Particle and Astroparticle Theory Seminar
MPIK, Heidelberg, 8 February 2021

SUPERNOVAE AS COSMIC LABORATORIES FOR AXIONS

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OUTLINE

- Introduction on axions
- 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

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THE STRONG CP PROBLEM

The QCD Lagrangian includes a term which violates CP (and T)

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G \cdot \tilde{G}$$

where $\theta = \theta_{QCD} + \arg \det M_q$

⟹ Prediction of an electric dipole moment for the neutron:

$$|d_n| \approx |\theta| (0.04 - 2.0) \times 10^{-15} e \text{ cm}$$

Present experimental limit : $| d_n | < 2.9 \times 10^{-26} \text{ e cm}$

[Baker et al., hep-ex/0602020]

⟹ $| \theta | < 10^{-10}$ Why so small ?

THE PECCEI-QUINN MECHANISM

[Peccei & Quinn 1977, Wilczek 1978, Weinberg 1978]

- **PQ Symmetry**

Introduce a symmetry that results in a term which **dynamically minimize** θ.

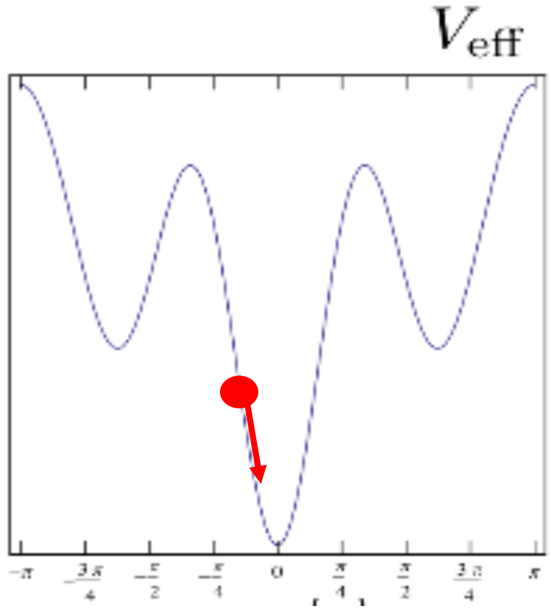
Introduction of a new global $U(1)_{PQ}$ simmetry, spontaneously broken at a scale f_a .

Existence of a massless pseudoscalar field a(x), the axion, interacting with the gluon field.

Re-interpret θ as a dynamical variable: $\theta \to \frac{a(x)}{f_a}$

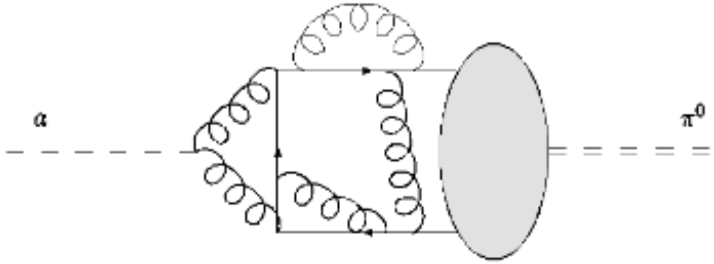
$$\mathrm{L}_\theta \to \mathrm{L}_a = \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{\alpha_s}{8\pi f_a} a\, G \cdot G$$

At low energy (Λ_{QCD}) the *gga* vertex generates the potential *V(a)* which has its minimun at a_0=0, restoring dynamically CP-simmetry.



Potential (mass term) induced by L_a drives a(x) to CP-conserving minimum

CP-symmetry dynamically restored

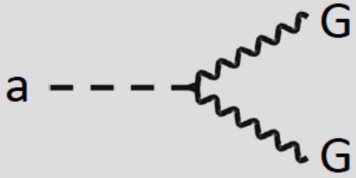
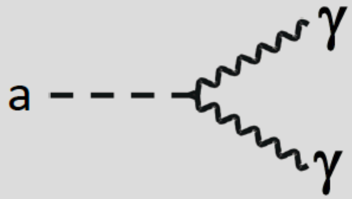
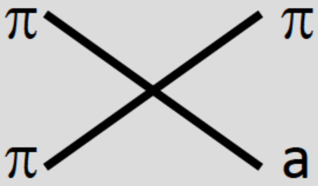
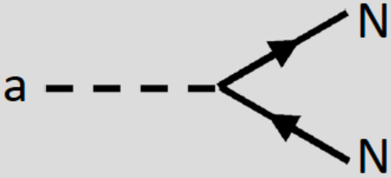
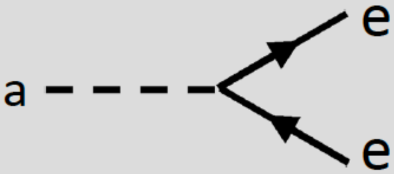


Axions generically couple to gluons and mix with π^0

⟹ Axions pick up a small mass

$$m_a \approx \frac{z^{1/2}}{1+z}\frac{f_\pi m_\pi}{f_a} = \frac{6.0\ eV}{f_a/10^6\ GeV}$$

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	$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}(\pi^0\pi^+\partial_\mu\pi^- + \cdots)\partial^\mu a$ 
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)	$\mathcal{L}_{ae} = \frac{C_e}{2f_a}\overline{\Psi}_e\gamma^\mu\gamma_5\Psi_e\partial_\mu a$ 

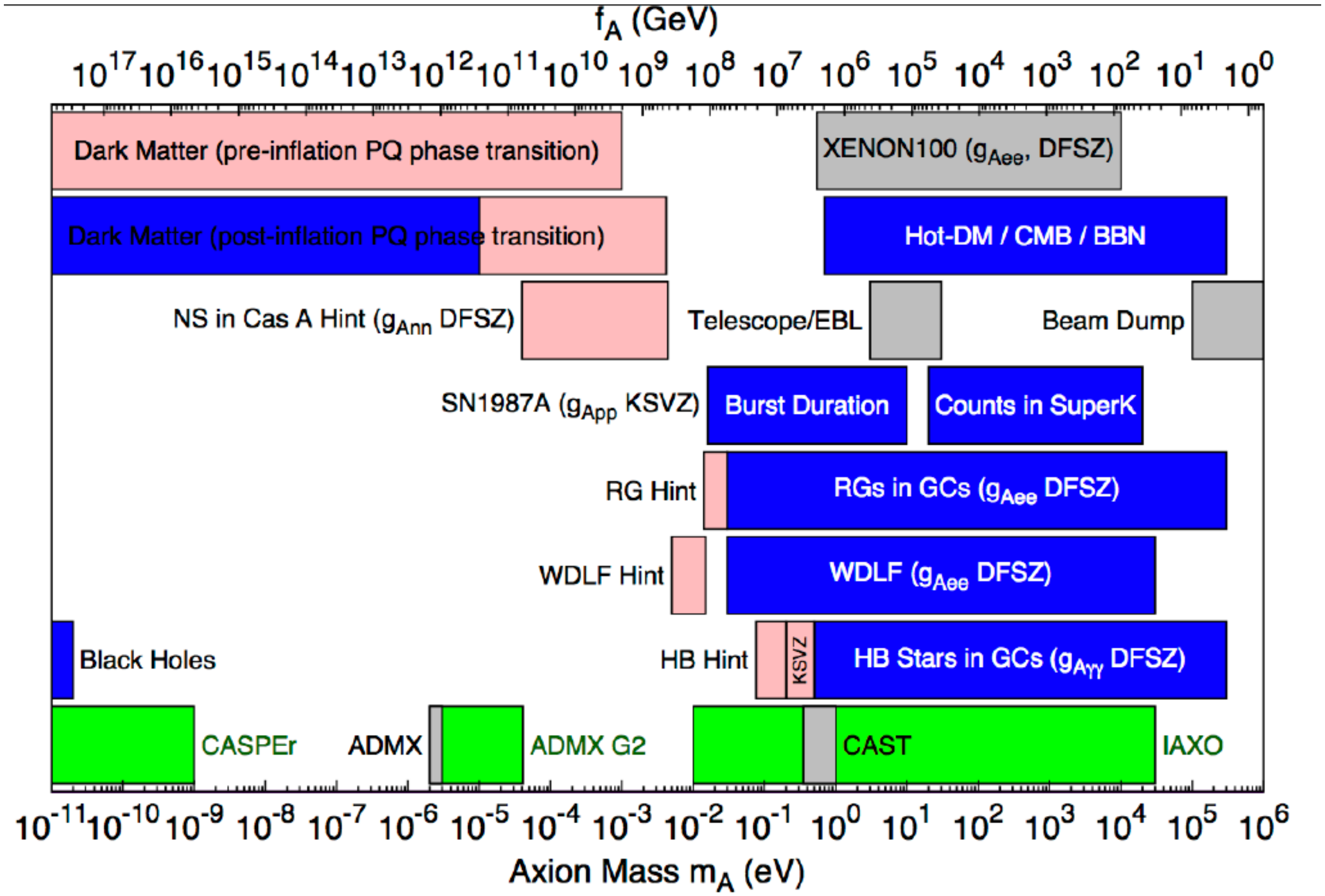
MAIN AXION MODELS

[see Di Luzio, Giannotti, Nardi & Visinelli, Phys. Rept. 870, 1-117 (2020), 2003.0110 [hep-ph]]

- 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 BOUNDS



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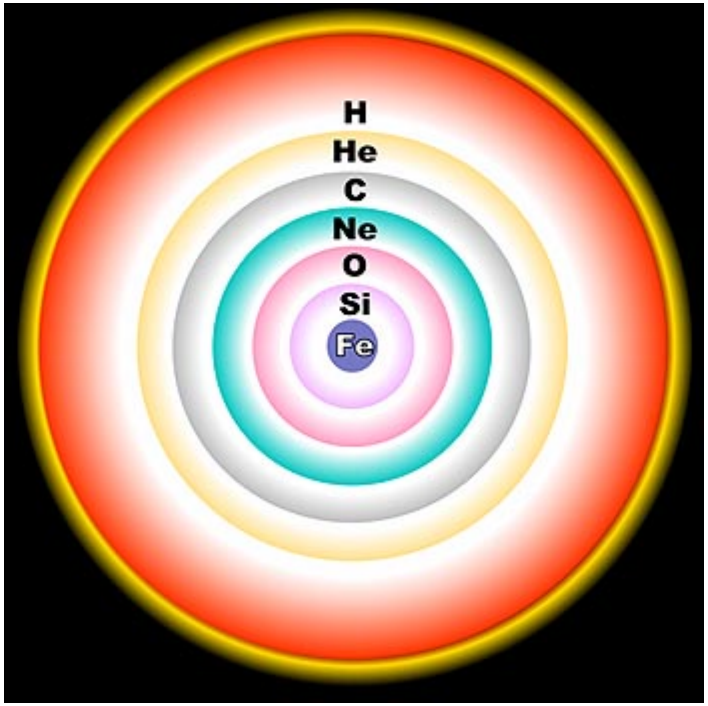
SUPERNOVAE

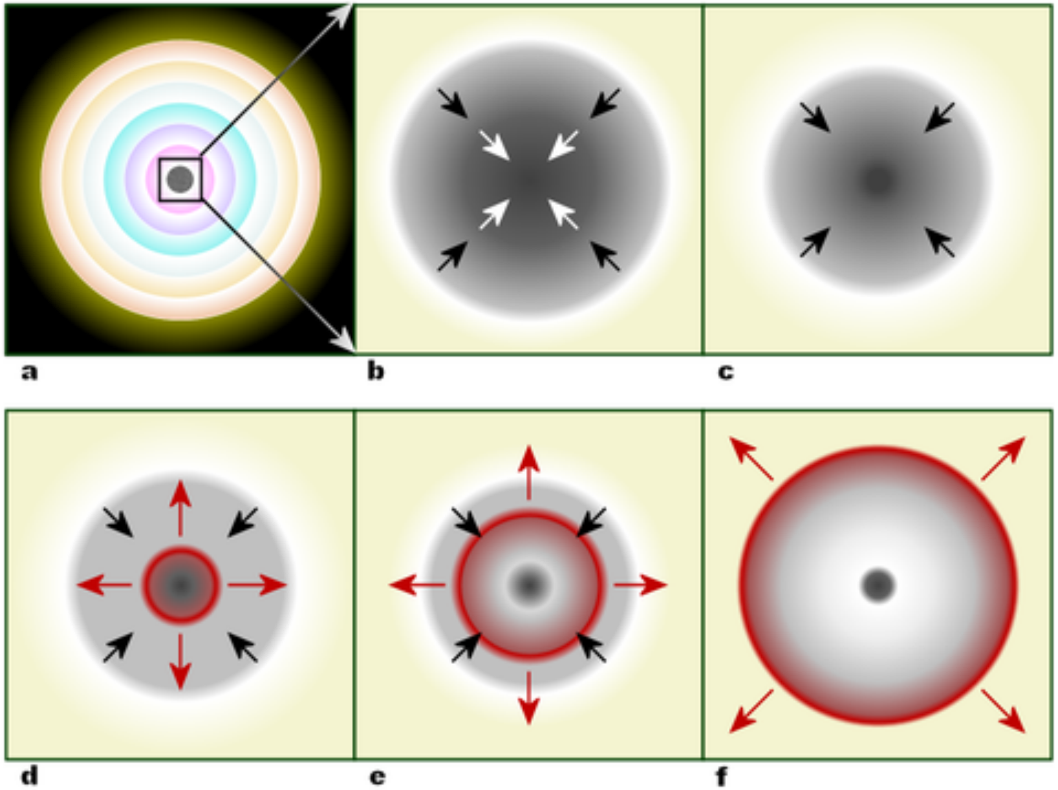
Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\ M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **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).

LIFE AND DEATH OF A MASSIVE STAR

Onion-like layers of a massive, evolved star just before core collapse.





Collapse

Nuclear density

Core-bounce & shock wave

shock-wave stalling

Shock revival

THREE PHASES OF NEUTRINO EMISSION

[Figure adapted from *Fischer et al. (Basel group), arXiv: 0908.1871*]

10. 8 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)

Neutronization burst

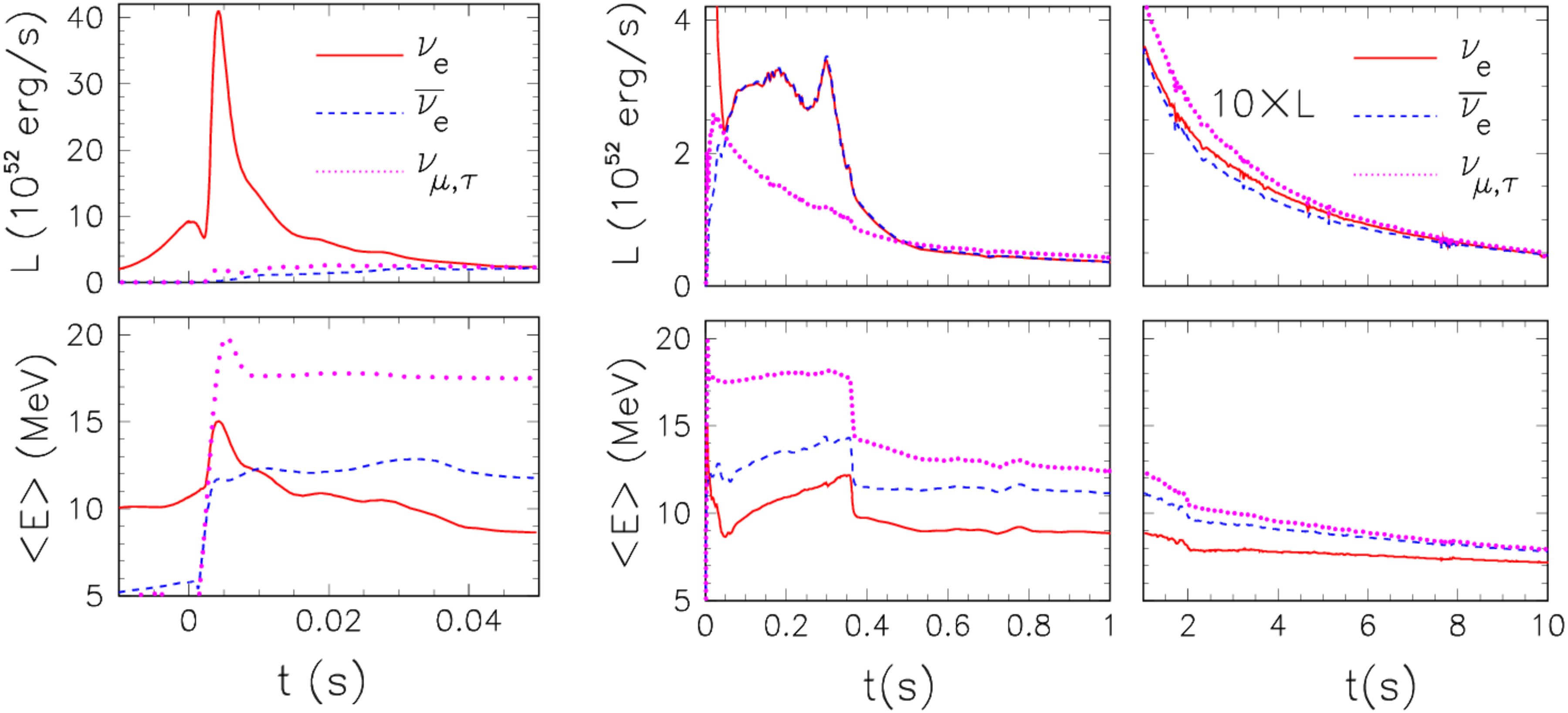
- Shock breakout
- De-leptonization of outer core layers

Accretion

- Shock stalls ~ 150 km
- ν powered by infalling matter

Cooling

- Cooling on ν diffusion time scale



Sanduleak −69 202

Supernova 1987A

23 February 1987

Neutrino Burst Observation :
First verification of stellar evolution mechanism

MARCH 23, 1987

No. 12

TIME

ISRAEL

The Spy Case Furor

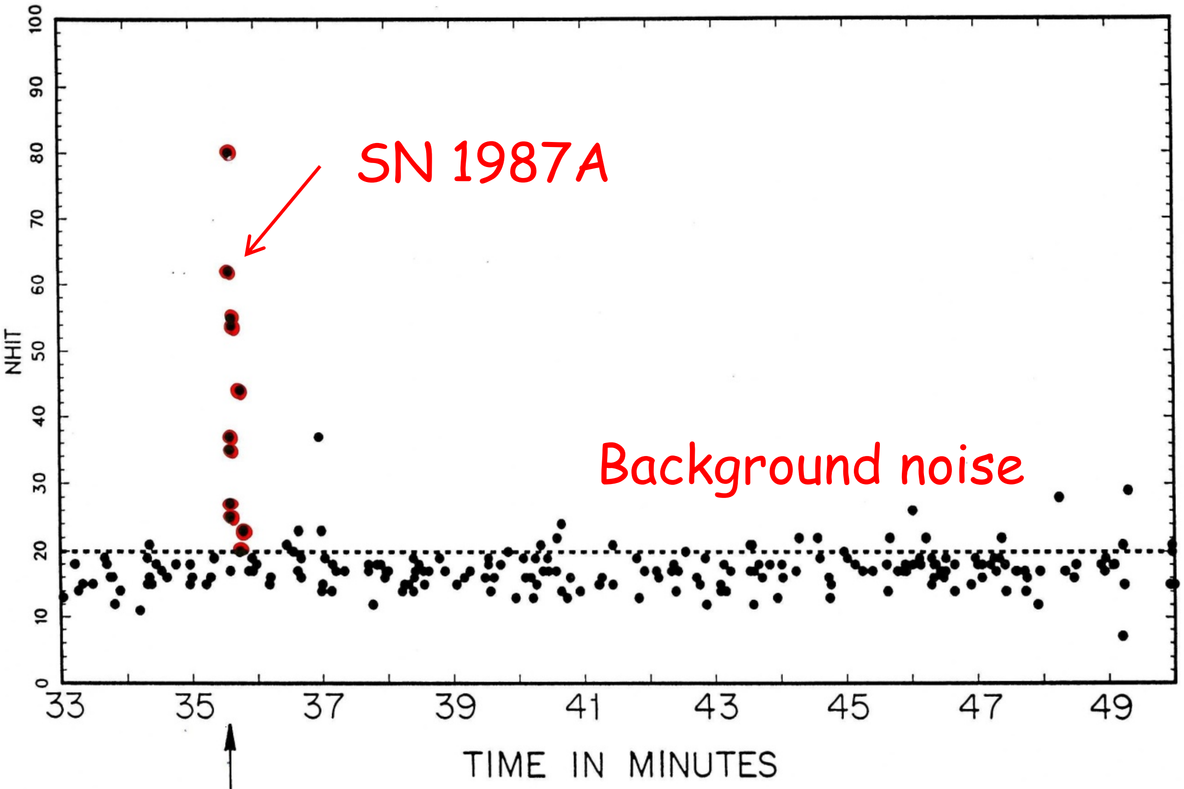
BANG!

A Star Explodes, Providing New Clues
To the Nature of the Universe

OPEN

Neutrino Astronomy

NEUTRINO SIGNAL OF SN 1987A IN KAMIOKANDE

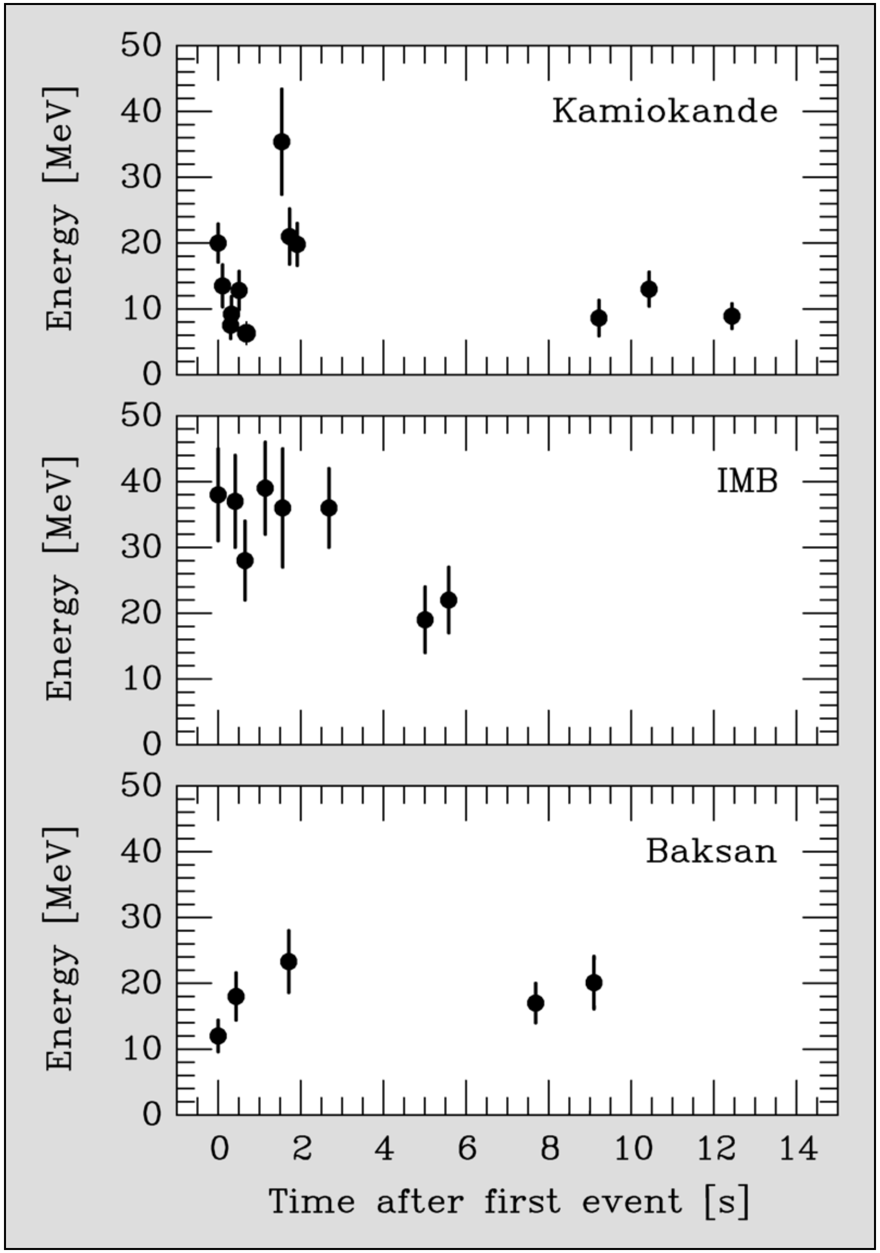


SN 1987A

Background noise

7:35:35 (UT)

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

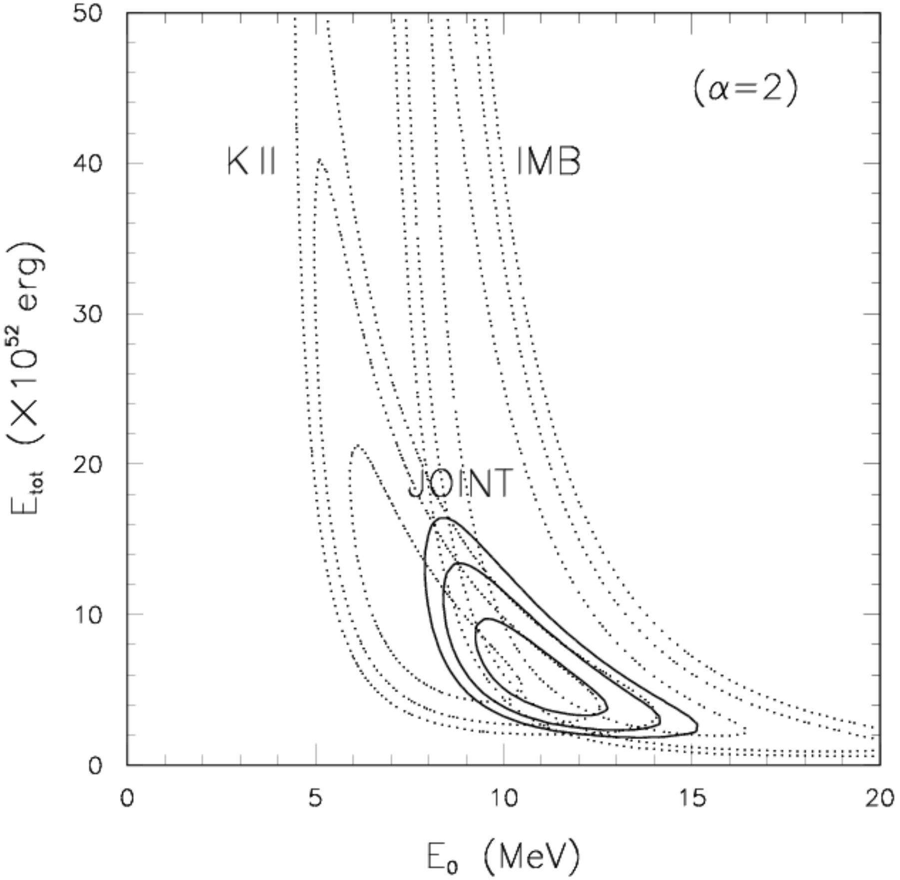
Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

INTERPRETING SN 1987A NEUTRINOS

[e.g.,B. Jegerlehner, F. Neubig and G. Raffelt, PRD **54**, 1194 (1996); A.M., and G. Raffelt, PRD **72**, 063001 (2005)]

Total binding energy



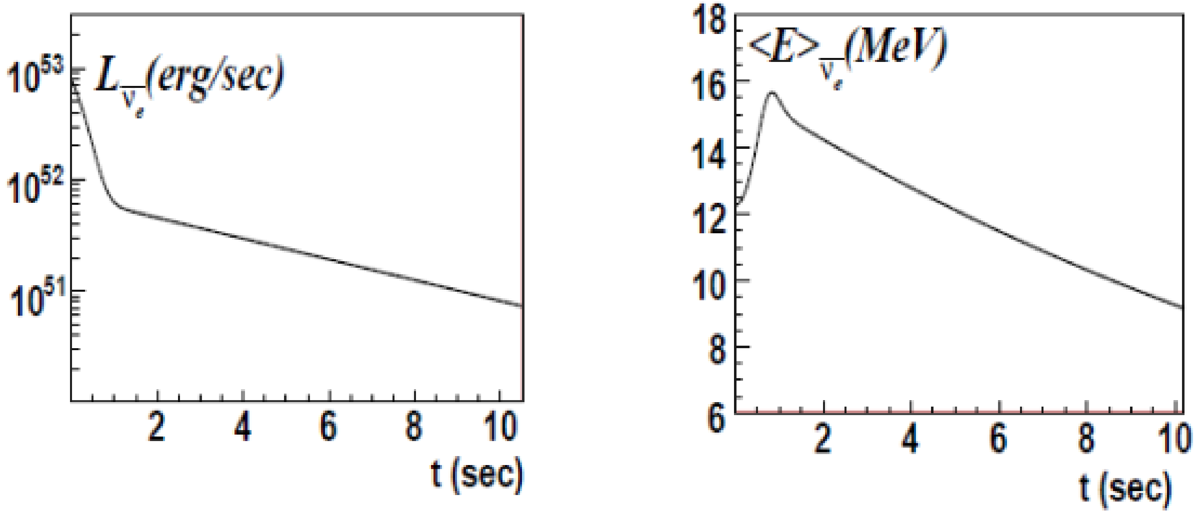
Average $\overline{\nu}_e$ energy

In agreement with the most recent theoretical predictions (i.e. Basel & Garching models)

SN NEUTRINO LIGHT CURVE FROM SN 1987A

[Loredo & Lamb, astro-ph/0107260 ; Pagliaroli, Vissani, Costantini & Ianni,arXiV:0810.0466]

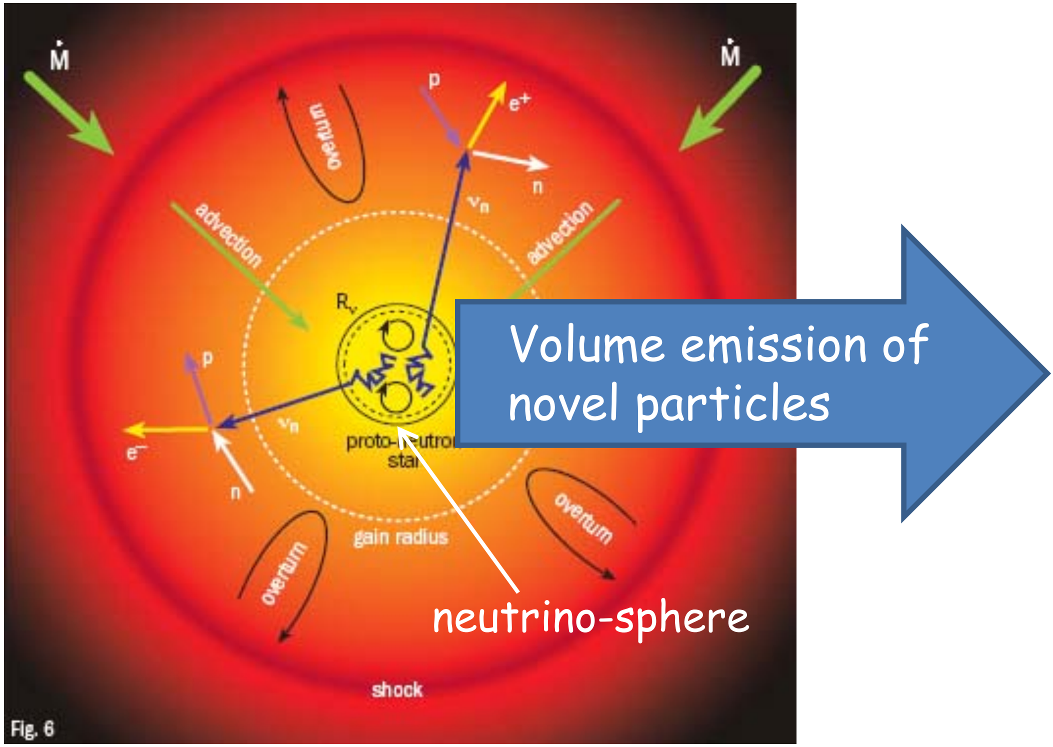
Figure 6: *Pagliaroli et al. model: antineutrino luminosity and average energy in the best fit point.*



$$R_c = 16 \text{ km}, \quad T_c = 4.6 \text{ MeV}, \quad \tau_c = 4.7 \text{ s}, \quad \text{cooling}$$
$$M_a = 0.2\ M_\odot, \quad T_a = 2.4 \text{ MeV}, \quad \tau_a = 0.6 \text{ s}. \quad \text{accretion}$$

Light curve in reasonable agreement with generic expectations of delayed explosion scenario

ENERGY-LOSS ARGUMENT



Volume emission of novel particles

neutrino-sphere

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

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

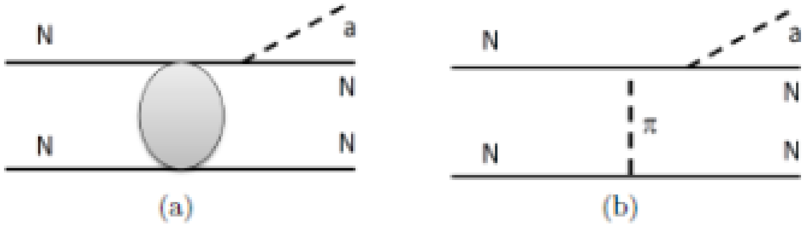
$$\varepsilon_x < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

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

AXION EMISSION FROM A NUCLEAR MEDIUM

$$NN \to NNa$$

nucleon-nucleon bremsstrahlung



Bulk nuclear interaction One pion exchange

$$\boxed{L_{aN} = \frac{g_{aN}}{2m_N} \bar{N}\gamma_\mu\gamma_5 N\partial^\mu a}$$

$$g_{aN} = C_N \frac{m}{f_a}$$

Non-degenerate energy-loss rate $\varepsilon_a = g_{aN}^2 \, 2\times 10^{39} \, \mathrm{erg\,g^{-1}\,s^{-1}} \rho_{15} T_{30}^{3.5}$

$$\begin{pmatrix} T_{30} = T/30\,\mathrm{MeV} \\ \rho_{15} = \rho/10^{15}\,\mathrm{g\,cm^{-3}} \end{pmatrix}$$

$$\langle \rho_{15} \rangle \approx 0.4$$

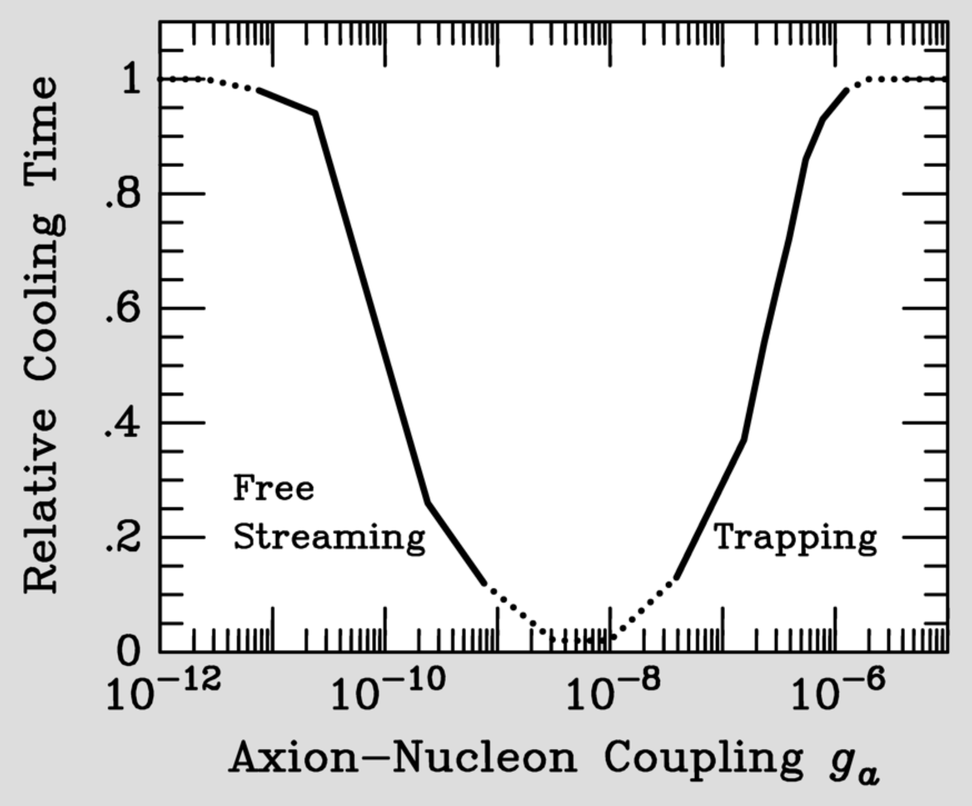
$$\langle T_{30}^{3.5} \rangle \approx 1.4$$

$$\Rightarrow \quad g_{aN} < 9\times 10^{-10}$$

SN 1987A AXION LIMITS

Free streaming
[*Burrows, Turner & Brinkmann, PRD 39:1020,1989*]

Volume emission of axions



Trapping
[*Burrows, Ressell & Turner, PRD 42:3297,1990*]

Axion diffusion from an "axion-sphere"

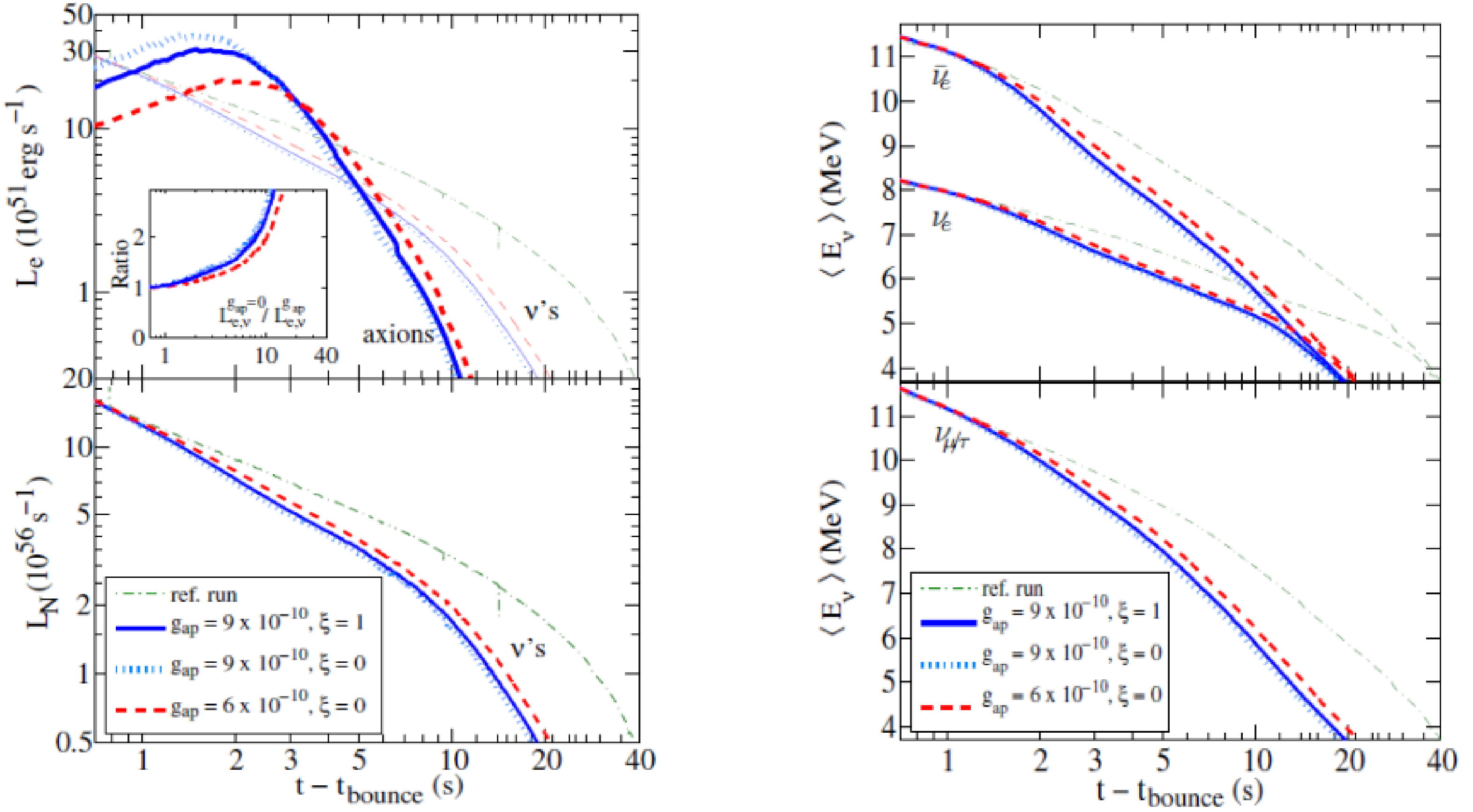
Possible detection in a water Cherenkov detector via oxygen nuclei excitation

SHORTENING OF NEUTRINO BURST

[Fischer, Chakraborty, Giannotti *A.M.* , *Payez & Ringwald, 1605.08780*]

18 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)



(a) Energy and number luminosities

(b) Average neutrino energies

KSVZ hadronic axion model (g_{an} =0)

SN 1987A AXION LIMITS FROM NU BURST DURATION

- 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)

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NEW CALCULATION OF SN AXION EMISSION RATE

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

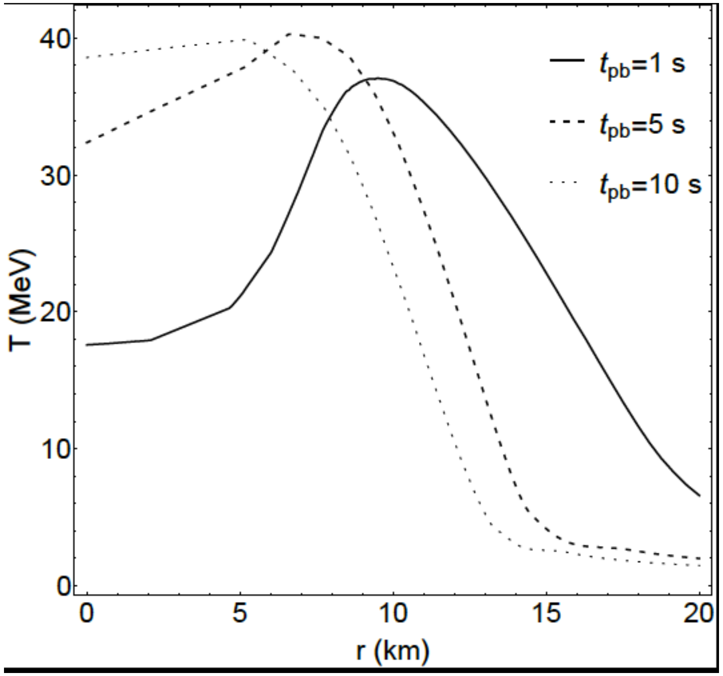
We performed an improved calculation of axion emissivity via NN process, including self-consistently different corrections on top of the naive OPE prescription

- 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]

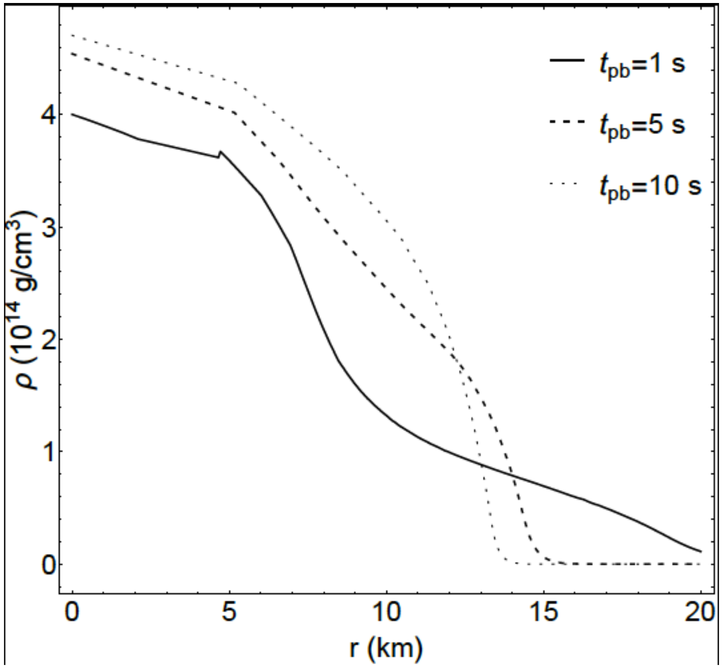
STATE OF-THE-ART SN MODEL

18 M_{sun} progenitor mass
(spherically symmetric with Boltzmnann ν transport)

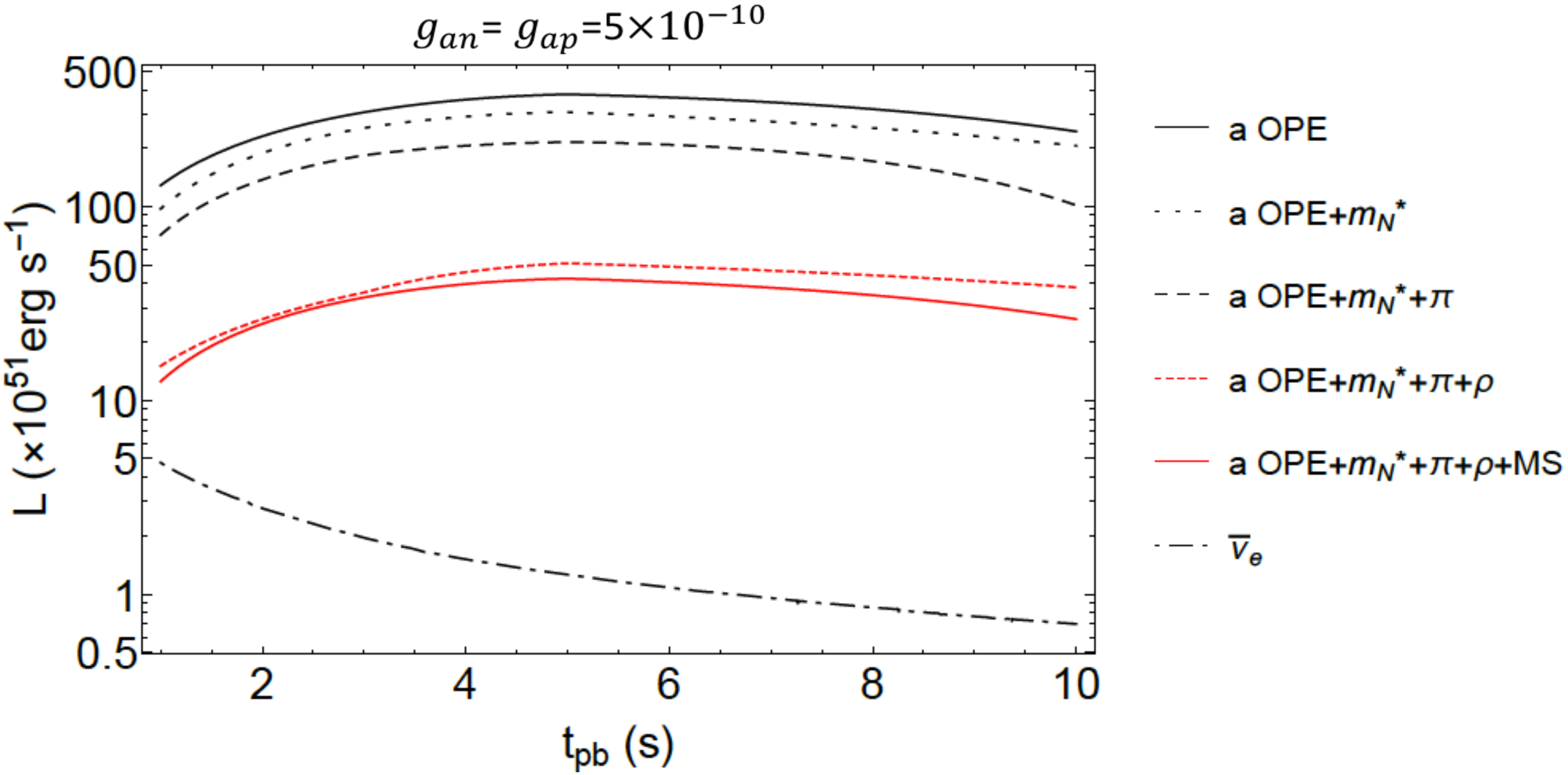
Temperature



Density



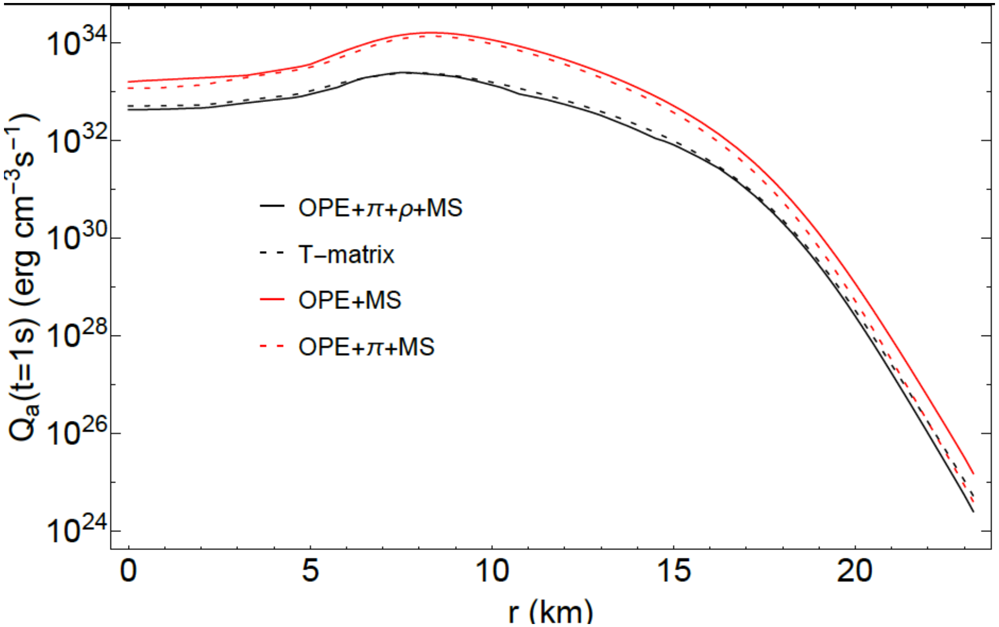
IMPACT OF THE CORRECTIONS



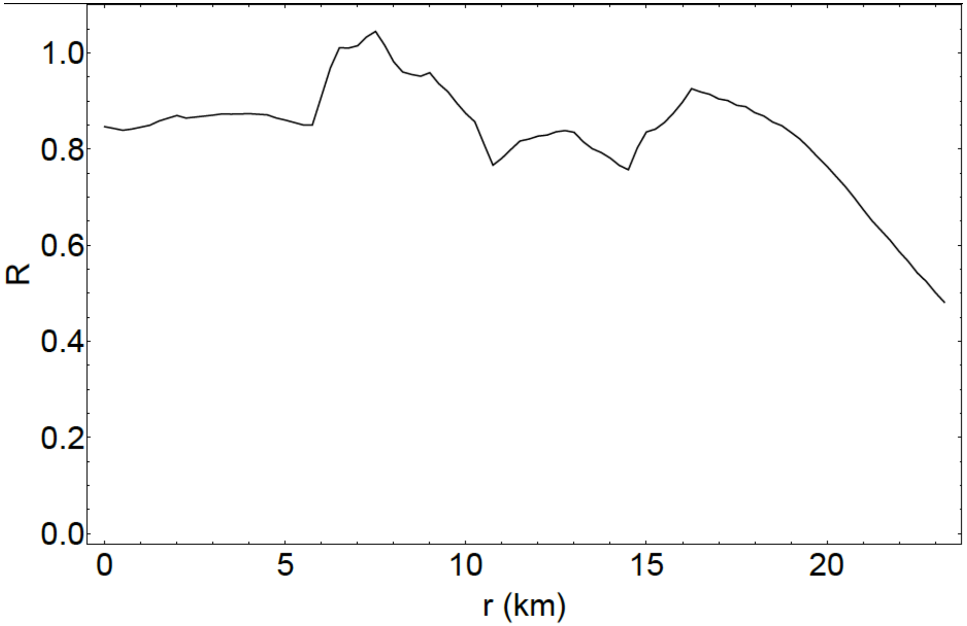
- Reduction of L_a by one order of magnitude when all the corrections are included

- Major impact due to effective nucleon mass and rho-exchange

COMPARISON WITH T-MATRIX



We compared our modified OPE prescription with results of T-matrix based on the chiral effective potential [see Guo and Martinez-Pinedo, 1905.13634]



In the region relevant for axion production we find differences < 20 %.

AXION LUMINOSITY

The SN 1987A neutrino burst lasted ~ 10 s, then

$$L_a < 10^{52} \text{ erg s}^{-1}$$

(*Raffelt, hep-ph/0611350*)

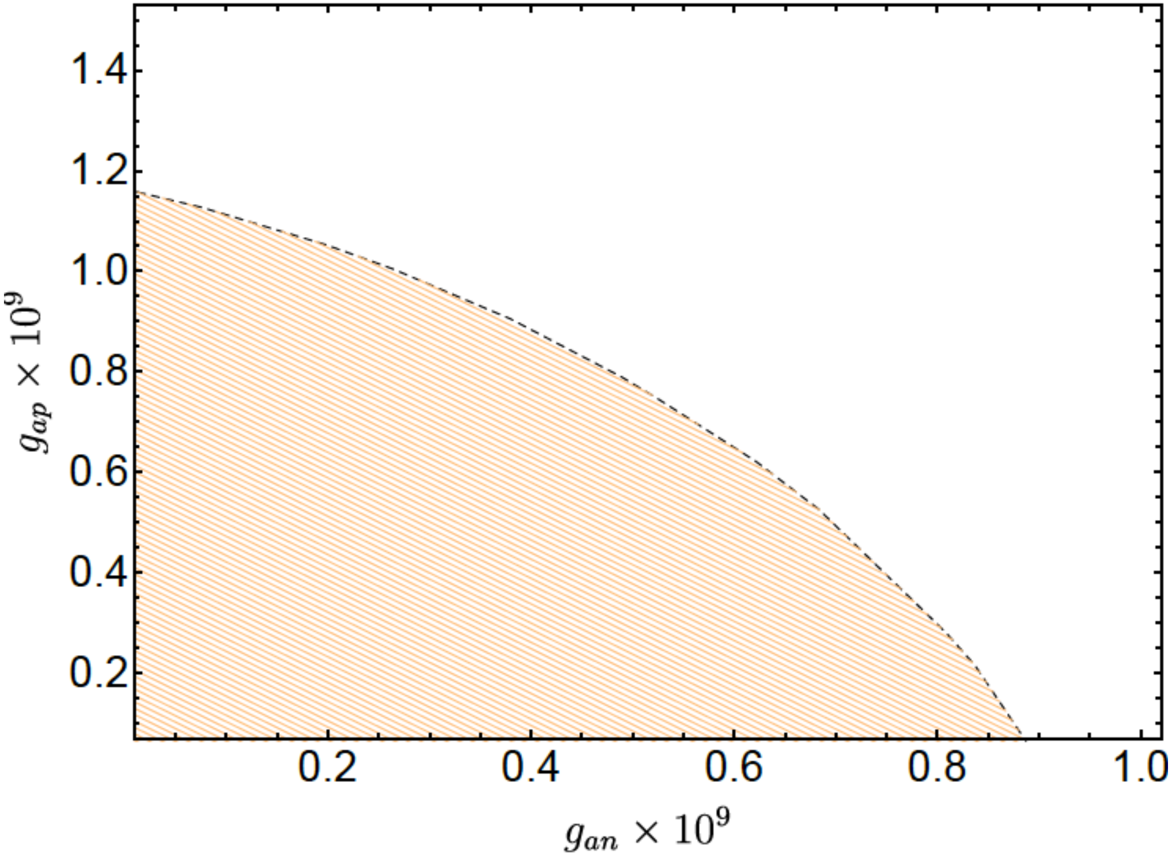
The axion luminosity for our model at t=1 s is

$$L_a \simeq 2.42 \times 10^{70} \ \text{erg} \ \text{s}^{-1} (g_{an}^2 + 0.61 g_{ap}^2 + 0.53 g_{an} g_{ap})$$

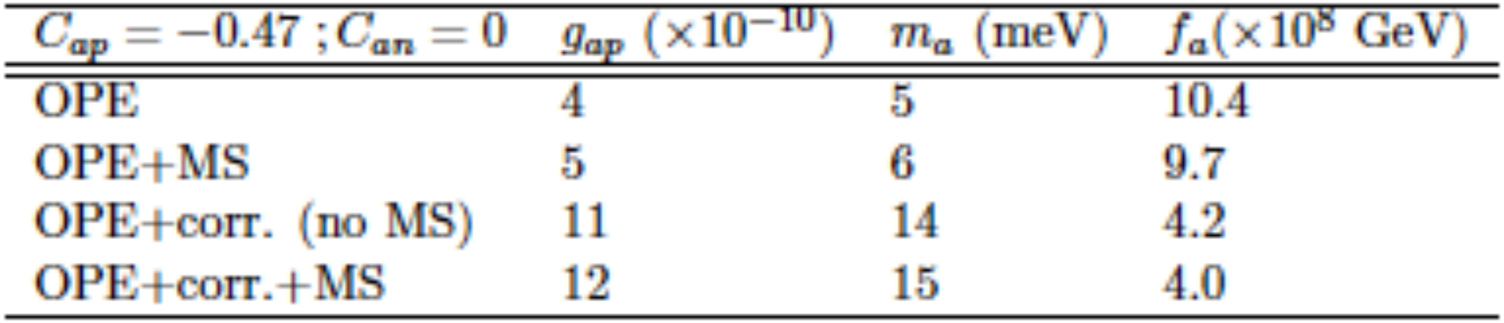
THE SN AXION BOUND

This implies a bound on axion-nucleon coupling

$$g_{an}^2 + 0.61 g_{ap}^2 + 0.53 g_{an} g_{ap} \lesssim 8.26 \times 10^{-19}$$



KVSZ AXION BOUND

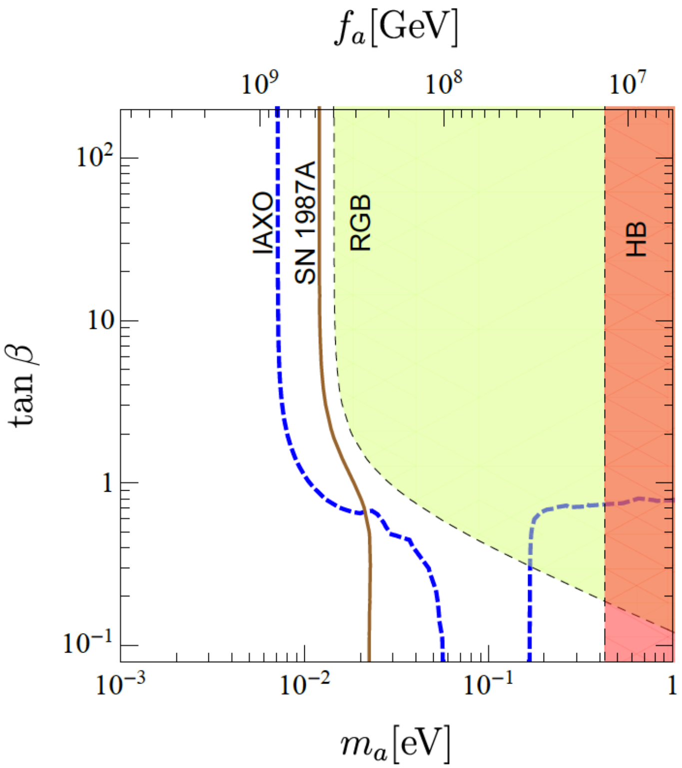


$C_{ap}=-0.47\,;C_{an}=0$	g_{ap} ($\times 10^{-10}$)	m_a (meV)	f_a($\times 10^{8}$ GeV)
OPE	4	5	10.4
OPE+MS	5	6	9.7
OPE+corr. (no MS)	11	14	4.2
OPE+corr.+MS	12	15	4.0

- 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

DFSZ AXION BOUND



- Our analysis indicates a mass bound $m_a < 15\text{-}20$ meV

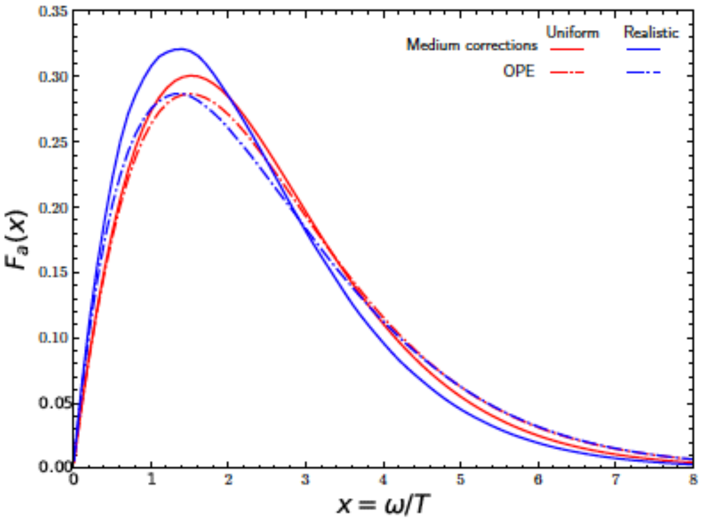
- SN 1987A bound is slightly more stringent than the RGB one and dominates over it for for small values of tanβ.

- There is still part of parameter space available for next generation experiments, like IAXO

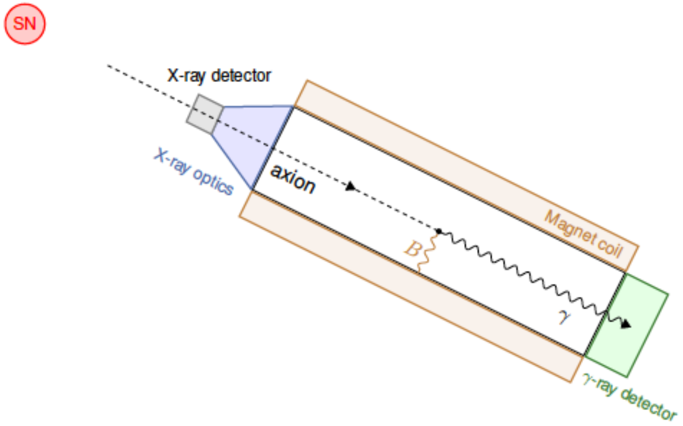
SN AXION SCOPE

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

SN axion flux

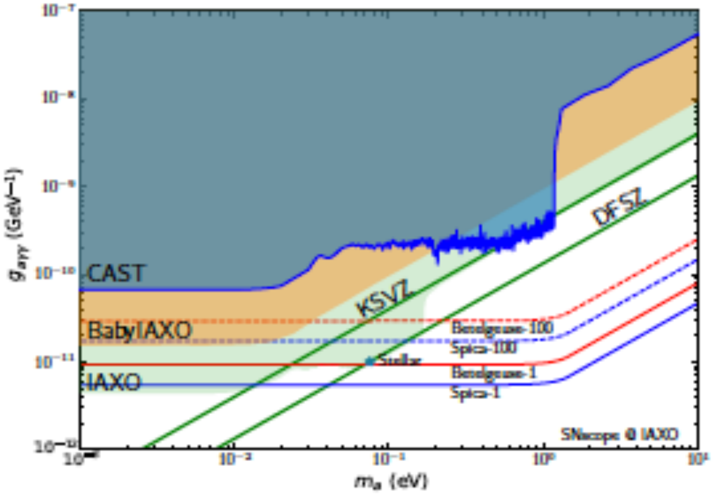


SN axion scope



(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

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THERMAL PIONS IN A SUPERNOVA CORE

- Neutron-rich dense stellar matter, electrically neutral and in beta-equilibrium ($e\,p \leftrightarrow n\nu_e$) contains a high density of electrons. Beta equilibrium requires

$$\mu_e + \mu_p = \mu_n + \mu_{\nu_e}$$

$\hat{\mu} = \mu_n - \mu_p = \mu_e - \mu_{\nu_e}$ source for negatively charged particles

$\mu_{\mu}^{-} = \mu_{\pi}^{-} = \hat{\mu}$

(π^+, π^0abundance suppressed wrt to π^- by $Ae^{-\hat{\mu}/T}$)

- At high-temperature and low-density population of thermal pions (no Bose Einstein condensate)

NEW CALCULATION OF PION ABUNDANCE

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

- Pion density

$$n_{\pi^-} = z_\pi \left(I_\pi + \sum_{i=n,p} z_i \, b_2^{i\pi^-} + \mathcal{O}(z_i^2) \right) + \mathcal{O}(z_\pi^2) \,,$$

- Thermal contribution

$$I_\pi = \int \frac{d^3k}{(2\pi)^3} \exp\left[\beta(m_\pi - \sqrt{p^2 + m_\pi^2})\right]$$

- Attractive p-wave strong interactions between thermal pions and nucleons lowers the energy cost associated of introducing pions in dense matter

  - ➢ $b_2^{n\pi^-}$ and $b_2^{p\pi^-}$ the second virial coefficient including the contribution of π^- interactions with neutrons and protons in terms of the measured pion-nucleon phase shifts

  - ➢ $z_\pi = \exp(\beta(\hat{\mu} - m_\pi)) \ll 1$ pion fugacity

PION DENSITY

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

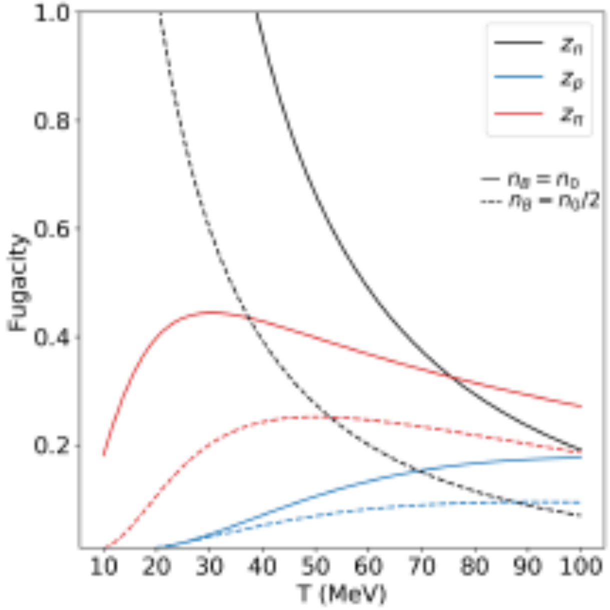


FIG. 3. Pion and nucleon fugacities in charge-neutral dense matter in β-equilibrium at $n_B = n_0$ (solid-curves) and $n_B = n_0/2$ (dashed-curves) are shown as function of temperature.

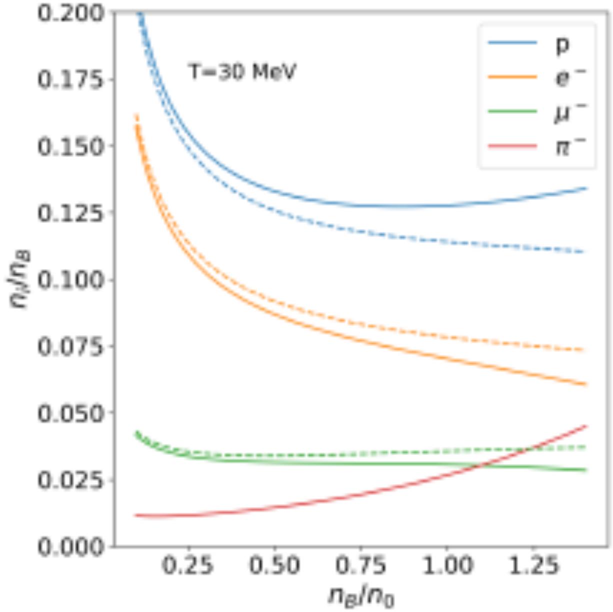
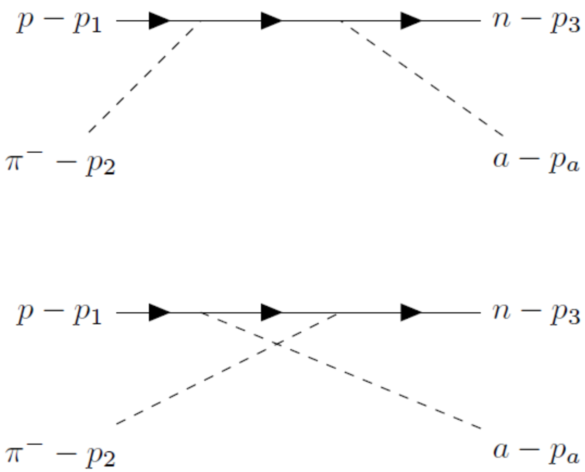


FIG. 2. Number fraction of charged particles at $T = 30$ MeV in β-equilibrium. Solid curves include pions and dashed curves only contain nucleons and leptons.

Around the saturation density $n_0 = 1.6 \times 10^{38} cm^{-3}$ the pion abundance can reach few % of the baryon one

AXION EMISSIVITY VIA PIONIC PROCESS

A population of π^- would lead to an additional channel of axions via Compton pionic process $\pi^- p \rightarrow n\, a$



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) [astro-ph/9312019]
- Keil, Janka, Schramm, Sigl, Turner and Ellis, Phys. Rev. D 56, 2419 (1997) [astro-ph/9612222]

IMPACT ON AXION LUMINOSITY AND MASS BOUND

[Carenza, Force, Giannotti, A.M., Reddy, 2010.02943]

- Axion emissivity

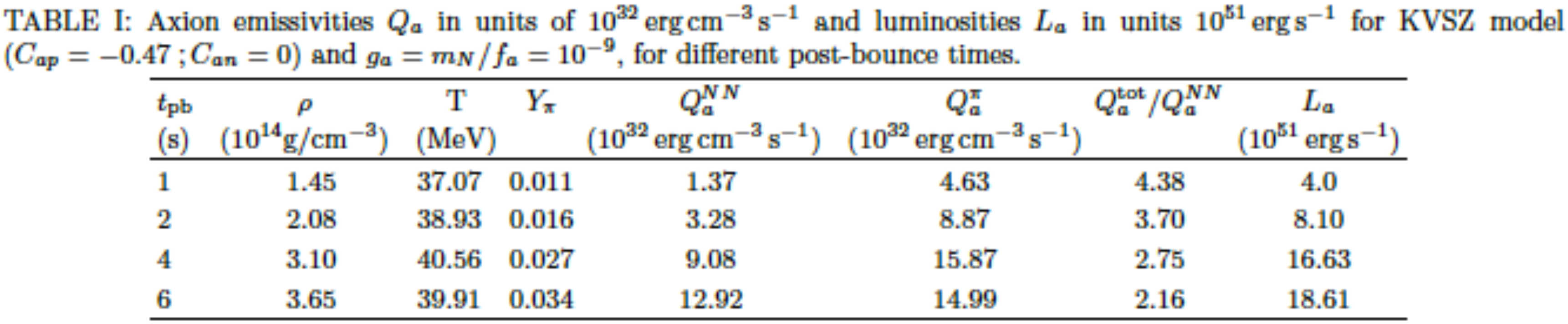


TABLE I: Axion emissivities Q_a in units of $10^{32}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$ and luminosities L_a in units $10^{51}\,\mathrm{erg\,s^{-1}}$ for KVSZ model ($C_{ap} = -0.47\,; C_{an} = 0$) and $g_a = m_N/f_a = 10^{-9}$, for different post-bounce times.

t_{pb} (s)	ρ (10^{14}g/cm^{-3})	T (MeV)	Y_π	Q_a^{NN} ($10^{32}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$)	Q_a^{π} ($10^{32}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$)	Q_a^{tot}/Q_a^{NN}	L_a ($10^{51}\,\mathrm{erg\,s^{-1}}$)
1	1.45	37.07	0.011	1.37	4.63	4.38	4.0
2	2.08	38.93	0.016	3.28	8.87	3.70	8.10
4	3.10	40.56	0.027	9.08	15.87	2.75	16.63
6	3.65	39.91	0.034	12.92	14.99	2.16	18.61

Axion emissivity increased by a factor 4 due to pionic processes at t_{pb}= 1 s

- Axion Mass bound

  Schematic SN model. T= 30 MeV, Y_p=0.3, ρ_{sat}= 2.6 x 10^{14} g/cm^3

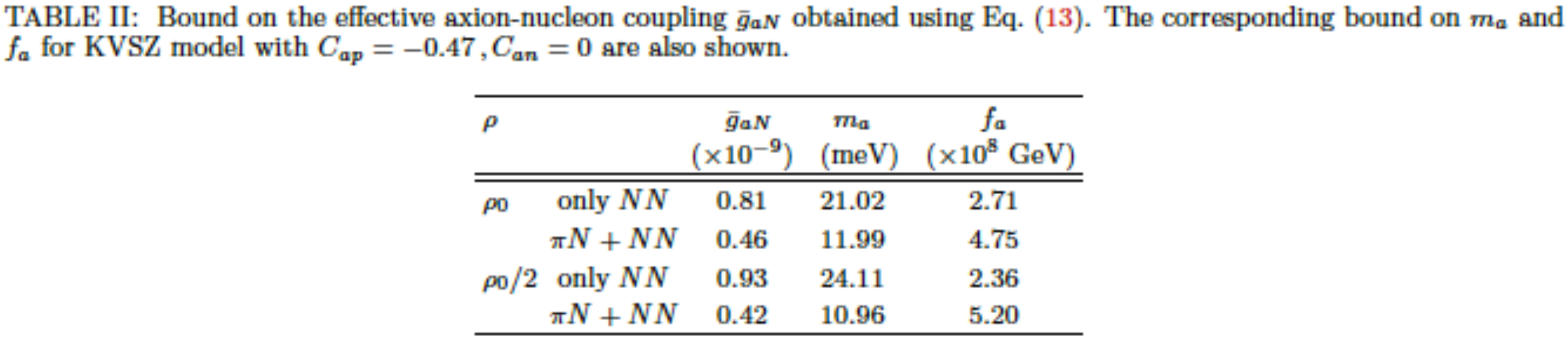


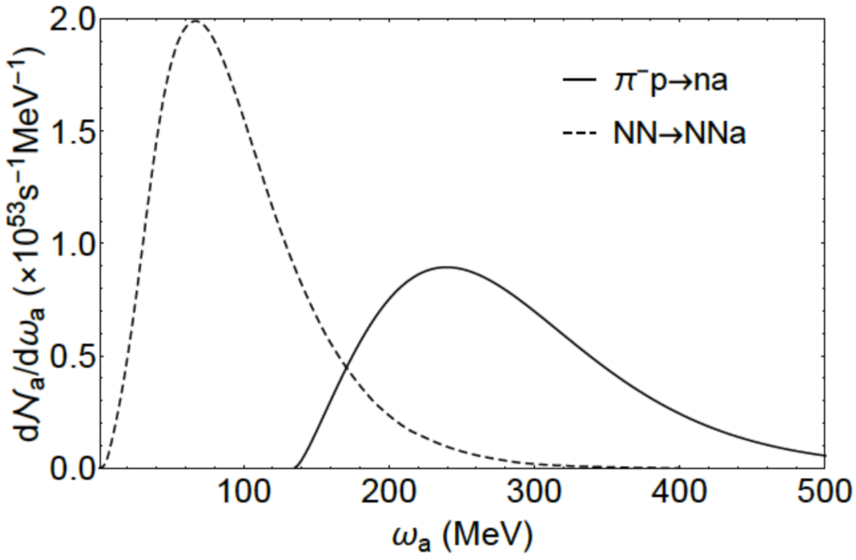
TABLE II: Bound on the effective axion-nucleon coupling $\bar{g}_{aN}$ obtained using Eq. (13). The corresponding bound on m_a and f_a for KVSZ model with $C_{ap} = -0.47\,, C_{an} = 0$ are also shown.

ρ		$\bar{g}_{aN}$ ($\times10^{-9}$)	m_a (meV)	f_a ($\times10^{8}$ 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

Axion mass bound strengthened by a factor 2 when πN processes are included

DETECTION PERSPECTIVES FOR SN AXION BURST

[Carenza, Force, Giannotti, A.M., Reddy, 2010.02943]



- πN process produces a harder axion spectrum (E~ 200 MeV) with respect to the NN process
- High-energy axions would produce neutral and charged π in a water Cherenkov detector, due to processes a+ p → N + π
- For E~ 200-300 MeV resonant enhancement of the a-N cross section due to Δ intermediate state

Simple estimation of the axion events

$$\sigma_{aN} = (F_\pi \;/f_a \;)^2\, \sigma_{\pi N}$$

→ 1000 pions !

$$\sigma_{\pi N} \approx 100\; mbarn$$

@ $f_a = 10^9\; GeV$

(m_a=5.7 meV)

d_{SN}= 1 kpc

1 Mton detector

Intriguing possibility to be investigated

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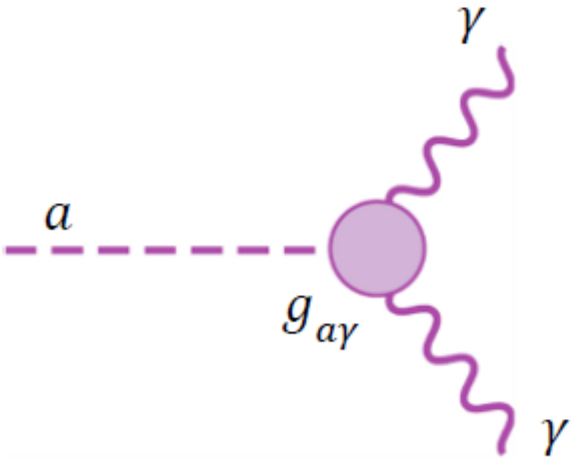
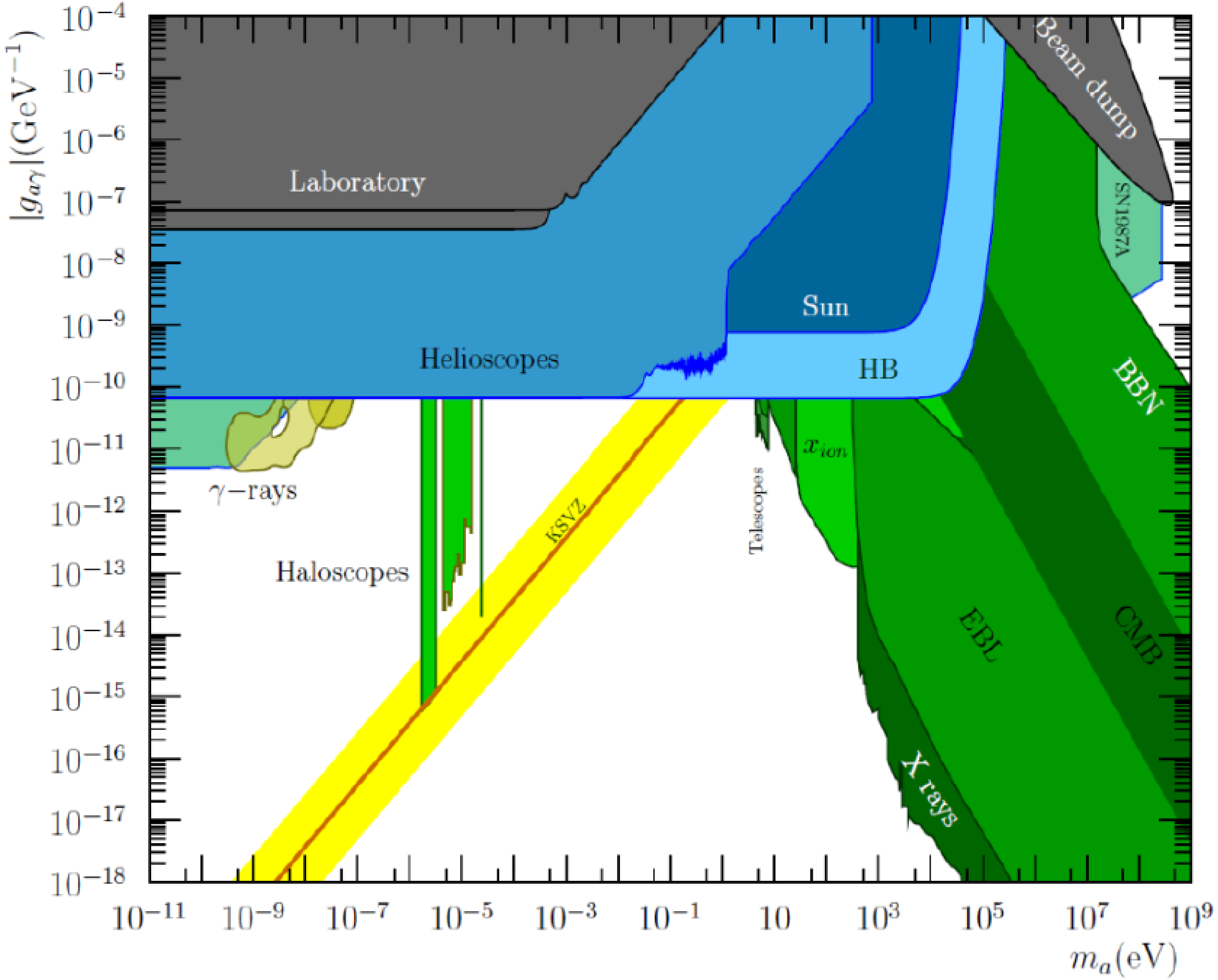
AXION-LIKE PARTICLES (ALPs)

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



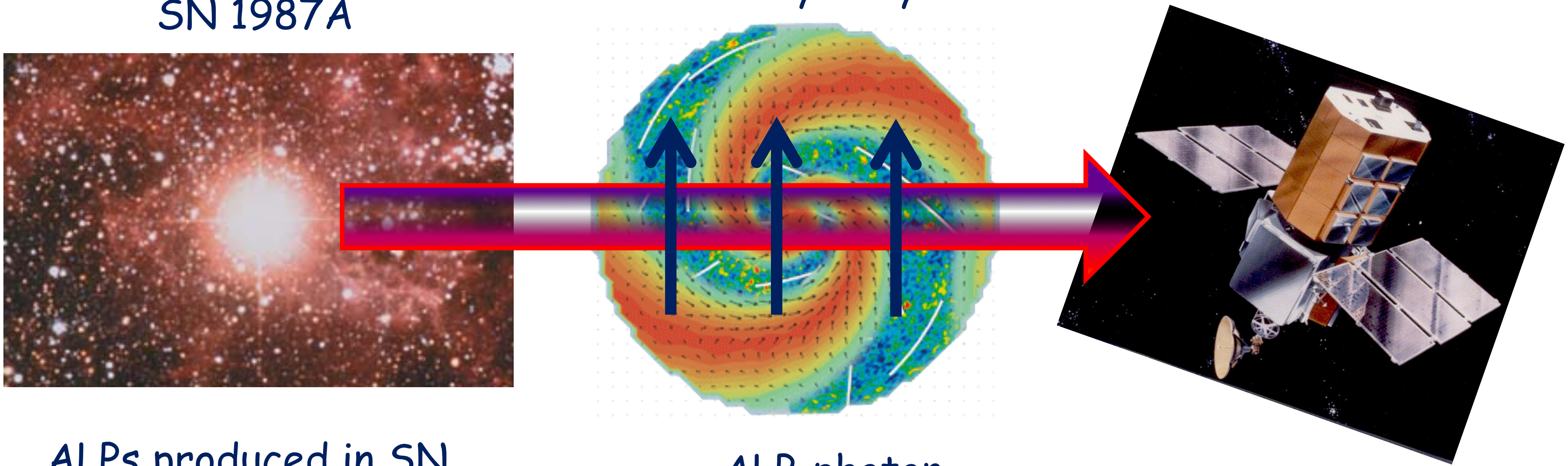
- Primakoff process: Photon-ALP transitions in external static E or B field
- Photon-ALP conversions in macroscopic B-fields

SEARCHING FOR ALPS USING THEIR ELECTROMAGNETIC COUPLING



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

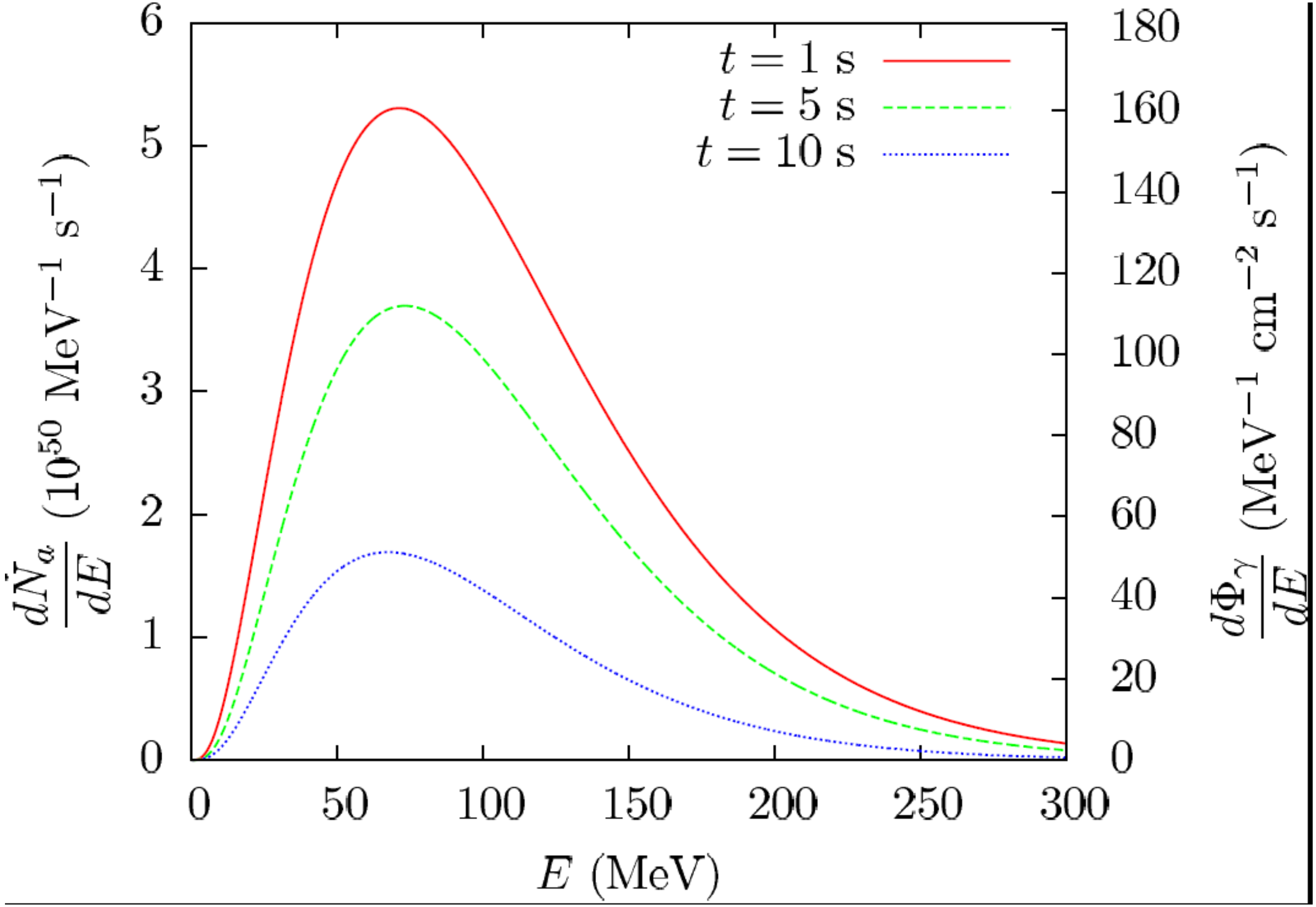
No excess gamma-rays in coincidence with SN 1987A

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

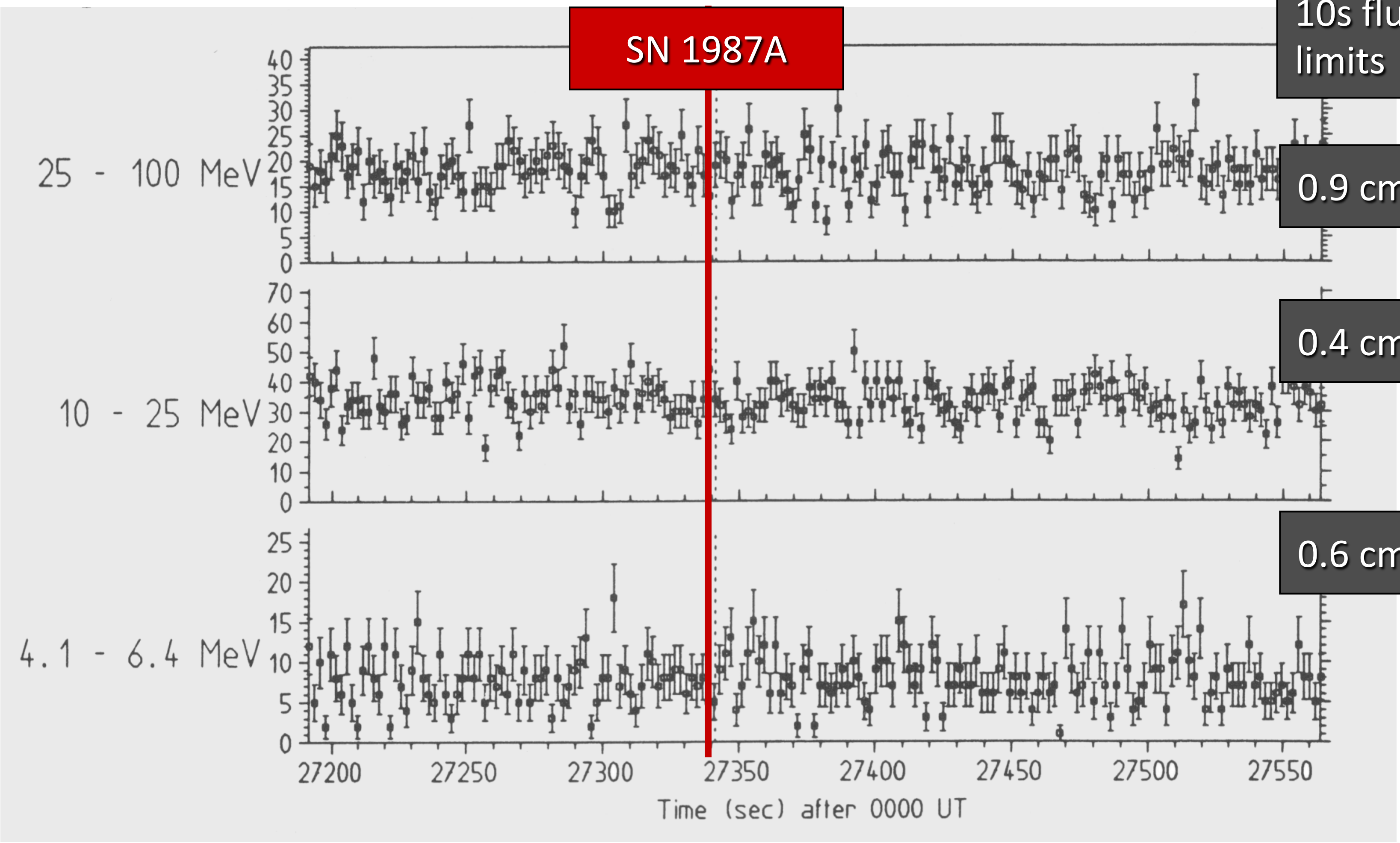
ALP-PHOTON FLUXES FOR SN 1987A

[*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



SN 1987A

10s fluence limits

$0.9\ cm^{-2}$

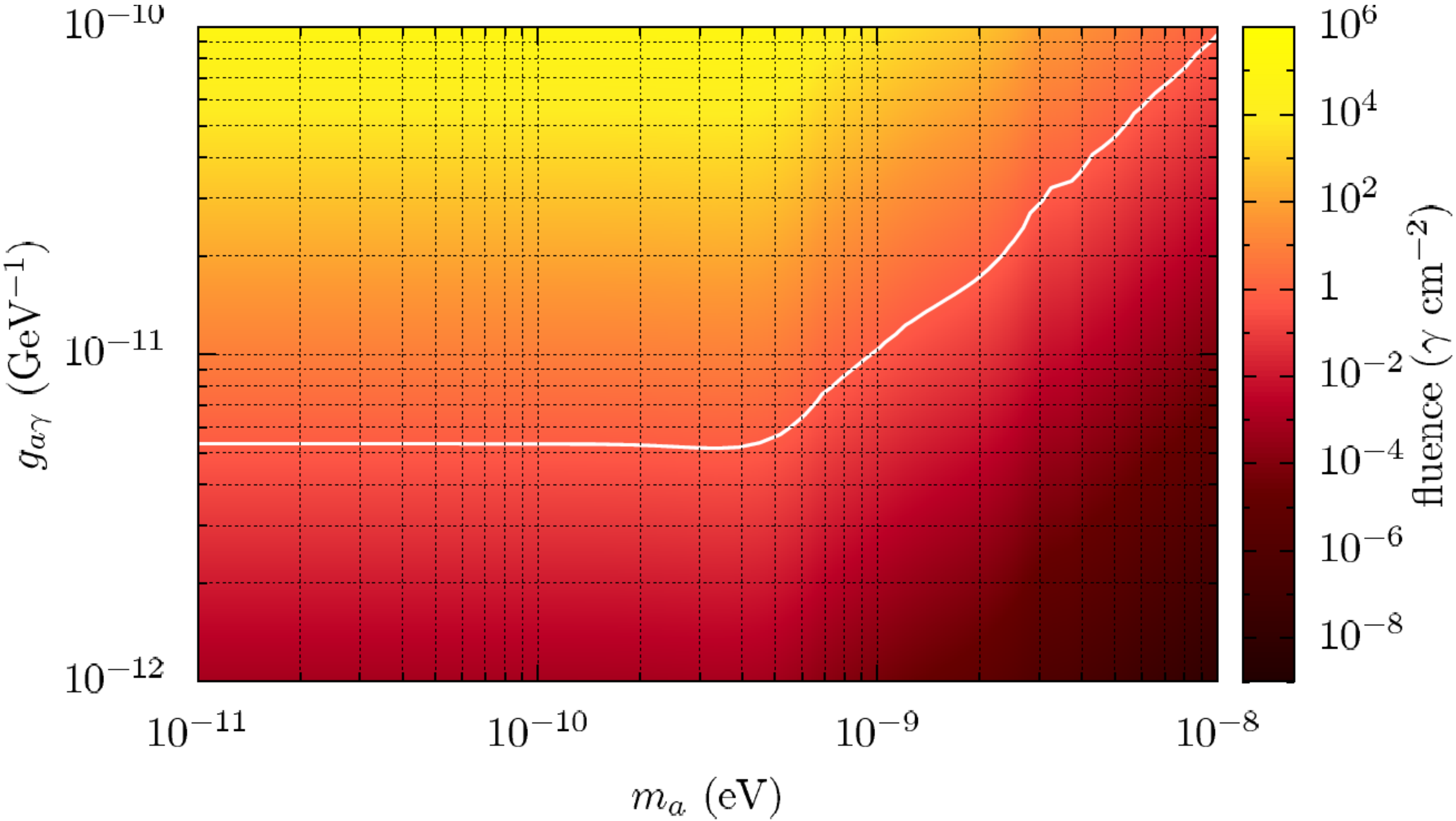
$0.4\ cm^{-2}$

$0.6\ cm^{-2}$

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

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

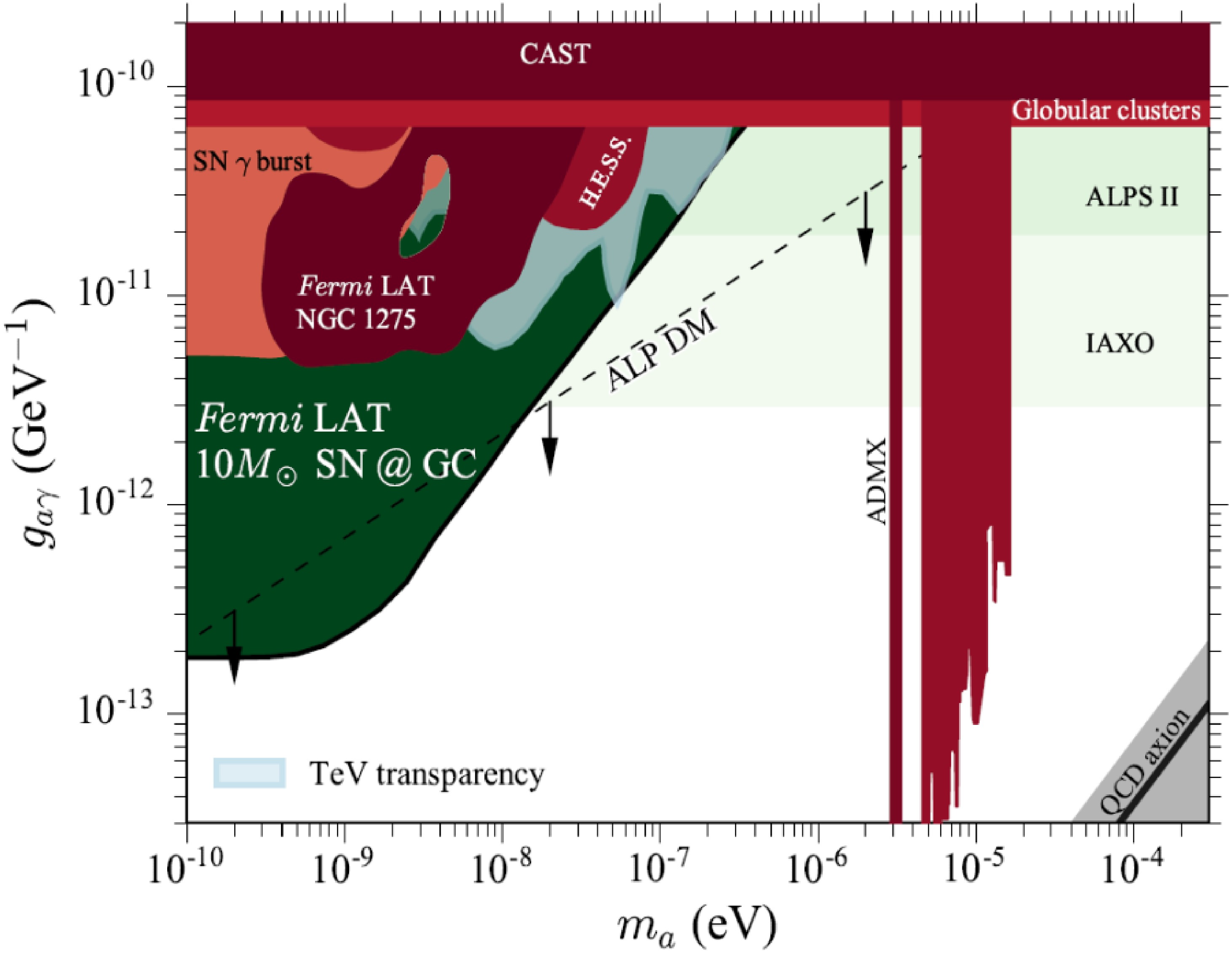
Stockholm University

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 !

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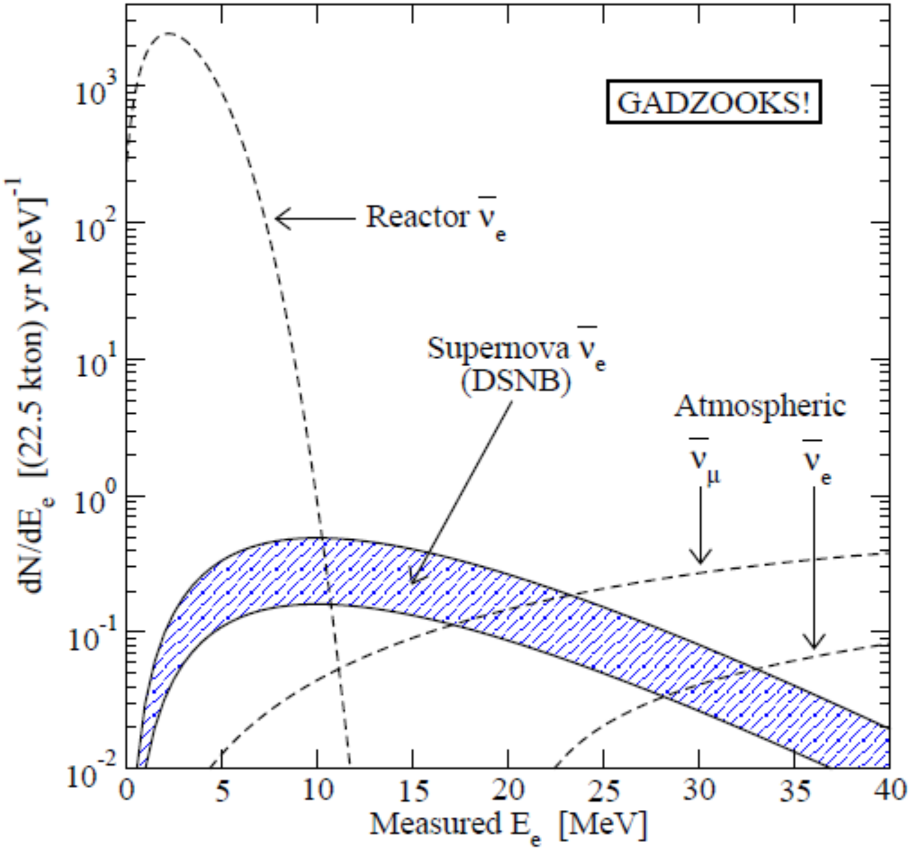
DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

- Approx. 10 core collaspes/sec in the visible universe
- Emitted ν energy density
  ~extra galactic bkg light
  ~ 10% of CMB density
- Detectable $\overline{\nu}_e$ flux at Earth
  ~ 10 $cm^{-2}s^{-1}$
  mostly from redshift z~1
- Confirm the star formation rate
- Nu emission from average core-collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!

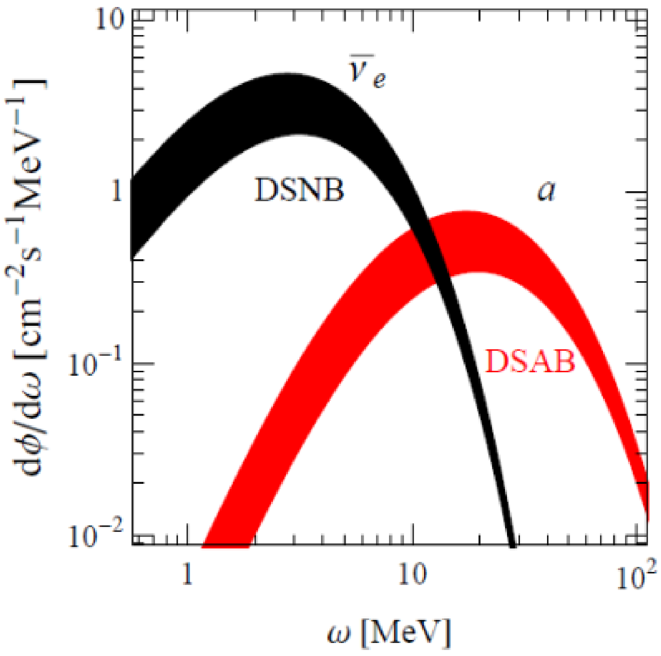
[Beacom & Vagins, hep-ph/0309300]



Windows of opportunity btw reactor $\overline{\nu}_e$ and atmospheric ν bkg

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

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

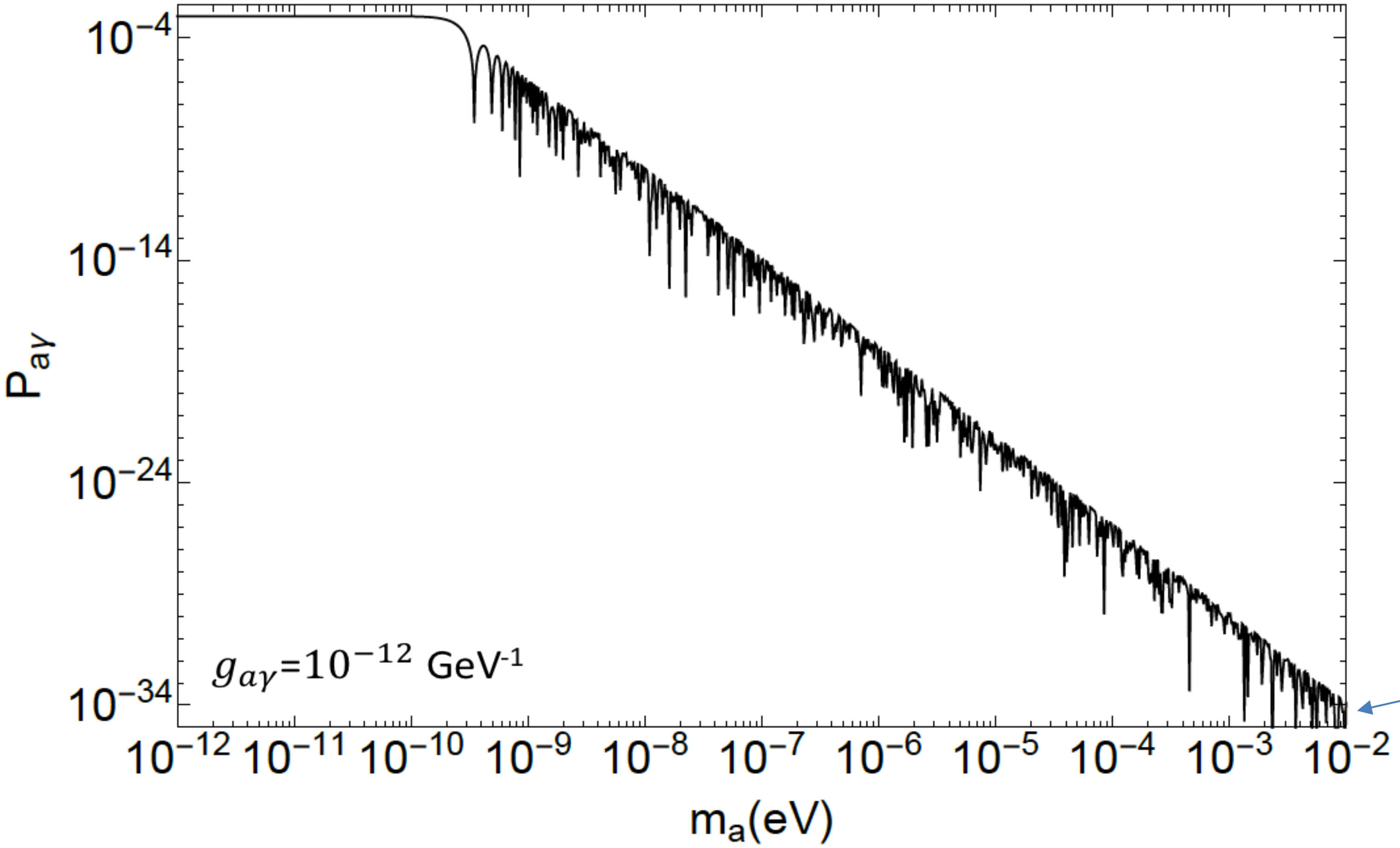
too small for QCD axions !

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

L_{GAL}=25 kpc

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

ALP-PHOTON CONVERSION PROBABILITY

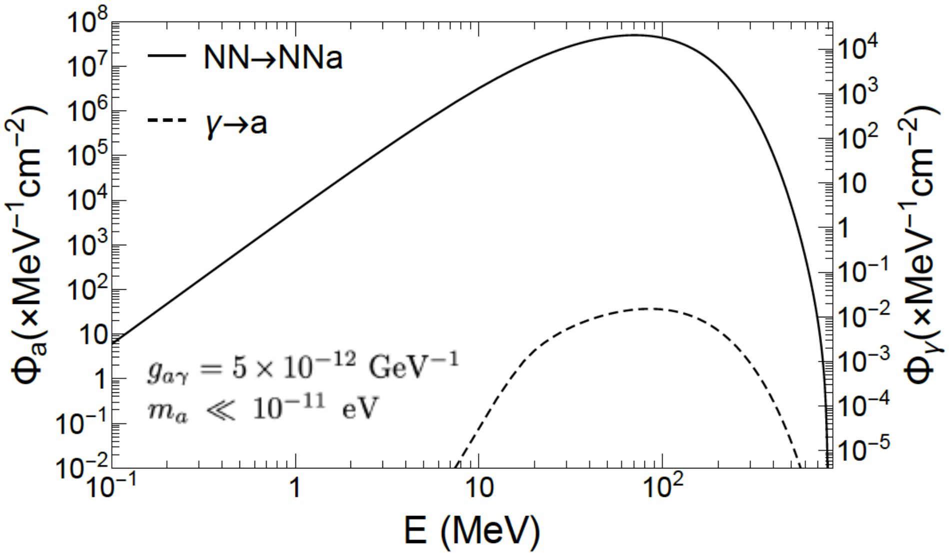


QCD
Axion

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

ALPs PRODUCTION AND GAMMA-RAY FLUX

[Calore, Carenza, Giannotti, Jaeckel, A.M., arXiv:2008.11741]



ALPs flux at Earth and gamma-ray flux for SN 1987A

- NN brems. Enhances the ALPs production and final gamma-ray flux
- Gamma-ray spectrum peaked @ 100 MeV, in the sensitivity range of Fermi-LAT

⇒ Revisited limit from SN 1987A

⇒ New constraints from DSNALPB

DSALPB SIGNAL

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

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

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

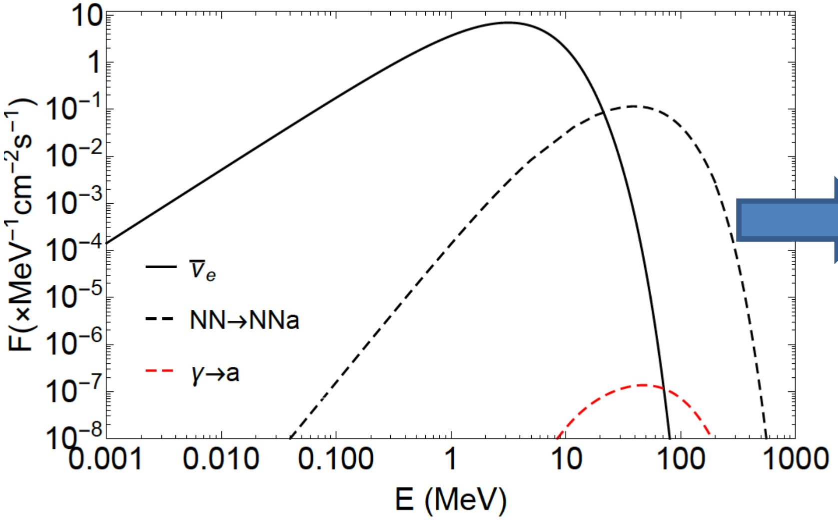
$$\left|\frac{dt}{dz}\right|^{-1} = H_0(1+z)\left[\Omega_\Lambda + \Omega_m(1+z)^3\right]^{1/2}$$

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

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

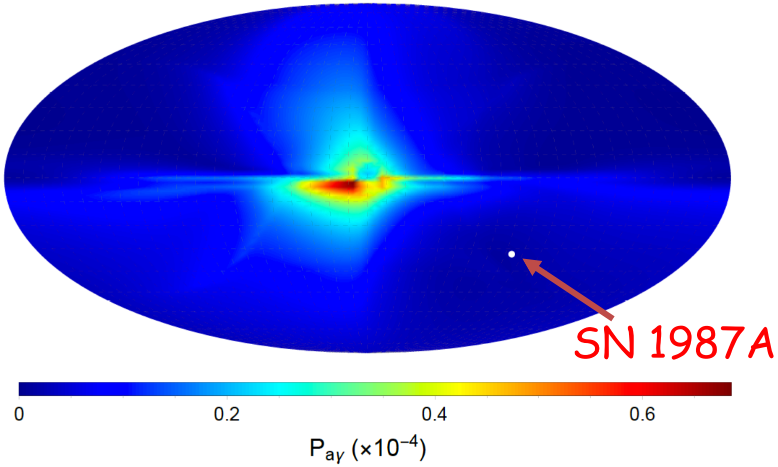
DSNALPB GAMMA-RAY FLUX

DSNALPB flux

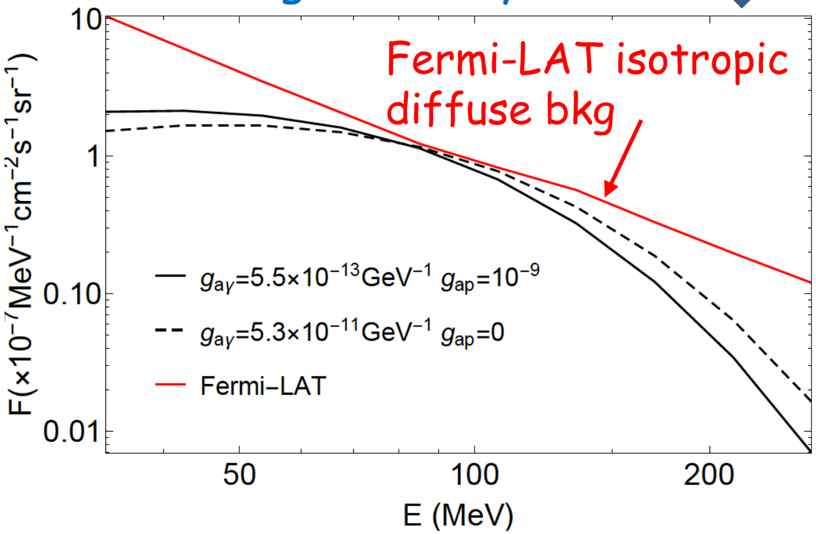


Conversions in Galactic B-field

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



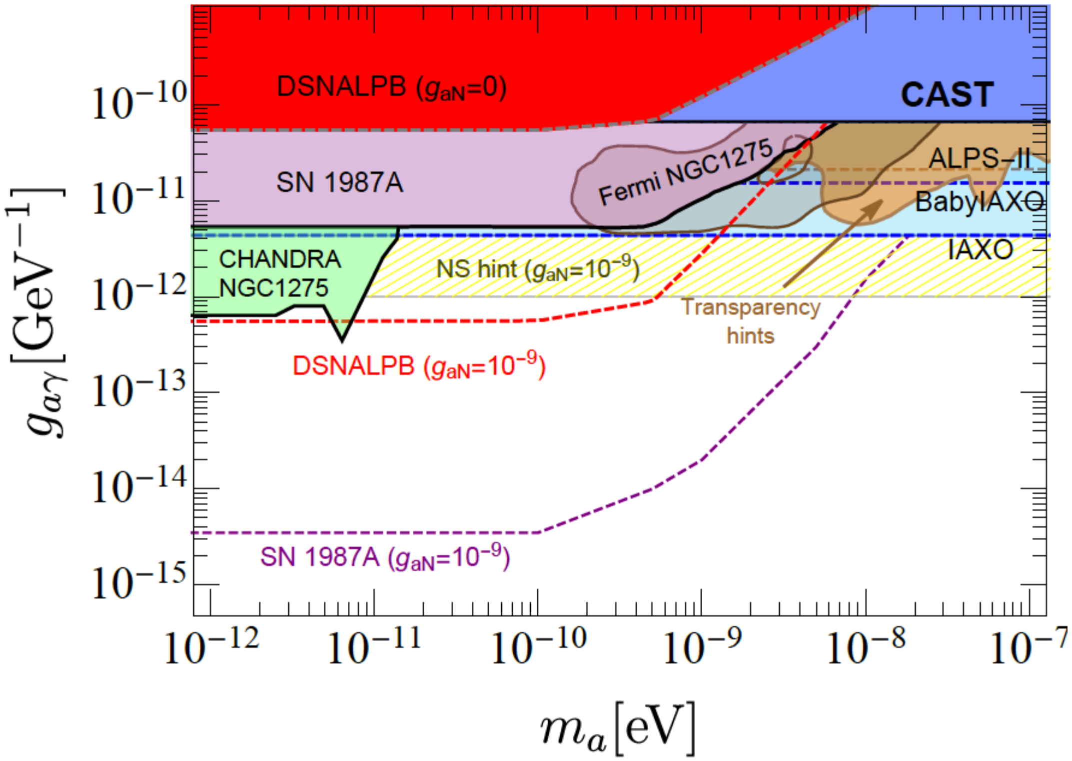
gamma-ray flux



Fermi-LAT isotropic diffuse bkg

CONSTRAINTS FROM DSNALPB

[Calore, Carenza, Giannotti, Jaeckel, A.M., arXiv:2008.11741]



- For g_{aN}=0 DNSALPB constraint
  - ✓ Comparable with CAST
  - ✓ Less stringent than SN 1987A
- For $g_{aN}=10^{-9}$ DNSALPB constraint
  - ✓ Competitive with IAXO sensitivity
  - ✓ Excludes part of the NS hint
- For $g_{aN}=10^{-9}$ SN 1987A Constraint
  - ✓ improves by $O(10^3)$

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CONCLUSIONS

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

- We perfomed a reliable calculation of the NN axion emissivity including relevant corrections beyond OPE
- We pointed out that 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 the combination of couplings with nucleons and photons might lead to a large gamma-ray flux from DSNALPB

A Galactic SN is a lifetime opportunity for axions !


CAST
EUROPAMETALLI – LMI
E. ZANON
Axion