THE "INVISIBLE" AXION IN ASTROPHYSICS

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Slides prepared with Giuseppe Lucente

THE FOUR MUSKETEERS

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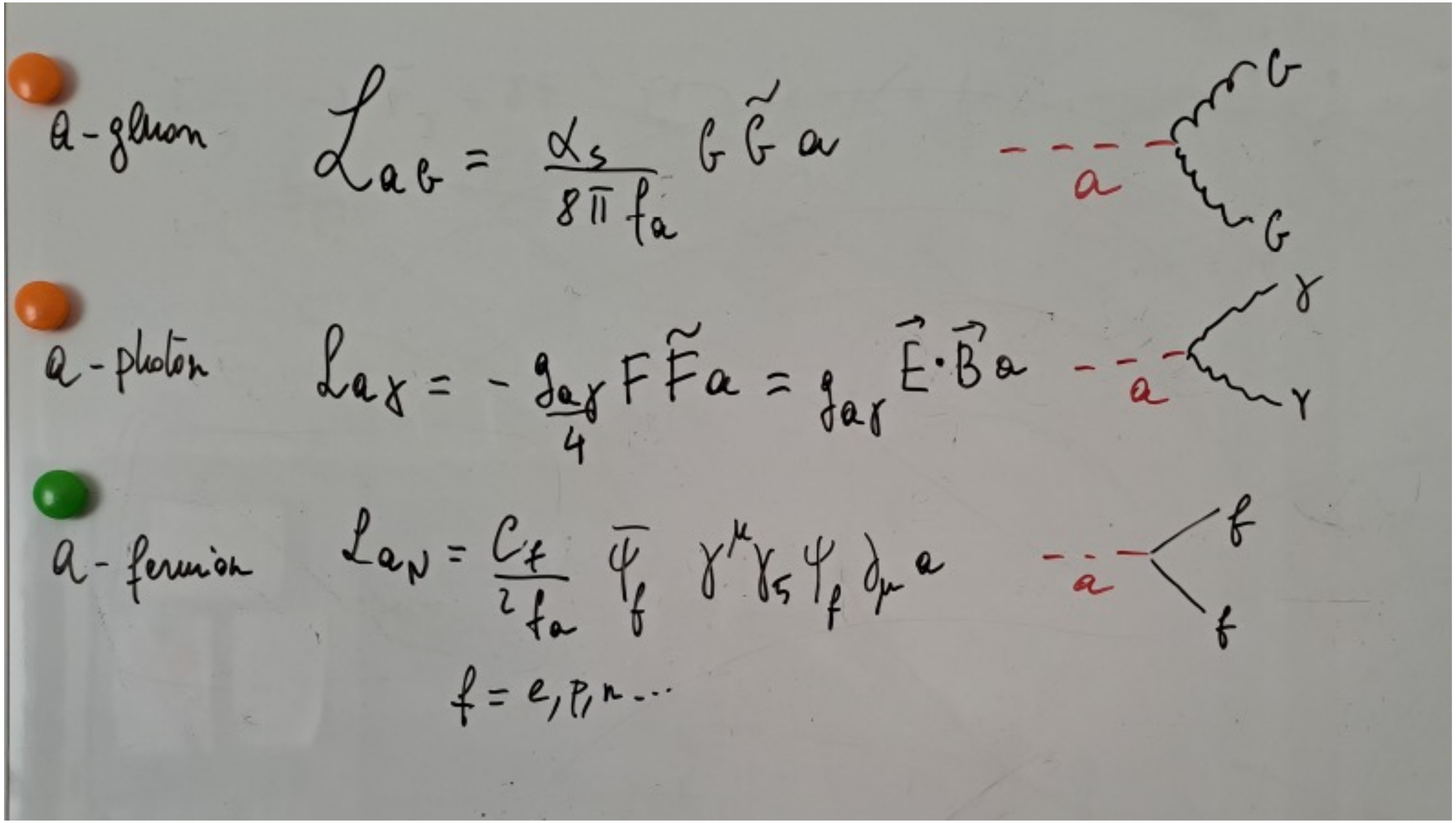
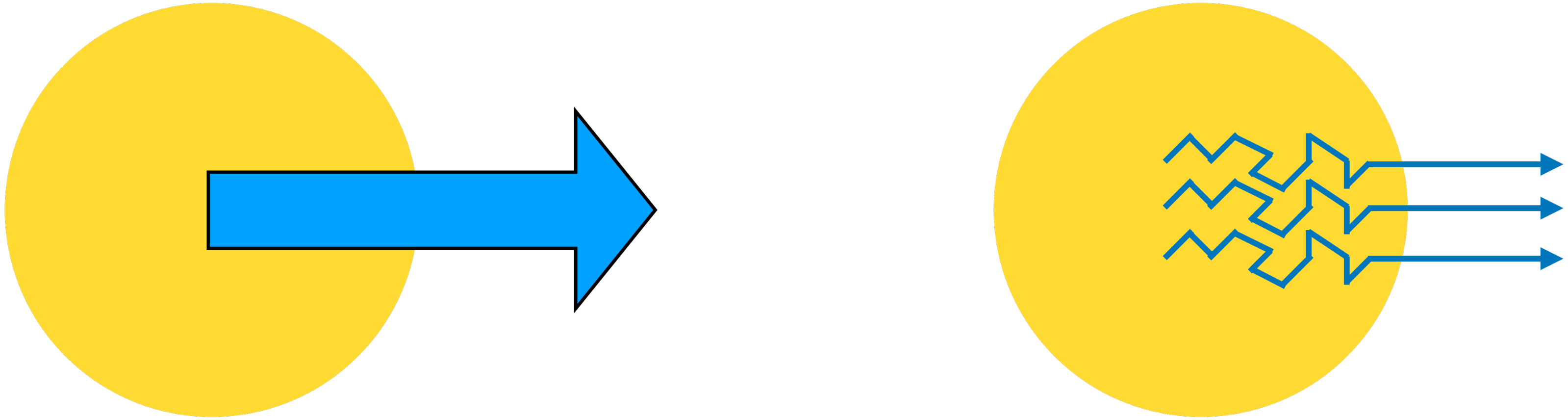
AXION PROPERTIES

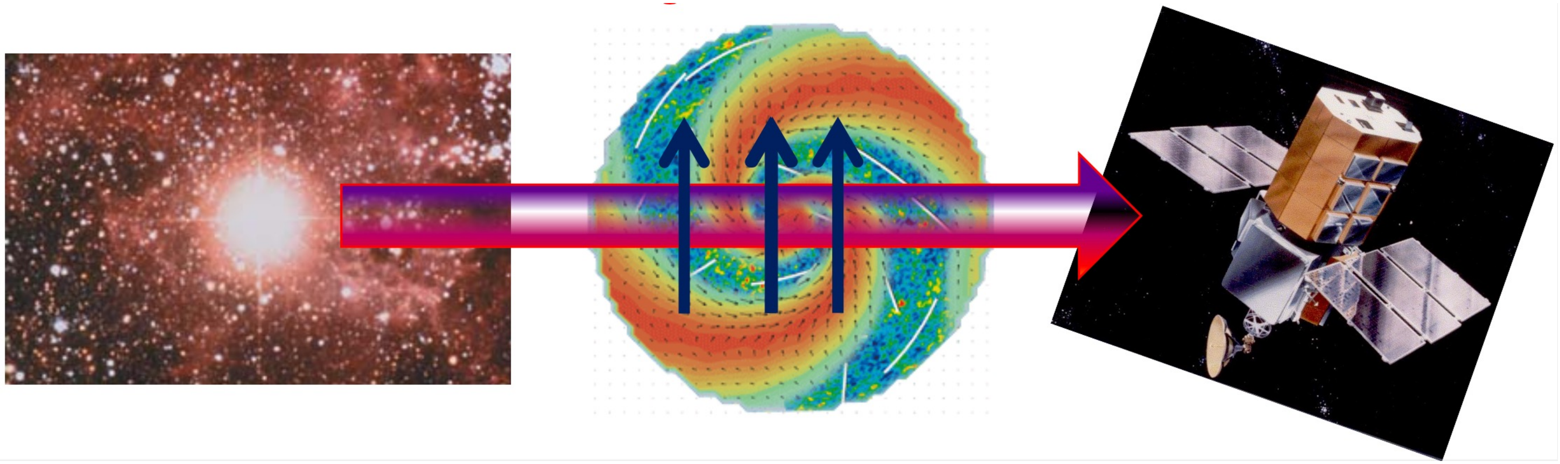


AXIONS IN ASTROPHYSICS

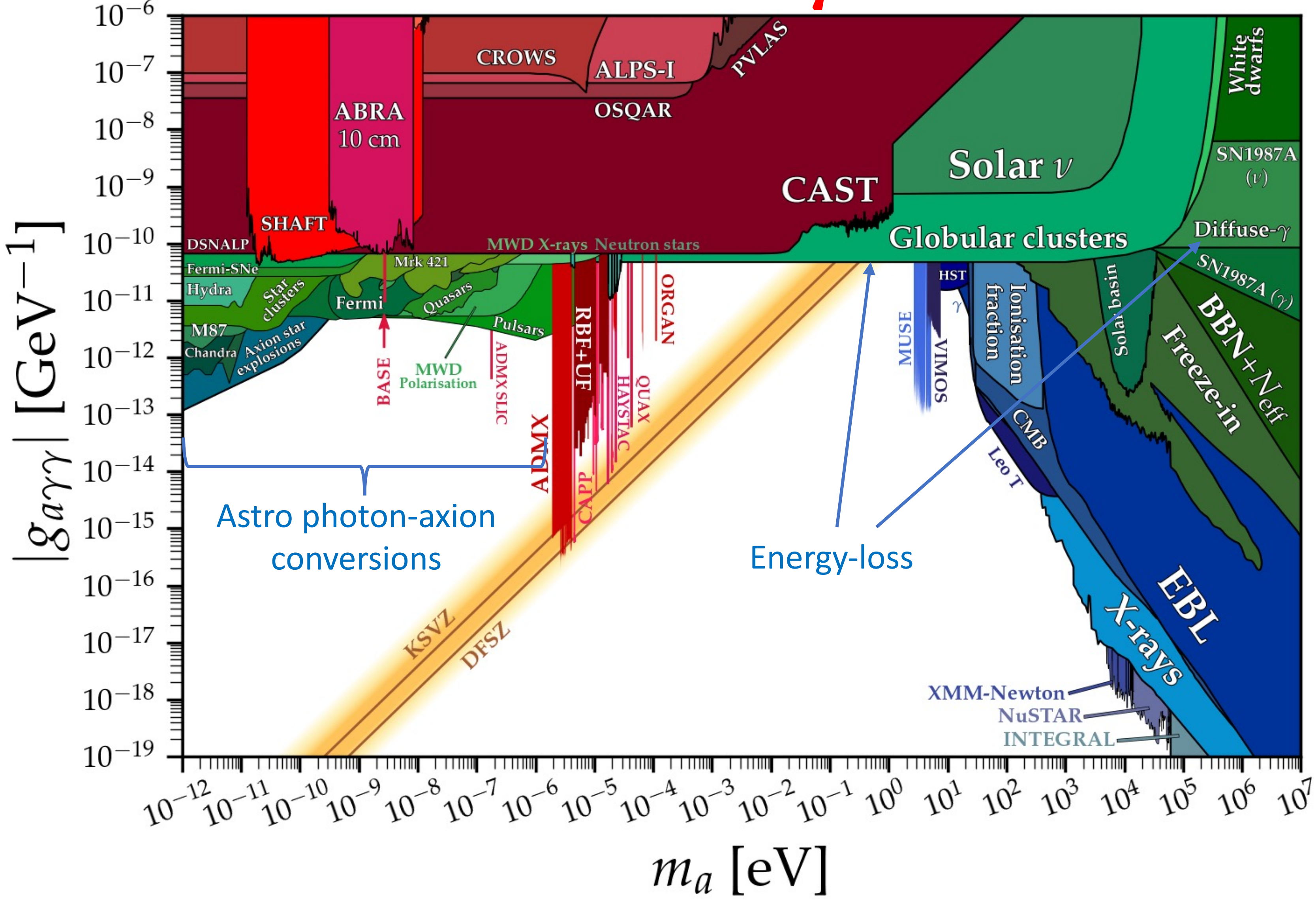
- Impact on the standard stellar evolution



- Direct signature on Earth

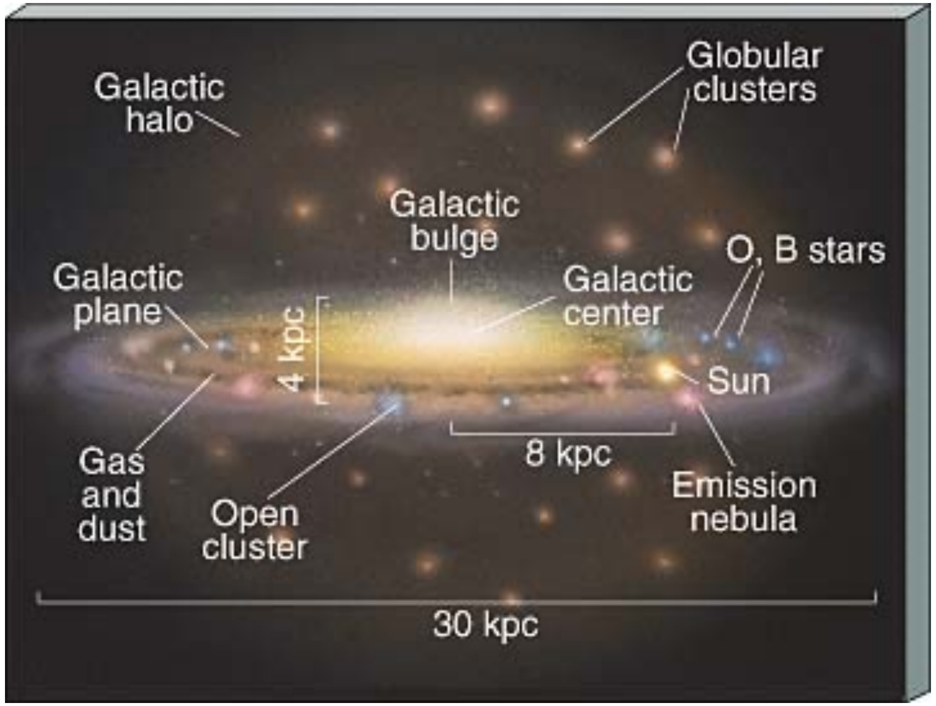


BOUNDS ON $g_{a\gamma}$ VS m_a



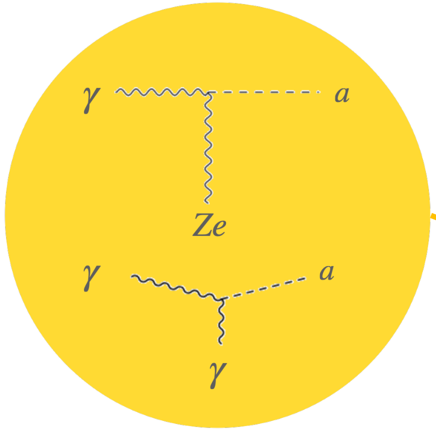
(Plot by Ciaran O’Hare https://cajohare.github.io/AxionLimits/)

GLOBULAR CLUSTERS



- Globular clusters are gravitationally bound associations of typically 10^6 stars.
- The low metallicity is one indicator for their great age.
- All stars in a given cluster are coeval; they differ only in their mass.

SENSITIVITY TO AXION EMISSION

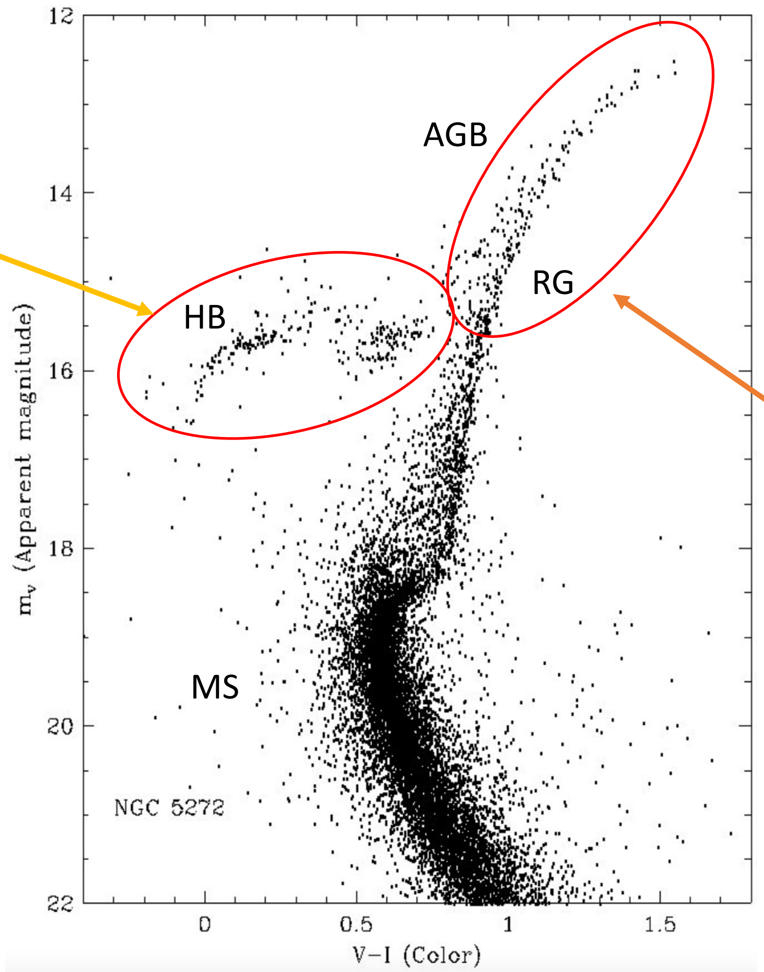


HB: non-degenerate core.

Sensitive to $g_{a\gamma}$.

[Raffelt & Dearborn, PRD 36 (1987)
Ayala, AM et al., PRL 113 (2014)
Dolan et al., JCAP 10 (2022)]

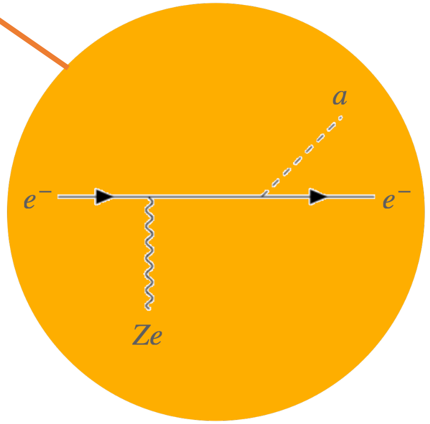
$$R = N_{HB}/N_{RG}$$



RG: degenerate core.

Sensitive to g_{ae}.

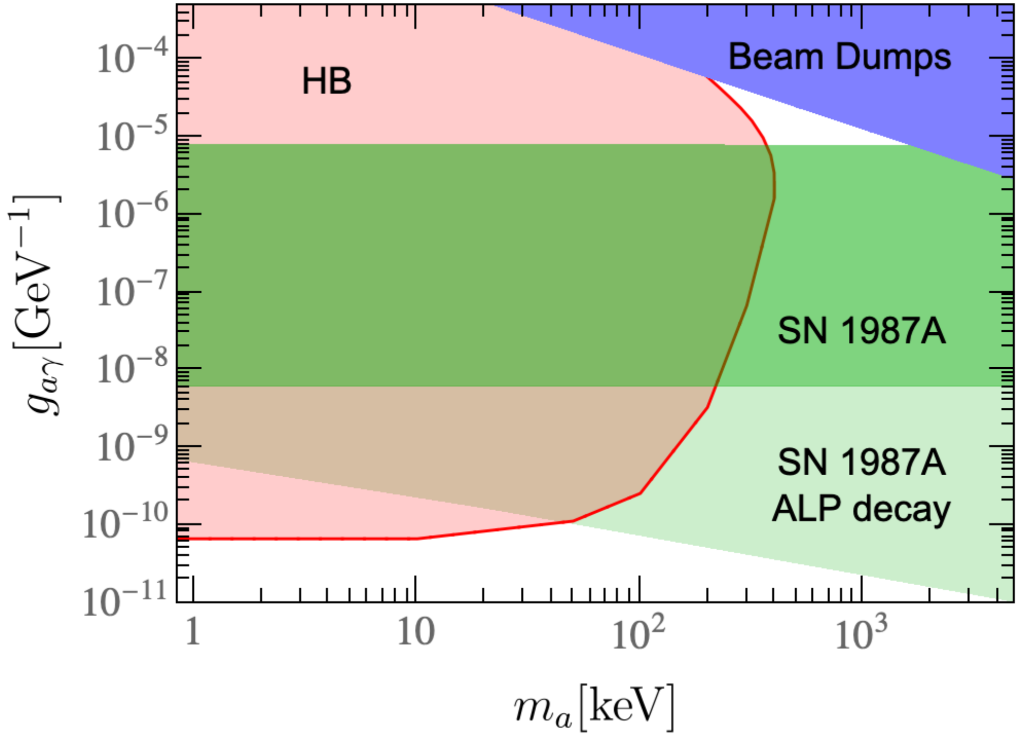
[Viaux et al., PRL 111 (2013)
Capozzi & Raffelt, PRD 102 (2020)
Straniero, AM et al., A.Astroph. 644 (2020)]



HB STAR BOUND ON AXIONS

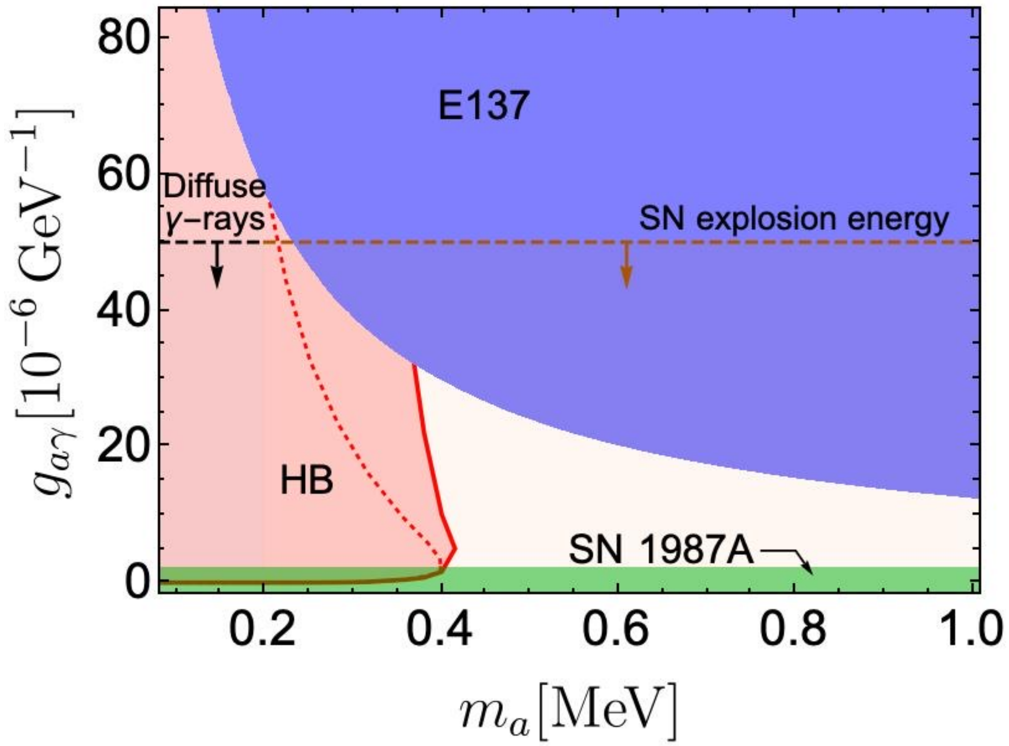
Axions coupled with photons would reduce the lifetime of stars in HB, while producing negligible change in RGB evolution. [Raffelt & Deaborn, PRD 36, 2211 (1987)]

[Carenza, Straniero, Dobrich, Giannotti, Lucente, Mirizzi, PLB 809 (2020), 135709]



HB bound extended to massive axions ($m_a \gtrsim 10\ \mathrm{keV}$): interplay with supernova and beam dump experiments.

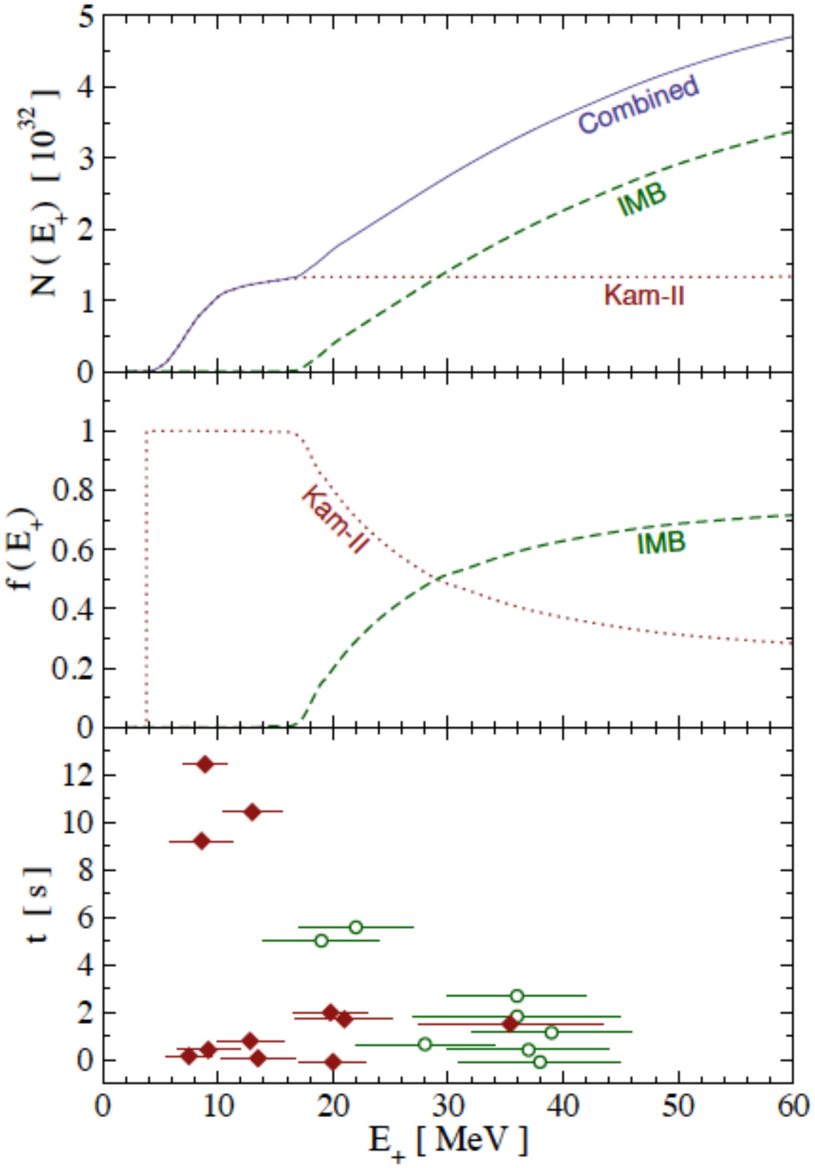
[Lucente, Carenza, Giannotti, Mirizzi, Straniero, PRL 129 (2022) 1, 011101]



Energy deposition inside the star due to $a \to \gamma\gamma$. Axion energy transfer causes early disappearance of the convective core ➡ stronger constraint.

NEUTRINO SIGNAL FROM SN 1987A

[Yuksel & Beacom, PRD 76, 083007 (2007)]



- **THEORY:**
  - **ENERGY SCALES:** 99% of the released energy ($\sim 10^{53}$ erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies $E \sim 15$ MeV.
  - **TIME SCALES:** Neutrino emission lasts $\sim$ **10 s**.
- **OBSERVATIONS:**

Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons

Despite the sparseness of data, energetics and duration roughly in agreement with SN models.

ENERGY-LOSS ARGUMENT

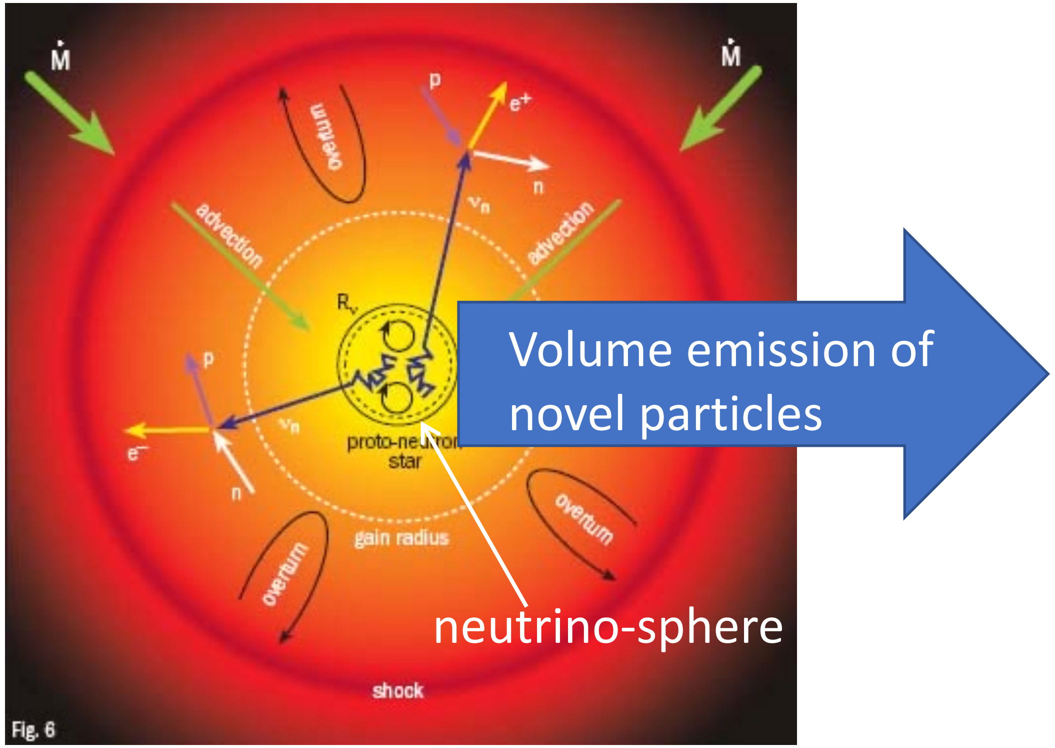


Fig. 6

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 ~ 1/2 leads to an approximate requirement on a novel energy-loss rate of

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

``Raffelt criterion''

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

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

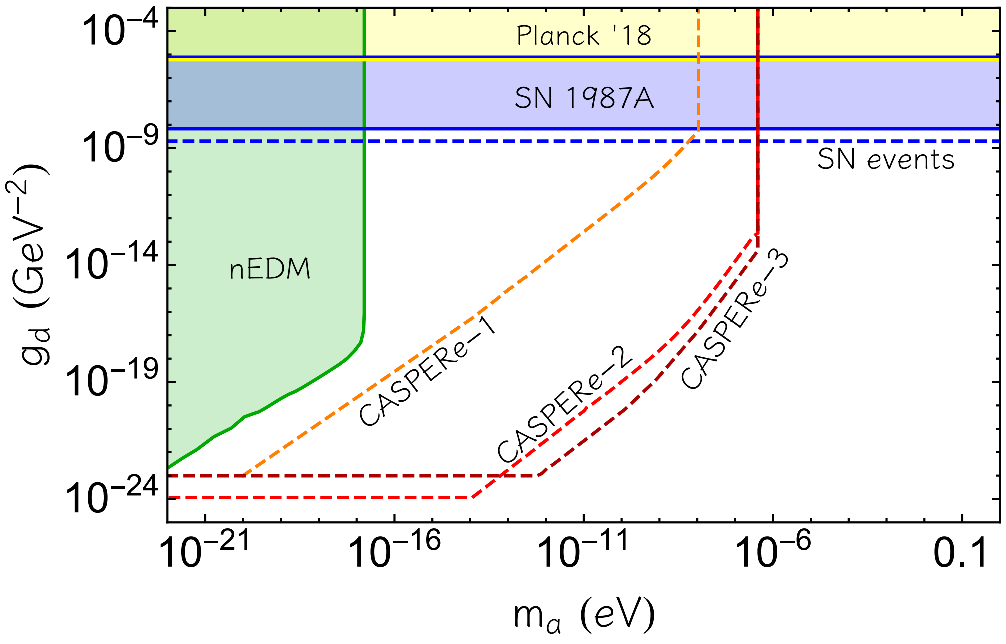
AXION SIGNATURES FROM SUPERNOVA EXPLOSIONS

[Lucente, Carenza, Giannotti, Di Luzio, Mirizzi, Mastrototaro, PRD 105 (2022) 12, 123020)]

$$\mathcal{L}_a^{nEDM} = -\frac{i}{2} g_d \, a \, \bar{N} \gamma_5 \sigma_{\mu\nu} \, N \, F^{\mu\nu}$$ [Graham & Rajendran (2013)]

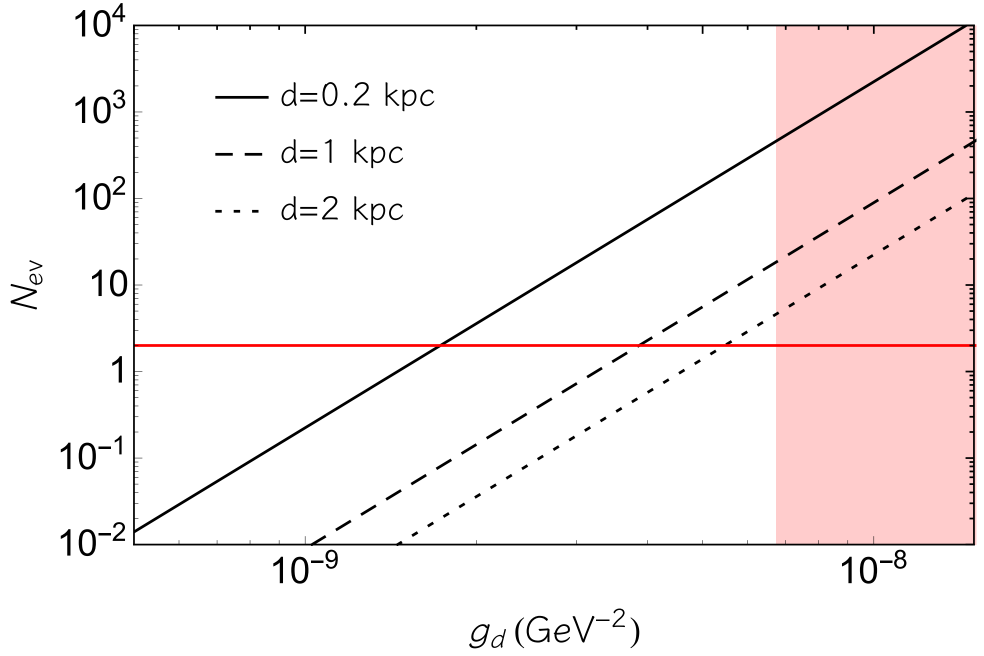
Axion emission must not shorten the observed duration of the SN1987A neutrino burst ➡ Bound on the axion luminosity: [Raffelt & Seckel (1988)]

$L_a \lesssim 3\times10^{52}$ erg/s at 1 s after core bounce



For $g_d \gtrsim 2\times10^{-9}\ \mathrm{GeV}^{-2}$ axions can be detected in future neutrino detectors, such as Hyperkamiokande.

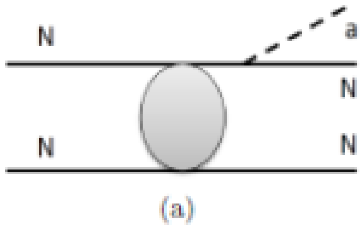
$$a + p \to p + \gamma$$



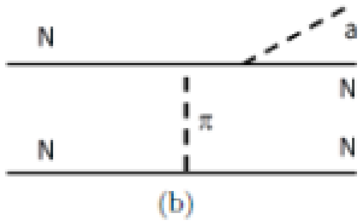
AXION EMISSION FROM A NUCLEAR MEDIUM

- 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), Carenza et al., JCAP 10, 016 (2019), PRD 104, 10 (2021)]

$$NN \rightarrow NNa$$

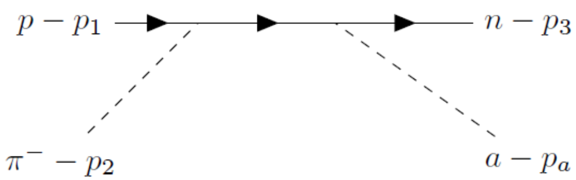


Bulk nuclear interaction



One pion exchange

- Compton pionic processes $\pi^{-} p \rightarrow n\, a$



Initial investigations suggested that the thermal pion population was too small for the pionic reactions to be competitive with the NN process. [Turner, PRD 45, 1066 (1992), Raffelt and Seckel, PRD 52, 1780 (1995), Keil, Janka, Schramm, Sigl, Turner and Ellis, PRD 56, 2419 (1997)] Recent studies show that this contribution can be comparable or larger than the NN one. [Carenza et al., PRL 126, 7 (2021), Lella et al., PRD 107, 10 (2023)]

SN AXION LUMINOSITY

[Lella, Carenza, Co', Lucente, Giannotti, Mirizzi, Rauscher, arXiv: 2306.01048 [hep-ph]]

Modified luminosity criterion [Chang et al., JHEP 01 (2017), JHEP 09 (2018), Caputo et al., PRD 105 (2022)]

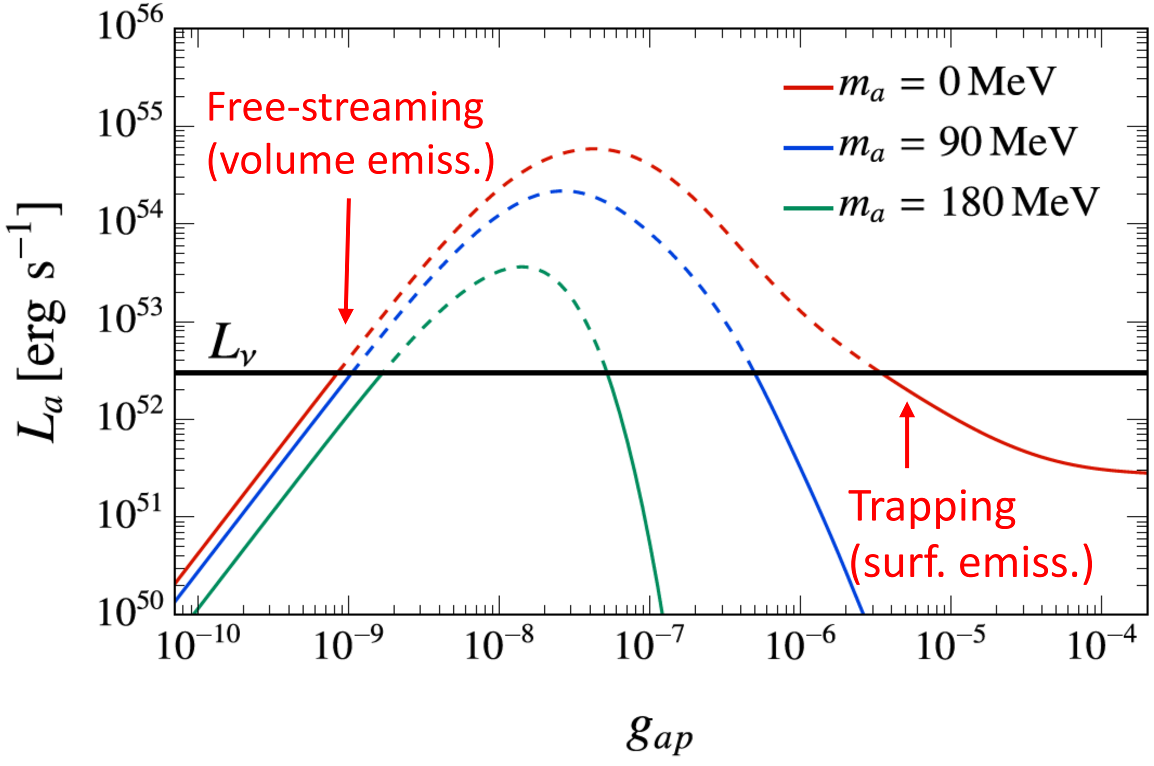
$$L_a = \int_0^\infty 4\pi r^2\, dr \int_{m_a/\alpha}^\infty dE_a\, E_a\, \alpha(r)^2 < e^{-\tau(E_a,r)} > \frac{d^2 n_a}{dE_a dt} \leq L_\nu$$

Integration over SN model

Gravitational redshift

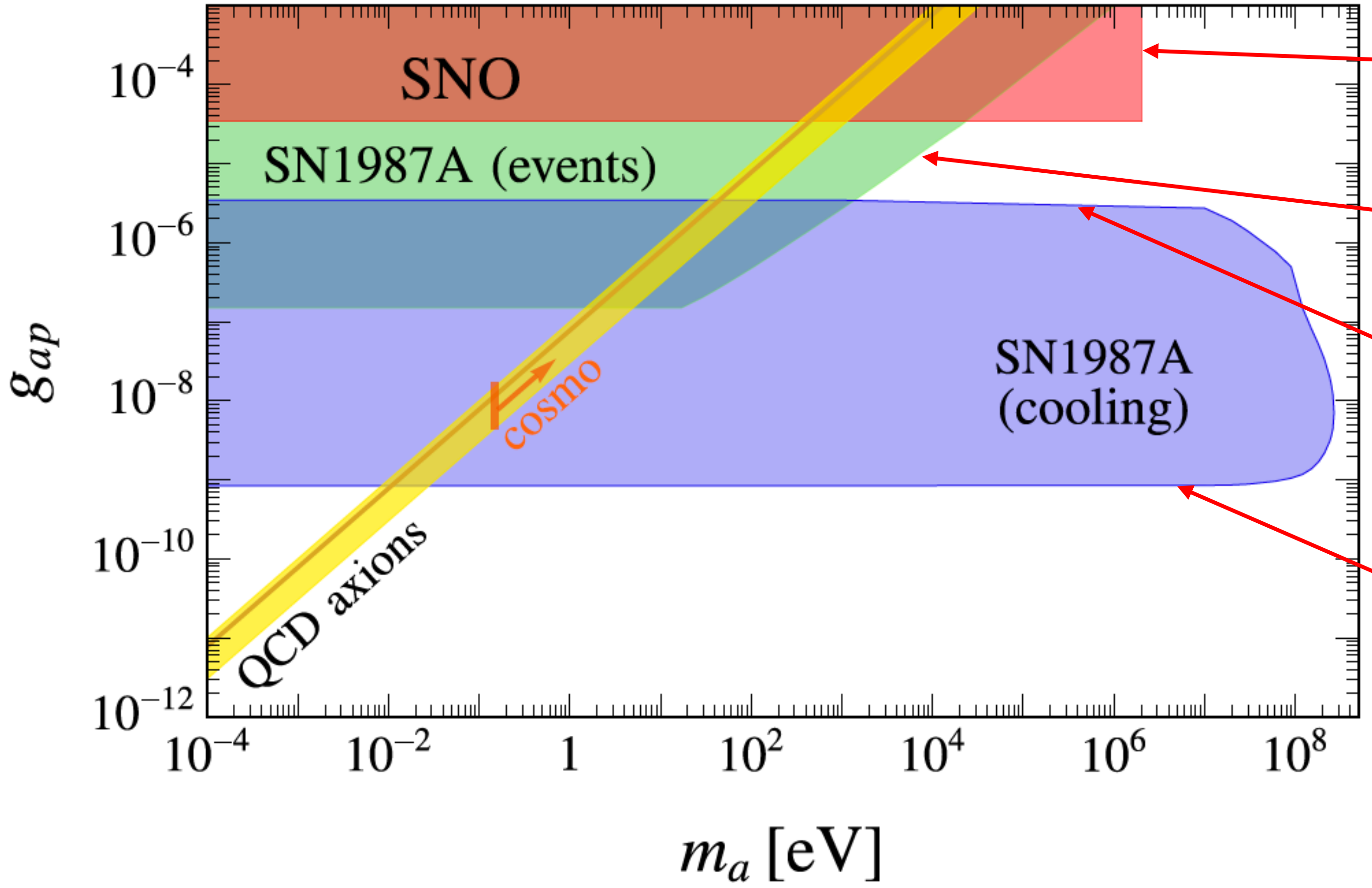
Angle-averaged optical depth

Axion spectrum



SN AXION BOUNDS

[Lella, Carenza, Co', Lucente, Giannotti, Mirizzi, Rauscher, arXiv: 2306.01048 [hep-ph]]



solar axion

$p + d \to {}^3\text{He} + a$ (5.5 MeV)

$a + {}^{16}\text{O} \to {}^{16}\text{O}^* \to {}^{16}\text{O} + \gamma$

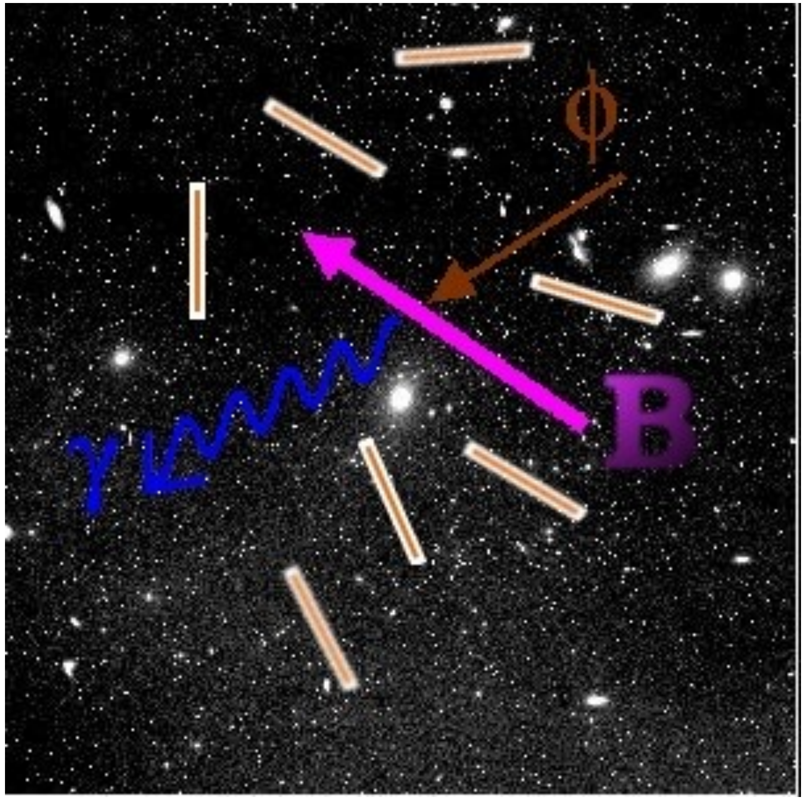
Trapping

Free-streaming

SN bounds exclude $m_a \gtrsim 10^{-2}$ eV ➡ The possibility for cosmological survey to detect a signal of the axion mass is excluded.

AXION-PHOTON CONVERSIONS IN COSMIC B-FIELDS

Photons from cosmic sources can mix with axions in the large scale cosmic magntic fields.

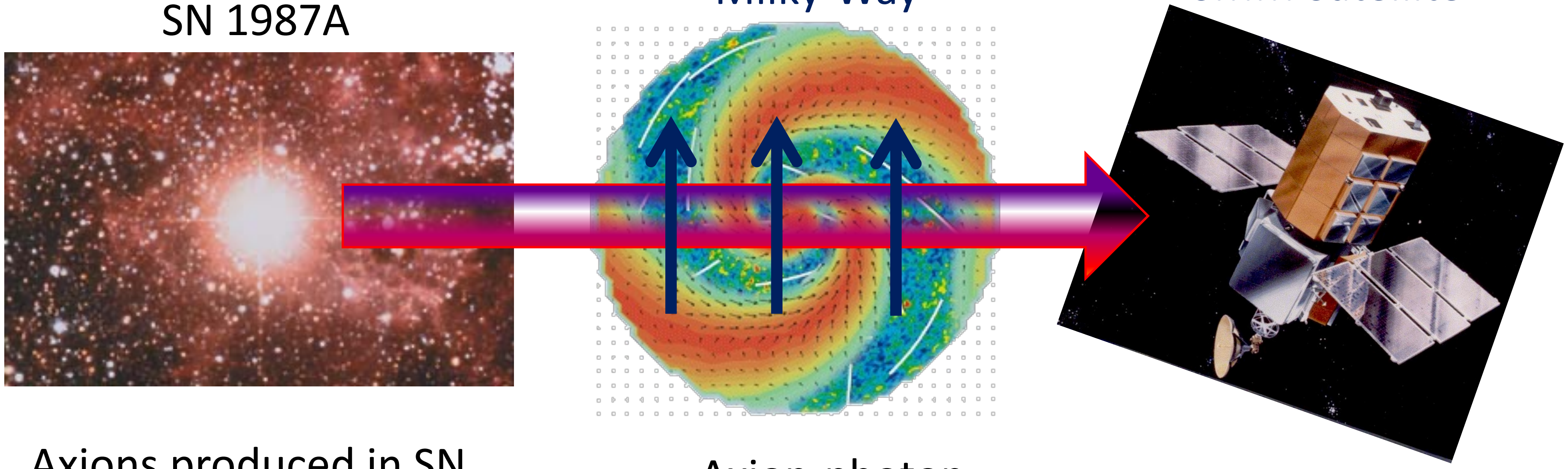


In the last recent years, different constraints and hints of ultralight axions have emerged from various astrophysical observations ranging from CMB to Very High Energy photons.

AXION CONVERSIONS FROM SN 1987A

[Brockway, Carlson, Raffelt, PLB 383 (1996) 439-443, Masso & Toldra PRL 77 (1996) 2372-2375]

SN 1987A | Milky-Way | SMM Satellite



Axions produced in SN core by Primakoff process

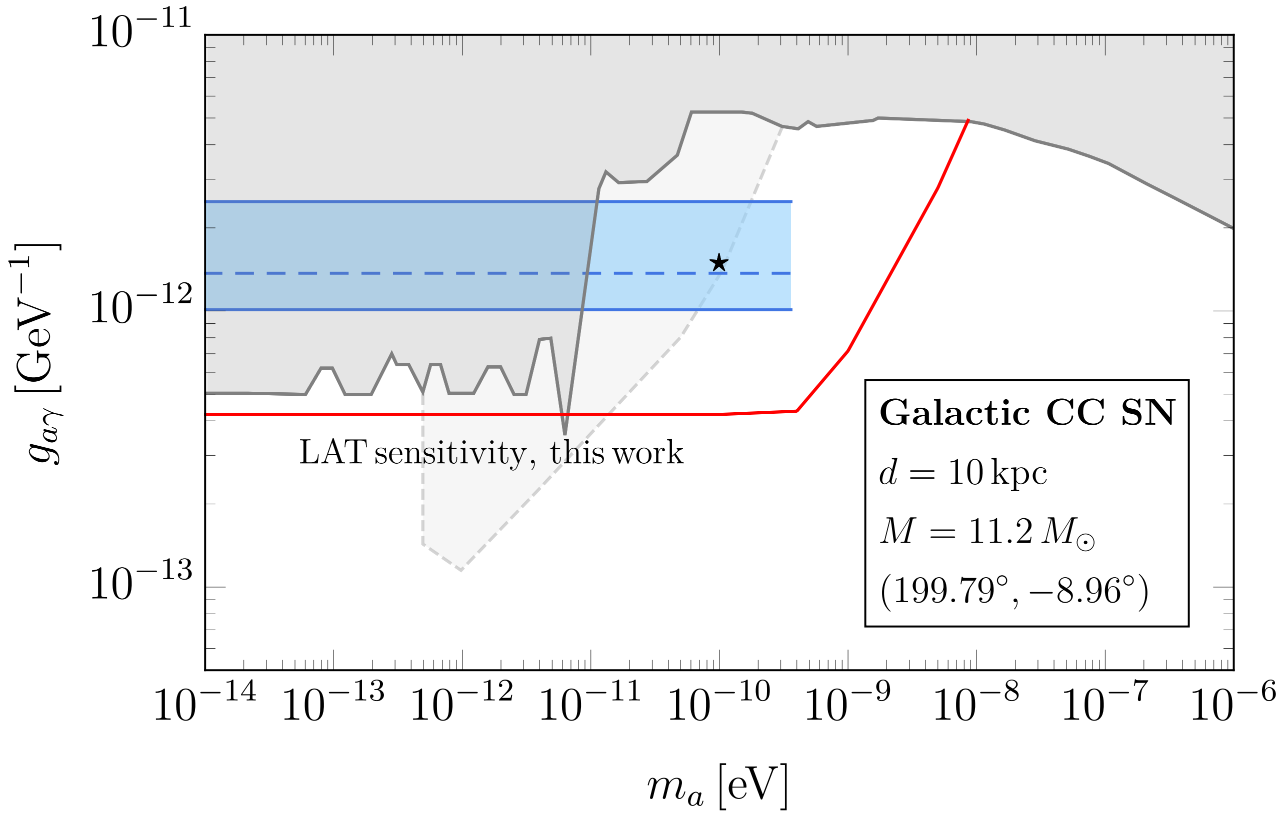
Axion-photon conversions in the Galactic B-fields

No excess gamma-rays in coincidence with SN 1987A

DISCOVERING POTENTIAL OF FERMI-LAT

[Calore, Carenza, Eckner, Giannotti, Lucente, Mirizzi, Sivo, arXiv:2306.03925 [astro-ph.HE]]

We have assessed the sensitivity of Fermi-LAT in the case of future Galactic SN explosion.



In case of signal, Fermi-LAT would reconstruct the axion-photon coupling with a factor ~ 2 uncertainty.

VIRTUAL WORKSHOP

Shoot for the stars,
Aim for the Axions

(4^{th} – 7^{th} October 2022)

Organized by **P. Carenza, G. Lucente**, O. Ghosh (DESY)

Supported by the MITP Youngstars Project

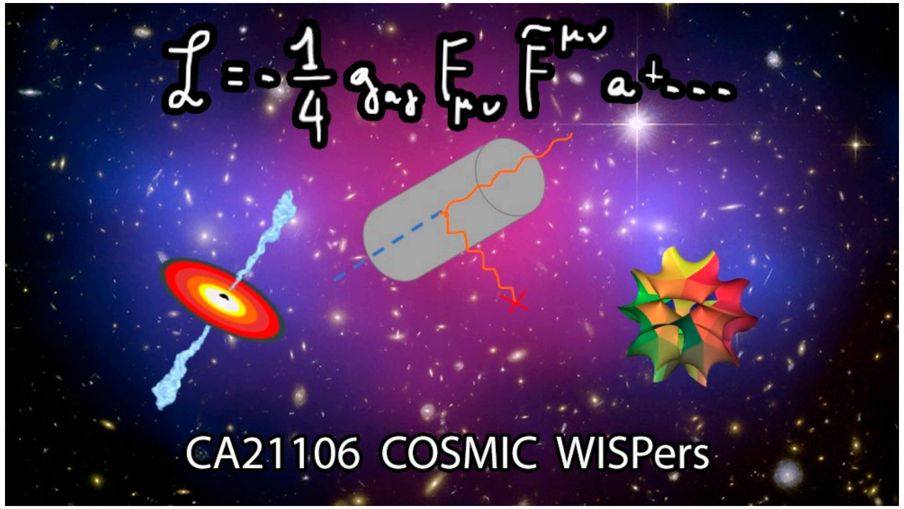
COST ACTION CA21106

COSMIC WISPers in the Dark Universe:

Theory, astrophysics and experiments

Action Chair: Alessandro Mirizzi (Bari Univ, IT)

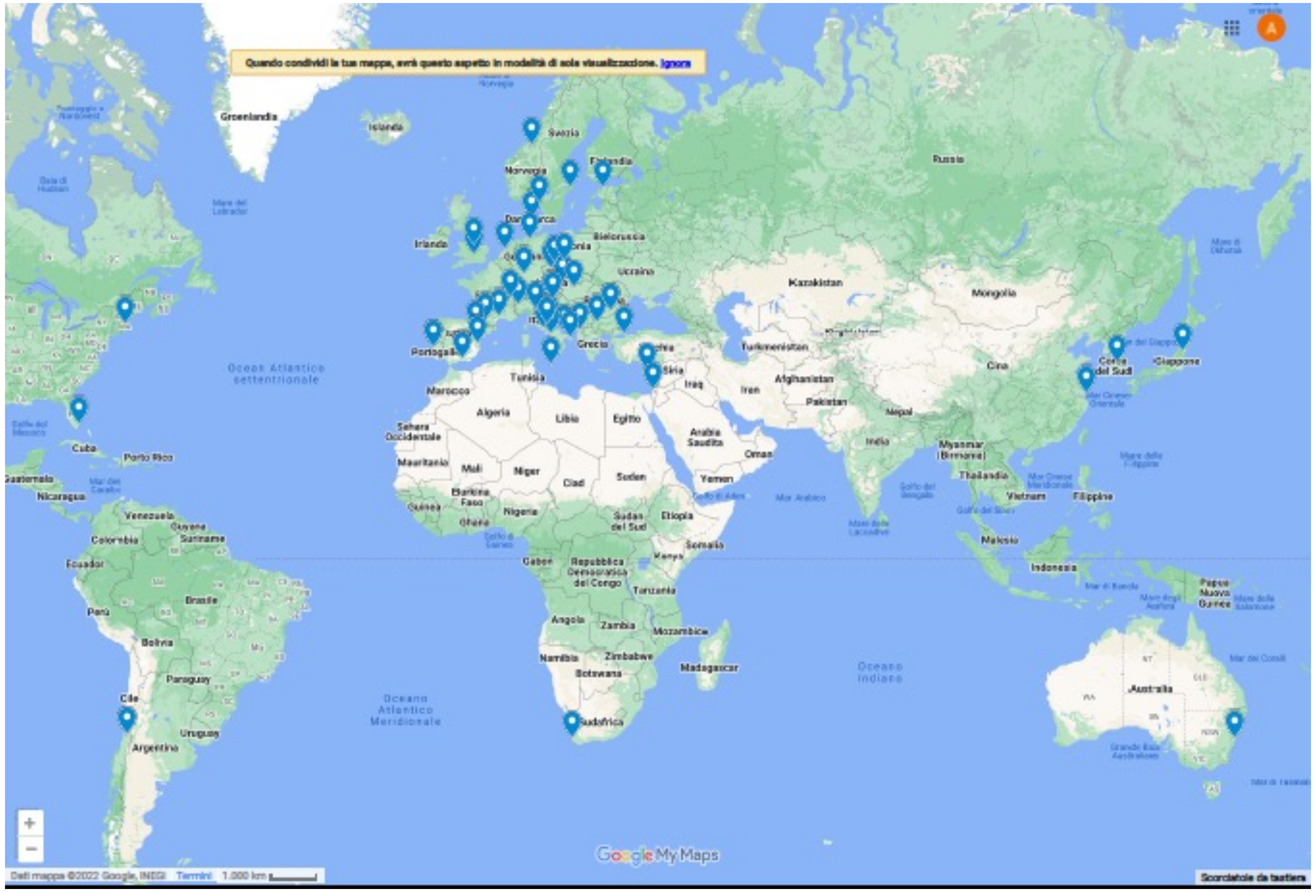
COSMIC WISPERS CA21106



cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

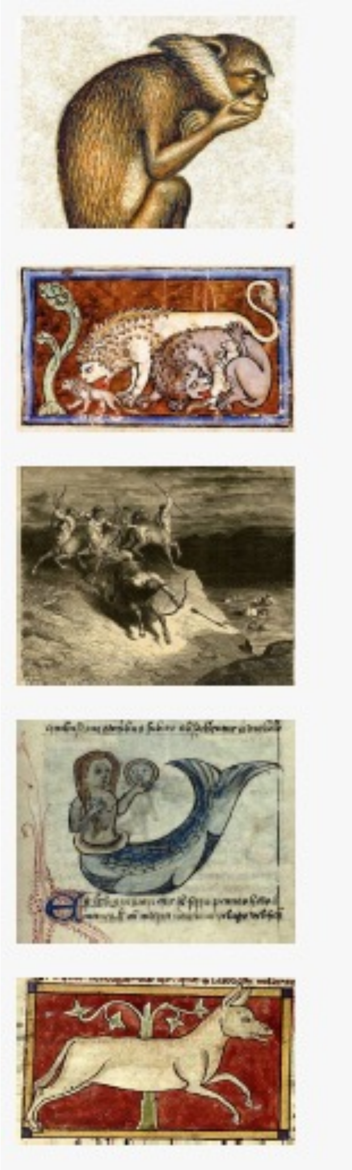
COSMIC WISPers NETWORK



~ 70 proposers

Currently more than 200 participants!

COST Country(25) : Albania , Austria , Bulgaria , Croatia , Cyprus , Czech Republic , Denmark , Estonia , France , Germany , Hungary , Israel , Italy , Malta , Netherlands , Norway , Poland , Portugal , Romania , Slovenia , Spain , Sweden , Switzerland , Turkey , United Kingdom
International Partner Country(7) : Australia, Chile, China, Japan, South Africa, South Korea, United States



WISPs

WISPs are very Weakly Interacting Slim (m<GeV) Particles which emerge in several extensions of the Standard Model of Particle Physics.

CHALLENGE

The aim of this Action is an exhaustive study of these WISPs, notably axions, axion-like particles (ALPs) and dark photons, ranging from their theoretical underpinning, over their indirect observational consequences in astrophysics, to their search at colliders and beam-dump and their direct detection in laboratory experiments.

2023 EVENTS

22-23 Febr: Kick-off Meeting
(Frascati, IT)

5-8 Sept: General Meeting + MC Meeting
(Bari, IT)

11-14 Sept: Training School
(Lecce, IT)