Astrophysical transient constraints on BSM physics

Dark Matter and Cosmic Rays
Napoli, Italy
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Stuff that happens in little time in the sky

Astrophysical transient constraints on BSM physics

Particles with mass below the GeV scale

Matter and Cosmic Rays

2024

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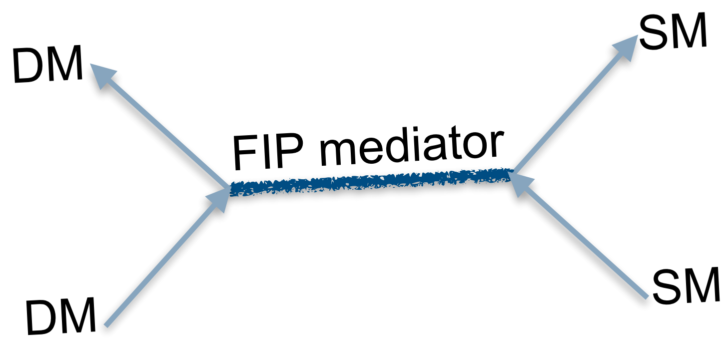
Crises in particle physics

Known unknowns

- Nature of dark matter
- Neutrino masses
- Matter-antimatter asymmetry
- Many others (inflation, nature of dark energy, Hubble tension, $g_\mu - 2 \ldots$)

Why sub-GeV FIPs?



- Could be DM mediators → information on DM-SM cross sections (Pospelov et al. *Phys. Lett. B* 662 (2008) 53, Knapen et al. *Phys. Rev. D* 96 (2017) 115021 etc.)
- Can be top-down inspired (Hook et al. *Phys.Rev.Lett.* 124 (2020) 22, 221801, Di Luzio et al. *Phys.Rept.* 870 (2020) 1-117 etc.)
- Relation to particle-physics conundra (neutrino masses, secret ν interactions, $g_\mu - 2$, string theory etc.) (Chen et al. *Phys. Rev. D* 95 (2017) 115005, Svrcek & Witten JHEP 06 (2006) 051, Arvanitaki et al. *Phys.Rev.D* 81 (2010) 123530)

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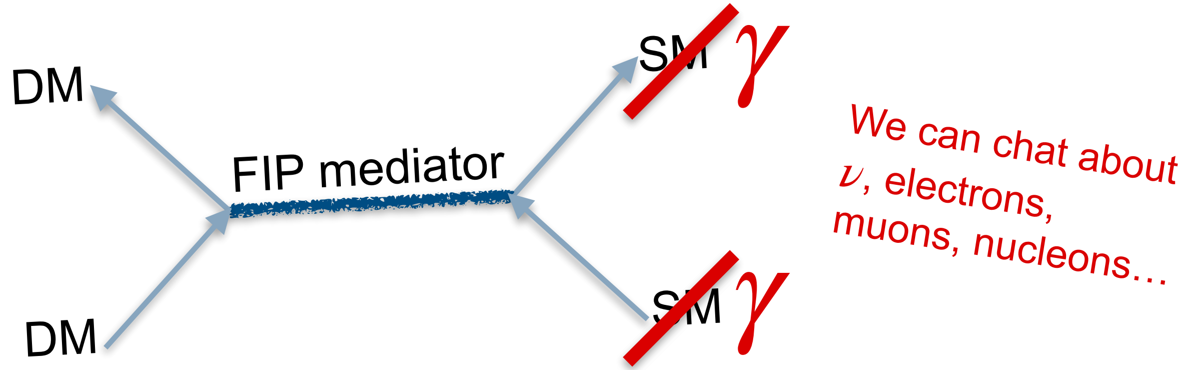

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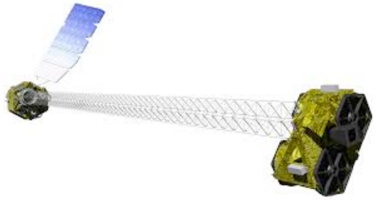
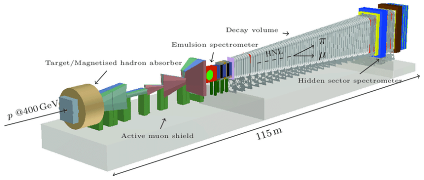
Discovering sub-GeV FIPs

Decay length

Universe size ⟷ ~100 Meters

Cosmo probes | Beam dumps





Discovering sub-GeV FIPs

$\times 10^{25}$

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Universe size

~100 Meters

Cosmo probes

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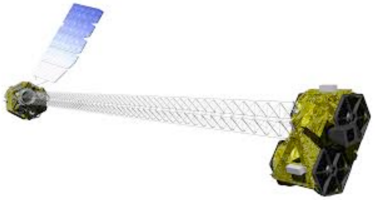

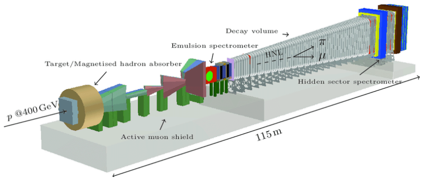

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???

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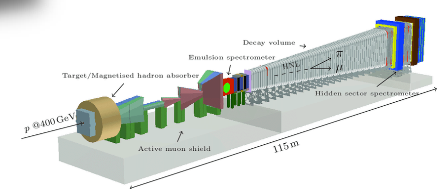

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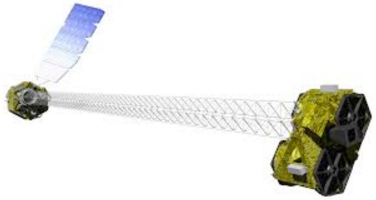
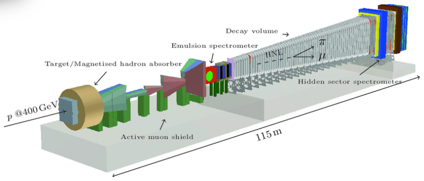
Cosmo probes



ASTROPHYSICAL TRANSIENTS

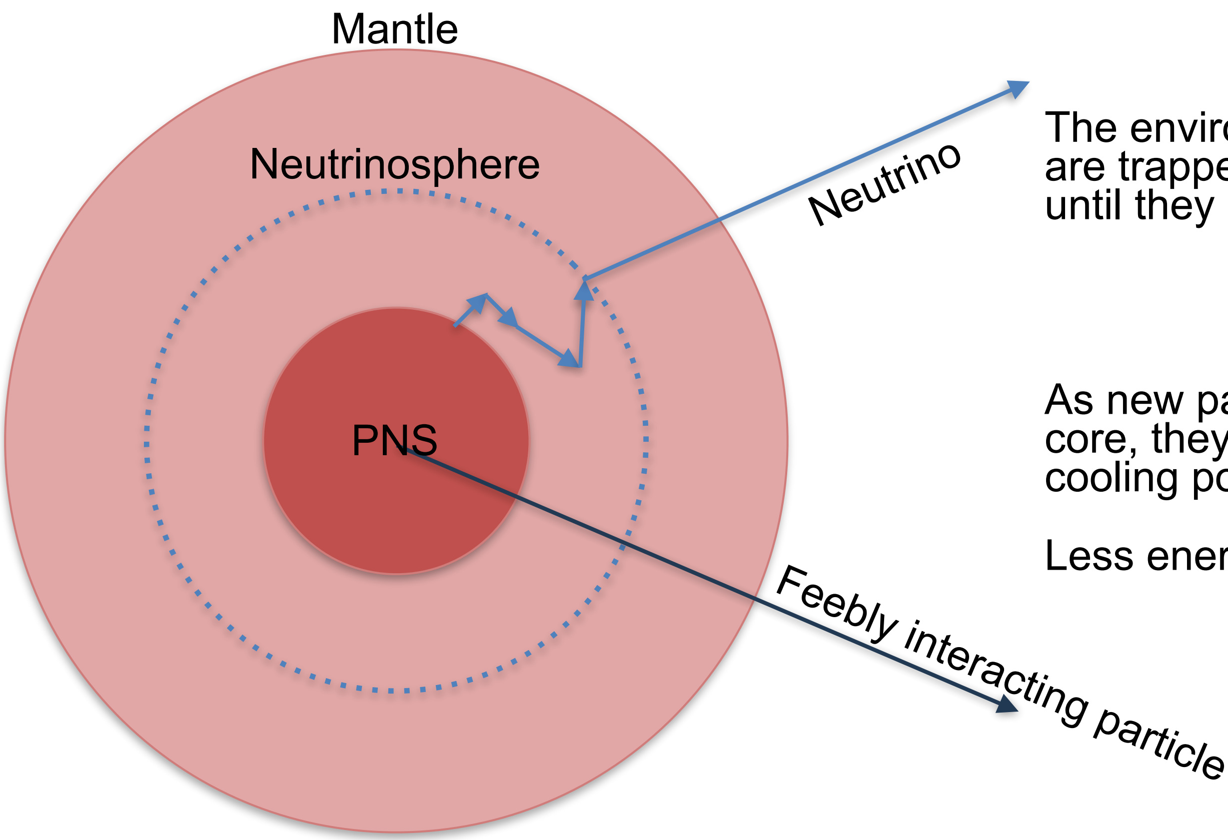
~100 Meters

Beam dumps



Energy loss bounds from supernovae

The existence of a feebly interacting particle can affect the duration of the neutrino signal of a supernova



The environment is so dense neutrinos are trapped and cannot escape freely, until they reach the neutrinosphere

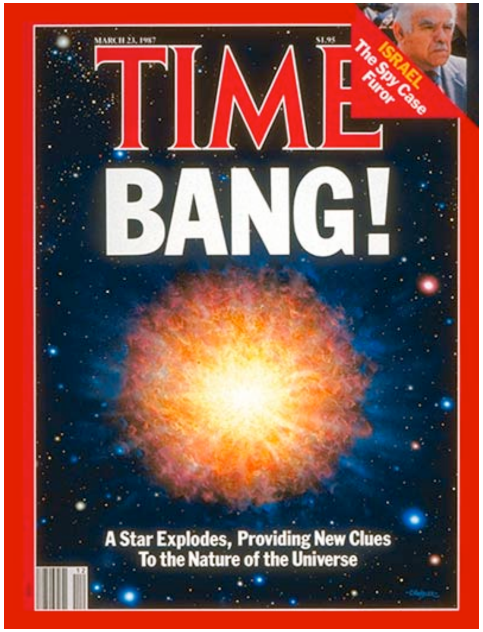
As new particles are produced in the core, they take away energy from the cooling porto-neutron star

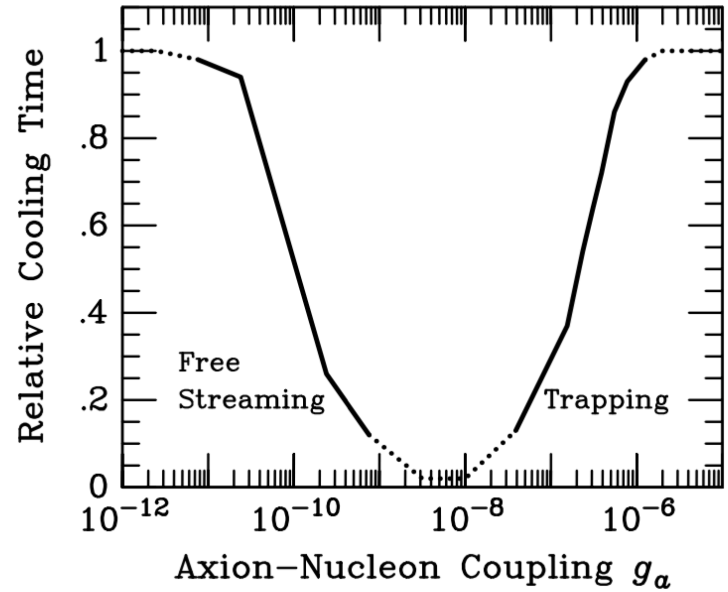
Less energy available to neutrinos!

PNS:

- $T_{\text{surface}} = \mathcal{O}(10\,\text{MeV})$
- $T_{\text{core}} \gg T_{\text{surface}}$
- $\rho = 3 \times 10^{14} \text{g/cm}^3$

Energy loss bounds from supernovae

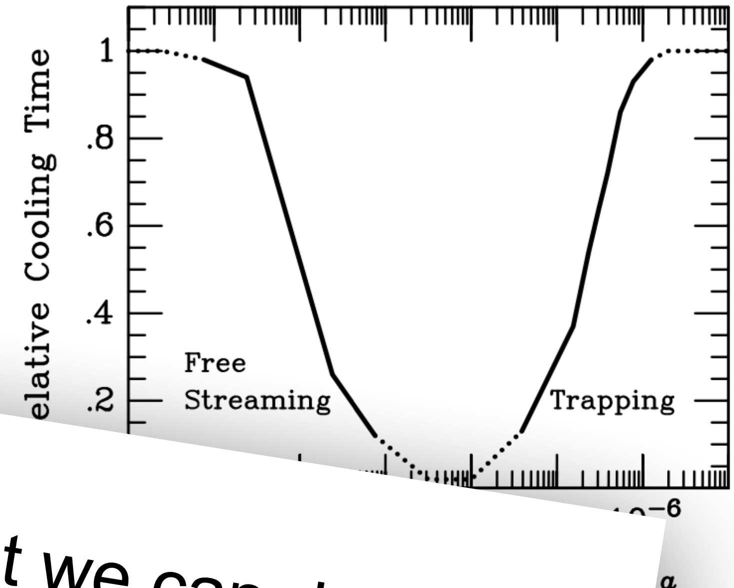




Raffelt (1994)

- The emission of new particles affect the cooling time of the protoneutron star
- Several papers in the 1980s (1D simulations with an energy sink) found the relative cooling time (right figure, axion-nucleon coupling).
  Observable: duration of the neutrino signal at IMB and KII

Energy loss bounds from supernovae



Is this the best we can do?

- The emission of new particles affect the cooling time

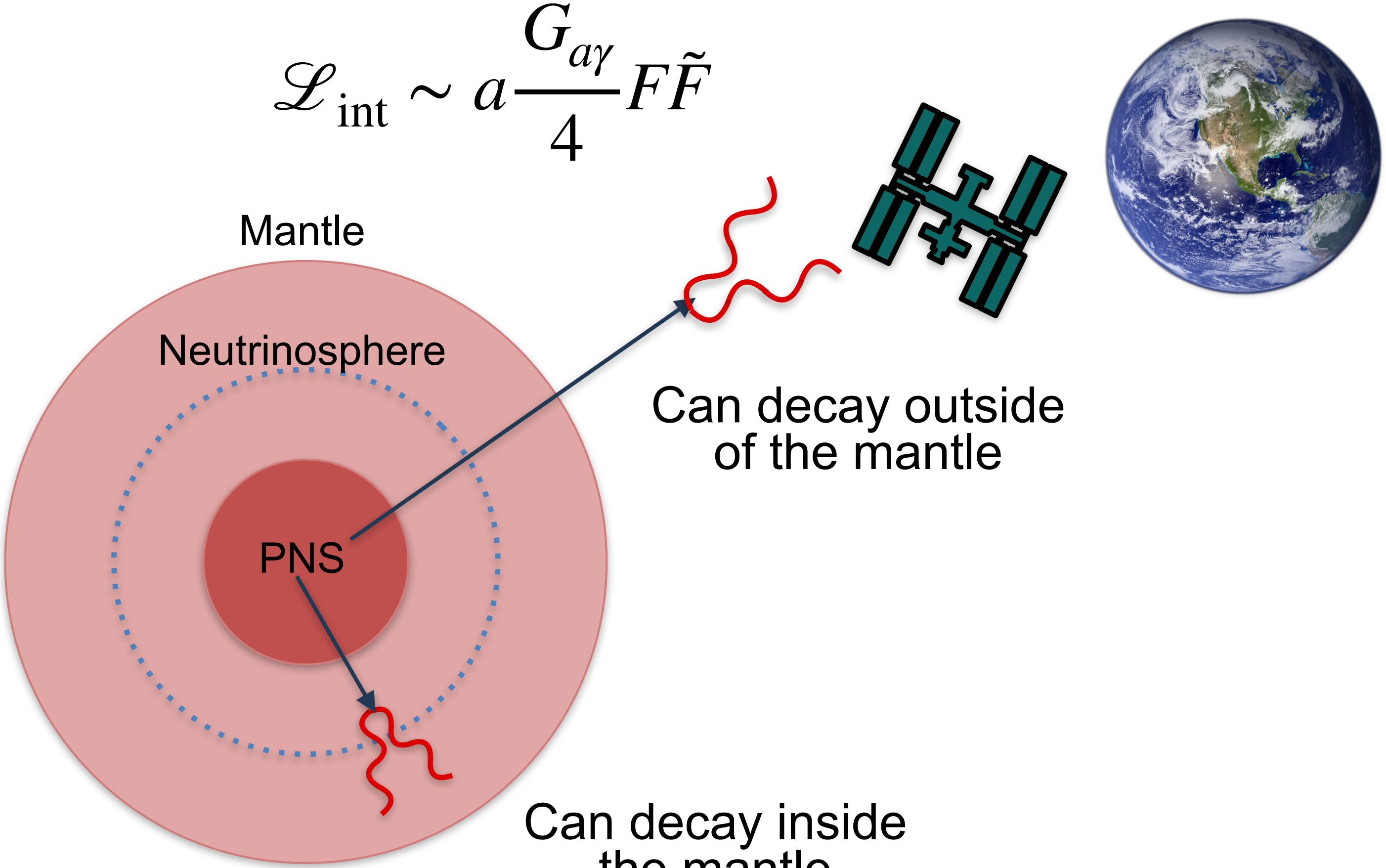
- Several papers in the 1980s (1D simulations with an energy sink) found the relative cooling time (right figure, axion-nucleon coupling).
  Observable: duration of the neutrino signal at IMB and KII

Look for different observables

Supernovae (and other transients) are far (a long baseline for **conversion** or **decay**) and **hot/dense** (they can produce **heavy feebly interacting particles**)

Axion-like particles with a coupling to photons at tree-level or at one-loop

$$\mathscr{L}_{\text{int}} \sim a \frac{G_{a\gamma}}{4} F\tilde{F}$$



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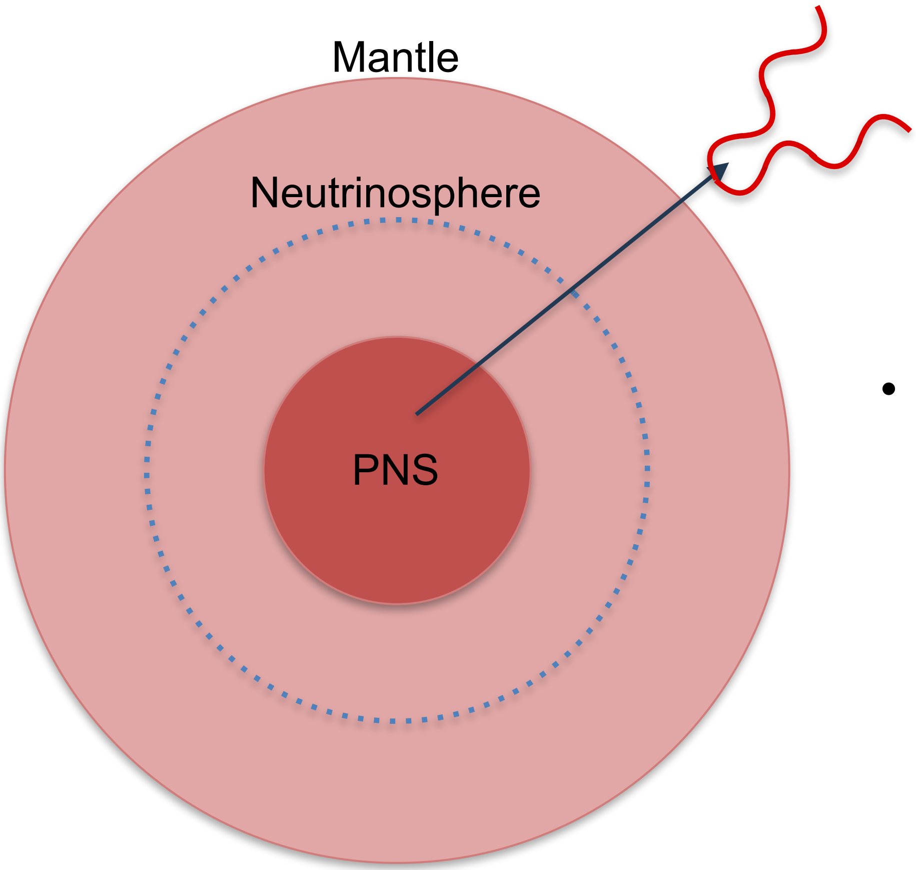


- **Gamma-ray decay** observed by the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite that operated 02/1980–12/1989

Oberauer et al. Astropart.Phys. 1 (1993) 377-386
Chupp et al. *Phys.Rev.Lett.* 62 (1989) 505-508
Jaeckel et al., Phys.Rev.D 98 (2018) 5, 055032
Caputo, Raffelt, **Vitagliano**, *Phys.Rev.D* 105 (2022) 3, 035022
Hoof and Schulz (2022)

- They also create a **diffuse** from all the SNe in the history of the universe

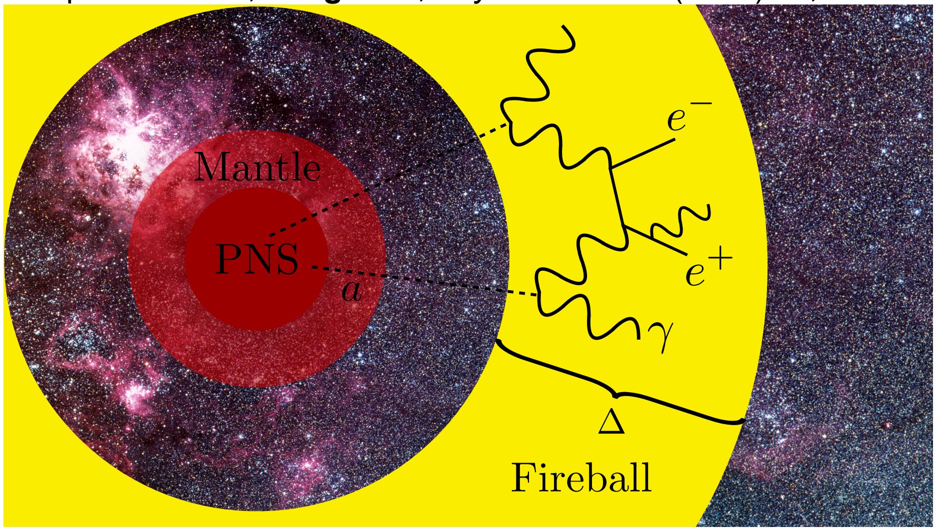
Calore et al. Phys. Rev. D 102 (2020) 123005
Caputo, Raffelt, **Vitagliano**, *Phys.Rev.D* 105 (2022) 3, 035022

BUT…

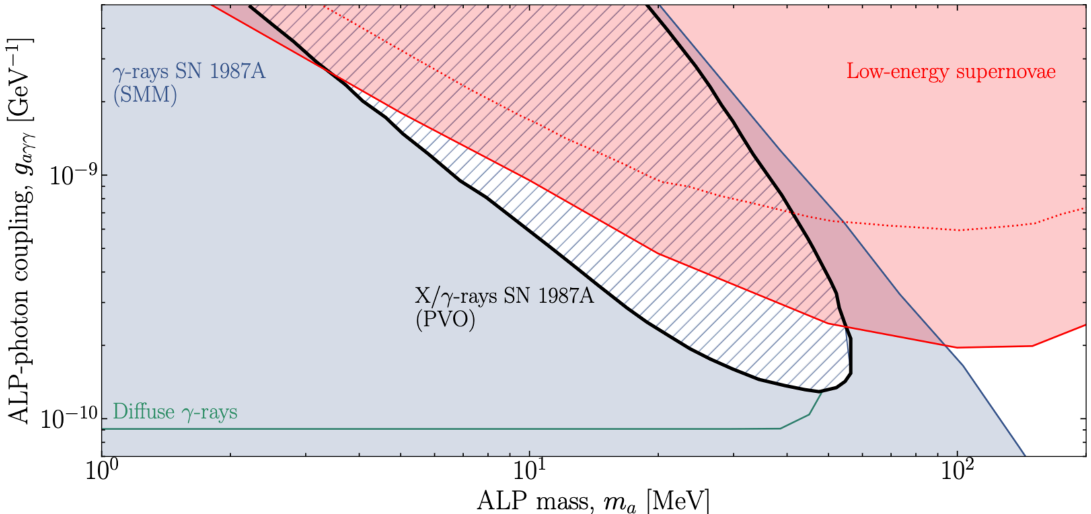
Long lifetimes: fireball formation

Editors' Suggestion

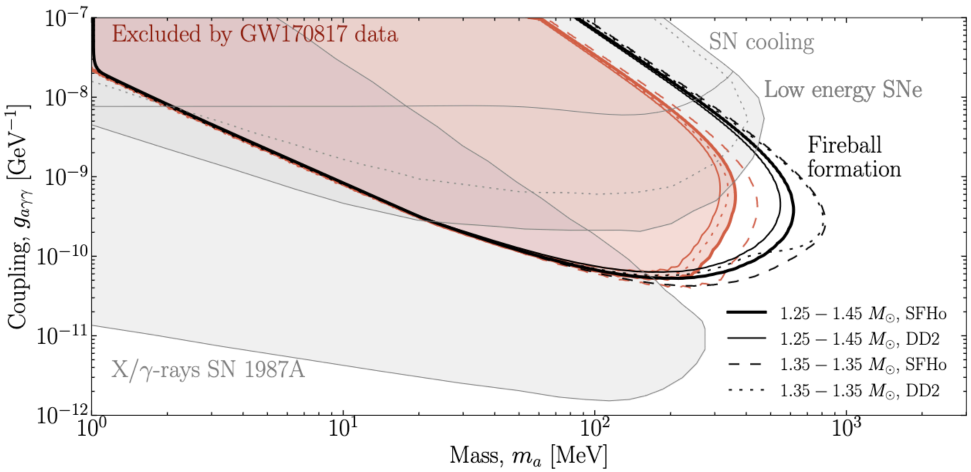
Diamond, Fiorillo, Marques-Tavares, **Vitagliano**, *Phys.Rev.D* 107 (2023) 10, 103029



- The bounds from decay to gamma-ray do not apply everywhere!
- For a large region of masses and couplings, axions form a fireball
- The expected flux is at much smaller frequencies
- New bounds from Pioneer Venus Observatory

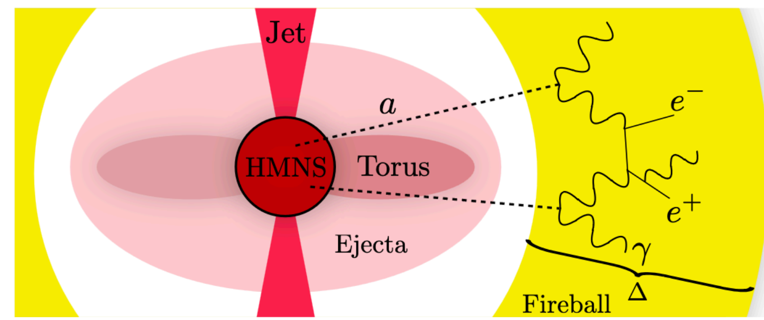


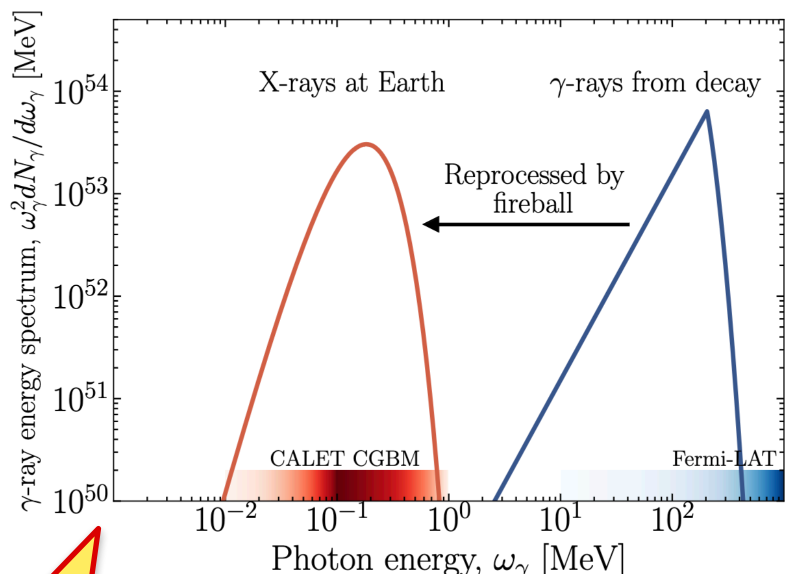
Bounds from GW170817



Diamond, Fiorillo, Marques-Tavares, Tamborra, **Vitagliano**, *Phys.Rev.Lett.* 132 (2024) 10, 10

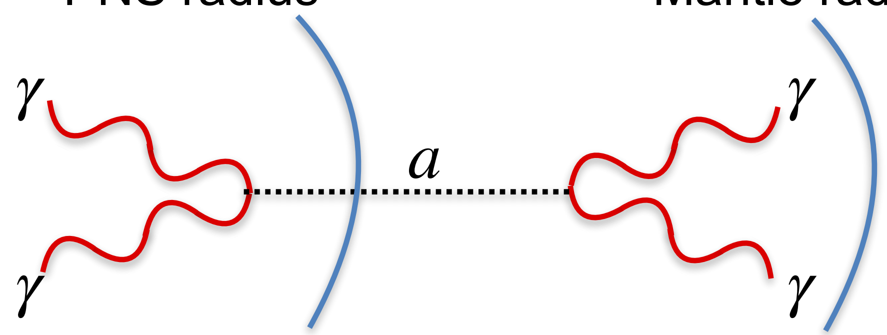
- Neutron star mergers produce a heavy mass NS remnant without a mantle!
- Huge temperature and densities
- Extremely sensitive measurements by X-ray detectors of GW 170817
- Fresh bounds on $m_a > 1\,\mathrm{MeV}$ axions



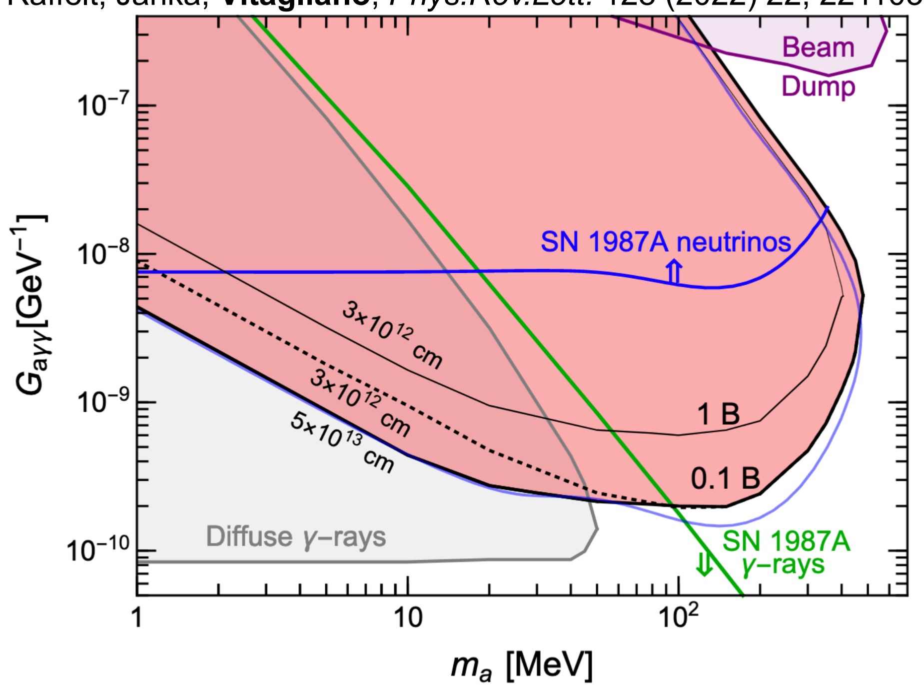


Brand new! 2023

Short lifetimes: New bound from decay in the mantle



Caputo, Raffelt, Janka, **Vitagliano**, *Phys.Rev.Lett.* 128 (2022) 22, 221103

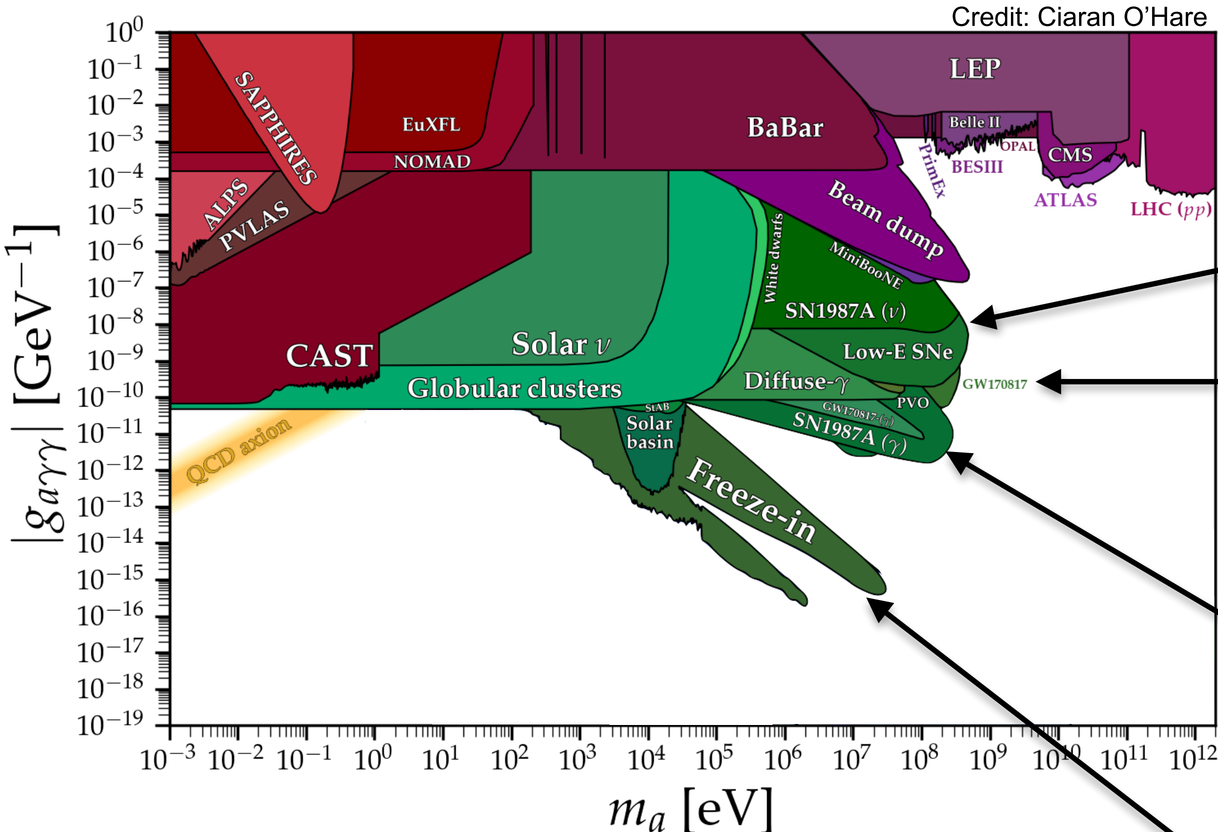


- Neutron star binding energy 200-400 B
- Some SNe have very small observed explosion energies < 0.1 B
- New restrictive limits from low-energy SNe

$1\ \mathrm{B\ (bethe)} = 10^{51}\ \mathrm{erg}$

Conclusions

Axion-like particles with photon coupling



Heats up the mantle of low-energy SNe
(see Caputo, Raffelt, Janka, **Vitagliano**, *Phys.Rev.Lett.* 128 (2022) 22, 221103)

GW170817
(see Diamond, Fiorillo, Marques-Tavares, Tamborra, **Vitagliano**, *Phys.Rev.Lett.* 132 (2024) 10, 10)

SN 1987A at SMM and PVO
(see Diamond, Fiorillo, Marques-Tavares, **Vitagliano**, *Phys.Rev.D* 107 (2023) 10, 103029)

Cosmo bounds lowest $T_{\rm RH}$
(see Langhoff, Outmezguine, Rodd *Phys.Rev.Lett.* 129 (2022) 24, 241101)

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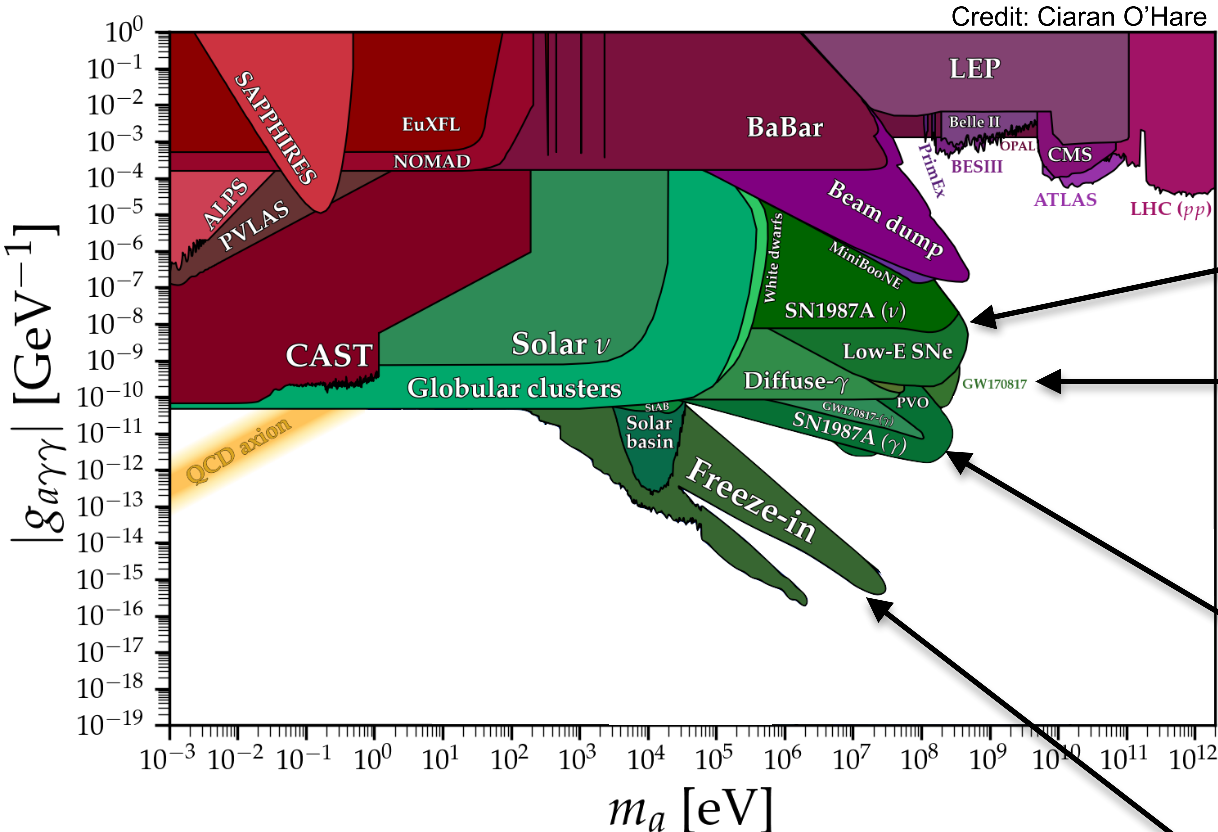

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Resonant production and subsequent decay in rare events

see e.g. Axions from Hypernovae,
Caputo, Carenza, Lucente, **Vitagliano** et al. *Phys.Rev.Lett.* 127 (2021) 18, 181102

Conclusions

Sub-GeV particles can be probed with astrophysics (axion, majoron, ALP…).
Astro bounds cover the gap between beam dumps and cosmology

Novel observables have been proposed in the last ~2 years

- Energy deposited in the mantle of *low-energy SNe*
- *Fireballs* from SN and NS mergers
- *Energy spectrum* of the neutrino flux from galactic Supernovae
- *Time and flavor information* of the detected events can be used to reconstruct the model

ν OR MATTER COUPLINGS!

Outlook

- High-frequency GW detection
- New ideas for DM detection (selected superconductors, conducting polymers, novel modes…)
- Revisiting astrophysical bounds with new results in nuclear physics, thermal field theory…
- Neutron-star mergers as laboratories of particle physics

Apply these bounds to your favorite model!
New gauge bosons, dark photons, sterile neutrinos, scalars…
And let us hope for a discovery!