2nd Training School COST Action Cosmic Wispers (CA21106)

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SN ALPs coupled to nucleons shining into photons

Based on ArXive: 2405.00153, accepted on PRD

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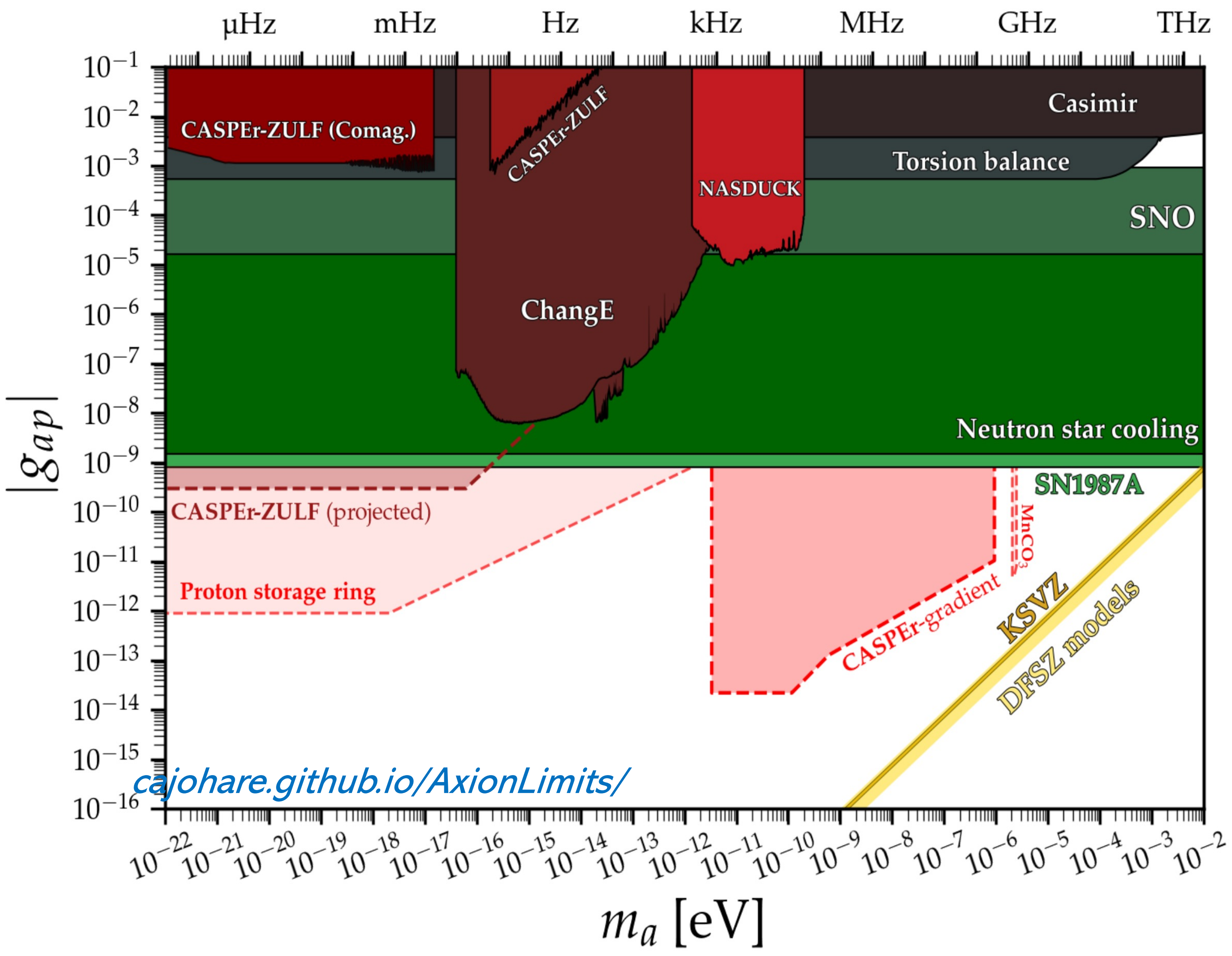
ALP nuclear couplings



ChPT Lagrangian:

[Ho & al., Phys. Rev. D 107 (2023)]

$$\mathcal{L}_{\rm int} = g_a \frac{\partial_\mu a}{2m_N}\Big[C_{ap}\bar{p}\gamma^\mu\gamma_5 p + C_{an}\bar{n}\gamma^\mu\gamma_5 n + \frac{C_{a\pi N}}{f_\pi}(i\pi^+\bar{p}\gamma^\mu n - i\pi^-\bar{n}\gamma^\mu p) + C_{aN\Delta}\left(\bar{p}\,\Delta^+_\mu + \overline{\Delta^+_\mu}\,p + \bar{n}\,\Delta^0_\mu + \overline{\Delta^0_\mu}\,n\right)\Big]$$

- couplings to nucleons
- couplings to pions
- couplings to baryonic resonances

The UV theory

Above $\Lambda_{QCD} \simeq 200\ \mathrm{MeV}$ interactions with quark and gluons

$$\mathcal{L}_{\rm aQCD} = c_g \frac{g_s^2}{32\pi^2}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \sum_q c_q \frac{\partial_\mu a}{2f_a}\bar{q}\gamma^\mu\gamma_5 q + \frac{(m_{a,0})^2}{2}a^2$$

Then, at loop level *[Bauer et al., JHEP 12 (2017)]*

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

Irreducible photon coupling related to nuclear couplings ($C_n = 0, c_g = 1$)

$$g_{a\gamma} \simeq -9.5 \times 10^{-4}\ \mathrm{GeV}^{-1}\left[\frac{1.53}{c_d - 0.33} + \frac{c_d + 0.24}{c_d - 0.33}\frac{m_a^2}{m_\pi^2 - m_a^2}\right] g_{ap}$$

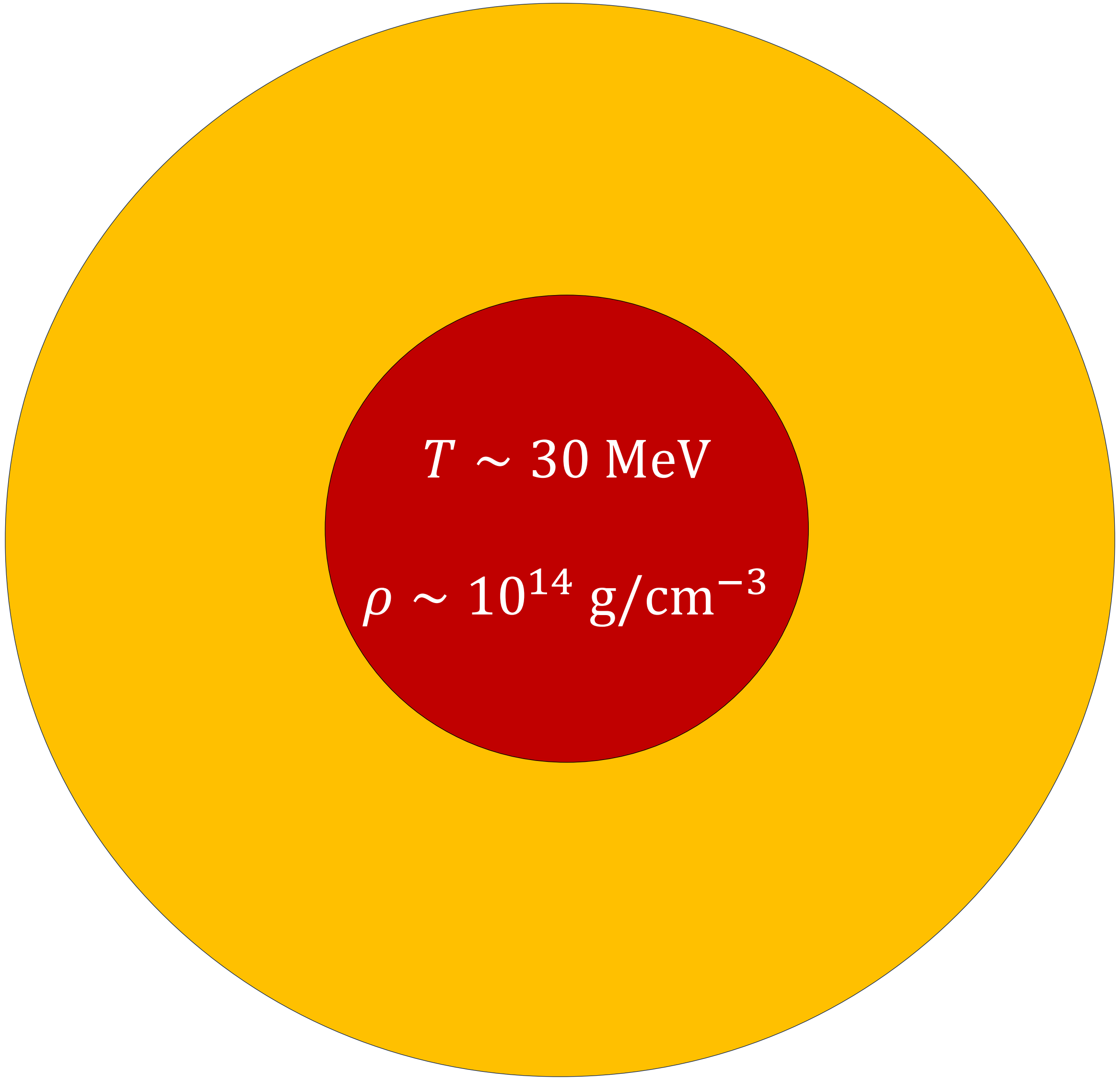
ALP production in SNe

- Terminal phase of a massive star $[\mathrm{M} \geq 8\, M_{\odot}]$, undergoing gravitational collapse

- Extreme conditions of temperature and density in the core

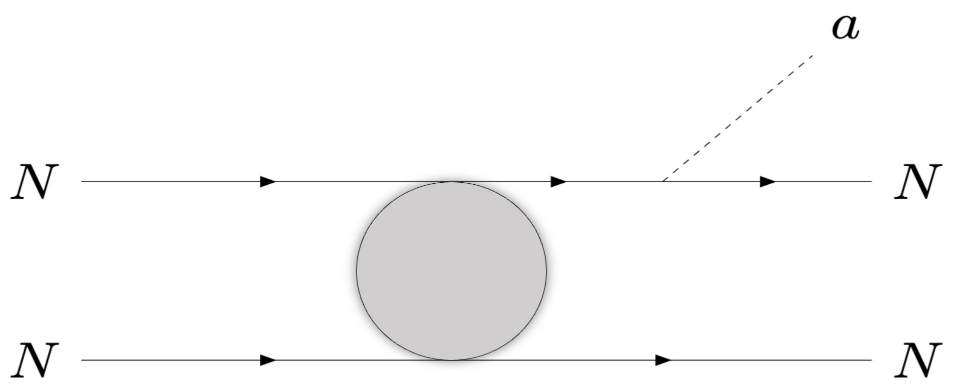
- Cooling via neutrino emission

$$E_{cool} \sim 10^{53}\ \mathrm{erg}$$

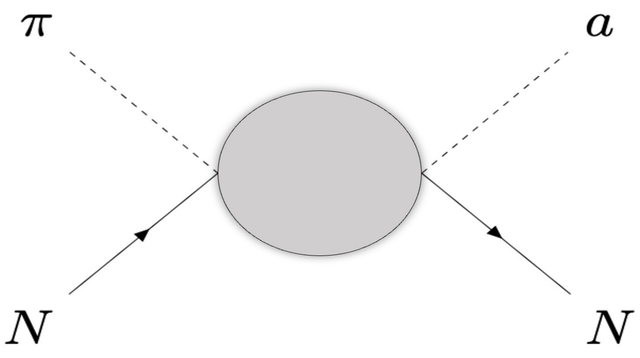


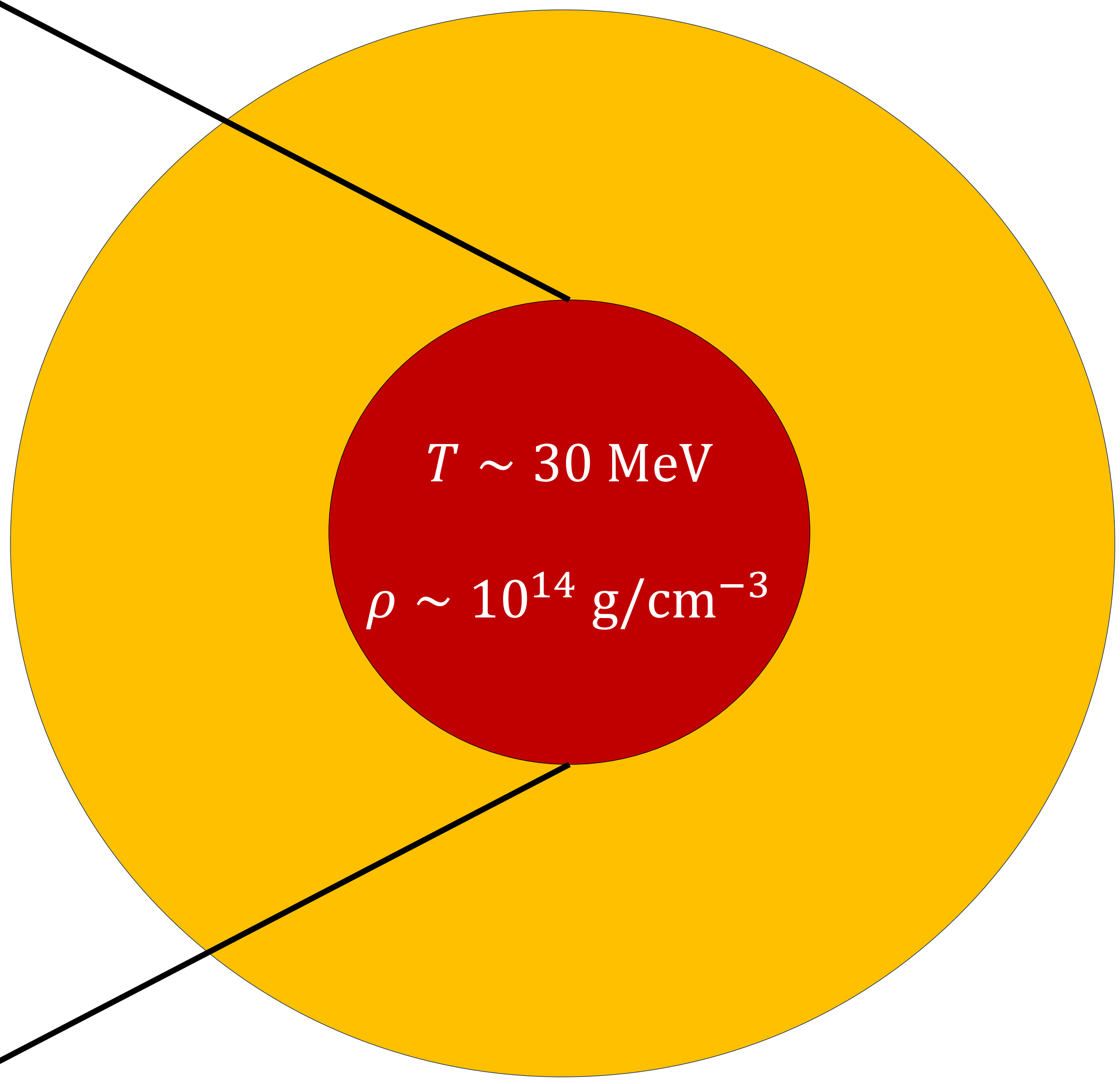
ALP production in SNe

Nucleon-Nucleon bremsstrahlung *[Carenza & al., JCAP 10 (2019) 10]*



Pion conversion *[Carenza & al., Phys.Rev.Lett.* 126 (2021), *Choi & al., JHEP* 02 (2022) 143, *Ho & al., Phys. Rev. D 107 (2023)]]*

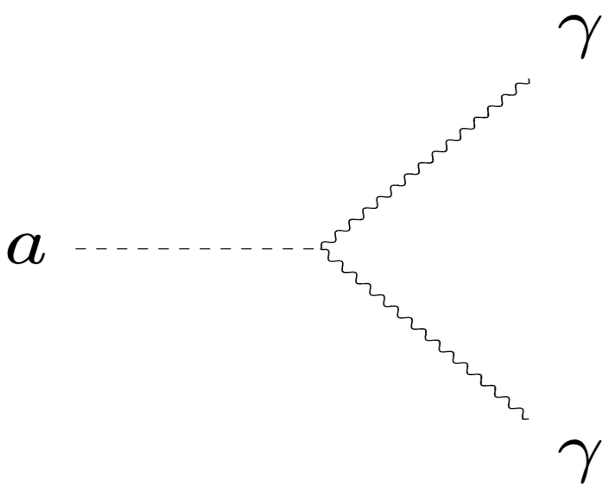




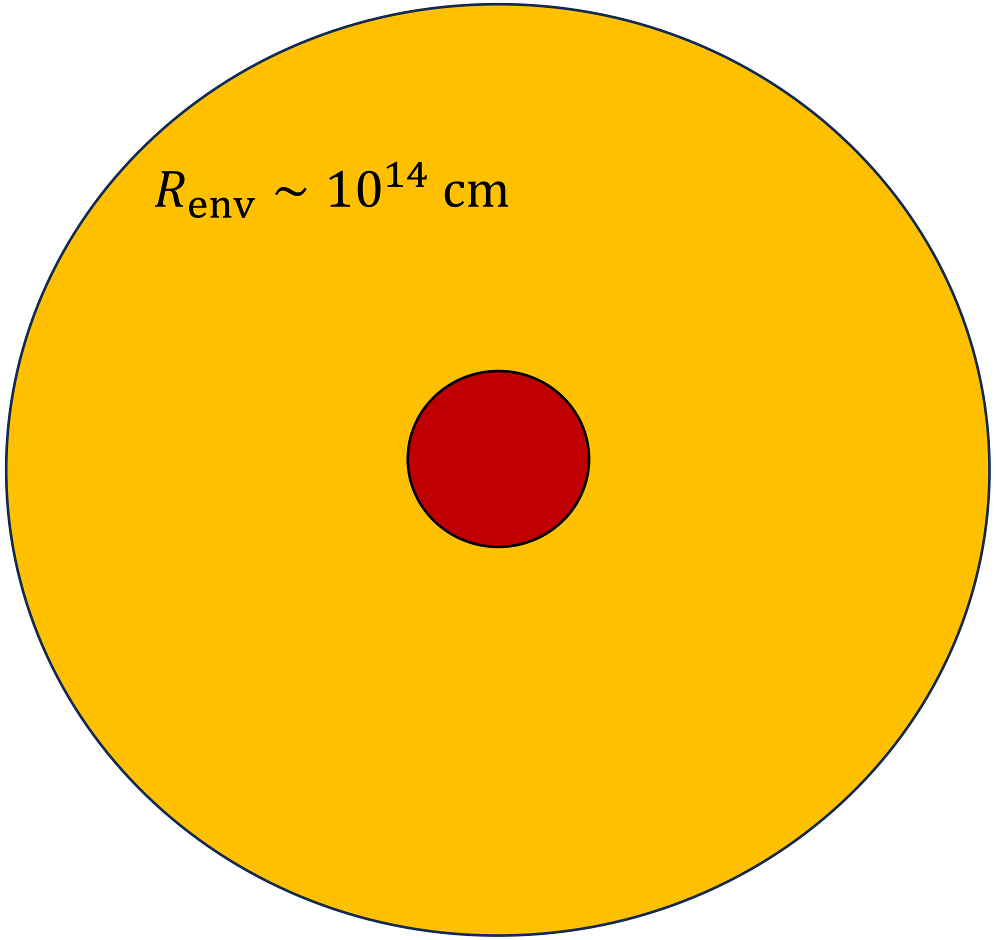
ALP decays

After being produced in the core, massive ALPs could decay into photon pairs.

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$



$$\Gamma_{a\gamma\gamma} = g_{a\gamma}^2 \frac{m_a^3}{64\pi}$$



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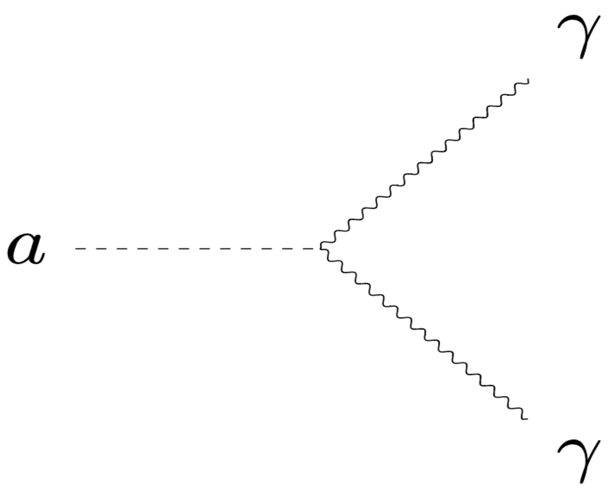

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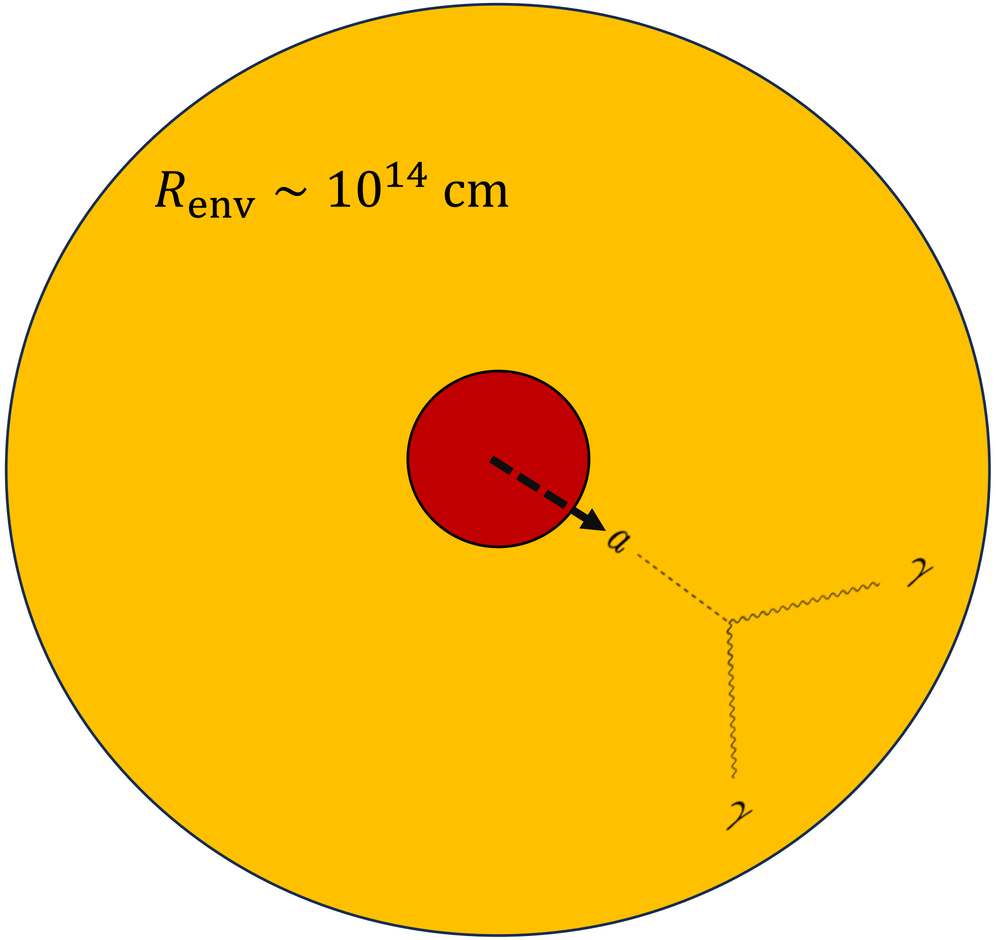

- $\lambda_\gamma < R_{\rm env}$
  - Energy deposition

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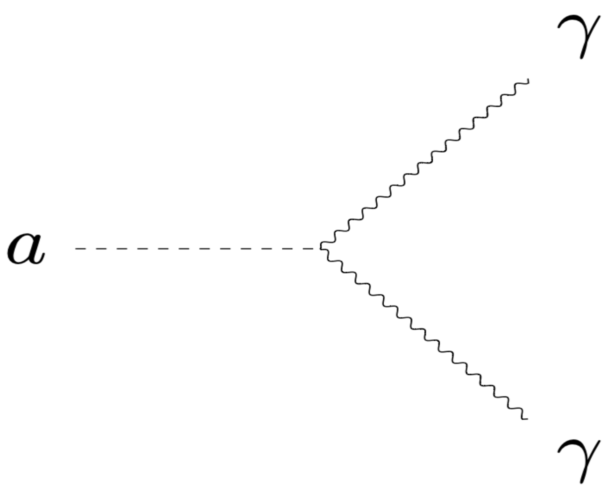

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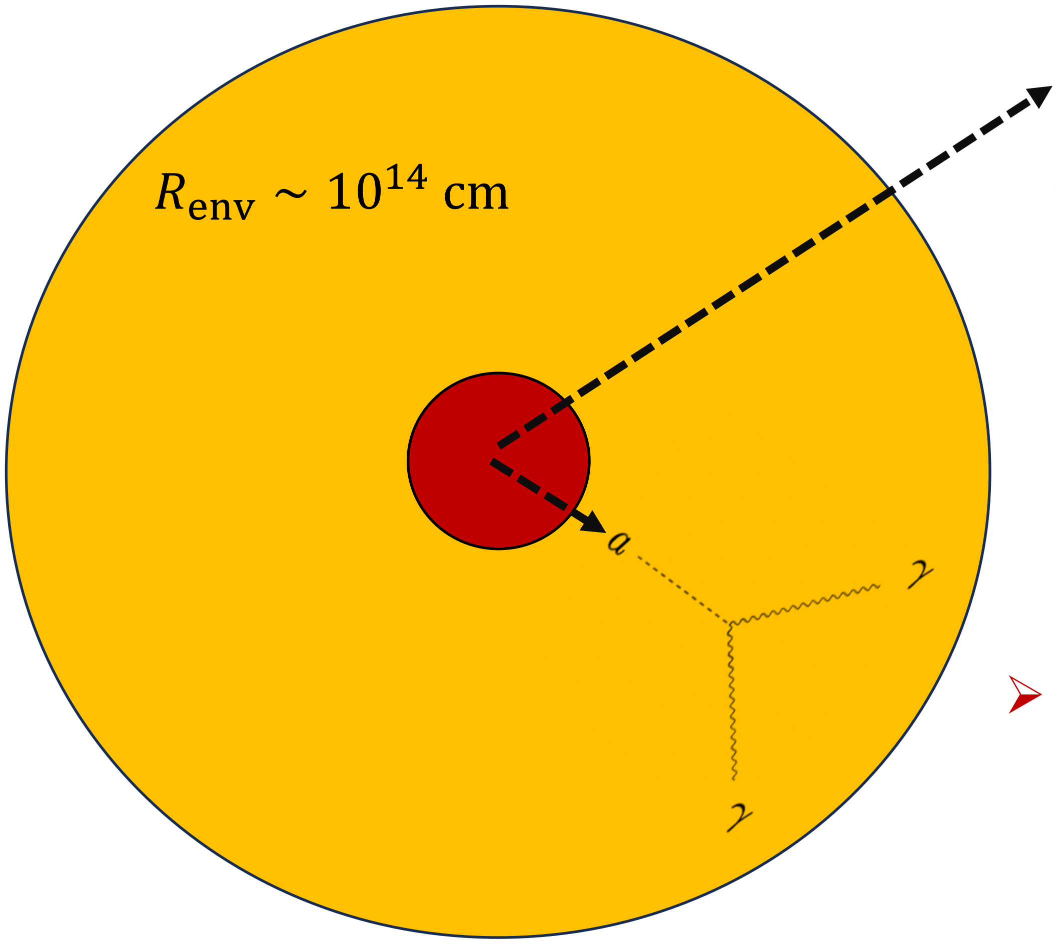
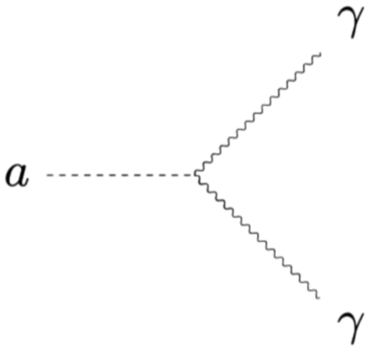




- $\lambda_\gamma > R_{\rm env}$
  - γ-ray flux
  - DSNALPB
- $\lambda_\gamma < R_{\rm env}$
  - Energy deposition

Energy deposition

[Caputo et al., Phys. Rev. Lett. 128 (2022)]

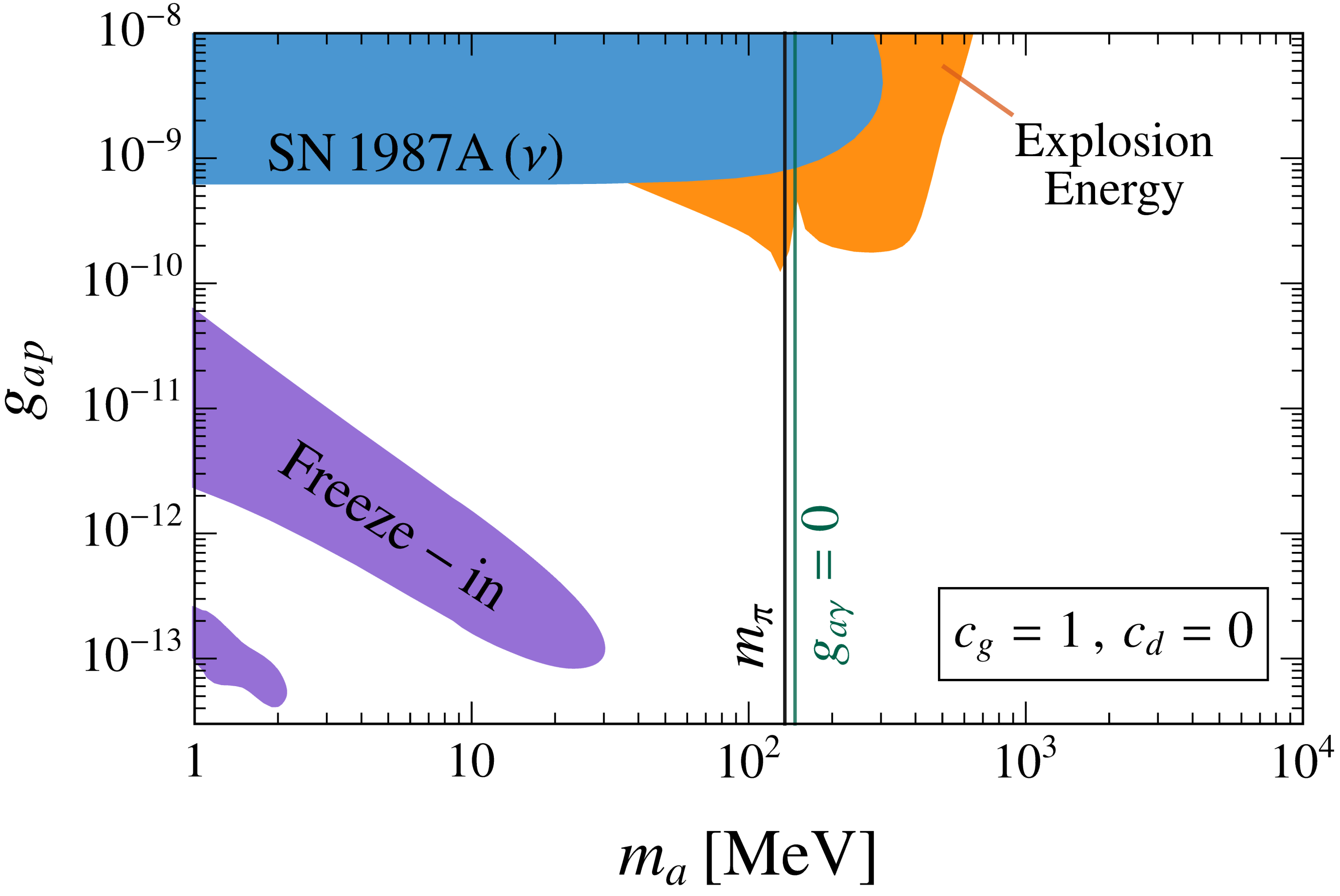
- ALPs decaying inside the SN envelope deposit energy in the mantle

$$E_{\rm dep} = \int dt \int_0^{R_{\rm PNS}} dr 4\pi r^2 \int_0^\infty d\omega_a \omega_a \frac{dn_a}{d\omega_a\, dt} \times \left[e^{-(R_{\rm PNS}-r)/\lambda_\gamma} - e^{-(R_{\rm env}-r)/\lambda_\gamma}\right]$$

- For low-energy SNe

$$E_{\rm dep} < E_{\rm exp} \sim 10^{50}\ {\rm erg}$$

AL & al., ArXive: 2405.00153



γ-ray bursts from SNe

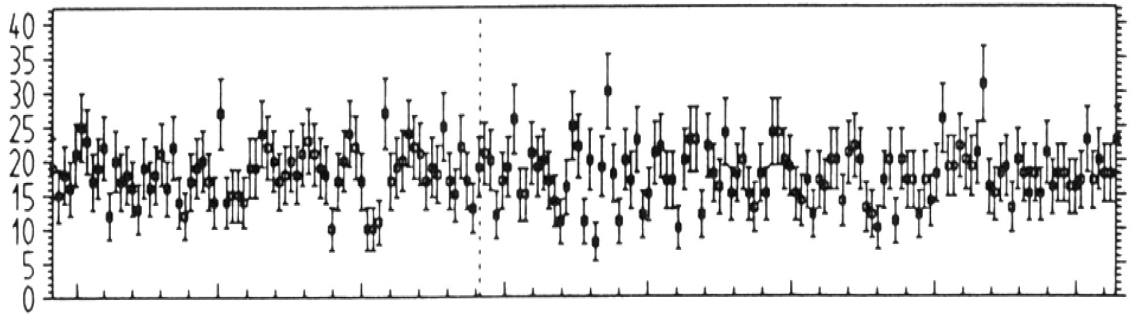
[Jaeckel et al., Phys. Rev. D 98 (2018)]
[Hoof & Schulz, JCAP 03 (2023) 054]
[Ravensburg et al., JCAP 07 (2023) 056]

- ALPs decaying outside the SN envelope produce a photon burst

$$F_\gamma = \int_{m_a}^{\infty} d\omega_a \int_{\omega_\gamma^{\min}}^{\omega_\gamma^{\max}} d\omega_\gamma\, \Theta(\Delta\omega_\gamma) \frac{\mathrm{BR}_{a\to\gamma\gamma}}{2\pi d_{\rm SN}^2}\, p_a^{-1} \frac{dN_a}{d\omega_a} \times \left[\exp\left(-\frac{m_a R_*}{\tau_a p_a}\right) - \exp\left(-\frac{2\omega_\gamma \Delta t}{\tau_a m_a}\right)\right]$$

- No excess in SMM/GRS experiment

*[Chupp et al., Phys. Rev. Lett. **62**, 505]*



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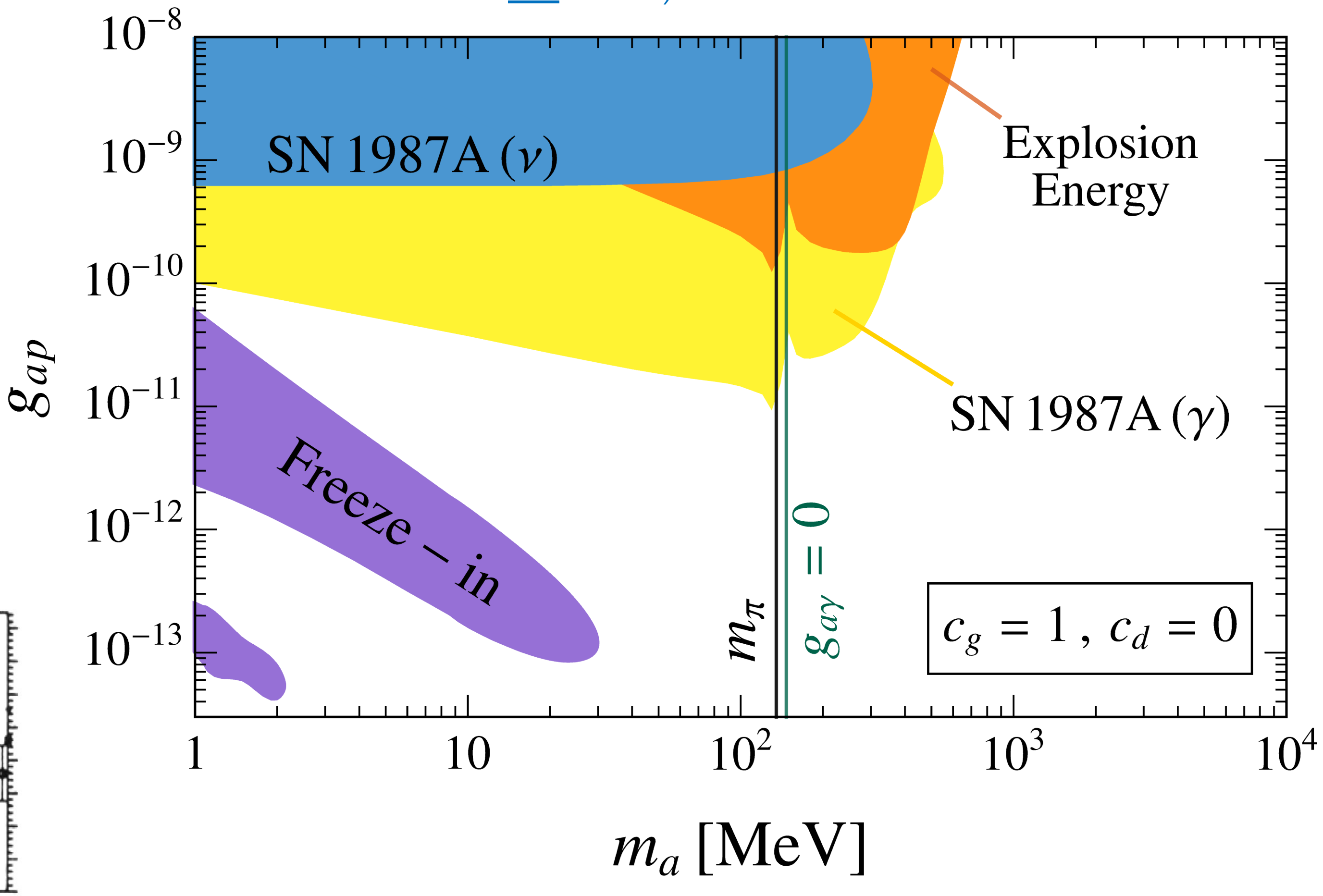
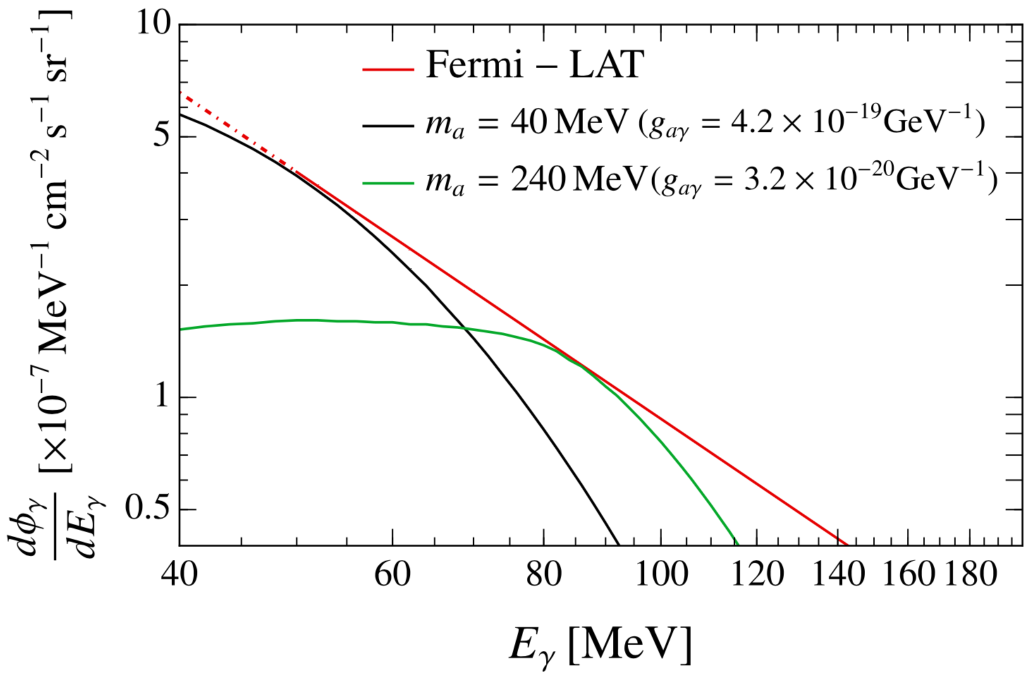


DSNALPB

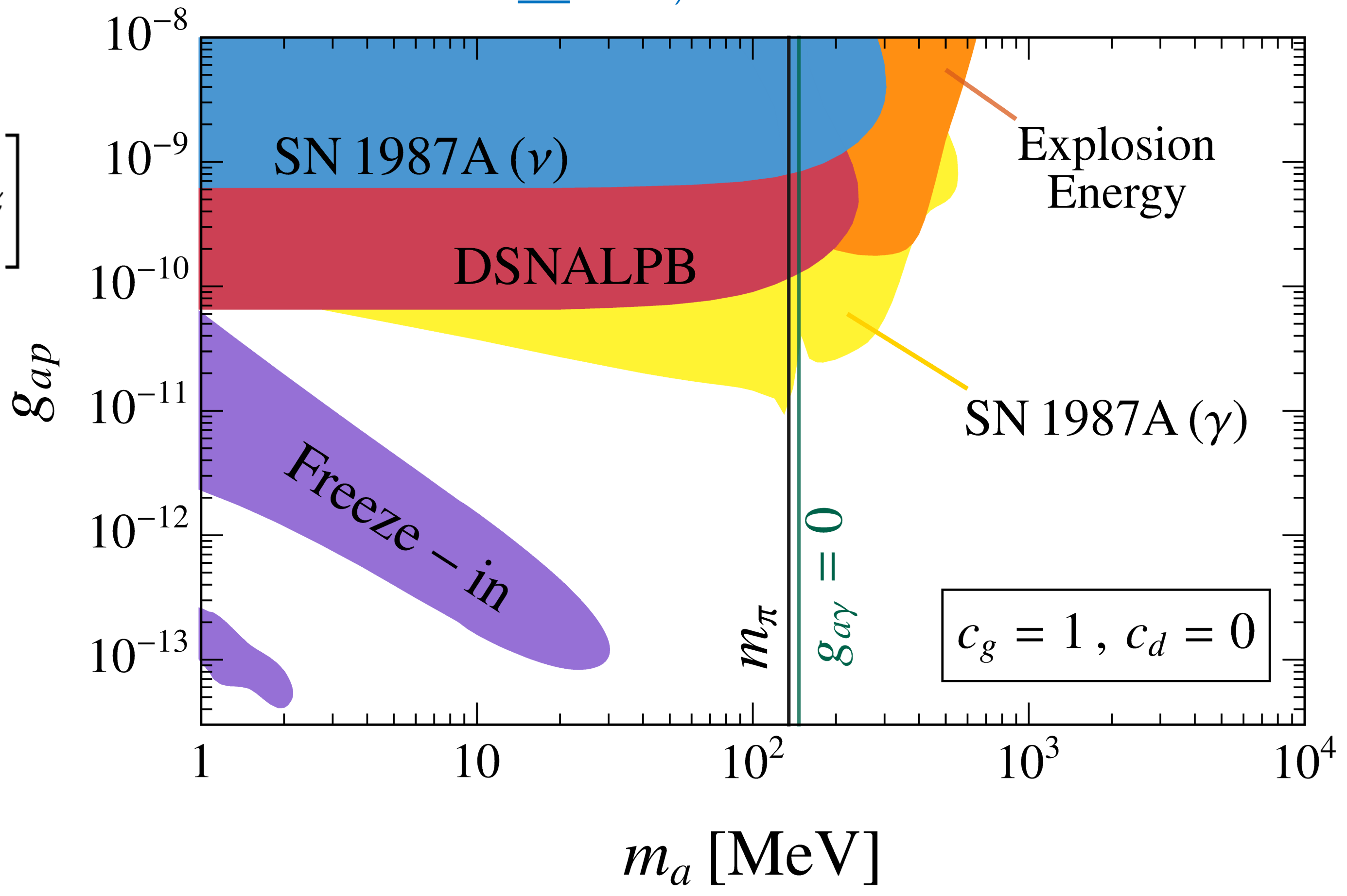
[Beacom et al., Ann. Rev. Nucl. Part. Sci. 60 (2010)]
[Calore et al., Phys. Rev. D 102 (2020)]

- ALPs decaying outside the SN envelope produce a photon burst

$$\frac{d\phi_\gamma^{\rm dif}}{dE_\gamma} = \int_0^\infty (1+z)\frac{dN_\gamma(E_\gamma(1+z))}{dE_\gamma}[R_{SN}(z)]\left[\left|\frac{dt}{dz}\right|dz\right]$$



AL & al., ArXive: 2405.00153



Take-home messages

- ALPs with masses $m_a \sim 10 - 100$ MeV can be copiously produced in SN cores by means of their nuclear coulings

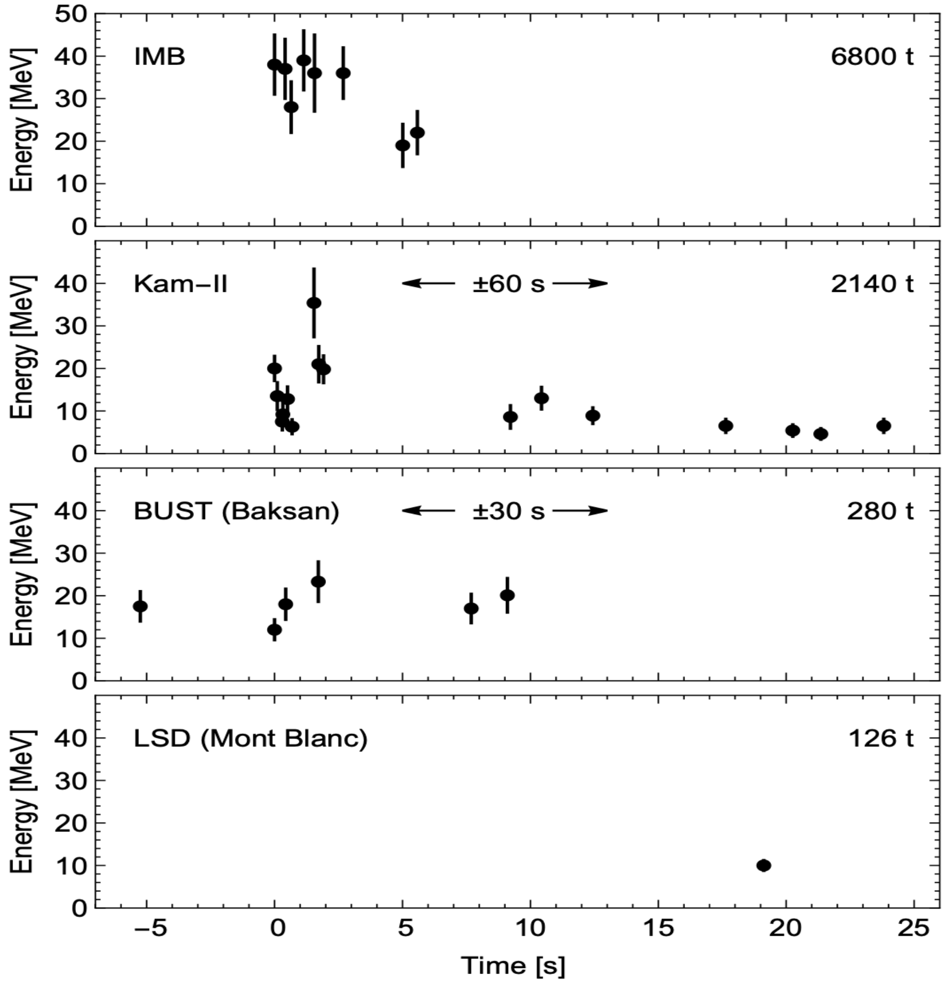
- ALP-nucleon couplings must descend from a UV including couplings to QCD.
  This implies an natural coupling to photons

- ALPs coupled to nucleons experience the phenomenology related to photon couplings, implying strong bounds on the parameter space.

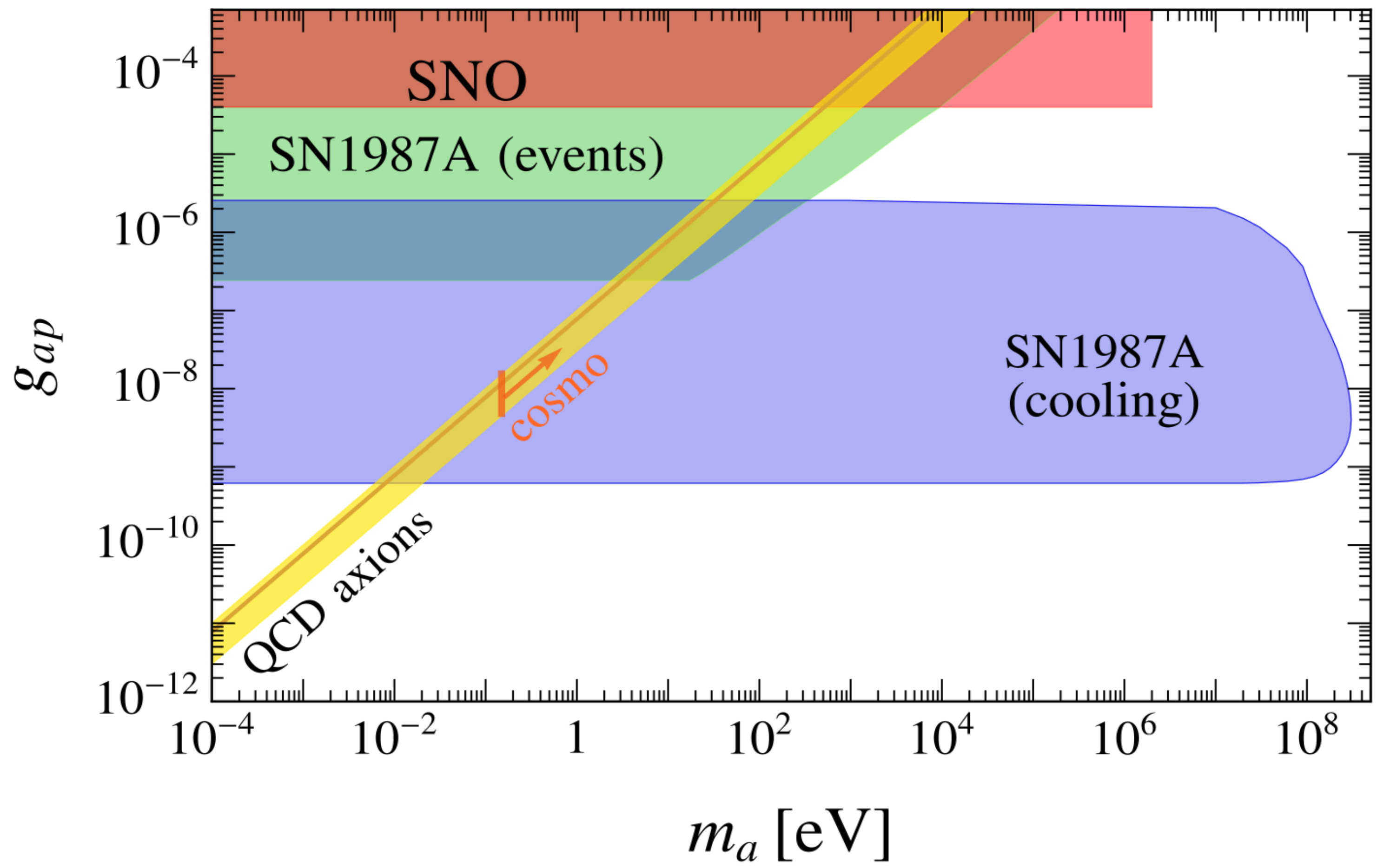

Thank you for your attention

Constraints from SN 1987A

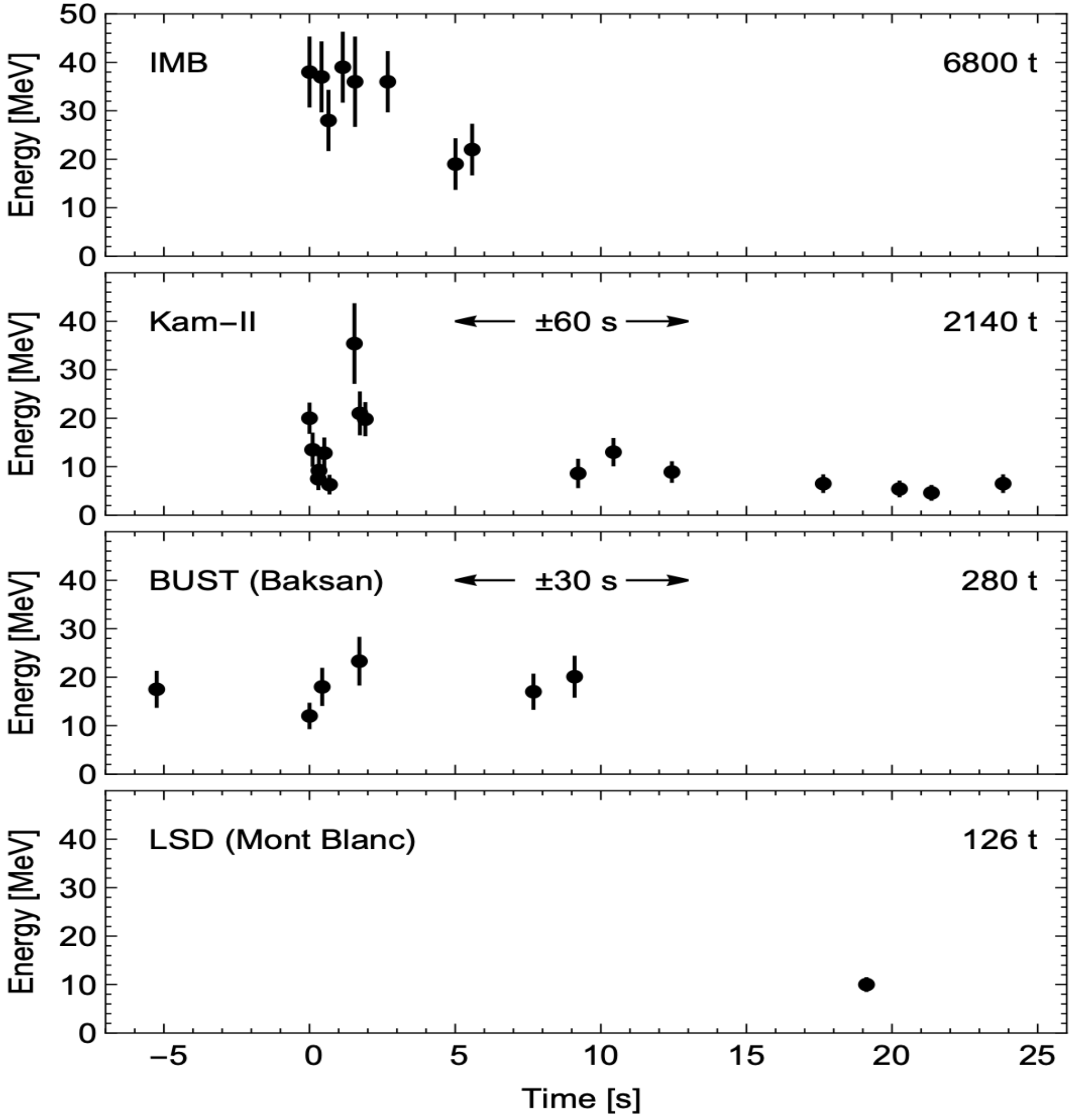
Observations of SN 1987A neutrino burst constrain the ALP parameter space



[AL & al., Phys. Rev. D 109 (2024) 2]



SN 1987A



- From SN 1987A neutrino burst observations:
  - Duration of the burst ~ 10 s.
  - $< E_\nu > \approx 15$ MeV.

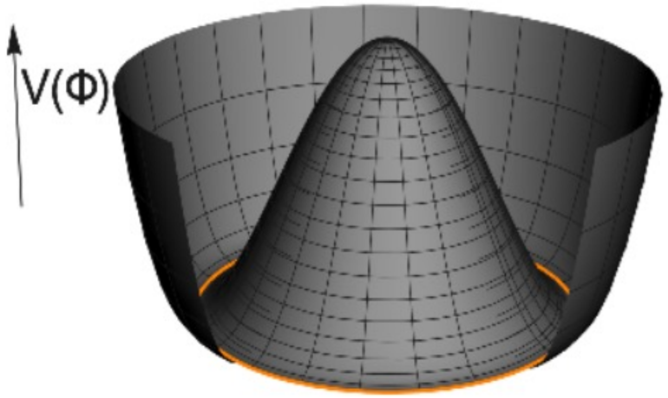
- Confirmed standard picture from SN simulations

Recent re-analysis of SN 1987A neutrino burst with current SN simulations.
[Fiorillo et al., Phys. Rev. D 108 (2023)]

Axions and Axion-like particles

The QCD axion is a hypothetical pseudoscalar particle postulated to solve the strong-CP problem of QCD *[Peccei & Quinn, Phys. Rev. Lett. 38 (1977)] [Weinberg, Phys. Rev. Lett. 40 (1978)] [Wilzcek, Phys. Rev. Lett. 40 (1978)]*.

The QCD axion acquires a small mass below Λ_{QCD} from its coupling to QCD



$$m_a f_a \approx f_\pi m_\pi$$

Axion-like particles (ALPs) emerge in UV completions of the Standard Model

→ No relation between their masses and couplings

ALP emission spectra

- If ALPs interact weakly with nuclear matter, they can *free-stream* through the SN volume

$$\frac{d^2 N_a}{dE_a\, dt} = \int_0^\infty 4\pi r^2 dr \frac{d^2 n_a}{dE_a\, dt}$$

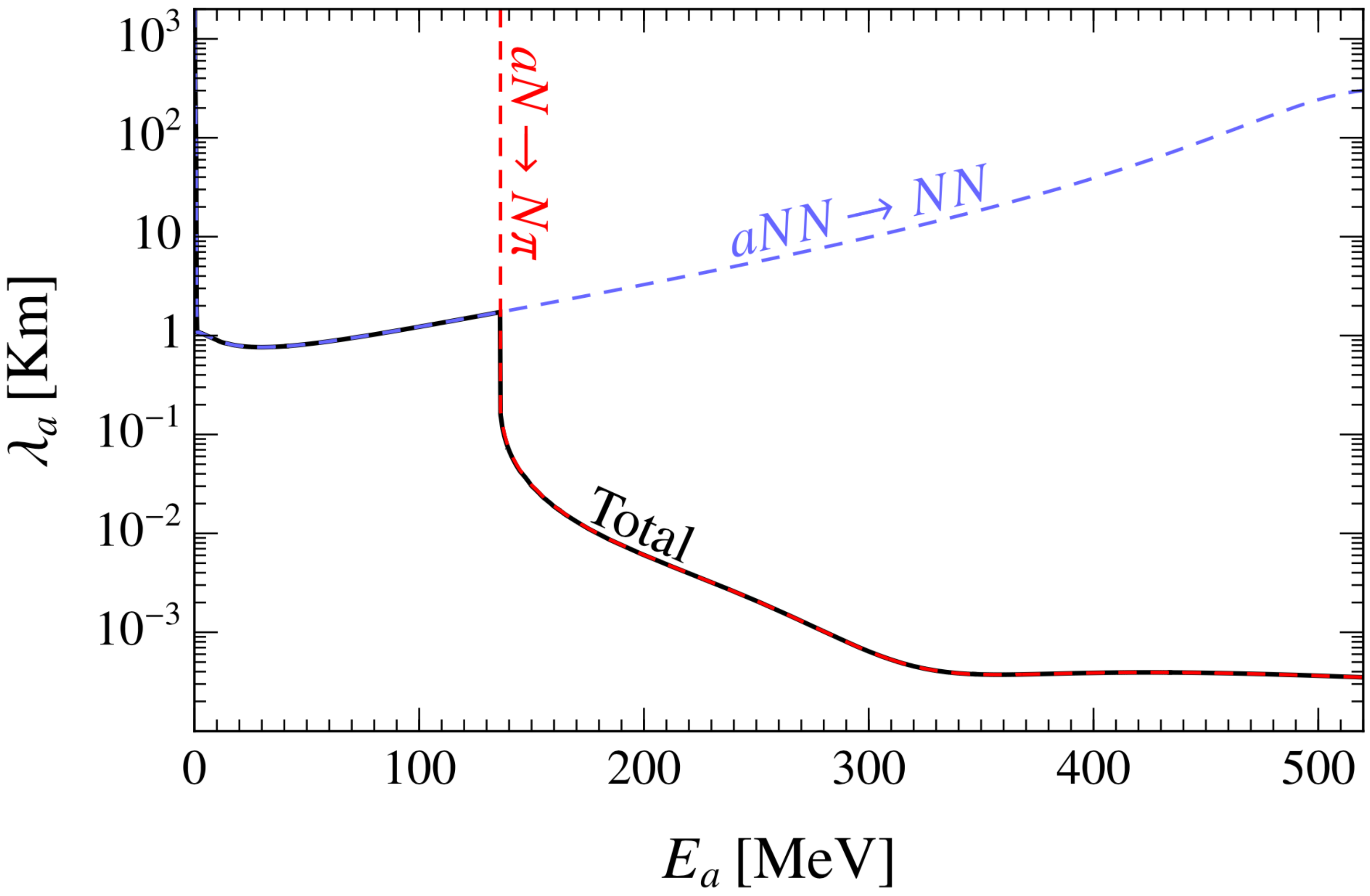
- In case of strongly coupled ALPs, they could enter the *Trapping regime*
  [Caputo & al., Phys. Rev. D 105 (2022)*]*

$$\frac{d^2 N_a}{dE_a\, dt} = \int_0^\infty 4\pi r^2 dr \left\langle e^{-\tau(E_a, r)} \right\rangle \frac{d^2 n_a}{dE_a\, dt}$$

$\tau \sim \int_0^\infty dr\, \lambda_a^{-1}$ optical depth for nuclear processes

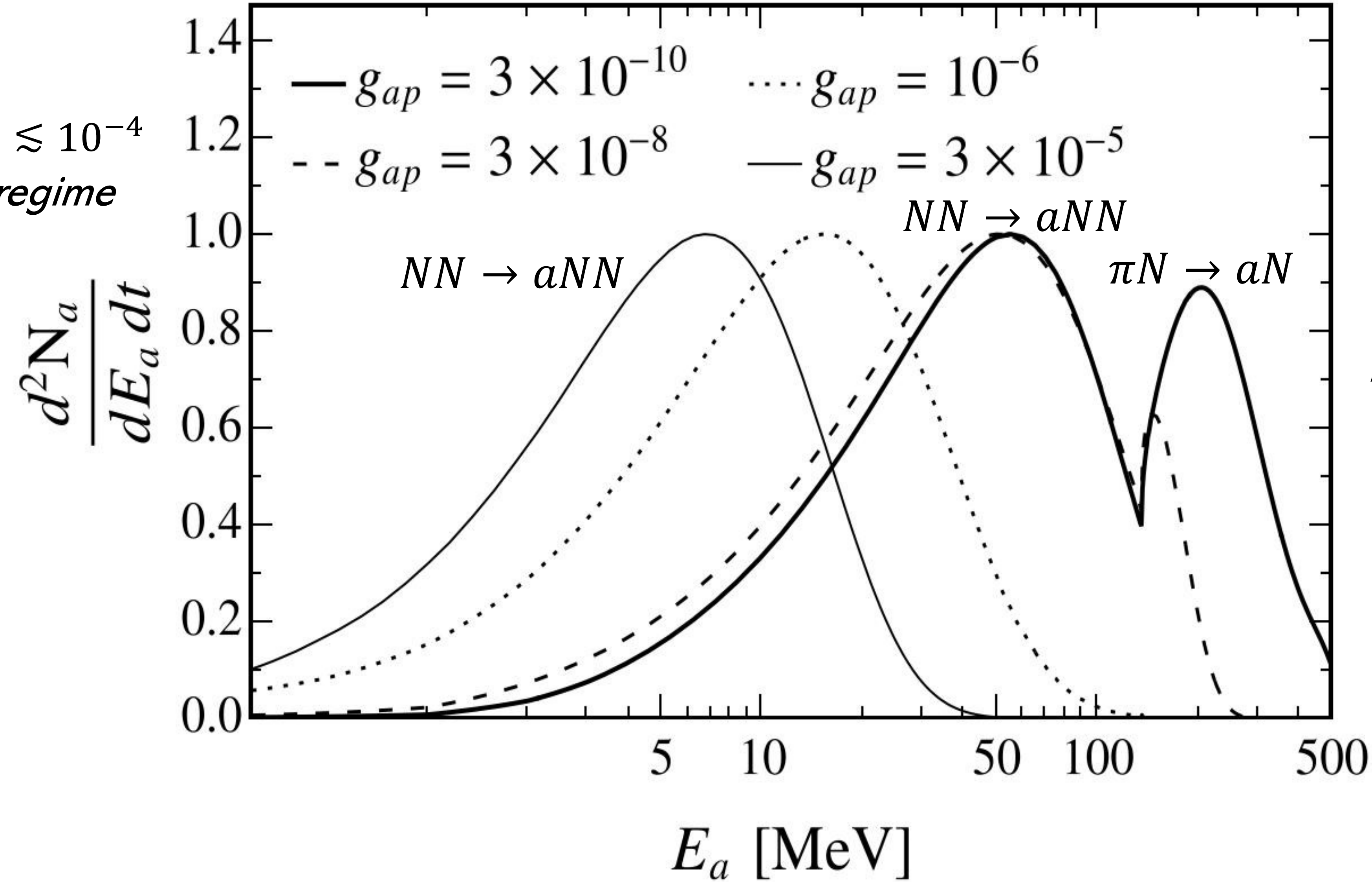
ALP mean free path

$$\lambda_a^{-1}(E_a) = \frac{1}{2|\mathbf{p}_a|}\frac{d^2 n_a(\chi\, E_a)}{d\Pi_a\, dt}$$



ALP emission spectra

$10^{-7} \lesssim g_{ap} \lesssim 10^{-4}$
trapping regime

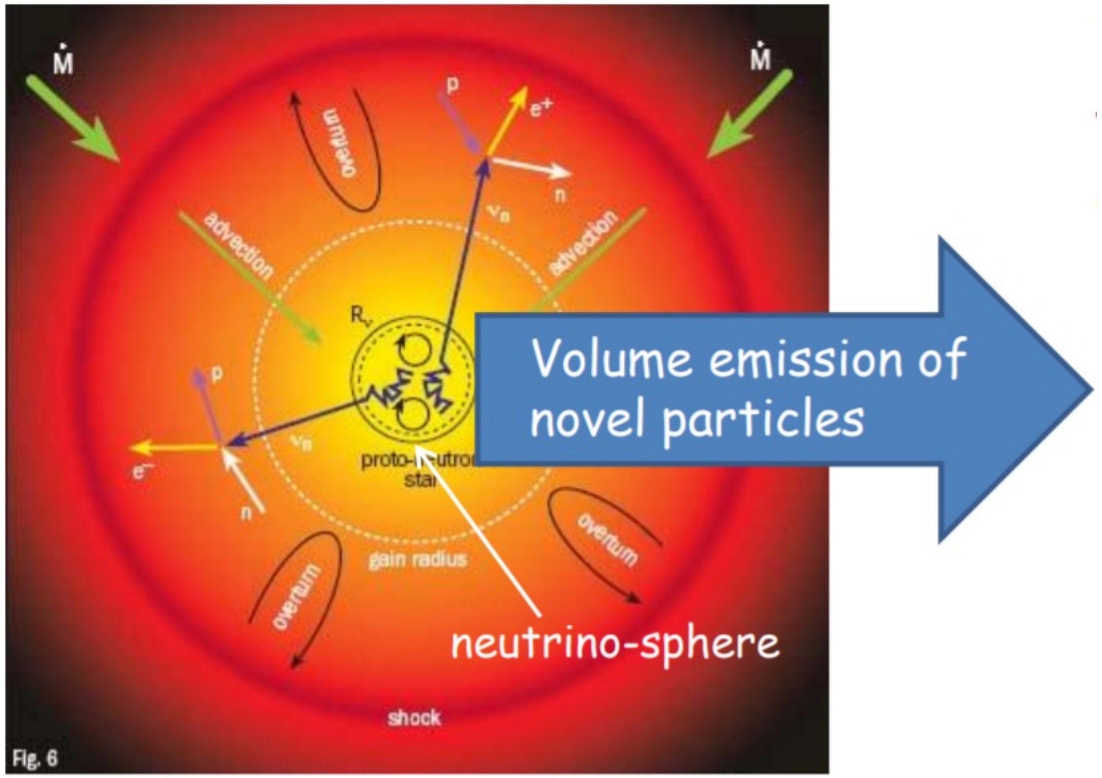


$10^{-10} \lesssim g_{ap} \lesssim 10^{-7}$
free-streaming regime

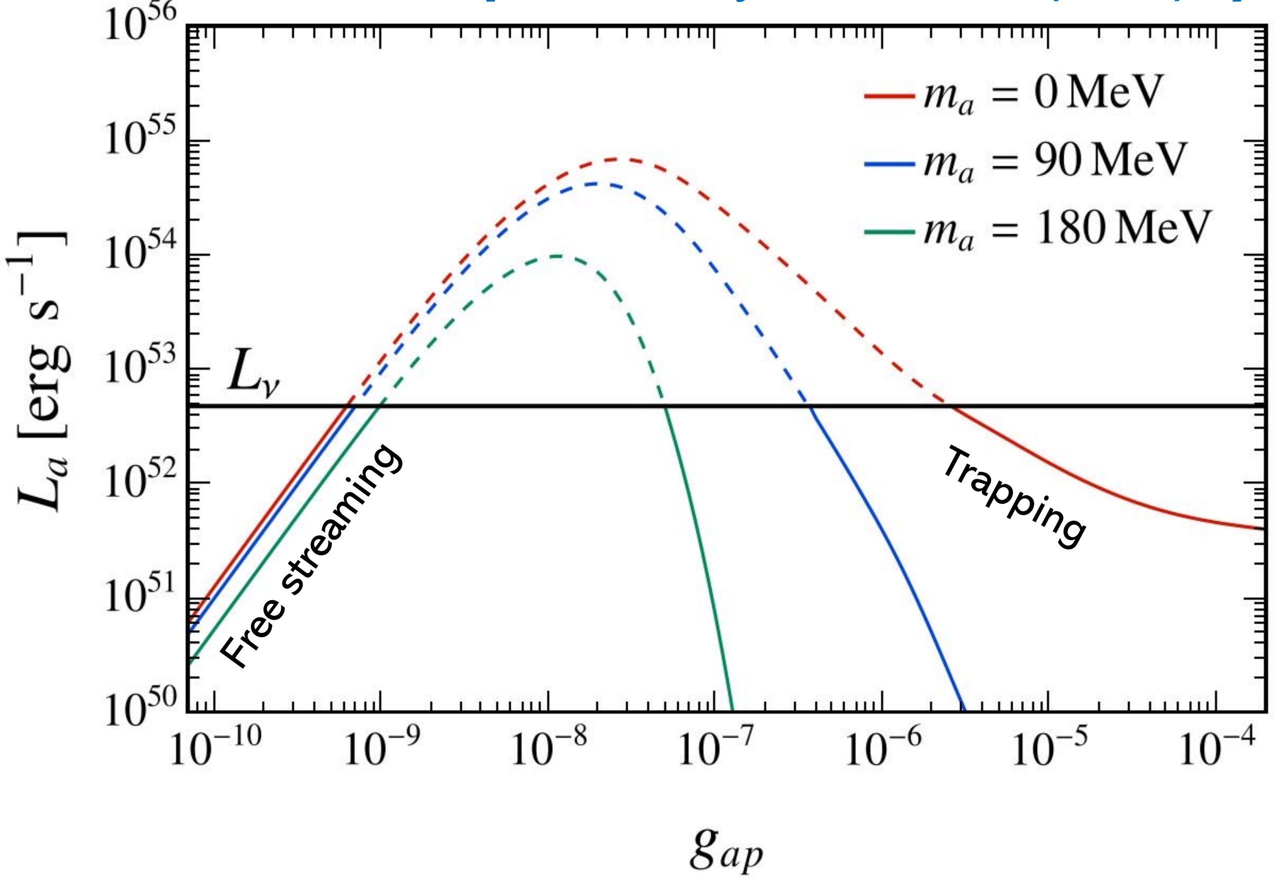
The energy-loss argument

Emission of exotic particles could cause an excessive energy-loss from SN, affecting the neutrino burst.

[AL & al., Phys. Rev. D 109 (2024) 2]



[Raffelt & Seckel, Phys. Rev. Lett.60 (1998)]



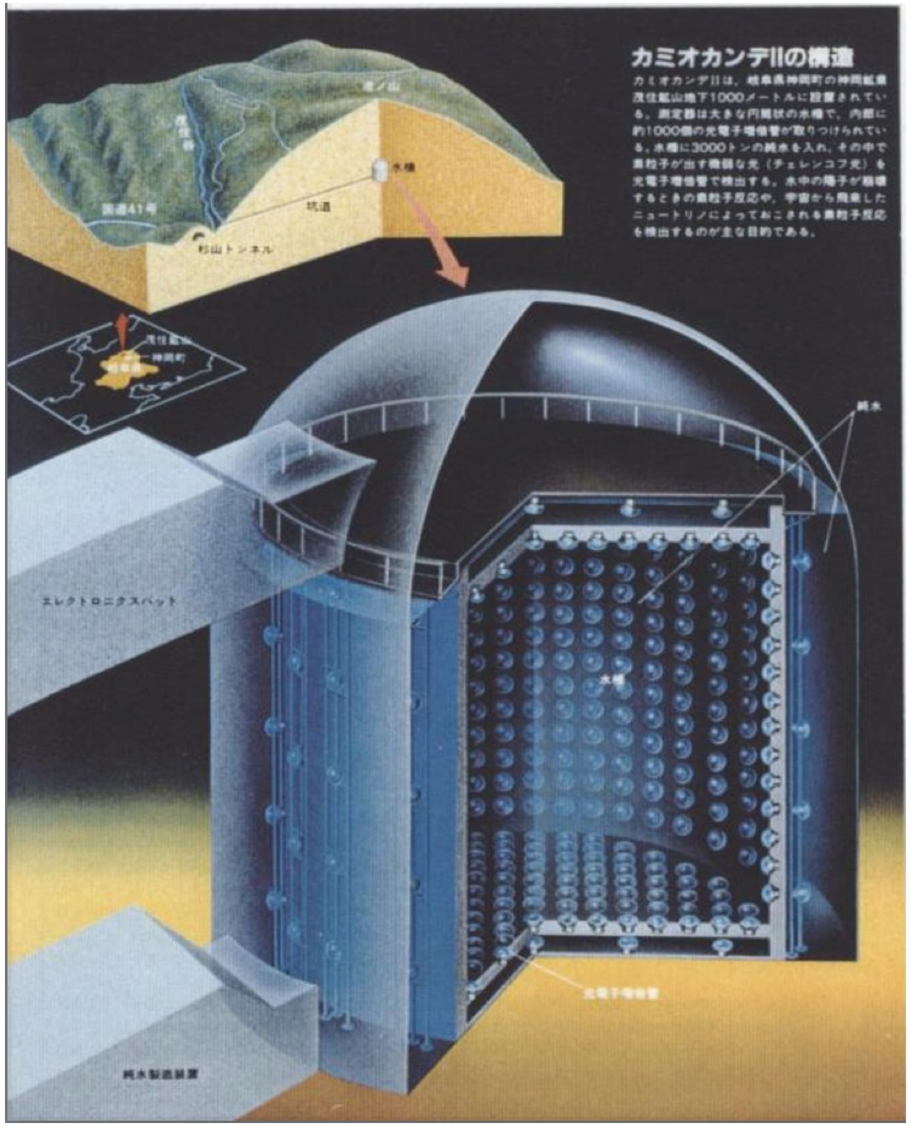
Axion signal in Kamiokande II

- In case of strong couplings the ALP flux would have produced a signal in Kamiokande II.

- Seminal idea by Engel, Seckel and Hayes: look for axion-induced excitation of oxygen nuclei *[Engel et al., Phys. Rev. Let. 65 (1990)]* .

$$a + {}^{16}\mathrm{O} \to {}^{16}\mathrm{O}^* \to {}^{16}\mathrm{O} + \gamma$$

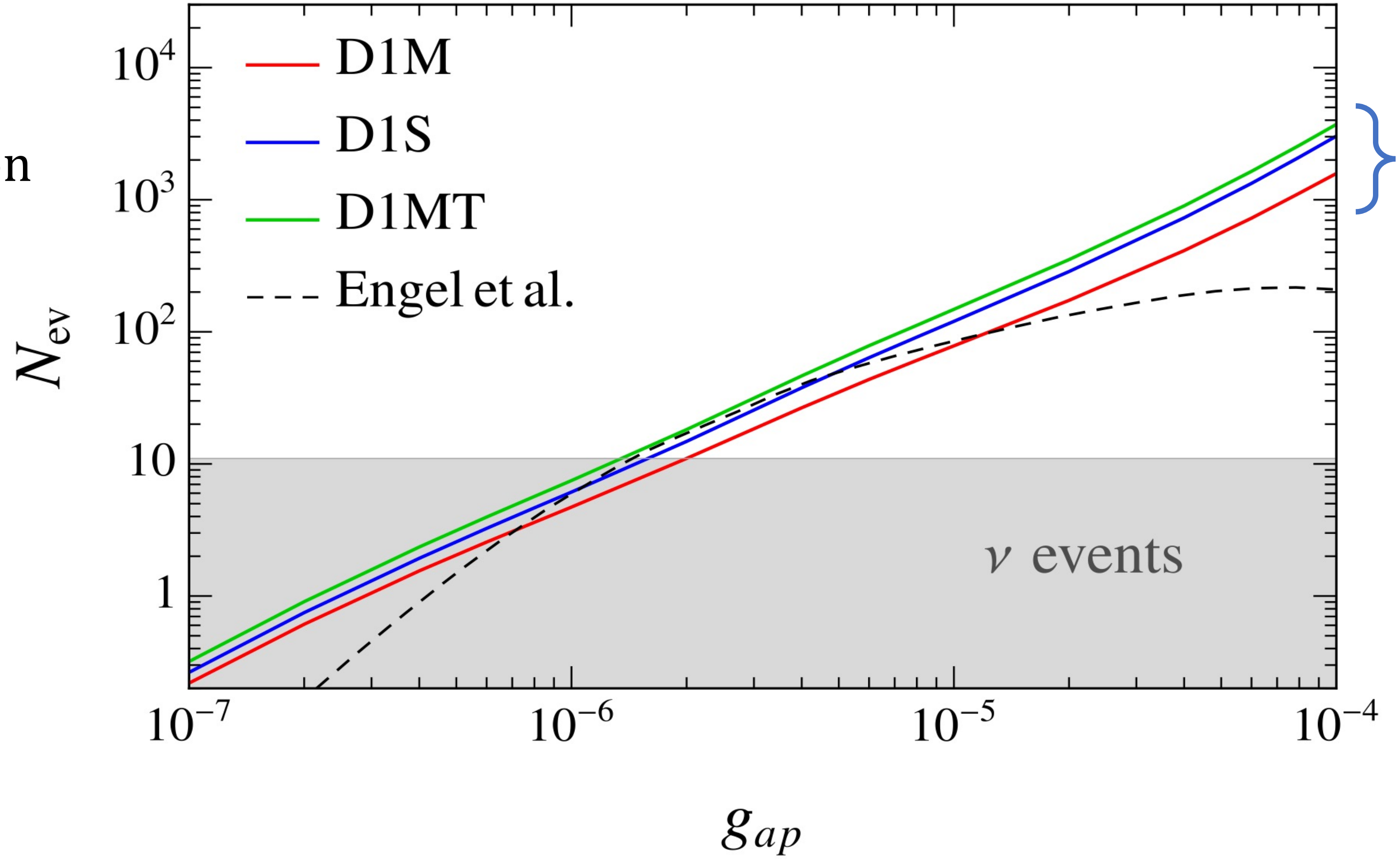
- The computation of the event rate requires:
  - SN explosion models
  - An adequate treatment of trapping regime
  - State-of-the-art nuclear models



Events number in Kamiokande-II

$$N_{\rm ev} = F_a \otimes \sigma \otimes \mathcal{R} \otimes \mathcal{E}$$

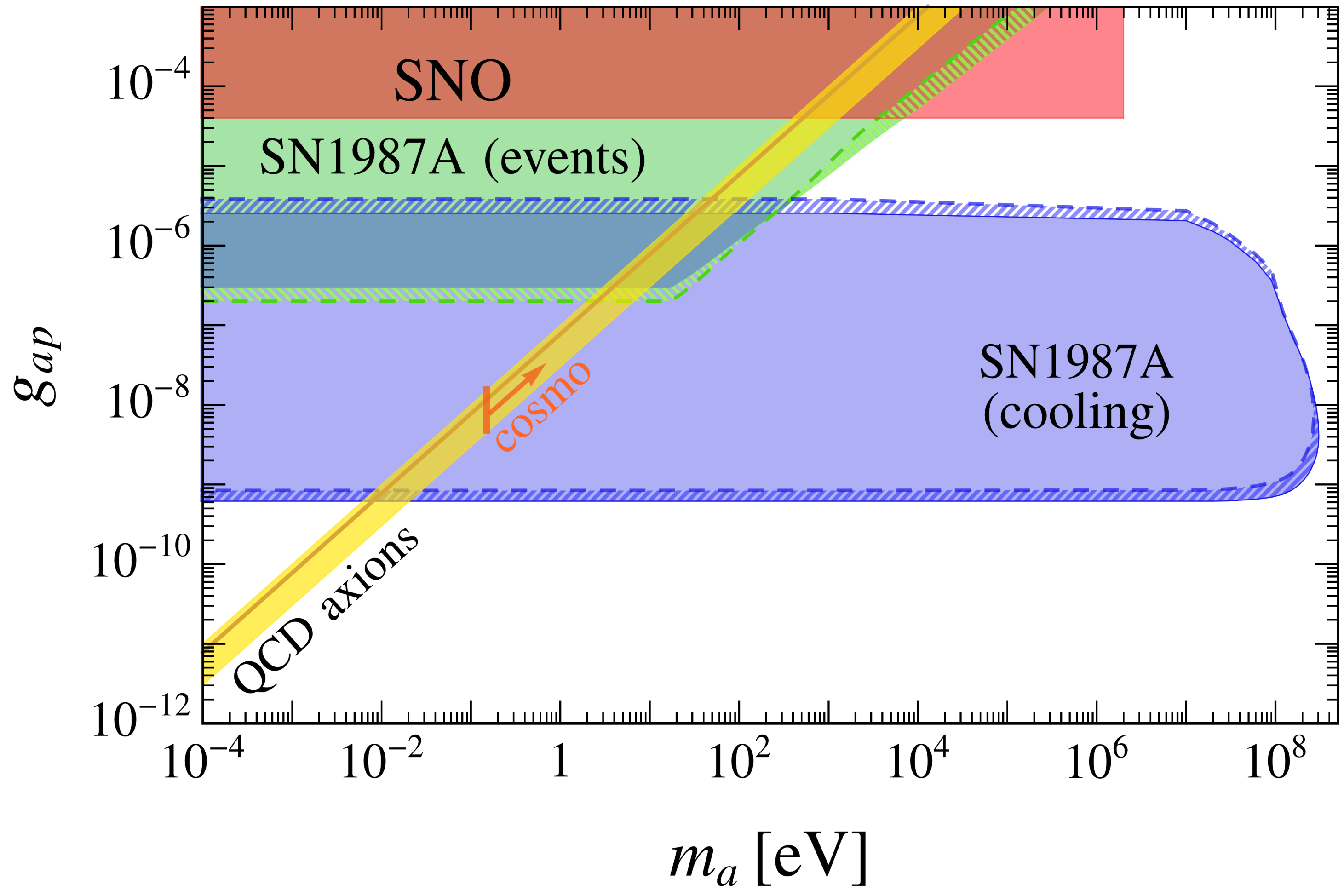
$M_{KII} \sim 2.4$ kton



Uncertainties $\mathcal{O}(60\ \%)$ over the nuclear model

Uncertainties on SN Bounds

Different SN models from same progenitors ($\sim 18\, M_{\odot}$) show different temperature and density profiles.



AGILE BOLTZTRAN

[Mezzacappa & al., Astrophys. J. 405 (1993) 669]
[Liebendoerfer & al., Astrophys. J. Suppl. 150 (2004) 263]

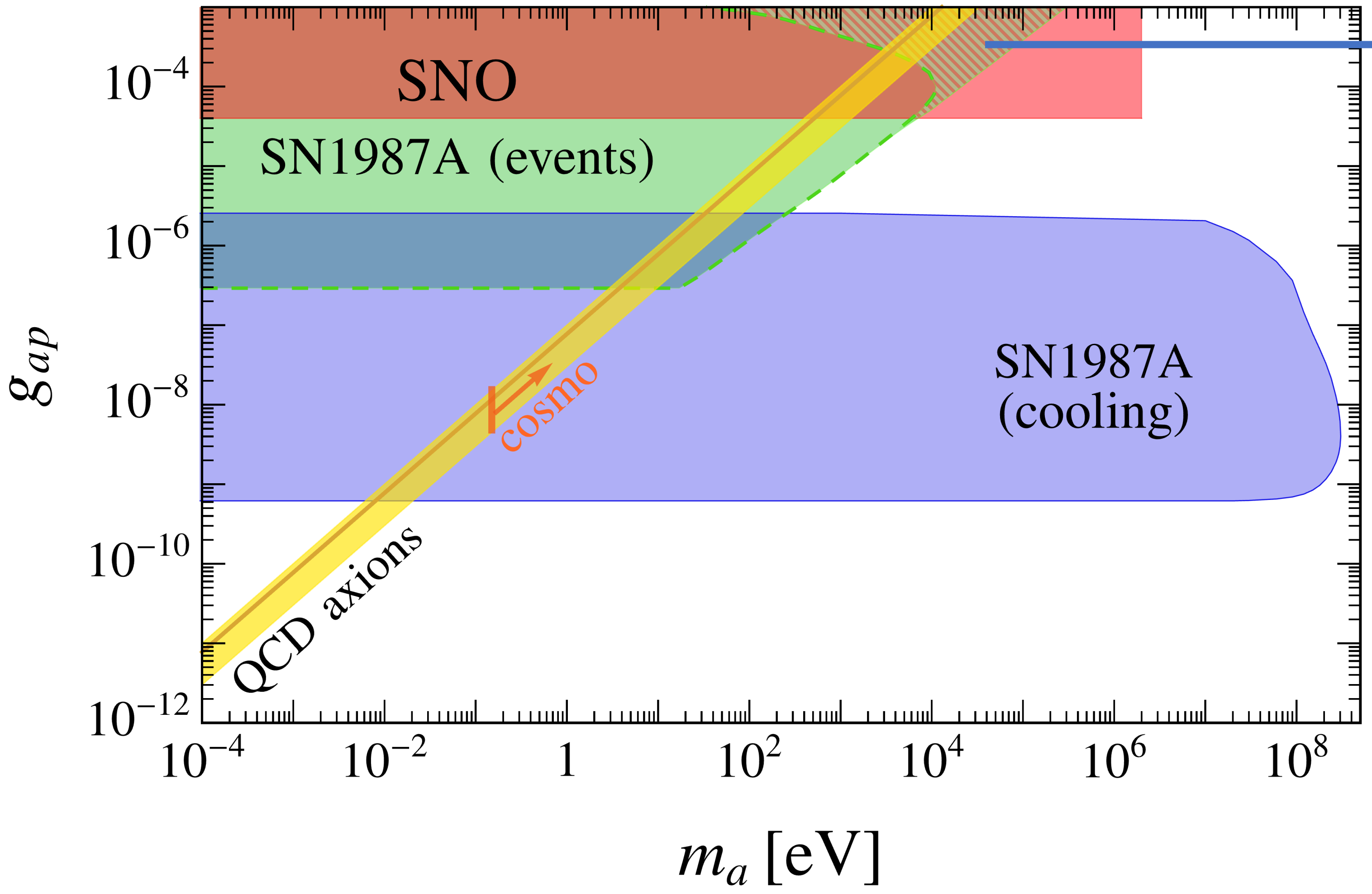
Similar impact over standard and new physics → Similar bounds

GARCHING

[Sukhobold & al., Astrophys. J. 860 (2018) 93]
[Rampp & Janka, Astron. Astrophys. 396 (2002) 361]

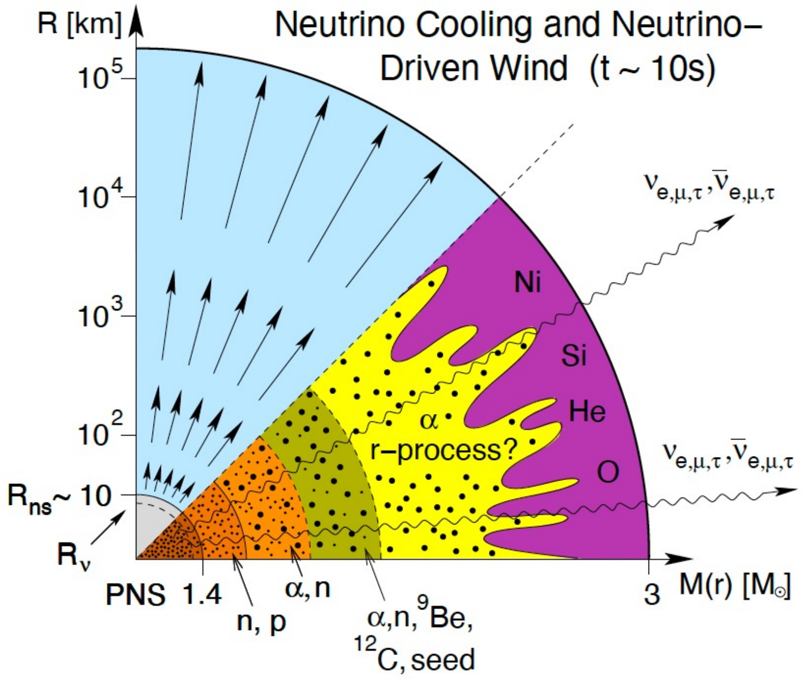
Uncertainties over SN Bounds

At very high couplings, escaping ALPs can be absorbed by heavy nuclei in the neutrino driven wind



$$\eta_H(E) = \exp\left[-\int_{R_H}^{\infty} \Gamma_H(E,r)\,dr\right]$$

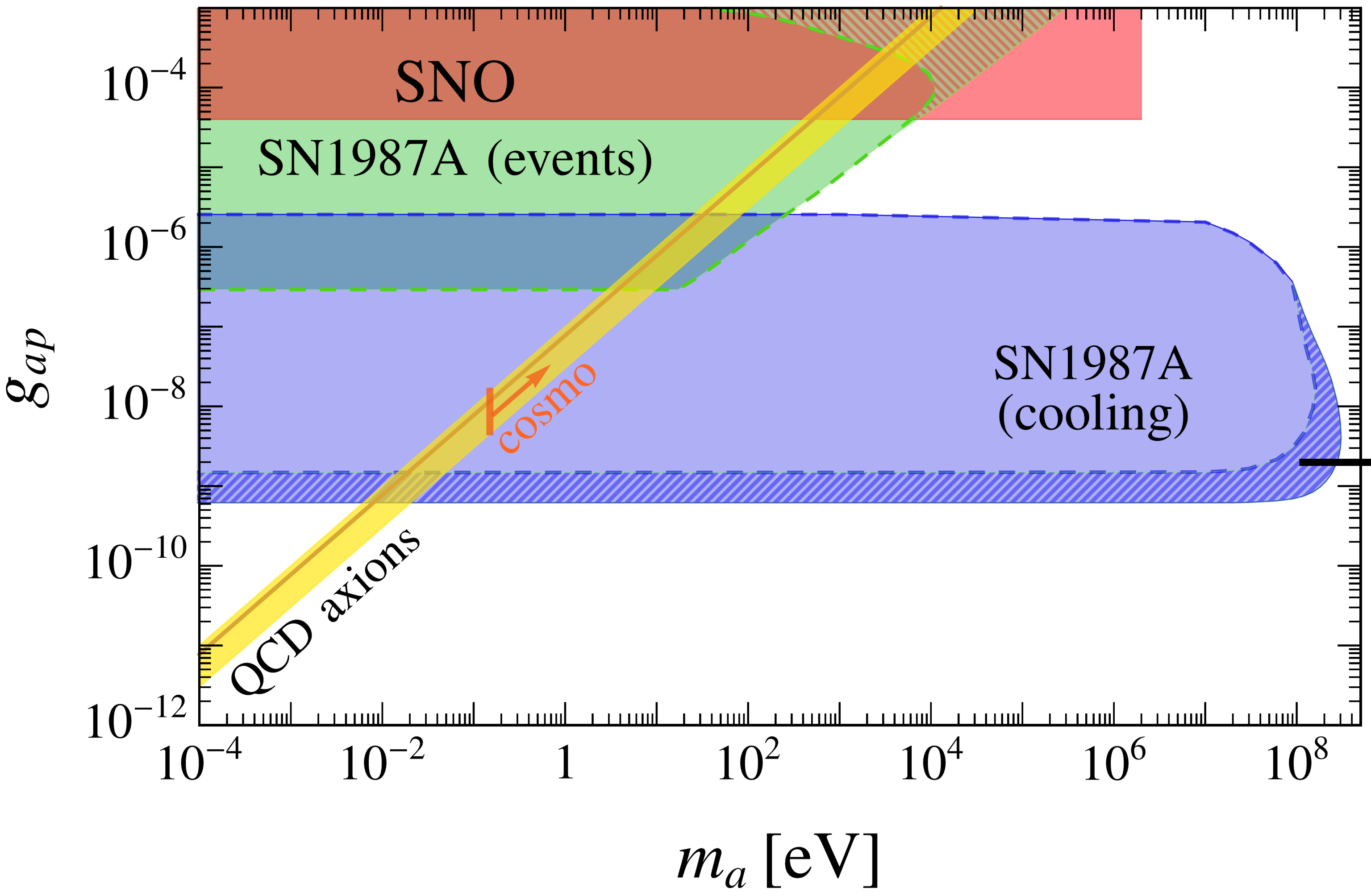
$$\Gamma_H(E,r) \sim n_H(r)\,\sigma(E)$$



Uncertainties on SN Bounds

Strong interactions can enhance the pion fraction in the SN core

[Fore & Reddy, Phys.Rev.C 101 (2020) 3]

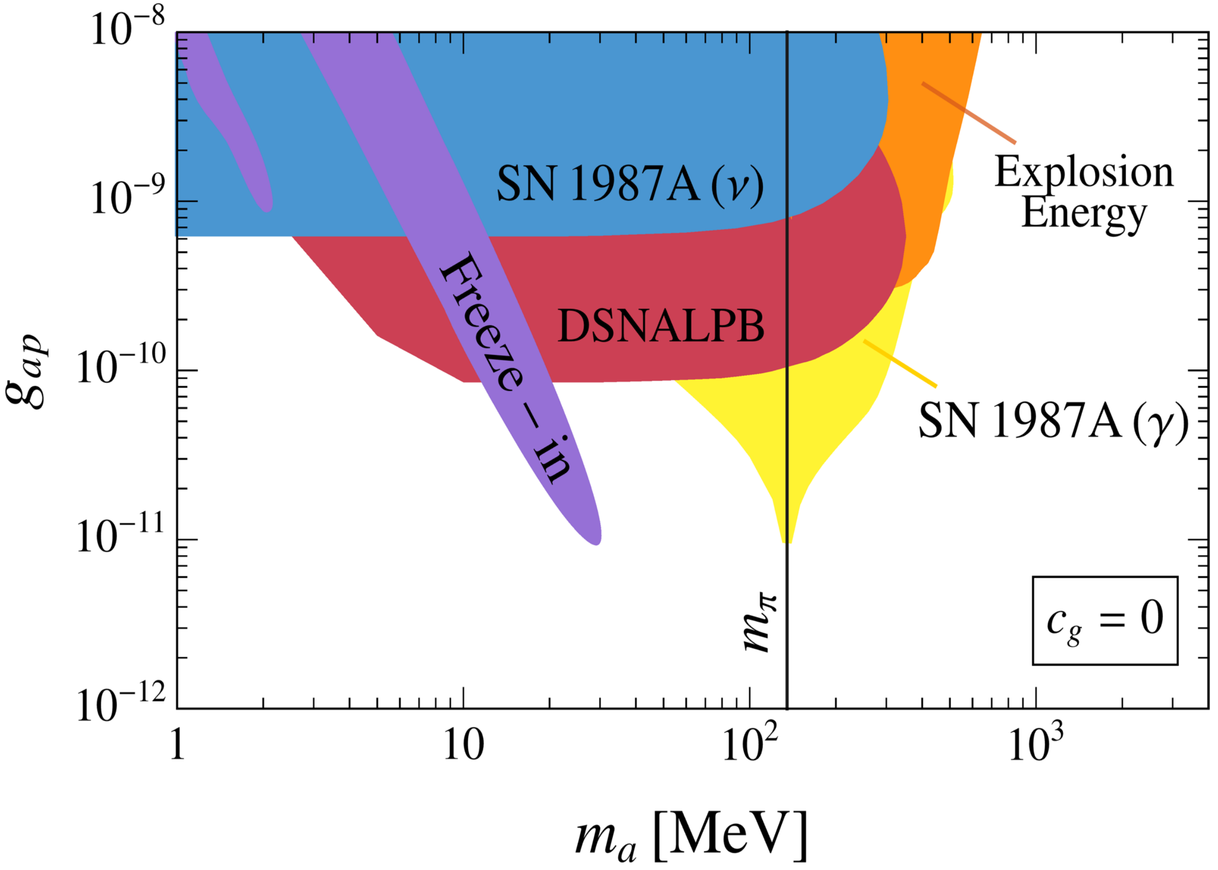


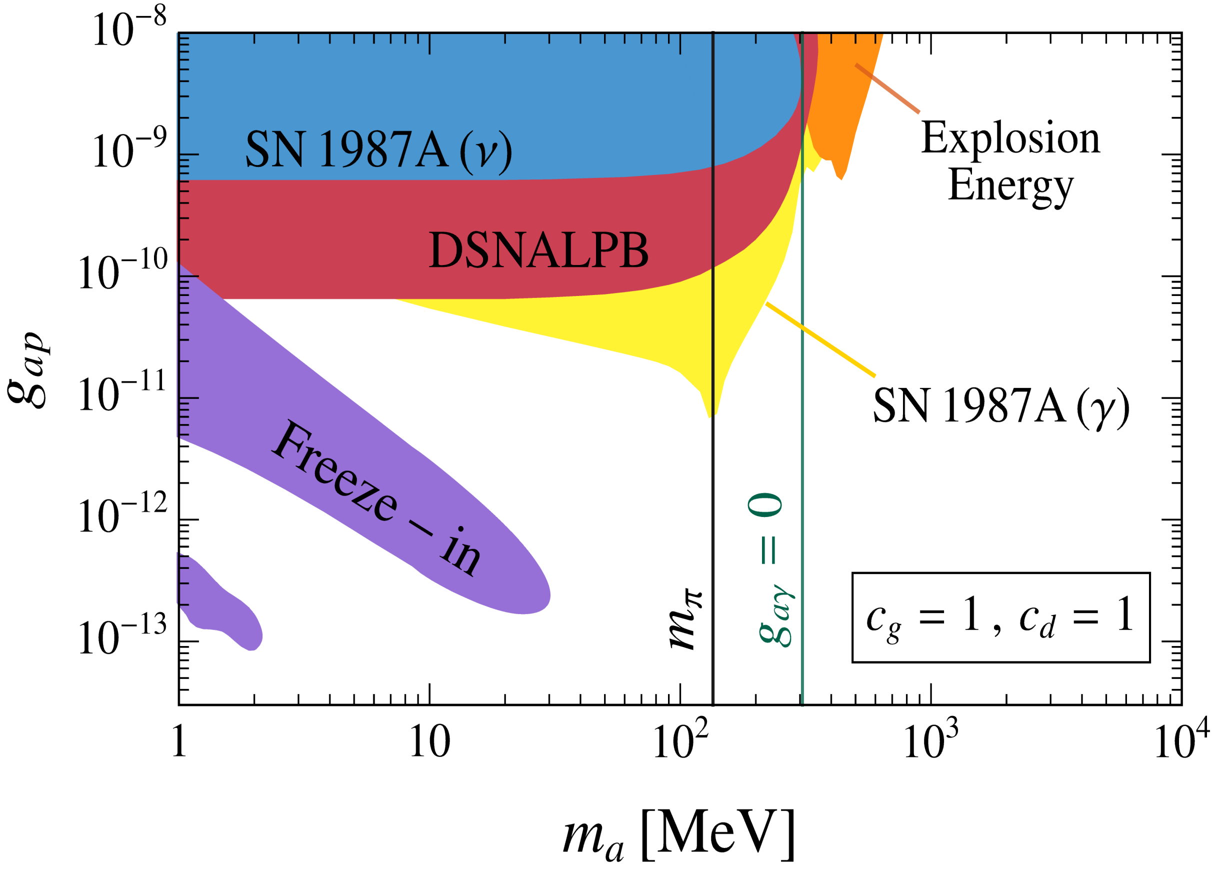
Pions still not self-consistently included in SN simulations

Fore & Reddy , e-Print: 2301.07226 [nucl-th]

Without pions, cooling bound relaxes by a factor ~ 2

Different choice of parameters





Photon coupling vs mass