Axion-Like Particles in Radiative Quarkonia Decays

Xavier Ponce Díaz

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with Luca Di Luzio, Alfredo Guerrera and Stefano Rigolin

Università degli Studi di Padova

INFN

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Motivation

$$\mathcal{L}_a = \frac{\partial_\mu a}{2 f_a} \sum_{f \neq t} c_{aff}\, \bar{f} \gamma^\mu \gamma_5 f + c_{a\gamma\gamma} \frac{\alpha_{em}}{4\pi} \frac{a}{f_a} F_{\mu\nu} \widetilde{F}^{\mu\nu} + c_{agg} \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{\mu\nu}_a + \frac{1}{2} m_a^2\, a^2$$

Shift-symmetric

Symmetry breaking

Quarkonia states

$J/\Psi \to m_{J/\Psi} \sim 3\,\mathrm{GeV}$

$\Upsilon(nS) \to m_\Upsilon \sim 10\,\mathrm{GeV}$

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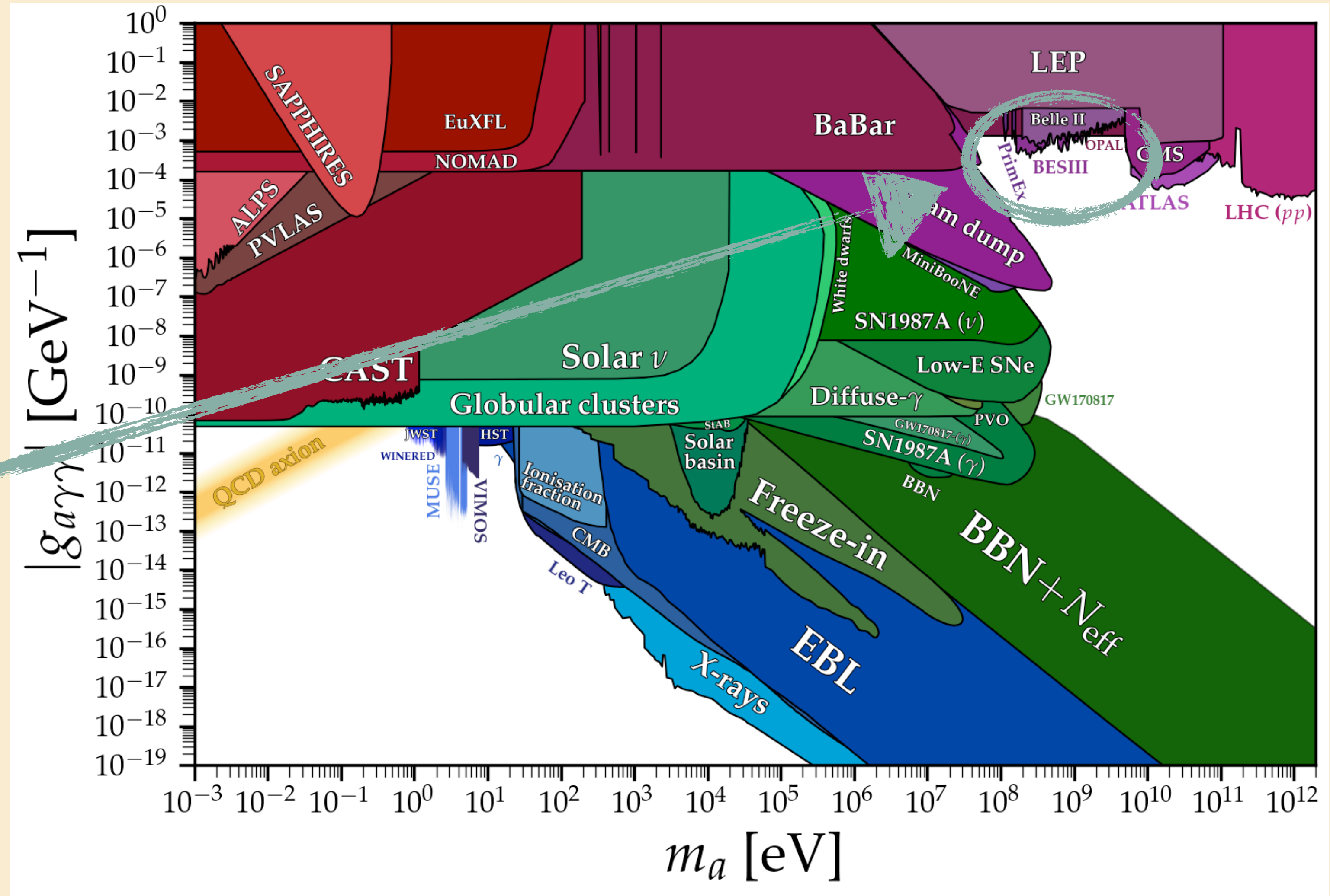
$$m_a \in [100\,\mathrm{MeV},\ 10\,\mathrm{GeV}]$$

Studied previously in Pobbe, Merlo, Rigolin, Sumensari, JHEP 06 (2019) 091



from O'Hare

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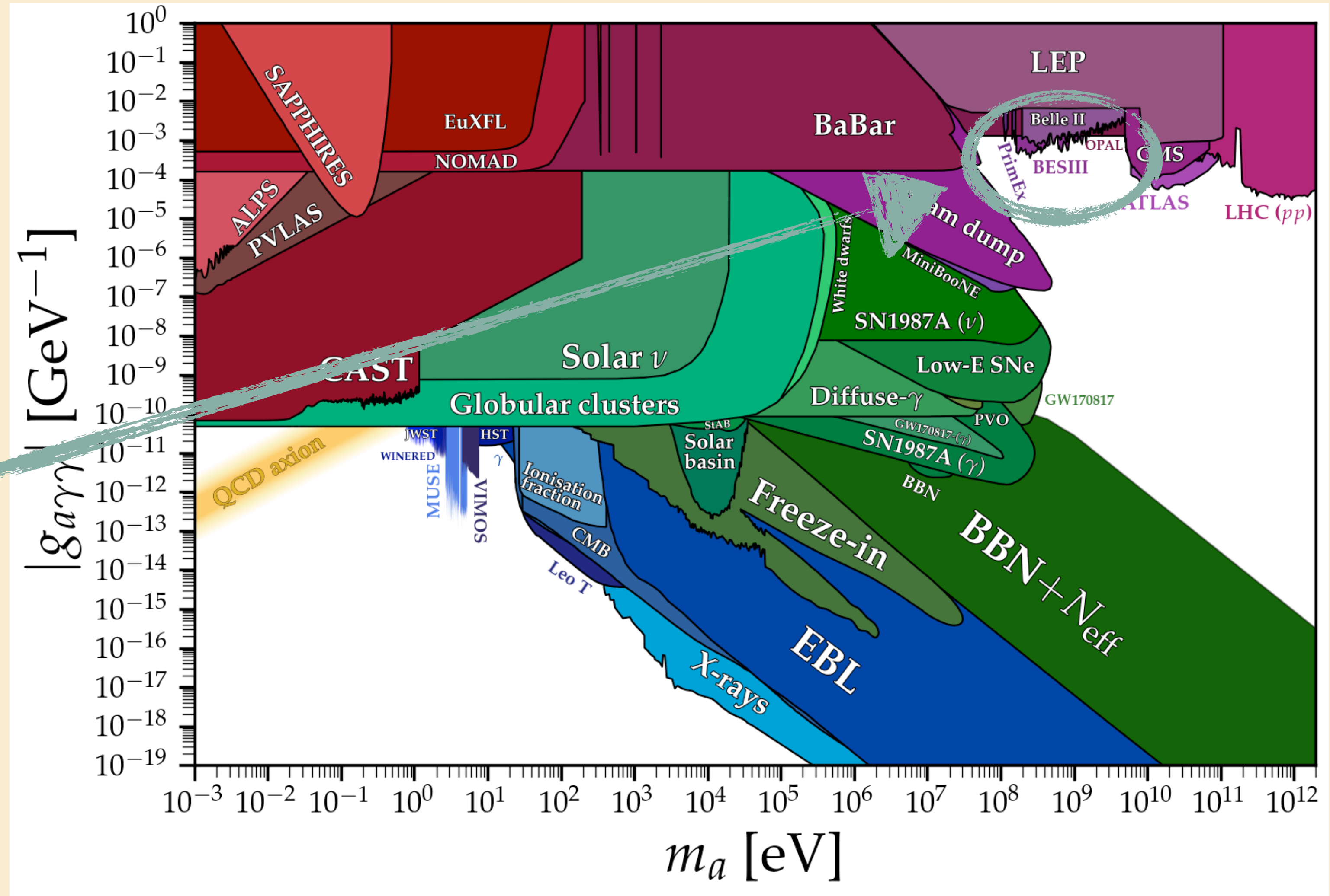

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New Experimental Results: Belle-II, BESIII

Invisible Searches

Exp.	Mass range [GeV]	Type of search	Resonance	ALP Decay
BaBar	0 – 7.8	Mixed	$\Upsilon(3S)$	Invisible
BaBar	0 – 9.2	Resonant	$\Upsilon(1S)$	Invisible
Belle	0 – 8.97	Resonant	$\Upsilon(1S)$	Invisible
Belle II	0.2 – 9.7	Non-resonant	$\Upsilon(4S)$	$\gamma\gamma$ (recast)
BESIII	0 – 1.2	Resonant	J/ψ	Invisible
BESIII	0.165 – 2.84	Resonant	J/ψ	$\gamma\gamma$ (recast)

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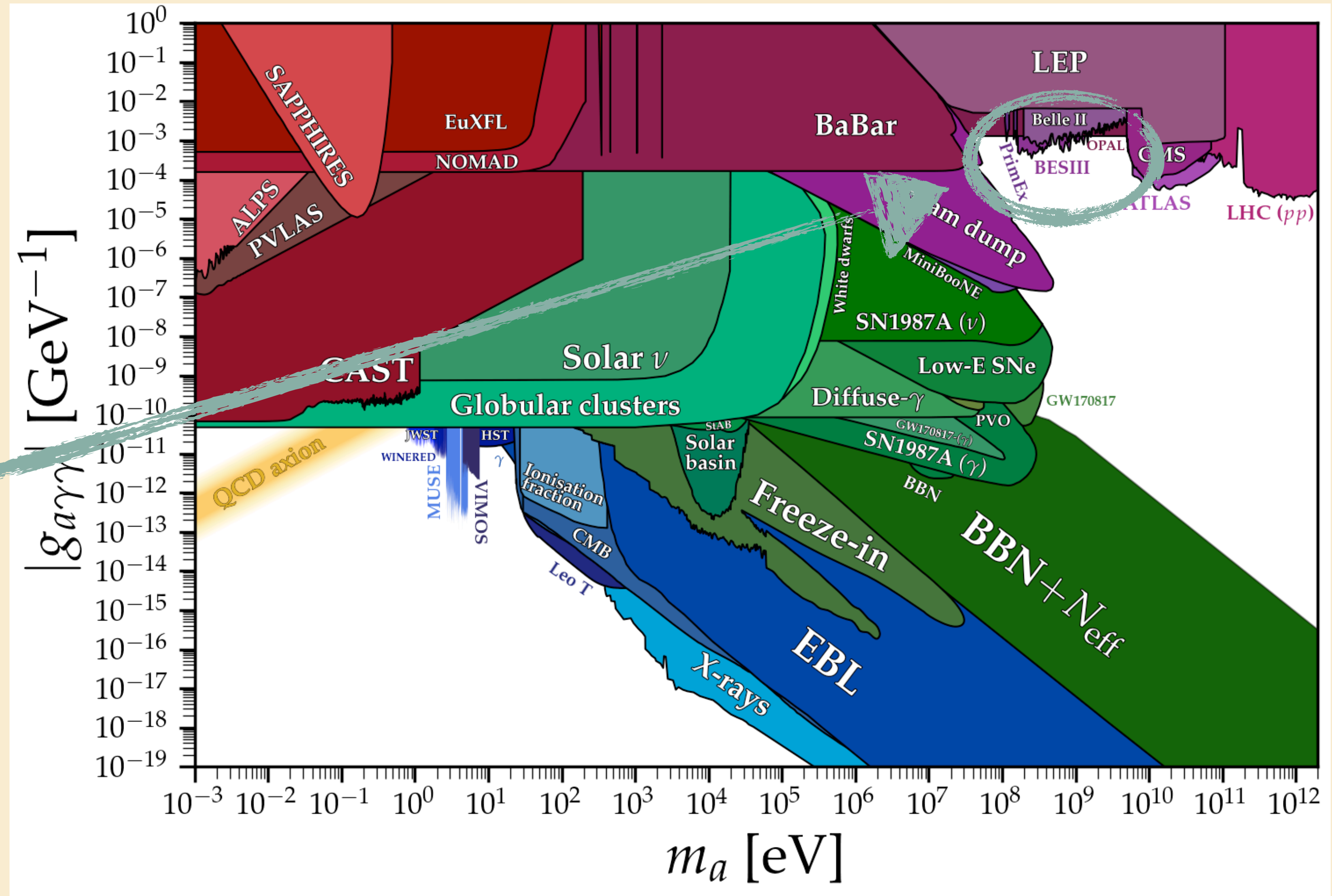

New Experimental Results: Belle-II, BESIII

Include different visible channels

from O'Hare

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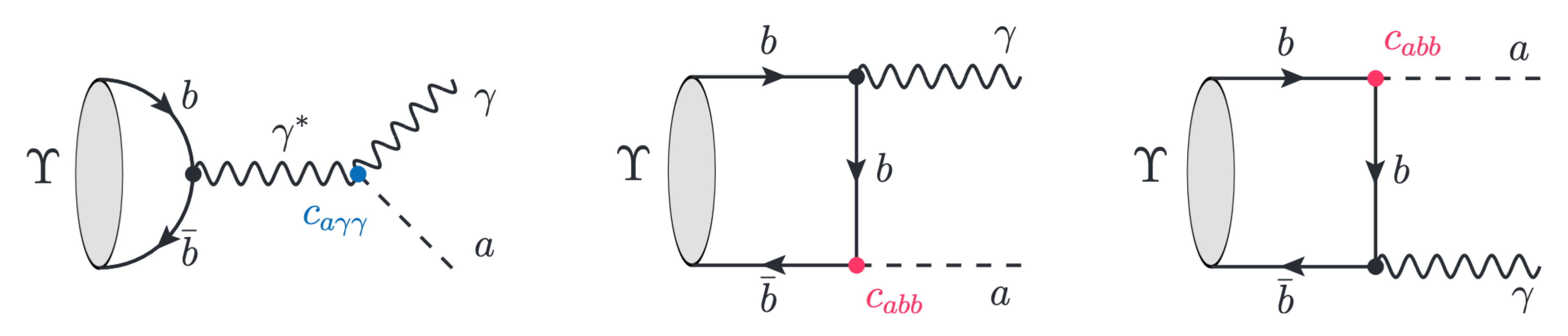
New

Visible Searches

Exp.	Mass range [GeV]	Type of search	Resonance	Decay
BaBar	0.3 – 7	Mixed	$\Upsilon(2S)$, $\Upsilon(3S)$	Hadrons
BaBar	0.212 – 9.2	Resonant	$\Upsilon(1S)$	$\mu^+\mu^-$
BaBar	4 – 9.25	Resonant	$\Upsilon(1S)$	$\bar c c$
Belle	$2m_\ell$ – 9.2	Resonant	$\Upsilon(1S)$	$\tau^+\tau^-$, $\mu^+\mu^-$
Belle II	0.2 – 9.7	Non-Resonant	$\Upsilon(4S)$	$\gamma\gamma$
BESIII	0.212 – 3	Mixed	J/ψ	$\mu^+\mu^-$
BESIII	0.165 – 2.84	Resonant	J/ψ	$\gamma\gamma$

Production and decays

Resonant production



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$$\mathcal{B}(V \to \gamma a) = \frac{\alpha_{\rm em} Q_Q^2}{24} \frac{m_V\, f_V^2}{\Gamma_V\, f_a^2} \left(1 - \frac{m_a^2}{m_V^2}\right) \left[c_{a\gamma\gamma} \frac{\alpha_{\rm em}}{\pi} \left(1 - \frac{m_a^2}{m_V^2}\right) - 2\, c_{aQQ} \right]^2$$

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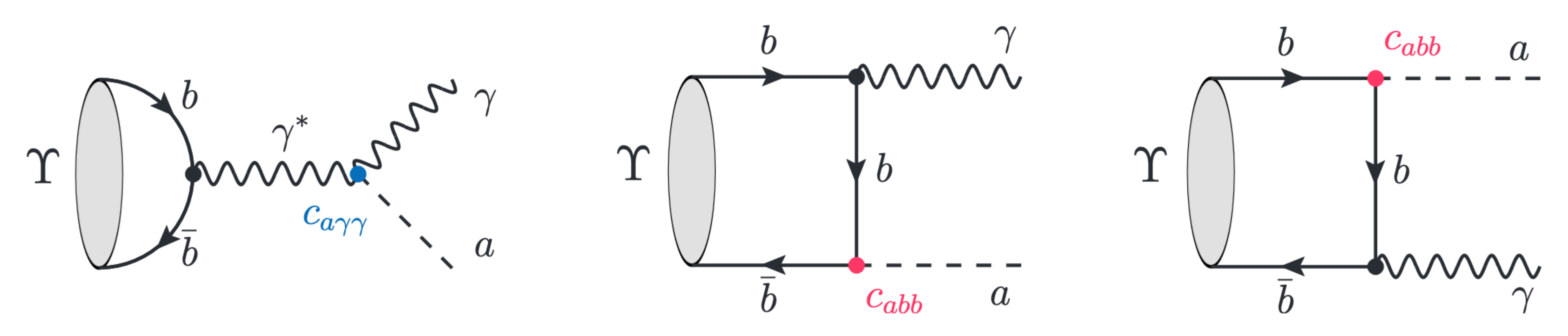

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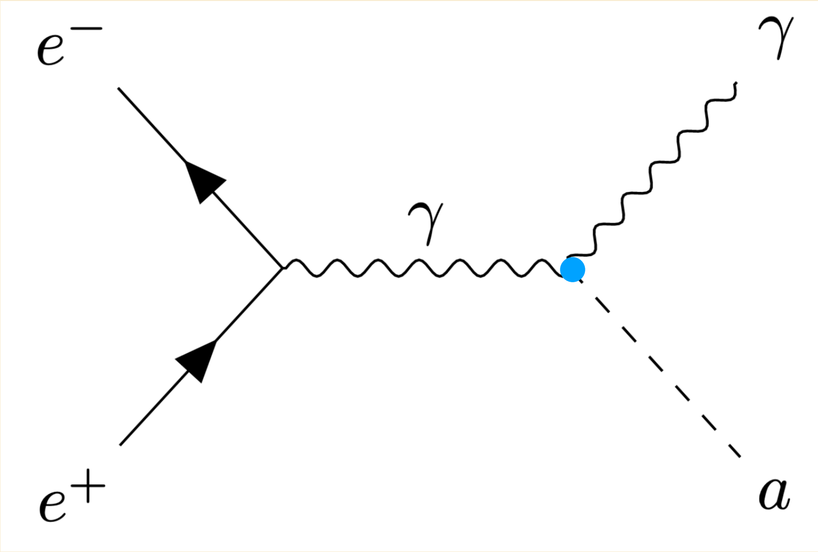
$$\sigma_{\rm NR}(s) = \frac{\alpha_{\rm em}^3}{24\pi^2} \frac{c_{a\gamma\gamma}{}^2}{f_a^2} \left(1 - \frac{m_a^2}{s}\right)^3$$



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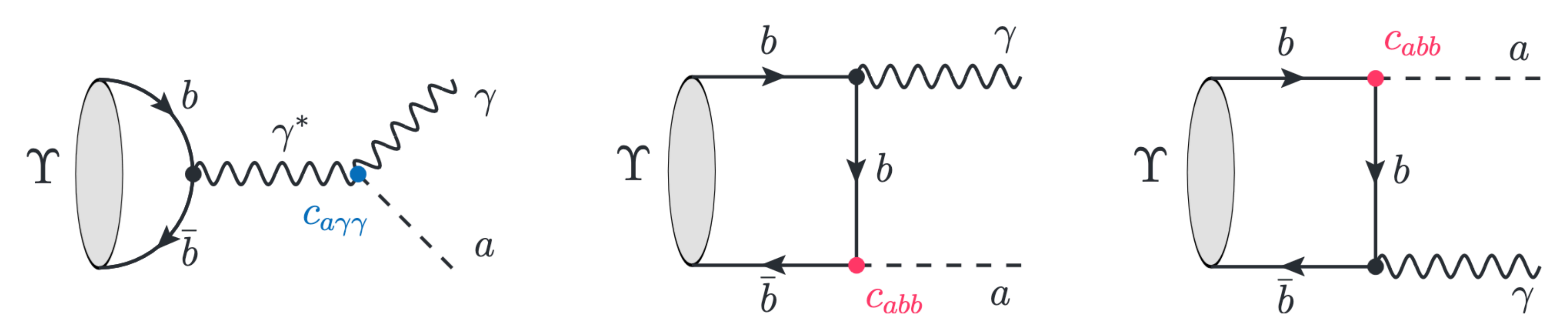

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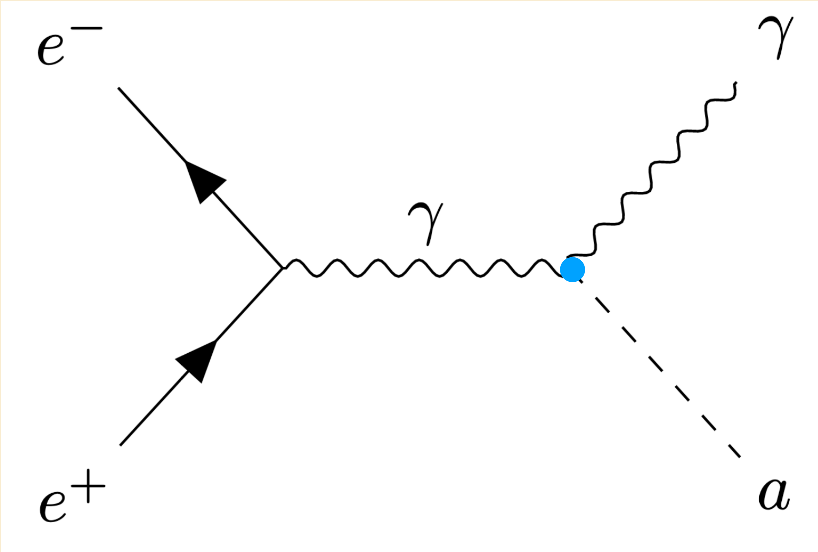

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$$\langle \sigma_{\rm mix}(s) \rangle \approx \sigma_{\rm NR}(s) + \langle \sigma_{\rm R}(s) \rangle_{\rm exp}$$

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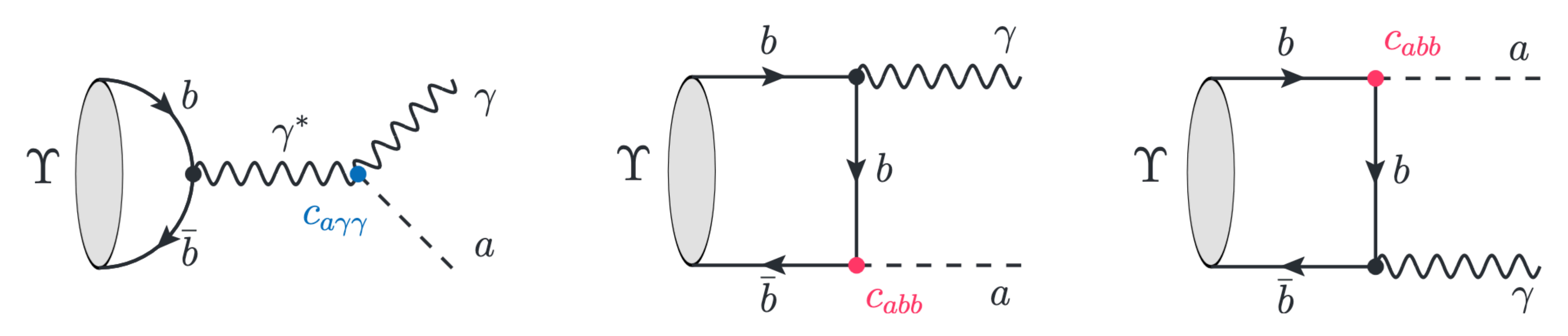

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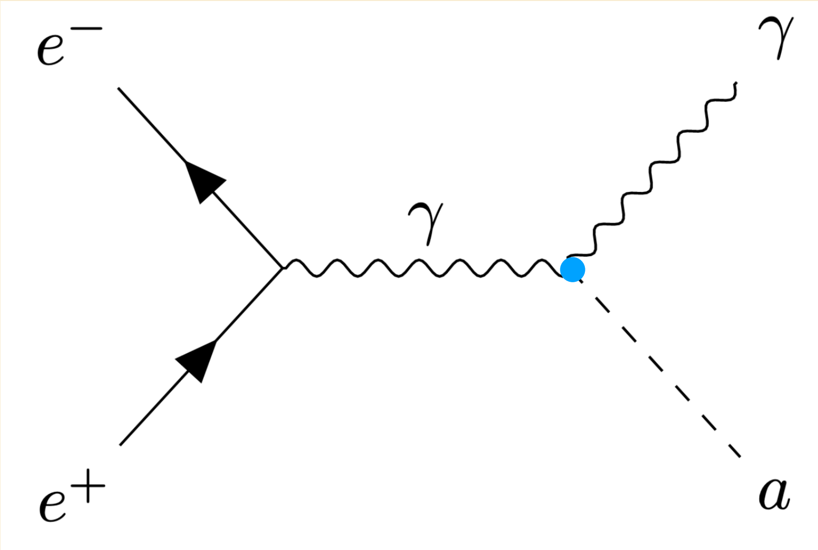

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Invisible Channel

The ALP is long-lived/stable and it is detected as missing energy

$$J/\Psi \to \gamma + E_{mis.} \qquad \Upsilon \to \gamma + E_{mis.}$$

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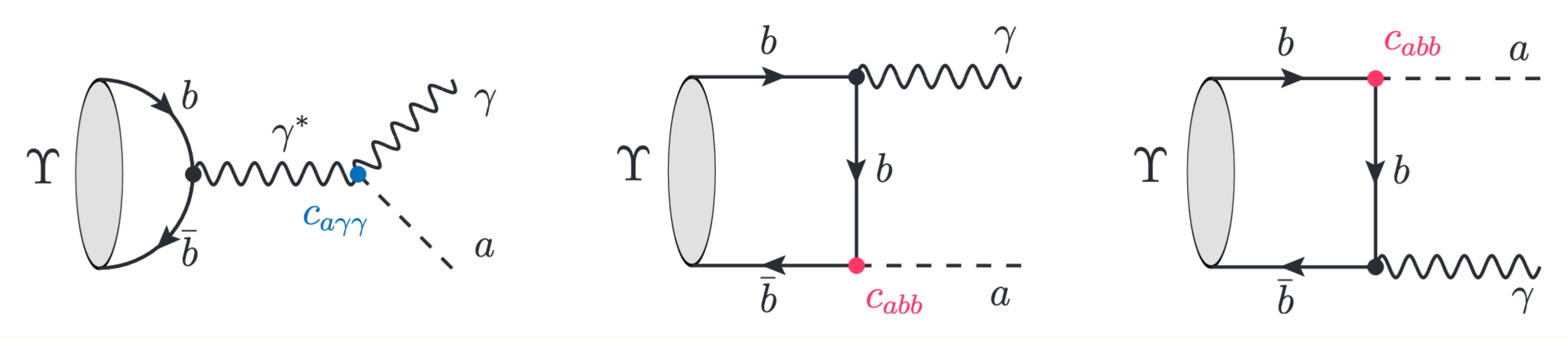

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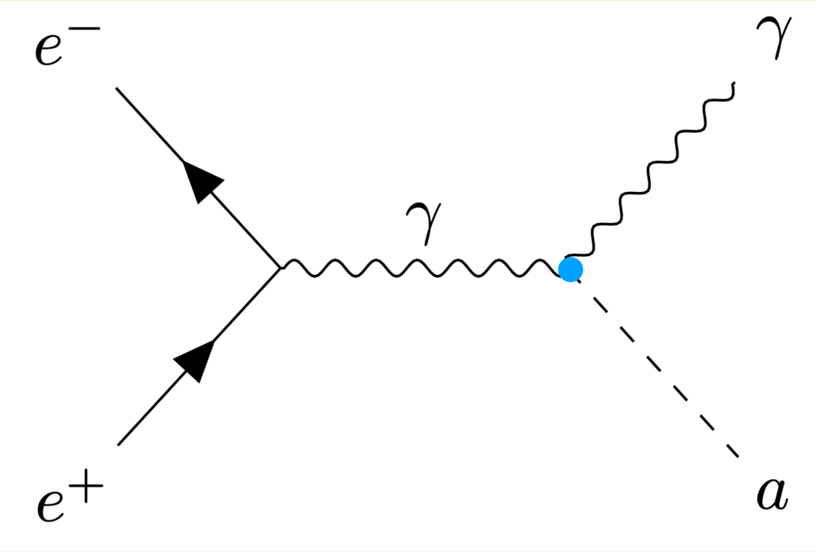

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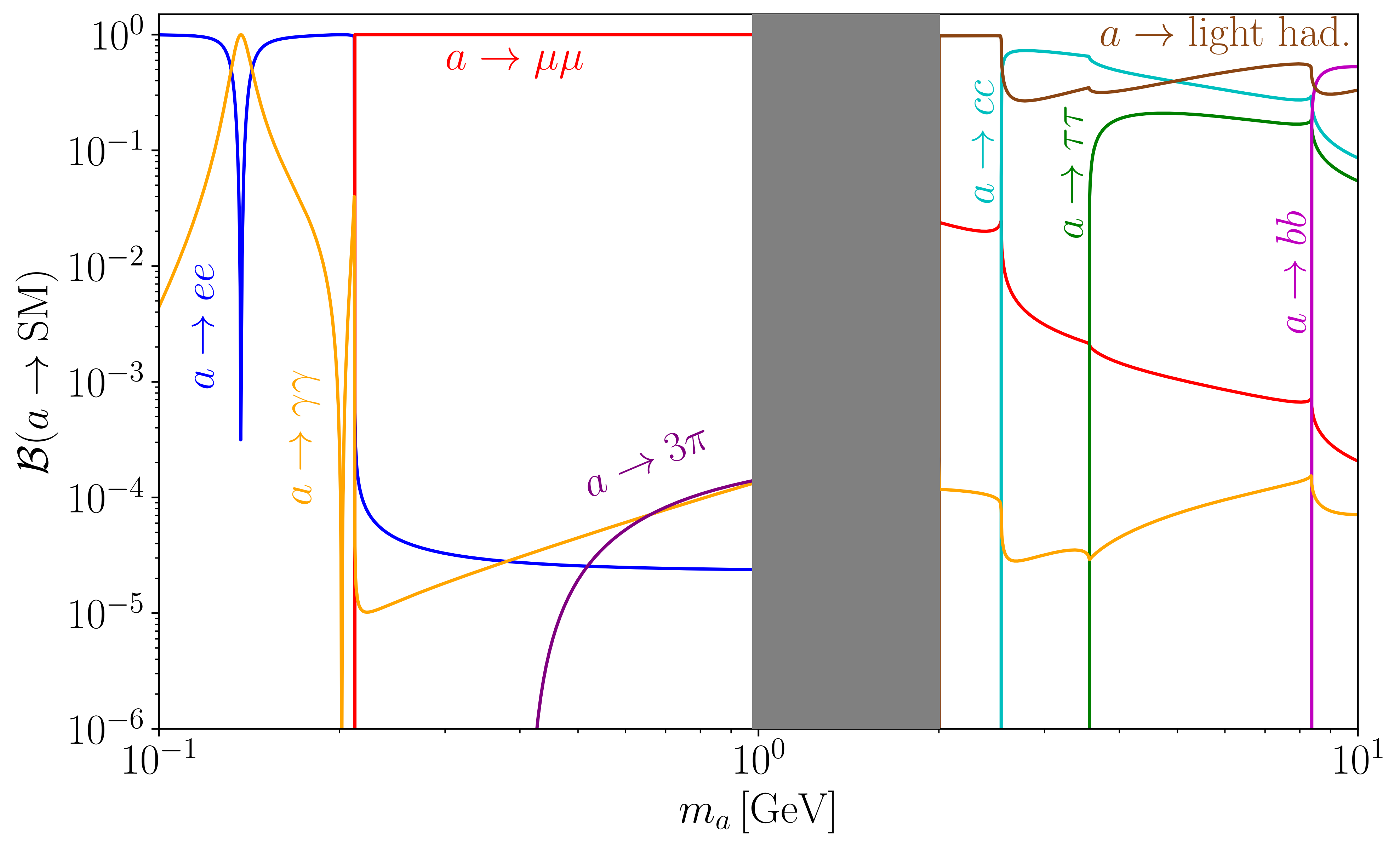
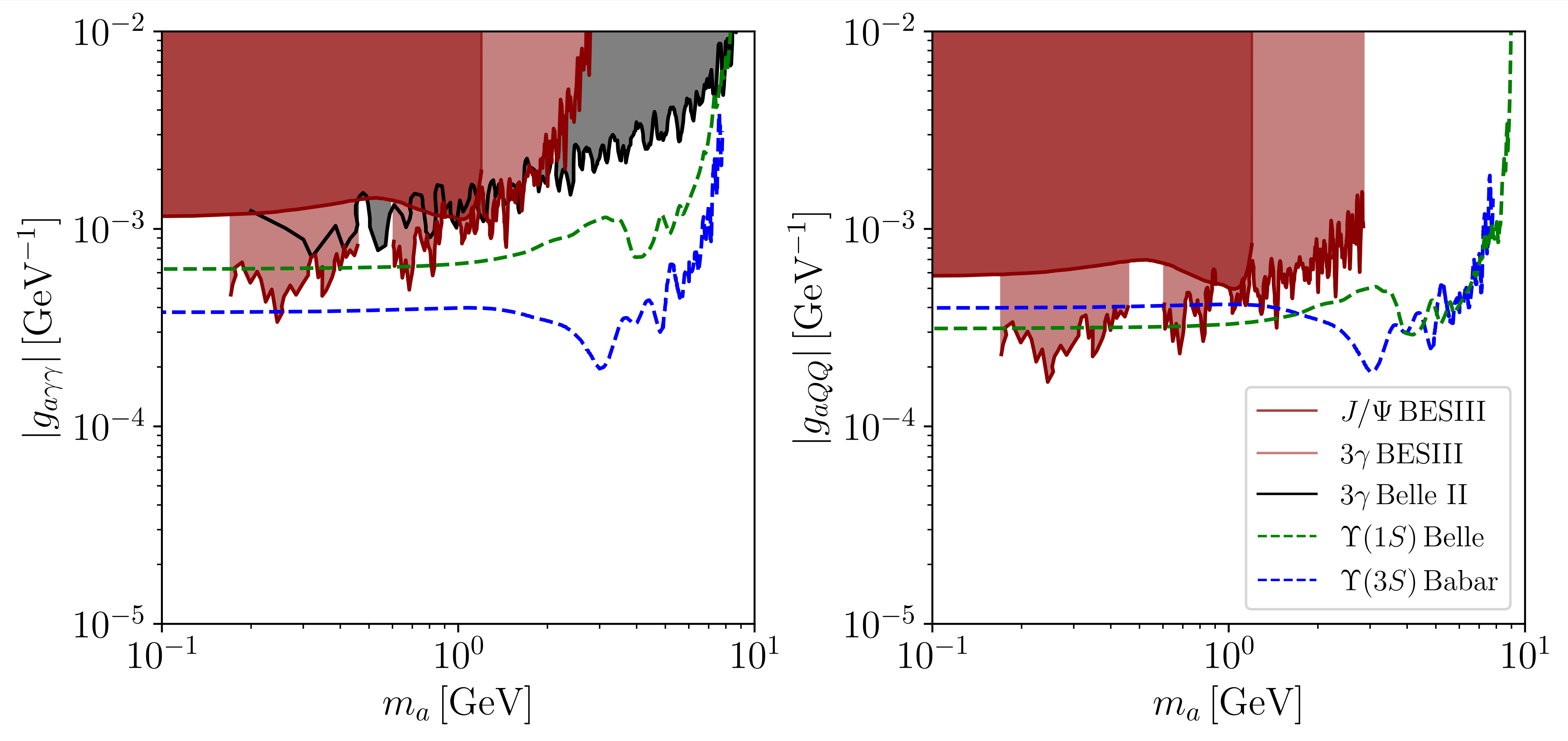


Invisible Searches

Using the following definitions:

$$g_{aff} = \frac{c_{aff}}{f_a}\,, \qquad g_{a\gamma\gamma} = c_{a\gamma\gamma}\frac{\alpha_{em}}{\pi f_a}\,, \qquad g_{agg} = c_{agg}\frac{\alpha_s}{\pi f_a}\,.$$

One Coupling



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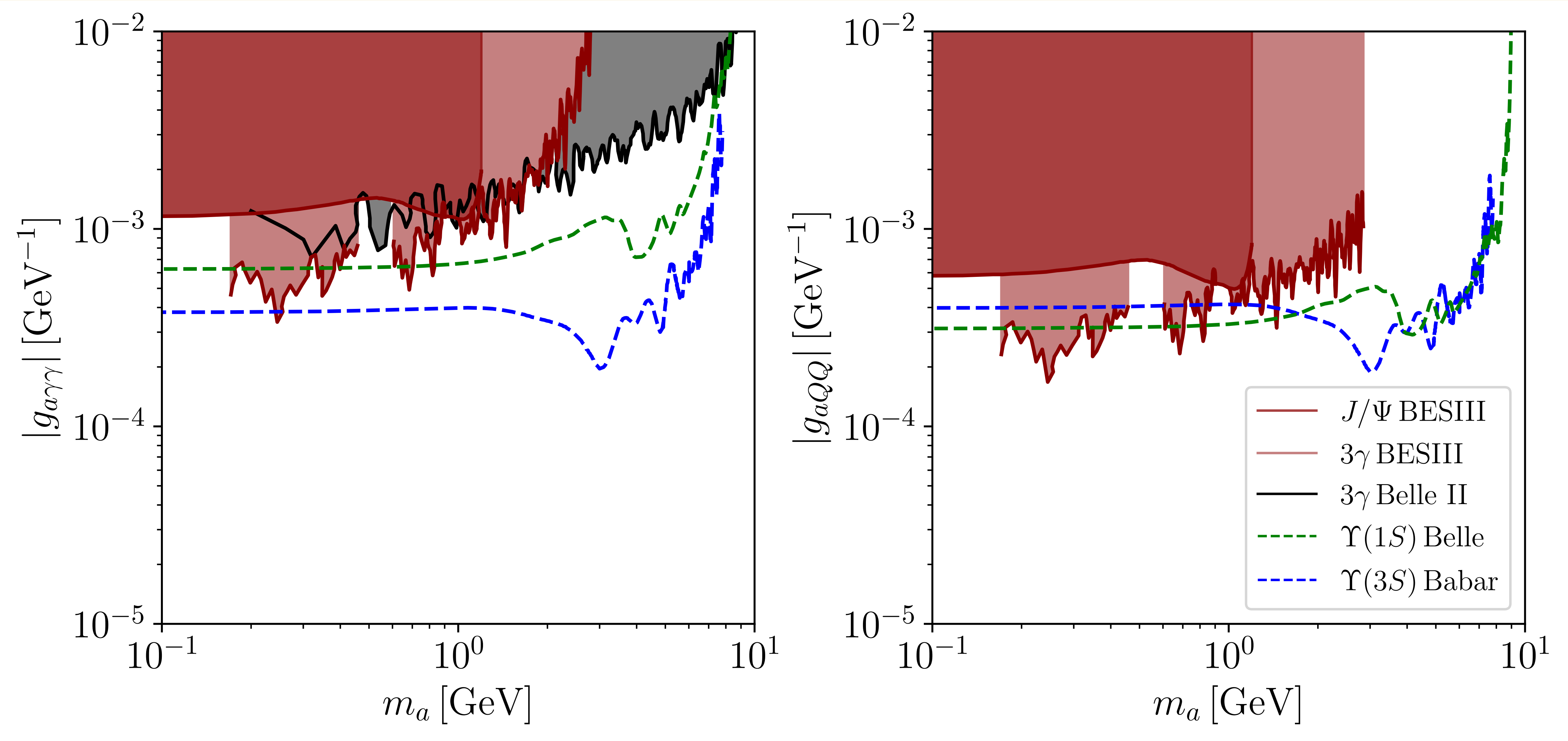
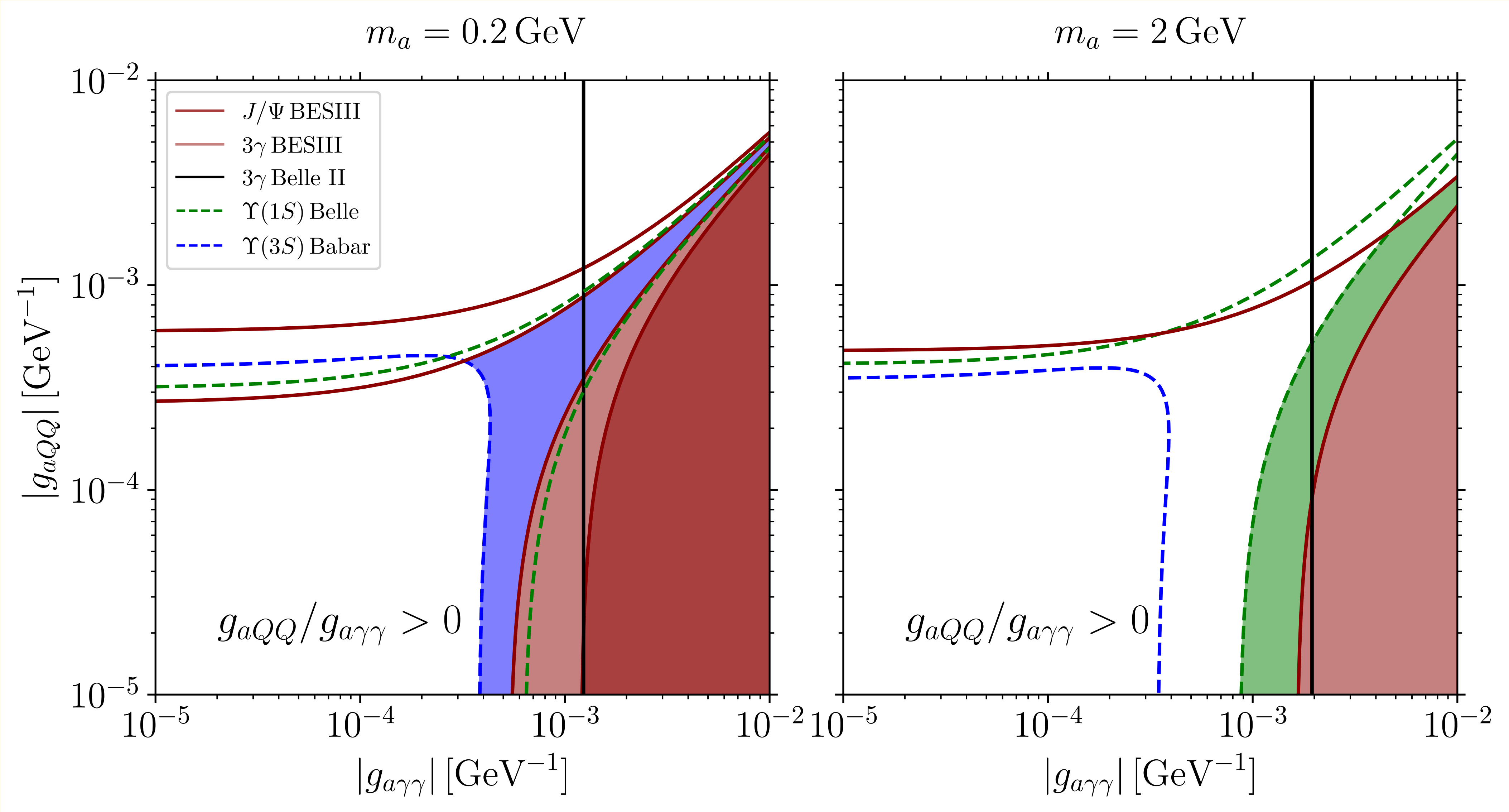


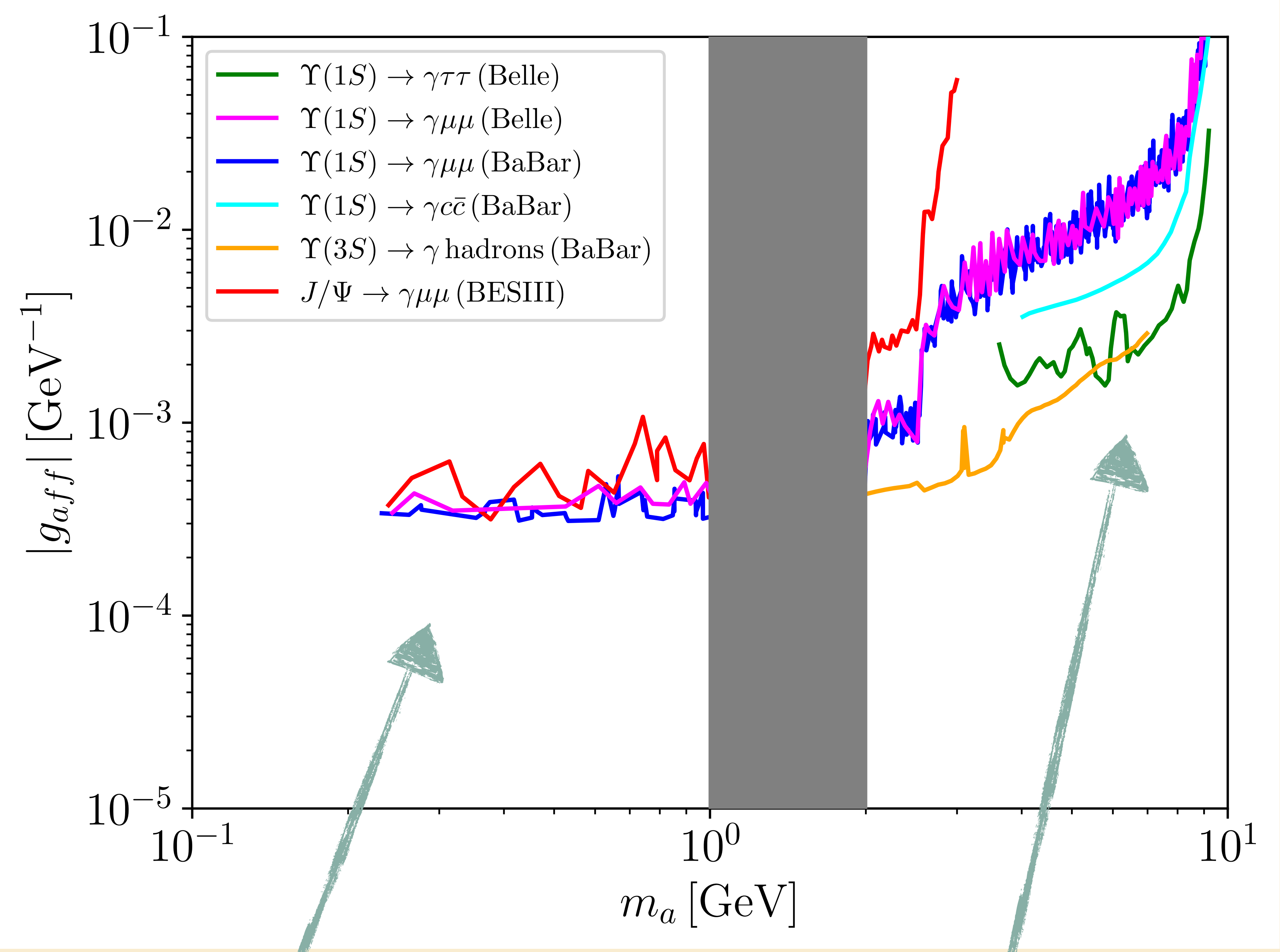
Two independent couplings



There may be cancellations in resonant production. Non-resonant or mixed searches needed to constrain the full parameter space.

Visible Searches

Universal fermion coupling



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Hadrons and tau channels best for larger masses.

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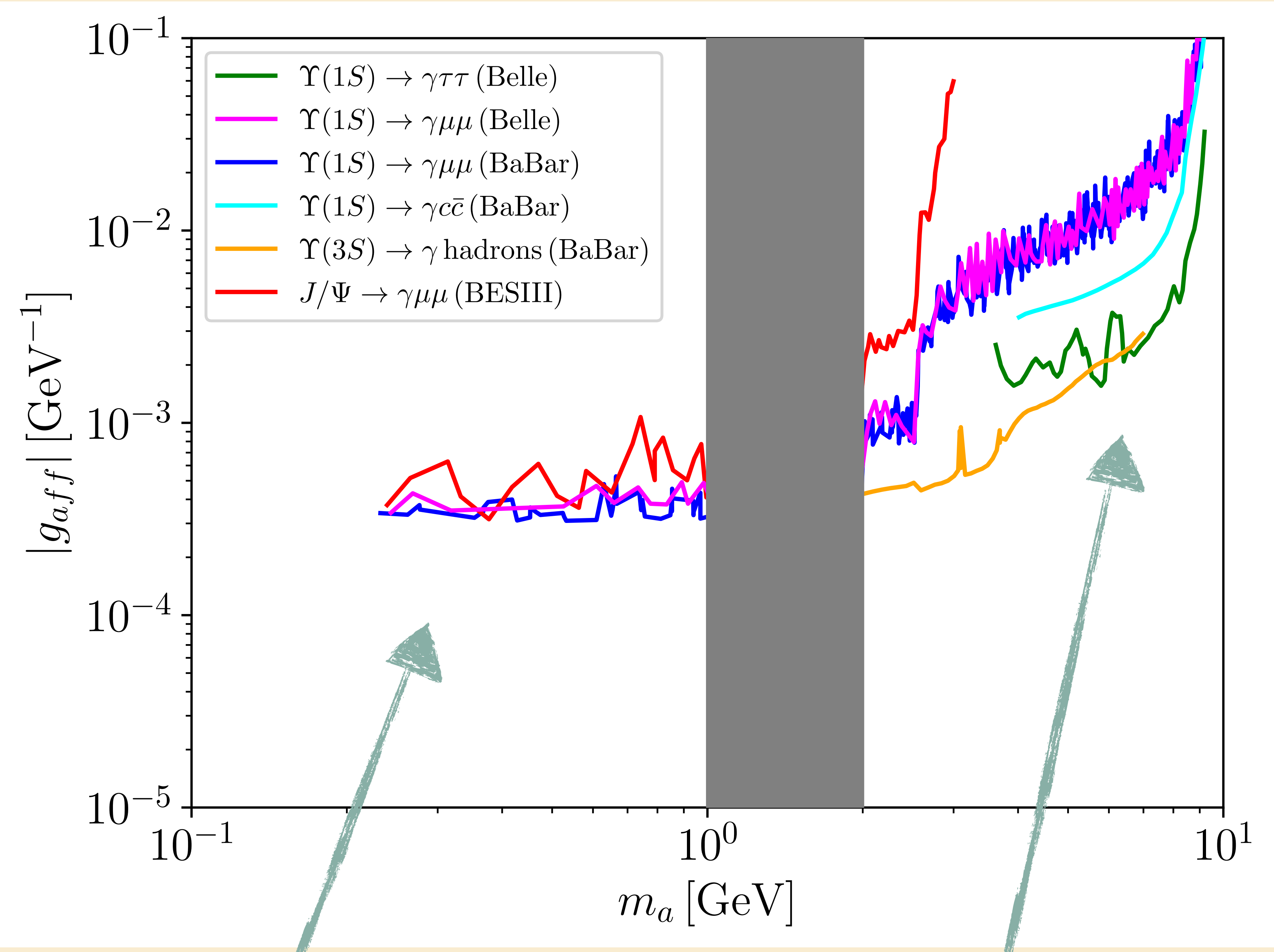

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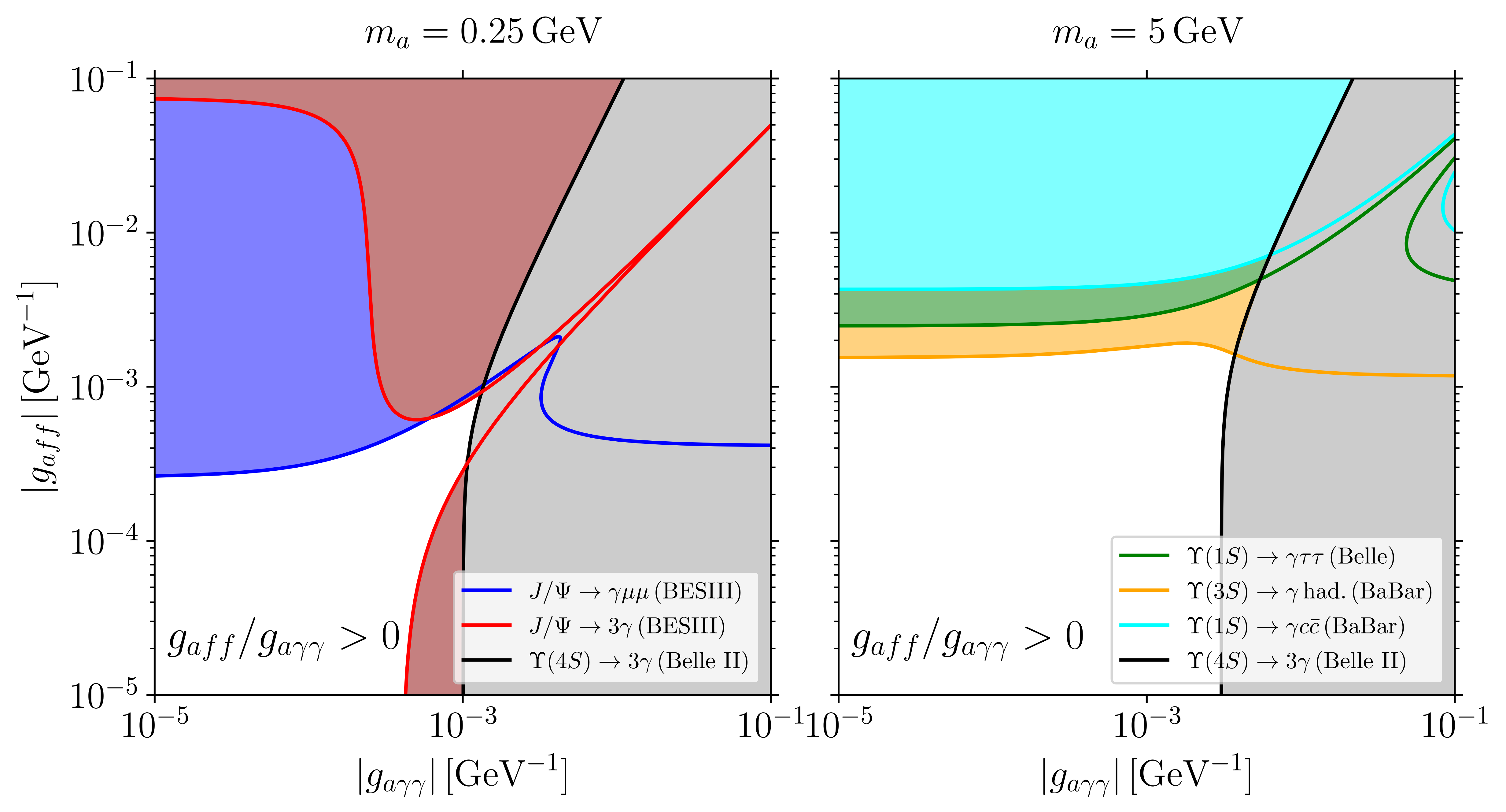

Again, the combination of searches is important to constrain all parameter space!

Conclusions

- We have explored the ALP parameter space bounded by quarkonia radiative decays
  - Different production channels are necessary to constrain possible flat directions.
  - Invisible scenario $c_{a\gamma\gamma},\, c_{aQQ} \lesssim \mathcal{O}(1) \times 10^{-4}\,\mathrm{GeV}^{-1}$
  - Visible scenario $\begin{cases} c_{a\mu\mu} \lesssim 3 \times 10^{-4}\,\mathrm{GeV}^{-1} \text{ for } m_a \lesssim 1\,\mathrm{GeV} \\ c_{aff} \lesssim \mathcal{O}(1) \times 10^{-3}\,\mathrm{GeV}^{-1} \text{ for } m_a \gtrsim 2\,\mathrm{GeV} \end{cases}$
  - If you are interested in more details come to the poster!

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Thanks for your attention!

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 860881.

Production Details

Resonant production

$$\sigma_{\rm R}(s) = \sigma_{\rm peak} \frac{m_V^2 \Gamma_V^2}{(s - m_V^2)^2 + m_V^2 \Gamma_V^2} \mathcal{B}(V \to \gamma a)$$

$$\sigma_{\rm peak} = \frac{12\pi \mathcal{B}(V \to e^+ e^-)}{m_V^2}$$

When producing the resonance there is an uncertainty in the beam energy

$$\sigma_W \approx 2 - 5\,\mathrm{MeV}$$

$$\langle \sigma_{\rm R}(s) \rangle_{\rm exp} = \frac{1}{\sqrt{2\pi}} \int dq \, \frac{\sigma_R(q^2)}{\sigma_W} \exp\left[-\frac{(q - \sqrt{s})^2}{2\sigma_W^2} \right]$$

$V(nS)$	m_V [GeV]	Γ_V [keV]	$\sigma_{\rm peak}$ [nb]	ρ	$\langle \sigma_{\rm R} \rangle_{\rm exp} / \sigma_{\rm NR} \|_{s=m_V^2}$
$J/\Psi(1S)$	3.096	92.6	$91.2(5) \times 10^3$	31×10^{-3}	0.92(1)
$\Upsilon(1S)$	9.460	54.02	$3.9(2) \times 10^3$	6.1×10^{-3}	0.53(5)
$\Upsilon(2S)$	10.023	31.98	$2.8(2) \times 10^3$	3.7×10^{-3}	0.21(3)
$\Upsilon(3S)$	10.355	20.32	$3.0(3) \times 10^3$	2.3×10^{-3}	0.16(3)
$\Upsilon(4S)$	10.580	20.5×10^3	2.1(1)	0.83	$3.0(3) \times 10^{-5}$

Details on ALP Decays

Decays

$$\Gamma(a \to \mathrm{SM}) = \frac{\alpha_{\rm em}^2}{64\pi^3 f_a^2}\left|c_{a\gamma\gamma}^{\rm eff}\right|^2 m_a^3 + \sum_f \frac{N_c^f \left|c_{aff}\right|^2}{8\pi f_a^2} m_a m_f^2 \sqrt{1-\frac{4m_f^2}{m_a^2}}\,\Theta\left(m_a - 2m_f\right) + \Gamma_{a\to \rm lh}\,,$$

Photons | Leptons and heavy quarks | Light Hadrons

Light Hadrons

$$\Gamma_{a\to \rm lh} = \begin{cases} \dfrac{m_a m_\pi^4}{6144\pi^3 f_\pi^2 f_a^2}\left|c_{a\pi}\right|^2 \left(g_{00}\left(\dfrac{m_\pi^2}{m_a^2}\right) + g_{+-}\left(\dfrac{m_\pi^2}{m_a^2}\right)\right) & m_a \lesssim 1\,\mathrm{GeV}\,, \\ \dfrac{\alpha_s^2}{8\pi^3 f_a^2}\left|c_{agg}^{\rm eff}\right|^2 m_a^3 \left(1 + \dfrac{\alpha_s}{4\pi}\,\dfrac{291 - 14\,n_q}{12}\right) & m_a \gtrsim 2\,\mathrm{GeV}\,, \end{cases}$$

$$c_{a\pi} = -\left(2c_{agg}\frac{m_d - m_u}{m_d + m_u} + c_{auu} - c_{add}\right)\,,$$

$$c_{agg}^{\rm eff} = c_{agg} + \frac{1}{2}\sum_{q\neq t} c_{aqq} B_1\left(\frac{4m_q^2}{m_a^2}\right)$$

Photon Coupling

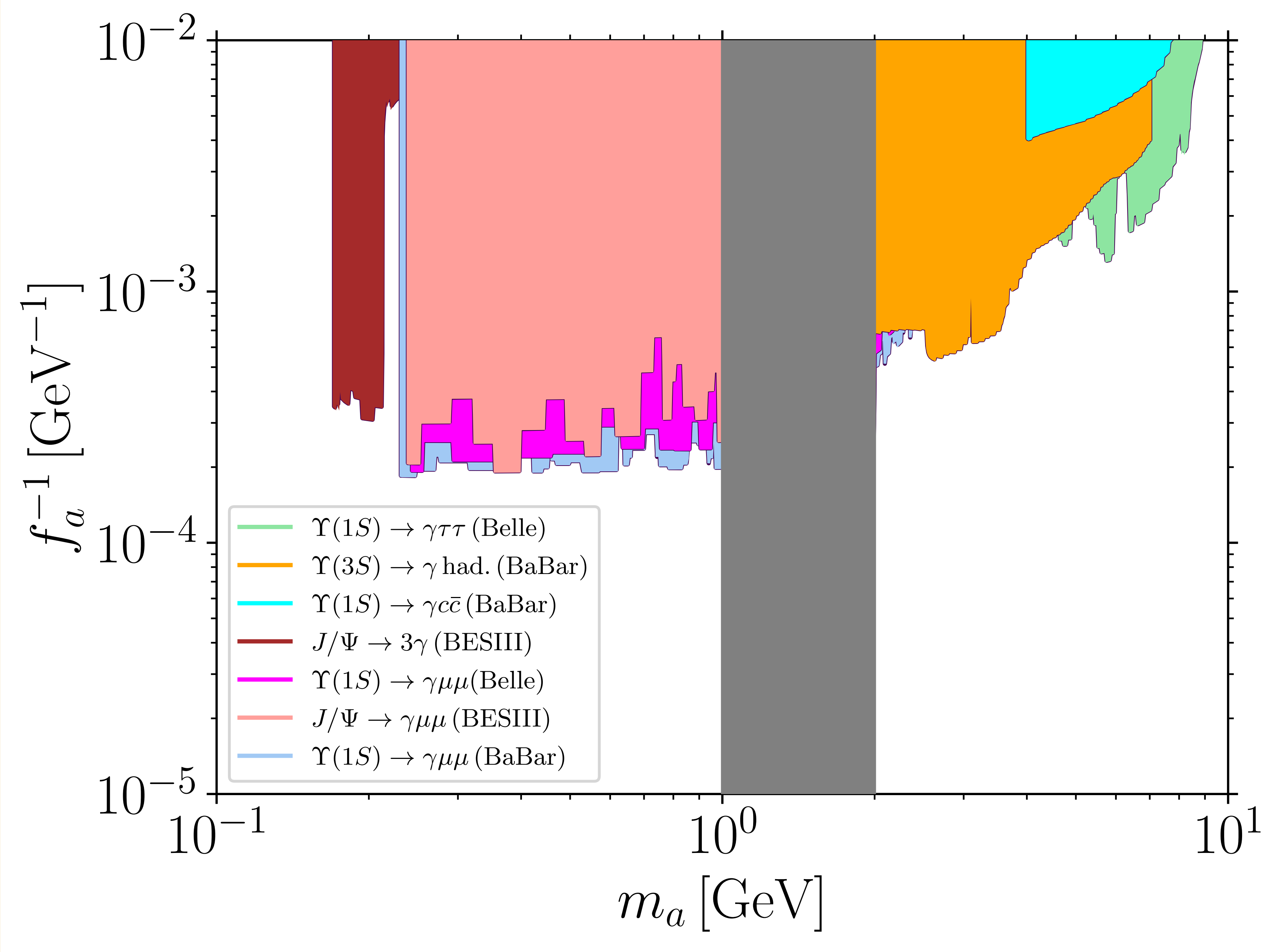
$$c_{a\gamma\gamma}^{\rm eff} = \begin{cases} c_{a\gamma\gamma} - 1.92\,c_{agg} + \dfrac{f_a}{f_\pi}U_{a\pi} + \displaystyle\sum_{f=\ell,c,b} N_c^f Q_f^2 c_{aff} B_1(\tau_f)\,, \\ c_{a\gamma\gamma} + \displaystyle\sum_{f\neq t} N_c^f Q_f^2 c_{aff} B_1(\tau_f) \end{cases}$$

$$\tau_f = \frac{4m_f^2}{m_a^2}$$

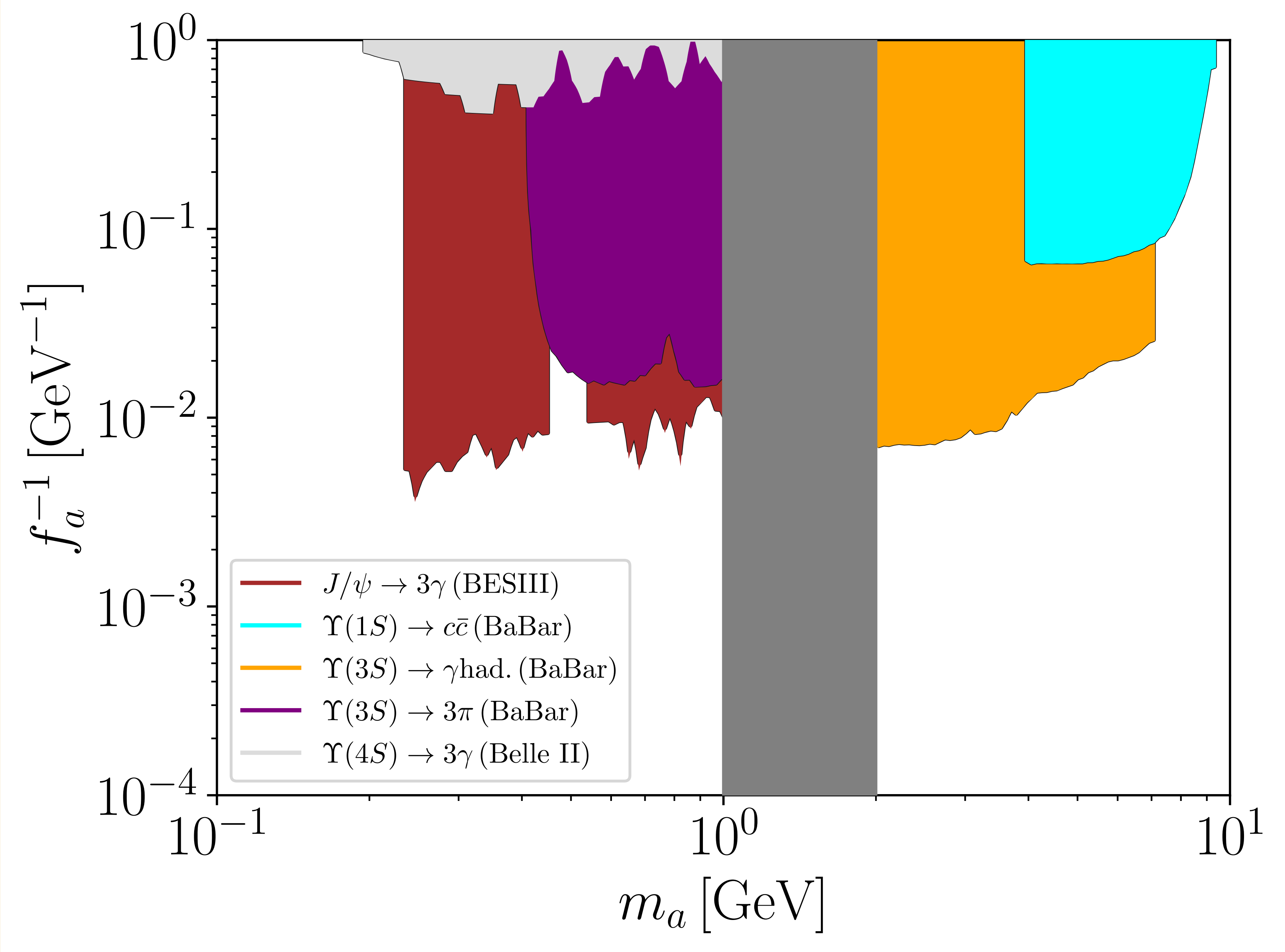
$$B_1(\tau) = 1 - \tau f(\tau)^2 \quad \text{with} \quad f(\tau) = \begin{cases} \arcsin\left(\dfrac{1}{\sqrt{\tau}}\right) & \tau \geq 1\,, \\ \dfrac{\pi}{2} + \dfrac{i}{2}\log\left(\dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) & \tau < 1\,, \end{cases}$$

Benchmark Models

DFSZ-like ALP



KSVZ-like ALP



DFSZ-like: $c_{auu} = -c_{add} = -2s_\beta^2\,,\; c_{aee} = -2c_\beta^2\,,\; c_{a\gamma\gamma} = 6\,,\; c_{agg} = 0\,,$

KSVZ: $c_{auu} = c_{add} = c_{aee} = 0\,,\; c_{a\gamma\gamma} = 0\,,\; c_{agg} = 1/2\,.$