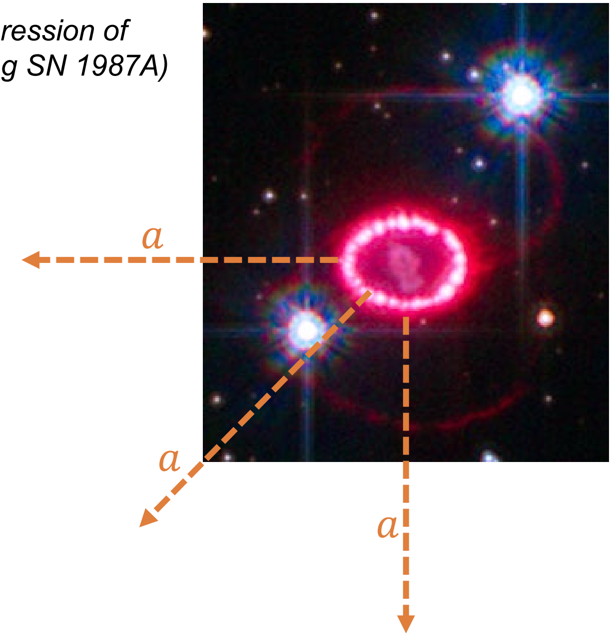
(“artist’s” impression of
axions leaving SN 1987A)



Searches for axionlike particles from supernovae beyond tree-level

Eike Ravensburg (prev. Müller),
Postdoc @ University of Southern Denmark (SDU) Odense

SDU

Suprise 2025, Madrid

Axionlike particles

→ **ALPs** are **naturally light**, **weakly interacting** pseudoscalar particles that appear in many BSM theories

→ Both axions and ALPs are pseudo-Goldstone bosons of chiral $U(1)$ theories (hence “axion-like”)

→ At low energies $E \ll \Lambda$, all these models are described by the same *effective field theory* (EFT):

$$\mathcal{L} \supset -\frac{1}{2} a(\Box + m_a^2) a + \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \sum_{\ell} \hat{g}_{a\ell} (\partial^{\mu} a) \bar{\ell} \gamma_5 \gamma_\mu \ell + \sum_{N} g_{aN} \frac{\partial_\mu a}{2 m_N} \bar{N} \gamma^{\mu} \gamma_5 N$$

Mass (free parameter,
not related to couplings)

Photon coupling

Lepton couplings

Non-relativistic
nucleon couplings

→ Are all these couplings independent? **No**, Quantum effects mix them!

For collider phenomenology, see, e.g., Bauer et al.: 1708.00443, 2012.12272

→ If you are interested in the phenomenology of one of these couplings, others might be unavoidable

Axionlike particles: (Photophilic) ALPs

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Supernovae – a great lab for new physics

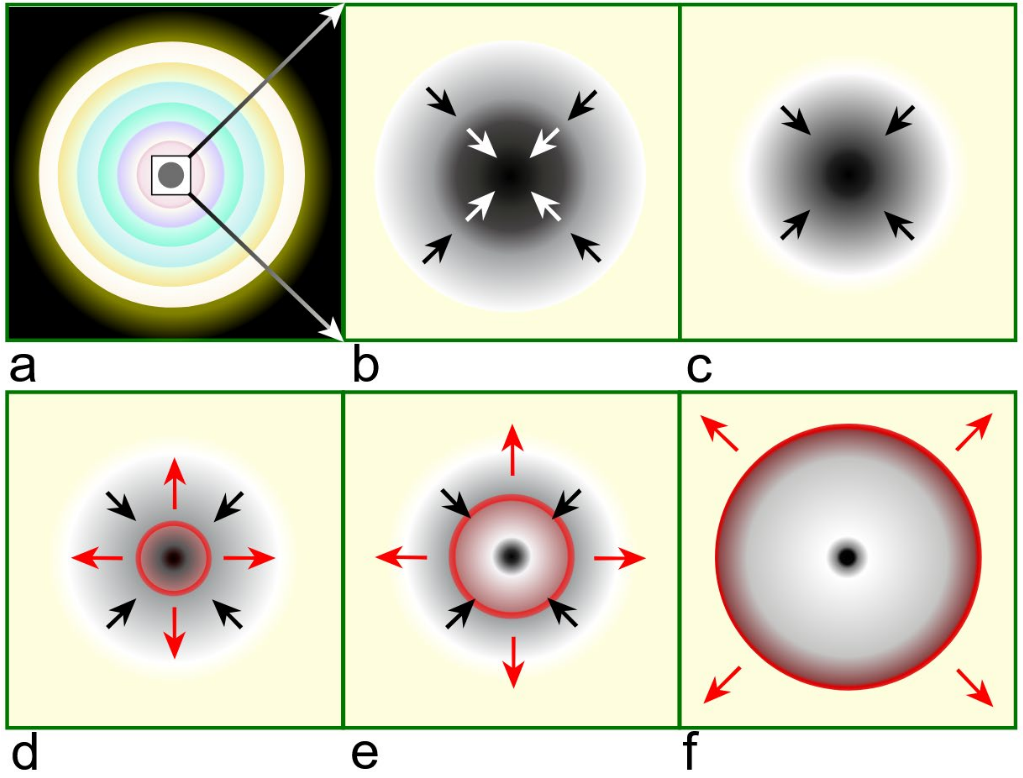
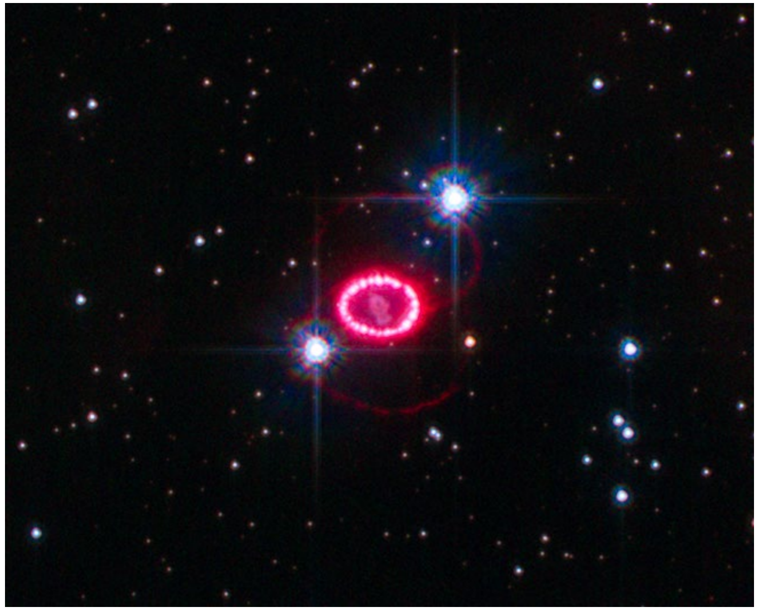


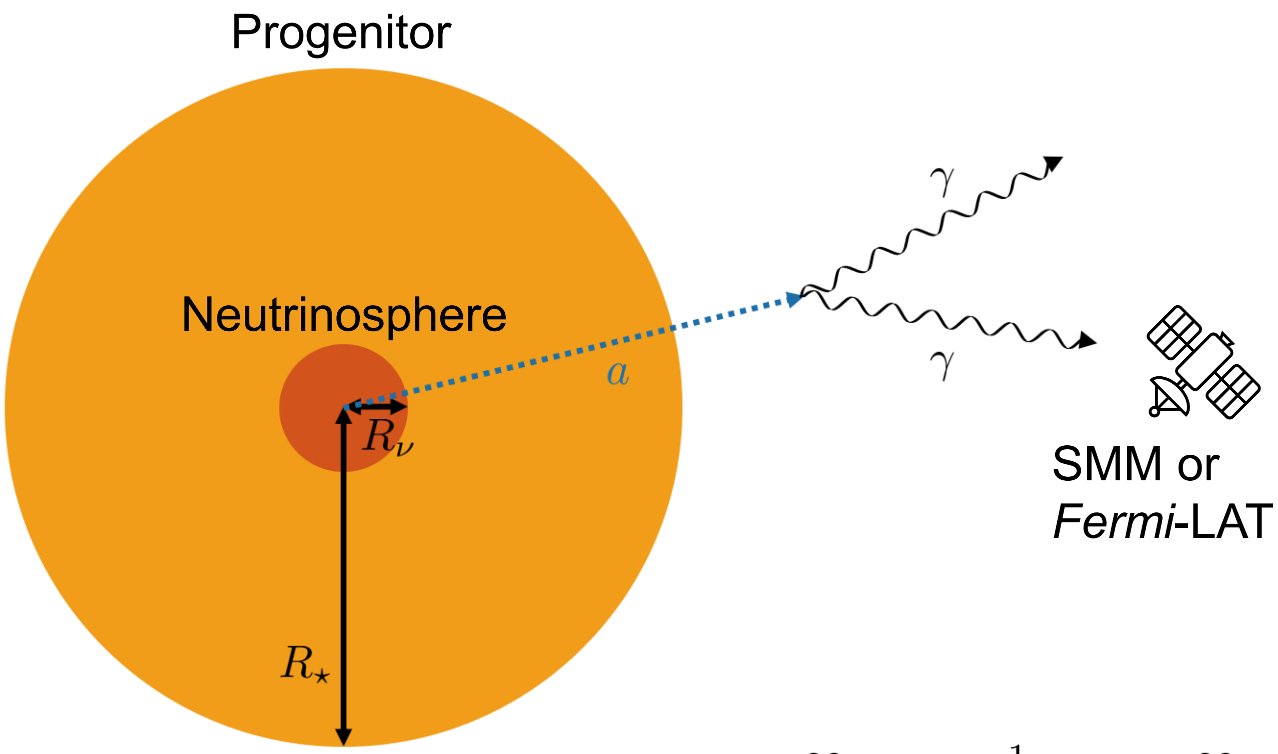
Illustration by R.J. Hall taken from Wikipedia, based on Janka et al., Physics Reports. 442 (1–6): 38–74



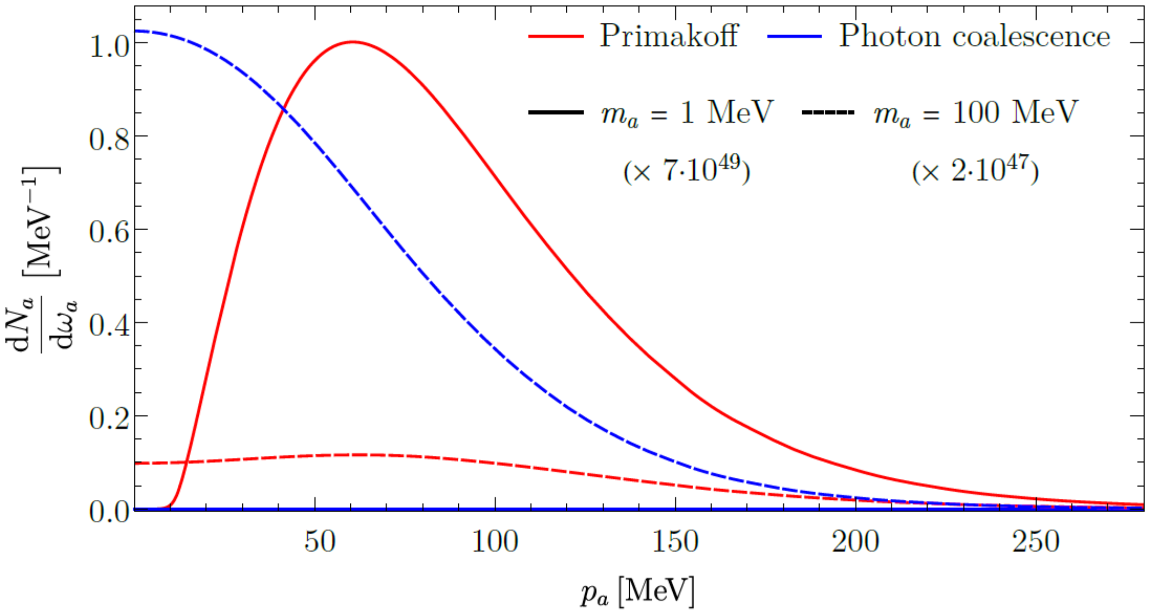
SN 1987A remnant as seen by the Hubble telescope

See also Jaeckel et al., Phys.Rev.D 98 (2018) 5, 055032; Hoof & Schulz, JCAP 03 (2023) 054; ***EM*** *et al., JCAP 07 (2023) 056*

SN-ALP decay: γ-ray signals



Spectrum of massive ALPs from a SN1987A-like event

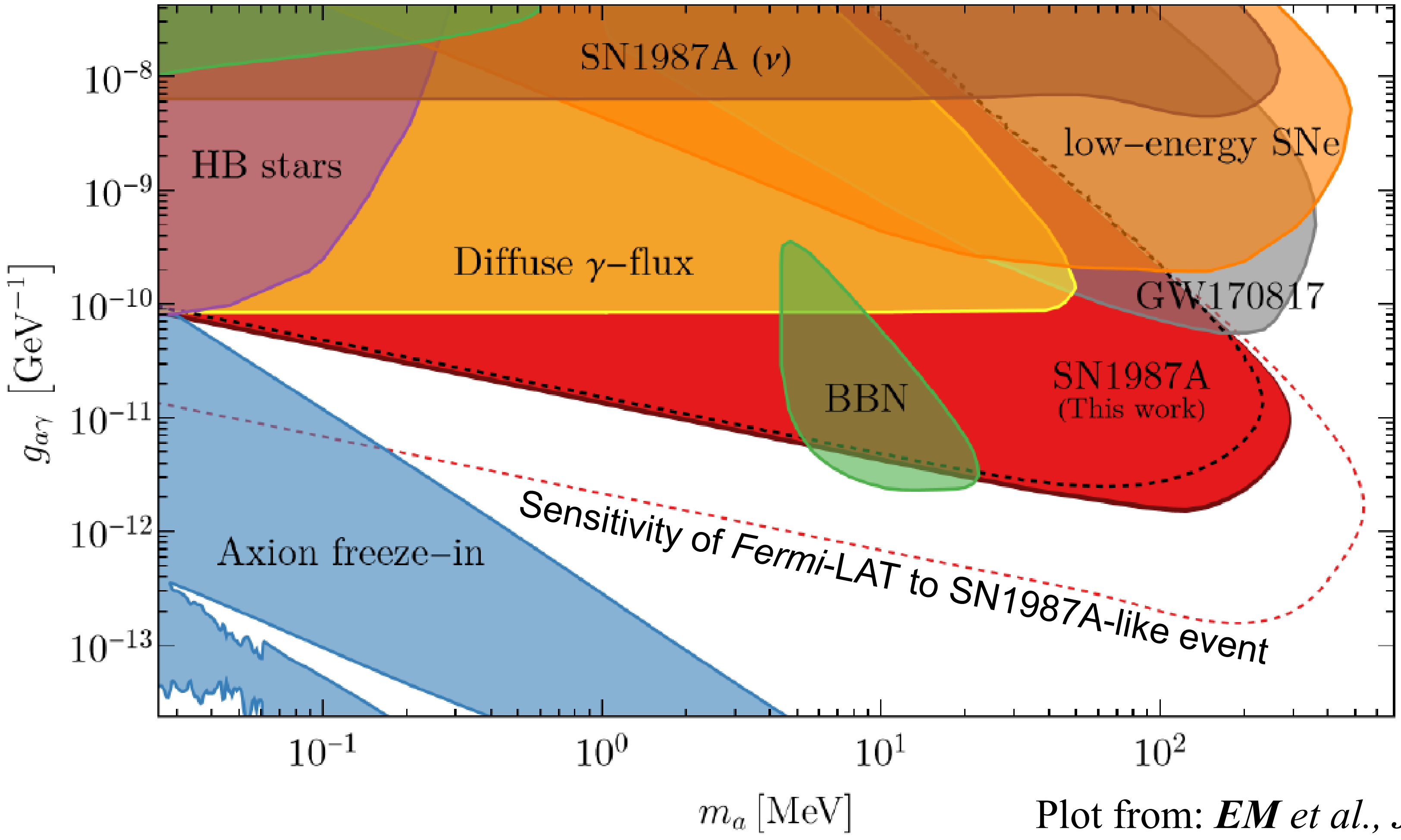


$$F_\gamma = \mathrm{BR}_{a\to\gamma\gamma} \int_{m_a}^{\infty} \mathrm{d}\omega_a \int_{-1}^{1} \mathrm{d}c_\alpha \int_0^\infty \mathrm{d}L\, 2 \cdot \frac{\mathrm{d}N_a/\mathrm{d}\omega_a}{4\pi\, R_{\mathrm{SN}}^2} \cdot \frac{\omega_a^2 - p_a^2}{2\,(\omega_a - c_\alpha p_a)^2} \cdot \frac{\exp[-L/\ell_a(\omega_a)]}{\ell_a(\omega_a)}$$

$$\cdot\, \Theta_{\mathrm{cons.}}(\omega_a, c_\alpha, L)$$

SN-ALP decay: γ-ray signals

No γ-rays above background were observed by the Solar Maximum Mission after SN 1987A:

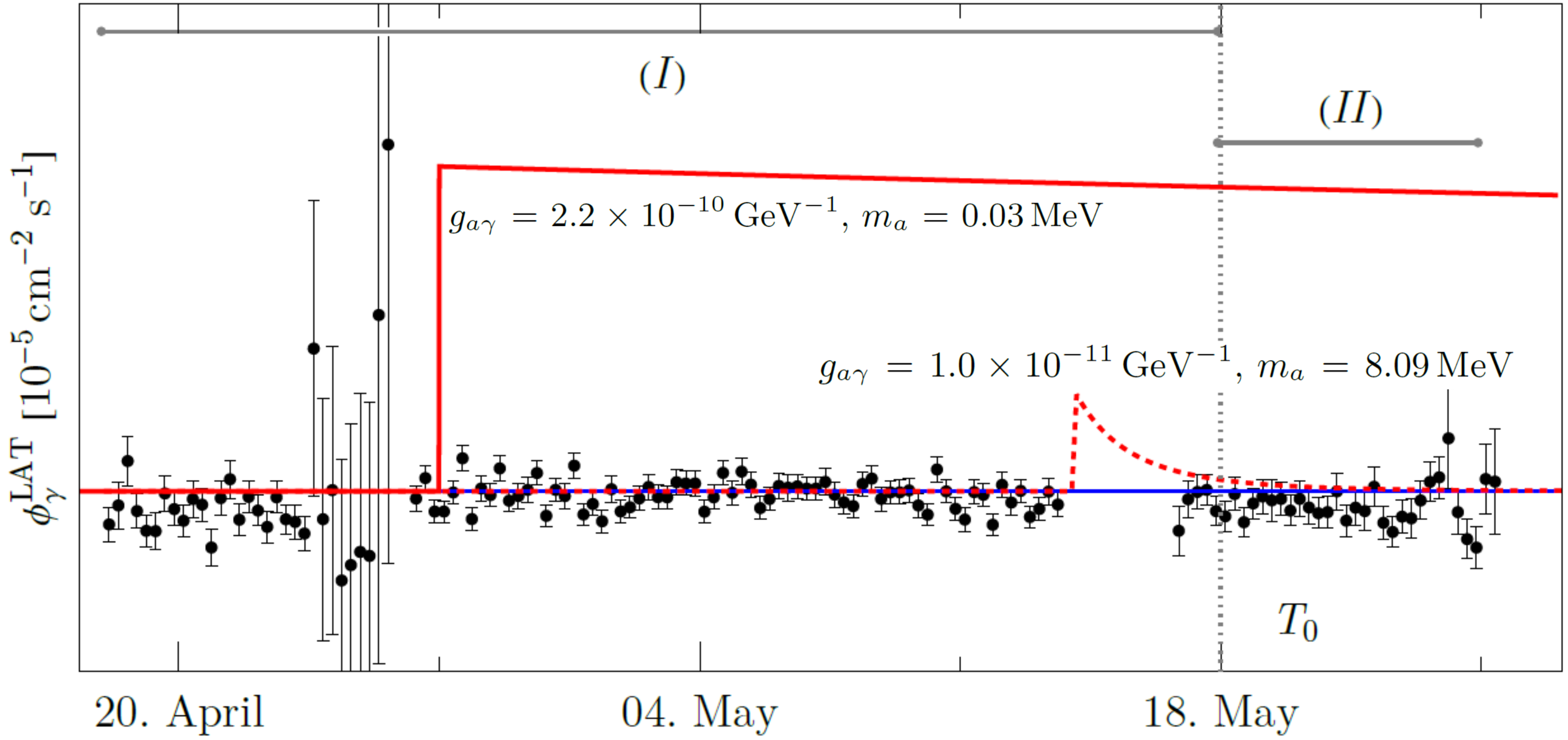


Plot from: ***EM** et al., JCAP 07 (2023) 056*

SDU

SN-ALP decay: γ-ray signals from beyond the Galaxy

On May 18th 2023, SN 2023ixf was observed at an estimated distance of ~7 Mpc (more than 100x further away than SN 1987A). This is what *Fermi*-LAT could have seen:

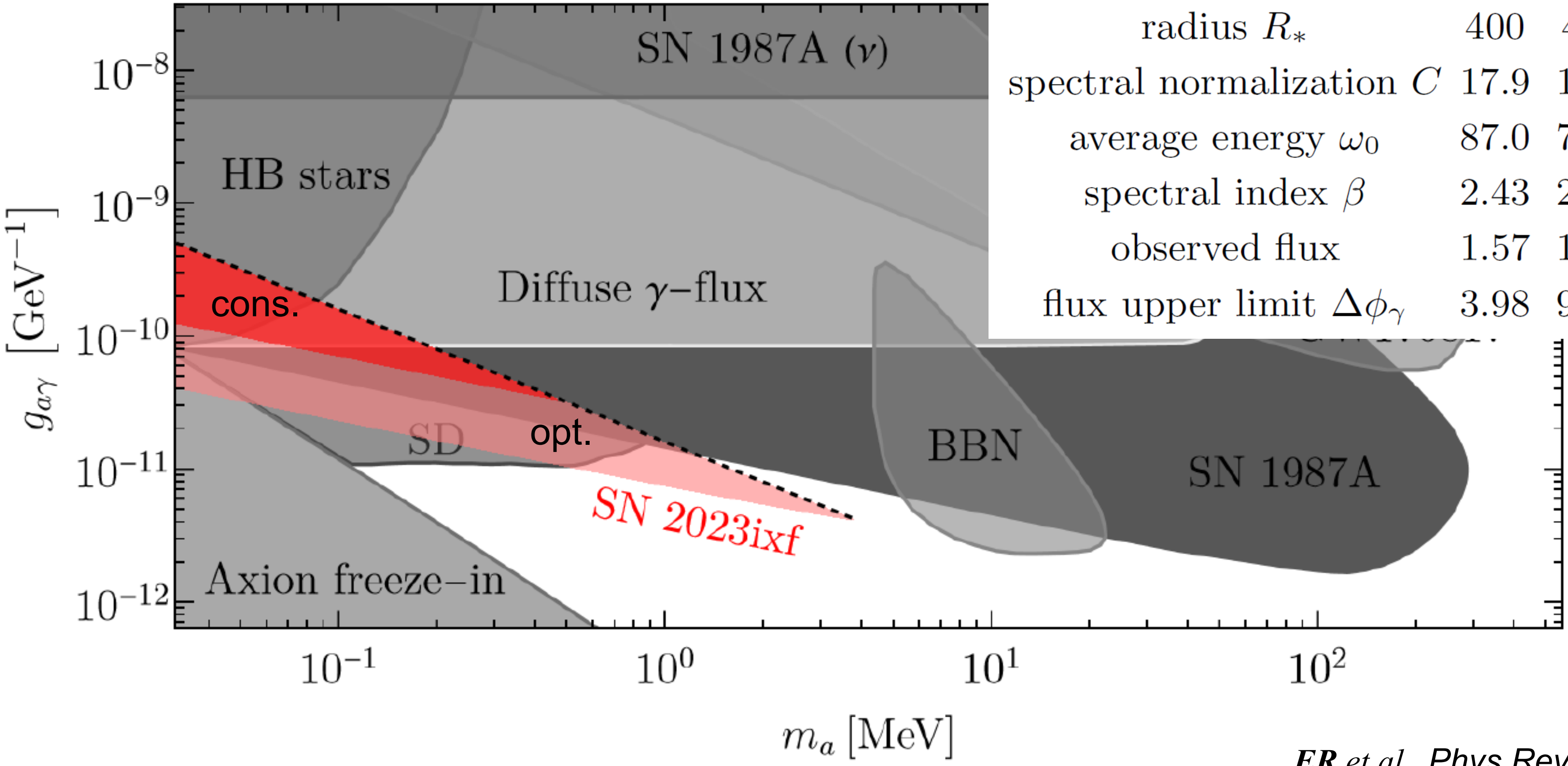


***ER** et al.*, *Phys.Rev.D 109 (2024) 2, 2*

SN-ALP decay: γ-ray signals from beyond the Galaxy

…but nothing was observed:

Parameter	opt.	cons.	Unit
distance R_{SN}	6.70	7.00	Mpc
mass M	13	9	$M_\odot$
radius R_*	400	420	$R_\odot$
spectral normalization C	17.9	1.36	$10^{48}\,\mathrm{MeV}^{-1}$
average energy ω_0	87.0	71.2	MeV
spectral index β	2.43	2.86	1
observed flux	1.57	1.47	$10^{-5}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
flux upper limit $\Delta\phi_\gamma$	3.98	9.10	$10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



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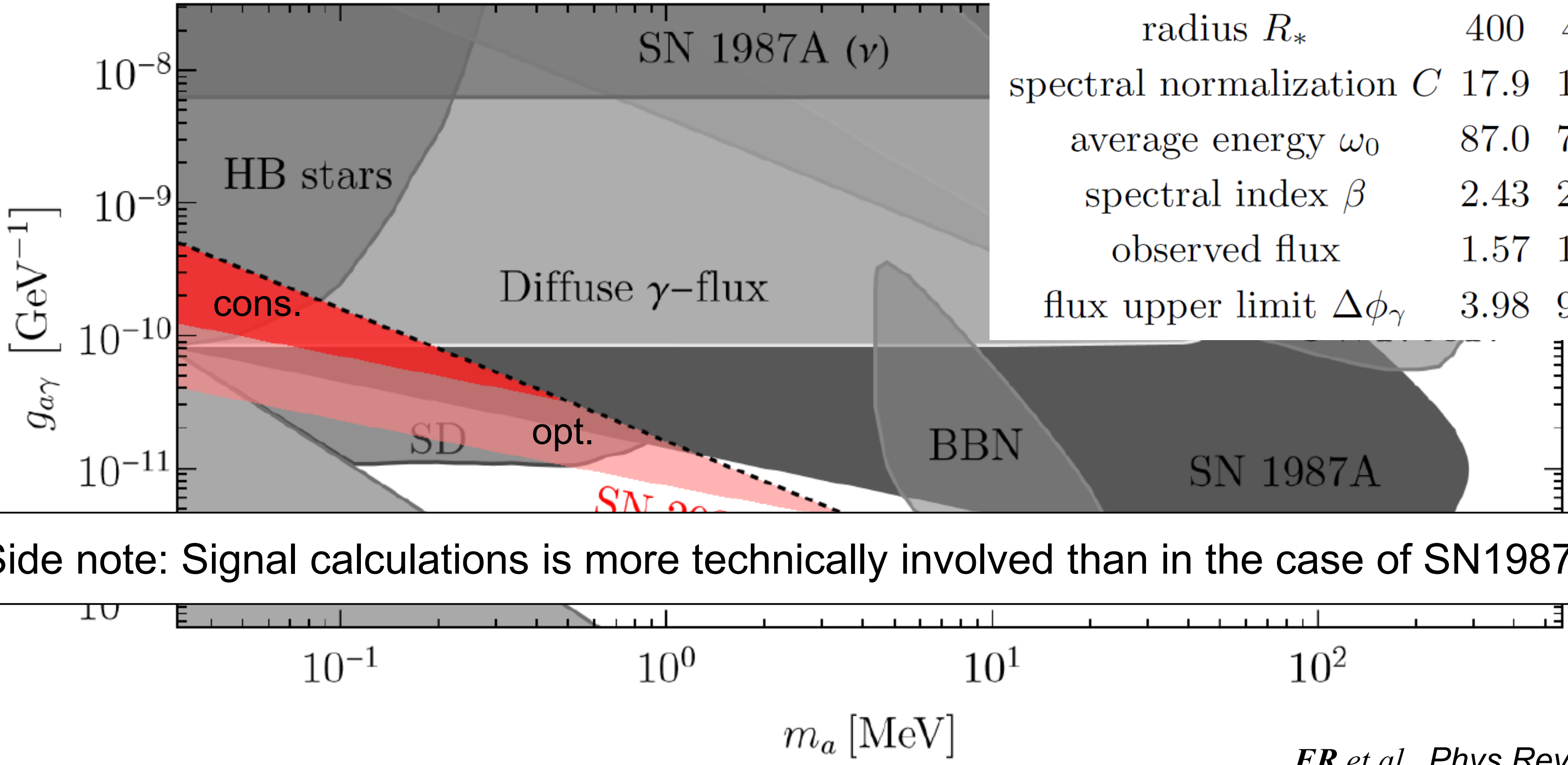

Side note: Signal calculations is more technically involved than in the case of SN1987A!

ER *et al., Phys.Rev.D 109 (2024) 2, 2*

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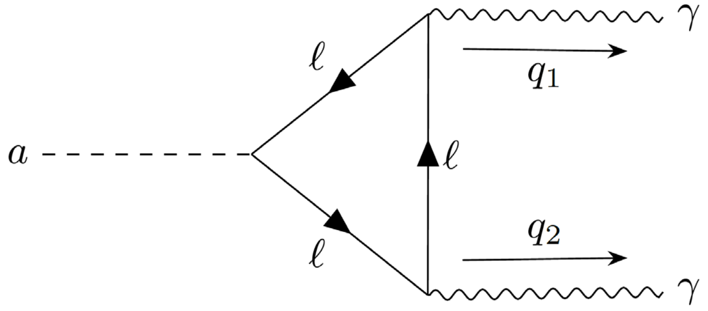
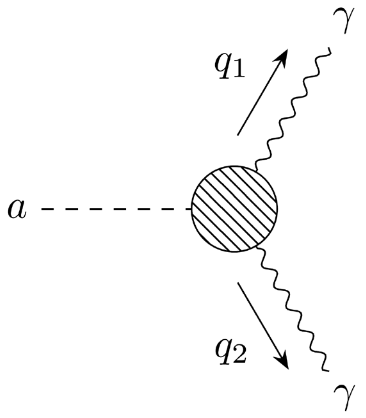
$$\mathcal{L}_{1-\text{loop}} \supset -\frac{1}{2} a(\Box + m_a^2) a + \sum_\ell \hat{g}_{a\ell} (\partial^\mu a) \bar{\ell} \gamma_5 \gamma_\mu \ell$$

Effective photon coupling

Couplings between ALPs and gauge bosons are not induced by RGE running!
Still, the full lepton loop can nevertheless yield an effective photon vertex:



$$= \underbrace{i \frac{e^2 \hat{g}_{a\ell}}{2\pi^2} \left[1 + 2 m_\ell^2 C_0 \left(q_1^2, q_2^2, (q_1+q_2)^2, m_\ell^2, m_\ell^2, m_\ell^2\right)\right]}_{= i\, g_{a\gamma}^{\text{eff}}(q_1, q_2)} q_1^\alpha q_2^\beta \varepsilon^{\mu\nu\alpha\beta}$$



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

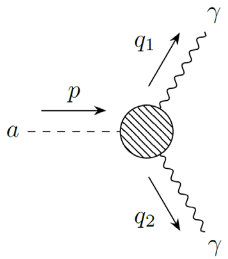
R. Ferreira, D. Marsh, ***EM****, JCAP 11 (2022) 057*

The effective ALP-photon coupling

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

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

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



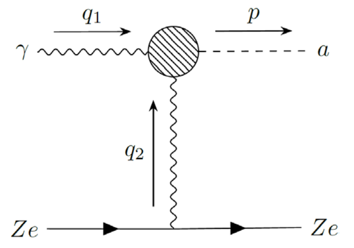
$$g_{a\gamma}^{(\mathrm{D})} \equiv g_{a\gamma}^{\mathrm{eff}}(q_1^2 = q_2^2 = 0, p^2 = m_a^2) = \frac{2\alpha}{\pi}\hat{g}_{ae}\left[1 - \frac{4m_e^2}{m_a^2} f^2\left(\frac{4m_e^2}{m_a^2}\right)\right]$$

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

This effective coupling vanishes for massless ALPs, but it is only the right coupling for on-shell photons!
If a photon in the t-channel is off-shell, we get the effective Primakoff coupling:

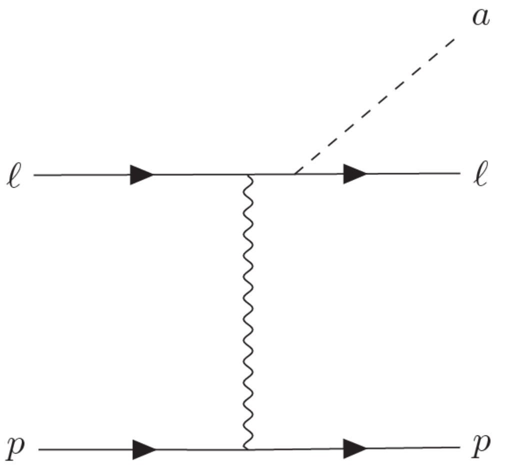
$$g_{a\gamma}^{(\mathrm{P})} \equiv g_{a\gamma}^{\mathrm{eff}}(q_1^2 = 0, q_2^2 = t, p^2 = m_a^2) = \frac{2\alpha}{\pi}\hat{g}_{ae}\left\{1 + \frac{4m_e^2}{m_a^2 - t}\left[f^2\left(\frac{4m_e^2}{t}\right) - f^2\left(\frac{4m_e^2}{m_a^2}\right)\right]\right\}$$

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

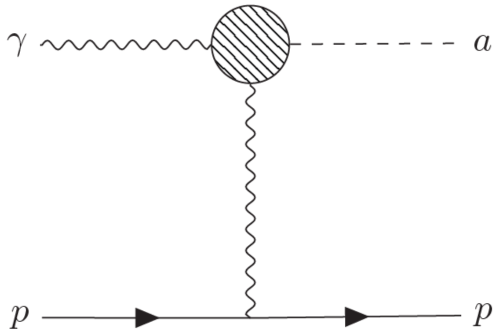


*R. Ferreira, D. Marsh, **EM**, JCAP 11 (2022) 057*
& soon to be published work

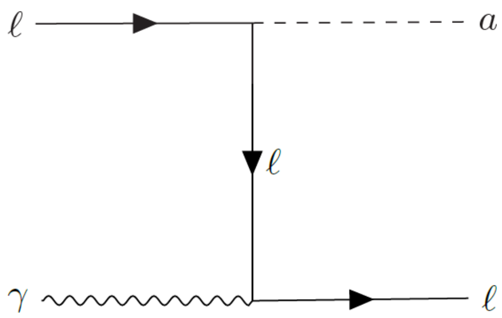
Leptonic ALPs produced in SNe



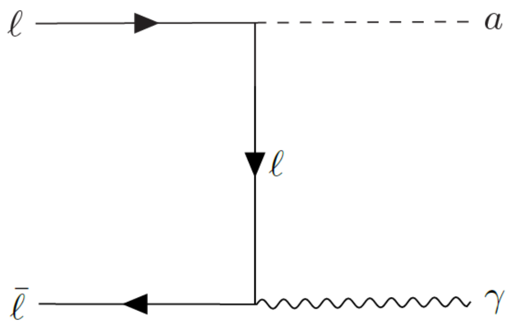
(a) Bremsstrahlung



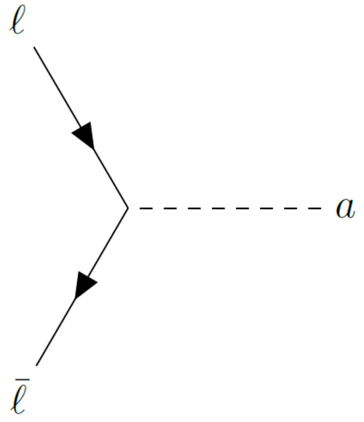
(b) Primakoff process



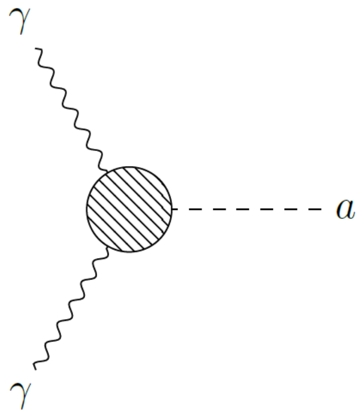
(c) Compton



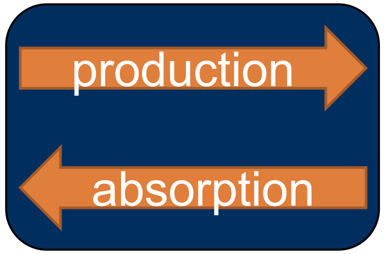
(d) Pair annihilation



(e) Lepton fusion



(f) $\gamma\gamma$-coalescence


production
absorption

ALPs from a SN plasma

The spectral rate of change in the number density of ALPs (“production spectrum”) can be calculated as the integrated collision term of the Boltzmann equation:

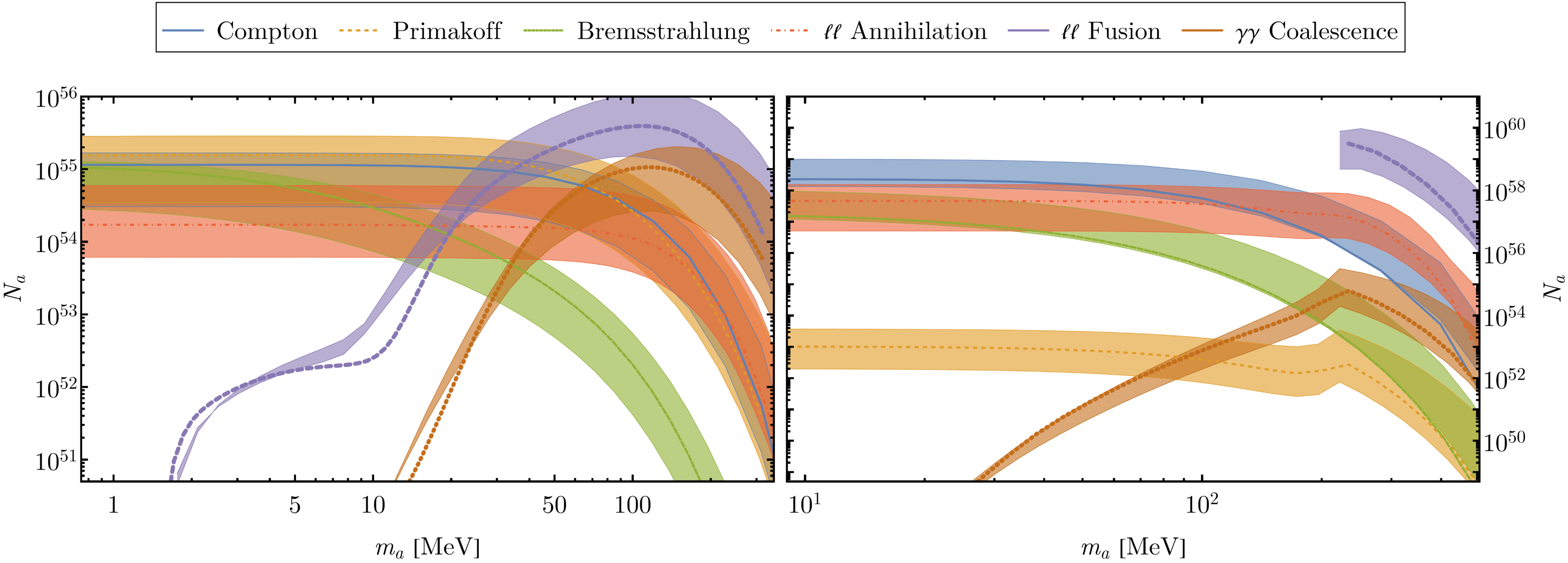
$$\frac{\mathrm{d}^2 n_a}{\mathrm{d}t\,\mathrm{d}\omega_a} = \left[\prod_i \int \frac{\mathrm{d}^3\mathbf{p}_i}{(2\pi)^3 2E_i} f_i(E_i)\right]\left[\prod_{j\neq a} \int \frac{\mathrm{d}^3\mathbf{p}'_j}{(2\pi)^3 2E'_j}\,[1 \pm f_j(E'_j)]\right]$$

$$\times\,(2\pi)^4\delta^{(4)}\left(\sum_i p_i - \sum_j p'_j\right) S\,\frac{|\mathbf{p}'_a|}{4\pi^2}|\mathcal{M}|^2\,,$$

for every relevant production process $\{i\} \rightarrow \{j\} + a$.

Leptonic ALPs produced in SNe

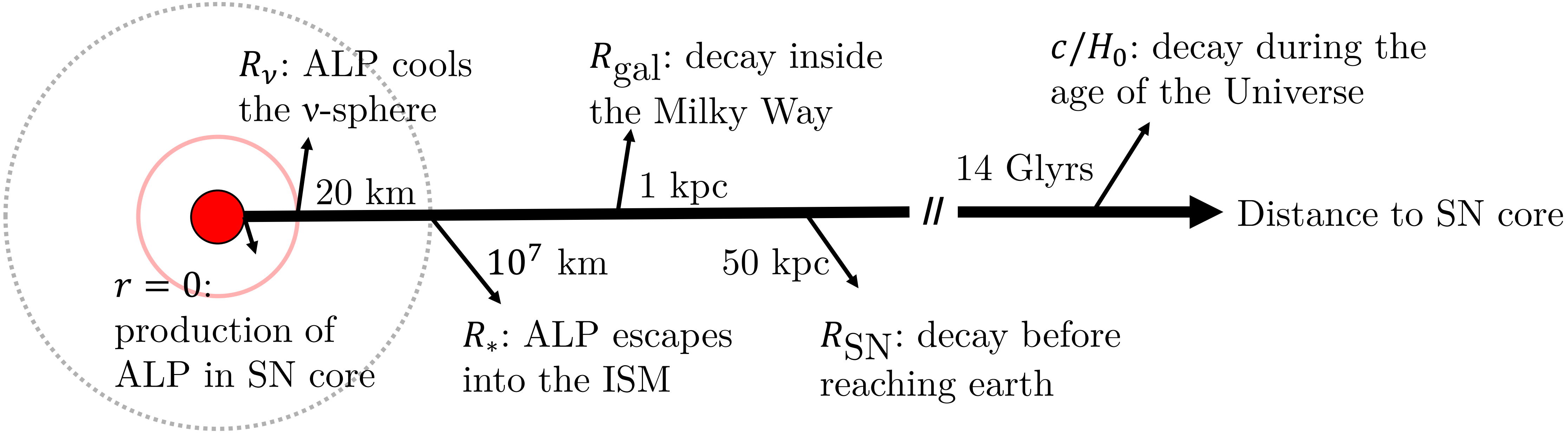
Shading corresponds to three different SN simulations: Agile-Boltztran (solid line, Fischer et al., PRD 104 (2021) 103012) and Garching SN Archive (upper/lower shading for hottest/coldest model of R. Bollig et al., Phys. Rev. Lett. 125 (2020) 051104)



$\hat{g}_{ae} = 10^{-10}\mathrm{MeV}^{-1}$

$\hat{g}_{a\mu} = 10^{-10}\mathrm{MeV}^{-1}$

ALPs from SNe: Observables (incomplete list)



R_ν: ALP cools the ν-sphere

20 km

$R_{\rm gal}$: decay inside the Milky Way

1 kpc

c/H_0: decay during the age of the Universe

14 Glyrs

Distance to SN core

$r = 0$: production of ALP in SN core

10^7 km

R_*: ALP escapes into the ISM

50 kpc

$R_{\rm SN}$: decay before reaching earth

Anomalous cooling	Explosion energy of the mantle	Galactic positrons	Gamma-ray burst from nearby SNe	Diffuse gamma rays from all past SNe
$L_a < L_\nu$	$E^a_{\rm mantle} < E^{\rm obs}_{\rm mantle}$	$\mathrm{BR}_{a\to e^+e^-} N_a < \langle \delta N^{\rm bkg.}_{\rm pos} \rangle$	$F_\gamma < \langle \delta F^{\rm bkg.}_\gamma \rangle$	$n^a_\gamma < n^{\rm obs}_\gamma$

ALPs from SNe: Observables

Cooling bound, from the duration of the neutrino burst of SN 1987A

See also Lucente & Carenza, Phys.Rev.D 104 (2021) 10, 103007

$$L_a = \int_0^{R_\nu} \mathrm{d}r\, 4\pi r^2 \lambda^2(r) \int_{m_a/\lambda}^{\infty} \mathrm{d}\omega_a\, \omega_a \frac{\mathrm{d}^2 n_a}{\mathrm{d}t\, \mathrm{d}\omega_a}(r, \omega_a) \cdot \mathcal{T}(r, R_{\mathrm{far}}, \omega_a)$$

Decay bound, from the non-observation of gamma-rays following core-collapse SNe

See also Jaeckel et al., Phys.Rev.D 98 (2018) 5, 055032; Hoof & Schulz, JCAP 03 (2023) 054; ***EM*** *et al., JCAP 07 (2023) 056*

$$F_\gamma = \mathrm{BR}_{a\to\gamma\gamma} \int_{m_a}^{\infty} \mathrm{d}\omega_a \int_{-1}^{1} \mathrm{d}c_\alpha \int_0^{\infty} \mathrm{d}L\, 2 \cdot \frac{\mathrm{d}N_a/\mathrm{d}\omega_a}{4\pi\, R_{\mathrm{SN}}^2} \cdot \frac{\omega_a^2 - p_a^2}{2\,(\omega_a - c_\alpha p_a)^2} \cdot \frac{\exp[-L/\ell_a(\omega_a)]}{\ell_a(\omega_a)} \cdot \Theta_{\mathrm{cons.}}(\omega_a, c_\alpha, L)$$

Explosion energy bound, from the observed kinetic energy of the SN explosion

See also Caputo et al., Phys.Rev.Lett. 128 (2022) 22, 221103

$$E_{\mathrm{mantle}} = \int \mathrm{d}t \int_0^{R_\nu} \mathrm{d}r \int_{m_a/\lambda}^{\infty} \mathrm{d}\omega_a\, 4\pi r^2 \lambda\, \omega_a \frac{\mathrm{d}n_a}{\mathrm{d}t\, \mathrm{d}\omega_a}\Big(r, t, \omega_a\Big)\, T(r, t, \omega_a) \left[1 - \exp\left(-\frac{R_* - r}{\ell_a(\lambda\omega_a)}\right)\right]$$

ALPs from SNe: Observables

511 keV-line bound, from Galactic positrons annihilating into X-rays

$$N_{\rm pos} = \int {\rm d}\omega_a \, {\rm BR}_{a\to e^+e^-} \frac{{\rm d}N_a}{{\rm d}\omega_a} \left[\exp(-R_*/\ell_a) - \exp(-R_{\rm Gal}/\ell_a)\right]$$

See also Calore et al., Phys. Rev. D 104 (2021) 043016; De La Torre Luque et al. Phys.Rev.D 109 (2024) 10, 103028

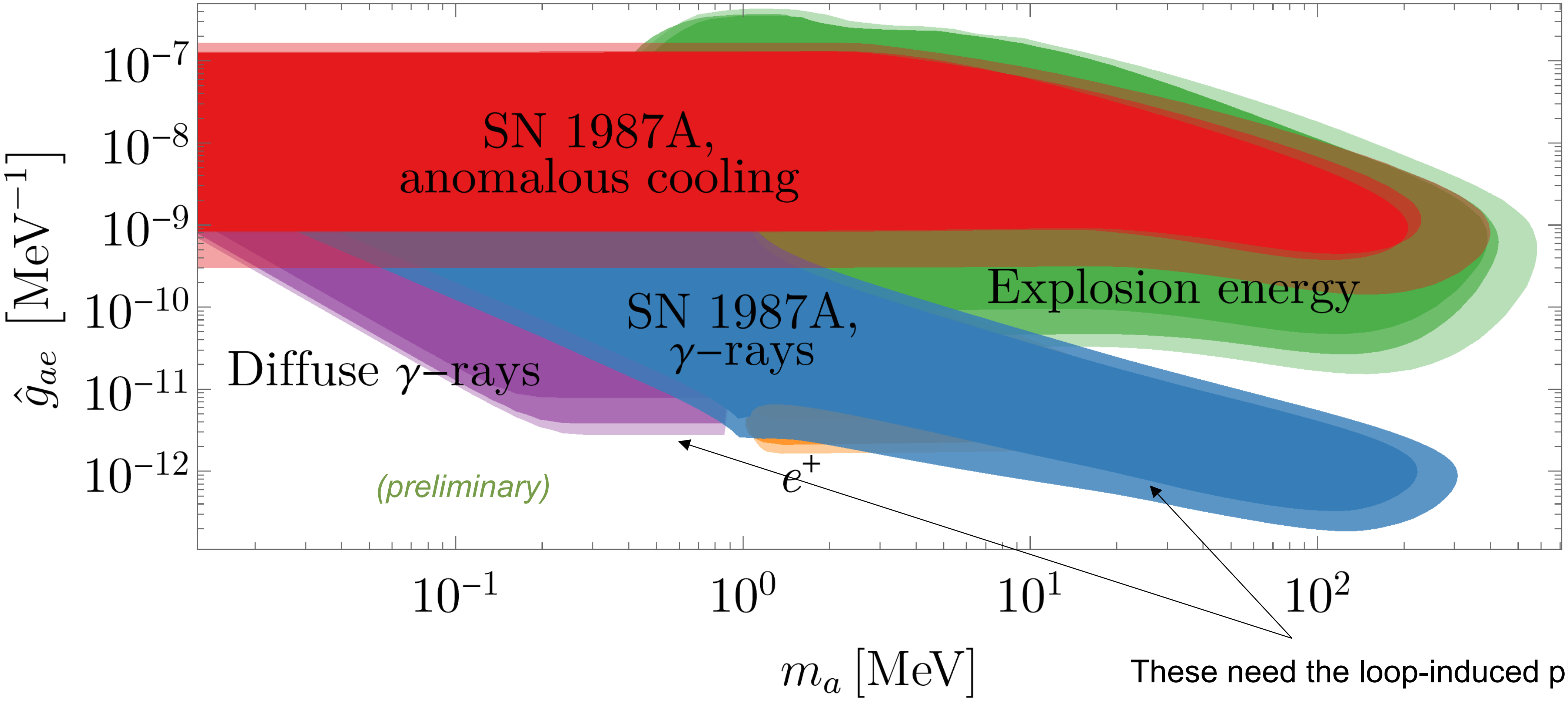
Diffuse gamma-ray bound, from all past SNe

$$\frac{{\rm d}\phi_\gamma}{{\rm d}\omega_\gamma} \simeq \frac{1}{2\pi}\int_0^\infty {\rm d}z(1+z)n'_{\rm cc}(z)\int_{\omega_\gamma^z}^\infty {\rm d}\omega_a \frac{f_{\rm D}(\omega_a)}{\omega_a}\frac{{\rm d}N_a}{{\rm d}\omega_a}$$

See also Calore et al., Phys.Rev.D 102 (2020) 12, 123005; Caputo et al., Phys.Rev.D 105 (2022) 3, 035022

(In fact, the diffuse flux is calculated in a much more cumbersome way, soon to be published, but for light-enough ALPs the above approximation holds.)

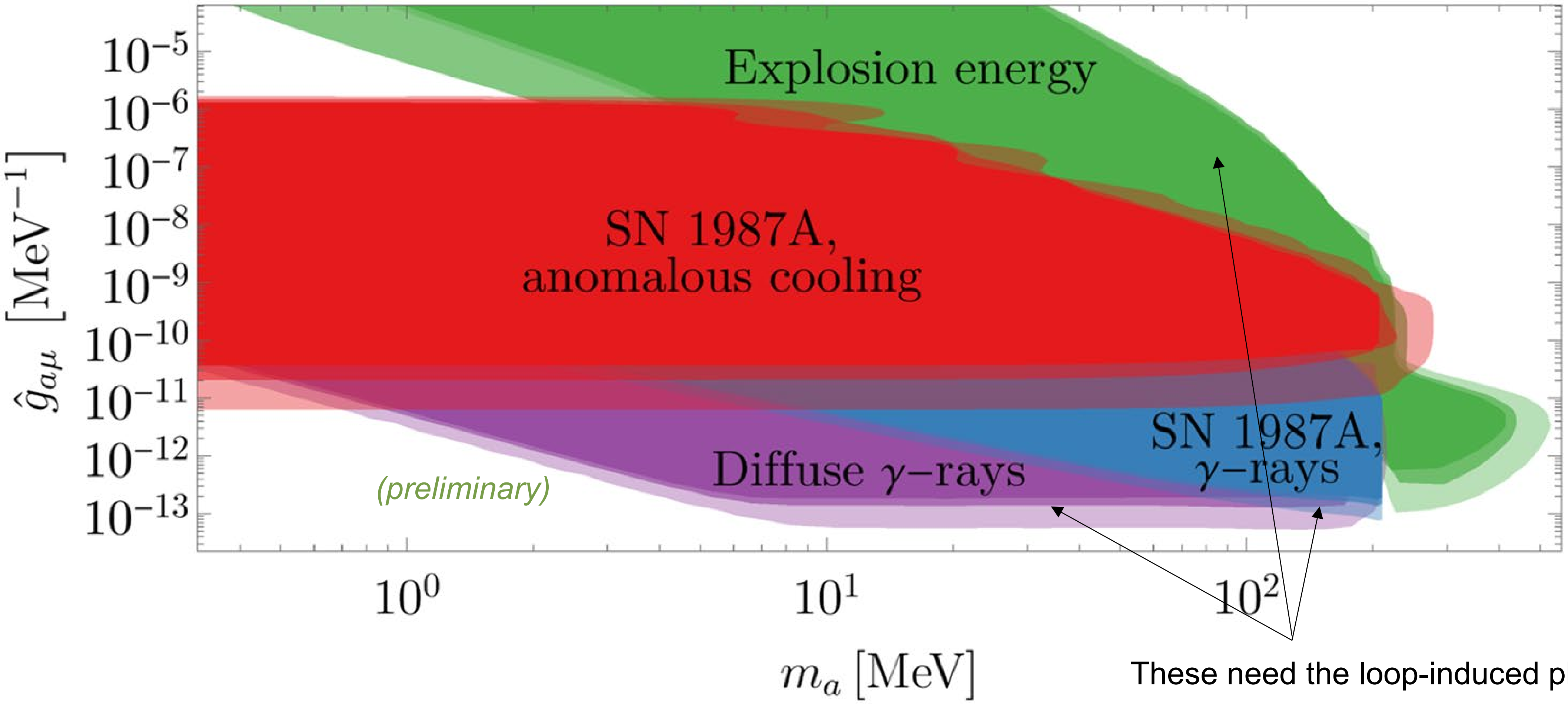
Leptonic ALPs from SNe: Results (electrons)



These need the loop-induced photon coupling

SDU

Leptonic ALPs from SNe: Results (muons)



These need the loop-induced photon coupling

Axionlike particles: “QCD ALPs”

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→ If you are interested in the phenomenology of one of these couplings, others might be unavoidable

SDU

“QCD ALPs” have photon couplings!

→ ALPs that interact with gluons and/or quarks (but are not the QCD axion!)
→ Interesting for phenomenology: low-energy couplings to nucleons and pions are very efficient in SNe

$$\mathcal{L}_{\rm nuc} = \frac{\partial^\mu a}{2 f_a}\left[C_p \bar{p}\gamma^\mu\gamma_5 p + C_n \bar{n}\gamma^\mu\gamma_5 n \right.$$
$$+ \frac{C_{a\pi N}}{f_\pi}\left(i\pi^+ \bar{p}\gamma^\mu n - i\pi^- \bar{n}\gamma^\mu p\right)$$
$$\left. + C_{aN\Delta}\left(\bar{p}\,\Delta^+_\mu + \overline{\Delta^+_\mu}\,p + \bar{n}\,\Delta^0_\mu + \overline{\Delta^0_\mu}\,n\right)\right]$$

Couplings to quarks and gluons: c_u, c_d, c_g

$$C_p(c_g, c_u, c_d) = -0.47\,c_g + 0.88 c_u - 0.39 c_d - 0.038 c_s$$
$$- 0.012 c_c - 0.009 c_b - 0.0035 c_t\,,$$
$$C_n(c_g, c_u, c_d) = -0.02\,c_g + 0.88 c_d - 0.39 c_u - 0.038 c_s$$
$$- 0.012 c_c - 0.009 c_b - 0.0035 c_t\,.$$

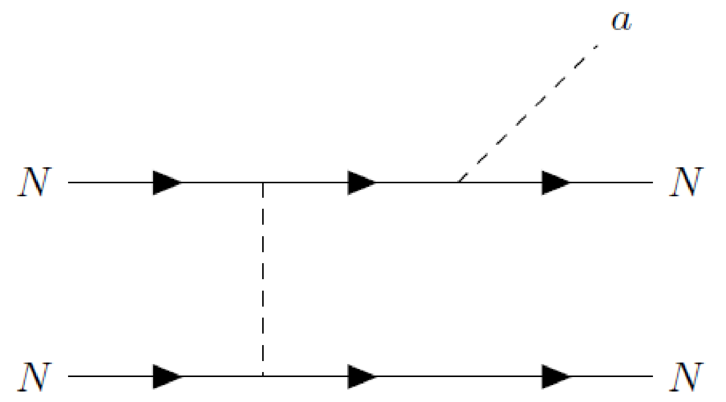
Grilli di Cortona, et al., JHEP 01 (2016) 034

$$g_{a\gamma} = \frac{\alpha}{2\pi\, f_a}\left\{-1.92\, c_g - \frac{m_a^2}{m_\pi^2 - m_a^2}\left[c_g \frac{m_d - m_u}{m_d + m_u} + (c_u - c_d)\right]\right\}$$

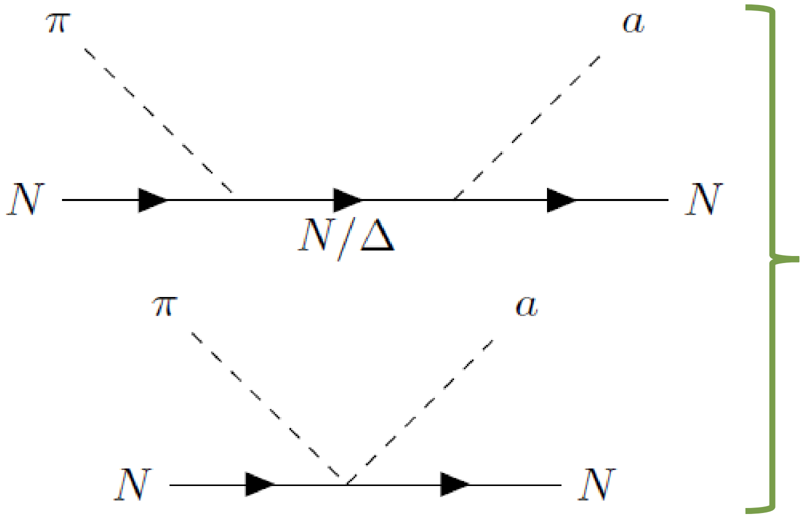
In general, there is an “irreducible” photon coupling as well!

*Lella, **ER**, et al., Phys.Rev.D 110 (2024) 4, 043019*

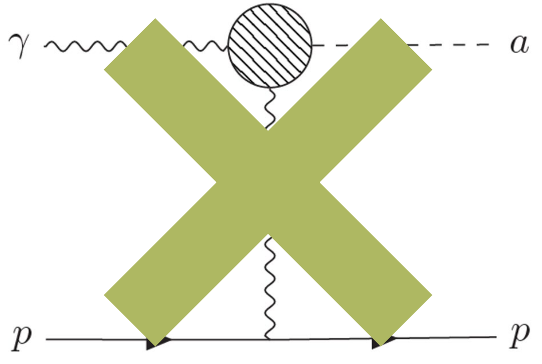
“QCD ALPs” produced in SNe



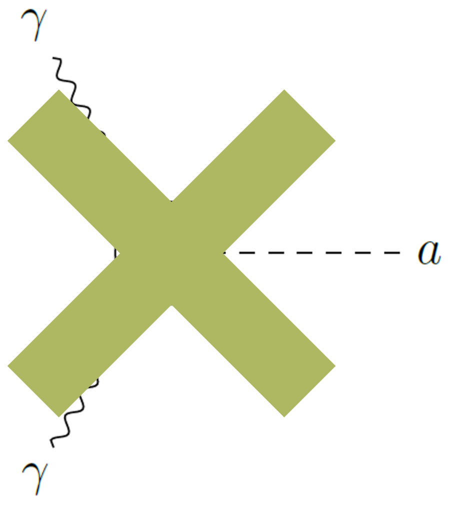
Nucleon-nucleon Bremsstrahlung



Pion-axion conversion

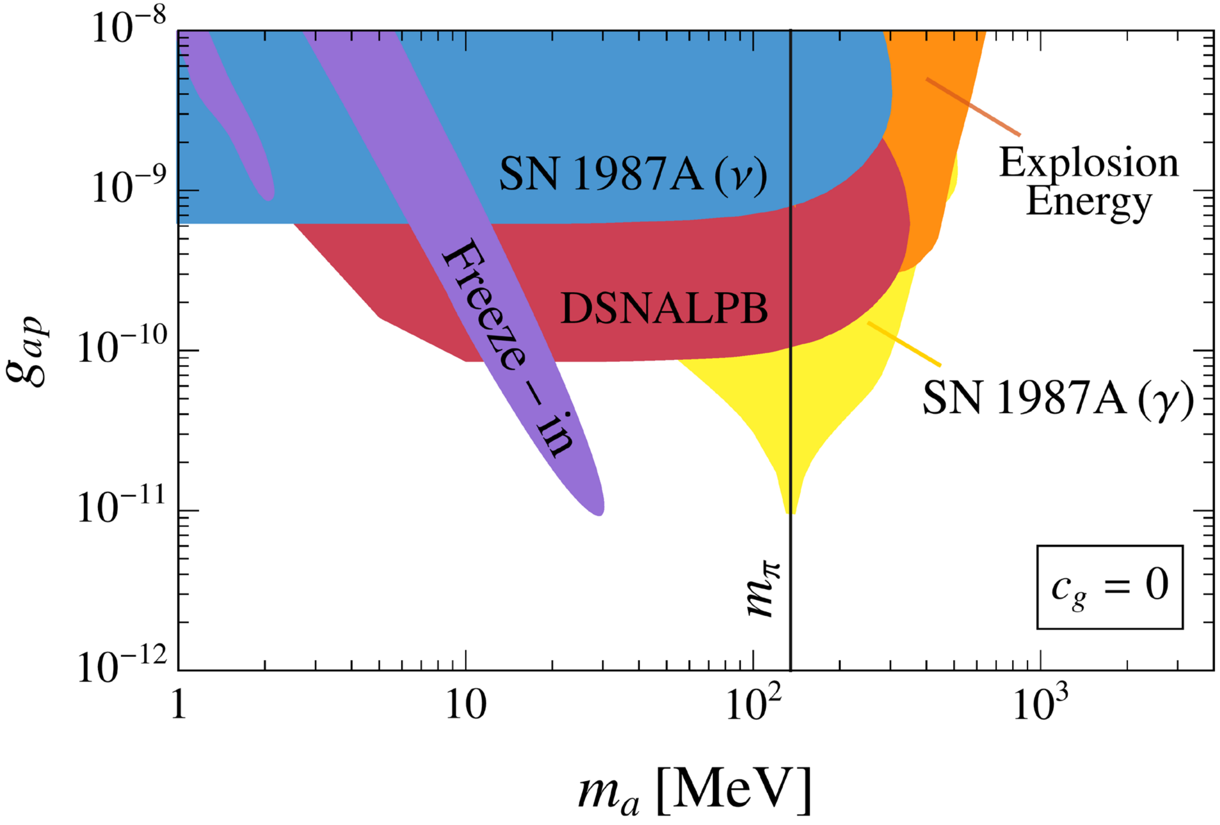


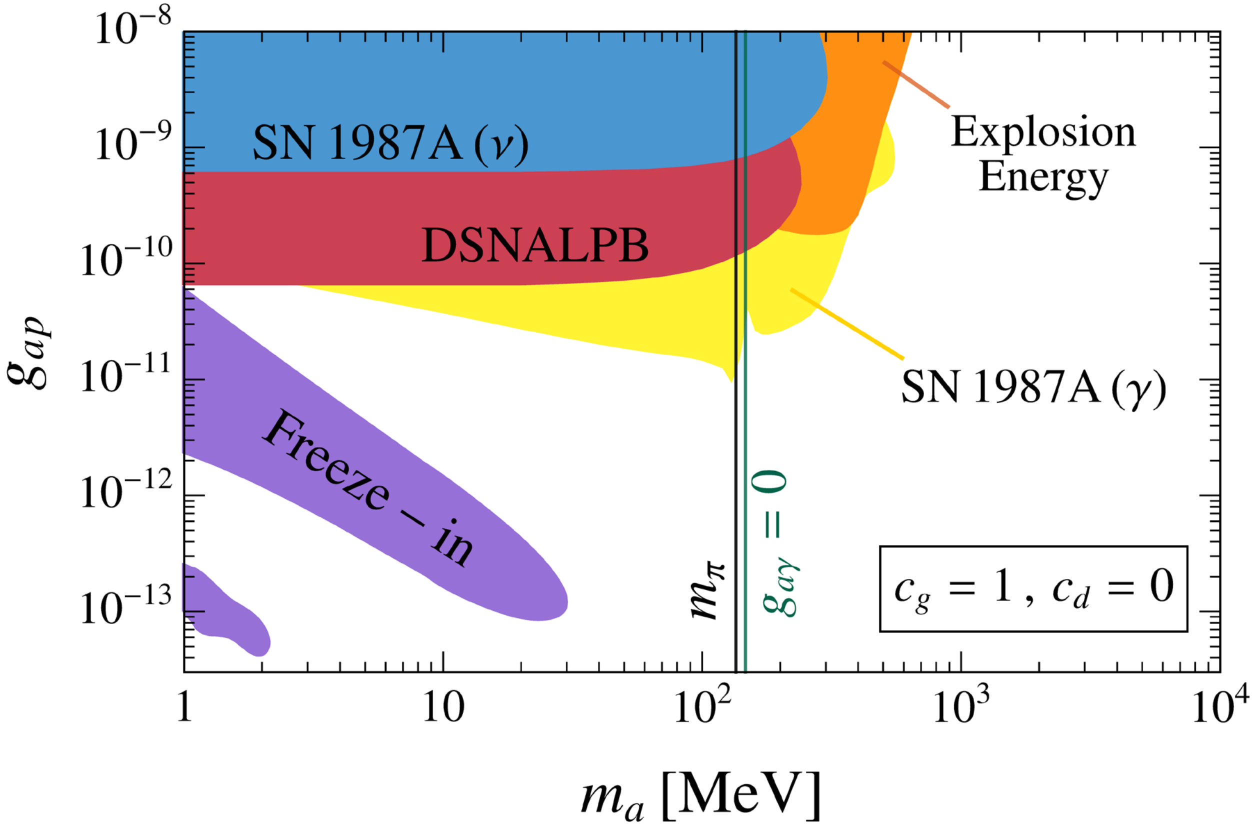
Production via “irreducible” photon interaction is negligible here



For a review of nuclear ALP-production see
Carenza, Eur.Phys.J. Plus (2023) 138:836

“QCD ALPs” from SNe: Results

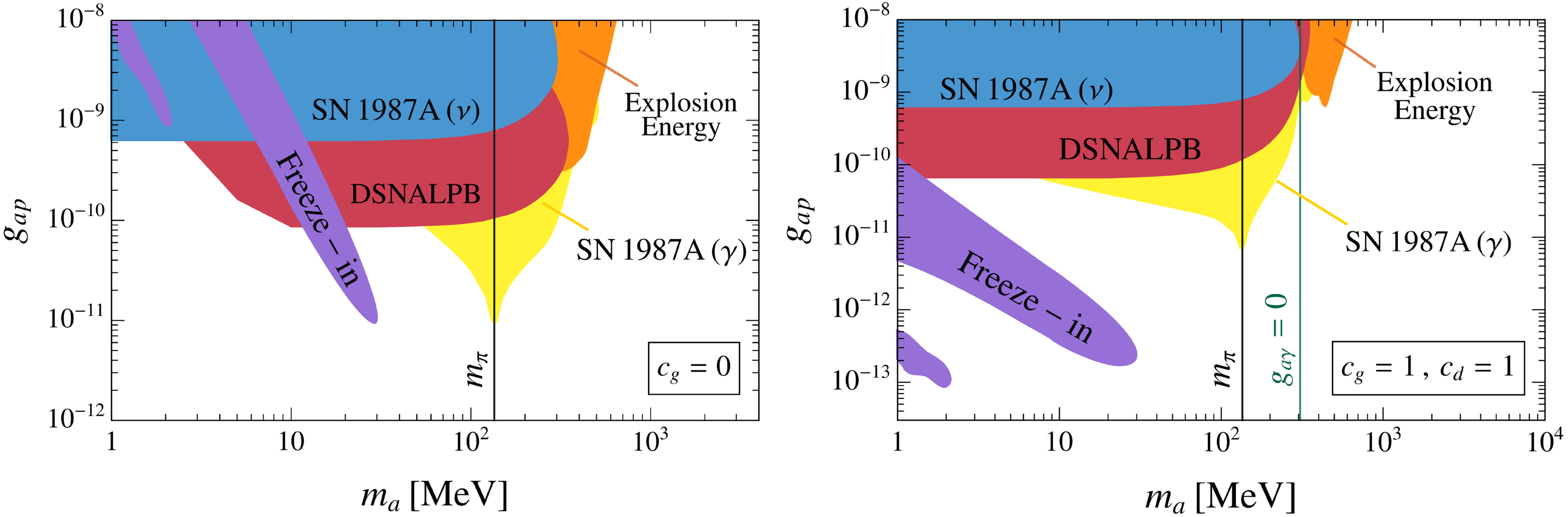




*Lella, **ER**, et al., Phys.Rev.D 110 (2024) 4, 043019*

These results assume $g_{an} = 0$ for definiteness.

“QCD ALPs” from SNe: Results



*Lella, **ER**, et al., Phys.Rev.D 110 (2024) 4, 043019*

These results assume $g_{an} = 0$ for definiteness.

Axionlike particles: (Photophilic) ALPs

→ **ALPs** are **naturally light**, **weakly interacting** pseudoscalar particles that appear in many BSM theories

→ Both axions and ALPs are pseudo-Goldstone bosons of chiral $U(1)$ theories (hence “axion-like”)

→ At low energies $E \ll \Lambda$, all these models are described by the same effective field theory (EFT):

$$\mathcal{L} \supset -\frac{1}{2}a(\Box + \boxed{m_a^2})a + \frac{1}{4}\boxed{g_{a\gamma}}\,a\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_{\ell}\boxed{\hat{g}_{a\ell}}(\partial^{\mu}a)\bar{\ell}\gamma_5\gamma_{\mu}\ell + \sum_{N}\boxed{g_{aN}}\frac{\partial_{\mu}a}{2m_N}\bar{N}\gamma^{\mu}\gamma_5 N$$

Mass (free parameter,
not related to couplings)

Photon coupling

Lepton couplings

Non-relativistic
nucleon couplings

→ Are all these couplings independent? No, Quantum effects mix them!
For collider phenomenology, see, e.g., Bauer et al.: 1708.00443, 2012.12272

→ If you are interested in the phenomenology of one of these couplings, others might be unavoidable

From: *Manzari, Park, Safdi, Savoray, Phys.Rev.Lett. 133 (2024) 21, 211002*

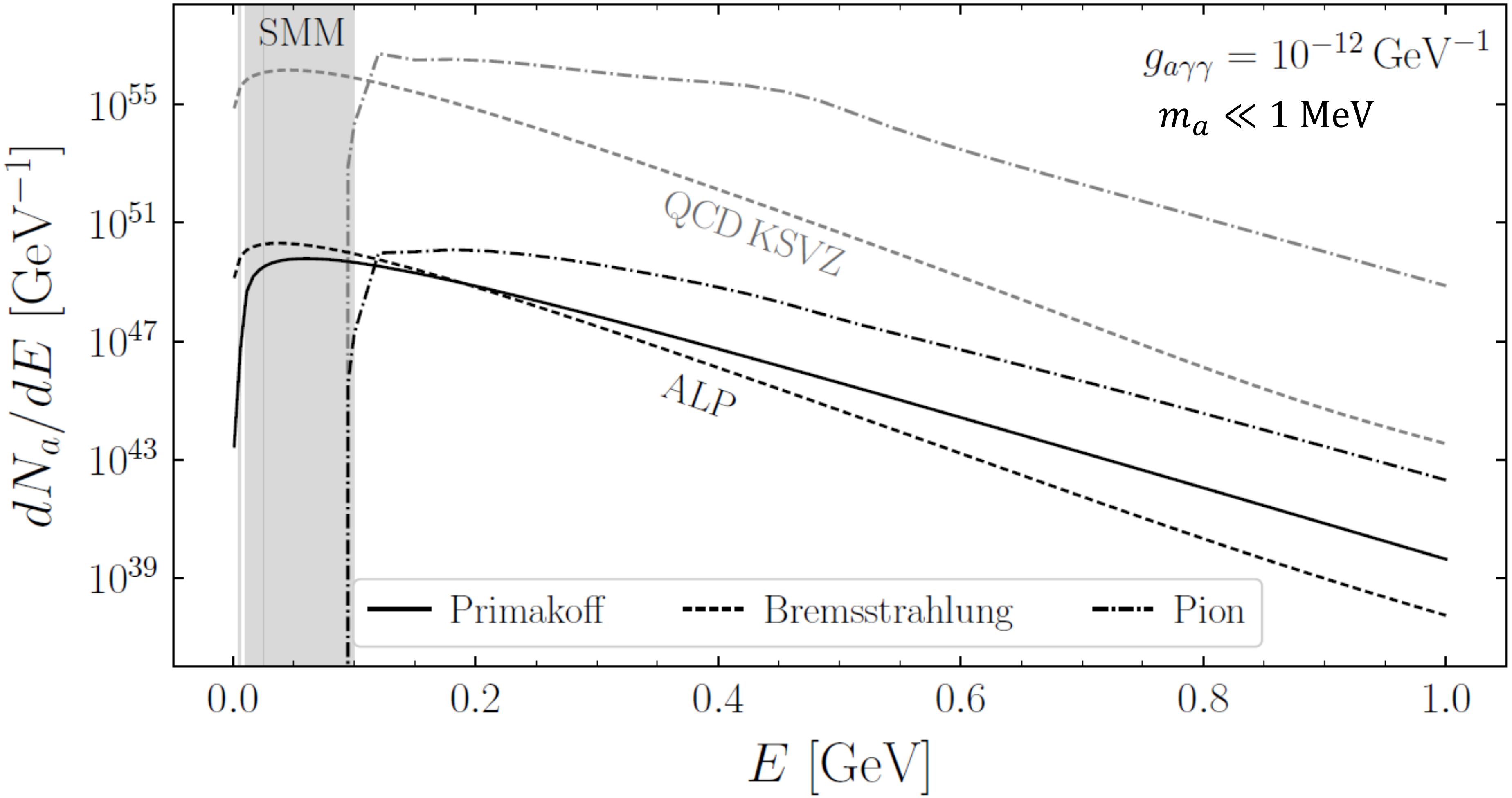
Standard ALP production

RG-induced running couplings to nucleons and pions:

$$C_p \simeq C_n \simeq 10^{-4}\,\frac{2\pi\, f_a}{\alpha}\, g_{a\gamma}$$

Even though these are small, the resulting QCD processes seemingly dominate ALP production!

→ This should be included in all ALP-studies
(after a careful check)



Axionlike particles:
One-loop effects for astro-phenomenology

Studying the phenomenology of	…you cannot ignore	Disclaimer
ALP-lepton couplings g_{ae}, $g_{a\mu}$, $g_{a\tau}$	ALP-photon coupling $g_{a\gamma}$ (structure factor (not RG running))	For high-energetic ALPs with $E \gtrsim m_\ell$; Probably also g_{aN}, $g_{a\pi}$, …
ALP-photon coupling $g_{a\gamma}$	ALP-QCD couplings g_{aN}, $g_{a\pi}$, … (via RG running)	For ALP-production in SNe at least (with a high density of nuclear matter)
ALP-QCD couplings g_{aN}, $g_{a\pi}$, …	ALP-photon coupling $g_{a\gamma}$ (construction of IR EFT)	Yields observable signals

Conclusion & Outlook

→There are many observables to look for, and predicting them is numerically quite costly

→Even in phenomenological EFT models, higher-order QFT effects play an important role

→**Effective ALP couplings are not independent!** And corrections are important in SNe

→Stay tuned for our comprehensive results for leptonic ALPs and technical improvements

→Upcoming: search for the time signature of ALP-induced gamma-ray bursts from nearby SNe (following first steps in ***EM***, *P. Carenza, C: Eckner, A. Goobar, Phys.Rev.D 109 (2024) 2, 2*) & loop-induced detection in neutrino detectors

Thanks for your attention!

Back-up slides

ALPs from SNe: Observables

→ Among the technical advances in our recent work: anisotropic ALP-absorption probability

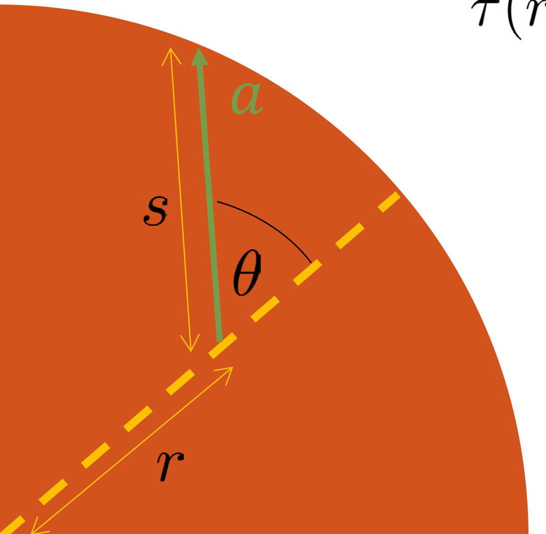
→ In the **Cooling bound** and **Explosion energy bound**, the transmissivity is given as an angular average

$$T(r,t,\omega_a) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}\cos\theta\, e^{-\tau(r,t,\omega_a,\cos\theta)}$$

with the optical depth

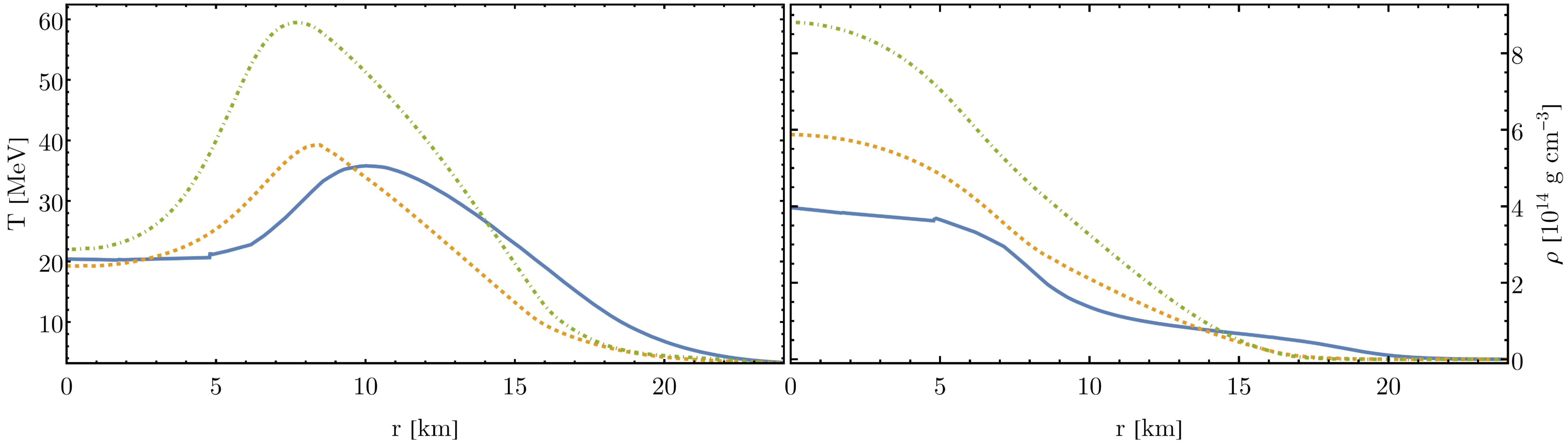
$$\tau(r,\omega_a,\cos\theta) = \frac{1}{2\pi^2}\int_0^{s_\mathrm{max}} \mathrm{d}s\, \frac{\omega_a^2 - m_a^2}{\exp[\omega_a/T(r'(s))]-1}\left[\frac{\mathrm{d}^2 n_a}{\mathrm{d}t\,\mathrm{d}\omega_a}(r'(s),\omega_a)\right]^{-1},$$

$$\text{with } r'(s) = \sqrt{r^2+s^2+2rs\cos\theta}\,,\ s_\mathrm{max} = \sqrt{R_\mathrm{far}^2-(1-\cos^2\theta)r^2} - r\cos\theta$$



Following Caputo et al., JCAP 08 (2022) 08, 045

Supernovae – a great lab for new physics

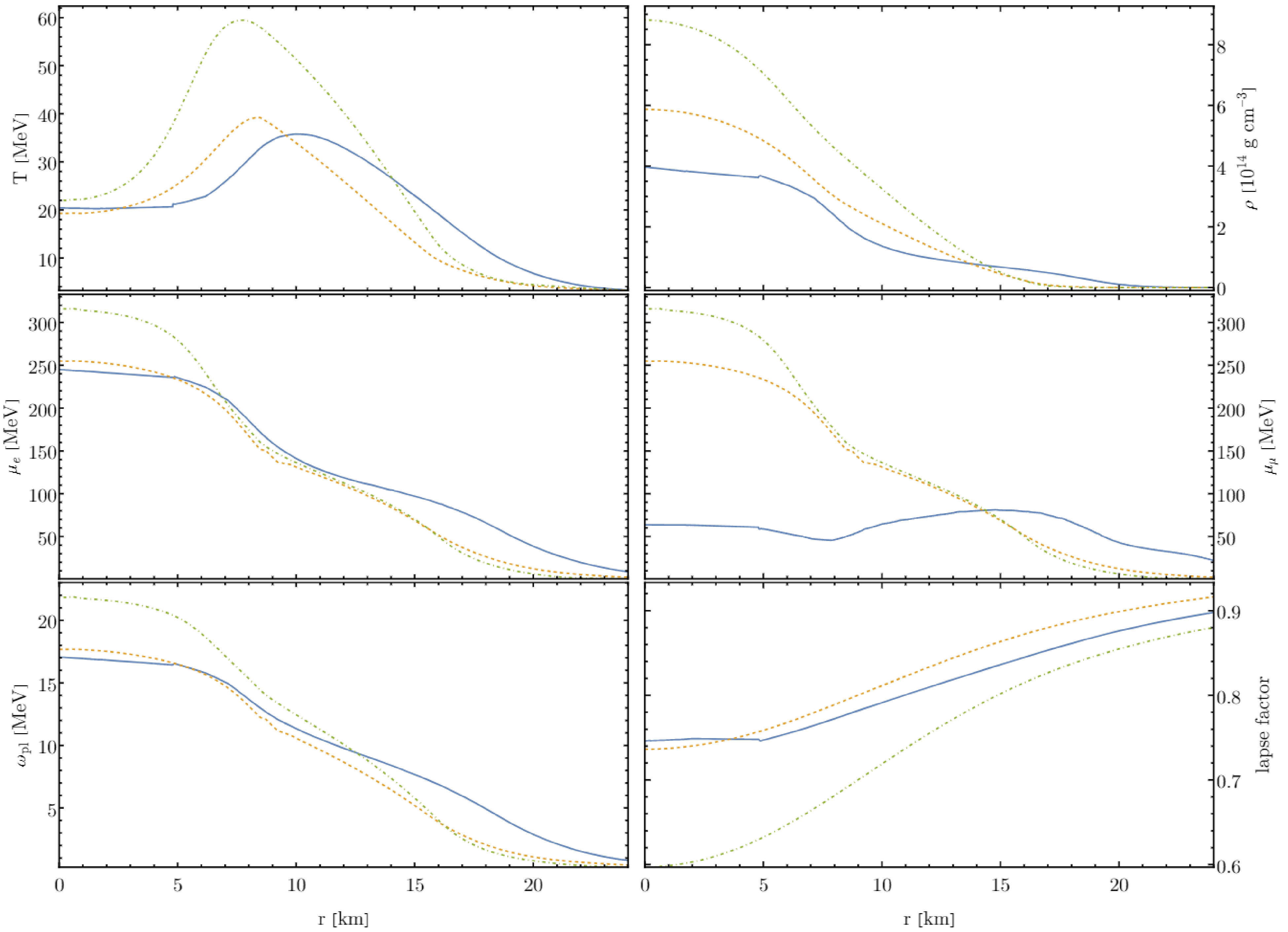


Blue line: “Agile-Boltztran” SN simulation, Fischer et al., PRD 104 (2021) 103012
Green and orange lines: models of the “Garching SN Archive”, R. Bollig et al., Phys. Rev. Lett. 125 (2020) 051104

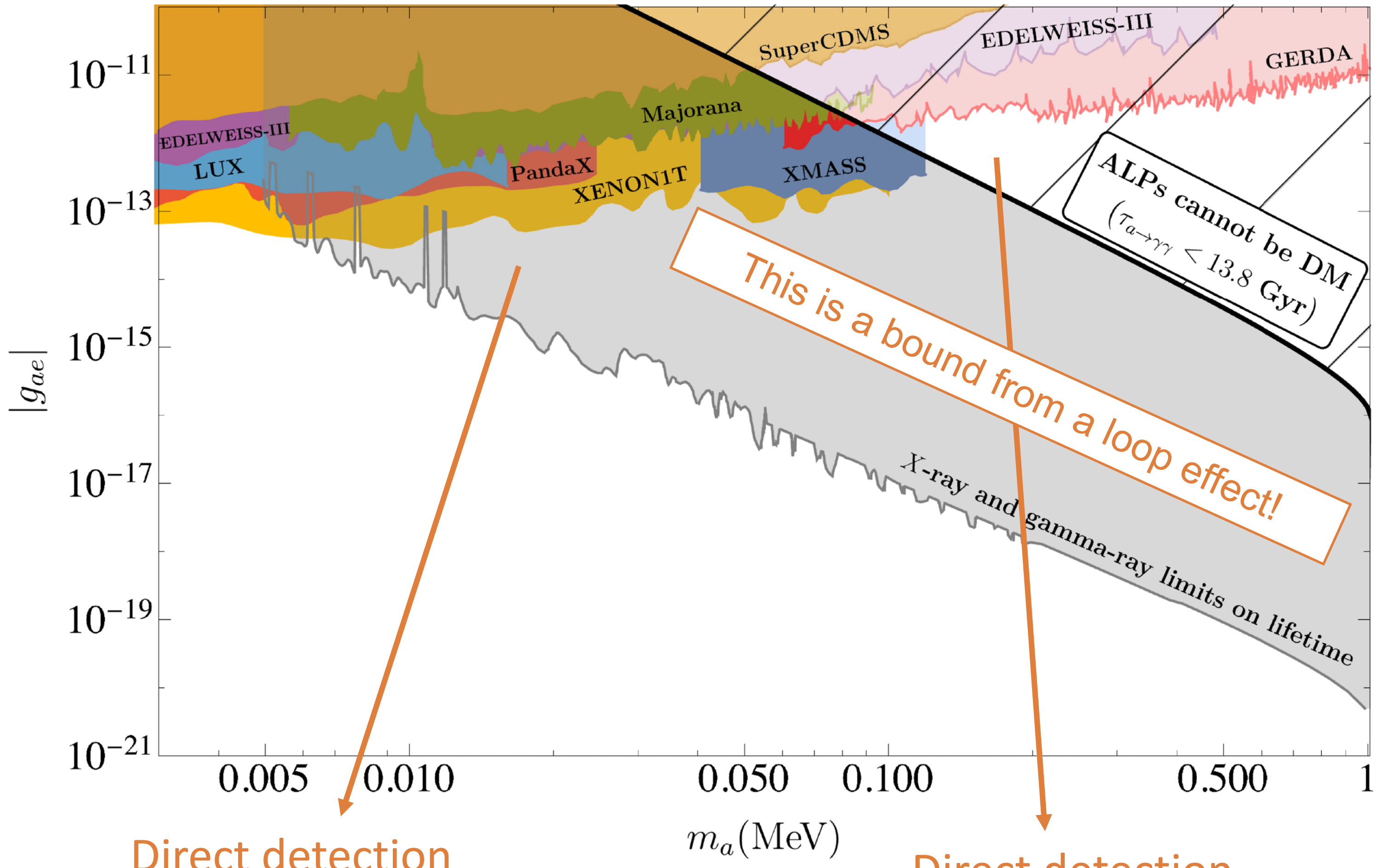
Hot and dense plasma
→ even weakly interacting particles are produced

… and they can escape!

Supernova models from simulations



ALPs decay into photons



This is a bound from a loop effect!

Direct detection limits are superseded here

Direct detection limits do not apply here

Photophobic ALPs decay at one-loop level with a lifetime of

$$\tau_{a\to\gamma\gamma} \simeq 13.8\,\mathrm{Gyr}\left(\frac{1.2\cdot 10^{-12}}{g_{ae}}\right)^2\left(\frac{100\,\mathrm{keV}}{m_a}\right)^7$$

Ricardo Z. Ferreira, M. C. David Marsh, and **EM**
Phys. Rev. Lett. 128, 221302

See also Pospelov et al. 2008, Arias et al. 2012 for earlier work on this

ALP-electron interactions in a plasma

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

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

Taking plasma effects into account

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

$$\left|\mathcal{M}^{\text{derivative}}_{\text{brems}}\right|^2 = 4p_e^2\hat{g}_{ae}^2 f(m_e^{\text{eff}}, \dots) = (2m_e^{\text{eff}}\hat{g}_{ae})^2 f(m_e^{\text{eff}}, \dots)$$

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

$$\mathcal{L}_{\rm QCD} = \sum \bar{q}\left(i\not{D} - m_q e^{i\theta_q\gamma_5}\right) q - \frac{1}{4}G^{a\,\mu\nu}G^{a}_{\mu\nu} + \theta\frac{g_s^2}{32\pi^2}G^{a\,\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

$$\bar{\theta} = \theta + \theta_q$$

The landscape of QCD axion models, di Luzio et al., 2003.01100

The original axion

The strong CP problem

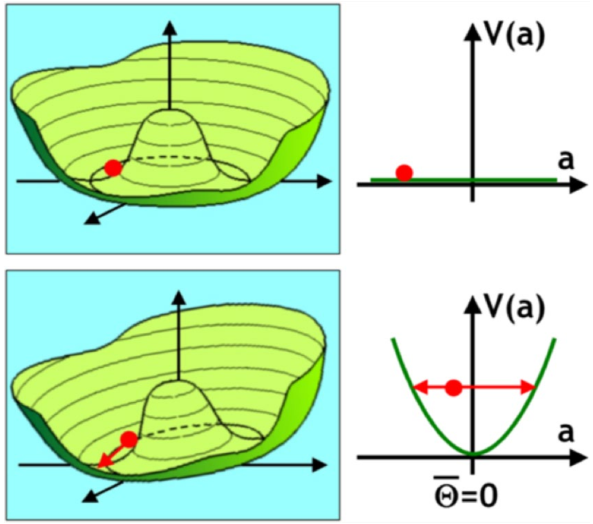
The neutron has no observable electric dipole moment:

$$d_n \lesssim 10^{-26} e \text{ cm}$$

However, d_n can be calculated from QCD:

$$d_n \simeq 10^{-16}\bar{\theta}\ e \text{ cm},$$

where a priori $\bar{\theta} \in [0, 2\pi)$, but is experimentally found to be very close to zero → fine-tuning problem



Credit: S. Hannestad

Peccei-Quinn solution

Implement a new, chiral $U(1)_{PQ}$ symmetry that allows $\bar{\theta}$ to dynamically relax to zero

The pseudo-Goldstone boson of the spontaneously broken $U(1)_{PQ}$ is the **axion**

$$\mathcal{L}_a = \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G}$$

Running photon coupling

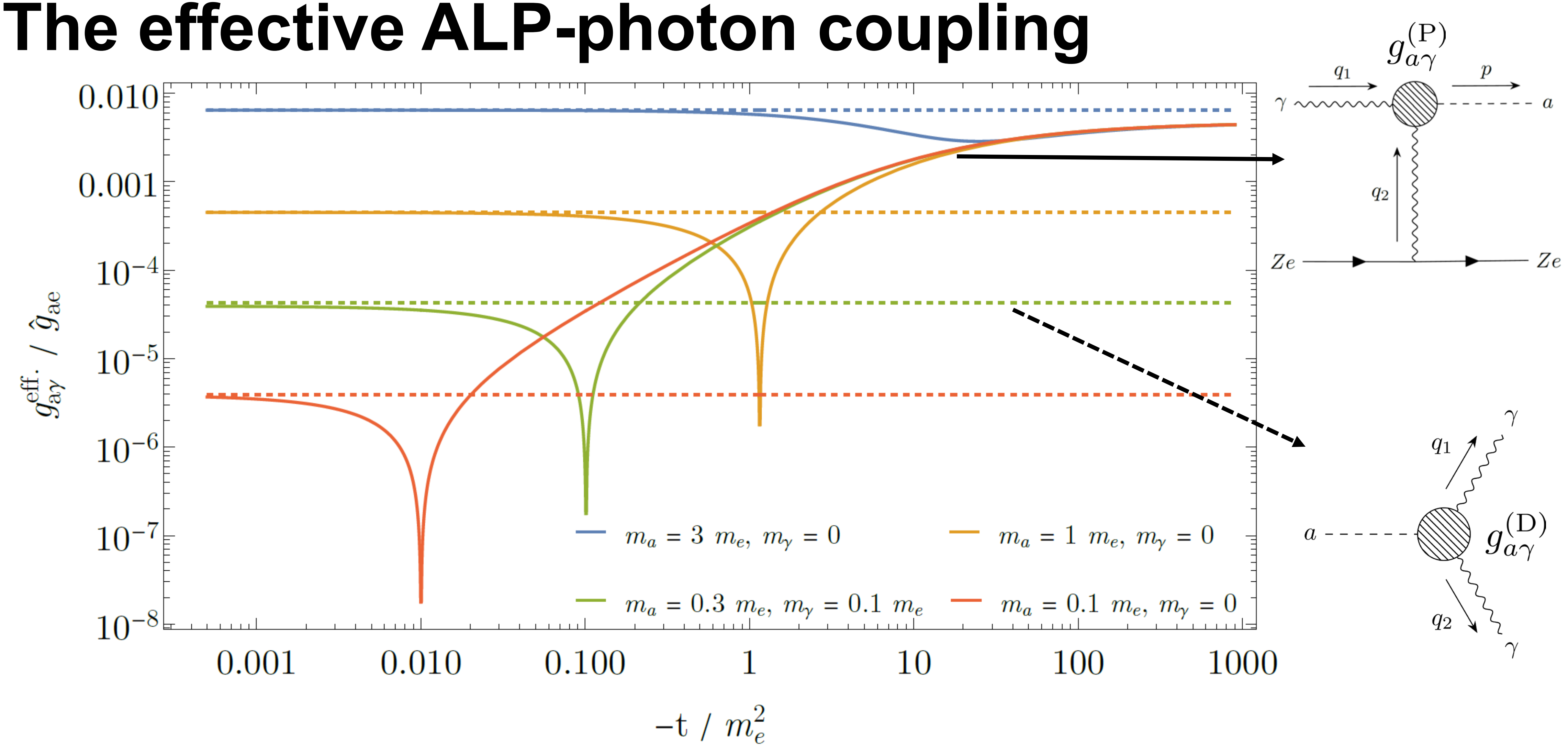
For leptonic ALPs (here $\ell = e$), derive the **renormalization group equations**:

$$
\begin{aligned}
\mu\frac{\mathrm{d}e}{\mathrm{d}\mu} &= -\epsilon\, e + \frac{1}{12\pi^2}e^3 \\
\mu\frac{\mathrm{d}\hat{g}_{ae}}{\mathrm{d}\mu} &= -\epsilon\, \hat{g}_{ae} + \frac{3}{16\pi^2}e^2 g_{a\gamma} \\
\mu\frac{\mathrm{d}g_{a\gamma}}{\mathrm{d}\mu} &= -\epsilon\, g_{a\gamma} + \frac{1}{6\pi^2}e^2 g_{a\gamma}
\end{aligned}
\quad\Longrightarrow\quad
\begin{aligned}
\alpha(\mu) \equiv \frac{e^2(\mu)}{4\pi} &= \alpha_0\left(1 - \frac{\alpha_0}{3\pi}\ln\frac{\mu^2}{\mu_0^2}\right)^{-1} \\
\boxed{\hat{g}_{ae}(\mu)} &= \boxed{\hat{g}_{ae}^{\Lambda}} - \frac{9}{8}\boxed{\xcancel{g_{a\gamma}^{\Lambda}}}\left[1 - \frac{\alpha(\mu)}{\alpha(\Lambda)}\right] \\
\boxed{\xcancel{g_{a\gamma}(\mu)}} &= \boxed{\xcancel{g_{a\gamma}^{\Lambda}}}\,\frac{\alpha(\mu)}{\alpha(\Lambda)}
\end{aligned}
$$

→ There is **no RG-induced running photon coupling** for leptonic ALPs
(This is also true in the full SM)

SDU

The effective ALP-photon coupling



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