

Direct detection of dark sectors from supernovae

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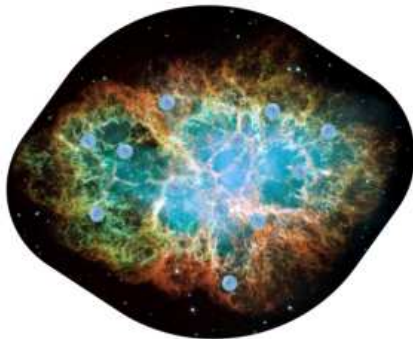
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Supernovae as dark sector factories

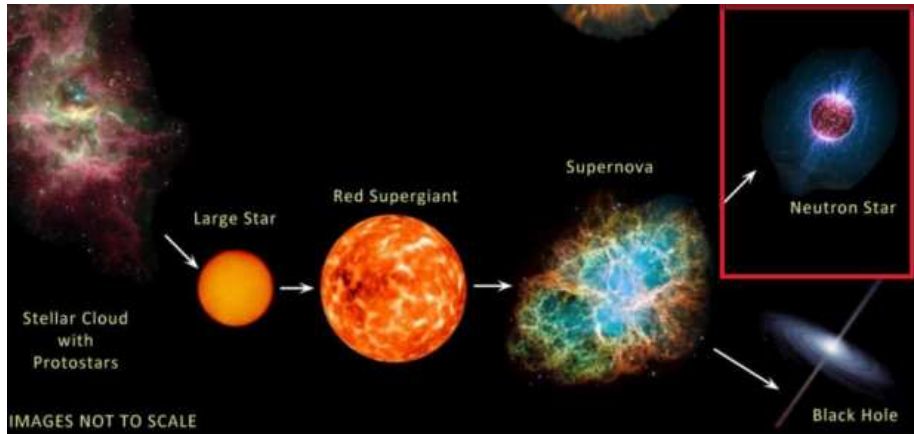
- Strong motivation for **new weakly interacting particles**: dark matter, new mediators, hidden sectors (axions, axion-like particles, dark photons)
- Terrestrial experiments face important limitations: small couplings, sub-GeV masses
- Core-collapse supernovae (SNe) provide **extreme conditions**
 - ▶ $T \sim O(10)$ MeV
 - ▶ $\rho \sim 10^{14} - 10^{15}$ g/cm³

Dark sectors interacting with SM particles \Rightarrow **production in core-collapse SNe**



Core-collapse supernovae

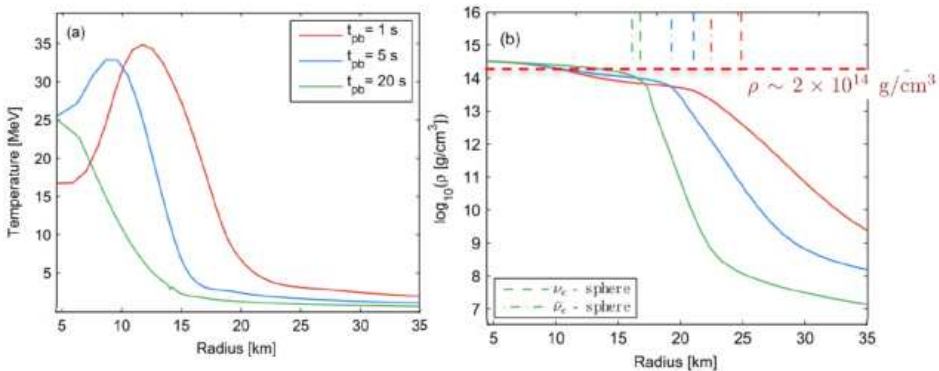
SNe are violent stellar phenomena happening when stars with $M > 8 M_{\odot}$ have burned out their nuclear fuel \Rightarrow gravitational core collapse \Rightarrow proto-neutron star (proto-NS)



Proto-neutron star medium properties

In the first seconds the proto-NS core ($R \sim 20$ km) reaches temperatures $T \sim 30$ MeV and baryonic densities $\rho \sim 10^{14} - 10^{15}$ g/cm³

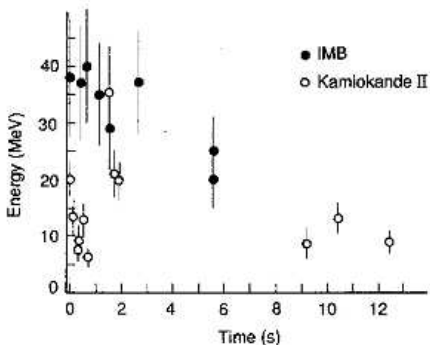
Fischer et al., PRD 85 (2012) 083003



SN neutrinos and SN 1987A

During the final phases of core-collapse SNe, ν and $\bar{\nu}$ of all flavours are copiously produced and trapped in the proto-NS core. After a second, they are emitted as the star cools down

- $\sim 10^{58}$ ν s with $E_\nu \sim O(10)$ MeV
- Energy released in neutrinos $\sim 10^{53}$ erg
- Neutrino burst duration ~ 10 s
- Standard Model predictions compatible with the SN 1987A observation (first and only SN neutrinos detected)

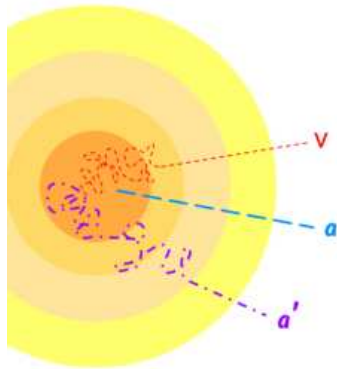


Weakly interacting particles in supernovae

If new particles interact with the components of the proto-neutron star core (n, p, e^-, μ^-, ν), they can be copiously produced

Depending on their coupling strength to the SM:

- **Free-streaming regime:** once produced, particles escape the star, as their mean free path exceeds the proto-NS radius
- **Trapping regime:** particles have a mean free path smaller than the proto-NS radius and can lose energy or be reabsorbed before escaping



Probing dark sectors with supernovae

Different probes (and some references):

- **Energy loss:** constraints from supernova cooling

*Raffelt, Seckel, PRL 60 (1988) 1793, Burrows, Turner, Brinkmann, PRD 39 (1989) 1020, Raffelt, Physics Reports 198 (1990) 1, Fischer et al., PRD 94 (2016) 085012, Chang, Essig, McDermott, JHEP 01 (2017) 107, JHEP 09 (2018) 051, Carenza et al., JCAP10 (2019) 016, Croon et al., JHEP 01 (2021) 107, Cerdeño, **Cermeño**, Farzan, PRD 107 (2023) 123012, Manzari et al., PRD 108 (2023) 103020*

- **Indirect signals:** photons or other secondary products

Chupp et al. PRL 62 (1989) 505, Payez et al., JCAP 1502 (2015) 006, Meyer et al., PRL 118 (2017) 011103, Raffelt, Redondo, Viaux, PRD 84 (2011) 103008, Calore et al. PRD 102 (2020) 123005, Lella et al., PRD 107 (2023) 103017, Manzari et al., PRL 133 (2024) 211002, Carenza et al., PRD 109 (2024) 063010, Ferreira, Marsh, Ravensburg JCAP 11 (2022) 057, (2025) arXiv: 2510.14469, Fiorillo, Pitik, Vitigliano (2025) arXiv:2503.15630

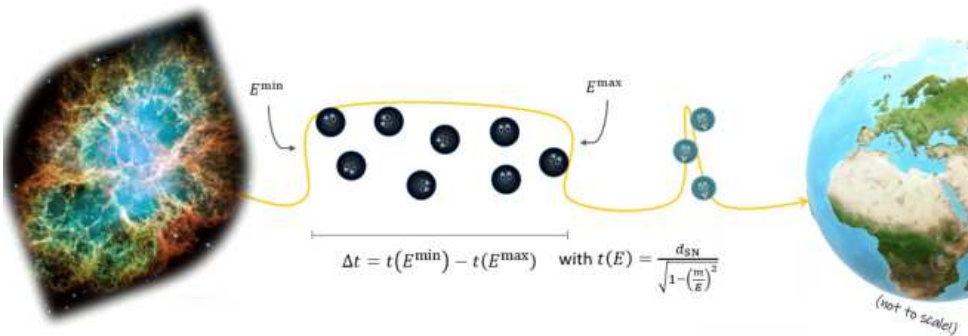
- **Direct detection:** particles produced in SNe detected at Earth

*DeRocco et al. PRD 100 (2019) 075018, Baracchini, Derocco, Dho, PRD 102 (2020) 075036, Bhalla et al., (2025) arXiv:2506.15765, Bell et al., (2026) arXiv:2603.10434, Carenza et al., PRC 109 (2024) 015501, Alonso-González, Cerdeño, **Cermeño**, Perez, PRD 111 (2025) 083019, PRD 111 (2025) 083029, (2026) arXiv:2602.17597*

Focus of this talk: direct detection

Particles from supernovae at Earth

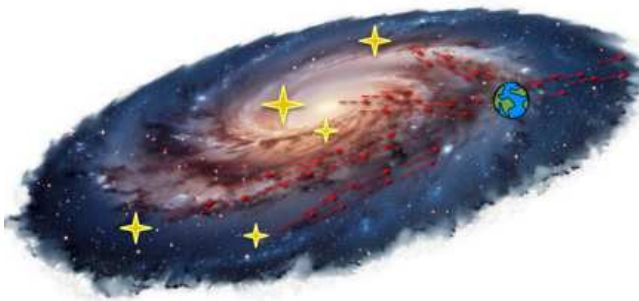
- Massive particles travel slower than neutrinos, semi-relativistic velocities
- Particles with mass m emitted with energies $E \sim m - \mathcal{O}(100)$ MeV
- Spread in arrival times Δt (increasing with m and Earth-SN distance d_{SN})



©D. Alonso-González

Flux of MeV particles from galactic supernovae

- For a SN at the Galactic Center and $m \simeq 1 - 100$ MeV, $\Delta t \sim 10^2 - 10^4$ yr
- Galactic SN rate ~ 1.63 per century *Rozwadowska et al. New Astron 83 (2021)*
- $\sim 10 - 100$ SN fluxes of particles overlap at Earth
- Near constant flux and smooth approximation *DeRocco et al. PRD 100 (2019) 075018, Alonso-González, Cerdeño, Cermeño, Perez, PRD 111 (2025) 083019*



©A. D. Perez

Flux of MeV particles from galactic supernovae: smooth approximation

The flux of MeV particles from past galactic SNe that reaches Earth

$$\frac{d\Phi}{dE^{\text{Earth}}} = \frac{dN}{dE^{\text{Earth}}} \int_{-\infty}^{\infty} \int_0^{2\pi} \int_0^{\infty} \frac{dn_{SN}}{dt} \frac{r}{4\pi (\vec{r} - \vec{R}_E)^2} dr d\theta dz$$

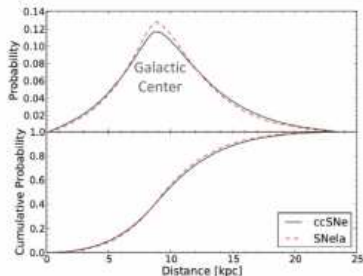
- $\frac{dN}{dE^{\text{Earth}}}$ number of particles per unit energy at Earth from one SN (spectral fluence)
- The galactic SN rate *Adams et al., ApJ 778 (2013) 164, McMillan MNRAS 466 (2017)*

$$\frac{dn_{SN}}{dt} = A e^{-\frac{r}{R_d}} e^{-\frac{|z|}{H}}$$

For ccSNe:

$R_d = 2.6$ kpc $H = 0.3$ kpc
SN rate: 1.63 per century

$$A = 1.65 \times 10^{-3} \text{ kpc}^{-3} \text{ yr}^{-1}$$



$|\vec{R}_E| = 8.23$ kpc Earth-GC distance and $z_E = 20.8$ pc its position above the the mid-plane of the disk

Flux of MeV particles from galactic supernovae: smooth approximation

The flux of MeV particles from past galactic SNe that reaches Earth

$$\frac{d\Phi}{dE^{\text{Earth}}} = 1.3 \times 10^{-55} \text{ cm}^{-2} \text{ s}^{-1} \frac{dN}{dE^{\text{Earth}}}$$

- $\frac{dN}{dE^{\text{Earth}}}$ model dependent

Axion-like particles (ALPs), a , coupled to nucleons, N

$$\mathcal{L}_{\text{int}} \sim g_{aN} \frac{\partial_{\mu} a}{2m_N} \bar{N} \gamma^{\mu} \gamma_5 N$$

Production:

- $NN \rightarrow NN a$

Dark fermions, χ , coupled to SM fermions via a heavy dark photon, A'

$$\mathcal{L}_{\text{int}} \sim \frac{\epsilon g_d}{m_{A'}^2} \bar{\chi} \gamma_{\mu} \chi J_{\text{em}}^{\mu}$$

Production:

- $e^+ e^- \rightarrow \chi \bar{\chi}$
- $np \rightarrow np \chi \bar{\chi}$

Absorption via the inverse processes is also taken into account

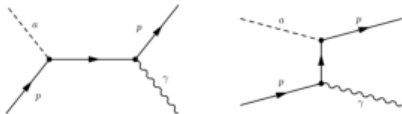
Direct detection of MeV particles from galactic SNe

Number of events per energy in a detector with N_t targets during an observation time Δt_{obs}

$$\frac{dN}{dE_{\text{obs}}} = N_t \Delta t_{\text{obs}} \int dE^{\text{Earth}} \frac{d\Phi}{dE^{\text{Earth}}} \frac{d\sigma}{dE_{\text{obs}}}$$

ALPs

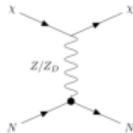
Signals in neutrino water Cherenkov detectors



- ALPs interacting on free protons
- Photon signal peaking at ~ 30 MeV
- Energy range with very low background
- Detection channel proposed for the first time in *Alonso-González, Cerdeño, Cermeño, Perez, PRD 111 (2025) 083019*

Dark fermions

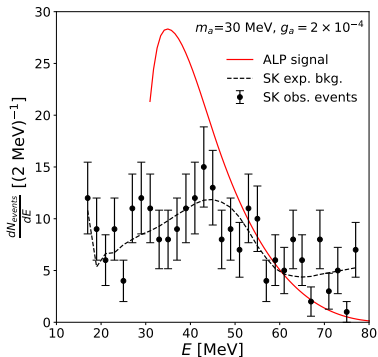
Signals in liquid xenon detectors



- Nuclear recoils
- Semi-relativistic flux \Rightarrow keV recoil energy
- Energy threshold \sim keV, matching the recoil signal
- Very low background (self-shielding and signal discrimination)

Events in terrestrial detectors: smooth approximation

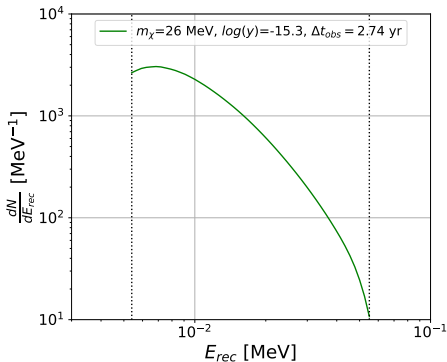
ALPs in Super-Kamiokande (SK)



Alonso-González, Cerdeño, **Cermeño**, Perez,
PRD 111 (2025) 083019

- SK phase IV, exposure 22.5×2970 kton-day
- Energy window $E = 16\text{--}78$ MeV (DSNB search)
- Background from muon spallation and atmospheric neutrinos

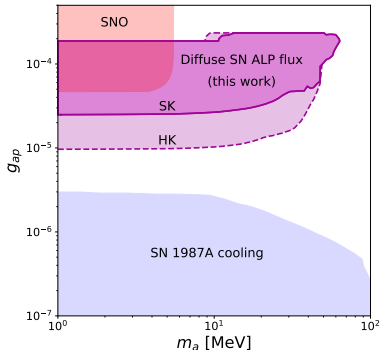
Dark fermions in LZ



$$y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}} \right)^4, \alpha_D = g_d^2 / 4\pi$$

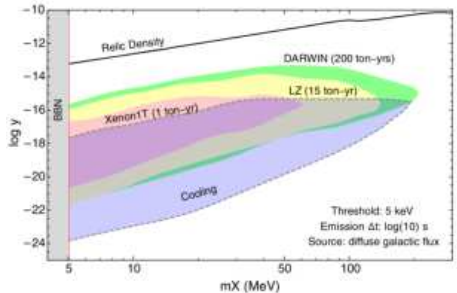
- LZ, 15 tonne-year exposure (projection)
- Energy window $E_{\text{rec}} = 5.4\text{--}55$ keV
- Background-free limit: $N = 2.3$ (90% C.L.)

Bounds from the smooth flux of ALPs and dark fermions



Alonso-González, Cerdeño, **Cermeño**, Perez,
PRD 111 (2025) 083019

- Binned analysis with 2 MeV bin width
- All SK exposure, but dominated by phase IV
- Projections for Hyper-Kamiokande (HK), exposure 187×10 kton yrs
- Background from HK report, [16-50] MeV



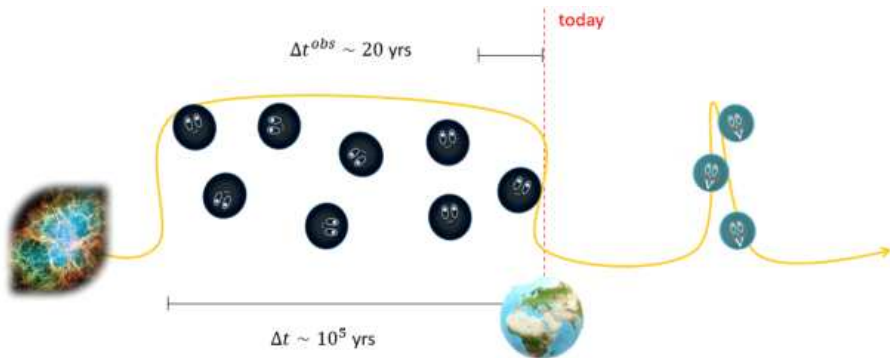
DeRocco et al. PRD 100 (2019) 075018

- Counting experiments in nuclear recoil region
- Background-free assumption
- Limit set by total number of events
- $N = 2.3$ (90% C.L.)

Limitations of the smooth approximation: time window

Alonso-González, Cerdeño, **Cermeño**, Perez, (2026) arXiv:2602.17597

- $\Delta t_{\text{obs}} \ll \Delta t \sim 10^5 \text{ yr}$
- Experiments probe only a limited time interval
- Only a portion of the energy spectrum is observed (the energy and width depend on the explosion time, d_{SN} and m)



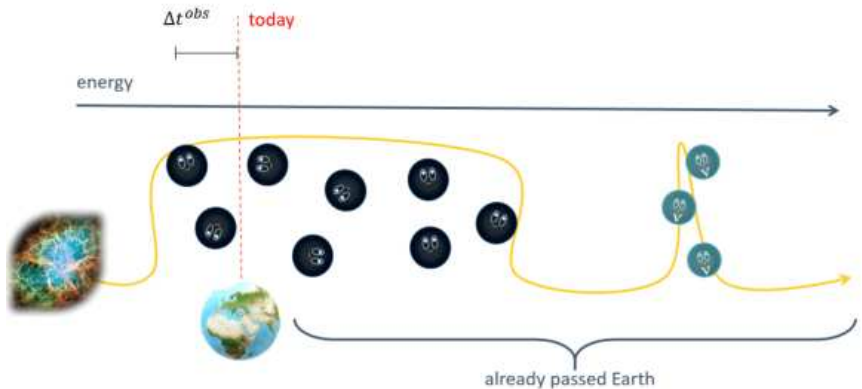
©D. Alonso-González



Limitations of the smooth approximation: energy-dependent arrival

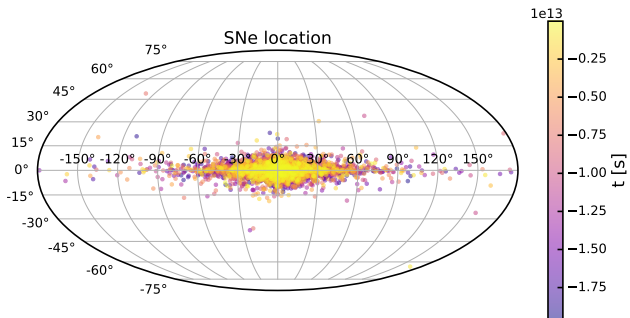
*Alonso-González, Cerdeño, **Cermeño**, Perez, (2026) arXiv:2602.17597*

- Sensitivity to a limited energy range
- For some combinations of the explosion time, d_{SN} and m , part of the relevant signal has already passed \Rightarrow reduction of the flux



Numerical simulation of the galactic supernova history

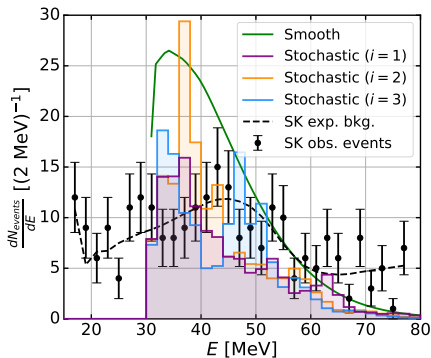
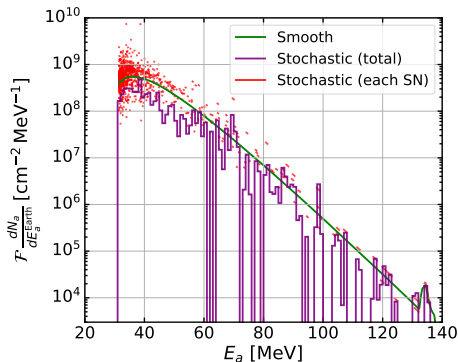
- SNe distributed in space and time according to the galactic rate (~ 14250 SNe expected over 8.8×10^5 yr)



- Only SNe contributing to the flux at present time are considered
- Flux obtained by summing the contribution of all SNe in each realization
- Repeated for multiple (20) realizations
- Code available on <https://github.com/AndresDanielPerez/SGaSNoF>

ALPs: Flux and signal in SK

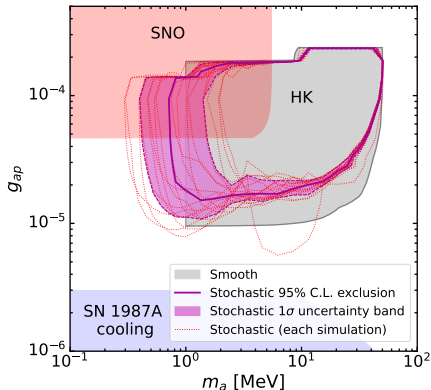
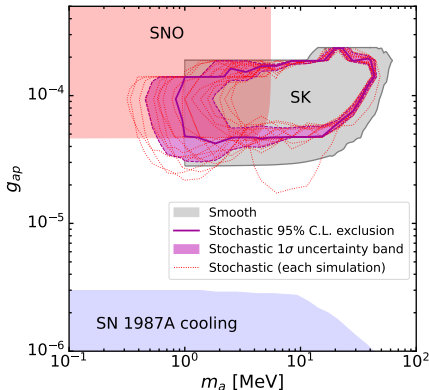
$$m_a = 30 \text{ MeV}, \quad g_{ap} = 9.4 \times 10^{-5}$$



Alonso-González, Cerdeño, Cermeño, Perez, (2026) arXiv:2602.17597

- Left: fluence of ALPs, $\int dt \frac{d\Phi}{dE_{\text{Earth}}}$, in $\Delta t_{\text{obs}} = 20$ yr for one SN history simulation
- Purple line obtained integrating all individual SN contributions in 1 MeV bins
- Right: Number of events per energy in SK phase IV for 3 simulations

ALPs: impact on bounds

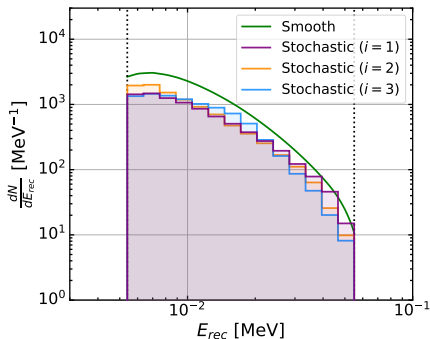
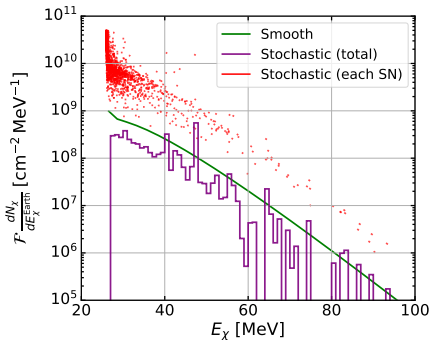


Alonso-González, Cerdeño, Cermeño, Perez, (2026) arXiv:2602.17597

- Binned likelihood analysis comparing signal + background with data
- Bounds obtained from multiple SN realizations
- Central limit from mean χ^2 , with a 1σ spread

Dark fermions: flux and signal in LZ

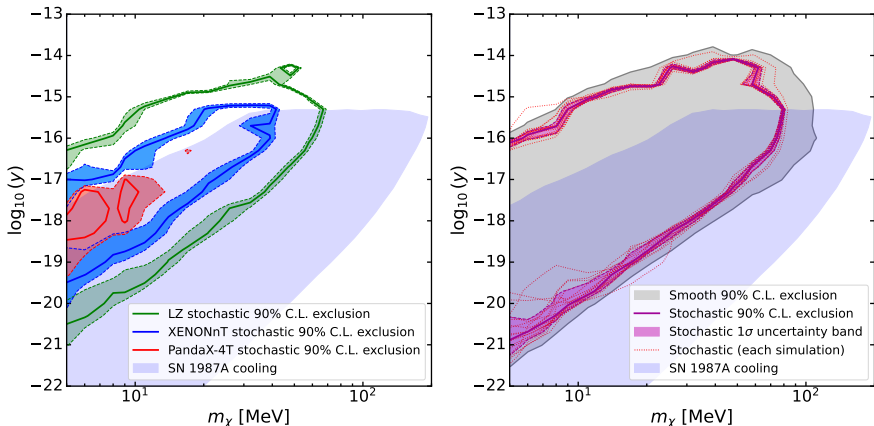
$$m_\chi \sim 26 \text{ MeV}, \quad \log(y) \sim -15, \quad \text{with } y = \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}} \right)^4 \text{ and } \alpha_D = g_d^2/4\pi, \quad \Delta t_{\text{obs}} = 2.74 \text{ yr}$$



*Alonso-González, Cerdeño, **Cermeño**, Perez, (2026) arXiv:2602.17597*

- Left: fluence of dark fermions, $\int dt \frac{d\Phi}{dE_{\text{Earth}}}$, for one SN history simulation
- Purple line obtained integrating all individual SN contributions in 1 MeV bins
- Right: Number of events per energy in LZ for 3 simulations

Dark fermions: impact on bounds



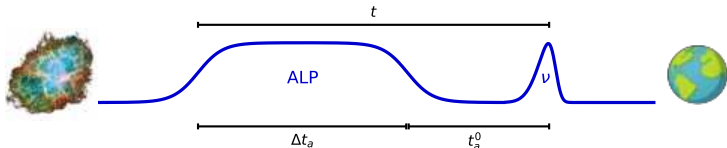
Alonso-González, Cerdeño, Cermeño, Perez, (2026) arXiv:2602.17597

- Constraints: LZ, XENONnT and PandaX-4T, with 4.2, 3.1 and 1.54 tonne-year exposures
- Projection: LZ 15 tonne-year exposure
- Central limit from mean expected number of events, with a 1σ spread

What happens for lighter ALPs

Alonso-González, Cerdeño, **Cermeño**, Perez, PRD 111 (2025) 083029

Expected signals in neutrino water Cherenkov detectors from a single future supernova



- ALPs from a SN located at a distance d_{SN} will arrive with a time delay with respect to the first neutrino event $t_a \simeq \frac{d_{SN} m_a^2}{2E_a^2} \sim 2 \times 10^6 \text{ s} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2 \left(\frac{16 \text{ MeV}}{E_a} \right)^2$
- The arrival time window of ALPs $\Delta t_a \simeq t_a(E_a^{\text{low}}, m_a, d_{SN}) - t_a(E_a^{\text{high}}, m_a, d_{SN})$

$$E_a^{\text{low}} \sim 16 \text{ MeV}, E_a^{\text{high}} \sim 80 \text{ MeV}, t_a^0(m_a, d_{SN}) = E_a(80 \text{ MeV}, m_a, d_{SN}) \sim 8 \times 10^4 \text{ s} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2$$

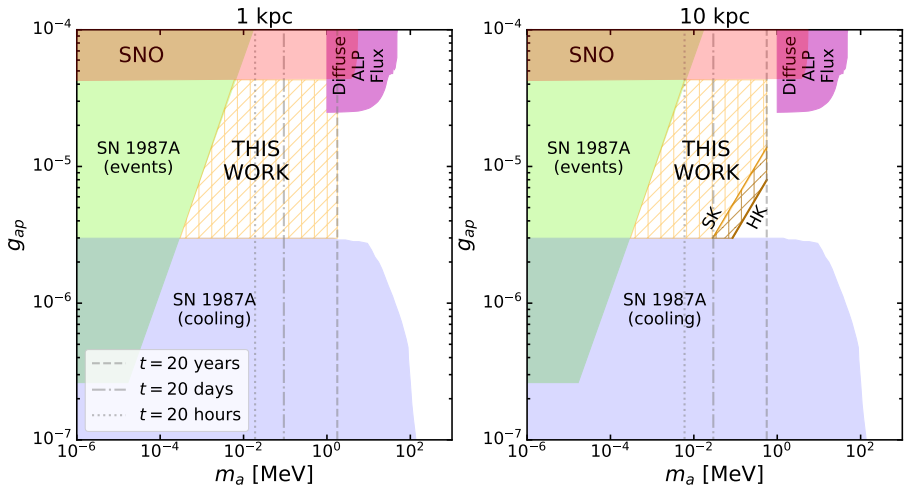
$$t_a^0(m_a, d_{SN}) \sim 1 \text{ day} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2, \Delta t_a \sim 20 \text{ days} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2$$

ALP region that can be probed with future galactic SNe

$$Z(\Delta t_a) = \frac{N_\gamma(\Delta t_a)}{\sqrt{\bar{n}_{bkg} \Delta t_a}}, \quad N_\gamma(\Delta t_a) \geq \max\left[2, 2\sqrt{\bar{n}_{bkg} \Delta t_a}\right], \quad \bar{n}_{bkg} \text{ background events per unit time}$$

t the time it takes for the last ALP to arrive

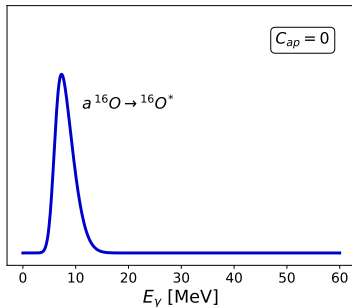
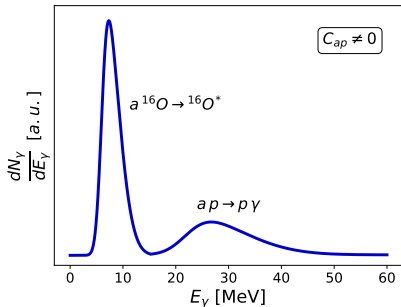
Alonso-González, Cerdeño, Cermeño, Perez, PRD 111 (2025) 083029



Disentangling ALP-proton and ALP-neutron couplings

- Rate from $ap \rightarrow p\gamma$ peaking at $E_\gamma \sim 20 - 30$ MeV smaller than the oxygen excitation one with peak at $E_\gamma \sim 5 - 10$ MeV *Carenza et al., PRC 109 (2024) 015501*
- $ap \rightarrow p\gamma$ signal only sensitive to ALP-proton coupling
- Oxygen de-excitation depends on both ALP-proton and ALP-neutron couplings

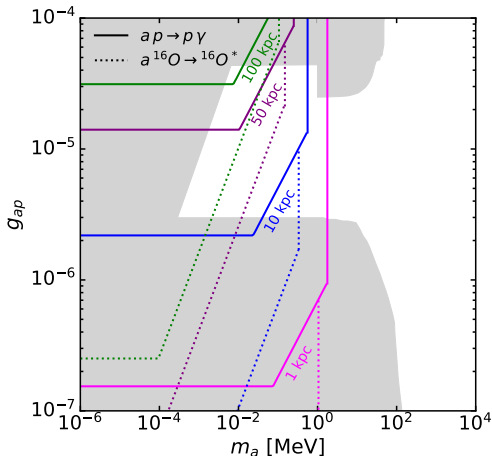
The comparison of both signals in a future observation \Rightarrow measure of g_{ap}/g_{an}



Disentangling ALP-proton and ALP-neutron couplings

The comparison of both signals in a future observation \Rightarrow measure of g_{ap}/g_{an}

Alonso-González, Cerdeño, Cermeño, Perez, PRD 111 (2025) 083029



This can be applied to SNe up to ~ 100 kpc

Conclusions

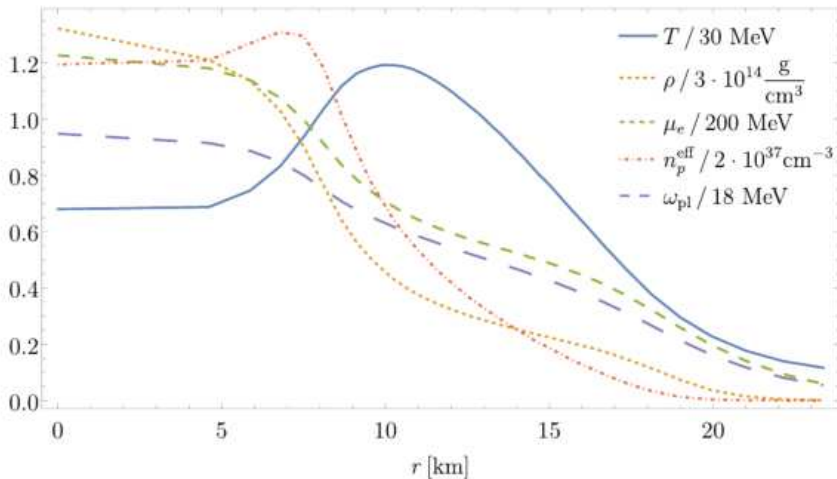
- Core-collapse supernovae are powerful probes of dark sectors
- MeV particles from past galactic supernovae can form a diffuse flux at Earth, enabling direct detection in terrestrial experiments
- We derive new constraints on axion-like particles coupled to nucleons and dark fermions coupled to SM fermions from current experiments
- We performed a simulation of the galactic supernova history and demonstrated that the diffuse flux is not smooth but stochastic, affecting the expected signal and weakening previous limits
- ALPs lighter than 1 MeV from a future nearby supernova would produce signals in neutrino water Cherenkov detectors that would allow us to disentangle ALP-proton and ALP-neutron couplings

Backup slides

SN profiles

Ferreira, Marsh, Müller, JCAP 11 (2022) 057

1D simulation AGILE-BOLTZTRAN code, $18 M_{\odot}$ progenitor, $t = 1$ s post-bounce



Proto-neutron star composition

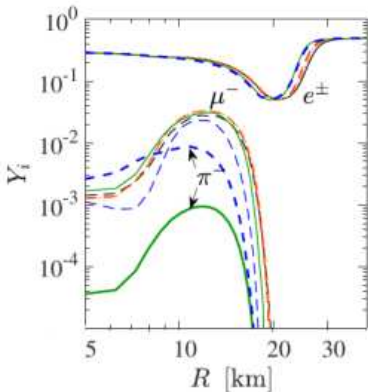
Baryonic density $n_B = n_n + n_p = \frac{\rho}{m_N}$, particle fraction $Y_i = \frac{n_i}{n_B}$, charge neutrality $Y_p = Y_e + Y_\mu + Y_\pi$

n_{π^-} enhancement due to π - N interactions (virial expansion) *Fore, Reddy, PRC 101 (2020) 035809*

$$\frac{n_{\pi^0}}{n_{\pi^-}} \sim \frac{n_{\pi^+}}{n_{\pi^0}} \sim \frac{n_p}{n_n} = \mathcal{O}(0.1)$$

Fischer et al., PRD 104 (2021) 103012

- green solid line: non-interacting
- blue dashed line: virial expansion



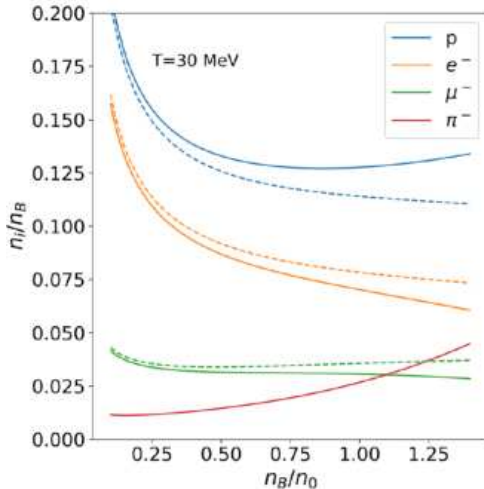
Recent works predict n_{π^-} smaller than the non-interacting case using heavy-baryon chiral perturbation theory *Fore et al., PRC 110 (2024) 025803*, *Fischer, Making Neutron Stars a Laboratory for New Physics, CERN 2025*

Proto-NS composition

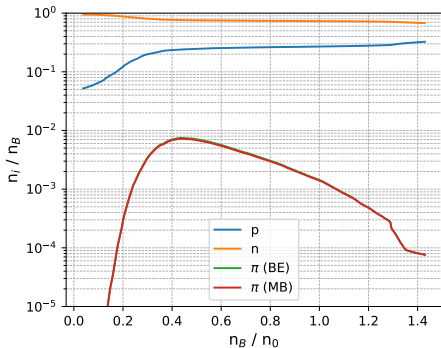
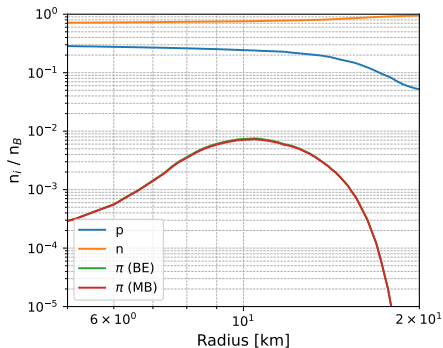
$$n_B = n_n + n_p = \frac{\rho}{m_N}, \text{ the nuclear saturation density } n_0 = 0.15 \text{ fm}^{-3}$$

$$n_p = n_{e^-} + n_{\mu^-} + n_{\pi^-}, \quad n_{\pi^+} \ll n_{\pi^0} \ll n_{\pi^-}, \quad \frac{n_{\pi^0}}{n_{\pi^-}} \sim \frac{n_{\pi^+}}{n_{\pi^0}} \sim \frac{n_p}{n_n} = O(0.1)$$

Fore, Reddy, PRC 101 (2020) 035809 (solid lines with pions)

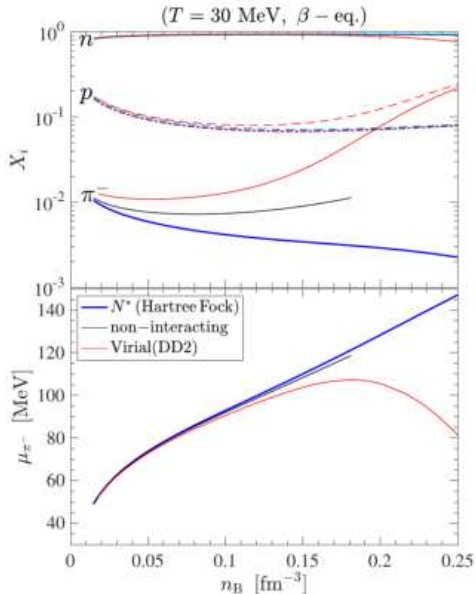


Proto-NS composition



Pion abundance in SN

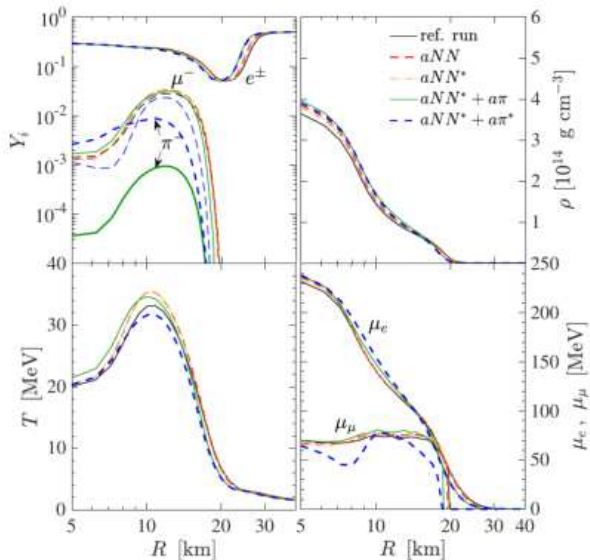
Fischer, Making Neutron Stars a Laboratory for New Physics, CERN 2025



Effect of ALPs on the profiles

Fischer et al., PRD 104 (2021) 103012

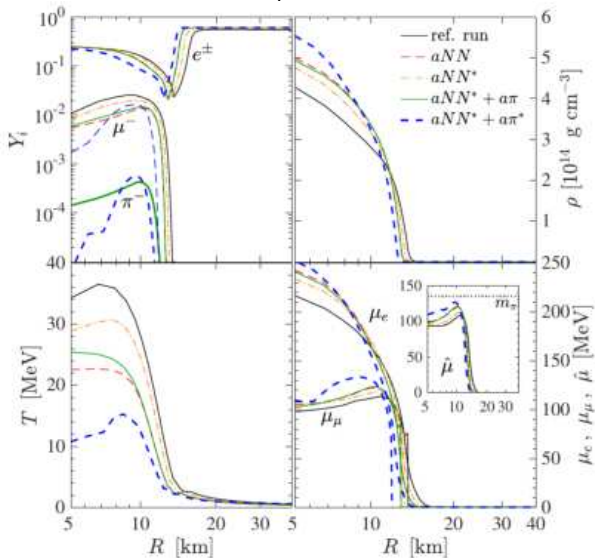
1D sim AGILE-BOLTZTRAN code, $18 M_{\odot}$ progenitor, $t = 1$ s post-bounce, DD2 RMF EOS



Effect of ALPs on the profiles

Fischer et al., PRD 104 (2021) 103012

$t = 7$ s post-bounce



Cumulative percentage of SN vs progenitor star mass

Sukhbold et al., ApJ. 821 (2016) 38

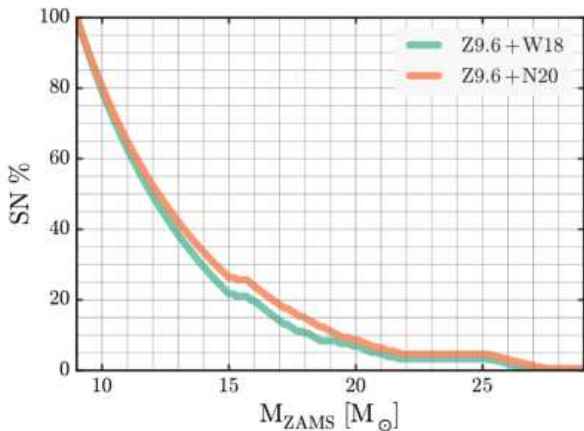


FIG. 14.— The percentage of Type II supernovae above a given main sequence mass for explosions using the Z9.6 and W18 or N20 engines. A Salpeter IMF has been assumed. Successful explosions above $30 M_{\odot}$ do not make Type II supernovae.

SN profiles for different progenitor masses

Calore et al., PRD 105 (2022) 063028

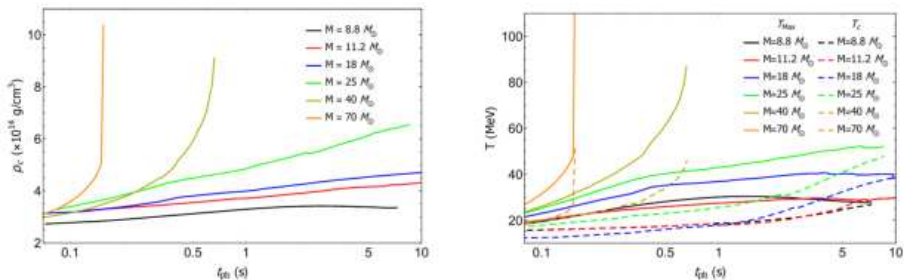


FIG. 1. PNS evolution during the deleptonization phase for the SN explosion models launched from different progenitors with ZAMS masses of 8.8, 11.2, 18.0 and 25 M_\odot . *Left panel:* central density, ρ_{centre} . *Right panel:* central and maximum temperatures, T_{centre} (dashed lines) and T_{Max} (solid lines).

Uncertainties in SN bounds

Lella et al., PRD 109 (2024) 023001

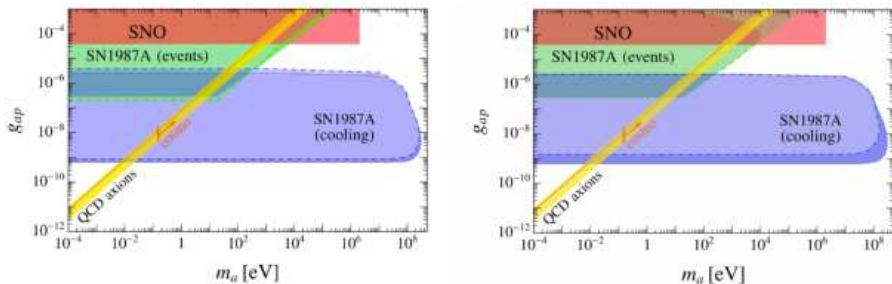
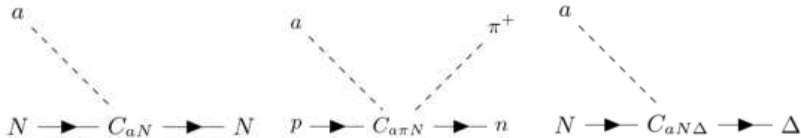


FIG. 4. Summary of the bounds with their uncertainties in the g_{ap} vs m_a plane together with the QCD axion band. The color code is the same as Fig. 3. *Left panel:* The hatched regions show the uncertainty on the bounds from the SN 1987A cooling (blue region) and the non-observation of extra events in the KII experiment in coincidence with SN 1987A (green region). In both the cases, solid thin lines delimit the region excluded by the GARCHING model while the dashed thick lines delineate the one excluded using the AGILE-BOLTZTRAN code. *Right panel:* The blue hatched region showing the uncertainty on the cooling bound is obtained by assuming the presence of pions in the SN core, or not. The green hatched region displays uncertainties regarding ALP absorption by heavy nuclei in the neutrino-driven wind.

ALP-nucleon interactions



Di Luzio et al., Phys. Rep. 870 (2020) 1, Chang, Choi, PLB 316 (1993) 51

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

C_{aN} model-dependent $O(1)$ axion-nucleon coupling, $g_{aN} = g_a C_{aN}$, $N = p, n$

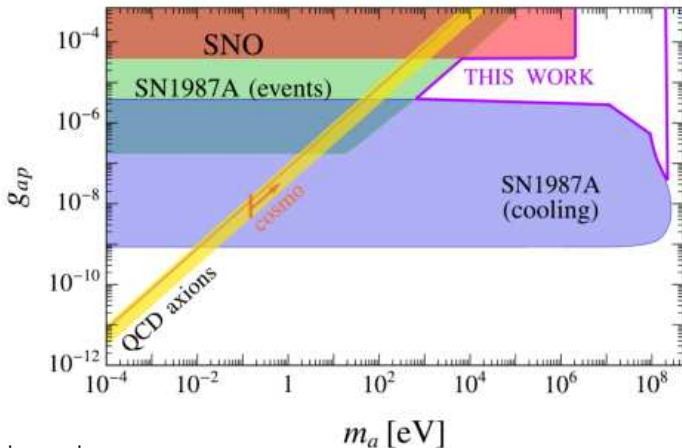
$$C_{a\pi N} = (C_{ap} - C_{an}) / \sqrt{2} g_A, \quad C_{aN\Delta} = -\sqrt{3}/2 (C_{ap} - C_{an})$$

$g_A \simeq 1.28$ the axial coupling, $f_\pi = 92.4$ MeV pion decay constant

ALP-nucleon bounds

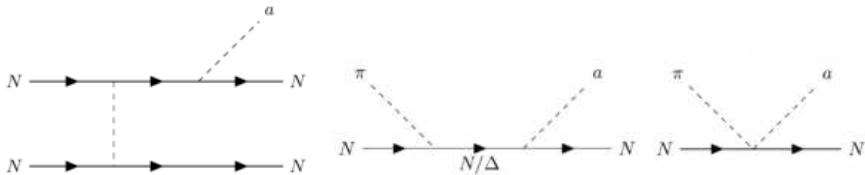
Benchmark values $C_{ap} = -0.47$, $C_{an} = 0$, inspired by the Kim-Shifman-Vainshtein-Zakharov (KSVZ) axion model *Grilli di Cortona, et al., JHEP 01 (2016) 034*; $g_{ap} = C_{ap}g_a$

Lella et al., PRD 109 (2024) 023001



- Trapping regime
- $m_a \gtrsim 200$ MeV, no SN production

ALP production in SN



ALP production spectrum (number density of ALPs produced per unit time and energy)

$$\frac{d^2 n_a}{dE_a dt} = \prod_i \int \frac{g_i d^3 \vec{p}_i}{(2\pi)^3 2E_i} f_i(E_i) \prod_{j \neq a} \int \frac{d^3 \vec{p}'_j}{(2\pi)^3 2E'_j} [1 - f_j(E'_j)] (2\pi)^4 \delta^4 \left(\sum_i p_i - \sum_{j \neq a} p'_j - p_a \right) \frac{|\vec{p}_a|}{4\pi^2} |\overline{\mathcal{M}}|^2$$

Fermi-Dirac distribution function for nucleons $f(E_N) = \frac{1}{1 + \exp\left(\frac{E_N - \mu_N}{T}\right)}$, Bose-Einstein distribution function for pions $f(E_\pi) = \frac{1}{1 + \exp\left(\frac{E_\pi - \mu_\pi}{T}\right)}$, nucleon and pion chemical potentials μ_N and μ_π

Absorption effects in the ALP spectrum

ALPs can be reabsorbed in the nuclear medium through $N+N+a \rightarrow N+N$ and $N+a \rightarrow N+\pi$

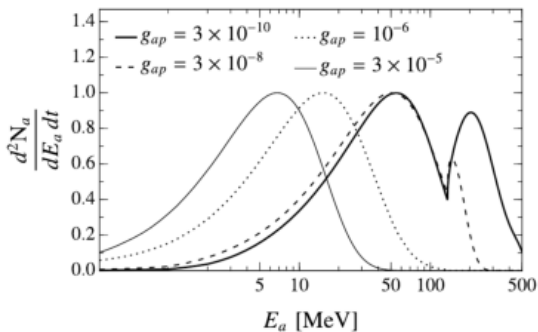
$$\frac{d^2 N_a}{dE_a dt} = \int_0^\infty 4\pi r^2 dr \langle e^{-\tau(E_a, r)} \rangle \frac{d^2 n_a}{dE_a dt}(E_a, r)$$

Absorption effects averaged over the cosine of the emission angle

$$\langle e^{-\tau(E_a, r)} \rangle = \frac{1}{2} \int_{-1}^{+1} d\mu e^{-\int_0^\infty ds \Gamma_a(E_a^*, \sqrt{r^2 + s^2 + 2rs\mu})}$$

Absorption rate $\Gamma_a(E_a, r) = \lambda_a^{-1}(E_a, r) \left[1 - e^{-\frac{E_a}{T(r)}} \right]$, $\lambda_a(E_a, r)$ ALP mean free path

For $m_a \leq 1$ MeV, *Lella et al., PRD 109 (2024) 023001*



ALP spectrum at Earth from one SN

The spectral fluence of ALPs from an isotropic production spectrum far away from the SN

$$\frac{dN_a}{dE_a^{*\infty}} = \int_{t_{\min}}^{t_{\max}} dt \int_0^{\infty} \alpha(r)^{-1} 4\pi r^2 dr \left\langle e^{-\tau(E_a^*, r)} \right\rangle \frac{d^2 n_a}{dE_a dt} (r, t, \alpha(r)^{-1} E_a^{*\infty}),$$

$\alpha(r) \leq 1$ the lapse factor accounting for the gravitational redshift inside and outside the star

$E_a^{*\infty} = \alpha(r) E_a$ the observed energy at infinity

$E_a^* = \frac{\alpha(r)}{\alpha(\sqrt{r^2 + s^2 + 2rs\mu})} E_a$ redshifted from the point of ALP production to the point of absorption

Diffuse galactic SN ALP flux at Earth

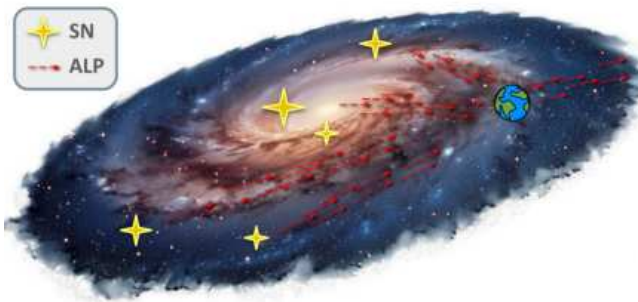
D. Alonso-González, D. Cerdeño, **M. Cermeño**, A. D. Perez, PRD 111 (2025) 083019

- SN MeV ALPs travel with semi-relativistic velocities due to their massive nature
- ALPs are produced with $E_a = [m_a - \mathcal{O}(100) \text{ MeV}] \Rightarrow$ spread in arrival time Δt

For a SN at the Galactic Center and $m_a \simeq 1 - 100 \text{ MeV}$, $\Delta t \sim 5 \times 10^2 - 5 \times 10^3 \text{ yrs}$

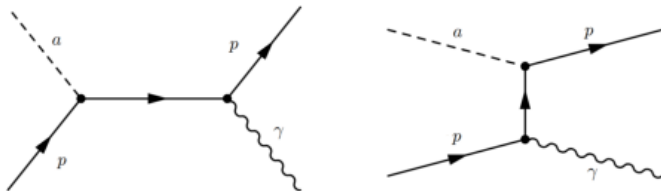
Galactic SN rate ~ 1.63 per century *Rozwadowska et al. New Astron 83 (2021)* \Rightarrow

$\sim 10 - 100$ SN ALP fluxes overlap at Earth \Rightarrow near constant flux for $m_a \gtrsim 1 \text{ MeV}$



Detection of the diffuse SN ALP flux in neutrino detectors

ALPs reach neutrino detectors and produce MeV photons after interacting on free protons



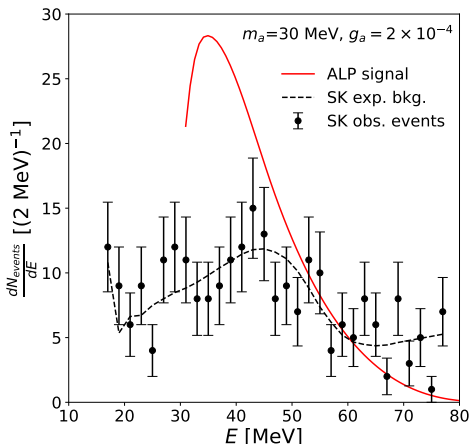
Number of photons per energy and time produced at an experiment with N_t targets

$$\frac{dN_\gamma}{dE_\gamma} = N_t \int_{E_a^{\min}(E_\gamma)}^{E_a^{\max}(E_\gamma)} dE_a^{\text{Earth}} \frac{d\Phi_a}{dE_a^{\text{Earth}}} \frac{d\sigma_{ap \rightarrow p\gamma}}{dE_\gamma}$$

$$E_a^{\max}(E_\gamma) \sim E_a^{\min}(E_\gamma) \sim E_\gamma, \text{ for } 1 \text{ MeV} < E_a < 100 \text{ MeV} \quad (10^{-3} \text{ MeV} < E_\gamma^{\max} - E_\gamma^{\min} < 18 \text{ MeV})$$

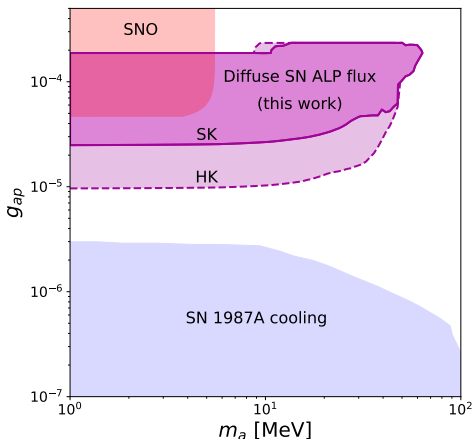
Novel signature, expected in models with ALP-proton couplings

Events from the diffuse ALP flux in Super-Kamiokande



- Super-Kamiokande (SK) phase IV, exposure 22.5×2970 -kton-day
- Energy region $E = 16 - 78$ MeV optimized to search for the DSNB by identifying positrons from inverse beta decay, without neutron coincidence *SK Collaboration, PRD 104 (2021) 122002*
- Background dominated by cosmic ray muon spallation, electrons produced by the decays of low energy muons and pions, and charged current interactions of atmospheric neutrinos

Bounds from SK and projections for HK

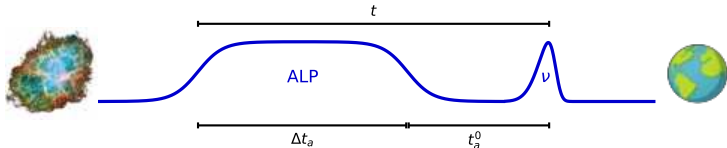


- No observation of anomalous events in SK \Rightarrow constraints on the ALP-proton coupling
Binned analysis with 2 MeV bin width
Considering all SK exposure, but dominated by phase IV
- Projections for Hyper-Kamiokande (HK), exposure 187×10 kton yrs
Background from the HK report, limited to [16-50] MeV

What happens for lighter ALPs

D. Alonso-González, D. Cerdeño, **M. Cermeño**, A. D. Perez, PRD 111 (2025) 083029

Expected signals in neutrino water Cherenkov detectors from a single future supernova



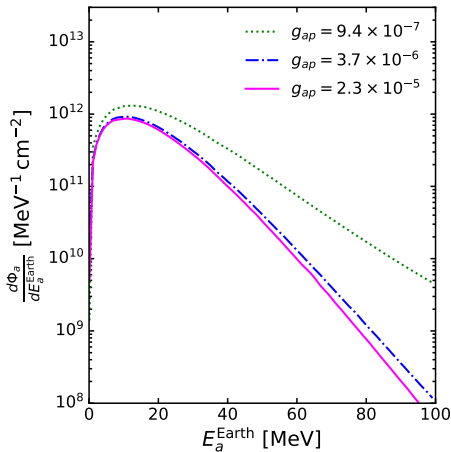
- ALPs from a SN located at a distance d_{SN} will arrive with a time delay with respect to the first neutrino event $t_a \simeq \frac{d_{SN} m_a^2}{2E_a^2} \sim 2 \times 10^6 \text{ s} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2 \left(\frac{16 \text{ MeV}}{E_a} \right)^2$
- The arrival time window of ALPs $\Delta t_a \simeq t_a(E_a^{\text{low}}, m_a, d_{SN}) - t_a(E_a^{\text{high}}, m_a, d_{SN})$

$$E_a^{\text{low}} \sim 16 \text{ MeV}, E_a^{\text{high}} \sim 80 \text{ MeV}, t_a^0(m_a, d_{SN}) = E_a(80 \text{ MeV}, m_a, d_{SN}) \sim 8 \times 10^4 \text{ s} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2$$

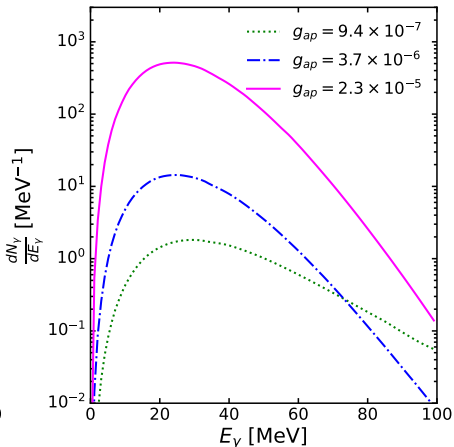
$$t_a^0(m_a, d_{SN}) \sim 0.3 \text{ days} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2, \Delta t_a \sim 23 \text{ days} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2$$

ALP flux and event rate at SK from a single SN

$$\frac{d\Phi_a}{dE_a^{\text{Earth}}} = \frac{1}{4\pi d_{SN}^2} \int_{t_{\min}}^{t_{\max}} dt \int_0^\infty \alpha(r)^{-1} 4\pi r^2 dr \langle e^{-\tau(E_a^*, t, r)} \rangle \frac{d^2 n_a}{dE_a^{\text{loc}} dt} (r, t, \alpha(r)^{-1} E_a^{\text{Earth}})$$



$$d_{SN} = 1 \text{ kpc}, \quad m_a \leq 1 \text{ MeV}$$

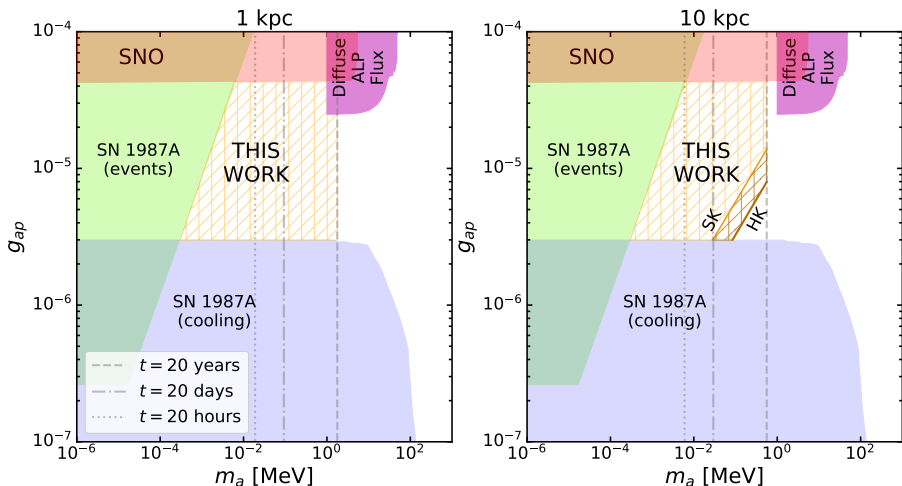


$$\frac{dN_\gamma}{dE_\gamma} = N_t \int_{E_a^{\min}(E_\gamma)}^{E_a^{\max}(E_\gamma)} dE_a^{\text{Earth}} \frac{d\Phi_a}{dE_a^{\text{Earth}}} \frac{d\sigma_{ap \rightarrow p\gamma}}{dE_\gamma}$$

ALP region that can be probed with future galactic SNe

$$Z(\Delta t_a) = \frac{N_\gamma(\Delta t_a)}{\sqrt{\bar{n}_{bkg} \Delta t_a}}, \quad N_\gamma(\Delta t_a) \geq \max\left[2, 2\sqrt{\bar{n}_{bkg} \Delta t_a}\right], \quad \bar{n}_{bkg} \text{ background events per unit time}$$

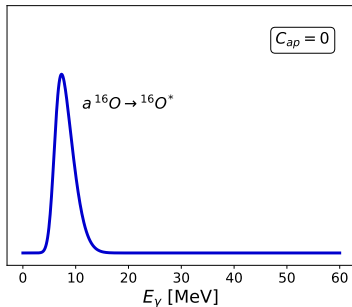
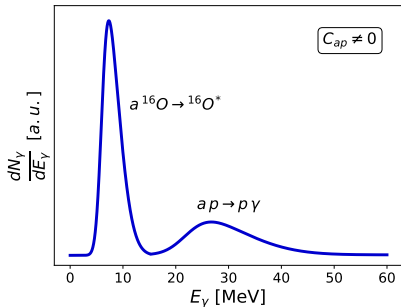
t the time it takes for the last ALP to arrive



Disentangling ALP-proton and ALP-neutron couplings

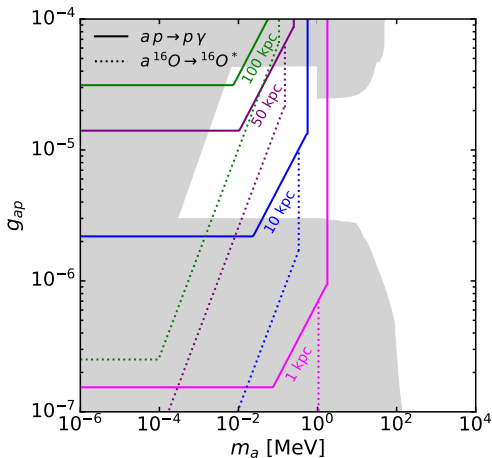
- Rate from $ap \rightarrow p\gamma$ peaking at $E_\gamma \sim 20 - 30$ MeV smaller than the oxygen excitation one with peak at $E_\gamma \sim 5 - 10$ MeV *Carenza et al., PRC 109 (2024) 015501*
- $ap \rightarrow p\gamma$ signal only sensitive to ALP-proton coupling
- Oxygen de-excitation depends on both ALP-proton and ALP-neutron couplings

The comparison of both signals in a future observation \Rightarrow measure of g_{ap}/g_{an}



Disentangling ALP-proton and ALP-neutron couplings

The comparison of both signals in a future observation \Rightarrow measure of g_{ap}/g_{an}



This can be applied to SNe up to ~ 100 kpc

QCD ALPS

The lagrangian for QCD ALPs with interactions to quarks and gluons

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

$f_a = \frac{m_N}{g_a}$, $G_{\mu\nu}^a$ the gluon field strength tensor, $\tilde{G}_{\mu\nu}^a = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma} G^{a\rho\sigma}$ its dual, c_g and c_q model-dependent constants, with $q = u, d, s, c, t, b$

Below the QCD confinement scale $\mathcal{L}_{\text{aQCD}}$ induces ALP couplings with baryons and mesons. The nuclear interaction Lagrangian derived in the context of Heavy Baryon Chiral Perturbation Theory

$$\mathcal{L}_{\text{nuc}} = \frac{\partial^\mu a}{2f_a} \left[C_p \bar{p} \gamma^\mu \gamma_5 p + C_n \bar{n} \gamma^\mu \gamma_5 n + \frac{C_{a\pi N}}{f_\pi} \left(i\pi^+ \bar{p} \gamma^\mu n - i\pi^- \bar{n} \gamma^\mu p \right) + C_{aN\Delta} \left(\bar{p} \Delta_\mu^+ + \bar{\Delta}_\mu^+ p + \bar{n} \Delta_\mu^0 + \bar{\Delta}_\mu^0 n \right) \right]$$

$$C_{a\pi N} = \frac{(C_p - C_n)}{\sqrt{2}g_A}, \quad C_{aN\Delta} = -\frac{\sqrt{3}}{2} (C_p - C_n),$$

$f_\pi = 92.4\text{MeV}$, $g_A = 1.28$,

$$C_p(c_g, c_u, c_d) = -0.47c_g + 0.88c_u - 0.39c_d - 0.038c_s \\ - 0.012c_c - 0.009c_b - 0.0035c_t$$

$$C_n(c_g, c_u, c_d) = -0.02c_g + 0.88c_d - 0.39c_u - 0.038c_s \\ - 0.012c_c - 0.009c_b - 0.0035c_t$$

Nucleon electric-dipole portal for QCD-ALPs

The gluonic part of the lagrangian

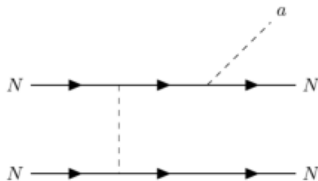
$$\mathcal{L}_{ag} = c_g \frac{g_s^2}{32\pi^2} \frac{a}{f_a} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

induces a model independent nucleon EDM portal interaction *Pospelov, Ritz, PRL 83 (1999) 2526*

$$\mathcal{L}_a^{\text{nEDM}} = -\frac{i}{2} g_{d,N} a \bar{N} \gamma_5 \sigma_{\mu\nu} N F^{\mu\nu}$$

with $g_{d,N} = \frac{C_{aN\gamma}}{m_N f_a}$, with $f_a = \frac{m_N}{g_a}$ and $C_{an\gamma} = -C_{ap\gamma} = 0.0033(15)$

ALP production in SN: bremsstrahlung



Axion emission spectrum

Giannotti, Nesti, PRD 72 (2005) 063005, Carenza et al., JCAP 10 (2019) 016

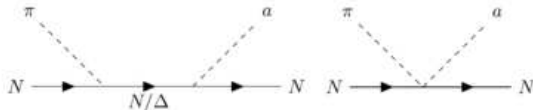
$$\left(\frac{d^2 n_a}{dE_a dt}\right)_{NN} = \frac{g_a^2}{16\pi^2} \frac{n_B}{m_N^2} (E_a^2 - m_a^2)^{\frac{3}{2}} e^{-\frac{E_a}{T}} S_\sigma(E_a) \Theta(E_a - m_a),$$

nucleon structure function $S_\sigma(E_a) = \frac{\Gamma_\sigma}{E_a^2 + \Gamma^2} s\left(\frac{E_a}{T}\right)$, $s\left(\frac{E_a}{T}\right)$ dimensionless nuclear function

nucleon spin fluctuation rate $\Gamma_\sigma = 4\pi^{-1.5} \left(\frac{g_A}{2f_\pi}\right)^4 T^{0.5} m_N^{0.5} \rho$, $\Gamma = g\Gamma_\sigma$,

g from scattering kernel normalization

ALP production in SN: pion-axion conversion



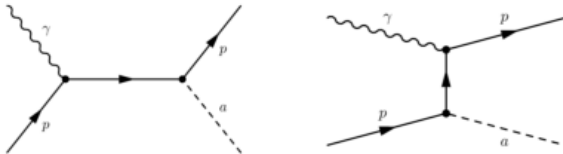
Axion emission spectrum *Carenza et al., PRL 126 (2021) 071102*

$$\begin{aligned} \left(\frac{d^2 n_a}{dE_a dt} \right)_{N\pi} &= \frac{g_a^2 T^{1.5}}{2^{1.5} \pi^5 m_N^{0.5}} \left(\frac{g_A}{2f_\pi} \right)^2 (E_a^2 - m_a^2)^{\frac{1}{2}} \\ &\times C_a^{p\pi^-} \frac{\Theta(E_a - \max(m_a, m_\pi))}{\exp(x_a - y_\pi - \hat{\mu}_\pi) - 1} (E_a^2 - m_\pi^2)^{\frac{1}{2}} \frac{E_a^2}{E_a^2 + \Gamma^2} \\ &\times \int_0^\infty dy y^2 \frac{1}{\exp(y^2 - \hat{\mu}_p) + 1} \frac{1}{\exp(-y^2 + \hat{\mu}_n) + 1} \end{aligned}$$

$C_a^{p\pi^-} = \frac{m_N^2}{g_A^2} \beta_a^2 \mathcal{G}_a(|\mathbf{p}_\pi|)$ term related to the matrix element with $\mathcal{G}_a(|\mathbf{p}_\pi|)$ a dimensionless function

$\hat{\mu}_i = \frac{\mu_i - m_i - U_i}{T}$ the degeneracy parameter with μ_i and U_i the chemical potential and the self-energies of the particles, $y_\pi = m_\pi/T$, $x_a = E_a/T$

ALP photo-production in SN



Axion emission spectrum

$$\left(\frac{d^2 n_a}{dE_a dt} \right)_{p\gamma} = n_p^{\text{eff}} \frac{6}{(2\pi)^2} \int dE_\gamma \frac{1}{e^{E_\gamma/T} - 1} (E_\gamma^2 - m_\gamma^2) \frac{d\sigma_{\gamma p \rightarrow p a}}{dE_a}$$

$n_p^{\text{eff}} \equiv 2 \int \frac{d^3 \vec{p}}{(2\pi)^3} f_p(E) (1 - f_p(E))$ effective number density of protons,

f_p the Fermi-Dirac distribution function

m_γ effective photon mass

Differential cross section for ALP photo-production in SN



$$\frac{d\sigma_{\gamma p \rightarrow p a}}{dE_a} = \frac{1}{32\pi} \int_{-1}^1 \frac{|\overline{\mathcal{M}}|^2}{|\vec{p}_\gamma|^2 m_p^*} \delta(\cos \theta_a - \cos \theta_a^0) d \cos \theta_a$$

with

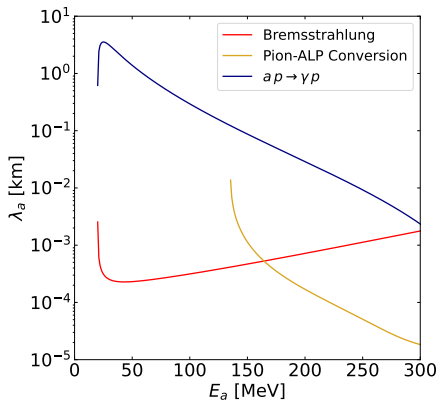
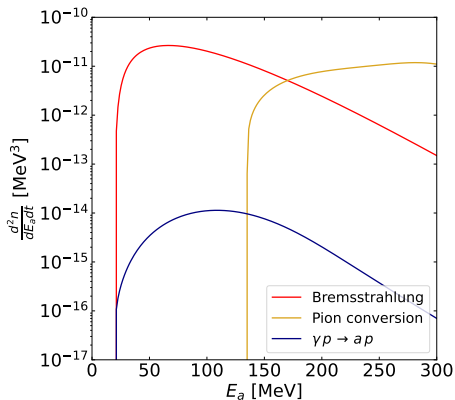
$$\cos \theta_a^0 = \frac{E_\gamma E_a - m_p^*(E_\gamma - E_a) - \frac{1}{2}(m_a^2 + m_\gamma^2)}{\sqrt{E_\gamma^2 - m_\gamma^2} \sqrt{E_a^2 - m_a^2}} \quad (1)$$

determined by energy conservation, and with the averaged squared amplitude given by

$$\begin{aligned} |\overline{\mathcal{M}}|^2 = \frac{4}{3} C_{ap}^2 e^2 g_a^2 m_p^* & \left[\frac{2E_a(m_a^2 + E_\gamma m_p^*) + m_a^2(m_p^* - E_\gamma) - 4E_a^2 m_p^* + E_a m_\gamma^2}{(m_a^2 - 2E_a m_p^*)^2} \right. \\ & \left. + \frac{m_a^2(m_p^* - E_\gamma)}{(2E_\gamma m_p^* + m_\gamma^2)^2} + \frac{2m_a^2 m_p^* - 2E_a^2 m_p^* - E_a m_a^2}{(m_a^2 - 2E_a m_p^*)(2E_\gamma m_p^* + m_\gamma^2)} \right]. \quad (2) \end{aligned}$$

ALP production in SN: comparison

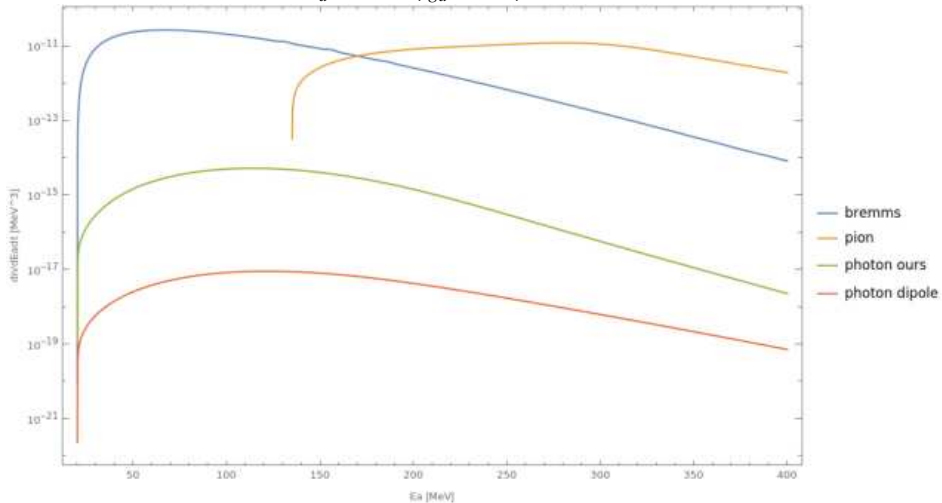
$$R = 10 \text{ km}, m_a = 20 \text{ MeV}, g_a = 10^{-5}$$



Negligible ALP photo-production, no absorption via $ap \rightarrow \gamma p$

ALP production in SN: comparison

$$m_a = 20\text{MeV}, g_a = 10^{-5}, R = 10\text{ km}$$



Absorption effects in the ALP spectrum

ALPs can be reabsorbed in the nuclear medium through $N+N+a \rightarrow N+N$ and $N+a \rightarrow N+\pi$

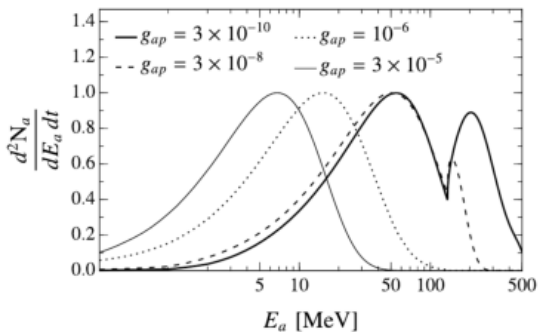
$$\frac{d^2 N_a}{dE_a dt} = \int_0^\infty 4\pi r^2 dr \langle e^{-\tau(E_a, r)} \rangle \frac{d^2 n_a}{dE_a dt}(E_a, r)$$

Absorption effects averaged over the cosine of the emission angle

$$\langle e^{-\tau(E_a, r)} \rangle = \frac{1}{2} \int_{-1}^{+1} d\mu e^{-\int_0^\infty ds \Gamma_a(E_a^*, \sqrt{r^2 + s^2 + 2rs\mu})}$$

Absorption rate $\Gamma_a(E_a, r) = \lambda_a^{-1}(E_a, r) \left[1 - e^{-\frac{E_a}{T(r)}} \right]$, $\lambda_a(E_a, r)$ ALP mean free path

For $m_a \leq 1$ MeV, *Lella et al., PRD 109 (2024) 023001*



ALP spectrum at Earth from one SN

The spectral fluence of ALPs from an isotropic production spectrum far away from the SN

$$\frac{dN_a}{dE_a^{*\infty}} = \int_{t_{\min}}^{t_{\max}} dt \int_0^{\infty} \alpha(r)^{-1} 4\pi r^2 dr \left\langle e^{-\tau(E_a^*, r)} \right\rangle \frac{d^2 n_a}{dE_a dt} (r, t, \alpha(r)^{-1} E_a^{*\infty}),$$

$\alpha(r) \leq 1$ the lapse factor accounting for the gravitational redshift inside and outside the star

$E_a^{*\infty} = \alpha(r) E_a$ the observed energy at infinity

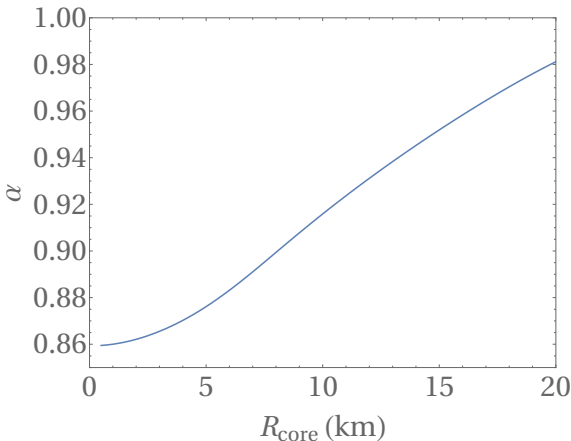
$E_a^* = \frac{\alpha(r)}{\alpha(\sqrt{r^2 + s^2 + 2rs\mu})} E_a$ redshifted from the point of ALP production to the point of absorption

Lapse function

The lapse function encodes effects due to the proto-NS gravitational potential $\Phi(r)$ evaluated locally in the proto-NS interior

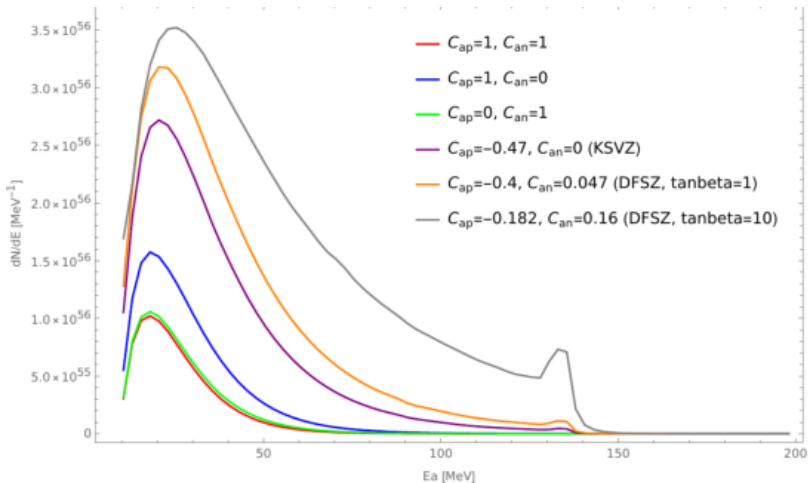
$$\alpha(r) = \sqrt{1 - 2\Delta\Phi(r)}$$

$\Delta\Phi(r) = G \int_r^\infty \frac{m_{\text{enc}}(r')}{r'^2} dr'$ change in potential from r to ∞ and $m_{\text{enc}}(r')$ mass enclosed in r'



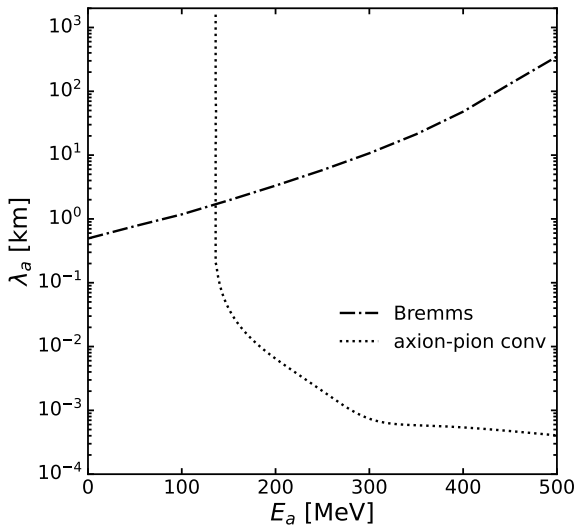
ALP spectrum at Earth for other models

$$m_a = 10 \text{ MeV}, g_a = 10^{-6}$$



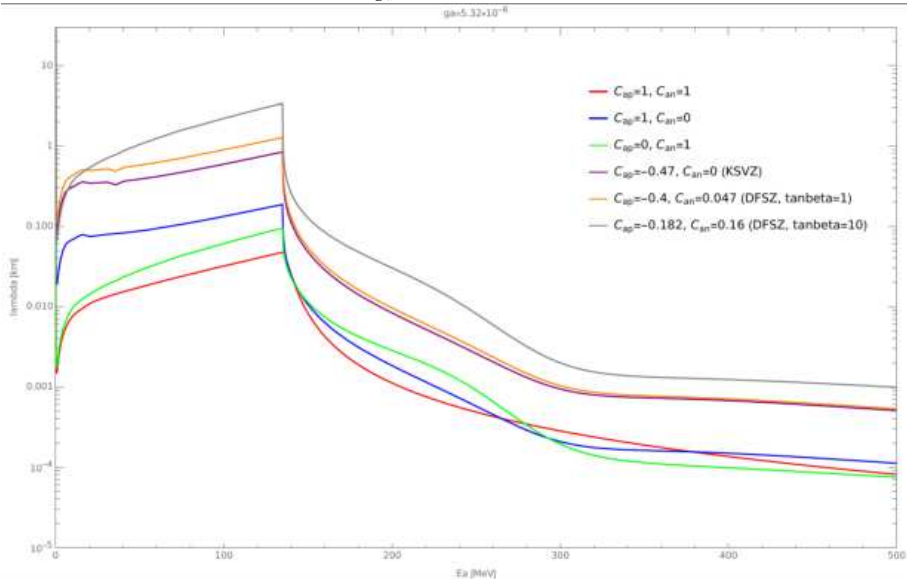
Mean-free path

$R = 20 \text{ km}$, $g_a = 5 \cdot 10^{-6}$, massless ALPs



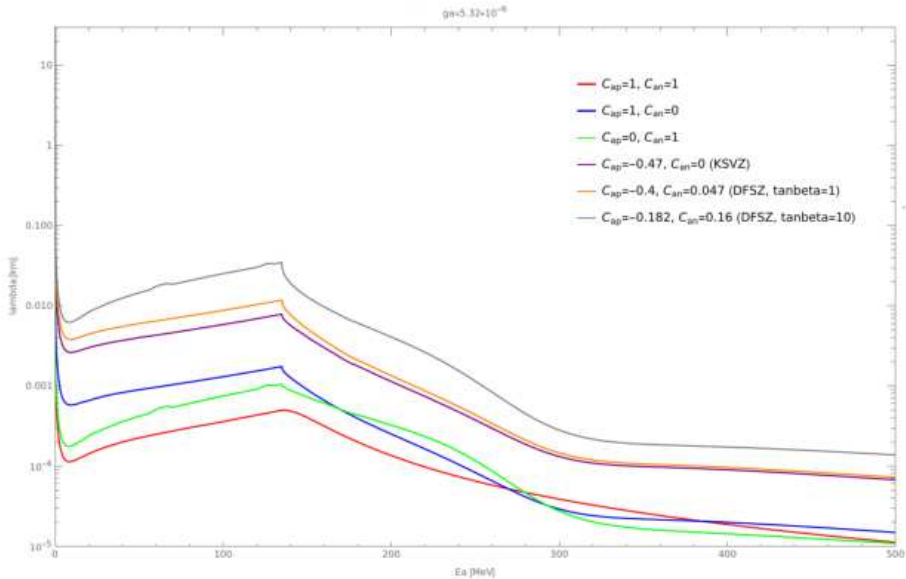
Mean-free path

$R = 20 \text{ km}$, $g_a = 5 \cdot 10^{-6}$, massless ALPs



Mean-free path

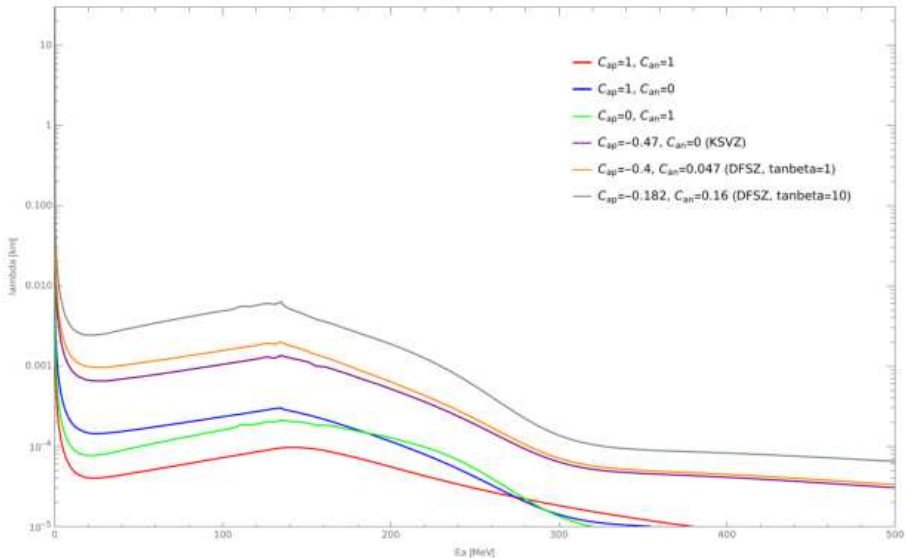
$R = 15 \text{ km}$, $g_a = 5 \cdot 10^{-6}$, massless ALPs



Mean-free path

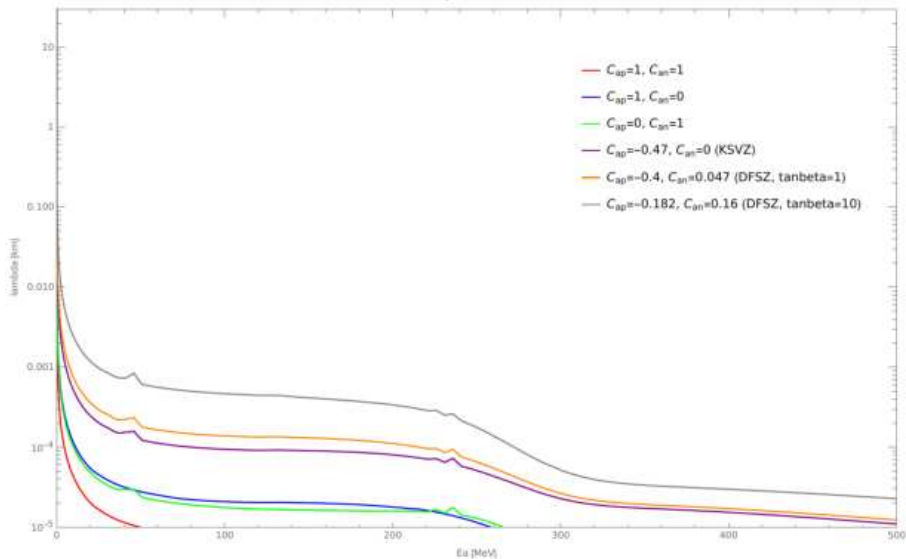
$R = 10 \text{ km}$, $g_a = 5 \cdot 10^{-6}$, massless ALPs

$g_a = 5.32 \cdot 10^{-6}$

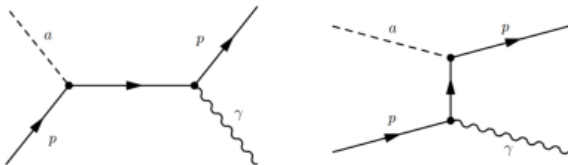


Mean-free path

$R = 5 \text{ km}$, $g_a = 5 \cdot 10^{-6}$, massless ALPs



Feynman amplitude for $a p \rightarrow p \gamma$



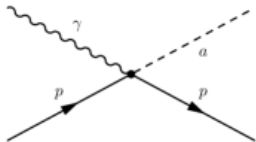
$$a(p_1) + p(p_2) \rightarrow p(p_3) + \gamma(p_4)$$

$$\mathcal{M}_s = \bar{u}(p_3) [e\gamma^\mu] \frac{i}{(\not{p}_1 + \not{p}_2) - m_p} \left[\frac{g_a C_{ap}}{2m_p} \gamma^\nu \gamma_5 \right] u(p_2) (p_1)_\nu \epsilon_\mu^*(p_4)$$

$$\mathcal{M}_t = \bar{u}(p_3) \left[\frac{g_a C_{ap}}{2m_p} \gamma^\rho \gamma_5 \right] \frac{i}{(\not{p}_3 - \not{p}_1) - m_p} [e\gamma^\lambda] u(p_2) (p_1)_\rho \epsilon_\lambda^*(p_4)$$

$$|\overline{\mathcal{M}}|^2 = \frac{C_{ap}^2 e^2 g_a^2}{E_\gamma^2 m_p (2E_a m_p + m_a^2)^2} \times 4m_p^3 (E_a - E_\gamma)^2 (2E_a E_\gamma + m_a^2) \\ + 4m_a^2 m_p^2 (E_a - E_\gamma) (E_\gamma (E_a - E_\gamma) + m_a^2) + m_a^4 m_p (2E_a E_\gamma + m_a^2) + E_\gamma m_a^6$$

Feynman amplitude dipole interaction



$$a(p_1) + p(p_2) \rightarrow p(p_3) + \gamma(p_4)$$

$$\mathcal{M}_{\text{dipole}} = \bar{u}(p_3) \left[-\frac{i}{2} g_{d,p} \gamma_5 \sigma^{\mu\nu} \right] \bar{u}(p_2) \left[(p_4)_\mu \epsilon_\nu^*(p_4) - (p_4)_\nu \epsilon_\mu^*(p_4) \right]$$

$$g_{d,N} = \frac{C_{apy} g_a}{m_N^2}, \quad C_{apy} = 0.0033$$

$$|\overline{\mathcal{M}}|_{\text{dipole}}^2 = 8 C_{apy}^2 g_a^2 \frac{E_\gamma (2E_a m_p + m_a^2)}{m_p^3}$$

Differential cross section $a p \rightarrow \gamma p$

$$\frac{d\sigma_a}{dE_\gamma} = \int \frac{1}{32\pi} \frac{|\overline{\mathcal{M}}|^2}{|\vec{p}_a|^2 m_A} d\cos\theta \delta(\cos\theta - \cos\theta^0)$$

the cosine of the angle between the photon and ALP momenta is fixed by energy conservation

$$\cos\theta_0 = \frac{2E_\gamma(m_p + E_a) - 2m_p E_a - m_a^2}{2E_\gamma \sqrt{E_a^2 - m_a^2}}$$

$|\cos\theta^0| \leq 1 \Rightarrow E_\gamma^{\min}(E_a), E_\gamma^{\max}(E_a)$ or $E_a^{\min}(E_\gamma), E_a^{\max}(E_\gamma)$

$$E_\gamma^{\min} = \frac{m_a^2 + 2E_a m_p}{2(m_p + E_a) + 2\sqrt{E_a^2 - m_a^2}} \quad E_\gamma^{\max} = \frac{m_a^2 + 2E_a m_p}{2(m_p + E_a) - 2\sqrt{E_a^2 - m_a^2}}$$

For $1 \text{ MeV} < E_a < 100 \text{ MeV}$, $10^{-3} \text{ MeV} < E_\gamma^{\max} - E_\gamma^{\min} < 18 \text{ MeV}$

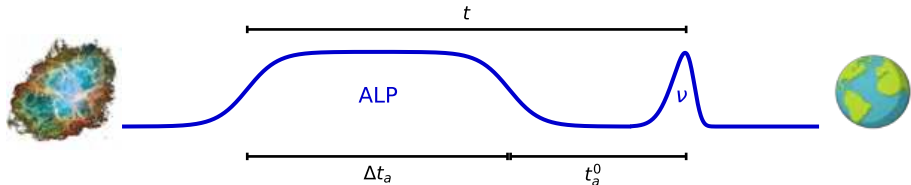
ALP-nucleon photo-production cross section: comparison with nucleon electric-dipole portal

For $m_a = 20$ MeV, $E_a = 30$ MeV and $g_a = 5 \cdot 10^{-5}$

$$\sigma \sim 7.50 \times 10^{-41} \text{ cm}^2$$

$$\sigma_{\text{dipole}} \sim 1.11 \times 10^{-43} \text{ cm}^2$$

Spread in the arrival time of ALPs

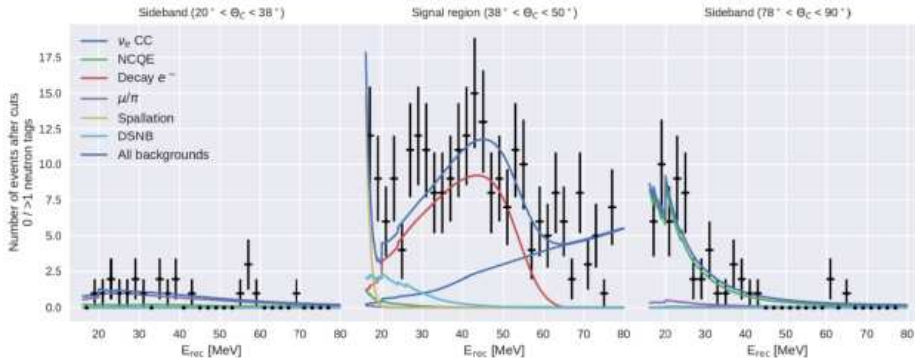


$$t_a = \frac{d}{v_a} = \frac{d}{\sqrt{1 - \left(\frac{m_a}{E_a}\right)^2}} \Rightarrow \Delta t_a = t^{\max} - t^{\min} = d \left(\frac{1}{\sqrt{1 - \left(\frac{m_a}{E_a^{\min}}\right)^2}} - \frac{1}{\sqrt{1 - \left(\frac{m_a}{E_a^{\max}}\right)^2}} \right) = d \frac{\sqrt{1 - \left(\frac{m_a}{E_a^{\max}}\right)^2} - \sqrt{1 - \left(\frac{m_a}{E_a^{\min}}\right)^2}}{\sqrt{1 - \left(\frac{m_a}{E_a^{\min}}\right)^2} \sqrt{1 - \left(\frac{m_a}{E_a^{\max}}\right)^2}}$$

$$\Delta t_a = \frac{d \Delta v}{\sqrt{1 - \left(\frac{m_a}{E_a^{\min}}\right)^2} \sqrt{1 - \left(\frac{m_a}{E_a^{\max}}\right)^2}} \simeq \frac{d \Delta v}{\bar{v}^2}$$

Background Super-Kamiokande

Super-Kamiokande Collaboration, PRD 104 (2021) 122002



Background Hyper-Kamiokande

Hyper-Kamiokande Collaboration, e-Print: 1805.04163

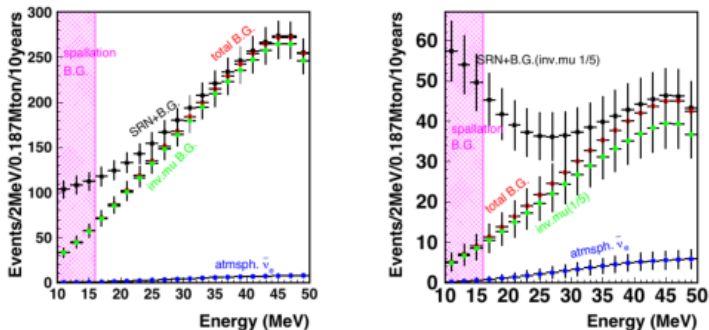


FIG. 188. Expected spectrum of SRN signals at Hyper-K with 10 years of livetime without tagging neutrons. Left figure shows the case without tagging neutrons, assuming a signal selection efficiency of 90%. Neutron tagging were applied for right figure, with the tagging efficiency of 67% and the pre-gamma cut for invisible muon background reduction. The black dots show the sum of the signal and the total background, while the red shows the total background. Green and blue show background contributions from the invisible muon and ν_e components of atmospheric neutrinos. The SRN flux prediction in [2906] is applied.

Constraints from SK and projections for HK

Profiled log-likelihood-ratio test

$$q(\theta) = -2 \ln \left(\frac{\mathcal{L}(\theta)}{\mathcal{L}(\hat{\theta})} \right)$$

Binned statistical treatment assuming that the number of events in each bin follows a Poisson distribution,

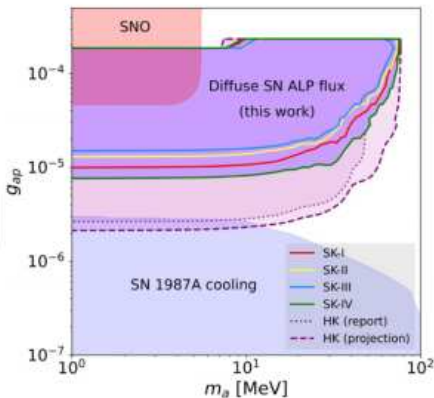
$$q(\theta) = 2 \left[\sum_{i=1}^{n_{\text{bins}}} N_{th}^i(\theta) - N_{\text{obs}}^i + N_{\text{obs}}^i \ln \left(\frac{N_{\text{obs}}^i}{N_{th}^i(\theta)} \right) \right]$$

follows a χ^2 distribution.

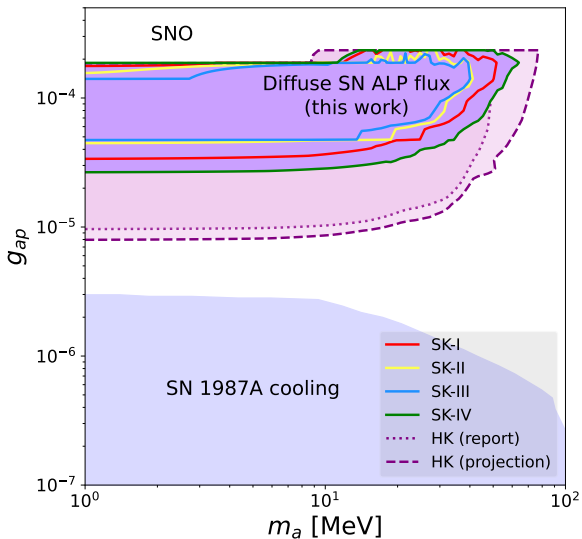
For the projected exclusion limits for HK:

$$Z(\theta) = \left[2 \sum_{i=1}^{n_{\text{bins}}} S_{th}^i(\theta) + B_{th}^i \ln \left(\frac{B_{th}^i}{S_{th}^i(\theta) + B_{th}^i} \right) \right]^{1/2}$$

95% C.L. at $Z = 1.96$



Constraints from SK and projections for HK



Simulation: Diffuse ALP flux from galactic SNe

Galactic SN rate and distribution:

$$\frac{dn_{SN}}{dt} = A e^{-\frac{r}{R_d}} e^{-\frac{|z|}{H}}$$

For ccSNe:

$R_d = 2.6$ kpc $H = 0.3$ kpc

SN rate: 1.63 per century

$A = 1.65 \times 10^{-3} \text{ kpc}^{-3} \text{ yr}^{-1}$

Simulation

SN time window: 6.34e+05 [yr]

Average number of expected SNe: 13237.29

Iteration	SN count
1	13441
2	13268
3	13136
4	13222
5	13071
6	13104
7	13281
8	13045
9	13271
10	13388
11	13127
12	13288
13	13245
14	13033
15	13277

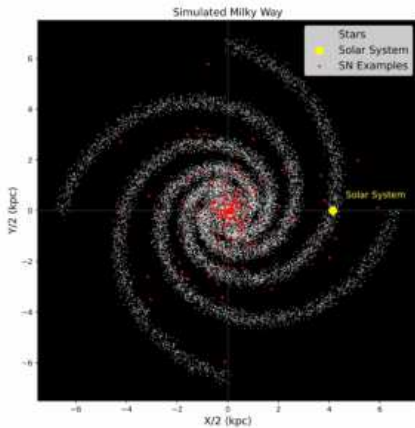
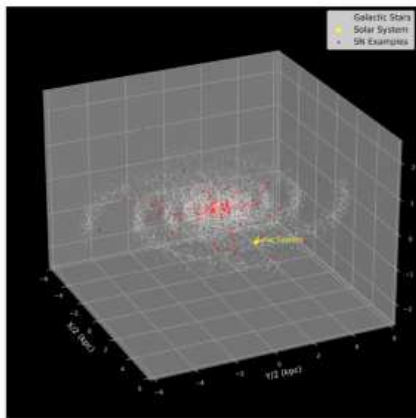
SN position
w.r.t GC

$t_{\text{today}} - t_{\text{SN}}$

	r [kpc]	#	z [kpc]	t [e]
0	0.122868	1.283047	0.051144	1.037383e-10
1	1.772018	1.361232	0.305451	1.079115e-10
2	1.182192	3.705303	0.028259	1.440616e-10
3	5.563034	2.271568	-0.097046	1.531587e-10
4	1.073842	2.382373	0.026703	1.821946e-10
5	2.203187	5.402907	-0.146469	1.624385e-10
6	0.735043	2.982266	0.140886	2.085627e-10
7	1.852696	3.040194	0.202884	2.292907e-10
8	2.748283	4.606253	0.118484	2.599070e-10
9	2.712416	1.668001	-0.165745	2.850984e-10

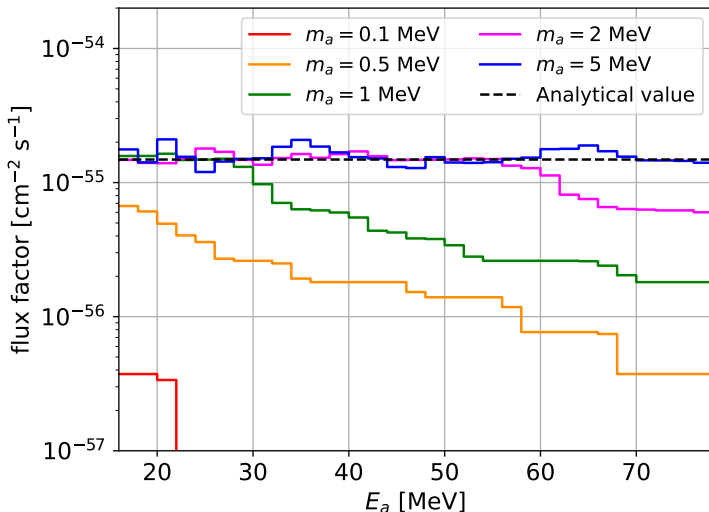
Simulation: Diffuse ALP flux from galactic SNe

The position of the last 200 SN (simulated)

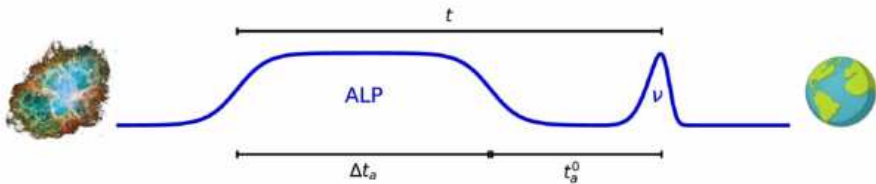


Simulation: Diffuse ALP flux from galactic SNe

$$\text{flux factor} = \int_{-\infty}^{\infty} \int_0^{2\pi} \int_0^{\infty} \frac{dn_{SN}}{dt} \frac{r}{4\pi (\vec{r} - \vec{R}_E)^2} dr d\theta dz$$



Timing information of the signal

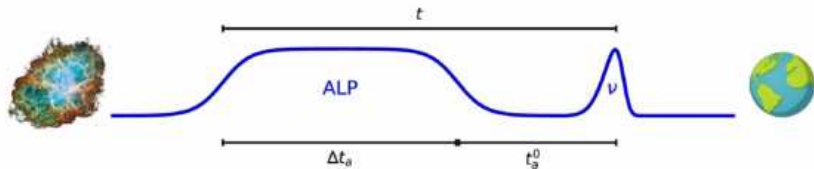


However, due to their massive nature, they travel more slowly than neutrinos.

Leads to a **time delay** t_a between the ALP arrival and the first neutrino event:

$$t_a \simeq \frac{d_{SN} m_a^2}{2E_a^2} \sim 2.01 \times 10^6 \text{ s} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2 \left(\frac{16 \text{ MeV}}{E_a} \right)^2$$

Timing information of the signal



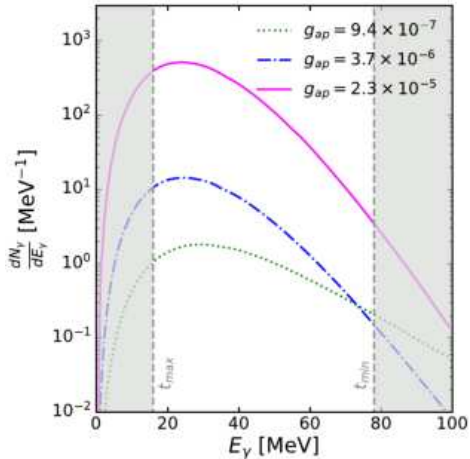
In addition, since ALPs are produced with different energies, there will be a **time window** Δt_a between the first (most energetic) and the last measured ALPs.

$$a + p \rightarrow p + \gamma \quad \Delta t_a^{a p \rightarrow p \gamma} \simeq 1.93 \times 10^6 \text{ s} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2 \quad E_a = [16, 78] \text{ MeV}$$

Event rate at SK from a single SN

$$d_{SN} = 1 \text{ kpc}, m_a \leq 1 \text{ MeV}$$

- Energy region [16 – 78] MeV, optimized to search for the DSNB by identifying positrons from inverse beta decay
- Background: cosmic ray muon spallation, electrons from the decays of low energy muons and pions, and atmospheric ν s
- Huge background increase for $E \lesssim 16$ MeV



Comparison with the oxygen excitation signal

- Our signature is only sensitive to **ALP-proton** coupling.

$$a + p \rightarrow p + \gamma \quad \Delta t_a^{\alpha p \rightarrow p \gamma} \simeq 1.93 \times 10^6 \text{ s} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2 \quad E_a = [16, 78] \text{ MeV}$$



$$E_\gamma \sim E_a$$

peaks at
 $E_\gamma \sim 30 \text{ MeV}$

- Oxygen de-excitation depends on both **ALP-proton** and **ALP-neutron** couplings.

$$a + {}^{16}\text{O} \rightarrow {}^{16}\text{O}^* \rightarrow {}^{16}\text{O} + \gamma \quad \Delta t_a^{\alpha O \rightarrow O^*} \simeq 4.99 \times 10^6 \text{ s} \left(\frac{d_{SN}}{1 \text{ kpc}} \right) \left(\frac{m_a}{0.1 \text{ MeV}} \right)^2 \quad E_a = [9.55, 28] \text{ MeV}$$



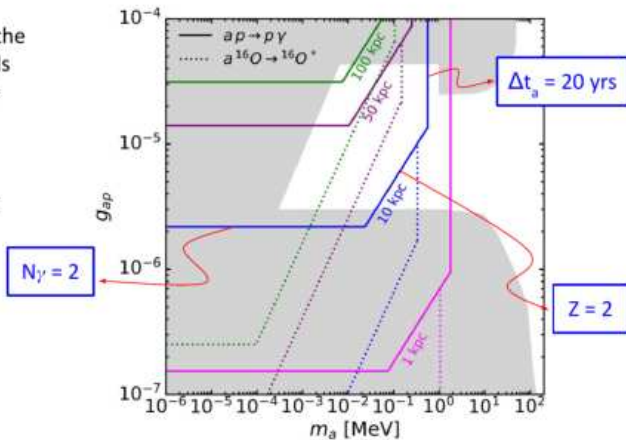
$$E_\gamma \sim 5 - 10 \text{ MeV}$$

peaks at
 $E_\gamma \sim 7 \text{ MeV}$

Sensitivity in a future SN event

In a future SN observation, the comparison of both channels can be used to **measure the ratio** of both couplings.

This can be applied to supernovae up to ~ 100 kpc



Bounds using the delayed signal from the SN 1987A?

For some masses, ALPs produced in the SN 1987A ($d_{\text{SN}}=51.4$ kpc) could have been already detected by Super-Kamiokande.

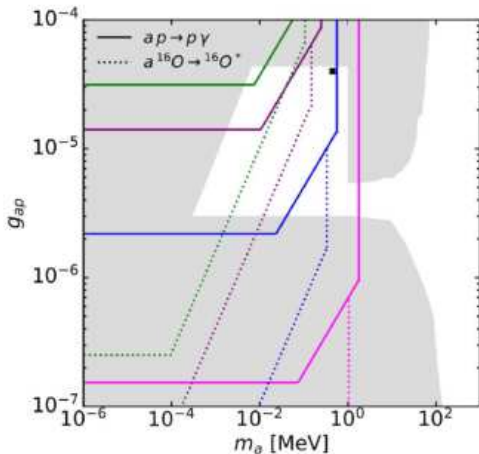
The scenario that maximizes the signal corresponds to:

$$\begin{aligned} m_a &= 0.45 \text{ MeV} \\ g_{ap} &= 4 \times 10^{-5} \\ E_a &= 23.5 - 43.6 \text{ MeV} \end{aligned}$$

taking into account the operation period of the first four SK phases (9 to 31 years after SN 1987A neutrinos).

But the statistical significance of the signal is only $Z = 0.5$.

No constraints can be derived!



Proto-NS birth

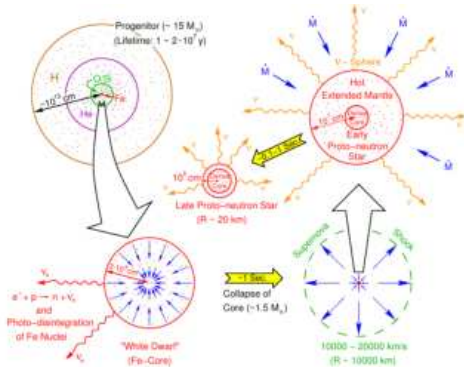
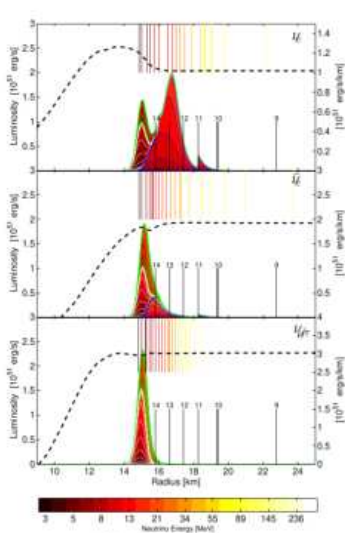


Fig. 2 Evolution of a massive star from the onset of iron-core collapse to a neutron star. The progenitor has developed a typical onion-shell structure with layers of increasingly heavier elements surrounding the iron core at the center (upper left corner). Like a white dwarf star, this iron core (enlarged on the lower left side) is stabilized mostly by the fermion pressure of nearly degenerate electrons. It becomes gravitationally unstable when the rising temperatures begin to allow for partial photo-disintegration of iron-group nuclei to α -particles and nucleons. The contraction accelerates to a dynamical collapse by electron captures on bound and free protons, releasing electron neutrinos (ν_e), which initially escape freely. Only fractions of a second later, the catastrophic infall is stopped because nuclear-matter density is reached and a proto-neutron star begins to form. This gives rise to a strong shock wave which travels outward and disrupts the star in a supernova explosion (lower right). The nascent neutron star is initially very extended (enlarged in the upper right corner), and contracts to a more compact object while accreting more matter (visualized by the mass-accretion rate \dot{M}) within the first second of its evolution. This phase as well as the subsequent cooling and neutronization of the compact remnant are driven by the emission of neutrinos and antineutrinos of all flavours (indicated by the symbol ν), which diffuse out from the dense and hot super-nuclear core over tens of seconds. (Figure adapted from [Burrows, 1990b](#))

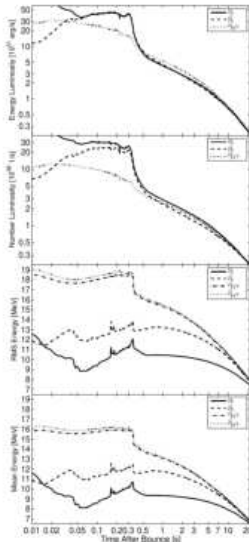
Neutrino luminosity

Fischer et al., PRD 85 (2012) 083003

$$M_{\text{proj}} = 18 M_{\odot}$$



(a) 5 seconds post bounce

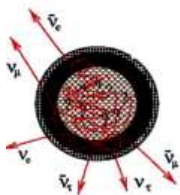


SN neutrinos

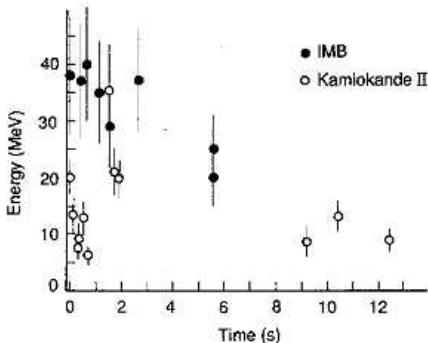
ν 's are crucial in proto-NS evolution \Rightarrow good sites to test new ν interactions

During the final phases of core collapse SN ν 's are copiously produced in the proto-NS interior ($n_\nu \sim 10^{36} \text{ cm}^{-3}$) and trapped due to their scattering with N s

After a second, they are emitted as the star cools down (Kelvin-Helmholtz cooling)



- Emitted ν 's observed during $t_{\text{signal}} \sim 10$ s from the SN 1987A
- t_{signal} proportional to the ν diffusion time in the stellar material $t_{\text{signal}} \sim 10 t_{\text{diff}}$
- The observed emission time is compatible with the one predicted by the SM



Relevant interactions inside SN

Janka arXiv: 1702.08713. In 'Handbook of Supernovae,' Springer

Table 1 Most important neutrino processes in supernova and proto-neutron star matter.

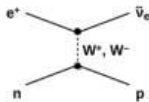
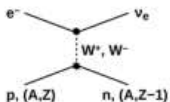
Process	Reaction ^a
Beta-processes (direct URCA processes)	
electron and ν_e absorption by nuclei	$e^- + (A, Z) \longleftrightarrow (A, Z - 1) + \nu_e$
electron and ν_e captures by nucleons	$e^- + p \longleftrightarrow n + \nu_e$
positron and $\bar{\nu}_e$ captures by nucleons	$e^+ + n \longleftrightarrow p + \bar{\nu}_e$
“Thermal” pair production and annihilation processes	
Nucleon-nucleon bremsstrahlung	$N + N \longleftrightarrow N + N + \nu + \bar{\nu}$
Electron-positron pair process	$e^- + e^+ \longleftrightarrow \nu + \bar{\nu}$
Plasmon pair-neutrino process	$\tilde{\gamma} \longleftrightarrow \nu + \bar{\nu}$
Reactions between neutrinos	
Neutrino-pair annihilation	$\nu_e + \bar{\nu}_e \longleftrightarrow \nu_x + \bar{\nu}_x$
Neutrino scattering	$\nu_x + \{\nu_e, \bar{\nu}_e\} \longleftrightarrow \nu_x + \{\nu_e, \bar{\nu}_e\}$
Scattering processes with medium particles	
Neutrino scattering with nuclei	$\nu + (A, Z) \longleftrightarrow \nu + (A, Z)$
Neutrino scattering with nucleons	$\nu + N \longleftrightarrow \nu + N$
Neutrino scattering with electrons and positrons	$\nu + e^\pm \longleftrightarrow \nu + e^\pm$

^a N means nucleons, i.e., either n or p , $\nu \in \{\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$, $\nu_x \in \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$

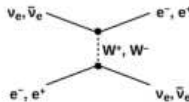
Relevant interactions inside SN

Janka arXiv: 1702.08713. In 'Handbook of Supernovae,' Springer

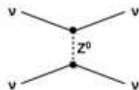
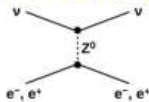
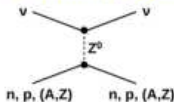
CC β -processes



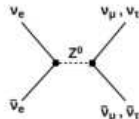
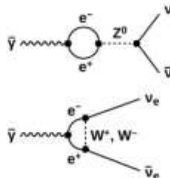
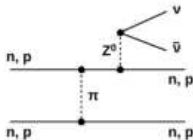
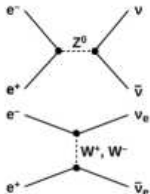
CC scattering process



NC scattering processes ($\nu = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$)



Neutrino-pair ("thermal") processes



Neutrino decoupling SM

Janka arXiv: 1702.08713. In 'Handbook of Supernovae,' Springer

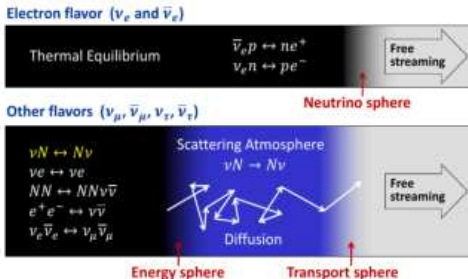


Fig. 4 Sketch of the transport properties of electron-flavor neutrinos and antineutrinos (*upper part*) compared to heavy-lepton neutrinos (*lower part*). In the supernova core ν_e and $\bar{\nu}_e$ interact with the stellar medium by charged-current absorption and emission reactions, which provide a major contribution to their opacities and lead to a strong energetic coupling up to the location of their neutrinospheres, outside of which both chemical equilibrium between neutrinos and stellar matter (indicated by the black region) and diffusion cannot be maintained. In contrast, heavy-lepton neutrinos are energetically less tightly coupled to the stellar plasma, mainly by pair creation reactions like nucleon bremsstrahlung, electron-positron annihilation and $\nu_e \bar{\nu}_e$ annihilation. The total opacity, however, is determined mostly by neutrino-nucleon scatterings, whose small energy exchange per scattering does not allow for an efficient energetic coupling. Therefore heavy-lepton neutrinos fall out of thermal equilibrium at an energy sphere that is considerably deeper inside the nascent neutron star than the transport sphere, where the transition from diffusion to free streaming sets in. The blue band indicates the scattering atmosphere where the heavy-lepton neutrinos still collide frequently with neutron and protons and lose some of their energy, but cannot reach equilibrium with the background medium any longer. (Figure adapted from Raffelt [2012] courtesy of Georg Raffelt)

SN phases

Janka arXiv: 1702.08713. In 'Handbook of Supernovae,' Springer

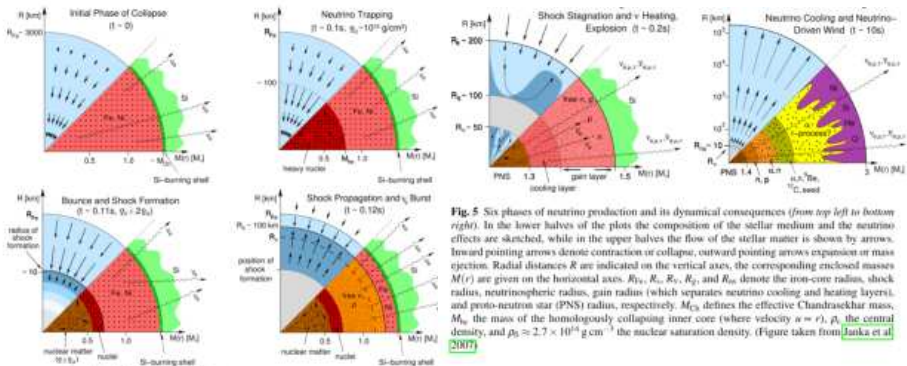


Fig. 5 Six phases of neutrino production and its dynamical consequences (from top left to bottom right). In the lower halves of the plots the composition of the stellar medium and the neutrino effects are sketched, while in the upper halves the flow of the stellar matter is shown by arrows. Inward pointing arrows denote contraction or collapse, outward pointing arrows expansion or mass ejection. Radial distances R are indicated on the vertical axis, the corresponding enclosed masses $M(r)$ are given on the horizontal axes. R_{Fe} , R_s , R_{NS} , R_2 , and R_{CS} denote the iron-core radius, shock radius, neutrinospheric radius, gain radius (which separates neutrino cooling and heating layers), and proto-neutron star (PNS) radius, respectively. M_{CS} defines the effective Chandrasekhar mass, M_{ho} the mass of the homologously collapsing inner core (where velocity $v = r$), ρ_c the central density, and $\rho_s \approx 2.7 \times 10^{14}$ g cm⁻³ the nuclear saturation density. (Figure taken from Janka et al. (2017))

Description of the proto-neutron star interior

- The temperature, T , baryonic density, n_B , and electron fraction, Y_e , profiles at 1 s after the bounce from SN simulations *Fischer et al., PRD 85 (2012) 083003*
- The neutron, proton and electron neutrino chemical potentials, μ_n^* , μ_p^* and $\mu_{\nu_e}^*$, and the nucleon effective mass m_N^* obtained solving the equations of motion and setting the equilibrium conditions *Cerdeño, Cermeño, Pérez-García and Reid, PRD 104 (2021) 063013*

	R (km)	T (MeV)	n_B (fm $^{-3}$)	Y_e	μ_n^* (MeV)	μ_p^* (MeV)	$\mu_{\nu_e}^*$ (MeV)	m_N^* (MeV)
$k = 1$	5.0	15	0.5	0.3	496.6	405.4	114.6	249.6
$k = 2$	7.5	20	0.3	0.28	530.0	458.3	102.7	384.9
$k = 3$	10.0	28	0.15	0.25	656.5	601.9	79.9	599.4
$k = 4$	15.0	33	0.06	0.2	779.8	723.0	29.0	786.0
$k = 5$	17.5	18	0.03	0.1	858.7	813.1	14.4	857.0
$k = 6$	20.0	7	0.008	0.05	917.2	893.9	12.5	915.9

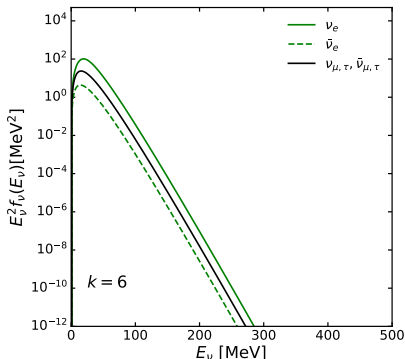
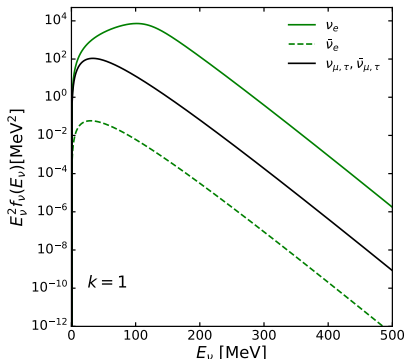
The energy distribution of nucleons and leptons inside the star described by the Fermi-Dirac distribution $f(E) = \frac{1}{1 - e^{(E-\mu)/T}}$, where E is the energy of the particle

Neutrino energy distribution inside the proto-NS

	R (km)	T (MeV)	$n_B(\text{fm}^{-3})$	Y_e	μ_n^* (MeV)	μ_p^* (MeV)	$\mu_{\nu_e}^*$ (MeV)	m_N^* (MeV)
$k = 1$	5.0	15	0.5	0.3	496.6	405.4	114.6	249.6
$k = 2$	7.5	20	0.3	0.28	530.0	458.3	102.7	384.9
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The ν energy distribution function $f_\nu(E_\nu) = \frac{1}{1 - e^{(E_\nu - \mu_\nu^*)/T}}$, with $\mu_{\nu_{\mu,\tau}} = \mu_{\bar{\nu}_{\mu,\tau}} = 0$ and $\mu_{\bar{\nu}_e}^* = -\mu_{\nu_e}^*$

The average energy for muon/tau ν 's $\langle E_\nu \rangle = \pi T$, while for the electron ν 's $\langle E_\nu \rangle = (3/4)\mu_{\nu_e}^*$



Effective nucleon masses and chemical potentials

Considering the TM1 model for a $18 M_{\odot}$ progenitor in a relativistic mean field approach:

- The baryonic density, n_B , temperature, T , and electron fraction, Y_e , derived by *Fischer et al.*, *PRD 85 (2012) 083003*
- The effective nucleon masses, m_N^* , and the neutrino and nucleon effective chemical potentials, $\mu_{\nu_e}^*$, μ_n^* , μ_p^* obtained by *Cerdeño, Cermeño, Pérez-García and Reid*, *PRD 104 (2021) 063013*
- $\mu_{\nu_e}^*$ is obtained solving the equilibrium equation that involves effective meson fields:
 $\mu_n^* + \mu_{\nu_e}^* = \mu_p^* + \mu_e^* + 2g_{\rho}\langle\rho\rangle$, where ρ is an effective field responsible of the strong interaction

	R (km)	T (MeV)	n_B (fm $^{-3}$)	Y_e	μ_n^* (MeV)	μ_p^* (MeV)	$\mu_{\nu_e}^*$ (MeV)	m_N^* (MeV)
$k = 1$	5.0	15	0.5	0.3	496.6	405.4	114.6	249.6
$k = 2$	7.5	20	0.3	0.28	530.0	458.3	102.7	384.9
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TABLE I. Values of neutron effective chemical potential, μ_n^* , proton effective chemical potential, μ_p^* , electron neutrino effective chemical potential, $\mu_{\nu_e}^*$, and nucleon effective mass, m_N^* , for the spherical shells (labeled by the index k and defined by an outer radius R) that we consider at 1 s after bounce, with a baryonic density, n_B , temperature, T and electron fraction, Y_e . Temperatures, densities and electron fraction are taken from Ref. [45].

Effective nucleon masses and chemical potentials

The equation of state of nuclear matter is constructed using the relativistic mean field (RMF) theory with the TM1 parameter set *Sugahara and H. Toki, Nucl. Phys. A 579 (1994) 557, Shen et al., Nucl. Phys. A 637 (1998) 435*

- In the RMF approach baryons are considered Dirac quasiparticles moving in classical meson fields and the field operators, ϕ , are replaced by their expectation values, $\langle\phi\rangle$
- The TM1 model is a representative example where the set of parameters used can smoothly connect low and high density regions in the dynamical stellar description
- The presence of an effective nucleon mass and effective chemical potential is due to the non vanishing values of the Lorentz scalar meson, $\langle\sigma\rangle$, Lorentz vector, $\langle\omega_\mu\rangle$, and vector-isovector, $\langle\vec{\rho}_\mu\rangle$, meson fields

The effective nucleon mass $m_N^* = m_N - g_{\sigma N}\langle\sigma\rangle$

Effective nucleon chemical potentials, $\mu_i^* = \mu_i - g_{\omega N}\langle\omega\rangle - g_{\rho N}t_{3i}\langle\rho\rangle$ ($i = n, p$)

$g_{\sigma N}$, $g_{\omega N}$, and $g_{\rho N}$ are dimensionless constants that couple nucleons to the σ , ω , and ρ mesons t_{3i} is the third component of the isospin of the proton or the neutron, $i = p, n$

This parameter set includes self-interaction terms from scalar, vector and vector-isovector mesons in non isospin symmetric nuclear matter at finite temperature

TM1 interaction terms are constrained by the nuclear masses, radii, neutron skins and their excitations

When applied to the derived proto-NS, the mass-radius diagram allows to fulfil the subsequent two solar mass constraint from recent observations of older objects.

Relativistic mean field theory lagrangian

The relativistic mean field theory lagrangian

Sugahara and H. Toki, Nucl. Phys. A 579 (1994) 557, Shen et al., Nucl. Phys. A 637 (1998) 435

$$\begin{aligned} \mathcal{L}_{RMF} = & \bar{\psi} \left[i\gamma_{\mu} \partial^{\mu} - M - g_{\sigma} \sigma - g_{\omega} \gamma_{\mu} \omega^{\mu} - g_{\rho} \gamma_{\mu} \tau_a \rho^{a\mu} - e\gamma_{\mu} \frac{1 - \tau_3}{2} A^{\mu} \right] \psi \\ & + \frac{1}{2} \partial_{\mu} \sigma \partial^{\mu} \sigma - \frac{1}{2} m_{\sigma}^2 \sigma^2 - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 \\ & - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \frac{1}{2} m_{\omega}^2 \omega_{\mu} \omega^{\mu} + \frac{1}{4} c_3 (\omega_{\mu} \omega^{\mu})^2 \\ & - \frac{1}{4} R_{\mu\nu}^a R^{a\mu\nu} + \frac{1}{2} m_{\rho}^2 \rho_{\mu}^a \rho^{a\mu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \end{aligned}$$

where

$$\begin{aligned} W^{\mu\nu} &= \partial^{\mu} \omega^{\nu} - \partial^{\nu} \omega^{\mu}, \\ R^{a\mu\nu} &= \partial^{\mu} \rho^{a\nu} - \partial^{\nu} \rho^{a\mu} + g_{\rho} \epsilon^{abc} \rho^{b\mu} \rho^{c\nu}, \\ F^{\mu\nu} &= \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu}. \end{aligned}$$

The nucleon field ψ having the mass M interacts with σ , ω_{μ} and ρ_{μ}^a mesons and the photon field A_{μ} .

Self-coupling terms with the coupling constants g_2 and g_3 for the σ meson and with the coupling constant c_3 for the ω meson

The coupling strengths, g 's, and the meson masses, m 's, are the parameters of this theory.

Different parameter sets for the Lagrangian

Sugahara and H. Toki, Nucl. Phys. A 579 (1994) 557

Table 2

The parameters of the lagrangian determined by the least-squares fitting procedure are listed under TM1 for the heavy nuclei and TM2 for the light nuclei. For comparison, the parameters of NL1 and NL-SH are also listed under the column of NL1 and NL-SH, respectively

	TM1	TM2	NL1	NL-SH
M (MeV)	938.0	938.0	938.0	939.0
m_σ (MeV)	511.198	526.443	492.250	526.059
m_ω (MeV)	783.0	783.0	795.359	783.0
m_ρ (MeV)	770.0	770.0	763.0	763.0
g_σ	10.0289	11.4694	10.1377	10.444
g_ω	12.6139	14.6377	13.2846	12.945
g_ρ	4.6322	4.6783	4.9757	4.383
g_2 (fm $^{-1}$)	-7.2325	-4.4440	-12.1724	-6.9099
g_3	0.6183	4.6076	-36.2646	-15.8337
c_3	71.3075	84.5318	0.0	0.0

Relation between ν emission time and diffusion time

- At the onset of the cooling phase (~ 1 s after the bounce), the luminosity is of the order of 10^{52} erg s^{-1} for each ν and $\bar{\nu}$ species
- The outer layers cool down fast, the neutrinosphere recedes to smaller radii and the luminosity quickly drops
- The neutrino emission is backed up with the diffusion of ν 's from the inner layers. Due to multiple scattering, ν 's take a sizable time to reach the outer layers of the proto-NS, from where they are radiated out with a time scale of
Janka arXiv: 1702.08713. In 'Handbook of Supernovae,' Springer

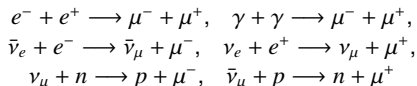
$$t_{\text{signal}} \sim \frac{3}{\pi^2} \frac{E_{th}^{tot}}{2E_{th}^{\nu}} R_{ns}^2 \left\langle \frac{1}{\lambda} \right\rangle \sim 10 \text{ s},$$

- E_{th}^{tot} and E_{th}^{ν} are the total baryon and neutrino thermal energies, $E_{th}^{tot}/(2E_{th}^{\nu}) \sim 10$
- $\langle 1/\lambda \rangle$ the average of the inverse of the neutrino mean free path
- $R_{ns}^2 \langle 1/\lambda \rangle$ (where R_{ns} is the radius of the neutrinosphere) gives the time scale of the diffusion of a single particle with a velocity of light and with random walk steps of λ
- In order to fulfill $t_{\text{signal}} \sim 10$ s, $R_{ns}^2 \langle 1/\lambda \rangle \sim 3$ s/c. From our calculation we get $R_{ns}^2 \langle 1/\lambda \rangle \sim 2.9$ s/c for electron neutrinos and 1.3 s/c for muon and tau neutrinos

Muon production in SN in the SM

- The proto-NS may reach $T \sim 50$ MeV before it is cooled by ν diffusion (first 10 s)
- The proto-NS is born with a significant electron to baryon number ratio (from the core of the progenitor star) but no initial muon or tau population
- A net excess of e^- over e^+ occurs due to the high initial electron fraction compensating the positive charge of the protons
- Electrons highly degenerate with a chemical potential $\mu_e > m_\mu$
- The thermal distribution of photons and ν reach well beyond 100 MeV

Under these conditions μ^- and μ^+ are produced via



Net muon population in SN in the SM

- Once core-collapse SN is initiated, e^- and p in the progenitor combine and ν_e quickly diffuse out of the star, decreasing the net lepton number \Rightarrow neutron-rich core
- Due to the excess of e^- over e^+ as well as the one of neutrons over protons, an excess of μ^- over μ^+ is built up
- Due to weak magnetism corrections, the interaction cross section for $N + \nu \rightarrow N + \bar{\nu}$ is slightly larger than for $N + \bar{\nu} \rightarrow N + \bar{\nu} \Rightarrow \bar{\nu}$ diffuse out of the star faster than $\nu \Rightarrow \mu_\nu \neq 0$
- $\bar{\nu}_\mu$ diffuse out of the star faster than $\nu_\mu \Rightarrow$ net ν_μ population over $\bar{\nu}_\mu$ population \Rightarrow increase of the net μ^- population over μ^+

The process of muonization that leads to an excess of μ^- over μ^+ in the final NS is facilitated by the previous reactions as well as $\nu_\mu + n \rightleftharpoons p + \mu^-$, $\bar{\nu}_\mu + p \rightleftharpoons n + \mu^+$ and

$\nu + \mu^- \rightleftharpoons \nu' + \mu'^-$	$\nu + \mu^+ \rightleftharpoons \nu' + \mu'^+$
$\nu_\mu + e^- \rightleftharpoons \nu_e + \mu^-$	$\bar{\nu}_\mu + e^+ \rightleftharpoons \bar{\nu}_e + \mu^+$
$\nu_\mu + \bar{\nu}_e + e^- \rightleftharpoons \mu^-$	$\bar{\nu}_\mu + \nu_e + e^+ \rightleftharpoons \mu^+$
$\bar{\nu}_e + e^- \rightleftharpoons \bar{\nu}_\mu + \mu^-$	$\nu_e + e^+ \rightleftharpoons \nu_\mu + \mu^+$
$\nu_\mu + n \rightleftharpoons p + \mu^-$	$\bar{\nu}_\mu + p \rightleftharpoons n + \mu^+$

Effect of a net muon number density on the profiles

Negligible effect of the net muon population in the temperature and density profiles *Bollia et al., PRL 125 (2020) 051104*

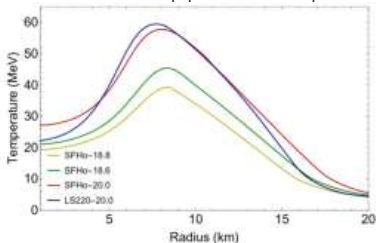


FIG. 1: Temperature profile for various models at 1 s post-bounce.

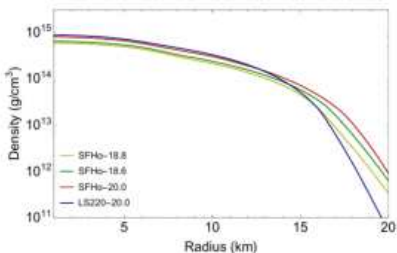


FIG. 2: Density profile for the models corresponding to Fig. 1

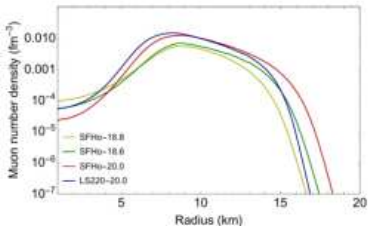


FIG. 3: Muon number density. Note that despite large differences in peak temperature, the muon number density does not change by more than an order of magnitude in the relevant region of high muon density ($5 \text{ km} \lesssim r \lesssim 15 \text{ km}$).

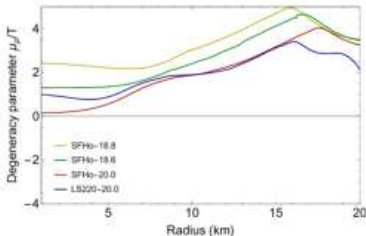


FIG. 4: Muon degeneracy parameter μ_μ/T for various profiles. This ratio never exceeds a small $\mathcal{O}(1)$ value in the relevant region of high muon density ($5 \text{ km} \lesssim r \lesssim 15 \text{ km}$).

Weak magnetism effect on μ_{ν_μ} and μ_{ν_τ}

Horowitz, PRD 65 (2002) 043001

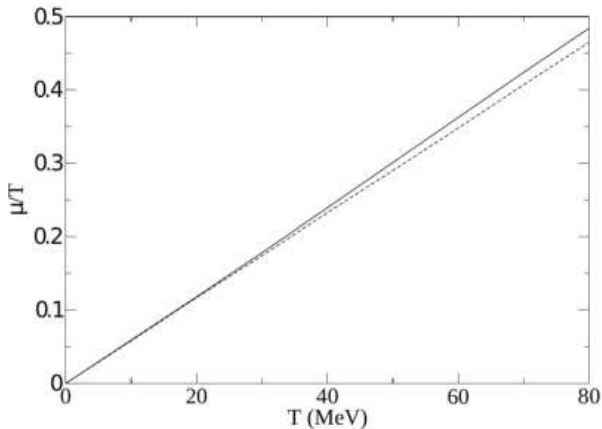


FIG. 3. Muon or Tau neutrino chemical potential over temperature μ_{ν_α}/T versus T for matter in steady state equilibrium. The solid line is the full result from the solution to Eq. (13) while the dashed line is correct to lowest order in k/M and μ/T , Eq. (4).