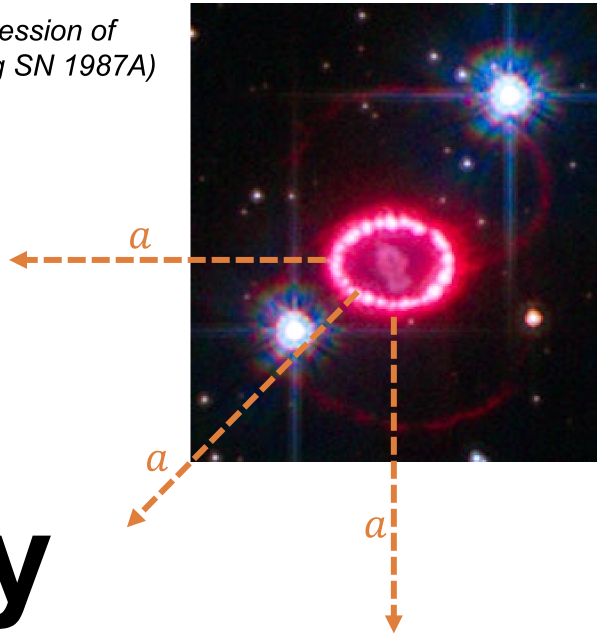


(“artist’s” impression of
axions leaving SN 1987A)

Observing axions from supernovae through their many (loop-induced) couplings

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

Based on work with David Marsh, Ricardo Z. Ferreira, Pierluca Carenza,
Alessandro Lella

SDU

19th Patras Workshop, September 2024

Axionlike particles

→ **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):

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

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

Here, study $\hat{g}_{a\ell} \to g_{a\gamma}$ and $g_{aN} \to g_{a\gamma}$, since photon coupling is very important for phenomenology

Supernovae – a great lab for new physics

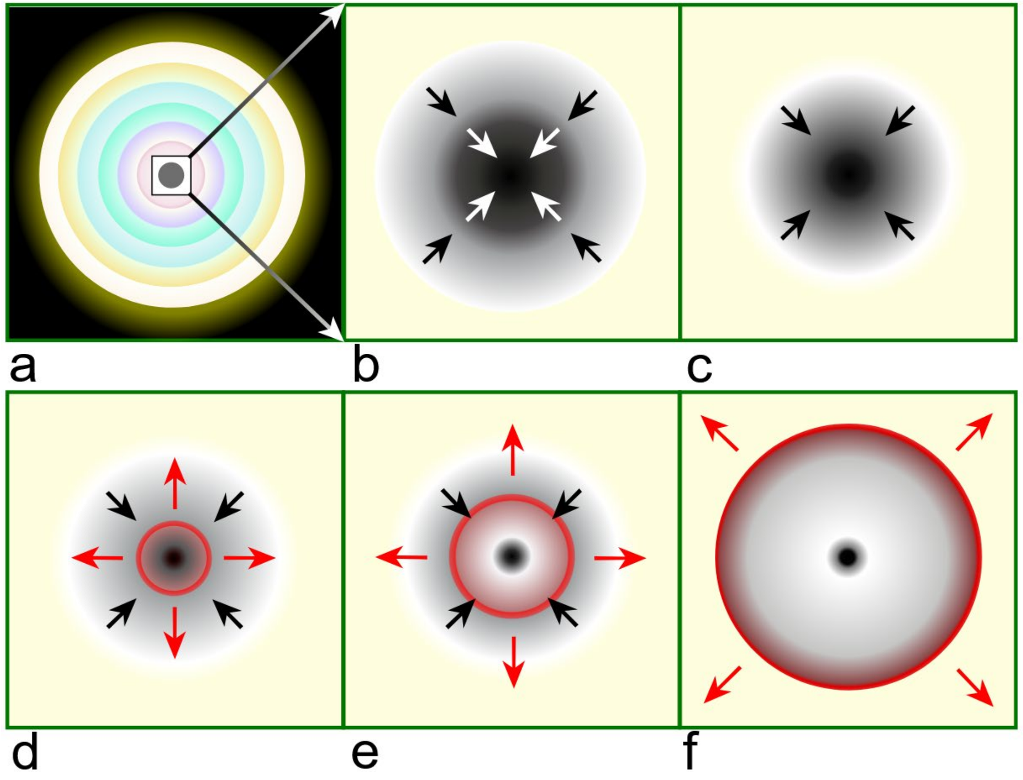
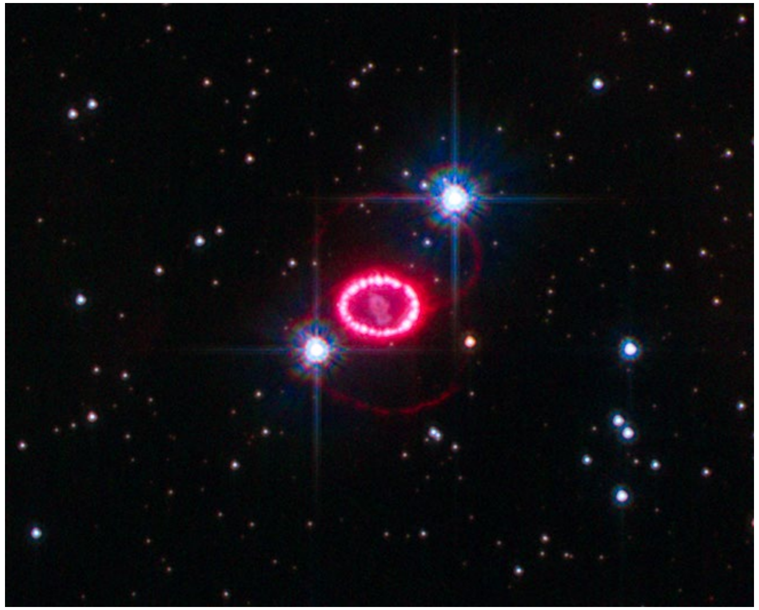
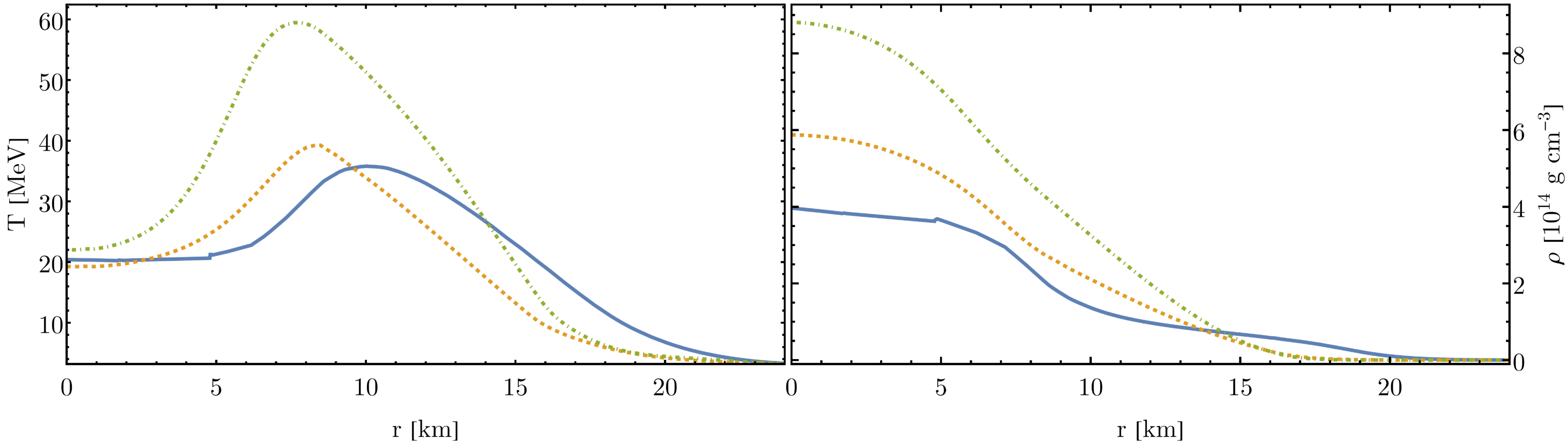


Illustration by R.J. Hall taken from Wikipedia, based on Janka et al., Physics Reports. 442 (1–6): 38–74



SN 1987A remnant as seen by the Hubble telescope

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!

SDU

Axionlike particles

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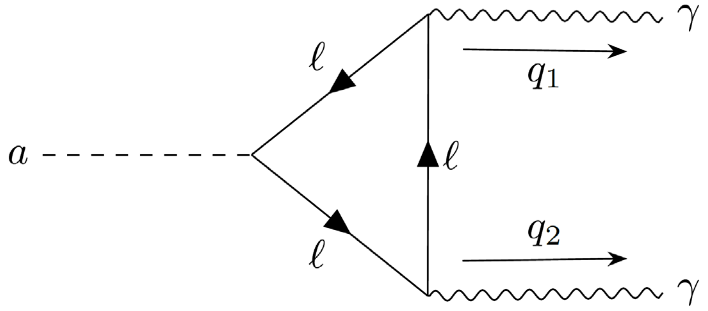
Leptonic ALPs

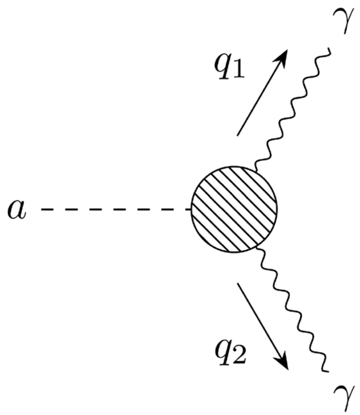
$$\mathcal{L}_{1-\text{loop}} \supset -\frac{1}{2}a(\Box + m_a^2)a + \sum_{\ell} \hat{g}_{a\ell}(\partial^{\mu} a)\bar{\ell}\gamma_5\gamma_{\mu}\ell + \frac{1}{4} g_{a\gamma}^{\text{eff}} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Leptonic ALPs

→ ALP that is only interacting with electrons or muons (taus are too heavy, not interesting for SNe(?))



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

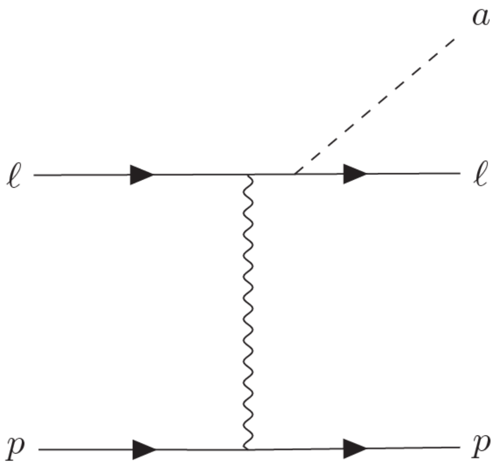


$$= i\,\boxed{g_{a\gamma}^{\text{eff}}(q_1, q_2)}\, q_1^{\alpha}\, q_2^{\beta}\varepsilon^{\mu\nu\alpha\beta}$$

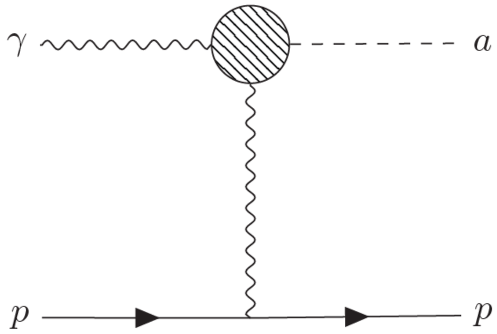
*R. Ferreira, D. Marsh, **EM**, JCAP 11 (2022) 057*

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

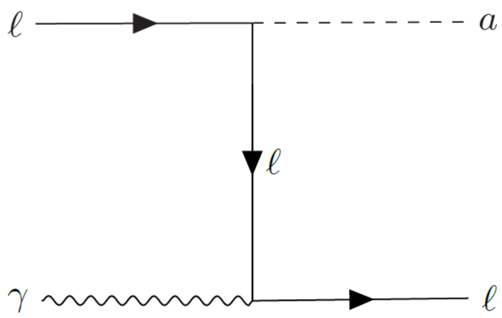
Leptonic ALPs produced in SNe



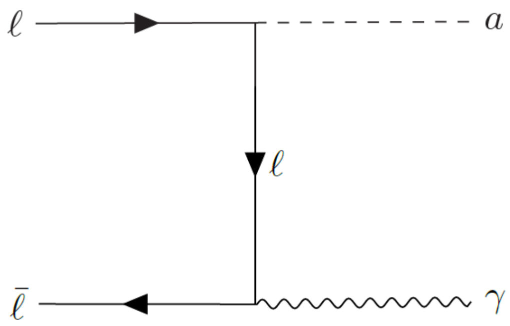
(a) Bremsstrahlung



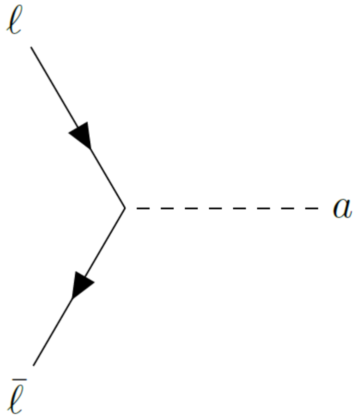
(b) Primakoff process



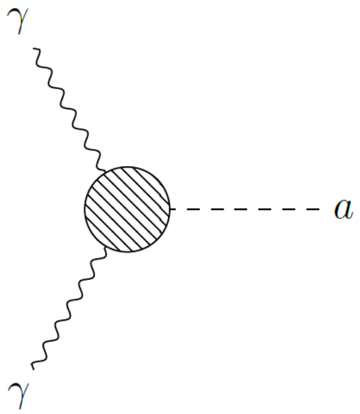
(c) Compton



(d) Pair annihilation



(e) Lepton fusion

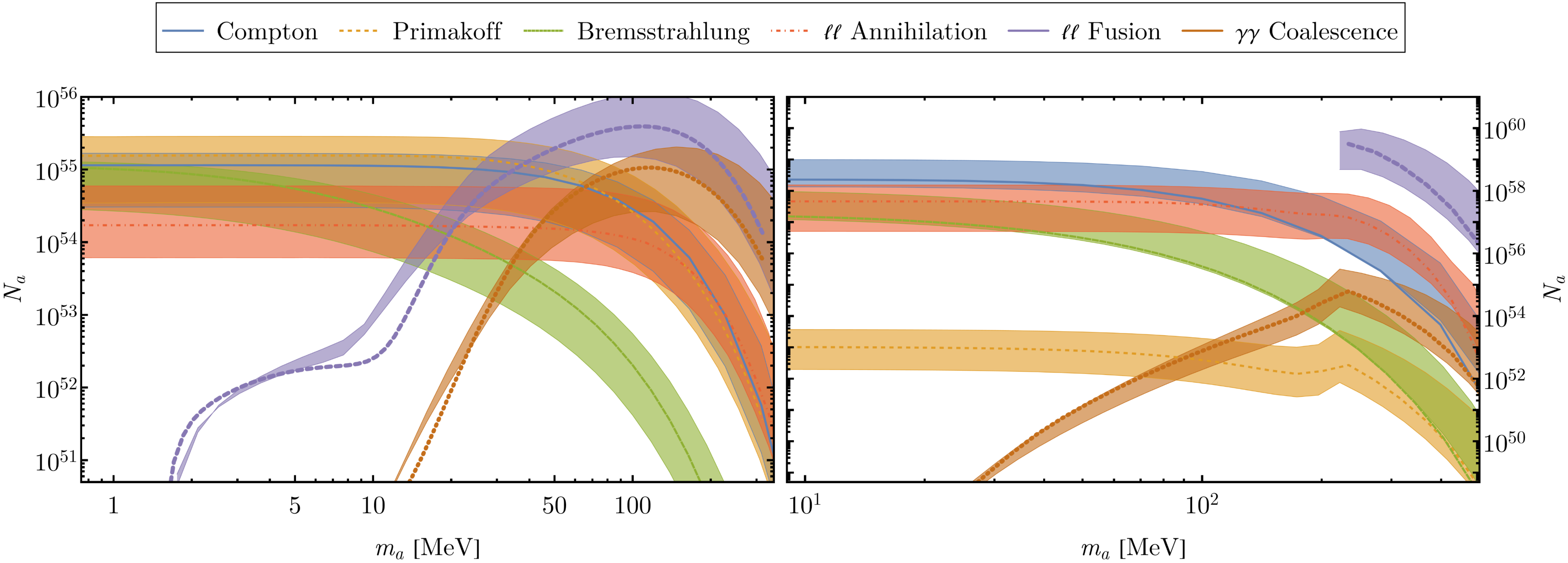


(f) $\gamma\gamma$-coalescence

production

absorption

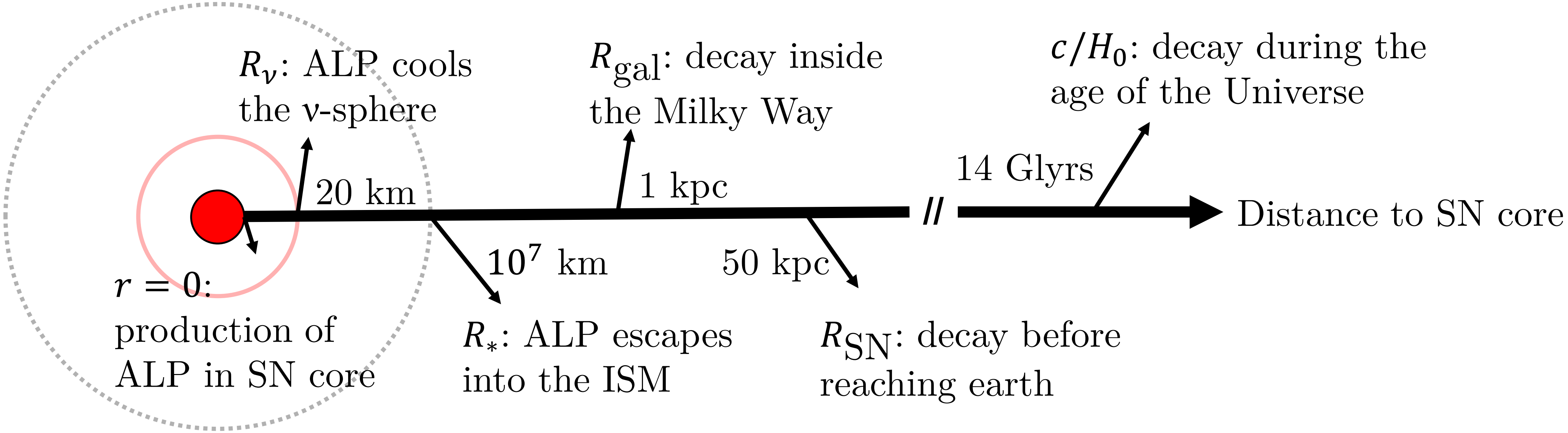
Leptonic ALPs produced in SNe



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

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

ALPs from SNe: Observables



R_ν: ALP cools the ν-sphere

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

c/H_0: decay during the age of the Universe

20 km

1 kpc

14 Glyrs

Distance to SN core

10^7 km

50 kpc

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

R_*: ALP escapes into the ISM

$R_{\rm SN}$: 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

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

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

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

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*

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

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

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

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

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

ALPs from SNe: Observables

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

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

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

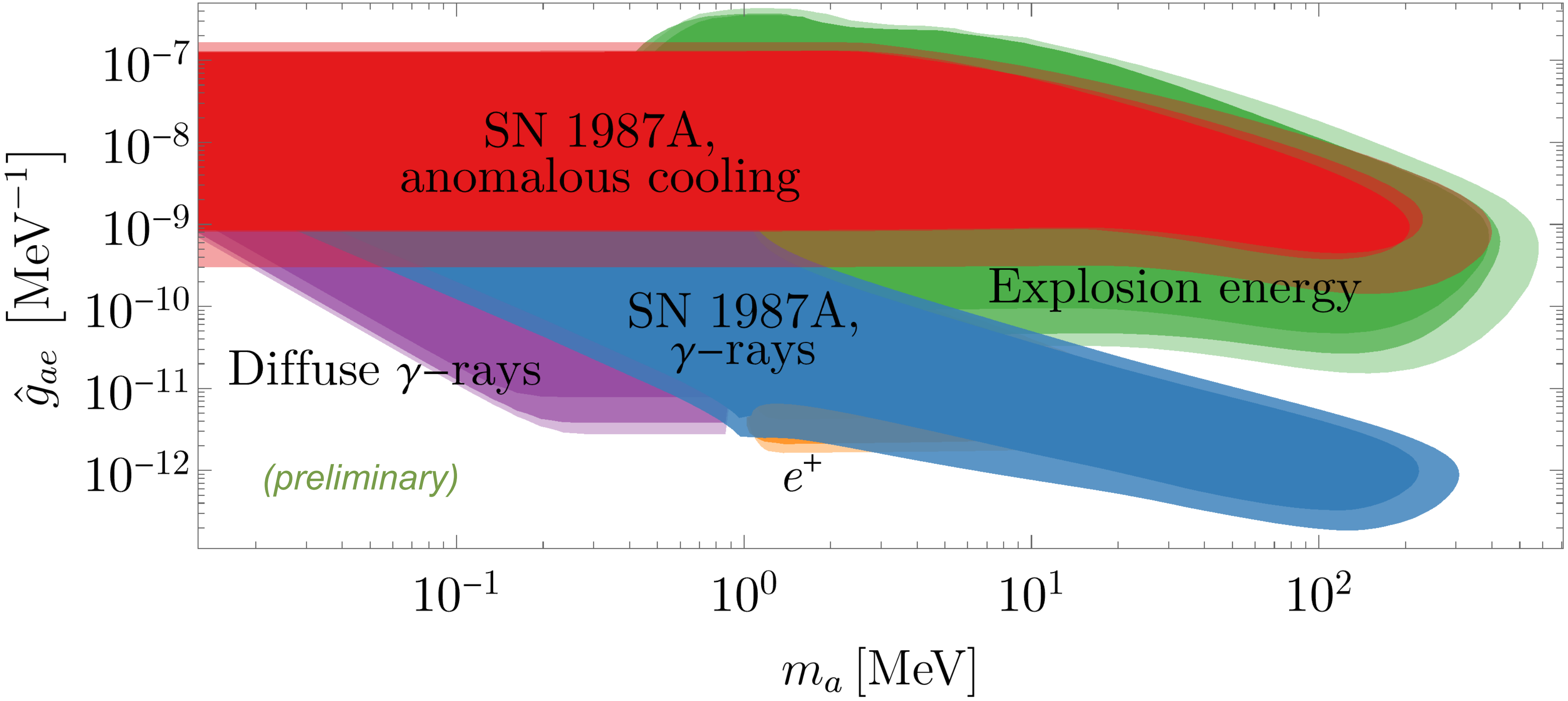
Diffuse gamma-ray bound, from all past SNe

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

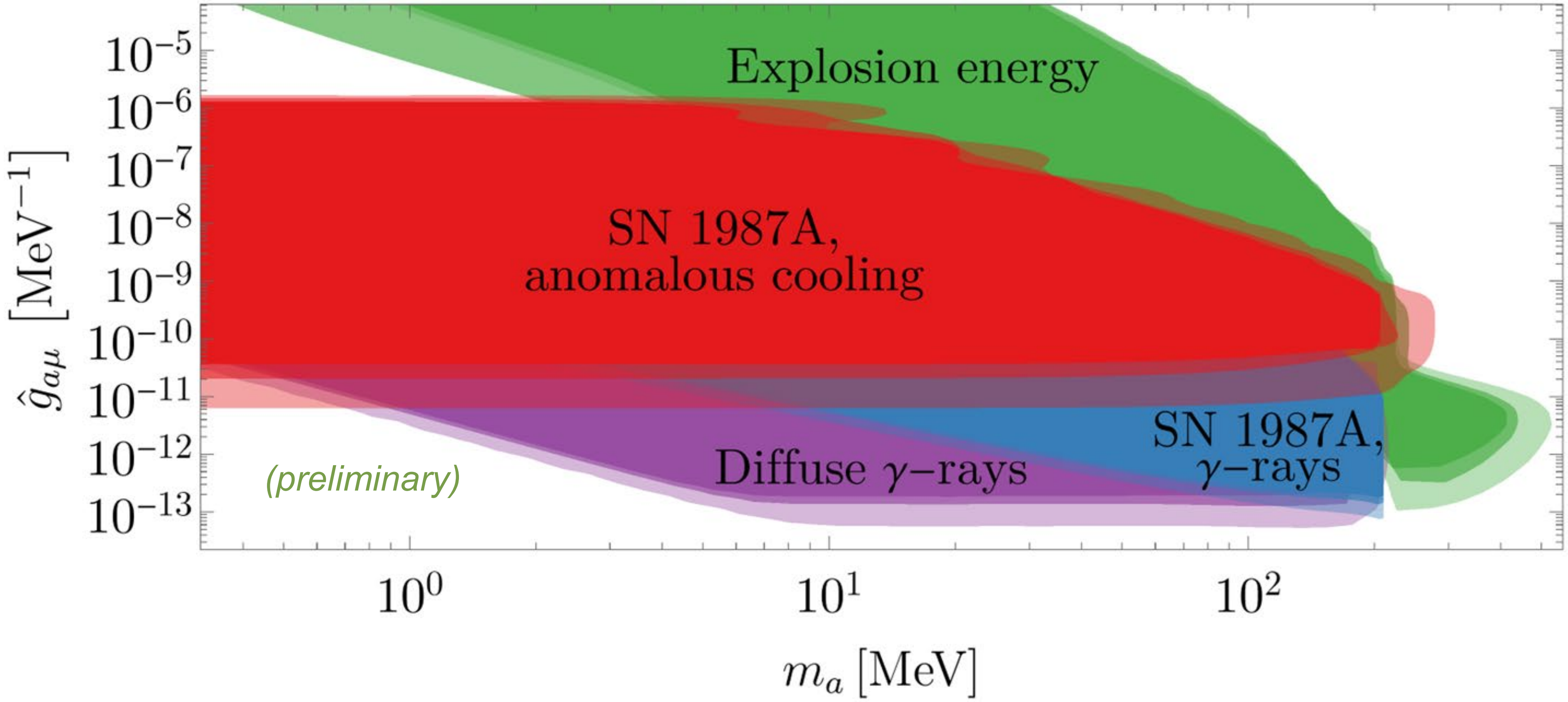
(preliminary)

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

Leptonic ALPs from SNe: Results (electrons)



Leptonic ALPs from SNe: Results (muons)



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“QCD ALPs”

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

→ 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

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

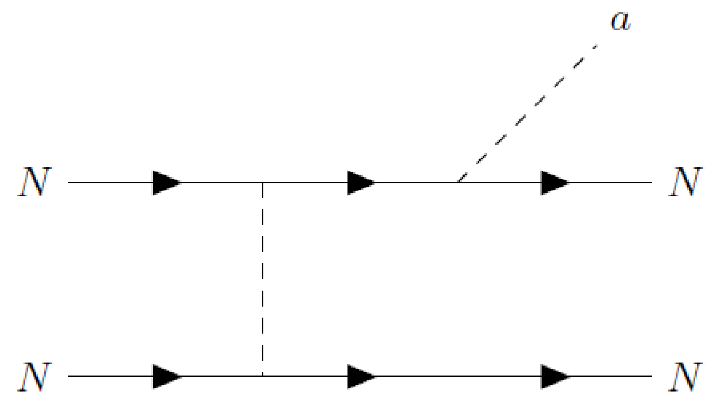
Fundamentally determined by

Couplings to quarks and gluons: c_u, c_d, c_g

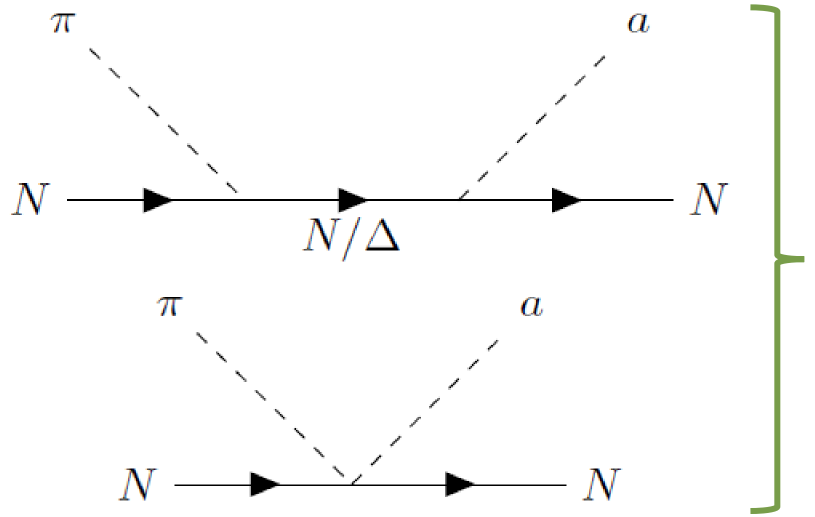
$$g_{a\gamma} = \frac{\alpha}{2\pi\, f_a}\left\{-1.92\, c_g - \frac{m_a^2}{m_\pi^2 - m_a^2}\left[c_g \frac{m_d - m_u}{m_d + m_u} + (c_u - c_d)\right]\right\}$$

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

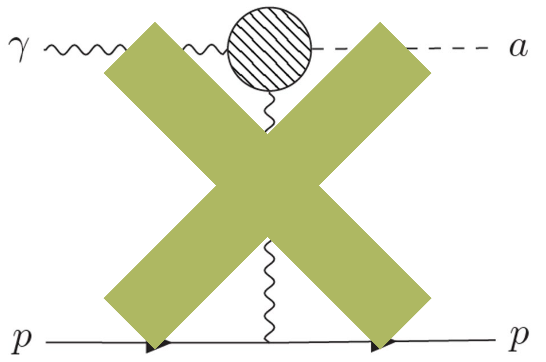
“QCD ALPs” produced in SNe



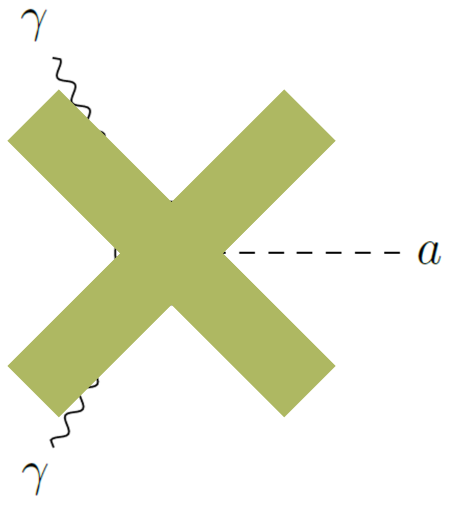
Nucleon-nucleon Bremsstrahlung



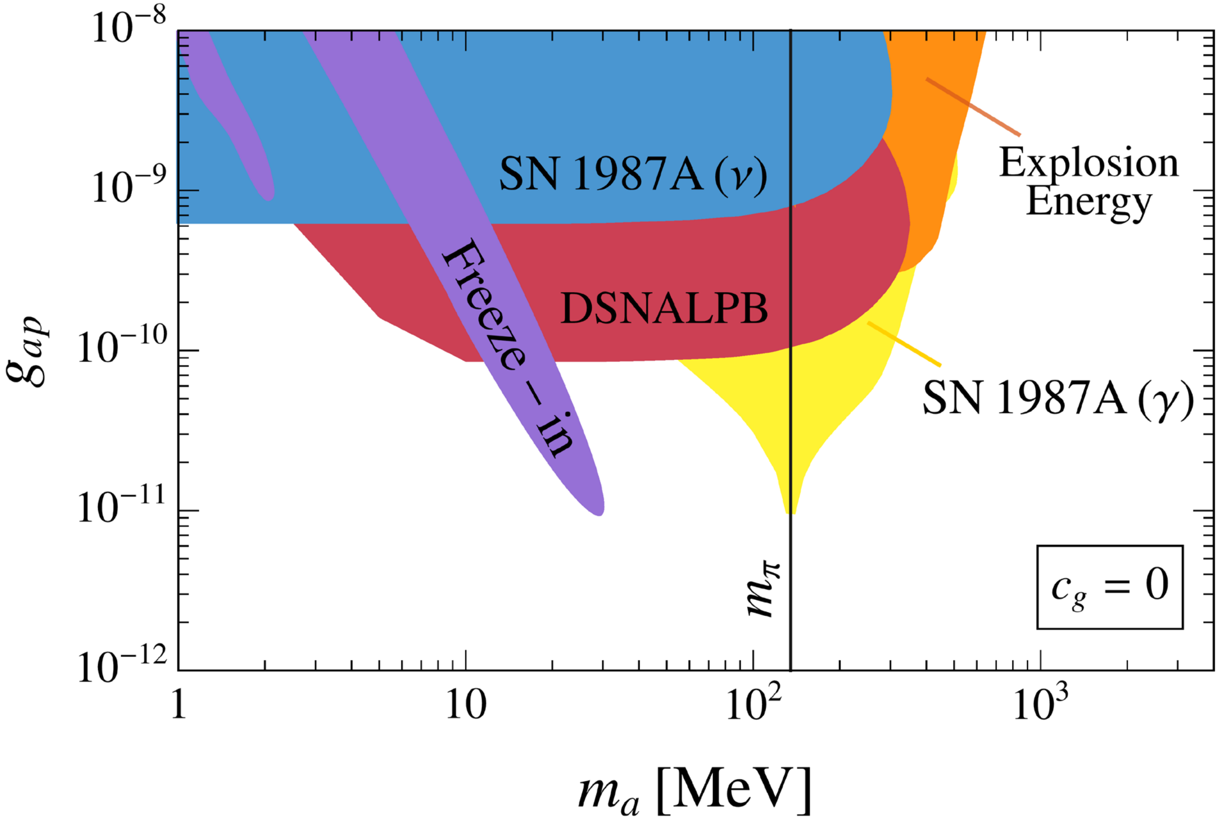
Pion-axion conversion

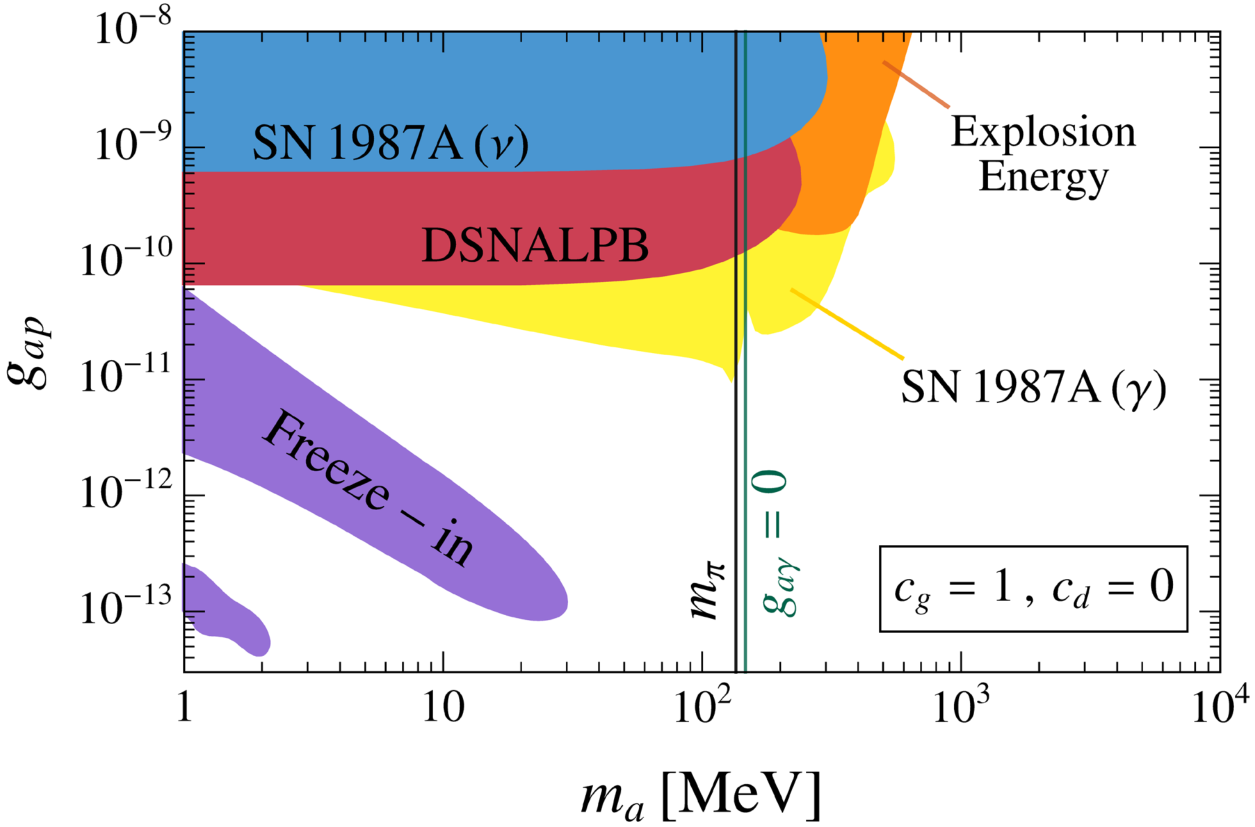


Production via “irreducible” photon interaction is negligible here



“QCD ALPs” from SNe: Results





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

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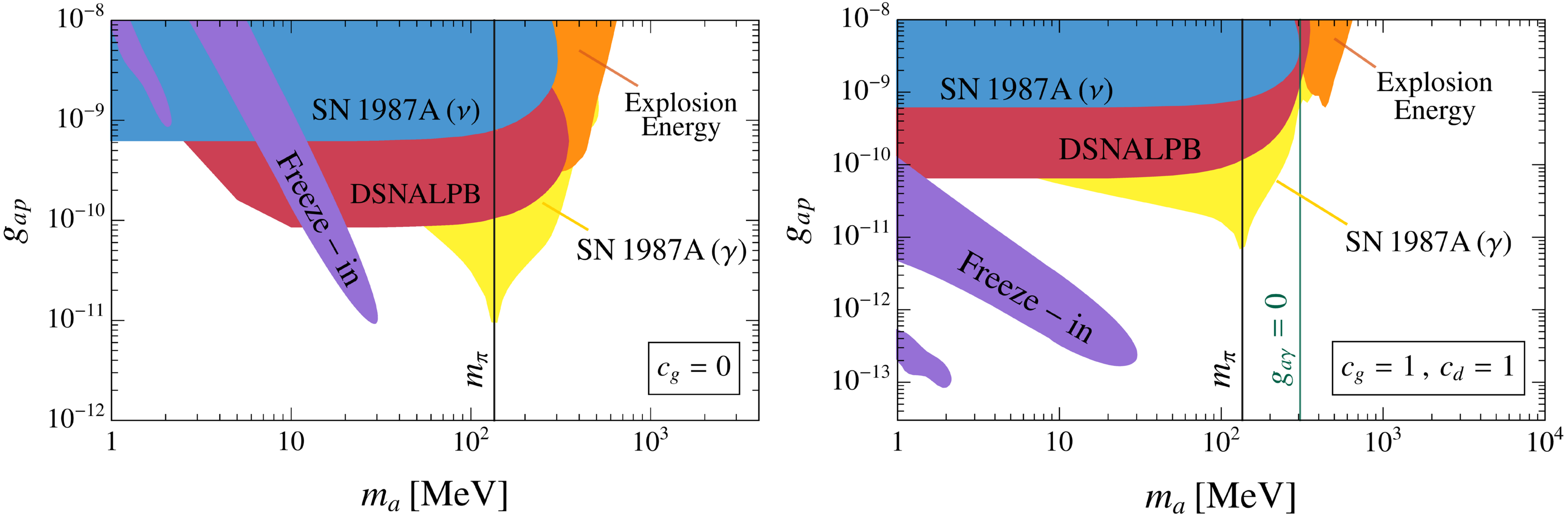


*Lella, **ER**, et al., Phys.Rev.D 110 (2024) 4, 043019*

Conclusion & Outlook

→Supernovae are great laboratories to search for axionlike particles

→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*)

Thanks for your attention!

Back-up slides

ALPs from SNe: Observables

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

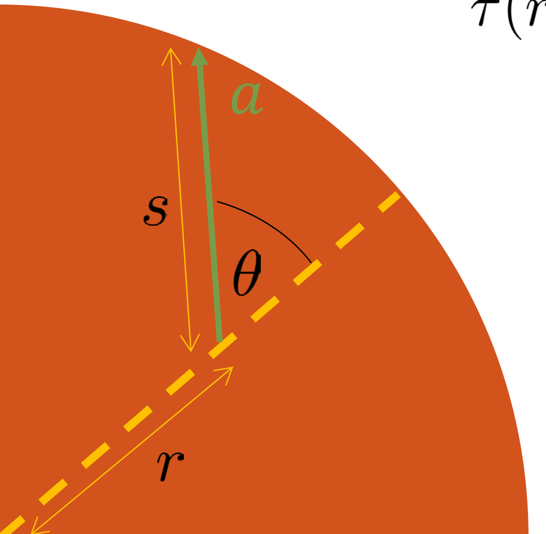
→ In the **Cooling bound** and **Explosion energy bound**, the transmissivity is given as an angular average

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

with the optical depth

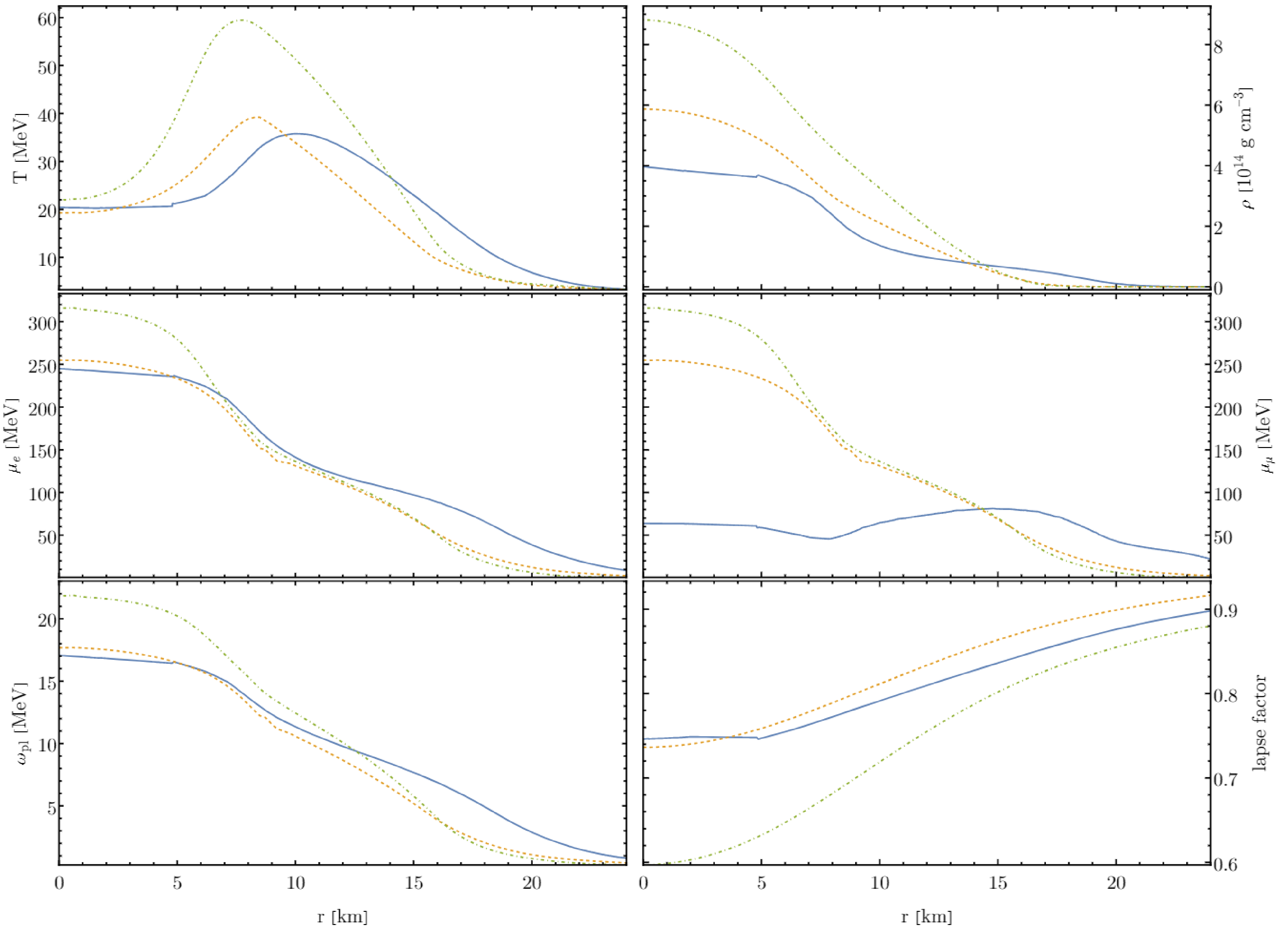
$$\tau(r,\omega_a,\cos\theta) = \frac{1}{2\pi^2}\int_0^{s_{\max}} \mathrm{d}s\, \frac{\omega_a^2 - m_a^2}{\exp[\omega_a/T(r'(s))]-1}\left[\frac{\mathrm{d}^2 n_a}{\mathrm{d}t\,\mathrm{d}\omega_a}(r'(s),\omega_a)\right]^{-1},$$

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

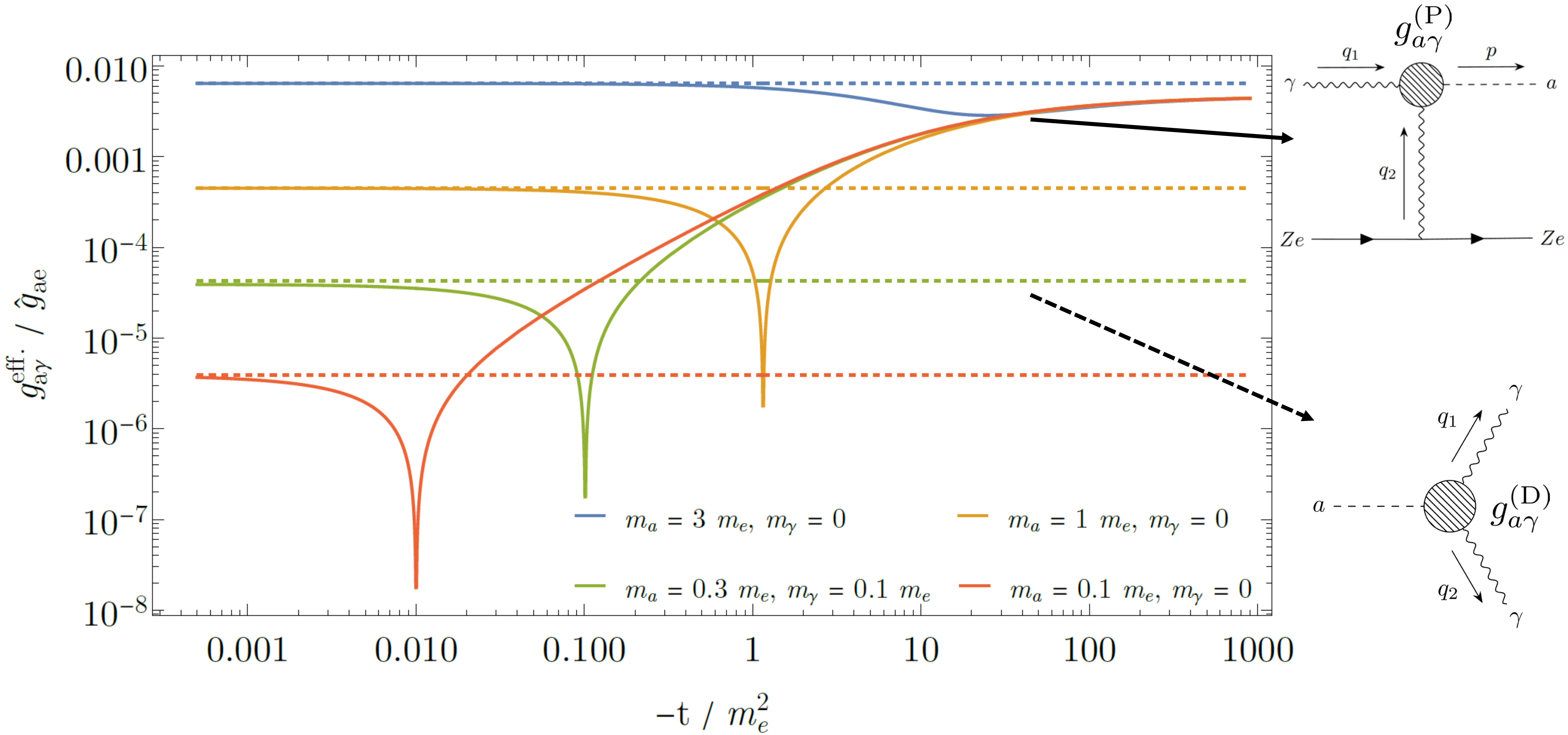


Following Caputo et al., JCAP 08 (2022) 08, 045

Supernova

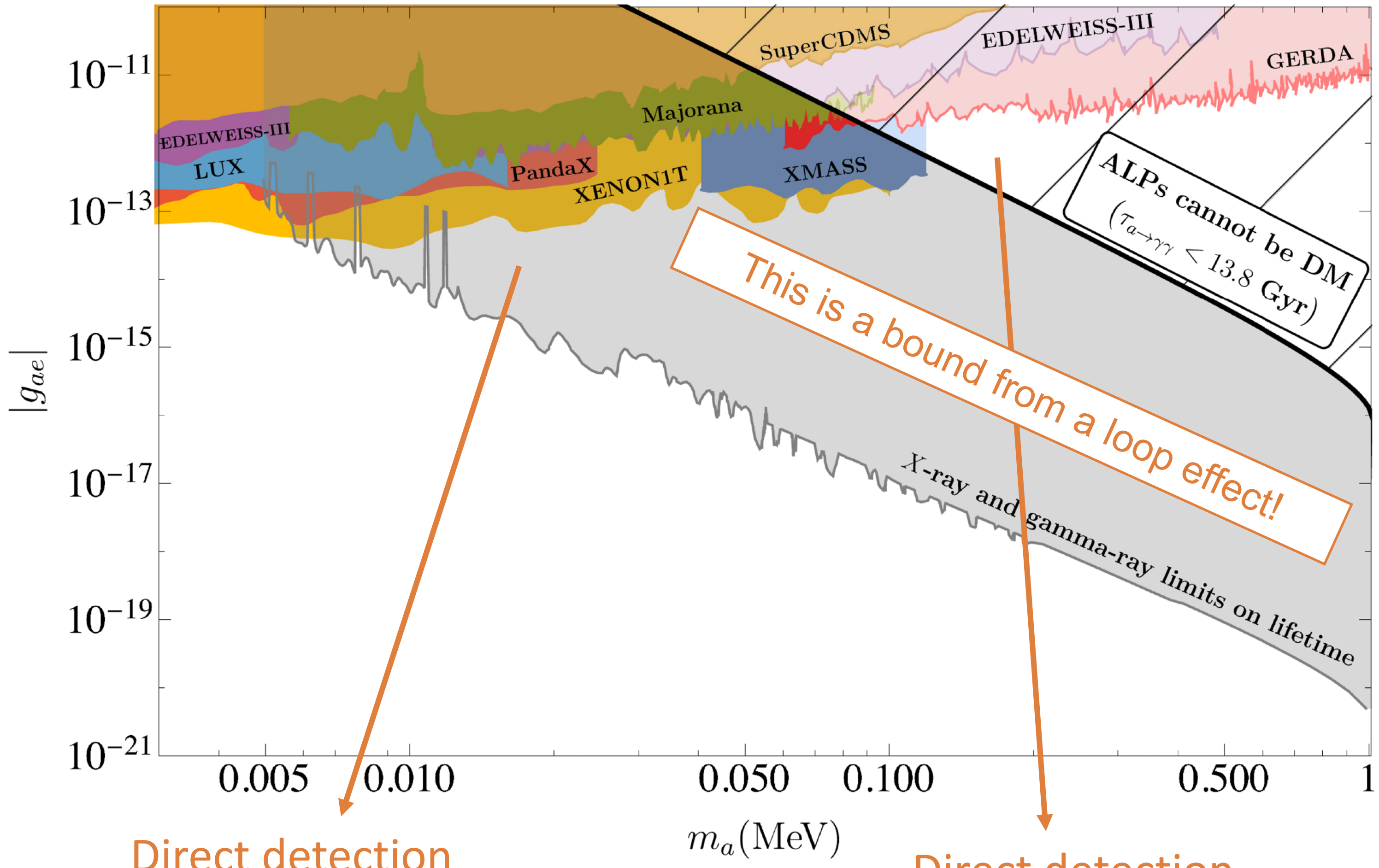

T [MeV]
60
50
40
30
20
10
ρ [10^14 g cm^-3]
8
6
4
2
0
μ_e [MeV]
300
250
200
150
100
50
μ_μ [MeV]
300
250
200
150
100
50
ω_pl [MeV]
20
15
10
5
lapse factor
0.9
0.8
0.7
0.6
0
5
10
15
20
r [km]
0
5
10
15
20
r [km]

The effective ALP-photon coupling



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

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

ALPs from a SN plasma

The spectral rate of change in the number density of ALPs (“production spectrum”) can be calculated using 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.

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

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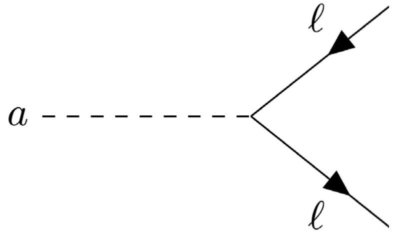
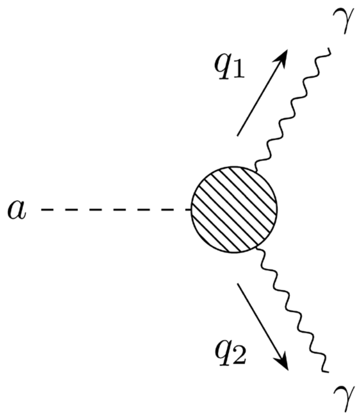
→ALP that is only interacting with electrons or muons (taus are too heavy, not interesting for SNe(?))





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

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