IBS-ICTP Workshop on Axion-Like Particles,

28^{th} October 2021

Supernovae as axion factories: the latest developments

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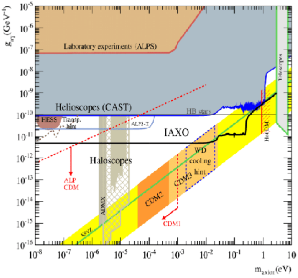
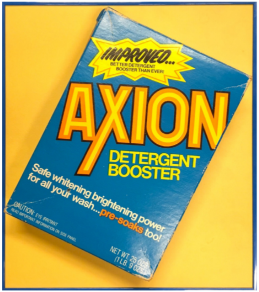
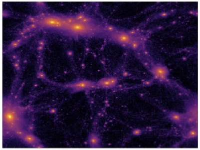
OKC, Stockholm University

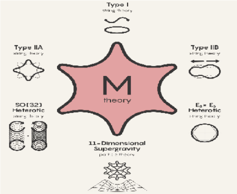
Brief introduction to axions and ALPs

Axions and ALPs are a window on high-energy physics







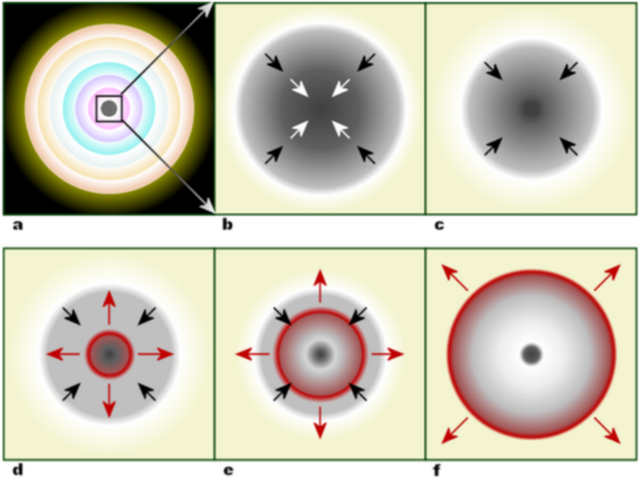


This hot topic is a motivation for interdisciplinary searches

Supernova axions

Core-Collapse Supernovae

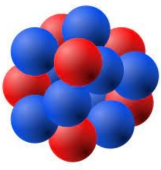
For massive stars ($M > 8M_\odot$) the nuclear fusion produces heavy elements in an onion structure and a degenerate iron core



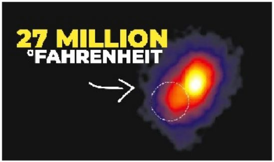
Iron in the core cannot be burnt and the star starts to collapse

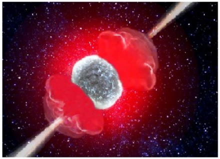
Orders of magnitude for SNe

The SN core is an extreme environment



1000x





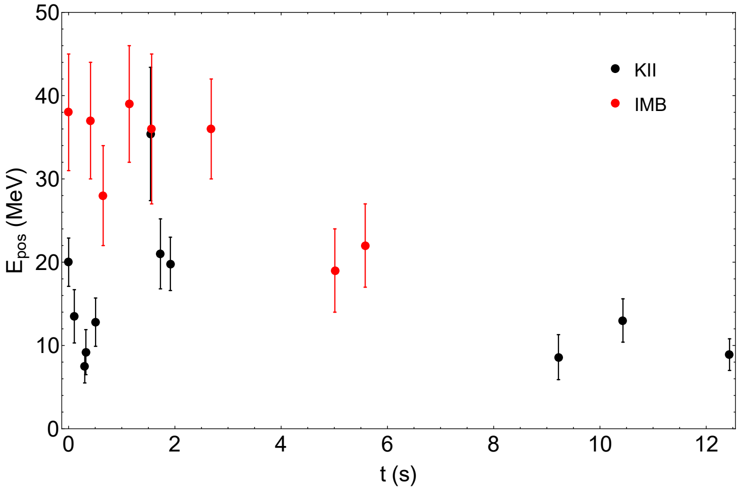
density 10^{14}g cm^{-3}

temperature 30 MeV

magnetic field 10^{15} G

SN1987A: neutrino signal

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

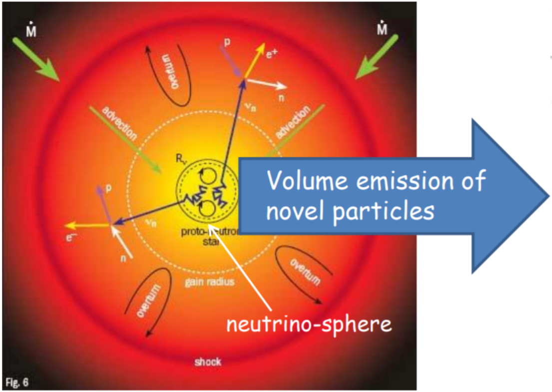


$\sim 10^{53}$ erg emitted as neutrinos with energy $\sim O(15\,\mathrm{MeV})$ in $\sim 10\,\mathrm{s}$

The energy-loss argument

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

Stars produce axions which escape, draining energy from the core

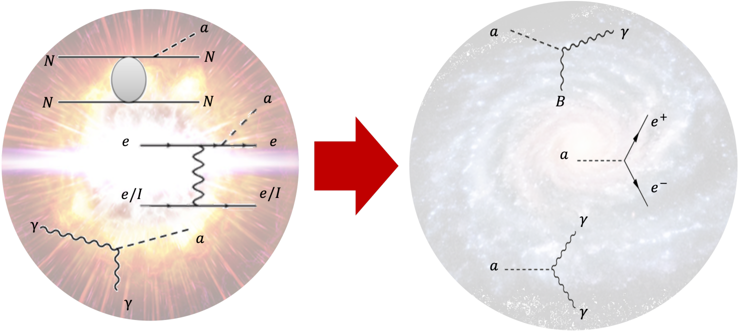


Axions affect strongly the SN neutrino burst if

$$L_a > L_\nu = 2 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

SN axion phenomenology: the cooling bound

Production **Signature**

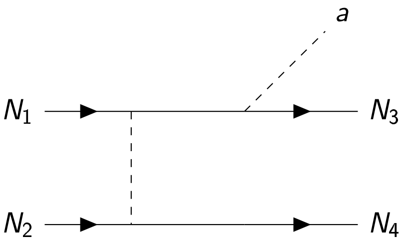


Axion production in nuclear matter

Axion-nucleon bremsstrahlung in SNe

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

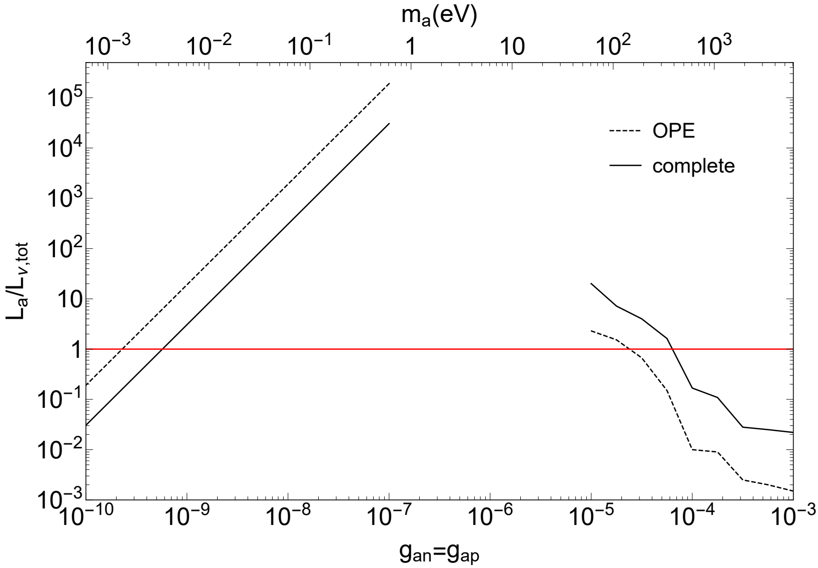
SN axions are produced by nucleon-axion bremsstrahlung



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

The SN axion bound

From the L_a/L_ν criterion at $t_{\rm pb} = 1$ s we obtain



The bound: KSVZ axion bound

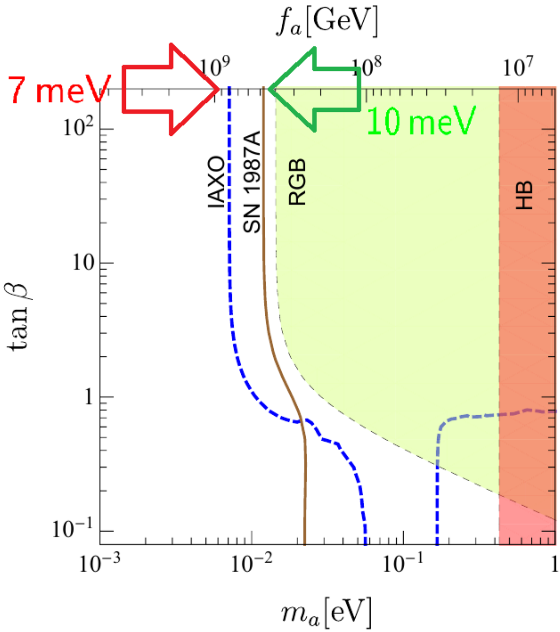
PC, T. Fischer *et al.*, JCAP **05** (2020) no.05, E01

- Literature: $m_a < 12\,\text{meV}$ OPE+MS
  G. G. Raffelt, Lect. Notes Phys. **741** (2008), 51-71

- Our bound:

$C_{ap} = -0.47$; $C_{an} = 0$	g_{ap} ($\times 10^{-10}$)	m_a (meV)	$f_a(\times 10^8$ GeV)
OPE	4	5	10.4
OPE+MS	5	6	9.7
OPE+corr. (no MS)	11	14	4.2
OPE+corr.+MS	12	15	4.0

The bound: DFSZ axion bound

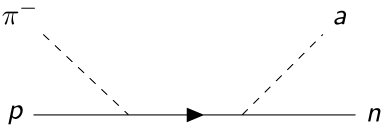


Axion production by pionic processes

The pion-axion conversion

M. S. Turner, Phys. Rev. D **45** (1992), 1066-1075
G. Raffelt and D. Seckel, Phys. Rev. D **52** (1995), 1780-1799

This process was found to be dominant for $n_\pi \sim O(n_B)$, but ...



... lost in literature because nobody knows the pion abundance

How much is the pion abundance?

Virial expansion

B. Fore and S. Reddy, Phys. Rev. C **101** (2020) no.3, 035809

The pion abundance is $\mathcal{O}(1\%)$

negligible thermal abundance

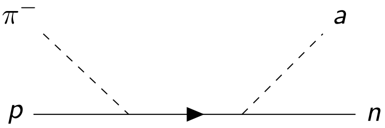
$$n_{\pi^-} = \boxed{\int \frac{d^3\mathbf{p}}{(2\pi)^3} e^{(\hat{\mu}-E)/T}} + \boxed{n_{\pi^-}^{\mathrm{int}}}$$

nucleons produce pions

Pion-axion conversion in SNe

PC, B. Fore *et al.*, Phys. Rev. Lett. **126** (2021) no.7, 071102

SN axions are produced by pion-axion conversion

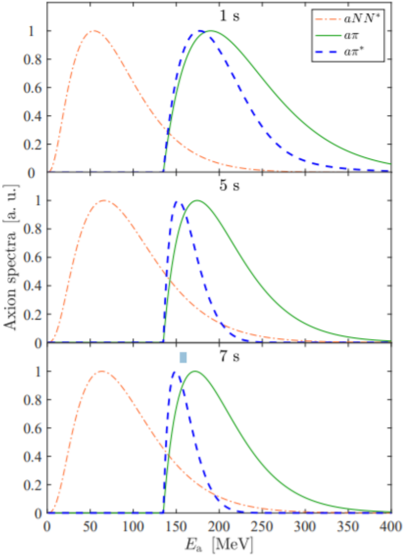


This is the leading axion production process in a SN!!

Flux from pion-axion conversion

T. Fischer, PC *et al.* [arXiv:2108.13726 [hep-ph]].

The harder spectrum is due to the pion rest mass



Consequences on the SN cooling

The SN cooling is accelerated by this new process, then the SN1987A bound is a factor 2 stronger

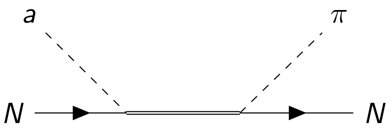
ρ		$\bar{g}_{aN}$ $(\times 10^{-9})$	m_a (meV)	f_a $(\times 10^8$ GeV)
ρ_0	only NN	0.81	21.02	2.71
	$\pi N + NN$	0.46	11.99	4.75
$\rho_0/2$	only NN	0.93	24.11	2.36
	$\pi N + NN$	0.42	10.96	5.20

Bound on the effective axion-nucleon coupling $\bar{g}_{aN}$ for KSVZ axions.

Detection perspectives in Cherenkov detectors

work in progress

Axions absorbed via the Δ resonance



We estimate at most ~ 1000 events from a SN at 1 kpc

- $\pi^0 \to 2\gamma \to 2e^+e^-$
- π^- absorbed by nuclear capture
- $\pi^+ \to \mu^+ \to e^+$

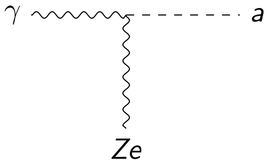
Axion-Like Particles from Supernovae: the photon coupling

ALP production channels

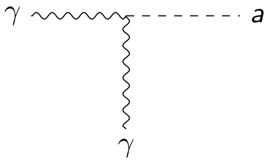
G. Lucente, PC *et al.*, JCAP **12** (2020), 008

ALPs are coupled with photons and are produced by:

Primakoff conversion

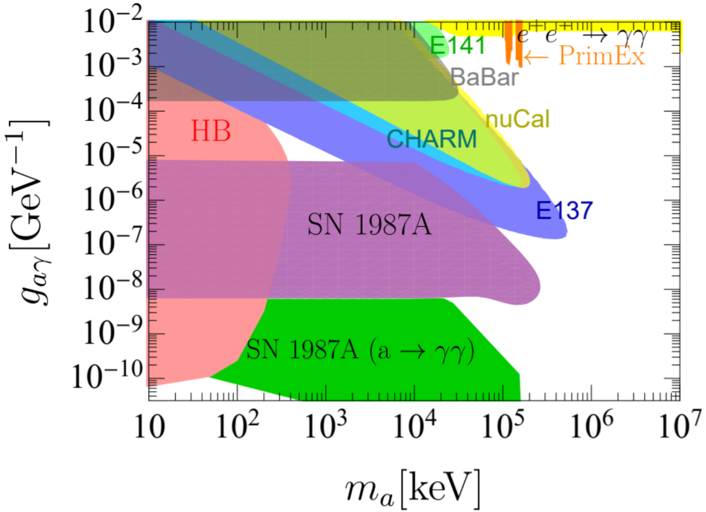


Inverse Decay



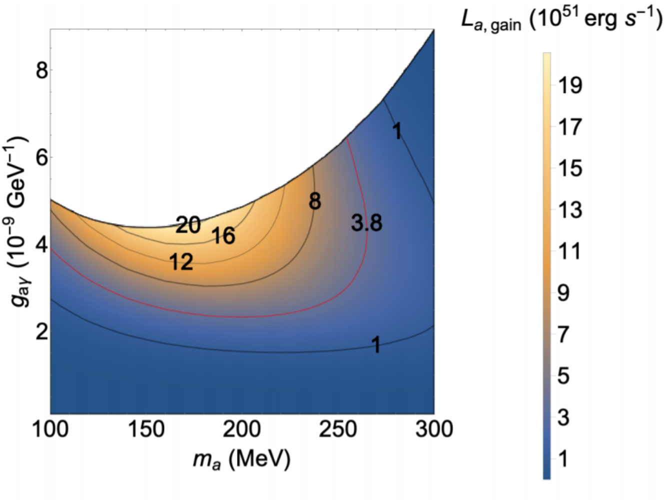
SN1987A ALP bound

Nice complementarity with other bounds



Can ALP revitalize the SN shock?

Massive ALP could decay inside the SN revitalizing the shock

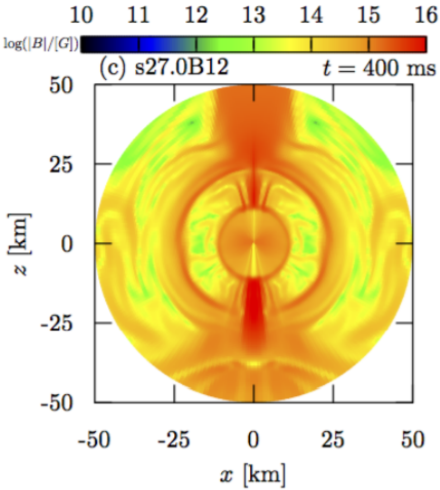


Energy deposited at $t_{\text{pb}} = 0.3$ s, the red line indicates where the ALP deposit the same energy as neutrinos

Another ALP production mechanism in hypernovae

J. Matsumoto *et al.*, Mon. Not. Roy. Astron. Soc. **499** (2020) no.3, 4174-4194

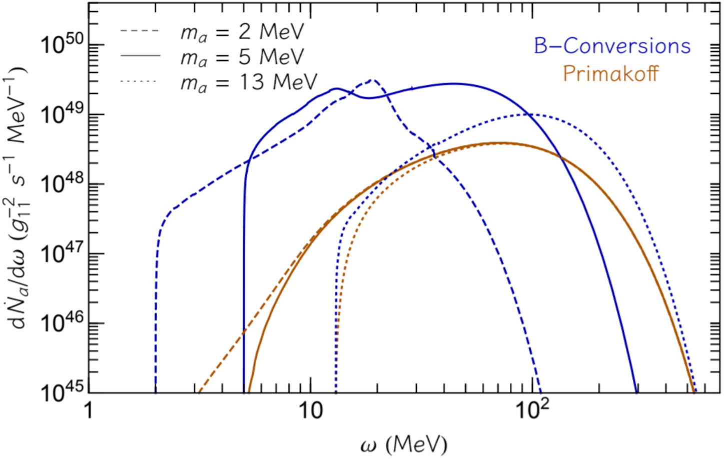
The huge magnetic field in hypernovae allows for the resonant photon-ALP conversion



Another ALP production mechanism in hypernovae

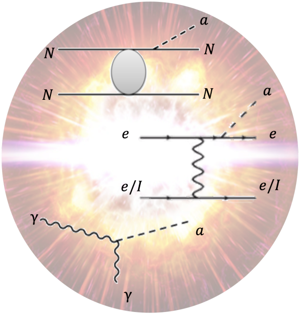
A. Caputo, PC *et al.*, [arXiv:2104.05727 [hep-ph]].

The flux is comparable or larger than the standard mechanism



SN axion phenomenology: γ-ray signal for heavy axions

Production



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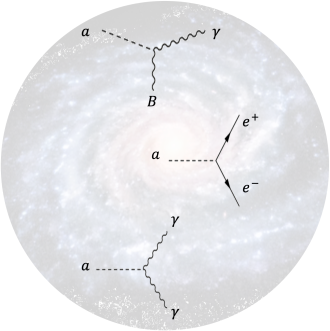
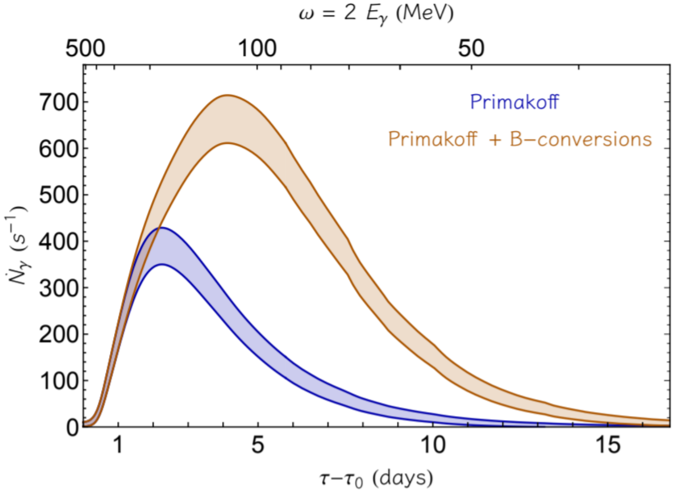


Observational signature in Fermi-LAT

The γ-ray signal would probe:

- B fields in a SN
- the existence of an ALP
- the ALP mass

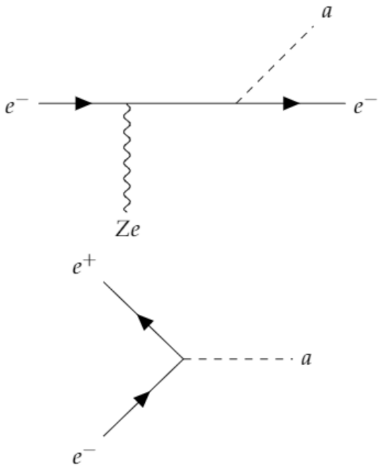


Axion-Like Particles from Supernovae: the electron coupling

ALP production channels

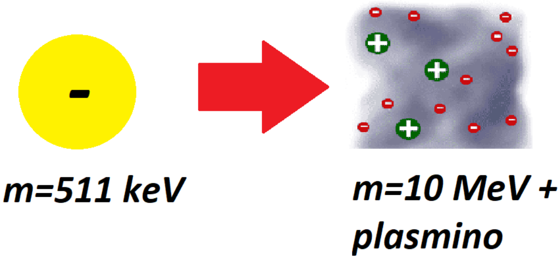
G. Lucente and PC, [arXiv:2107.12393 [hep-ph]].

ALPs are coupled with electrons and are produced by:



The electron (and positron) dispersion relation

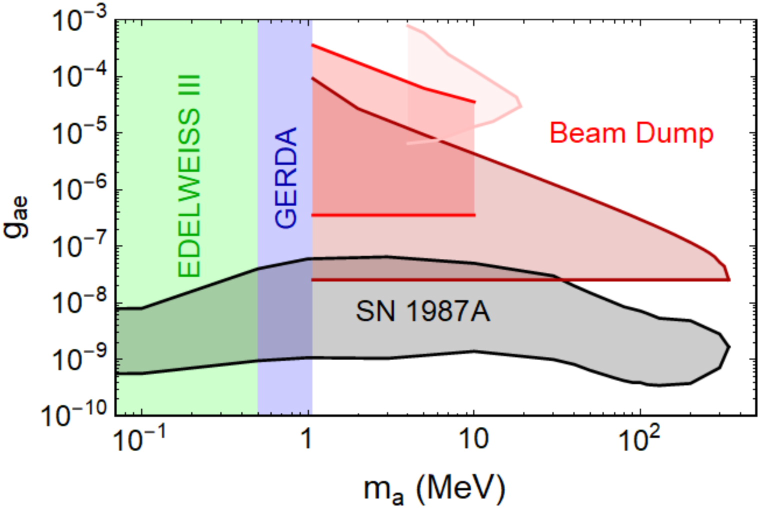
The plasma affects the electron (and positron) propagation



We proved that the plasmino contribution is negligible

The SN bound and laboratory experiments

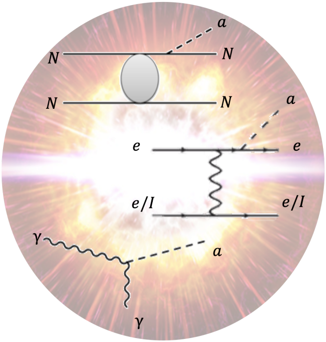
Also in this case the SN bound is complementary to beam dumps



Direct signatures from the Diffuse SN ALP Background

SN axion phenomenology: conversion of light axions

Production



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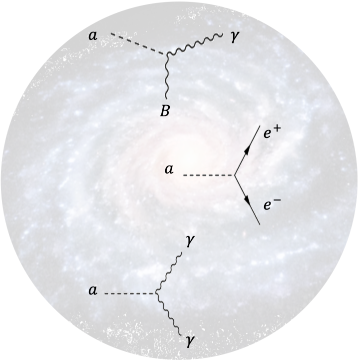
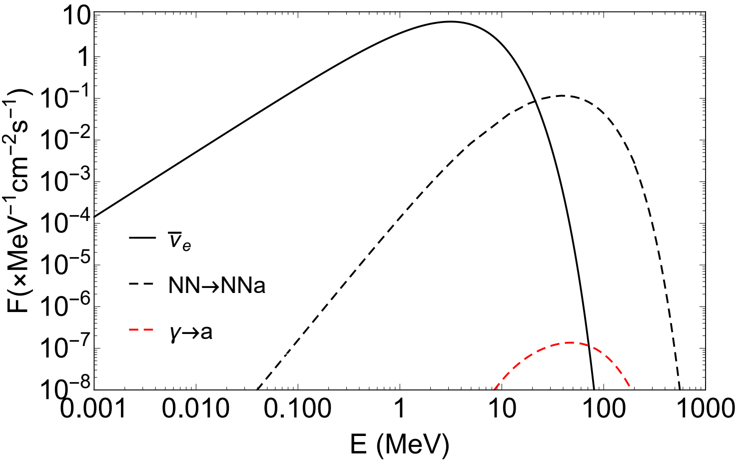


DSNALPB

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

The nucleon coupling is less constrained, larger flux with NN

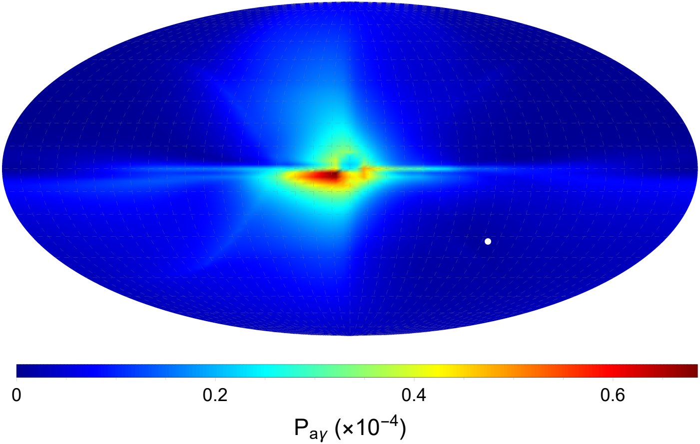


DSNALPB with $g_{ap} = 1.2 \times 10^{-9}$ and $g_{a\gamma} = 5.3 \times 10^{-12}\,\mathrm{GeV}^{-1}$

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

SN1987A bound

The γ−ray flux must be smaller than $0.6\,\mathrm{cm}^{-2}$ measured by the Solar Maximum Mission

The bound on $g_{a\gamma}$ for $m_a < 4 \times 10^{-10}\,\mathrm{eV}$ is strongly improved by the nucleon coupling

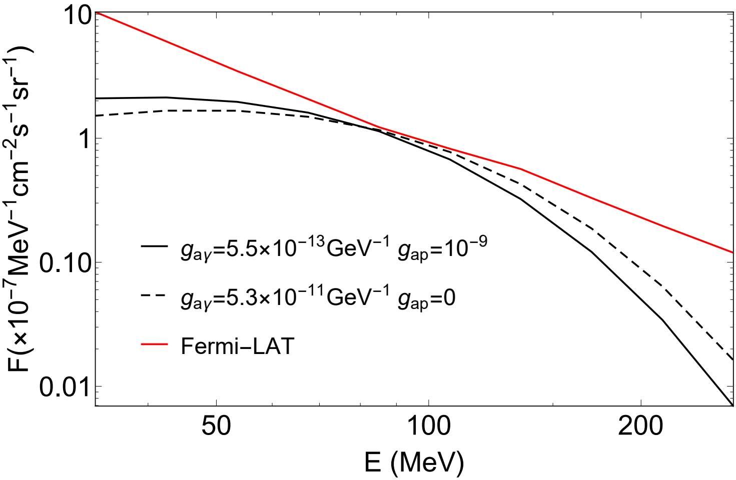
- $g_{ap} = 0$: $\quad g_{a\gamma} < 5.3 \times 10^{-12}\,\mathrm{GeV}^{-1}$
- $g_{ap} = 1.2 \times 10^{-9}$: $\quad g_{a\gamma} < 3.4 \times 10^{-15}\,\mathrm{GeV}^{-1}$

The case $g_{ap} = 0$ agrees with A. Payez *et al.*, JCAP **02** (2015), 006

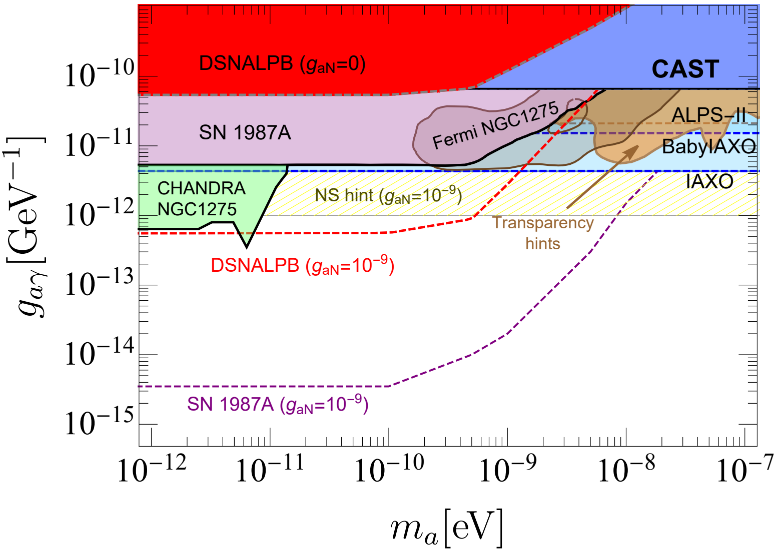
DSNALPB bound

M. Ackermann *et al.* [Fermi-LAT], Astrophys. J. **799** (2015), 86

The converted DSNALPB must be smaller than the diffuse γ−ray background measured by Fermi-LAT

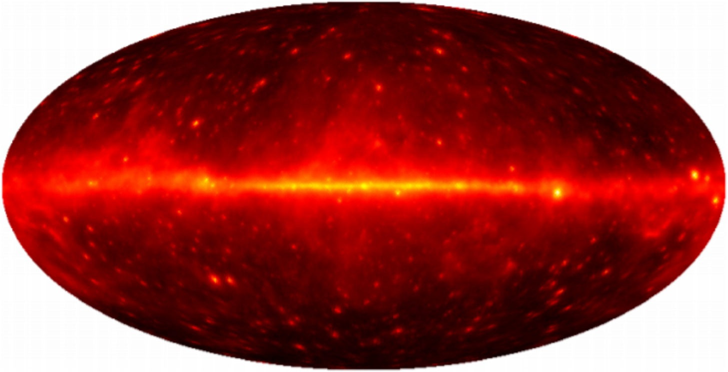


Overview plot

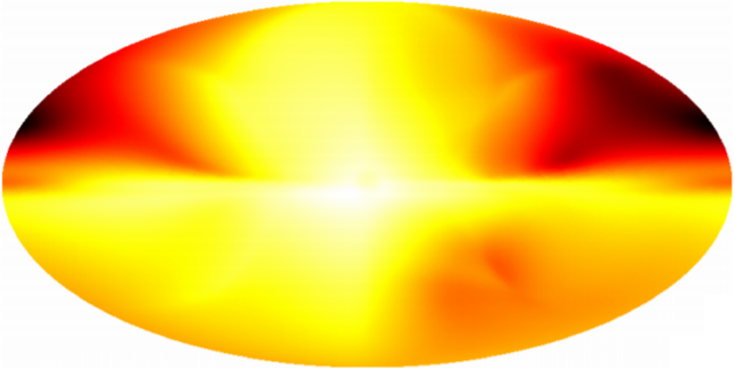


Improving the DSNALPB bound: Fermi-LAT data

Skymap of gamma-rays observed by Fermi-LAT



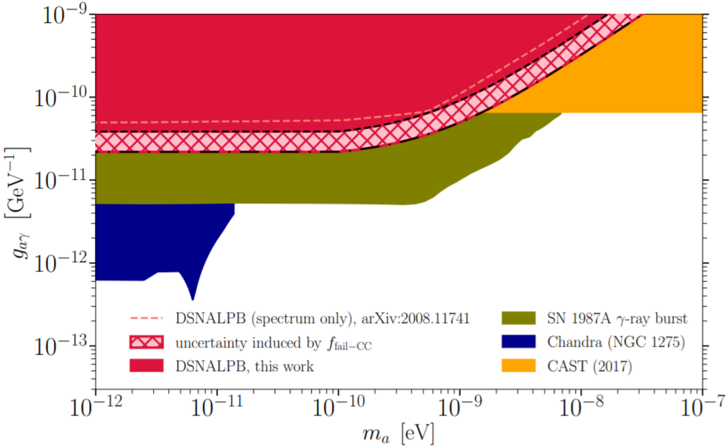
Improving the DSNALPB bound: the ALP signal



The bound

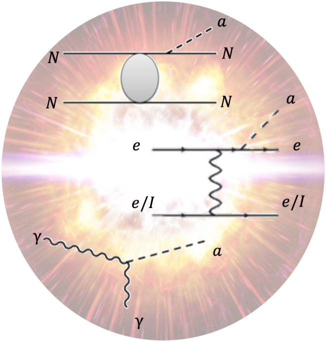
F. Calore, PC *et al.*, [arXiv:2110.03679 [astro-ph.HE]].

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



SN axion phenomenology: decay of heavy axions

Production



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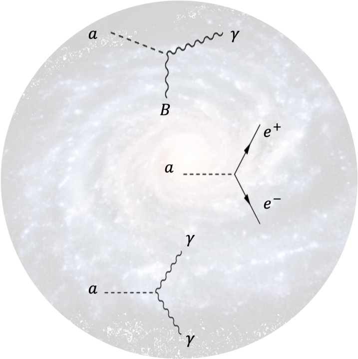
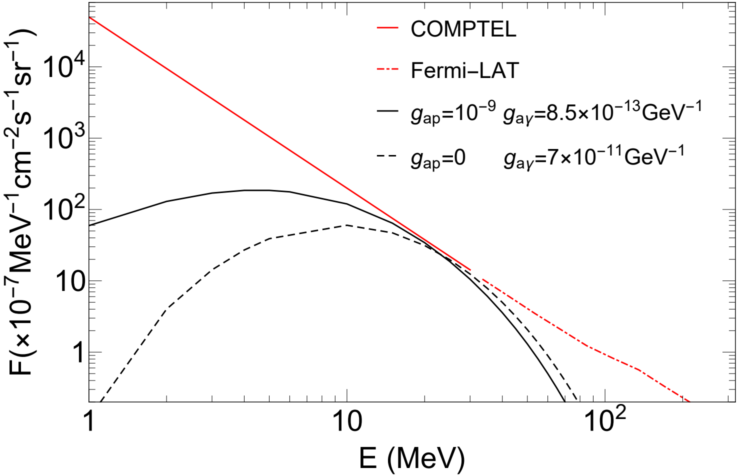


DSNALPB for massive ALPs

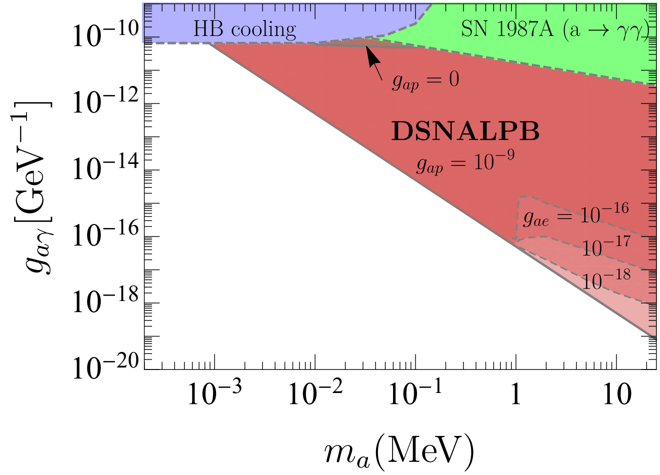
S. C. Kappadath, PhD thesis (U. of New Hampshire, 1998)

The DSNALPB produces a $\gamma-$ray background by decaying ALPs constrained by Fermi-LAT and COMPTEL ($m_a = 5\,\text{keV}$ in the plot)



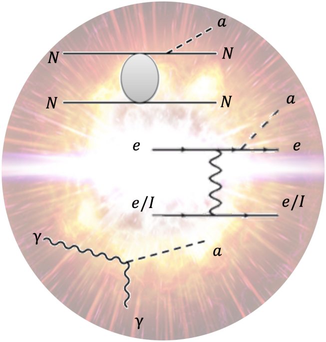
Coupling with electrons

If ALPs decay into e^+e^-, the $\gamma-$ray background is reduced



SN axion phenomenology: decay into electron-positron pairs

Production



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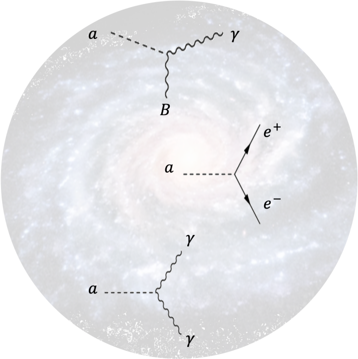
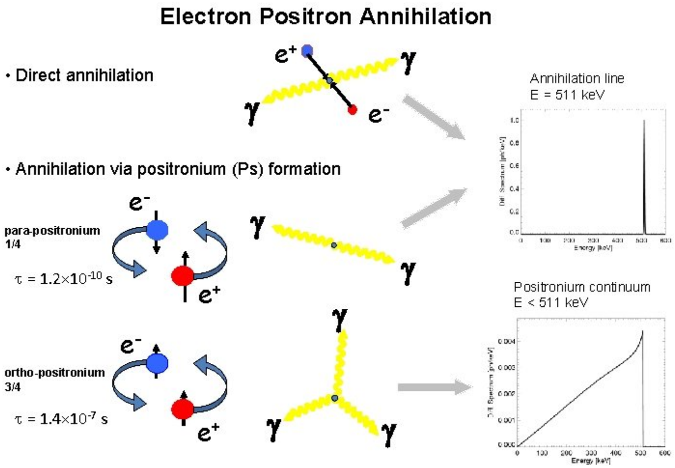


$a \to e^+e^-$ is not invisible

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



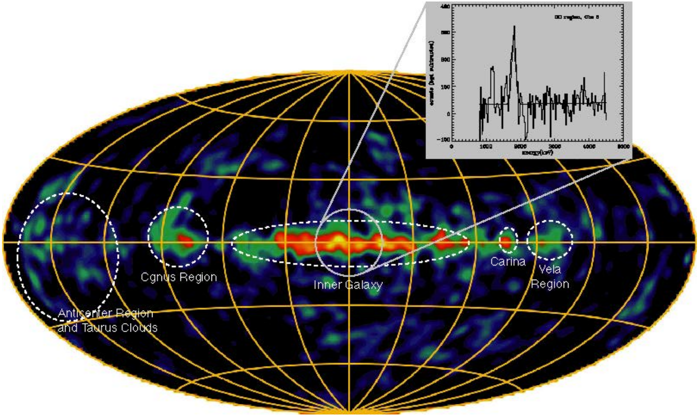
Is it possible to explain **a fraction of** the 511 keV line with ALPs?

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

The 511 keV line

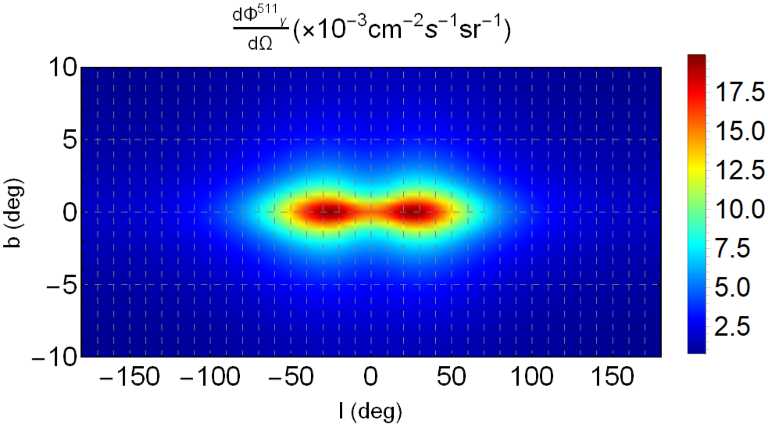
N. Prantzos *et al.* Rev. Mod. Phys. **83** (2011), 1001-1056

The Galactic flux at 511 keV is partially unexplained



511 keV photon skymap for $g_{ae} = 4 \times 10^{-12}$

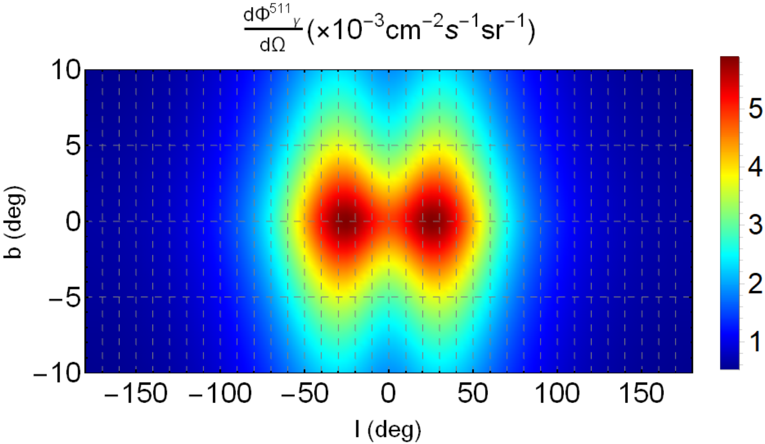
F. Calore, PC *et al.*, Phys. Rev. D **104** (2021) no.4, 043016



ALPs decay very close to the SN and positrons are trapped by $B \sim O(\mu G)$

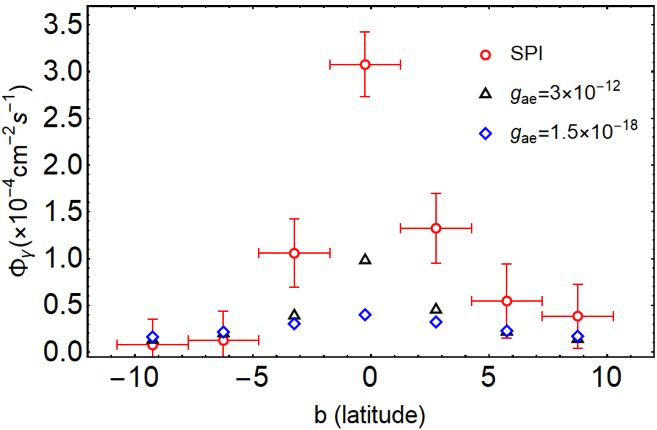
511 keV photon skymap for $g_{ae} = 2 \times 10^{-19}$

F. Calore, PC *et al.*, Phys. Rev. D **104** (2021) no.4, 043016



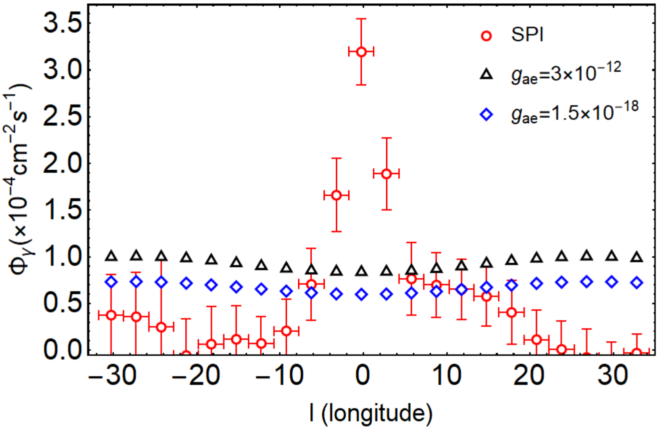
ALPs decay far from to the SN, smeared distribution

Let's compare with SPI data...



Very good agreement for the vertical distribution...

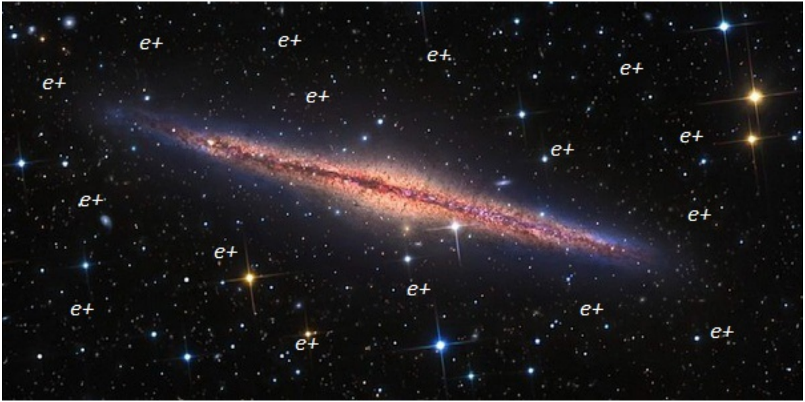
... much less agreement with the horizontal one



No ccSN-based mechanisms explains the 511 keV line!!

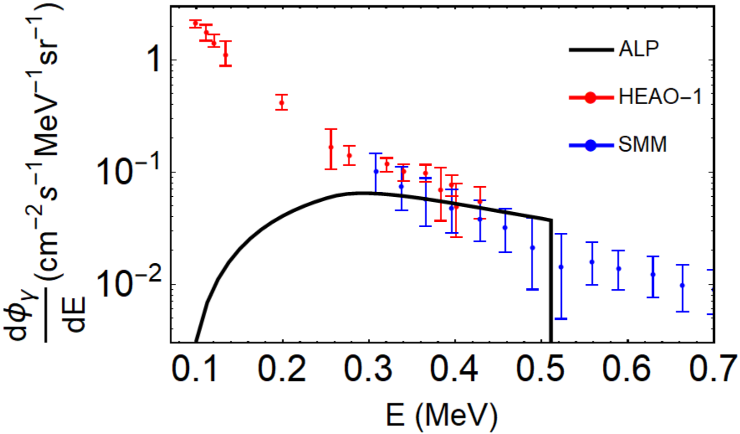
ALPs escaping from the Galaxy

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



Extragalactic X-ray diffuse flux

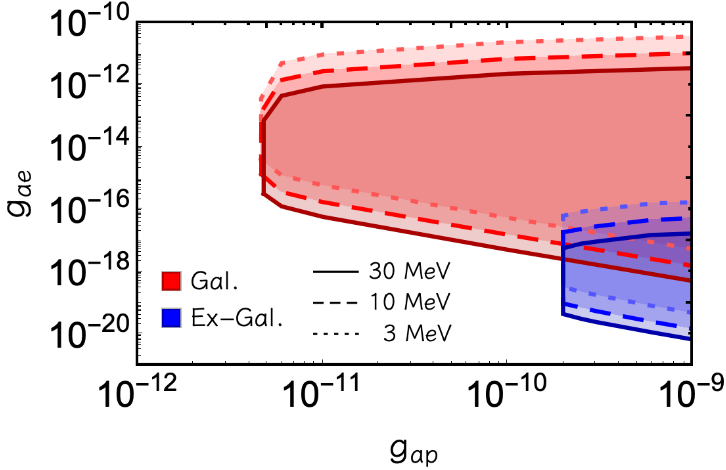
The extragalactic flux is redshifted, no more 511 keV line



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

Overwiev plot

F. Calore, PC *et al.*, Phys. Rev. D **104** (2021) no.4, 043016



Conclusions

Supernovae are the best axion factories... waiting the next SN explosion

THANKS FOR YOUR ATTENTION