The gamma-ray limit on ALPs from supernovae

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Based on 2304.01060, done with David Marsh, Pierluca Carenza, Christopher Eckner, and Francesca Calore (to appear in JCAP)

Axionlike particles

Stockholm University

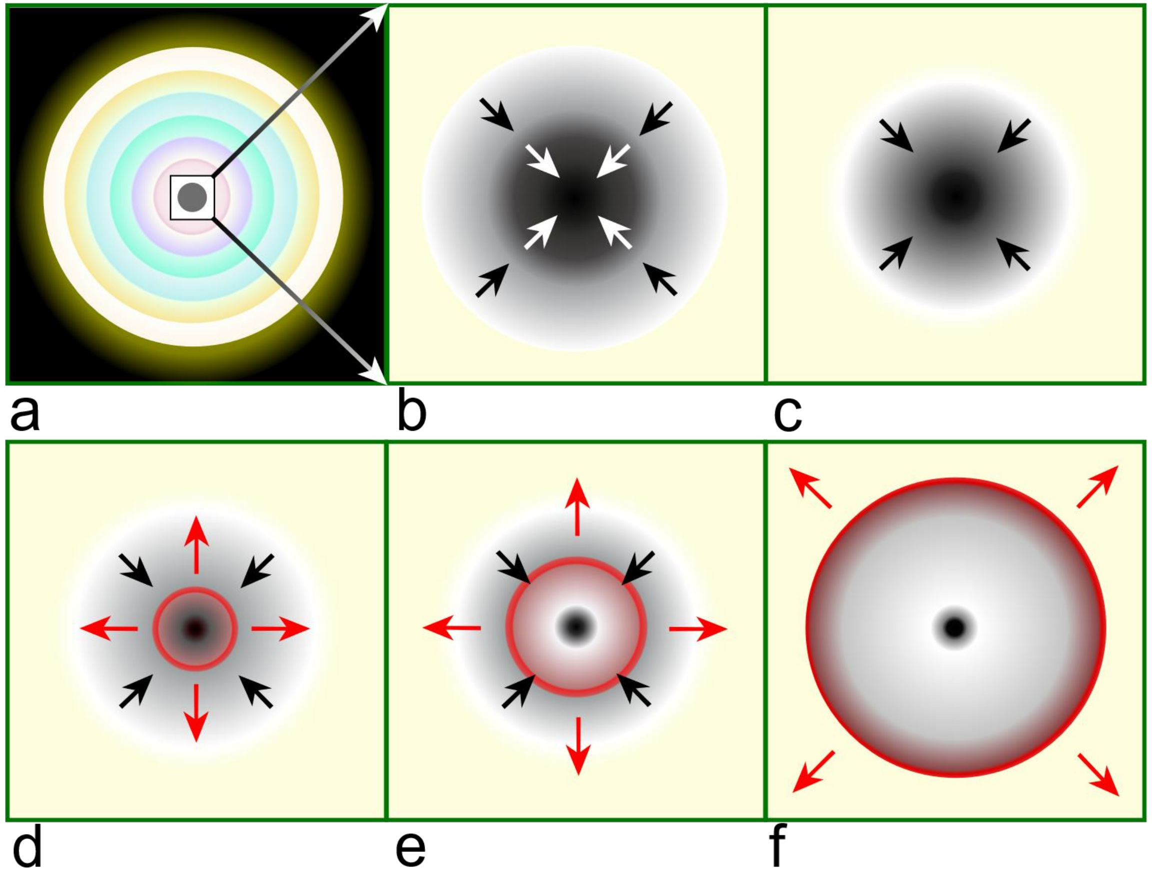
- ALPs are naturally light, weakly interacting pseudoscalar particles that appear in many BSM theories
- At low energies $E \ll \Lambda$, all these models contain the same *effective field theory* (EFT) of an ALP
- In this talk: study just two parameters of the EFT phenomenologically (no model building)

$$\mathcal{L}_{\mathrm{EFT}} \supset -\frac{1}{2} a(\Box + m_a^2) a + \frac{g_{a\gamma}}{4} a \, F \tilde{F}$$

Core-collapse supernovae

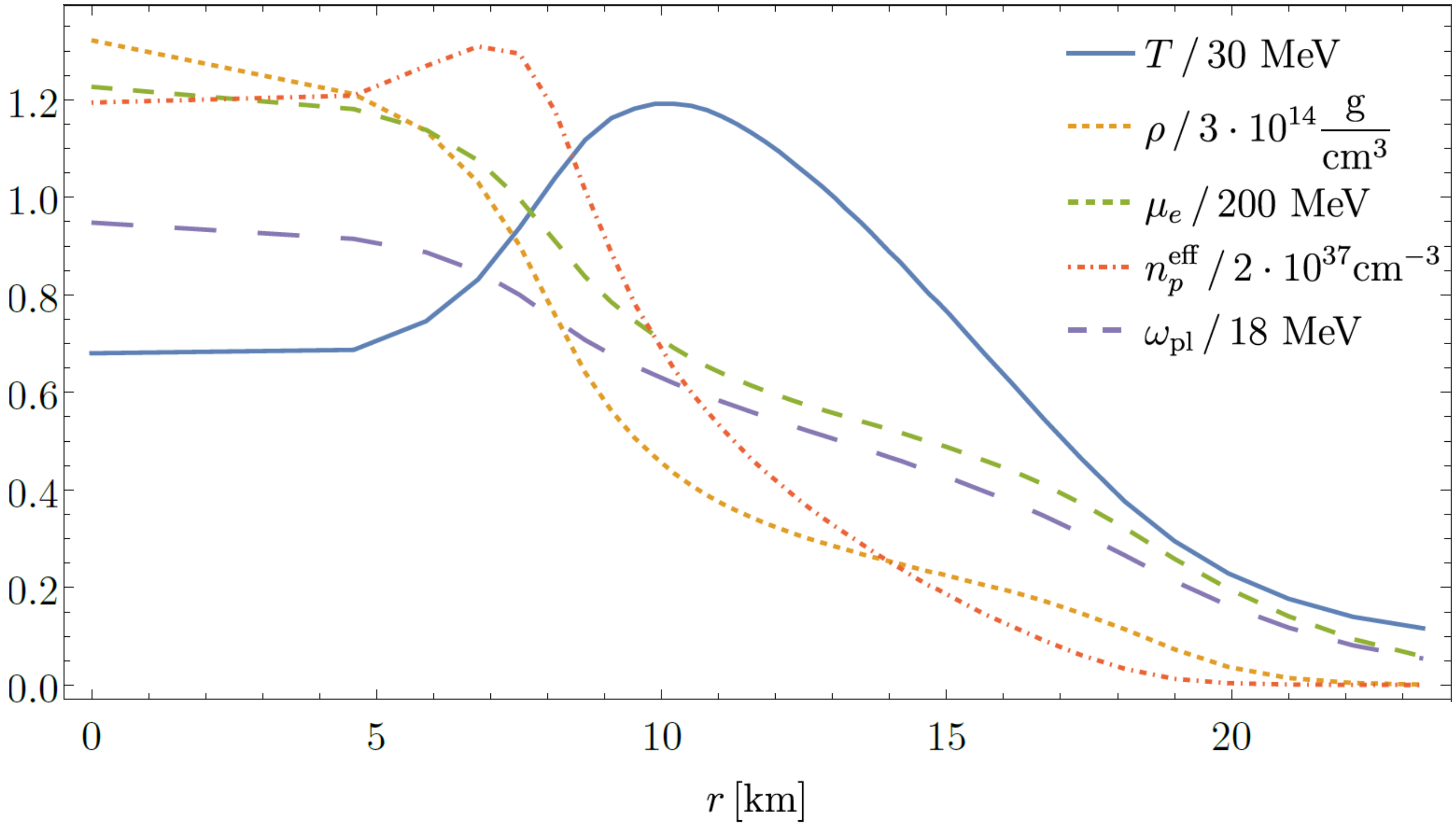
- The core of a massive star ($M \gtrsim 8\, M_\odot$) will undergo gravitational collapse
- In the Proto-Neutron Star at the center, very high temperatures and densities are reached

→ Even weakly interacting, light particles ($m \lesssim 10\, T$) can be produced in large numbers!



Credit: R.J. Hall & Wikimedia https://commons.wikimedia.org/wiki/File:Core_collapse_scenario.png

SN1987A Simulation



We use the Agile-Boltztran SN simulation by Fischer et al., see PRD 104 (2021) 103012

ALPs from a relativistic plasma

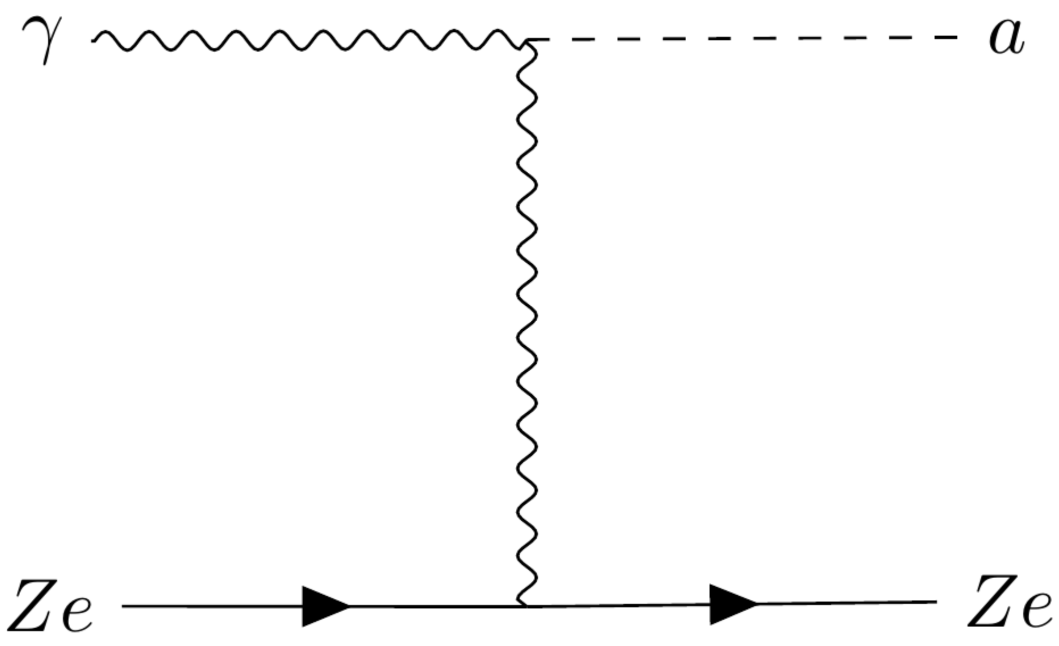
The spectral rate of change in the number density of ALPs ("production spectrum") can be calculated using the Boltzmann equation:

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

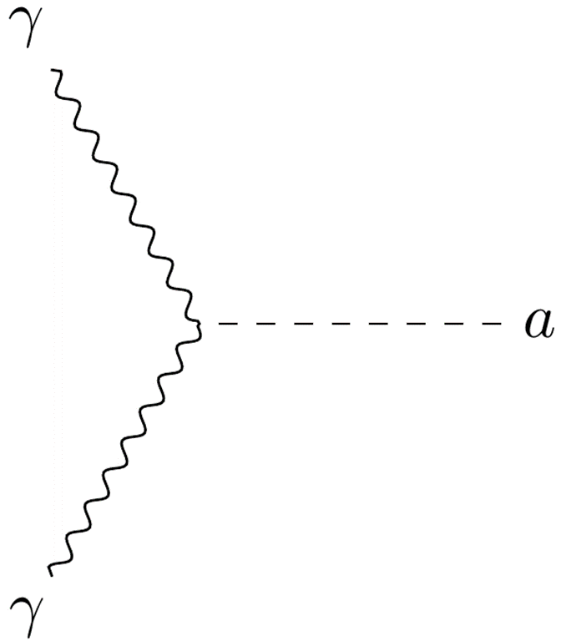
$$\times\,(2\pi)^4 \delta^{(4)}\left(\sum_i p_i - \sum_j p'_j\right) S\,\frac{|\mathbf{p}'_a|}{4\pi^2}|\mathcal{M}|^2\,,$$

ALPs from a relativistic plasma

Through their interaction with photons ALPs are produced by



Primakoff process



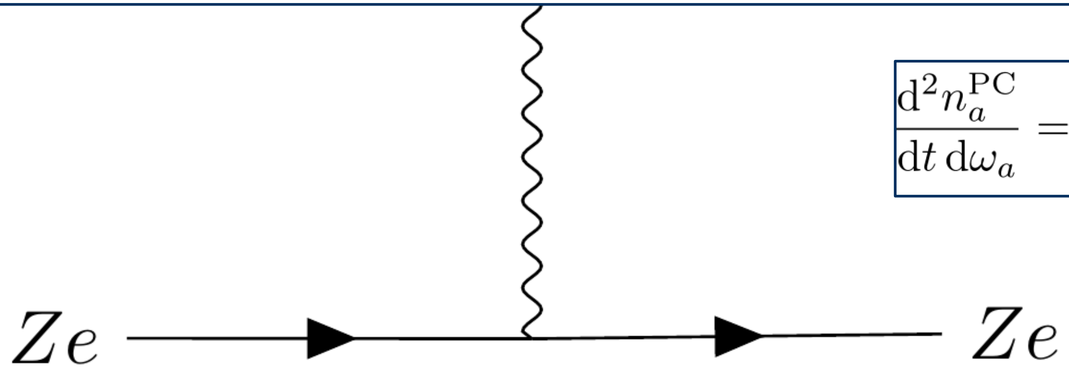
Photon coalescence

ALPs from a relativistic plasma

Through their interaction with photons ALPs are produced by

$$\frac{\mathrm{d}^2 n_a^{\mathrm{Prim.}}}{\mathrm{d}t\,\mathrm{d}\omega_a} = g_{a\gamma}^2 \frac{T\kappa_s^2}{32\pi^3}\frac{k\,p_a}{e^{\omega_a/T}-1}\left\{\frac{\left[(k+p_a)^2+\kappa_s^2\right]\left[(k-p_a)^2+\kappa_s^2\right]}{4kp_a\kappa_s^2}\ln\left[\frac{(k+p_a)^2+\kappa_s^2}{(k-p_a)^2+\kappa_s^2}\right] - \frac{\left(k^2-p_a^2\right)^2}{4kp_a\kappa_s^2}\ln\left[\frac{(k+p_a)^2}{(k-p_a)^2}\right]-1\right\},$$

$$\frac{\mathrm{d}^2 n_a^{\mathrm{PC}}}{\mathrm{d}t\,\mathrm{d}\omega_a} = \frac{g_{a\gamma}^2 m_a^4}{128\pi^3}\left(1-\frac{4m_\gamma^2}{m_a^2}\right)\int_{\omega_{\min}}^{\omega_{\max}}\mathrm{d}\omega_\gamma\left[\left(e^{\omega_\gamma/T}-1\right)\left(e^{(\omega_a-\omega_\gamma)/T}-1\right)\right]^{-1}$$



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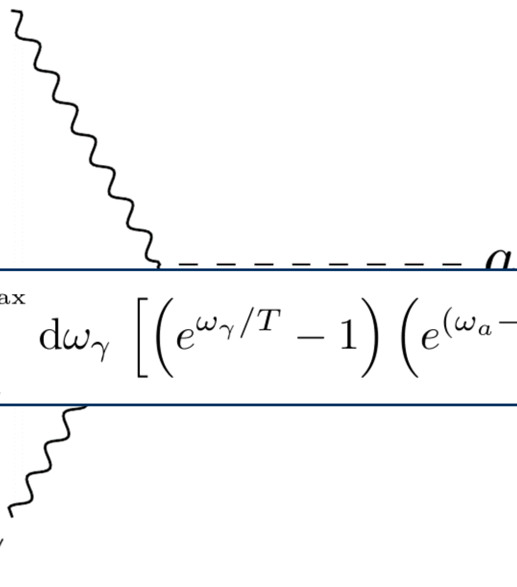
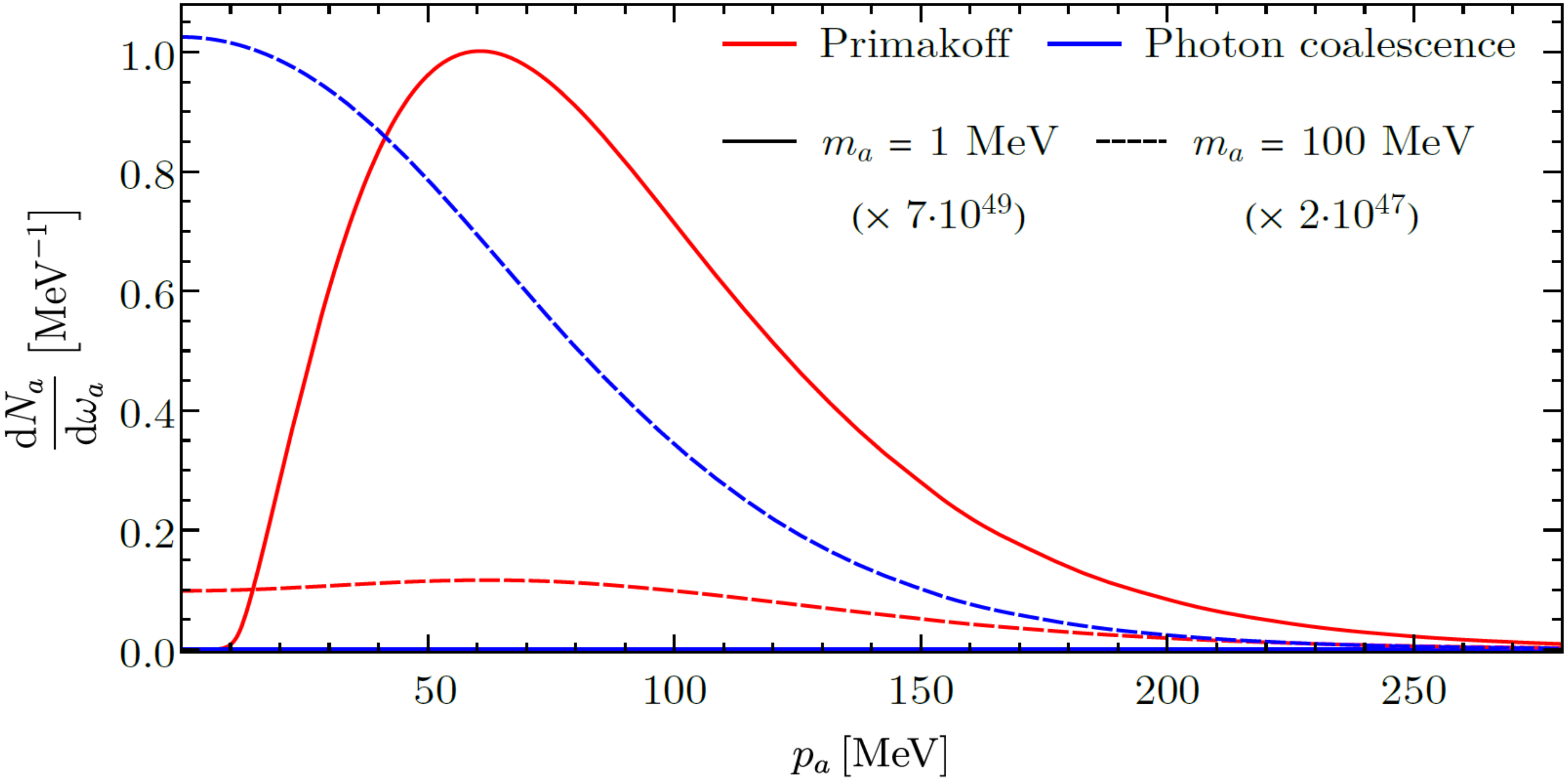
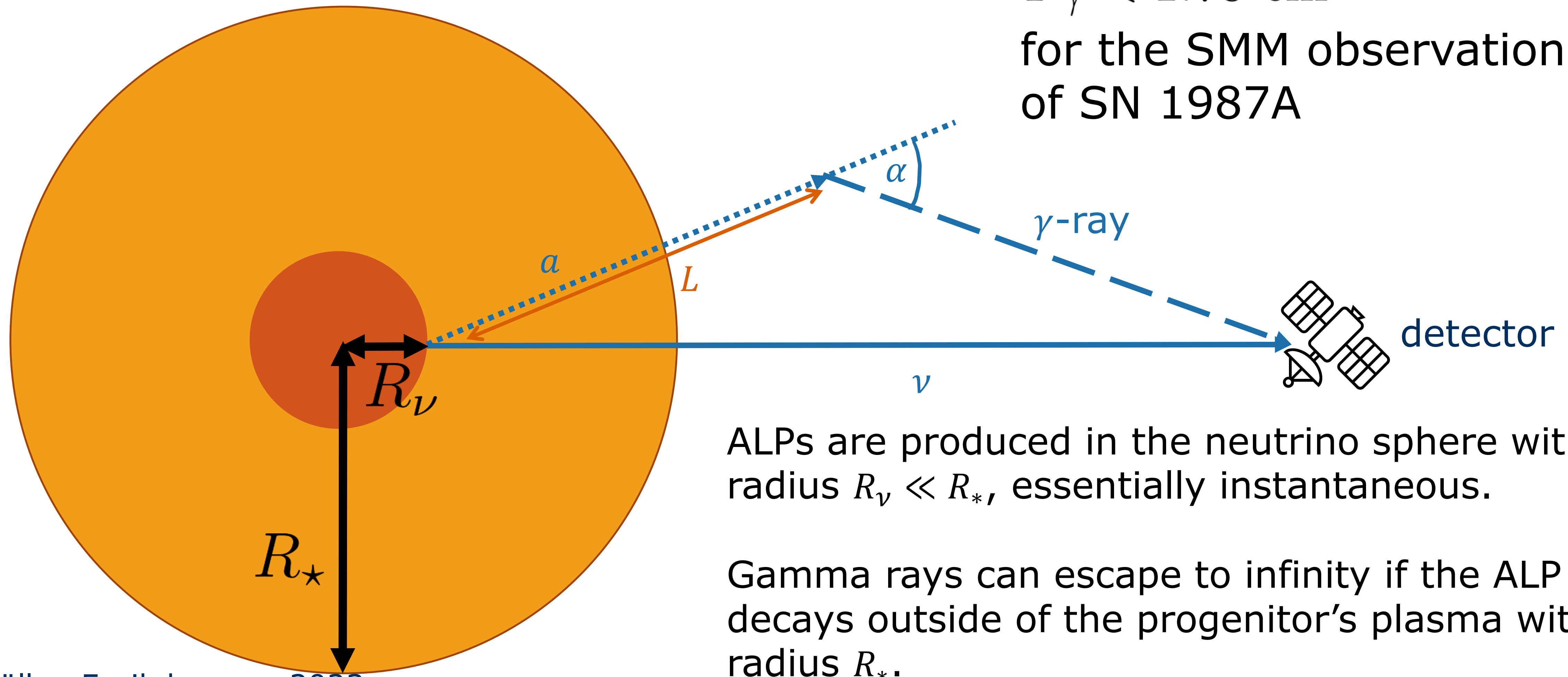


Photon coalescence

ALPs from a relativistic plasma



Gamma rays from ALP decays



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

for the SMM observation of SN 1987A

ALPs are produced in the neutrino sphere with radius $R_\nu \ll R_*$, essentially instantaneous.

Gamma rays can escape to infinity if the ALP decays outside of the progenitor's plasma with radius R_*.

Gamma rays from ALP decays

Stockholm University

Total production spectrum

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

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 more than 223s after the neutrino burst

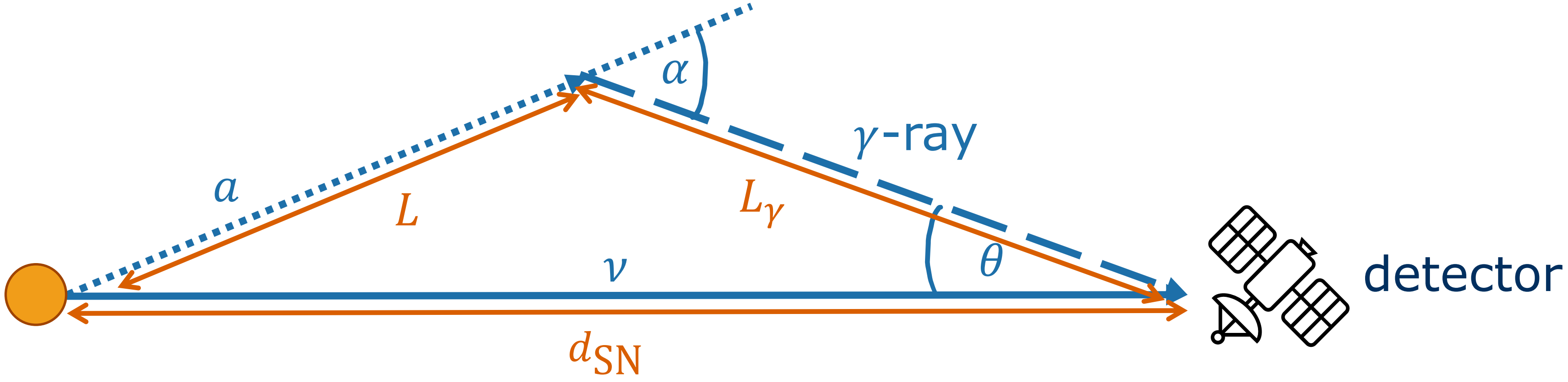
Following Jaffe and Turner, PRD 55 (1997) 7951-7959

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

$$c_\alpha \equiv \cos(\alpha)$$

Gamma rays from ALP decays

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



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

Gamma rays from ALP decays

With the variables $(\omega_\gamma,\, t,\, c_\theta)$ it is easy to show that if

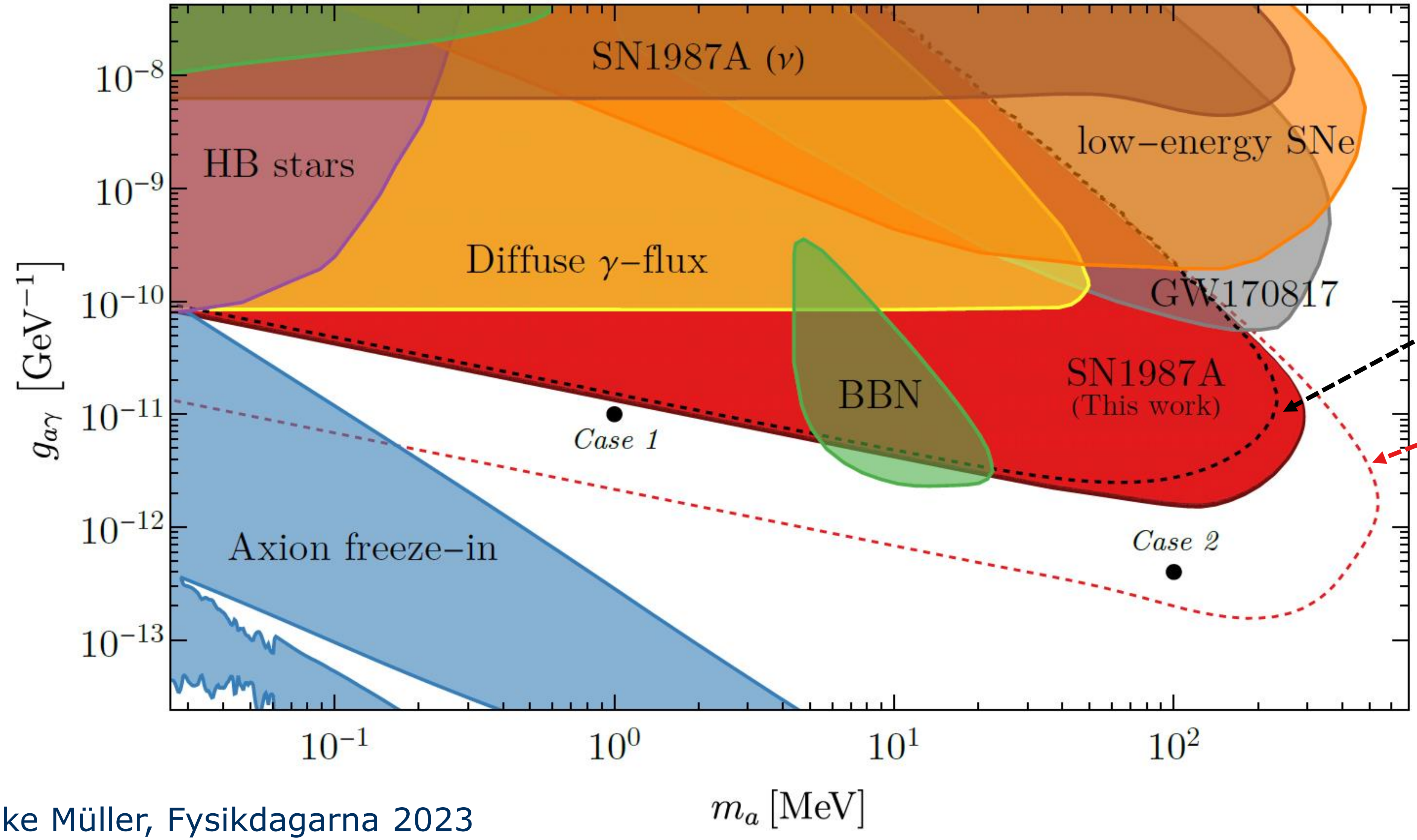
$$t \ll \min\left[1,\, \left(\frac{\omega_\gamma}{m_a}\right)^2,\, \frac{m_a^2}{\omega_\gamma \times 8\ \mathrm{GeV}}\right] d_{\mathrm{SN}} \simeq 6000\ \mathrm{s} \quad (\mathrm{for\ SN1987A})\,,$$

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

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

which was previously believed to hold for $\tau_a \ll d_{\mathrm{SN}}$. But his condition does not hold on relevant parts of the parameter space!

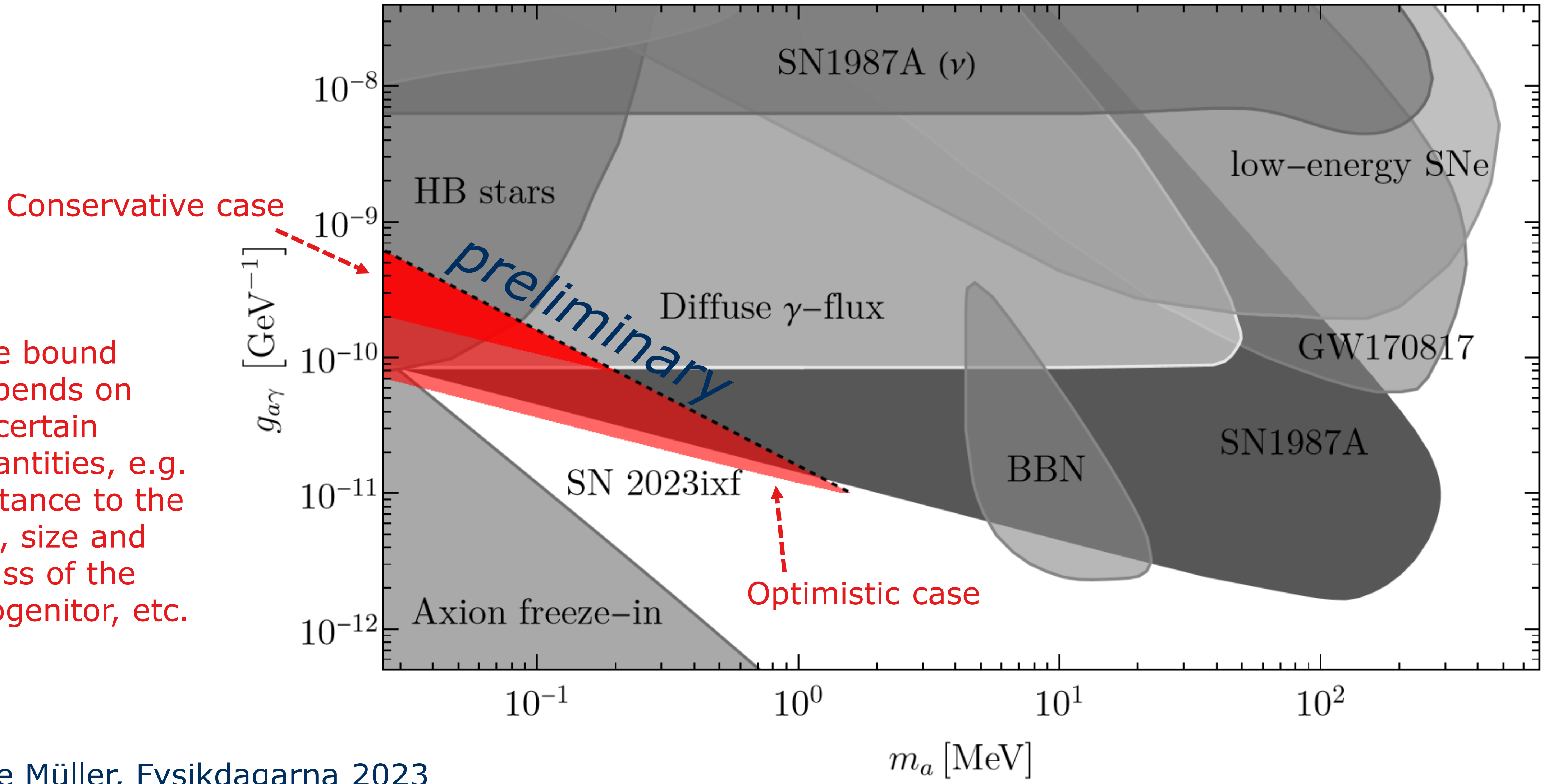
Constraint from SN1987A



Hoof & Schulz, 2212.09764

Sensitivity of *Fermi*-LAT to a future SN at 50 kpc (Fluence 5σ over background)

Extragalactic SNe, e.g. SN 2023ixf



The bound depends on uncertain quantities, e.g. distance to the SN, size and mass of the progenitor, etc.

Summary

- Core-collapse SNe are a great way to search for new physics
- Only assuming that ALPs are produced in the SN, we can put very stringent constraints on their decays into photons
- *Fermi*-LAT has a strong sensitivity to ALPs from nearby SNe, with the possibility to determine $g_{a\gamma}^2 m_a$ in case of an observation
- Even extragalactic SNe yield a relevant constraint (we don’t have to rely only on SN 1987A)

Summary

- Core-collapse SNe are a great way to search for new physics
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Thanks for your attention!

Back Up

Flux prediction for *Fermi*-LAT

In observer variables, the time-dependent spectral gamma-ray flux as *Fermi*-LAT would observe it is easily calculated:

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}\omega_\gamma} \equiv \frac{\mathrm{d}^2 F_\gamma}{\mathrm{d}\omega_\gamma \mathrm{d}t} = \int \mathrm{d}c_\theta \frac{\mathrm{d}^3 F_\gamma}{\mathrm{d}\omega_\gamma \,\mathrm{d}t\, \mathrm{d}c_\theta}$$

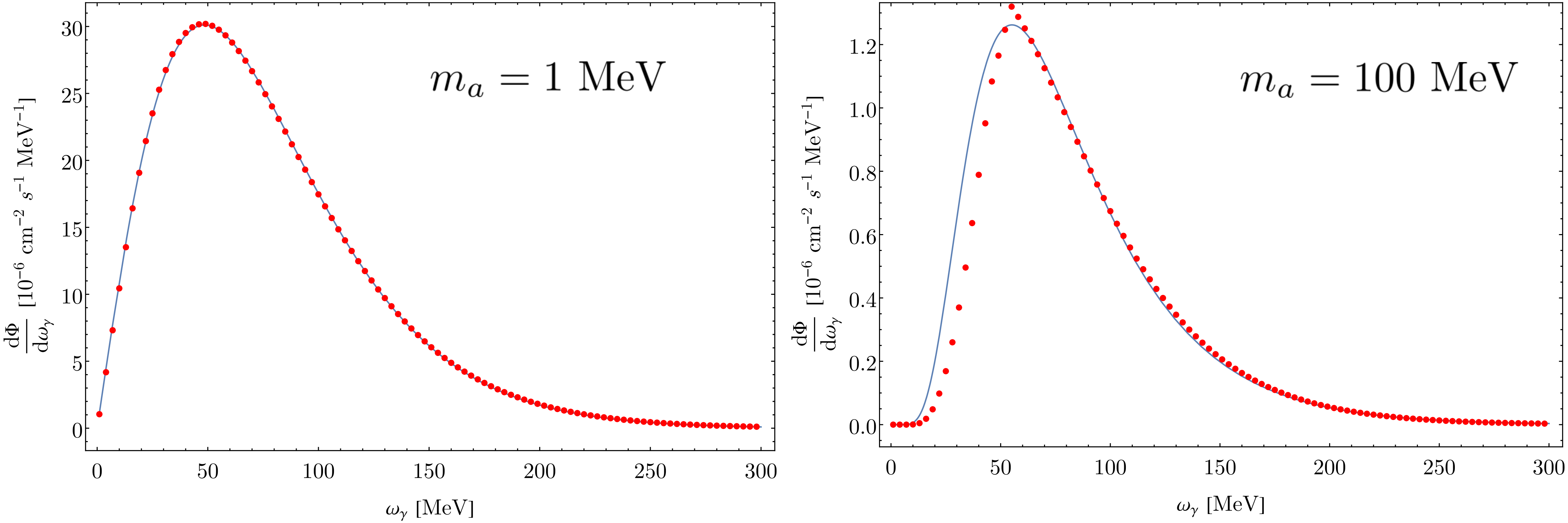
For masses $m_a \leq 50$ MeV, the ALP spectrum can be fitted as

$$\frac{\mathrm{d}N_a}{\mathrm{d}\omega_a} \simeq g_{a\gamma}^2\, C_0 \left(\frac{\omega_a}{\omega_a^0}\right)^\alpha \exp\left[-(1+\alpha)\frac{\omega_a}{\omega_a^0}\right]$$

and then, for times shorter than the ALP lifetime:

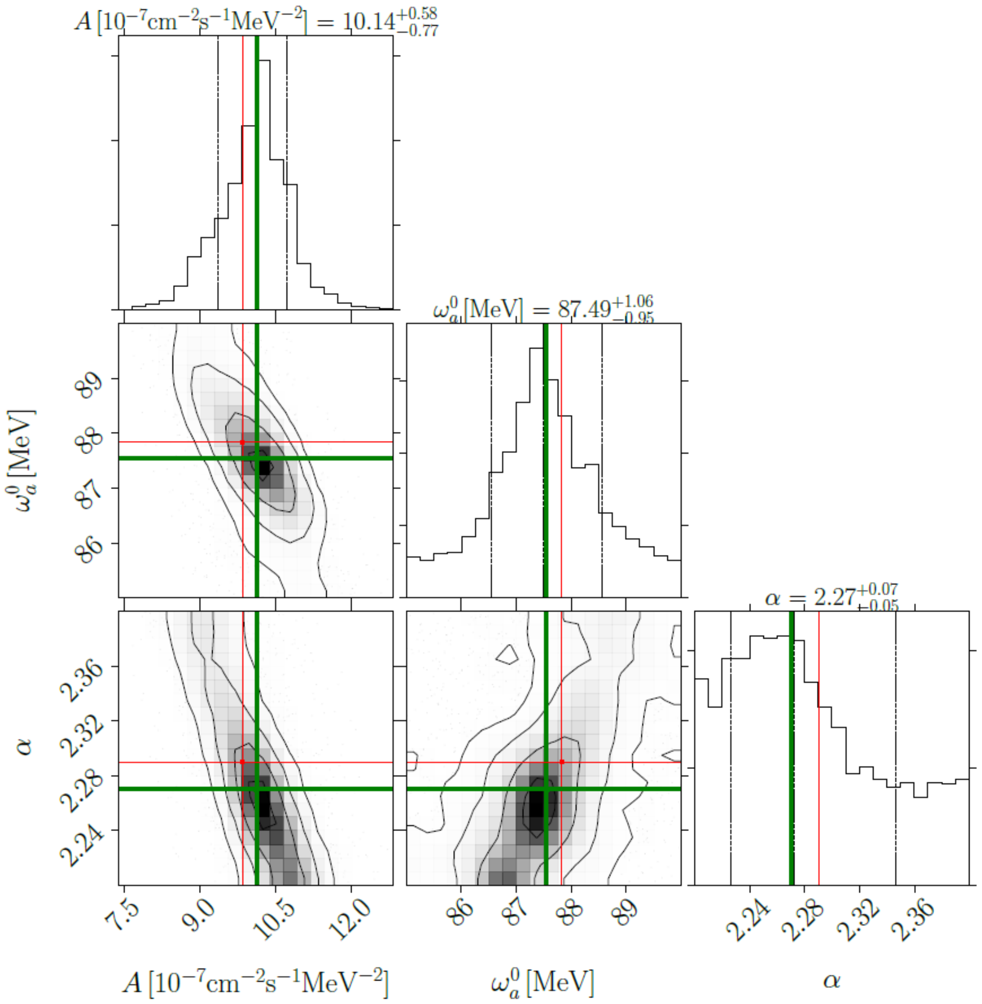
$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}\omega_\gamma} = A\,\omega_\gamma\,\Gamma\left[\alpha, (1+\alpha)\frac{\omega_\gamma}{\omega_a^0}\right] \qquad A = \frac{C_0(1+\alpha)^{-\alpha}}{64\pi^2\, d_{\mathrm{SN}}^2}\, g_{a\gamma}^4 m_a^2$$

Flux prediction for *Fermi*-LAT

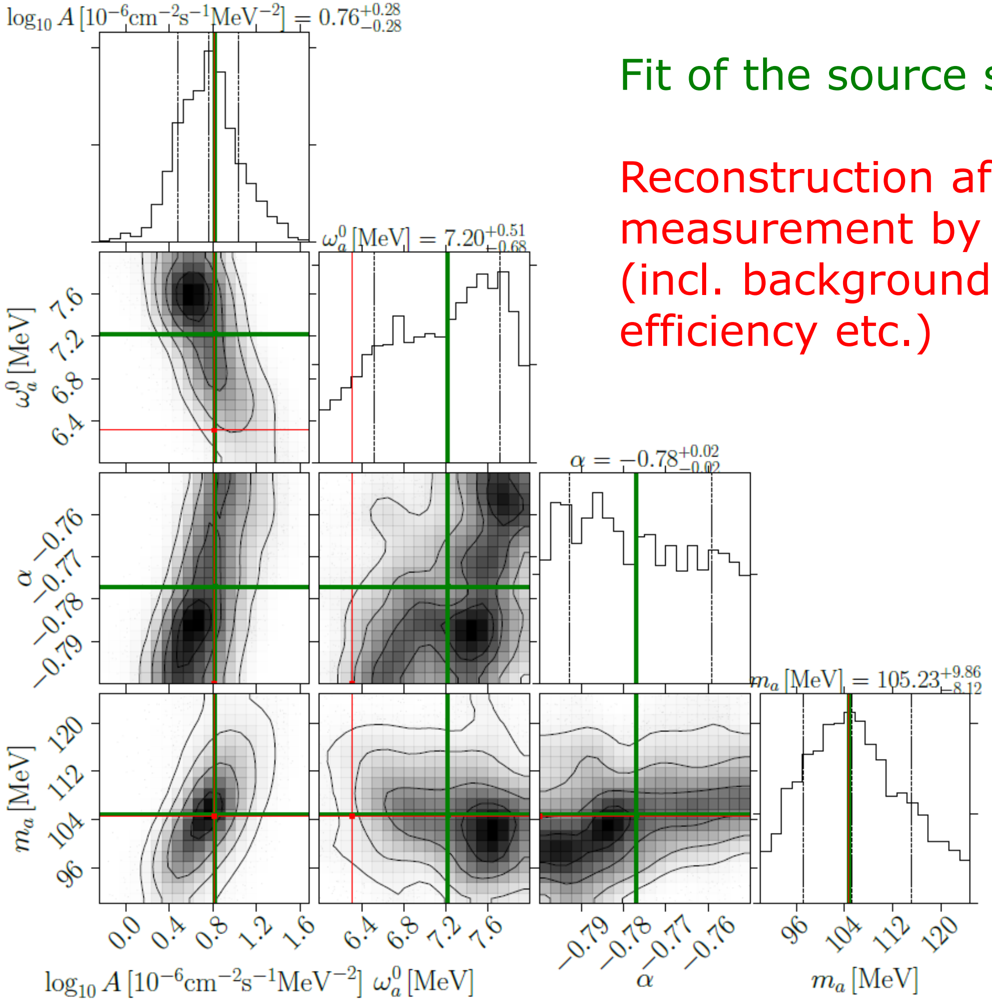


→ a bad fit is an indication for a large ALP mass

Flux prediction for *Fermi*-LAT



$m_a = 1$ MeV



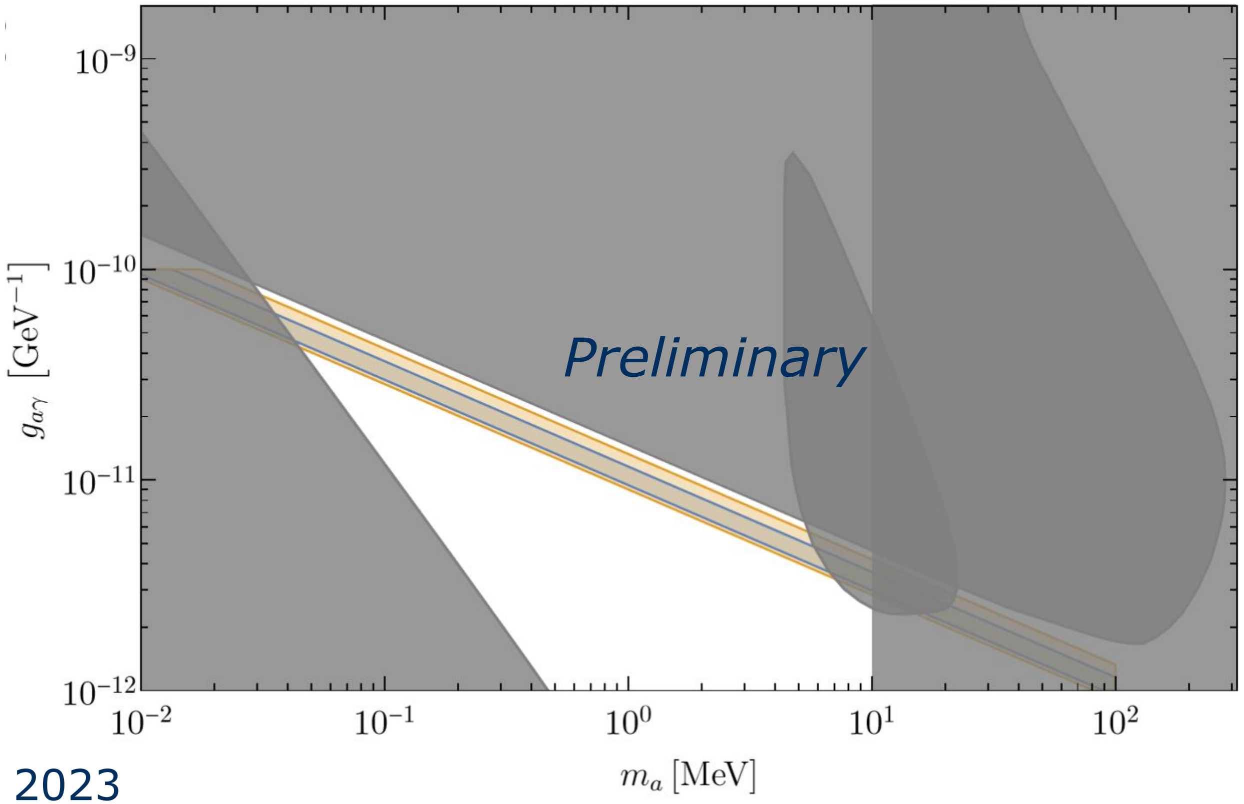
$m_a = 100$ MeV

Fit of the source spectrum

Reconstruction after measurement by *Fermi*-LAT (incl. background, detector efficiency etc.)

Flux prediction for *Fermi*-LAT

Using the best-fit parameters and a prediction for the parameter C_0 from the mass of the SN progenitor according to Calore et al., PRD 105 (2022) 063028, we can constrain $g_{a\gamma}^2 m_a$:



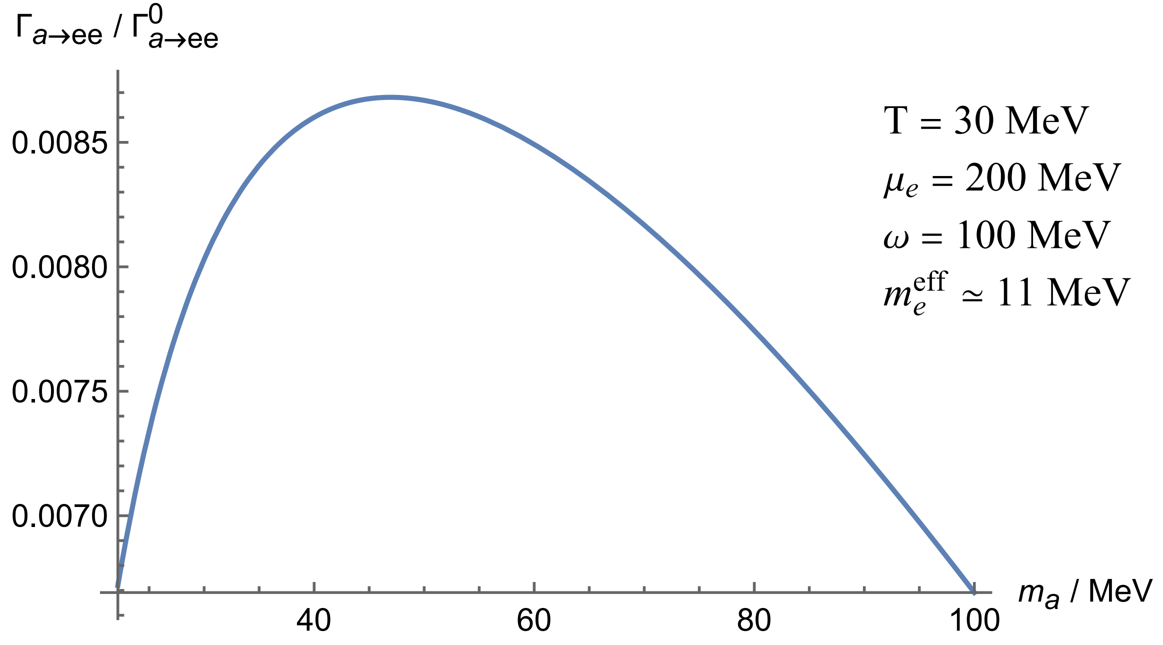
ALPs from SN1987A: Reabsorption

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

$$L_a = \int^{R_\nu} \mathrm{d}^3 r \int_{m_a}^{\infty} \mathrm{d}\omega\, \omega \frac{\mathrm{d}\dot{n}}{\mathrm{d}\omega}\, e^{-\int_r^{R_{\mathrm{far}}} \boxed{\frac{\mathrm{d}\tilde{r}}{\lambda(\tilde{r},\omega)}}}$$ Mean free path of the ALPs

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

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



ALP-fermion interactions

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$$\begin{aligned}\mathcal{L}_{\mathrm{aQED}} &= -\frac{1}{2}a(\Box + m_a^2)a - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}_e(i\not{D} - m_e)\psi_e \\ &\quad + \boxed{\frac{g_{a\gamma}}{4}}a\,F_{\mu\nu}\tilde{F}^{\mu\nu} + \cancel{\hat{g}_{ae}(\partial_\mu a)\bar{\psi}_e\gamma^\mu\gamma_5\psi_e} \\ &= -\frac{1}{2}a(\Box + m_a^2)a - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}'_e(i\not{D} - m_e)\psi'_e \\ &\quad + \boxed{\frac{1}{4}\left(g_{a\gamma} + \frac{2\alpha}{\pi}\hat{g}_{ae}\right)}a\,F_{\mu\nu}\tilde{F}^{\mu\nu} - i\boxed{\underbrace{2m_e\hat{g}_{ae}}_{\equiv g_{ae}}}a\,\bar{\psi}'_e\gamma_5\psi'_e + \mathcal{O}(\hat{g}_{ae}^2)\end{aligned}$$

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

ALP-electron interactions in a plasma

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- 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?

Supernova bounds at one loop

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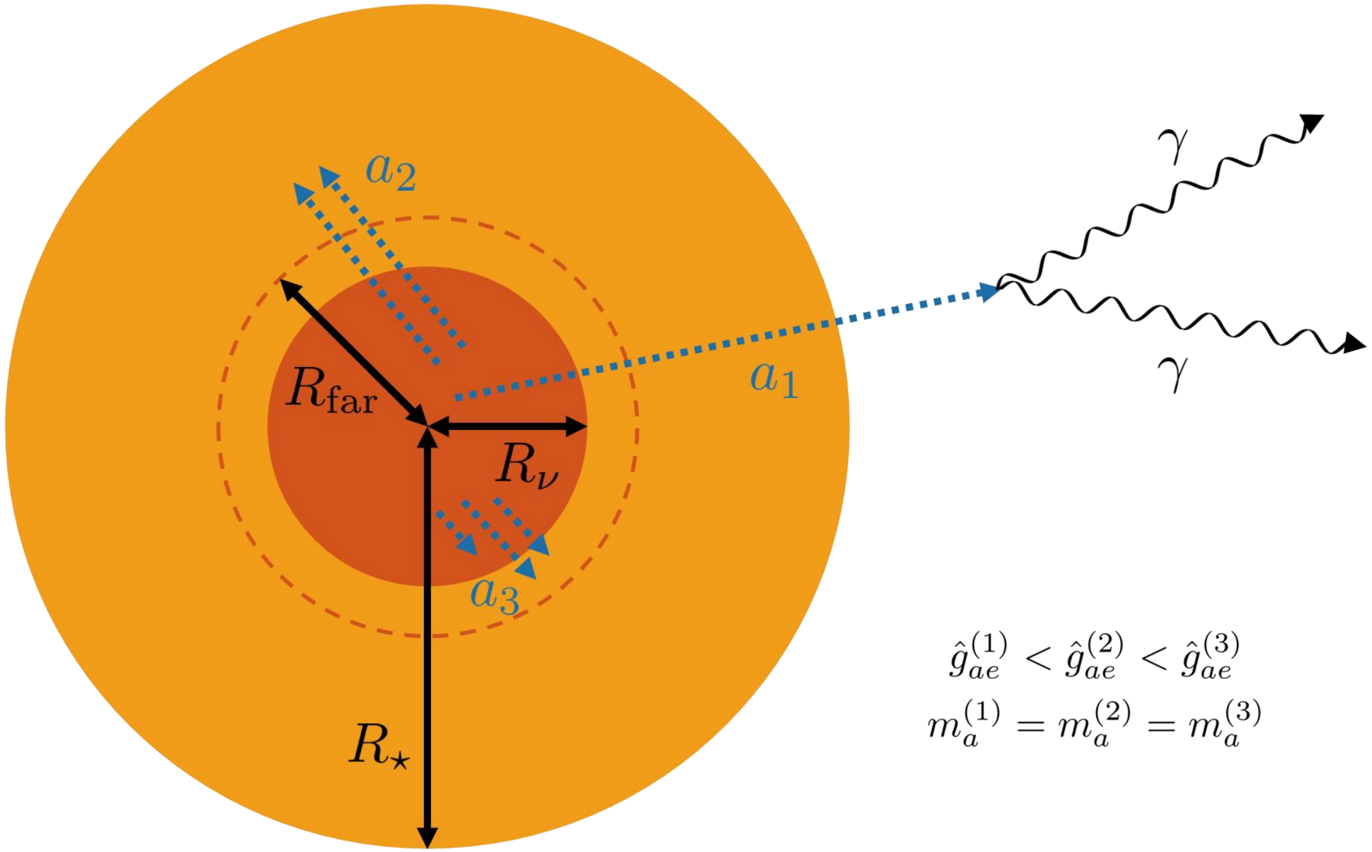

The neutrino burst of SN1987A would be shortened by ALPs, unless

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

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

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

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

Observer variables

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

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

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