Title: Probing New Physics with Supernovae

Speakers: Claudio Manzari

Series: Particle Physics

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Abstract: It is well known that the study and observation of core collapse Supernovae (SN) provide powerful tools to probe possible scenarios of physics beyond the Standard Model (SM). After reviewing the basics beyond the mechanism of a SN explosion and how these observations can constraint models of new physics, I will focus on two novel ideas to exploit the already available data from past SN and the observation of a future, long due, galactic one. Firstly. I will discuss constraints, from the cooling on the SN, on the interactions of SM particles with an hypothetical dark sector, leading to bounds on the mediators of such interactions competitive with collider ones. Then, I will turn on the constrains on the emission of axion-like particles (ALPs) that can convert into photons in an external magnetic field, leading to a gamma-ray signal. I will discuss the possibility that ALPs can convert to gamma-rays in the stellar magnetic fields of the progenitor stars. Applying this concept to gamma-ray data from SN1987A leads to the strongest constraints on axion-like particles for masses within a few orders of magnitude of 10^-5 eV. The implications for a future galactic blue supergiant supernova will be discussed.

Zoom link

Probing New Physics with Supernovae

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Perimeter Institute - 05.14.2024

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Outline

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  - Looking for a Dark Sector

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    In preparation

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Introduction

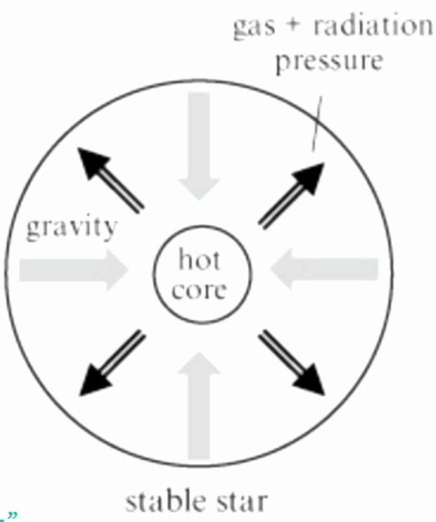
SN 1994D (Ia supernova) within its host galaxy, NGC 4526

Supernovae are explosions of stars at the end of their lives.

1604 The last galactic SN observed on earth.
It was located at a distance of ~6 kpc from earth.

Supernovae are a common phenomenon: every second, about seventy supernovae explode somewhere in the Universe. Given the size and mass of the Milky Way Galaxy, we expect it to host 2–3 supernovae per century.

Life and Death of Stars



From "Supernova"
By Or Graur

In massive hydrogen clouds, the pressure and temperature of the gas rise until the emergent gas pressure halts the gravitational collapse. However, in these clouds, the temperature and pressure in the innermost part of the nascent star—its core—rise high enough to also induce the nuclear fusion of hydrogen into helium.

The nuclear reactions in the star's core create a thermostat-like effect that both stabilizes the star and regulates its temperature and size.

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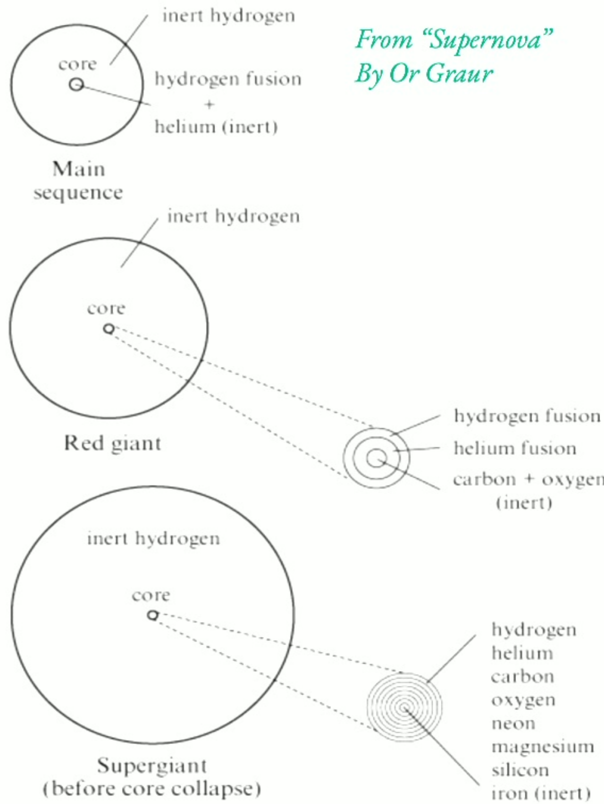
Life and Death of Stars

Once the hydrogen in the star's core is depleted, fusion will shut off and the star resume contracting...until hydrogen starts burning again in a layer of gas above the helium core. The core will continue to contract until its temperature reaches the point where helium can begin fusing into carbon and oxygen.



From "Supernova" By Or Graur

Life and Death of Stars

The final stage of evolution depends on the mass of the star.

$$12\, M_\odot \lesssim M \lesssim 25\, M_\odot$$

- ➔ ~7 million years fusing hydrogen into helium
- ➔ ~800,000 years burning helium
- ➔ ~500 years burning carbon
- ➔ ~1 year burning neon
- ➔ ~5 months burning oxygen
- ➔ ~1 day burning silicon

Core-Collapse Supernovae

- ➔ Iron fusion cannot be ignited
- ➔ Neutronization (photodisintegration and inverse beta decay)
- ➔ NEUTRON STAR (neutron degeneracy pressure counteracts gravity)
- ➔ Supernova Explosion - Shockwave

- **1987** The closest SN (in the Magellanic cloud, ~ 50 kPc away) to earth observed since first neutrino experiments. 25 neutrinos over an interval of ~10 s were detected.

Cooling Bound

Basic Idea

SN are extreme events where high temperatures and densities are reached.

If new particles are sufficiently light to be produced and escape, the new energy-loss rate accelerates the cooling of the proton-neutron star.

Therefore, the observed cooling speed allows one to constrain this process or to detect evidence for it.

For SN1987A, the total number of neutrinos, their energies, and the distribution over several seconds correspond reasonably well to theoretical expectations.

NP luminosity must be smaller than the estimate of the total neutrino luminosity emitted from the SN.

$$L_\chi \lesssim L_\nu \sim 3 \times 10^{52}\ \mathrm{erg\,s^{-1}}$$

At 1s post bounce

Imagine to have some new particle coupled to electrons or nucleons, that can be produced inside a SN core

I Regime: Free streaming — if particles are very weakly coupled, once produced, free stream out of the SN.

II Regime: Trapping — if particles have large couplings they thermalize with the medium and get trapped inside of the PNS.

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Free Streaming

In the free-streaming regime there is a volume emission of particles, leading to a total energy-loss rate per unit volume

$f_\chi = 0$ for the new particles, because their occupation numbers inside the PNS are very low and not thermalized by assumption

$$Q = \int \Big[\prod_{\text{init},\, i} \frac{d^3 p_i}{(2\pi)^3 2E_i} f_i \Big] \Big[\prod_{\text{final},\, j} \frac{d^3 p_j}{(2\pi)^3 2E_j} (1 \pm f_j) \Big]$$
$$\times (2\pi)^4 \delta^4 \Big(\sum_i p_i - \sum_j p_j \Big) \sum_{\text{spins}} |\mathcal{M}|^2 E_\chi \, .$$

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Trapping

In the deep trapping regime, the dark-sector particles are in thermal equilibrium with the plasma and they are emitted from a surface (dark sphere)

$$L_\chi^{\text{trap}} = \frac{\mathfrak{g}_\chi}{\pi} r_\chi^2 T_\chi^4 \int_{x_m}^{\infty} dx \frac{x^2\sqrt{x^2 - x_m^2}}{e^x + 1}$$

$$x_m = m_\chi / T_\chi$$

The radius r_χ is defined, as is conventional in astrophysics, through the optical depth

$$\tau_\chi(r_\chi) = \int_{r_\chi}^{\infty} \frac{dr}{\lambda(r)} = \frac{2}{3}$$

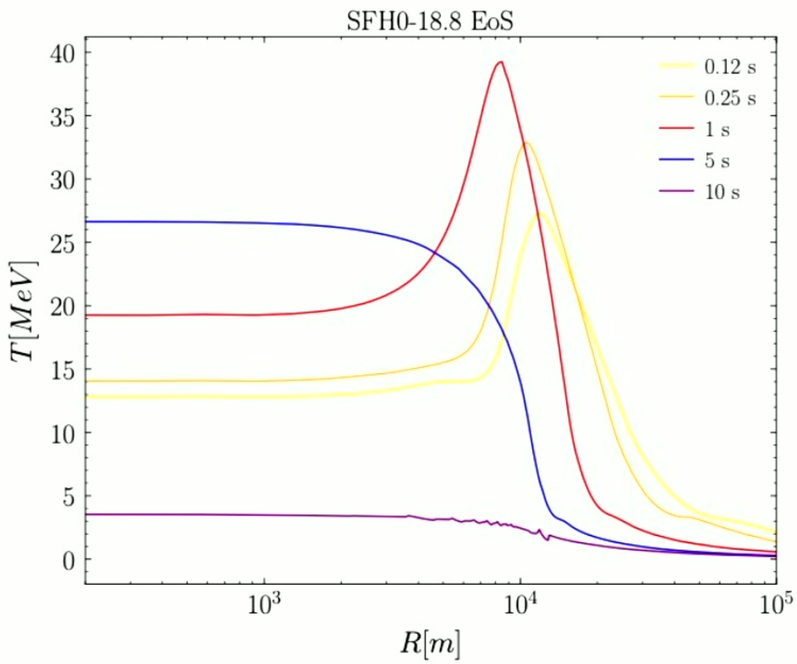
Inside a Supernova

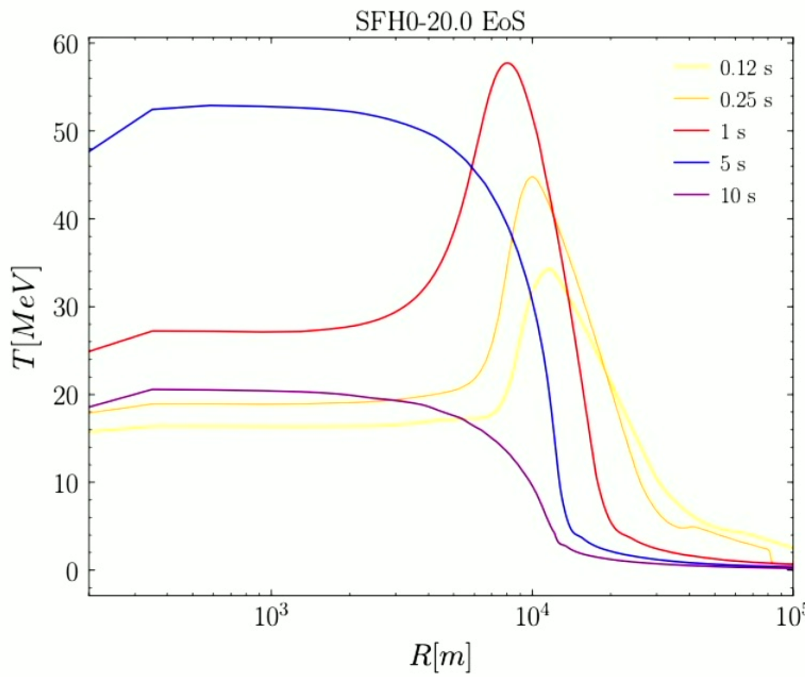
The Garching Core-Collapse Supernova Archive

For the numerical analyses we need a SN simulation with radial profiles for the relevant quantities: T, μ, ρ, etc.

Model name	Equation of state	Progenitor mass ($M_\odot$)	NS bary. mass ($M_\odot$)
SFHo-18.8	SFHo [47]	18.8 [48]	1.351
SFHo-18.6	SFHo [47]	18.6 [49]	1.553
SFHo-20.0	SFHo [47]	20.0 [50]	1.947
LS220-20.0	LS220 [51]	20.0 [50]	1.926

Inside a Supernova - Temperature





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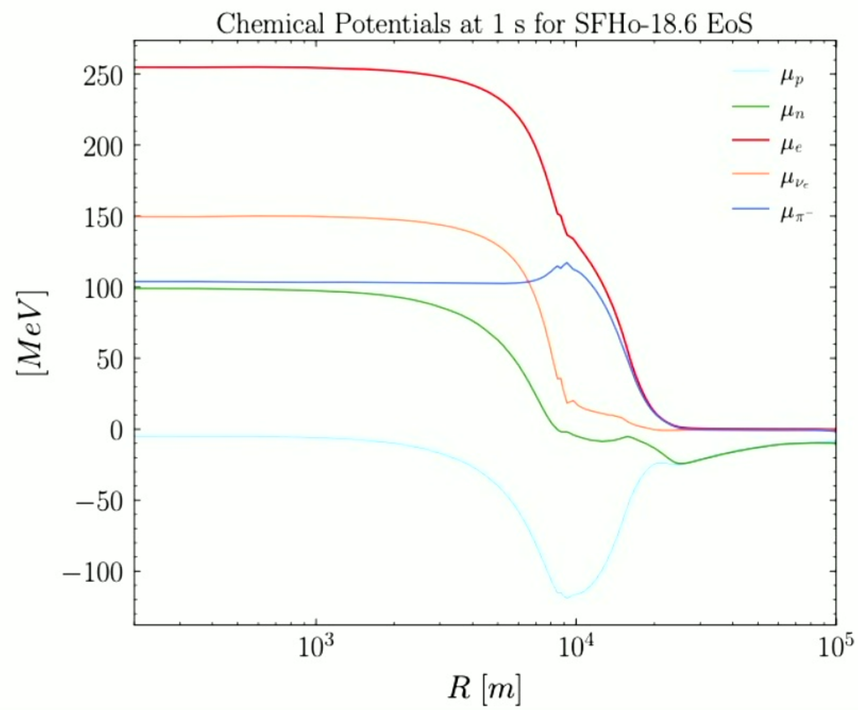
Inside a Supernova - Chemical Potentials

$$f = \frac{1}{\mathrm{epx}(\frac{E-\mu}{T}) \pm 1}$$

The SN is dominated by protons, neutrons and electrons.



R. Bollig, W. DeRocco, P.W. Graham and H.-T. Janka

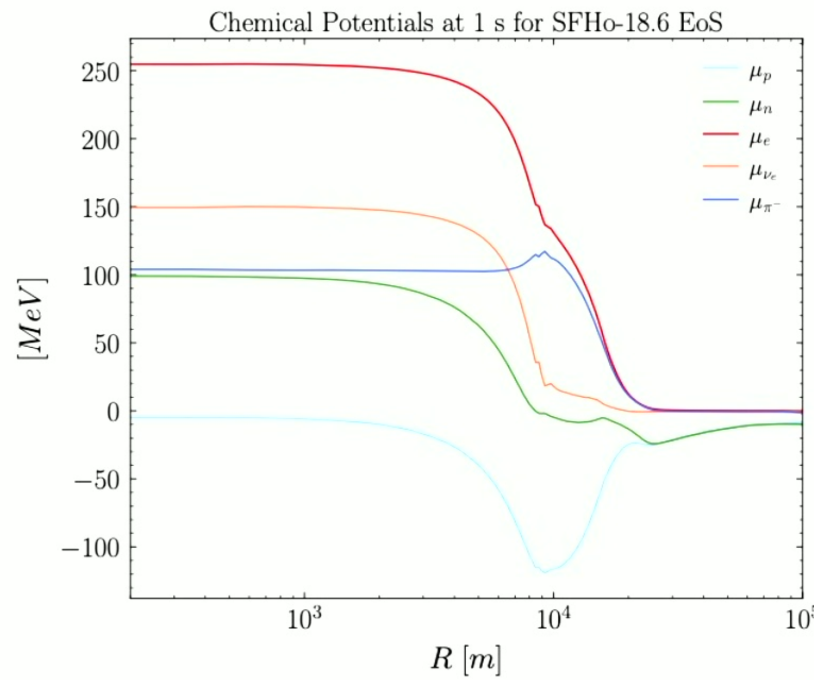
Muon Physics !

$$e^+e^- \to \mu^+\mu^- \qquad \gamma\gamma \to \mu^+\mu^-$$

Muons participate in β reactions:

$$\nu_\ell + n \rightleftarrows p + \ell^-$$
$$\bar{\nu}_\ell + p \rightleftarrows n + \ell^+$$

Which help to transfer the highly degenerate Fermi sea of electrons into muons.



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R. Bollig, W. DeRocco, P.W. Graham and H.-T. Janka

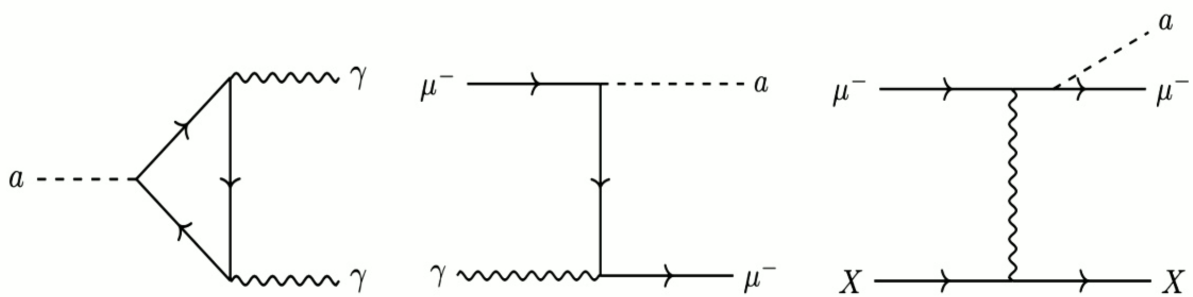
L. Calibbi, D. Redigolo, R. Ziegler and J. Zupan

D. Croon, G. Elor, R.K. Leane and S.D. McDermott

A. Caputo, G. Raffelt and E. Vitagliano

Looking for Light Particles

This allows to probe light particles coupled to muons that would lead to an anomalous energy loss.

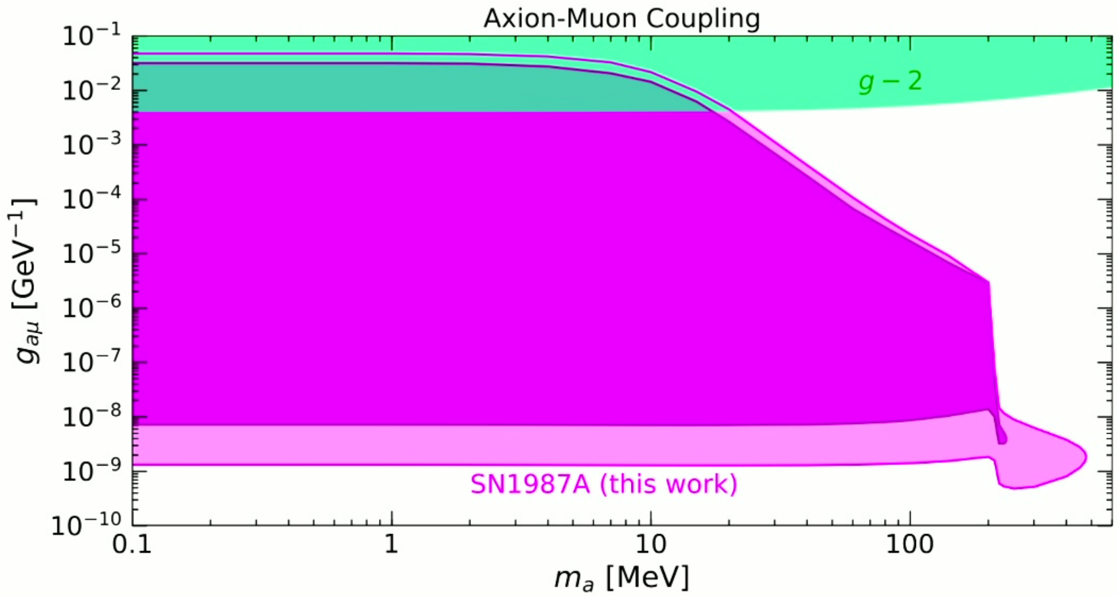


Similar ideas investigated also for electrons.

D. Croon, G. Elor, R.K. Leane and S.D. McDermott

Looking for Light Particles

This allows to probe light particles coupled to muons that would lead to an anomalous energy loss.



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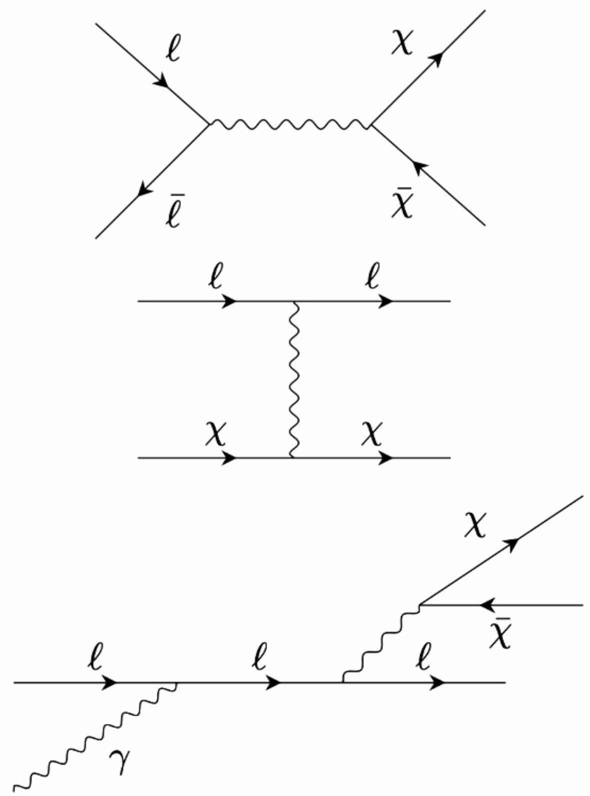
Looking for Dark Sectors

$$E_{\mu\mu} \sim 300\,\mathrm{MeV}$$

- Heavy regime: $m_B \gtrsim 1\,\mathrm{GeV} \gg E_{\mu\mu}$
- Resonant regime: the boson can be produced on-shell: $2m_\mu \leq m_B \leq E_{\mu\mu}$
- Light regime: boson masses below the two-muon threshold: $m_B \leq 2m_\mu$



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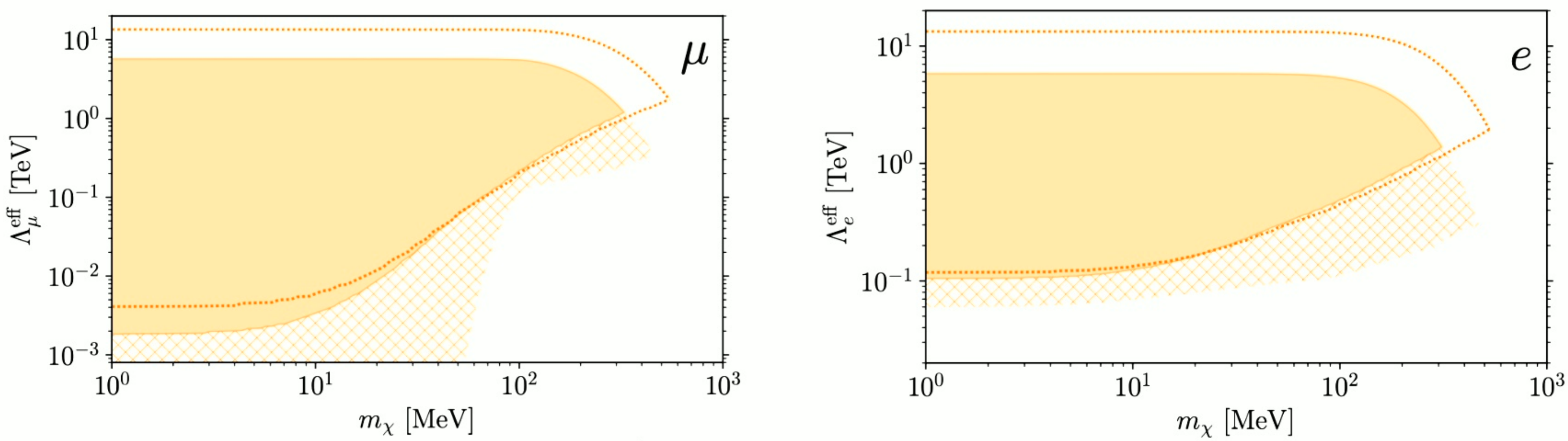
EFT regime - VV Interaction



$$\frac{1}{\Lambda^2}(\bar{\ell}\gamma^\mu \ell)(\bar{\chi}\gamma_\mu \chi)$$

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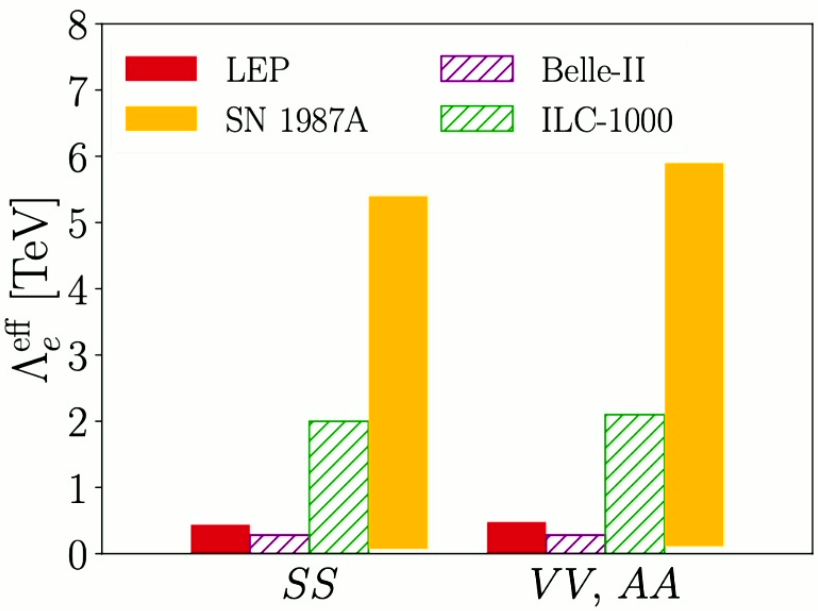
EFT regime

XY	$\Lambda_\mu^{\rm eff}$ [TeV]	$\Lambda_{\nu_\mu}^{\rm eff}$ [TeV]	$\Lambda_e^{\rm eff}$ [TeV]
SS	$0.0017 - 4.4$	$0.062 - 5.2$	$0.070 - 5.4$
PS	$0.00044 - 5.1$	$0.062 - 5.2$	$0.070 - 5.4$
VV	$0.0017 - 5.7$	$0.072 - 5.6$	$0.11 - 5.9$
AV	$0.0022 - 4.7$	$0.072 - 5.6$	$0.11 - 5.8$
LL	$0.0015 - 3.7$	$0.051 - 4.0$	$0.074 - 4.1$
LV	$0.0018 - 4.4$	$0.061 - 4.7$	$0.088 - 4.9$
TT	$0.0033 - 6.8$	$0.10 - 6.7$	$0.17 - 7.0$



$$m_\chi = 0$$

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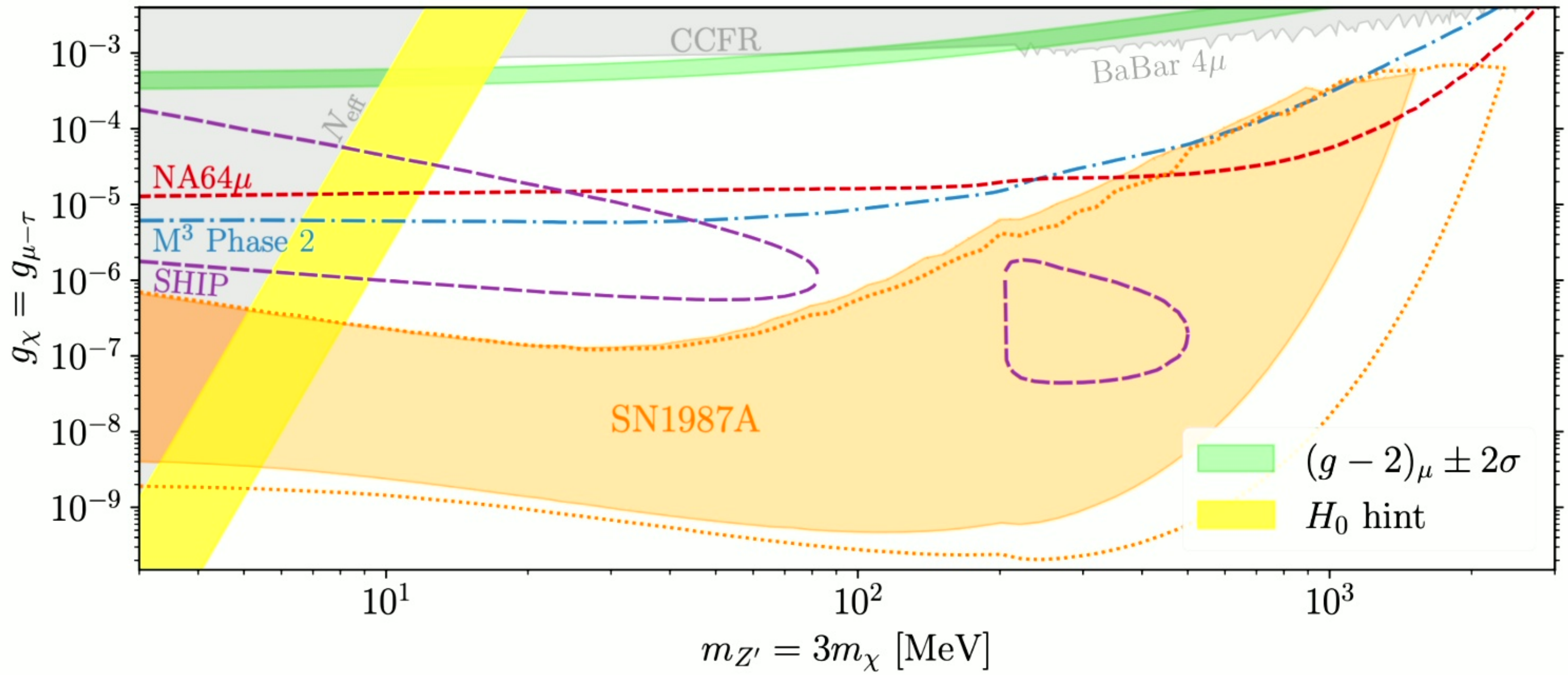
Example: $L_\mu - L_\tau$

$$\mathcal{L}_{\text{int}} = Z'_\mu \left(g_{\mu-\tau} j^\mu_{\text{SM}} + g_\chi \bar{\chi}\gamma^\mu\chi\right)$$



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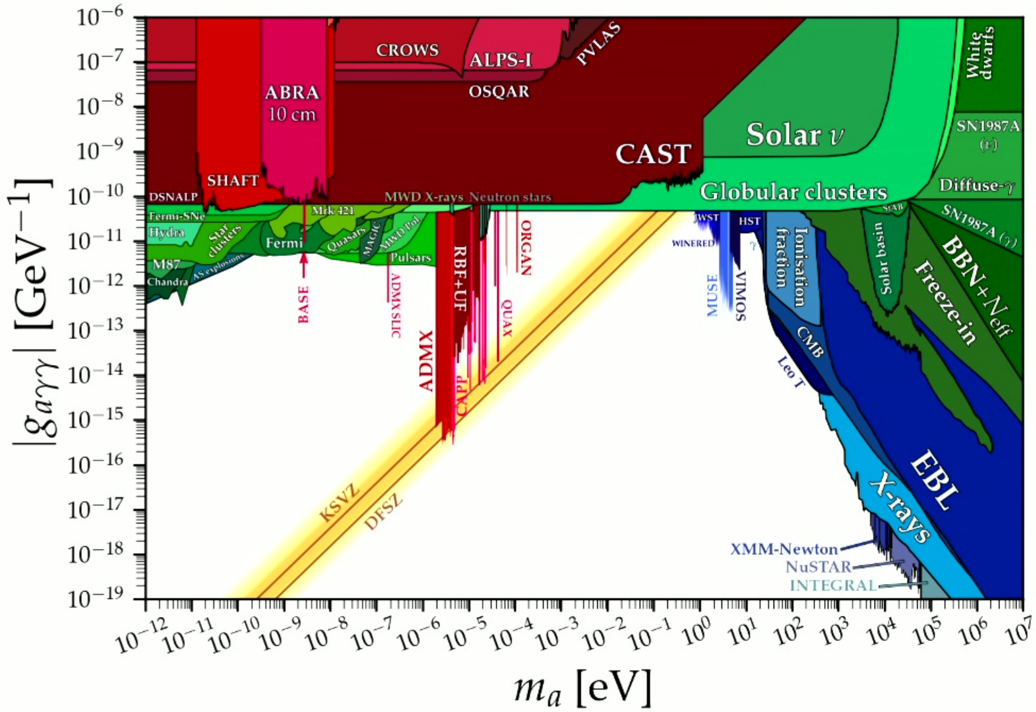
QCD Axion and ALPs

- The QCD axion (pseudo-scalar field) is a well motivated extensions of the SM, capable of explaining outstanding problems such as the strong CP problem and the nature of dark matter.



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Looking for Axion-like Particles

SN Constraints

SN1987A provides some of the most stringent and well-established constraints on a class of hypothetical ultra-light pseudo-scalar particles:

- ➔ axion production in the PNS core can modify the thermal evolution of the PNS, modifying the predicted luminosity evolution of neutrinos (cooling bound)
- ➔ ultralight axions that escape the PNS core could later convert to gamma-rays in Galactic magnetic fields. The latter probe is supported by the non-observations of gamma rays coincident with the neutrino burst by the Solar Maximum Mission (SMM), which happened to be looking in the direction of SN1987A when the explosion took place.

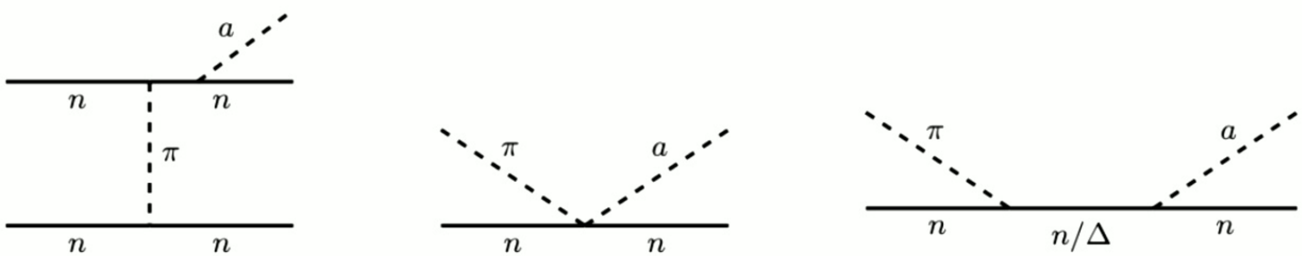
Production Mechanism - QCD Axion

The QCD axion is most dominantly produced through its couplings to nucleons

$$\mathcal{L} \supset C_{a\gamma\gamma}\frac{\alpha_{\rm EM}}{2\pi f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + C_{aqq}\frac{1}{2f_a}\partial^\mu a\bar{q}\gamma_\mu\gamma_5 q + \frac{\alpha_{\rm EM}}{32\pi^2 f_a} a\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

QCD axion

-1.92 KSVZ
0.75 DFSZ I
-1.25 DFSZ II



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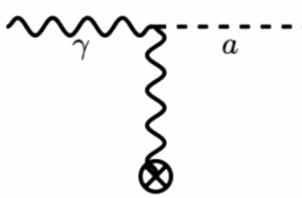
Production Mechanism - ALPs

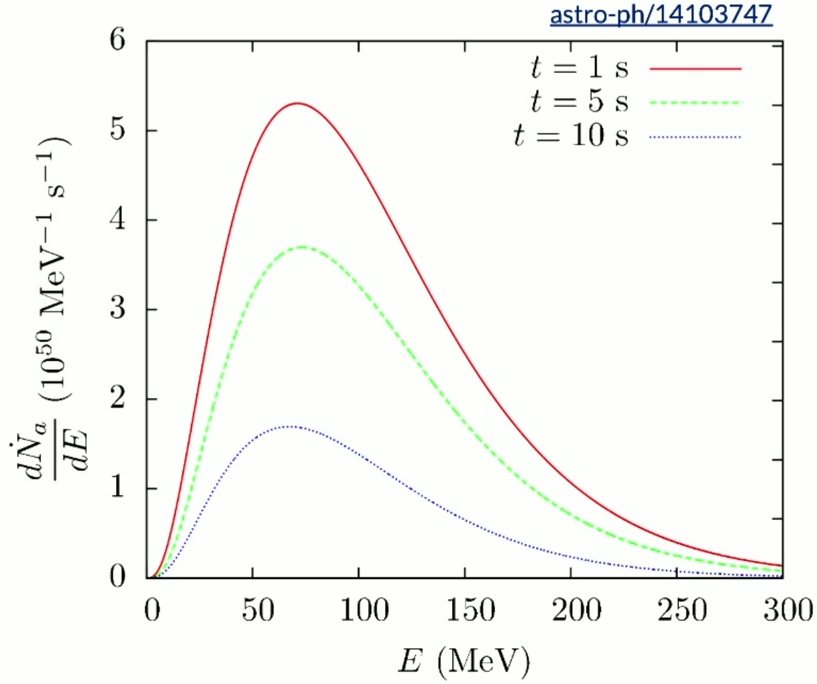
The minimal EFT scenario for axion-like particles is

$$\mathcal{L} \supset C_{a\gamma\gamma}\frac{\alpha_{\rm EM}}{2\pi f_a} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$$



astro-ph/14103747



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Production Mechanism - ALPs

However...there is an induced coupling to fermions through RG running.

Imagine to have the ALP coupled to electroweak gauge bosons at some UV scale Λ:

$$L \supset -\frac{1}{4} C_W \frac{g_2^2}{8\pi^2 f_a} a W^b_{\mu\nu} \tilde{W}^{b\,\mu\nu} - \frac{1}{4} C_B \frac{g_1^2}{8\pi^2 f_a} a B_{\mu\nu} \tilde{B}^{\mu\nu}$$

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Production Mechanism - ALPs

At the electroweak scale:

$$\mathcal{L} \supset -\frac{1}{4} C_\gamma \frac{e^2}{8\pi^2 f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{C_q}{2 f_a} \partial^\mu a \, \bar{q} \gamma_\mu \gamma_5 \, q$$

$$C_\gamma = C_W + C_B$$

$$C_q(m_Z) = \frac{3}{128\pi^4} \ln\left(\frac{\Lambda}{m_Z}\right) \left(\frac{3}{4} C_W g_2(\Lambda)^2 g_2(m_Z)^2 + (\mathcal{Y}_Q^2 + \mathcal{Y}_q^2) C_B g_1(\Lambda)^2 g_1(m_Z)^2\right)$$

Production Mechanism - ALPs

Below the electroweak scale:

$$\mathcal{L} \supset -\frac{1}{4} C_\gamma \frac{e^2}{8\pi^2 f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{C_q}{2 f_a} \partial^\mu a \, \bar{q} \gamma_\mu \gamma_5 \, q$$

$$C_\gamma = C_W + C_B$$

$$C_q(\mu) = C_q(m_Z) + \frac{3}{64\pi^4} \ln\left(\frac{m_Z}{\mu}\right) Q^2 e^2(m_Z) e^2(\Lambda_{\text{QCD}}) C_\gamma$$

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$\Lambda = 10^9\,\mathrm{GeV}$

Production Mechanism - ALPs

Running down to 2 GeV and matching on the nucleon couplings:

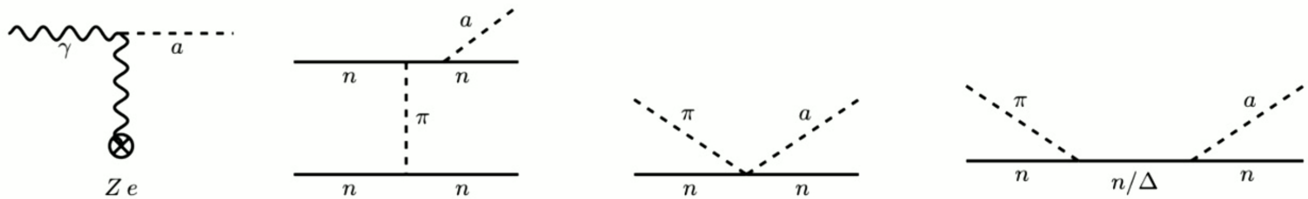
$$\mathcal{L} = -\frac{1}{4} g_{a\gamma} a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{g_{aN}}{2m_N}\partial_\mu a \bar{N}\gamma^\mu\gamma^5 N$$

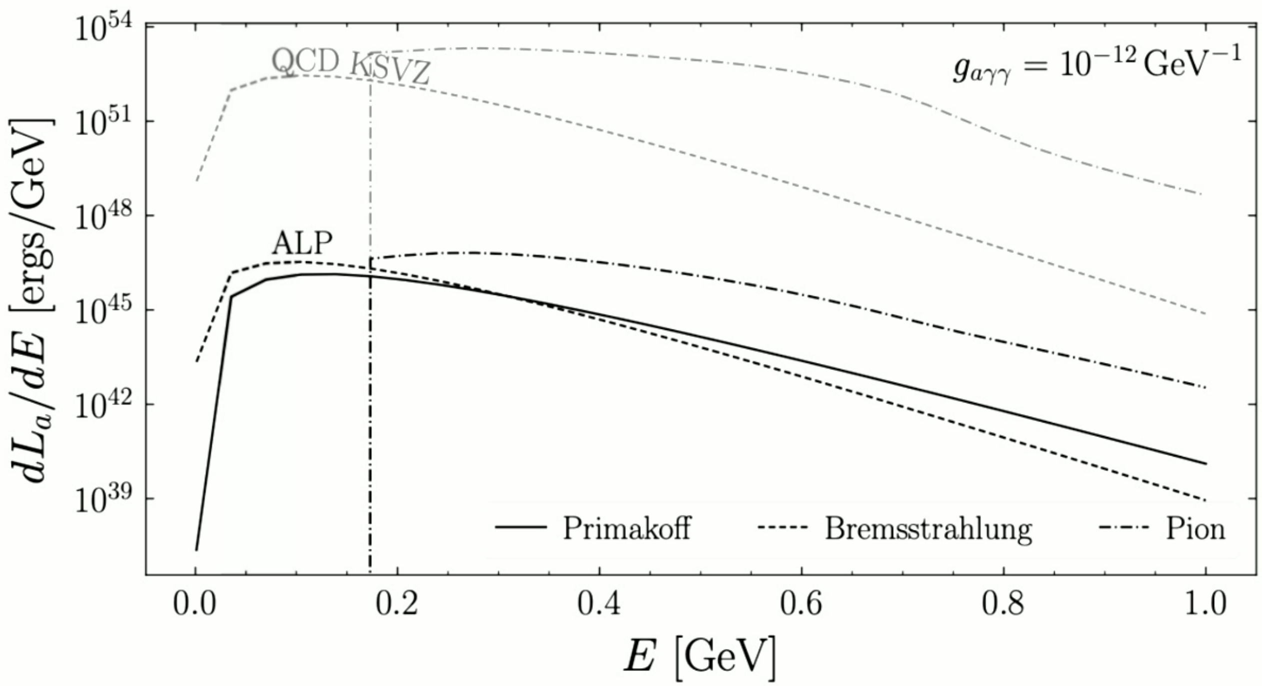
$$g_{a\gamma} = \frac{\alpha_{\mathrm{EM}}}{2\pi f_a}(C_W + C_B)$$

$$g_{a\,n} \sim -5.6\times 10^{-6}\,\frac{C_B}{f_a} + 2.1\times 10^{-4}\,\frac{C_W}{f_a}$$

$$g_{a\,p} \sim 3.5\times 10^{-5}\,\frac{C_B}{f_a} + 2.1\times 10^{-4}\,\frac{C_W}{f_a}$$

Axion Spectrum





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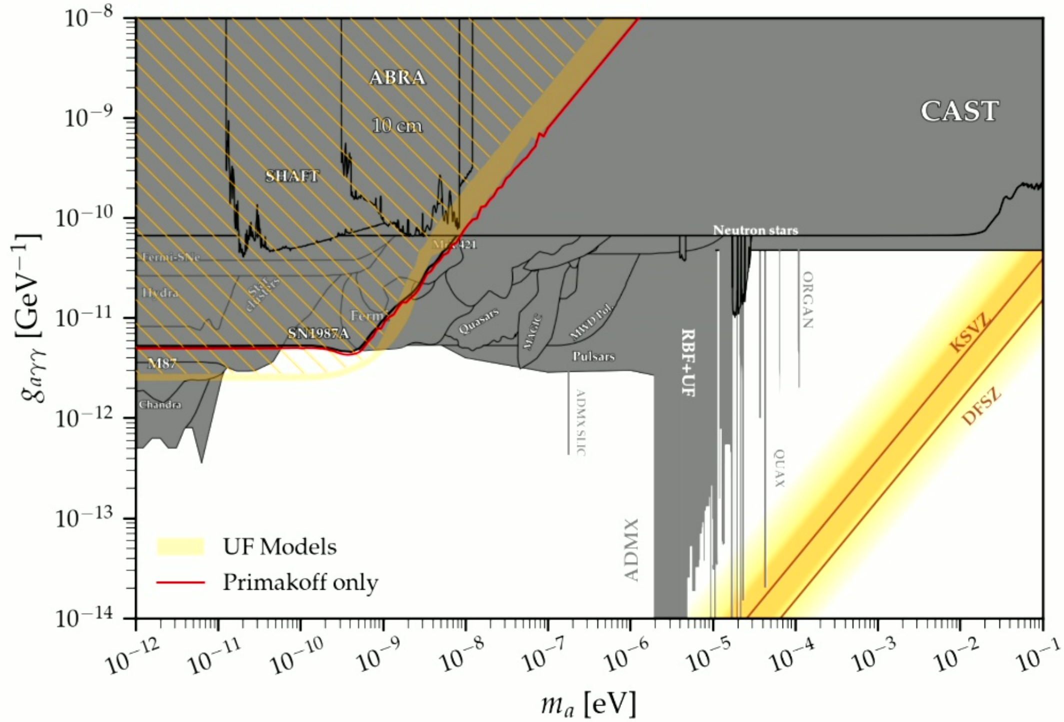
Conversion in the Galactic Magnetic Field

$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

For the Milky Way magnetic field, we used the models in astro-ph/2311.12120

We found no significative difference with using TNG simulations for Milky Way analogs.



Conversion in the Stellar Magnetic Field

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Conversion in the Stellar Magnetic Field

$$\frac{m_a^2}{2E} \times L \ll 1$$

$$P_{a\to\gamma} \sim g_{a\gamma\gamma}^2 B^2 L^2$$

Galactic MF

$$B \sim \mu\text{G} \qquad L \sim \text{kPc}$$

$$P_{a\to\gamma} \sim 10^{-5} (g_{a\gamma\gamma}/10^{-12}\ \text{GeV})^2$$

Stellar MF

$$B \sim \text{kG} \quad L \sim 45 R_\odot \sim \mu\text{Pc}$$

$$P_{a\to\gamma} \sim 10^{-5} (g_{a\gamma\gamma}/10^{-12}\ \text{GeV})^2$$

SN1987A progenitor was a BSG star (Sanduleak -69 202)

Conversion in the Stellar Magnetic Field

$$\frac{m_a^2}{2E} \times L \ll 1$$

Galactic MF

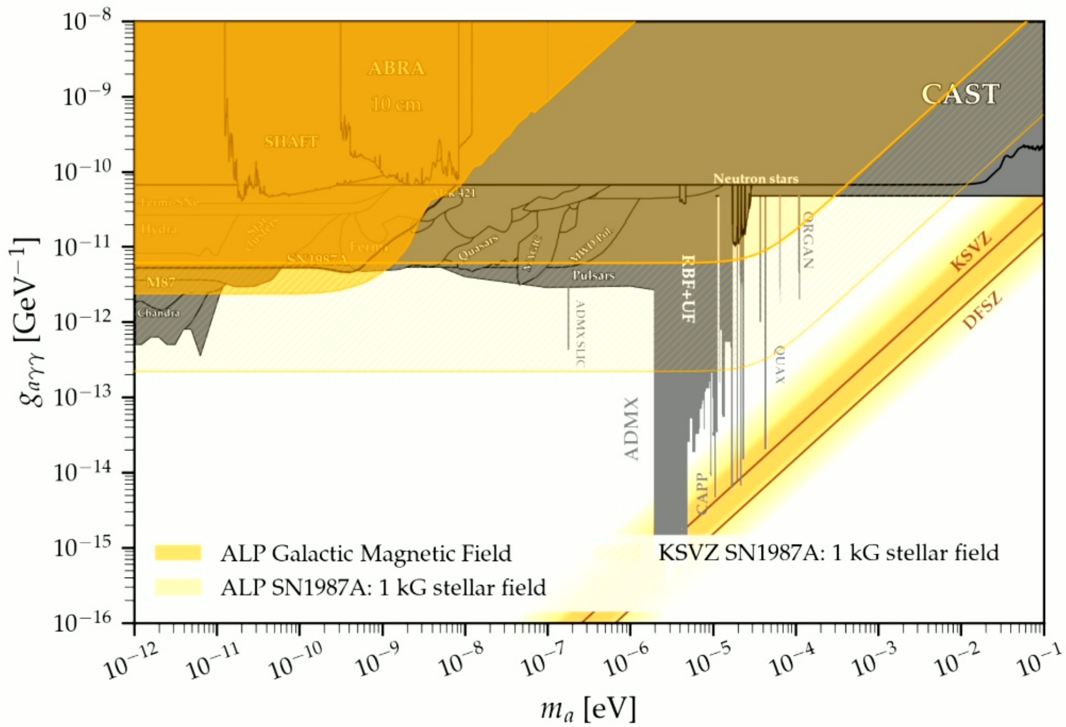
$$m_a \lesssim 2 \times 10^{-9} \mathrm{eV}$$

Stellar MF

$$m_a \lesssim 5 \times 10^{-5} \mathrm{eV}$$

$$E \sim 100\,\mathrm{MeV}$$

Conversion in the Stellar Magnetic Field



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Conversion in the Stellar Magnetic Field

For the numerical analysis, we studied the case of SN1987A and the possibility of a future galactic SN (d~10 kPc):

- A BSG with R~45 Rs and B~[0.1,10] kG. We model the magnetic field as a dipole field.
- A RSG with R~700 Rs. Here we have used the simulations of astro-ph/2110.03261 to take into account the photon optical depth and the equipartition theorem to model the magnetic field.

We then evaluated the axion-photon mixing equations including the effects of the plasma frequency and the Euler-Heisenberg term

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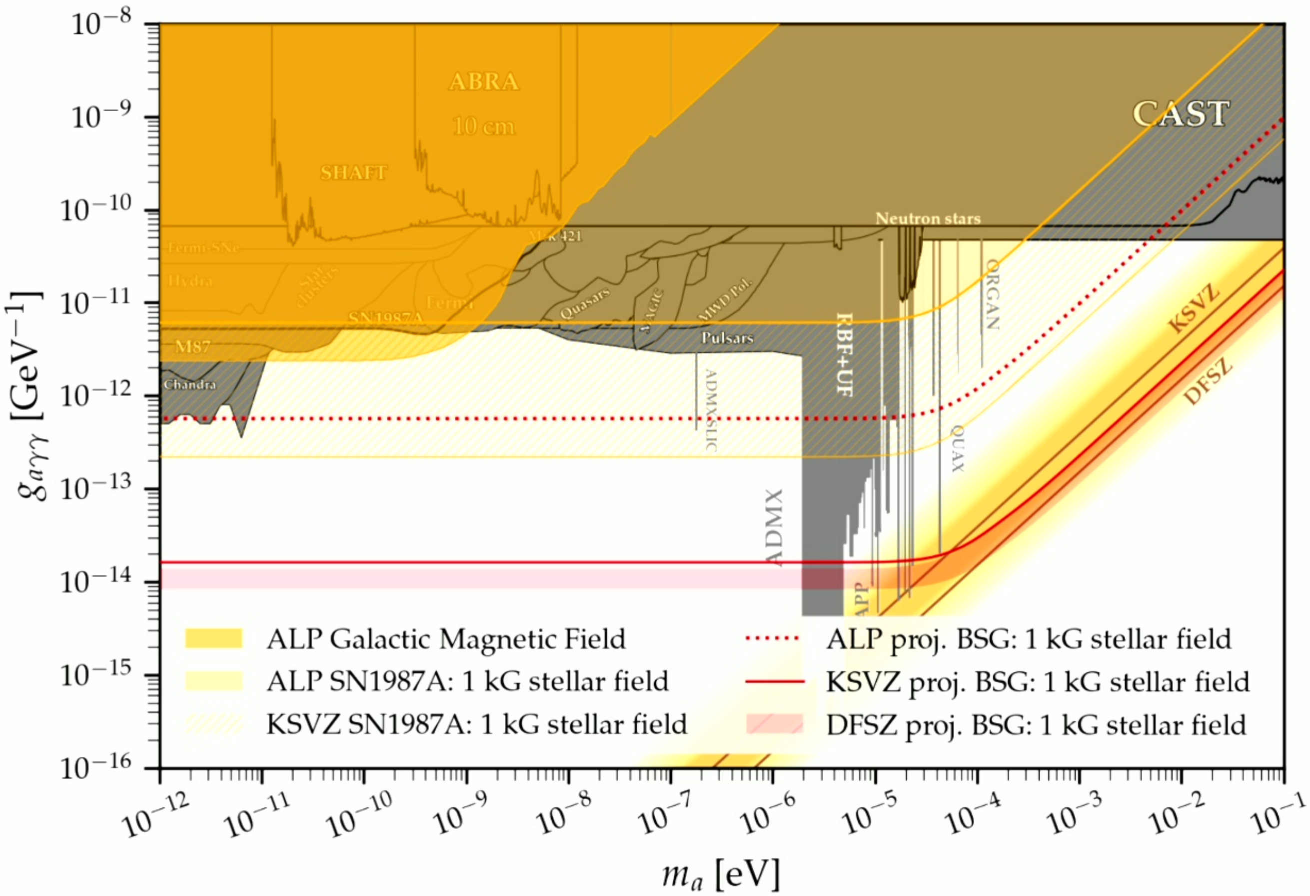
In preparation

Results



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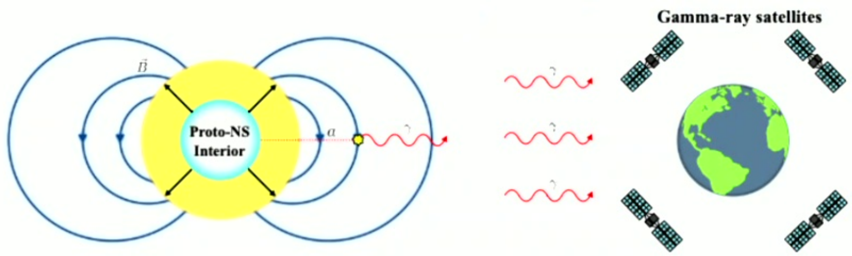

Comments

- SN1987A bounds obtained using the data and instrument response approximations in hep-ph/2212.09764. We find no evidence for an axion signal with the 95% upper limit.
- Projections obtained assuming SN went off directly above Fermi-LAT (at its zenith).
- If a Galactic SN went off today, we estimate that the chance Fermi-LAT would be looking at the correct place at the correct time is only around ~20% (FOV of the instrument and down-time during its orbit).
- We propose a GALactic AXion Instrument for Supernova (GALAXIS). A full-sky constellation of small gamma-ray satellites to provide continuous 4π coverage of the gamma-ray sky between ~10 MeV and ~1 GeV.

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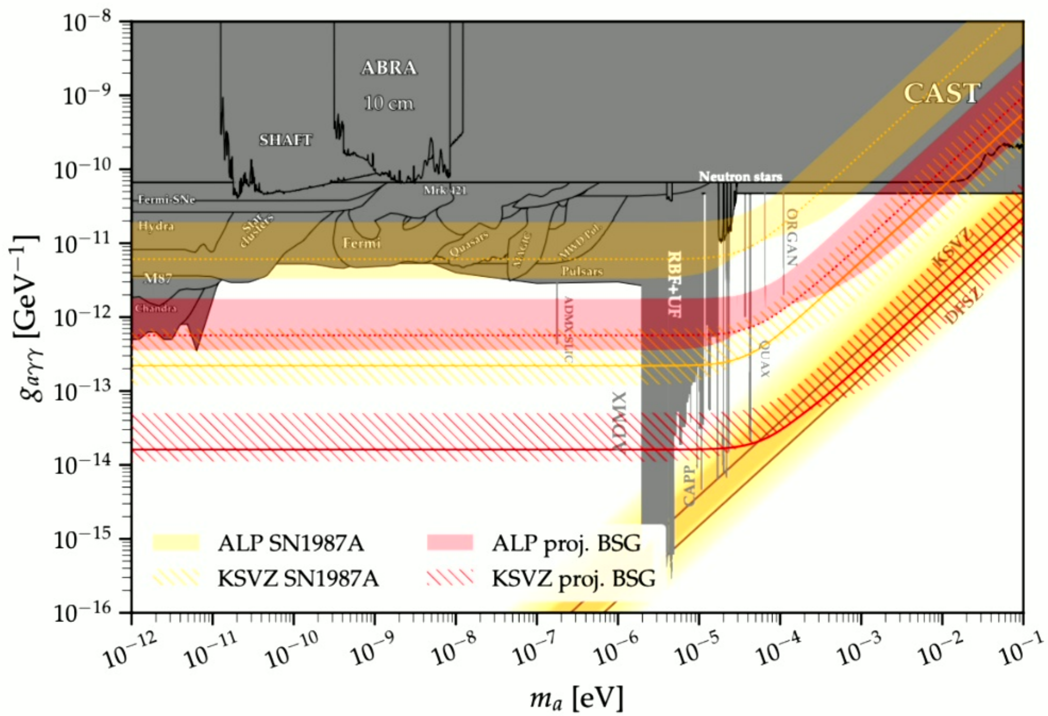
Results Varying B



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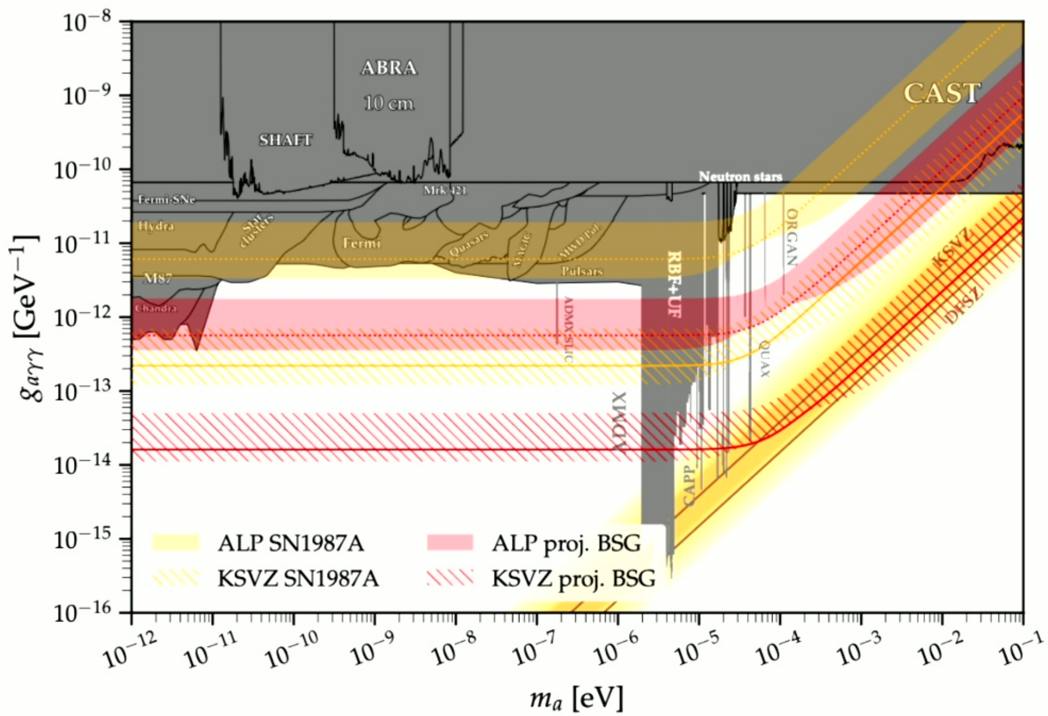
Results Varying B



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