ICRANet-ISFAHAN Astronomy Meeting,

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Axions in astrophysics

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The strong-CP problem and axions

The strong CP problem

The QCD Lagrangian includes a CP-odd term

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm QCD} - \bar{\theta}_{\rm QCD}\frac{g^2}{32\pi^2}\,\mathrm{tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

where $\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}G^{\alpha\beta}$ and $\bar{\theta}_{\rm QCD} = \theta_{\rm QCD} + \arg\det M_{\rm quark}$

Prediction of neutron electric dipole moment
$d_n \approx |\bar{\theta}_{\rm QCD}| \times 10^{-15}\,e\,\mathrm{cm}$
Experimental bound: $|\bar{\theta}_{\rm QCD}| < 10^{-10}$
Naturalness problem, why $\bar{\theta}_{\rm QCD}$ is so small?

The Peccei-Quinn mechanism

R. D. Peccei *et al.*, Phys. Rev. Lett. **38** (1977)

PQ symmetry
$U(1)_{PQ}$ is a chiral global symmetry that drives dynamically $\bar{\theta}_{PQ} \to 0$

$U(1)_{PQ}$ is broken at a scale f_a, the **Peccei-Quinn scale**, and the Goldstone boson is the **axion**

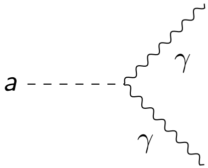
$$\mathcal{L}_{\rm ax} = \frac{1}{2}\partial_\mu a \partial^\mu a - \xi \frac{a}{f_a}\frac{g^2}{32\pi^2}\tilde{G}^a_{\mu\nu}G^{\mu\nu a} + \\ + \frac{g_a}{2m}\bar{\Psi}\gamma^\mu\gamma^5\Psi\partial_\mu a - \frac{g_{a\gamma}}{4} a\tilde{F}^{\mu\nu}F_{\mu\nu}$$

The minimum condition removes the CP-odd term: $\bar{\theta}_{\rm QCD} = 0$

Axion-SM interactions

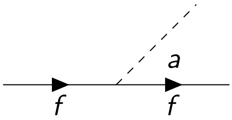
Axion-photon vertex

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma} a\, \mathrm{E}\cdot\mathrm{B} \quad g_{a\gamma} = C_\gamma \frac{\alpha}{2\pi f_a}$$



Axion-fermion vertex

$$\mathcal{L}_{af} = \frac{g_{af}}{2m_f}\bar{\Psi}\gamma^\mu\gamma^5\Psi\, \partial_\mu a \quad g_{af} = C_f \frac{m_f}{f_a}$$



Axions and Axion-Like Particles

In any axion model

$$m_a \sim \frac{1}{f_a} \quad g_{a\gamma} \sim \frac{1}{f_a} \quad f_a \gg 246\,\mathrm{GeV}$$

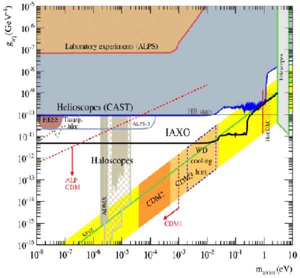
The typical QCD axion is **light** and **weakly interacting**

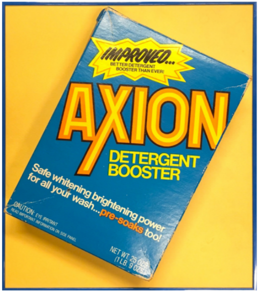
Axion-Like Particles (ALPs) are a generalization:

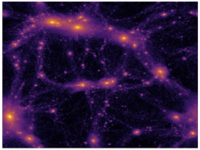
- Heavy ALP searches at collider
- Superlight ALPs as fuzzy Dark Matter
- Some ALPs could be the inflaton
- ALPs in flavor-violating processes...

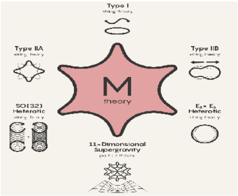
Motivations to study axions and ALPs

Axions and ALPs are a window on high-energy physics







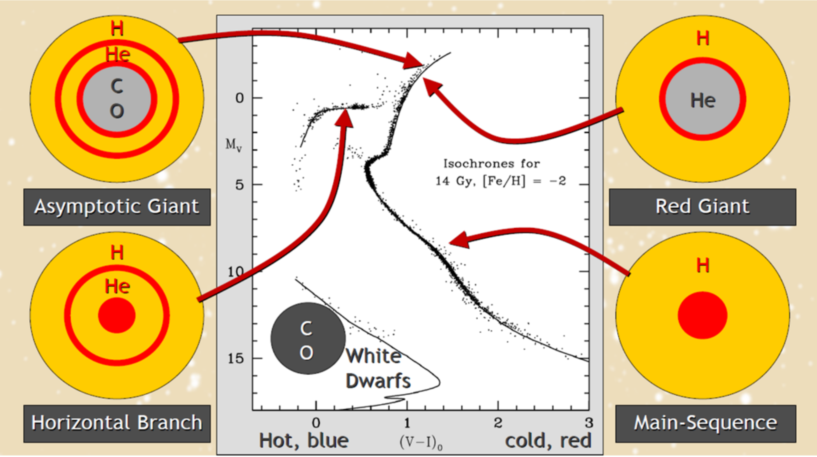


This hot topic is a motivation for interdisciplinary searches

Axions and ALPs in low-mass stars

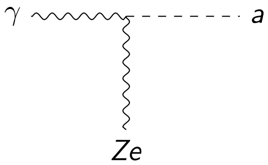
HR diagram

Diagram of stars with the same age and different initial masses

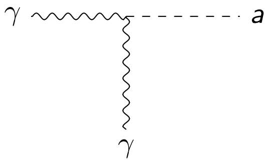


HB stars: ALP production

The main processes are Primakoff conversion



and Inverse Decay



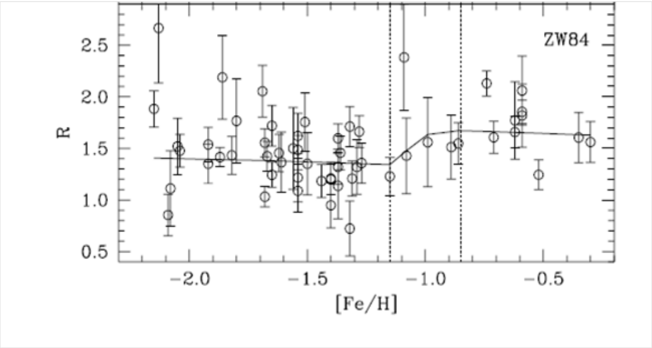
Bound on the R parameter

M. Salaris *et al.*, Astron. Astrophys. **420** (2004), 911-919

Observations on Globular Clusters measure the R parameter

$$R = \frac{N_{\mathrm{HB}}}{N_{\mathrm{RGB}}} = \frac{\tau_{\mathrm{HB}}}{\tau_{\mathrm{RGB}}} = 1.39 \pm 0.03$$

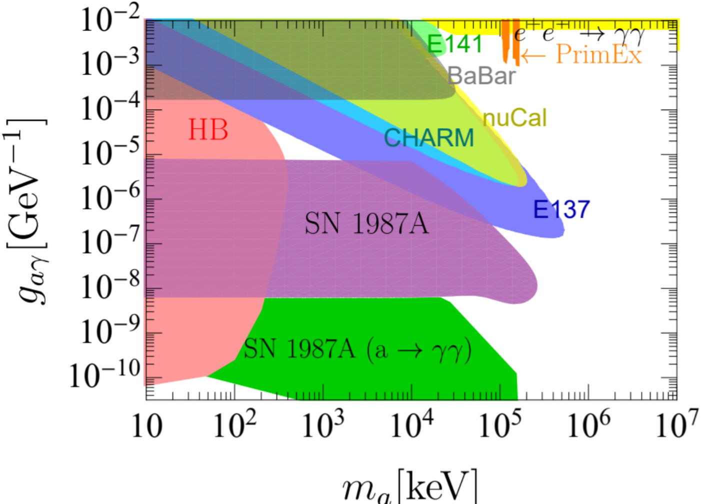
The duration of the HB phase can be reduced at most of $\sim 15\%$



HB star bound on heavy ALPs

PC, O. Straniero, B. Döbrich, M. Giannotti, G. Lucente and A. Mirizzi, Phys. Lett. B **809** (2020), 135709

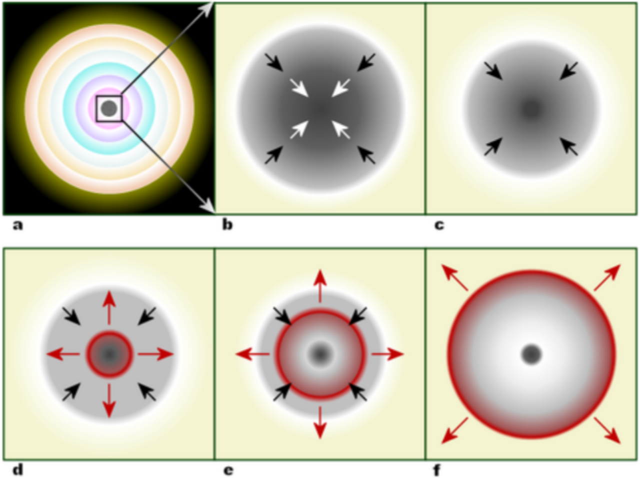
A small region is unconstrained: the "cosmological triangle"



Supernova axions

Core-Collapse Supernovae

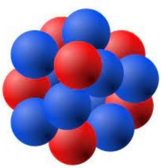
For massive stars ($M > 8M_{\odot}$) the nuclear fusion produces heavy elements in an onion structure and a degenerate iron core



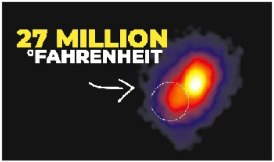
Iron in the core cannot be burnt and the star starts to collapse

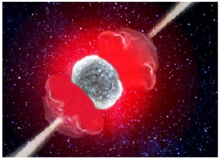
Orders of magnitude for SNe

The SN core is an extreme environment



1000x

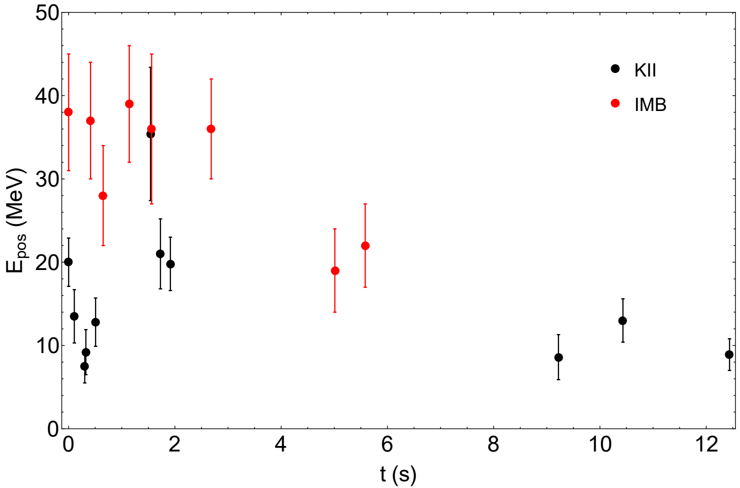




density	***temperature***	***magnetic field***
10^{14}g cm^{-3}	$30\ \text{MeV}$	$10^{15}\,\text{G}$

SN1987A: neutrino signal

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

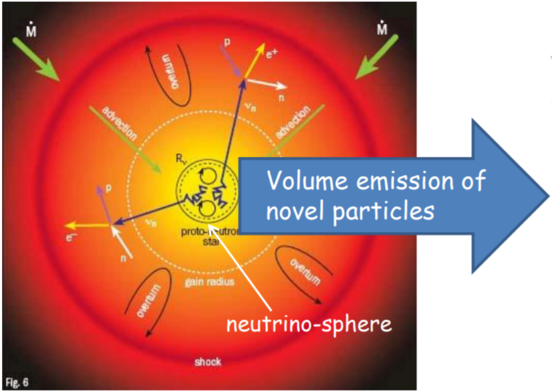


$\sim 10^{53}$ erg emitted as neutrinos with energy $\sim O(15\,\mathrm{MeV})$ in $\sim 10\,\mathrm{s}$

The energy-loss argument

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

Stars produce axions which escape, draining energy from the core



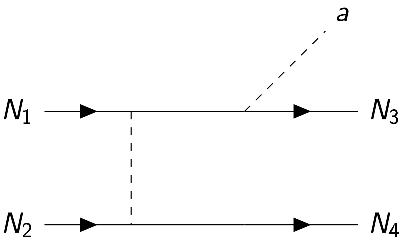
Axions affect strongly the SN neutrino burst if

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

Axion-nucleon bremsstrahlung in SNe

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

SN axions are produced by nucleon-axion bremsstrahlung

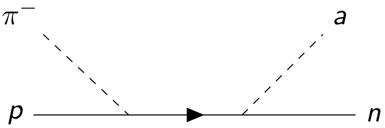


where we have to include detailed nuclear physics and many body effects

Pion-axion conversion in SNe

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

SN axions are produced by pion-axion conversion

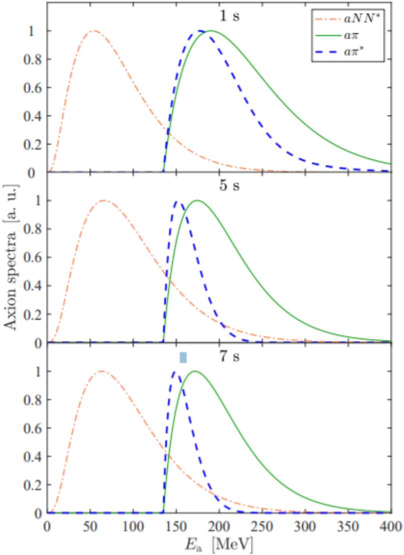


This is the leading axion production process in a SN despite the small density of pions ($\mathcal{O}(1\%)$)!!

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

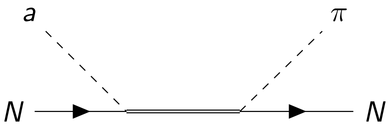
ρ		$\bar{g}_{aN}$ $(\times 10^{-9})$	m_a (meV)	f_a $(\times 10^8$ GeV)
ρ_0	only NN	0.81	21.02	2.71
	$\pi N + NN$	0.46	11.99	4.75
$\rho_0/2$	only NN	0.93	24.11	2.36
	$\pi N + NN$	0.42	10.96	5.20

Bound on the axion mass 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
- $\pi^+ \to \mu^+ \to e^+$

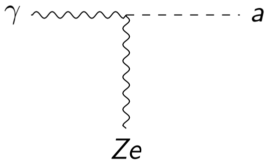
Axion-Like Particles from Supernovae: the photon coupling

ALP production channels

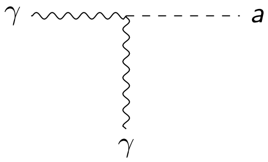
G. Lucente, PC *et al.*, JCAP **12** (2020), 008

ALPs are coupled with photons and are produced by:

Primakoff conversion

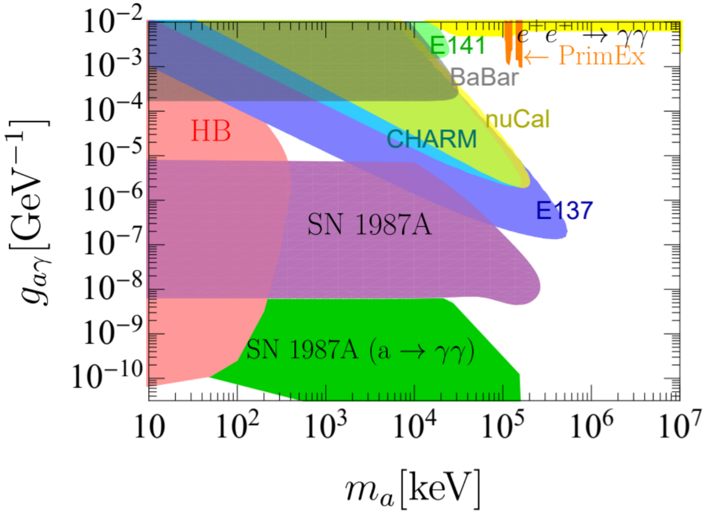


Inverse Decay



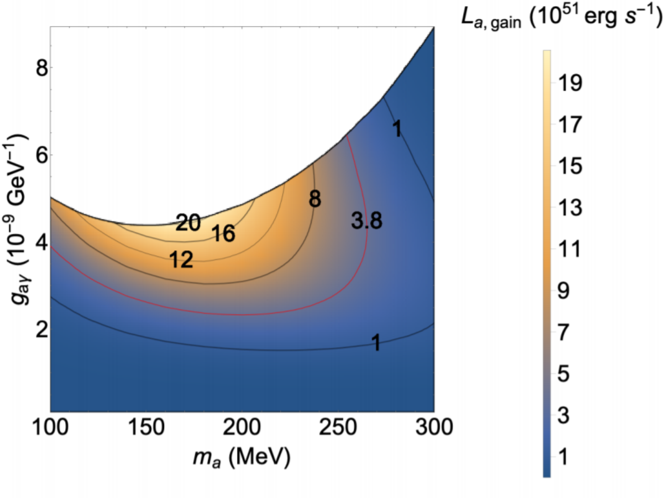
SN1987A ALP bound

Nice complementarity with other bounds



Can ALP revitalize the SN shock?

Massive ALP could decay inside the SN revitalizing the shock

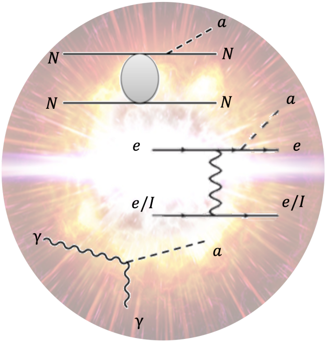


Energy deposited at $t_{\rm pb} = 0.3\,$s, the red line indicates where the ALP deposit the same energy as neutrinos

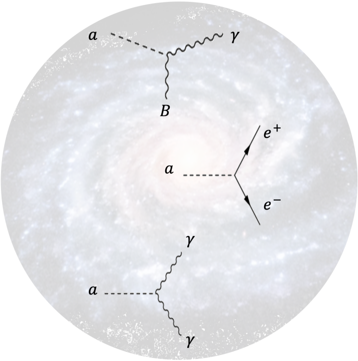
Direct signatures from the Diffuse SN ALP Background

SN axion phenomenology: conversion of light axions

Production



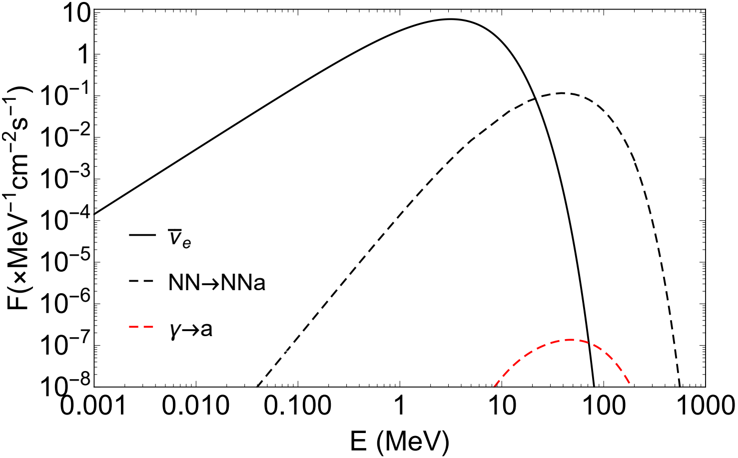
Signature



DSNALPB

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

The nucleon coupling is less constrained, larger flux with NN

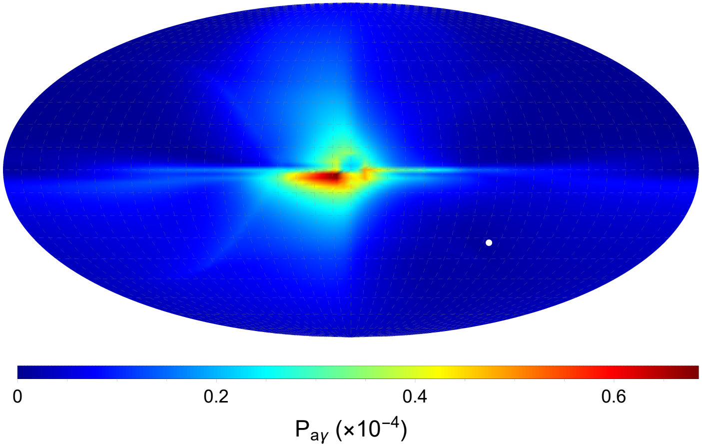


DSNALPB with $g_{ap} = 1.2 \times 10^{-9}$ and $g_{a\gamma} = 5.3 \times 10^{-12}\,\mathrm{GeV}^{-1}$

ALP conversion into photons

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

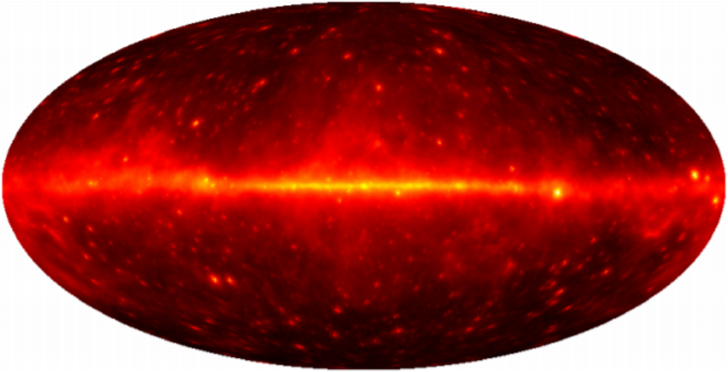
The Galactic magnetic field will convert into photons both the DSNALPB and the point-like ALP flux from SN1987A (white dot)



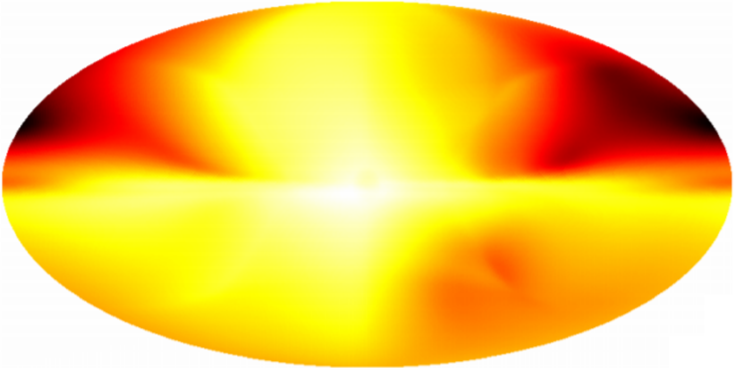
Conversion probability for $m_a \ll E = 50\,\text{MeV}$, $g_{a\gamma} = 3 \times 10^{-13}\,\text{GeV}^{-1}$

Fermi-LAT data

Skymap of gamma-rays observed by Fermi-LAT



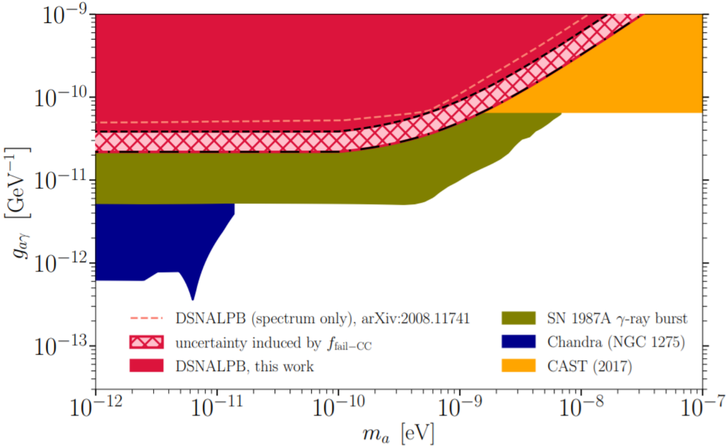
The ALP signal



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



Conclusions

- Axions and ALPs play a major role in astrophysics
- More on low-mass stars: energy transferred by ALPs?
- More on SNe: ALPs in hypernovae? ALPs coupled to electrons?
- Even more: ALPs and 511 keV line? ALP conversions in turbulent magnetic fields?

THANKS FOR YOUR ATTENTION