CURRENT TOPICS IN ASTROPARTICLE PHYSICS
Munich, MPP
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SUPERNOVAE AS COSMIC LABORATORIES FOR AXIONS

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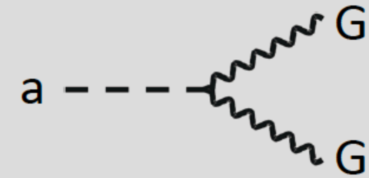
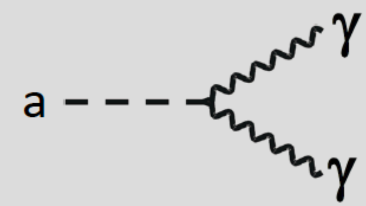
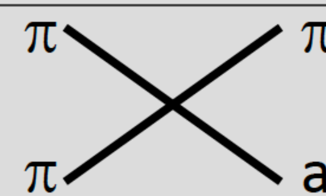
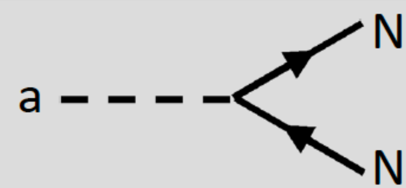
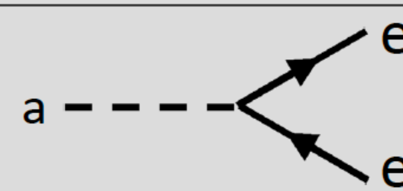
COSMIC WISPERS
CA21106

OUTLINE

- Axion interactions and models
- Axion bounds from SN 1987A
- Axion emissivity from NN bremsstrahlung: a state-of-the-art calculation
- A new axion emission channel from pionic processes
- SN 1987A bound on ALP-photon coupling
- Diffuse SN ALP backgrounds
- Conclusions

AXION PROPERTIES

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} \, G\tilde{G}a$ 
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \, \frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} \, F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$ 
Pion coupling	$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}\left(\pi^0\pi^+\partial_\mu\pi^- + \cdots\right)\partial^\mu a$ 
Nucleon coupling (axial vector)	$\mathcal{L}_{aN} = \frac{C_N}{2f_a} \, \overline{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \partial_\mu a$ 
Electron coupling (optional)	$\mathcal{L}_{ae} = \frac{C_e}{2f_a} \, \overline{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \partial_\mu a$ 

MAIN AXION MODELS

- DFSZ (Dine, Fischler, Srednicki, Zhitniskii) model

  ✓ Axions coupling to fermions and photons

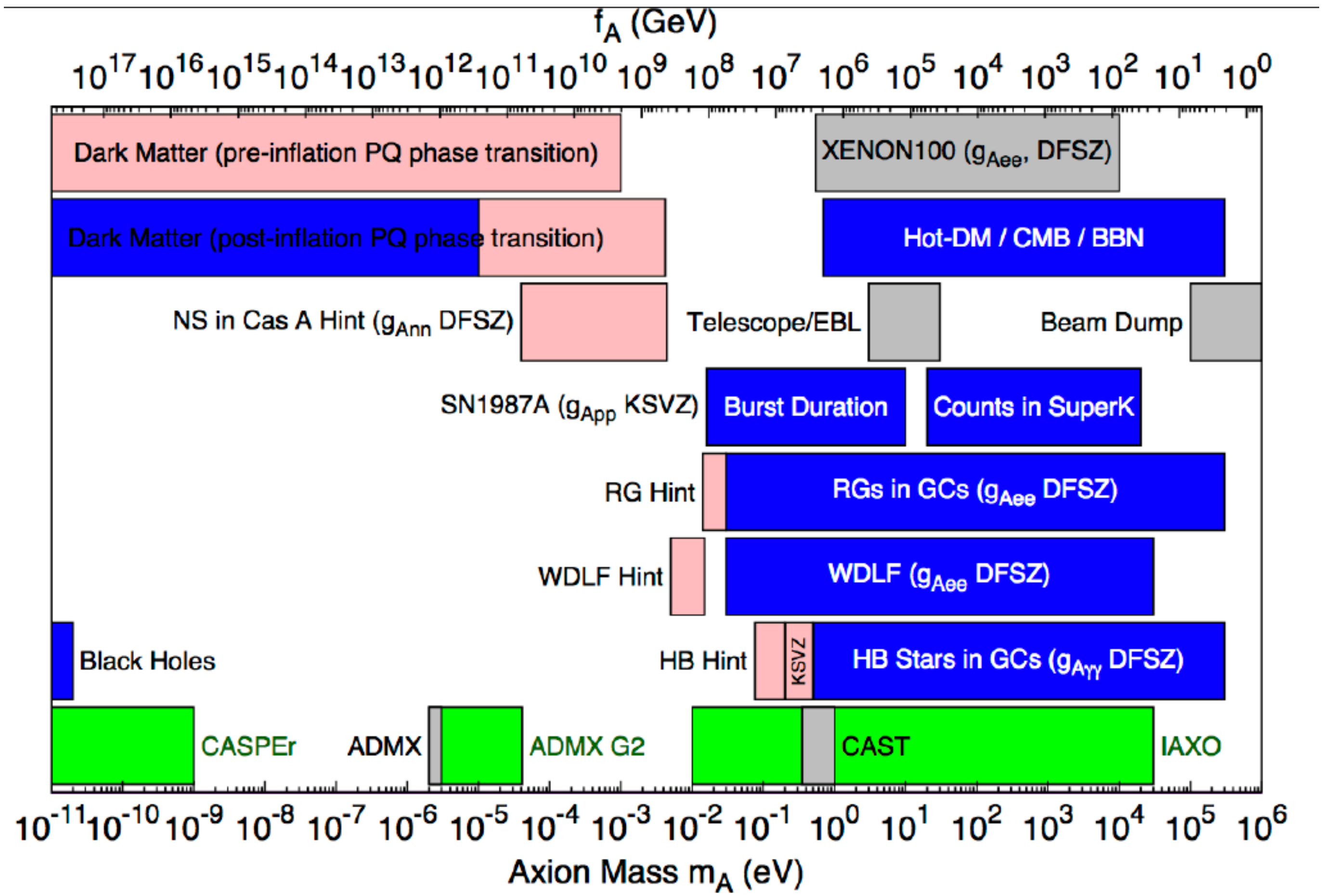
- KSVZ (Kim, Shifman, Vainshetein, Zakharov) model (hadronic axions)

  ✓ tree-level coupling to quarks and leptons suppressed
  ✓ Nucleon and photon couplings still possible
  ✓ Evades bounds of DFSZ model

- Axion-like particles (ALPs)

  ✓ Only coupling with photons by $a\gamma\gamma$ Lagrangian.
  ✓ No relation btw m_a and $g_{a\gamma}$

AXION BOUNDS

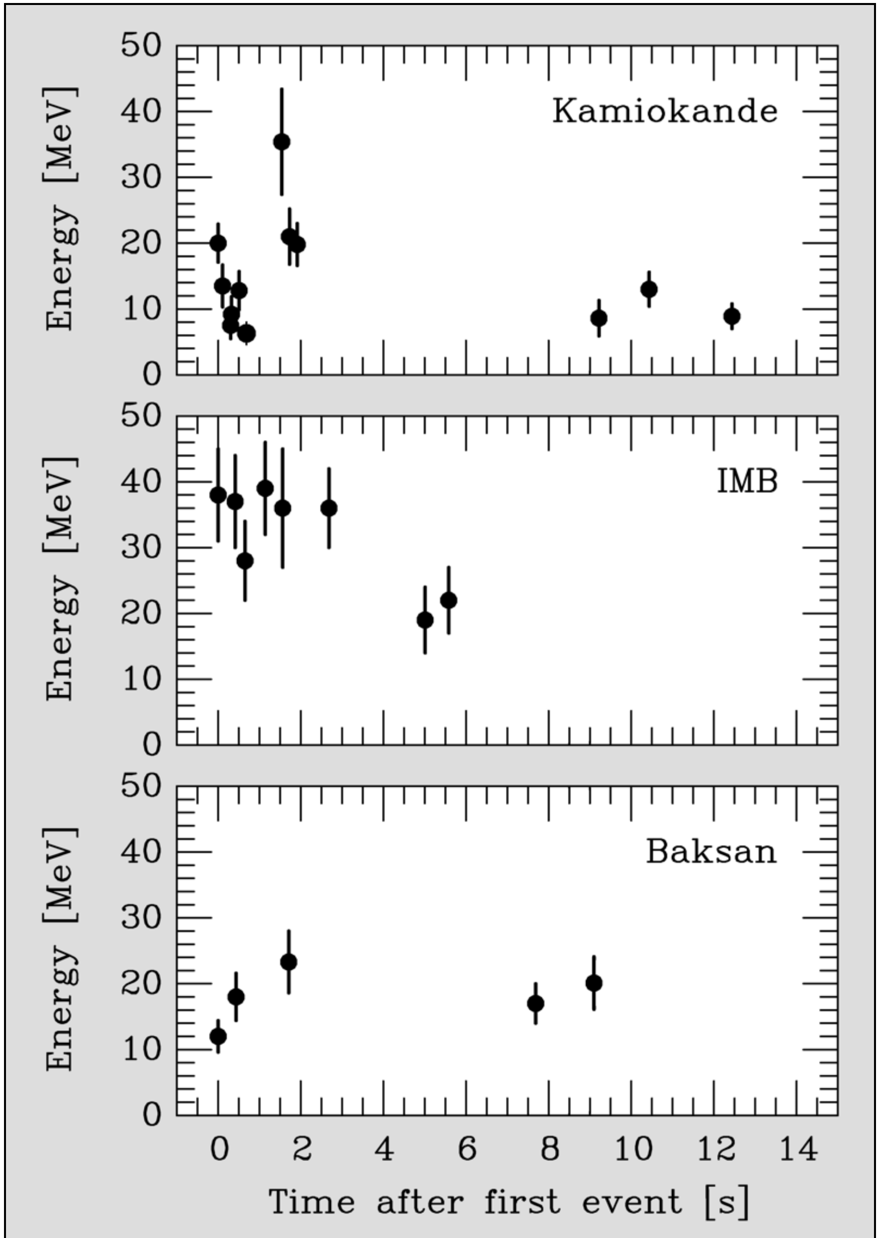


SUPERNOVAE

Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\, M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED:** **1-3 SN/century** in our galaxy (d ≈ $\mathcal{O}$(10) kpc).

NEUTRINO SIGNAL OF SUPERNOVA 1987A



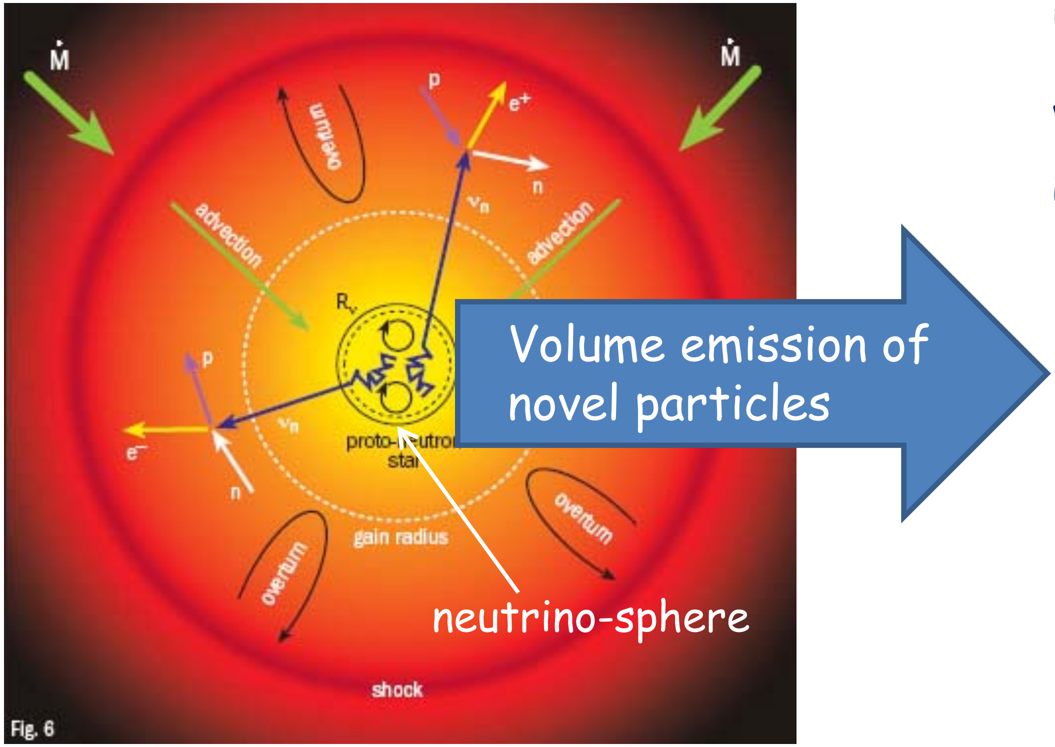
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ± 1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ± 50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

ENERGY-LOSS ARGUMENT



Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.

"Raffelt criterium" [Phys. Rept. 198, 113 (1990)]

Assuming that the SN 1987A neutrino burst was not shortened by more than ~½ leads to an approximate requirement on a novel energy-loss rate of

$$\varepsilon_X < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

for $\rho \approx 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$ and $T \approx 30\ \mathrm{MeV}$

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

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

The observation of a neutrino pulse from the supernova SN1987A constrains the production of light exotic particles in the proto neutron star. We derive a new bound on the axion decay constant, $f_a \gtrsim 10^{10}$ GeV. If right-handed (RH) neutrinos exist, the "RH Fermi constant" is $G_{RH} \lesssim 10^{-4} G_F$, 2 orders of magnitude below laboratory bounds. The Dirac mass of ν_μ can be constrained below laboratory limits.

PACS numbers: 97.60.Bw, 14.60.Gh, 14.80.Gt, 97.60.Jd

The recent supernova SN1987A in the Large Magellanic Cloud has triggered much excitement among particle physicists because the very first observation[1] of the neutrino pulse from a collapsing star allows one to use this astronomical event as a particle-physics laboratory.[2] The main effort has been directed toward extraction of information on neutrino masses, mixing parameters, and decay properties from the energy and time structure of the observed pulse. Furthermore, the measured neutrino pulse severely constrains the operation of an "exotic" cooling mechanism of the supernova (SN) core.[3] Therefore various species of light exotic particles (LEP's) cannot have been "overproduced" in the hot interior of the proto neutron star that has formed after collapse and so bounds on their interaction strengths can be derived. We shall use this argument to derive new and very restrictive limits on the axion decay constant, on right-handed weak currents, and on the Dirac masses of neutrinos.

To illustrate this argument we consider a LEP with a coupling strength g_x to ordinary matter. In Fig. 1 we show schematically how the luminosity in exotics, L_x, of the proto neutron star depends upon g_x. For small g_x, all LEP's freely escape so that L_x is proportional to g_x^2 and to a volume integral over the star. Therefore L_x increases with increasing g_x. However, the absorption cross sections also grow as g_x^2 until the star becomes "optically thick" for LEP's. In this situation the particles essentially emerge from the "LEP sphere" at a radius r_x, corresponding to an optical depth equal to unity. Then L_x may be approximated by blackbody emission from the LEP sphere so that $L_x \propto r_x^2 T^4(r_x)$. For the proto neutron star, $r^2 T^4(r)$ is a rapidly decreasing function of r so that L_x now *decreases* as g_x increases.

An application of these arguments to neutrinos shows that their coupling is on the "strong-interaction" side of Fig. 1, i.e., they are "trapped." Hence there will be a window of coupling strengths, $g_{min} < g_x < g_{max}$, where we may expect $L_x > L_\nu$. If g_x were to lie in this window, the gravitational binding energy, E_{tot}, of the neutron star would be emitted primarily in LEP's. However, the neutrino pulse from SN1987A has been observed[1] and its characteristics agree well with theoretical expectations,[2] leaving little room for LEP emission, so that coupling strengths in this window may be excluded. We are mostly interested in determining g_{min} because, in many cases, other astrophysical arguments or laboratory data exclude couplings as strong as g_{max}. Before we move on to a case-by-case study, we discuss how the energy lost to LEP's will change the neutrino signal and then consider

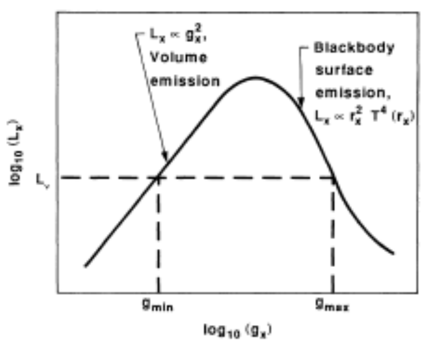


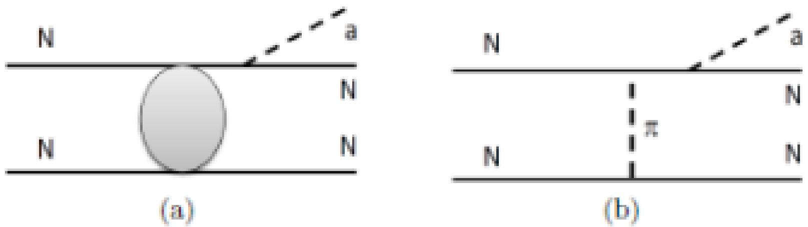
FIG. 1. Schematic dependence of L_x on the coupling strength g_x. The horizontal line denotes the neutrino luminosity L_ν. In the range $g_{min} < g < g_{max}$ the LEP emission L_x would exceed L_ν.

AXION EMISSION FROM A NUCLEAR MEDIUM

- Nucleon-Nucleon bremsstrahlung

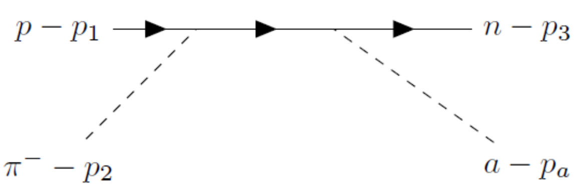
[Burrows et al., PRD 39, 4 (1989), Brinkmann and Turner, PRD 34, 8 (1988), Keil, Janka et al, PRD 56, 4 (1997)…]

$$NN \to NNa$$



Bulk nuclear interaction   One pion exchange

- Compton pionic process $\pi^- p \to n\, a$



Initial investigations suggested that that the thermal pion population was too small for the pionic reactions to be competitive wrt to the NN process.

[Turner, Phys. Rev. D 45, 1066 (1992); Raffelt and Seckel, Phys. Rev. D 52, 1780 (1995); Keil, Janka, Schramm, Sigl, Turner and Ellis, Phys. Rev. D 56, 2419 (1997)]

SN 1987A AXION LIMITS FROM NN PROCESS

- Raffelt, Lect. Notes Phys. 741 (2008) 51 [hep-ph/0611350]
  Burst duration calibrated by early numerical studies
  "Generic" emission rates inspired by OPE rates
  $f_a > 4 \times 10^8$ GeV and $m_a < 16$ meV

- Chang, Essig & McDermott, JHEP 1809 (2018) 051 [1803.00993]
  Various correction factors to the emission rate, specific SN core models
  $f_a > 1 \times 10^8$ GeV and $m_a < 60$ meV [KSVZ, based on proton coupling]

- Bar, Blum & D'Amico, Is there a SN bound on axions?
  PRD 101 (2020) 12 [1907.05020]
  Alternative picture of SN explosion (thermonuclear event)
  Observed signal not PNS cooling.
  However the possible detection of NS 1987A in SN 1987A would
  disfavor alternative mechanisms [see Page et al., 2004.06078]
  (We will neglect this possibility hereafter)

NEW CALCULATION OF SN AXION EMISSION RATE

[Carenza, Giannotti, Gang, Fischer, Martinez-Pinedo, A.M., JCAP 10 (2019) 016, 1906.11844, v2]

We performed an improved calculation of axion emissivity via NN process, including self-consistently different corrections on top of the naive OPE prescription

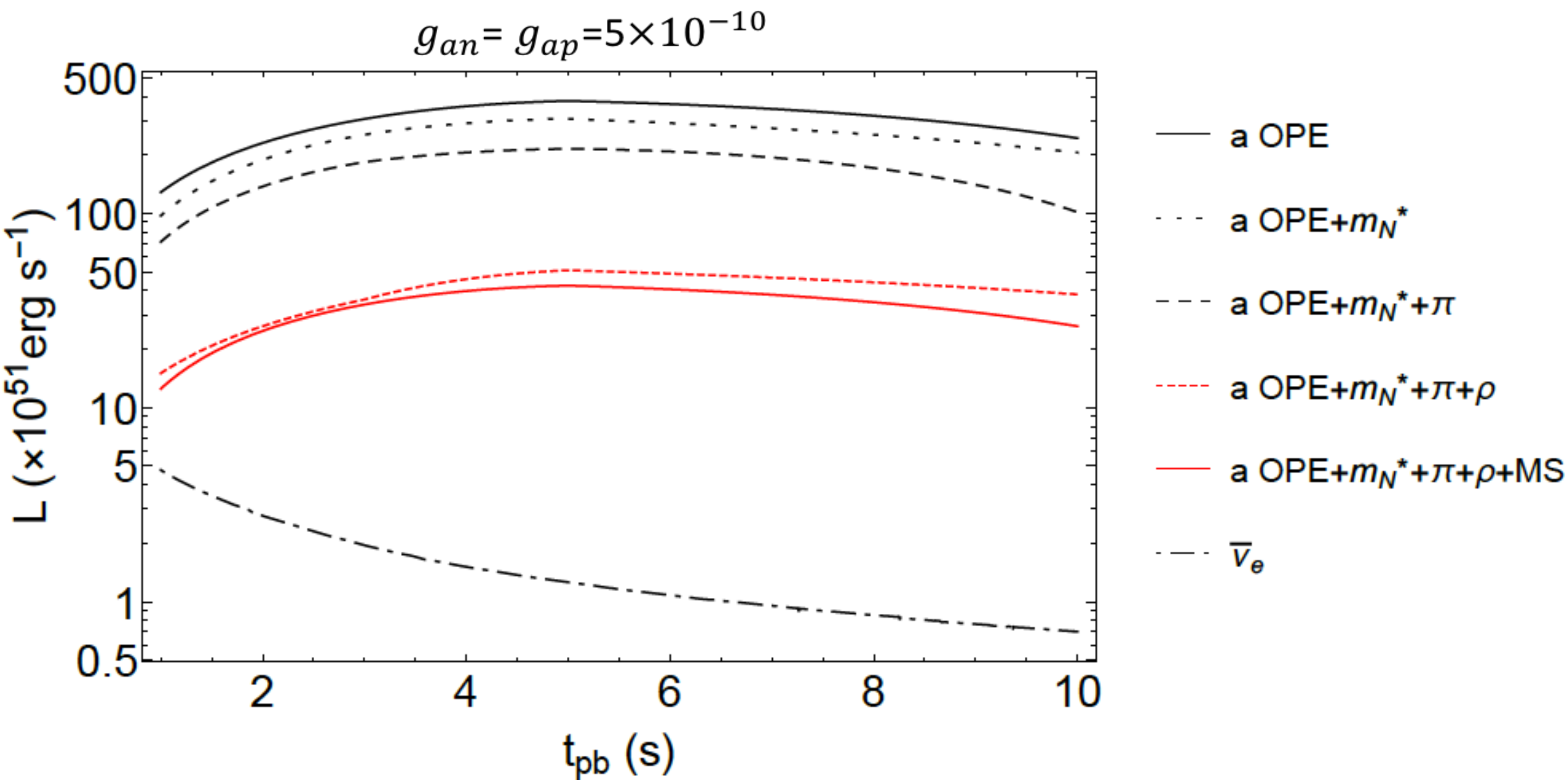
- Non-zero pion mass in the propagator → $\sqrt{3m_N T} \sim m_\pi$
  [Hannestad and Raffelt, astro-ph/9711132]

- Two-pions exchange → important around $2\, fm \approx 1.5\, m_\pi^{-1}$
  Mimicked by a rho-meson exchange with $m_\rho \approx 600\, MeV$
  [Ericson and Mathiot, PLB 219, 507 (1989)]

- Effective in-medium nucleon mass → $m_N^*(\rho)$
  [Hempel, 1410.6337]

- Multiple nucleon scatterings → Nucleon spin fluctuations
  [Raffelt and Seckel, PRL 67, 2605 (1991), Raffelt and Seckel, astro-ph/9312019]

IMPACT OF THE CORRECTIONS



- Reduction of L_a by one order of magnitude when all the corrections are included
- Major impact due to effective nucleon mass and rho-exchange

KVSZ AXION 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

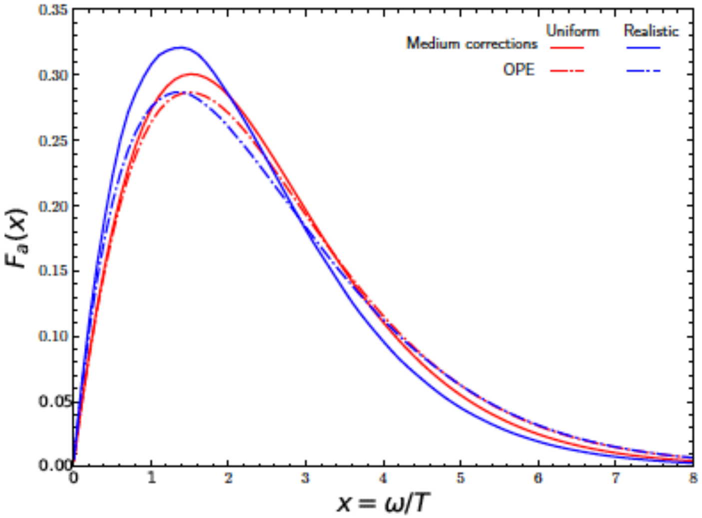
- Our bound is (accidentaly) comparable with Raffelt (2006). However, this latter includes only OPE+MS in a schematic SN model, assuming medium composed by only protons.

- Our approach similar to Chang et al. (2018). However, their implementation of the corrections beyond OPE is more schematic than ours. Implemented as simple fudge factors without taking into account correlations among them (e.g. normalization conditions). Amplification of the relaxation of the mass bound

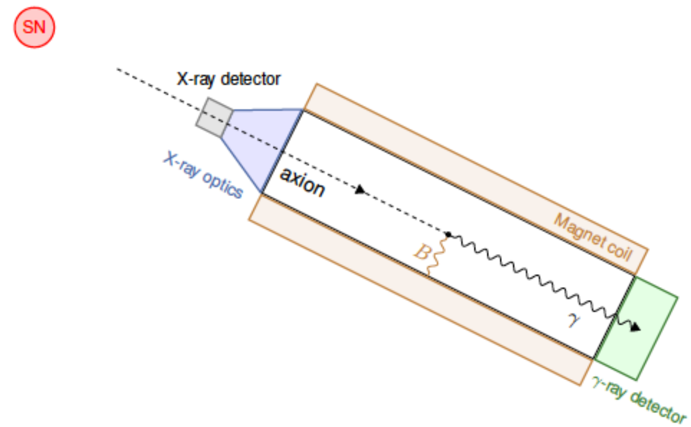
SN AXION SCOPE

[Shao-Feng Ge et al., 2008.03924 [hep-ph]]

SN axion flux

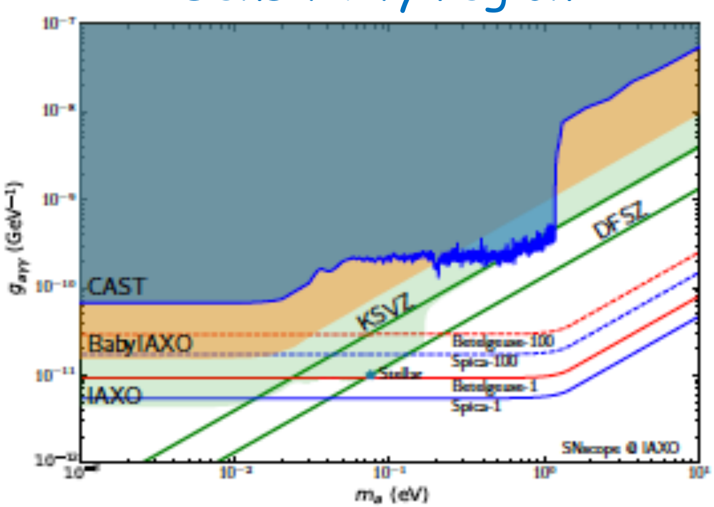


SN axion scope



(b) Axion SNscope

Sensitivity region



- A close-by SN (d < few hundreds pcs) can be pointed with a neutrino SN pre-alert system
- SN axions can be detected by a gamma-ray detector installed at the end of an helioscope
- It can extend IAXO sensitivity towards higer masses

THERMAL PIONS IN A SN CORE

[Force and Reddy, PRC 101 (2020) 035809, 1911.02632 [astro-ph.HE]]

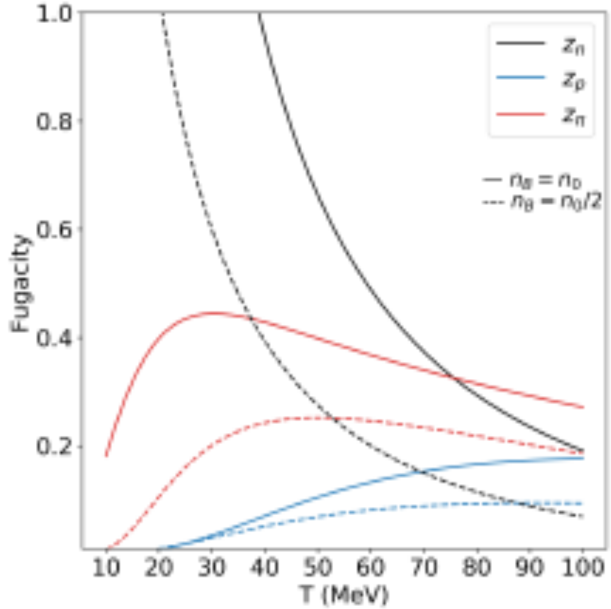


FIG. 3. Pion and nucleon fugacities in charge-neutral dense matter in β-equilibrium at $n_B = n_0$ (solid-curves) and $n_B = n_0/2$ (dashed-curves) are shown as function of temperature.

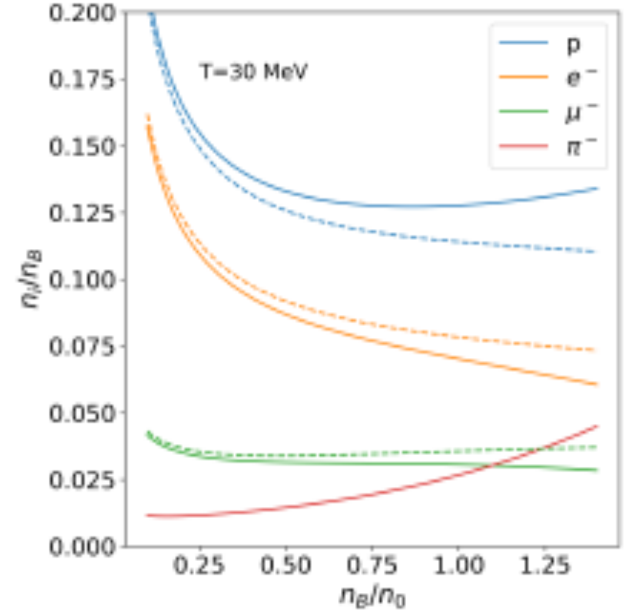
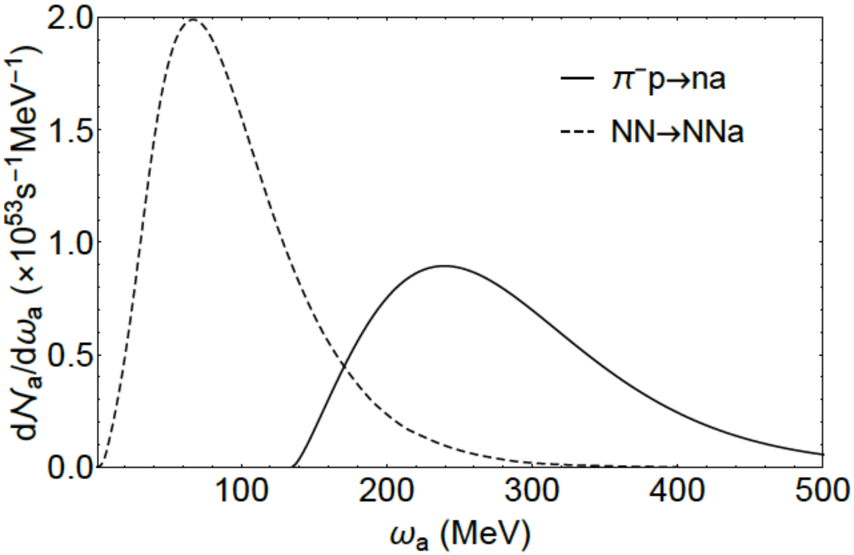


FIG. 2. Number fraction of charged particles at $T = 30$ MeV in β-equilibrium. Solid curves include pions and dashed curves only contain nucleons and leptons.

Around the saturation density $n_0 = 1.6\times10^{38} cm^{-3}$ the pion abundance can reach few % of the baryon one

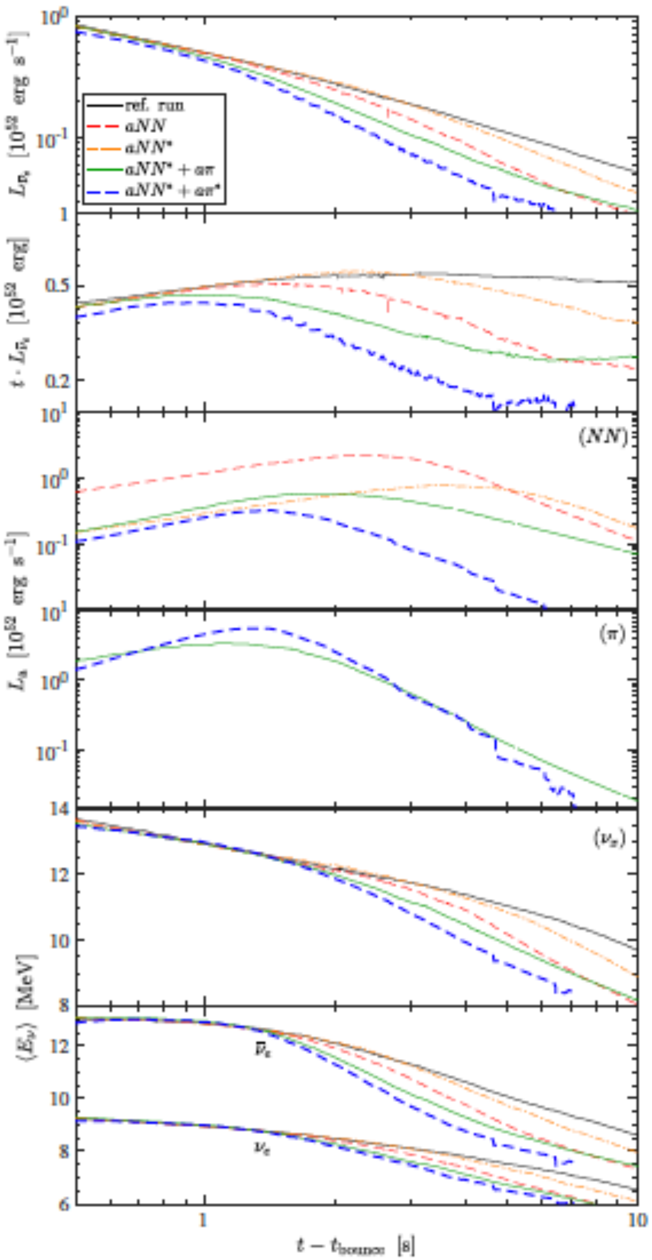
AXION EMISSIVITY FROM PIONIC PROCESSES

[Carenza, Force, Giannotti, A.M., Reddy, PRL 126, 7, 071002 (2020), 2010.02943]



- We pointed out that pionic processes might strongly enhance axion emissivity
- The axion mass bound would be strengthened by a factor ~2 when π^-N processes are included
- π^-N process produces a harder axion spectrum (E~ $200\ MeV$) with respect to NN process

SN SIMULATIONS WITH AXIONS



[Fischer, Fore, Reddy, Carenza, Giannotti, A.M., PRD 104, 10, 103012 (2021), 2108.13726]

g_{ap}=1.2 $\times 10^{-9}$ corresponding to bound from aNN*

- Remarkable differences wrt to reference case already at t_{pb}= 2 s
- Speed-up in SN neutrino cooling
- Pionic processes are the dominant channel of axion energy loss in SN

SN AXION EMISSION FROM EDM

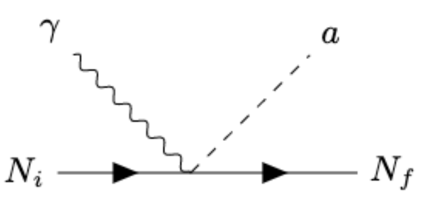
[Lucente, Mastrototaro, Carenza, Di Luzio, Giannotti, A.M., 2203.15812]

- Neutron electron dipole portal (EDM)

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

Model-independent feature of QCD axions

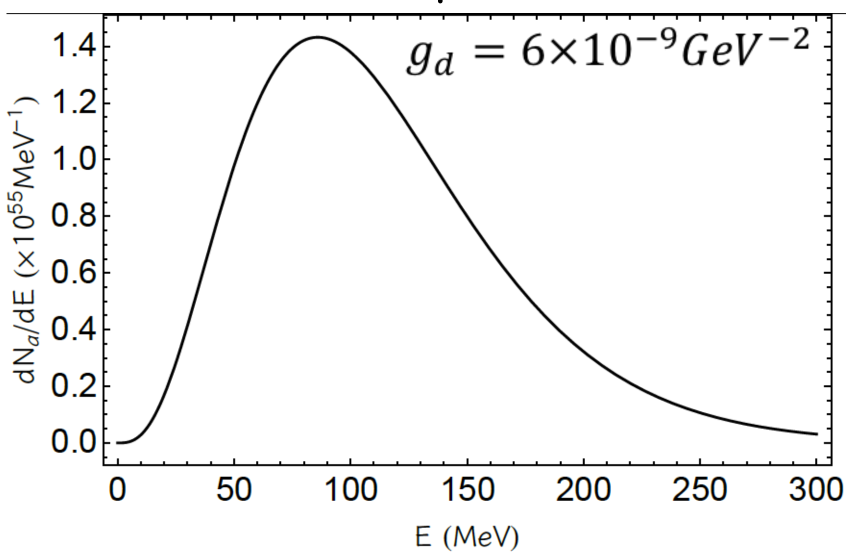
- In models where other couplings are suppressed, EDM portal is the only production channel in SNe



Compton process

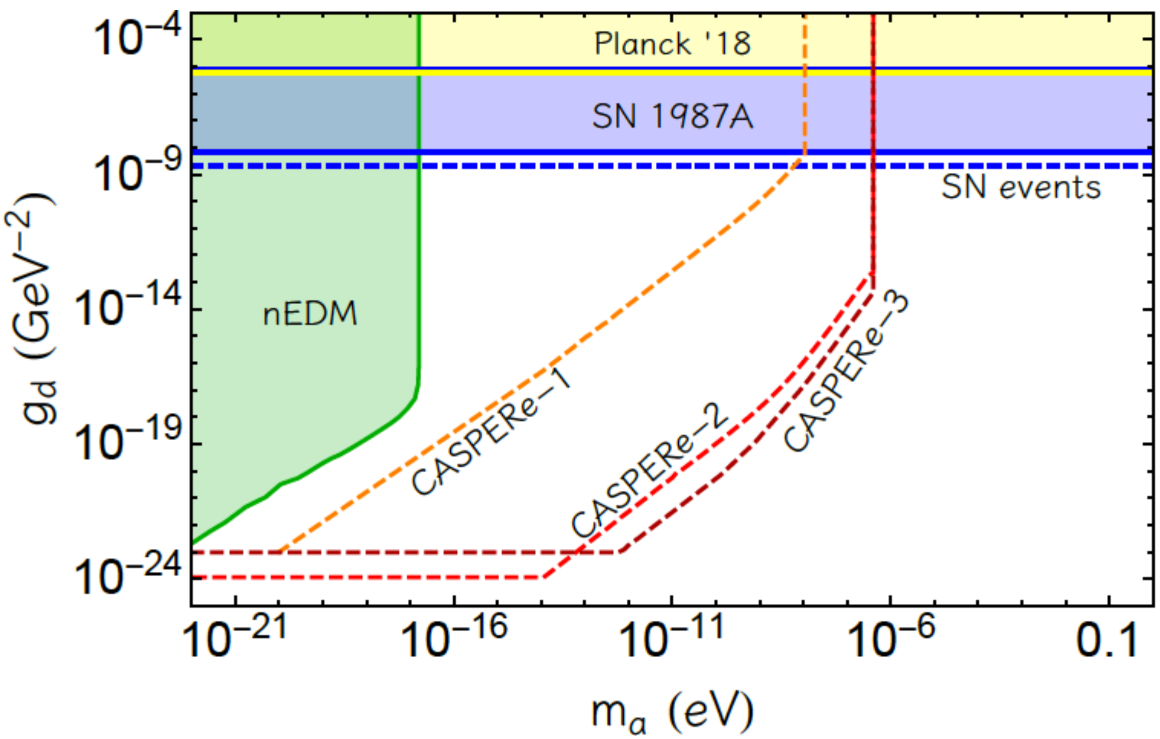
[Graham & Rajendran, 1306.0688]

Axion spectrum



BOUNDS FROM EDM

[Lucente, Mastrototaro, Carenza, Di Luzio, Giannotti, A.M., 2203.15812]



- SN 1987 A energy-loss bound $g_d < 6.7\times10^{-9} GeV^{-2}$
- Complementary with future CASPER search of oscillating EDM in DM axions

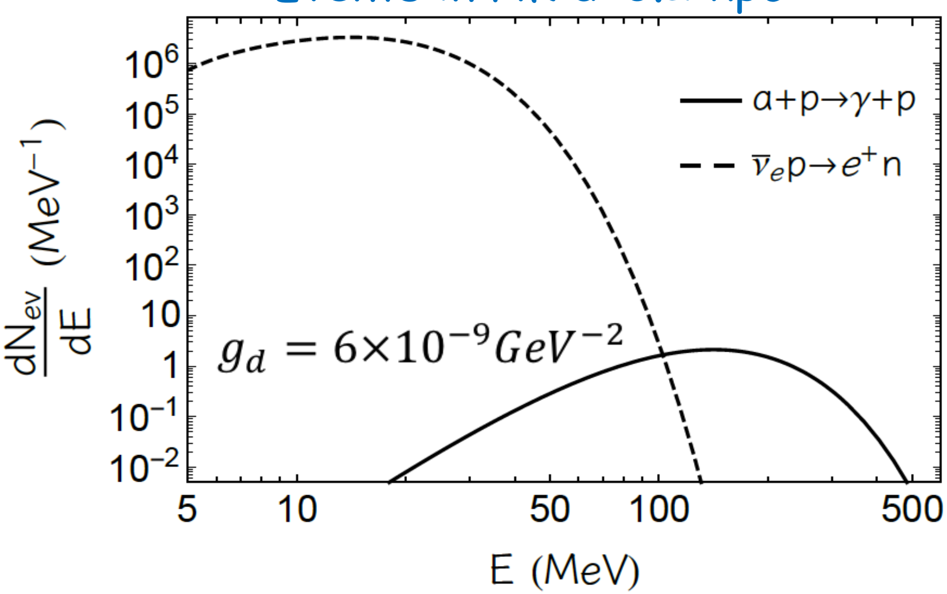
SN AXION SIGNATURES FROM EDM

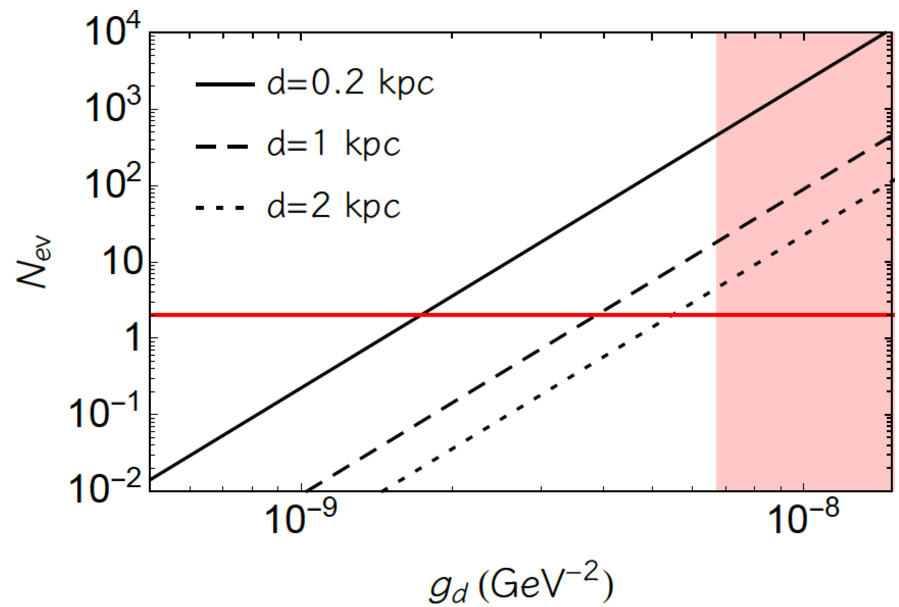
[Lucente, Mastrototaro, Carenza, Di Luzio, Giannotti, A.M., 2203.15812]

- Below the SN 1987A bound, axion can produce detectable events in large underground nu detectors, like HK

a + p -> p + gamma

Events in HK d=0.2 kpc

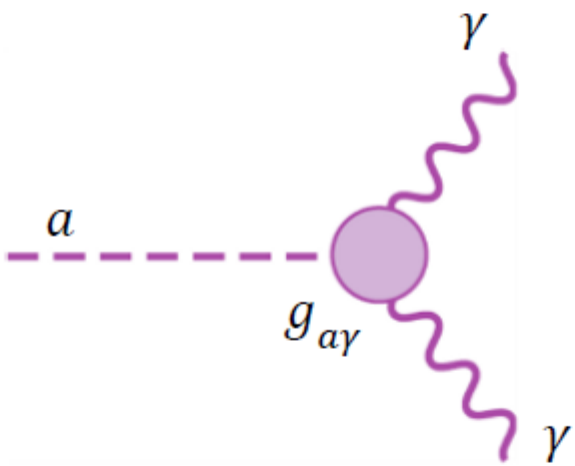




- For a close-by (d< 1 kpc) Galactic SN, the axion signal due to EDM would be clearly visible

AXION-LIKE PARTICLES (ALPs)

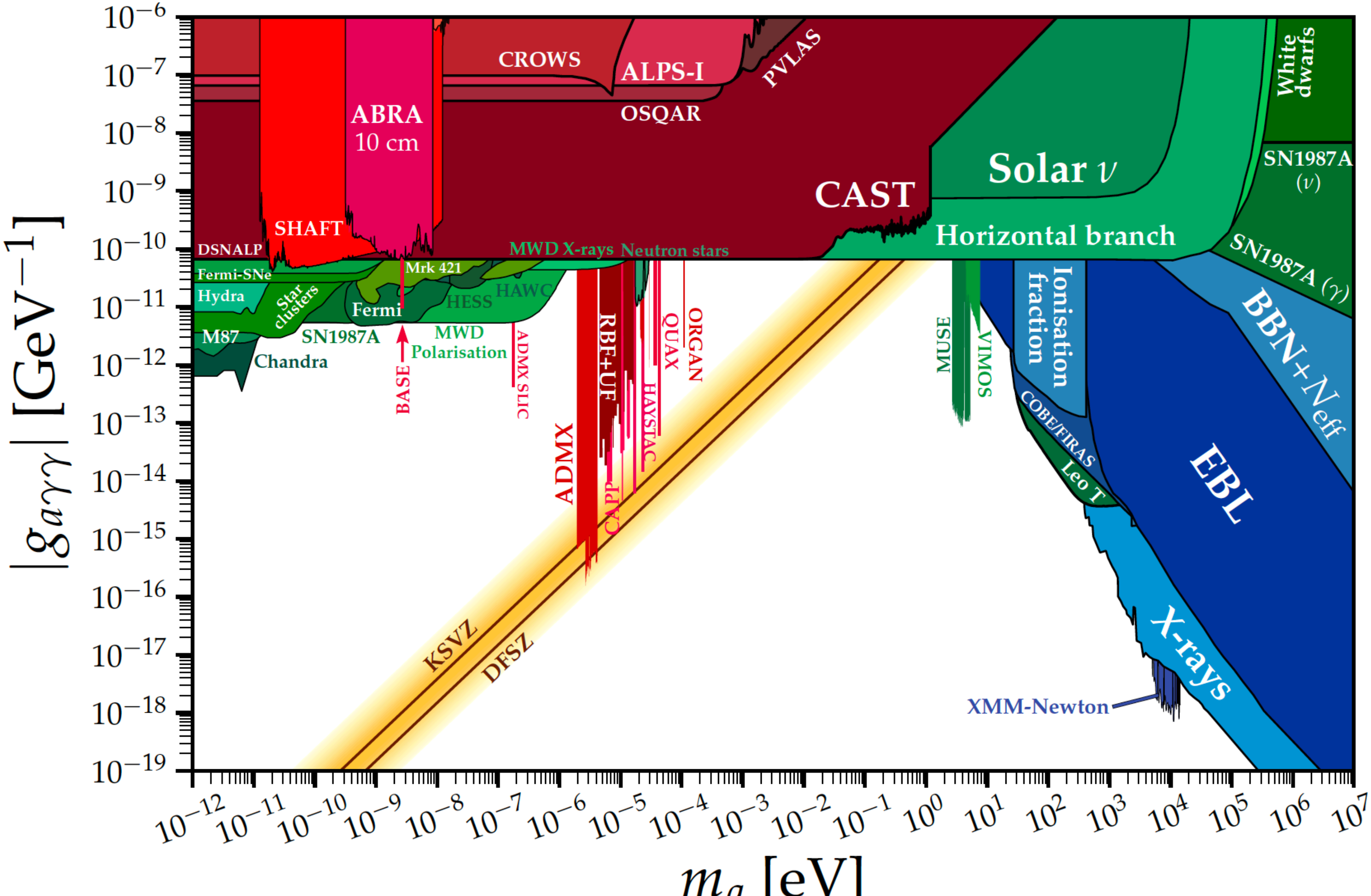
$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}_{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$



- Primakoff process: Photon-ALP transitions in external static E or B field

- Photon-ALP conversions in macroscopic B-fields

BOUNDS ON $g_{a\gamma}$ vs m_a

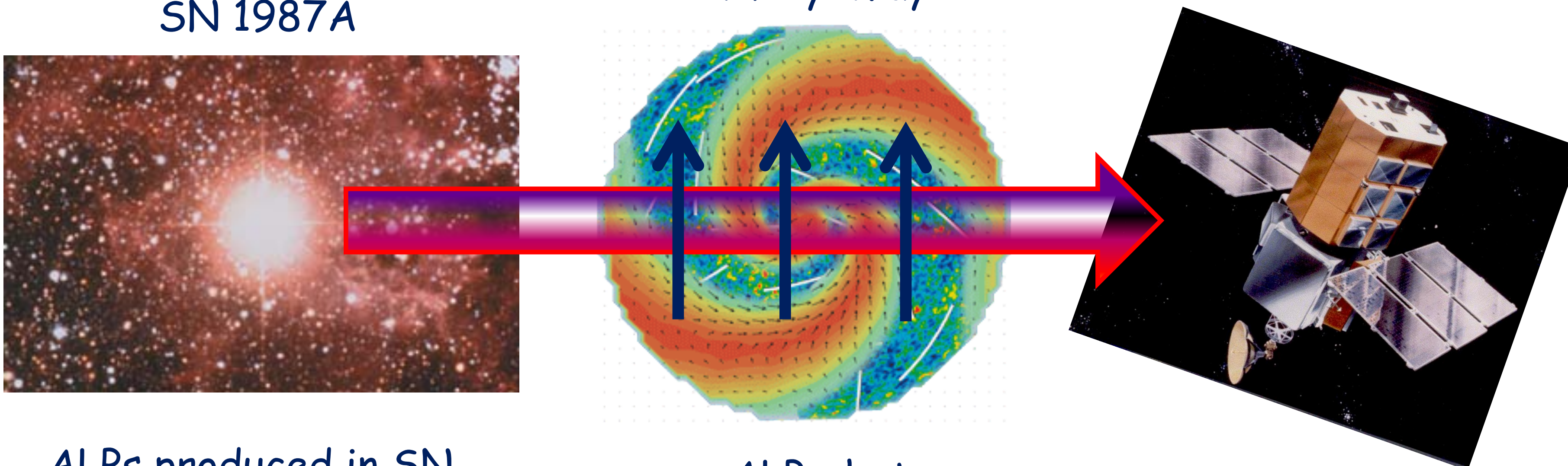


(plot by Ciaran O'Hare https://cajohare.github.io/AxionLimits/)

ALPs CONVERSIONS FOR SN 1987A

[*Brockway, Carlson, Raffelt, astro-ph/9605197, Masso and Toldra, astro-ph/9606028*]

SN 1987A | Milky-Way | SMM Satellite



ALPs produced in SN core by Primakoff process

ALP-photon conversions in the Galactic B-fields

No excess gamma-rays in coincidence with SN 1987A

In [*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*] we revaluate the bound with

- state-of-art models for SNe and Galactic B-fields
- accurate microscopic description of the SN plasma

SN 1987A gamma-ray limits on the conversion of pseudoscalars

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[b] Max-Planck Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany

Received 12 June 1996
Editor: H. Georgi

Abstract

Pseudoscalar particles ϕ usually couple electromagnetically by an interaction of the form $\frac{1}{4} g \phi F \widetilde{F}$, allowing them to convert to photons in the presence of magnetic fields. Notably, new low-mass pseudoscalars emitted from supernova (SN) 1987A would have been converted to γ-rays in the intervening magnetic field of the galaxy. Therefore, measurements by the Solar Maximum Mission (SMM) Gamma-Ray Spectrometer (GRS) can limit the inverse coupling constant to $g^{-1} > 1 \times 10^{11}$ GeV, assuming the pseudoscalar is massless. This is an improvement over other astrophysical limits of a factor of about 2.5.

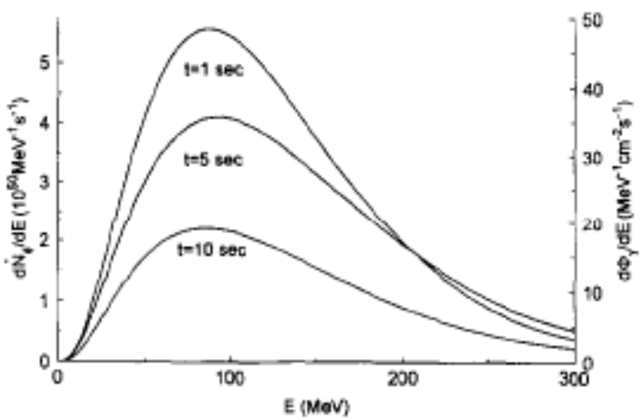
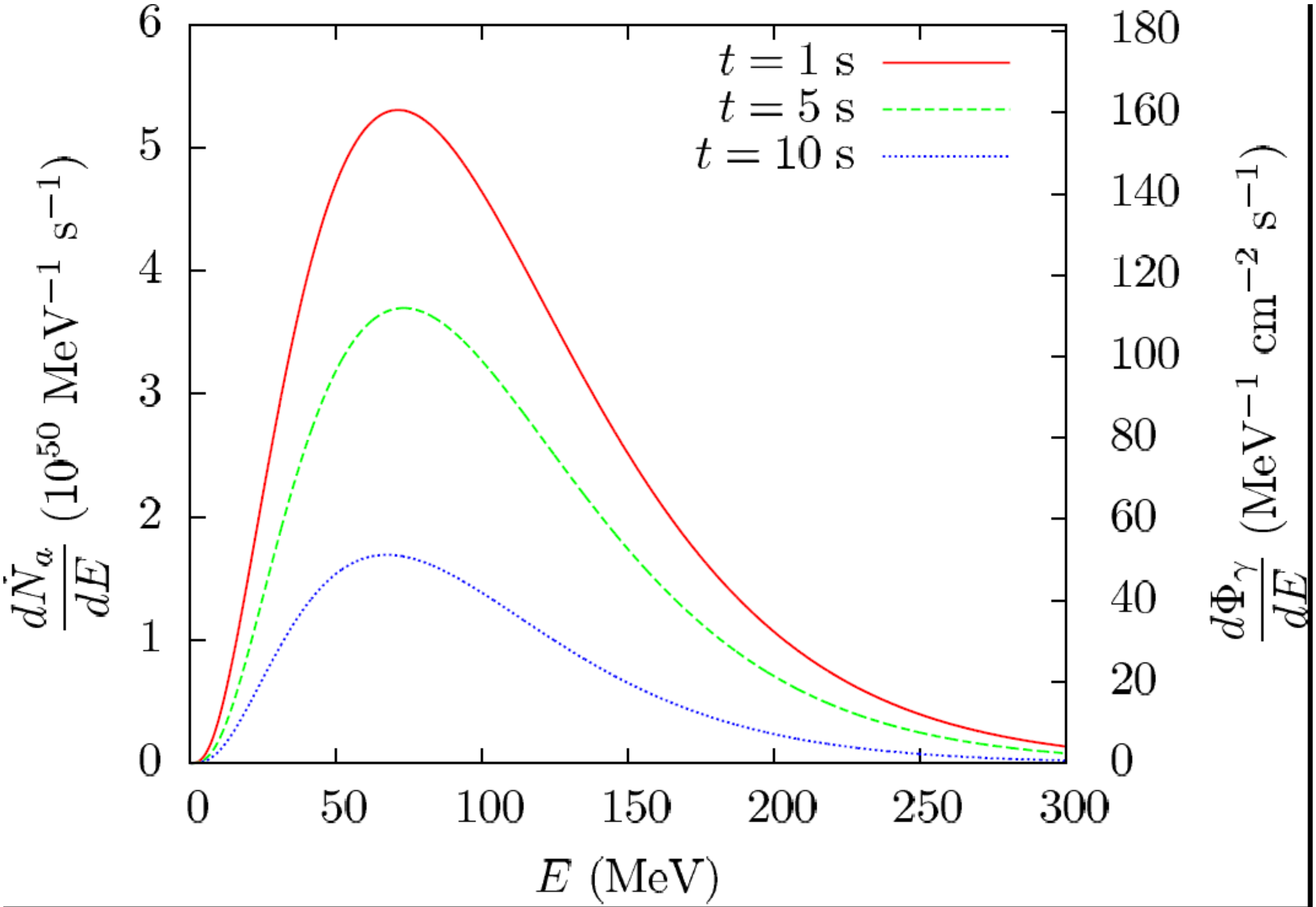


Fig. 3. The number of pseudoscalars produced (left scale) and resulting γ-ray photon flux at the Earth (right scale) for a coupling $g^{-1} = 10^{10}$ GeV for times $t = 1, 5$, and 10 seconds.

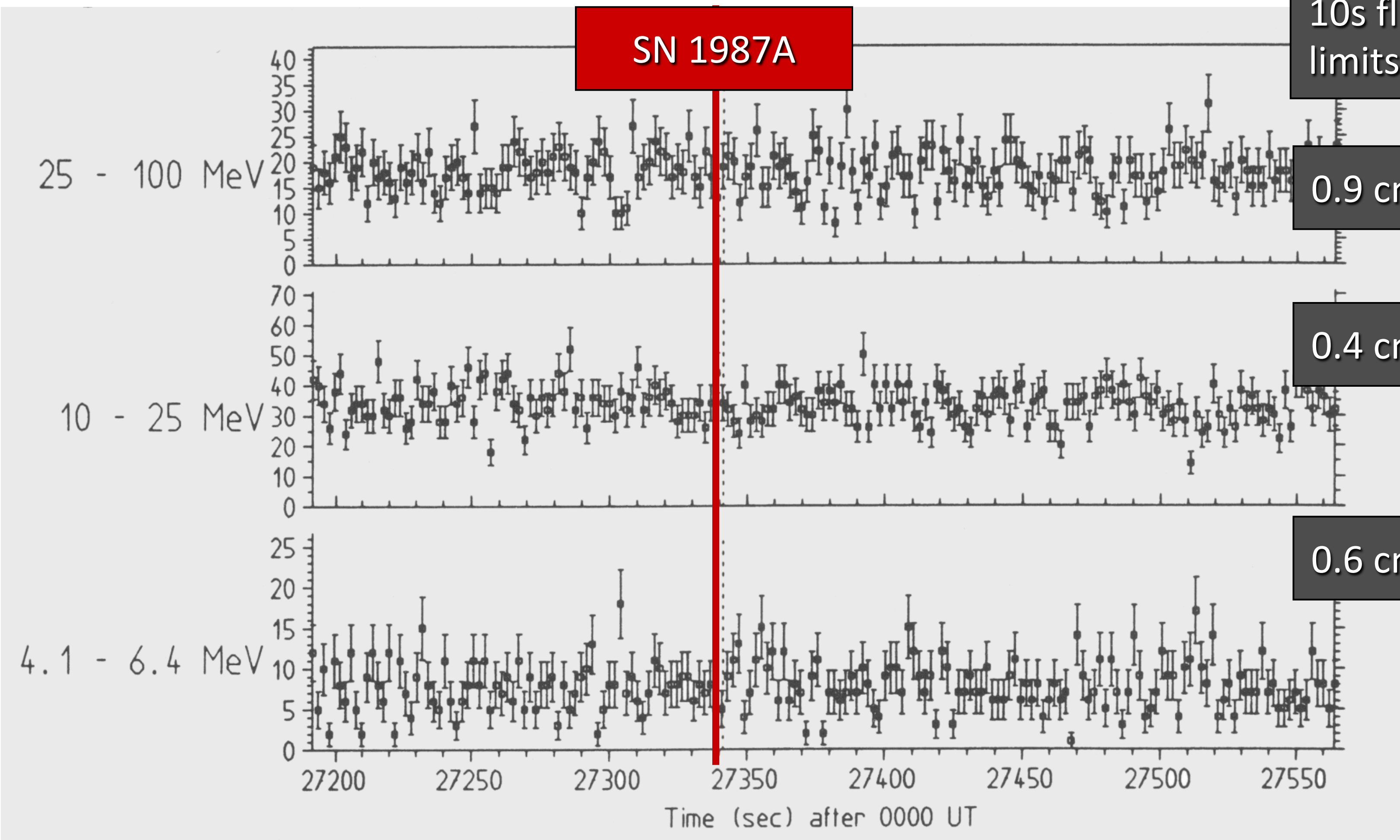
ALP-PHOTON FLUXES FOR SN 1987A

[*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*]



GAMMA-RAY OBSERVATION FROM SMM SATELLITE

Counts in the GRS instrument on the Solar Maximum Mission Satellite



10s fluence limits

$0.9\ cm^{-2}$

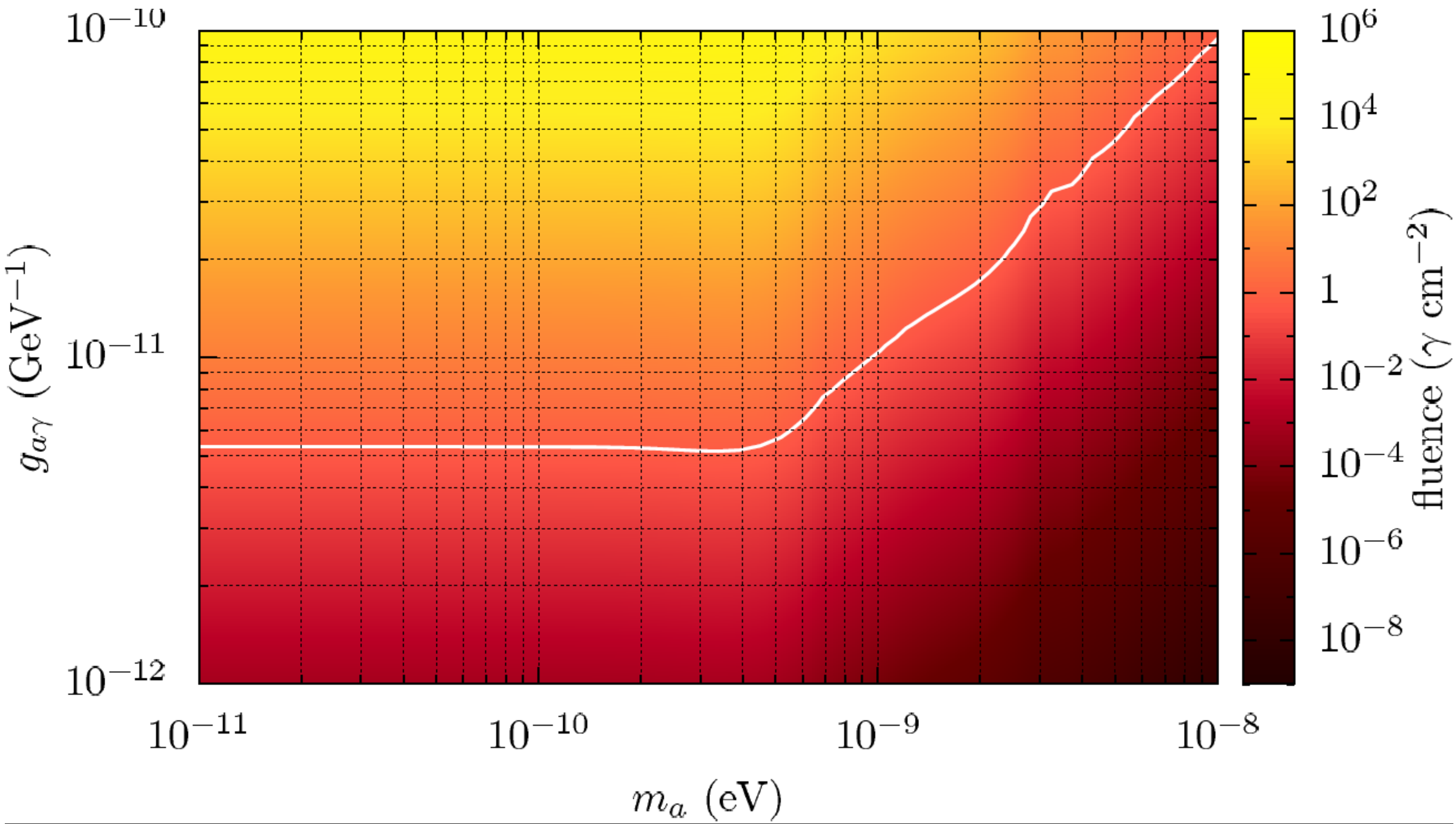
$0.4\ cm^{-2}$

$0.6\ cm^{-2}$

$$F(g_{a\gamma}) = 7.02 \times 10^4 \left(\frac{g_{a\gamma}}{10^{-10} GeV^{-1}}\right)^4 \gamma cm^{-2}$$

NEW BOUND ON ALPs FROM SN 1987A

[*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*]



$$g_{a\gamma} \leq 5.3 \times 10^{-12}\ GeV^{-1} \quad \text{for} \quad m_a < 4.4 \times 10^{-10}\text{eV}$$

SN 1987A provides the strongest bound on ALP-photon coversions for ultralight ALPs

Oskar Klein centre

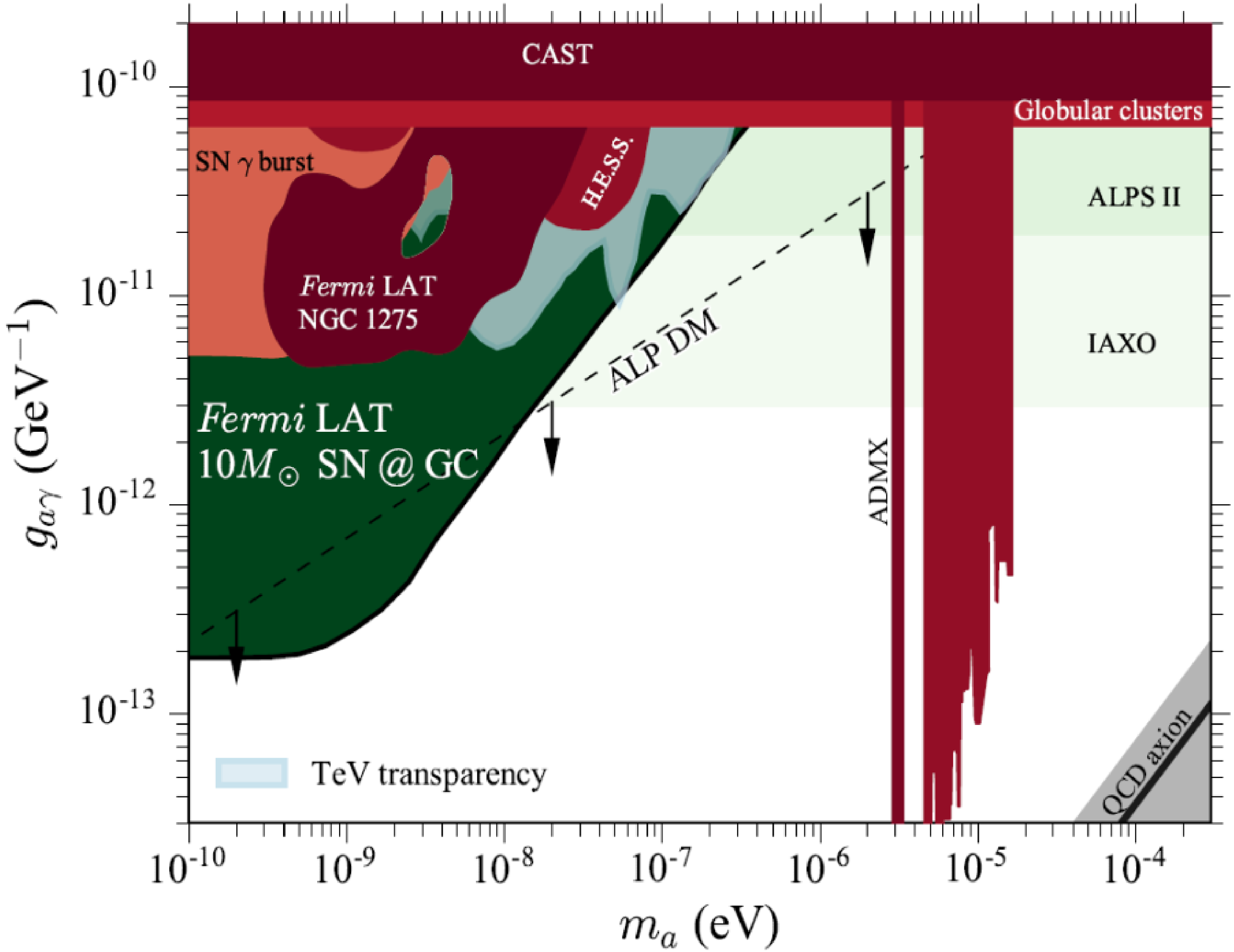
Stockholm University

Fermi Gamma-ray Space Telescope

SENSITIVITY OF THE FERMI LAT TO THE DETECTION OF A SN GAMMA-RAY BURST DUE TO AXIONLIKE PARTICLES

Alessandro Mirizzi, Manuel Meyer, Maurizio Giannotti, Jan Conrad, Miguel Sanchez-Conde

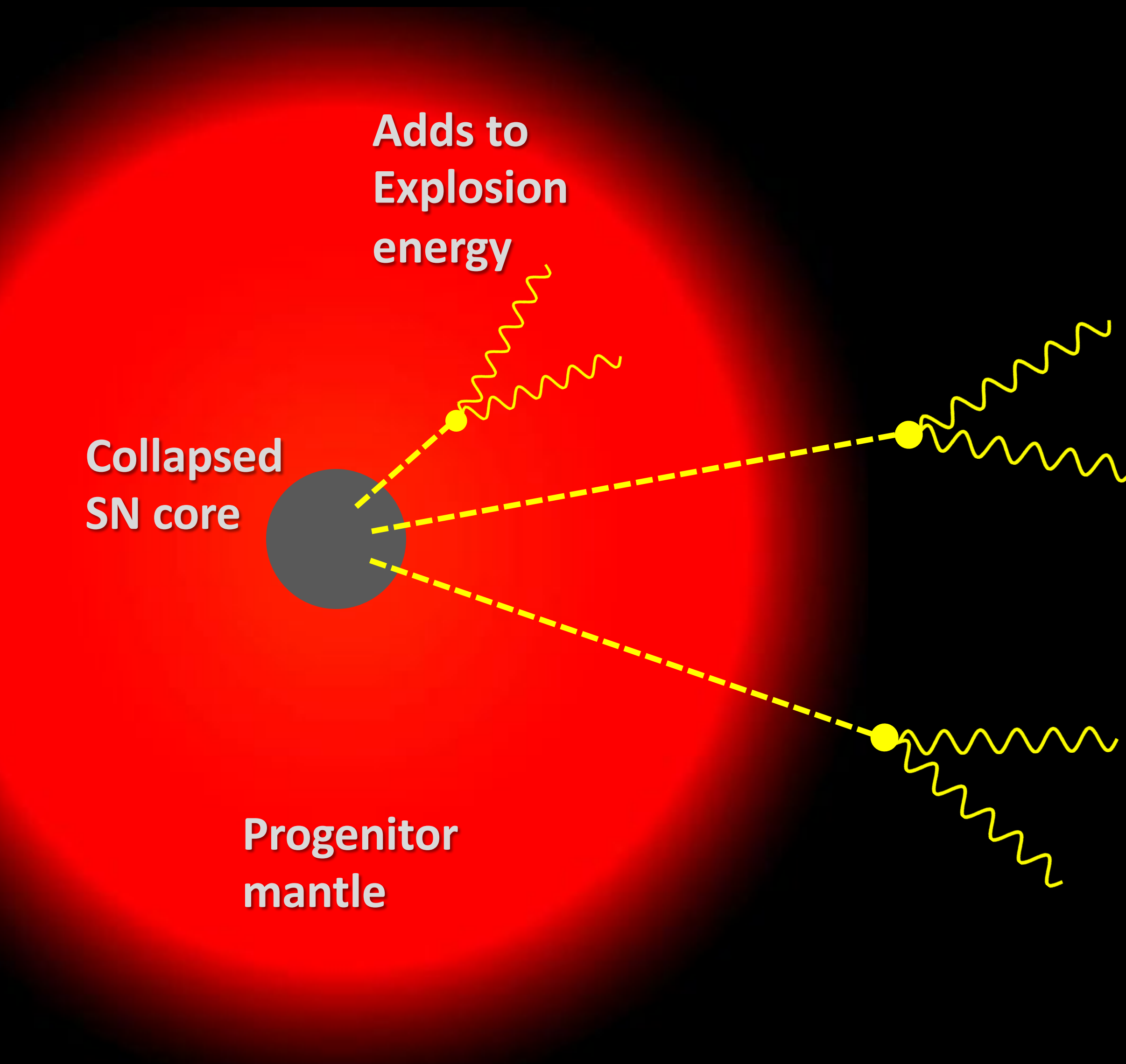
PRL 118 (2017) 1, 011103, arXiv: 1609.02350

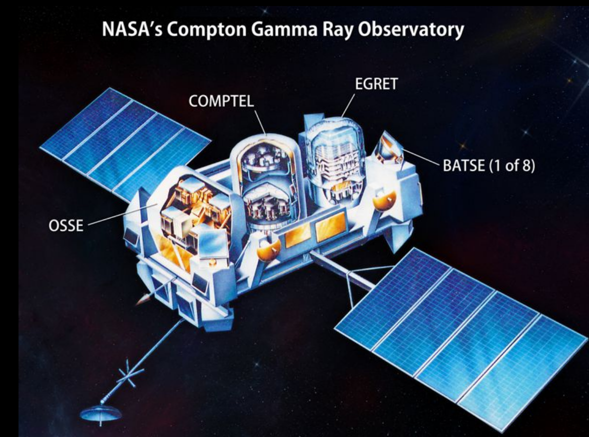


A Galactic SN explosion in the field of view of FERMI-LAT would allow us to improve the SN 1987A bound by more than one order of magnitude ...

or even detect DM ALPs !

Supernova Bounds on Radiative Particle Decays





Cosmic gamma ray
background
from all past supernovae

Solar Maximum Mission

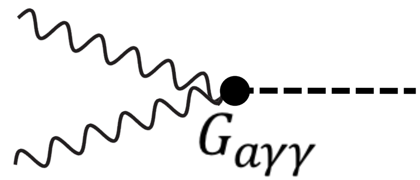
No excess gamma rays
@ SN 1987A neutrino burst

Low-Energy Supernovae Severely Constrain Radiative Particle Decays

Andrea Caputo[1,2] Hans-Thomas Janka[3] Georg Raffelt[4] and Edoardo Vitagliano[5]

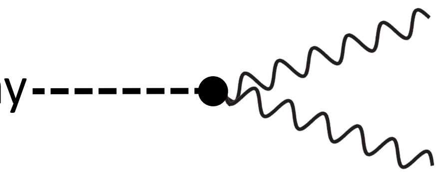
arXiv:2201.09890 (24 Jan 2022)

Brand New



Production of axion-like particles

ALP decay

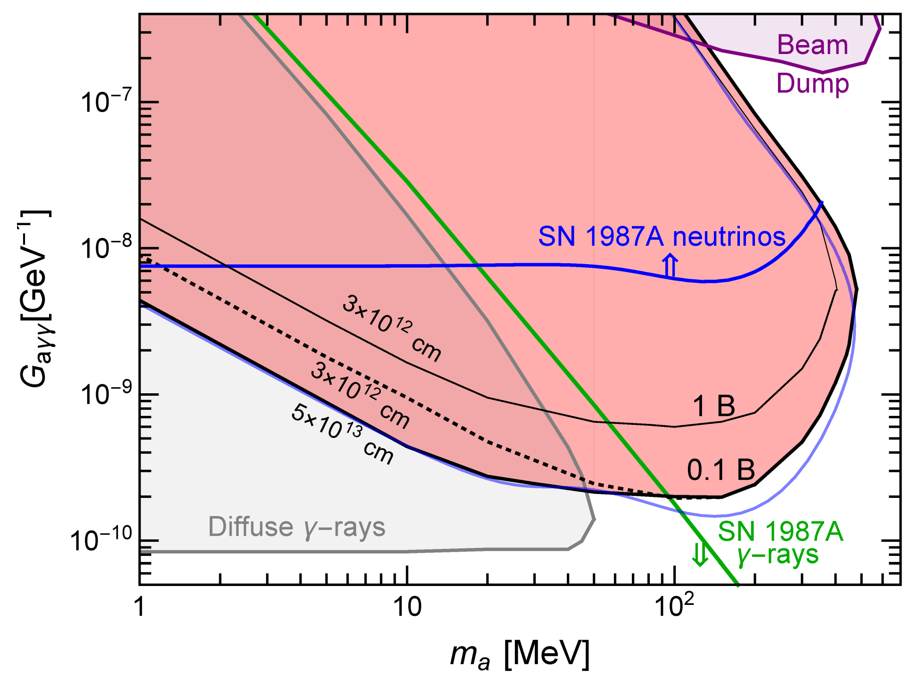


Typical SN explosion energy 1–2 B

Some SNe have very small observed explosion energies < 0.1 B
(e.g. subluminous type II-P SNe)

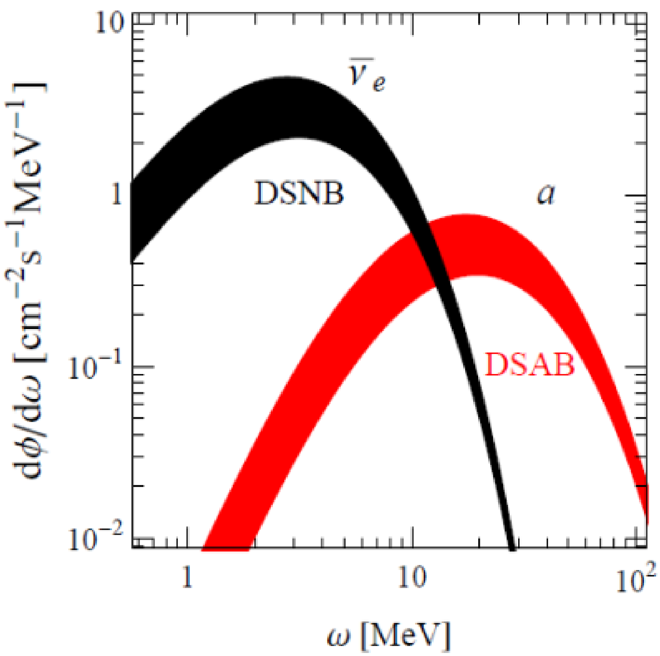
Restrictive limits on energy deposition in progenitor star by particle decays!

1 B (bethe) = 10^{51} erg
Neutron-star binding energy 200–400 B
(0.11–0.22 M_{SUN})



DIFFUSE SUPERNOVA AXION BACKGROUND

[Raffelt, Redondo & Viaux, arXiV:1110.6397]



- Axions with $m_a \sim 10$ meV near SN 1987A energy loss limit
- Provide DSAB flux comparable to the ν one.

Photon-axion conversions in the Galactic B-field

$P_{a\to\gamma} = (g_{a\gamma} B/q)^2 sin^2(qL/2)$ → $P_{a\to\gamma} = 6\times10^{-34}(B/\mu G)^2$

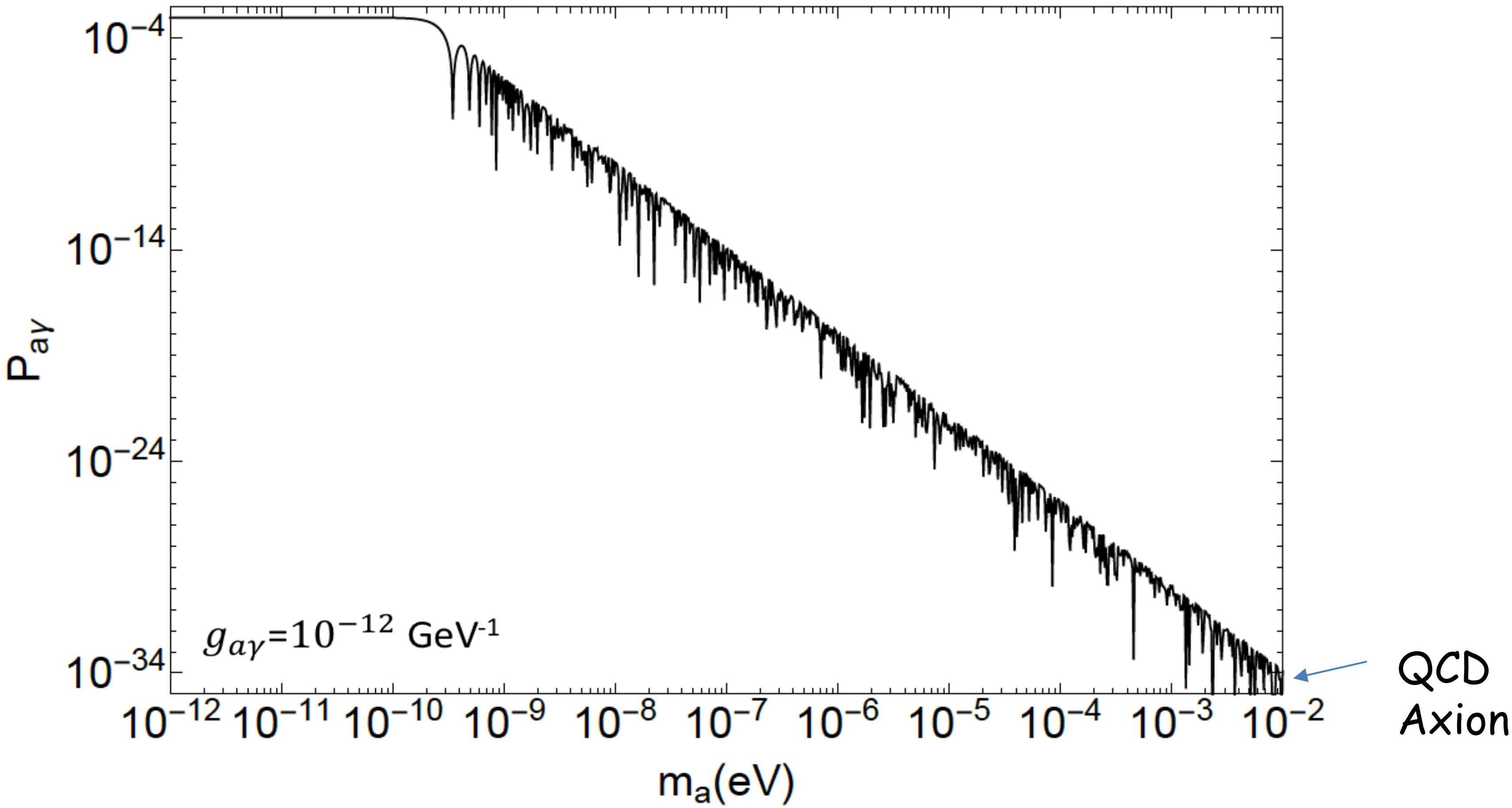
too small for QCD axions !

$$q = \frac{m_a^2 - m_\gamma^2}{2E}$$

L_{GAL}=25 kpc

$$\lambda = \frac{4\pi E}{m_a^2} \sim 1500km \ll L_{GAL}$$

ALP-PHOTON CONVERSION PROBABILITY



For ultralight ALPs $m_a \ll 10^{-10}$ eV, the $P_{a\gamma}$ becomes seizable

DSALPB SIGNAL

The DSALPB event rate spectrum, in units $cm^{-2}\ s^{-1}\ MeV^{-1}$, is

$$\frac{d\phi_a(E_a)}{dE_a} = \int [R_{SN}(z)][(1+z)\frac{dN_a(E_a(1+z))}{dE_a}]\left[\left|\frac{cdt}{dz}\right| dz\right]$$

comoving cosmic core-collapse rate, in units $Mpc^{-3}\ yr^{-1}$

average time-integrated emission per supernova, in units MeV^{-1}; redshift reduces emitted energies and compresses spectra

Differential distance

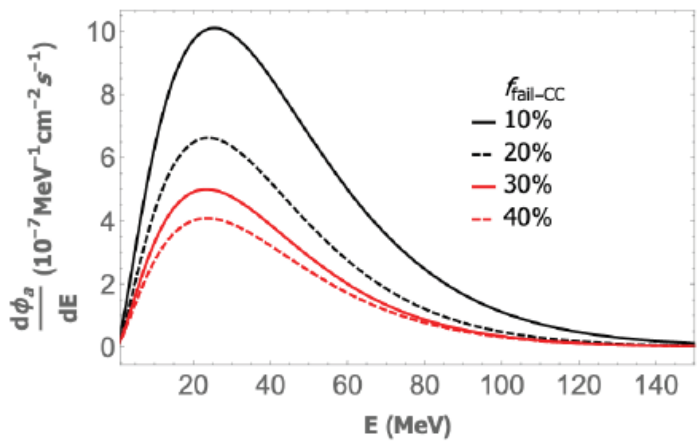
$$\left|\frac{dt}{dz}\right|^{-1} = H_0(1+z)\left[\Omega_\Lambda + \Omega_m(1+z)^3\right]^{1/2}$$

$$H_0 = 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

$$\Omega_m = 0.3\,, \Omega_\Lambda = 0.7$$

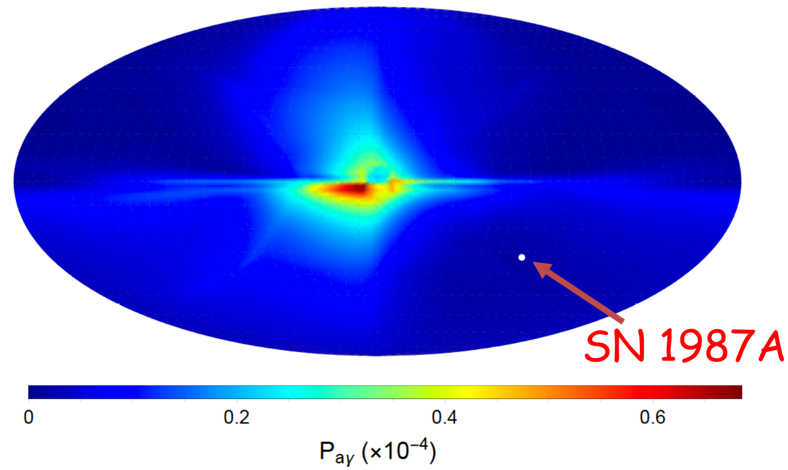
DSNALPB GAMMA-RAY FLUX

DSNALPB flux

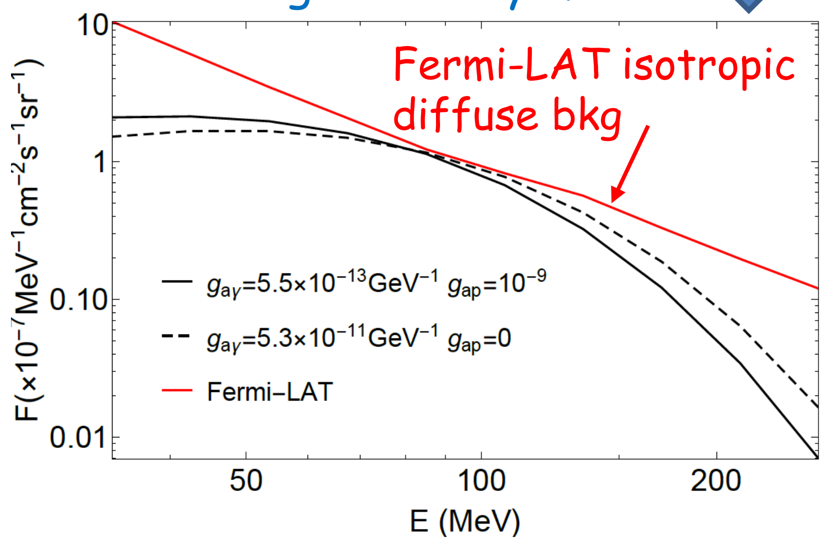


Conversions in Galactic B-field

Jansson-Farrar model [1204.3662[astro-ph]]



gamma-ray flux

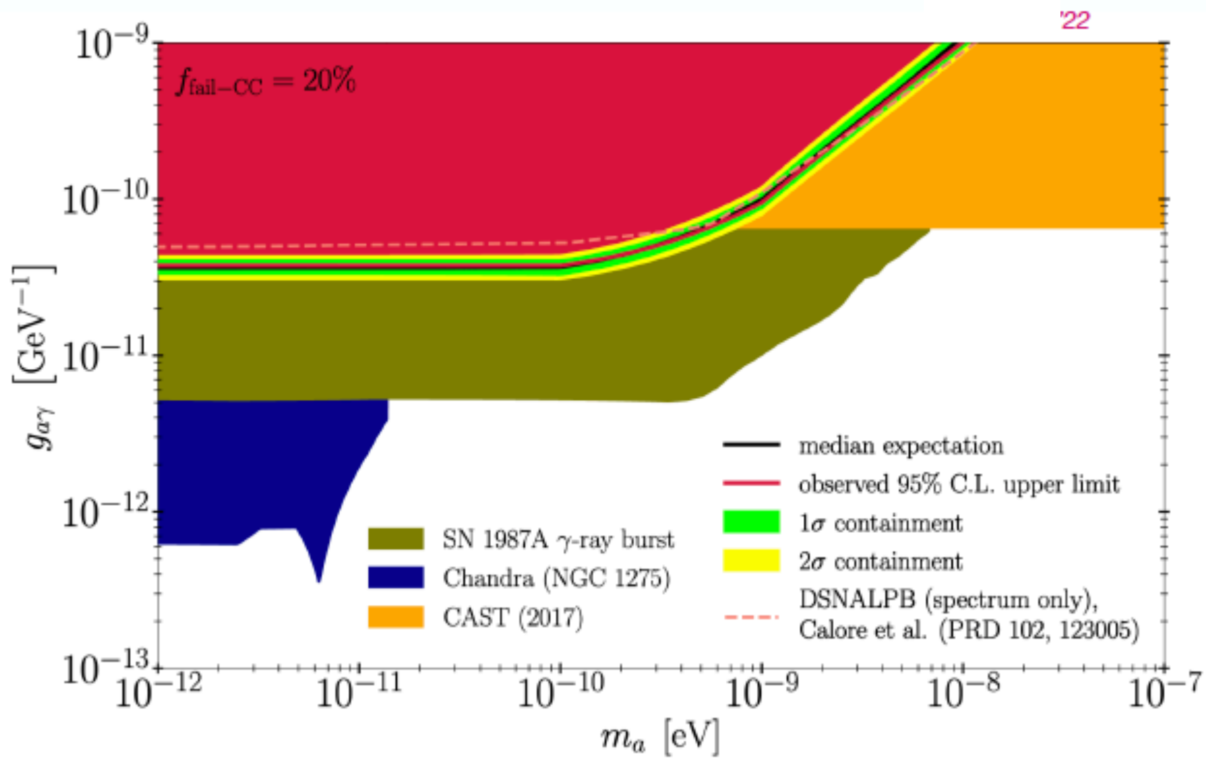


[*Calore, Carenza, Giannotti, Jaeckel, A.M., 2008.11741*]

DSALPB GAMMA-RAY CONSTRAINT

[Eckner, *Calore, Carenza, Giannotti, Jaeckel, A.M., Sivo, 2110.03679*]

Dedicated **template-based analysis** of 12yr Fermi-LAT data



$$g_{a\gamma} \lesssim 3.7 \times 10^{-11}\,\mathrm{GeV}^{-1}\,,\ 95\%\ \mathrm{CL}$$

$$m_a \ll 10^{-11}\,\mathrm{eV}$$

source of uncertainty	relative [%]
$f_{\rm fail-CC}$	51.1
IMF	7.2
SNR	10.4
IEM	13.8
GMF model	38.8
total	124

CONCLUSIONS

Core-collapse SNe represent powerful laboratories to constrain axions and ALPs

- Recent works provided reliable calculations of the NN axion emissivity including relevant corrections beyond OPE
- Pionic processes might strongly enhance axion emissivity
- It is mandatory to include self-consistently these processes in a SN simulation to determine the feed-back on the neutrino signal
- In case of ultra-light ALPs a large gamma-ray might be observed in Fermi-LAT from a Galactic explosion

A Galactic SN is a lifetime opportunity for axions !

COSMIC WISPERS

CA21106

Apply to join the WGs on the Action webpage

https://www.cost.eu/actions/CA21106/