALP-MUON INTERACTIONS

- Only ALP-muon interaction is considered:

$$\mathcal{L} \supset -i g_{a\mu\mu} a \bar{\mu} \gamma_5 \mu \,,$$

- For ALP mass larger than $2m_\mu$, ALP decays mostly into 2 muons. But for lighter than $2m_\mu$, it decays into a pair of photons. The loop-induced ALP-photon coupling is

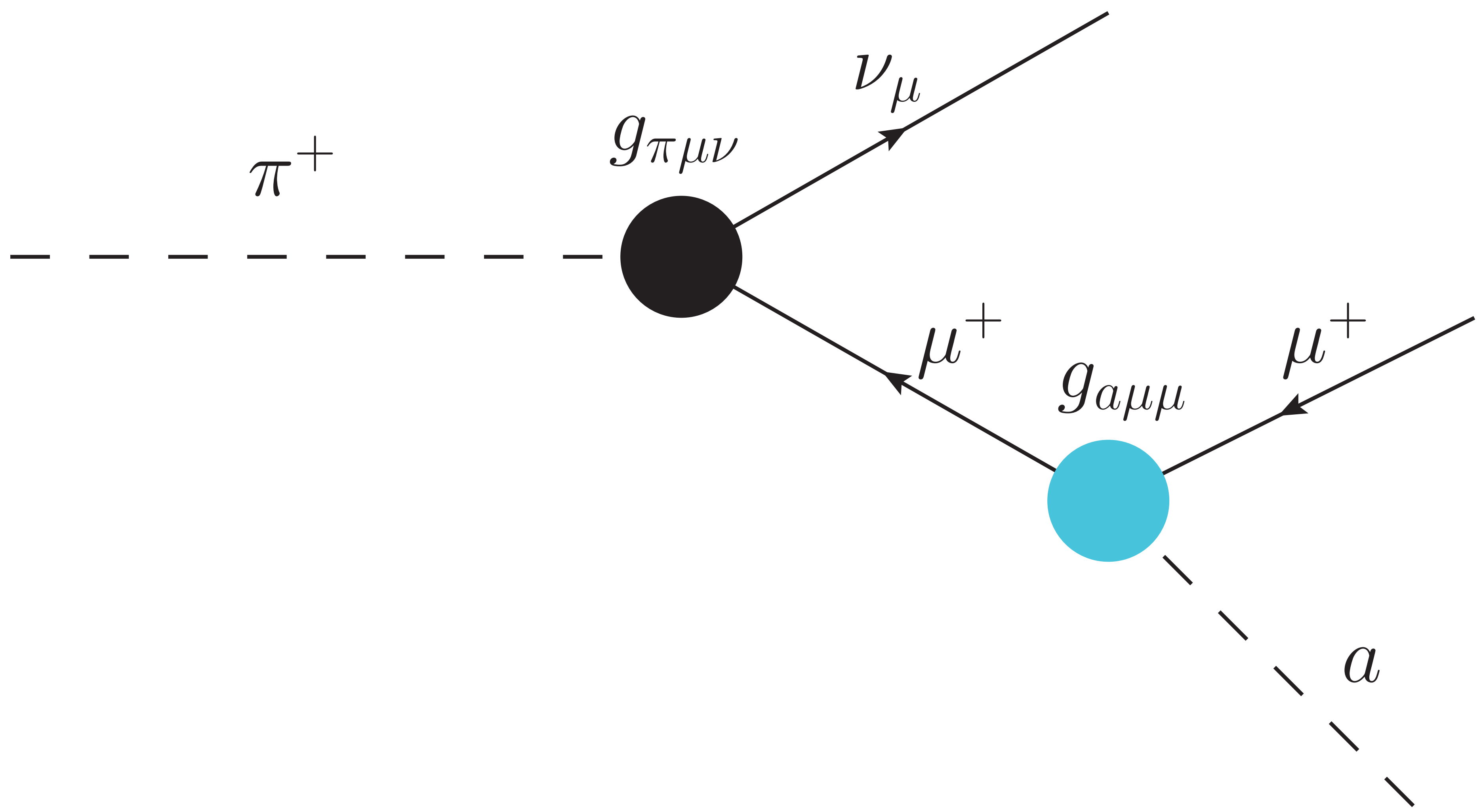
$$\mathcal{L}_{\rm loop} \supset -\frac{1}{4} g^{\rm eff}_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu} \,,$$

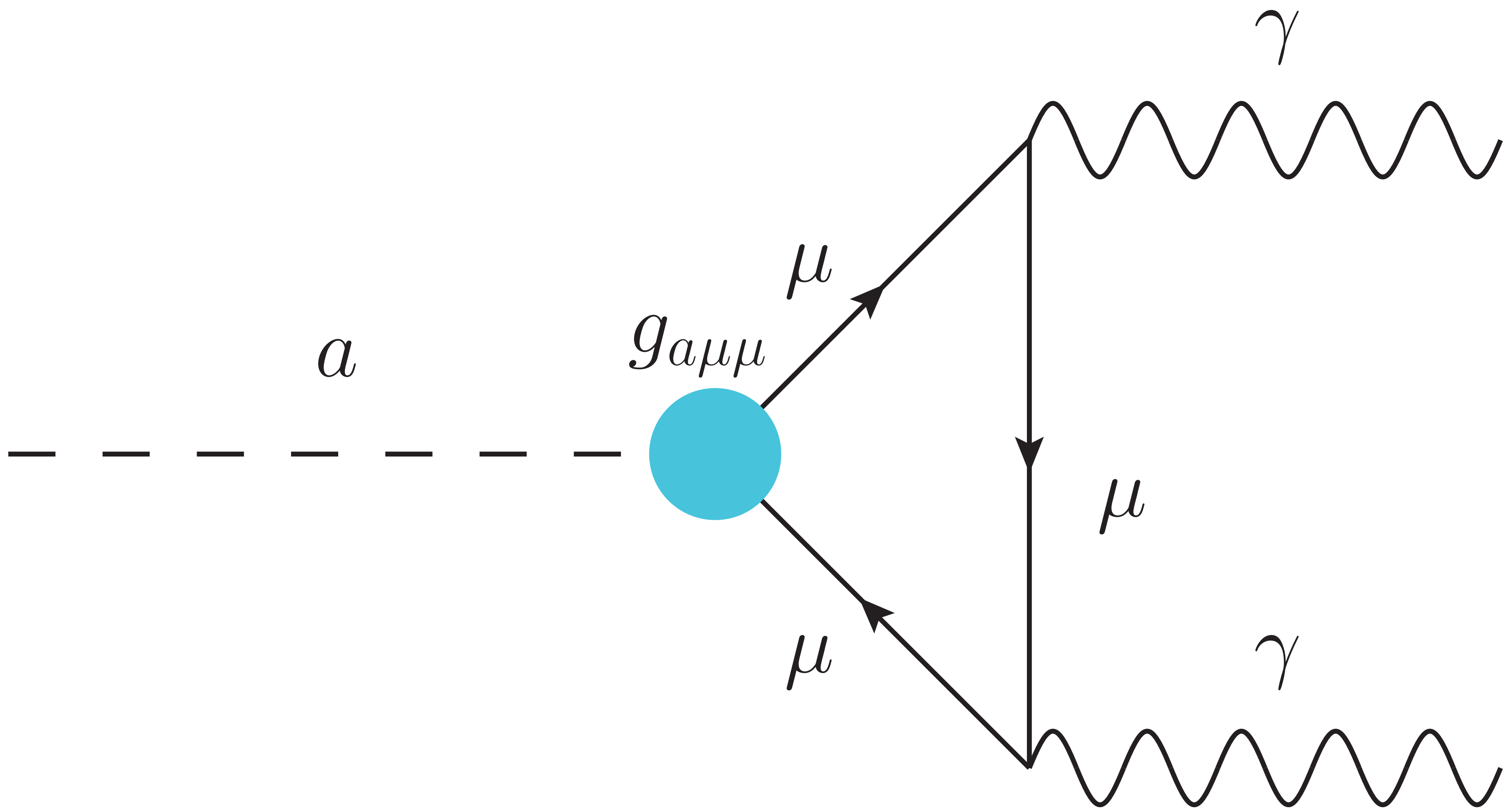
- The effective coupling is (valid for $m_a < 2m_\mu$), and the lifetime is

$$g^{\rm eff}_{a\gamma\gamma} = \frac{g_{a\mu\mu}\alpha}{m_\mu \pi}\left[1 - \frac{4m_\mu^2}{m_a^2}\arcsin^2\left(\frac{m_a}{2m_\mu}\right)\right] \qquad \tau_a = \Gamma^{-1}_{a\to\gamma\gamma} = \frac{64\pi}{(g^{\rm eff}_{a\gamma\gamma})^2 m_a^3} \,.$$

With the ALP-muon interaction the ALP can be produced in the charged pion decay

$$\pi^{\pm} \to \mu^{\pm}\nu a, \quad \text{with } 0 < m_a < m_\pi - m_\mu$$





Followed by $a \to \gamma\gamma$

ALP Flux from air shower

- We used the MCEq (Fedynitch et al., 1503.00544) to numerically solve the cascade equations of particles propagating in a dense medium.
- The ALP is produced throughout the propagation of the secondary cosmic rays.

$$\pi^\pm \to \mu^\pm \nu a$$

- To implement the process $\pi^\pm \to \mu^\pm \nu a$ into MCEq, we compute the decay matrix

$$D^{ij}_{\pi^\pm \to a} = \Delta T^i_{\pi^\pm} \frac{dN_a}{dT_a}\left(T^i_{\pi^\pm}, T^j_a\right)$$

where $T_{\pi^\pm}$ and T_a are k.e. of pion and ALP, $\Delta T_{\pi^\pm}$ is the bin width, j,i are bin labels

- The ALP energy spectrum dN_a/dE_a in lab frame is obtained by a Lorentz boost to that in the pion rest frame:

$$\frac{dN_a}{dE_a} = \int \frac{d\Omega}{4\pi} \frac{dN_a}{dE_a^*} \left| \frac{\partial E_a^*}{\partial T_a} \right|$$

- Production rate of $\pi^{\pm} \to \mu^{\pm}\nu a$ scales on the coupling-square $g_{a\mu\mu}^2$.

- Two cases for the decay of $a \to \gamma\gamma$:

  (1) the decay is determined by the decay length $c\tau_a$ in the ALP rest frame, independent of $g_{a\mu\mu}^2$. The results can be easily reinterpreted for other theoretical scenarios where the atmospheric charged pions decay to an LLP which then subsequently decays visibly in the SK detector.

  (2) Both decay and production depend on $g_{a\mu\mu}^2$.

ALP Detection on the Earth

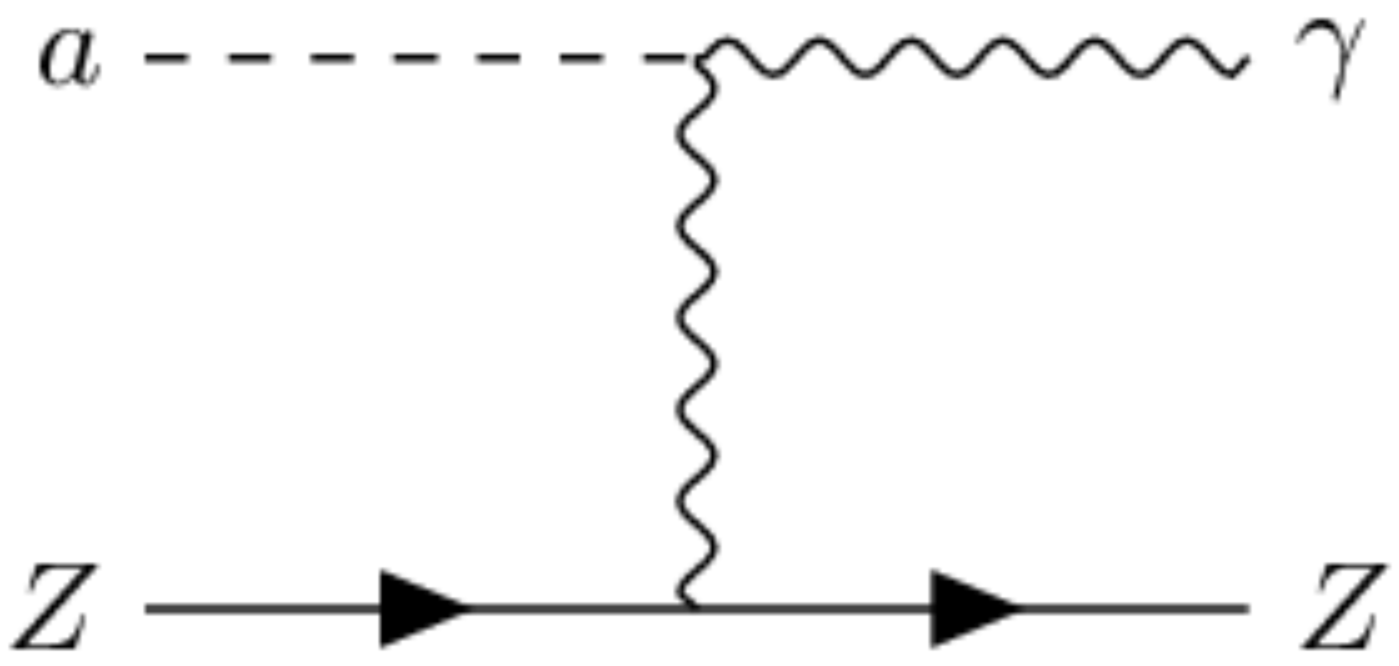
- After arriving at the Earth, the ALP decays into $\gamma\gamma$, which are detected by the Cherenkov detector in neutrino experiments.
- The event distribution is

$$\frac{d^2 N_{\text{event}}}{dT_a d\cos\theta} = \epsilon\,\Delta t\, A_{\text{eff}}(T_a,\ \cos\theta)\,\frac{d^2\Phi_a}{dT_a d\cos\theta}$$

where θ is the Zenith angle, A_{eff} is the effective detector area, ϵ is the efficiency, $\dfrac{d^2\Phi_a}{dT_a d\cos\theta}$ is the output from MCEq.

- The main SM background comes from $\pi^0 \to \gamma\gamma$ and neutrino-induced electron-like events that create multiple Cherenkov rings in the electromagnetic showers.

- Another possible signal of the ALP is via the inverse-Primakoff process. The ALP interacts with atoms to create a mono-γ signal with an energy similar to that of the ALP.



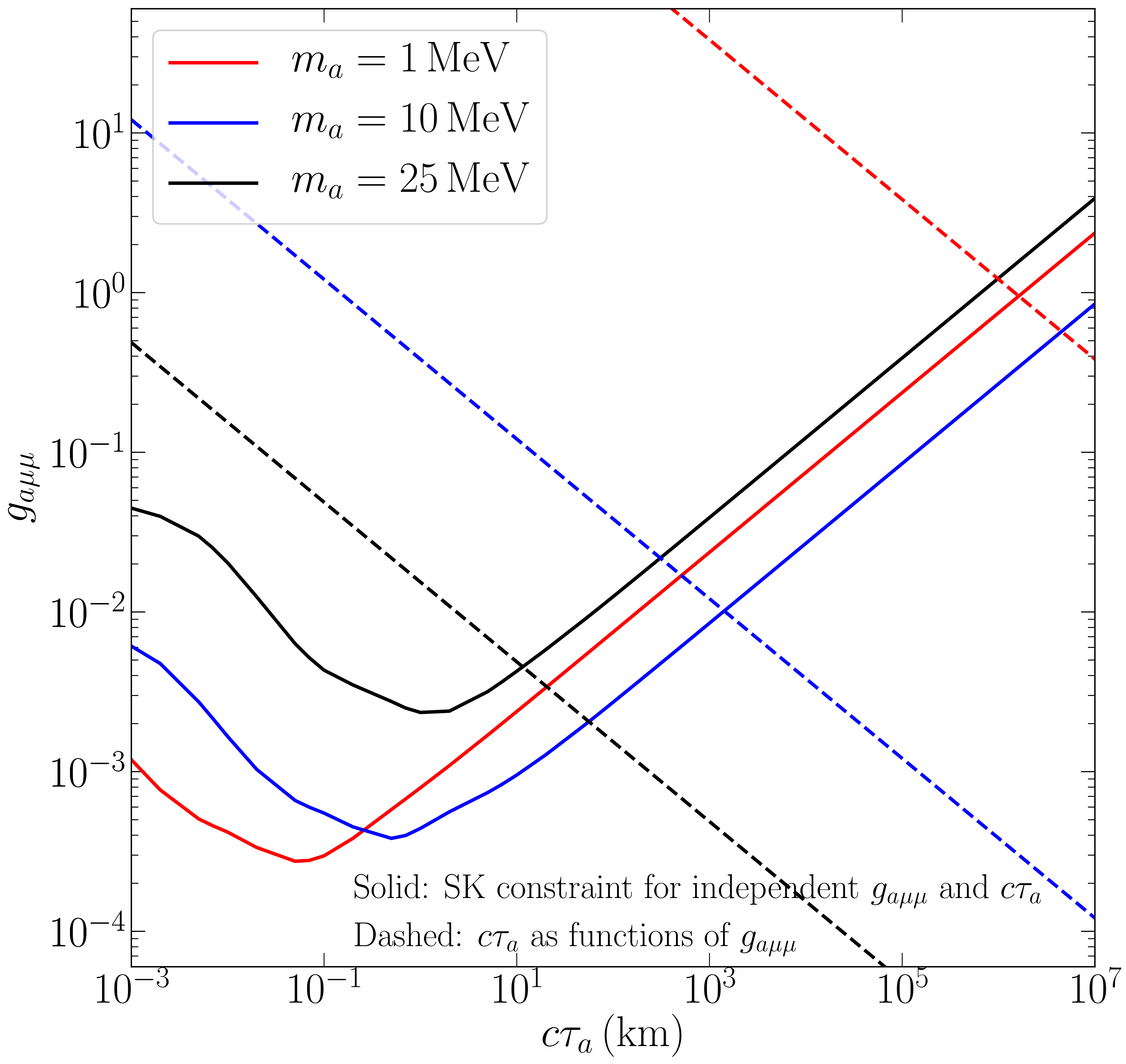
- The cross section of the inverse-Primakoff is

$$\sigma_{\rm IP} \simeq \left(\frac{g_{a\gamma\gamma}}{1\,{\rm GeV}^{-1}}\right) \times 2\ {\rm GeV}^{-2}$$

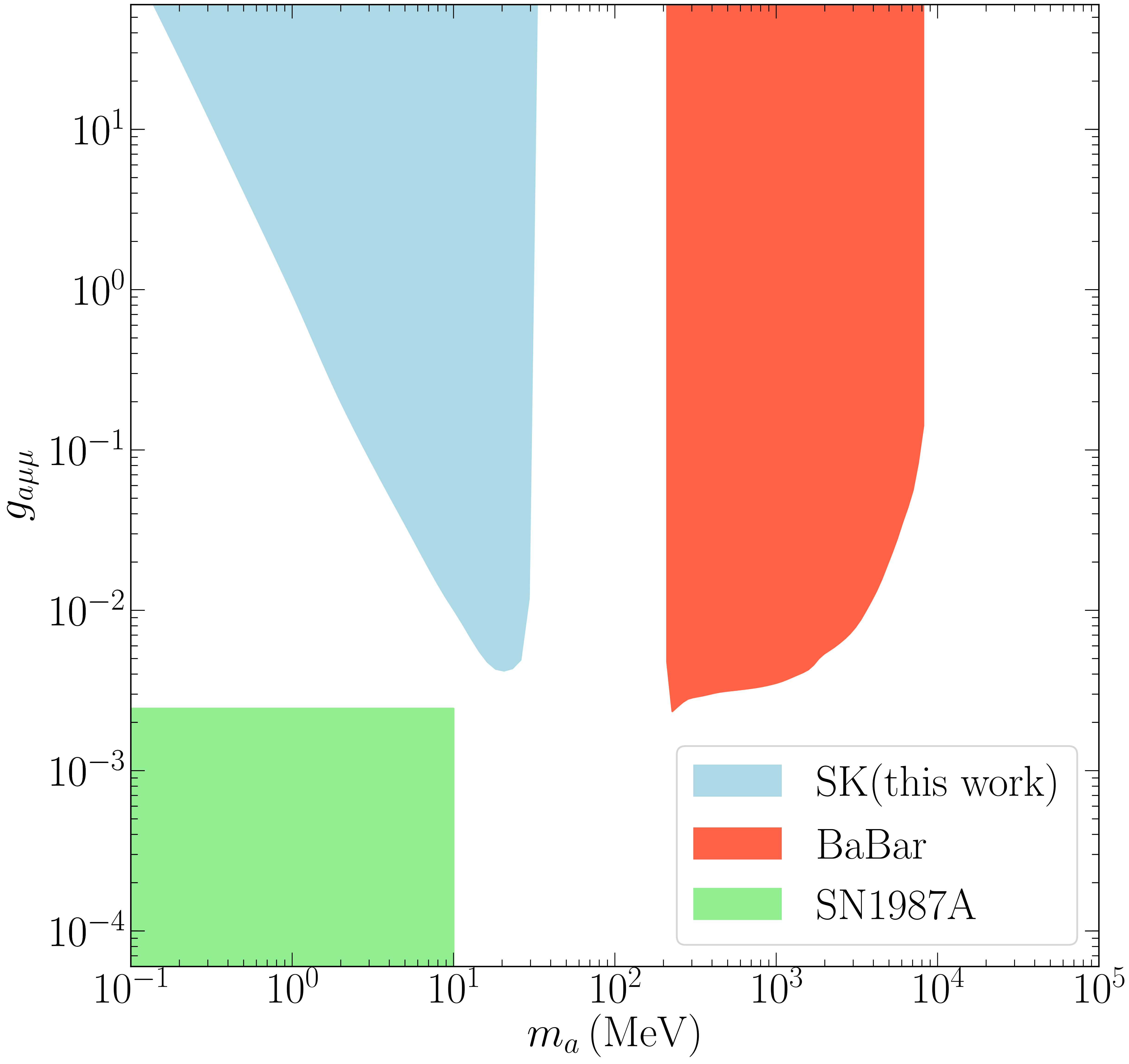
- However, $A_{\rm eff}$ for detecting ALP decay is orders of magnitude larger than the effective cross section of inverse-Primakoff $N_T\sigma_{\rm IP}$ with N_T the total number of atoms inside the fiducial volume of the detector.

Super-Kamiokande

- Only charged pion with energies below the critical energy $\varepsilon_{\rm crit} = 115\ {\rm GeV}$, can they decay well before reaching the Earth surface. So ALP flux with $T_a > \varepsilon_{\rm crit}$ is suppressed.
- Water-based Cherenkov detector of SK has good resolution at sub- and multi-GeV ranges.
- The geometry of SK: $R_{\rm SK} = 20\,{\rm m}$, $H_{\rm SK} = 40\,{\rm m}$. The lifetime is taken to be 5326 days and efficiency $\epsilon = 0.75$.
- Since the ALP decay signal consists of two e-like Cherenkov rings, we consider the data of π^0-like two-ring events in sub-GeV T_a, and e-like multi-ring events for multi-GeV T_a range.



- Solid: 90% C.L. sensitivity reach of SK for independent $g_{a\mu\mu}$ and $c\tau$.
- Dash: $c\tau$ as a function of $g_{a\mu\mu}$.



- Constraint on $(m_a, , g_{a\mu\mu})$, taking $c\tau \sim 1/g_{a\mu\mu}^2$.
- Production $\pi^{\pm} \to \mu^{\pm}\nu a$ scales as $g_{a\mu\mu}^2$
- SN1987A covers $g_{a\mu\mu} \sim [10^{-10}, 2\times 10^{-3}]$ for $m_a \leq 10$ MeV
- Future prospect at Hyper-K: judicial volume increased by 25 times.

Summary

- Higgs factories can improve the sensitivity to $g_{a\gamma\gamma} \sim 2 \times 10^{-4}\ \mathrm{GeV}^{-1}$ for $0.1\,\mathrm{MeV} \leq m_a \leq O(10)\ \mathrm{MeV}$.
- Search for the ALP at Super-K via $\pi^{\pm} \to \mu^{\pm}\nu a,\ a \to \gamma\gamma$ can cover a region of $g_{a\mu\mu}$ that is not covered before by SN1987A and BaBar.