BAM: Axions in the Sky!
Barolo, 12-15 June 2024

Axions From Supernovae

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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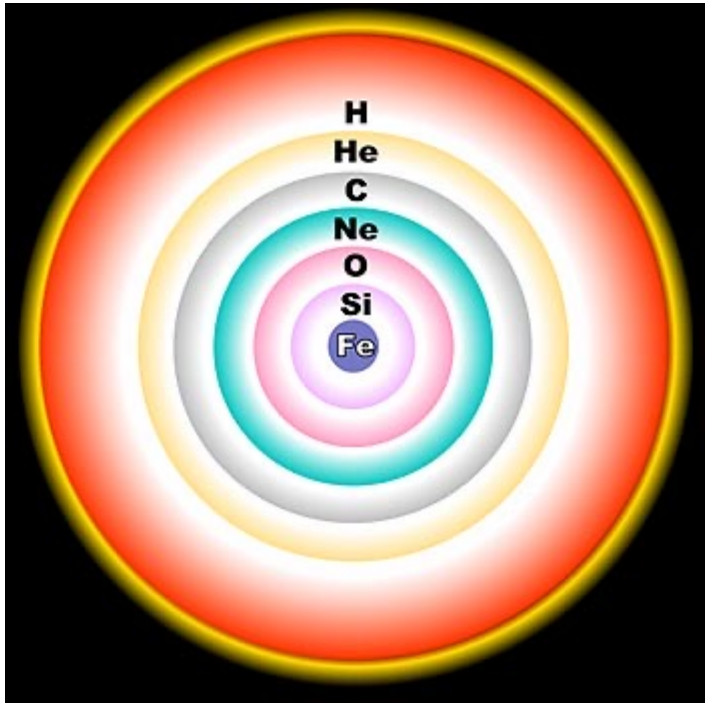
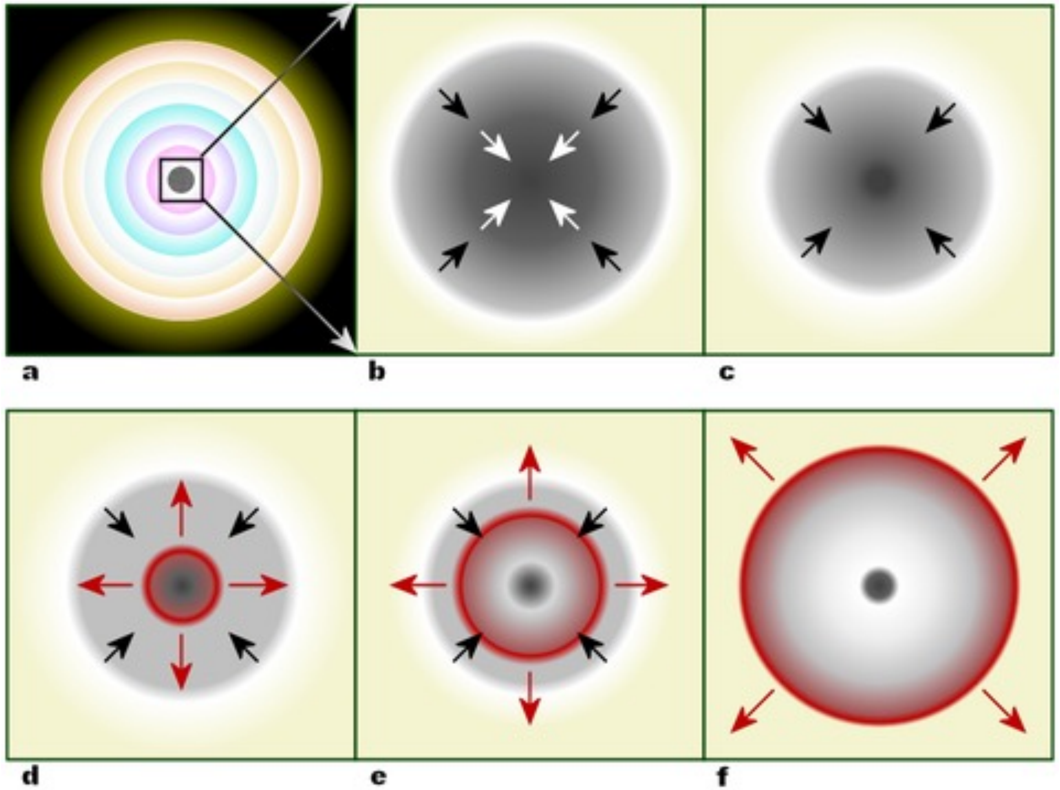
LIFE AND DEATH OF A MASSIVE STAR

Onion-like layers of a massive, evolved star just before core collapse.



Collapse

Nuclear density



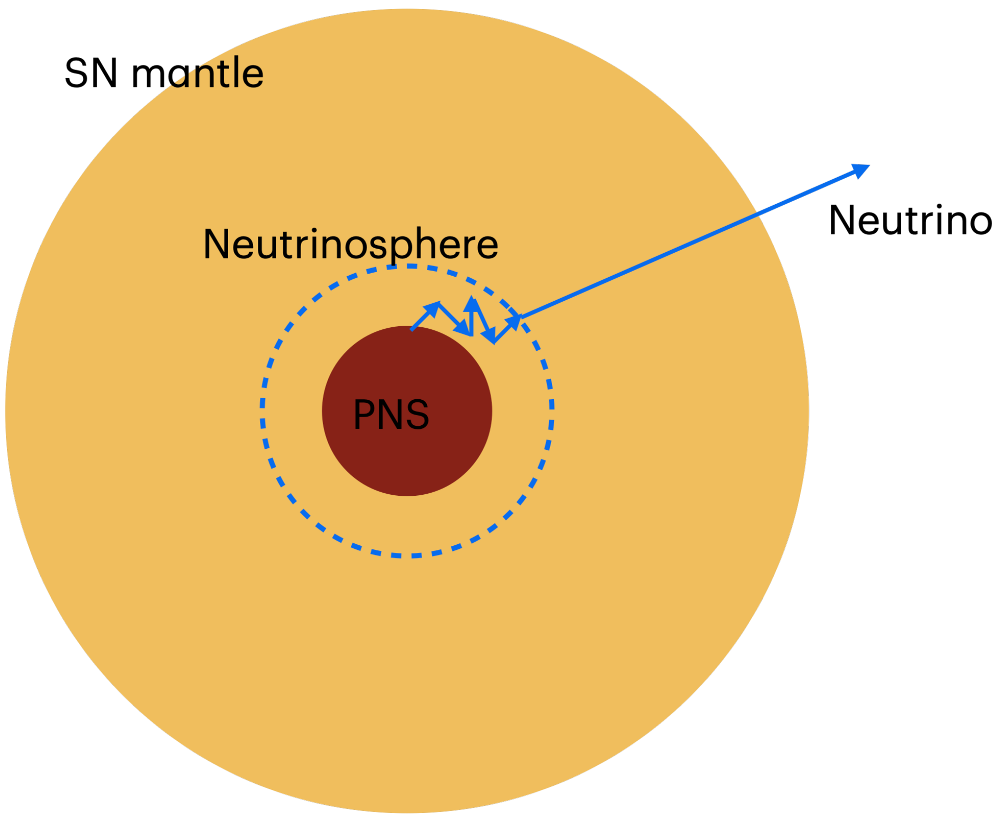
Core-bounce & shock wave

shock-wave stalling

Shock revival

SUPERNOVA PHYSICS

$T_{\mathrm{PNS}} \approx O(10)\ \mathrm{MeV}$ $\rho_{\mathrm{PNS}} \approx O(10^{14})\ \mathrm{g/cm^3}$ $B_{\mathrm{PNS}} \approx O(10^{15})\ \mathrm{G}$

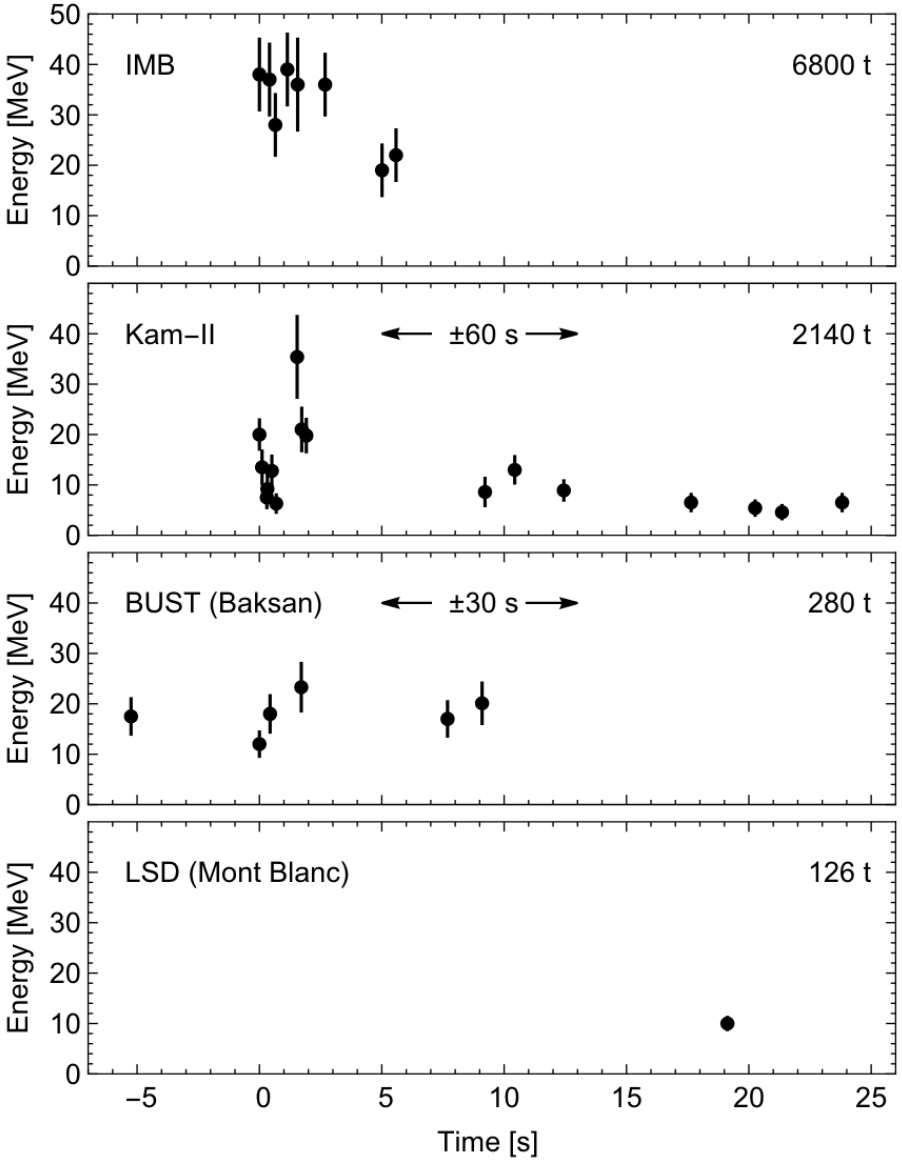


ENERGY SCALES: 99% of the released energy ($\sim 10^{53}$ erg) is emitted by ν and $\bar{\nu}$ of all flavors, with $E \sim O(15\ \mathrm{MeV})$.

TIME SCALES: ~ 10 s

EXPECTED: 1-3 SN/century in our galaxy (d $\approx O$ (10) kpc).

SN 1987A NEUTRINO OBSERVATIONS



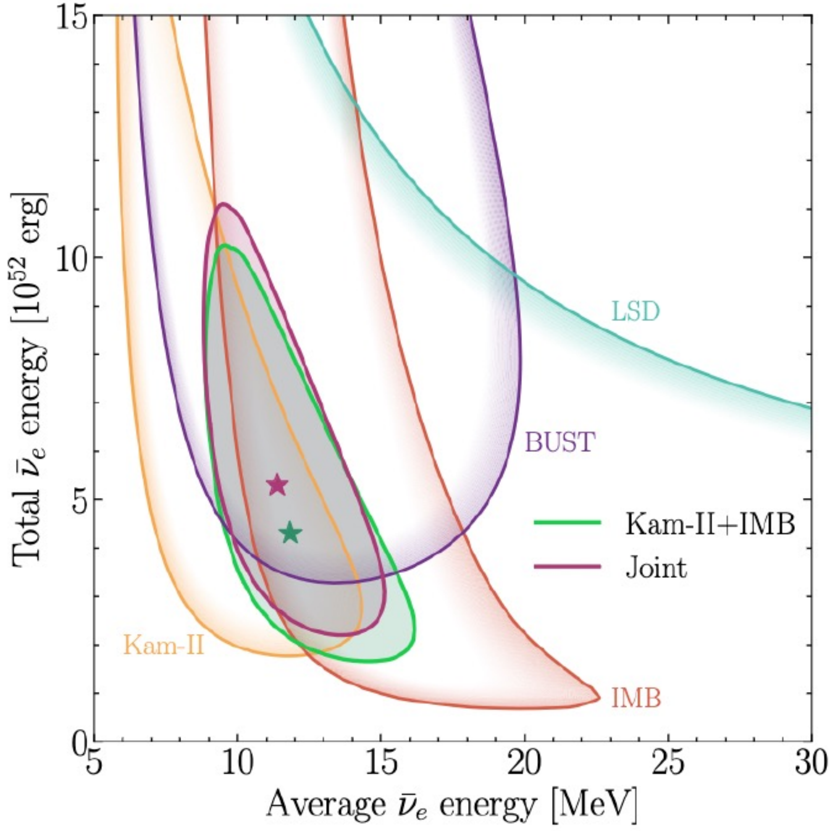
SN 1987A was the first and only SN event allowing for the observation of the associated neutrino burst so far.

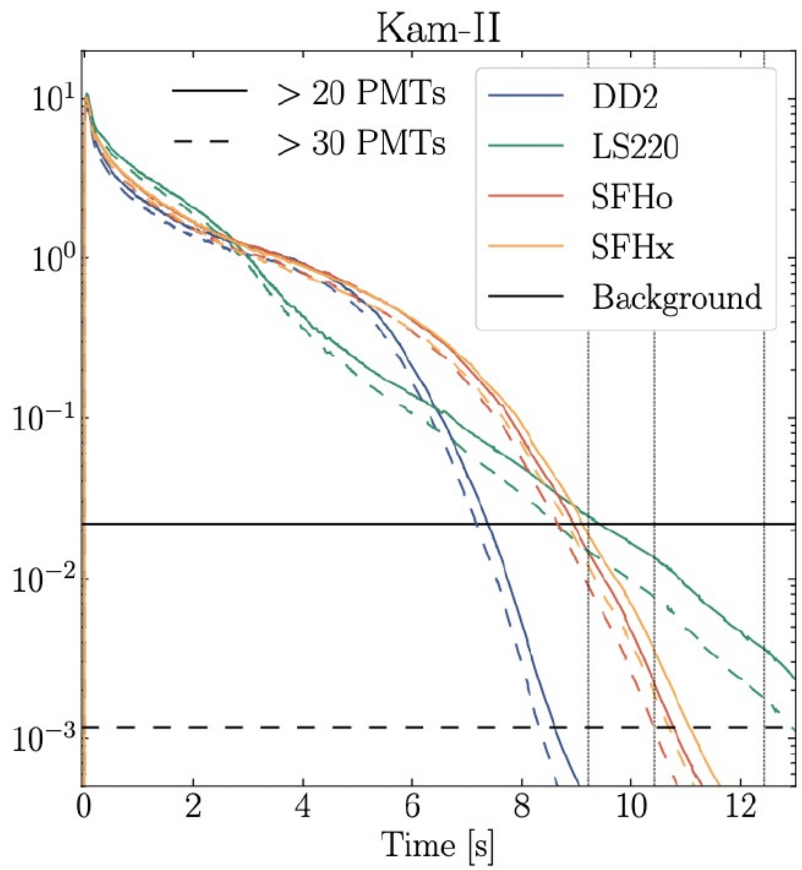
Standard picture confirmed by SN 1987A observation.

New comparisons to SN simulations from several groups
[Li et al., PRD 109 (2024)]
[Fiorillo et al., PRD 108 (2023)]

SN SIMULATIONS CONFRONT SN1987A

[Fiorillo et al., PRD 108 (2023)]





Good agreement in total and average neutrino energies.

Tension with late time events:

- Convection
- Updated neutrino-nucleon opacities

WHAT CAN WE LEARN ON AXIONS?
(AND OTHER FEEBLY INTERACTING PARTICLES)

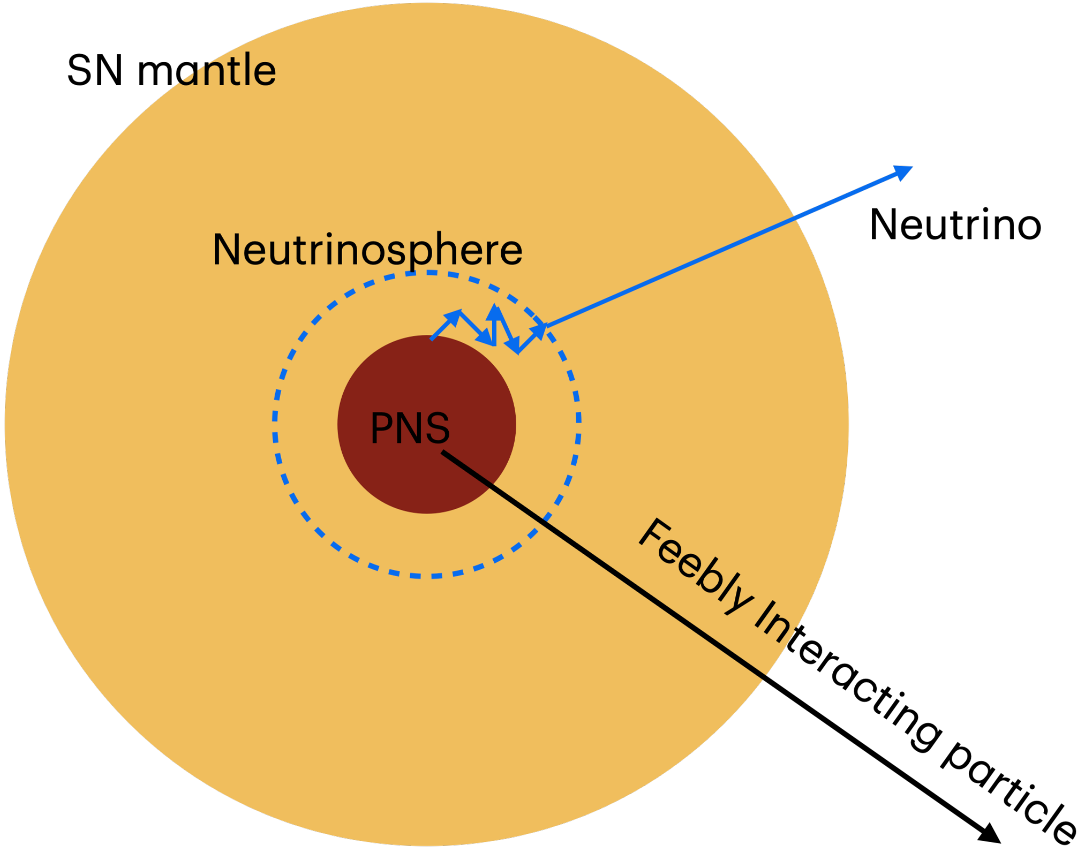
THE *ENERGY-LOSS* ARGUMENT

- Emission of feebly interacting particles would "steal" energy from the neutrino burst and shorten it. [Raffelt, Lect. Notes Phys. 741 (2008) 51]

- Assuming that the SN 1987A neutrino burst was not shortened by more than $\sim 1/2$ leads to an approximate requirement on the energy-loss rate

$$\varepsilon_a \lesssim 10^{19}\ \mathrm{erg\,g^{-1}\,s^{-1}}$$

at $T = 30$ MeV and $\rho = 3\times 10^{14}$ g/cm^3.



THE *ENERGY-LOSS* ARGUMENT

VOLUME 60, NUMBER 18 PHYSICAL REVIEW LETTERS 2 MAY 1988

Bounds on Exotic-Particle Interactions from SN1987A

Georg Raffelt
Astronomy Department, University of California, Berkeley, California 94720, and
Institute for Geophysics and Planetary Physics, Lawrence Livermore National Laboratory,
Livermore, California 94550

and

David Seckel
Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, Santa Cruz, California 95064
(Received 26 October 1987)

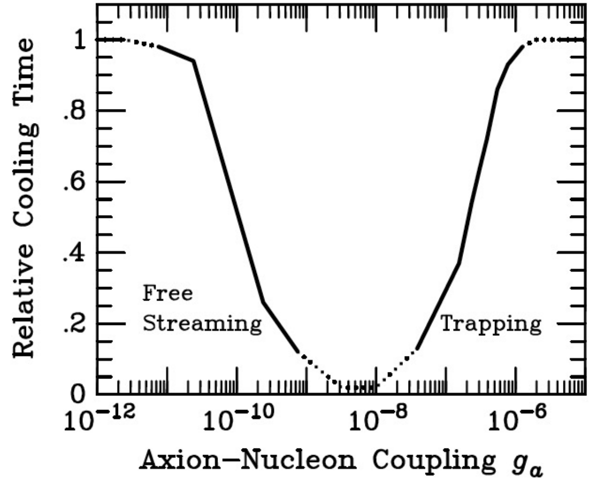


Fig. 13.1. Relative duration of neutrino cooling of a SN core as a function of the axion-nucleon Yukawa coupling g_a. In the free-streaming limit axions are emitted from the entire volume of the protoneutron star, in the trapping limit from the "axion sphere" at about unit optical depth. The solid line is according to the numerical cooling calculations (case B) of Burrows, Turner, and Brinkmann (1989) and Burrows, Ressell, and Turner (1990); the dotted line is an arbitrary completion of the curve to guide the eye. The signal duration is measured by the quantity $\Delta t_{90\%}$ discussed in the text; an average for the IMB and Kamiokande detectors was taken.

Based on 1980s 1D simulations with an energy sink:

$$\varepsilon_a \lesssim 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

at $T = 30$ MeV and $\rho = 3{\times}10^{14}\ \mathrm{g/cm^3}$

Or in terms of the total energy:

$$L_a < L_\nu(t_{\rm pb} = 1\ \mathrm{s}) \approx 3{\times}10^{52}\ \mathrm{erg/s}$$

Necessity to include axions in modern simulations! (Currently running at GARCHING)

AXION-NUCLEON INTERACTIONS

Axions can 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 et al., PRD 107 (2023)]

$$\mathcal{L}_{\rm int} = g_a \frac{\partial_\mu a}{2m_N}\Bigg[C_{ap}\bar{p}\gamma^\mu\gamma_5 p + C_{an}\bar{n}\gamma^\mu\gamma_5 n + $$

$$g_{aN} = C_{aN} g_a = C_{aN}\frac{m_N}{f_a}$$

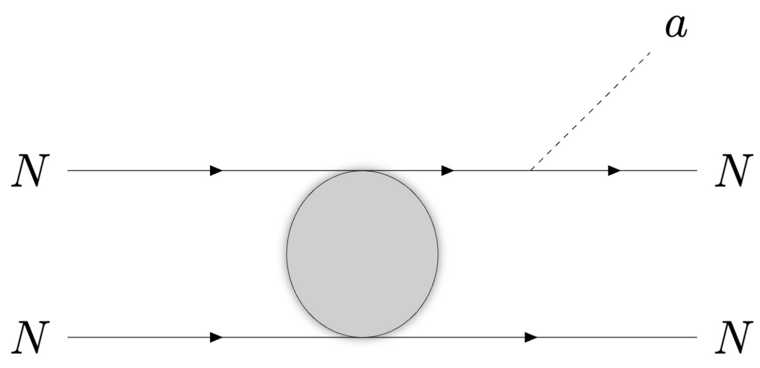
$$+\frac{C_{a\pi N}}{f_\pi}(i\pi^+\bar{p}\gamma^\mu n - i\pi^-\bar{n}\gamma^\mu p) +$$

$$+ C_{aN\Delta}\left(\bar{p}\,\Delta^+_\mu + \overline{\Delta^+_\mu}\,p + \bar{n}\,\Delta^0_\mu + \overline{\Delta^0_\mu}\,n\right)\Bigg]$$

AXION PRODUCTION IN SUPERNOVAE

- **Nucleon-Nucleon bremsstrahlung**

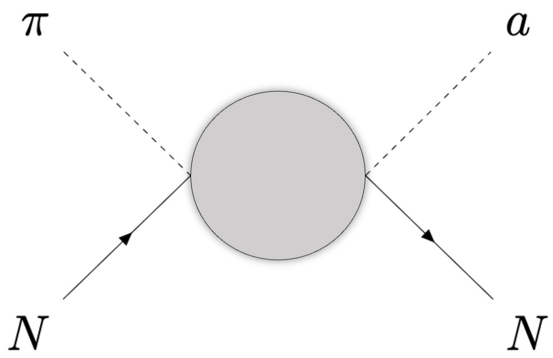
[Turner, PRL 60 (1988) , Ericson and Mathiot, PLB 219 (1989), Raffelt & Seckel, PRD 52 (1995), Hempel, PRC 91 (2015), Carenza et al., JCAP 10 (2019), Lella, GL, et al. PRD 107 (2023),...]



Detailed nuclear physics and many-body effects included.

- **Compton Pionic Processes**

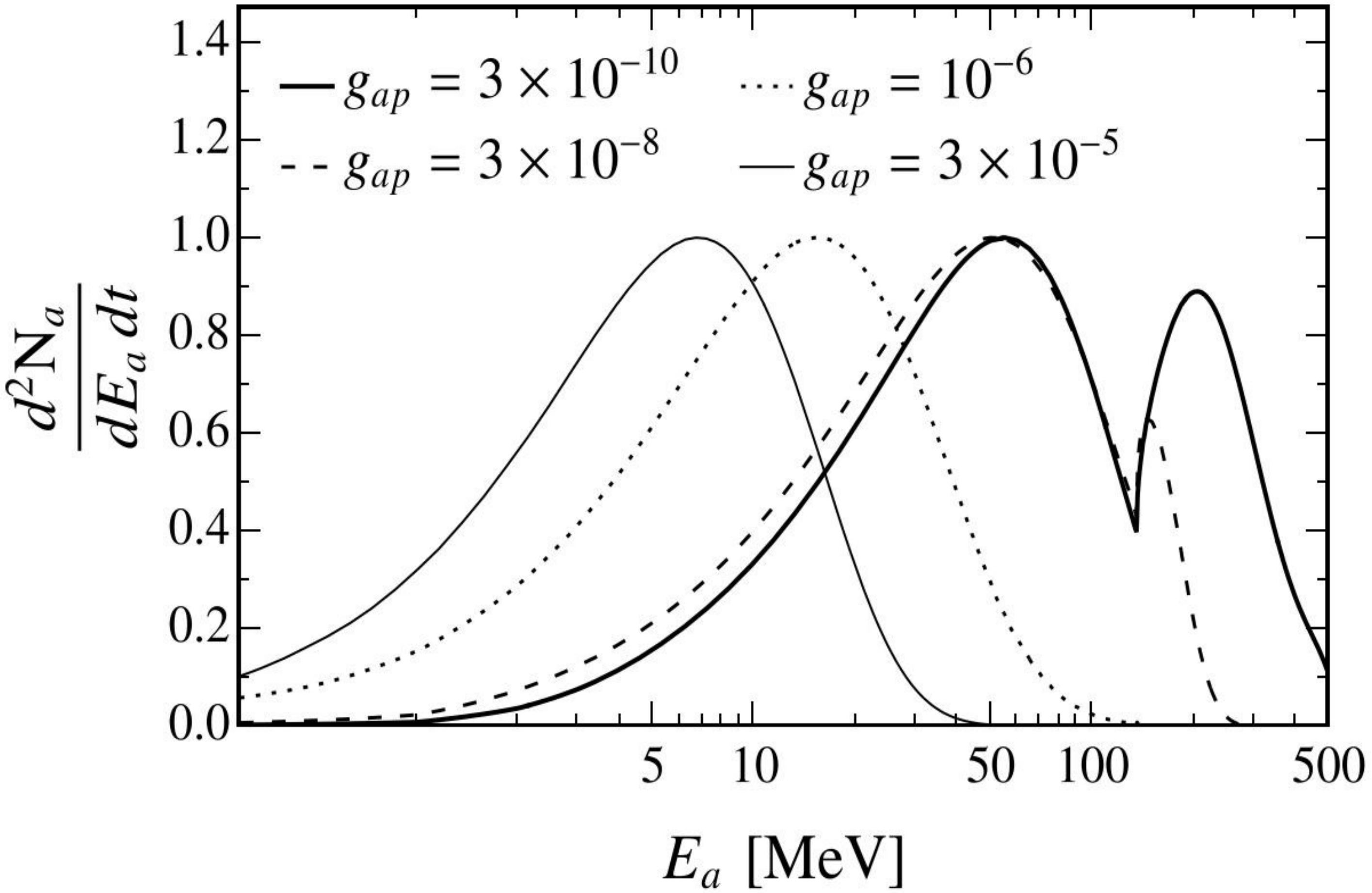
[Turner, PRD 45 (1992), Raffelt & Seckel, PRD 52 (1995), Keil et al., PRD 56 (1997), Carenza et al., PRL126 (2021), Choi et al., JHEP 02 (2022), Ho et al., PRD107 (2023),...]



Leading production process for SN axions despite the small density of pions ($\mathcal{O}(1\%)$ [Fore&Reddy , PRC 101 (2020)])

AXION EMISSION SPECTRA

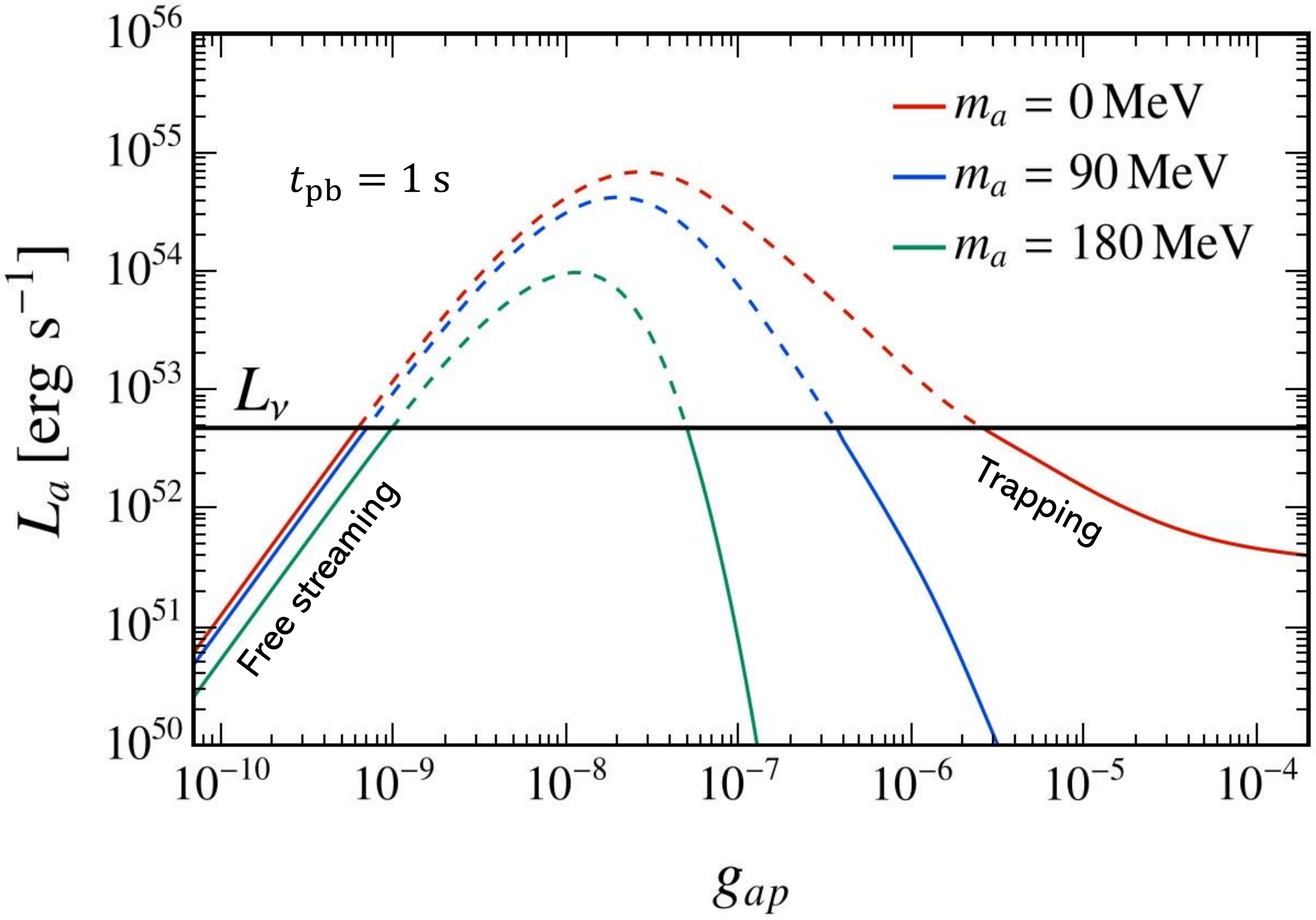
[Lella, Carenza, Giannotti, GL, Mirizzi, PRD 107 (2023), Lella, Carenza, Co, Giannotti, GL, Mirizzi, Rauscher, PRD 109 (2024)]



In the free-streaming regime, pion processes lead to a harder axion spectrum ($E_a \sim 200$ MeV).

SN AXION LUMINOSITY

[Lella, Carenza, Co, Giannotti, GL, Mirizzi, Rauscher, PRD 109 (2024)]



AXION SIGNAL IN KAMIOKANDE II

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

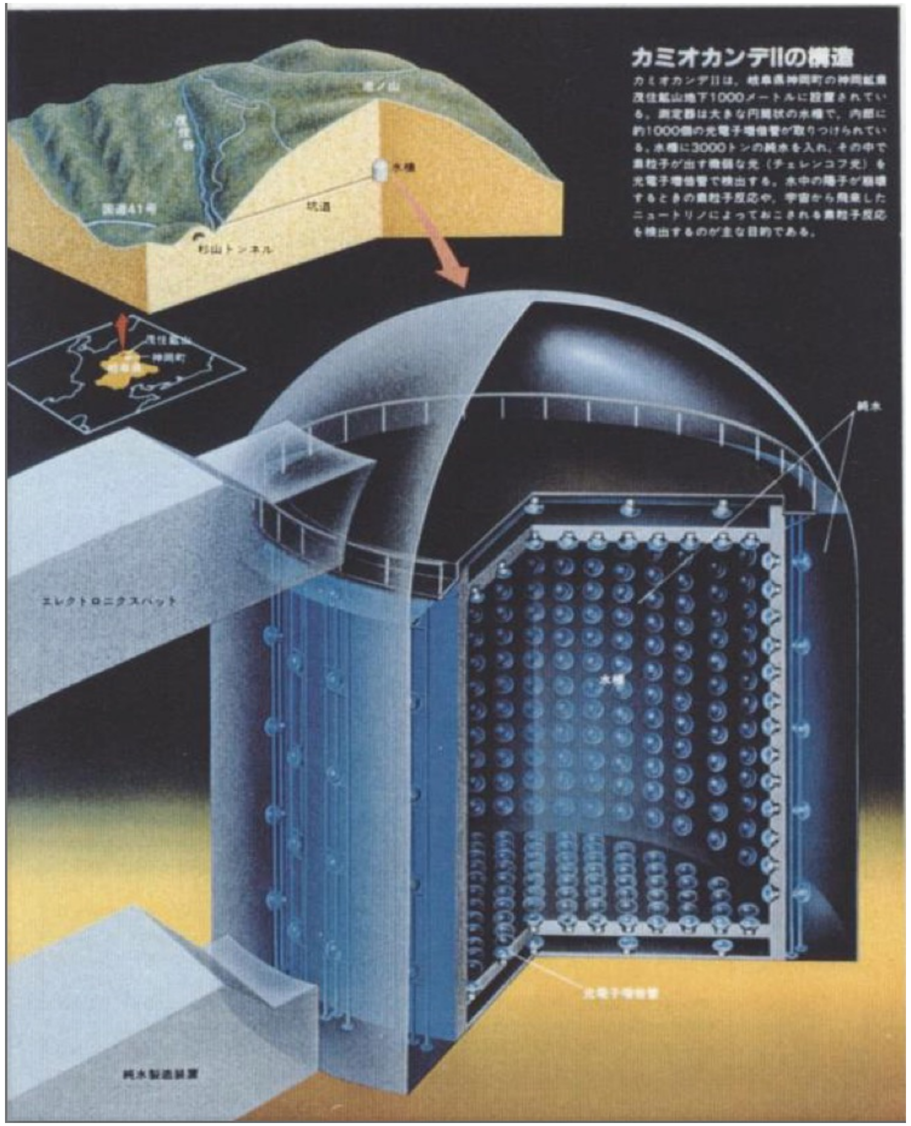
Seminal idea by Engel, Seckel and Hayes: look for axion-induced excitation of oxygen nuclei [Engel et al., PRL 65 (1990)].

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

We recently updated the calculation with

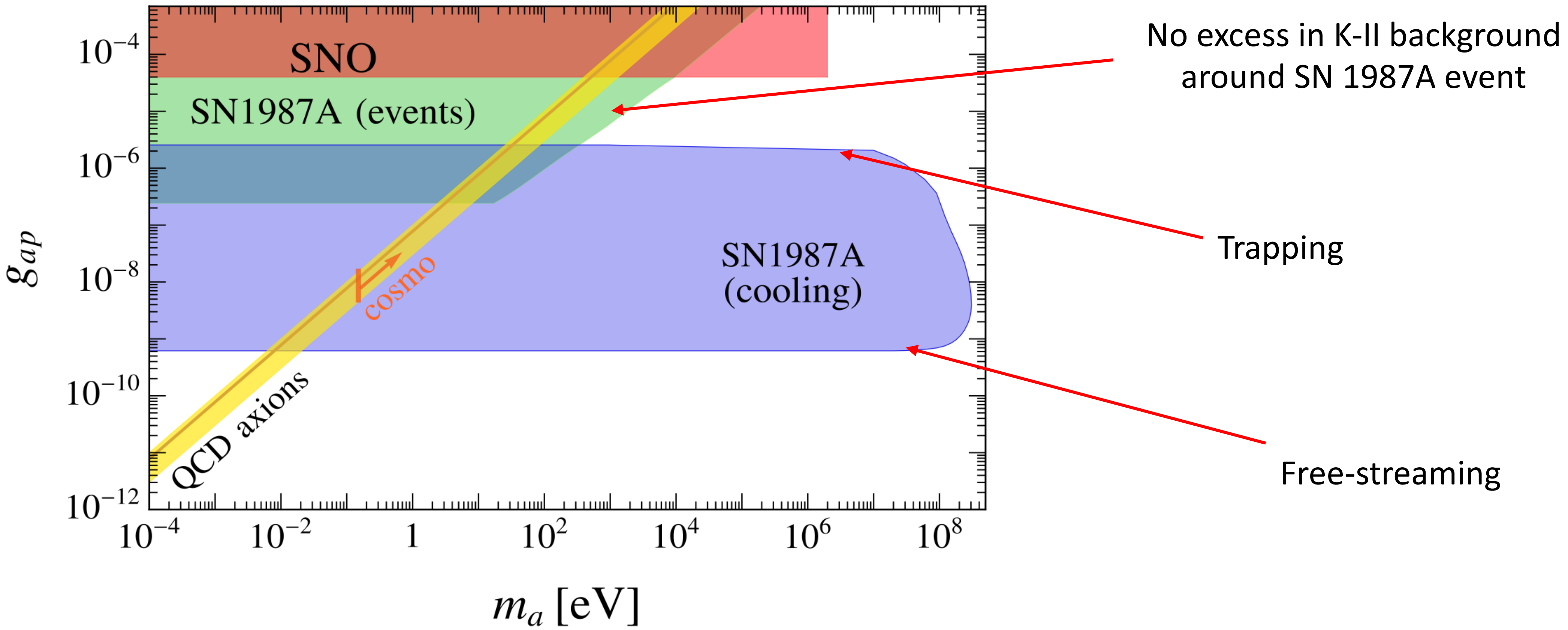
- State-of-the-art SN models
- Revised axion-oxygen cross section.

[Carenza, Co, Giannotti, Lella, GL, Mirizzi, Rauscher, PRC 109 (2024)]



AXION PARAMETER SPACE

[Lella, Carenza, Co, Giannotti, GL, Mirizzi, Rauscher, PRD 109 (2024)]



SNe exclude QCD axions with $m_a \gtrsim 10$ meV (comparable with NS cooling bound [Buschmann et al., PRL 128 (2022)]).

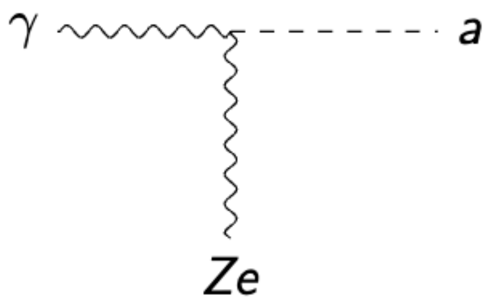
At $m_a \gtrsim 1$ MeV stronger constraints from QCD-induced coupling to photons. [Lella et al., 2405.00153]

AXION-PHOTON COUPLING

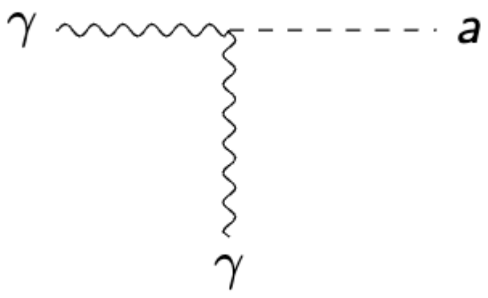
$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma}\, a\, \tilde{F}^{\mu\nu} F_{\mu\nu}$$

Two main production channels: [e.g., GL et al., JCAP 12 (2020), Caputo et al., PRD 105 (2022)]

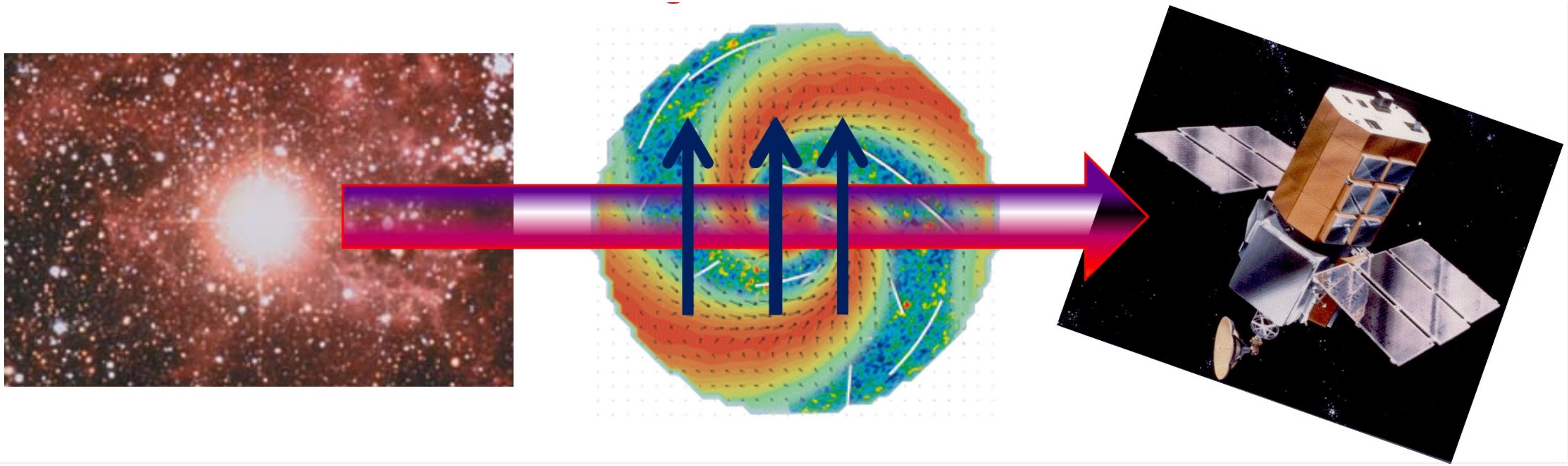
Primakoff effect



Photon coalescence



CONVERSIONS IN THE GALACTIC MAGNETIC FIELD



Bounds from non-observation of gamma-rays in coincidence with SN1987A.

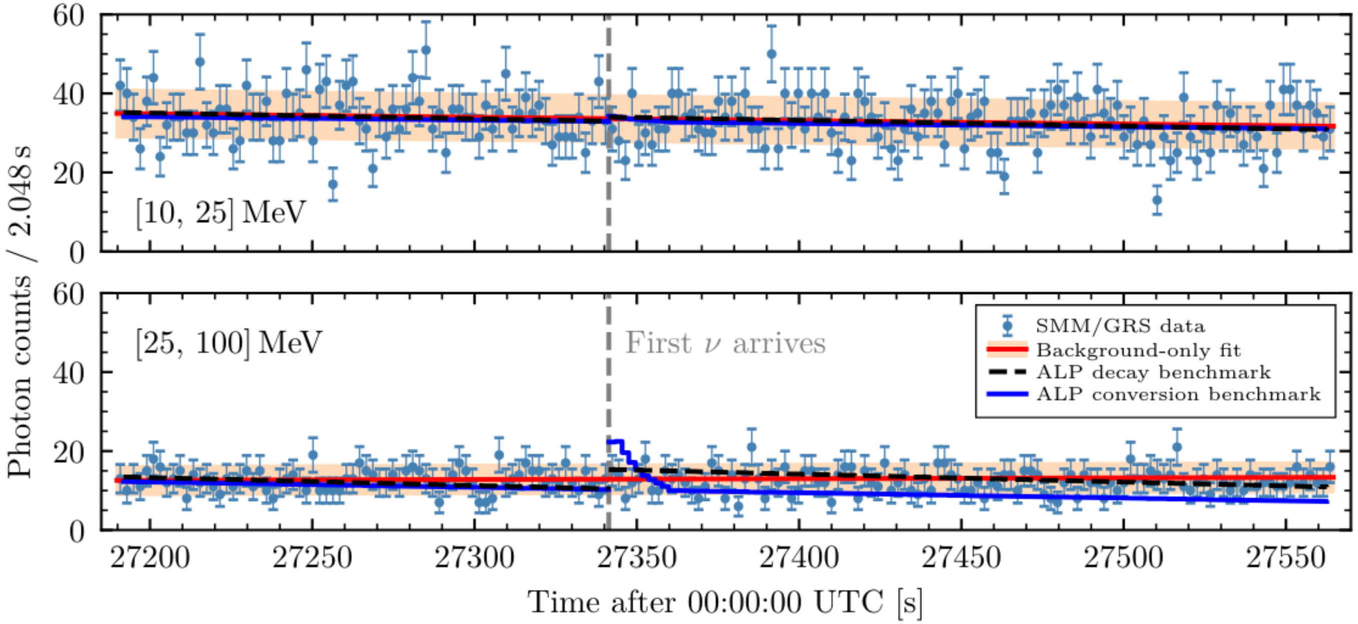
[Brockway et al., PLB 383 (1996), Masso & Toldra, PRL 77(1996), Payez et al., JCAP 02 (2014), Hoof & Schulz, JCAP 03 (2023)]

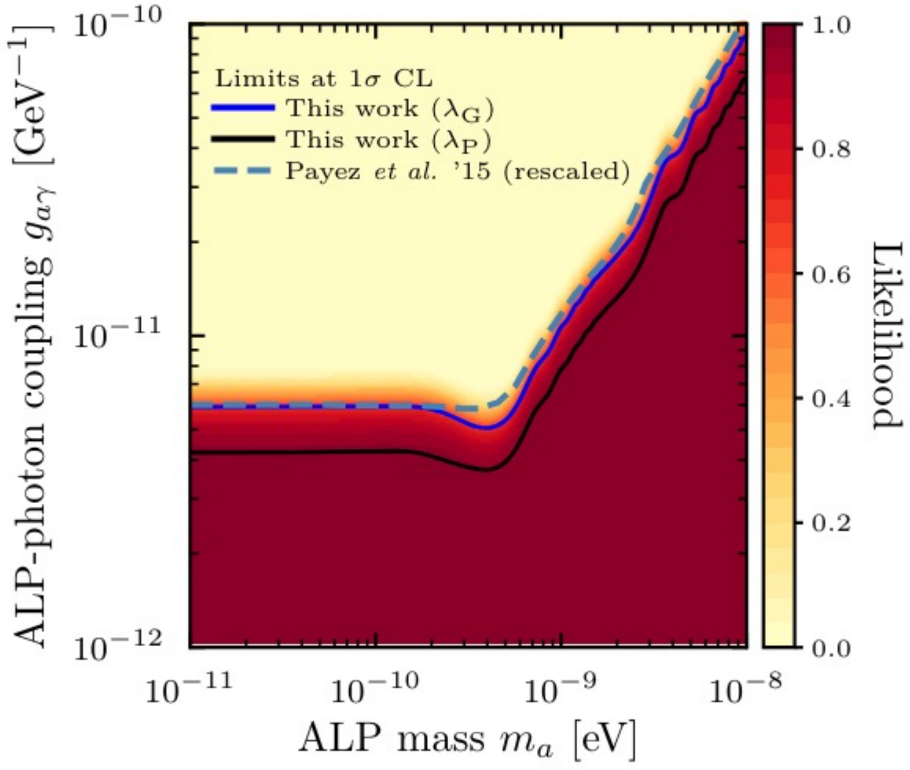
Diffuse from past core-collapse supernovae See Eckner 's talk!

[Raffelt et al., PRD 84 (2011), Calore et al., PRD 102 (2020), Calore et al., PRD 105 (2022)]

GAMMA-RAY OBSERVATIONS BY SMM

Counts in the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM)



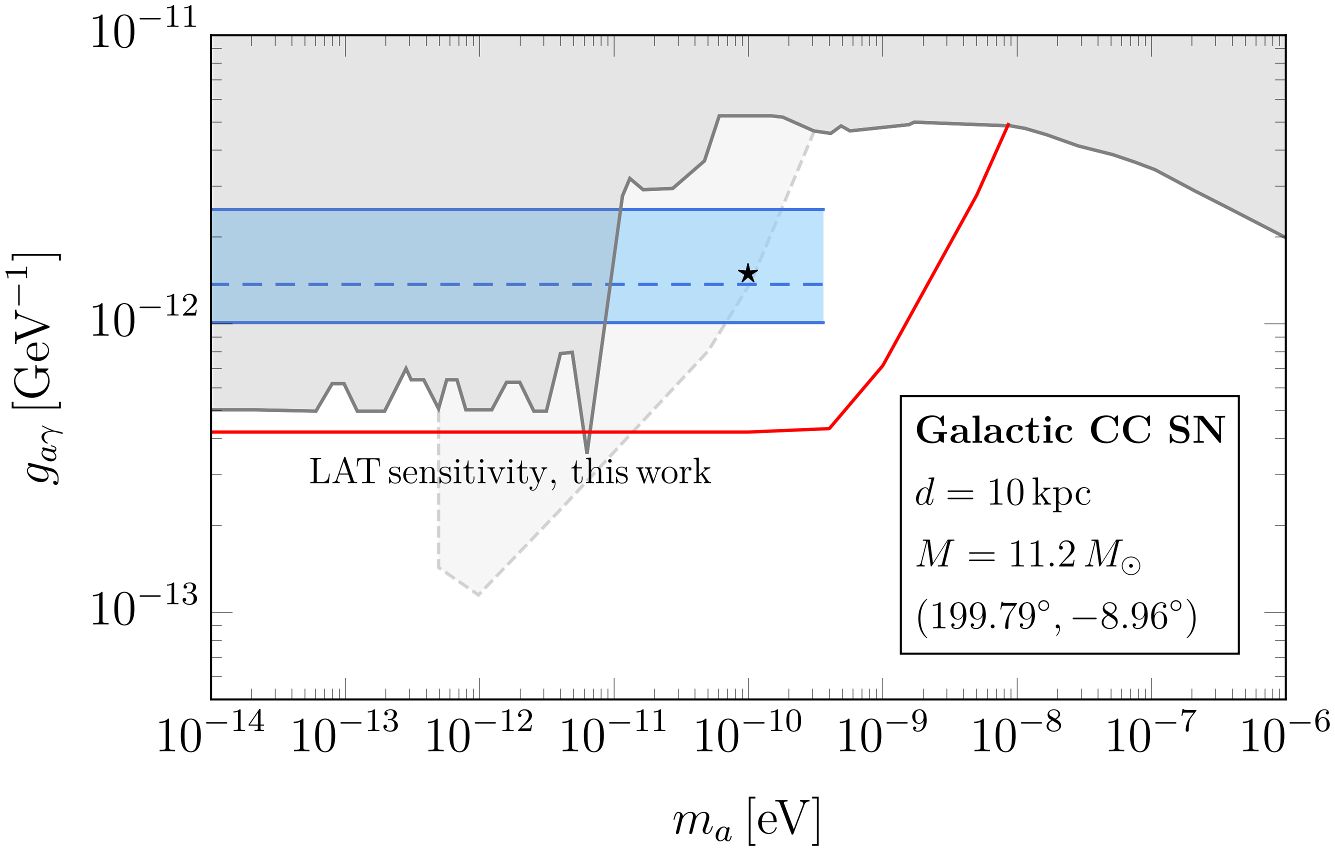


The most recent bound obtained using the temporal information of the signal.

[Hoof & Schulz, JCAP 03 (2023)]

DISCOVERY POTENTIAL OF FERMI-LAT

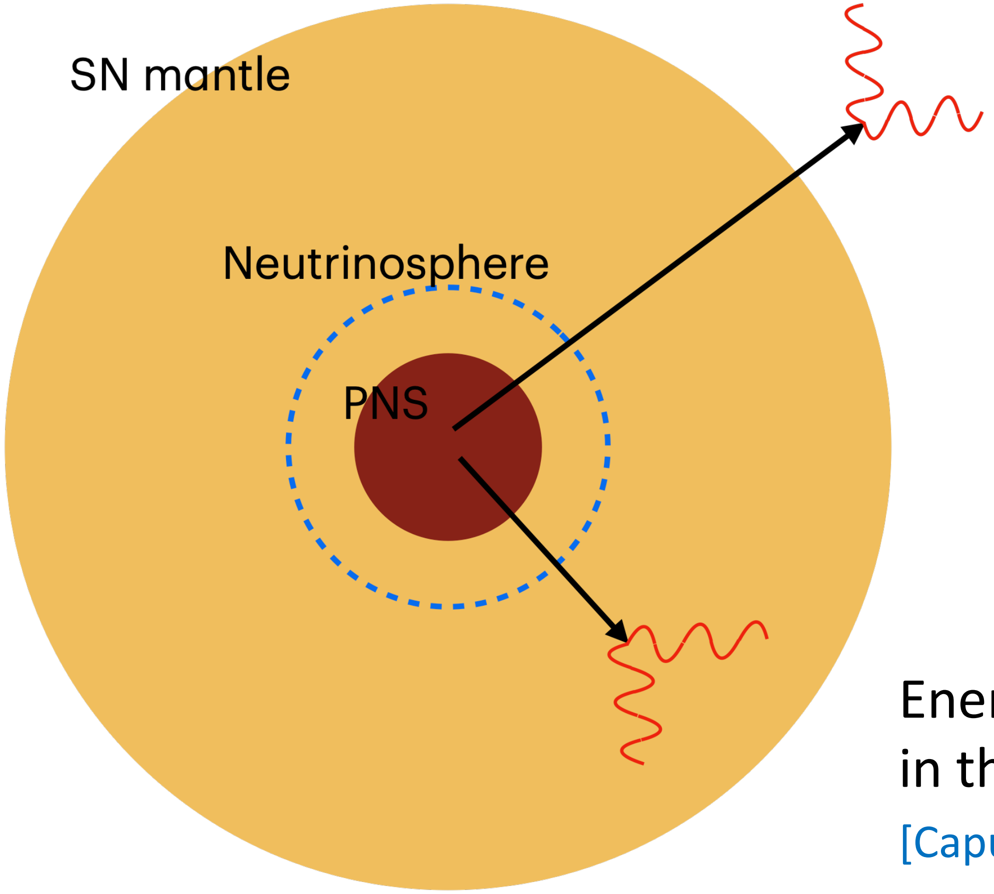
Eckner's talk



Future Galactic SN explosion in the field-of-view of Fermi-LAT:

- Reconstruction of the coupling with a factor 2 uncertainty. [Calore, Carenza, Eckner, Giannotti, GL, Mirizzi, Sivo, PRD 109 (2024)]
- Information from the SN core. [Calore, Carenza, Eckner, Giannotti, Lella, GL, Mirizzi, 2405.02395]

RADIATIVE DECAYS



Gamma-ray decay signal from a SN

[Oberauer et al., A.P. 1 (1993), Jaeckel et al., PRD 98 (2018), Caputo et al., PRD 105 (2022), Hoof & Schulz JCAP 03 (2023), Muller et al., JCAP 07 (2023)]

Diffuse from past SNe (Eckner’s talks)

[Calore et al., PRD 102 (2020), Caputo et al., PRD 105 (2022)]

Energy deposition in the mantle

[Caputo et al., PRL 128 (2022)]

SN BOUNDS ON RADIATIVE AXION DECAYS

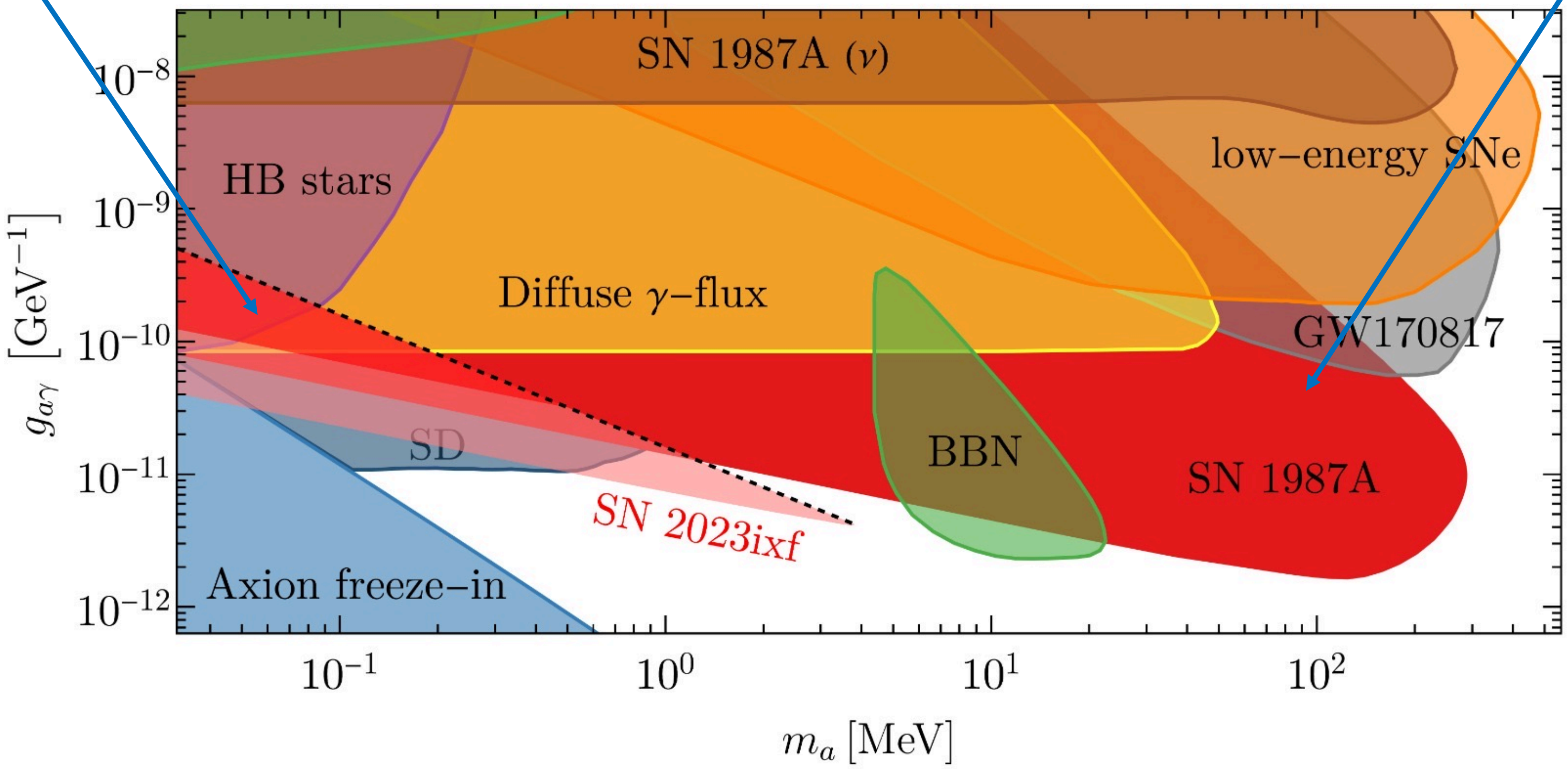
Eckner's talk

Fermi-LAT observations

[Muller et al., PRD 109 (2024)]

SMM observations

[Jaeckel et al., PRD 98 (2018), Caputo et al., PRD 105 (2022), Hoof & Schulz, JCAP 03 (2023), Muller et al., JCAP 07 (2023)]

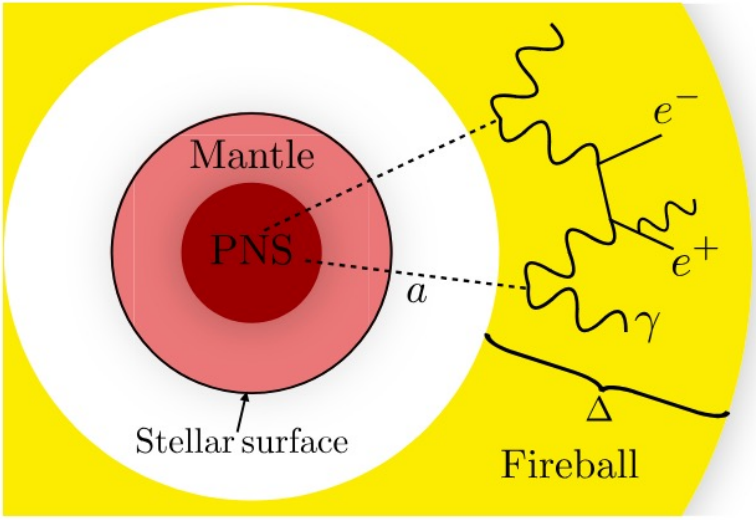


FIREBALL FORMATION

[Diamond et al., PRD 107 (2023)]

Bounds from decay not valid everywhere.

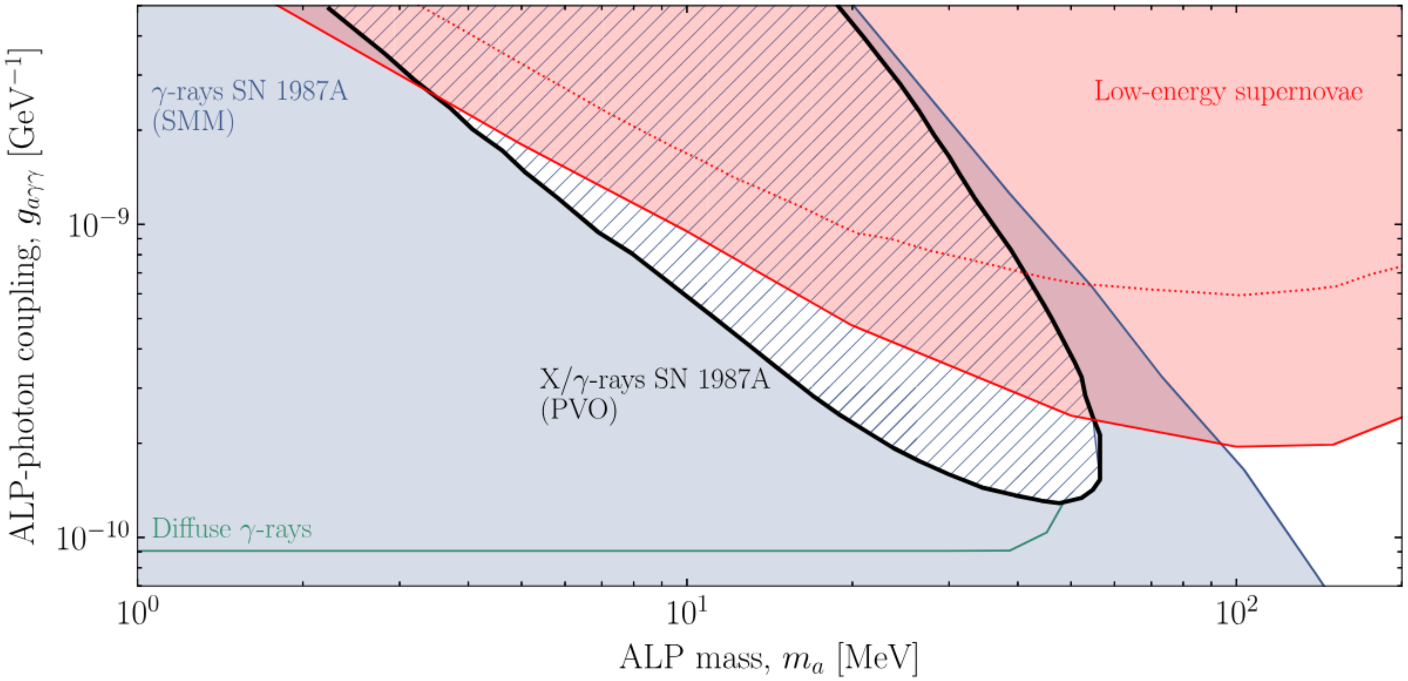
For some masses and couplings, axions form a fireball.



The expected flux is at smaller energies.

⬇

New bounds from
Pioneer Venus Observatory



Applied to constrain heavy axions from NS mergers.

[Diamond et al., PRL 132 (2024)]

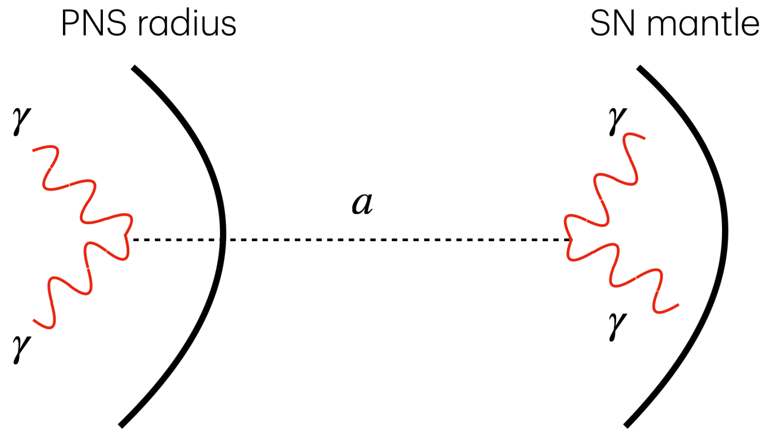
BOUNDS FROM EXPLOSION ENERGY

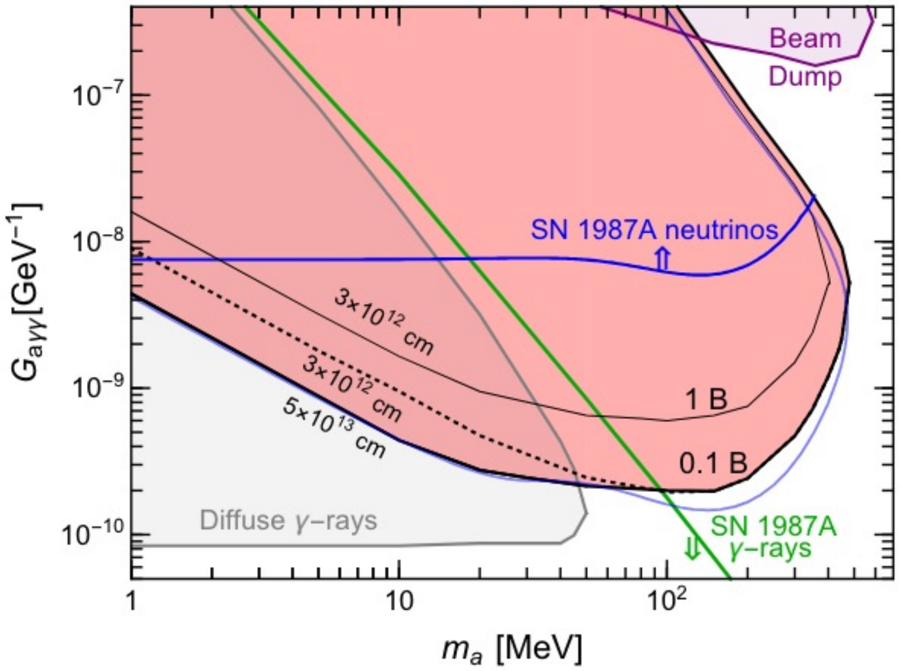
[Falk&Schramm, PLB 79 (1978),
Caputo et al., PRL 128 (2022)]

Typical SN explosion energy 1-2 B ($1\ \text{B} = 10^{51}$ erg).

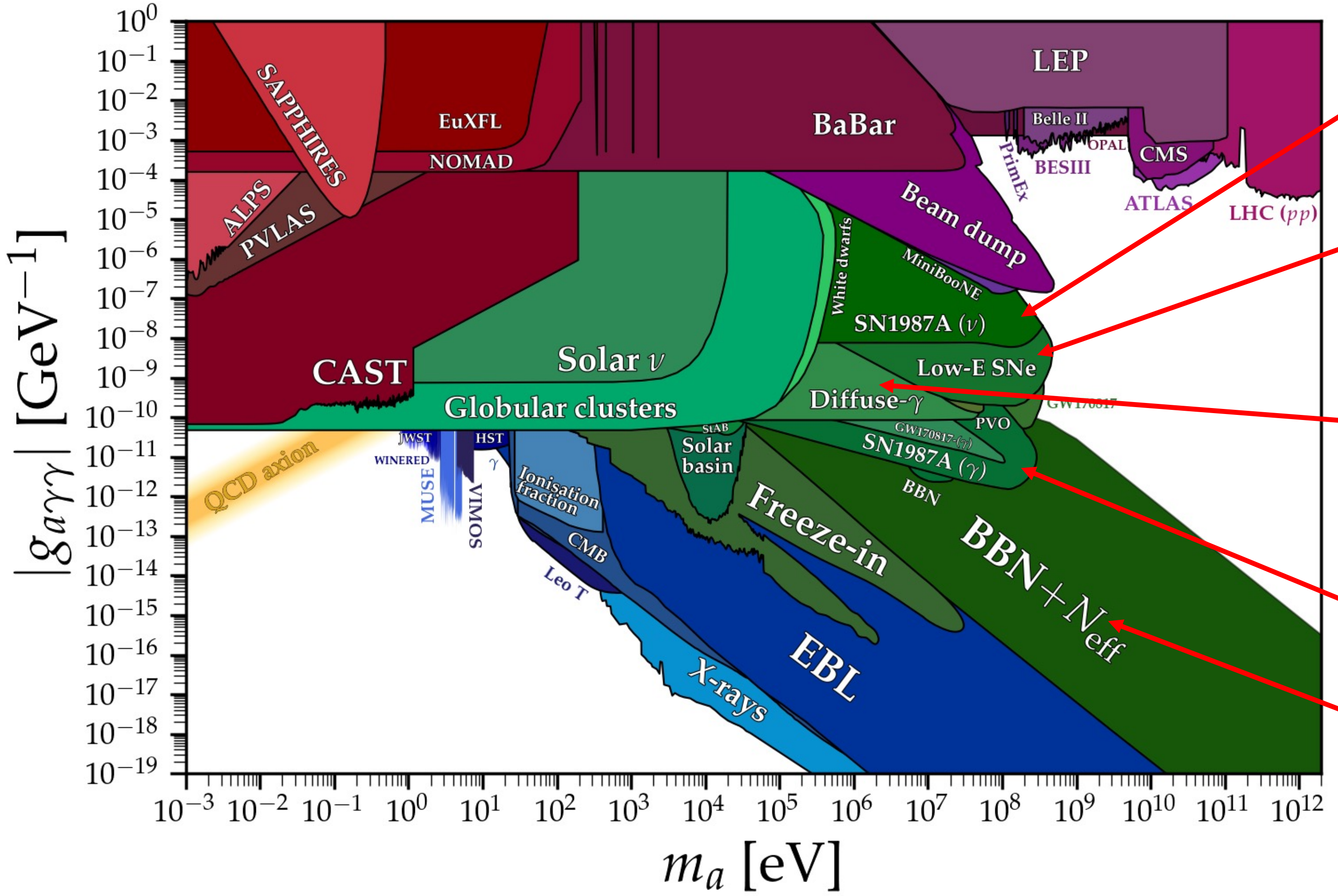
Some SNe have very small observed explosion energies < 0.1 B.

New restrictive limits from energy deposition by particle decays in progenitor stars of low-energy SNe.





HEAVY AXION PARAMETER SPACE



SN1987A cooling
[GL et al., JCAP 12 (2020), Caputo et al., PRD 105 (2022)]

Energy deposition in low-energy SNe
[Caputo et al., PRL 128 (2022)]

Diffuse gamma-ray background from past SNe
[Calore et al., PRD 102 (2020), Caputo et al., PRD 105 (2022)]

Gamma-ray from SN 1987A at SMM and PVO
[Muller et al., JCAP 07 (2023), Diamond et al. PRD 107 (2023)]

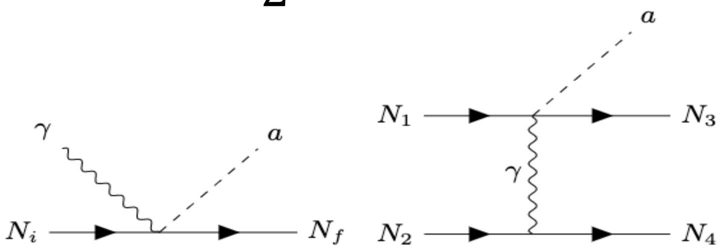
Vanishes for low T_{RH}
[Langhoff et al., PRL 129 (2022)]

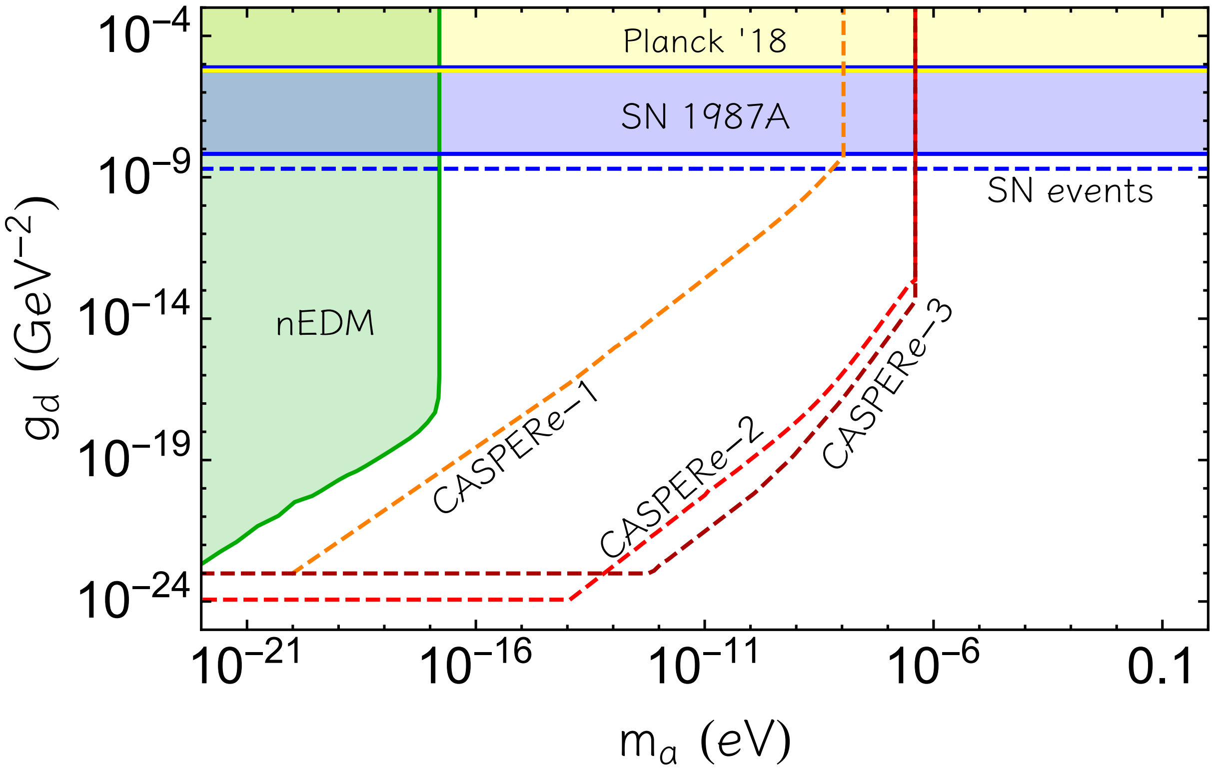
BOUNDS ON EDM PORTAL

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

[Graham & Rajendran, PRD 88 (2013)]

[GL, Mastrototaro, Carenza, Di Luzio, Giannotti, Mirizzi, PRD 105 (2022)]

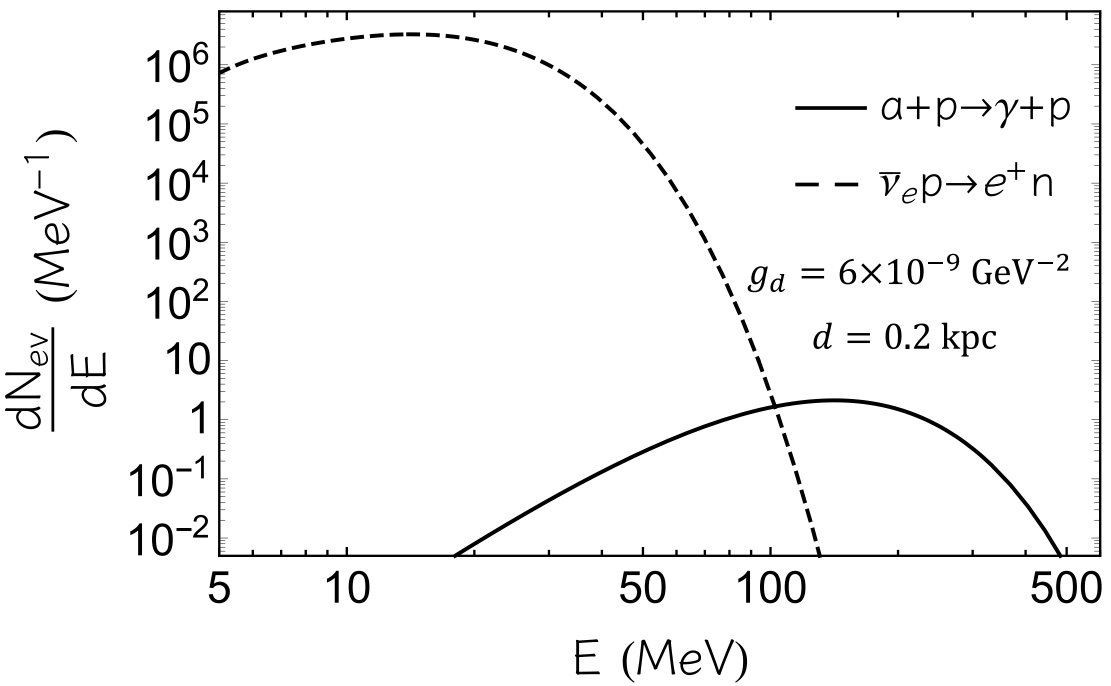


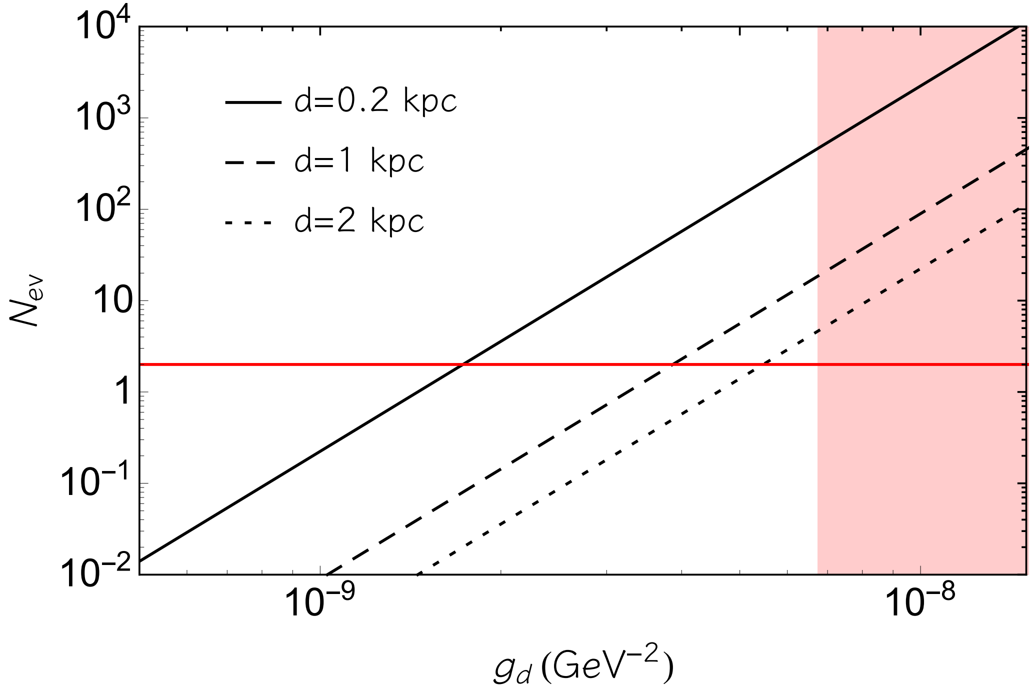


DETECTION PERSPECTIVES

Below the SN 1987A bound and for $g_d \gtrsim 2\times10^{-9}\ \mathrm{GeV}^{-2}$, axions can be detected in future neutrino detectors, such as HyperKamiokande. [GL, Mastrototaro, Carenza, Di Luzio, Giannotti, Mirizzi, PRD 105 (2022)]

Detection possibility complementary to *CASPERe* experiment. [Jackson Kimball et al., Springer Proc.Phys. 245 (2020)]



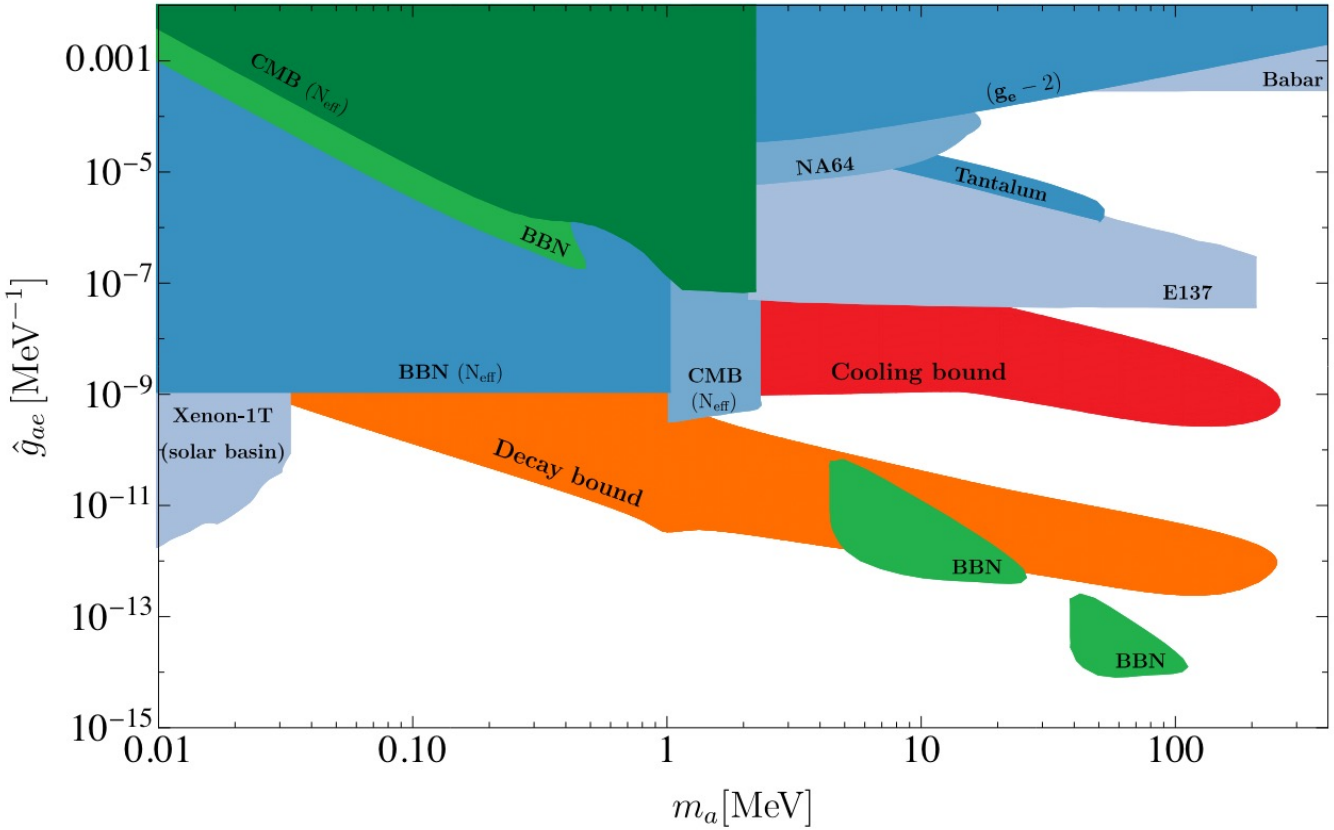


LEPTONIC COUPLING: ELECTRONS

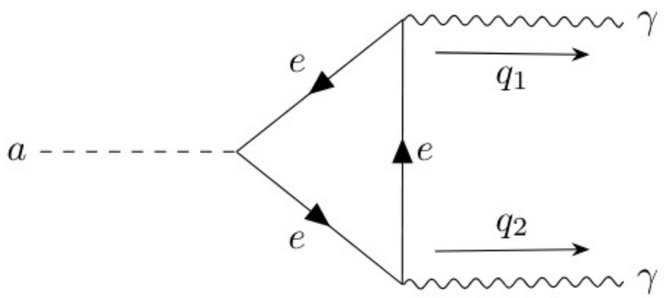
[Ferreira et al., JCAP 11 (2021)]

$$\mathcal{L}_{ae} = \hat{g}_{ae}(\partial_\mu a)\,\bar{\psi}_e\,\gamma^\mu\gamma_5\psi_e$$

$$\hat{g}_{ae} = \frac{g_{ae}}{2\,m_e}$$



Loop-induced coupling to photons



See [Caputo et al., PRD 105 (2022)] for axion interactions with muons.

LEPTONIC COUPLING: ELECTRONS

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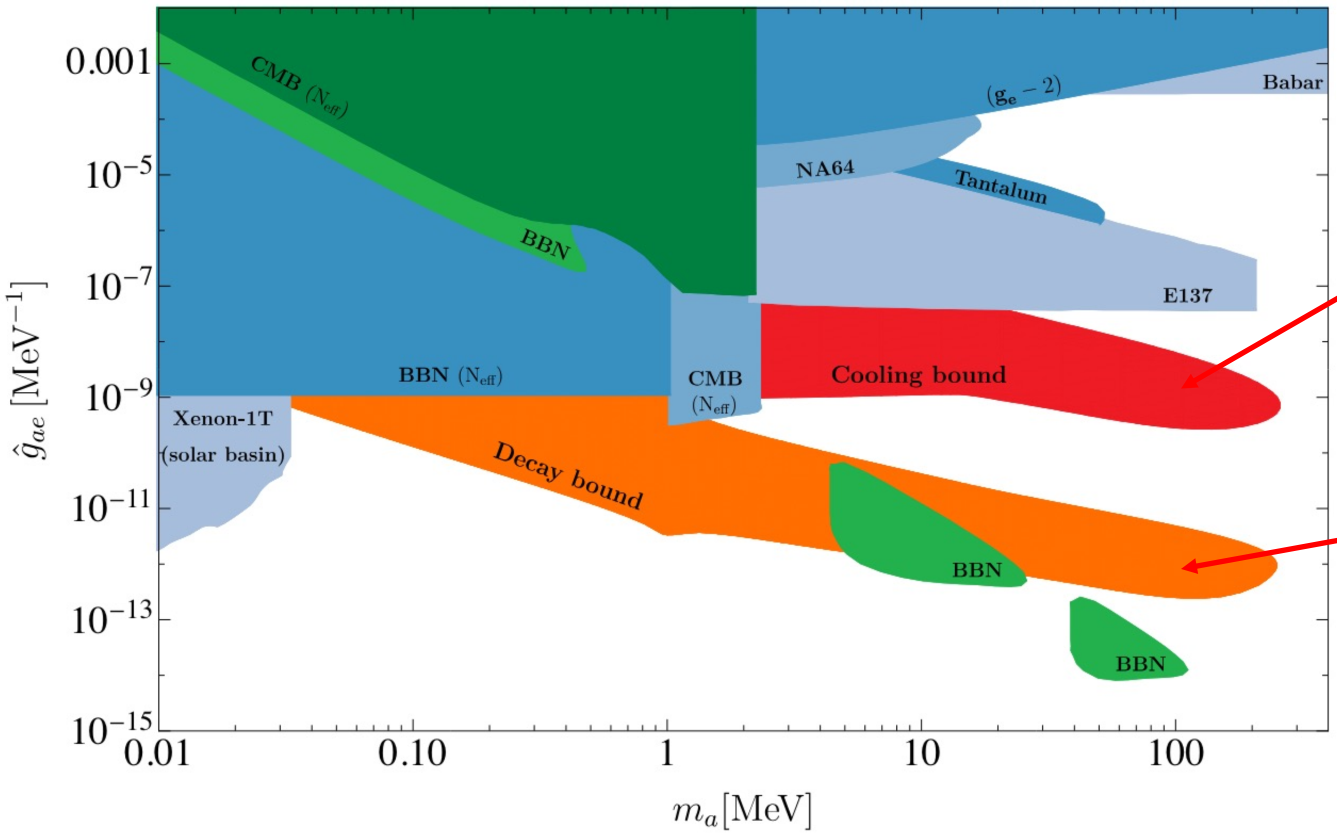

SN1987A cooling

[GL & Carenza, PRD 104 (2021), Ferreira et al., JCAP 11 (2021)]

Gamma-ray from SN1987A at SMM

[Ferreira et al., JCAP 11 (2021)]

See [Caputo et al., PRD 105 (2022)] for axion interactions with muons.

CONCLUSIONS

- SNe efficient laboratories to probe axions.
- Different observables for different couplings (very active field with many new ideas!)
- Next SN explosion great opportunity to improve knowledge on axion physics.

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

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BACKUP