Axions++ 2023
Annecy, 25-28 September 2023

Getting the most on Supernova axions

Alessandro Lella

Physics Department of «Aldo Moro» University in Bari
Istituto Nazionale di Fisica Nucleare

Based on…

- AL, P. Carenza, G. Co', G. Lucente, M. Giannotti, A. Mirizzi, T. Rauscher, *"Getting the most on Supernova axions"*, e-Print: 2306.01048 (2023)

- P. Carenza, G. Co', AL, G. Lucente, M. Giannotti, A. Mirizzi, T. Rauscher, *"Detectability of supernova axions in underground water Cherenkov detectors"*, e-Print: 2306.17055 (2023)

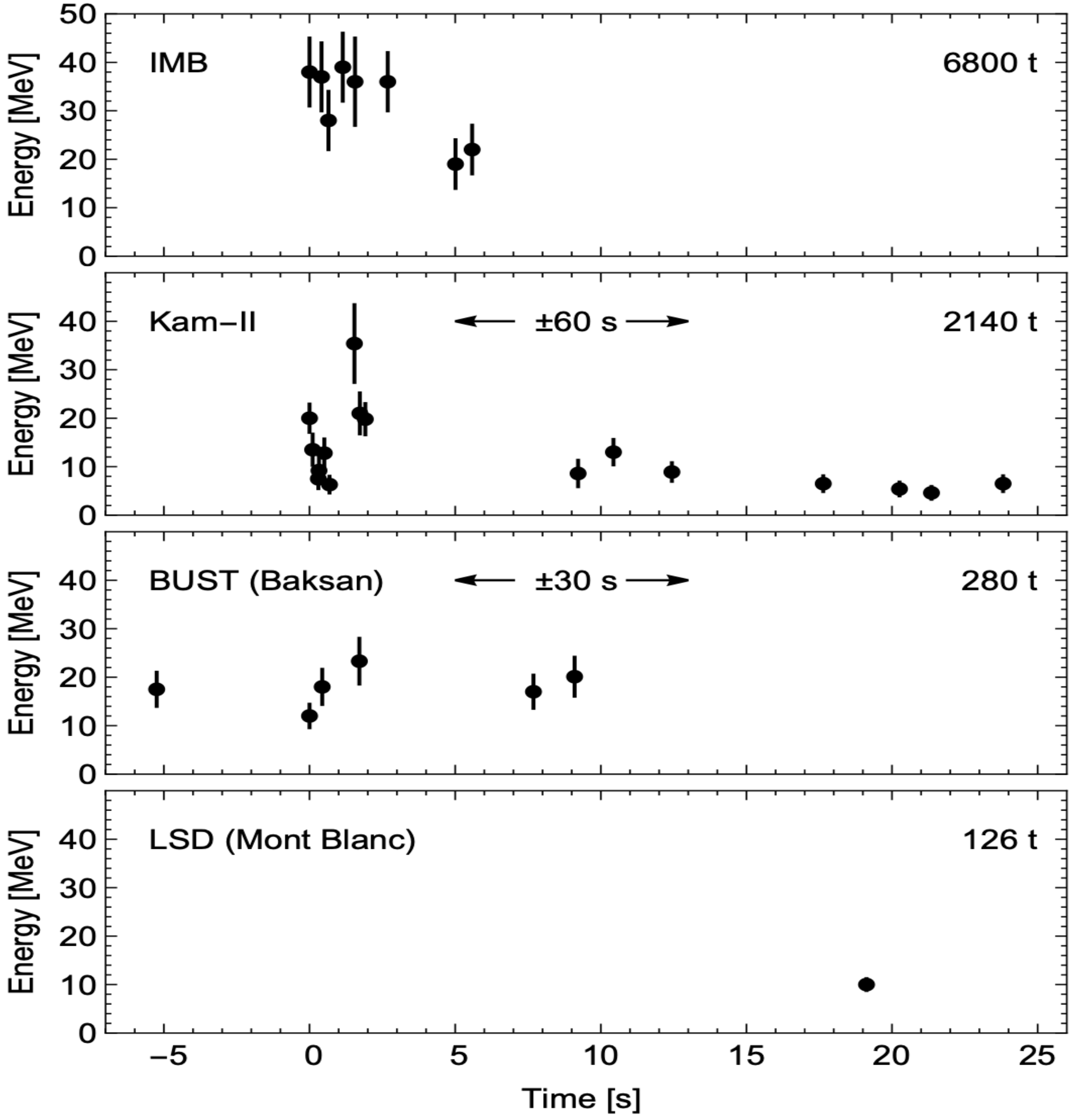
- AL, P. Carenza, G. Lucente, M. Giannotti, A. Mirizzi, *"Protoneutron stars as cosmic factories for massive axion-like particles"*, Phys. Rev. D 107 (2023) 10

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)]*

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

SN explosion and neutrino emission



A SN is the terminal phase of a massive star. $[\mathrm{M} \geq 8\, M_{\odot}]$. After the gravitational collapse, a shock-wave driven explosion occurs.

- 99% of energy($\sim 10^{53}$ erg) emitted in (anti)neutrinos.

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

- Standard picture confirmed by SN 1987A observation.

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),
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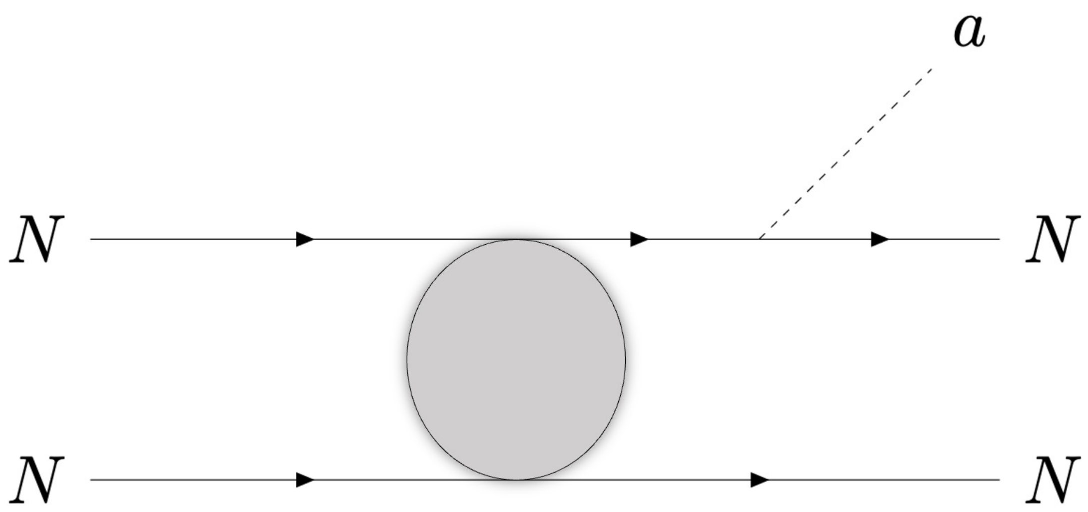

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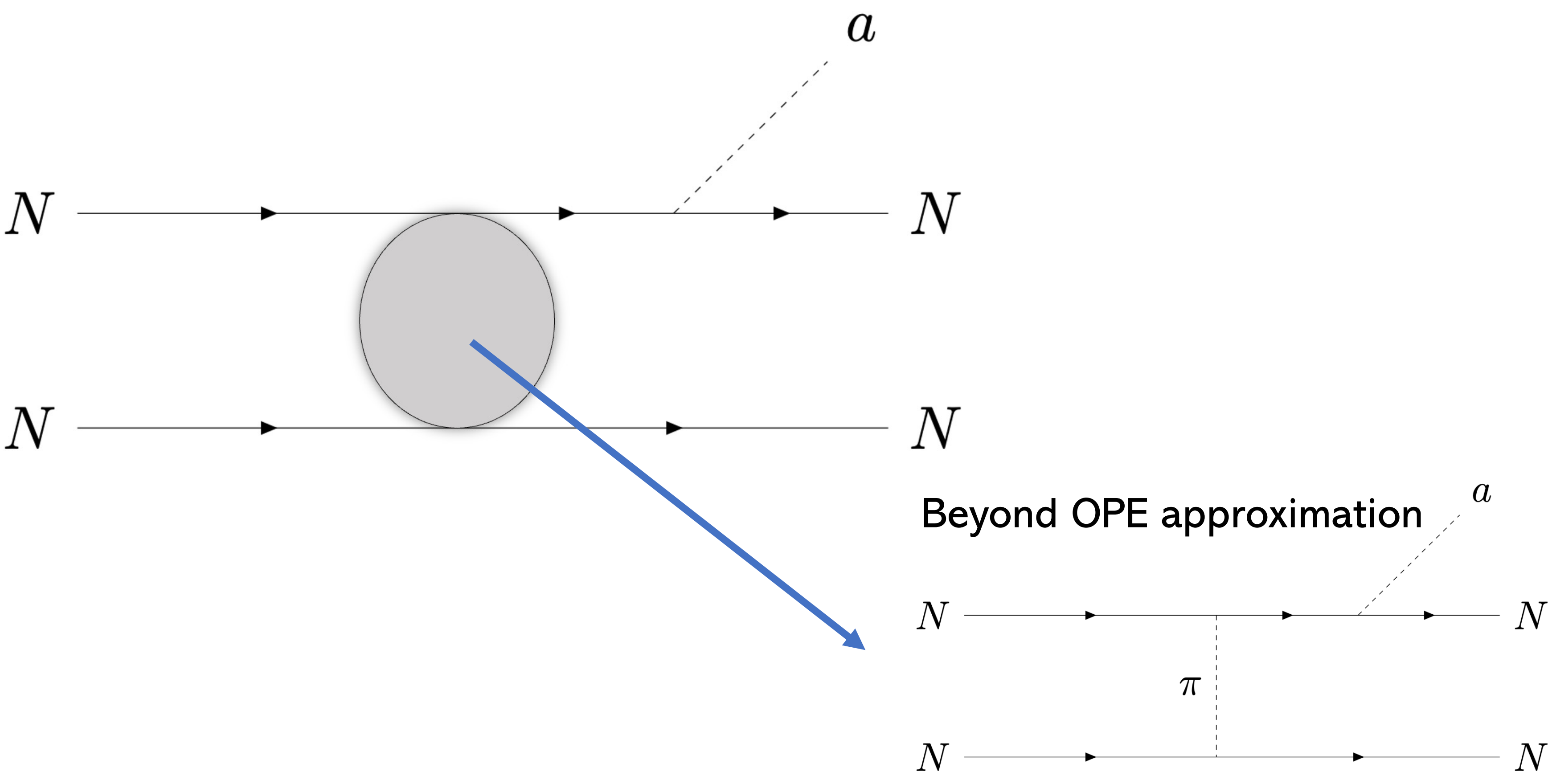

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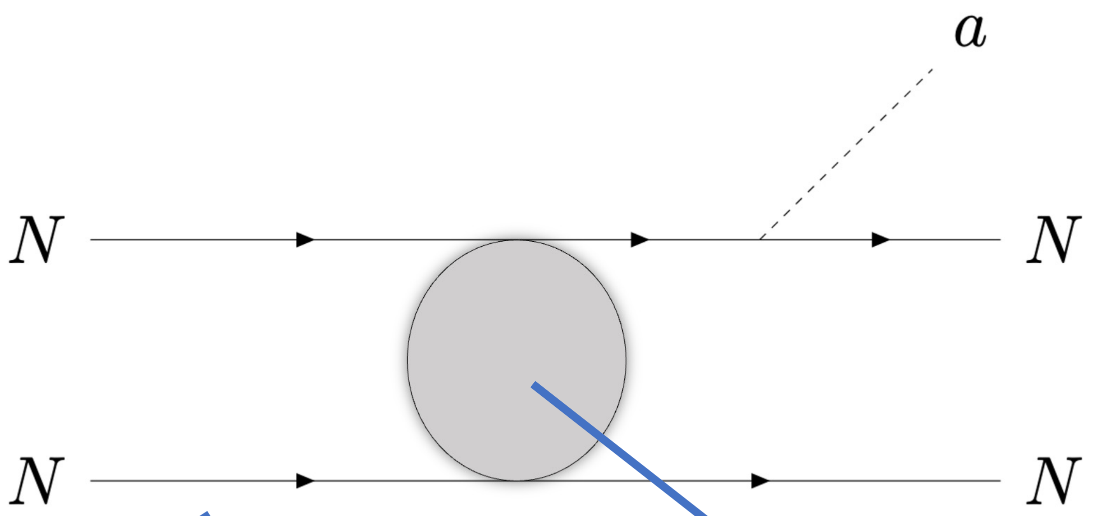
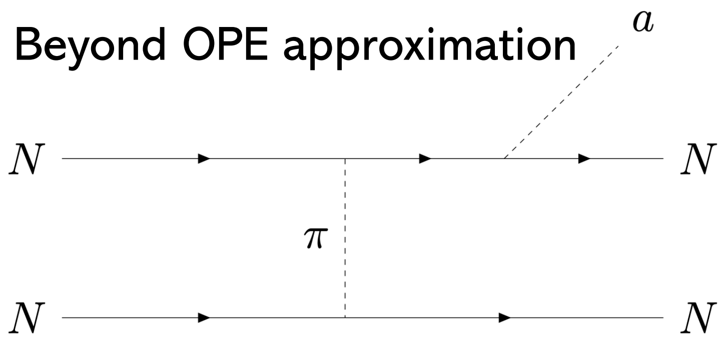


Nucleons multiple scattering

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

Beyond OPE approximation



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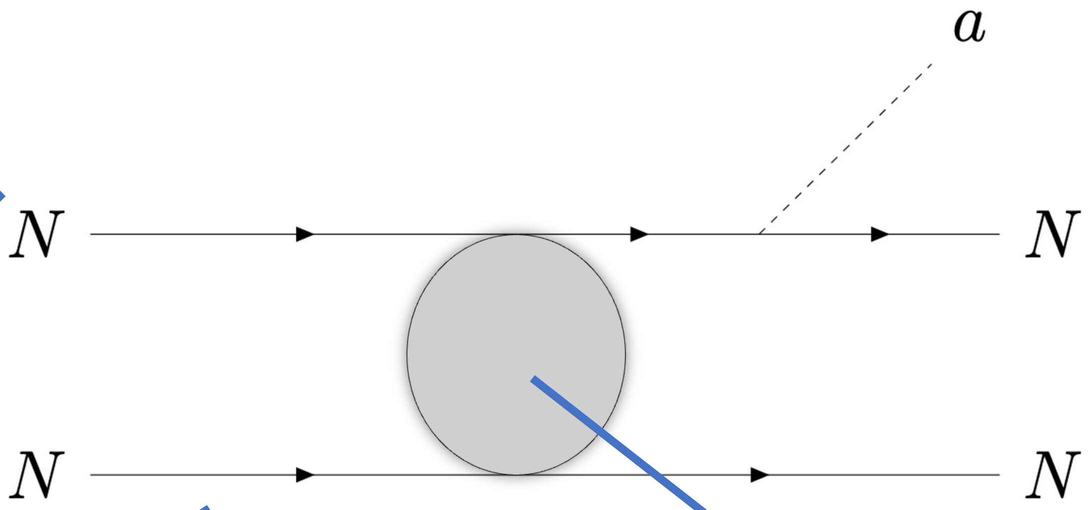
Effective nucleon masses

$$m_N \to m_N^*$$



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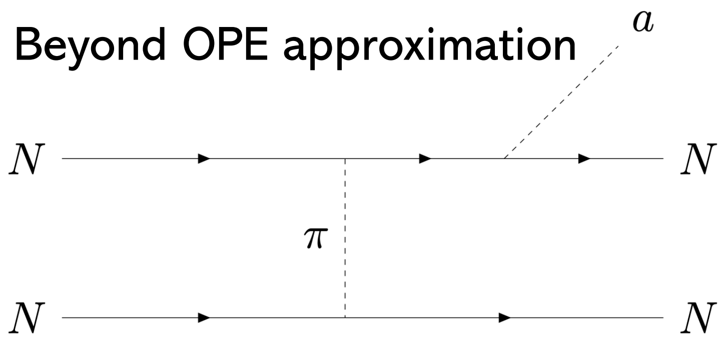

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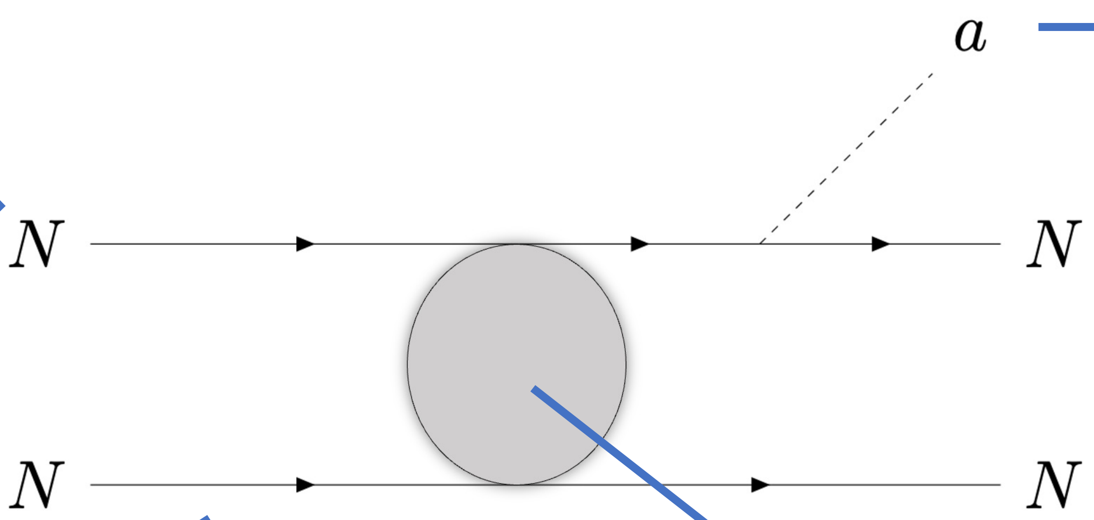

$$m_a \neq 0$$

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

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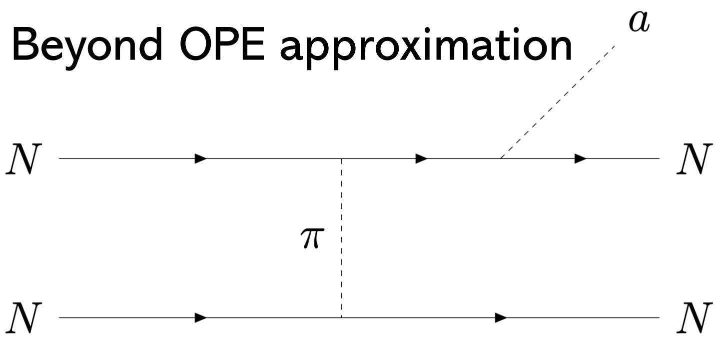

Axion production in SNe

- Pion Conversions

[Carenza & al., Phys.Rev.Lett. 126 (2021),
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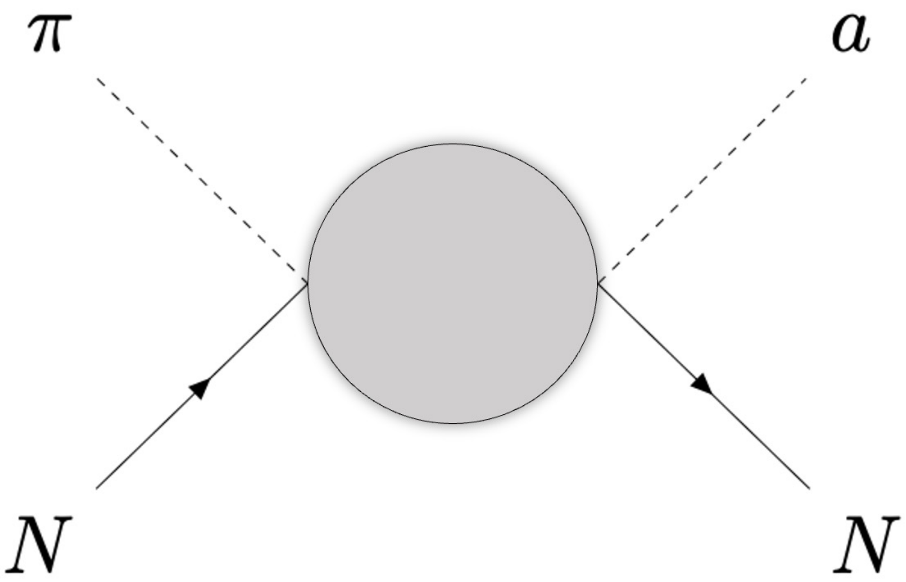

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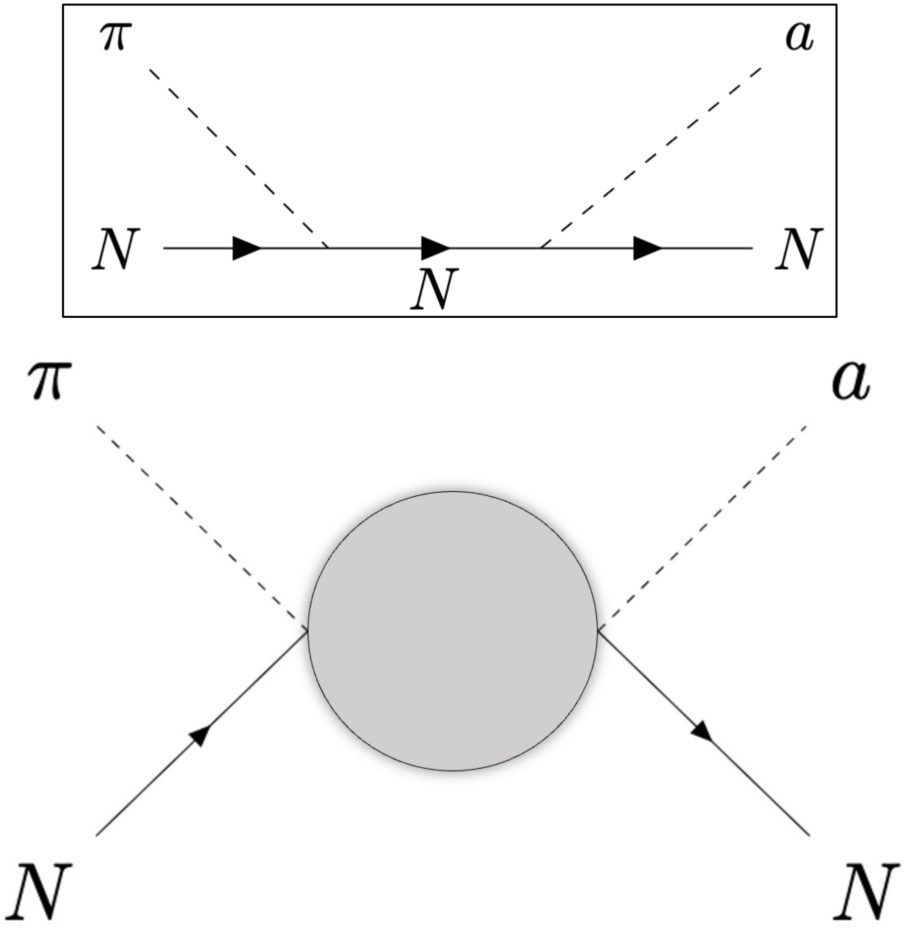

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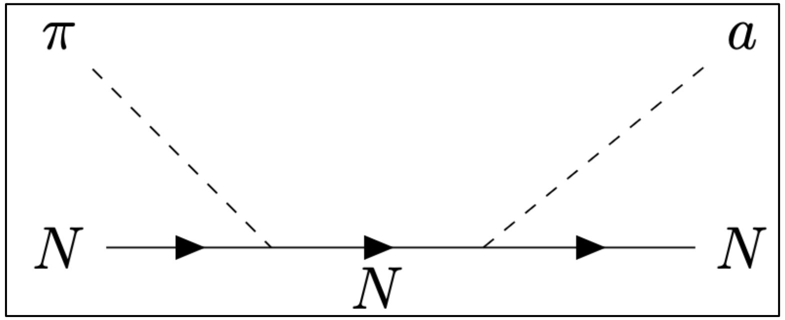

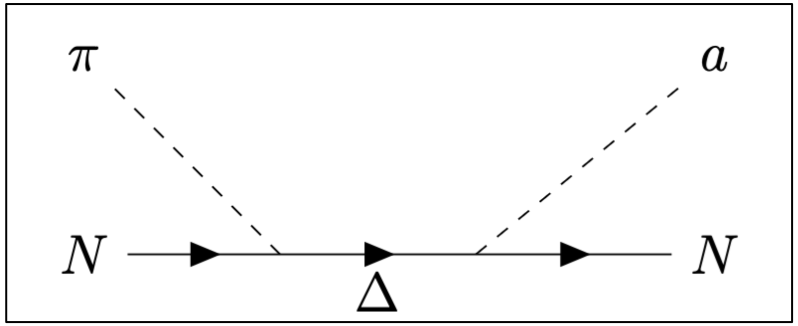

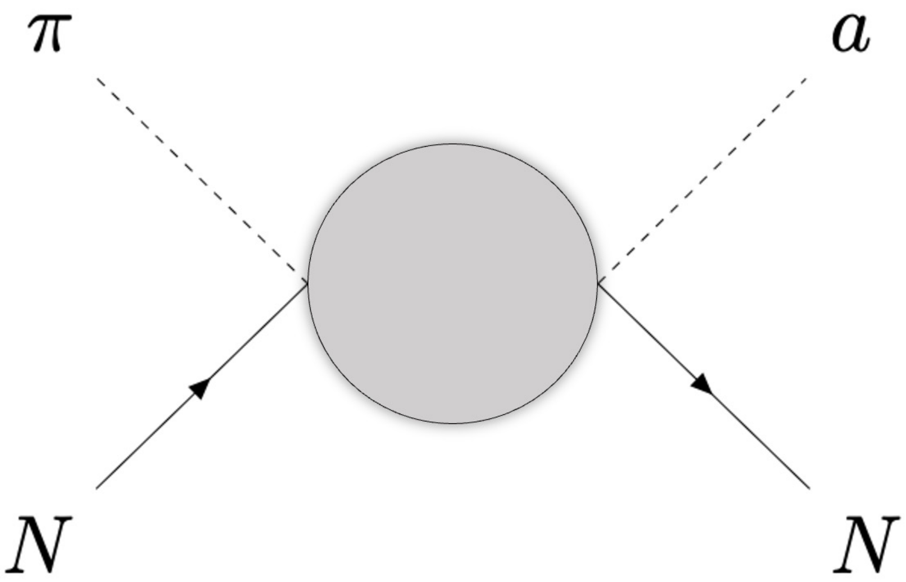

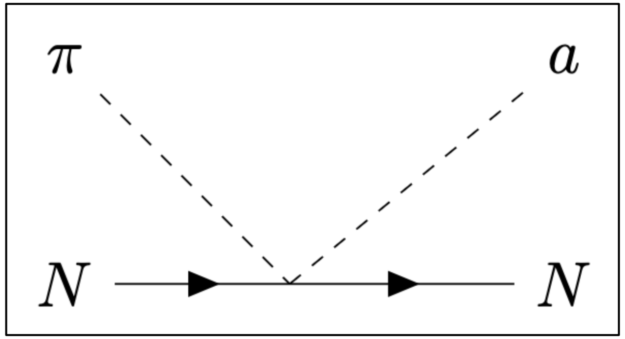

ALP emission spectra

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

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

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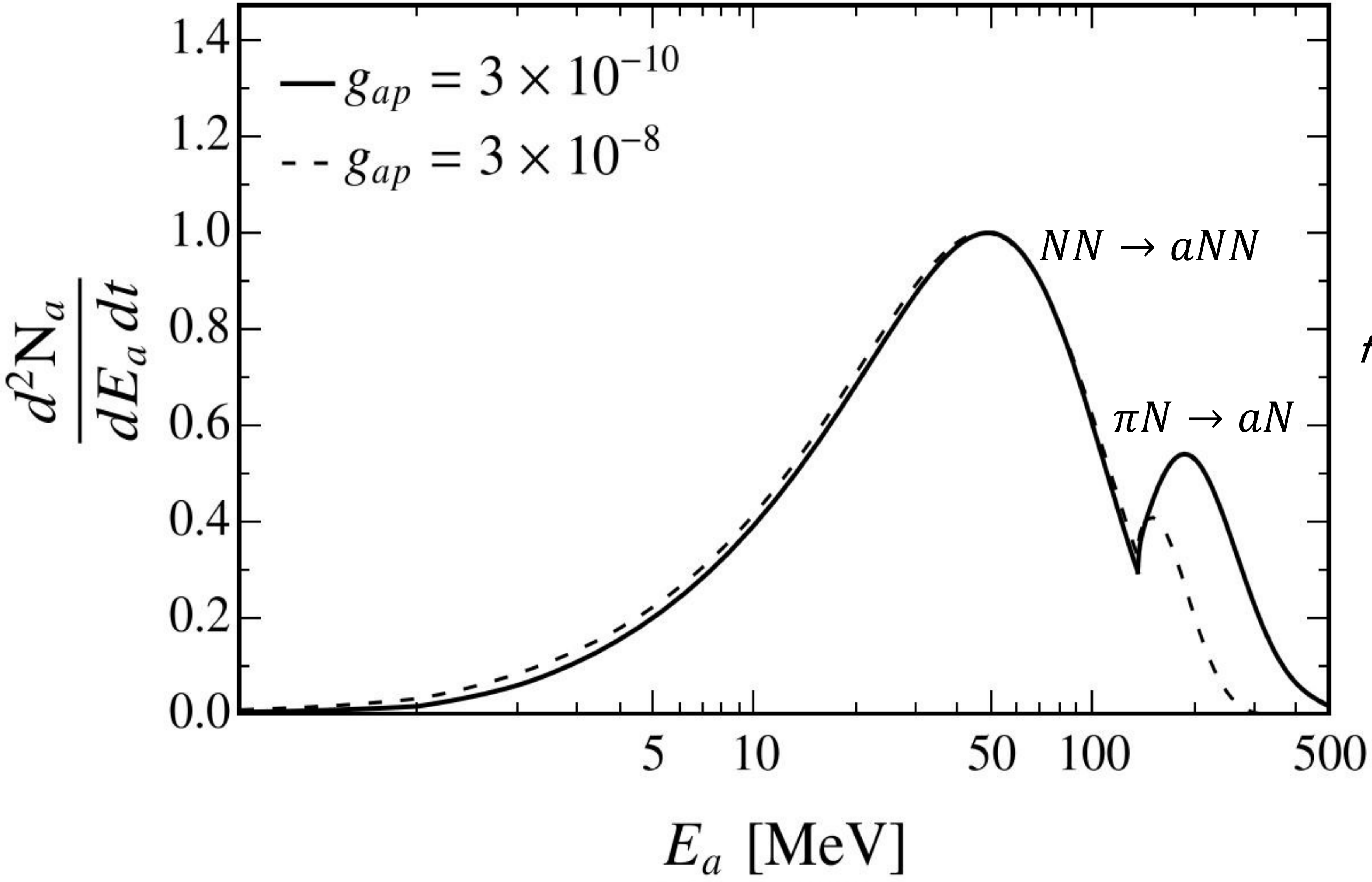
- In case of strongly coupled ALPs, they could enter the *Trapping regime*
  [Caputo & al., Phys. Rev. D 105 (2022)*]*

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

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

ALP emission spectra



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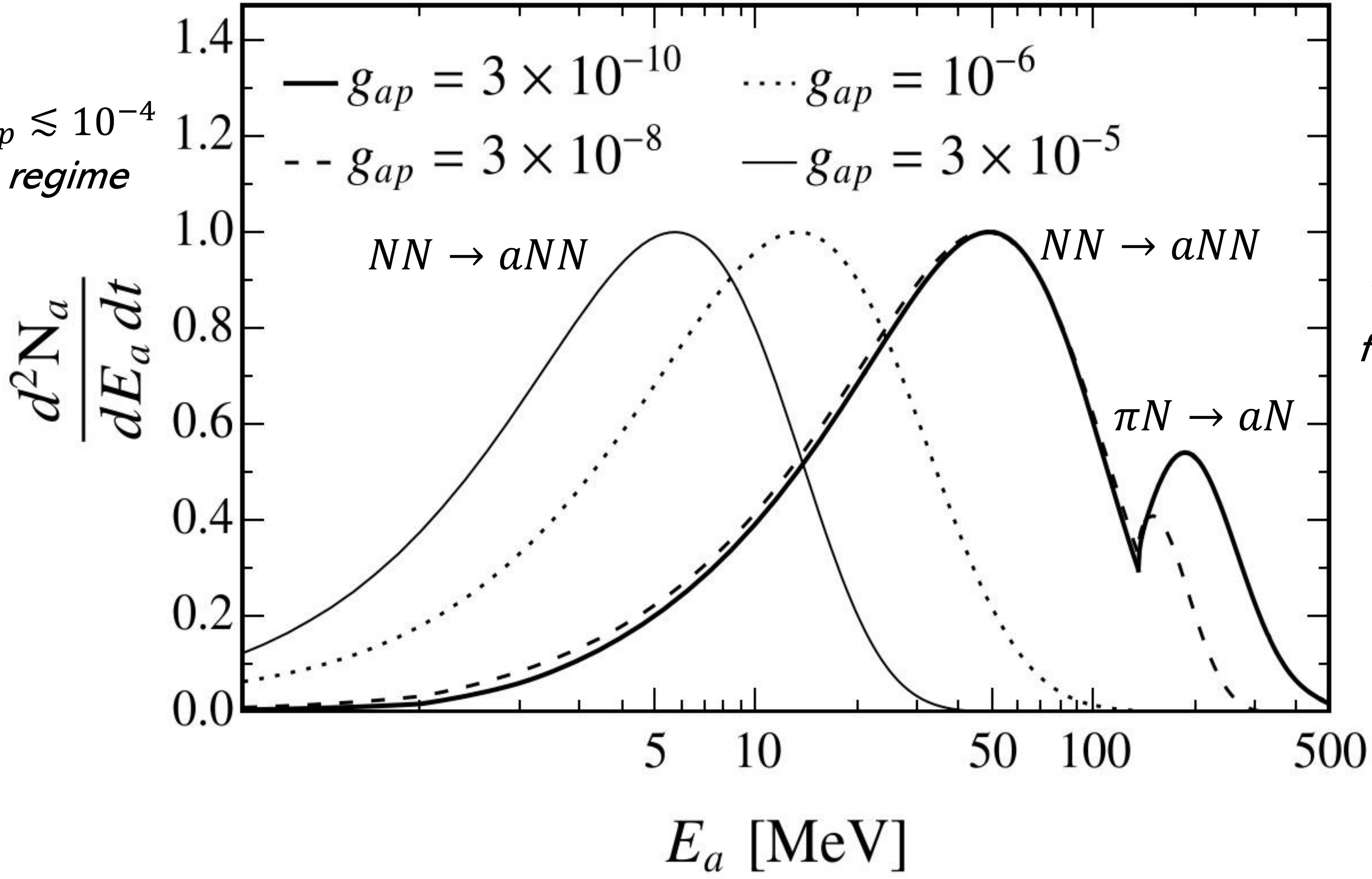
free-streaming regime

ALP emission spectra

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



$10^{-10} \lesssim g_{ap} \lesssim 10^{-7}$
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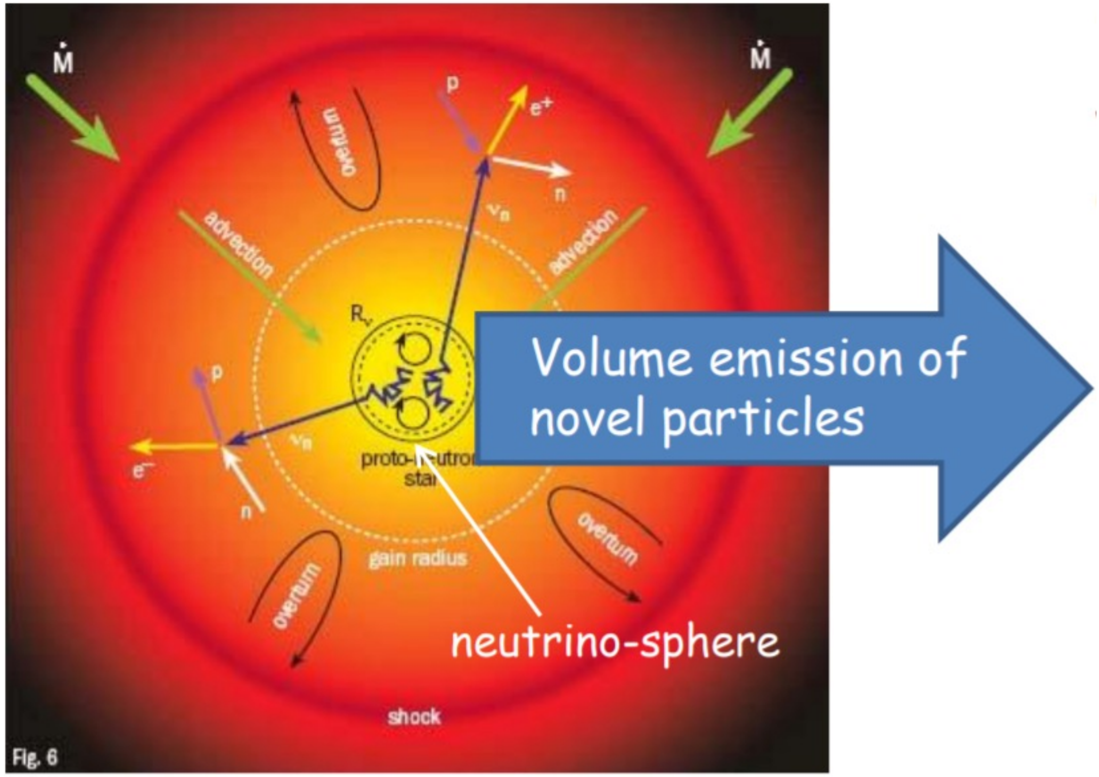
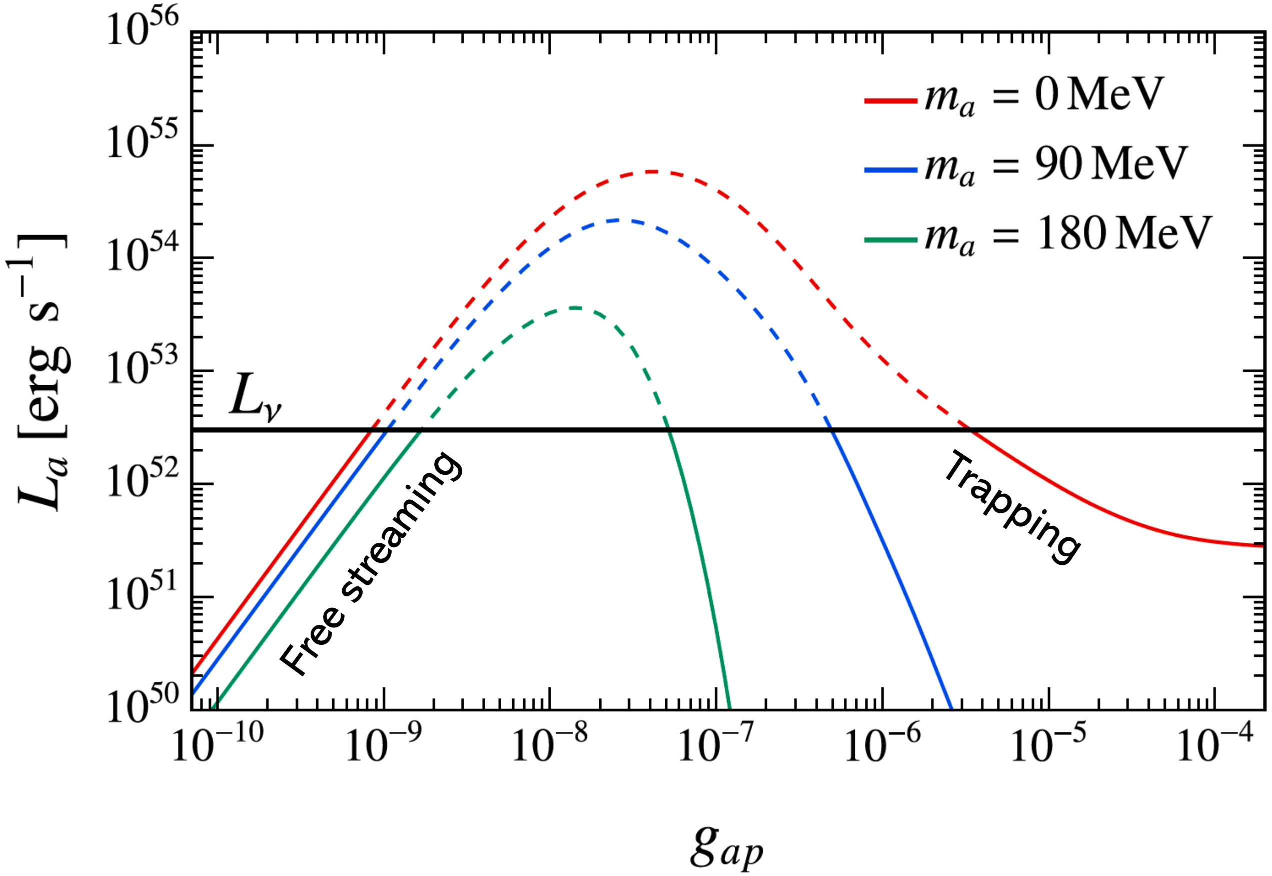
The energy-loss argument

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

[AL & al., e-Print: 2306.01048 (2023)]





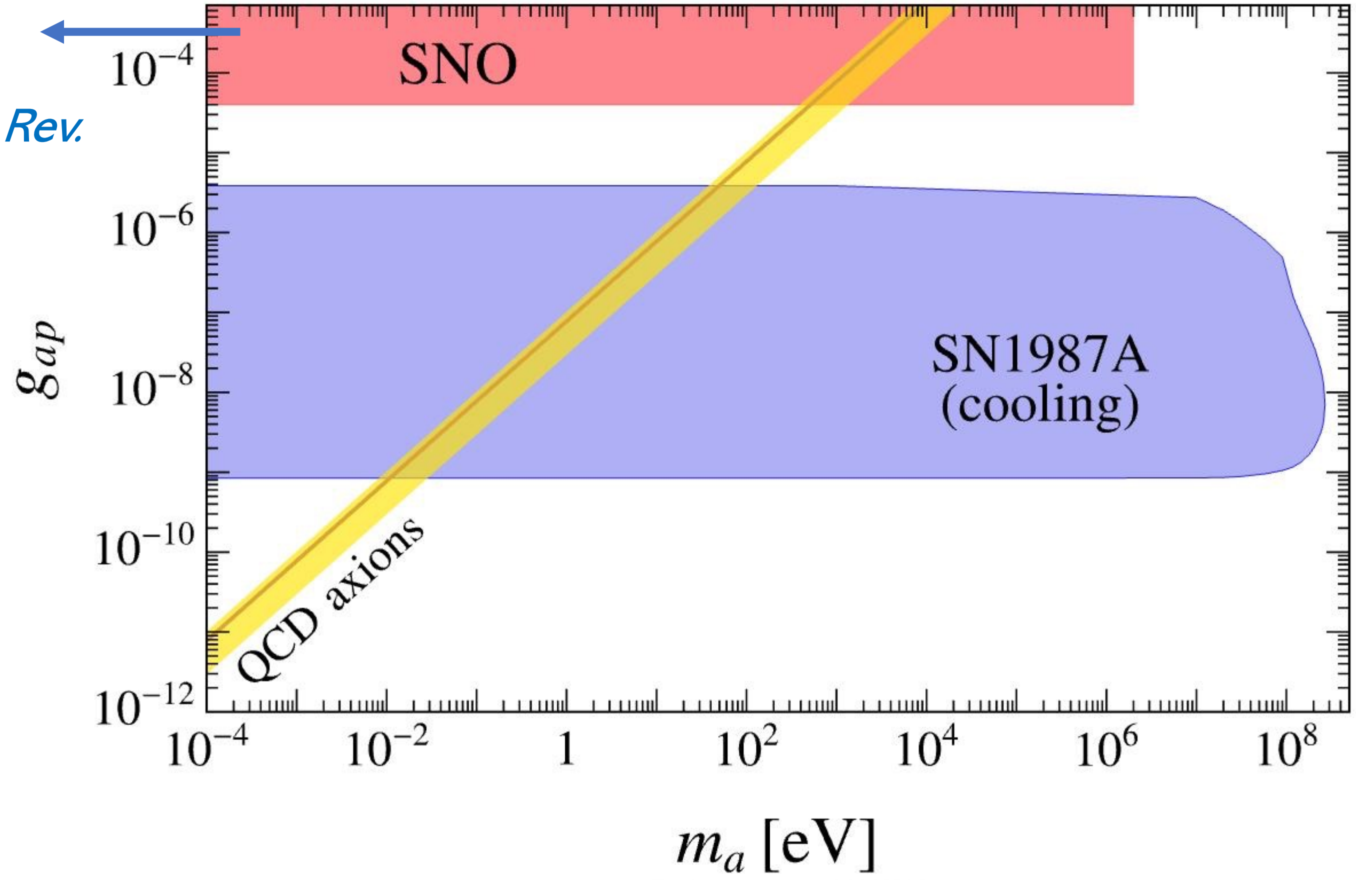
[Raffelt & Seckel, Phys. Rev. Lett.60 (1998)]

The energy-loss argument

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

$$L_a \lesssim L_\nu \approx 3 \times 10^{52}\ \mathrm{erg\ s^{-1}}$$

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



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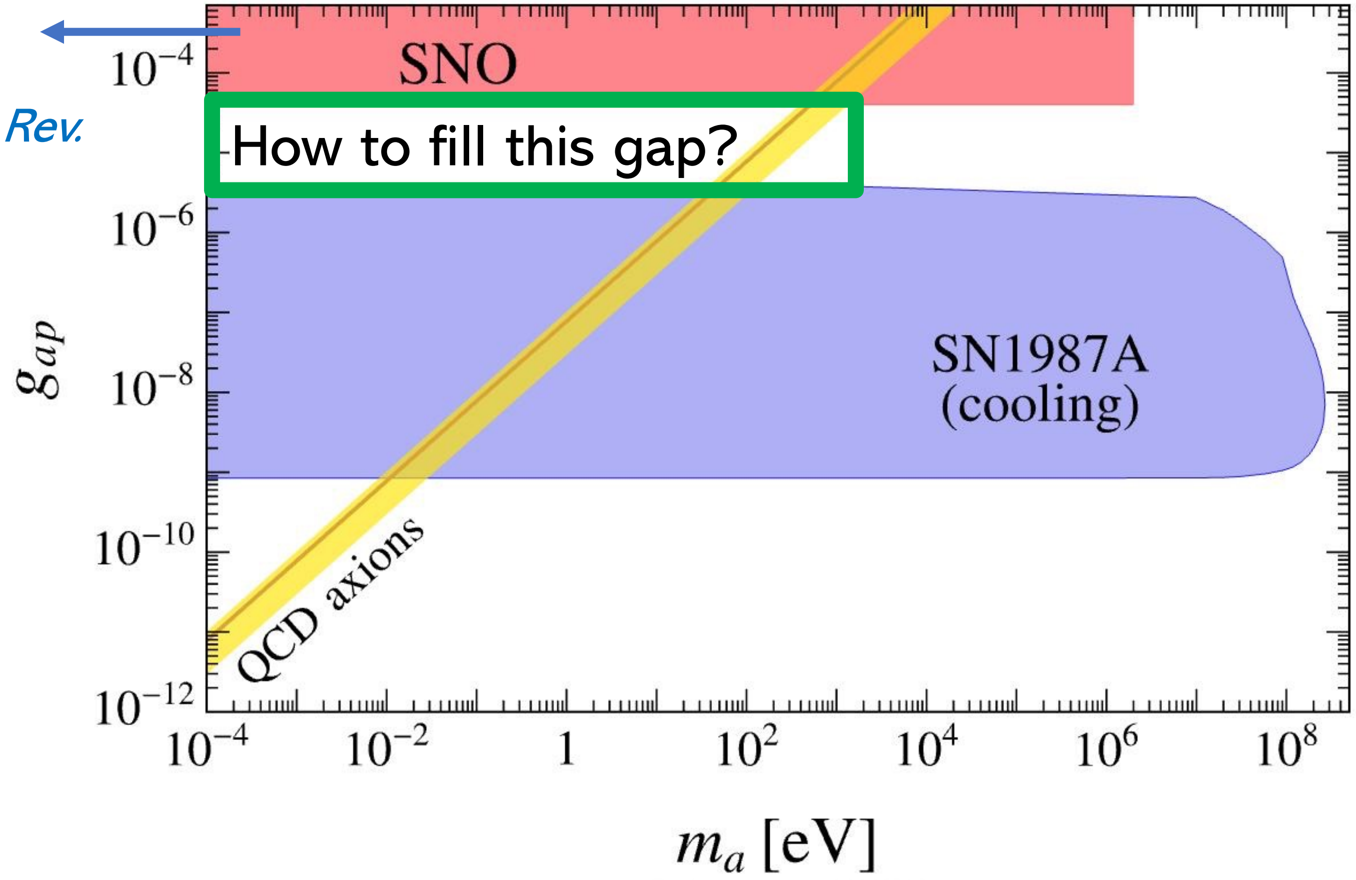


[AL & al., e-Print: 2306.01048 (2023)]

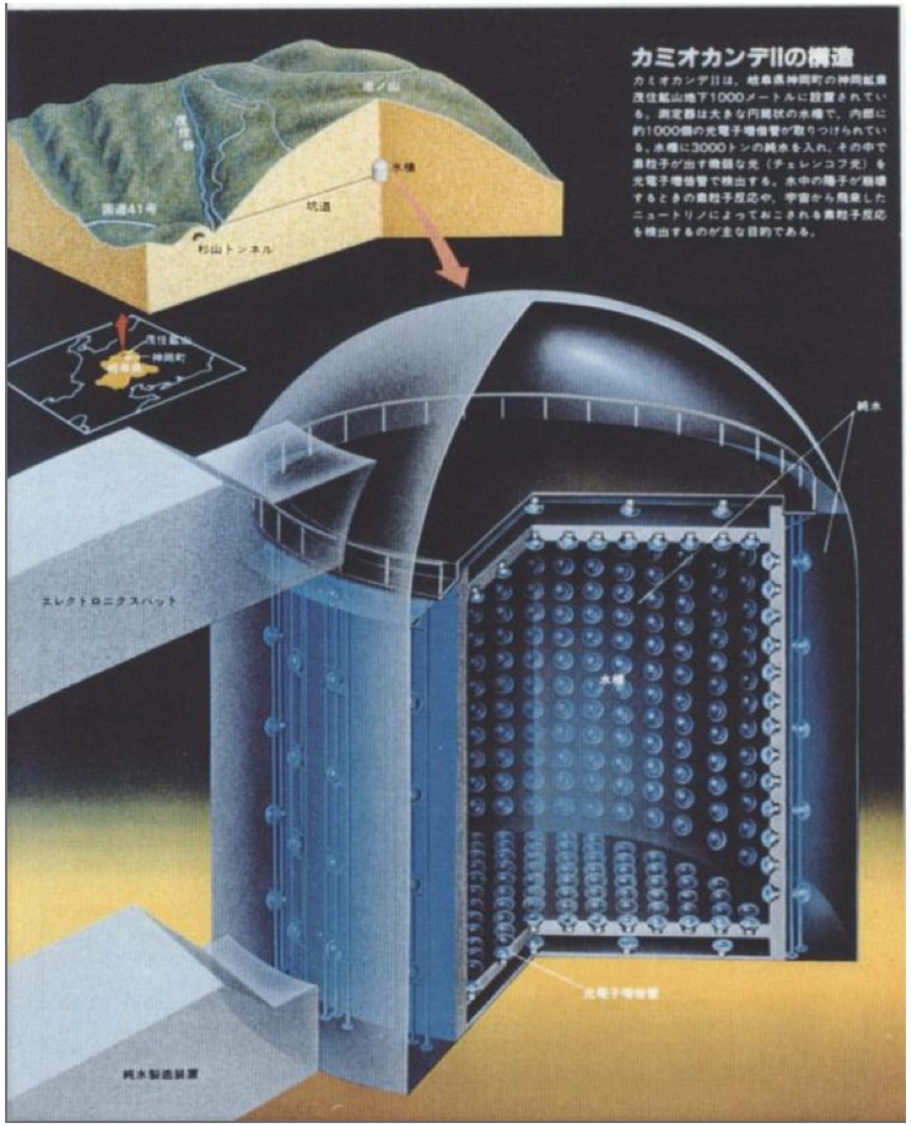
Axion signal in Kamiokande II

- 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



Axion-Oxygen cross section

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

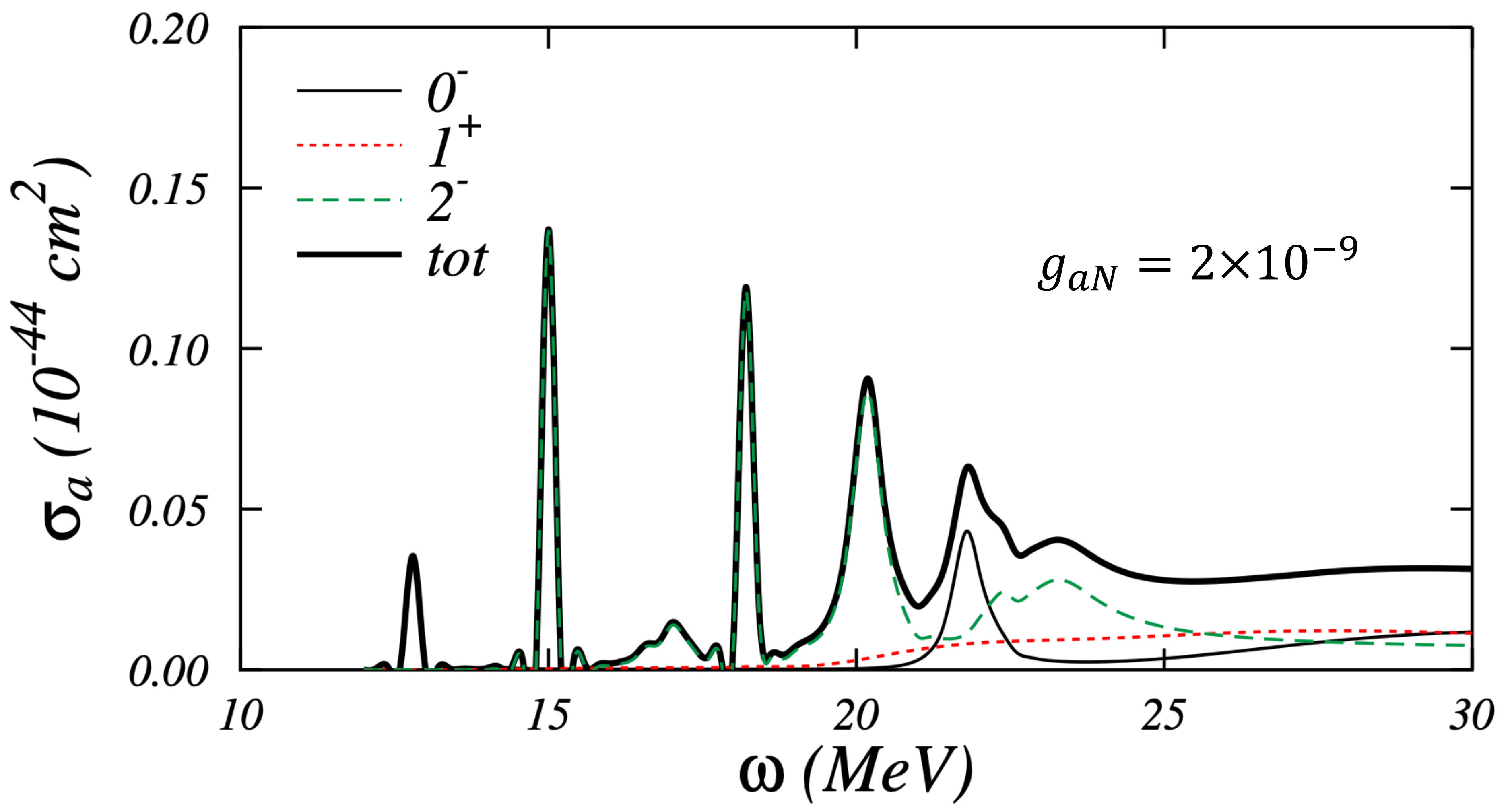
$$\mathcal{H}_{aN} = -\frac{g_{aN}}{2m_N}\partial_k a\, \underbrace{\bar{N}\gamma^k\gamma^5(C_0 + C_1\tau_3)N}_{\text{Hadronic current}}$$

By computing the transition matrix element, the total cross section is *[P. Carenza, G. Co', M. Giannotti, AL, G. Lucente, A. Mirizzi, T. Rauscher, e-Print: 2306.17055 (2023)]*

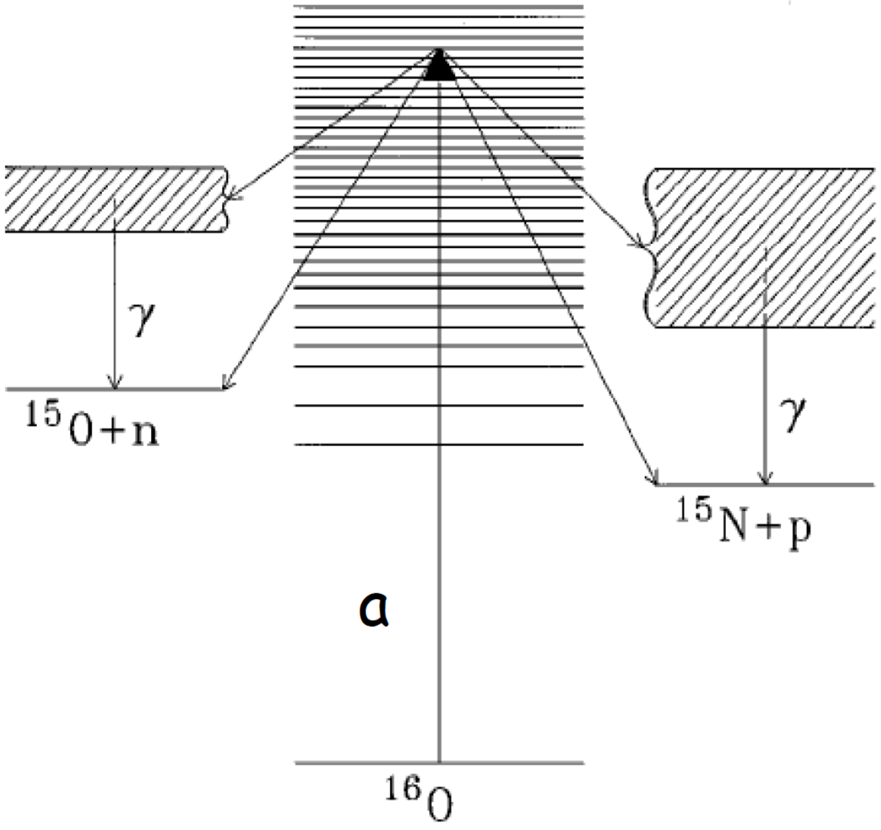
$$\sigma(E_a) \sim \underbrace{\frac{g_{aN}^2}{m_N^2}}_{\text{Strength of nuclear interactions}} E_a \sum_J \underbrace{\left|\langle J^\Pi || T_J || 0^+ \rangle\right|^2}_{\text{Nuclear transition matrix element}} \delta(E_a - E_J)$$

Nuclear transition matrix element → Computed in RPA approach

Axion-Oxygen cross section



Oxygen de-excitation



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

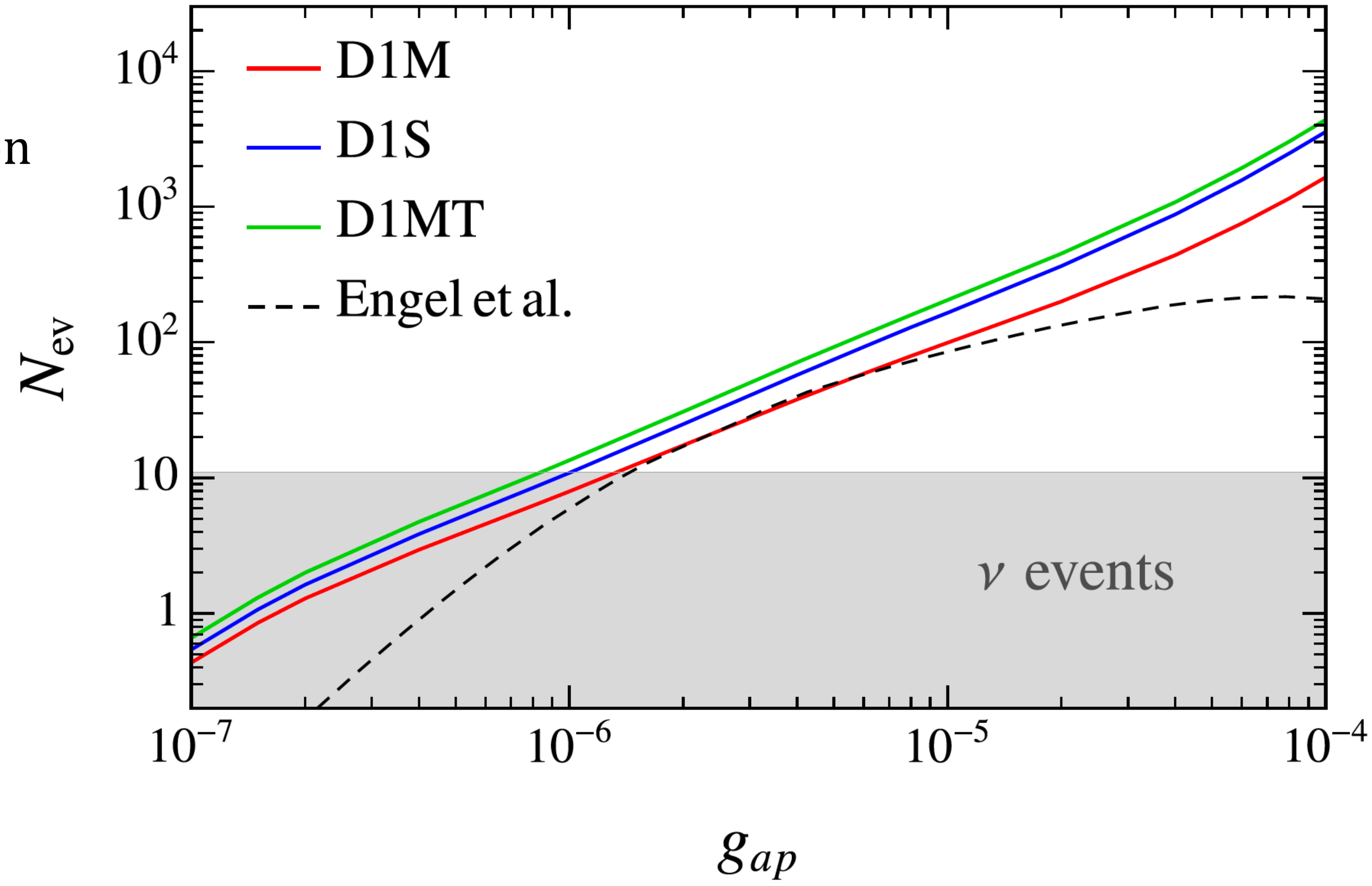
- Branching ratios computed through the *SMARAGD Hauser-Feshbach reaction code* *[T. Rauscher, computer code SMARAGD, version 0.9.3s, Vol. 103, 2015]*.

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

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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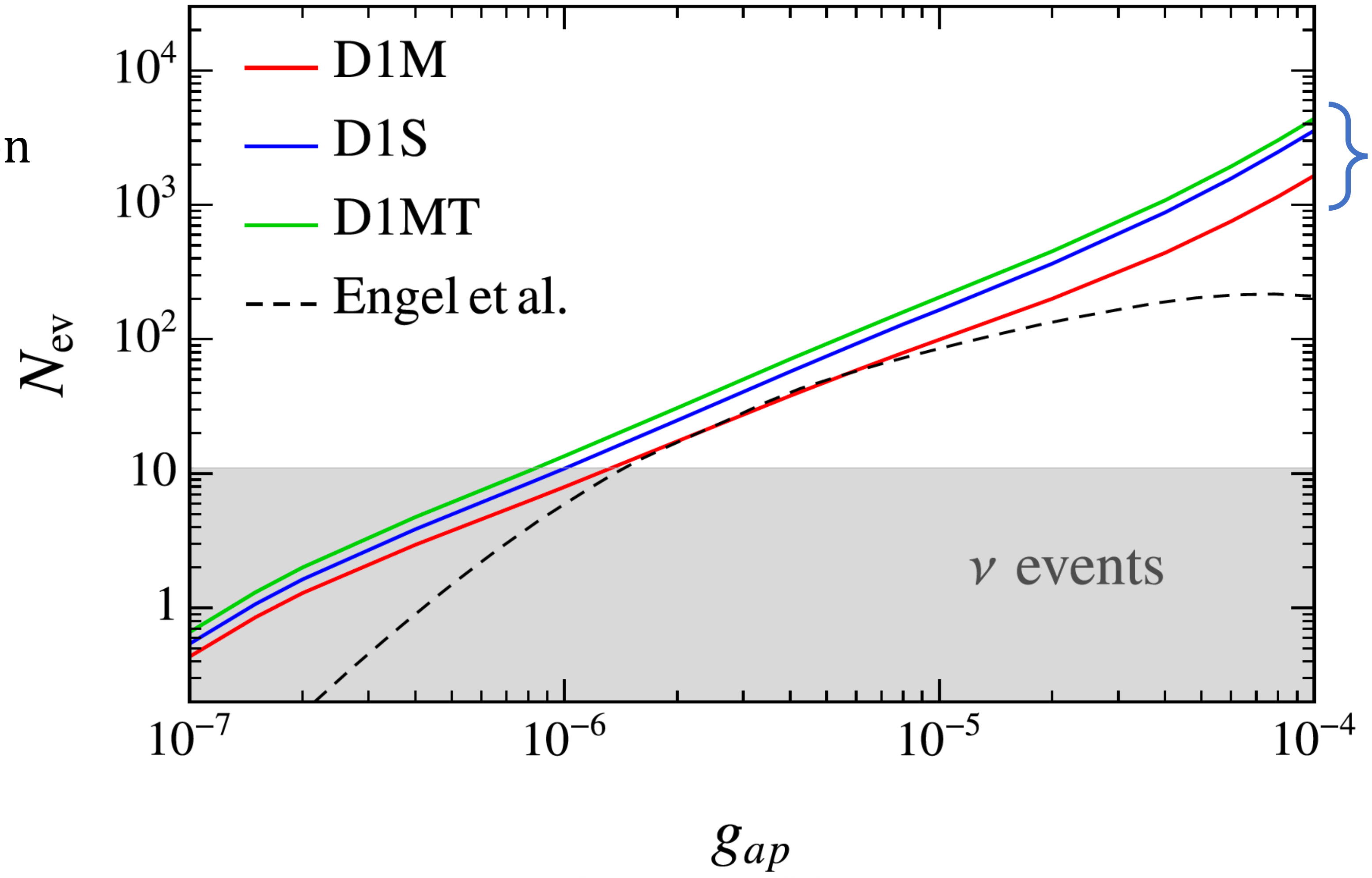
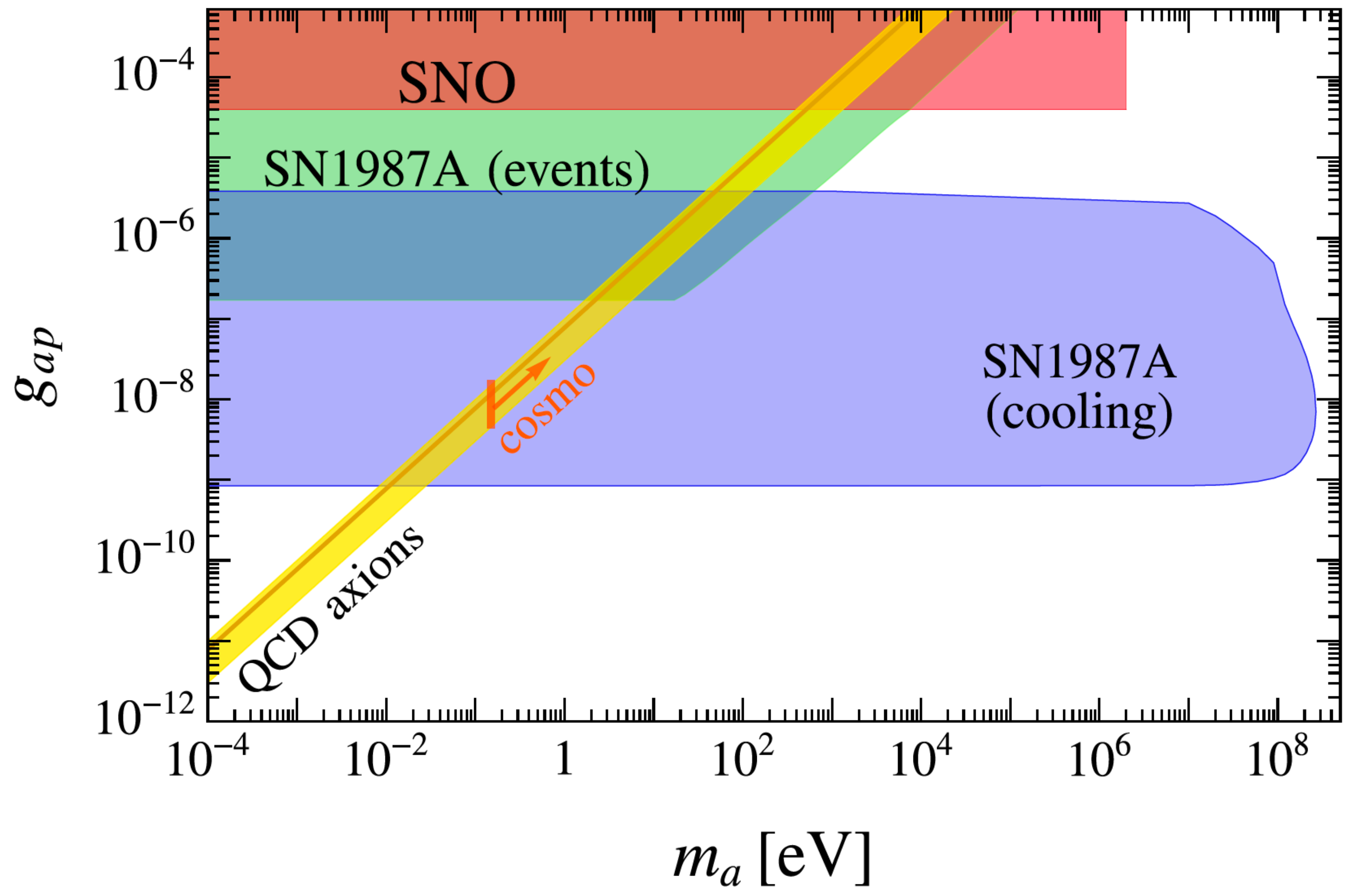


Uncertainties $\mathcal{O}(60\ \%)$ over the nuclear model

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].



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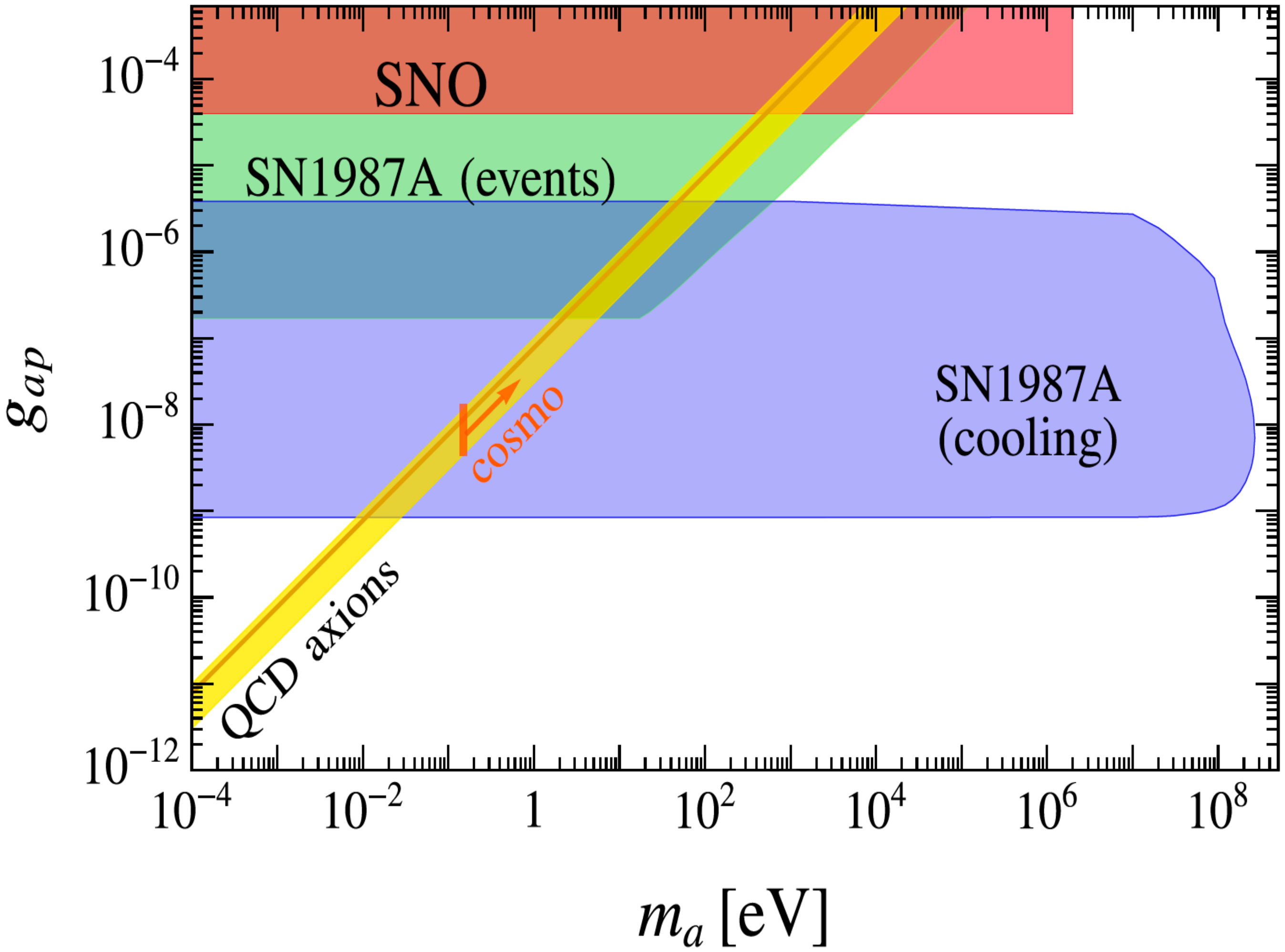
[P. Carenza, G. Co', M. Giannotti, AL, G. Lucente, A. Mirizzi, T. Ruascher, e-Print: 2306.17055 (2023)]

Concluding remarks

- Hadronic axions from SN in trapping regime require an adequate treatment.
- Supernova arguments alone exclude QCD axion masses $m_a \gtrsim 10^{-2}$ eV.
- No *"hadronic axion window"* *[Chang & Choi, Phys. Rev. Lett. 316 (1993)]* .
- No signatures due to mass of HDM axions in future cosmological surveys.

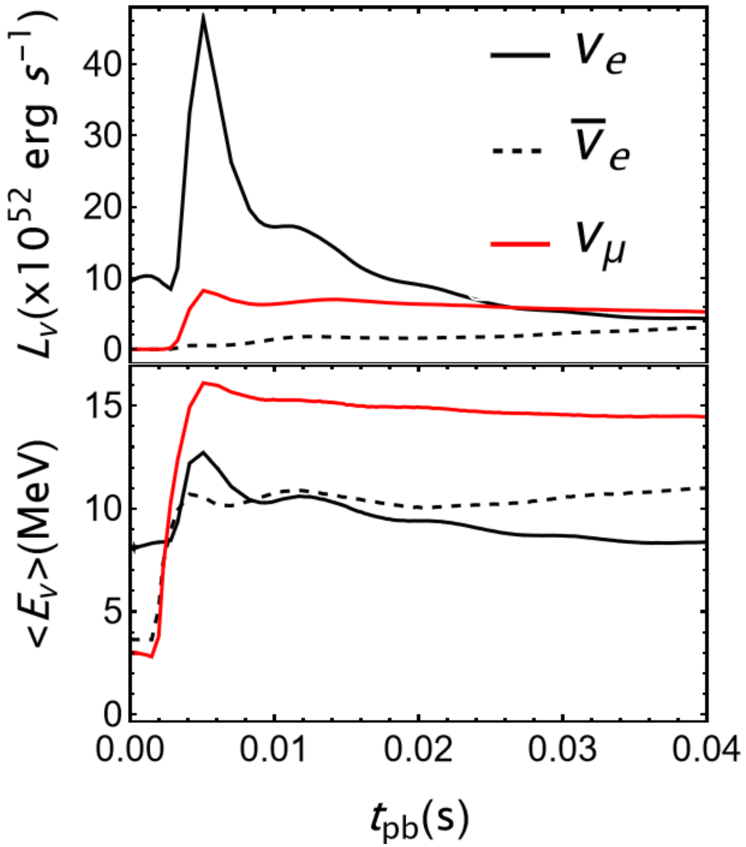



Thank you for your attention

Supernova Neutrinos

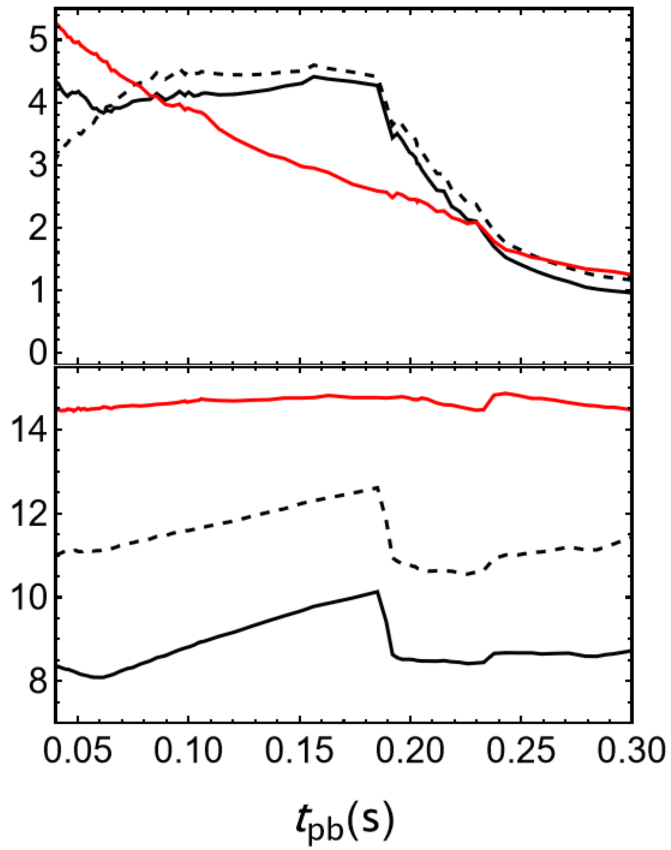
Neutronization burst

- Electron capture in the inner core



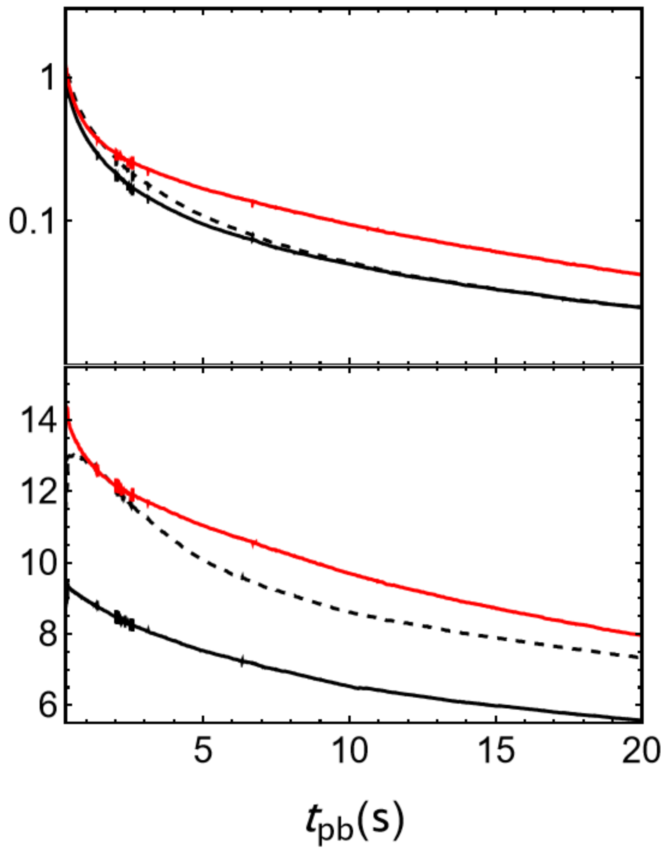
Accretion

- When shock stalls, ν powered by infalling matter



Cooling

- Cooling on ν diffusion time scale



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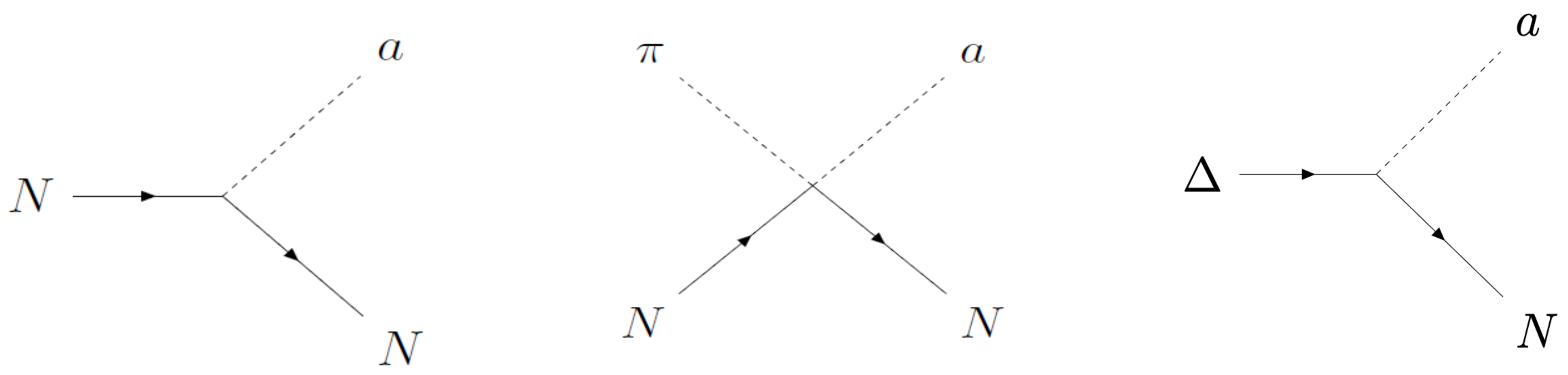
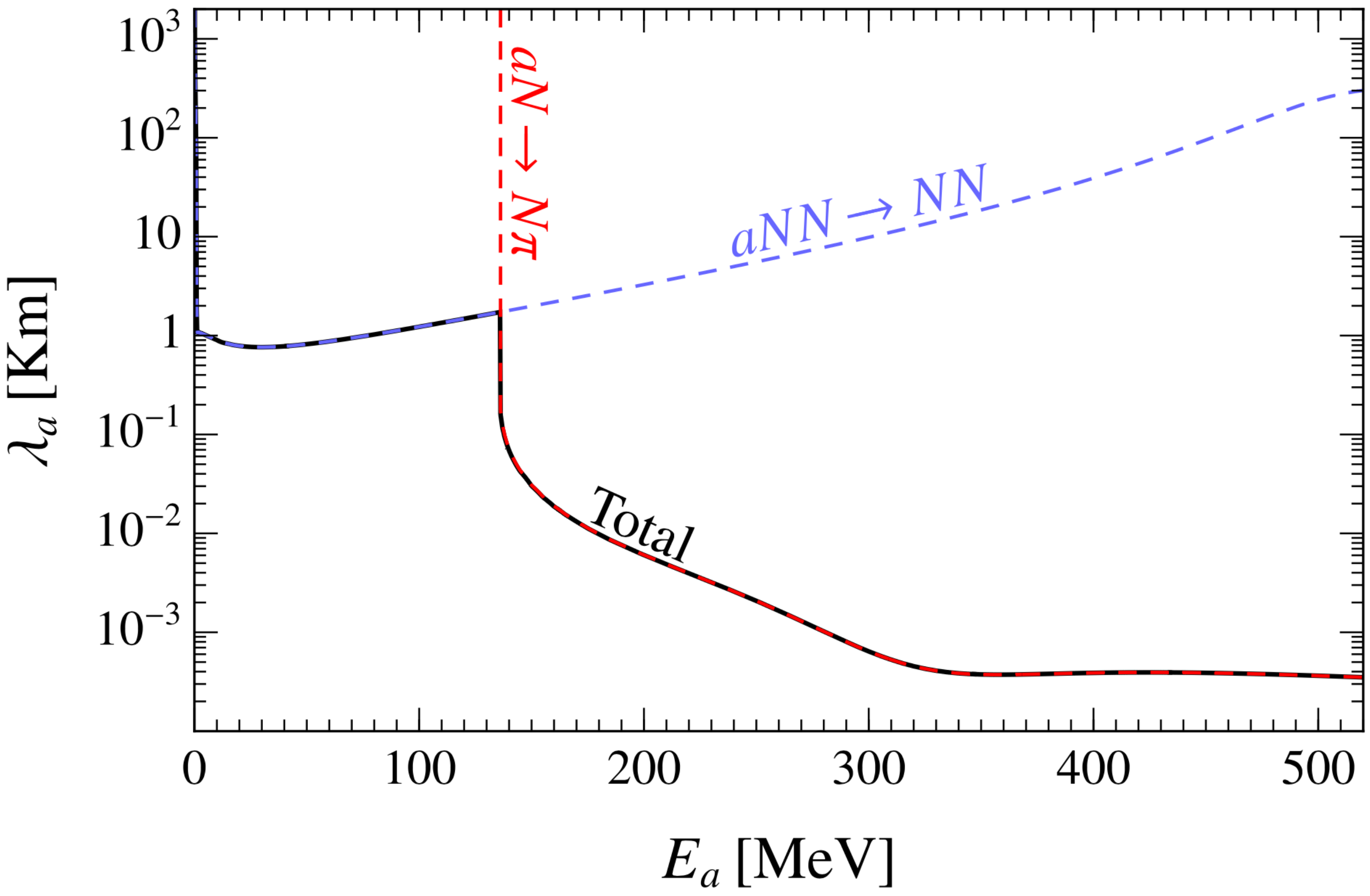


ALP mean free path

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



Axion events from SN 1987A

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

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

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

Detector resolution

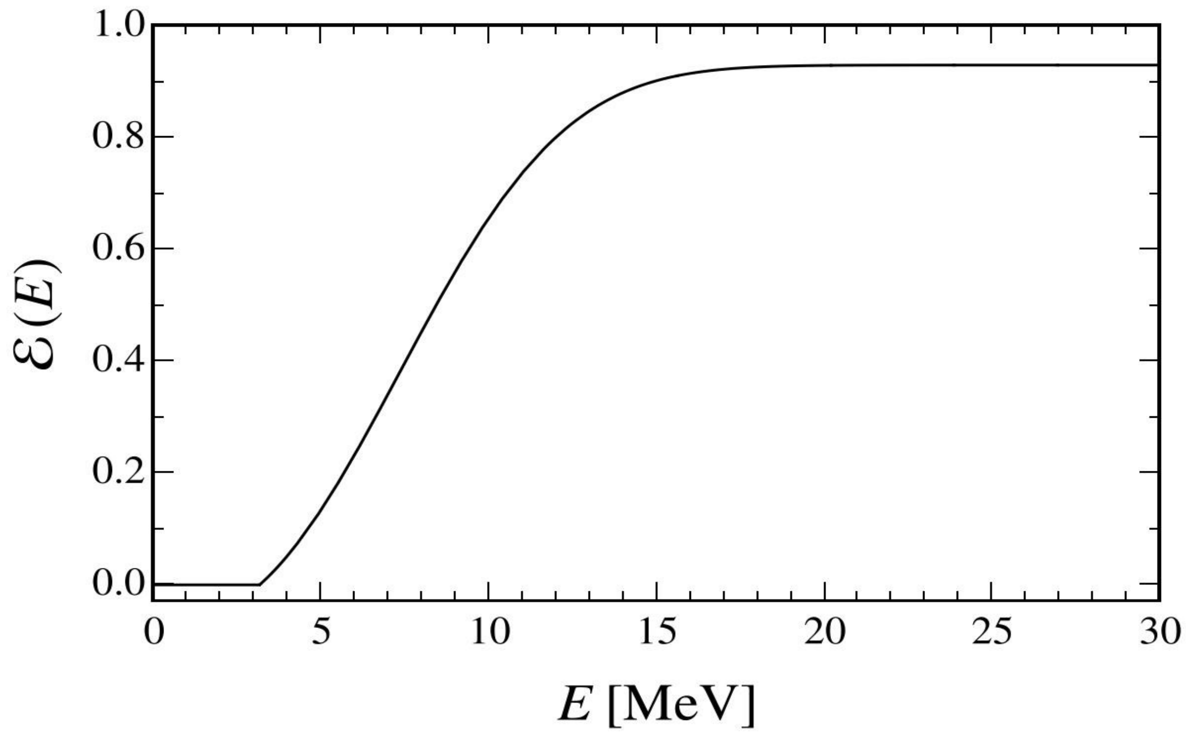
- Detector energy resolution spreads detected energies around true photon energies.

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

where $\sigma = 0.6\,\sqrt{\omega(\epsilon)/\,\mathrm{MeV}}$

- Detector efficiency can be modelled as *[Hirata et al., Phys. Rev. D 38 (1988)]*

$$\mathcal{E} = \max\left[0\,,\ 0.93 - e^{-(E/9\ \mathrm{MeV})^{2.5}}\right]$$



Summary plot, no pions