Firenze,

4^{th} May 2023

Progress on SN axions. New production mechanisms and prospects for detection

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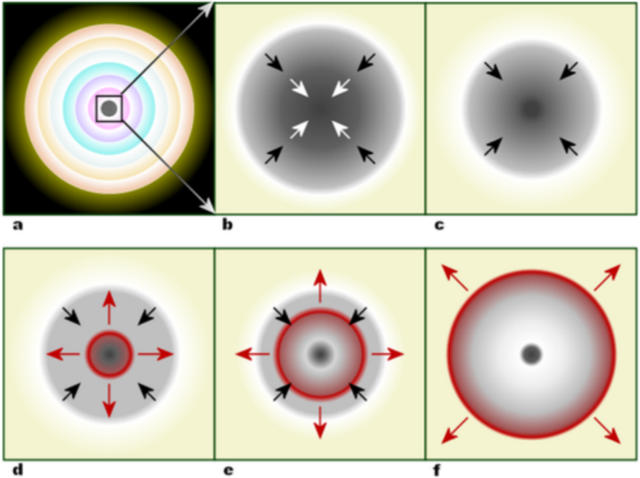
Core-Collapse Supernovae

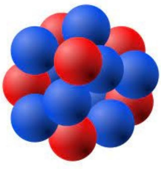
For massive stars ($M > 8M_\odot$) the nuclear fusion produces heavy elements in an onion structure and a degenerate iron core



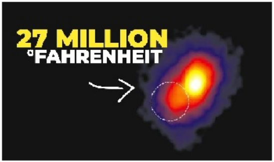
Iron in the core cannot be burnt and the star starts to collapse

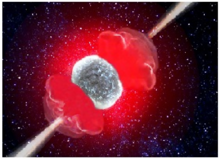
Orders of magnitude for SNe

The SN core is an extreme environment



1000x



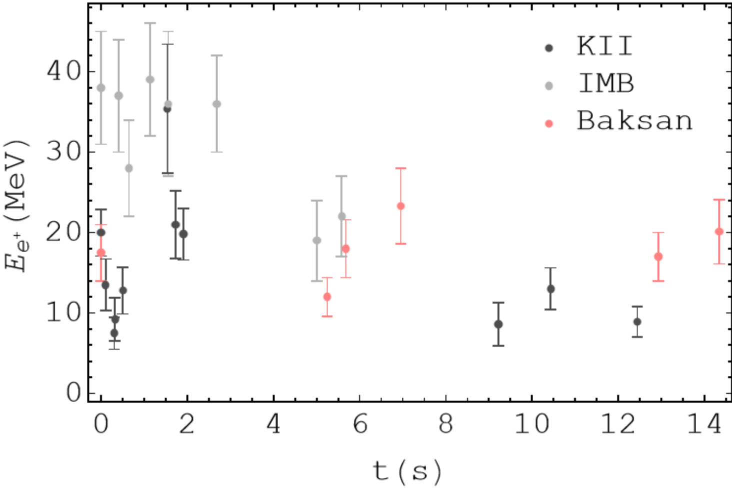


density **temperature** **magnetic field**

10^{14}g cm^{-3} 30 MeV 10^{15} G

SN1987A: neutrino signal

From the few $\bar{\nu}_e p \to n e^+$ events of SN 1987A we know that...

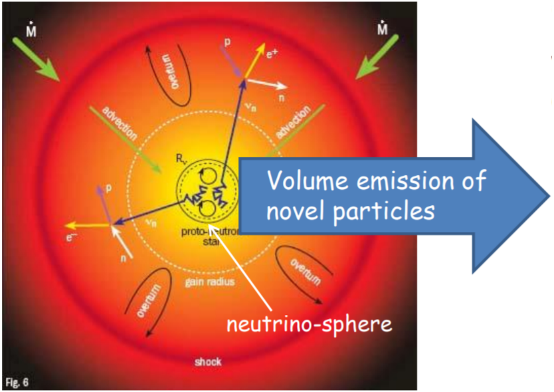


$\sim 10^{53}$ erg emitted as neutrinos with energy $\sim O(15\,\mathrm{MeV})$ in $\sim 10\,\mathrm{s}$

The energy-loss argument

G. Raffelt, Lect. Notes Phys. **741** (2008)

Stars produce axions which escape, draining energy from the core



Axions affect strongly the SN neutrino burst if

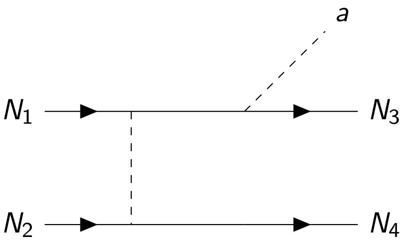
$$L_a \gtrsim L_\nu \approx 3 \times 10^{52}\,\mathrm{erg\,s^{-1}} \quad \text{at} \quad t_{\rm pb} = 1\ \mathrm{s}$$

Axion production in nuclear processes

Axion-nucleon bremsstrahlung in SNe

M. S. Turner, Phys. Rev. Lett. **60** (1988)

SN axions are produced by nucleon-axion bremsstrahlung

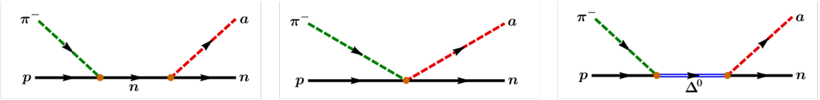


where we have to include detailed nuclear physics and many body effects

Pion-axion conversion in SNe

P. Carenza, B. Fore *et al.*, Phys. Rev. Lett. **126** (2021) no.7, 071102
K. Choi *et al.* JHEP **02** (2022) 143
S.-Y. Ho *et al.*, Phys. Rev. D **107** (2022) 075002

SN axions are produced by pion-axion conversion

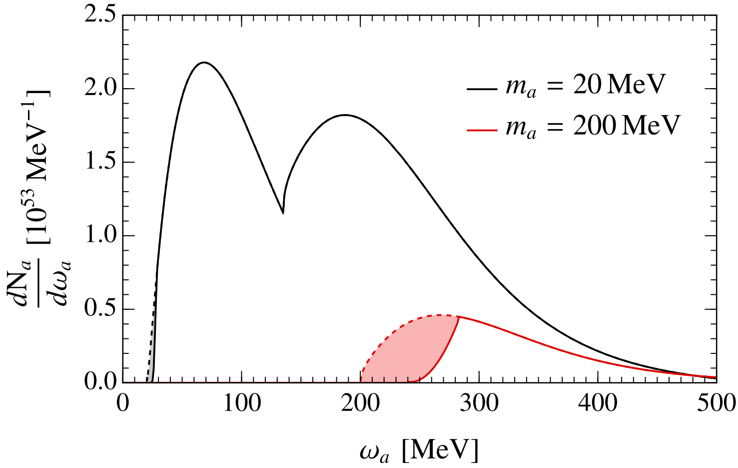


This is the leading axion production process in a SN despite the small density of pions ($\mathcal{O}(1\%)$)!!

Flux from pion-axion conversion

A. Lella *et al.*, [arXiv:2211.13760 [hep-ph]].

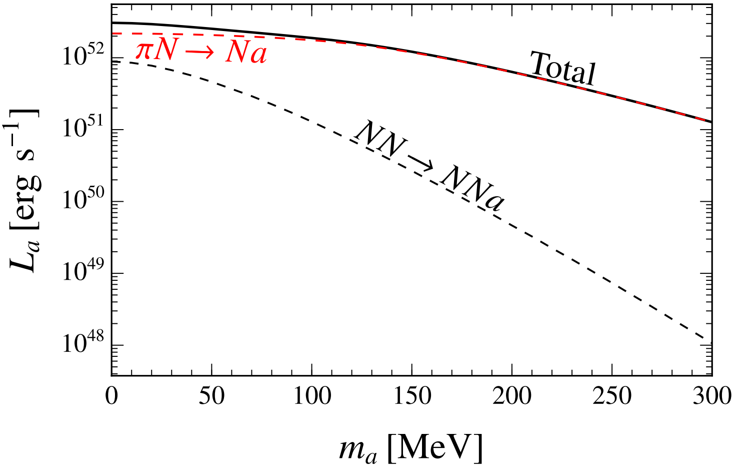
The harder spectrum is due to the pion rest mass



Comparison of axion fluxes integrated over 10 s for $g_{ap} = 10^{-10}$

Comparison of the luminosities

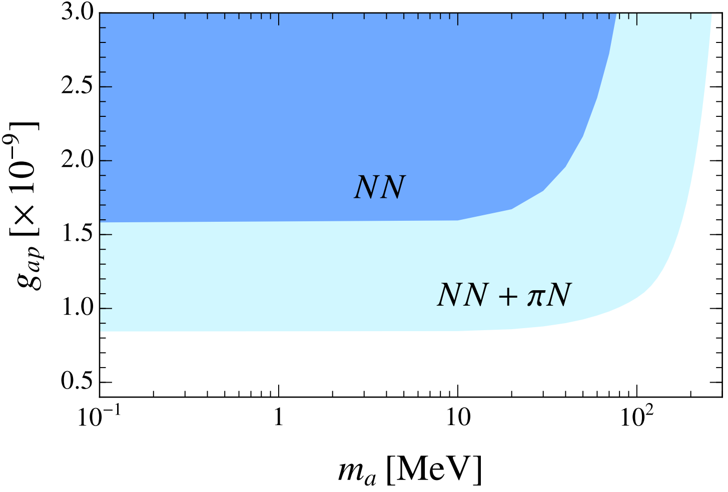
The pion conversion becomes even more important at high masses



Luminosity $t_{\rm pb} = 1$ s for $g_{ap} = 8.5 \times 10^{-10}$

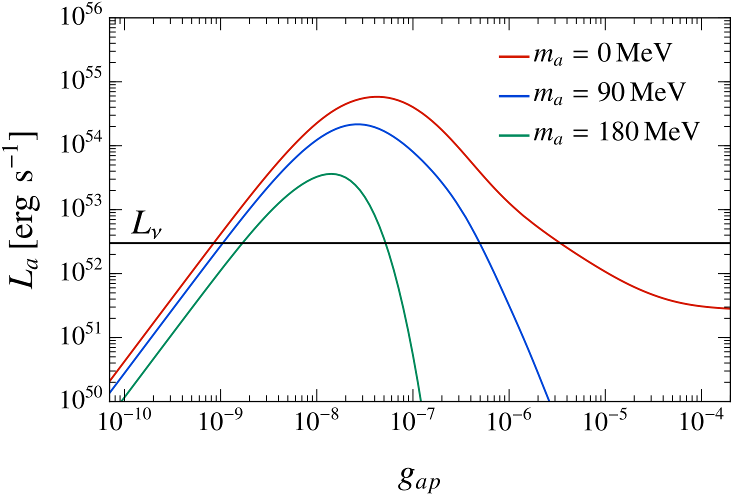
Consequences on the SN cooling

The SN bound improves of a factor 2 for light ALPs



Trapping regime

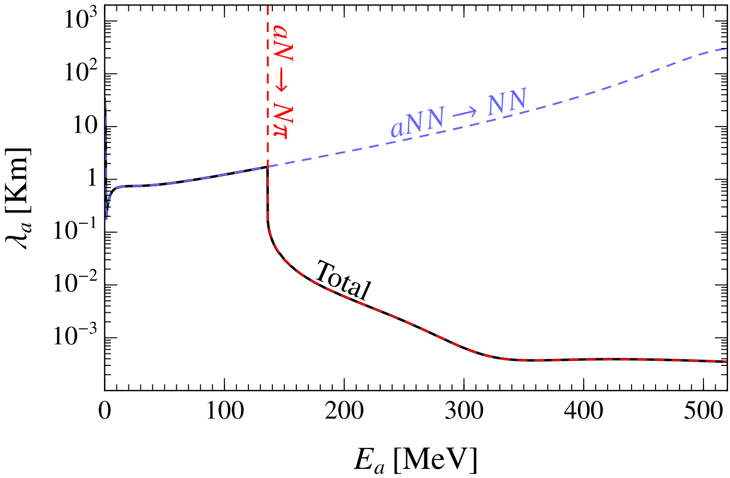
A. Lella, P. Carenza, GL, M. Giannotti, A. Mirizzi *et al.*, to appear



Luminosity at $t_{\rm pb} = 1$ s

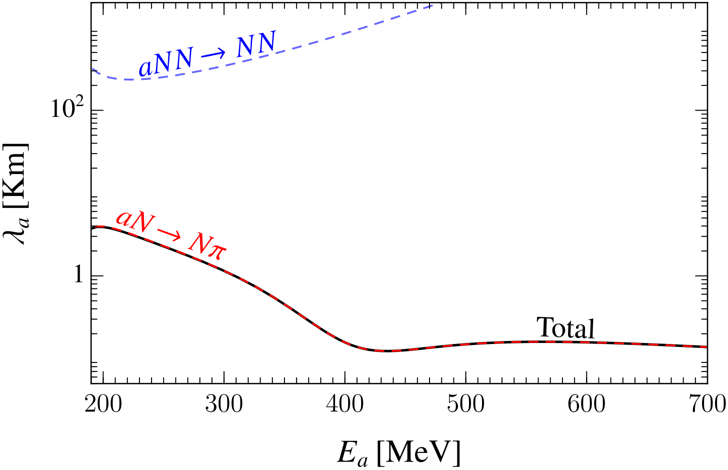
Processes responsible of the trapping: light ALPs

Interplay between the two processes, especially at low energy

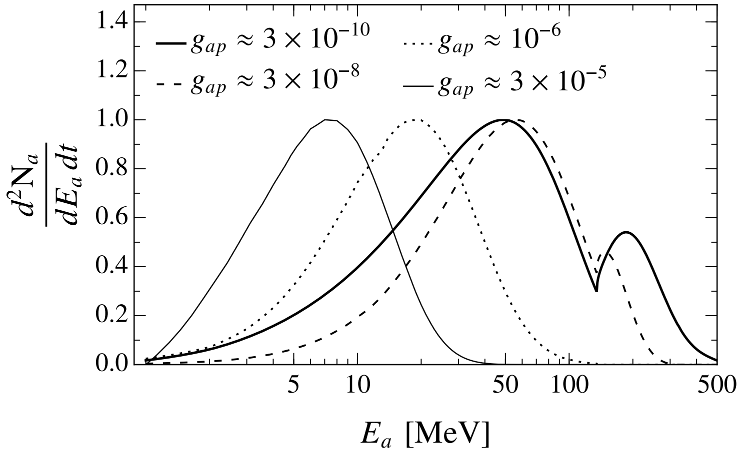


Processes responsible of the trapping: heavy ALPs, $m_a = 180$ MeV

The pion conversion is always the dominant absorption mechanism



How the spectrum looks like in the trapping

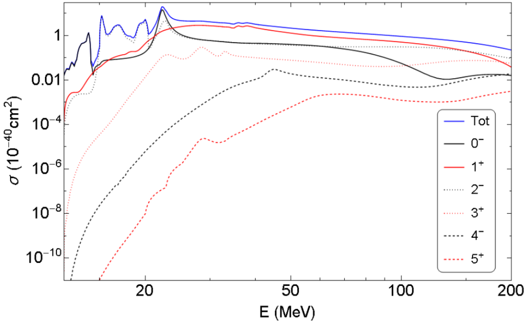


Normalized spectra in the massless case at $t_{\rm pb} = 1$ s for different values of the ALP-proton coupling g_{ap} and for $g_{an} = 0$.

Observing axions from SN 1987A in KII

Axions can excite oxygen in KII

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



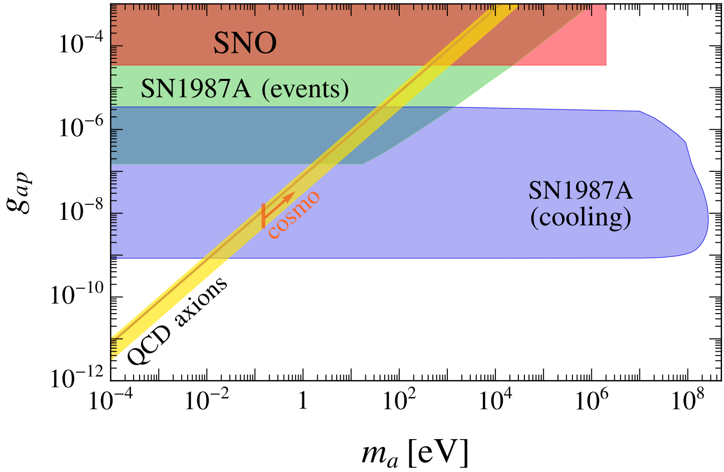
$$N_{\rm ev} < 2\sqrt{n_{\rm bkg}\Delta t_a} \qquad n_{\rm bkg} \simeq 0.02\,\mathrm{s}^{-1}$$

If $m_a \ll 30$ eV $\qquad \Delta t_a = \Delta t_\nu \simeq 12$ s

If $m_a \gtrsim 30$ eV $\qquad \Delta t_a = 1.82 \text{ s} \left(\frac{m_a}{10 \text{ eV}}\right)^2$

A complete overview of the SN bound

Only QCD axions below meV are allowed by the constraints



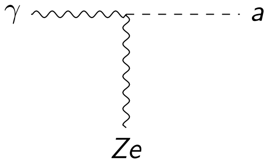
Axion-Like Particles from Supernovae: the photon coupling

ALP production channels

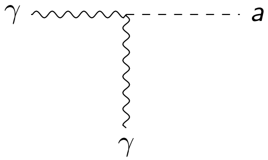
GL, P. Carenza *et al.*, JCAP **12** (2020), 008

ALPs are coupled with photons and are produced by:

Primakoff conversion

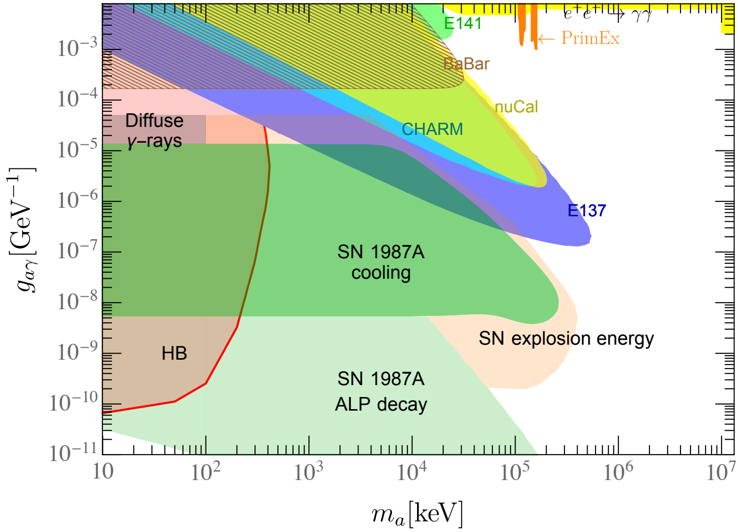


Photon Coalescence



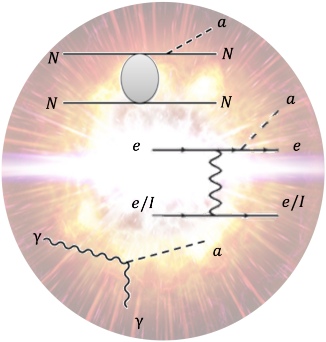
SN1987A ALP bound

Nice complementarity with other bounds

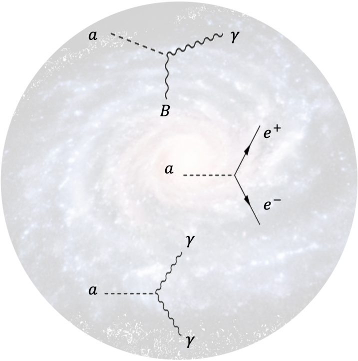


SN axion phenomenology: decay of heavy axions

Production



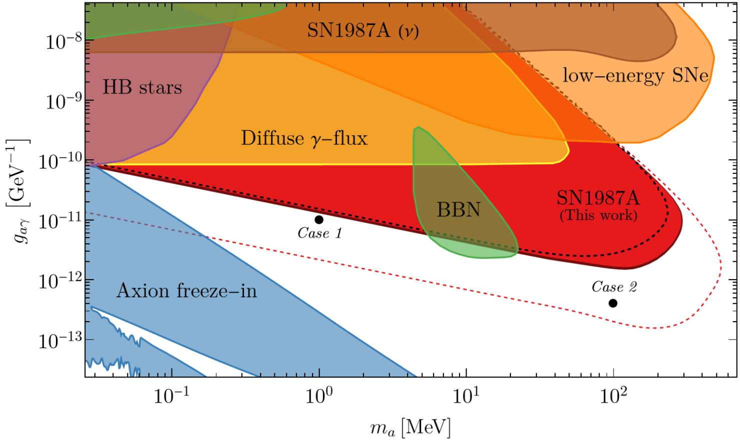
Signature



Revisiting the SN decay bound

E. Müller, *et al.*, [arXiv:2304.01060 [astro-ph.HE]].

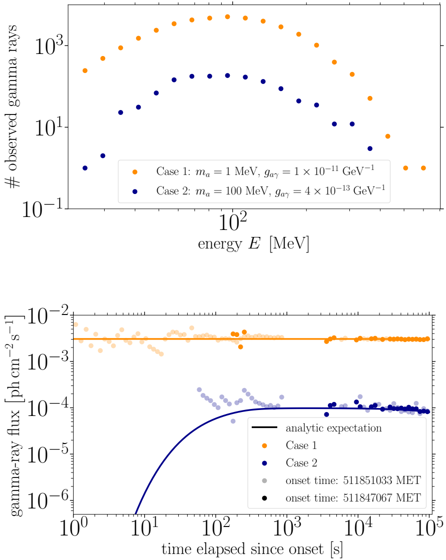
Fermi-LAT has the potential to improve the constraint of one order of magnitude



The dotted line indicates the *Fermi*-LAT sensitivity to a $d = 50$ kpc

Discovering ALPs with *Fermi*-LAT

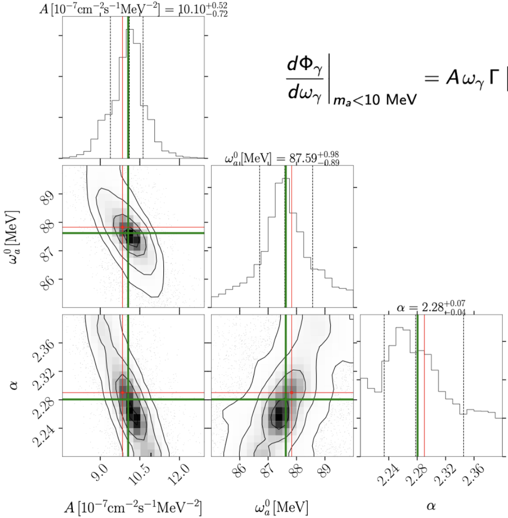
Energy and time-dependence of simulated spectra



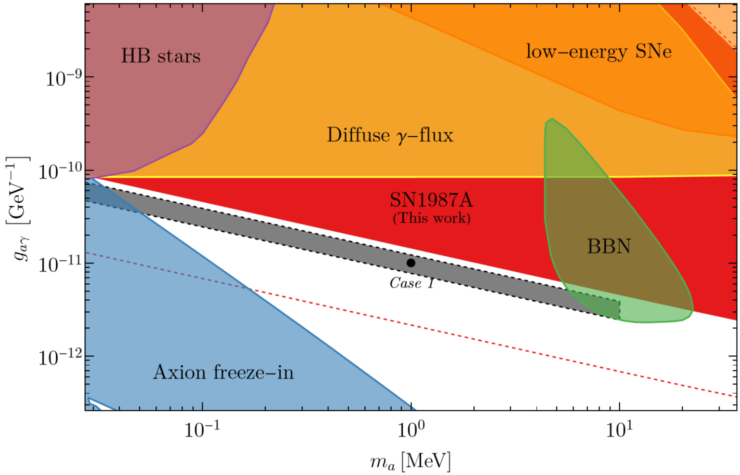
And reconstructing their properties: light ALPs, $m_a = 1$ MeV

The real values (red) are in good agreement with the measurement (green)

$$\left.\frac{d\Phi_\gamma}{d\omega_\gamma}\right|_{m_a<10\ \mathrm{MeV}} = A\,\omega_\gamma\,\Gamma\left[\alpha, (1+\alpha)\,\omega_a^{\min}/\omega_a^0\right]$$

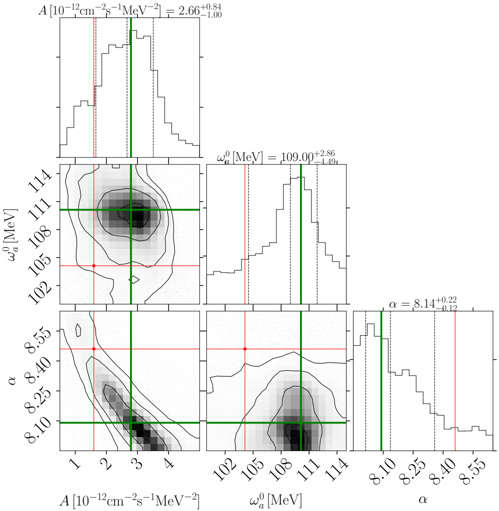


The degeneracy in $g_{a\gamma}^2 m_a$ cannot be easily broken



And reconstructing their properties: heavy ALPs, $m_a = 100$ MeV

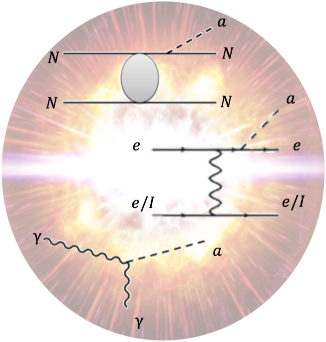
The real values (red) are not in good agreement with the measurement (green)



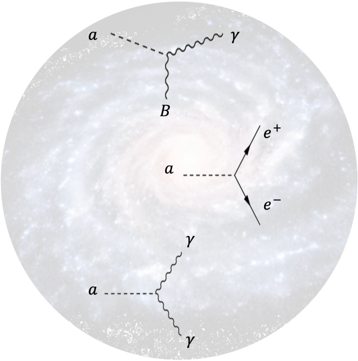
Direct signatures from the Diffuse SN ALP Background

SN axion phenomenology: conversion of light axions

Production



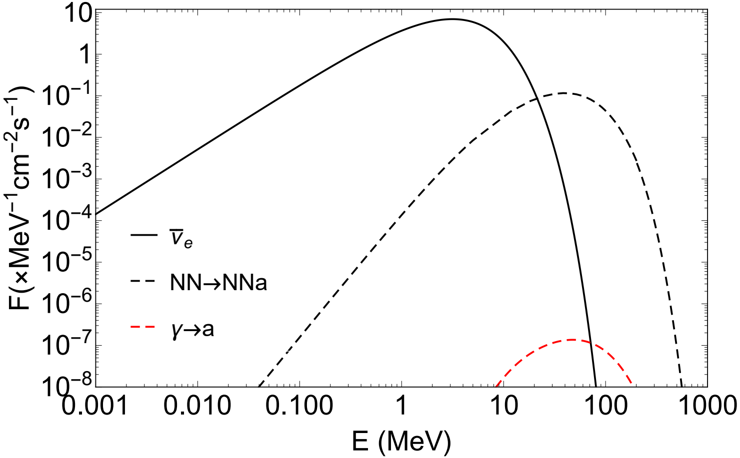
Signature



DSNALPB

F. Calore *et al.*, Phys. Rev. D **102** (2020) no.12, 123005

The nucleon coupling is less constrained, larger flux with NN

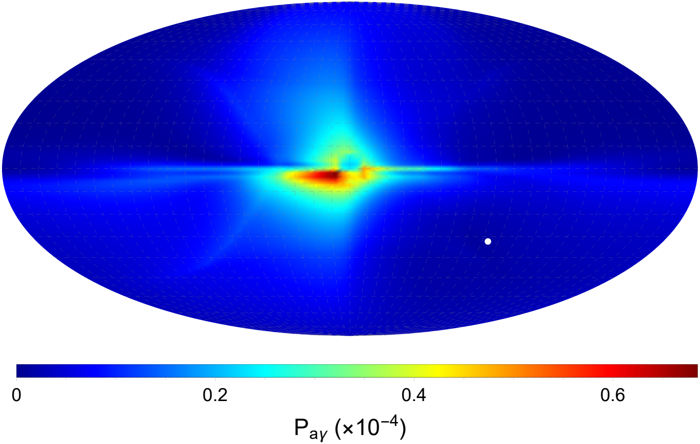


DSNALPB with $g_{ap} = 1.2 \times 10^{-9}$ and $g_{a\gamma} = 5.3 \times 10^{-12}\,\mathrm{GeV}^{-1}$

ALP conversion into photons

D. Horns *et al.*, Phys. Rev. D **86** (2012), 075024

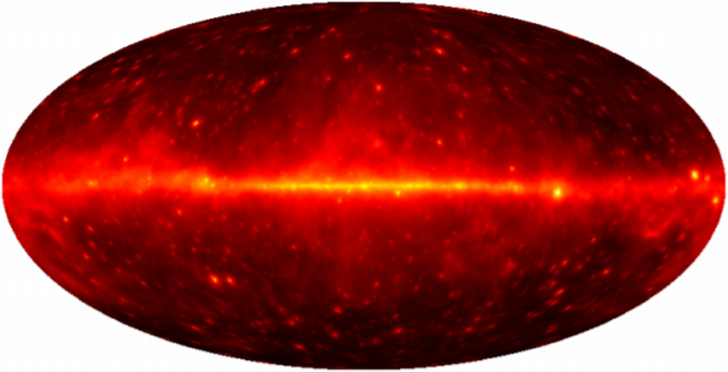
The Galactic magnetic field will convert into photons both the DSNALPB and the point-like ALP flux from SN1987A (white dot)



Conversion probability for $m_a \ll E = 50\,\mathrm{MeV}$, $g_{a\gamma} = 3 \times 10^{-13}\,\mathrm{GeV}^{-1}$

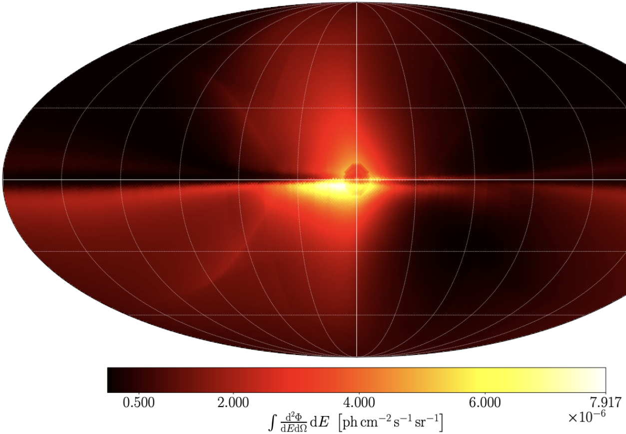
Fermi-LAT data

Skymap of gamma-rays observed by Fermi-LAT



The ALP signal

F. Calore *et al.*, Phys. Rev. D **105** (2022) no.6, 063028.

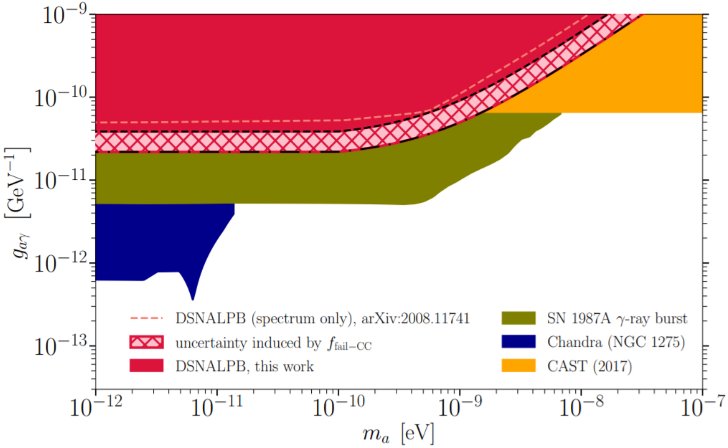


All-sky map of the photon flux from the DSNALPB, with $g_{a\gamma} = 3.76 \times 10^{-11}$ GeV^{-1} (for $m_a \ll 10^{-11}$ eV)

The bound

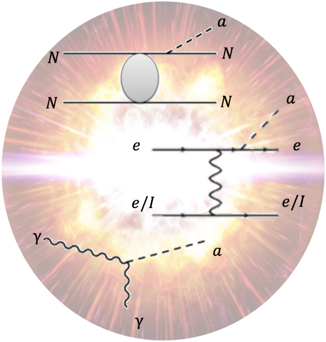
F. Calore *et al.*, Phys. Rev. D **105** (2022) no.6, 063028.

The bound is stronger than CAST and can be improved by future γ-ray measurements

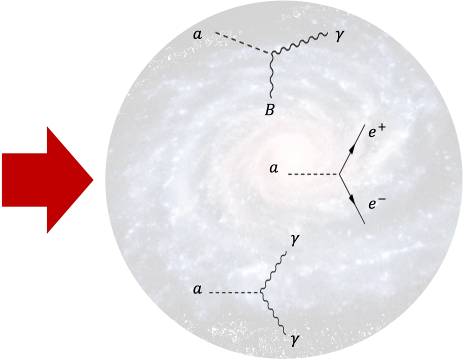


SN axion phenomenology: decay into electron-positron pairs

Production

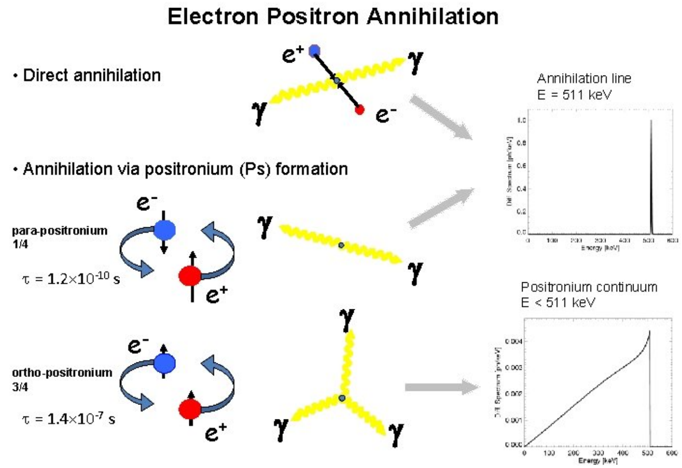


Signature



$a \to e^+e^-$ is not invisible

Positrons lose energy in $10^3 - 10^6$ yrs

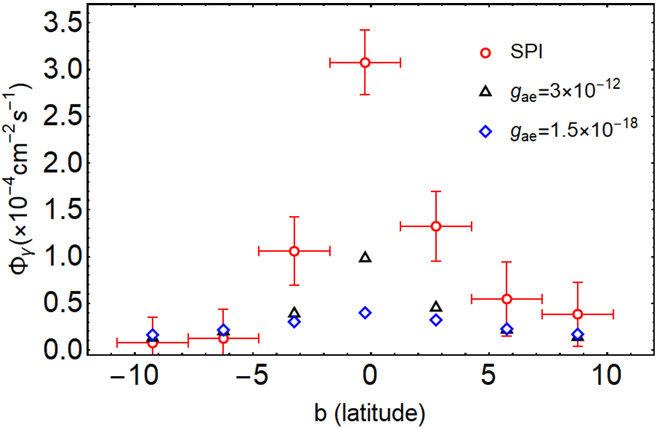


Is it possible to explain **a fraction of** the 511 keV line with ALPs?

Agaronyan, F. A., and A. M. Atoyan, 1981, Sov. Astr. Letters 7, 395

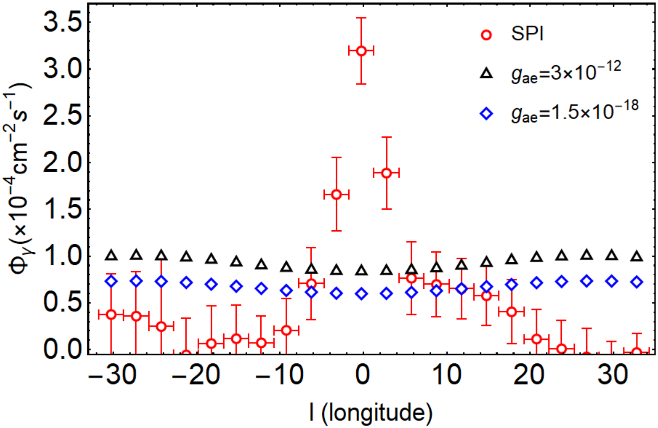
Let's compare with SPI data...

F. Calore, GL *et al.*, Phys. Rev. D **104** (2021) no.4, 043016 [arXiv:2107.02186 [hep-ph]].



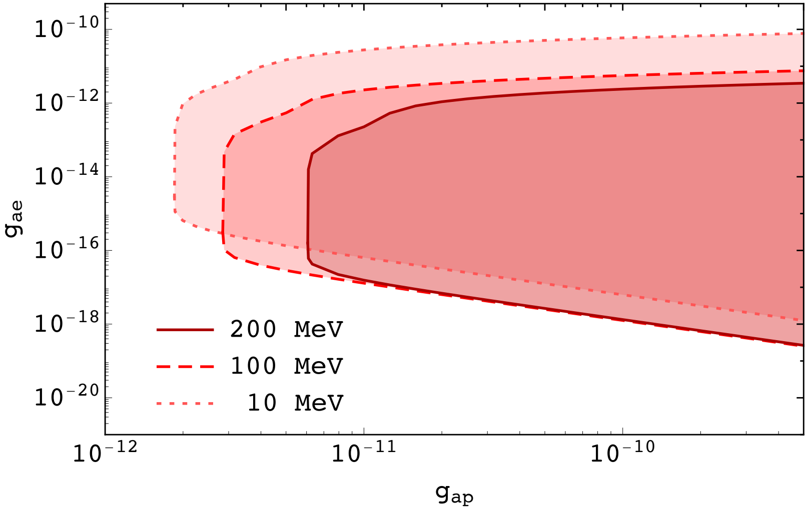
Very good agreement for the vertical distribution...

... much less agreement with the horizontal one



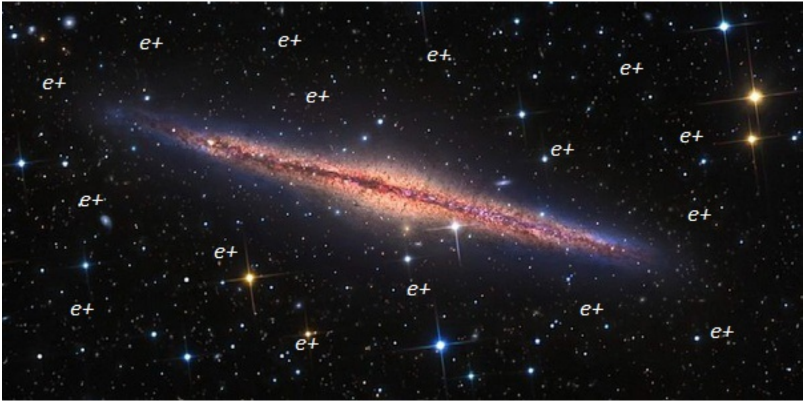
511 keV line bound from Galactic SNe

A. Lella, P. Carenza, GL *et al.*, [arXiv:2211.13760 [hep-ph]].



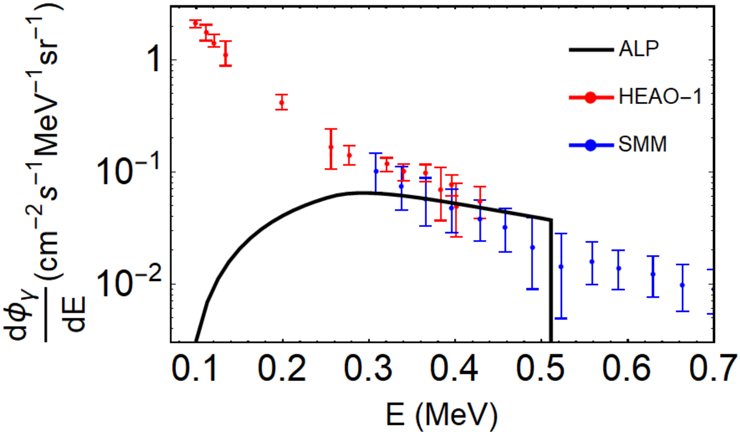
ALPs escaping from the Galaxy

Positrons trapped in the intergalactic medium ($B \sim \mathrm{nG}$) annihilate in $\sim \mathrm{Gyr}$ and photons are redshifted



Extragalactic X-ray diffuse flux

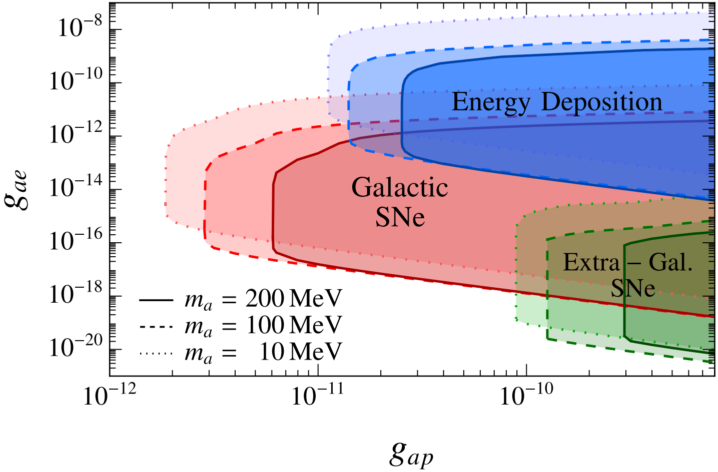
The extragalactic flux is redshifted, no more 511 keV line



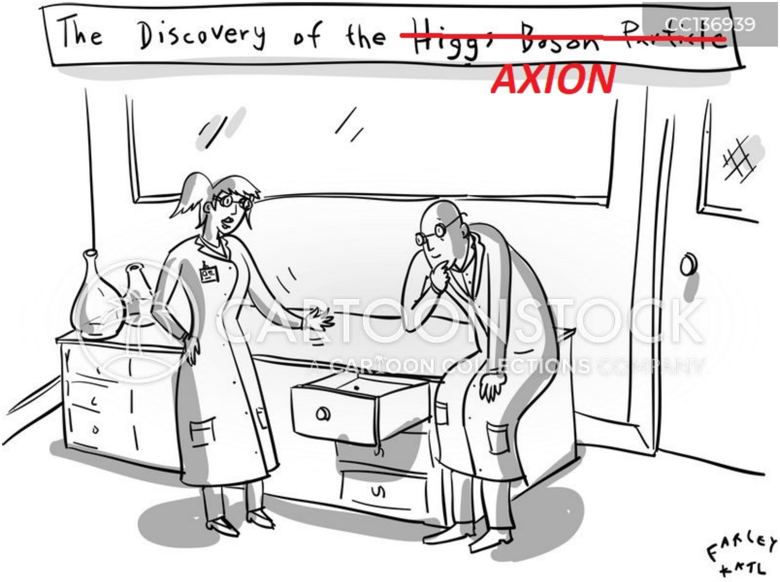
Diffuse flux for $g_{ae} = 7 \times 10^{-21}$

Overwiev plot

A. Lella, P. Carenza, GL *et al.*, [arXiv:2211.13760 [hep-ph]].



Conclusions



"Always the last place you look!"

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