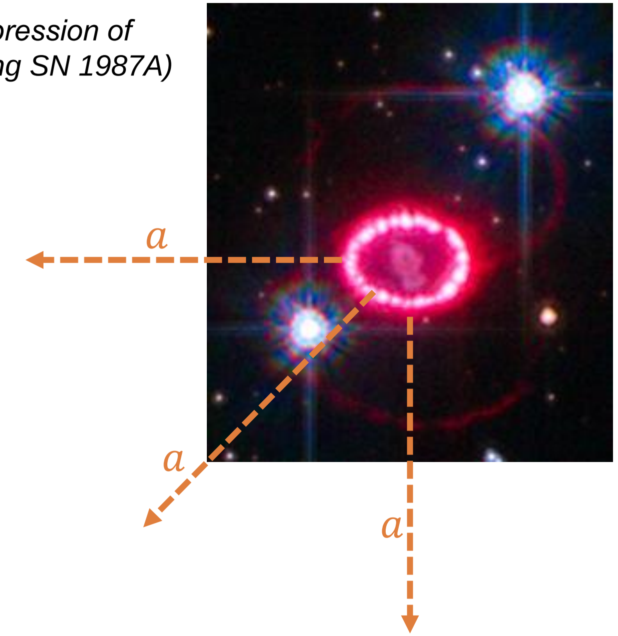
(“artist’s” impression of
axions leaving SN 1987A)



Astrophysical phenomenology of axions (at one-loop order)

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

Based on work with M.C.D. Marsh, R. Ferreira, P. Carenza, C. Eckner, A. Lella, F. Calore, A. Goobar, and M. Meyer

Axions in Stockholm workshop, 2025

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: Leptonic ALPs

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Running photon coupling

For leptonic ALPs (here $\ell = e$) the renormalization group equations are

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

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

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

$$\Rightarrow$$

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

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

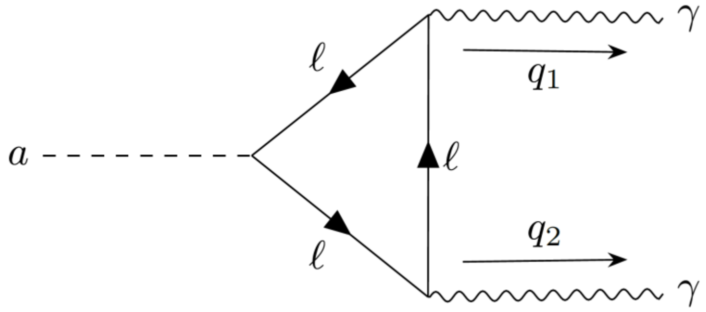
$$\boxed{\cancel{g_{a\gamma}(\mu)}} = \boxed{\cancel{g_{a\gamma}^{\Lambda}}} \frac{\alpha(\mu)}{\alpha(\Lambda)}$$

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

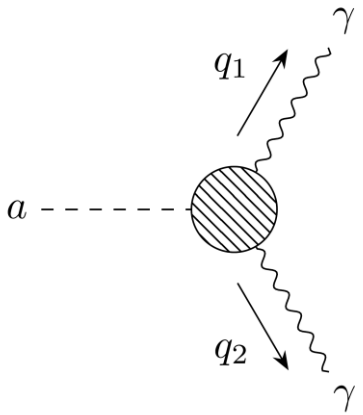
$$\mathcal{L}_{1-\text{loop}} \supset -\frac{1}{2} a(\Box + m_a^2)a + \hat{g}_{ae}(\partial^\mu a)\bar{e}\gamma_5\gamma_\mu e + \frac{1}{4} g_{a\gamma}^{\text{eff}} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Effective photon coupling

Even without an RG-induced coupling, the full lepton loop can still yield an effective photon vertex:



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



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

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

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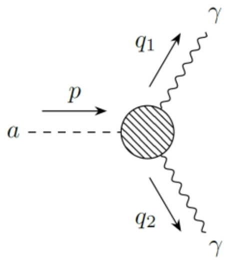
The effective ALP-photon coupling

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

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

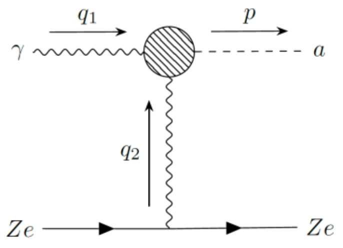
Known for a while: the effective coupling *on-shell*, i.e., in a decay process



$$g_{a\gamma}^{(\mathrm{D})} \equiv g_{a\gamma}^{\mathrm{eff}}(q_1^2 = q_2^2 = 0, p^2 = m_a^2) = \frac{2\alpha}{\pi}\hat{g}_{ae}\left[1 - \frac{4m_e^2}{m_a^2} f^2\left(\frac{4m_e^2}{m_a^2}\right)\right]$$
$$= -\frac{\alpha\hat{g}_{ae}}{6\pi}\left(\frac{m_a}{m_e}\right)^2 + \mathcal{O}\left(\frac{m_a}{m_e}\right)^4$$

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:

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



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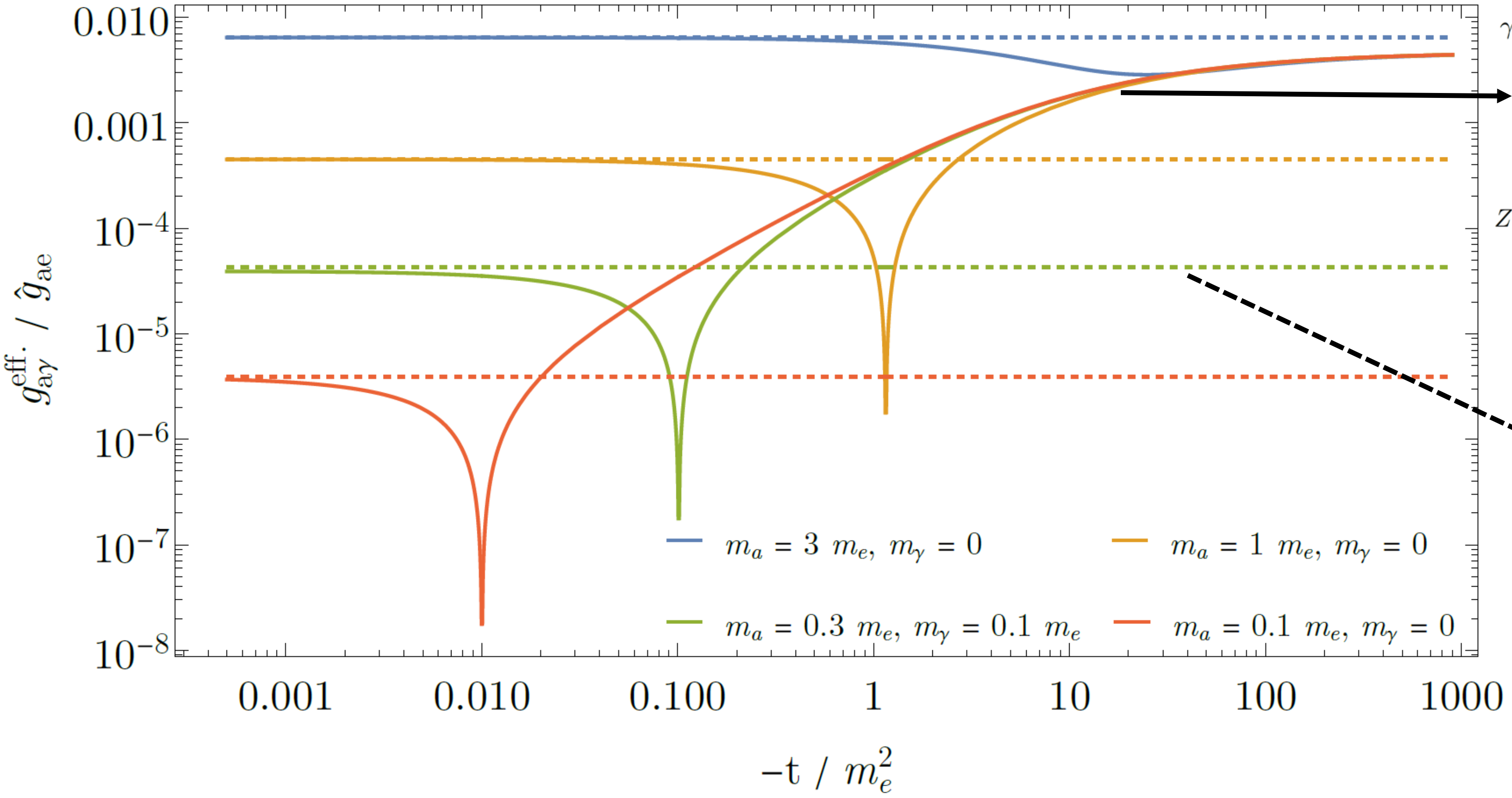
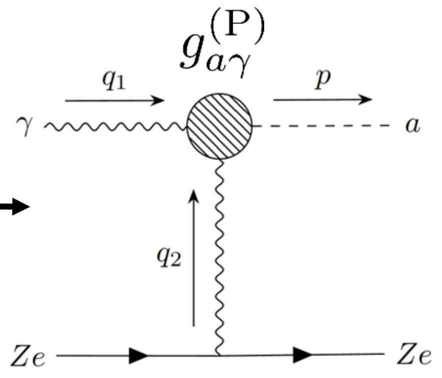
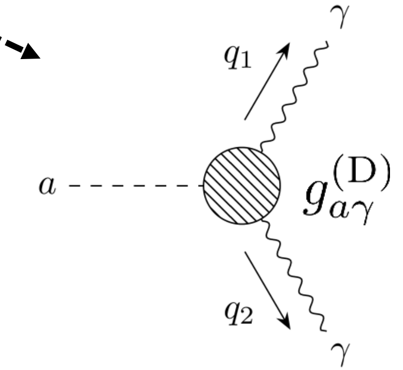
The effective ALP-photon coupling







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

Supernovae – a great lab for new physics

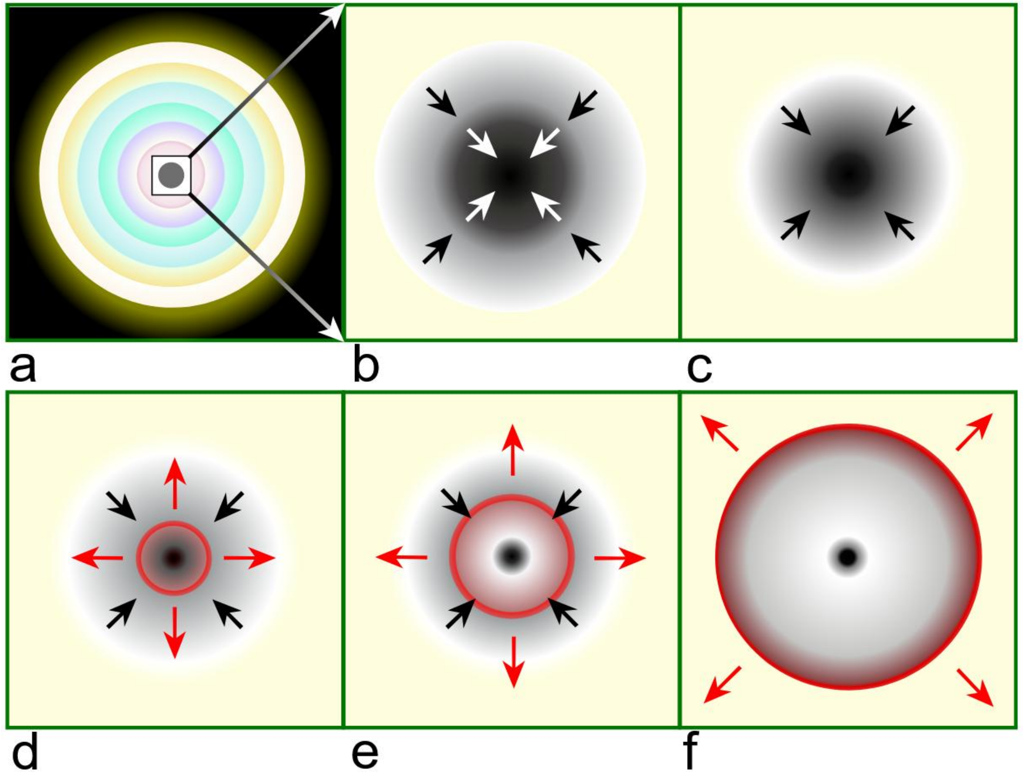
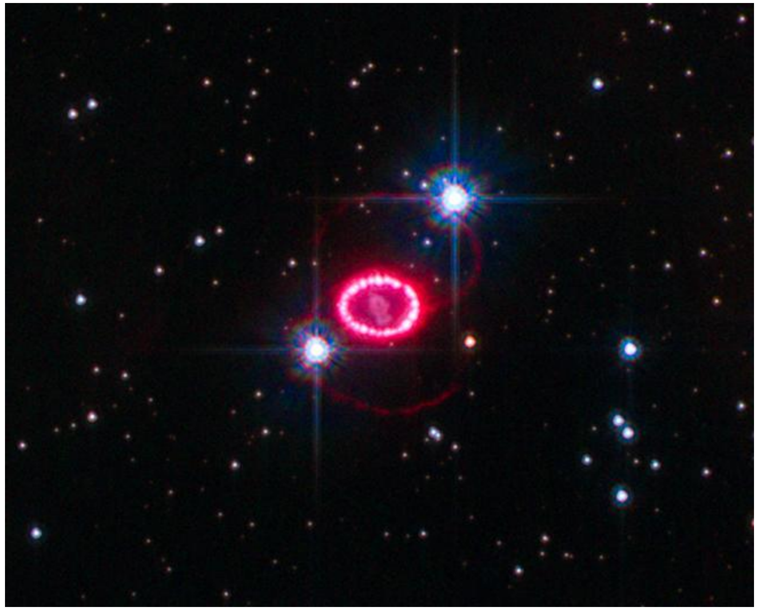
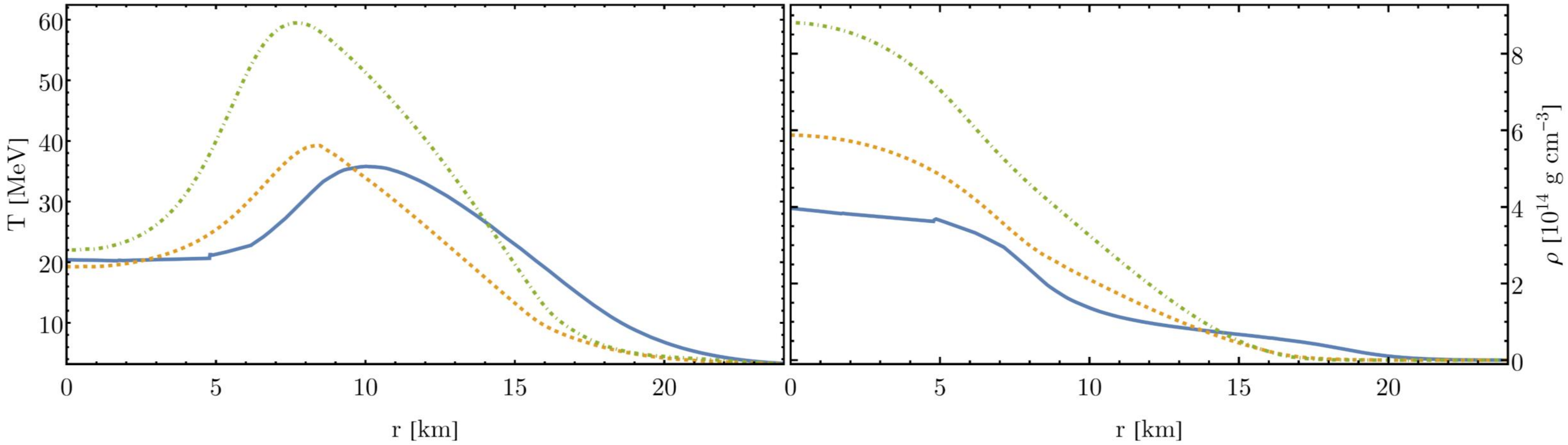


Illustration by R.J. Hall taken from Wikipedia, based on Janka et al., Physics Reports. 442 (1–6): 38–74



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!

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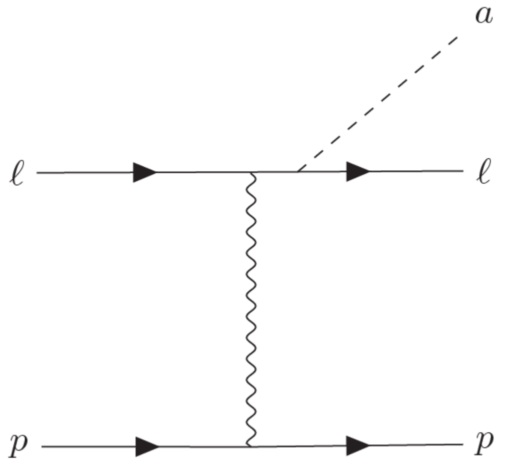
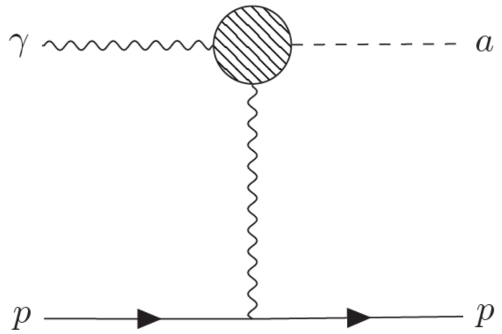
*R. Ferreira, D. Marsh, **EM**, JCAP 11 (2022) 057*
& soon to be published work

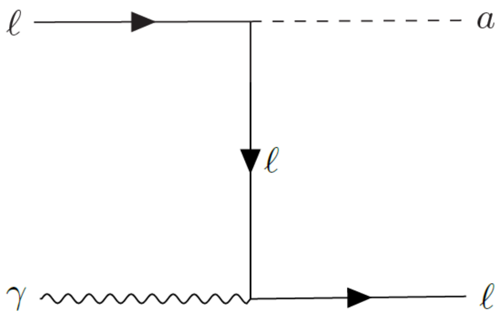
Leptonic ALPs produced in SNe



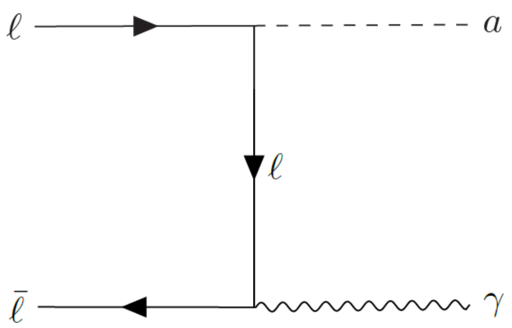
(a) Bremsstrahlung



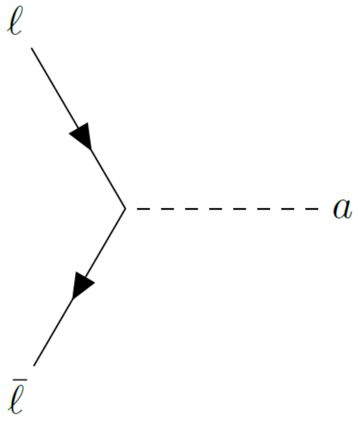
(b) Primakoff process



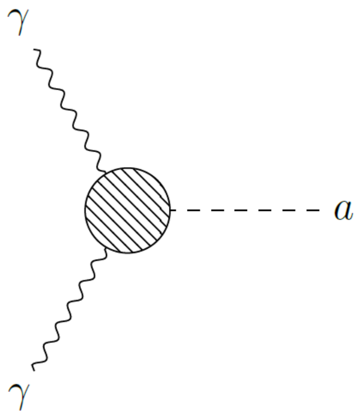
(c) Compton



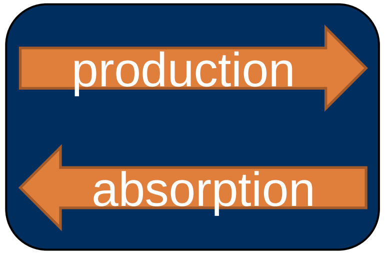
(d) Pair annihilation



(e) Lepton fusion



(f) $\gamma\gamma$-coalescence



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:

$$\frac{\mathrm{d}^2 n_a}{\mathrm{d}t\,\mathrm{d}\omega_a} = \left[\prod_i \int \frac{\mathrm{d}^3\mathbf{p}_i}{(2\pi)^3 2E_i} f_i(E_i)\right]\left[\prod_{j\neq a} \int \frac{\mathrm{d}^3\mathbf{p}'_j}{(2\pi)^3 2E'_j} \left[1 \pm f_j(E'_j)\right]\right]$$
$$\times (2\pi)^4 \delta^{(4)}\left(\sum_i p_i - \sum_j p'_j\right) S\, \frac{|\mathbf{p}'_a|}{4\pi^2} |\mathcal{M}|^2\,,$$

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

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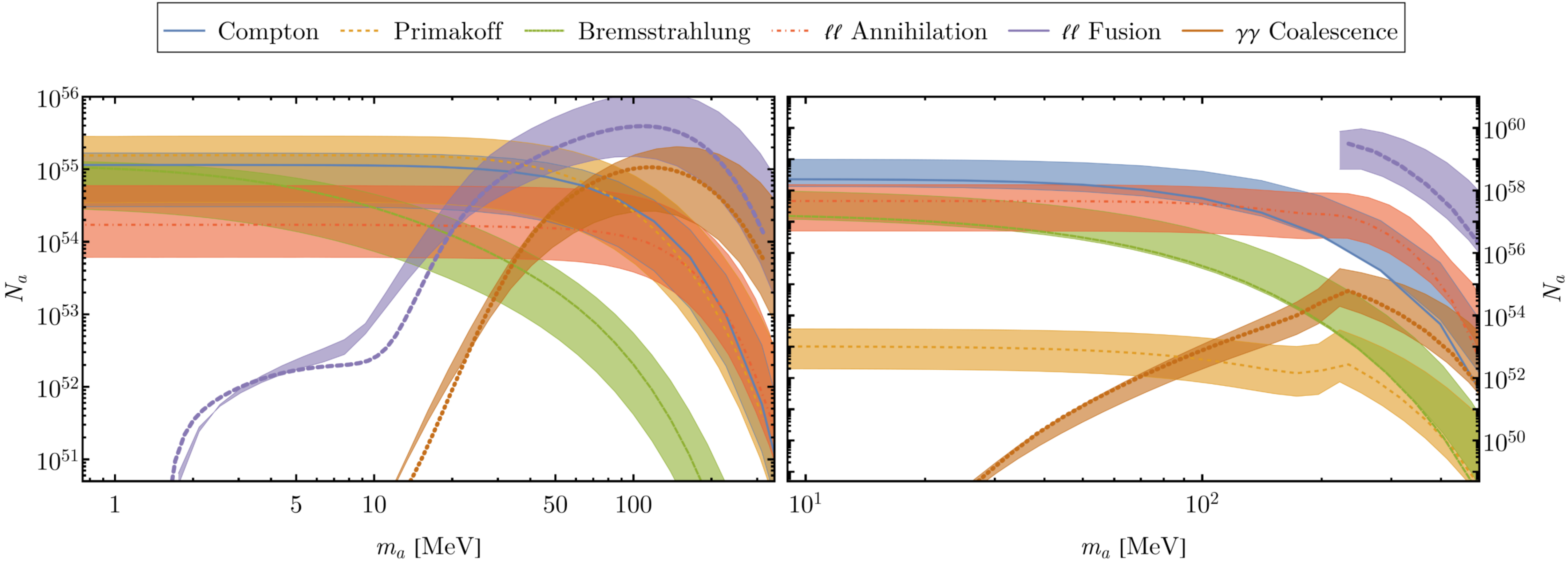
Leptonic ALPs produced in SNe



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

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

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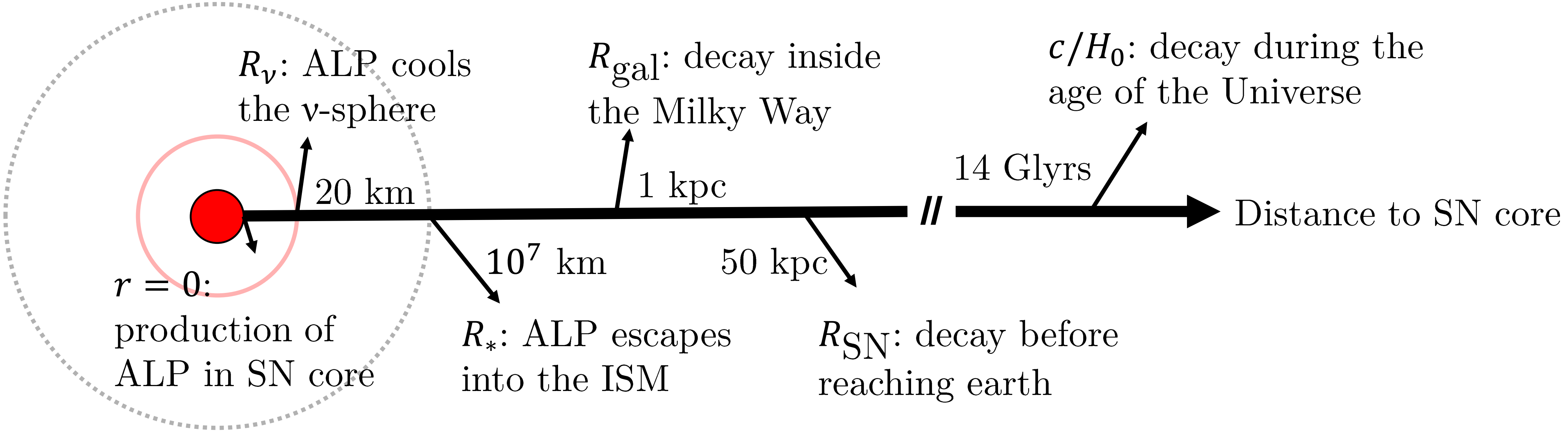
ALPs from SNe: Observables



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

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

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

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

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

ALPs from SNe: Observables

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

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

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

Diffuse gamma-ray bound, from all past SNe

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

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

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

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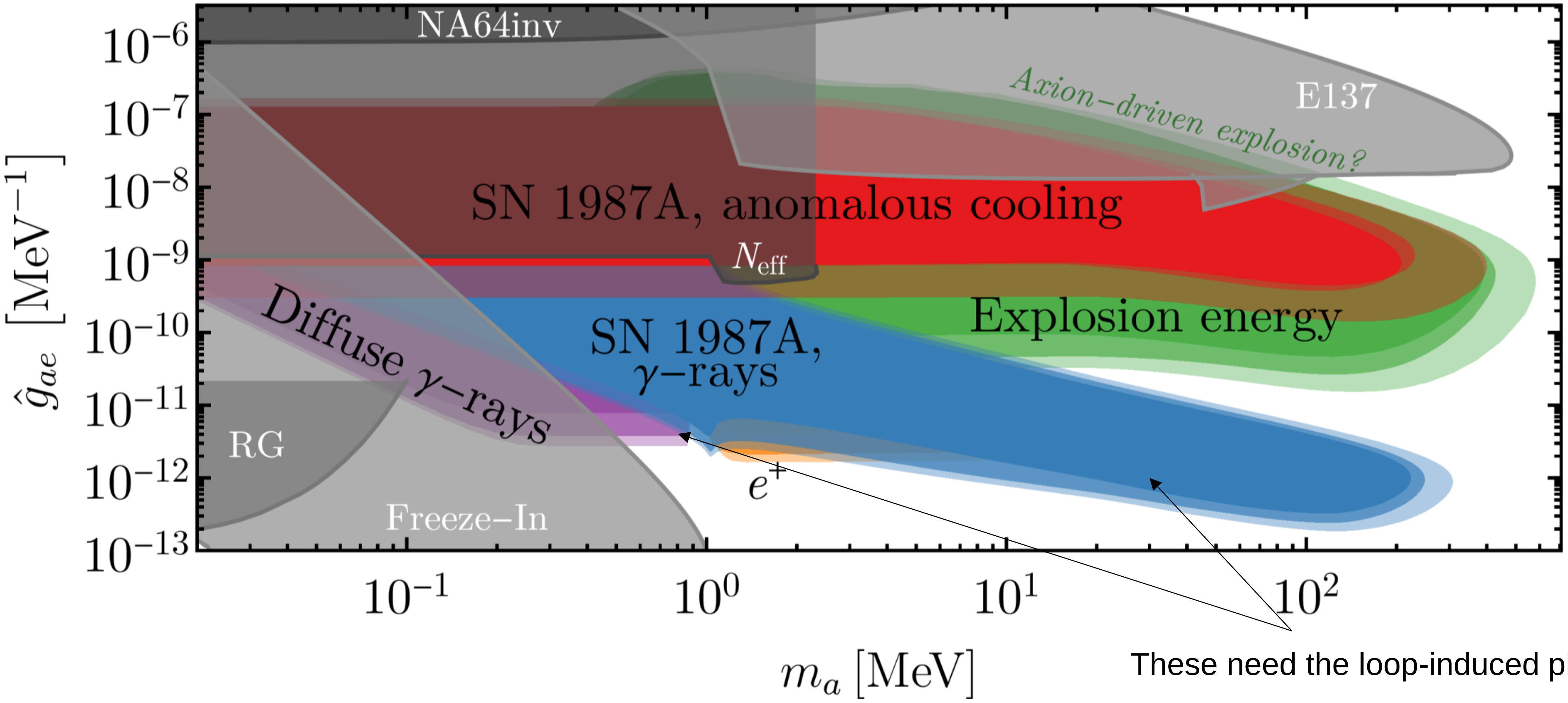
Leptonic ALPs from SNe: Results (electrons)



(preliminary)

These need the loop-induced photon coupling

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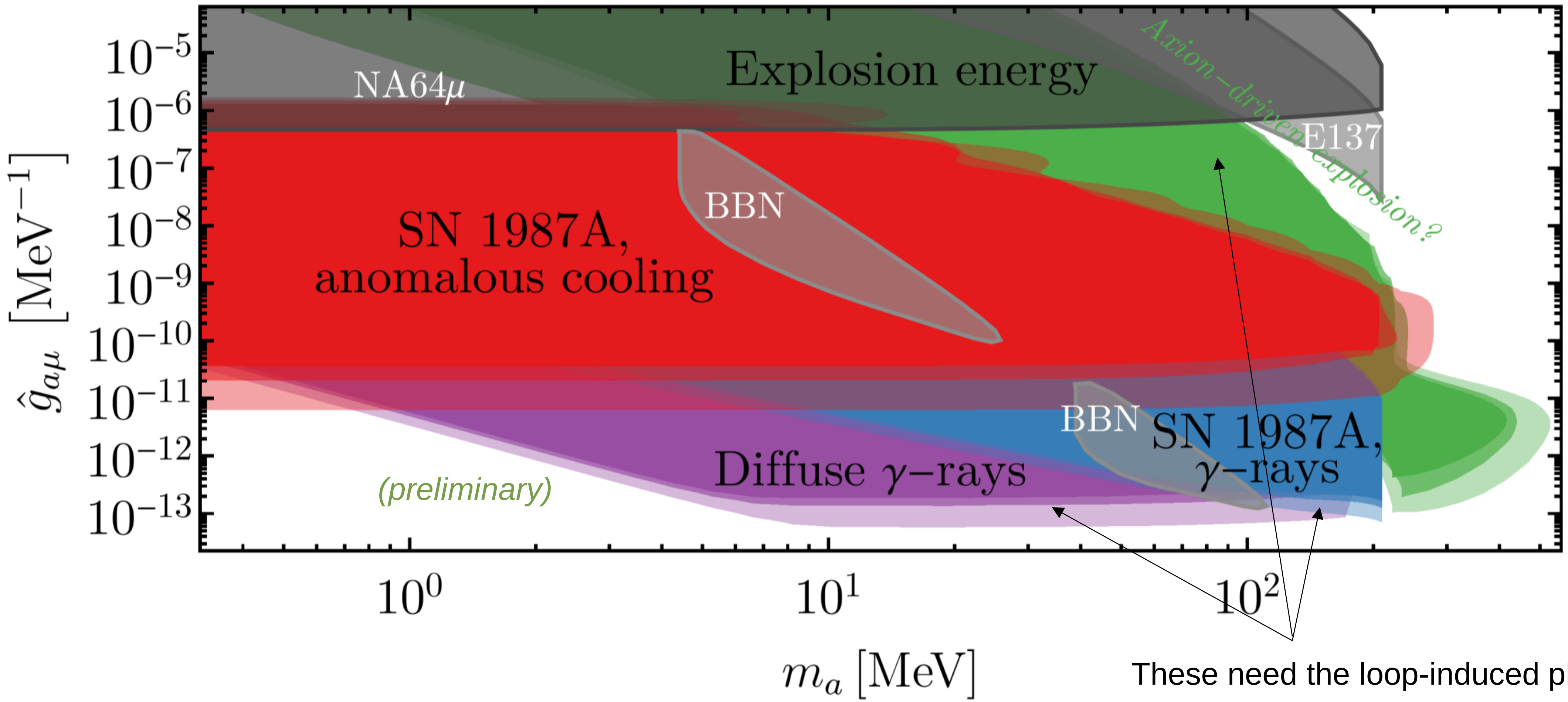
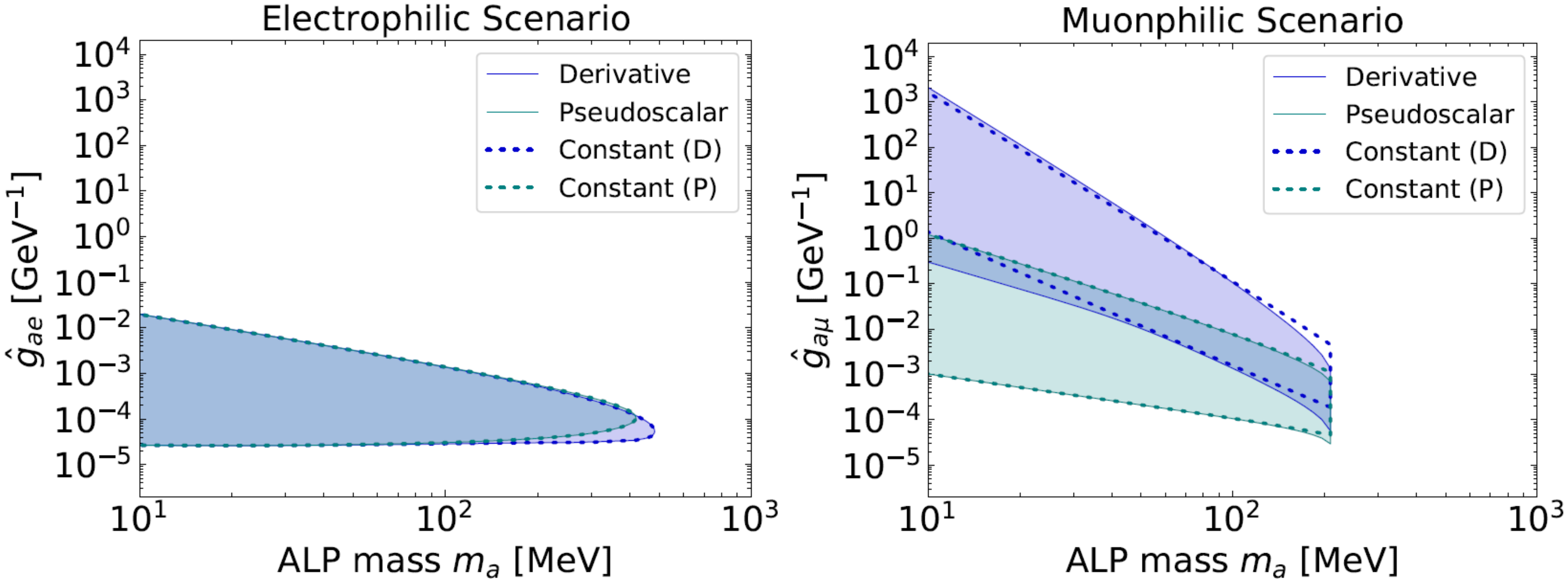
Leptonic ALPs from SNe: Results (muons)



These need the loop-induced photon coupling

Leptonic ALPs: Loops in E137 beamdump



Different colors ~ effect of 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

“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

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

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

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

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!

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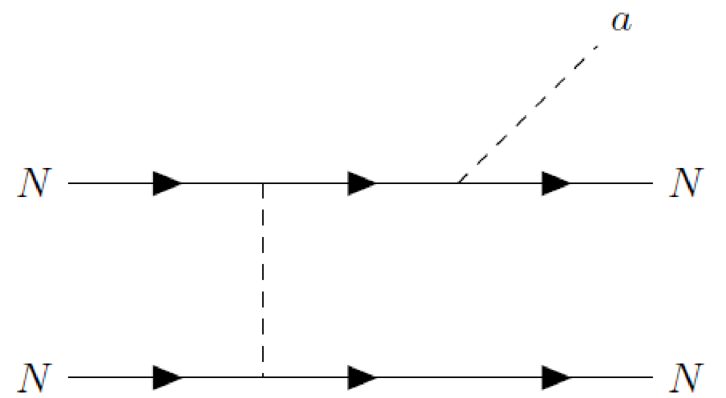
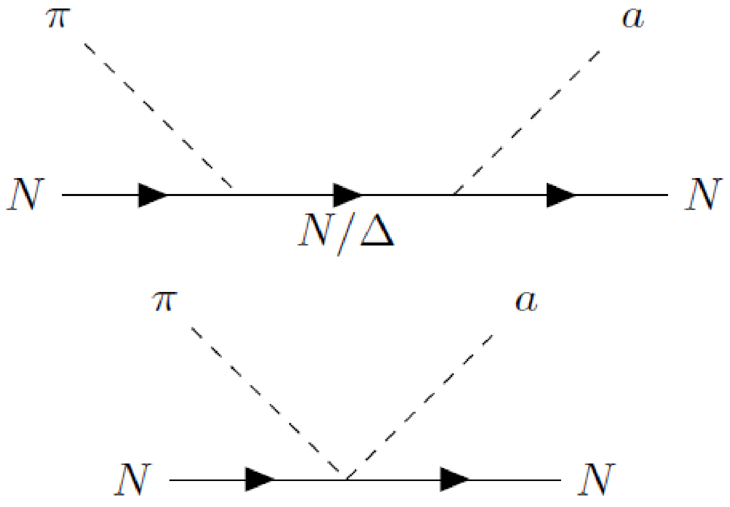
*Lella, **ER**, et al., Phys.Rev.D 110 (2024) 4, 043019*

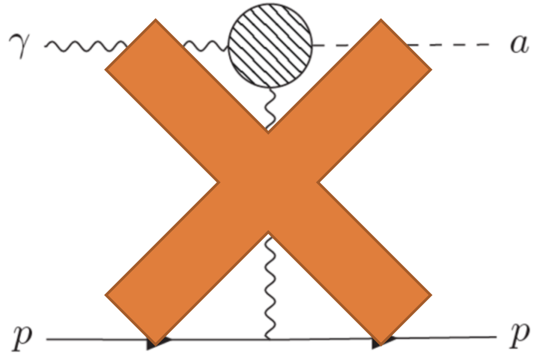
“QCD ALPs” produced in SNe



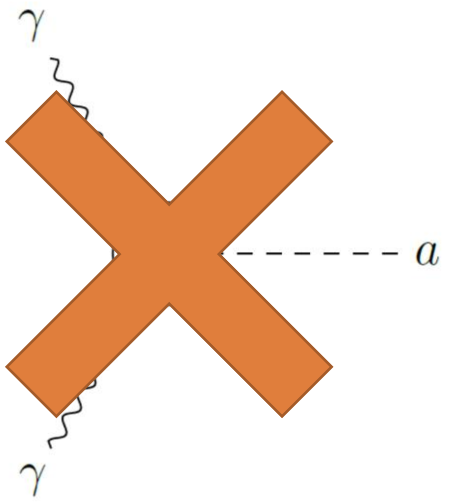
Nucleon-nucleon Bremsstrahlung



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

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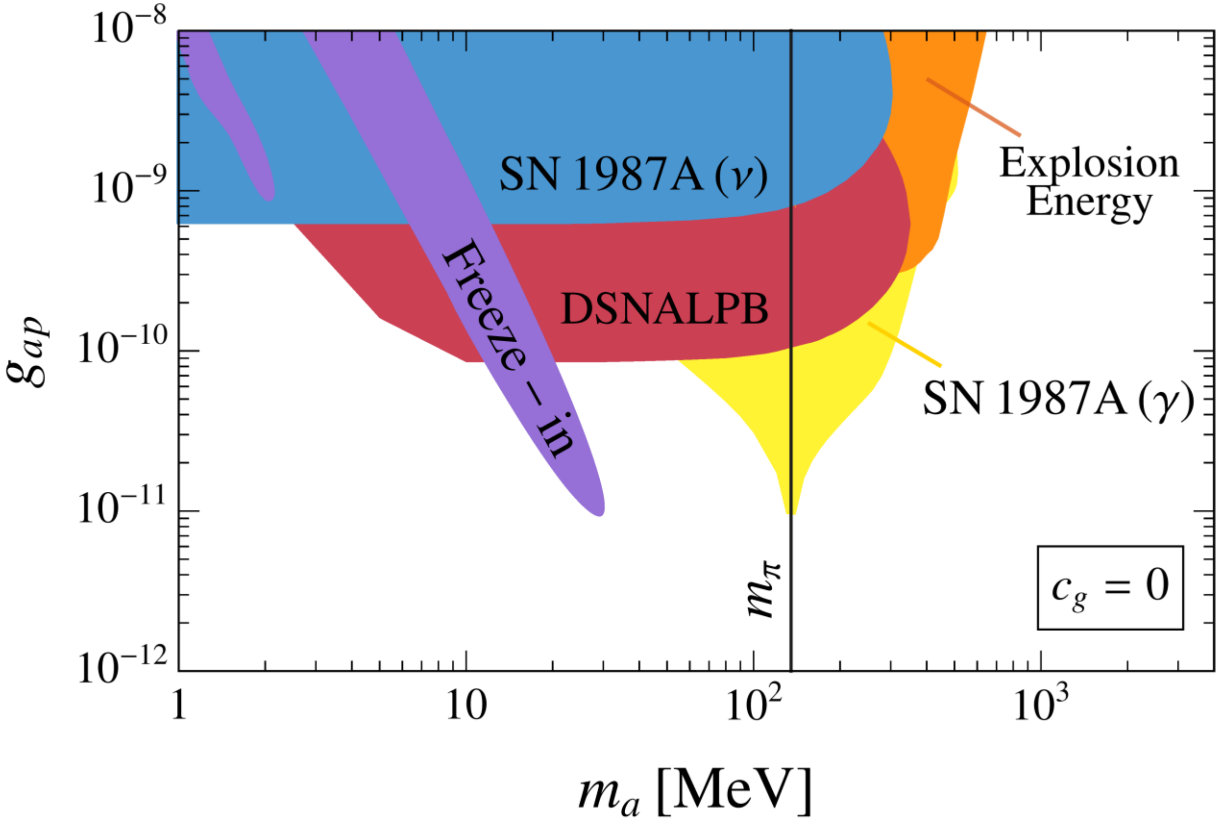
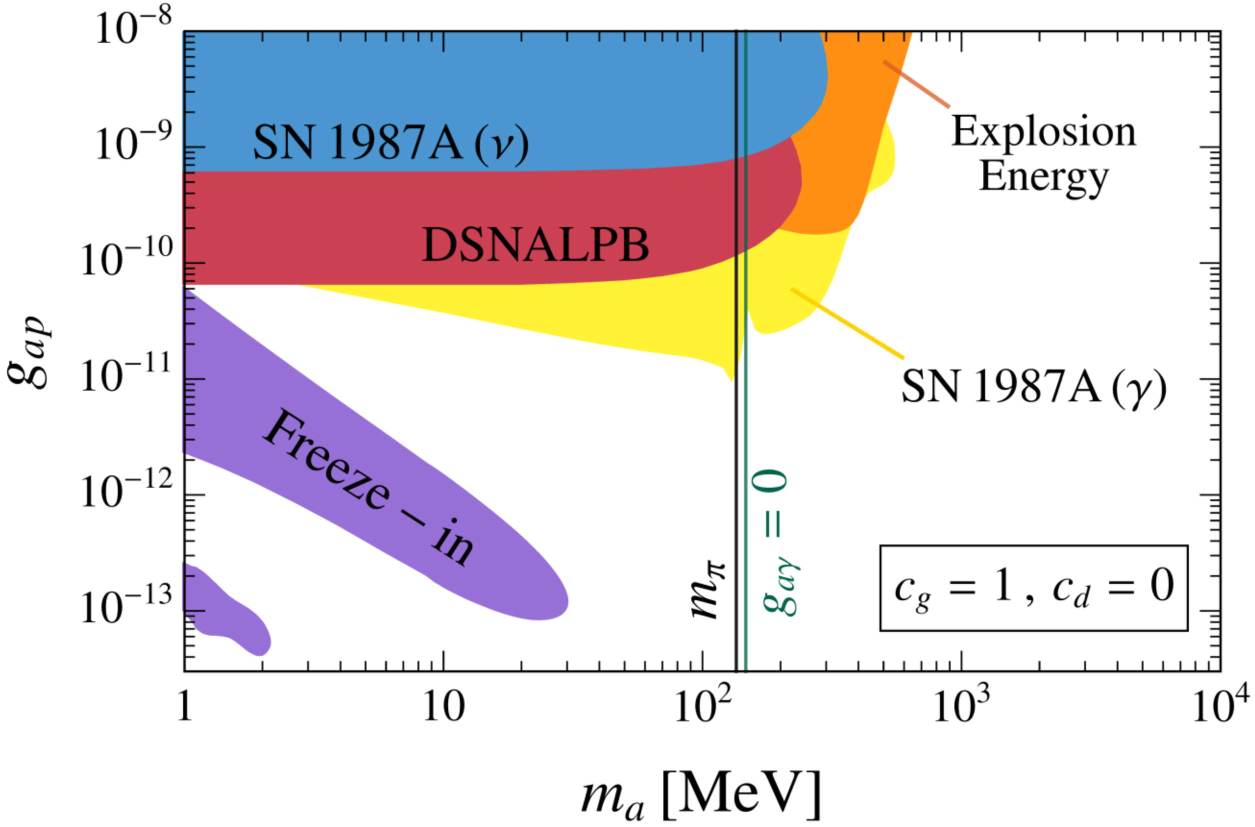
“QCD ALPs” from SNe: Results





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

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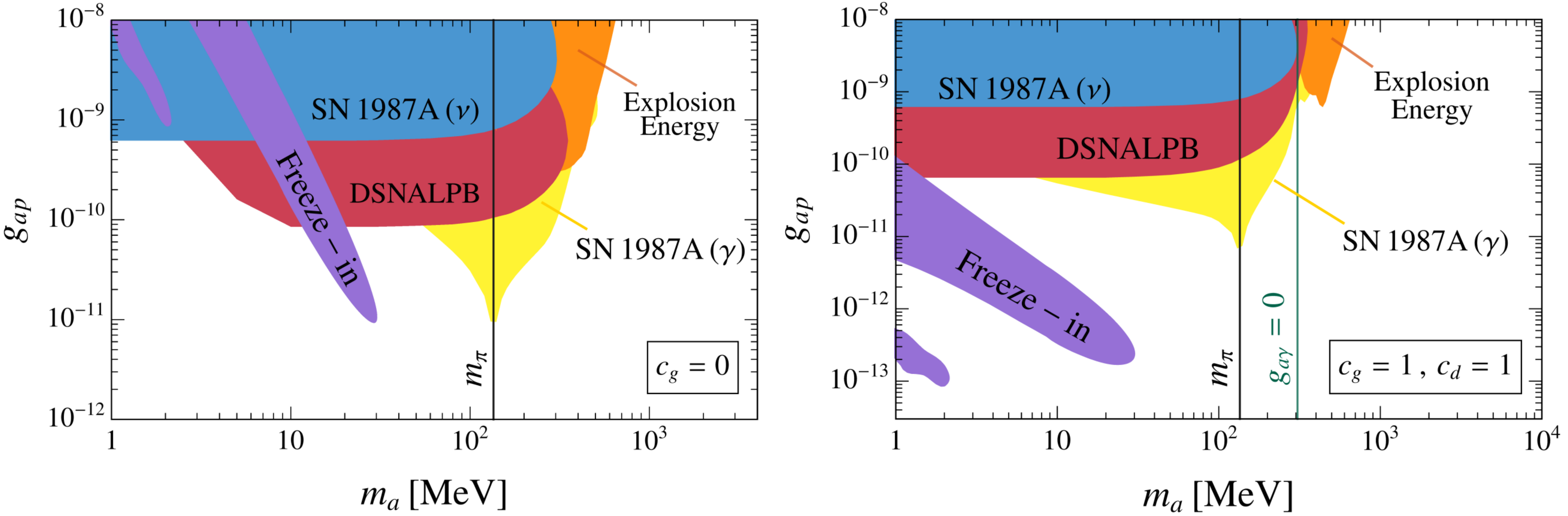
These results assume $g_{an} = 0$ for definiteness.

“QCD ALPs” from SNe: Results



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

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Axionlike particles: Standard, photophilic case

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→ 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

SDU

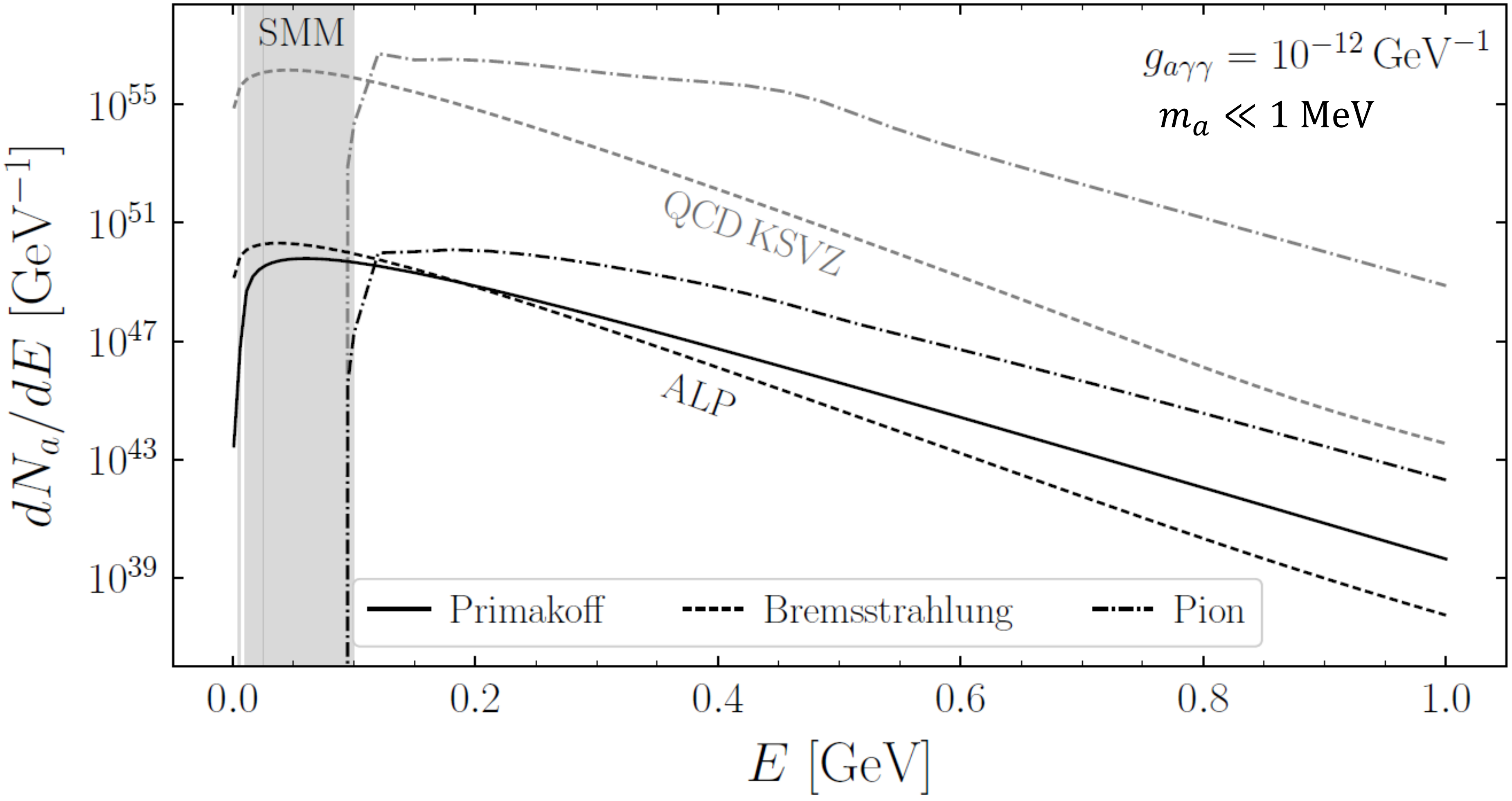
From: *Manzari, Park, Safdi, Savoray, Phys.Rev.Lett.* 133 (2024) 21, 211002

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)



SDU

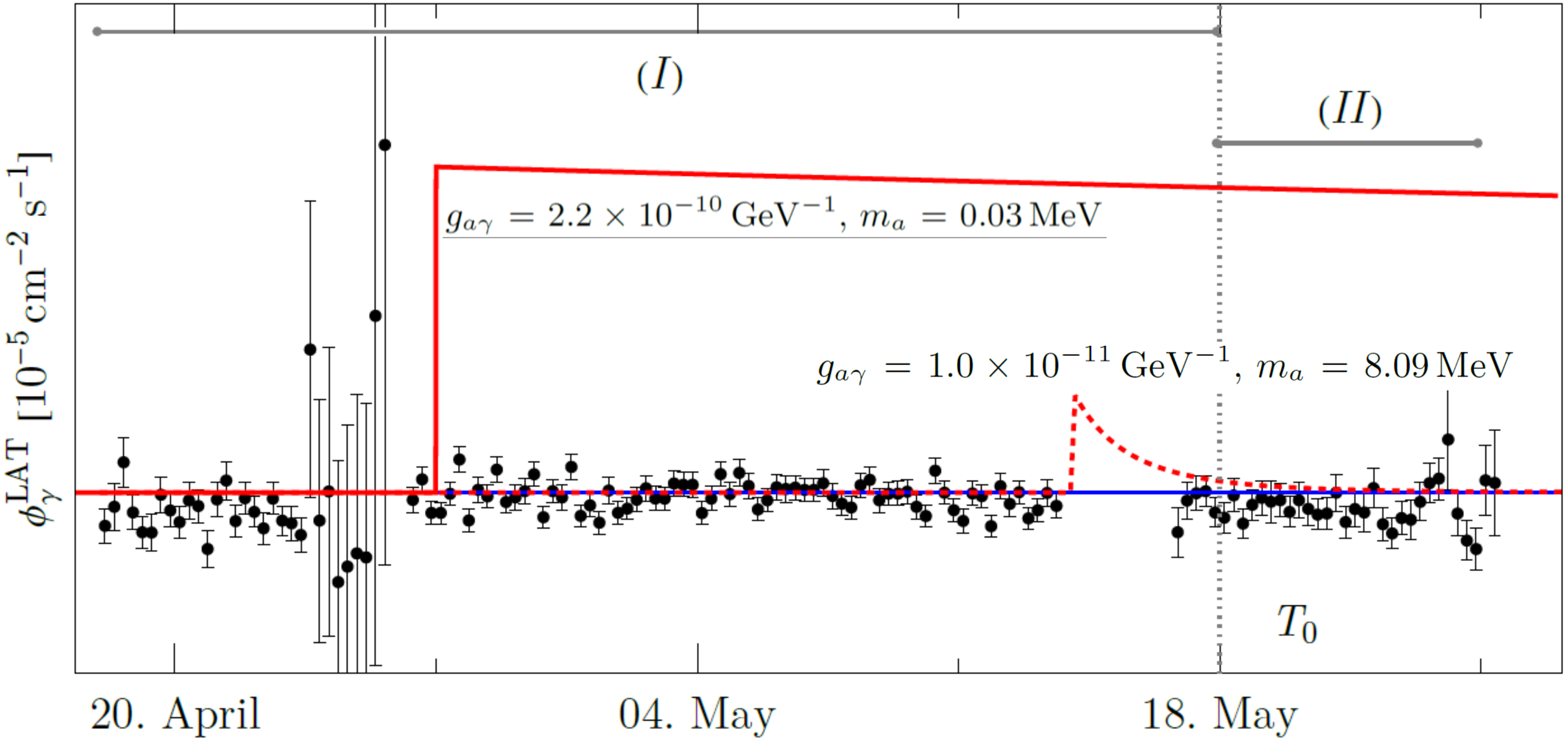
Axionlike particles:
One-loop effects for astro-phenomenology

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 $g_{aN},\ g_{a\pi}, \ldots$
ALP-photon coupling $g_{a\gamma}$	ALP-QCD couplings $g_{aN},\ g_{a\pi}, \ldots$ (via RG running)	For ALP-production in SNe at least (with a high density of nuclear matter)
ALP-QCD couplings $g_{aN},\ g_{a\pi}, \ldots$	ALP-photon coupling $g_{a\gamma}$ (construction of IR EFT)	Yields observable signals

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:



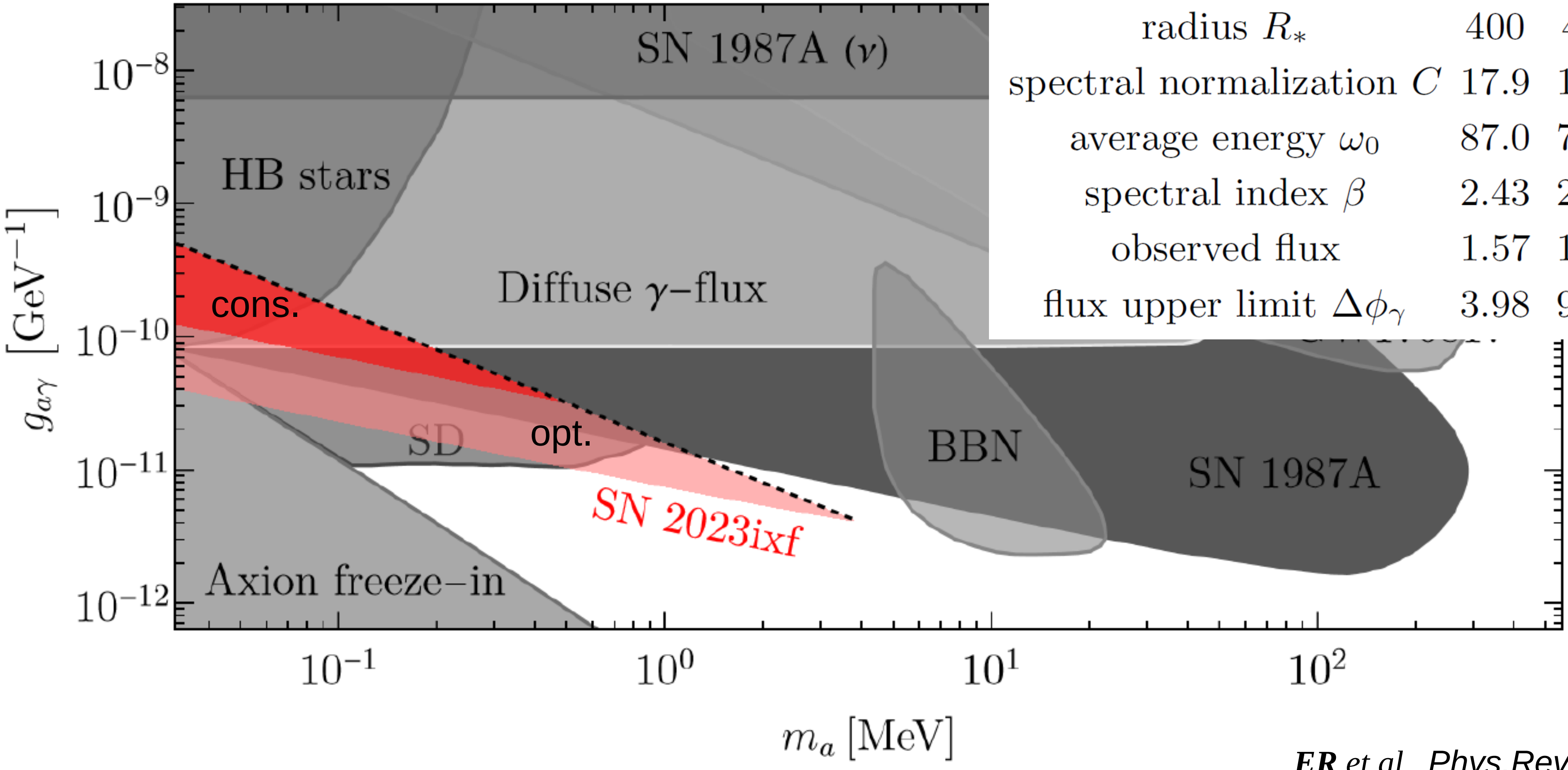
SDU

***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 $R_{\rm SN}$	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	$10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$



SDU

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

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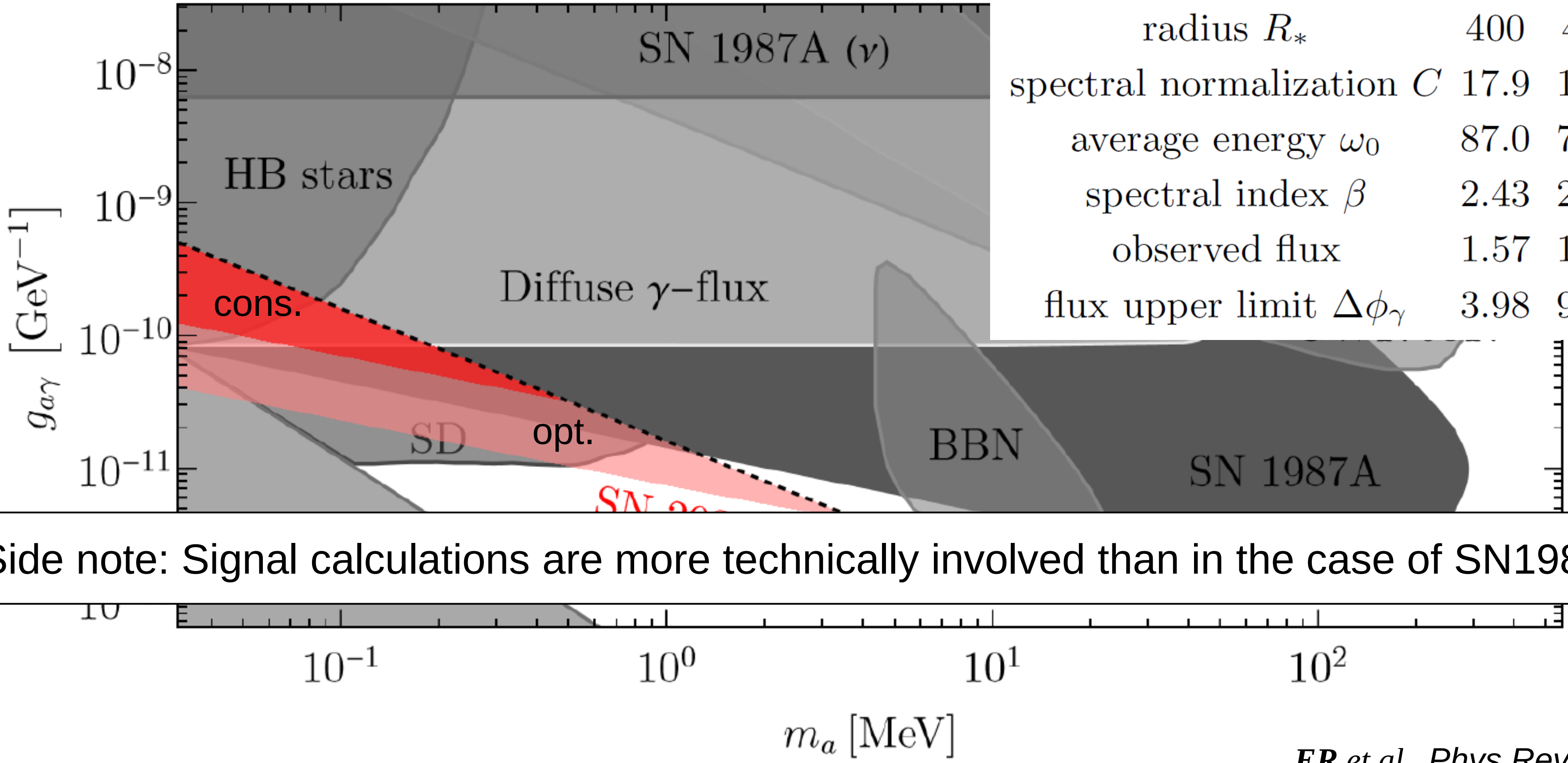


Side note: Signal calculations are more technically involved than in the case of SN1987A!

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

→ Upcoming:

- → Comprehensive SN constraints for leptonic ALPs
  (with M.C.D. Marsh and R. Ferreira)
- → *Fermi*-LAT search for the time signature of ALP-induced gamma-ray bursts from nearby SNe
  (with M. Meyer, P. Carenza, C. Eckner, A. Goobar)
- → Directly observing SN ALPs in neutrino detectors
  (with M. Meyer, N. Nath, P. Carenza)

Thanks for your attention!

SDU

Back-up slides

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

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

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

The QCD axion

The strong CP problem

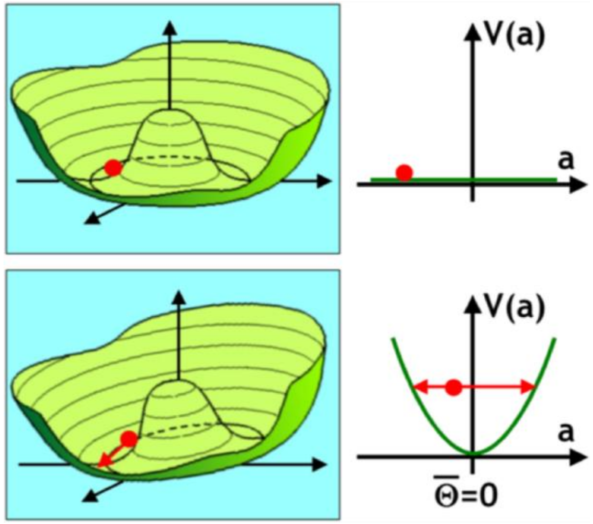
The neutron has no observable electric dipole moment:

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

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**

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

ALPs from SNe: Observables

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

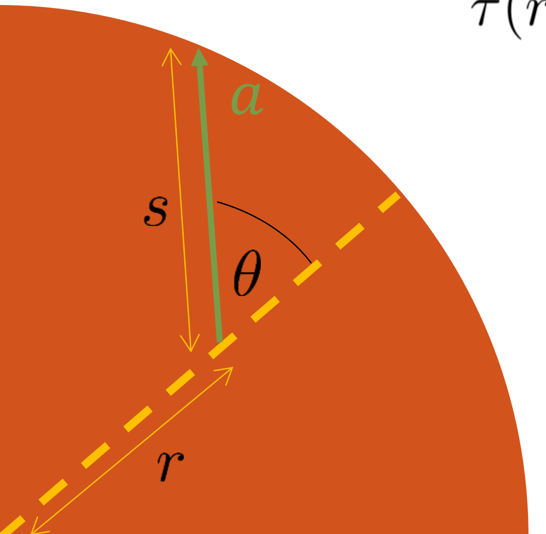
→ In the **Cooling bound** and **Explosion energy bound**, the transmissivity is given as an angular average

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

with the optical depth

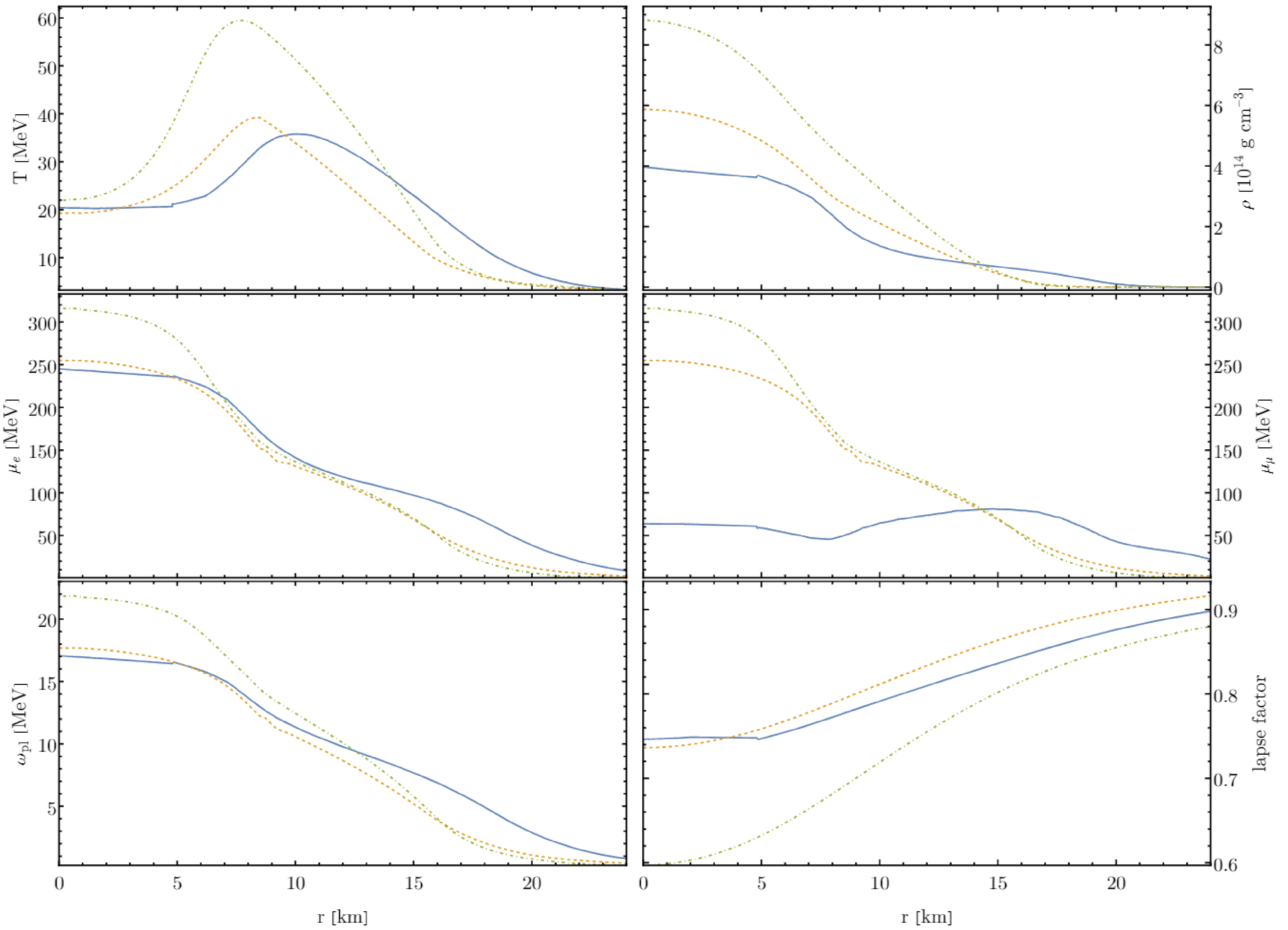
$$\tau(r,\omega_a,\cos\theta) = \frac{1}{2\pi^2}\int_0^{s_{\max}} \mathrm{d}s\, \frac{\omega_a^2 - m_a^2}{\exp[\omega_a/T(r'(s))]-1}\left[\frac{\mathrm{d}^2 n_a}{\mathrm{d}t\,\mathrm{d}\omega_a}(r'(s),\omega_a)\right]^{-1},$$

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



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

Supernova models from simulations



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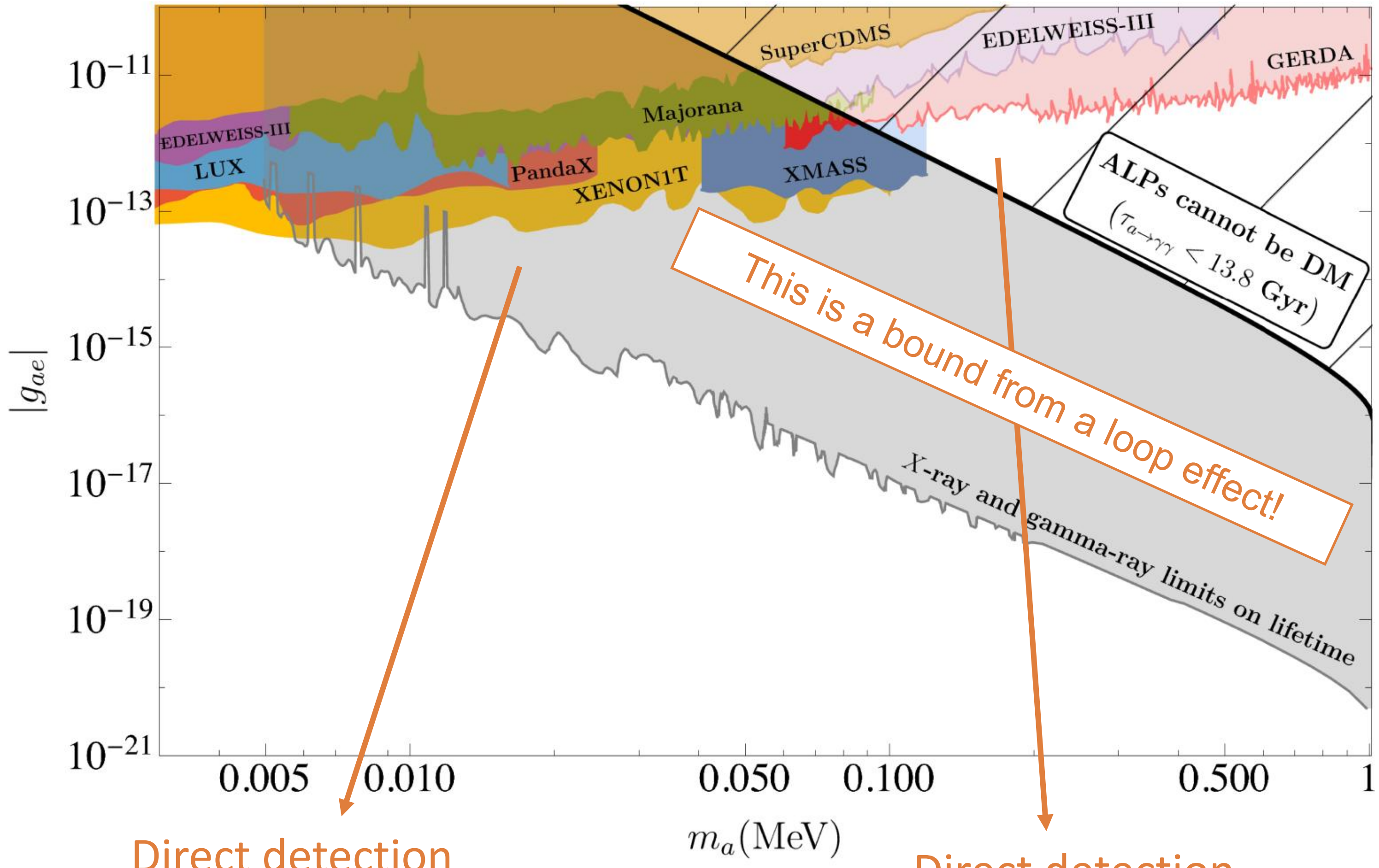
ALPs decay into photons



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

SDU

ALP-electron interactions in a plasma

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

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

Taking plasma effects into account

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

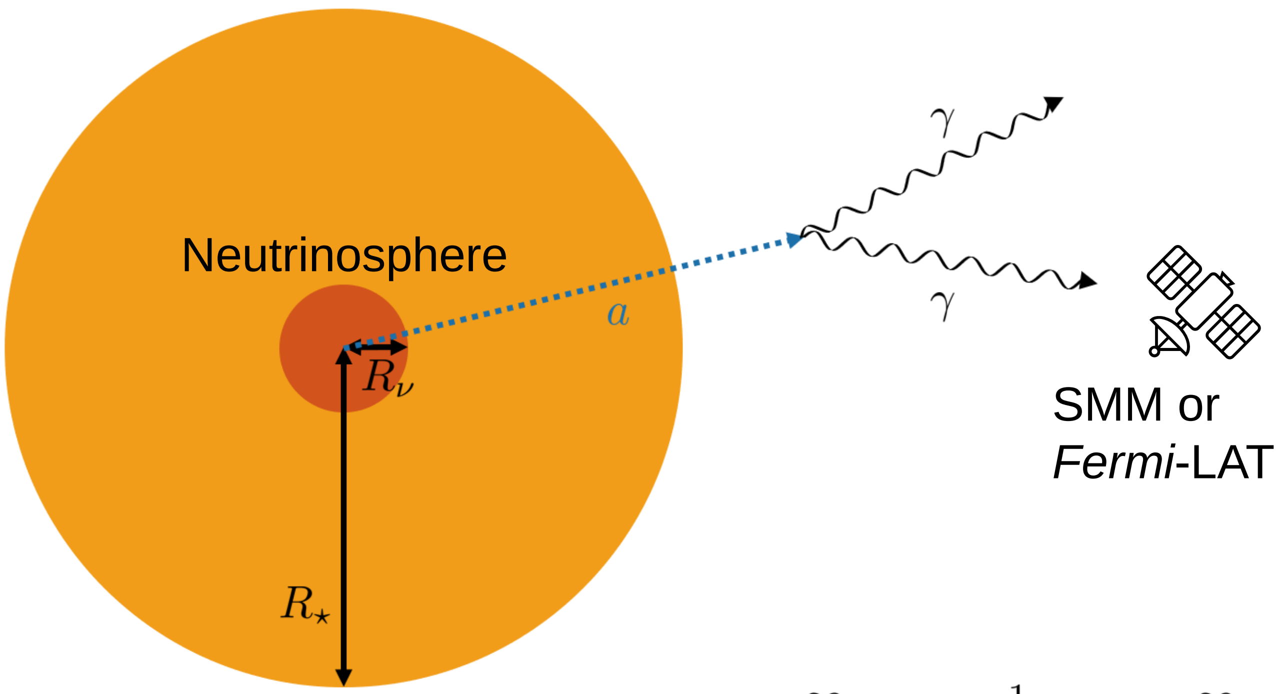
$$\left|\mathcal{M}_{\text{brems}}^{\text{derivative}}\right|^2 = 4p_e^2 \hat{g}_{ae}^2 f(m_e^{\text{eff}}, \dots) = (2m_e^{\text{eff}} \hat{g}_{ae})^2 f(m_e^{\text{eff}}, \dots)$$

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

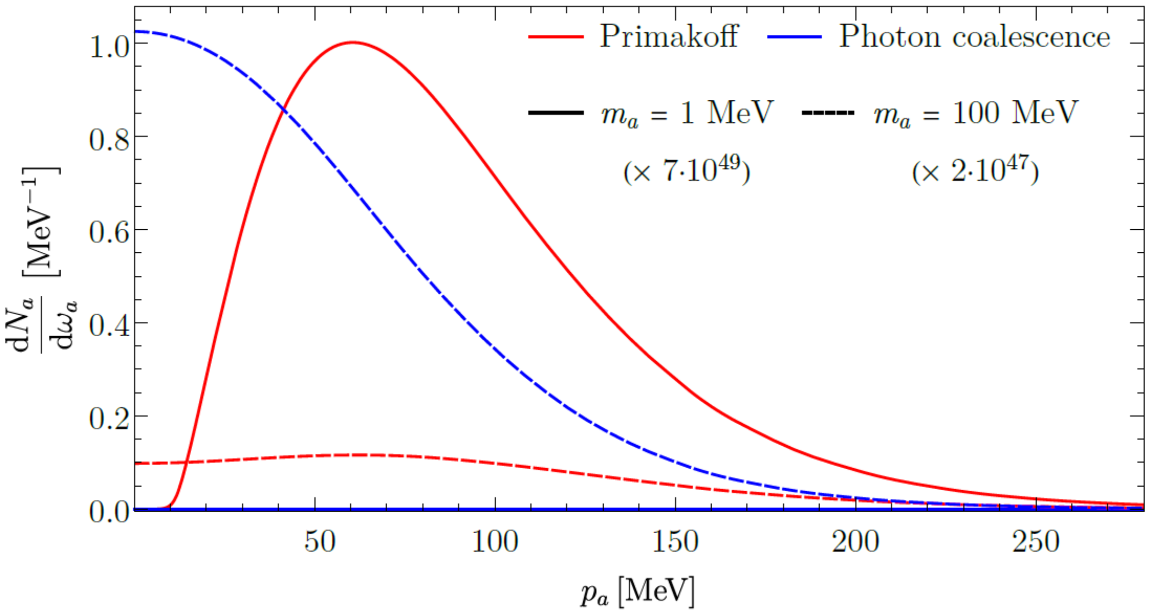
SDU

*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 SN 1987A-like event

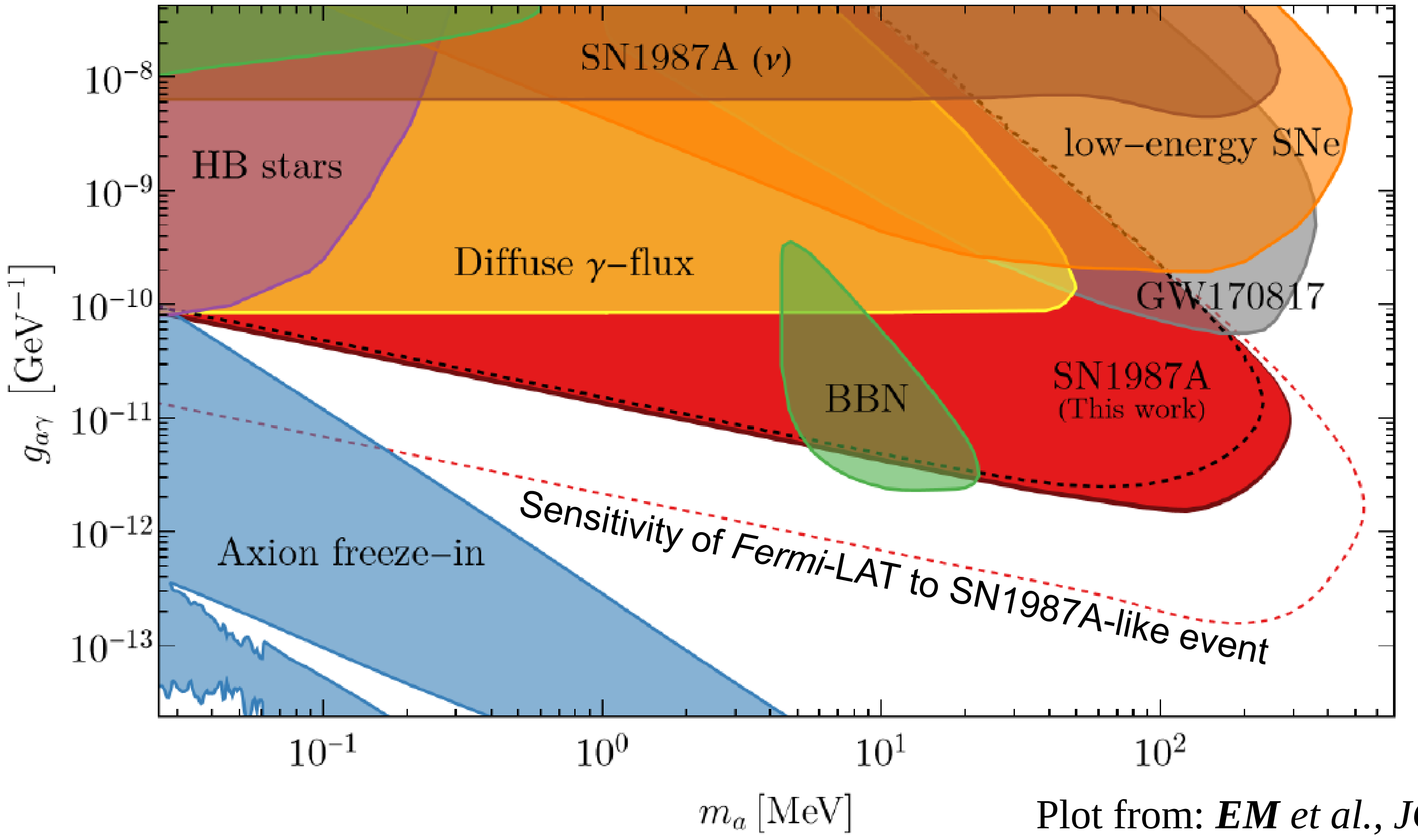


$$F_\gamma = \mathrm{BR}_{a\to\gamma\gamma} \int_{m_a}^{\infty} \mathrm{d}\omega_a \int_{-1}^{1} \mathrm{d}c_\alpha \int_0^\infty \mathrm{d}L\, 2 \cdot \frac{\mathrm{d}N_a/\mathrm{d}\omega_a}{4\pi\, R_{\mathrm{SN}}^2} \cdot \frac{\omega_a^2 - p_a^2}{2\,(\omega_a - c_\alpha p_a)^2} \cdot \frac{\exp[-L/\ell_a(\omega_a)]}{\ell_a(\omega_a)}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

SDU

SN-ALP decay: γ-ray signals

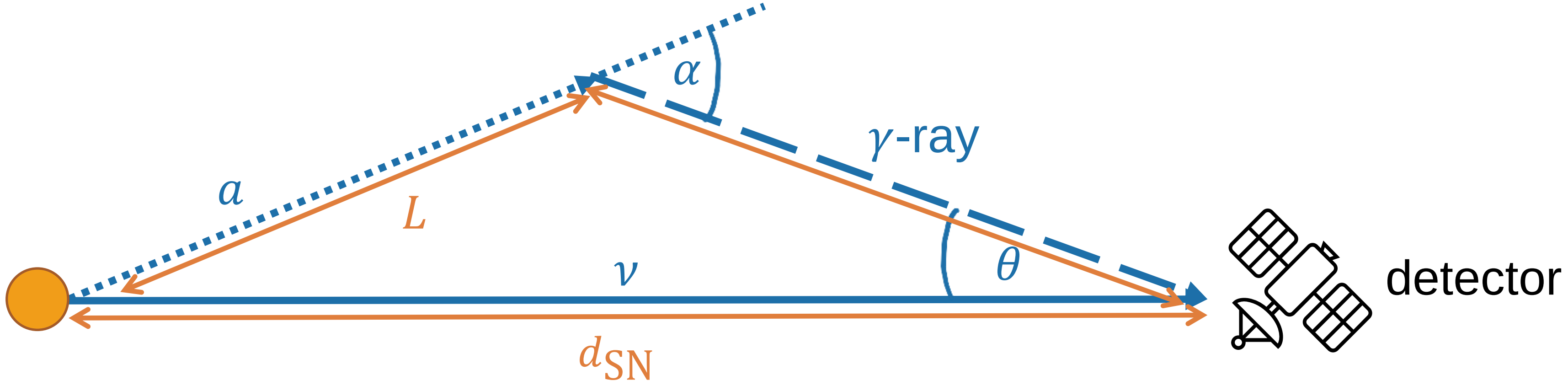
No γ-rays above background were observed by the Solar Maximum Mission after SN 1987A:



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

SN-ALP decay: Observer variables

We showed that there is a unique mapping $(\omega_a,\, c_\alpha,\, L) \leftrightarrow (\omega_\gamma,\, t,\, c_\theta)$, i.e. from variables describing the ALP to variables that the observer can control



$$t/c = \beta_a^{-1}\, L + L_\gamma - d_{\mathrm{SN}}$$

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

SDU

SN-ALP decay: Observer variables

$$\omega_a(\omega_\gamma, t, c_\theta) = \omega_\gamma + \frac{m_a^2}{4\omega_\gamma}\left(1 + \frac{1 - c_\theta^2}{(t/d_{\rm SN} + 1 - c_\theta)^2}\right),$$

$$L(\omega_\gamma, t, c_\theta) = \frac{2\omega_\gamma\, p_a(\omega_\gamma, t, c_\theta)}{m_a^2}\left(\frac{t}{d_{\rm SN}} + 1 - c_\theta\right) d_{\rm SN}$$

$$c_\alpha = \beta_a^{-1}\left(1 - \frac{m_a^2}{2\omega_a\,\omega_\gamma}\right) = p_a^{-1}\left(\omega_a - \frac{m_a^2}{2\,\omega_\gamma}\right),$$

With which one can prove that if

$$t \ll \min\left[1, \left(\frac{\omega_\gamma}{m_a}\right)^2, \frac{m_a^2}{\omega_\gamma \times 8\ \mathrm{GeV}}\right] d_{\rm SN} \simeq 6000\ \mathrm{s} \quad (\text{for SN1987A}),$$

then $\theta \sim \frac{t}{d_{\rm SN}} \sim 10^{-11}$ (for SN1987A) and in this case

$$\frac{\mathrm{d}^3 F_\gamma}{\mathrm{d}\omega_\gamma\,\mathrm{d}t\,\mathrm{d}\omega_a} = \frac{1}{\pi d_{\rm SN}^2}\frac{\omega_\gamma}{\tau_a\, p_a\, m_a}\frac{\mathrm{d}N_a}{\mathrm{d}\omega_a}(\omega_a)\, e^{-\frac{t}{\tau_a}\frac{2\omega_\gamma}{m_a}}\,\Theta_{\rm cons.}(\omega_\gamma, t, \omega_a)$$

which was previously assumed to hold for $\tau_a \ll d_{\rm SN}$ (see Oberauer et al. 1993, Jaffe & Turner 1997).

But this condition is not fulfilled for relevant parts of the parameter space!

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