The importance of quantum loops for astrophysical ALPs

Eike Müller

October 2022, 8th Symposium on Prospects in the Physics of Discrete Symmetries

Based on

- *Do Direct Detection Experiments Constrain Axionlike Particles Coupled to Electrons?*, Ricardo Z. Ferreira, M. C. David Marsh, and **EM,** Phys. Rev. Lett. 128, 221302
- *Strong supernovae bounds on ALPs from quantum loops,* Ricardo Z. Ferreira, M.C. David Marsh, and **EM**, arXiv:2205.07896 (submitted to JCAP)

Introduction: Axionlike particles

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- ALPs are naturally light, weakly interacting pseudoscalar particles that appear in many BSM theories
- At low energies $E \ll \Lambda$, all these models are described by the same *effective field theory* (EFT)
- In this talk: study just two parameters of the EFT phenomenologically at the one-loop level (no model building)

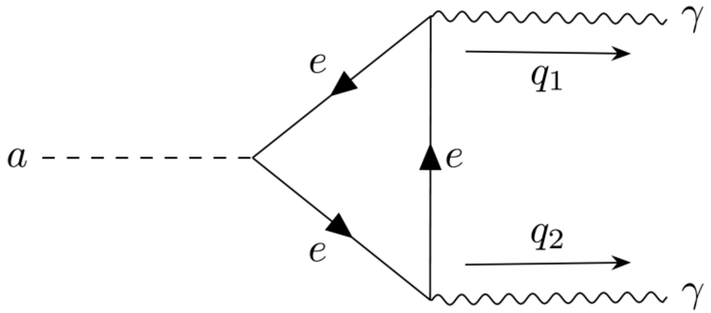
$$\mathcal{L}_{\rm EFT} \supset -\frac{1}{2}a(\Box + m_a^2)a + \hat{g}_{ae}(\partial_\mu a)\,\bar{\psi}_e\gamma^\mu\gamma_5\psi_e + \frac{g_{a\gamma}}{4}aF\tilde{F}$$

Theoretical basis

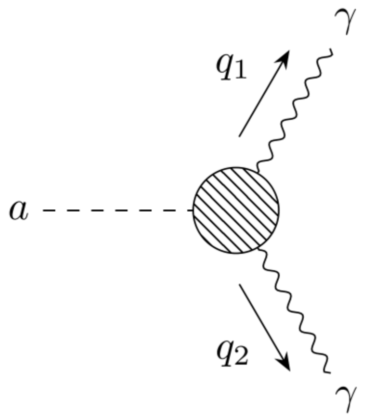
Effective, one-loop ALP-photon coupling

The effective ALP-photon coupling

The one-loop, off-shell matrix element has the same structure as the tree-level version:



$$= i\frac{e^2\hat{g}_{ae}}{2\pi^2}\left[1 + 2m_e^2\, C_0\left(q_1^2, q_2^2, (q_1+q_2)^2, m_e^2, m_e^2, m_e^2\right)\right] q_1^{\alpha}\, q_2^{\beta}\, \varepsilon^{\mu\nu\alpha\beta}$$



$$= i\, g_{a\gamma}^{\text{eff}}(q_1, q_2)\, q_1^{\alpha}\, q_2^{\beta}\, \varepsilon^{\mu\nu\alpha\beta}$$

The effective ALP-photon coupling

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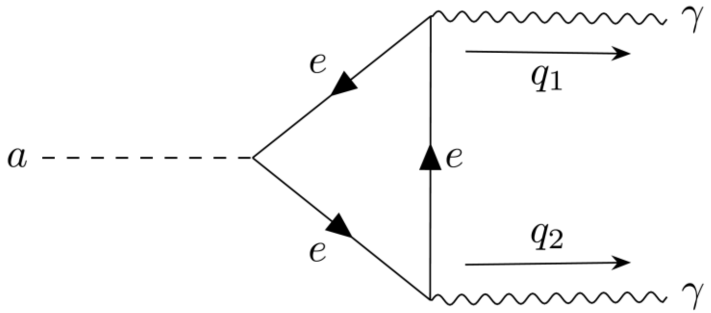

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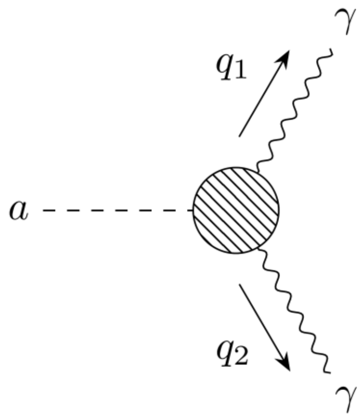

$$= i\, g_{a\gamma}^{\text{eff}}(q_1, q_2)\, q_1^\alpha\, q_2^\beta\, \varepsilon^{\mu\nu\alpha\beta}$$

Which let's us define an <u>off-shell</u> effective coupling

The effective ALP-photon coupling

Known for a while: the effective coupling *on-shell*, i.e. in a decay process

$$g_{a\gamma}^{(\mathrm{D})} \equiv g_{a\gamma}^{\mathrm{eff}}(q_1^2 = q_2^2 = 0, p^2 = m_a^2) = \frac{2\alpha}{\pi}\hat{g}_{ae}\left[1 - \frac{4m_e^2}{m_a^2} f^2\left(\frac{4m_e^2}{m_a^2}\right)\right]$$

$$= -\frac{\alpha\hat{g}_{ae}}{6\pi}\left(\frac{m_a}{m_e}\right)^2 + \mathcal{O}\left(\frac{m_a}{m_e}\right)^4$$

$$f(\tau) = \begin{cases} \arcsin\left(\frac{1}{\sqrt{\tau}}\right) & \text{for } \tau \geq 1 \\ \frac{1}{2}\left[\pi + i\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right)\right] & \text{for } \tau < 1 \end{cases}$$

Bauer, Neubert, Thamm, JHEP 12 (2017) 044

This effective coupling vanishes for massless ALPs, but it is only the right coupling for on-shell photons!

The effective ALP-photon coupling

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Bauer, Neubert, Thamm, JHEP 12 (2017) 044

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If a photon in the t-channel is off-shell, we get the effective Primakoff coupling:

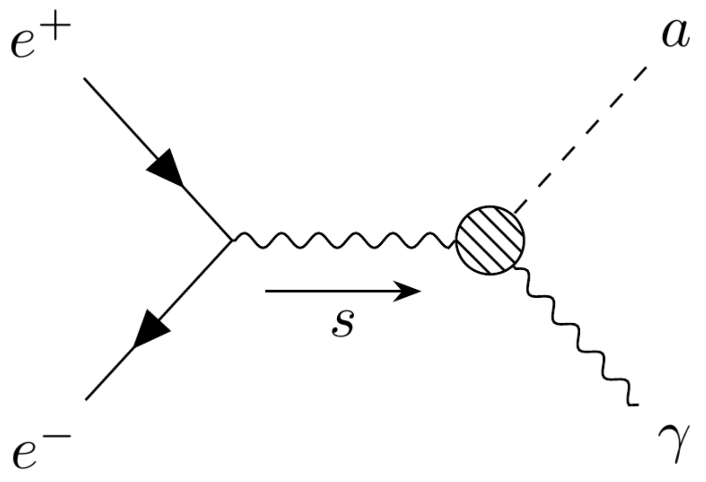
$$g_{a\gamma}^{(\mathrm{P})} \equiv g_{a\gamma}^{\mathrm{eff}}(q_1^2 = 0, q_2^2 = t, p^2 = m_a^2) = \frac{2\alpha}{\pi}\hat{g}_{ae}\left\{1 + \frac{4m_e^2}{m_a^2 - t}\left[f^2\left(\frac{4m_e^2}{t}\right) - f^2\left(\frac{4m_e^2}{m_a^2}\right)\right]\right\}$$

$$= \frac{2\alpha}{\pi}\hat{g}_{ae}\left[1 + \frac{4m_e^2}{m_a^2 - t} f^2\left(\frac{4m_e^2}{t}\right)\right] + \mathcal{O}\left(\frac{m_a}{m_e}\right)^2$$

The effective ALP-photon coupling

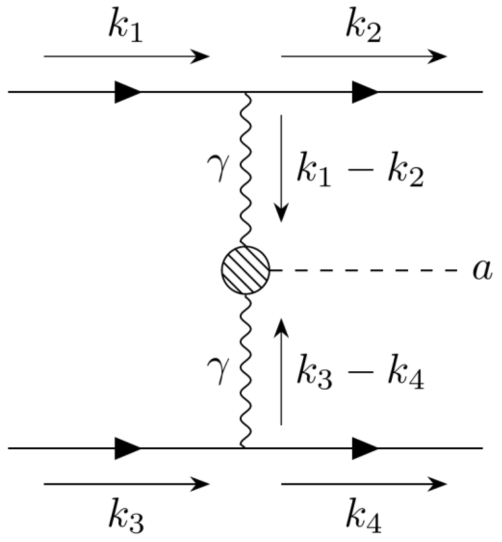
The effective coupling can be used in all processes involving ALPs.

Further phenomenologically relevant examples include:



ALP-strahlung

$$g_{a\gamma}^{\text{eff}}(q_1^2 = 0, q_2^2 = s, p^2 = m_a^2)$$



Photon fusion

$$g_{a\gamma}^{\text{eff}}(q_1^2 = (k_1 - k_2)^2, q_2^2 = (k_3 - k_4)^2, p^2 = m_a^2)$$

Phenomenlogical applications

Instability of heavy ALP dark matter

Instability of ALP DM

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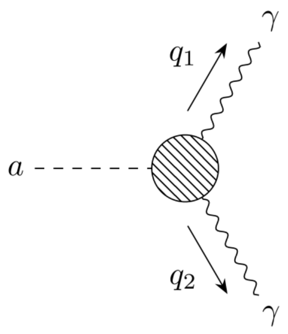
A simple consequence: also ALPs only coupled to electrons with $m_a < 2m_e$ decay (into photons)

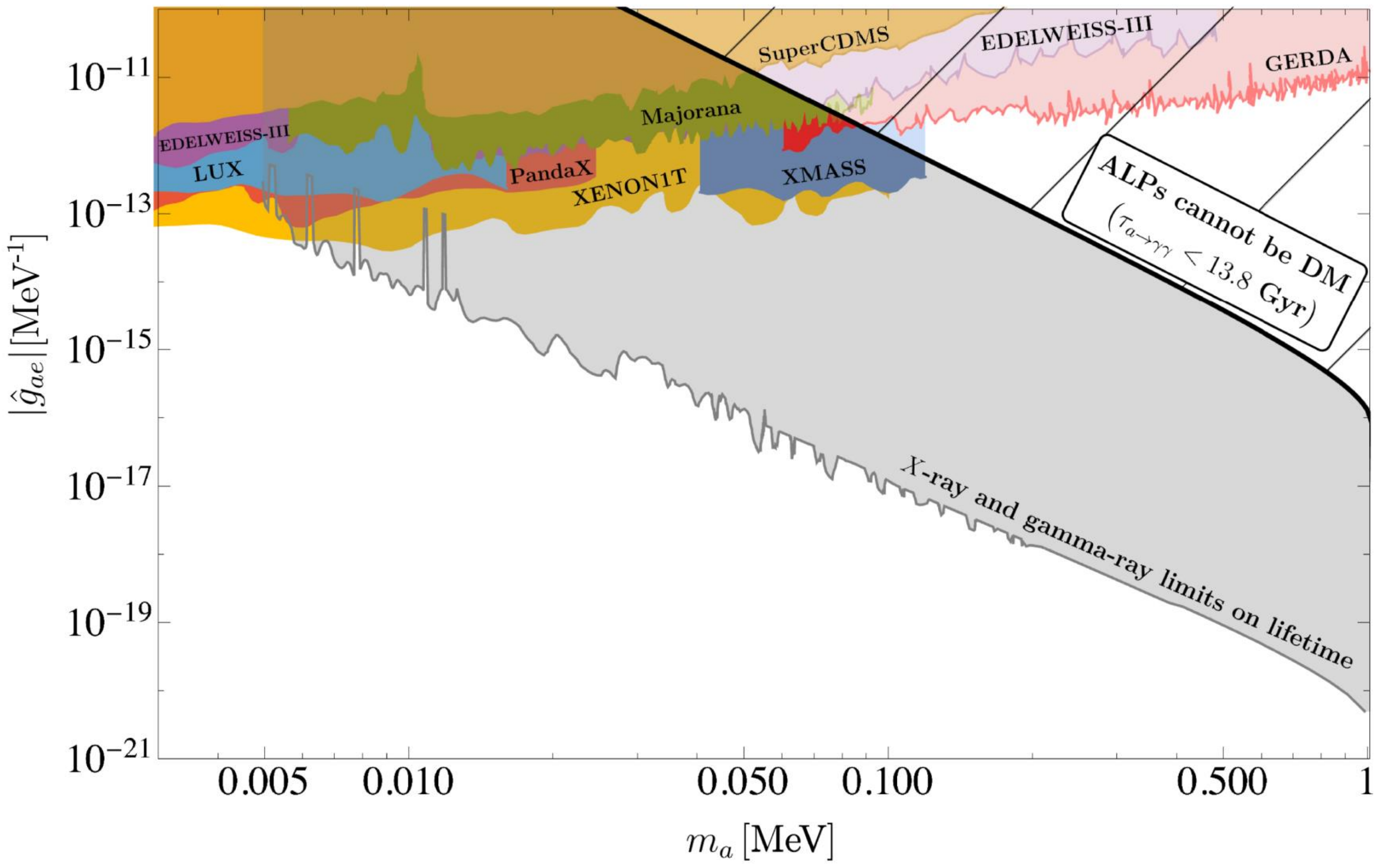


$$\Gamma_{a\to\gamma\gamma} \sim \left(g_{a\gamma}^{(\mathrm{D})}\right)^2 m_a^3 \sim \hat{g}_{ae}^2 m_a^7$$

$$\Rightarrow \tau_a \simeq 14\ \mathrm{Gyr} \left(\frac{10^{-12}\ \mathrm{MeV}^{-1}}{\hat{g}_{ae}}\right)^2 \left(\frac{100\ \mathrm{keV}}{m_a}\right)^7$$

→ ALP dark matter in the keV mass range is unstable

Instability of ALP DM



Ferreira, Marsh, **EM**,
PRL 128 (2022) 221302

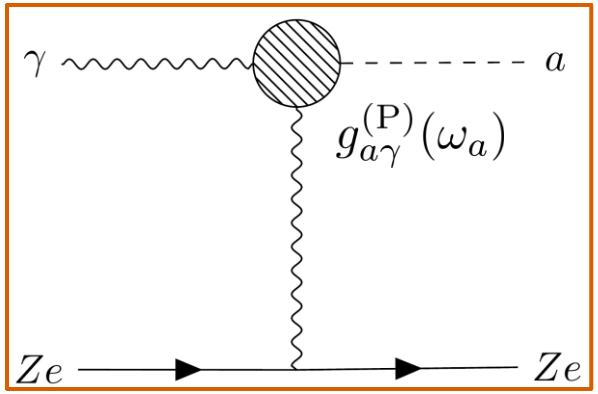
Phenomenlogical applications

Supernova bounds at one loop

Supernova bounds at one loop

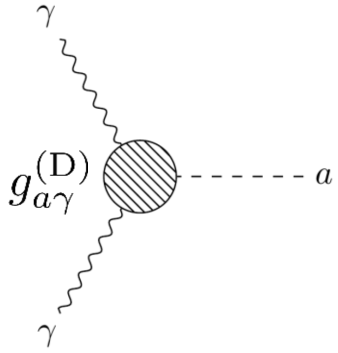
Loop level:

Primakoff process



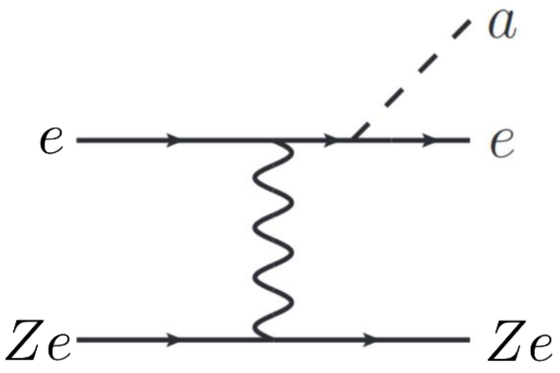
Dominates at $m_a \ll m_e$

Photon coalescence

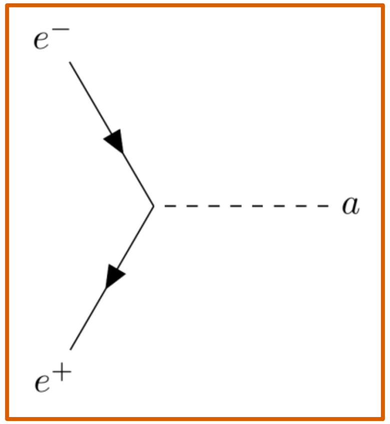


Dominates at $m_a \gg m_e$

Tree level:



Electron Bremsstrahlung



Electron-positron fusion

G. Lucente and P. Carenza, PRD 104 (2021) 103007

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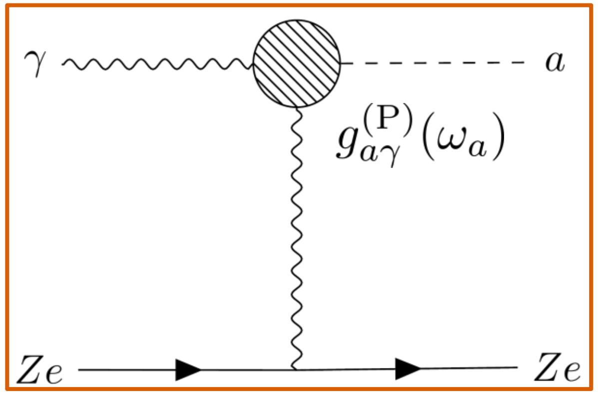
Supernova bounds at one loop

Loop level:

Primakoff process



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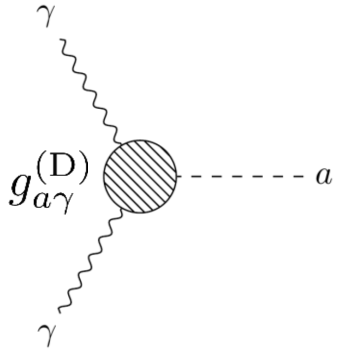

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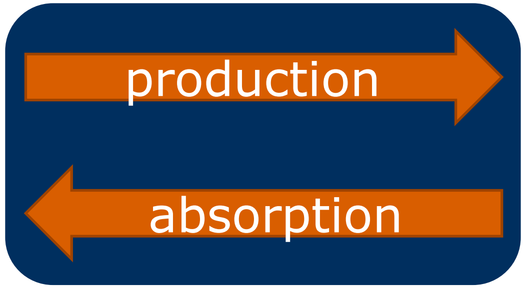
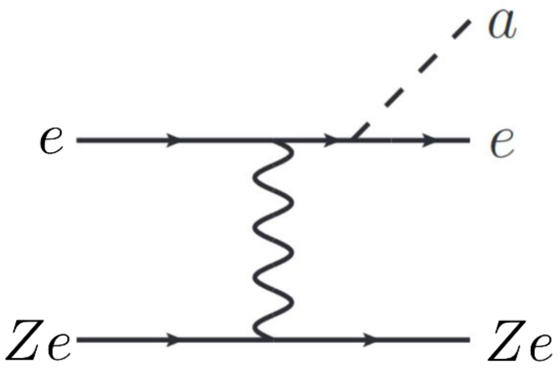


Tree level:



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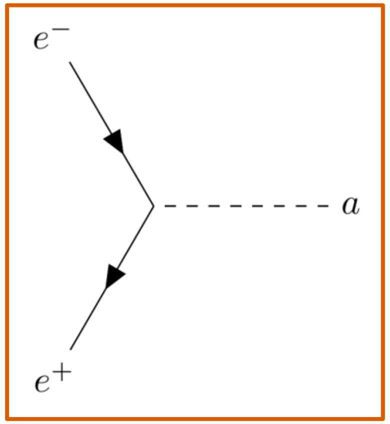


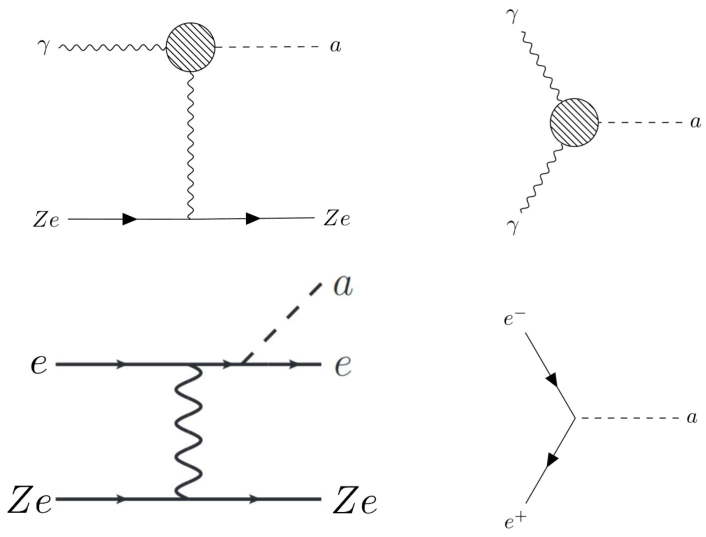
Electron-positron fusion

G. Lucente and P. Carenza, PRD 104 (2021) 103007

Supernova bounds at one loop: Cooling bound

Duration of SN1987A's neutrino burst constraints the ALP luminosity:

$$L_\nu = 3 \cdot 10^{52}\ \mathrm{erg\ s^{-1}} > L_a = 4\pi \int_0^{R_\nu} \mathrm{d}r\, r^2 \int_{m_a}^{\infty} \mathrm{d}\omega_a\, \omega_a \frac{\mathrm{d}^2 n_a^{\mathrm{tot}}}{\mathrm{d}t\, \mathrm{d}\omega_a} e^{-\tau(\omega_a, r)}$$

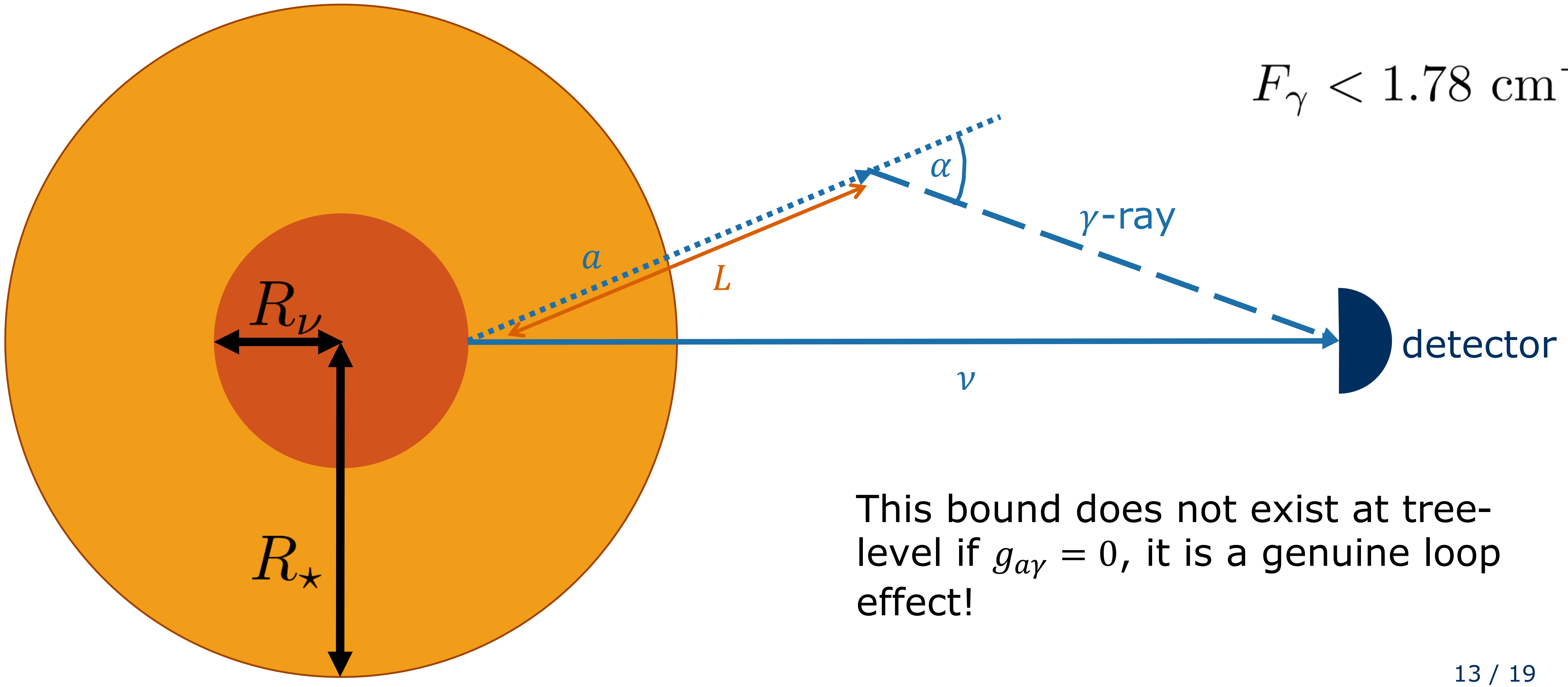


production

absorption

We use the Agile-Boltztran SN model from Fischer et al., PRD 104 (2021) 103012

Supernova bounds at one loop: Decay bound



$$F_\gamma < 1.78\ \mathrm{cm}^{-2}$$

This bound does not exist at tree-level if $g_{a\gamma} = 0$, it is a genuine loop effect!

Supernova bounds at one loop: Decay bound

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Total production spectrum

$$\mathrm{d}F_\gamma = 2 \cdot \mathrm{BR}_{a\to\gamma\gamma} \cdot \frac{\mathrm{d}N/\mathrm{d}\omega}{4\pi\, d_{\mathrm{SN}}^2}\mathrm{d}\omega \cdot f_{c_\alpha}(\omega, c_\alpha)\,\mathrm{d}c_\alpha \cdot \frac{\exp[-L/l_a(\omega)]}{l_a(\omega)}\mathrm{d}L$$
$$\cdot\, \Theta_{\mathrm{cons.}}(\omega, c_\alpha, L)$$

Distribution of decay angles

ALP decay length

Constraints, such as:

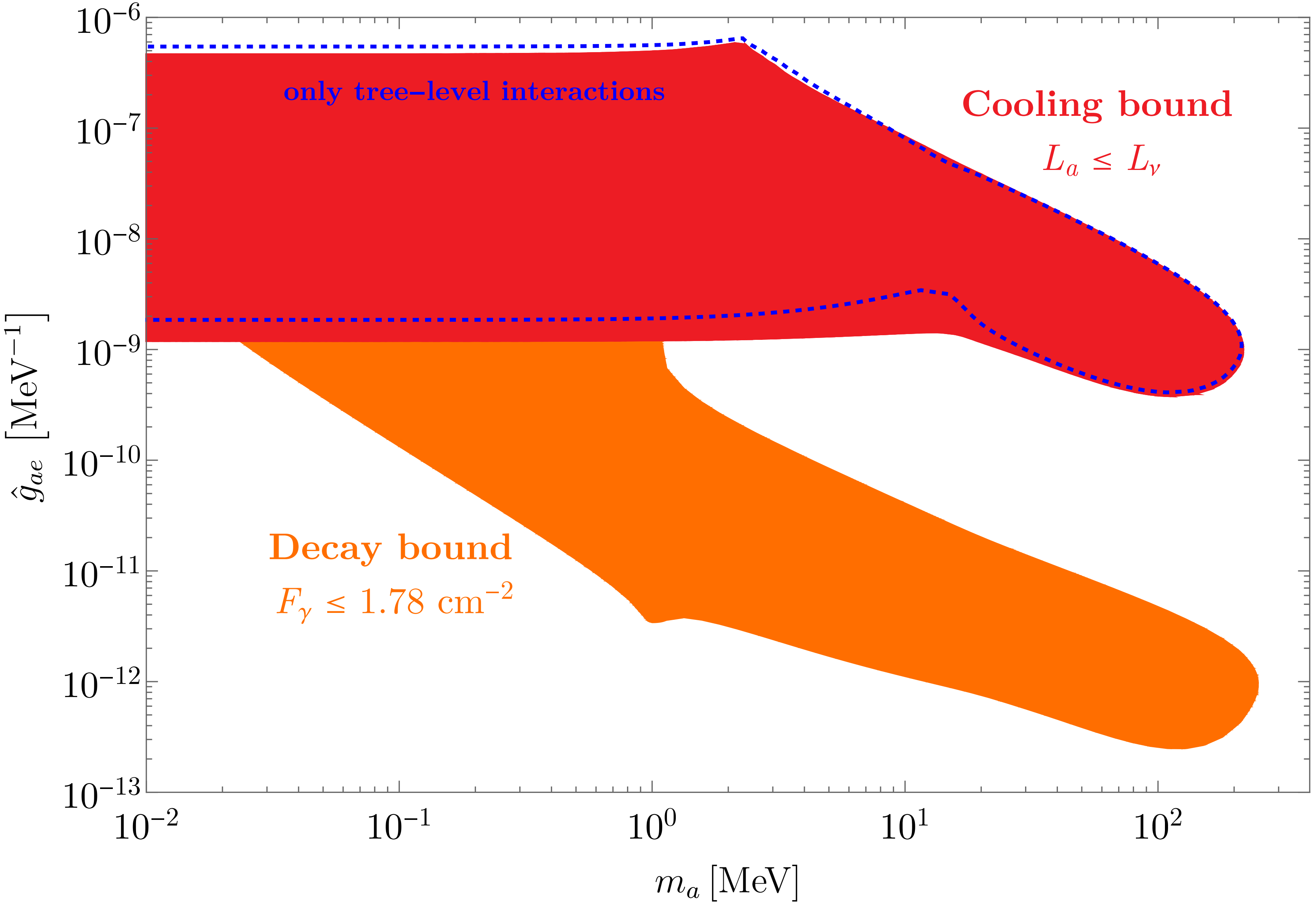
- The ALP should not decay inside the SN progenitor
- One can construct a triangle out of $L, d_{\mathrm{SN}}, \cos\alpha$
- The energy of the γ-ray is in the range of the detector
- The γ-ray does not arrive later than 223s after the neutrino burst

Following Jaffe and Turner, PRD 55 (1997) 7951-7959

See also Jaeckel, Malta, Redondo, Phys.Rev.D 98 (2018) 5, 055032 and Balázs et al., 2205.13549

Integrate numerically over $\omega, \cos\alpha, L$ to get the fluence of γ-rays at the detector

Supernova bounds at one loop



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Ferreira, Marsh, **EM**, 2205.07896 (to appear in JCAP)

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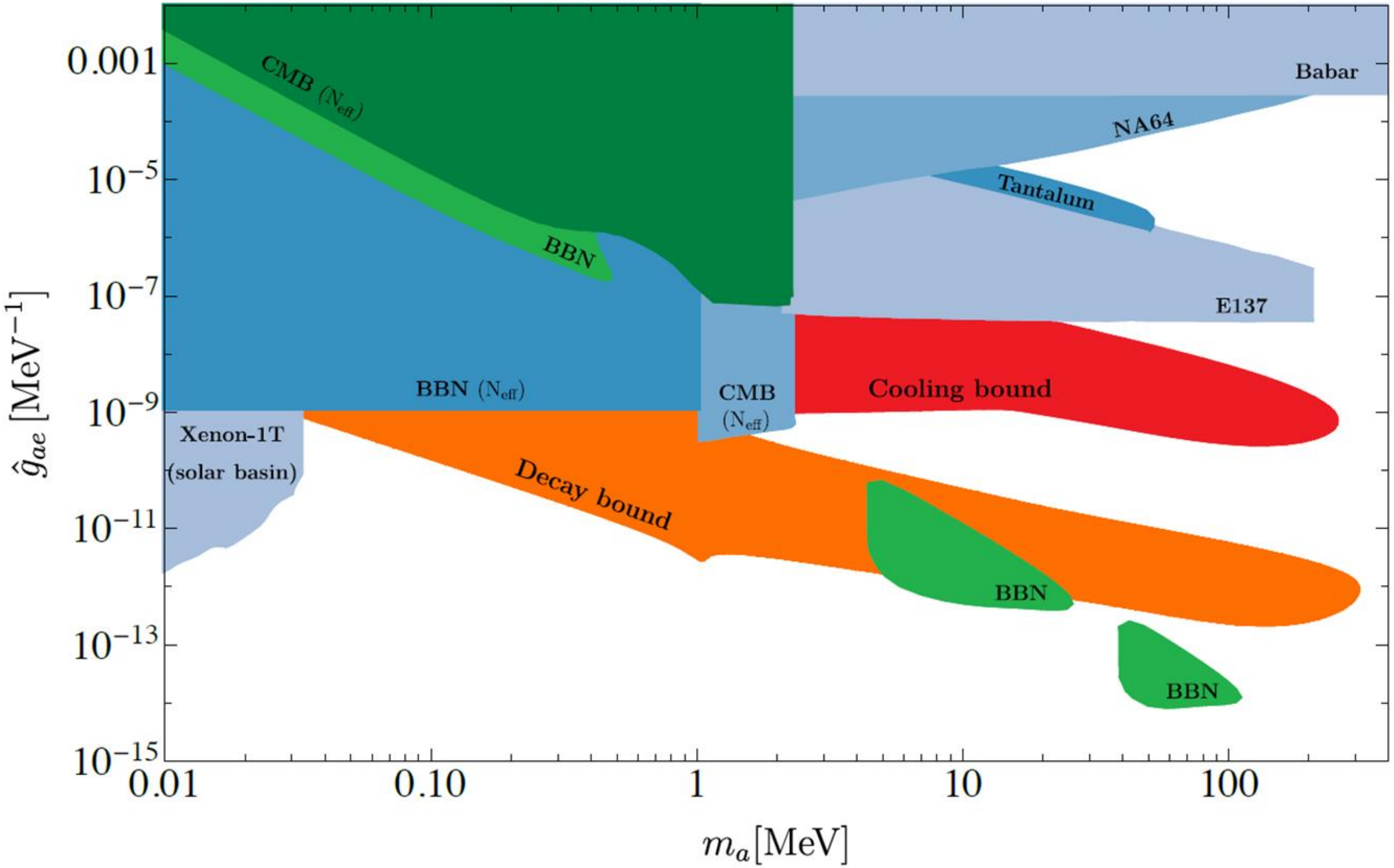

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Summary

- Can define an effective ALP-photon coupling at one-loop
- The coupling depends on the process in which it appears (e.g. decay or Primakoff)
- Loop induced decays place extremely strong bounds on ALP DM, and even exclude it for large masses/couplings
- Using the effective coupling at one loop, we can place the strongest bounds so far on $\hat{g}_{ae}$ from SN1987A

Summary

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Thanks for your attention!

Back Up

Motivation – Why are loops relevant?

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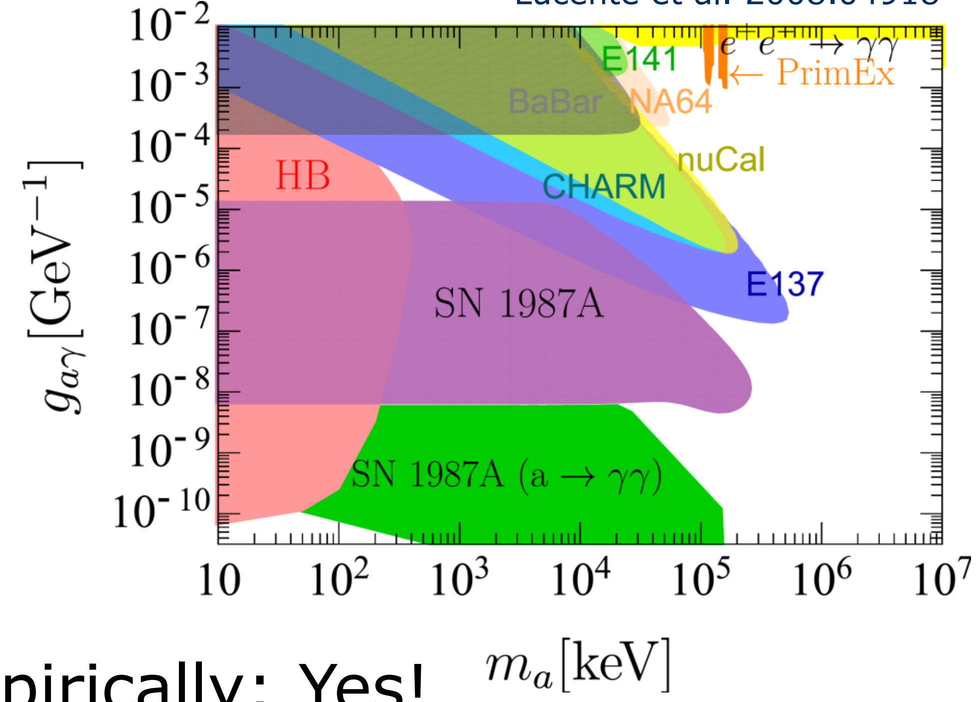
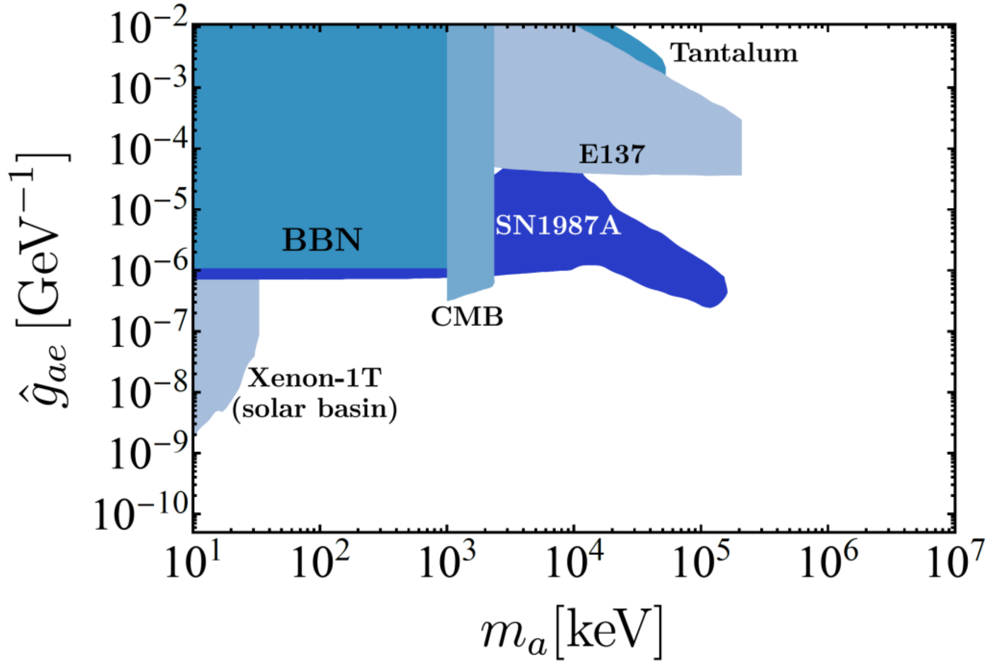
Can the ALP interact much more strongly with electrons than with photons?

Lucente et al. 2008.04918

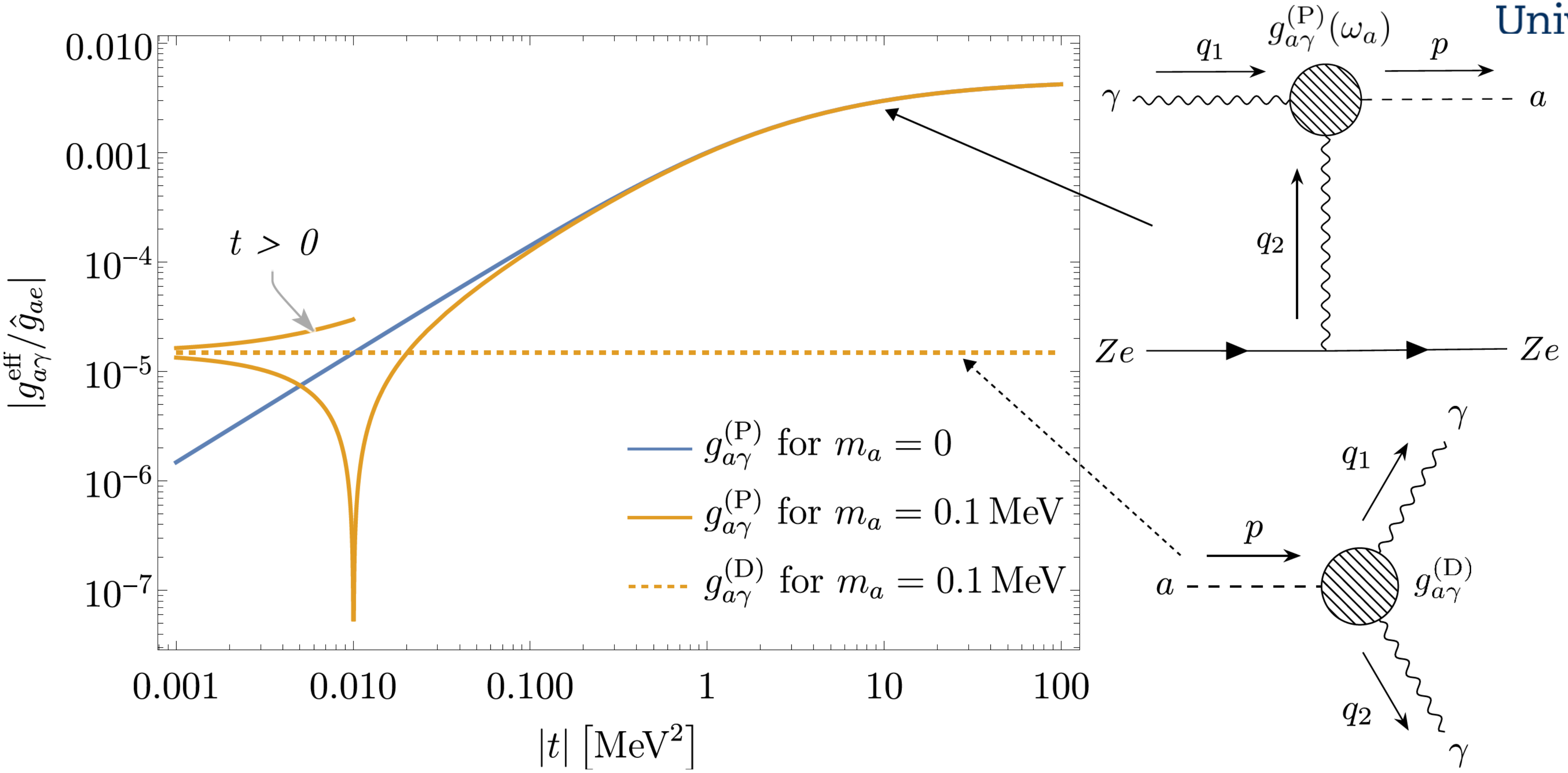




Empirically: Yes!

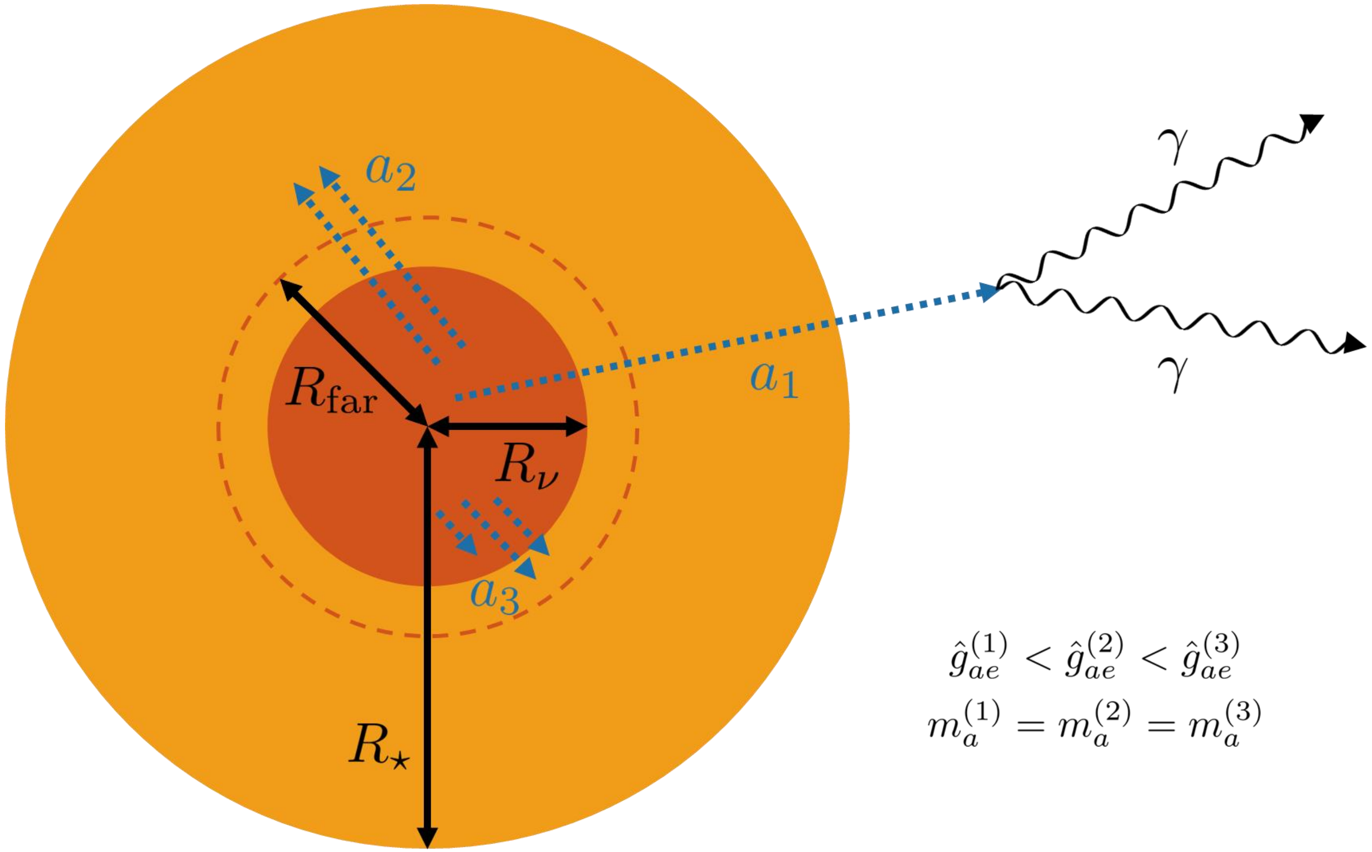
Theoretically: quantum loops yield a contribution $g_{a\gamma}^{\mathrm{eff}} \sim 10^{-2}\hat{g}_{ae}$

The effective ALP-photon coupling



$t = q_2^2 = (p - q_1)^2$

ALPs from SN1987A: two bounds



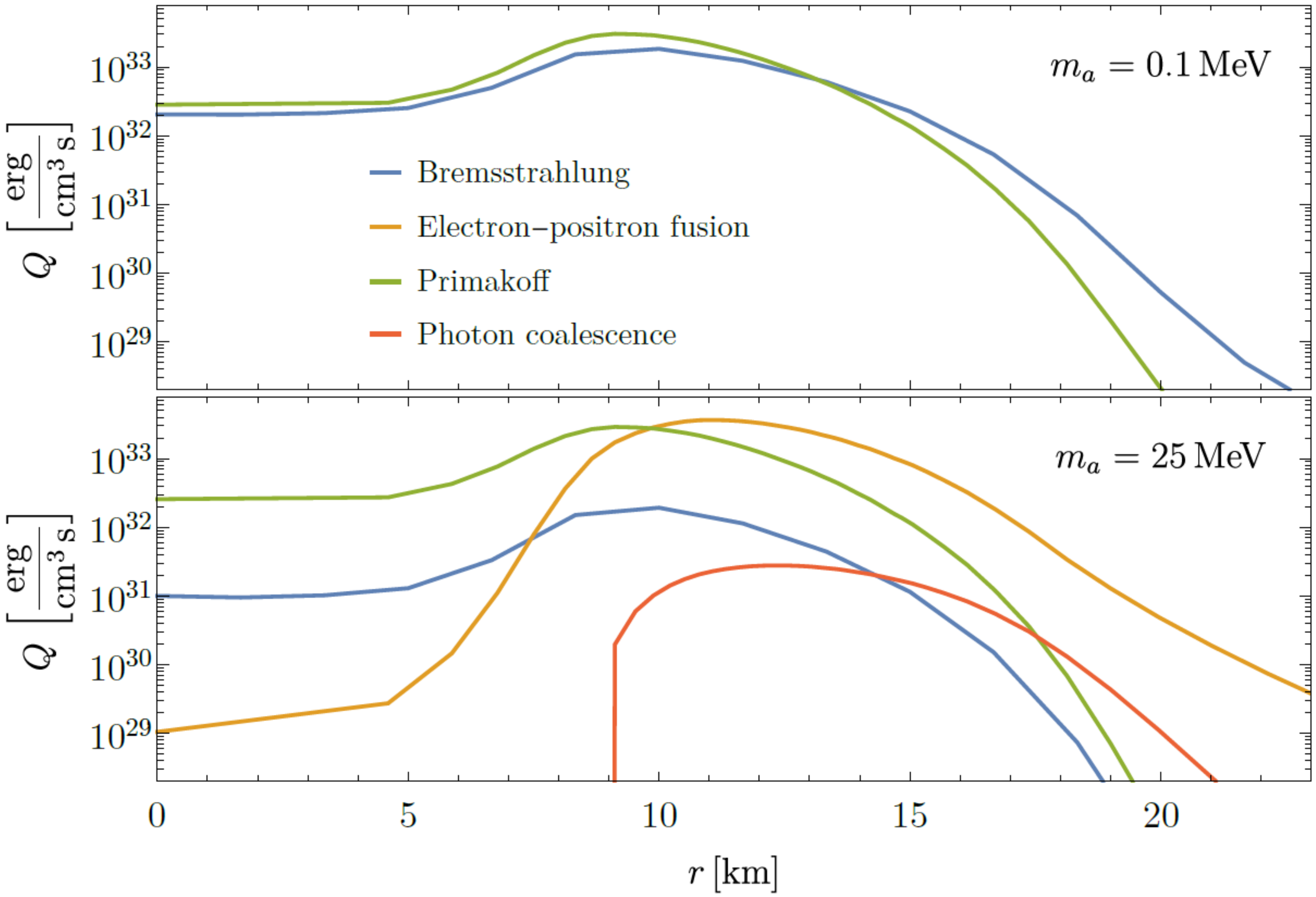
The neutrino burst of SN1987A would be shortened by ALPs, unless

$$L_a \lesssim L_\nu \simeq 3 \times 10^{52} \frac{\rm erg}{\rm s}$$

Gamma rays from decaying ALPs would have been detected near earth after the neutrino burst of SN1987A, unless

$$F_\gamma < 1.78\,{\rm cm}^{-2}$$

ALPs from SN1987A



SN model from:
T. Fischer, P. Carenza, B. Fore, M. Giannotti, A. Mirizzi and S. Reddy, *Observable signatures of enhanced axion emission from protoneutron stars*, Phys. Rev. D 104 (2021) 103012, [2108.13726]

ALPs from SN1987A: Reabsorption

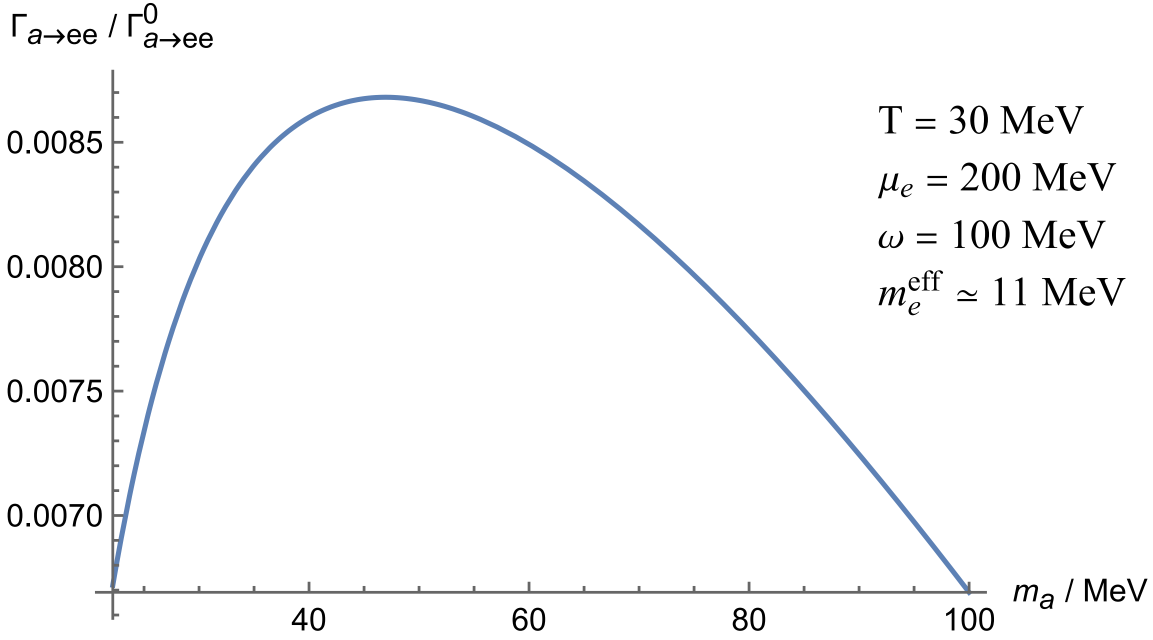
For large couplings, reabsorption of ALPs via inverse processes becomes important

$$L_a = \int^{R_\nu} \mathrm{d}^3 r \int_{m_a}^{\infty} \mathrm{d}\omega\, \omega \frac{\mathrm{d}\dot{n}}{\mathrm{d}\omega}\, e^{-\int_r^{R_{\rm far}} \frac{\mathrm{d}\tilde{r}}{\lambda(\tilde{r},\omega)}}$$

Mean free path of the ALPs

For $m_a \gtrsim 30$ MeV, the mean free path is dominated by decays into electrons.

In the degenerate SN plasma, Pauli blocking suppresses this decay!



Outlook & future work

- One can also derive a bound on the **total energy** deposited into the progenitor‘s plasma by ALPS ➡ easy way to close the gap between cooling & decay bound
- A similar analysis can be done for ALPs predominantly **coupling to muons** (this was already done, but only with the effective *decay* coupling)
- There are open questions regarding electron propagation and the ALP-electron interaction in hot and dense plasmas ➡ **thermal field theory** problem
- Use these results as input for SN simulations, including ALPs

ALP-fermion interactions

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$$\mathcal{L}_{\mathrm{aQED}} = -\frac{1}{2}a(\Box + m_a^2)a - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_e(i\not{D} - m_e)\psi_e$$

$$+ \boxed{\frac{g_{a\gamma}}{4}} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \hat{g}_{ae}(\partial_\mu a)\bar{\psi}_e\gamma^\mu\gamma_5\psi_e$$

$$= -\frac{1}{2}a(\Box + m_a^2)a - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}'_e(i\not{D} - m_e)\psi'_e$$

$$+ \boxed{\frac{1}{4}\left(g_{a\gamma} + \frac{2\alpha}{\pi}\hat{g}_{ae}\right)} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - i\,\boxed{\underbrace{2m_e\hat{g}_{ae}}_{\equiv g_{ae}}}\, a\,\bar{\psi}'_e\gamma_5\psi'_e + \mathcal{O}(\hat{g}_{ae}^2)$$

$$\psi_e = e^{i\hat{g}_{ae}a\gamma_5}\psi'_e$$

ALP-electron interactions in a plasma

- Calculating the bremsstrahlung matrix element with a pseudoscalar ALP-electron interaction yields:

Taking plasma effects into account

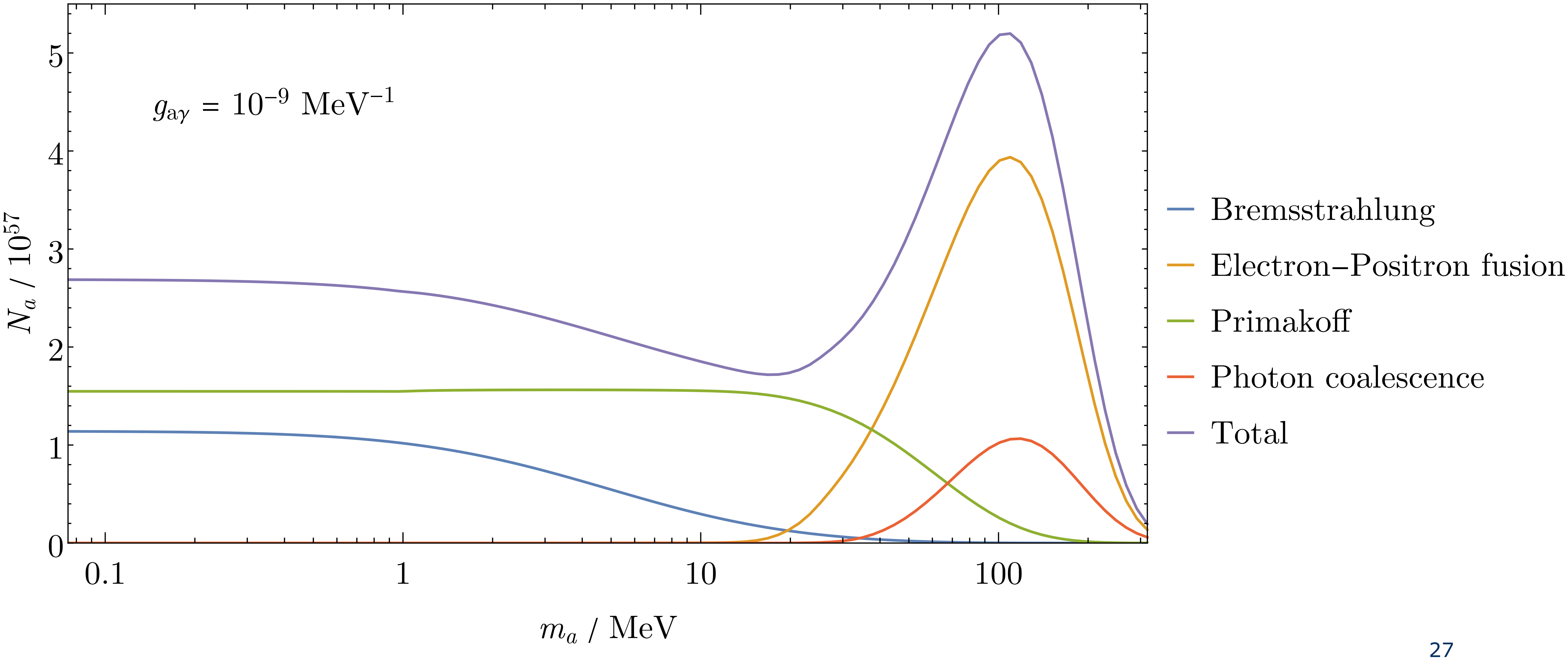
$$\mathcal{M}^{\text{scalar}}_{\text{brems}} = g_{ae} f(m_e^{\text{eff}}, \dots)$$
$$\equiv 2 m_e \hat{g}_{ae} f(m_e^{\text{eff}}, \dots)$$

- On the other hand, since the pseudoscalar and derivative interactions lead (in vacuum) to the same matrix element:

$$\mathcal{M}^{\text{derivative}}_{\text{brems}} = 2 m_e^{\text{eff}} \hat{g}_{ae} f(m_e^{\text{eff}}, \dots)$$

Therefore, apparently $\mathcal{M}^{\text{derivative}}_{\text{brems}} \neq \mathcal{M}^{\text{scalar}}_{\text{brems}}$ in a plasma. Why is that?

Total number of ALPs produced

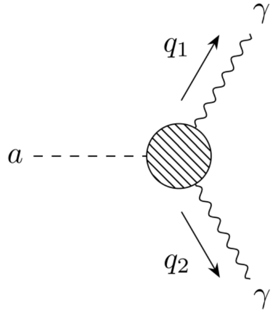


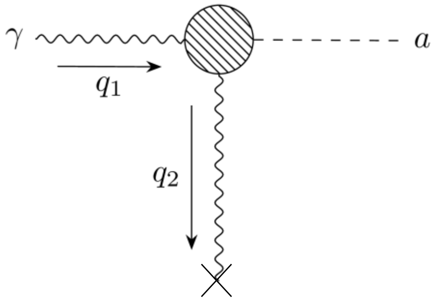
The effective photon couplings

$g_{a\gamma}^{\text{eff}}(q_1, q_2)$ depends on the 4-momenta of the photons

⟶ The effective coupling is different in every physical process!

$m_a \ll m_e$	**ALP to photon decay**	**Primakoff effect, with $\omega \gg m_e$**
q_1^2	0	0
q_2^2	0	$-2\omega^2(1-\cos\theta) = t$
$g_{a\gamma}^{\text{eff}}$	$-\frac{\alpha}{6\pi}\left(\frac{m_a}{m_e}\right)^2 \hat{g}_{ae}$	$\frac{2\alpha}{\pi}\hat{g}_{ae} + \mathcal{O}\left(\frac{m_e^2}{\omega^2}\right)$





Running couplings in aQED

By calculating all one-loop diagrams in aQED, derive the **renormalization group equations**:

$$\mu \frac{\mathrm{d}e}{\mathrm{d}\mu} = -\epsilon\, e + \frac{1}{12\pi^2} e^3$$

$$\mu \frac{\mathrm{d}\hat{g}_{ae}}{\mathrm{d}\mu} = -\epsilon\, \hat{g}_{ae} + \frac{3}{16\pi^2} e^2 g_{a\gamma}$$

$$\mu \frac{\mathrm{d}g_{a\gamma}}{\mathrm{d}\mu} = -\epsilon\, g_{a\gamma} + \frac{1}{6\pi^2} e^2 g_{a\gamma}$$

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$$\mu\frac{\mathrm{d}g_{a\gamma}}{\mathrm{d}\mu} = -\epsilon\, g_{a\gamma} + \frac{1}{6\pi^2}e^2 g_{a\gamma}$$

$\Rightarrow$

$$\alpha(\mu) \equiv \frac{e^2(\mu)}{4\pi} = \alpha_0\left(1 - \frac{\alpha_0}{3\pi}\ln\frac{\mu^2}{\mu_0^2}\right)^{-1}$$

$$\hat{g}_{ae}(\mu) = \hat{g}_{ae}^{\Lambda} - \frac{9}{8}g_{a\gamma}^{\Lambda}\left[1 - \frac{\alpha(\mu)}{\alpha(\Lambda)}\right]$$

$$g_{a\gamma}(\mu) = g_{a\gamma}^{\Lambda}\frac{\alpha(\mu)}{\alpha(\Lambda)}$$

Running couplings in aQED

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By calculating all one-loop diagrams in aQED, derive the **renormalization group equations**:

$$\mu \frac{\mathrm{d}e}{\mathrm{d}\mu} = -\epsilon\, e + \frac{1}{12\pi^2} e^3$$

$$\mu \frac{\mathrm{d}\hat{g}_{ae}}{\mathrm{d}\mu} = -\epsilon\, \hat{g}_{ae} + \frac{3}{16\pi^2} e^2 g_{a\gamma}$$

$$\mu \frac{\mathrm{d}g_{a\gamma}}{\mathrm{d}\mu} = -\epsilon\, g_{a\gamma} + \frac{1}{6\pi^2} e^2 g_{a\gamma}$$

$$\alpha(\mu) \equiv \frac{e^2(\mu)}{4\pi} = \alpha_0 \left(1 - \frac{\alpha_0}{3\pi} \ln \frac{\mu^2}{\mu_0^2}\right)^{-1}$$

$$\hat{g}_{ae}(\mu) = \hat{g}_{ae}^{\Lambda} - \frac{9}{8} g_{a\gamma}^{\Lambda} \left[1 - \frac{\alpha(\mu)}{\alpha(\Lambda)}\right]$$

$$g_{a\gamma}(\mu) = g_{a\gamma}^{\Lambda} \frac{\alpha(\mu)}{\alpha(\Lambda)}$$

Running couplings in aQED

From now on:
consider the EFT with $g_{a\gamma}^{\Lambda} \ll \hat{g}_{ae}^{\Lambda}$
i.e. $g_{a\gamma}(\mu) \ll \hat{g}_{ae}(\mu)$

$$\mu \frac{\mathrm{d}e}{\mathrm{d}\mu} = -\epsilon\, e + \frac{1}{12\pi^2} e^3$$

$$\mu \frac{\mathrm{d}\hat{g}_{ae}}{\mathrm{d}\mu} = -\epsilon\, \hat{g}_{ae} + \frac{3}{16\pi^2} e^2 g_{a\gamma}$$

$$\mu \frac{\mathrm{d}g_{a\gamma}}{\mathrm{d}\mu} = -\epsilon\, g_{a\gamma} + \frac{1}{6\pi^2} e^2 g_{a\gamma}$$

$\Rightarrow$

$$\alpha(\mu) \equiv \frac{e^2(\mu)}{4\pi} = \alpha_0 \left(1 - \frac{\alpha_0}{3\pi} \ln \frac{\mu^2}{\mu_0^2}\right)^{-1}$$

$$\hat{g}_{ae}(\mu) = \hat{g}_{ae}^{\Lambda} - \frac{9}{8} \cancel{g_{a\gamma}^{\Lambda}} \left[1 - \frac{\alpha(\mu)}{\alpha(\Lambda)}\right]$$

$$\cancel{g_{a\gamma}(\mu)} = \cancel{g_{a\gamma}^{\Lambda}} \frac{\alpha(\mu)}{\alpha(\Lambda)}$$