Working Group Meeting of COST Action:
Cosmic Wispers (CA21106)

DESY, 1-2 February 2023

Getting the most on Supernova axions

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Finanziato dall'Unione europea
NextGenerationEU

Based on...

- AL, P. Carenza, G. Co', G. Lucente, M. Giannotti, A. Mirizzi, T. Rauscher, *"Getting the most on Supernova axions", Phys. Rev. D 109 (2024) 2*

- P. Carenza, G. Co', AL, G. Lucente, M. Giannotti, A. Mirizzi, T. Rauscher, *"Detectability of supernova axions in underground water Cherenkov detectors", Phys. Rev. C 109 (2024) 1*

- AL, P. Carenza, G. Lucente, M. Giannotti, A. Mirizzi, *"Protoneutron stars as cosmic factories for massive axion-like particles",* Phys. Rev. D 107 (2023) 10

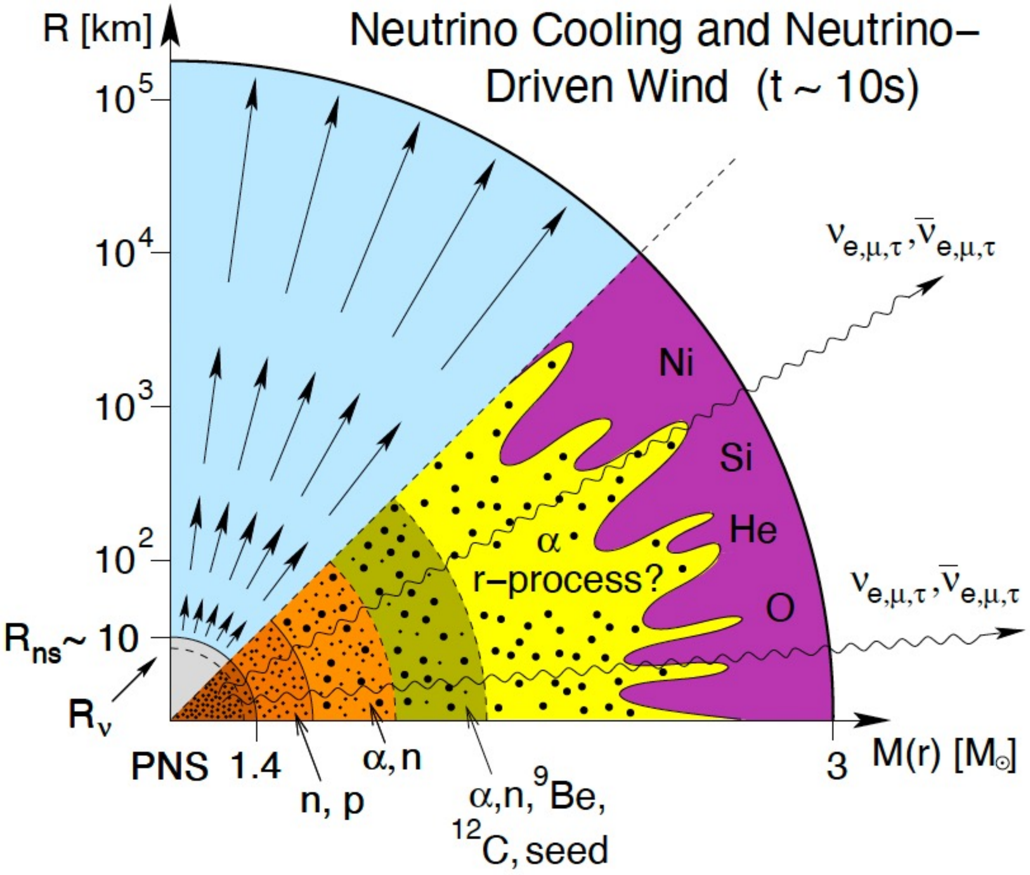
Core-Collapse Supernovae

A Supernova is the terminal phase of a massive star $[\mathrm{M} \geq 8\, M_{\odot}]$.
Gravitational collapse triggered by the formation of a degenerate iron core.

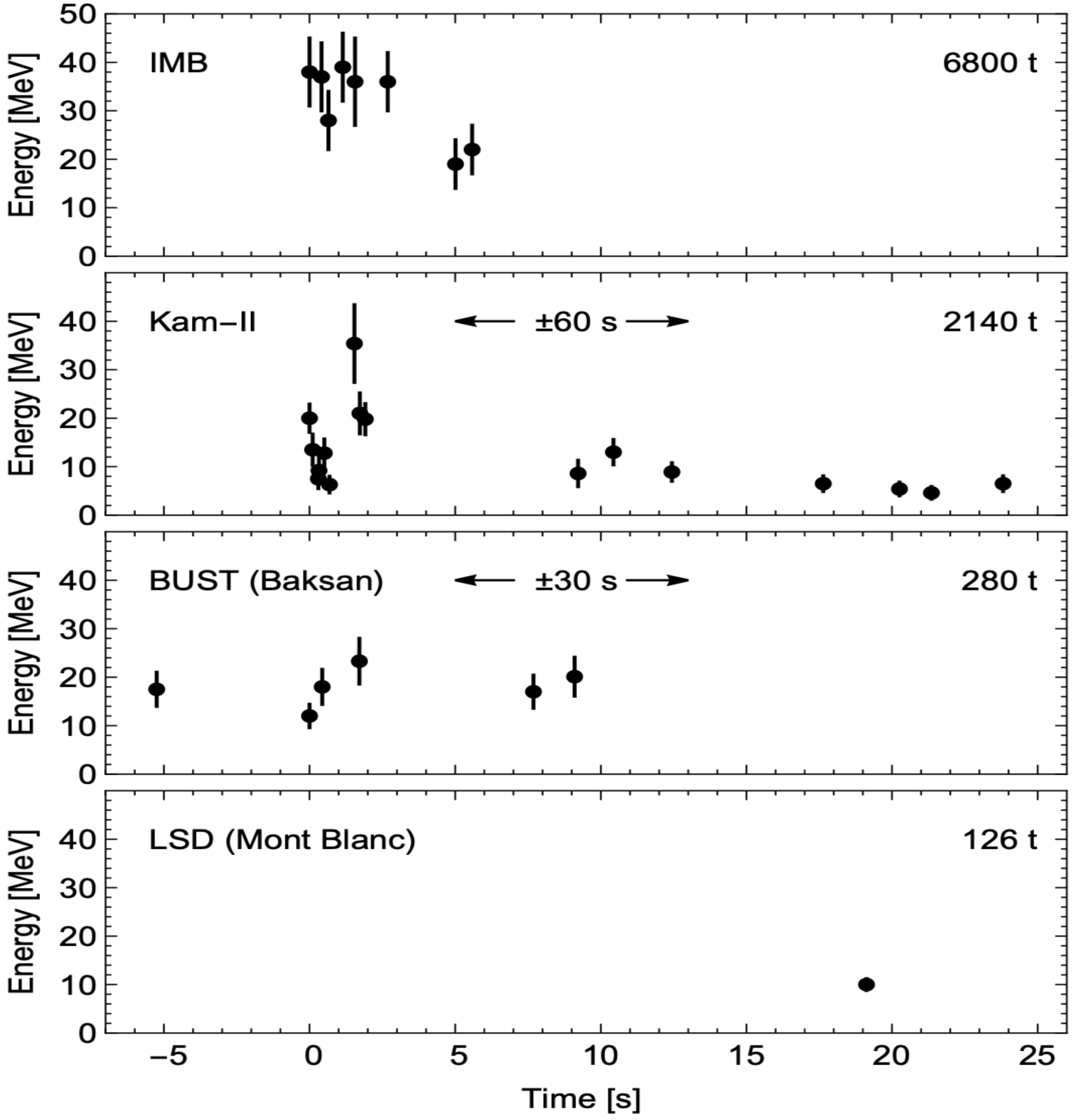
- Incompressible nuclear matter in the core
  → shock-wave driven explosion

- Formation of a Proto-Neutron star at the centre ($R \sim 20\, km$, $\mathrm{M} \sim 1.5\, M_{\odot}$).

- Cooling via neutrino emission of all species (99% of total energy)
  - $E \sim 10^{53}$ erg , $t \sim 10$ s.



SN 1987A



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

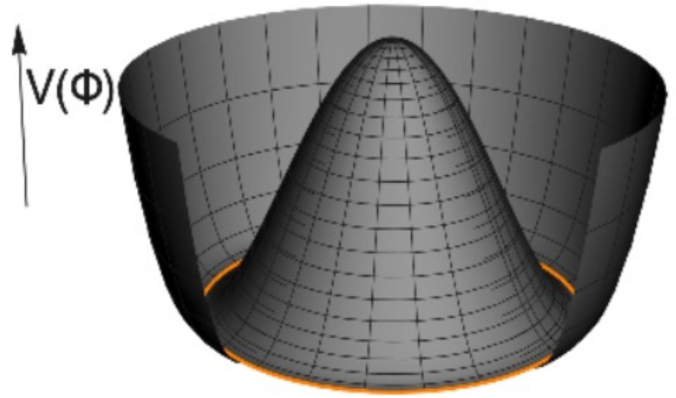
- Confirmed standard picture of SN explosion events

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

ALPs nuclear interactions

- Axions and ALPs could interact with all the Standard model particles *[Grilli di Cortona & al., JHEP 01 (2016) 034]*

$$\mathcal{L}_a \supset \frac{\alpha_s}{8\pi}\frac{C_g}{f_a} a G^a_{\mu\nu}\tilde{G}^{a\mu\nu} - \frac{1}{4} g_{a\gamma} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} - \sum_\psi \frac{g_{a\psi}}{2m_\psi}\bar{\psi}\gamma_\mu\gamma_5\psi\partial^\mu a$$

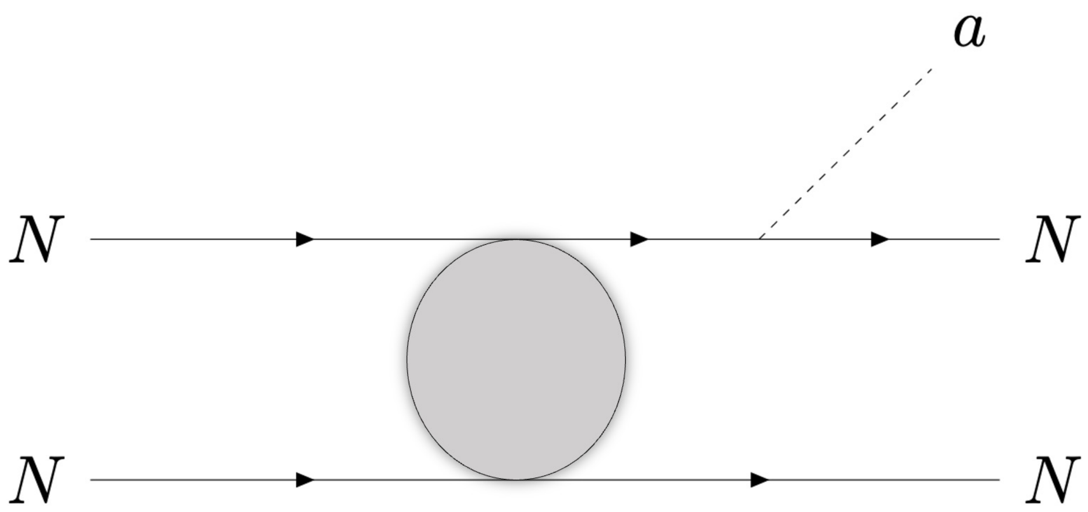
- In ChPT interaction verteces with baryons and mesons *[Ho & al., Phys. Rev. D 107 (2023)]*

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

Axion production in SNe

- Nucleon-Nucleon bremsstrahlung

[Carenza & al., JCAP 10 (2019) 10,
Raffelt & Seckel, Phys. Rev. D 52 (1995),
Hempel, Phys. Rev. C 91 (2015),
Ericson and Mathiot, Phys. Lett. B 219 (1989)]



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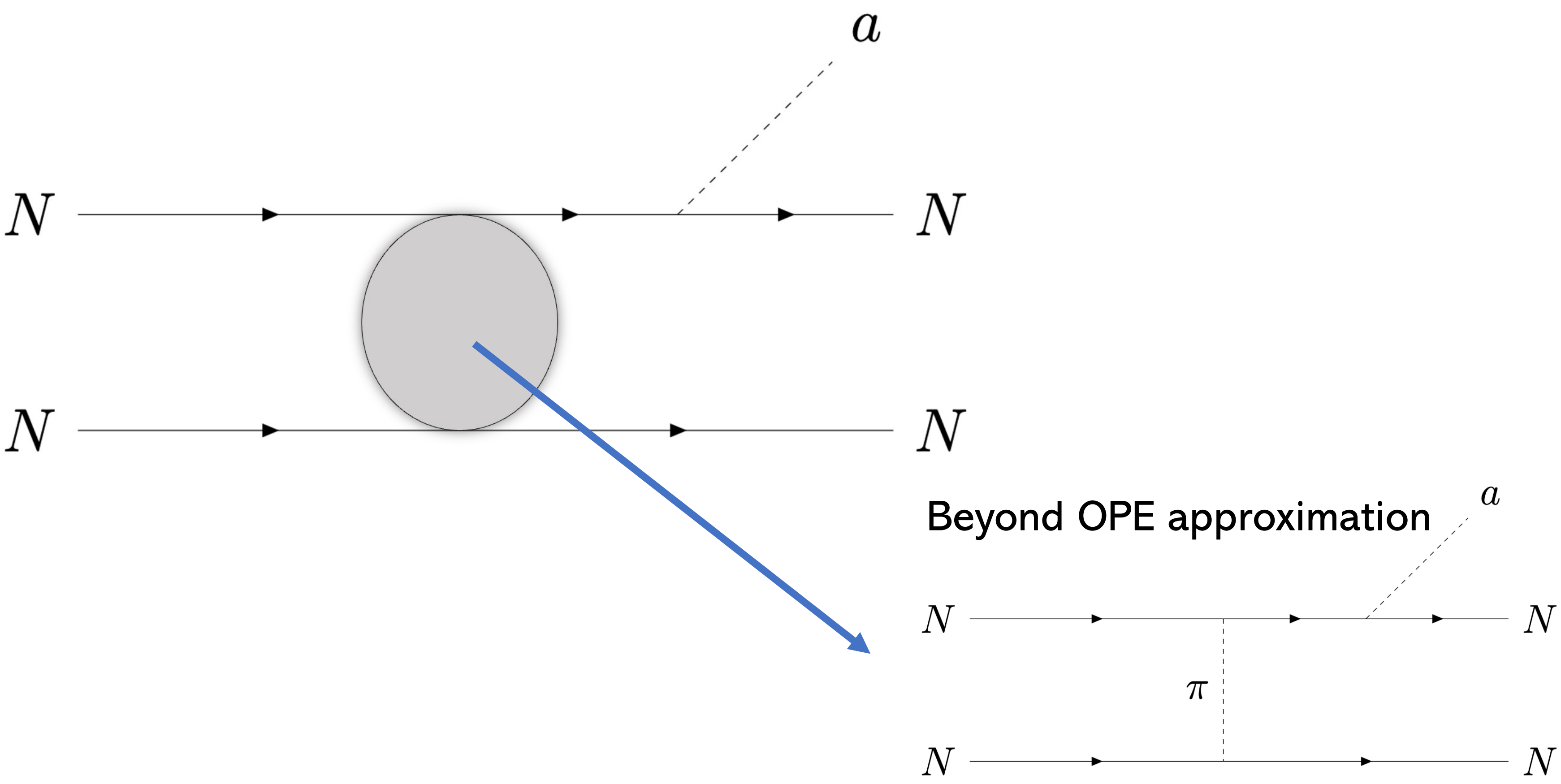

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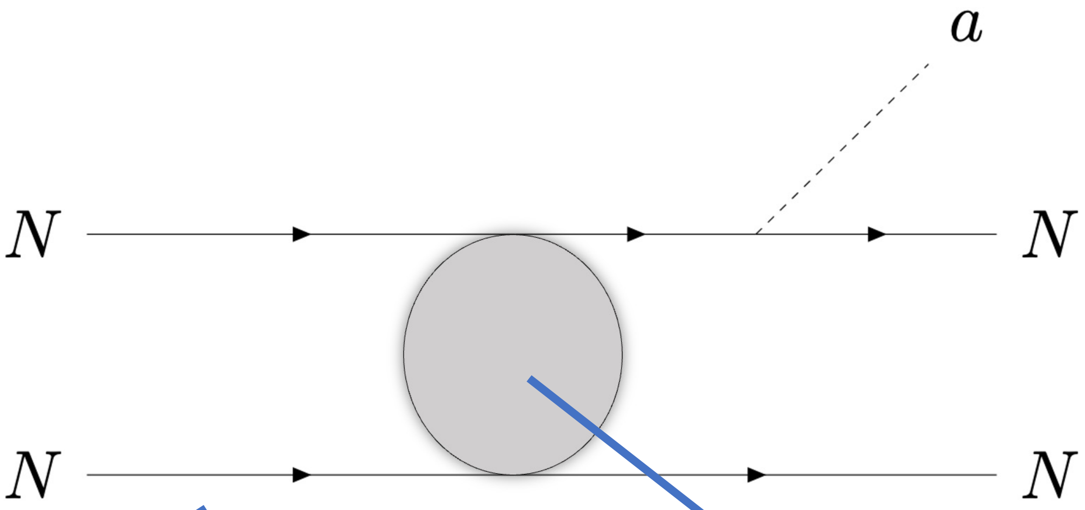
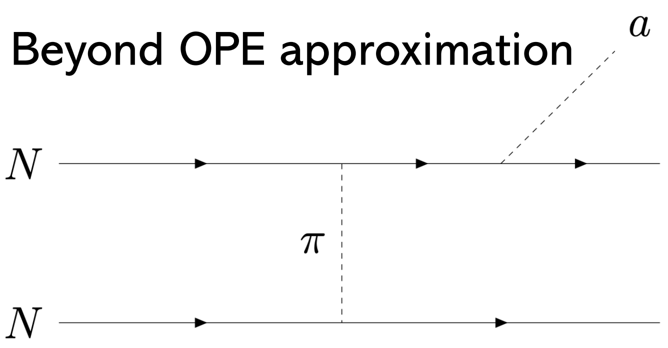


Nucleons multiple scattering

$$S_\sigma = \frac{\Gamma_\sigma}{\omega^2 + \Gamma^2} s_\sigma$$

Beyond OPE approximation



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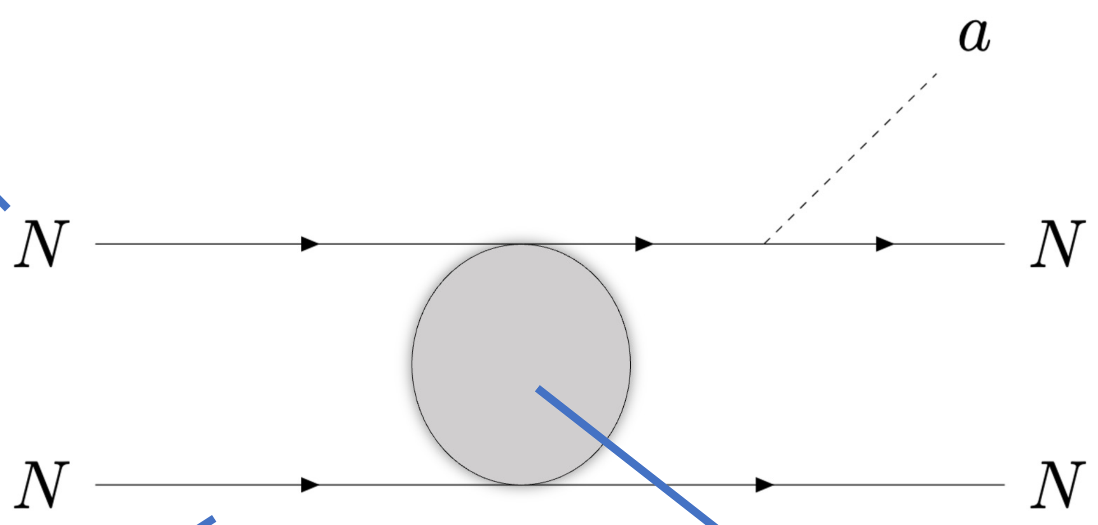
Effective nucleon masses

$$m_N \to m_N^*$$



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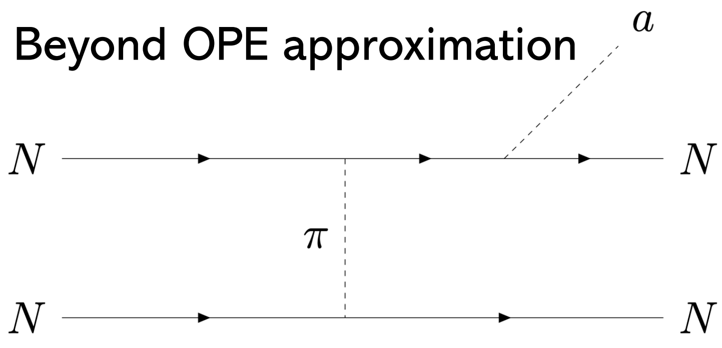

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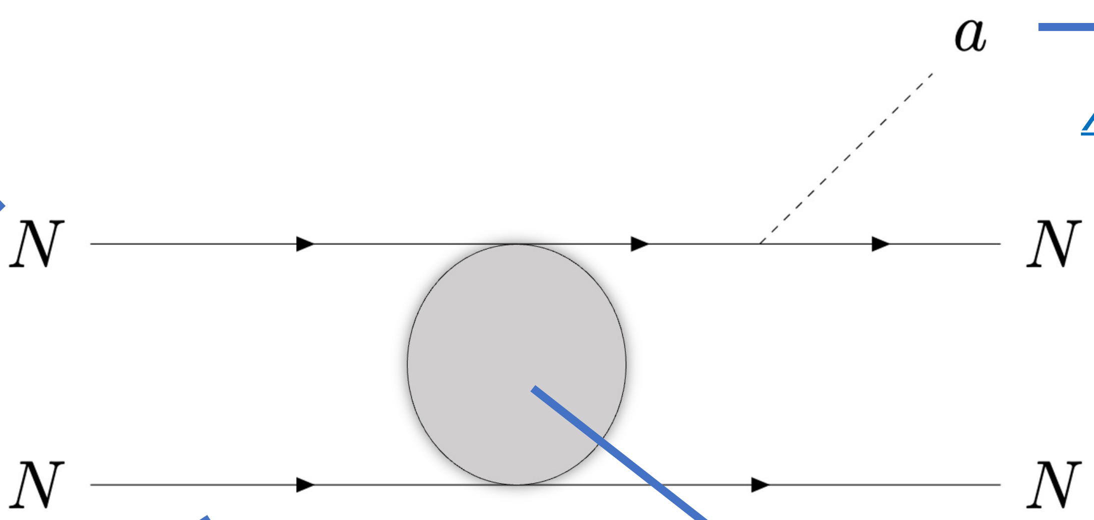

$$m_a \neq 0$$

AL & al., Phys. Rev. D 107 (2023)

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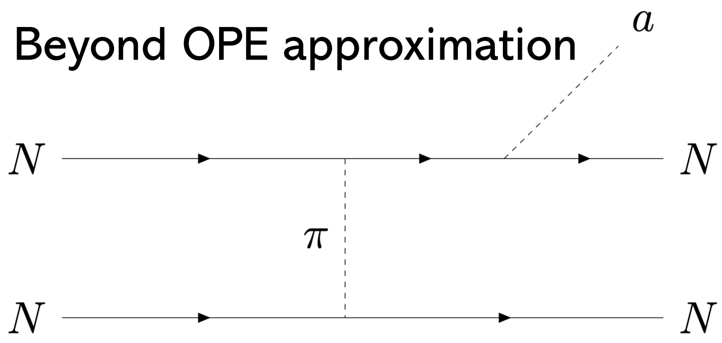
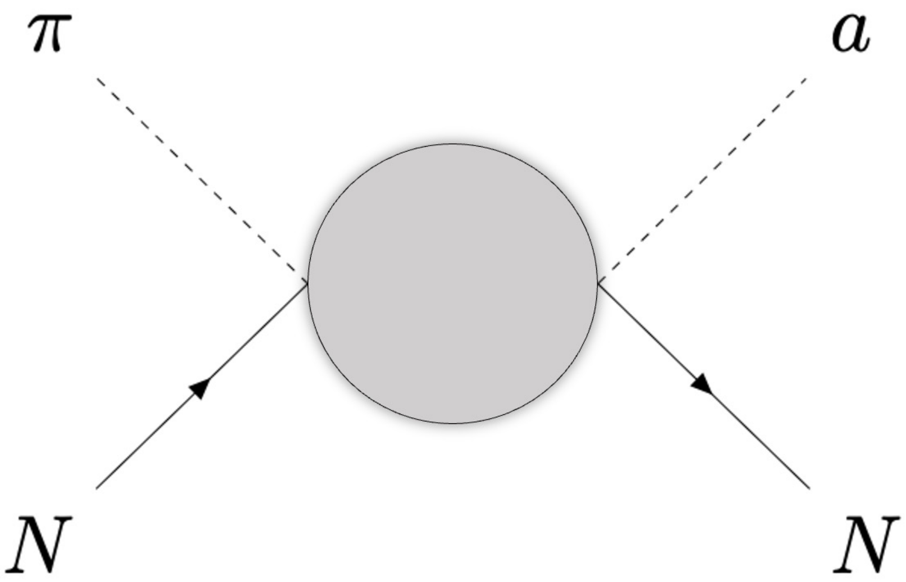


Axion production in SNe

- Pion Conversions

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



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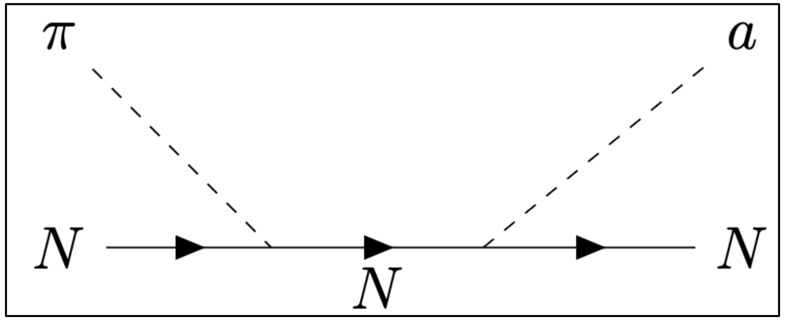

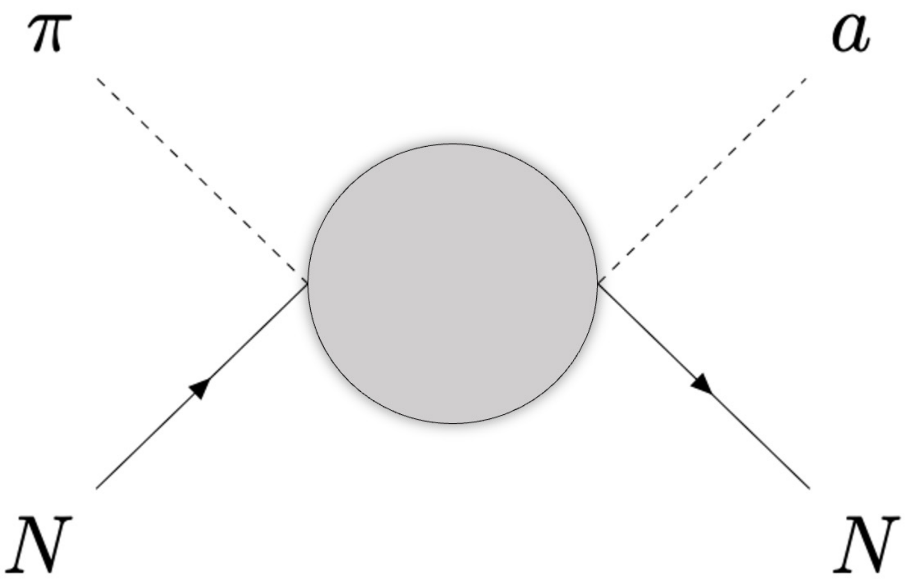

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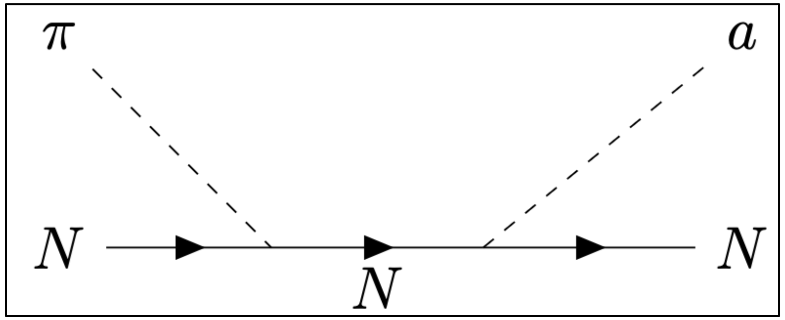

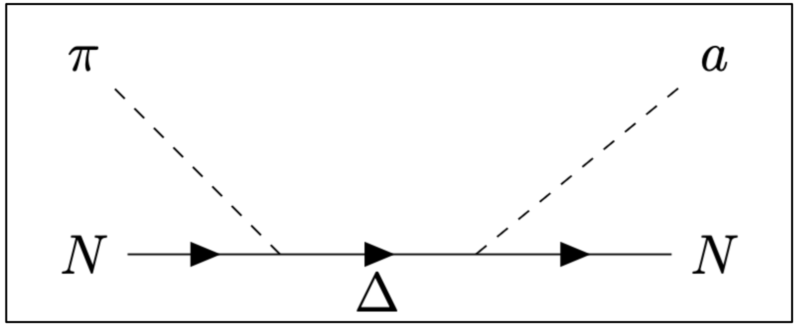

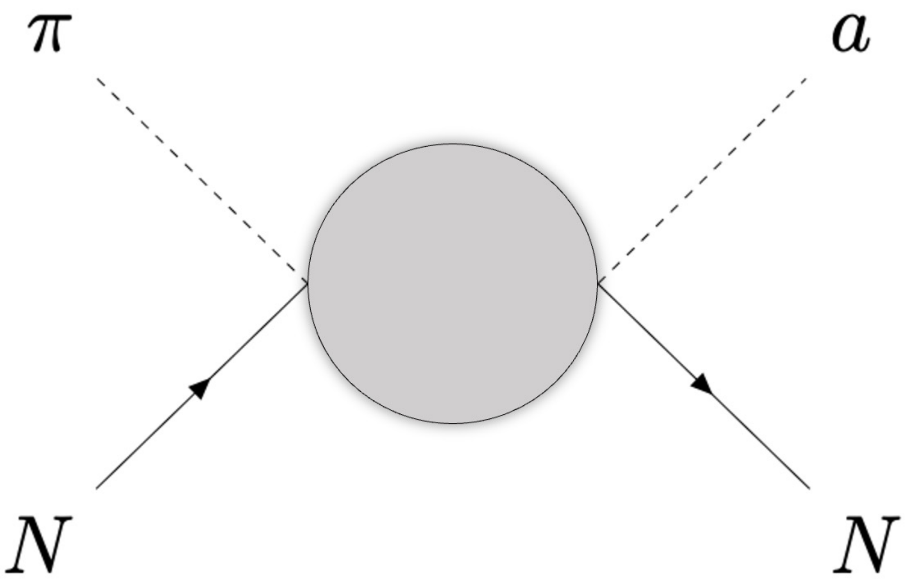

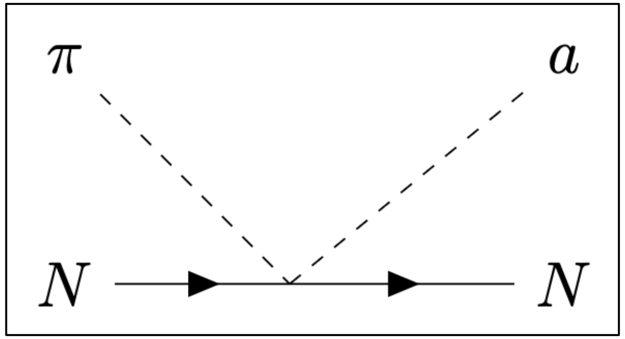

ALP emission spectra

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

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

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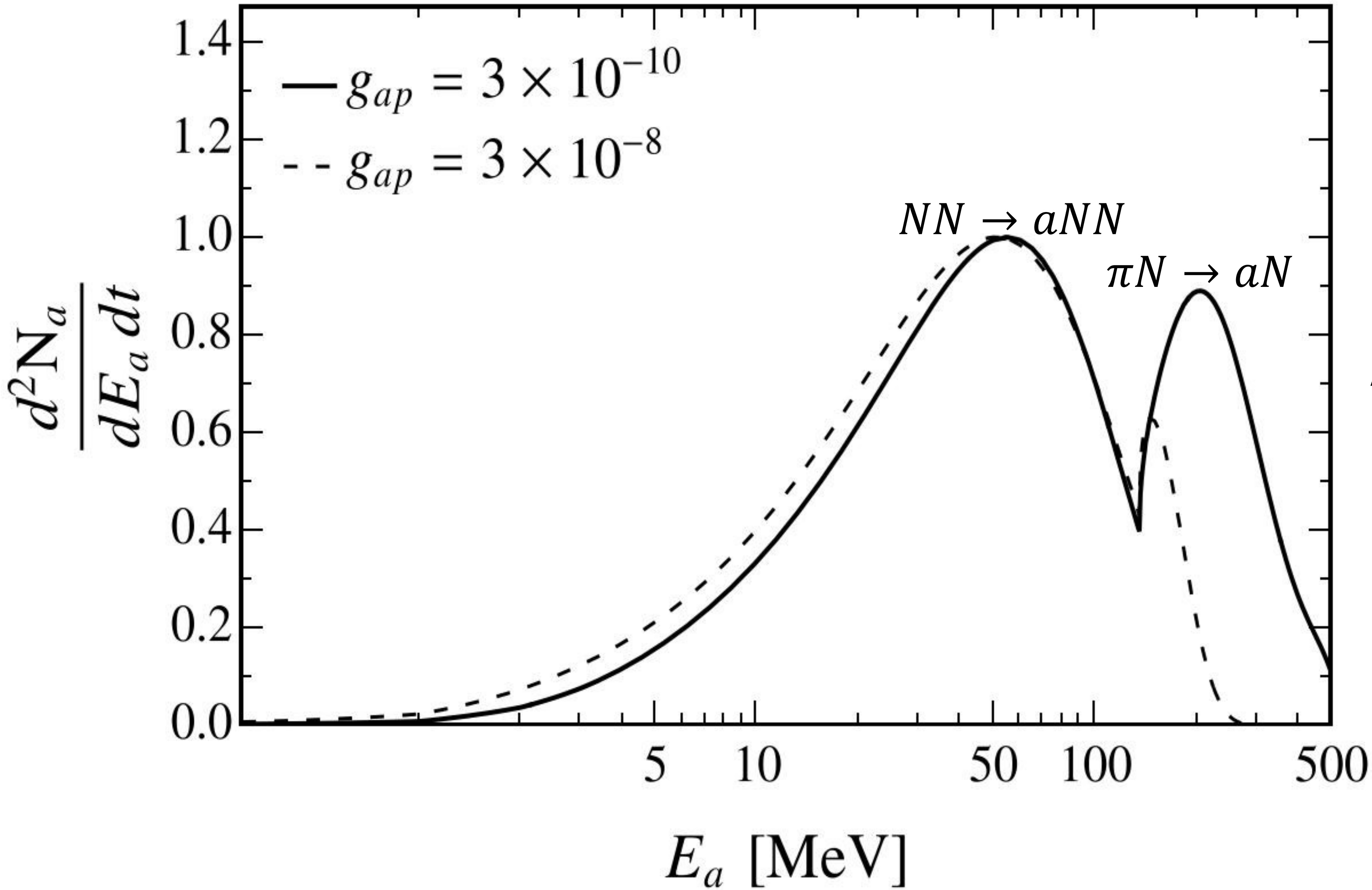
$$\frac{d^2 N_a}{dE_a\, dt} = \int_0^\infty 4\pi r^2 dr \frac{d^2 n_a}{dE_a\, dt}$$

- 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 emission spectra

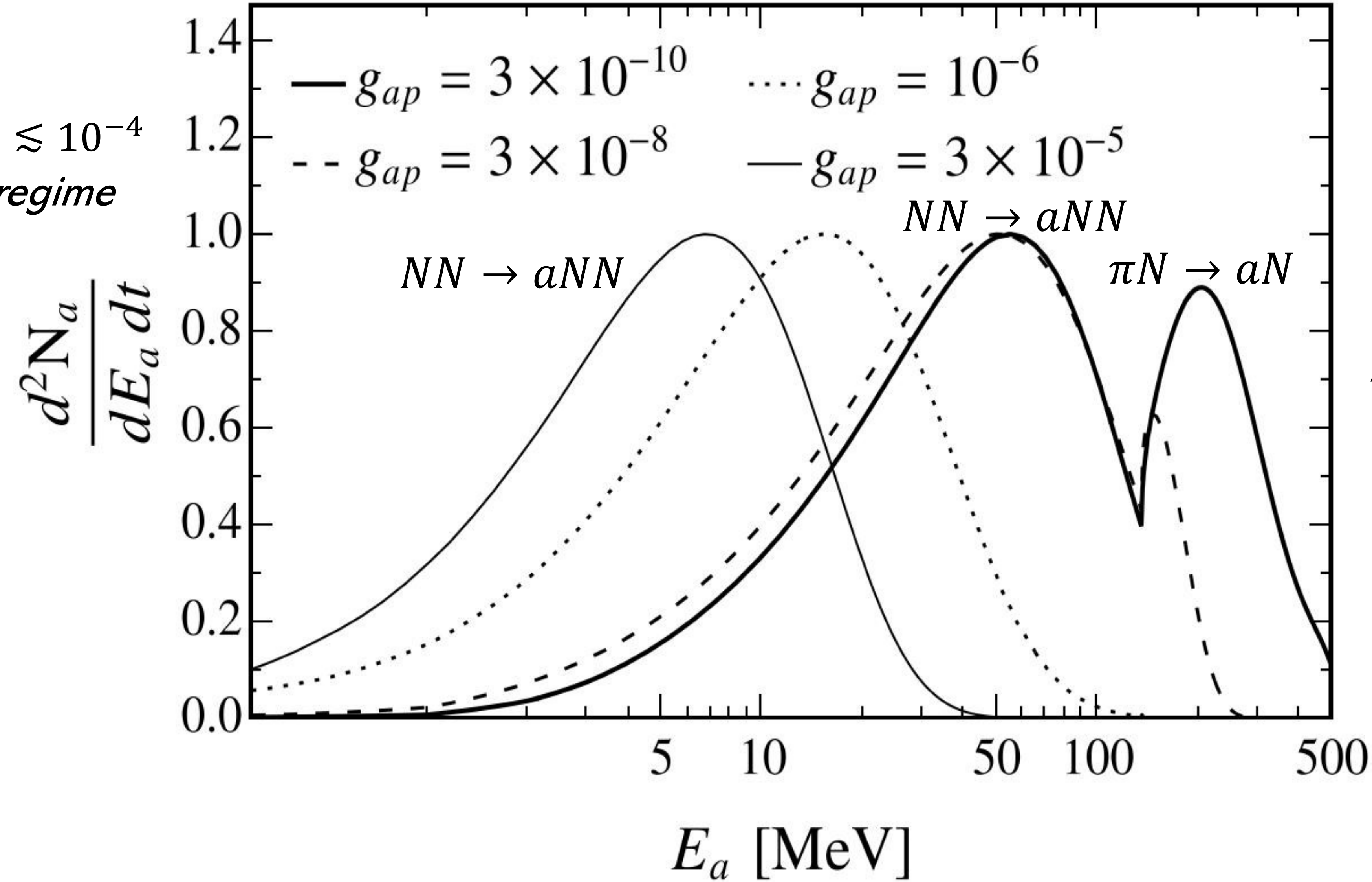


$10^{-10} \lesssim g_{ap} \lesssim 10^{-7}$

free-streaming regime

ALP emission spectra

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

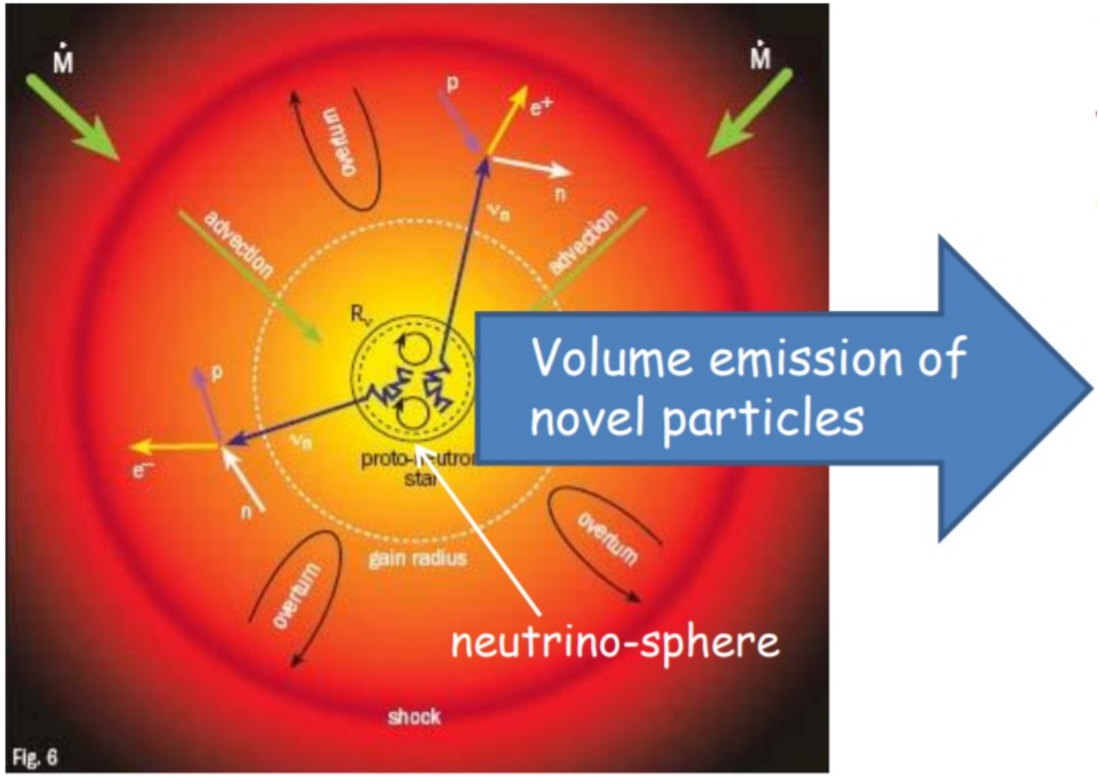


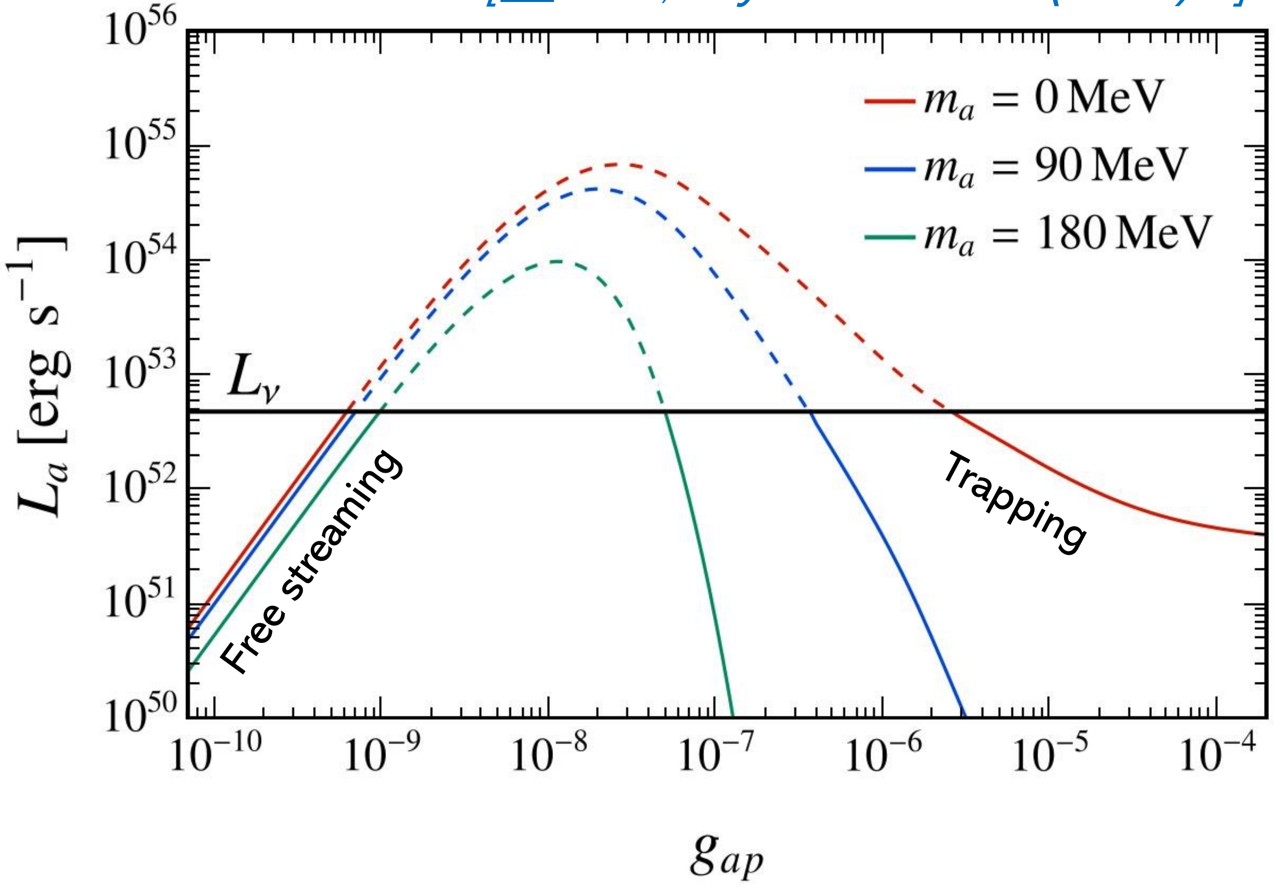
$10^{-10} \lesssim g_{ap} \lesssim 10^{-7}$
free-streaming regime

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]





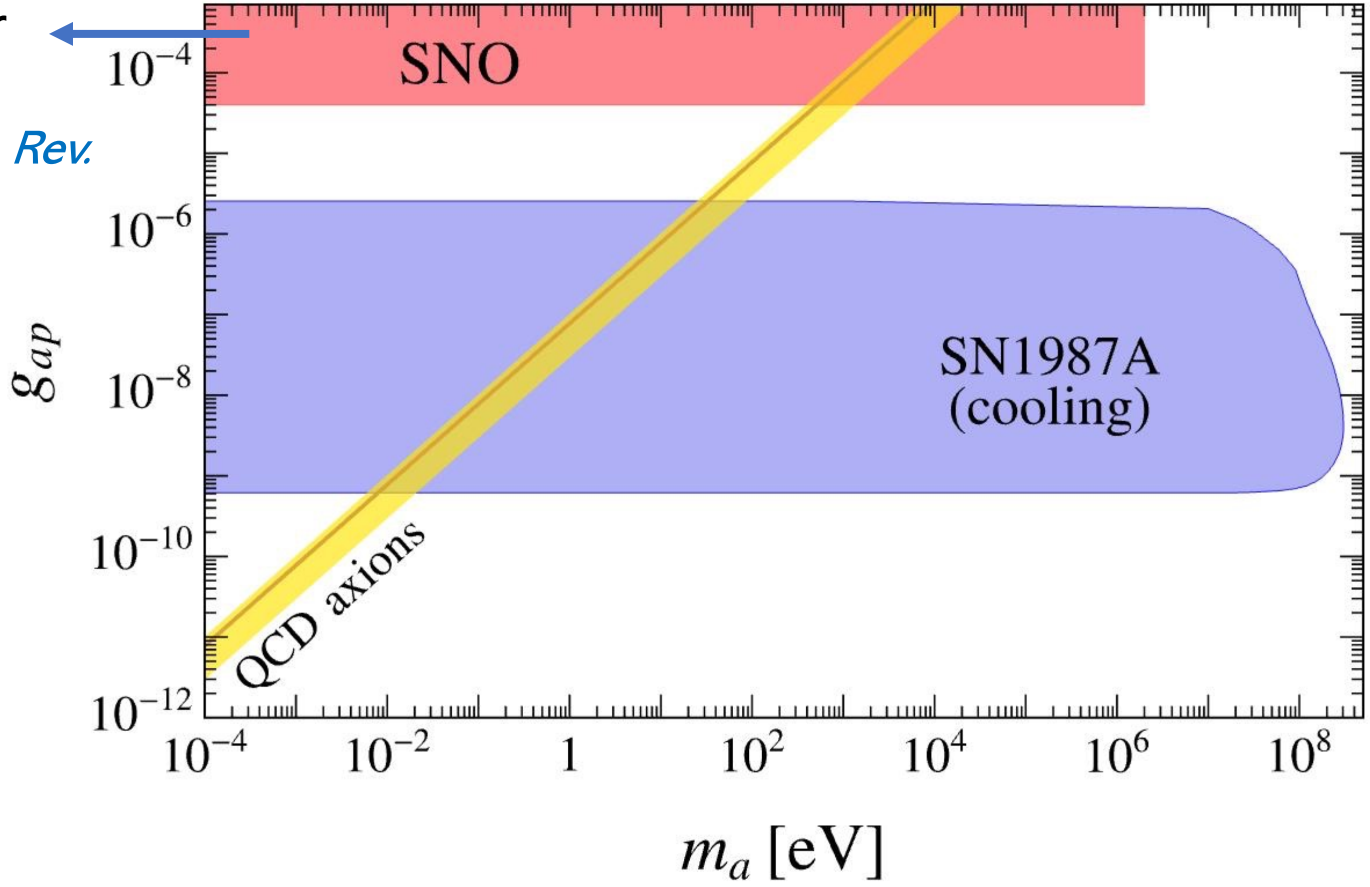
[Raffelt & Seckel, Phys. Rev. Lett.60 (1998)]

The energy-loss argument

Assuming that ALP emission did not shorten the duration of the neutrino burst more than $\sim 1/2$, we require that *[Raffelt, Phys. Rept. 198 (1990)]*:

$$L_a \lesssim L_\nu \quad \text{at } t_{\rm pb} = 1 \text{ s}$$

Searches for solar axions in SNO. *[Bhusal et al., Phys. Rev. Lett. 126 (2021)]*



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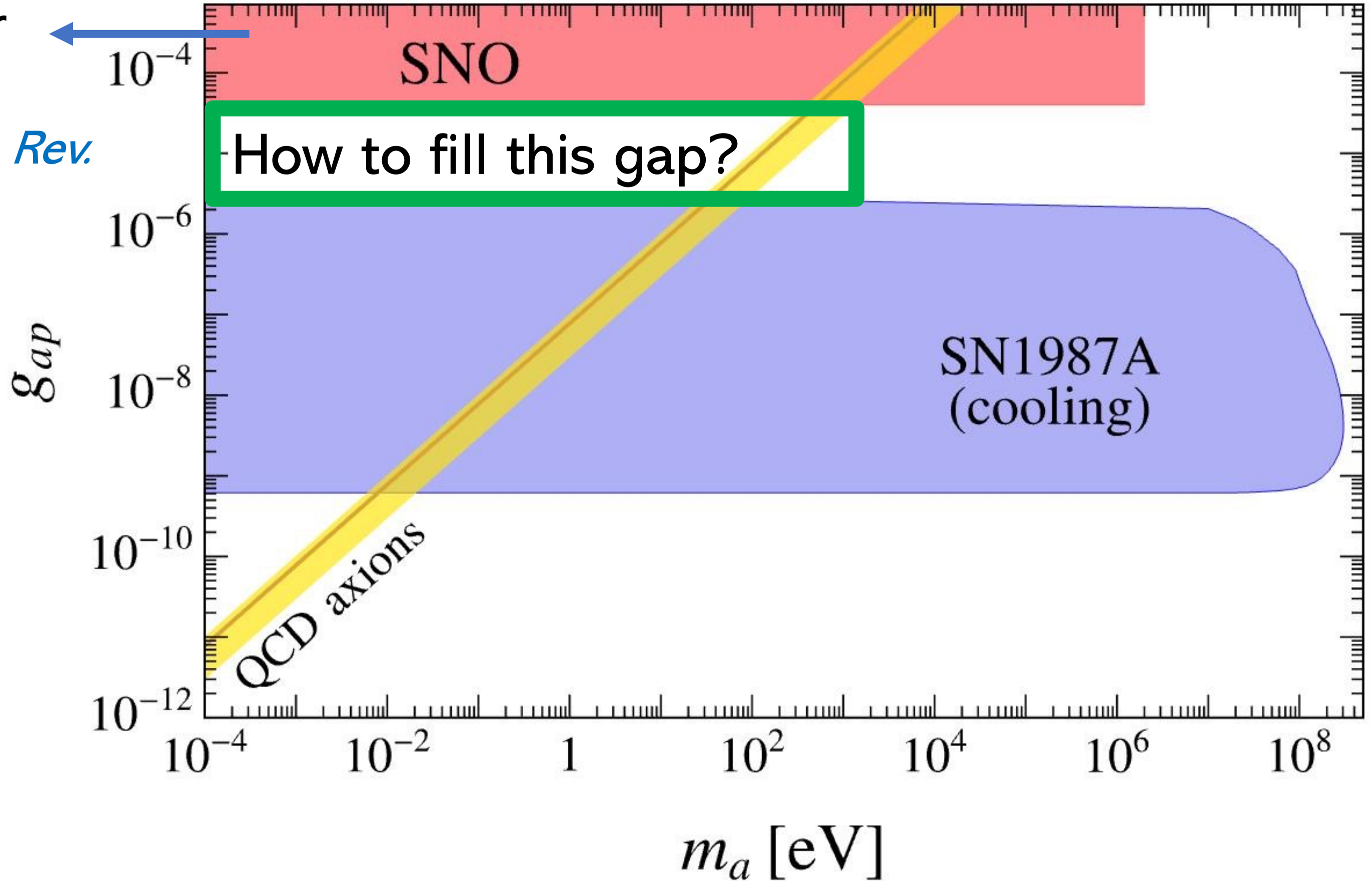


[AL & al., Phys. Rev. D 109 (2024) 2]

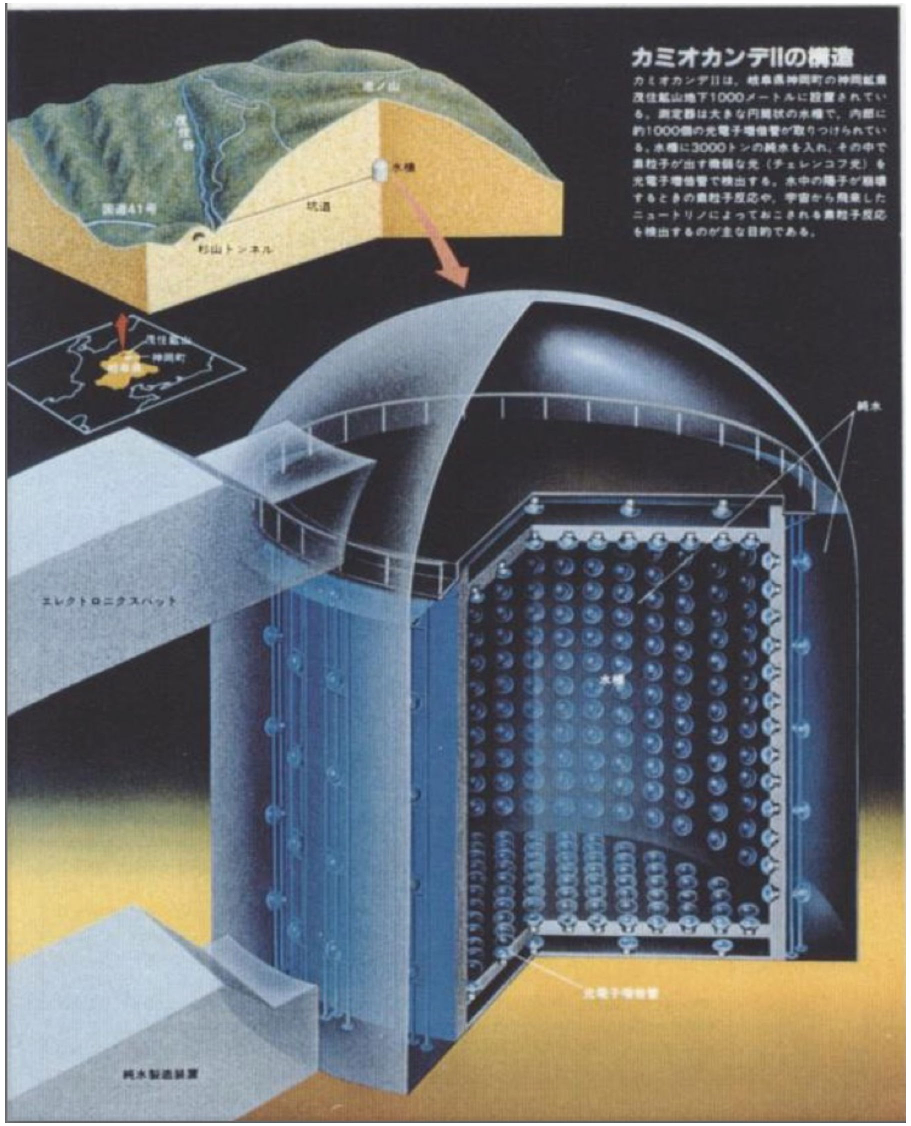
Axion signal in Kamiokande II

- 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)]* .

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

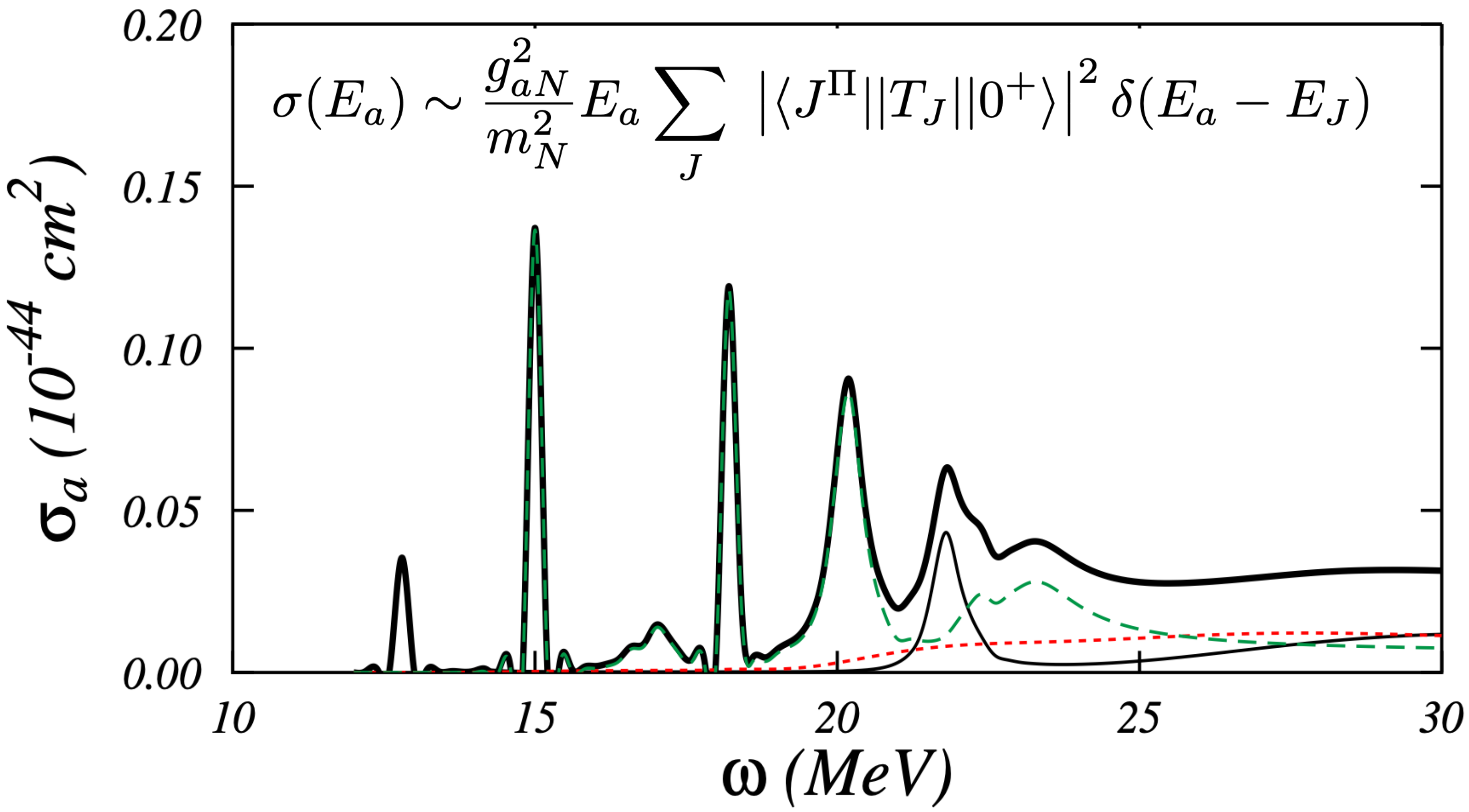
- The computation of the event rate requires:
  - SN explosion models
  - An adequate treatment of trapping regime
  - State-of-the-art nuclear models



ALP-Oxygen cross section

Introducing $C_0 = (C_p + C_n)/2$ and $C_1 = (C_p - C_n)/2$, Axion-nucleons interactions reads

$$\mathcal{H}_{aN} = -\frac{g_{aN}}{2m_N}\partial_k a \underbrace{\bar{N}\gamma^k\gamma^5(C_0 + C_1\tau_3)N}_{\text{Hadronic current}}$$



[P. Carenza, G. Co', M. Giannotti, AL, G. Lucente, A. Mirizzi, T. Rauscher, Phys. Rev. C 109 (2024) 1]

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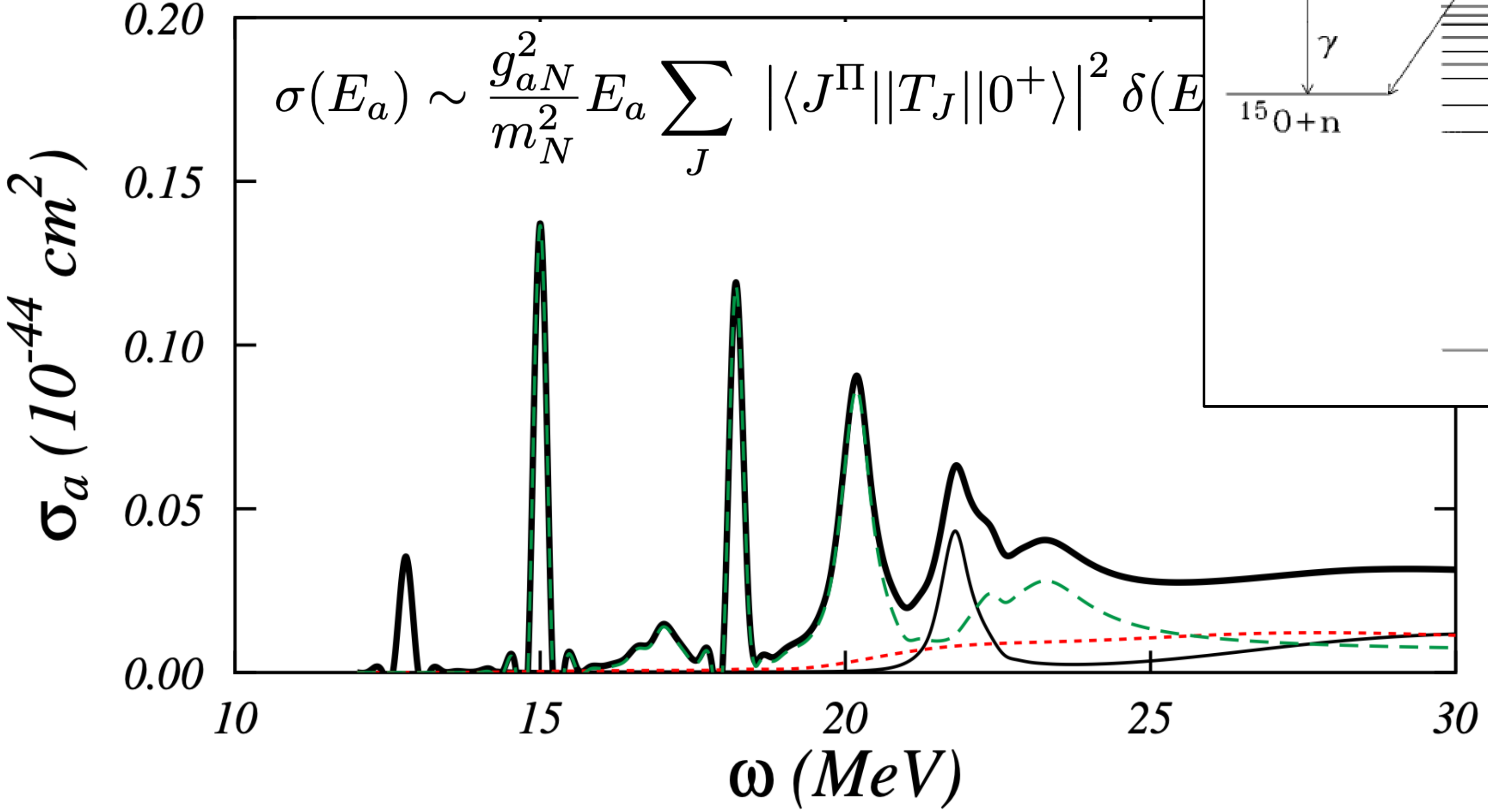
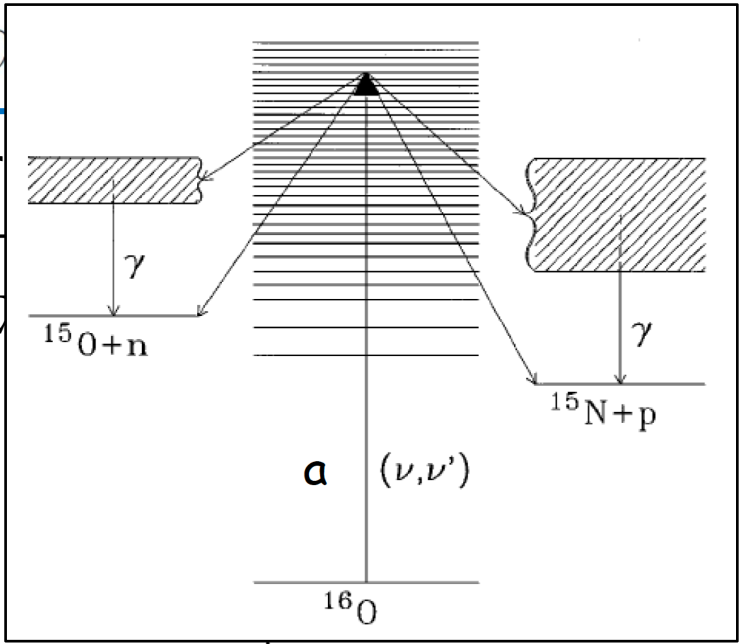
Hadronic cur



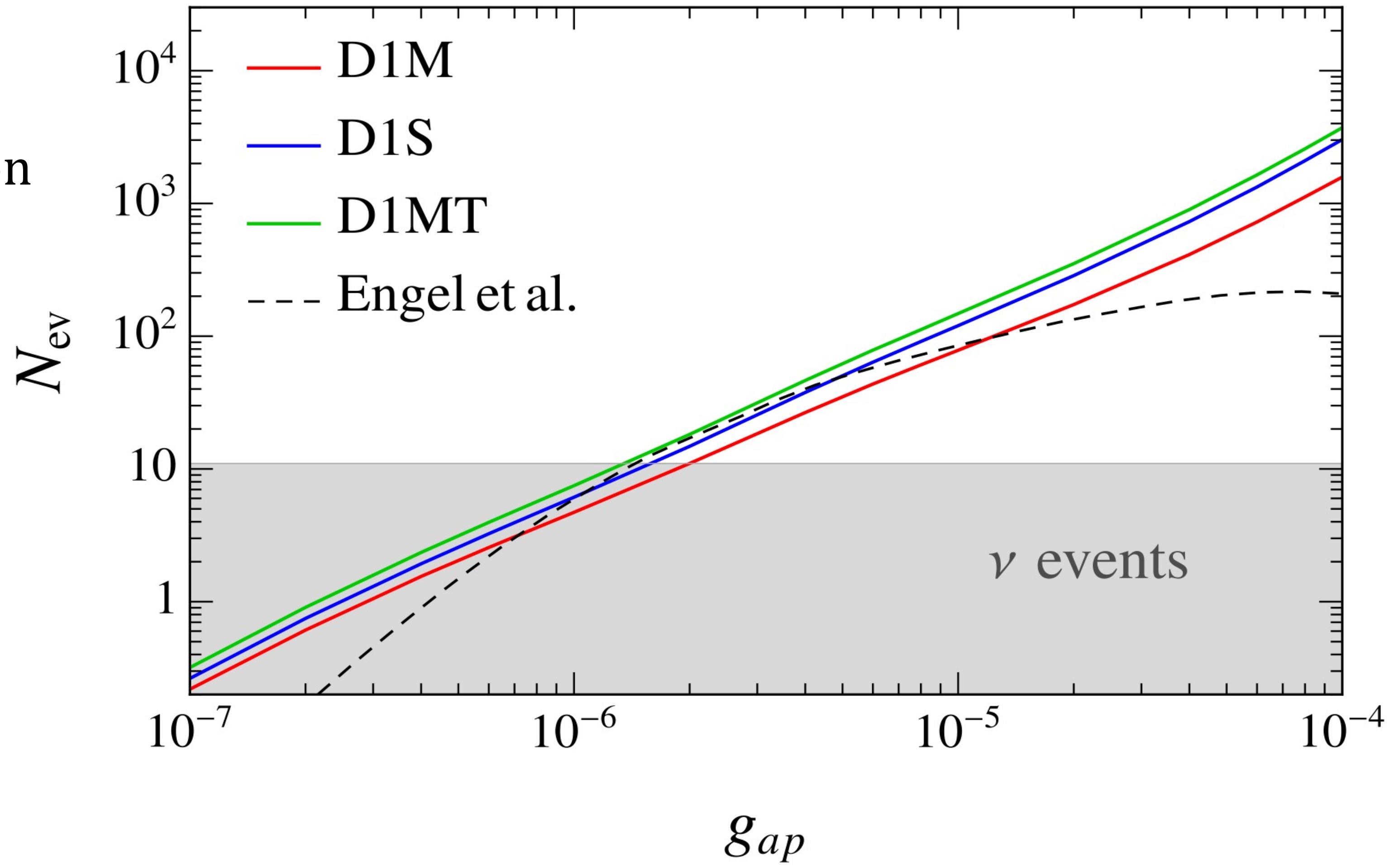


[P. Carenza, G. Co', M. Giannotti, AL, G. Lucente, A. Mirizzi, T. Rauscher, Phys. Rev. C 109 (2024) 1]

Events number in Kamiokande-II

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

$M_{KII} \sim 2.4$ kton



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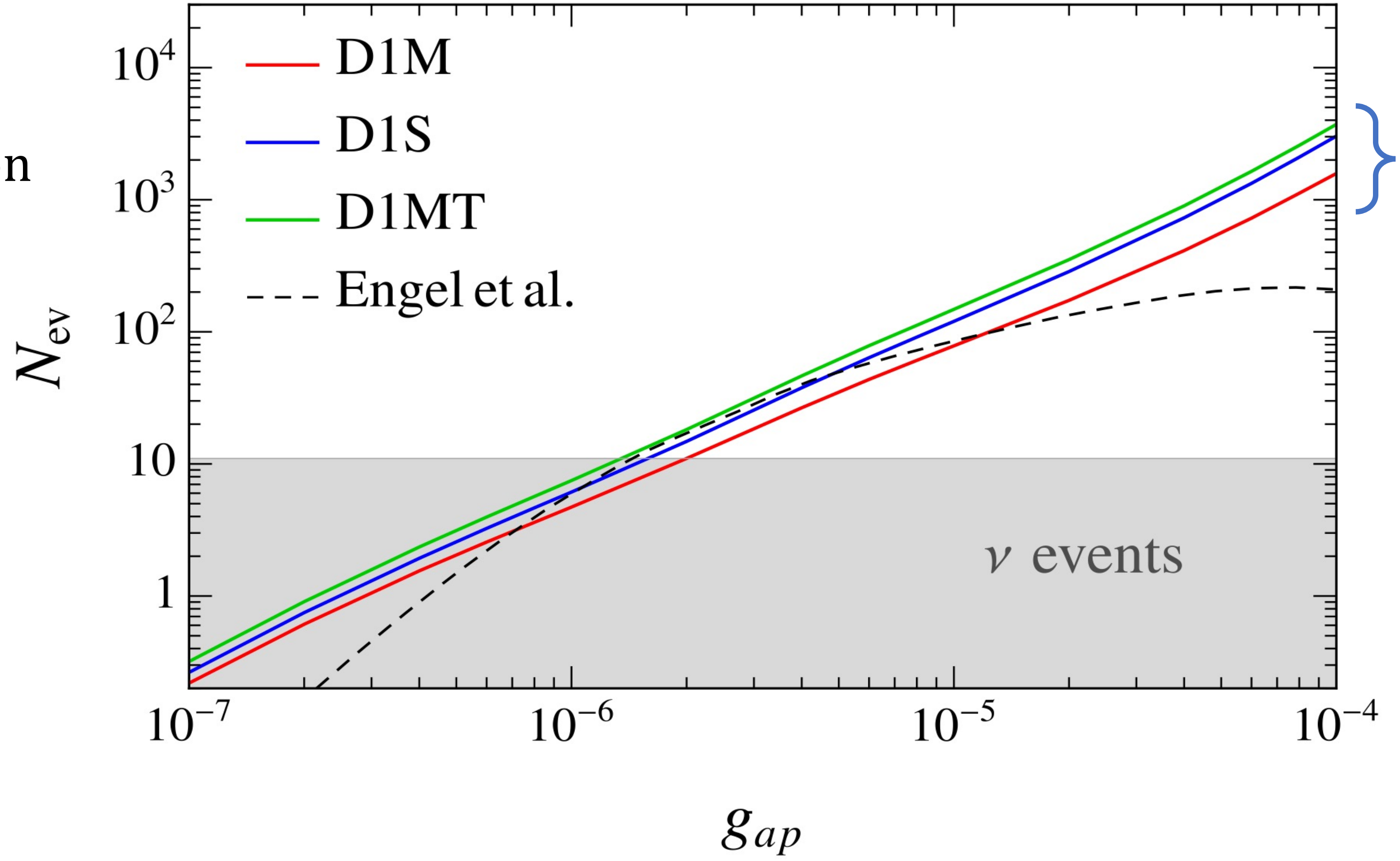
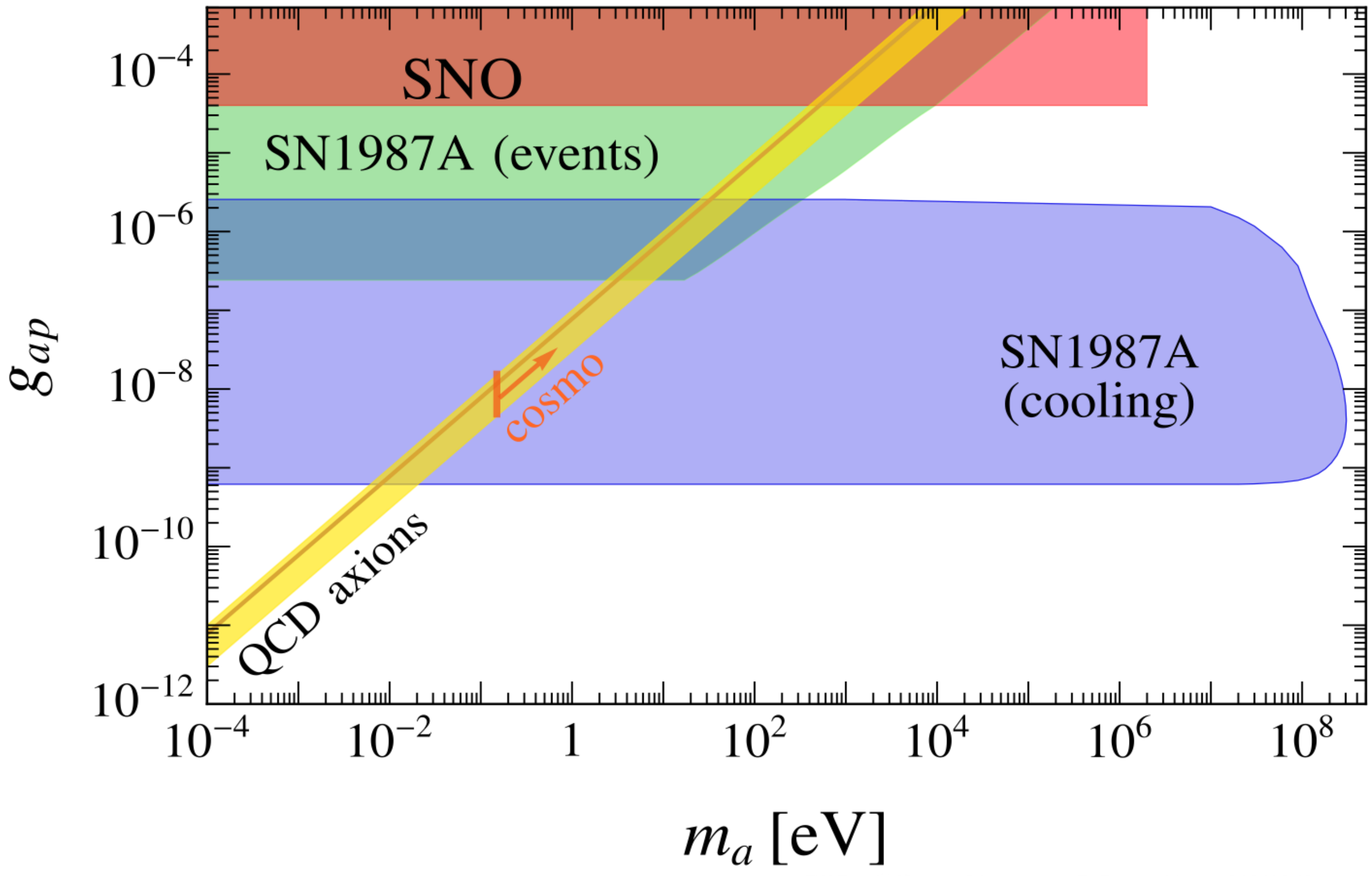


Uncertainties $\mathcal{O}(60\ \%)$ over the nuclear model

Axion events from SN 1987A

No excess in the background of K-II around SN 1987A event ($\bar{n}_{bkg} \simeq 0.02$ events/s)

[Kamiokande Coll., Phys. Rev. Lett. 58 (1987) 1490].



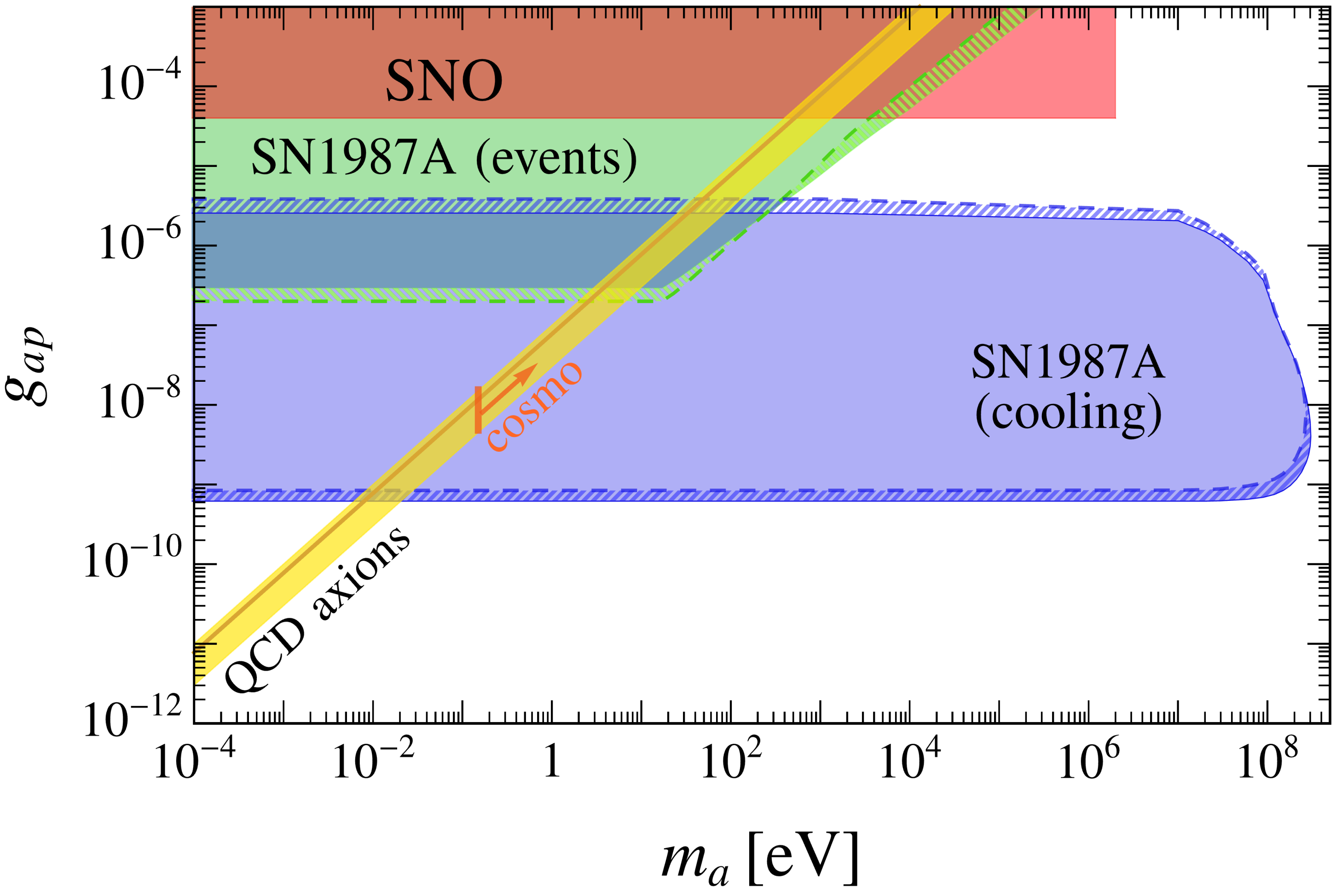
No *"hadronic axion window"*

[Chang & Choi, Phys. Rev. Lett. 316 (1993)]

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

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]

GARCHING

[Sukhobold & al., Astrophys. J. 860 (2018) 93]
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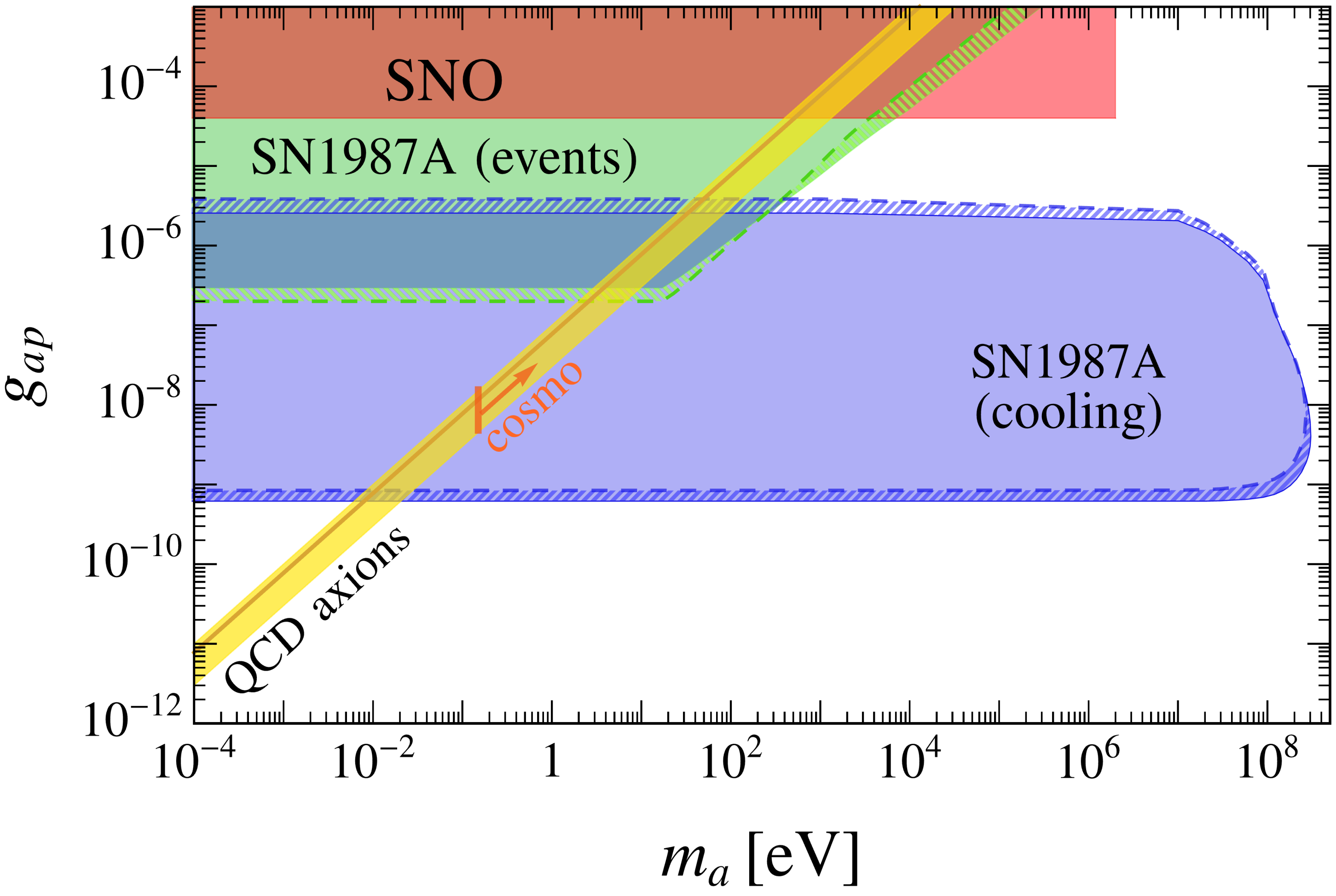

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Similar impact over standard and new physics → Similar bounds

GARCHING

[Sukhobold & al., Astrophys. J. 860 (2018) 93]
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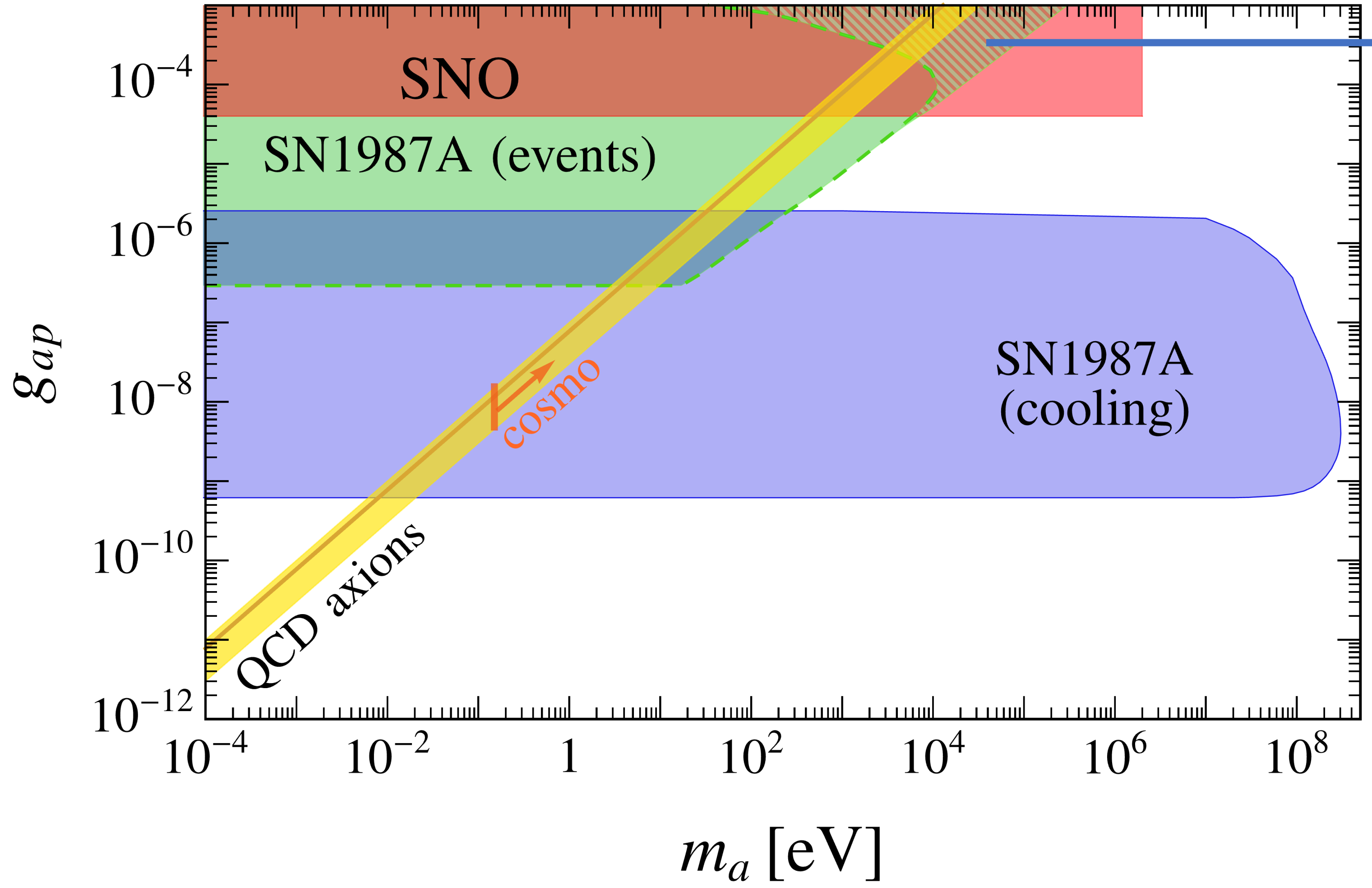
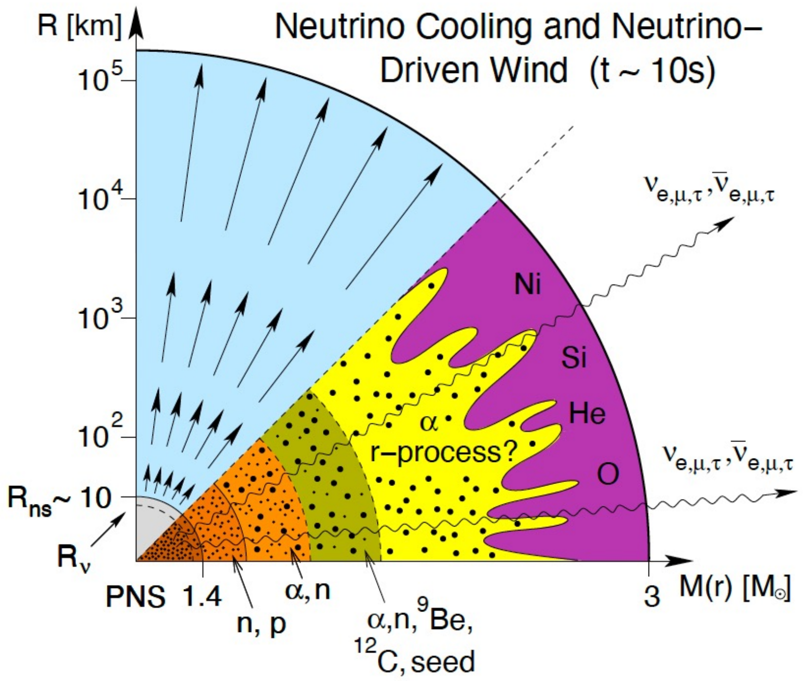
Uncertainties over SN Bounds

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



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

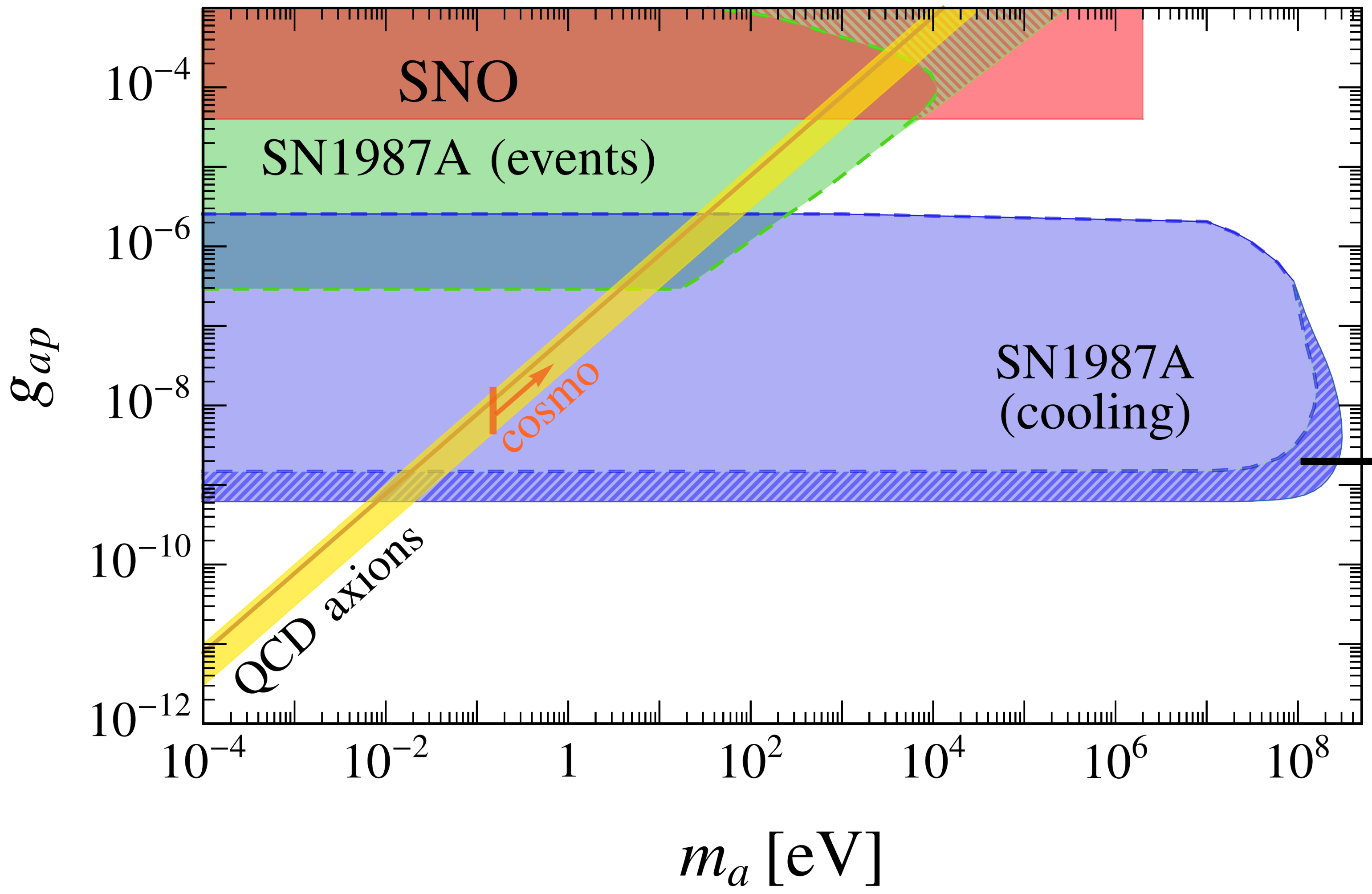
$$\Gamma_H(E,r) \sim n_H(r)\,\sigma(E)$$



Uncertainties on SN Bounds

Strong interactions can enhance the pion fraction in the SN core

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



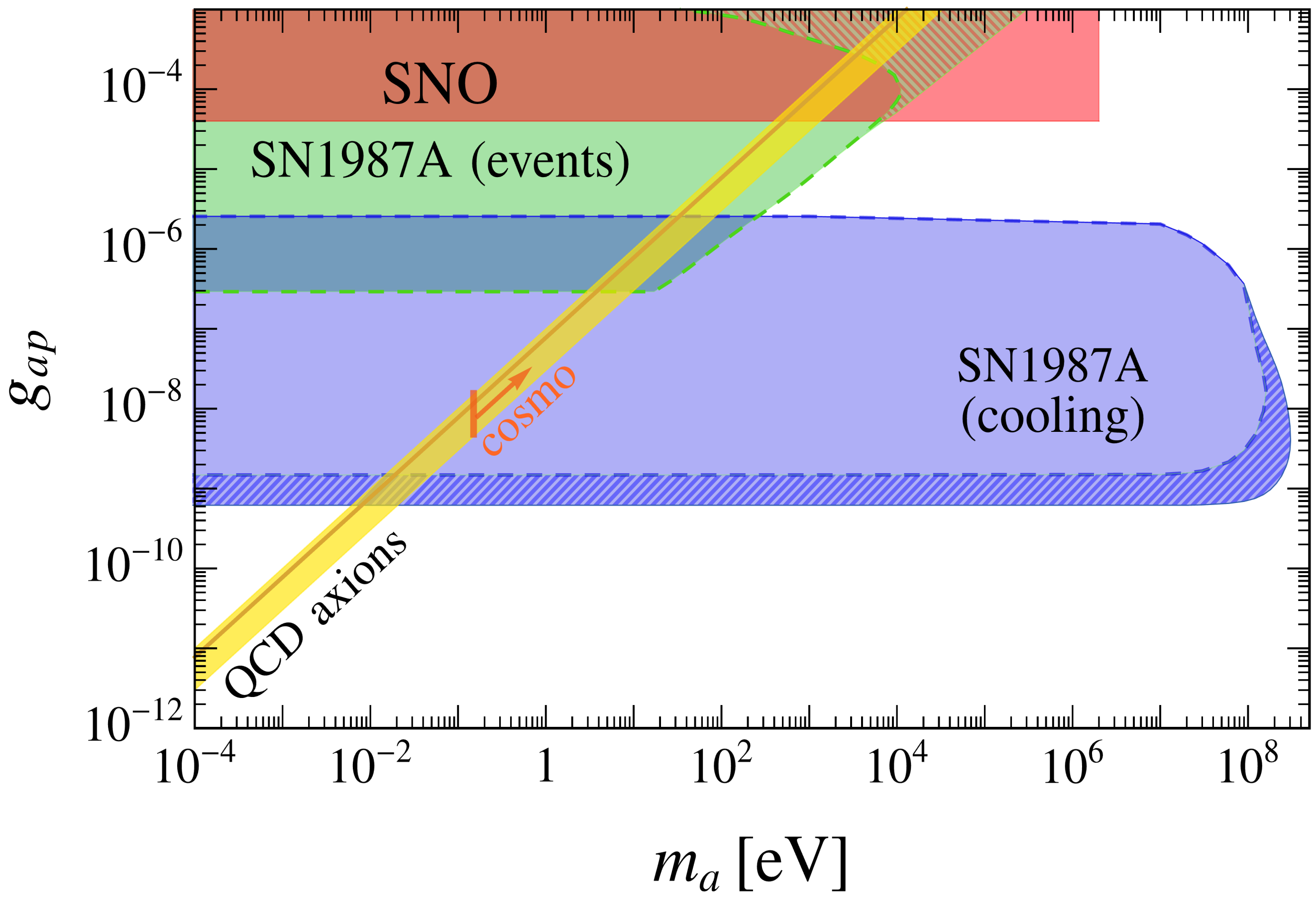
Pions still not self-consistently included in SN simulations

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

Without pions, cooling bound relaxes by a factor ~ 2

Concluding remarks

- Axions and ALPs could be copiously produced in SNe via nuclear processes.
- Adequate treatment required to span from free-streaming to trapping regime
- Supernova arguments alone exclude QCD axion masses $m_a \gtrsim 10^{-2}$ eV.
- Uncertainties on SN bounds do not affect significantly these results.



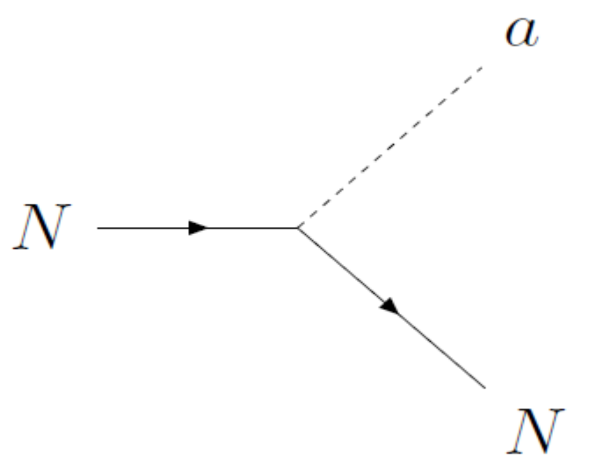

Thank you for your attention

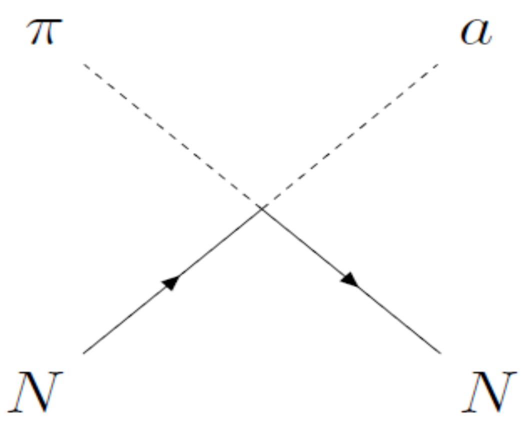
ALPs nuclear interactions

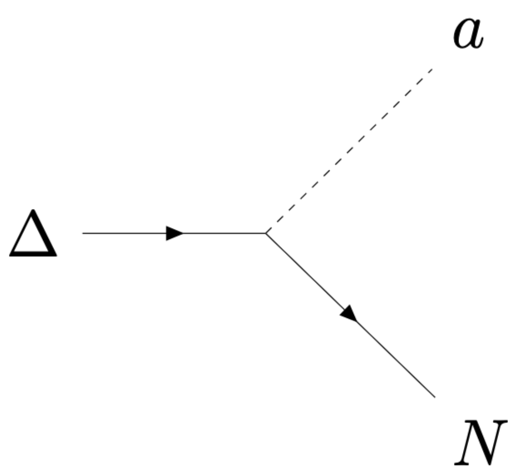
- Axions and ALPs could interact with all the Standard model particles.

- In ChPT interaction verteces with baryons and mesons *[Ho & al., Phys.Rev.D 107 (2023)]*

$$\mathcal{L}_{nuc} = \sum_N g_{aN} \frac{\partial^\mu a}{2m_N} \bar{N}\gamma_\mu\gamma_5 N + \frac{g_{a\pi N}}{f_\pi} \partial^\mu a\left(i\pi^+ \bar{p}\gamma_\mu n + h.c.\right) + g_{aN\Delta} \frac{\partial^\mu a}{2m_N} (\bar{p}\,\Delta_\mu^+ + h.c.)$$

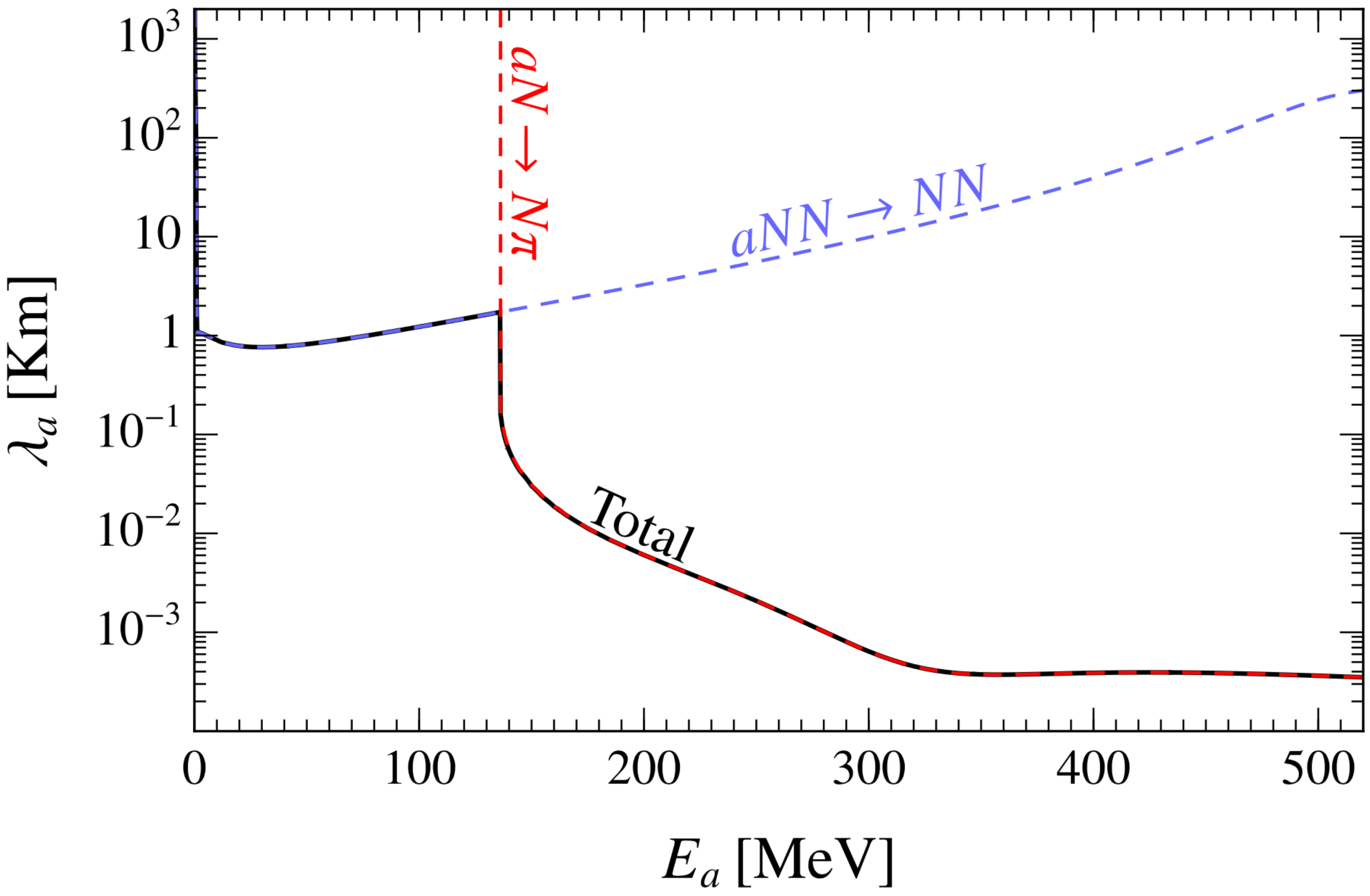




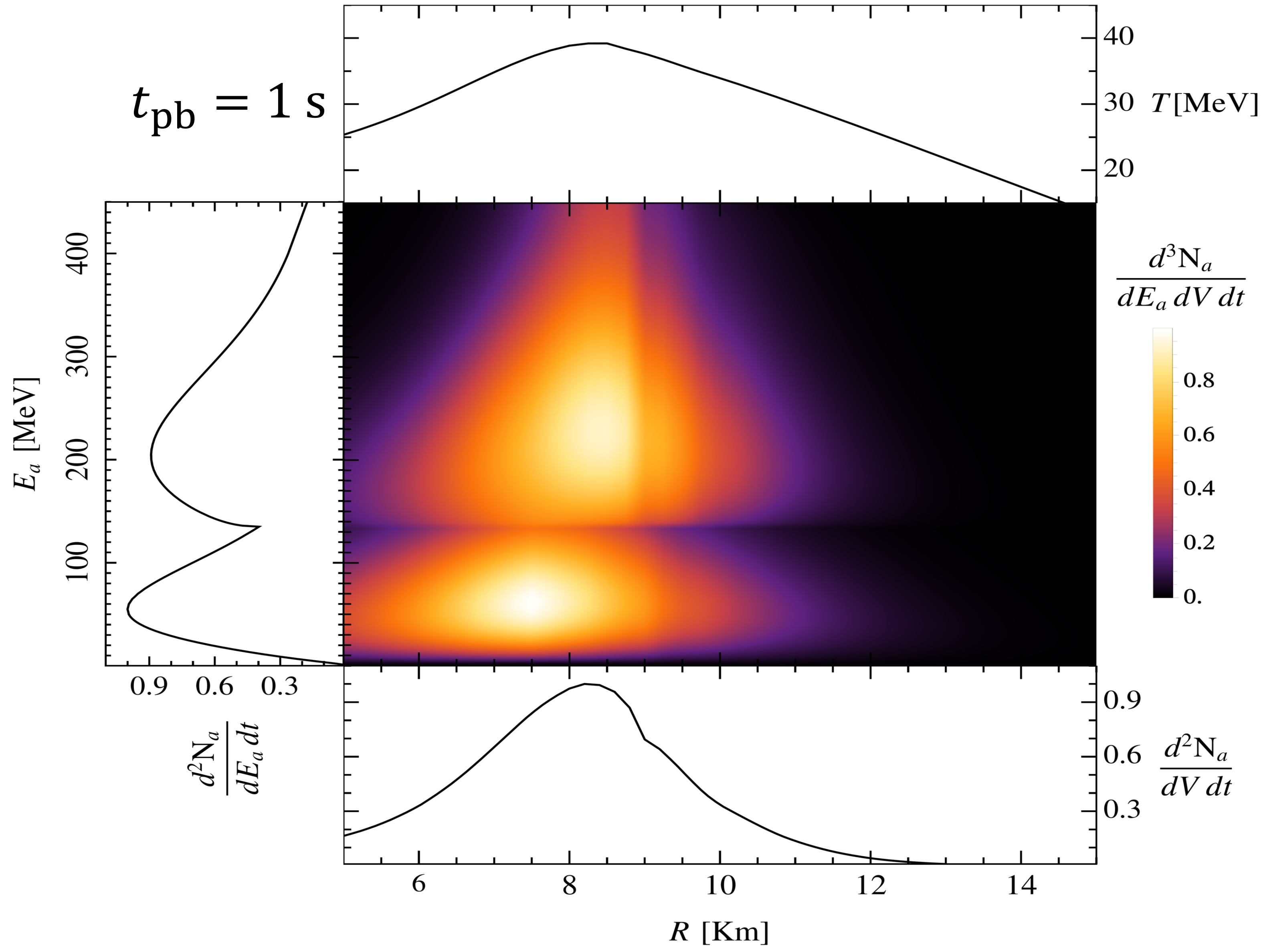


ALP mean free path

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



ALP production and SN profiles



ALP nuclear production is extremely sensitive to SN conditions.

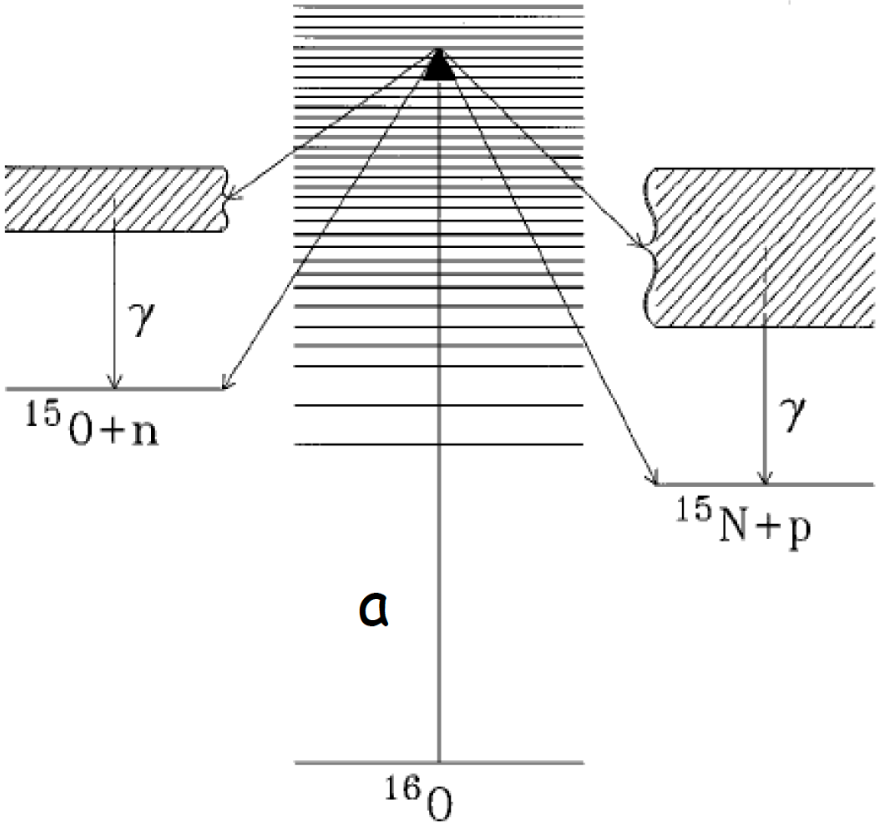
Axion events from SN 1987A

$$N_{\rm ev} \lesssim \begin{cases} 2\sqrt{\overline{n}_{\rm bkg}\Delta t} & \text{if } m_a \lesssim 17 \text{ eV} \\ 2\sqrt{\overline{n}_{\rm bkg}\Delta t_a} & \text{if } m_a > 17 \text{ eV} \end{cases}$$

$$\Delta t \approx 12 \text{ s}$$

$$\Delta t_a\left(m_a\right) \approx t\left(E_{\min}, m_a\right) - t\left(E_{\max}, m_a\right) \approx 1.82\,\text{s}\left(\frac{m_a}{10 \text{ eV}}\right)^2$$

Oxygen de-excitation



- Excited oxygen states can also decay through non radiative channels (α-particles, protons, neutrons together with secondary nuclei).

- Branching ratios computed through the *SMARAGD Hauser-Feshbach reaction code* *[T. Rauscher, computer code SMARAGD, version 0.9.3s, Vol. 103, 2015]*.

- γ-emission accounts for $\sim 50\ \%$ of the total de-excitation processes.

Detector resolution

- Detector energy resolution spreads detected energies around true photon energies.

$$\mathcal{R}(E,\epsilon) = \sum_{\omega(\epsilon)} \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-(E-\omega(\epsilon))^2/2\sigma^2}\, BR\,[\omega(\epsilon)]$$

where $\sigma_\gamma = \sqrt{0.6\, E_\gamma(\epsilon)/\,\mathrm{MeV}}$

- Detector efficiency can be modelled as
  [Fiorillo et al., Phys. Rev. D 108 (2023)]

$$\mathcal{E} = \begin{cases} 0 & x < 4 \\ \dfrac{0.932}{\sqrt{1+\left(\frac{34}{12-7x+x2}\right)^2}} & x \geq 4 \end{cases}$$

where $x = E/\,\mathrm{MeV}$