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Core-Collapse Supernovae shining in Axion-like particles

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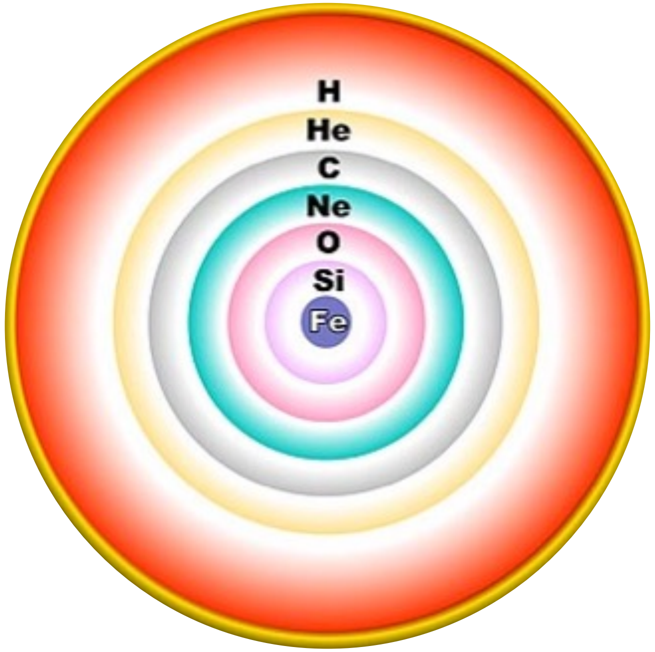
Core-collapse Supernovae

[H.T. Janka & al., Phys.Rept. 442 (2007)]

Massive Stars and Gravitational Collapse

Stars with masses $\mathrm{M} \geq 8\, M_\odot$ can induce heavier elements ignition.

Burning Phase	Dominant Process	T_c [keV]	ρ_c [g/cm^3]	L_γ [10^4 L_{sun}]	L_ν/L_γ	Duration [years]
Hydrogen	H $\rightarrow$ He	3	5.9	2.1	–	1.2×10^7
Helium	He $\rightarrow$ C, O	14	1.3×10^3	6.0	1.7×10^{-5}	1.3×10^6
Carbon	C $\rightarrow$ Ne, Mg	53	1.7×10^5	8.6	1.0	6.3×10^3
Neon	Ne $\rightarrow$ O, Mg	110	1.6×10^7	9.6	1.8×10^3	7.0
Oxygen	O $\rightarrow$ Si	160	9.7×10^7	9.6	2.1×10^4	1.7
Silicon	Si $\rightarrow$ Fe, Ni	270	2.3×10^8	9.6	9.2×10^5	6 days



Heavy elements collected in an "onion" structure with shells of burning elements around a degenerate iron core.

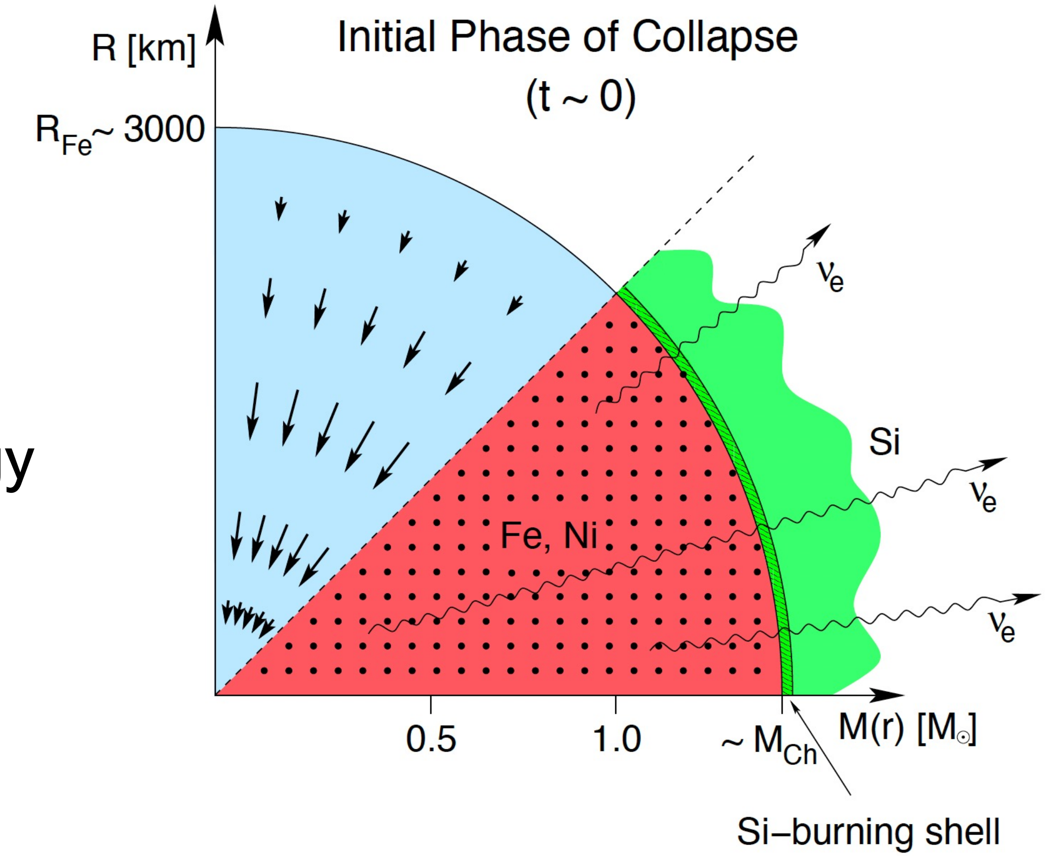
Phases of collapse

Electron degeneracy pressure counter-balances gravity until $\mathrm{M} > M_{ch} \sim 5.8\, Y_e^2 M_\odot$, $(Y_e \simeq 0.42)$.

➢ Instability is mainly due to:

- $e^- + p \rightarrow n + \nu_e$: reduces Y_e and enrich neutron fraction.
- $\gamma + {}^{56}Fe \rightarrow 13\alpha + 4n$: subtracts energy and reduces degeneracy pressure.

Onset of the Collapse



Phases of collapse

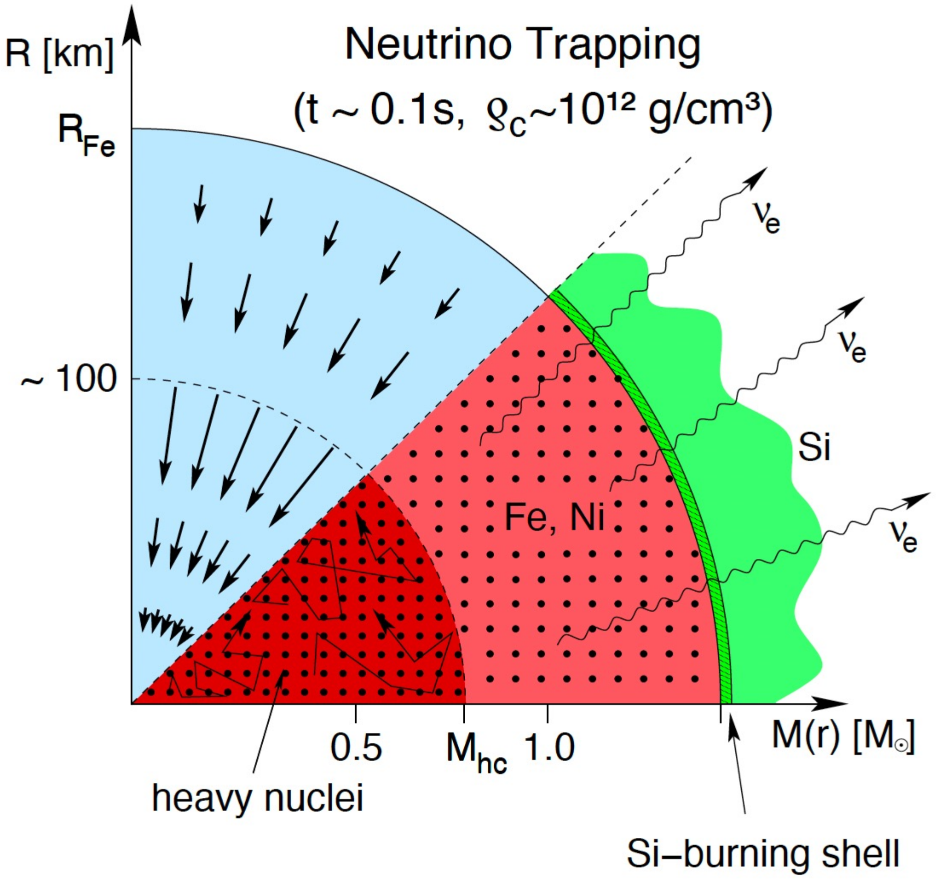
β-decays and other processes subtract energy from the core and collapse accelerates.

- Inner (homologous) core collapses at subsonic velocity, while outer layers at supersonic velocity

- When $\rho \sim 10^{12}\ \mathrm{g/cm^{-3}}$, ν-diffusion t_ν time is larger than the collapsing time scale t_d

↓

Neutrino Trapping:
Emission from $R_\nu \sim 20\ \mathrm{km}$



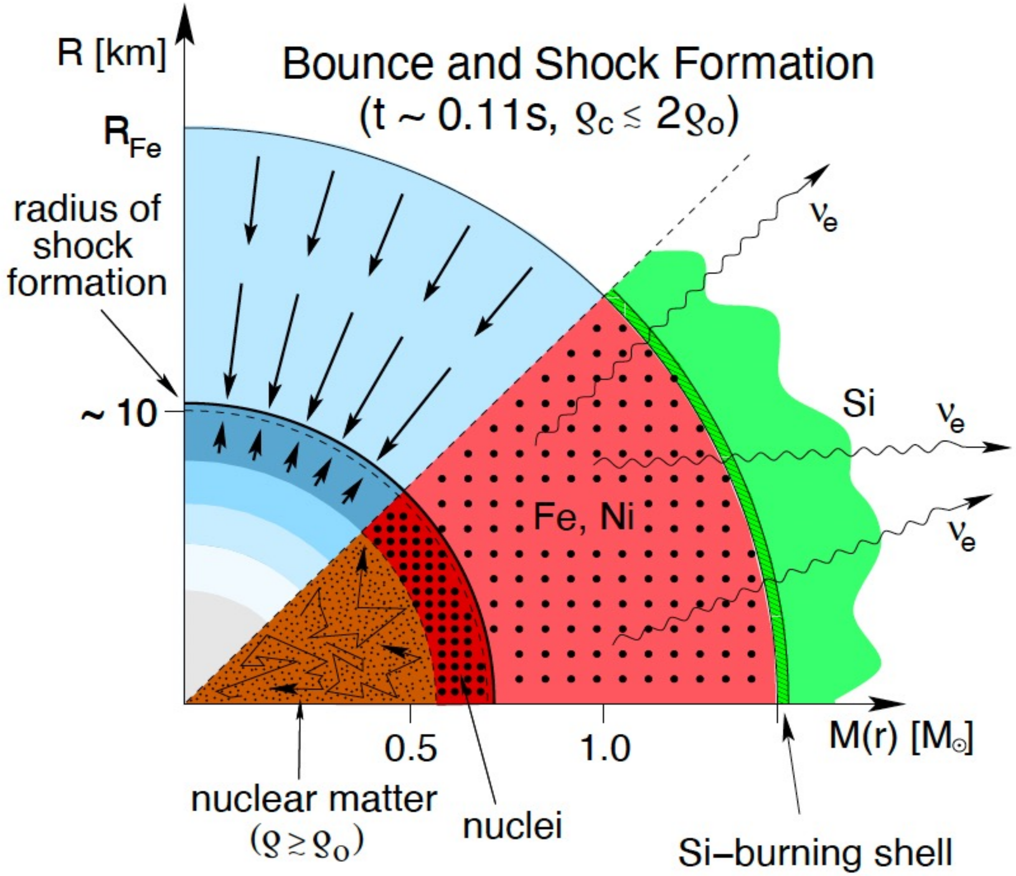
Phases of collapse

Nuclear density in the homologous core increases until $\rho > \rho_c \sim 10^{14}\mathrm{g/cm^{-3}}$.

- Outer layers keep collapsing at supersonic velocity.
- In inner regions nuclear matter becomes incompressible

↓

Formation of a shock-wave



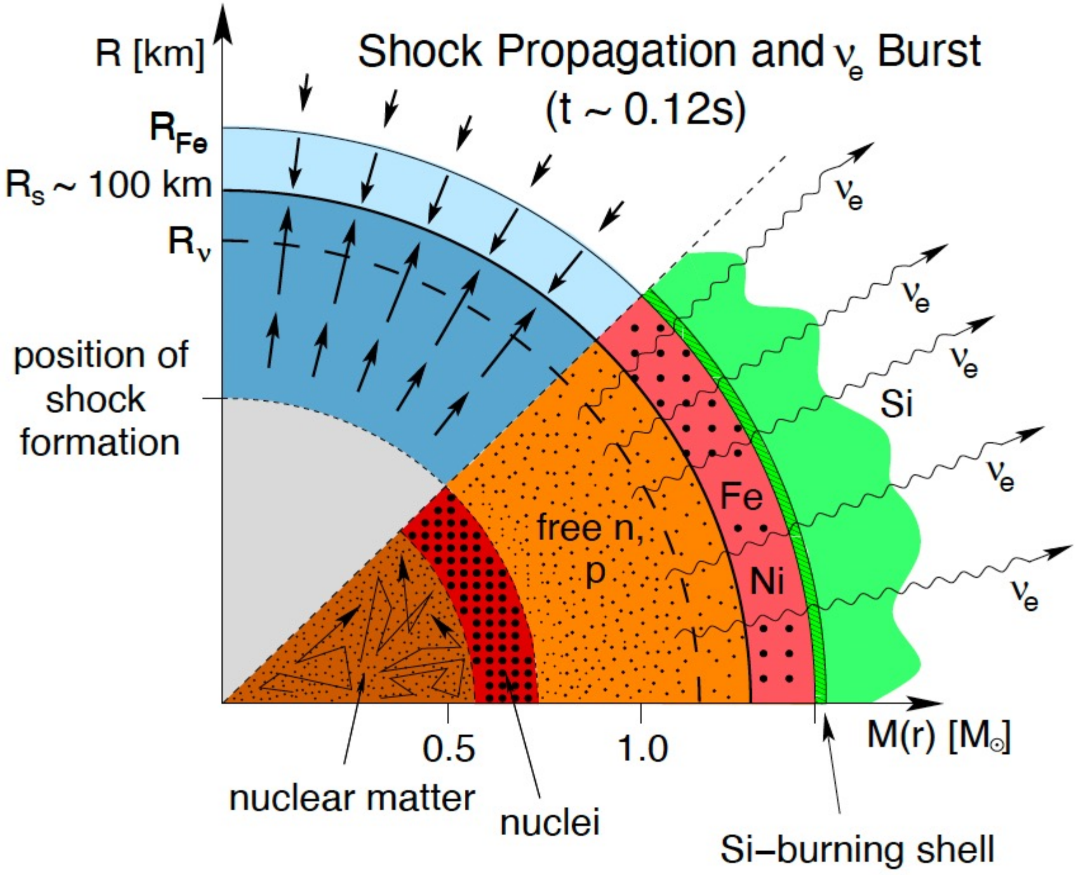
Phases of collapse

Along its path the shock wave disocciates heavy nuclei in outer layers of the core loosing some of its energy (8.8 MeV per nucleon).

- Reduction of coherent ν-scattering
- Strong enhancement of electron capture on free protons

Prompt ν_e-burst:

Short burst releasing $E \sim 10^{51}\text{erg}$



Phases of collapse

The shock wave looses almost all of its energy and stalls at $R_s \sim 200\ \mathrm{Km}$

- Matter keeps infalling from above

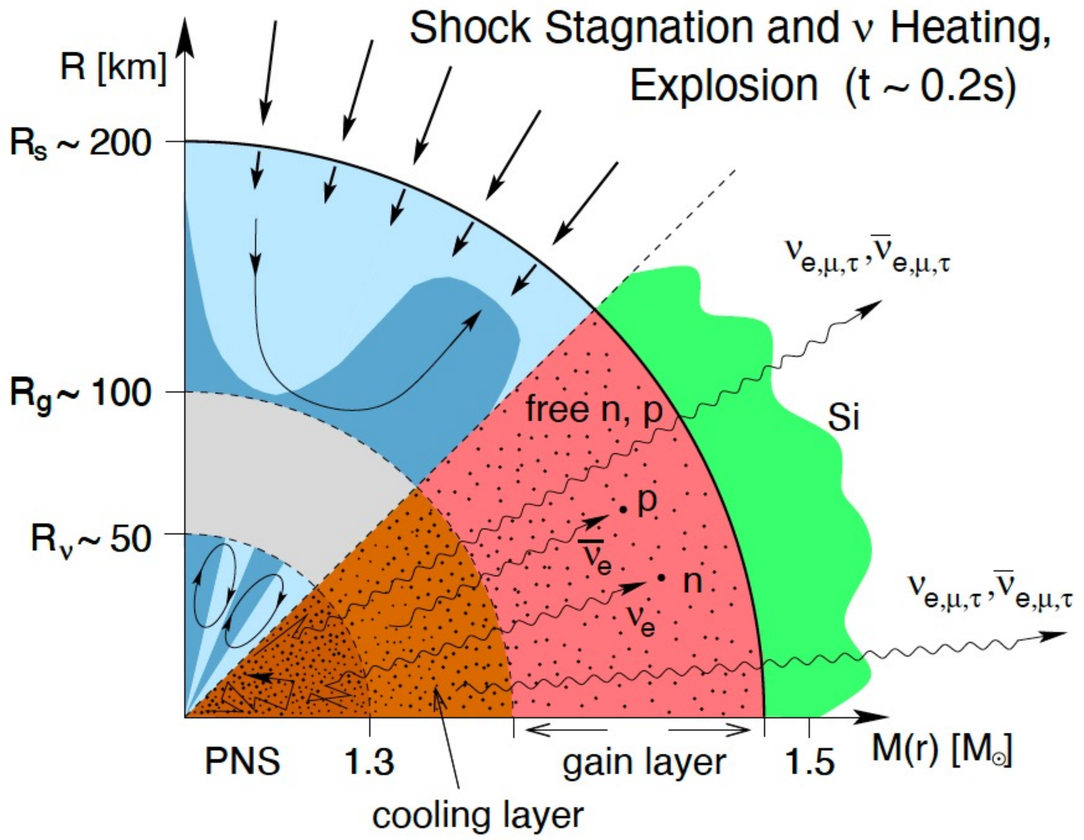
↓

Formation of the PNS

- Neutrinos deposit energy behind the shock front:
  - $\nu_e + n \rightarrow e^- + p$
  - $\bar{\nu}_e + p \rightarrow e^+ + n$

↓

ν-heating and "hot bubble"



Phases of collapse

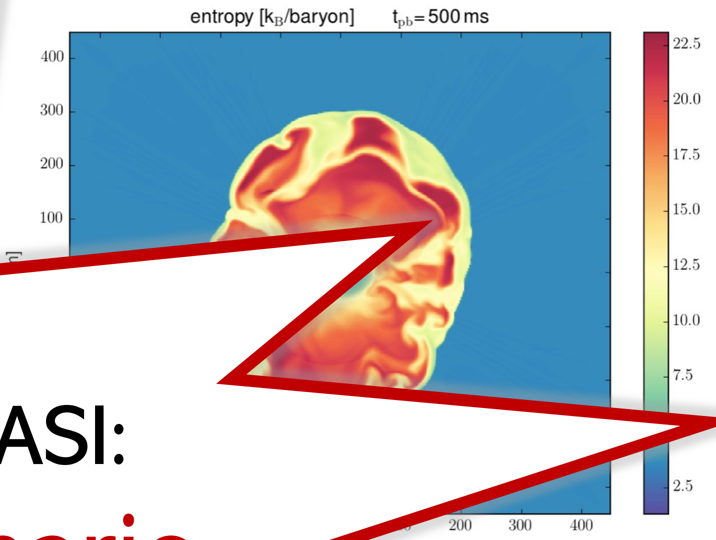
Neutrinos deposit energy in regions with low densities («Hot B bble»)

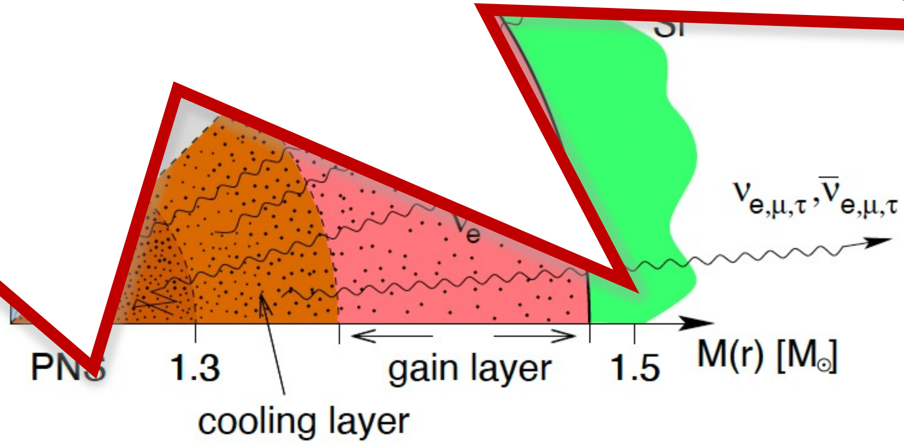
- At the upper e
  pressure, low ent
- At the lowe
  pressure, hi

Post-shock convection and S
They help the shock reviva

ν-heating + convection+ SASI:

Delayed Explosion Scenario



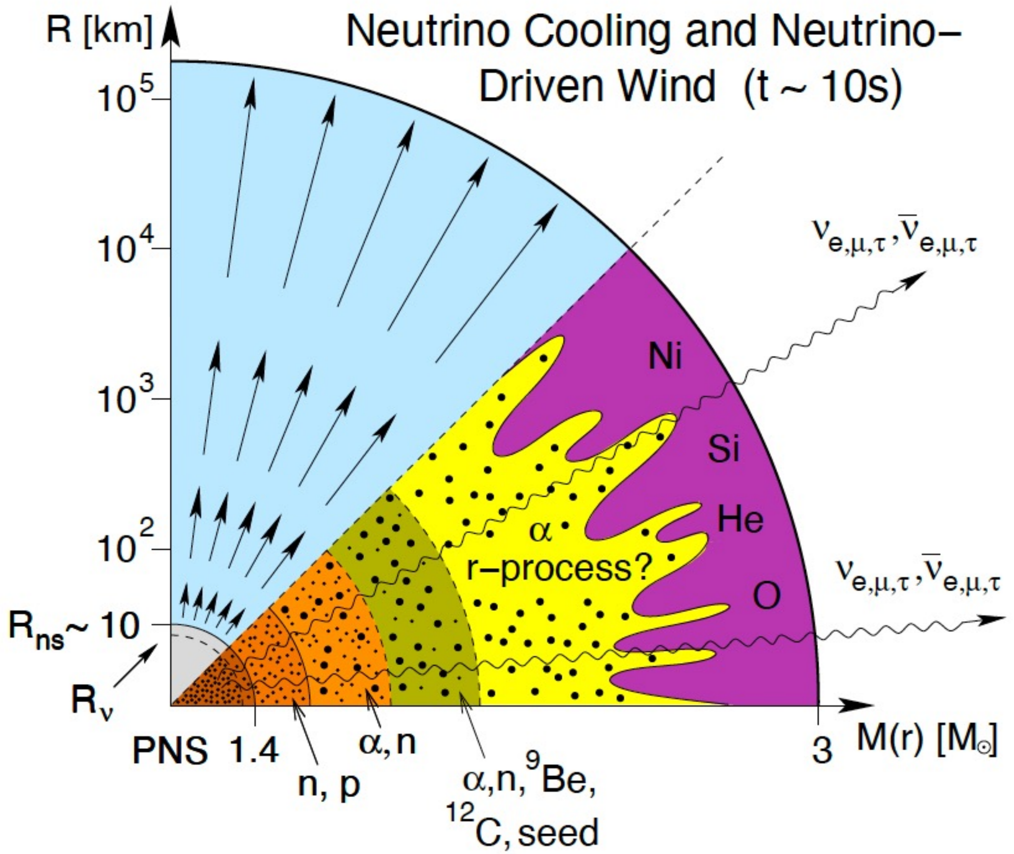


Phases of collapse

After the revival, the shock wave ejects all the SN mantle $E \sim 10^{51}$ erg.

- Formation of a young Neutron Star at the centre ($R \sim 10$ km, $\mathrm{M} \sim 1.5\ M_{\odot}$).

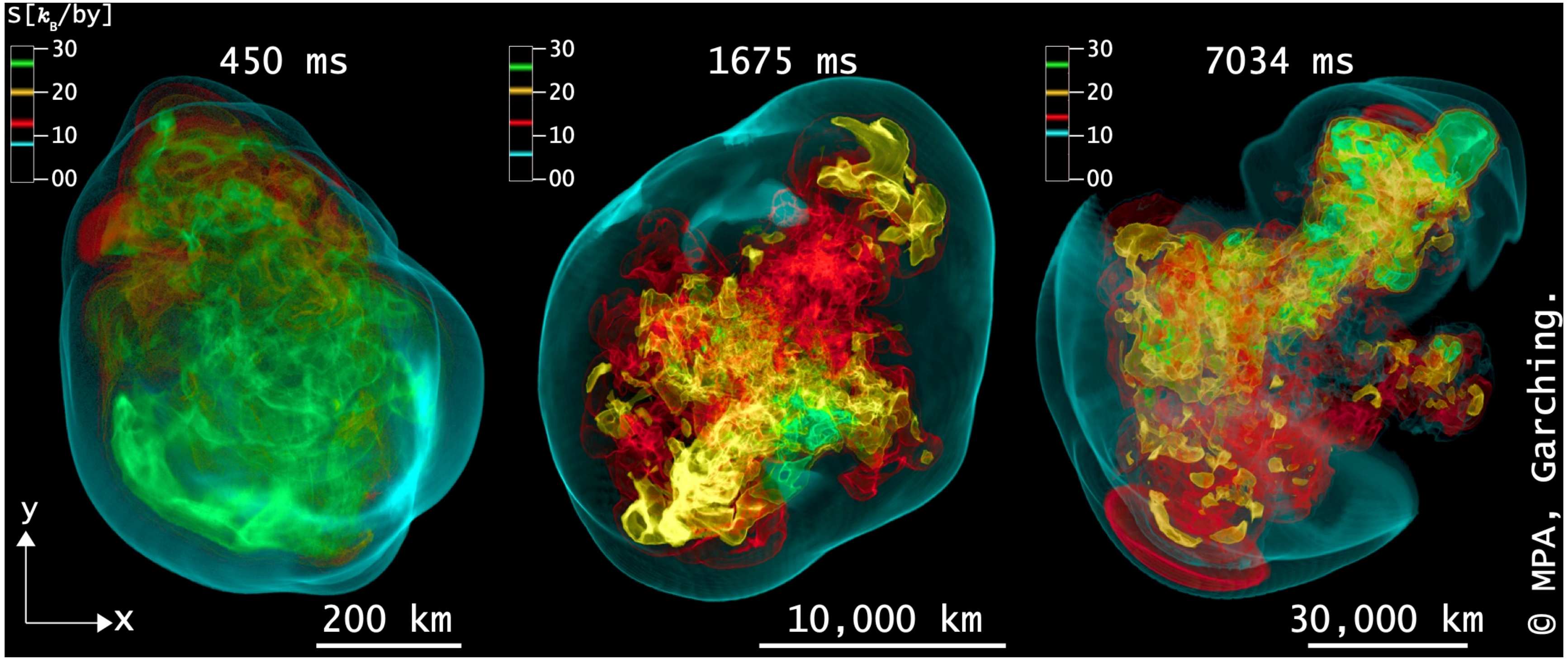
- Cooling via neutrino emission of all species ($E \sim 10^{53}$ erg , $t \sim 10$ s).



Supernova simulations

Most of our knowledge about SN explosions is based on complex 3D simulations.

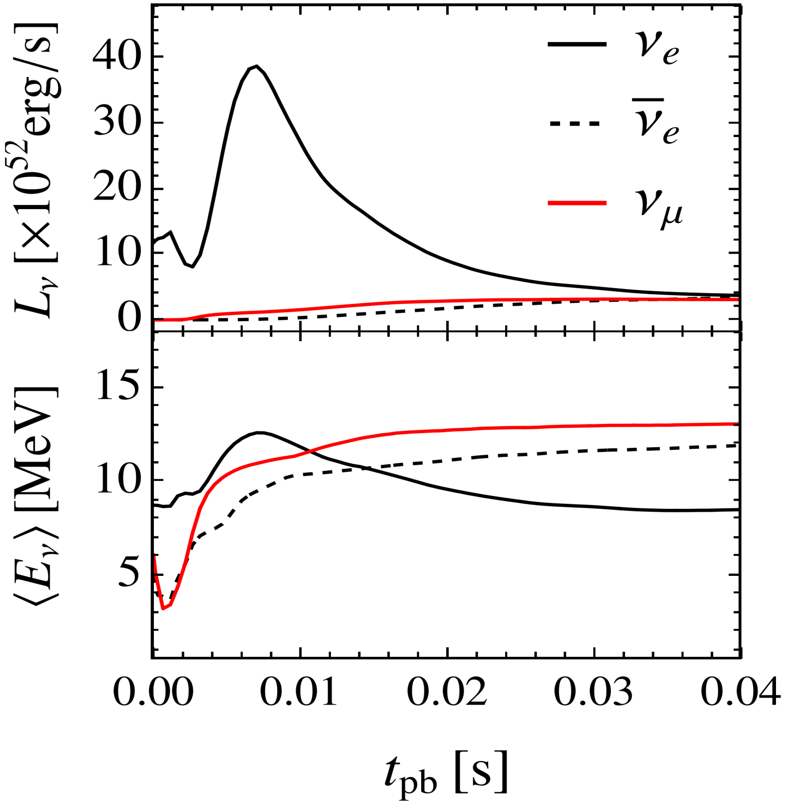
- Account for 3D neutrino transport equations
- Account for the effect of convection and SASI instabilities



Supernova neutrinos

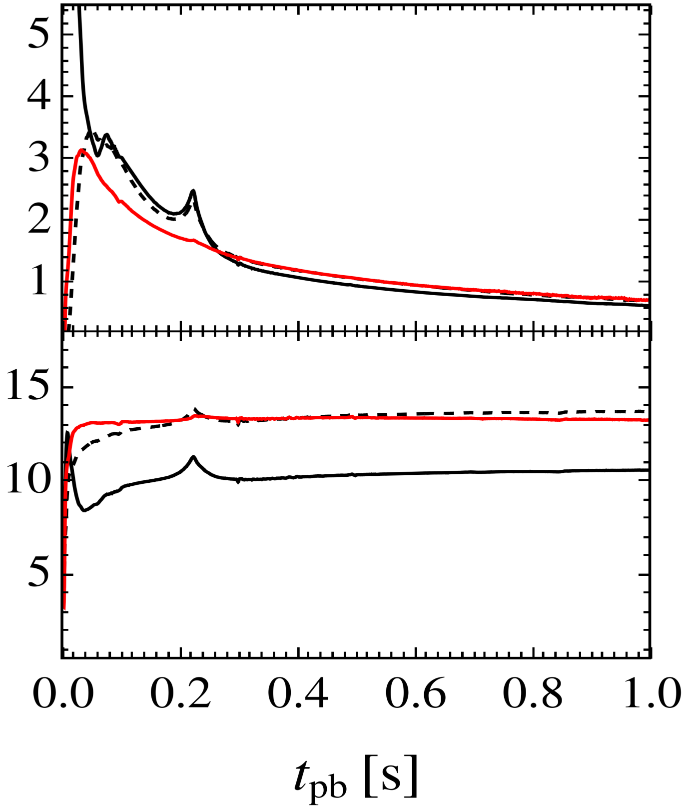
Neutronization burst

- Electron capture in the inner core



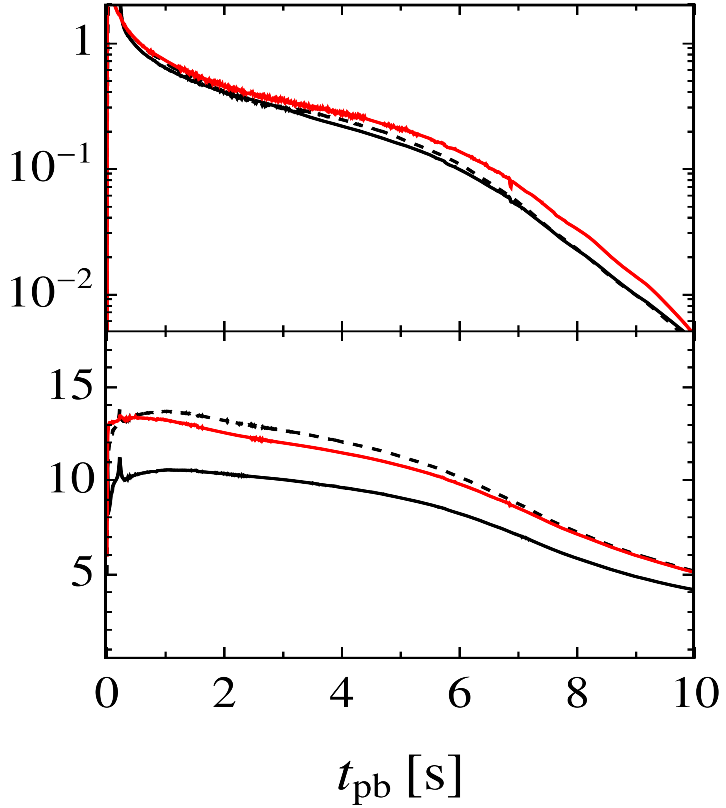
Accretion

- When shock stalls, ν powered by infalling matter



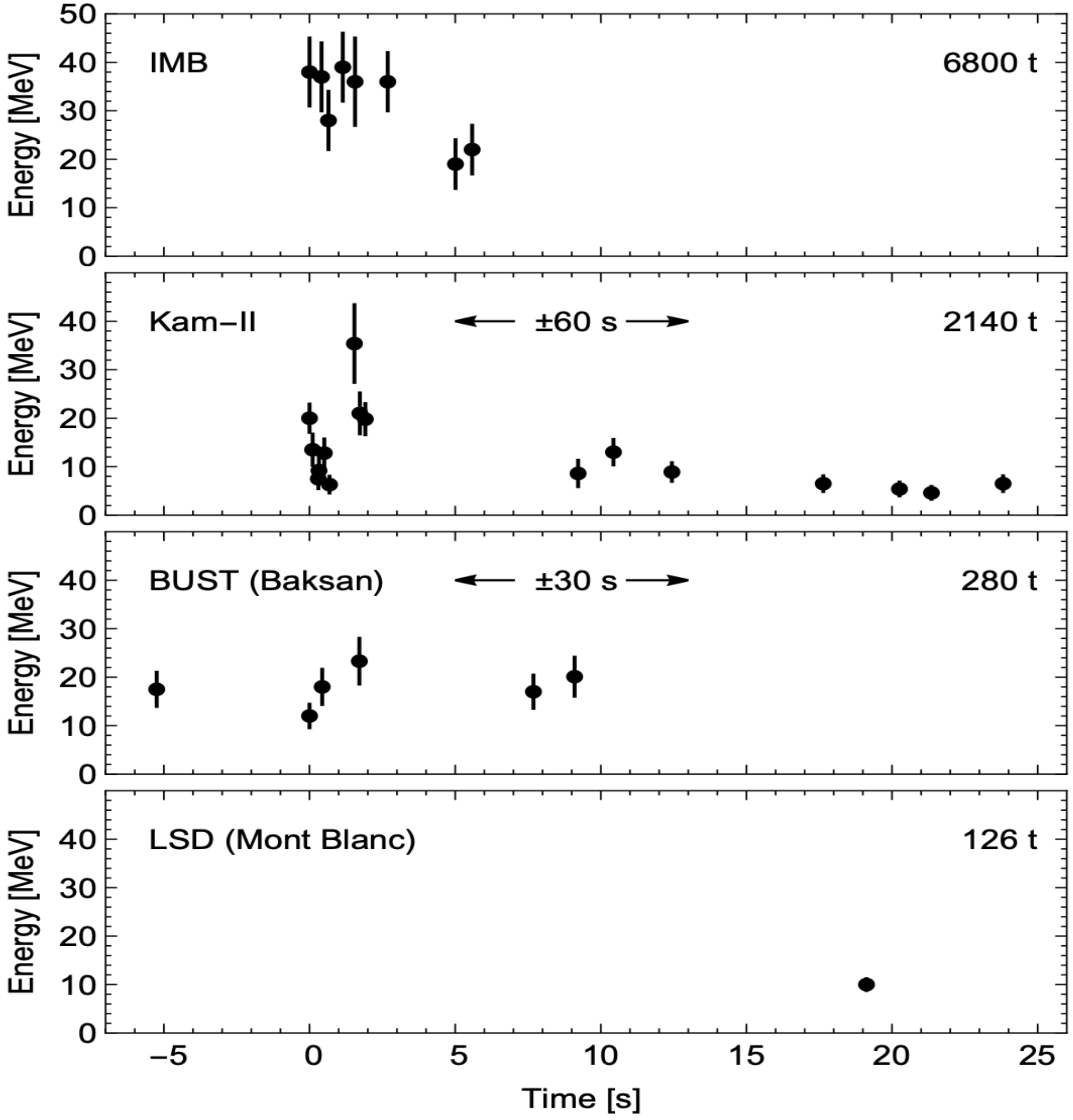
Cooling

- Cooling on ν diffusion time scale



https://wwwmpa.mpa-garching.mpg.de/ccsnarchive//

SN 1987A



SN 1987A was the first and only SN event allowing for the observation of the associated neutrino burst so far.

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

- Standard picture confirmed by SN 1987A observation.

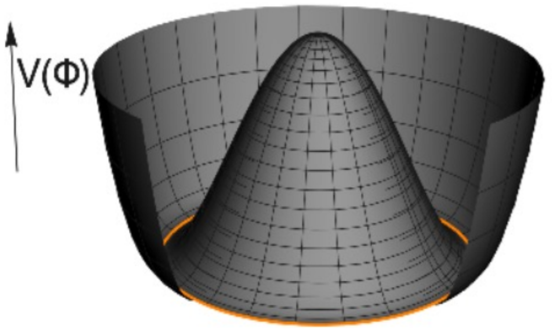
Recent re-analysis showed that late time events are in tension with SN simulations.
[Fiorillo et al., Phys. Rev. D 108 (2023)]

ALP production in SNe

The QCD axion

The *QCD axion* is a pseudoscalar particle postulated to solve the *Strong-CP problem* in QCD:

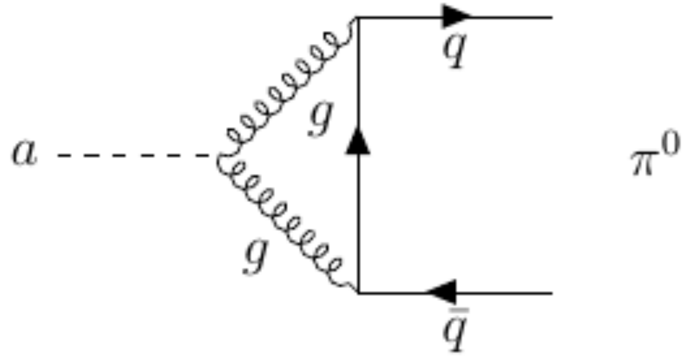
$$\mathcal{L}_{\mathrm{CP}} = \theta \, \frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G^{a\mu\nu}}$$



→ PQ mechanism: global symmetry $U(1)_{\mathrm{PQ}}$ spontaneously broken at f_a *[Peccei & Quinn, PRL 38 (1977)]*

The QCD axion acquires a small mass from its coupling to QCD.

$$m_a = 5.70(6)(4)\,\mu\mathrm{eV}\left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

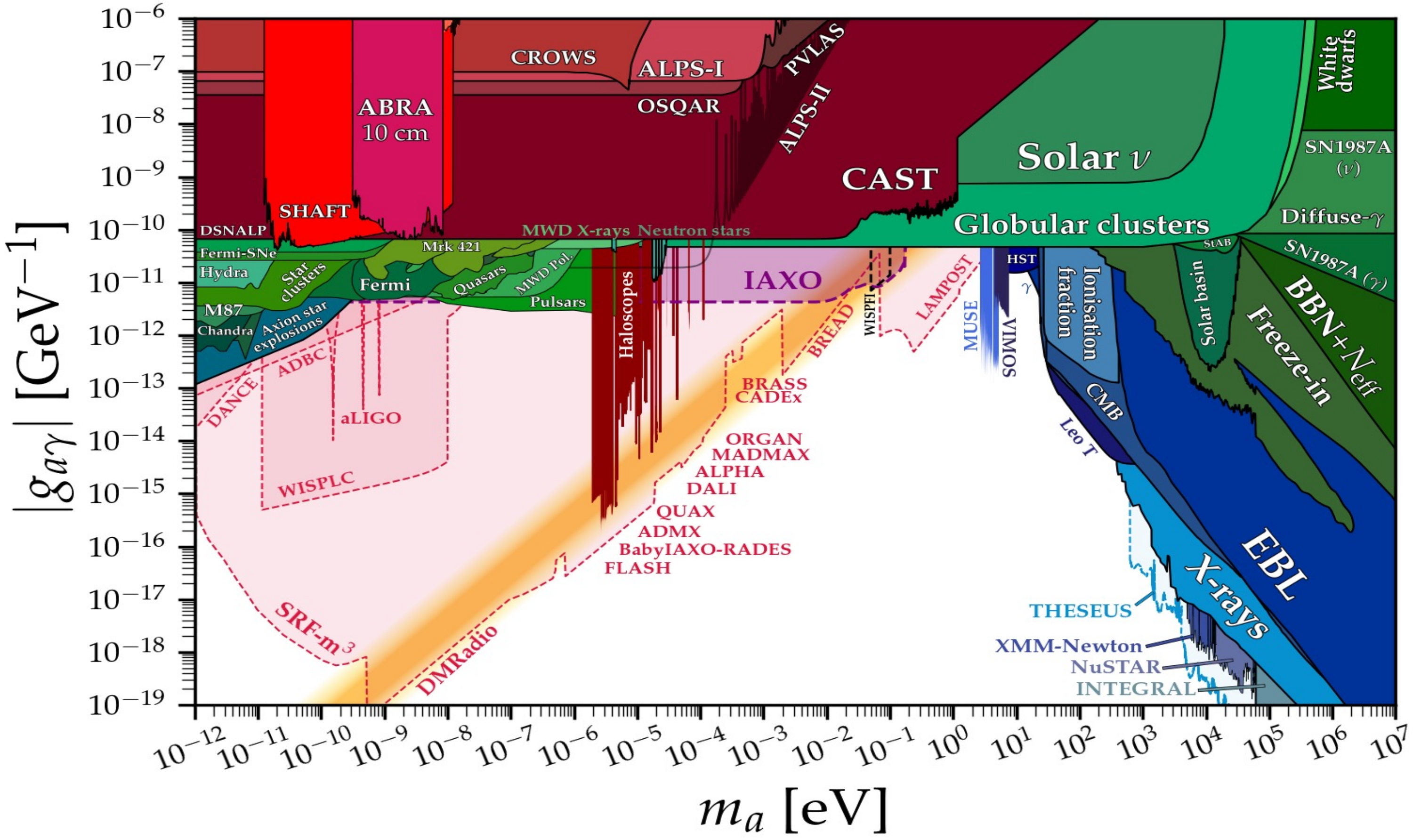


Axion-like particles

Many pseudoscalar particles behaving like the QCD axion emerge in UV extensions of Standard Model

- ➢ Vast landscape of axion-like particles (ALPs)
- ➢ No relation between ALP mass and couplings.

cajohare.github.io/AxionLimits/



ALP nuclear interactions

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

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

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

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

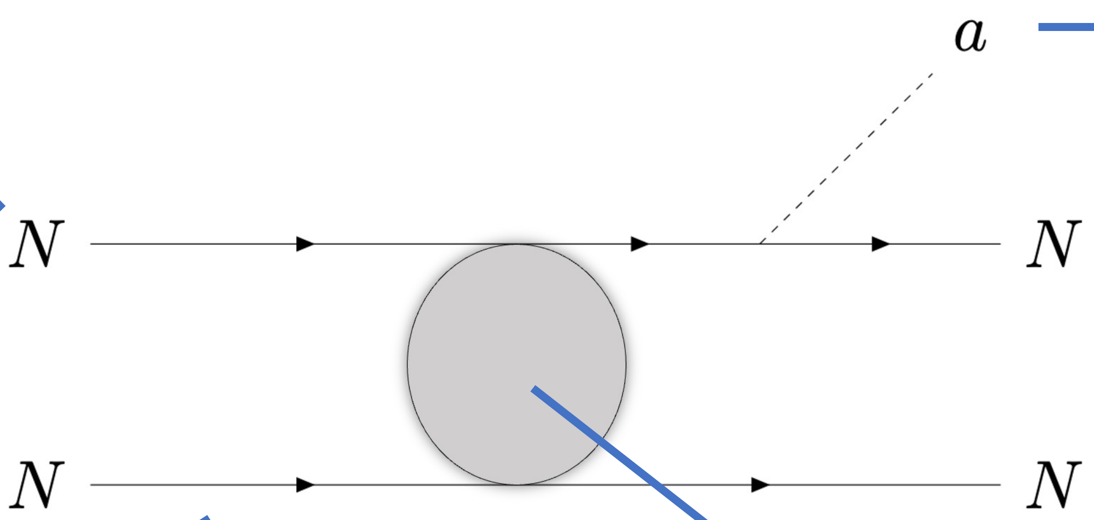
ALP production in SNe

- 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)]

Effective nucleon masses

$$m_N \to m_N^*$$



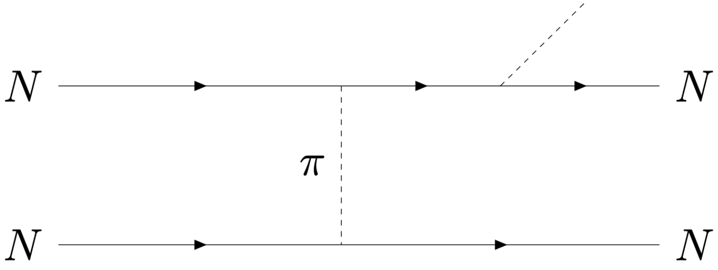
$$m_a \neq 0$$

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

Nucleons multiple scattering

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

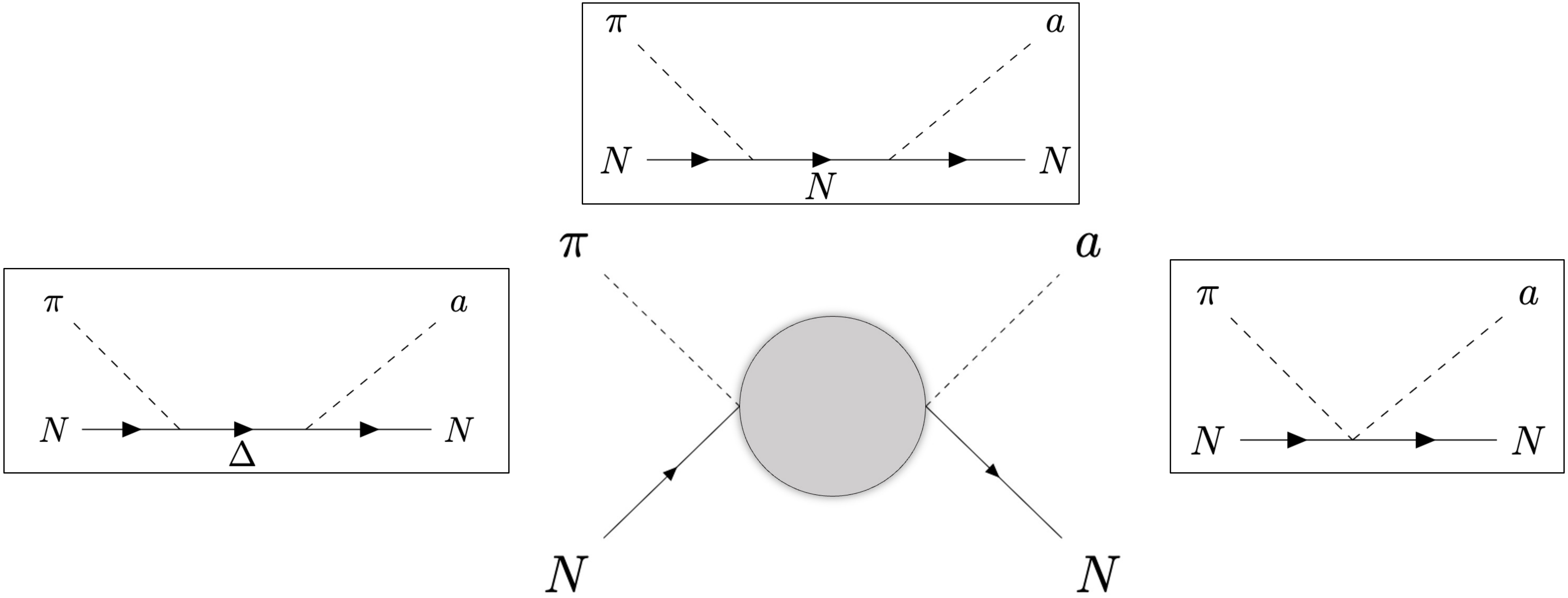
Beyond OPE approximation



ALP 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)]*



ALP emission spectra

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

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

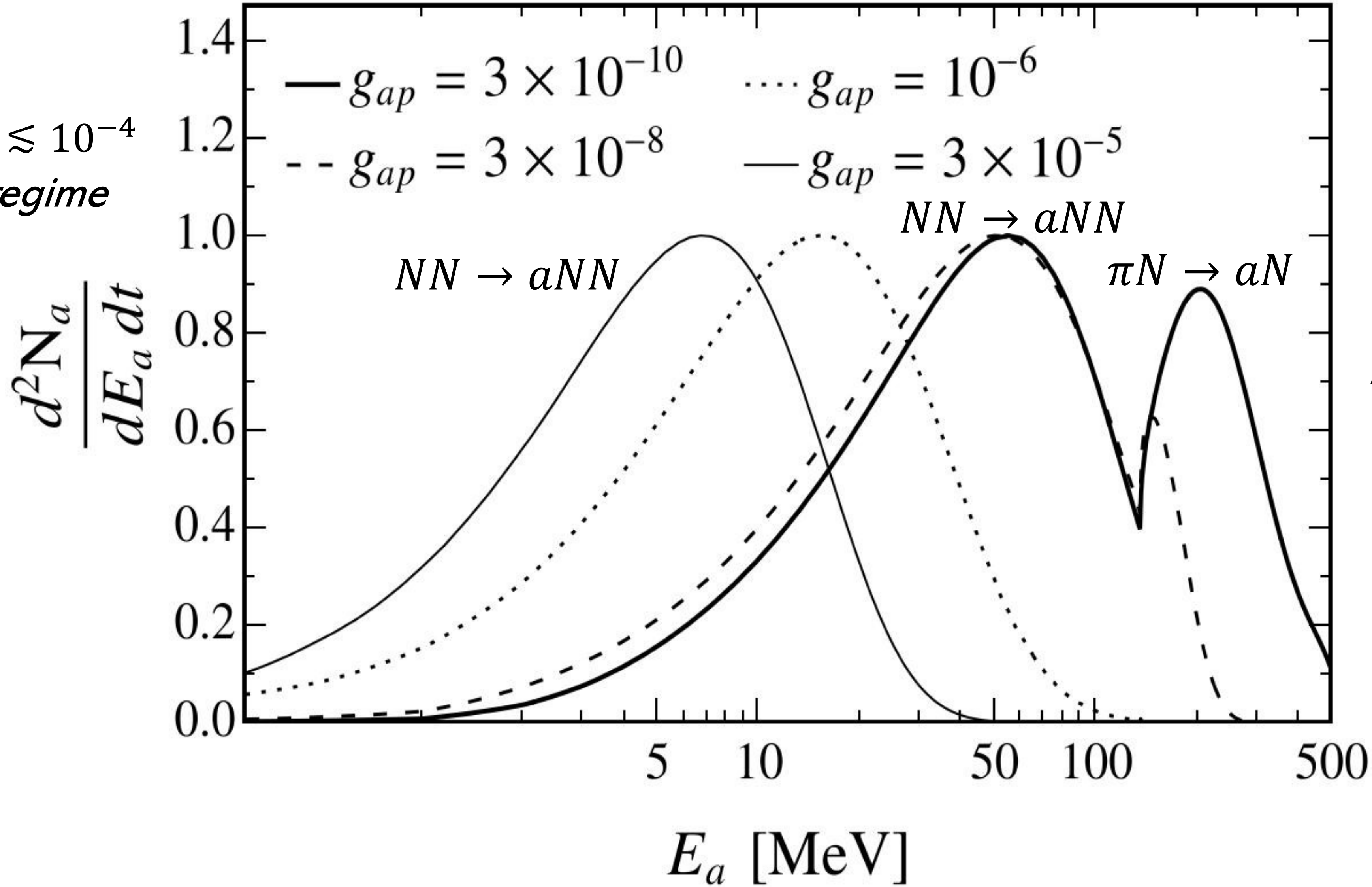
- In case of strongly coupled ALPs, they could enter the *trapping regime*
  [Caputo & al., Phys. Rev. D 105 (2022)]

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

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

ALP emission spectra

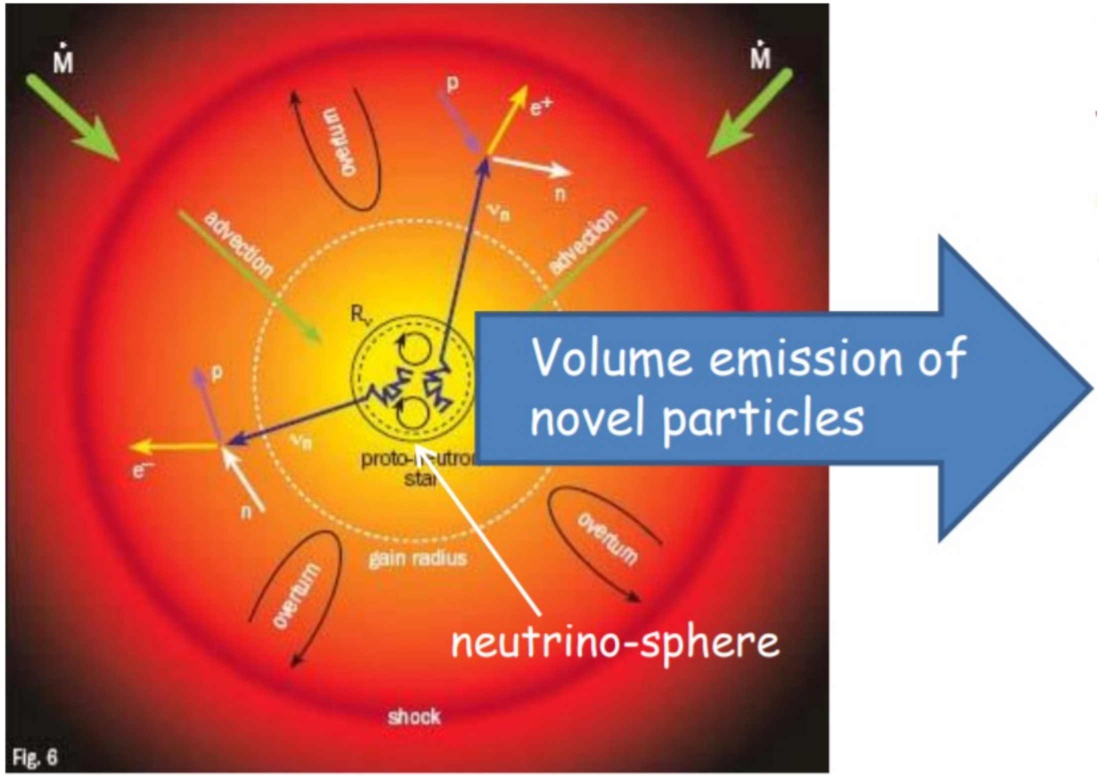
$10^{-7} \lesssim g_{ap} \lesssim 10^{-4}$
trapping regime



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

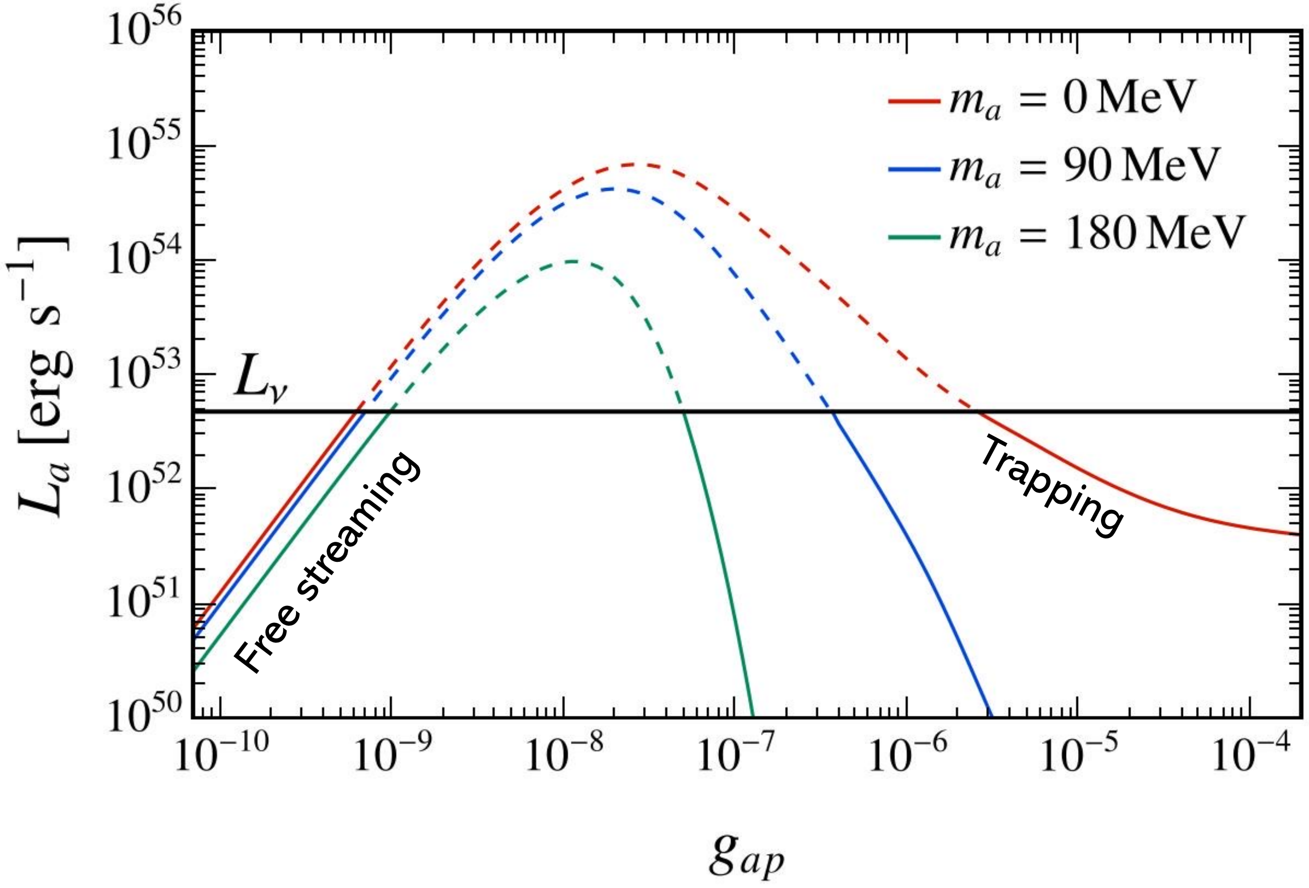
The energy-loss argument

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



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

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

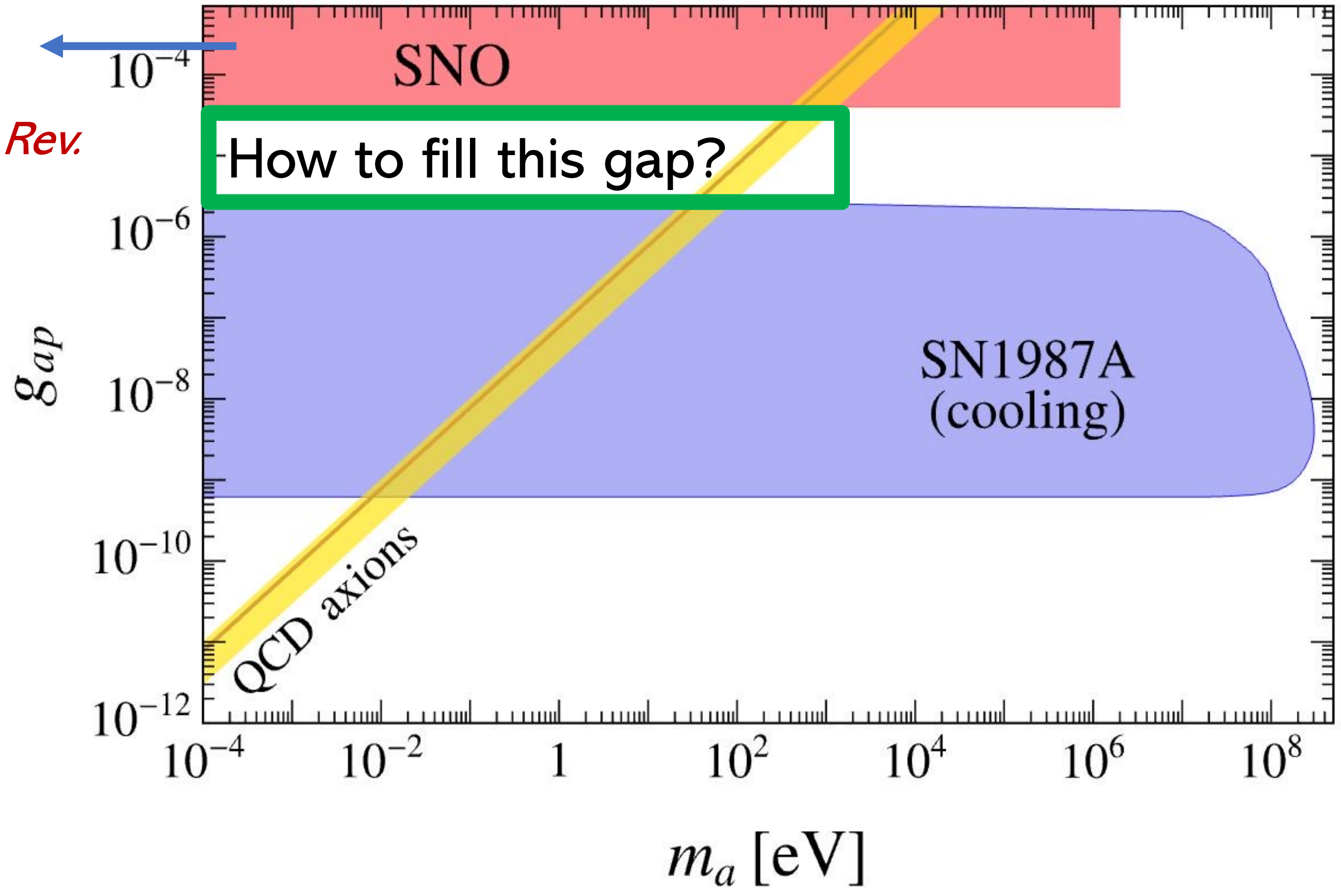


The energy-loss argument

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)]



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

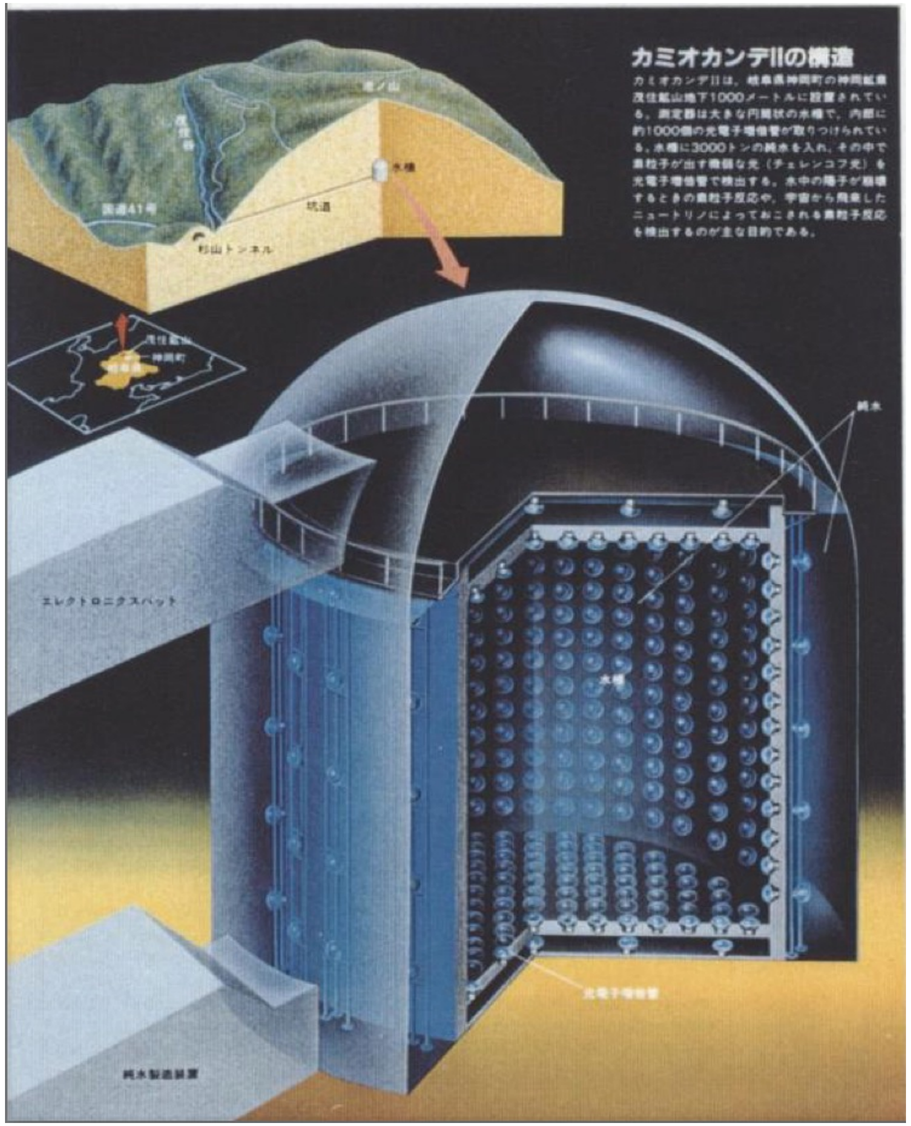
Axion signal in Kamiokande-II

- 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)]* .

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

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

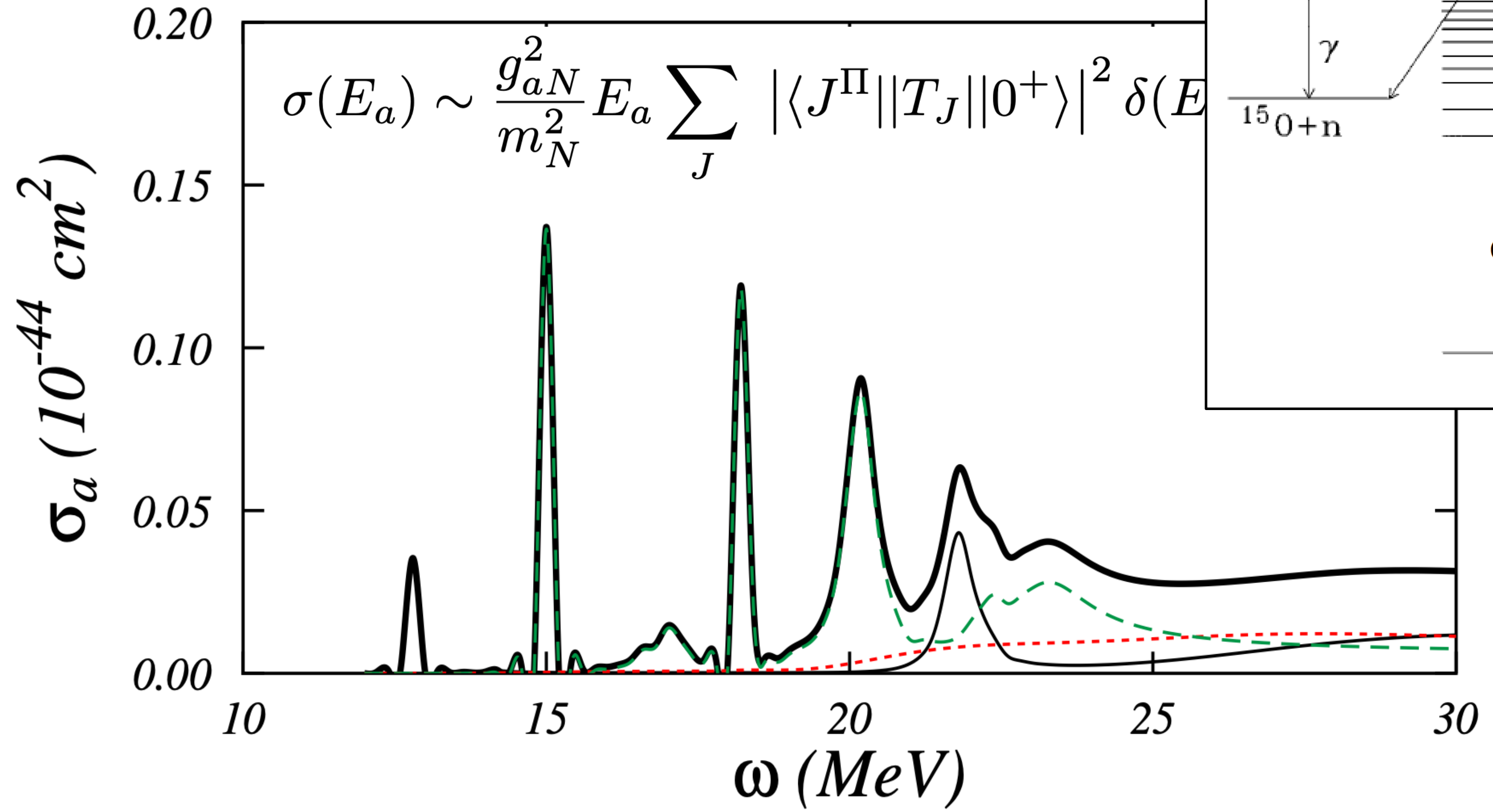


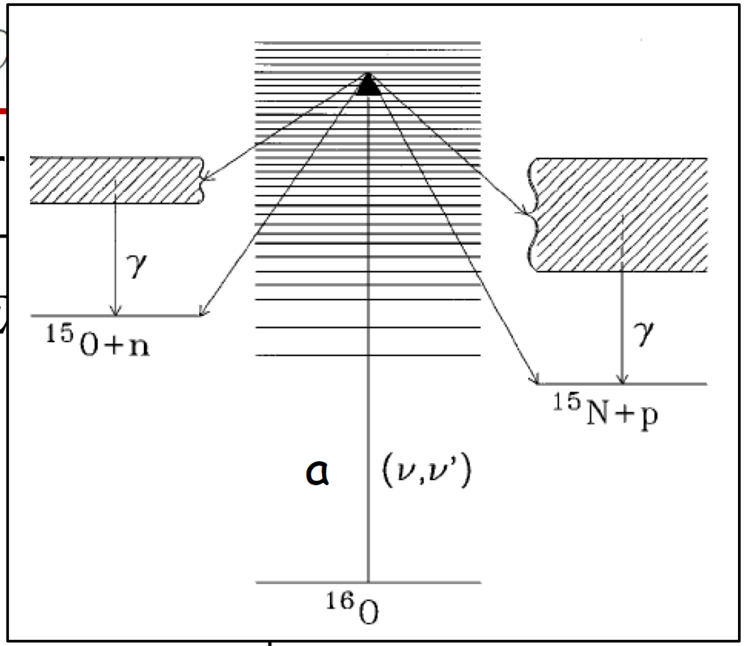
Axion-oxygen cross section

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

$$\mathcal{H}_{aN} = -\frac{g_{aN}}{2m_N}\partial_k a\, \underbrace{\bar{N}\gamma^k\gamma^5(C_0 + C}_{}$$

Hadronic cur



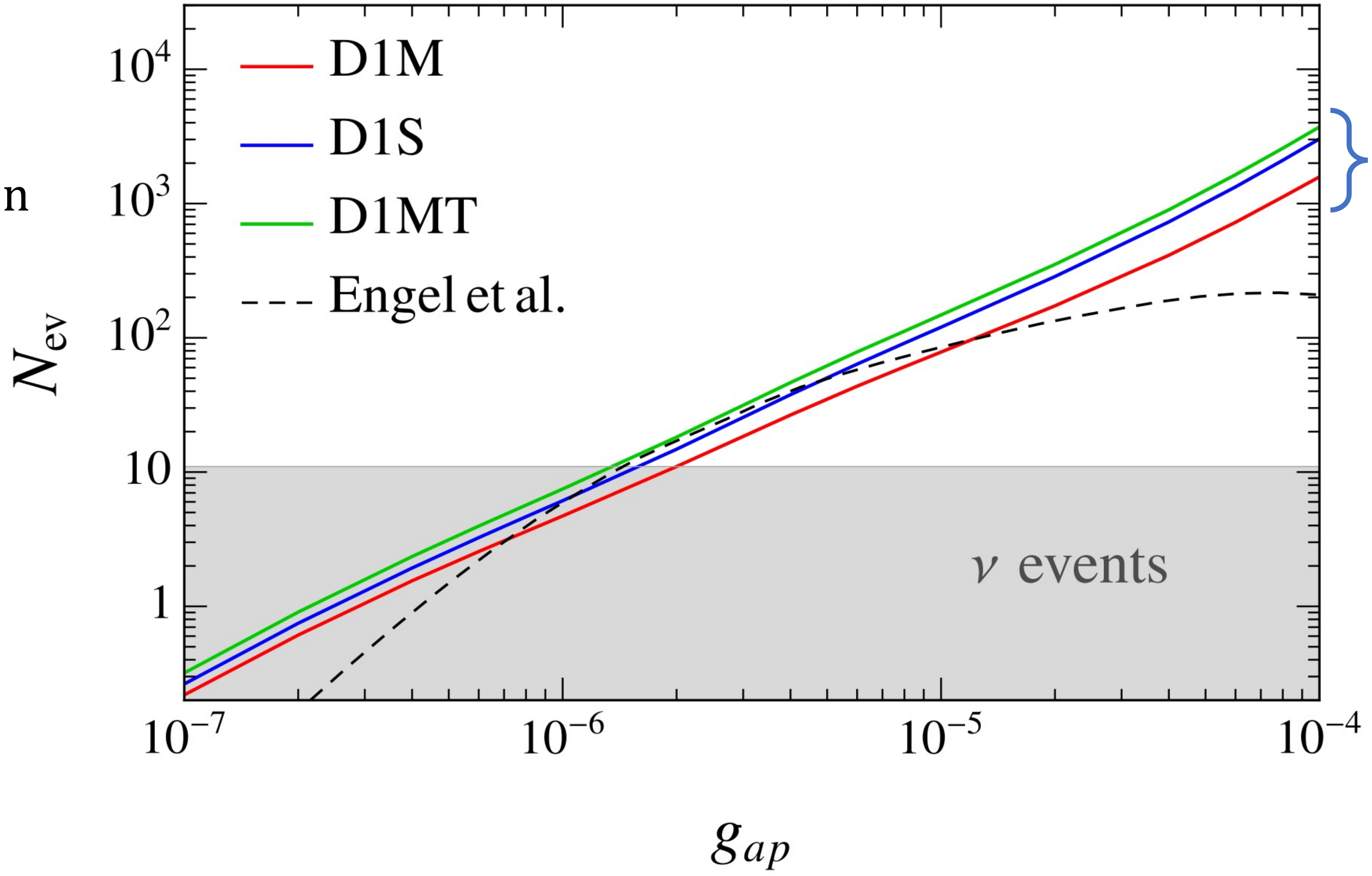


[P. Carenza, G. Co', M. Giannotti, AL, G. Lucente, A. Mirizzi, T. Rauscher, Phys. Rev. C 109 (2024) 1]

Events number in Kamiokande-II

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

$M_{KII} \sim 2.4$ kton

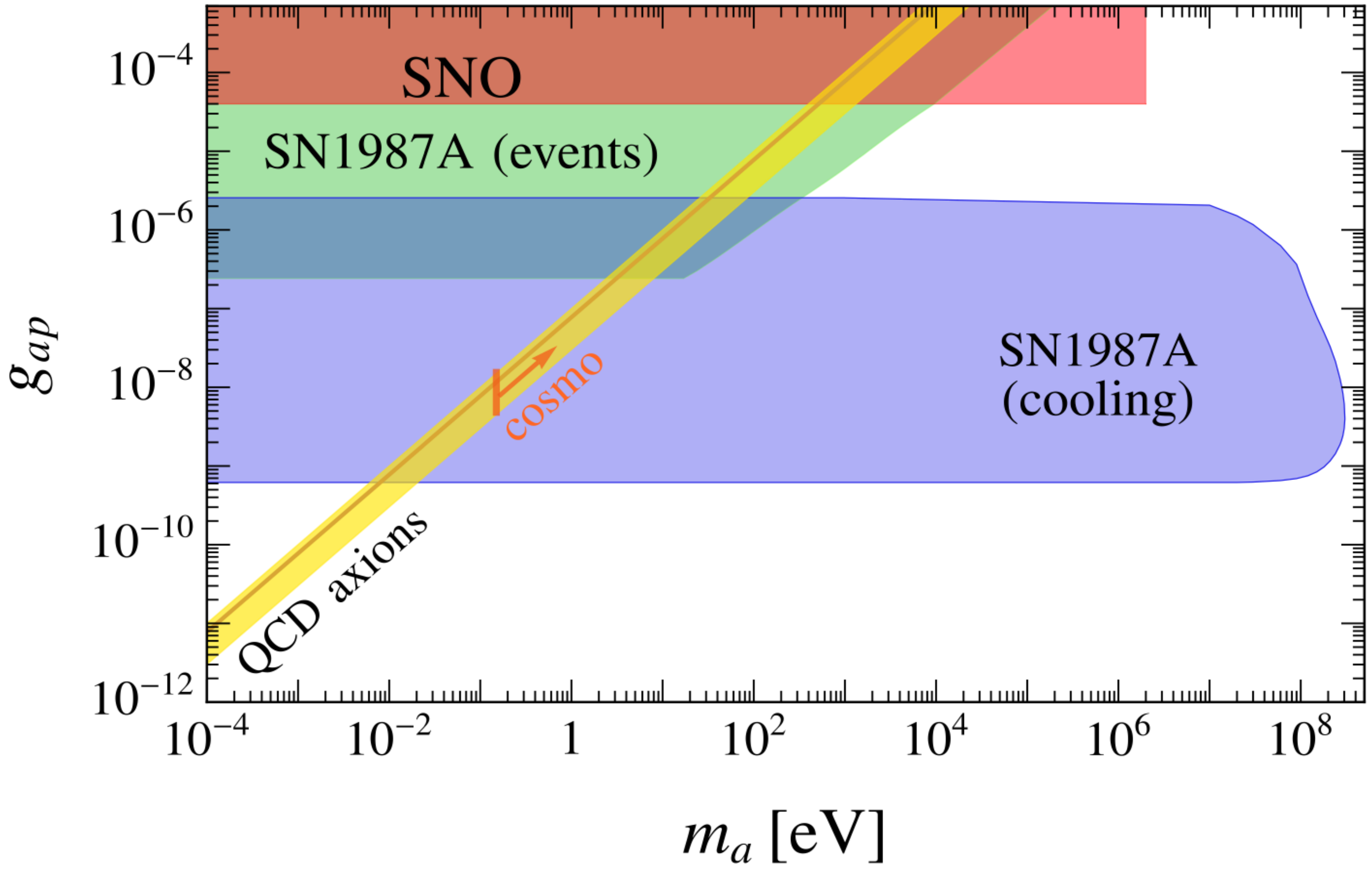


Uncertainties $\mathcal{O}(60\ \%)$ over the nuclear model

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].



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

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

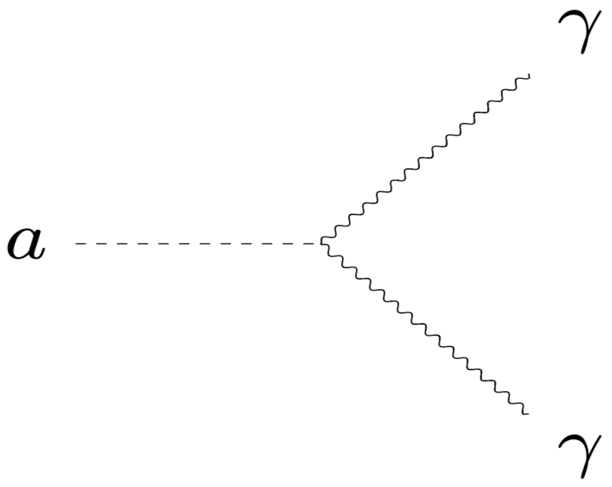
Observable signatures from decays

$[m_a \sim \mathcal{O}(10) MeV]$

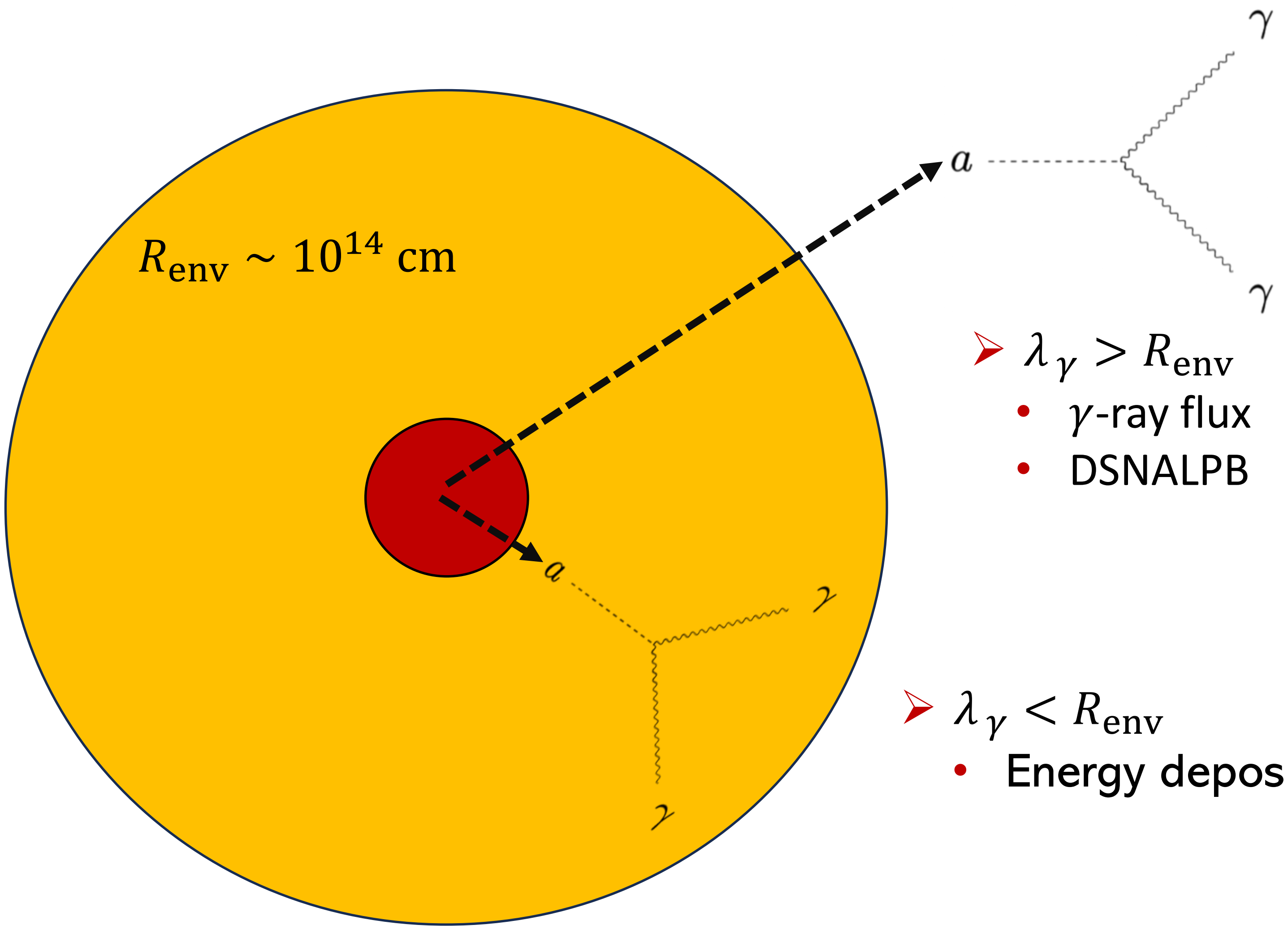
ALP decays

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

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



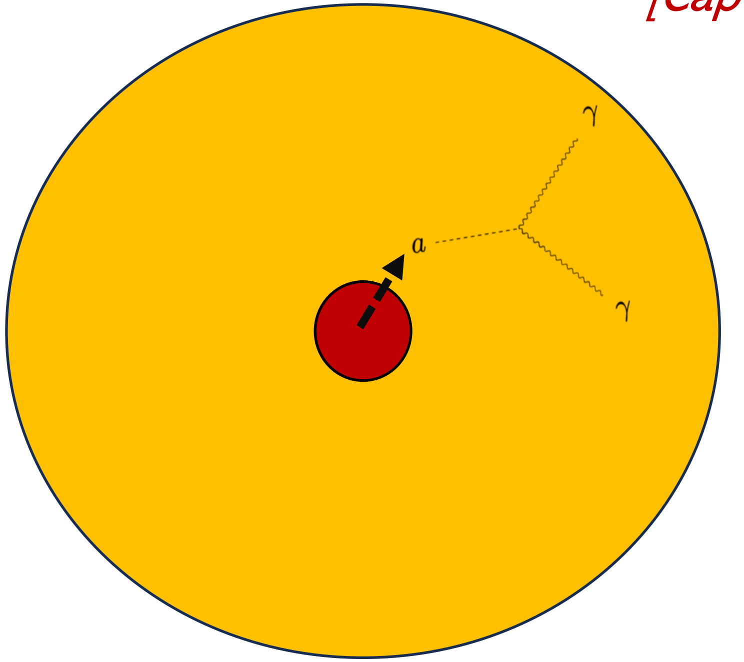
$$\Gamma_{a\gamma\gamma} = g_{a\gamma}^2 \frac{m_a^3}{64\pi}$$



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

Energy deposition

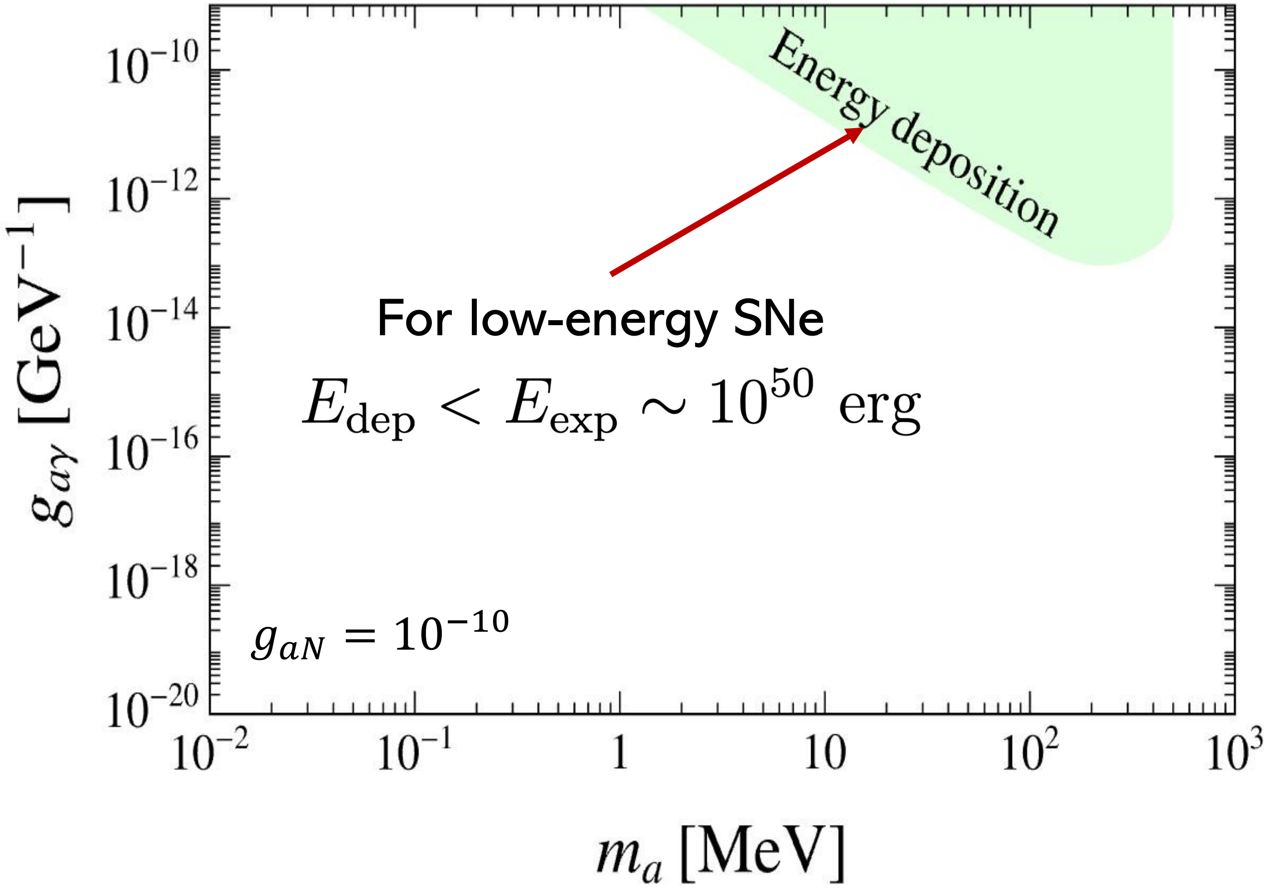
[Caputo et al., Phys. Rev. Lett. 128 (2022)]



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

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

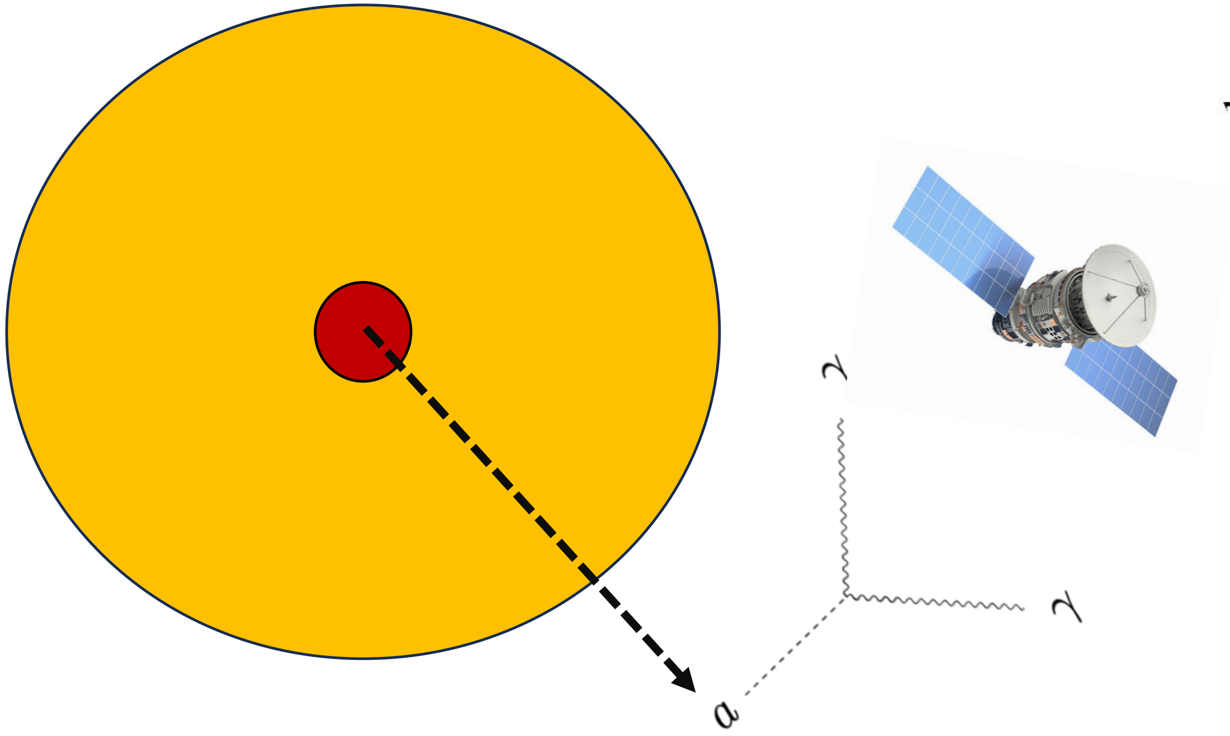
AL & al., Phys. Rev. D 107 (2023)



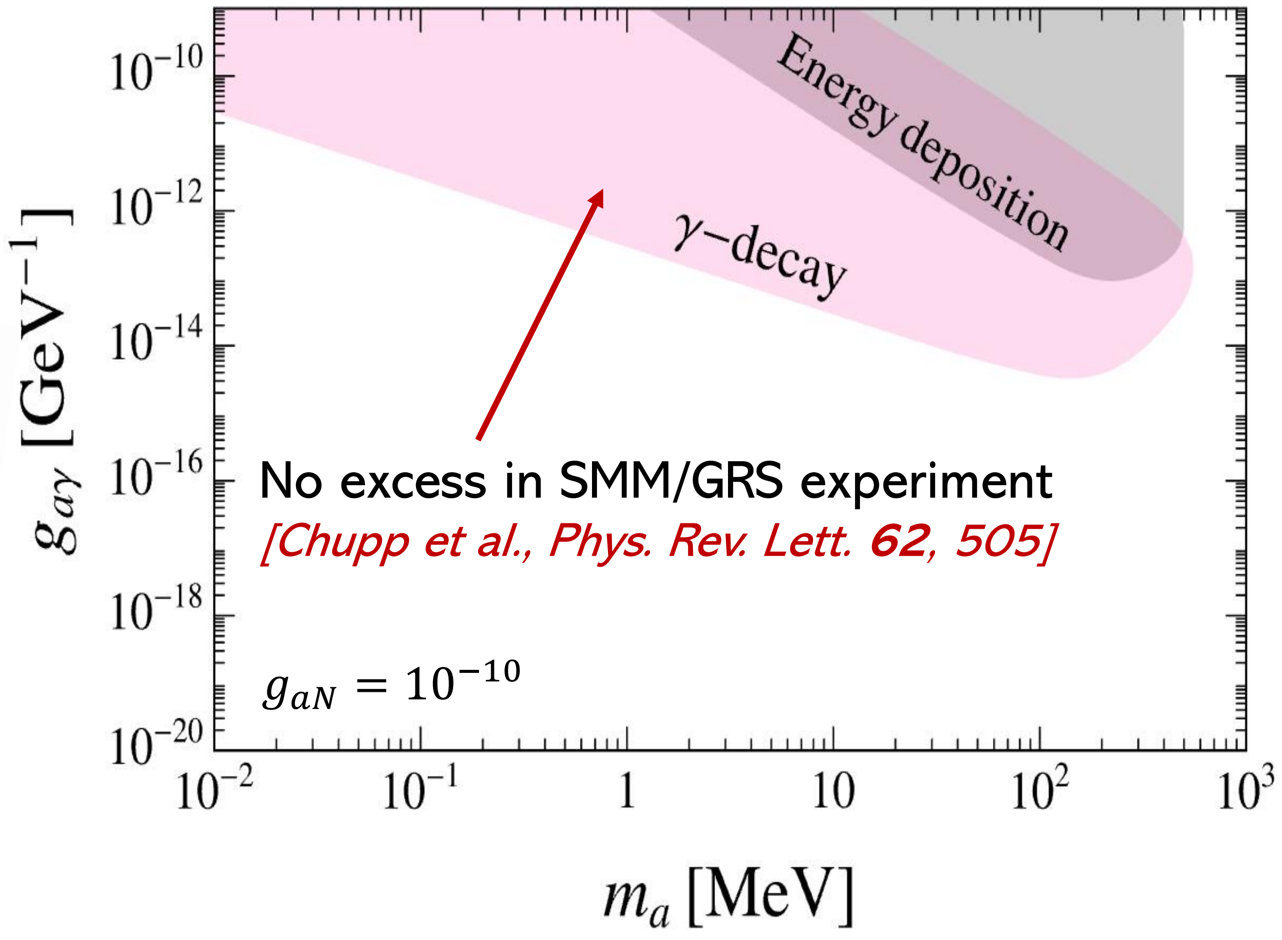
γ-ray bursts from SNe

[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 an additional photon flux



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

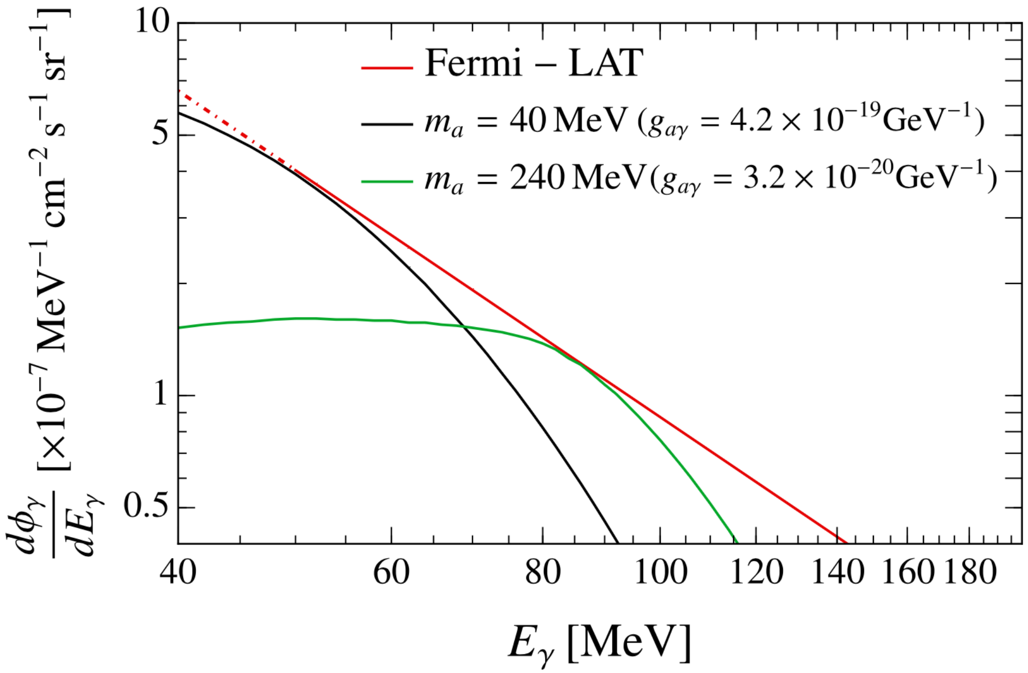


DSNALPB

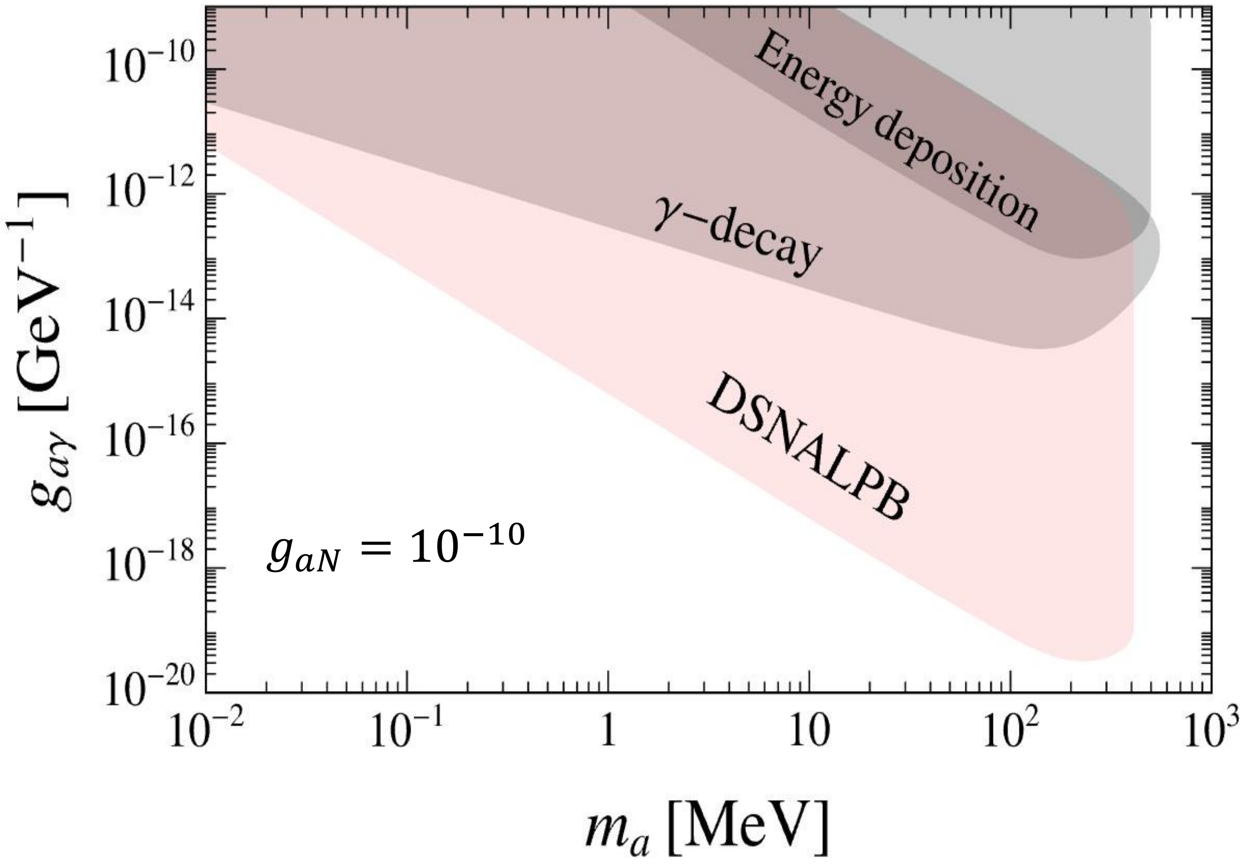
[Beacom et al., Ann. Rev. Nucl. Part. Sci. 60 (2010)]
[Calore et al., Phys. Rev. D 102 (2020)]

ALPs emitted during all the past SN explosion could have given rise to a diffuse ALP background

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



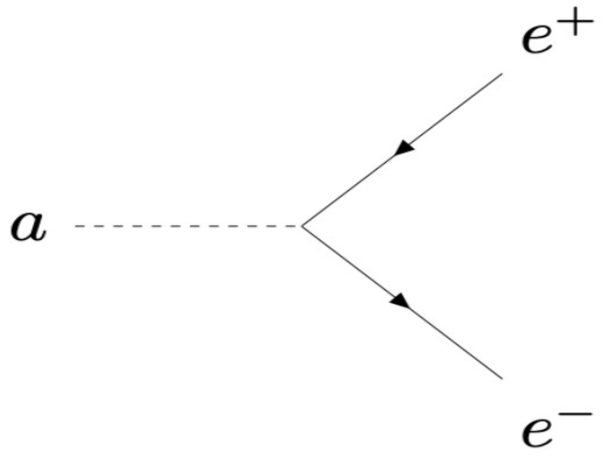
AL & al., Phys. Rev. D 107 (2023)



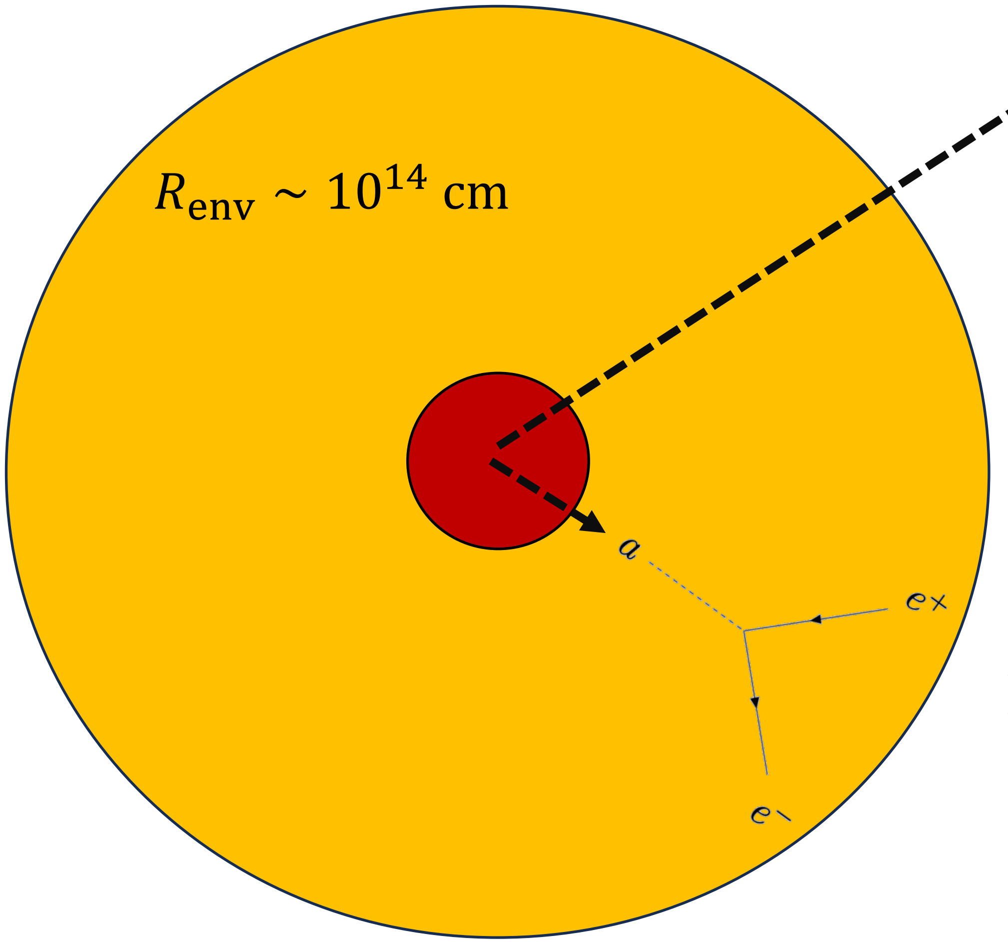
ALP decays

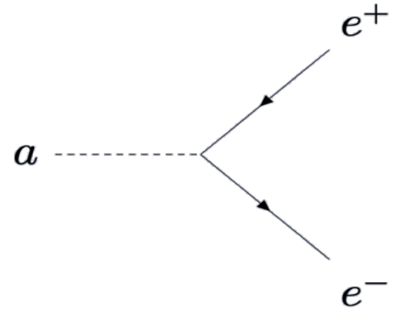
After being produced in the core, massive ALPs could decay into lepton pairs.

$$\mathcal{L}_{ae} = \frac{g_{ae}}{2m_e}(\bar{e}\gamma_\mu\gamma_5 e)\partial^\mu a$$



$$\lambda_e = \frac{8\pi}{g_{ae}^2 m_a}\sqrt{\frac{E_a^2 - m_a^2}{m_a^2 - 4m_e^2}}$$



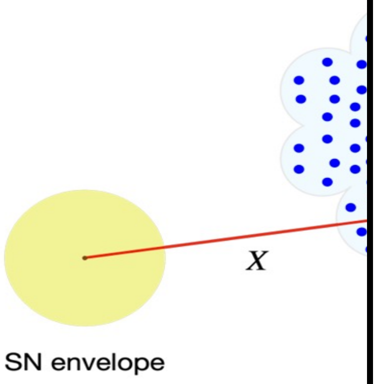


- $\lambda_e > R_{\mathrm{env}}$
  - 511 keV line
  - In-flight annihilation
- $\lambda_e < R_{\mathrm{env}}$
  - Energy deposition

ALP decays

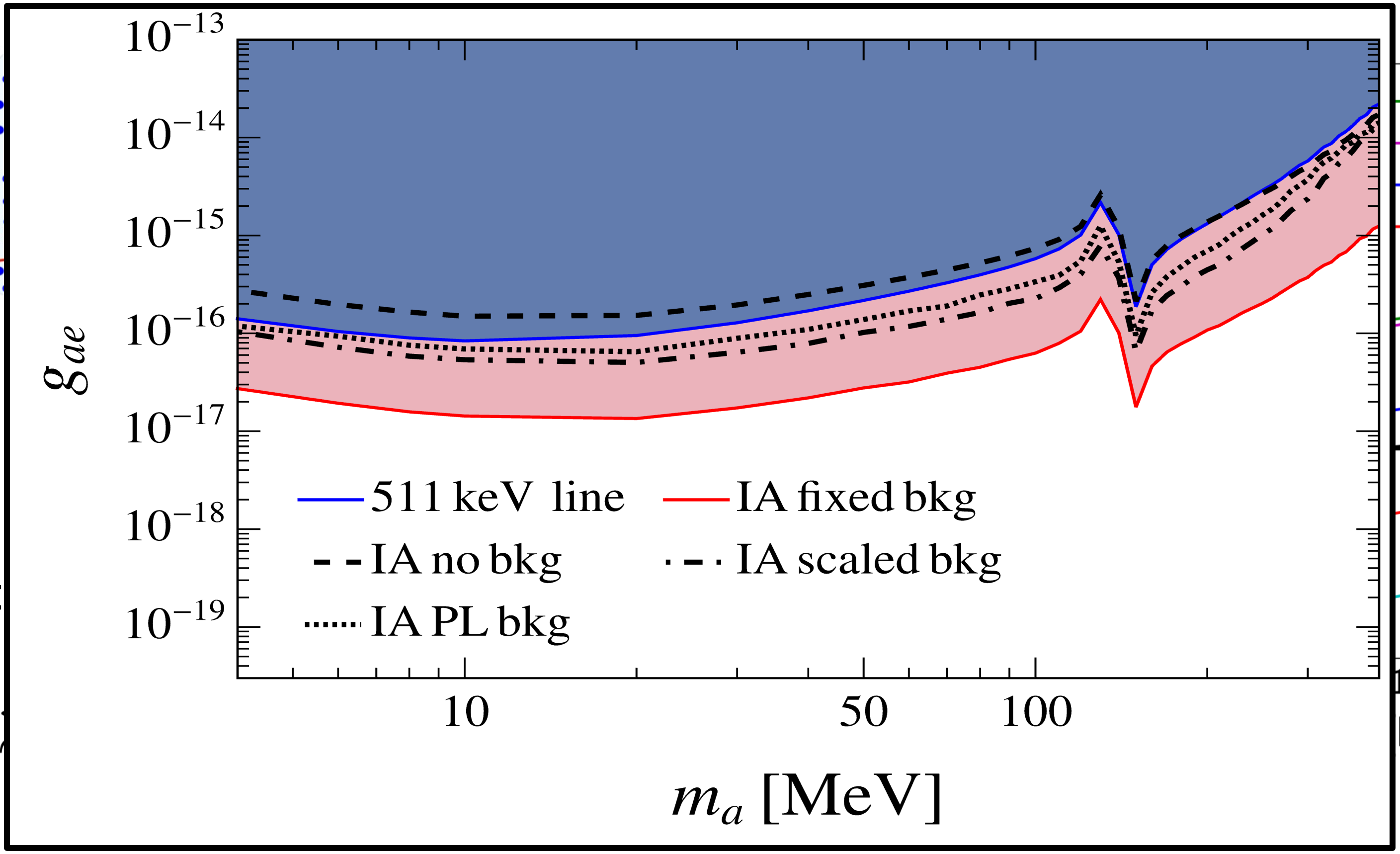
ALP decaying in electrons may inject positrons in the intergalactic medium.

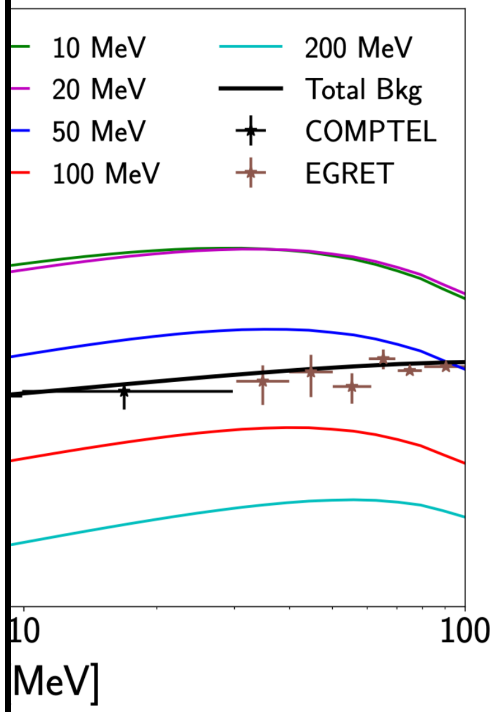
- Positrons annihilating at rest give contributions to the 511 keV signal
- Positrons annihilating in-flight may give rise to a diffuse bkg of soft gamma-rays



From obervations
spectrometer on t

$N_{\rm pos}$

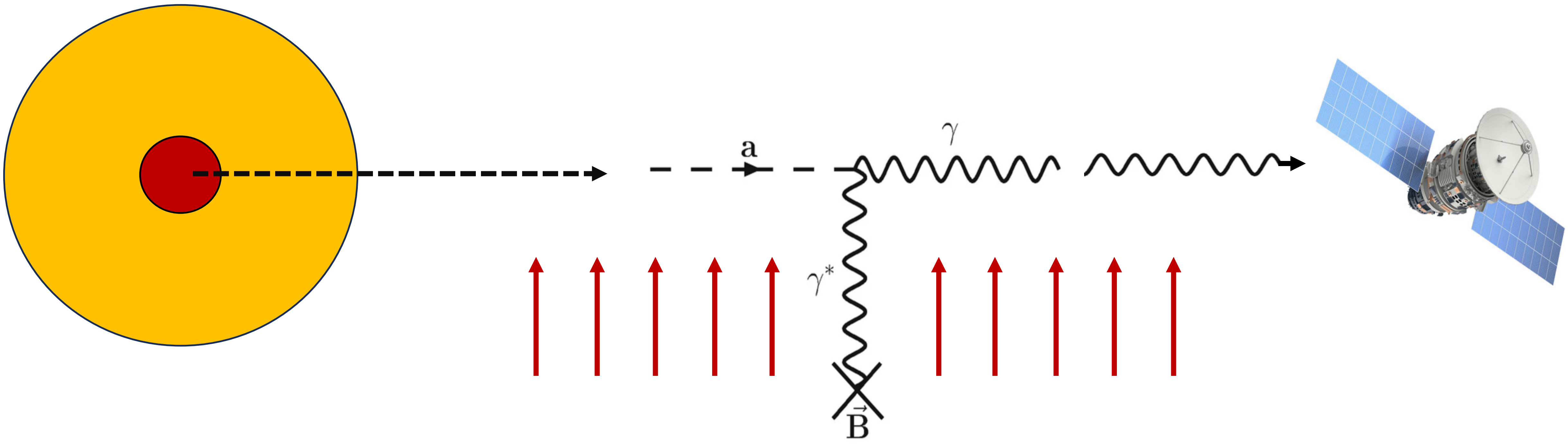




Observable signatures from conversions $[m_a < \mathcal{O}(1)\ neV]$

ALP conversions in B fields

Ultra-light ALPs can convert into photons in Galactic Magnetic fields



ALP conversions in B fields

Ultra-light ALPs can convert into photons in Galactic Magnetic fields

$$P_{a\gamma} = (\Delta_{a\gamma} L)^2 \frac{\sin^2(\Delta_{\rm osc} L/2)}{(\Delta_{\rm osc} L/2)^2}$$

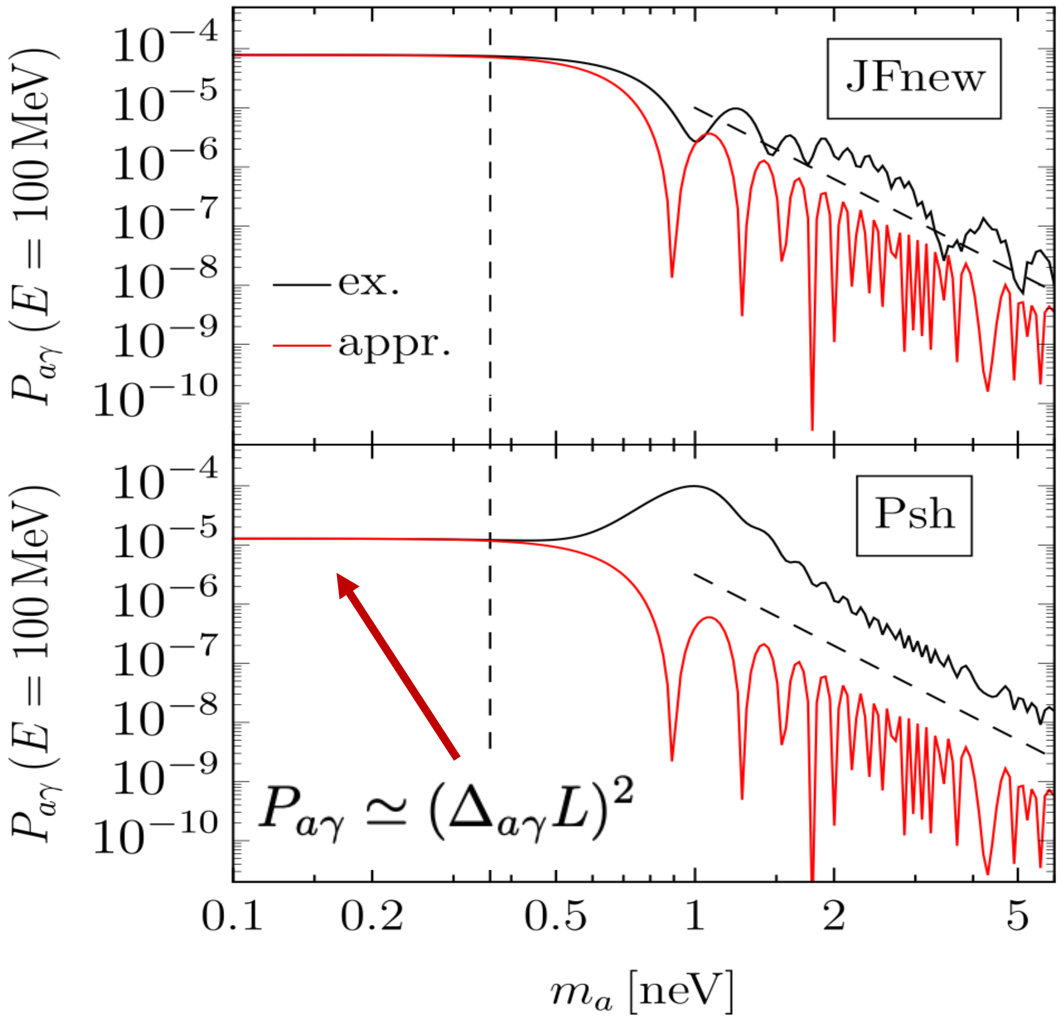
$$\Delta_{\rm osc} \equiv \left[(\Delta_a - \Delta_{\rm pl})^2 + 4\Delta_{a\gamma}^2\right]^{1/2}$$

$$\Delta_{a\gamma} \simeq 1.5 \times 10^{-3} \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)\left(\frac{B_T}{10^{-6}\ \mathrm{G}}\right) \mathrm{kpc}^{-1},$$

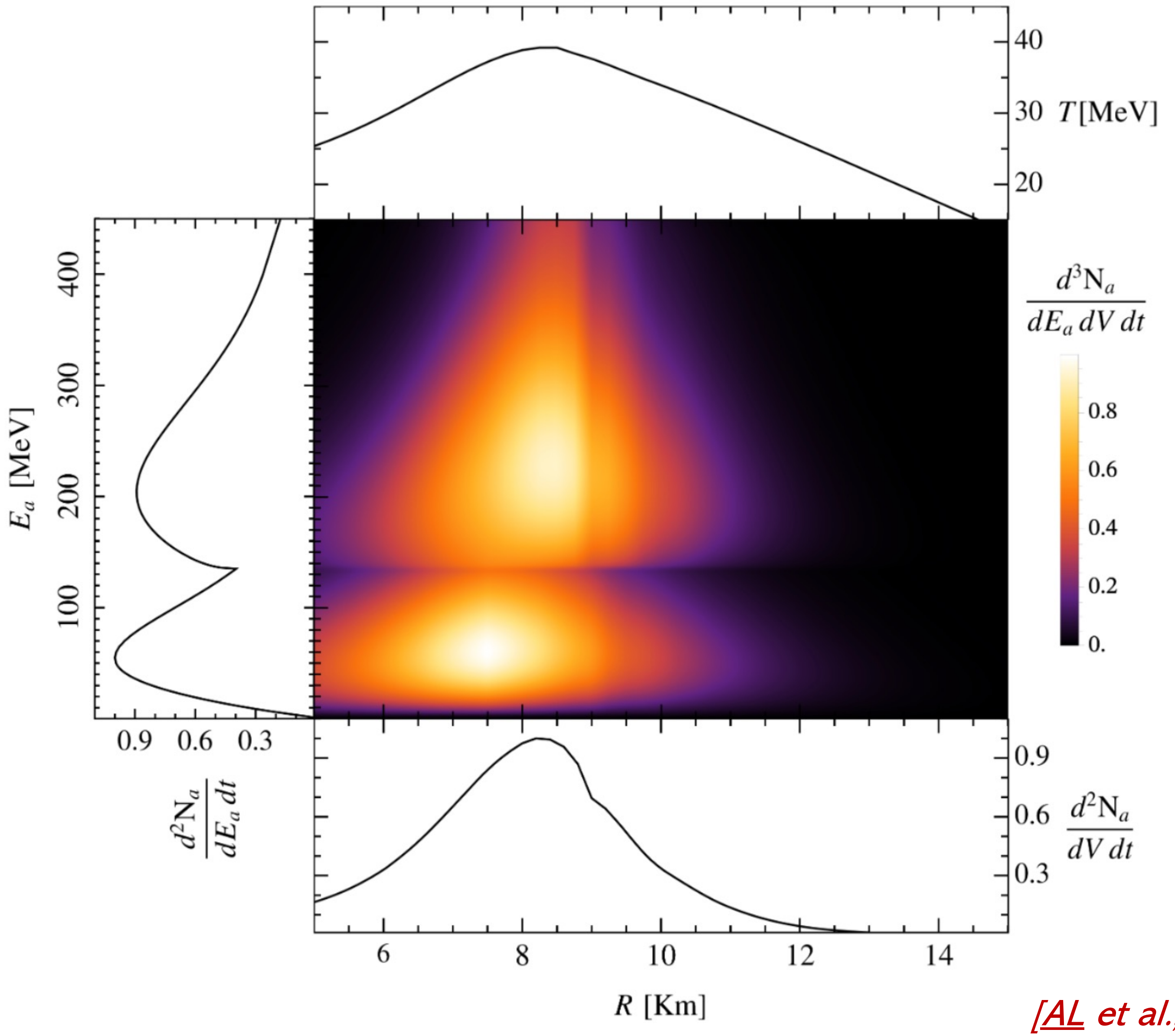
$$\Delta_a \simeq -7.8 \times 10^{-5} \left(\frac{m_a}{10^{-11}\ \mathrm{eV}}\right)^2 \left(\frac{E}{100\ \mathrm{MeV}}\right)^{-1} \mathrm{kpc}^{-1},$$

$$\Delta_{\rm pl} \simeq -7.8 \times 10^{-7} \left(\frac{\omega_{\rm pl}}{10^{-12}\ \mathrm{eV}}\right)^2 \left(\frac{E}{100\ \mathrm{MeV}}\right)^{-1} \mathrm{kpc}^{-1}.$$

[Calore et al., Phys. Rev. D 109 (2024)]



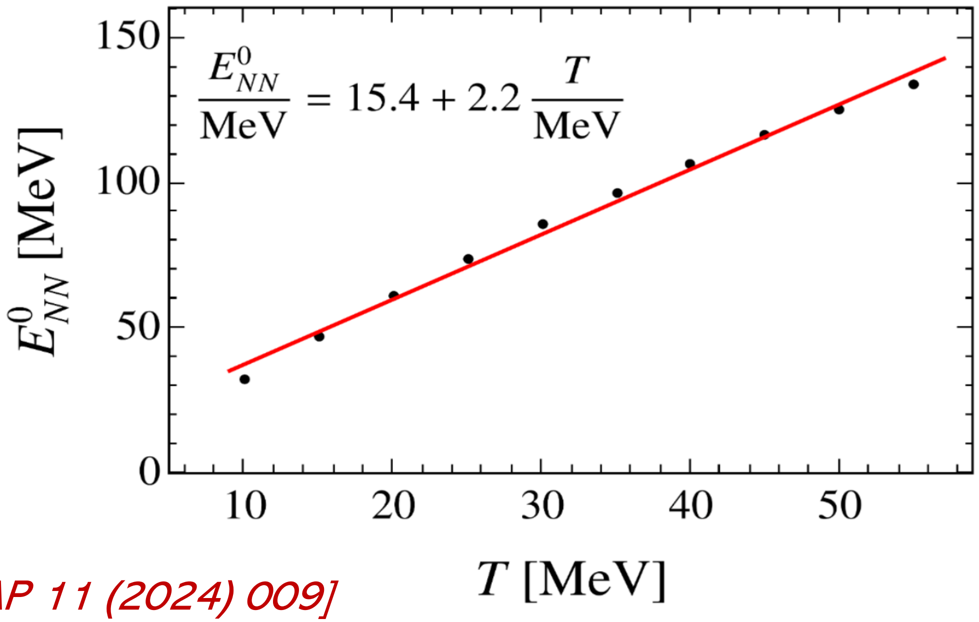
ALPs as messengers of PNS



ALPs can provide a lot of information about the PNS

$$\left(\frac{d^2 N_a}{dE_a\, dt}\right)_{NN} \propto \left(\frac{E_a}{E^0_{NN}}\right)^{\beta_{NN}} \exp\left[-(\beta_{NN}+1)\,\frac{E_a}{E^0_{NN}}\right]$$

$$\left(\frac{d^2 N_a}{dE_a\, dt}\right)_{\pi N} \propto \left(\frac{E_a-\omega_c}{E^0_{\pi N}}\right)^{\beta_{\pi N}} \exp\left[-(\beta_{\pi N}+1)\,\frac{E_a-\omega_c}{E^0_{\pi N}}\right]$$

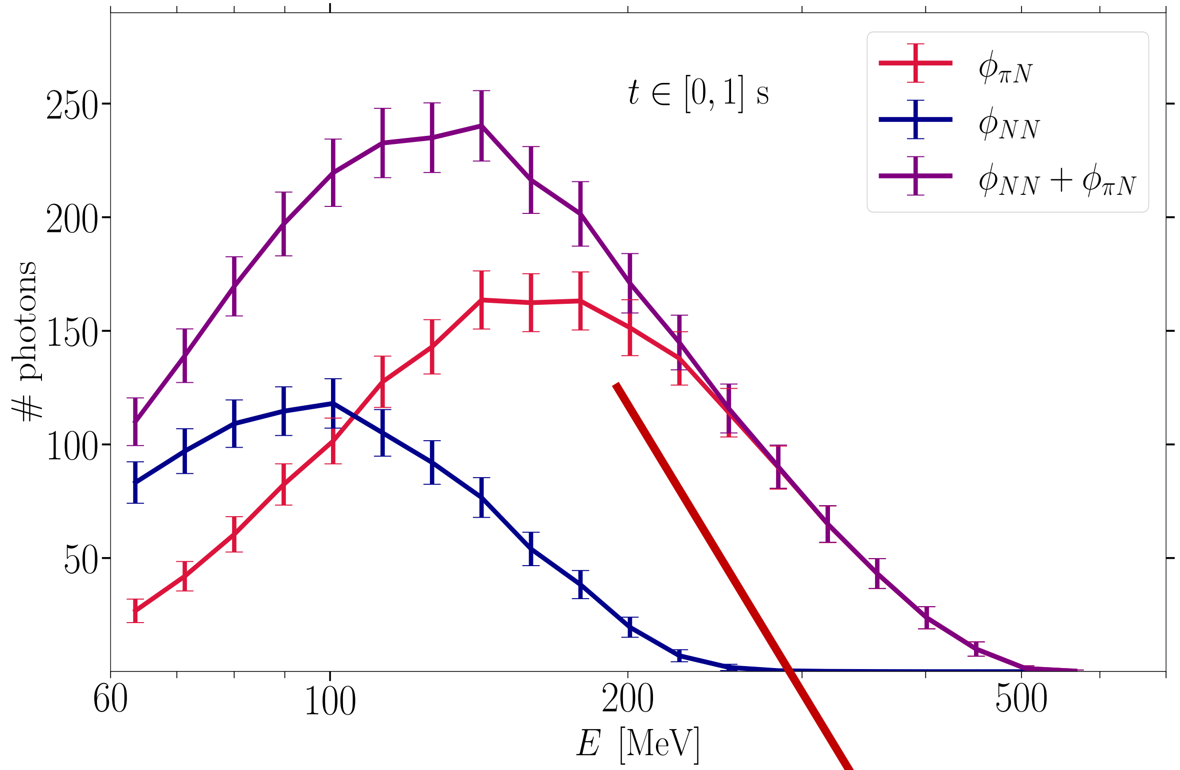


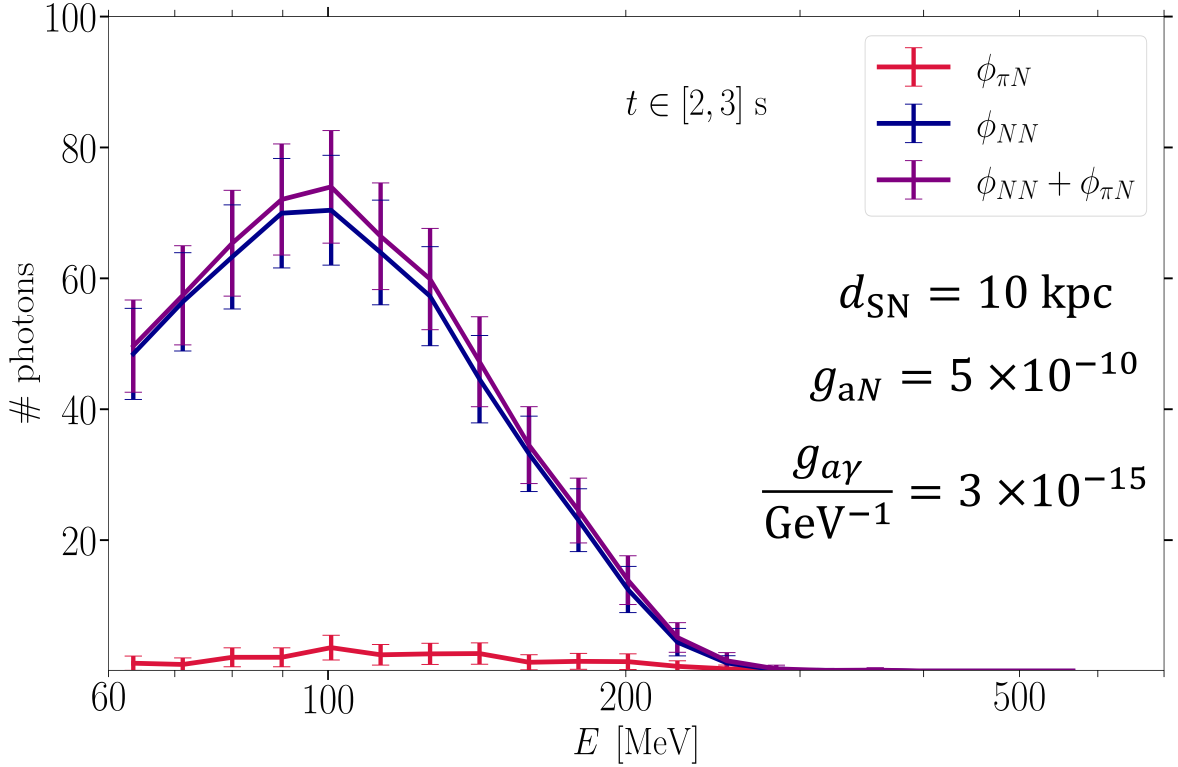
[AL et al., JCAP 11 (2024) 009]

Fermi-LAT reconstruction of the signal

The ALP induced gamma-ray burst might be detected by the Fermi-LAT experiment

[AL et al., JCAP 11 (2024) 009]





$d_{\rm SN} = 10$ kpc

$g_{aN} = 5 \times 10^{-10}$

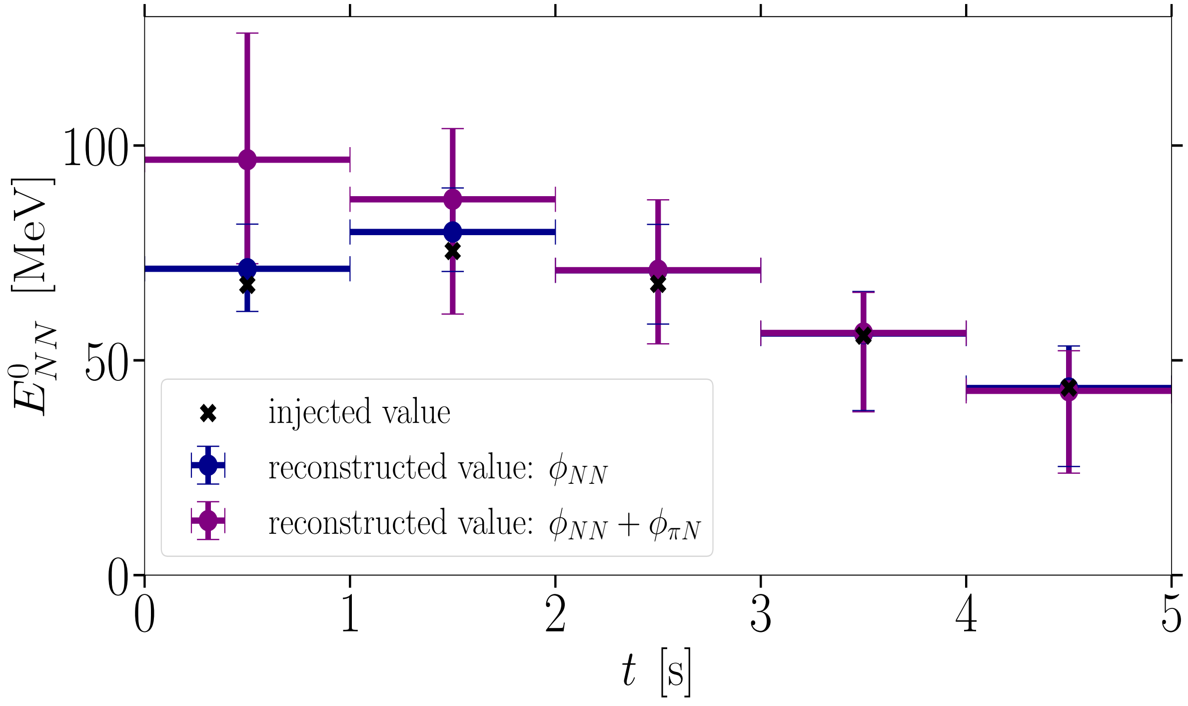
$\frac{g_{a\gamma}}{\rm GeV^{-1}} = 3 \times 10^{-15}$

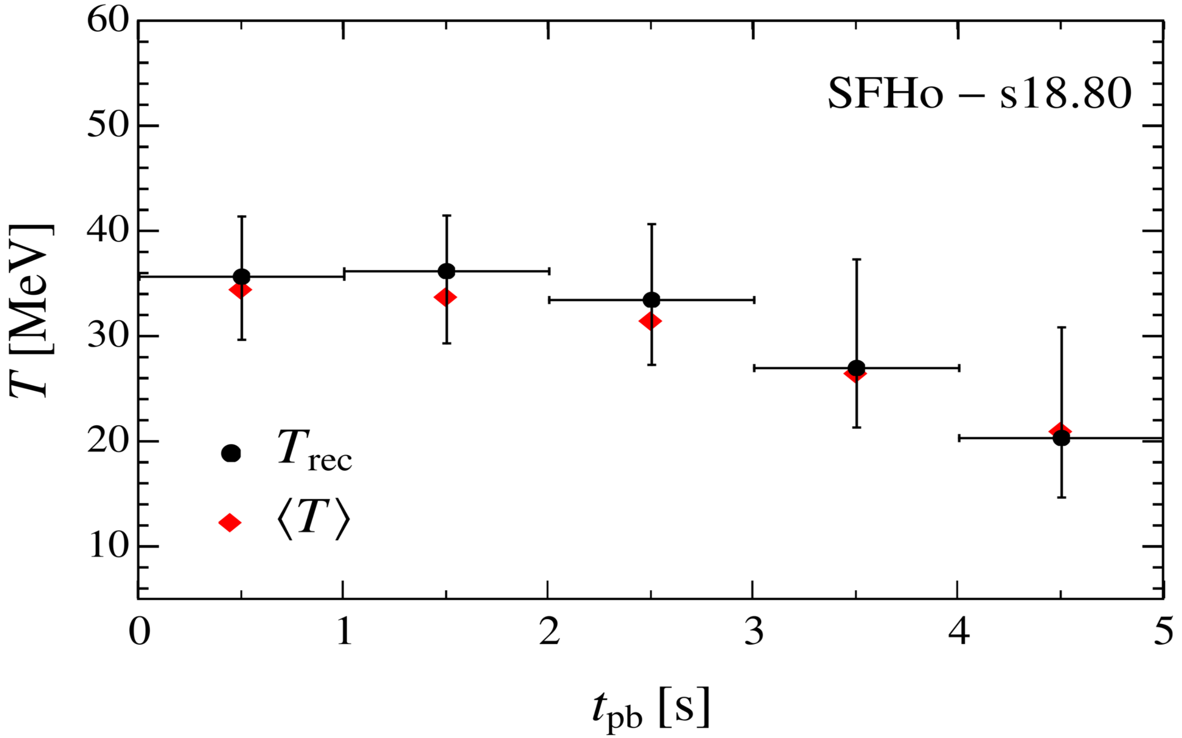
Evidence for the presence of pions in the core

Suppression of πN peak at $t_{pb} > 2$ s.

Fermi-LAT reconstruction of the signal

From parameter reconstruction one can estimate the average PNS temperature with high precision





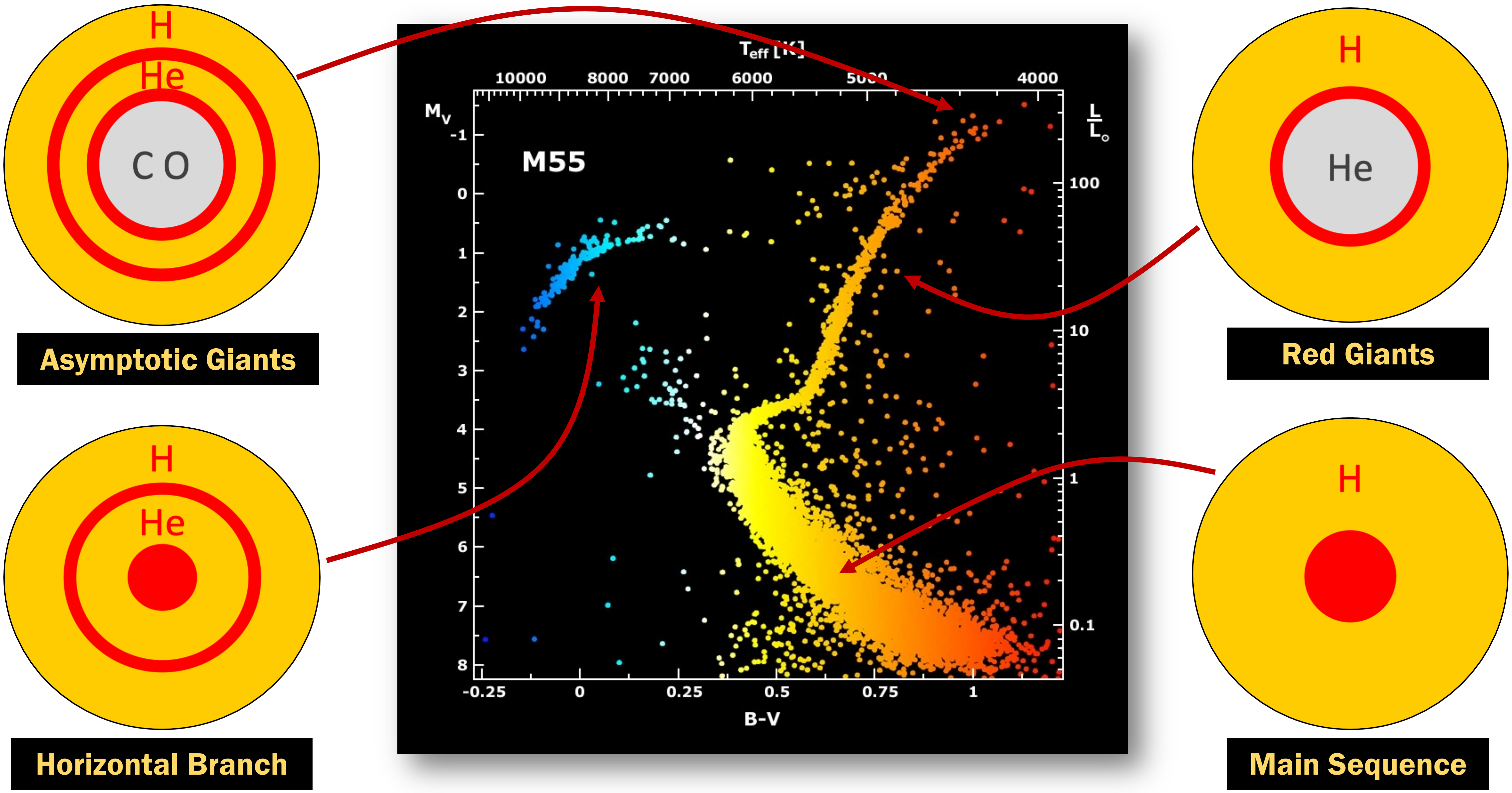
[AL et al., JCAP 11 (2024) 009]

Take-home messages

- Because of the extreme conditions in the interior of the core, SNe are a powerful source of FIPs
- Axions and ALPs might be copiously produced in nuclear processes inside the SN core
- Observations of SN 1987A neutrino burst severely constrain ALP production mechanism
- A vast phenomenology for ALPs coupled with photons and electrons.
- What could we learn about SN conditions?

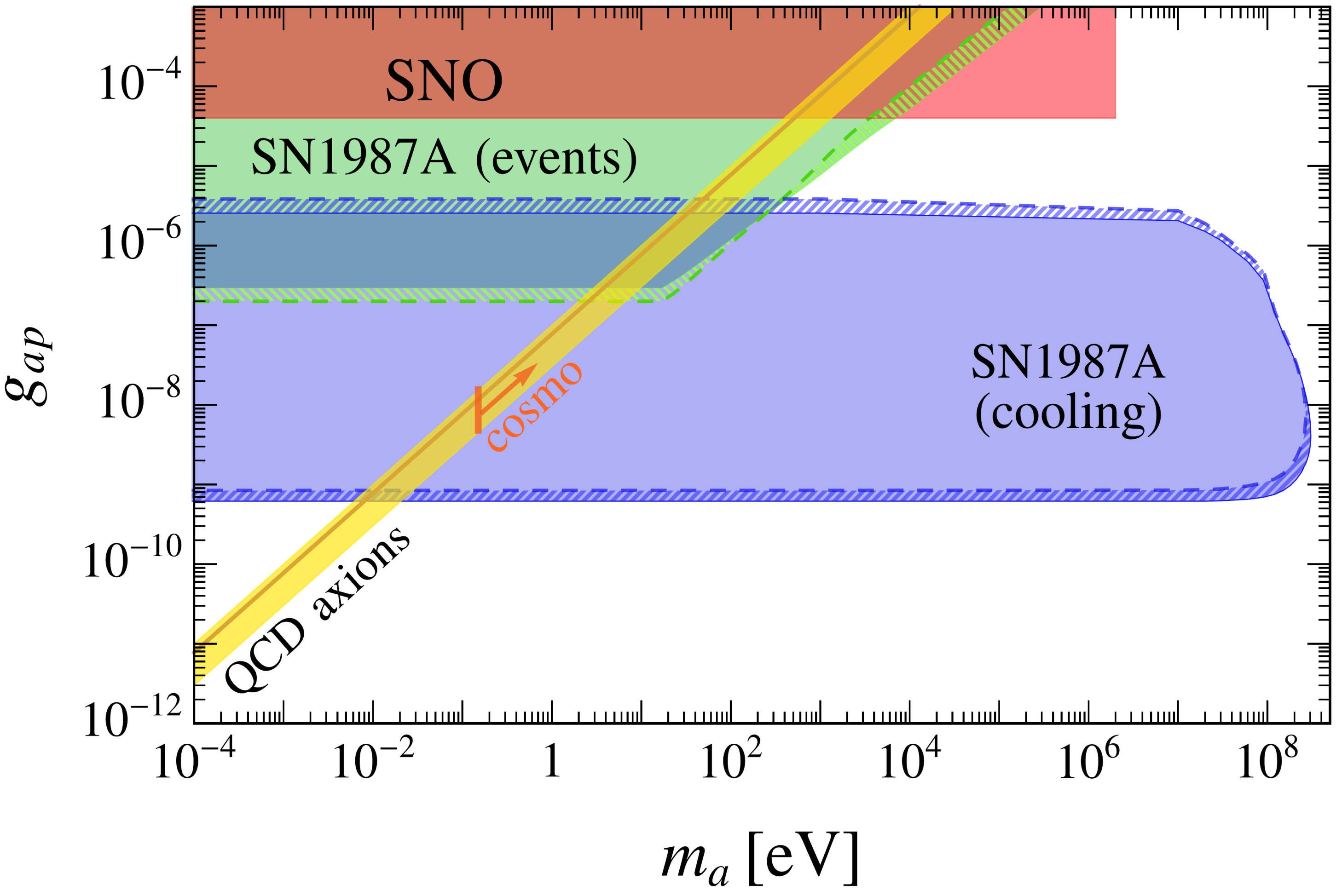

Thank you for your
attention

Low-mass stars ($M \leq 8M_\odot$)



Uncertainties on SN bounds

Different SN models from same progenitors ($18.88\ M_\odot$) show different temperature and density profiles.



AGILE BOLTZTRAN

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

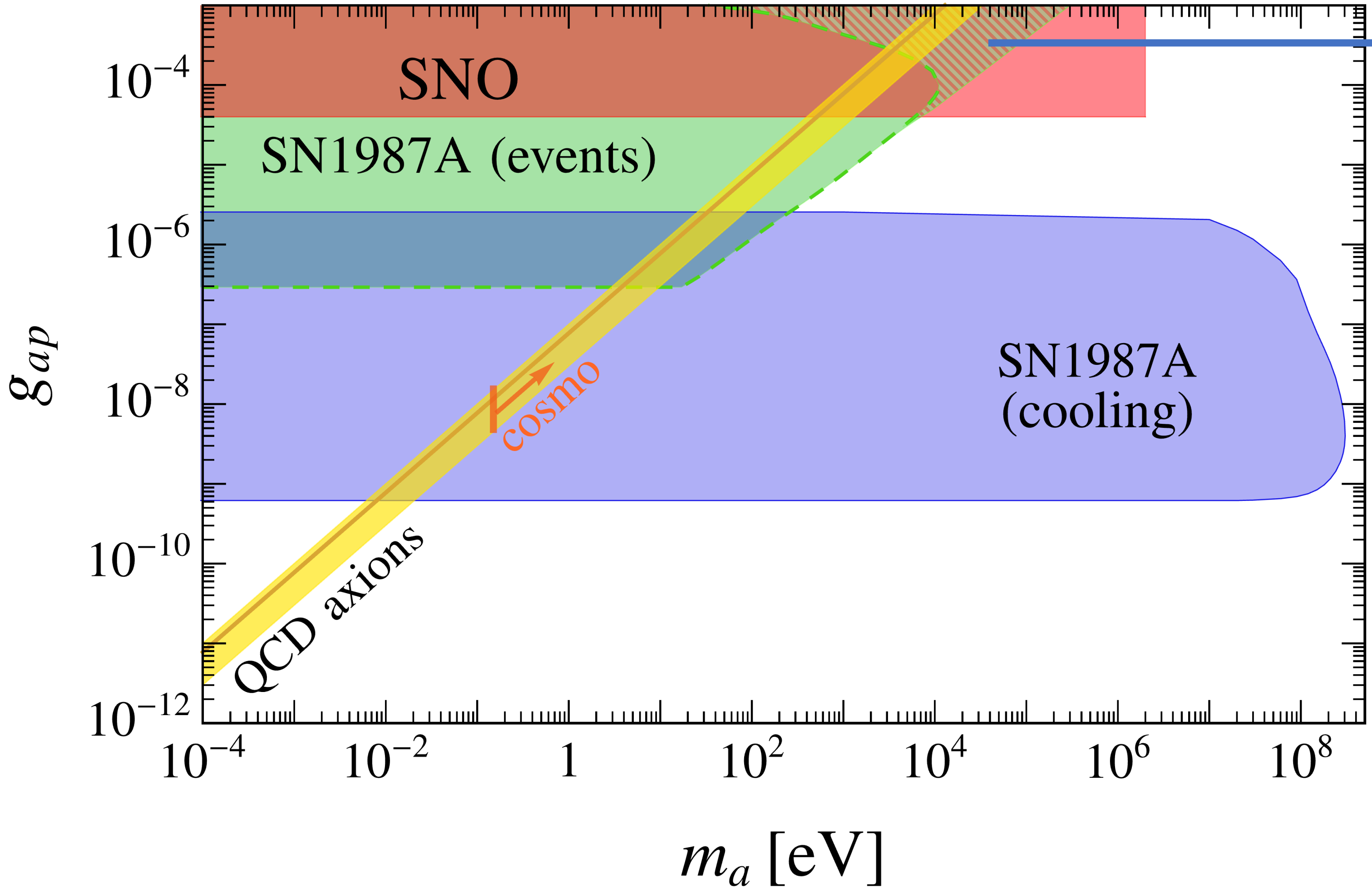
Similar impact over standard and new physics → Similar bounds

GARCHING

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

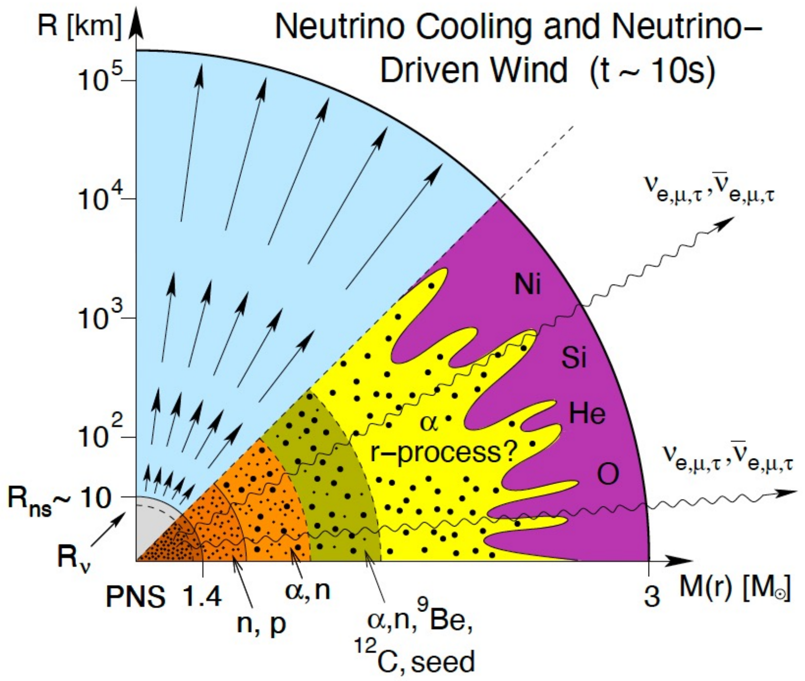
Uncertainties on SN bounds

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



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

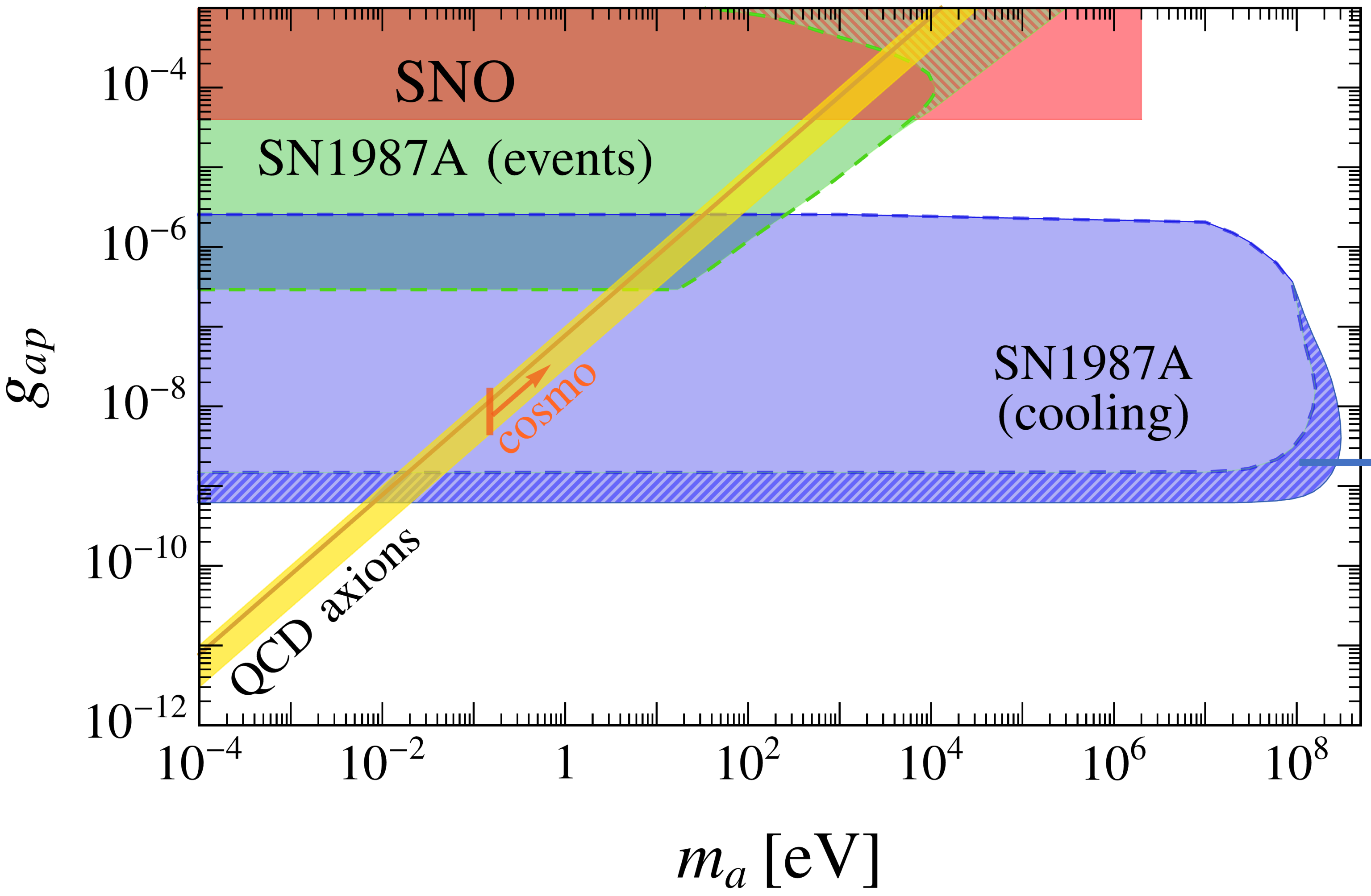
$$\Gamma_H(E,r) \sim n_H(r)\,\sigma(E)$$



Uncertainties on SN bounds

Strong interactions can enhance the pion fraction in the SN core

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



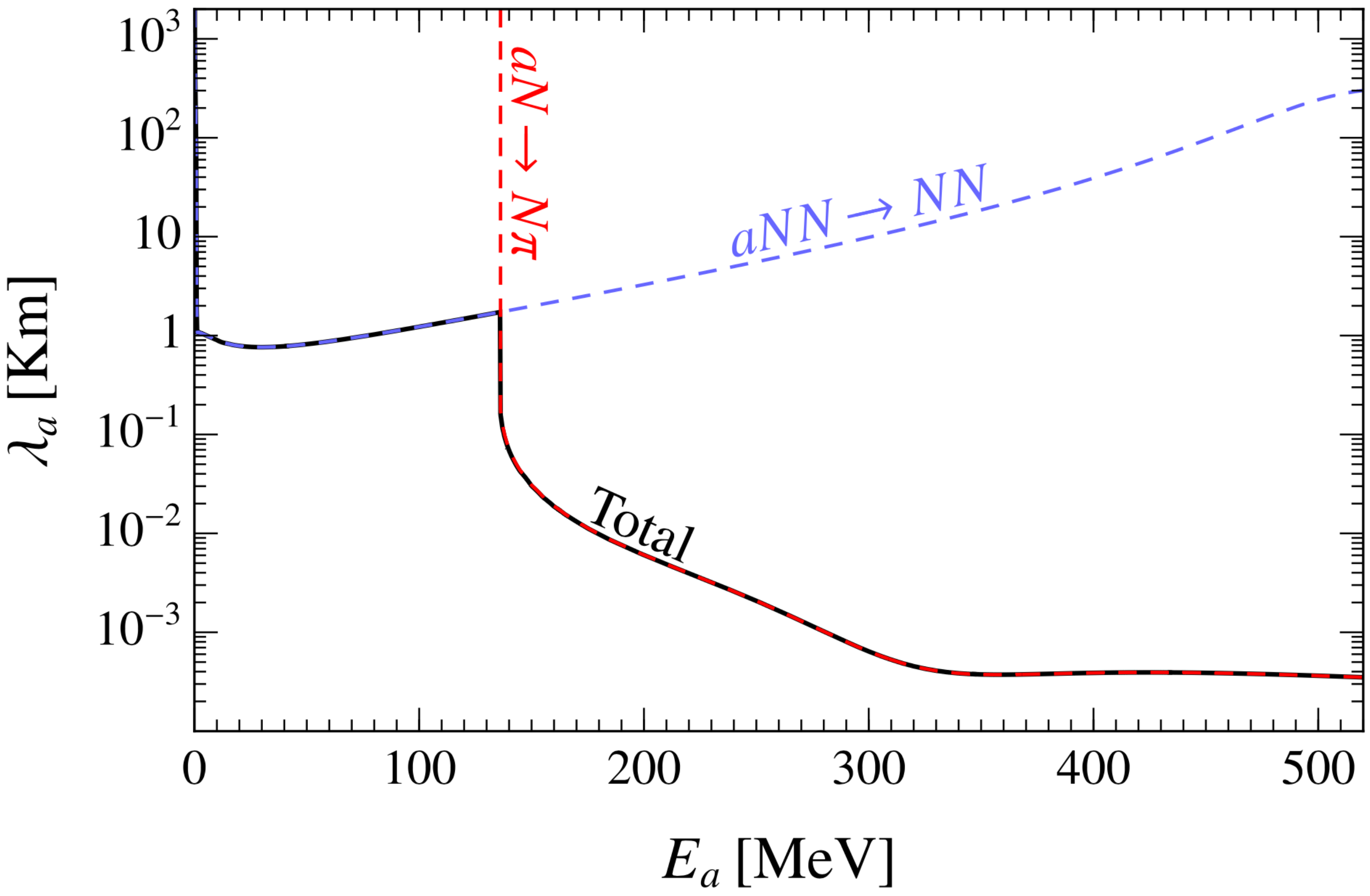
Pions still not self-consistently included in SN simulations

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

Without pions, cooling bound relaxes by a factor ~ 2

ALP mean free path

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



Detector resolution

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

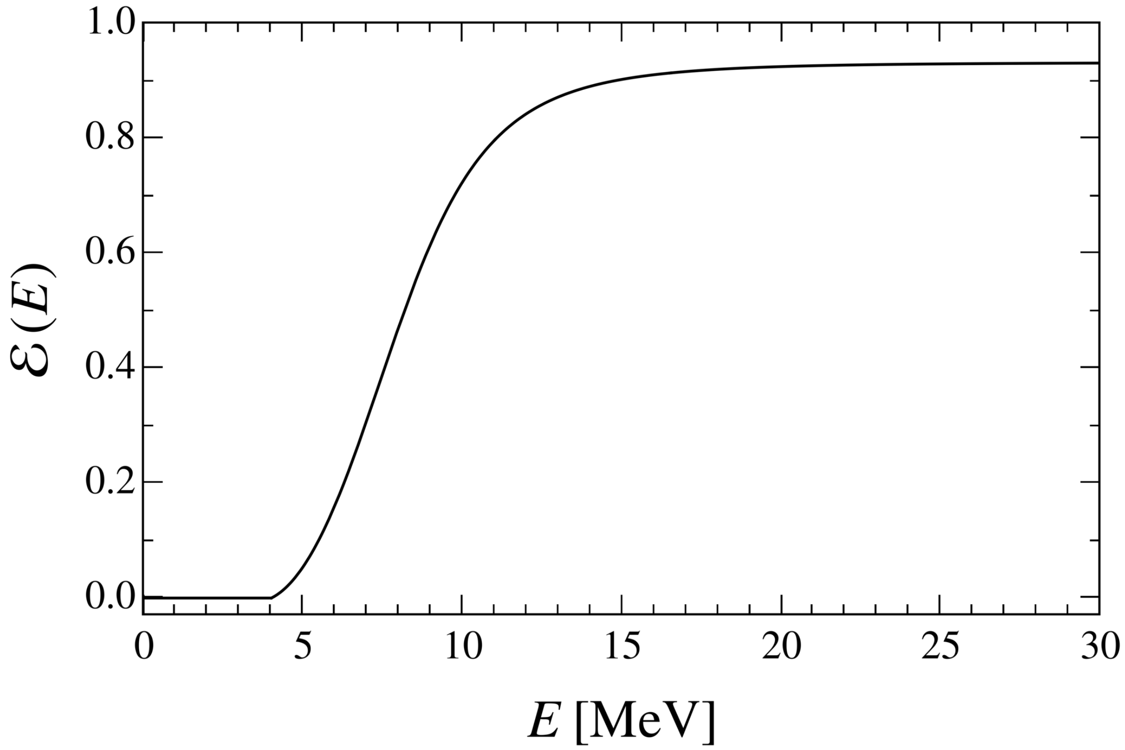
$$\mathcal{R}(E,\epsilon) = \sum_{\omega(\epsilon)} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(E-\omega(\epsilon))^2/2\sigma^2}\, BR\left[\omega(\epsilon)\right]$$

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



ALP events from SN 1987A

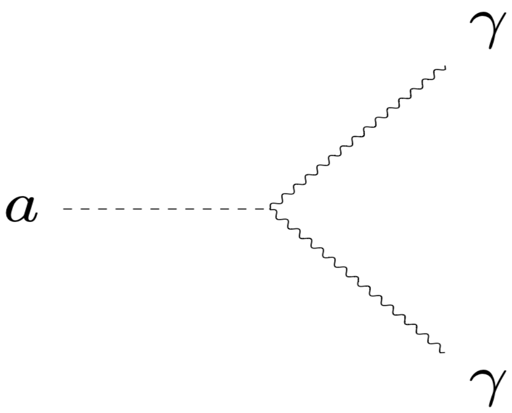
$$N_{\rm ev} \lesssim \begin{cases} 2\sqrt{\overline{n}_{\rm bkg}\Delta t} & \text{if } m_a \lesssim 17 \text{ eV} \\ 2\sqrt{\overline{n}_{\rm bkg}\Delta t_a} & \text{if } m_a > 17 \text{ eV} \end{cases}$$

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

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

ALP decays

- $\lambda_\gamma > R_{\rm env}$
  - γ-ray flux
  - DSNALPB
  - ALP baisins

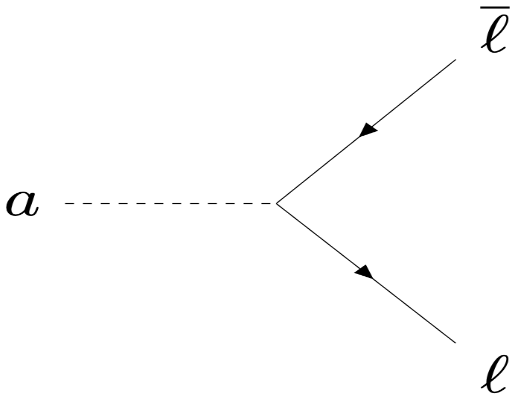


$$\lambda_\gamma = \frac{64\pi}{g_{a\gamma}^2}\frac{\sqrt{E_a^2 - m_a^2}}{m_a^4}$$

SN envelope radius $R_{\rm env} \sim 3{\times}10^{14}$ cm

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

$$\mathcal{L}_{a\ell} = \sum_{\ell=e,\mu}\frac{g_{a\ell}}{2m_\ell}(\bar{\ell}\gamma_\mu\gamma_5\ell)\partial^\mu a$$



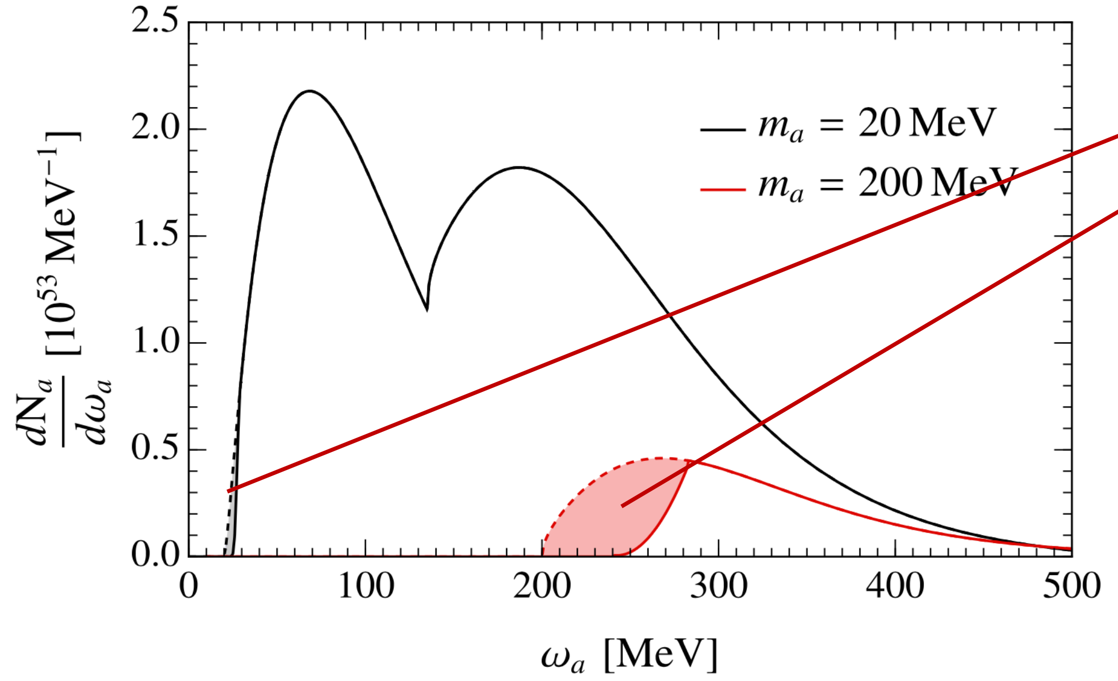
$$\lambda_\ell = \frac{8\pi}{g_{a\ell}^2 m_a}\sqrt{\frac{E_a^2 - m_a^2}{m_a^2 - 4m_\ell^2}}$$

SN envelope radius $R_{env} \sim 3{\times}10^{14}$ cm

- $\lambda_\gamma < R_{\rm env}$
  - Energy deposition
- $\lambda_\gamma > R_{\rm env}$
  - 511 keV line
  - CXB

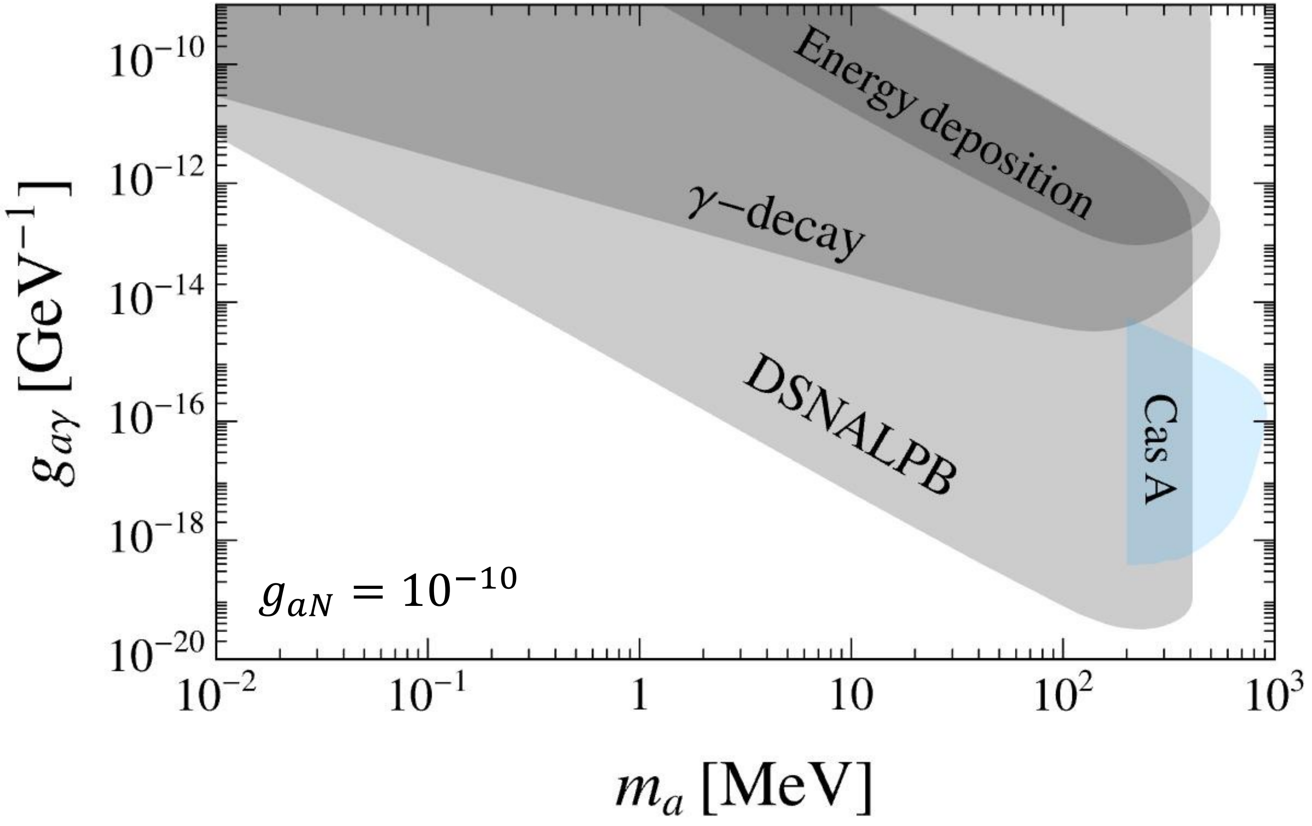
ALP Basins around SN remnants

[Hannestad & Raffelt, Phys. Rev. Lett. 88 (2002)]



Massive ALPs could remain trapped inside the PNS gravitational potential. Then, they decay at rest.

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

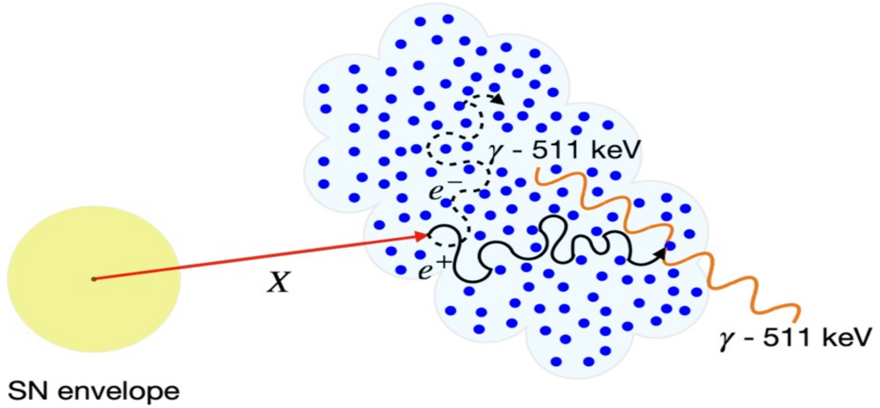


SN remnant Cas A ($d \approx 3.4$ kpc, t$\approx$ 320 yrs).
No photon flux has been observed by Fermi-LAT:

$$\phi_{E>100\,\mathrm{MeV}} \lesssim 2\times 10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

511 keV line

[Calore et al. , Phys. Rev. D 105 (2022) 4]
[Calore et al. , Phys. Rev. D 105 (2022) 6]



ALP leptonic decays would inject positrons in the inter-stellar medium. By annihilating with electrons, they may give rise to a photon signal at $511\ \mathrm{keV}$.

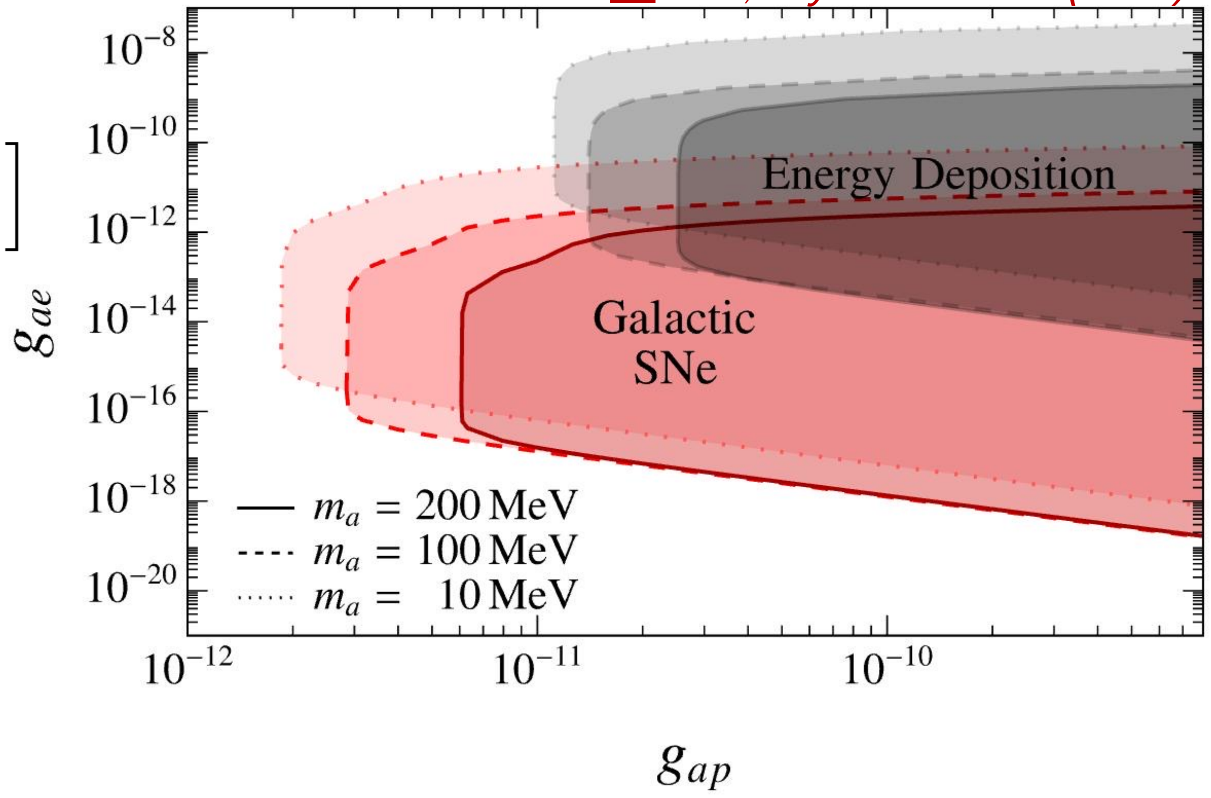
$$N_{\rm pos} = \int d\omega \frac{dN_a}{d\omega} \left(\epsilon_{II} e^{-R^{\rm II}_{\rm env}/\lambda_e} + \epsilon_I \, e^{-R^{\rm I}_{\rm env}/\lambda_e} \right) \left[1 - \exp\left(-\frac{r_{\rm G}}{\lambda_e} \right) \right]$$

with $R^{II}_{env} \sim 3{\times}10^{14}$ cm, $R^{I}_{env} \sim 10^{12}$ cm and $r_{\rm G} \sim 1$ kpc.

The SPI gamma-ray spectrometer on the INTEGRAL satellite provides the following constraint

$$N_{\rm pos} \lesssim 1.4 \times 10^{52}$$

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



Cosmic X-Ray Bacground

[Calore et al. , Phys. Rev. D 105 (2022) 6]

If ALPs are produced in extragalactic SNe, the signal from annihilation is redshifted and contributes to the CXB

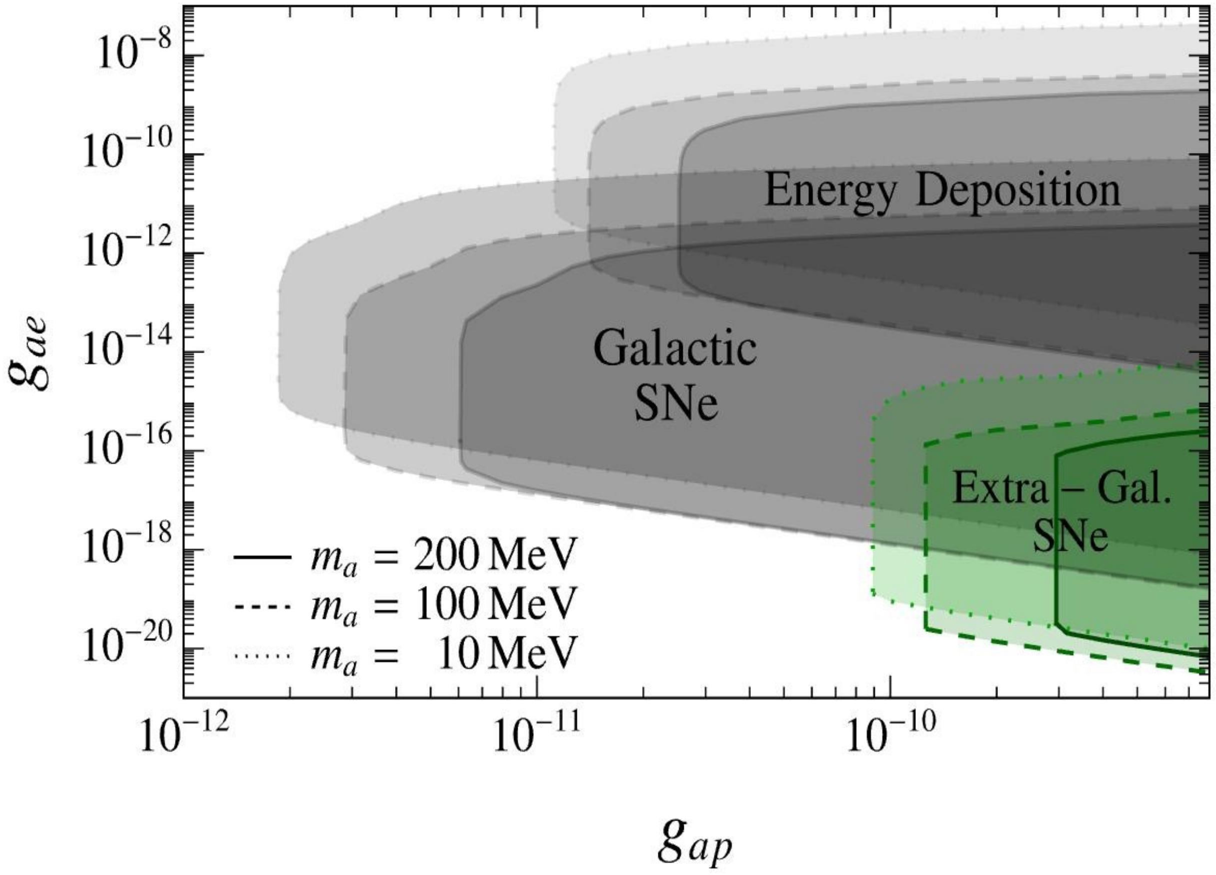
$$\frac{d\phi_\gamma}{dE_\gamma} = 2k_{ps}\frac{m_e}{E_\gamma^2}\int_{m_a}^{\infty} dE_a \frac{d^2\phi_a(E_a)}{dE_a dz_d}$$

Where

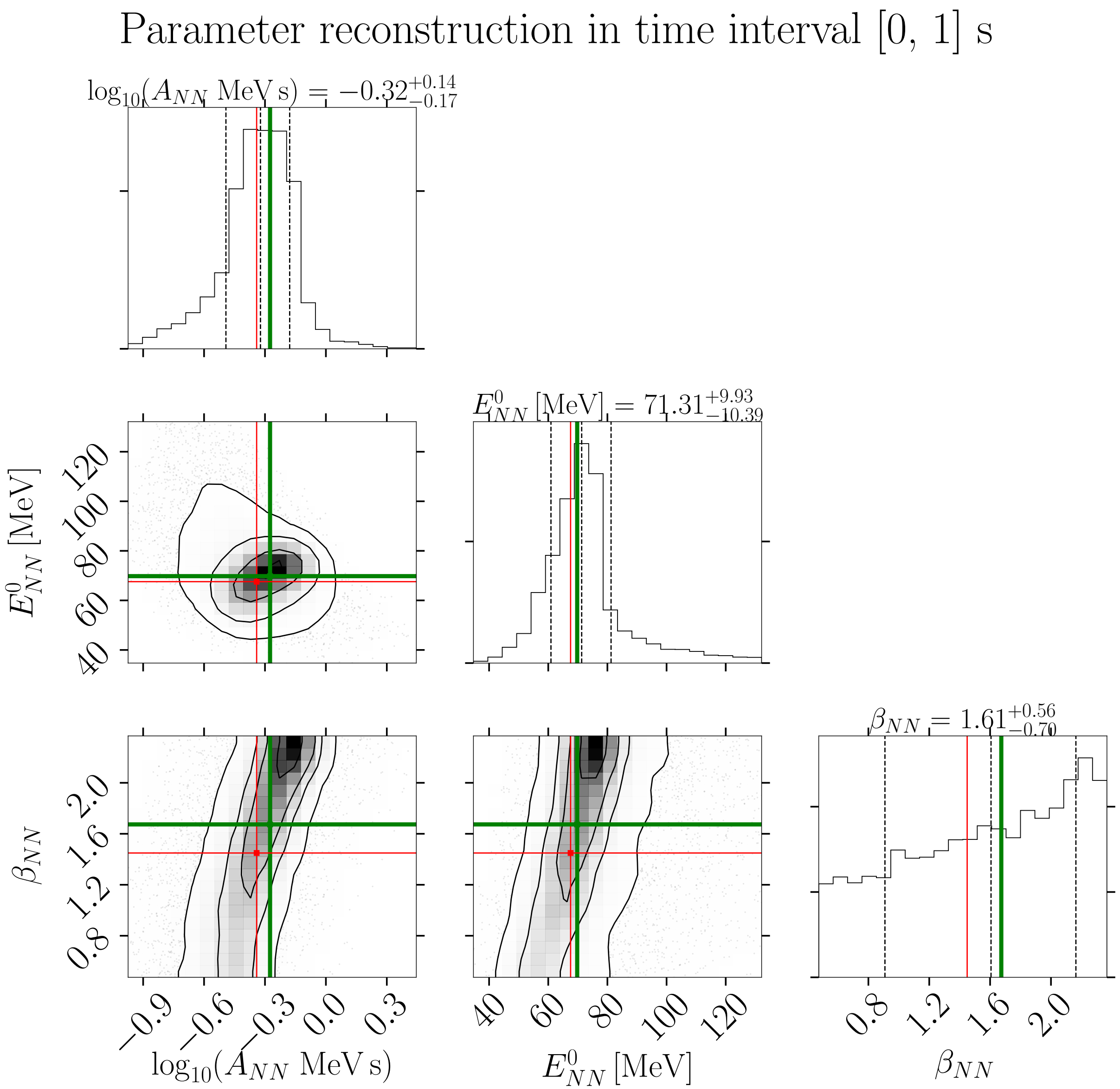
$$\frac{d^2\phi_a}{dE_a dz_d} = \int_{z_d}^{\infty}(1+z)\frac{dN_a(E_a(1+z))}{dE_a}\, e^{-\frac{z-z_d}{H_0\lambda_e}}\frac{R_{SN}(z)}{H_0\lambda_e}\left|\frac{dt}{dz}\right|dz$$

The induced CXB flux must not exceed the measurments by HEAO-1 and SMM experiments.

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



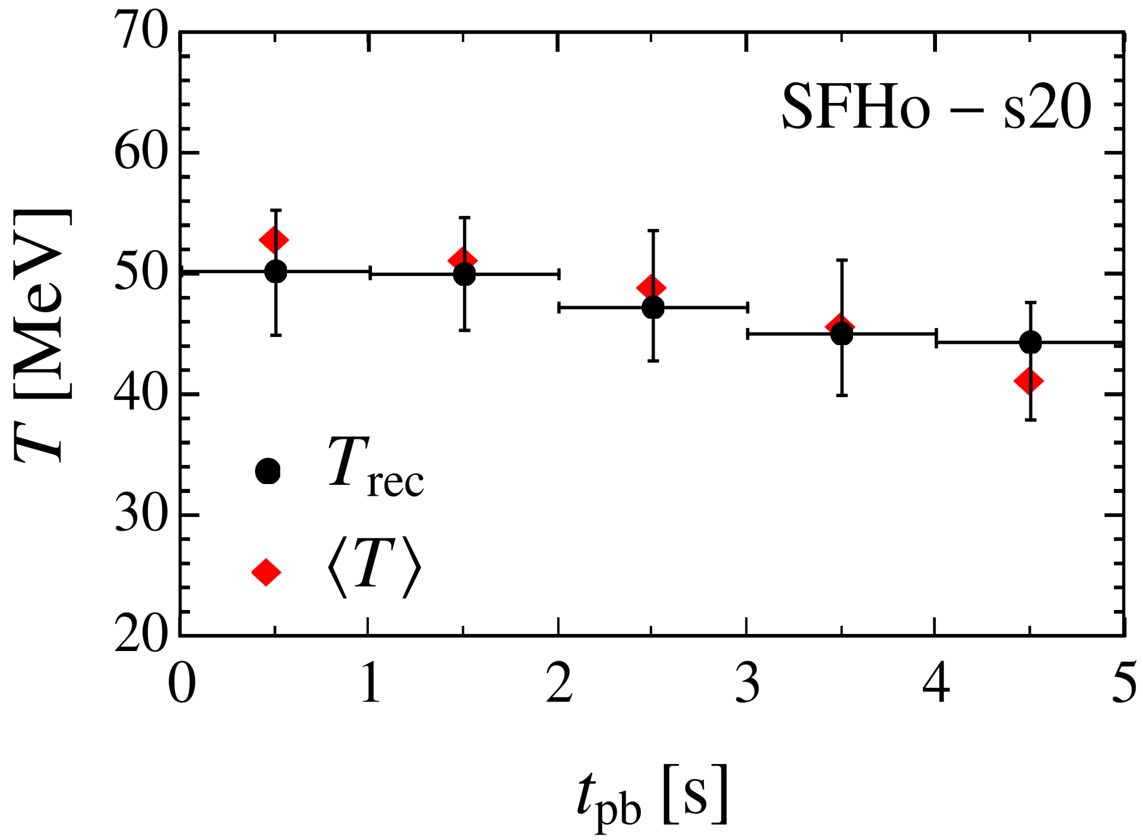
Fermi-LAT reconstruction of the signal

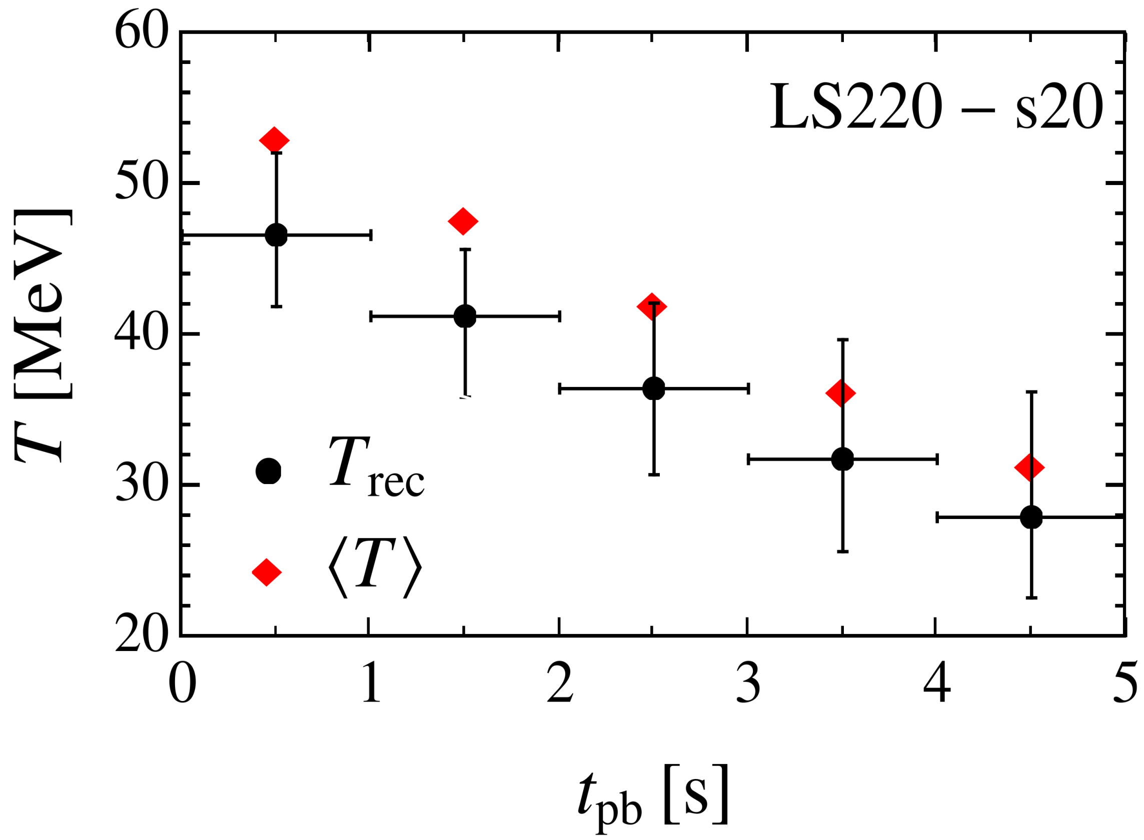


[AL et al., JCAP 11 (2024) 009]

Fermi-LAT reconstruction of the signal

Termperature reconstruction still works for other SN models.





[AL et al., JCAP 11 (2024) 009]

The UV Theory

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

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

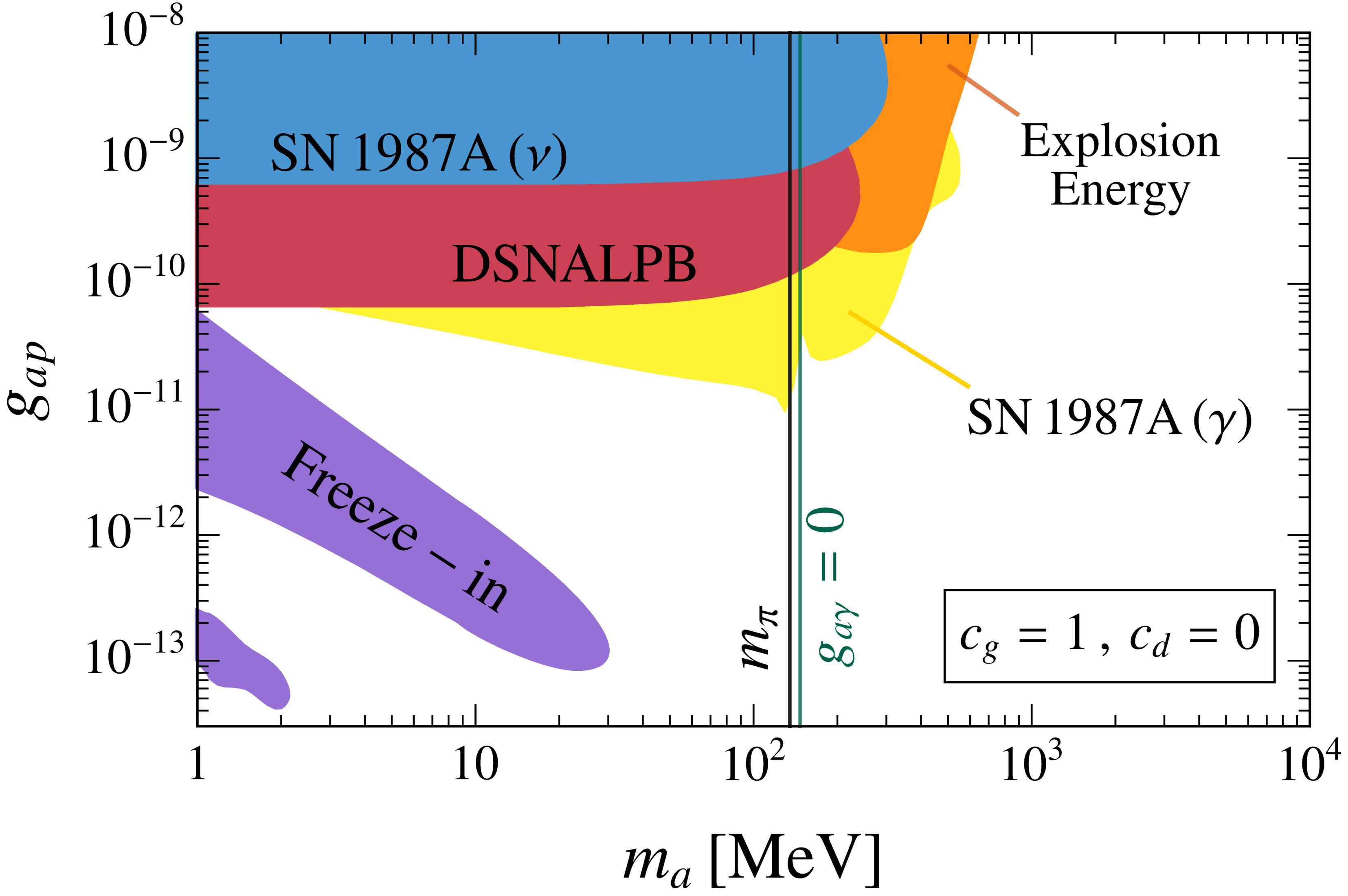
Then, at loop level *[Bauer et al., JHEP 12 (2017)]*

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

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

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

Bounds on g_{ap}



[AL & al., Phys.Rev.D 110 (2024)]