Credits: SN 1987A ESO (eso0708a), ESA/Euclid/Euclid Consortium/NASA

Astrophysical transient bounds on Feebly Interacting Particles

Invisibles Workshop 2024
Bologna, Italy
July 4, 2024

Edoardo Vitagliano
edoardo.vitagliano@unipd.it
University of Padua


Credits: SN 1987A ESO (eso0708a), ESA/Euclid/Euclid Consortium/NASA

Stuff that happens in little time in the sky

Astrophysical transient bounds on Feebly Interacting Particles

Particles with mass below the GeV scale

Invisibles Workshop 2024

Edoardo Vitagliano
edoardo.vitagliano@unipd.it
University of Padua

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)
- FIPs can have couplings to different SM particles (e.g. Bauer et al. *JHEP* 12 (2017) 044)

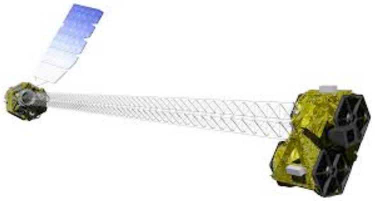
Discovering sub-GeV FIPs

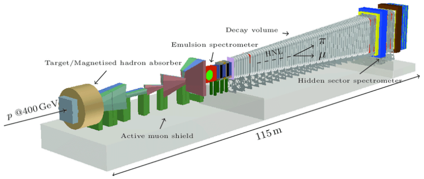
Mean free path

Universe size ←→ ~Meters

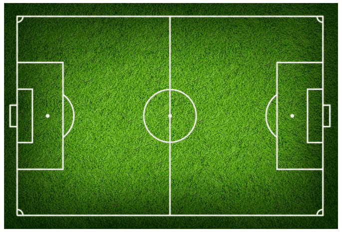
Cosmo probes

Beam dumps

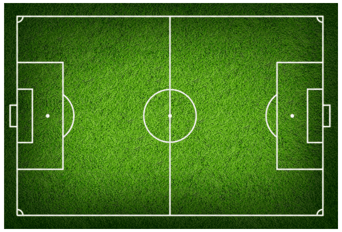




Discovering sub-GeV FIPs



$\times 10^{25}$



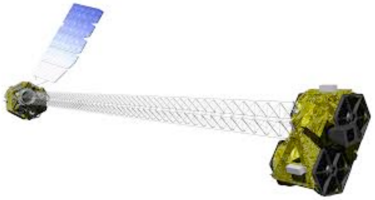
Mean free path

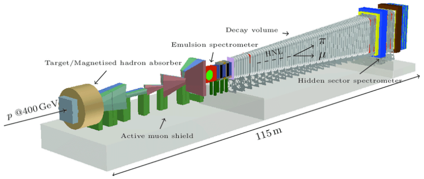
Universe size

~Meters

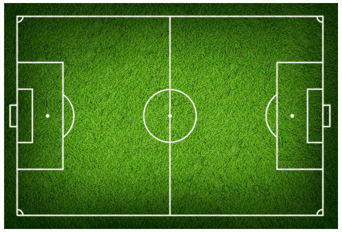
Cosmo probes

Beam dumps

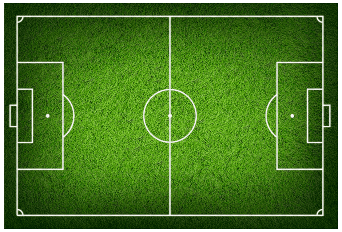




Discovering sub-GeV FIPs



$\times 10^{25}$



Mean free path

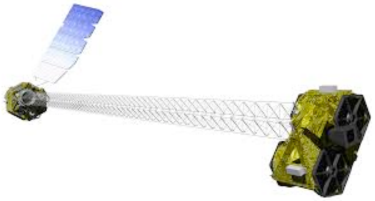
Universe size

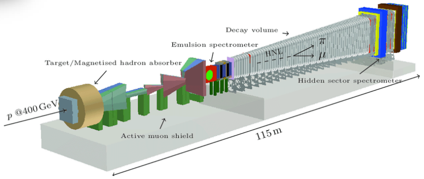
~Meters

Cosmo probes

???

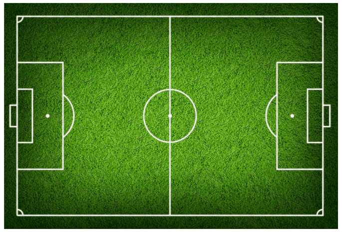
Beam dumps





Discovering sub-GeV FIPs

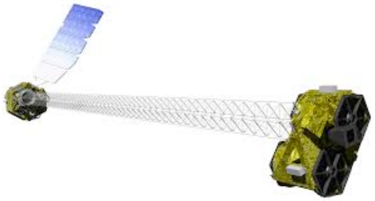
Mean
free
path



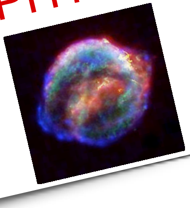
$\times 10^{25}$

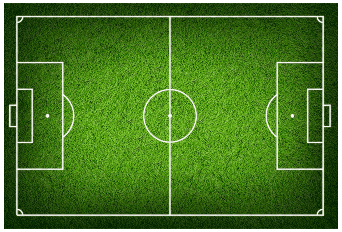
Universe size

Cosmo probes



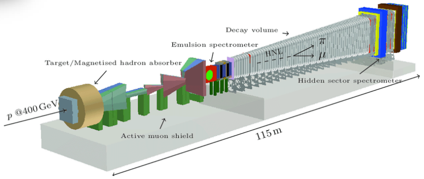
ASTROPHYSICAL TRANSIENTS





~Meters

Beam dumps



Take home messages

Take home messages

Light masses (DM candidates), $m_{\rm FIP} \lesssim 1\,{\rm keV}$

- Stellar bounds still the most constraining in large part of the parameter space

Heavy(ish) masses (DM mediators), $m_{\rm FIP} \gtrsim 1\,{\rm keV}$

- Look for other observables in other cases—decays!
- Best bounds on new feebly interacting particles coupling to photons, charged leptons, or neutrinos
- Supernovae and neutron star mergers can produce particles up to the GeV scale—cover the gap between beam dumps and cosmology

Cooling bounds (30+ years old)

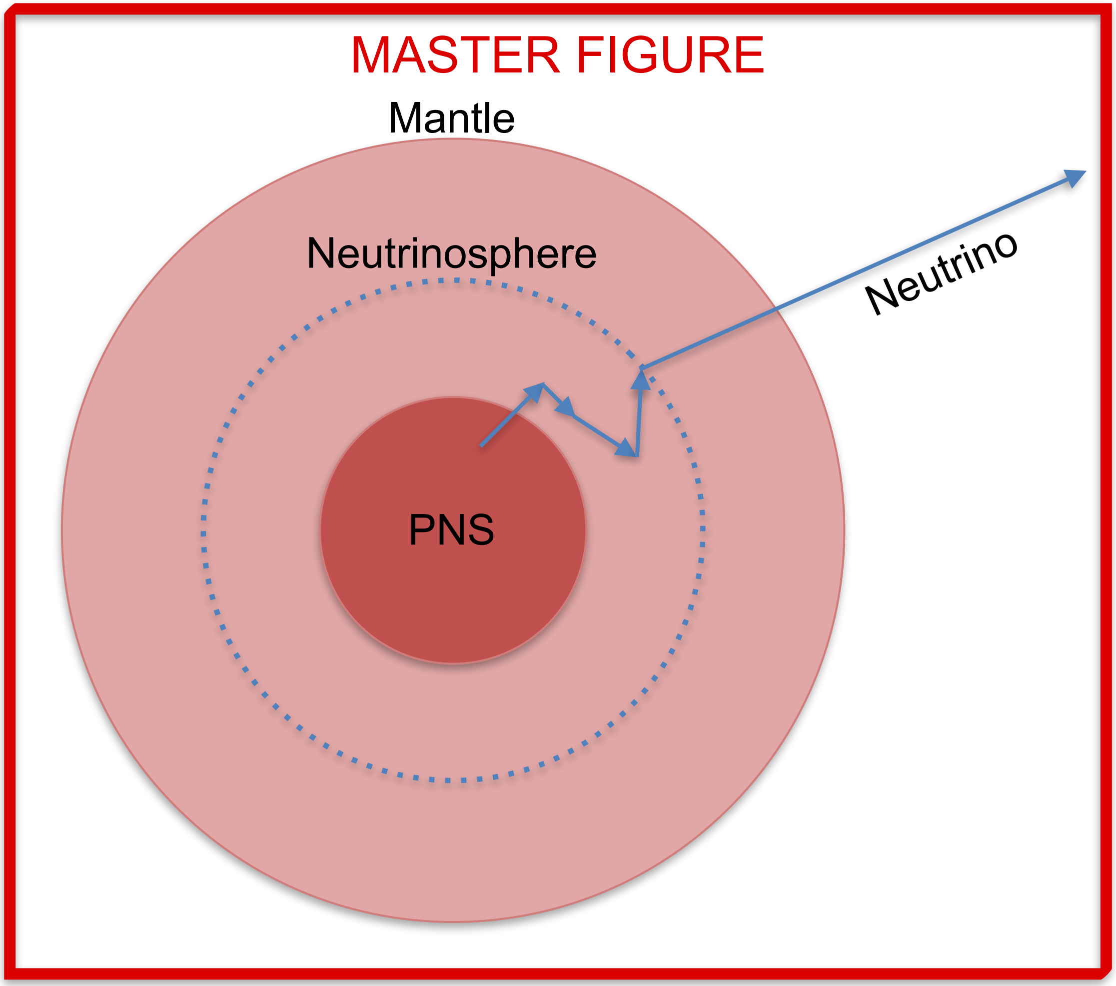
Stellar collapse

Protoneutron star, it has

- $T_{\text{surface}} = \mathcal{O}(10\,\text{MeV})$
- $T_{\text{core}} \gg T_{\text{surface}}$
- $\rho = 3 \times 10^{14}\text{g/cm}^3$
- $R_{\text{PNS}} = 20\,\text{km}$

And produce many neutrinos,

- $L_\nu = 3 \times 10^{53}\text{erg/3s}$
- Energy deposited: 1%
- Signal duration $\tau \simeq 10\,\text{s}$



(Analogous to photons in the Sun)

Energetic of the neutrino signal

We can get a feeling without simulations of the signal

The expected energy, flux, and duration of the neutrino signal can be evaluated roughly:

$$E_{\mathrm{binding}} \simeq \frac{3}{5}\frac{GM^2}{R} = 1.60 \times 10^{53}\,\mathrm{erg}\left(\frac{M}{M_\odot}\right)^2\left(\frac{10\,\mathrm{km}}{R}\right)$$

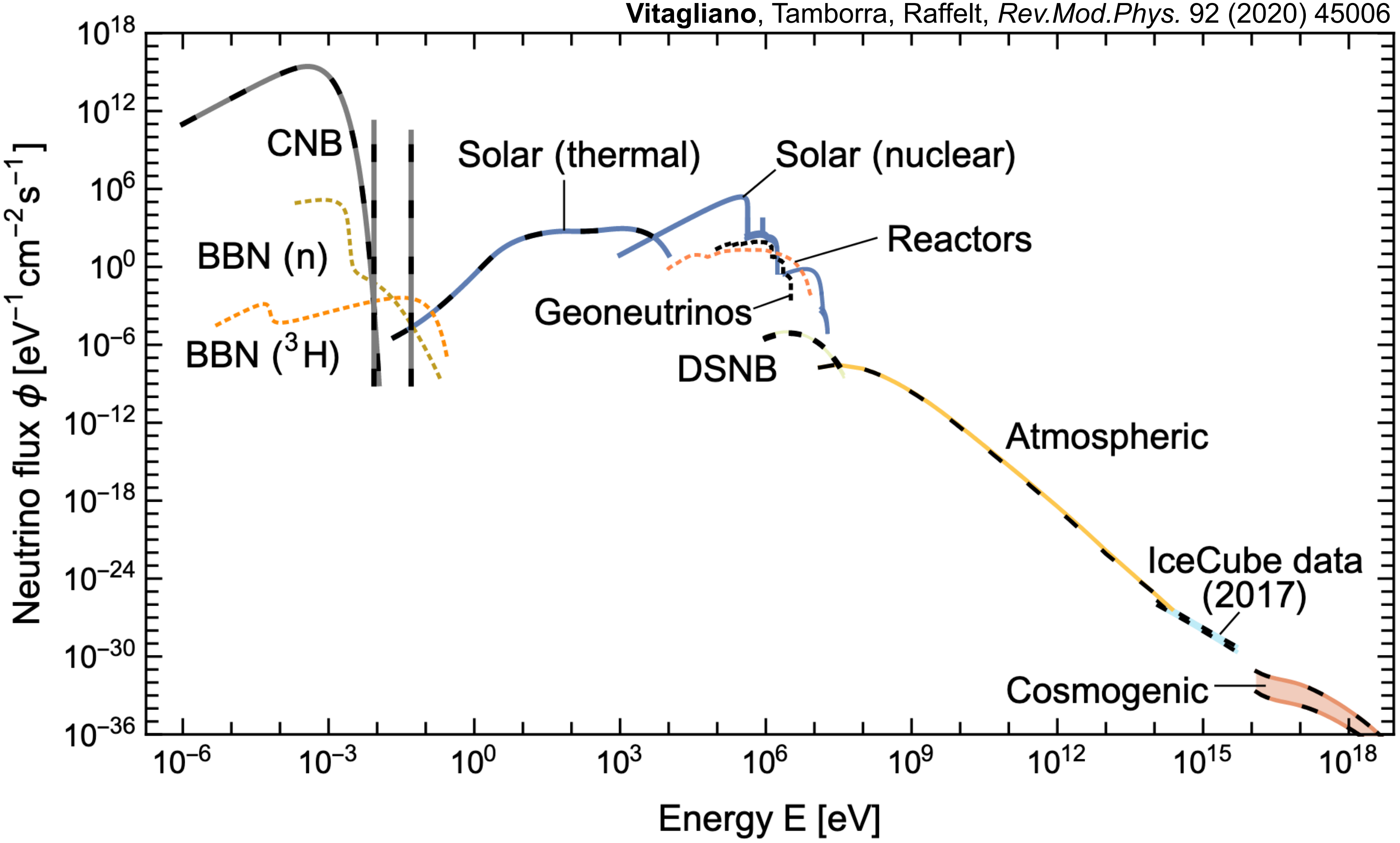
$$M \simeq 1.4 M_\odot, R = 15\,\mathrm{km} \to T = \frac{2}{3}\langle E_{\mathrm{kin}}\rangle \simeq 17\,\mathrm{MeV}$$

$t_{\mathrm{diff}} \simeq R^2/\lambda \simeq \mathcal{O}(10\mathrm{s})$ with caveats

Therefore: $0.5 \times 10^{53}\,\mathrm{erg}$ for each neutrino species, with energies $\mathcal{O}(10\,\mathrm{MeV})$ and a signal of $\mathcal{O}(1-10\,\mathrm{s})$

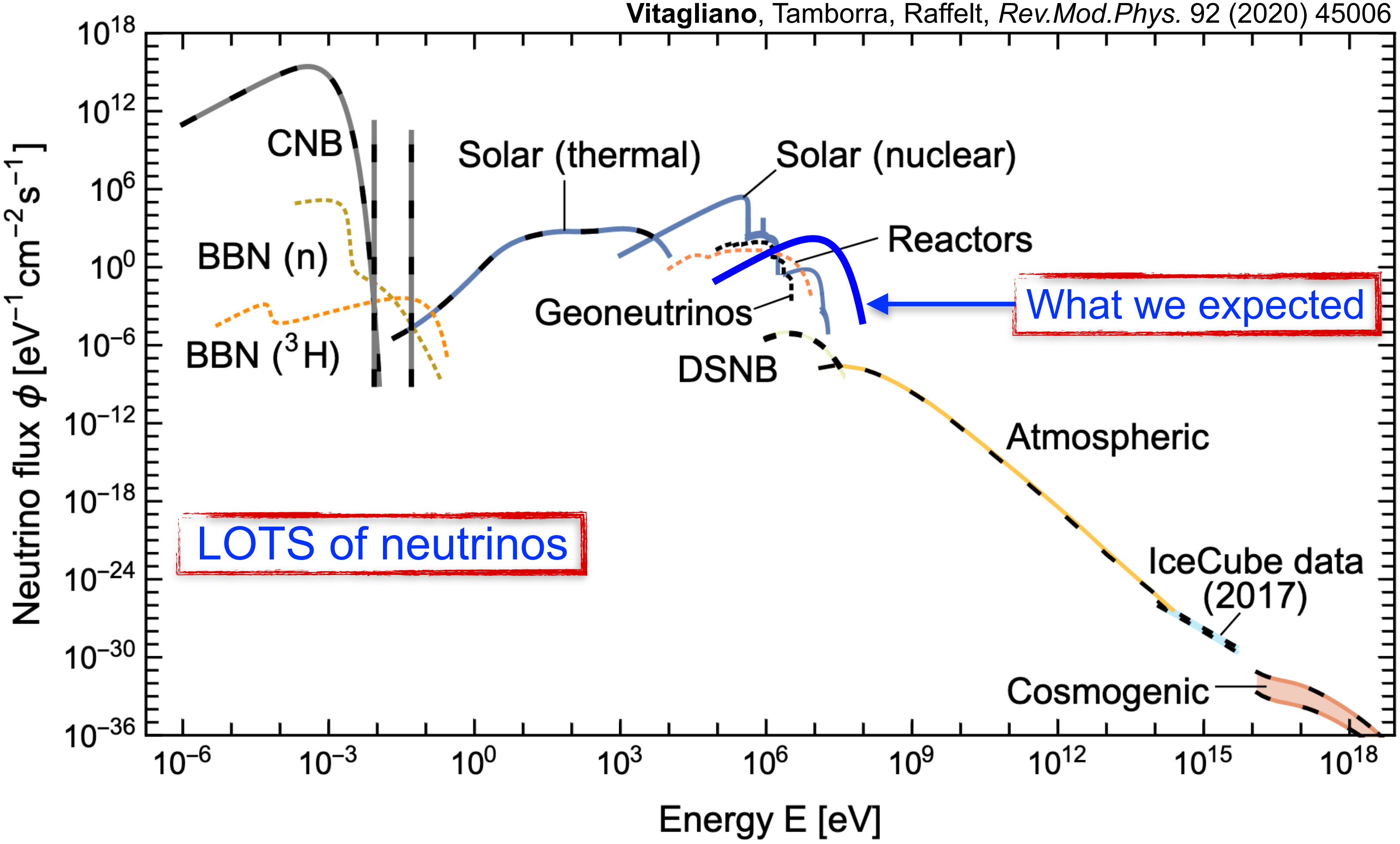
Grand unified neutrino spectrum at Earth

Vitagliano, Tamborra, Raffelt, *Rev.Mod.Phys.* 92 (2020) 45006



Grand unified neutrino spectrum at Earth

Vitagliano, Tamborra, Raffelt, *Rev.Mod.Phys.* 92 (2020) 45006



What we expected

LOTS of neutrinos

Tables available to produce your own GUNS plot on arXiv & supplemental material

Credit: Anglo-Australian Observatory

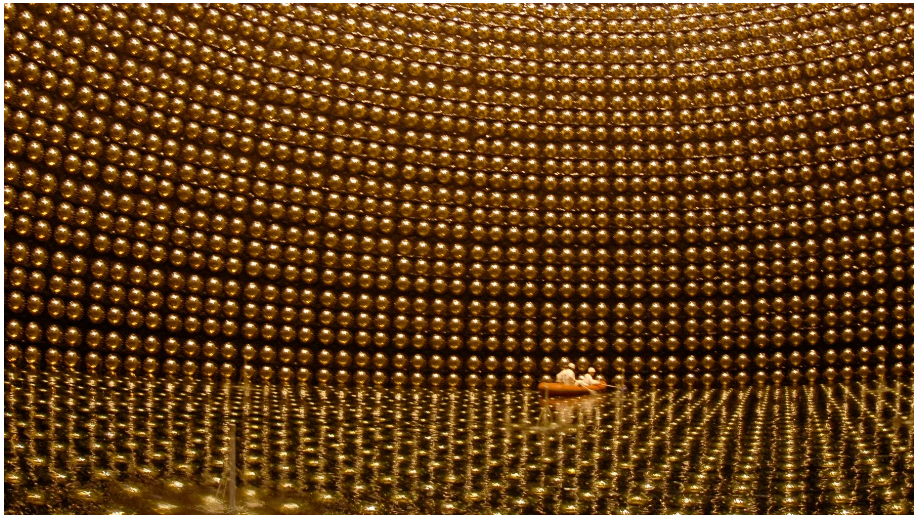
Credit: Anglo-Australian Observatory

SN 1987A Neutrino Observations

- Several **neutrino experiments were able to see events**
- **Cherenkov detectors:** Irvine-Michigan-Brookhaven (IMB) and Kamiokande II
- **Scintillator detectors:** Baksan Scintillator Underground Telescope (BUST), Liquid Scintillation Detector (LSD)

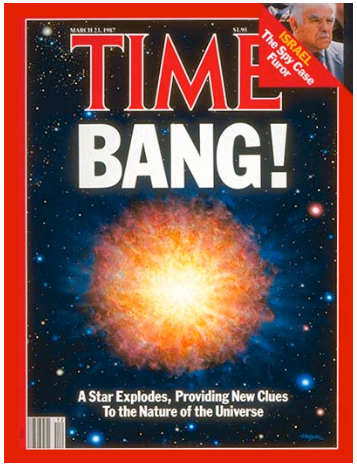
MOTHERBOARD
TECH BY VICE

Why Neutrino Detectors Look So Damn Cool



Credit: Super-Kamiokande

SN 1987A Neutrino Observations



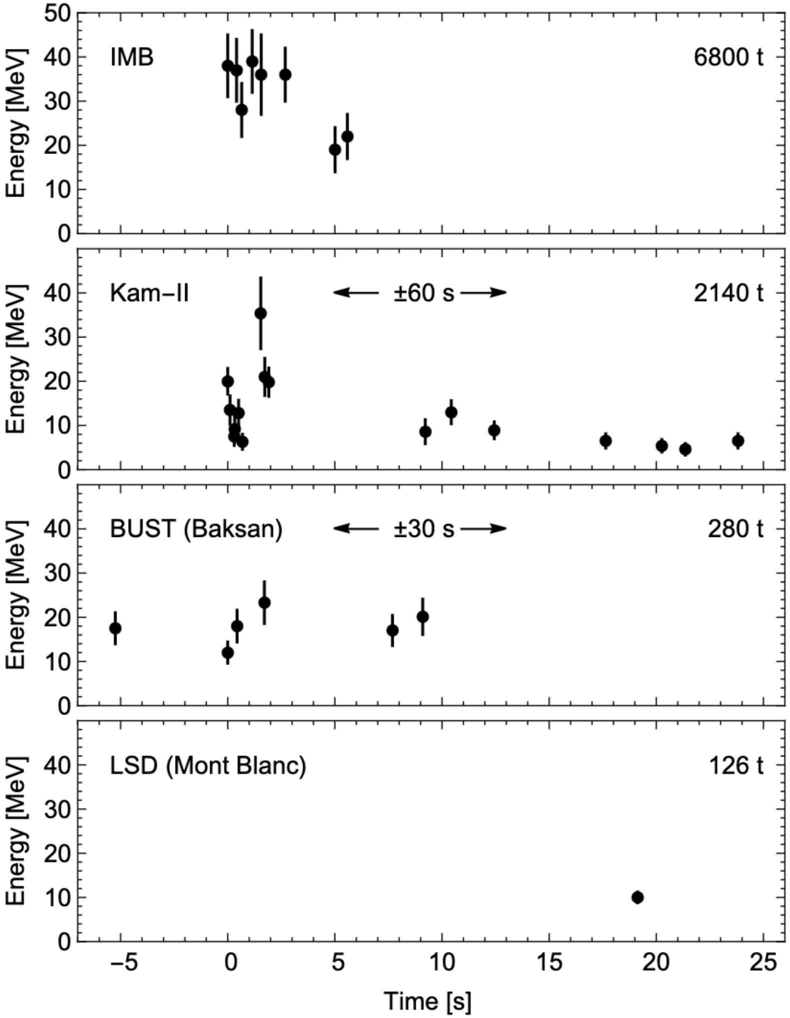
MARCH 23, 1987 $1.95

TIME

ISRAEL The Spy Case Furor

BANG!

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



2002 Nobel prize to Masatoshi Koshiba (Kamiokande)

2015 Nobel prize winner Takaaki Kajita was a postdoc there

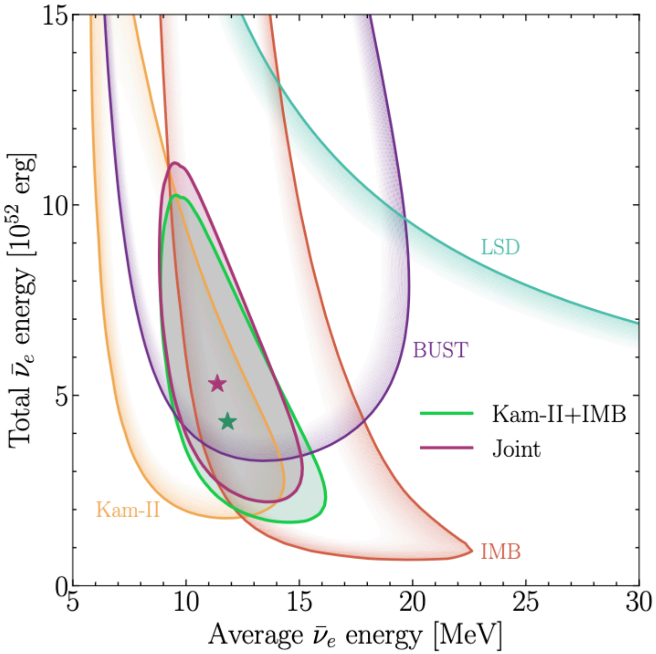
New comparisons to SN simulations from several groups

- Li, Beacom, Roberts, Capozzi (2023)
- Fiorillo, Heinlein, Janka, Raffelt, **Vitagliano**, Bollig (2023)

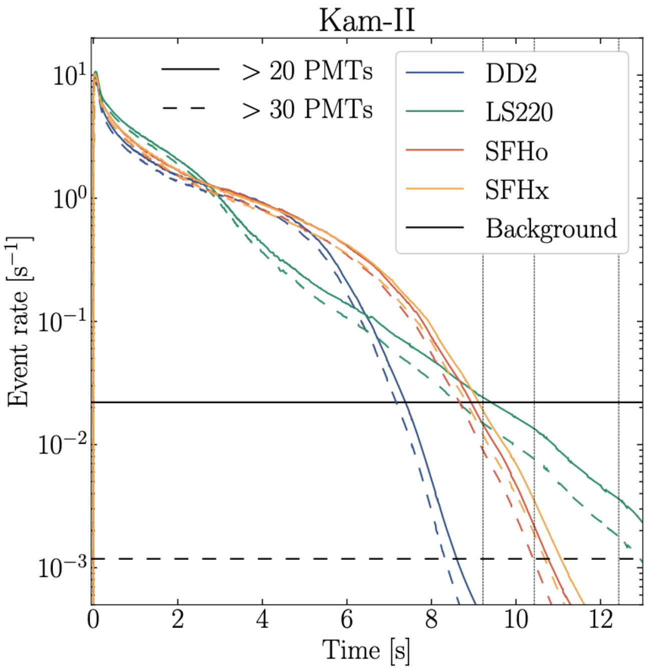
SN 1987A Neutrino Observations

New comparisons to SN simulations from several groups

- Li, Beacom, Roberts, Capozzi (2023)
- Fiorillo, Heinlein, Janka, Raffelt, **Vitagliano**, Bollig (2023)



Fiorillo, Heinlein, Janka, Raffelt, **Vitagliano**, Bollig (2023)

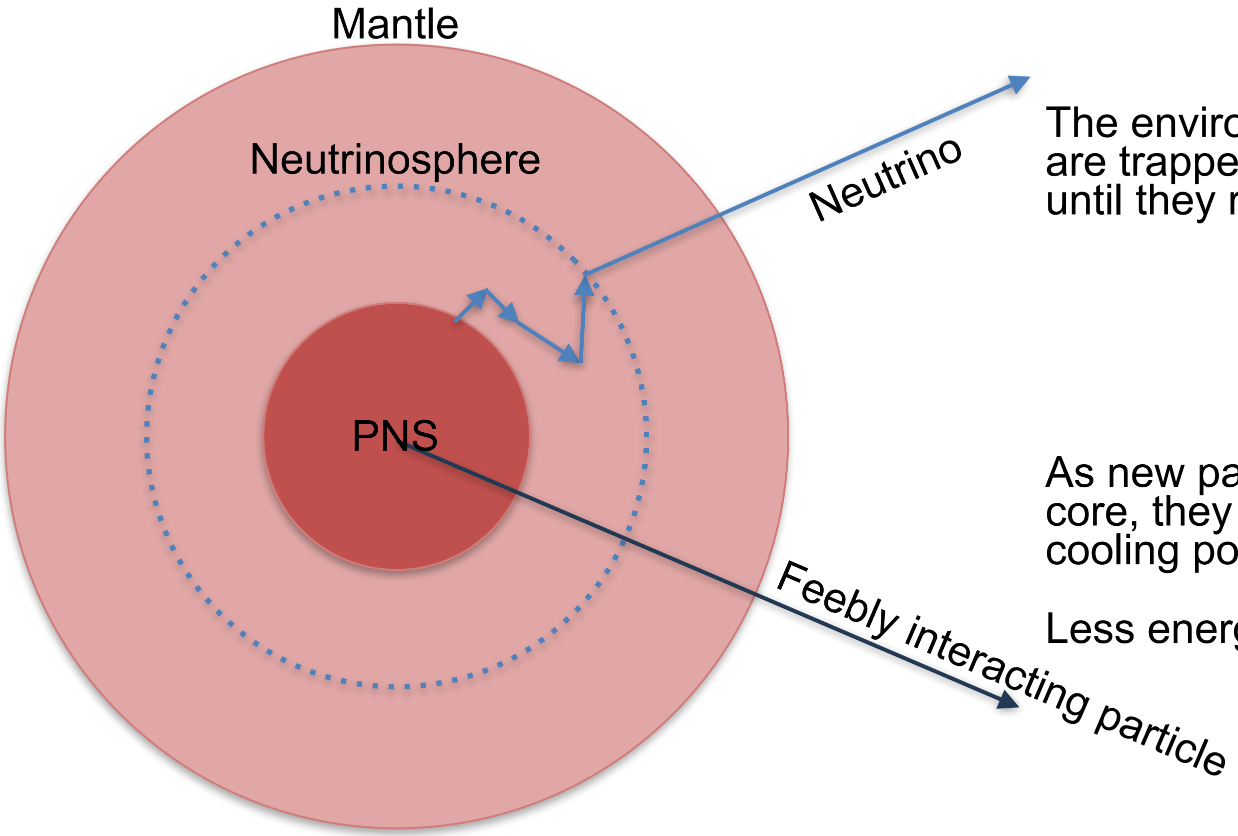


Fiorillo, Heinlein, Janka, Raffelt, **Vitagliano**, Bollig (2023)

Good overall agreement in total and average neutrino energies,
but puzzling results concerning event timing

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!

Energy loss bounds from supernovae

- 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**
- All simulations on a common footing: new particle emission should not exceed $\epsilon_a = 10^{19} \mathrm{erg\,g^{-1} s^{-1}}$, or in terms of the total energy

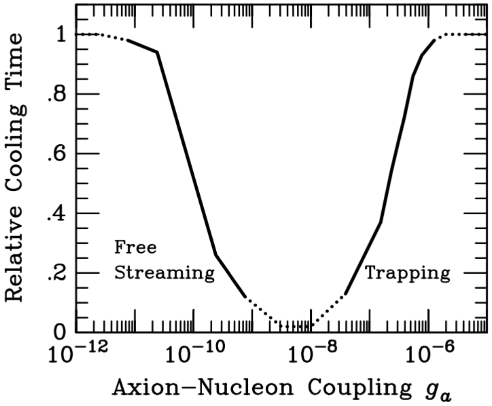


Fig. 13.1. Relative duration of neutrino cooling of a SN core as a function of the axion-nucleon Yukawa coupling g_a. In the free-streaming limit axions are emitted from the entire volume of the protoneutron star, in the trapping limit from the "axion sphere" at about unit optical depth. The solid line is according to the numerical cooling calculations (case B) of Burrows, Turner, and Brinkmann (1989) and Burrows, Ressell, and Turner (1990); the dotted line is an arbitrary completion of the curve to guide the eye. The signal duration is measured by the quantity $\Delta t_{90\%}$ discussed in the text; an average for the IMB and Kamiokande detectors was taken.

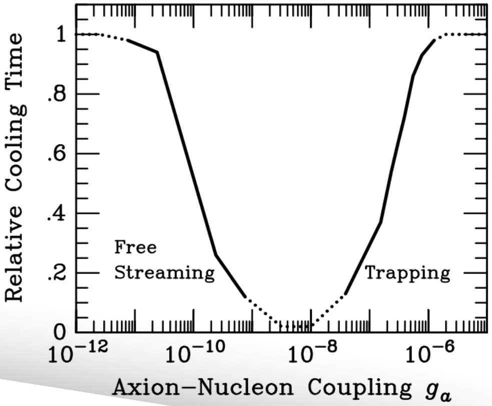
Raffelt (1994)

$$L_\phi \lesssim L_\nu(1\mathrm{s}) = 3 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

Computed at $T = 30\,\mathrm{MeV}$ and $\rho = 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$

Energy loss bounds from supernovae

- 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 c ling time (right figure, axion-nucle
  Observabl
  signal at I
- All simulations
  new particle emission should not
  $\epsilon_a = 10^{19} \mathrm{erg\,g^{-1} s^{-1}}$, or in terms of the total energy



as a function
ng limit axions
in the trapping
The solid line is
urrows, Turner,
and
990); the dotted
line is an arbitrary
eye. The signal
duration is measured by the quantity $\Delta t_{90\%}$
e text; an average
for the IMB and Kamiokande detectors was taken.

Raffelt (1994)

Is this the best we can do?

$$L_\phi \lesssim L_\nu(1\mathrm{s}) = 3 \times 10^{52}\,\mathrm{erg\,s^{-1}}$$

Computed at $T = 30\,\mathrm{MeV}$ and $\rho = 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$

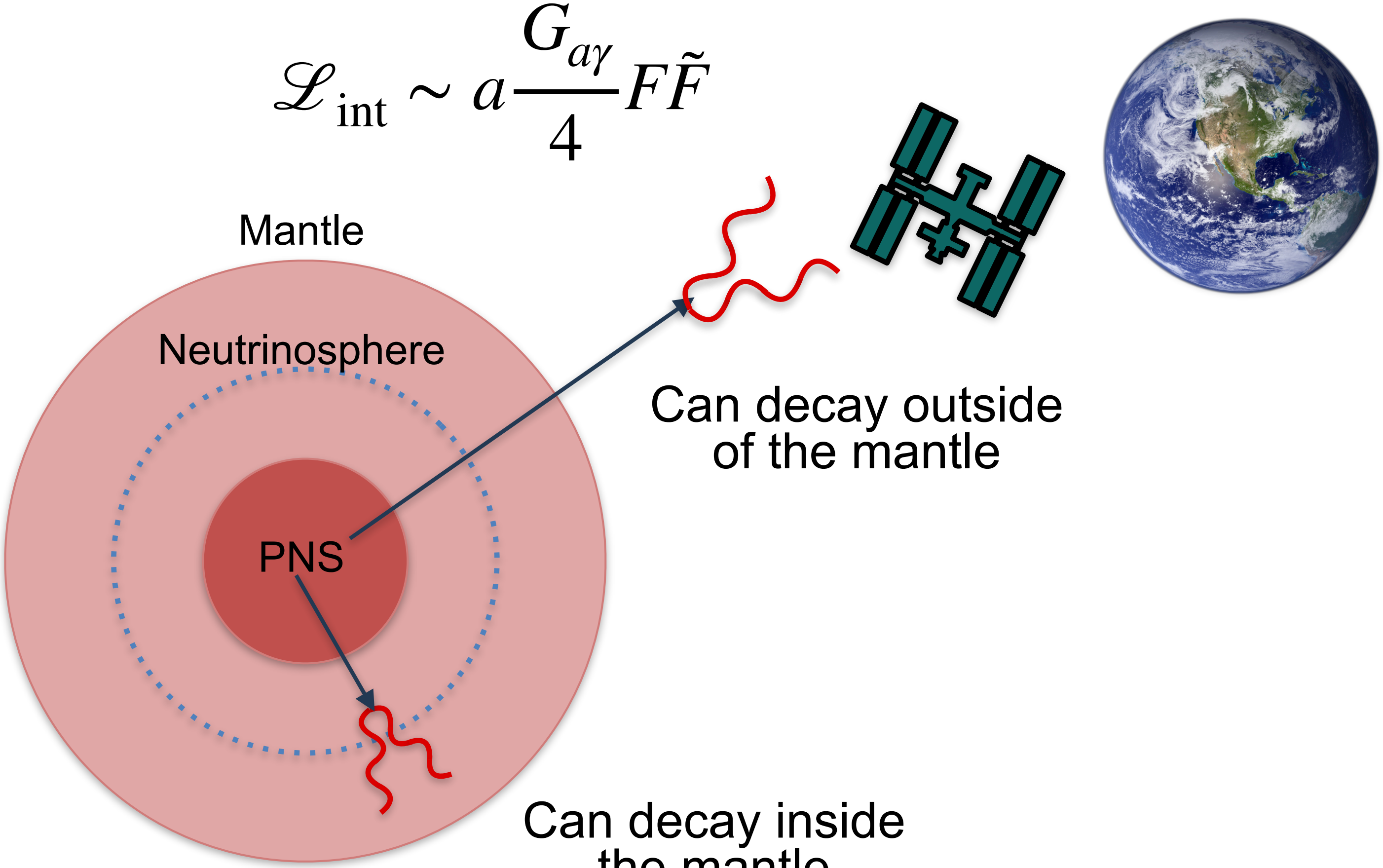
New bounds on photon, charged lepton, neutrino coupling

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

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



Mantle

Neutrinosphere

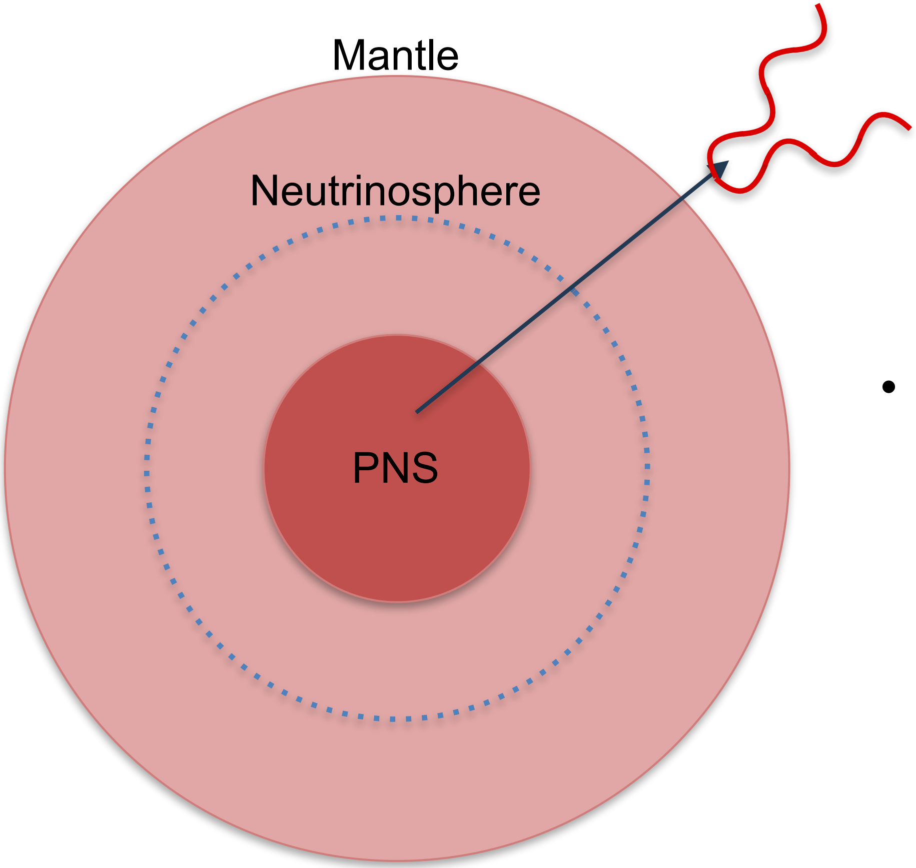
PNS

Can decay outside of the mantle

Can decay inside the mantle

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**)



- **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

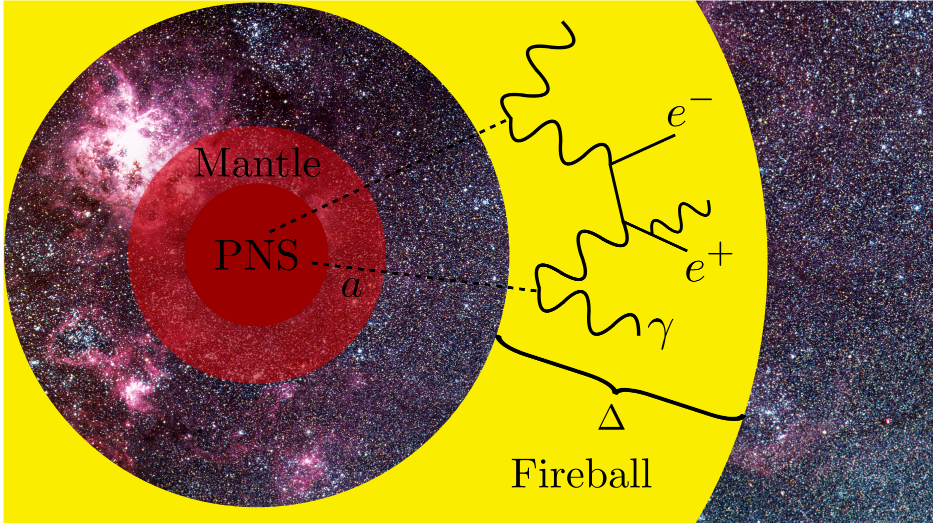
BUT…

Long lifetimes: fireball formation

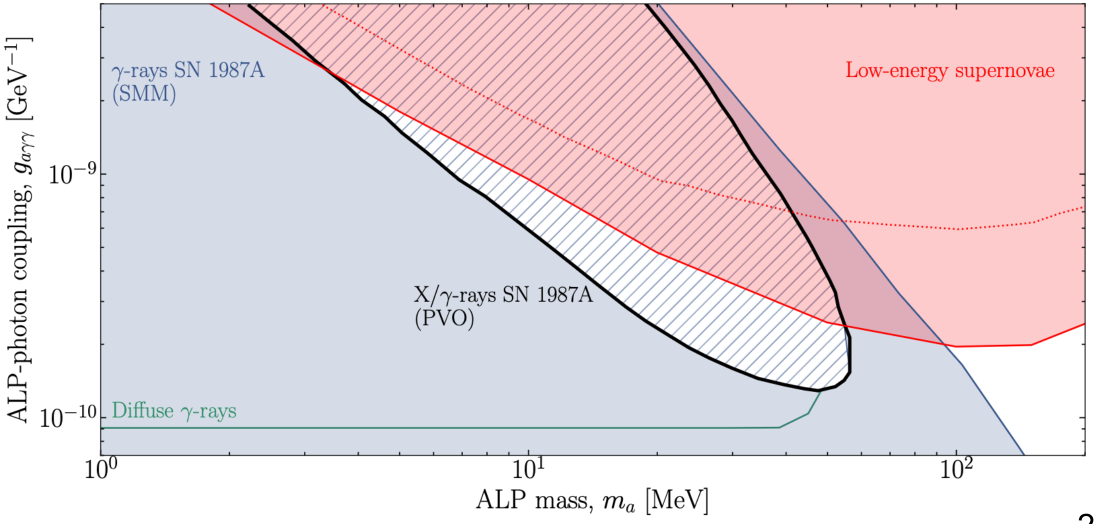
Brand new! 2023

Editors' Suggestion

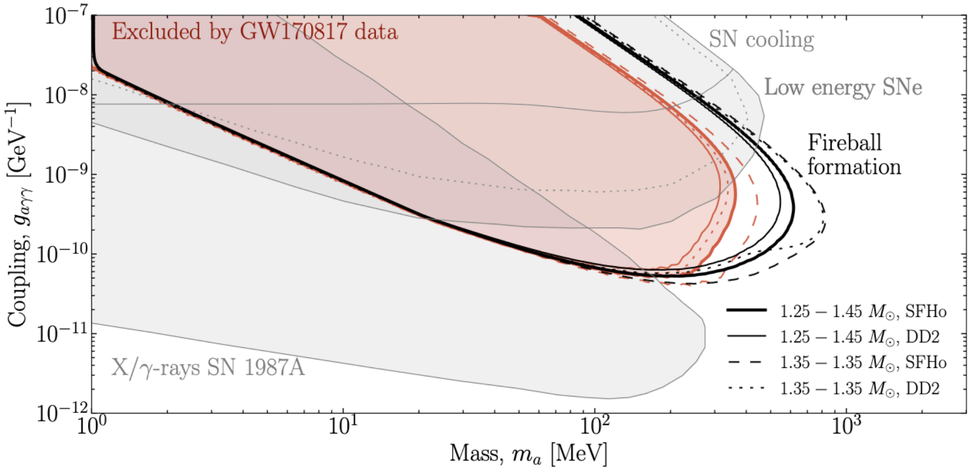
Diamond, Fiorillo, Marques-Tavares, **Vitagliano**, *Phys.Rev.D* 107 (2023) 10, 103029



- 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

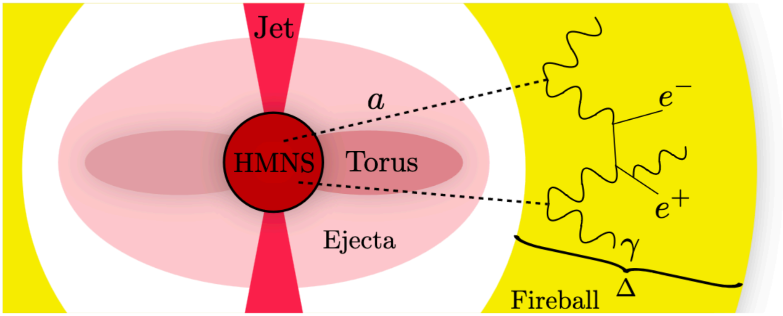


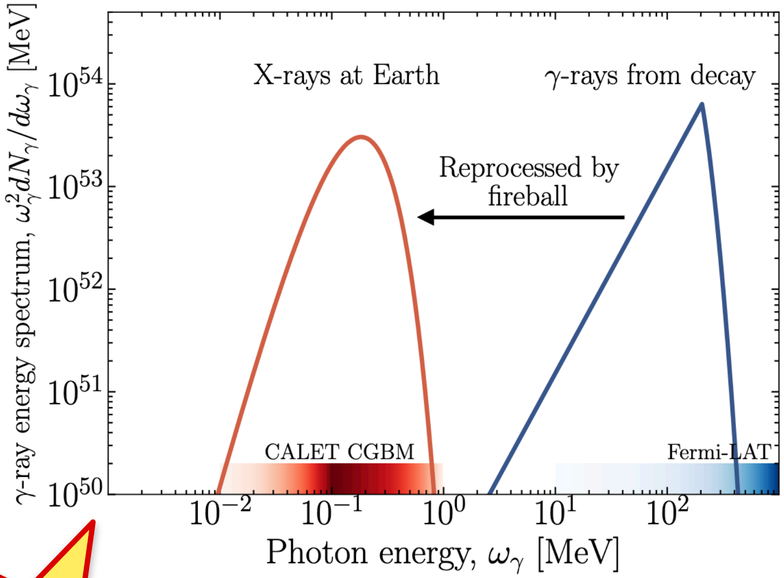
Bounds from GW170817



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

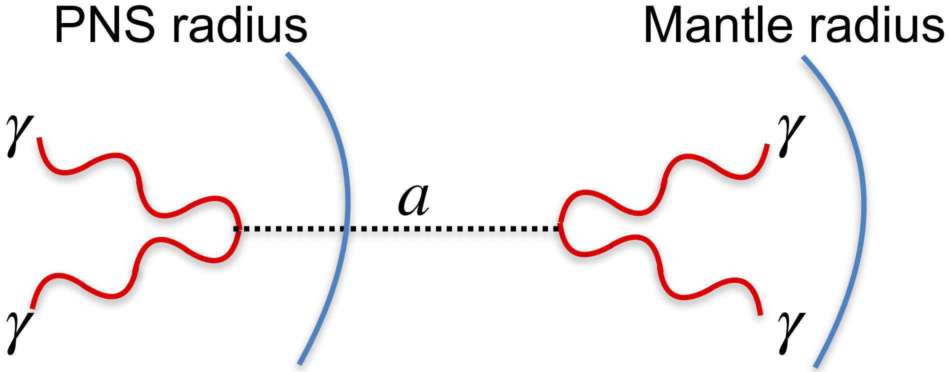
- Neutron star mergers produce a heavy mass NS remnant without a mantle!
- Huge temperature and densities
- Extremely sensitive measurements by X-ray detectors of GW 170817
- Fresh bounds on $m_a > 1\,\mathrm{MeV}$ axions





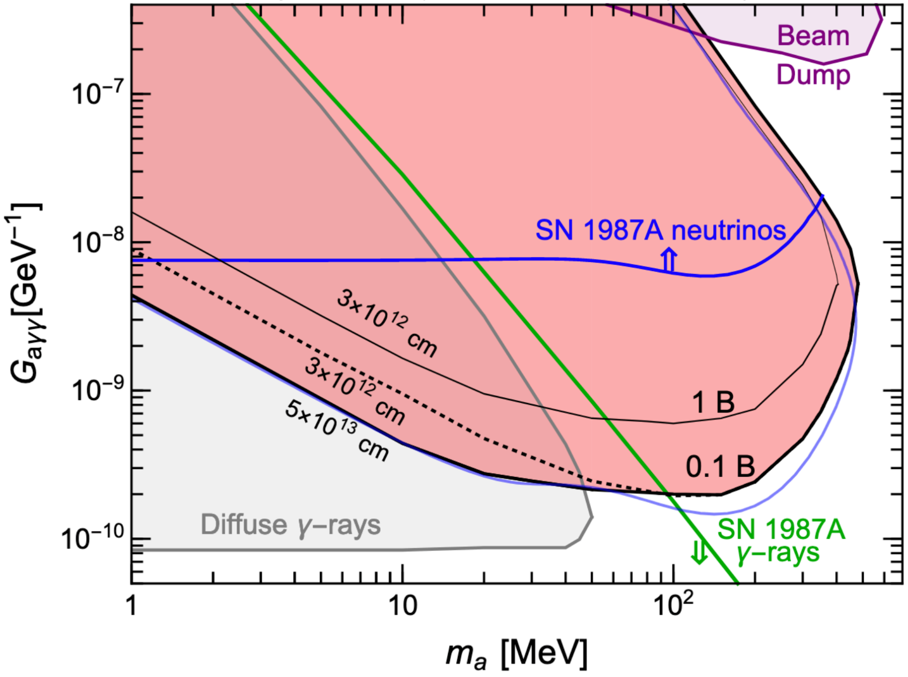
Brand new! 2023

Short lifetimes: New bound from decay in the mantle

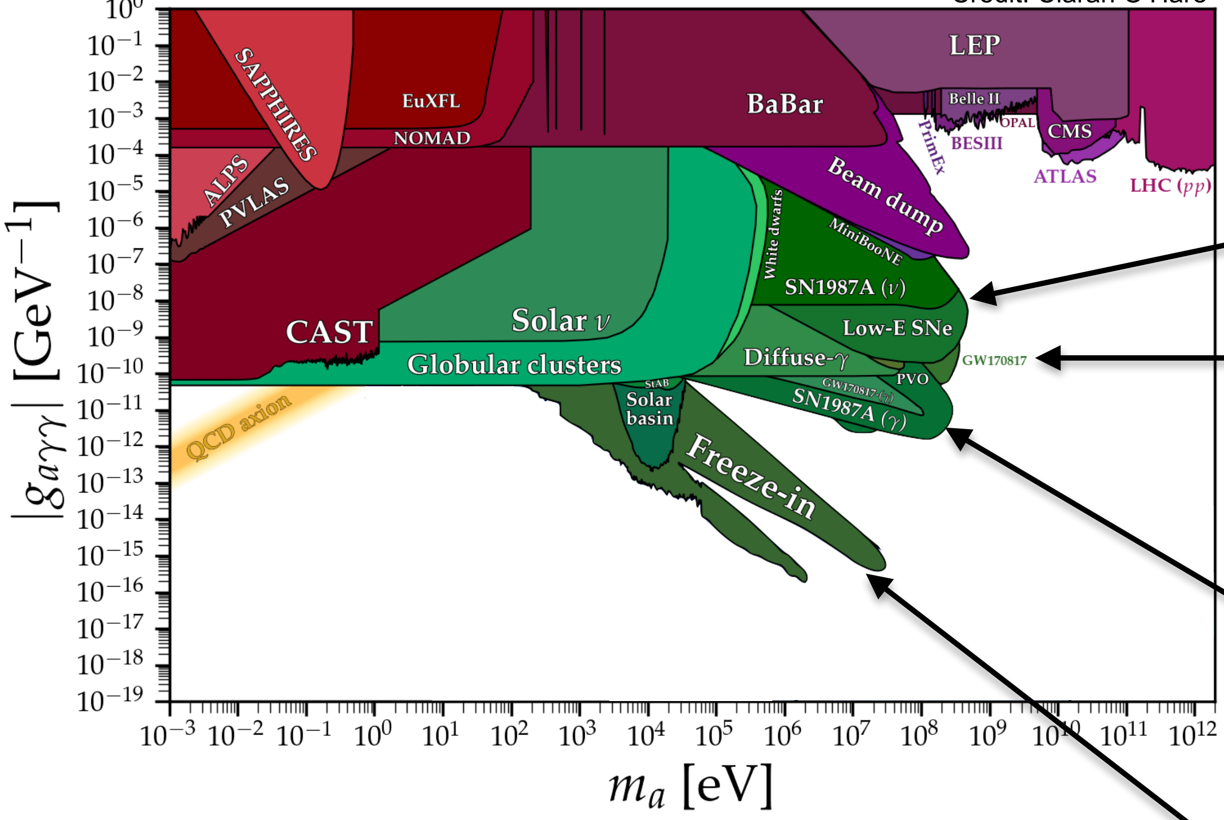


- Typical SN explosion energy 1-2 B
  $1\,\mathrm{B\ (bethe)} = 10^{51}\,\mathrm{erg}$
- Neutron star binding energy 200-400 B
- Some SNe have very small observed explosion energies < 0.1 B
- New restrictive limits from low-energy SNe

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



Axion-like particles with photon coupling



Credit: Ciaran O'Hare

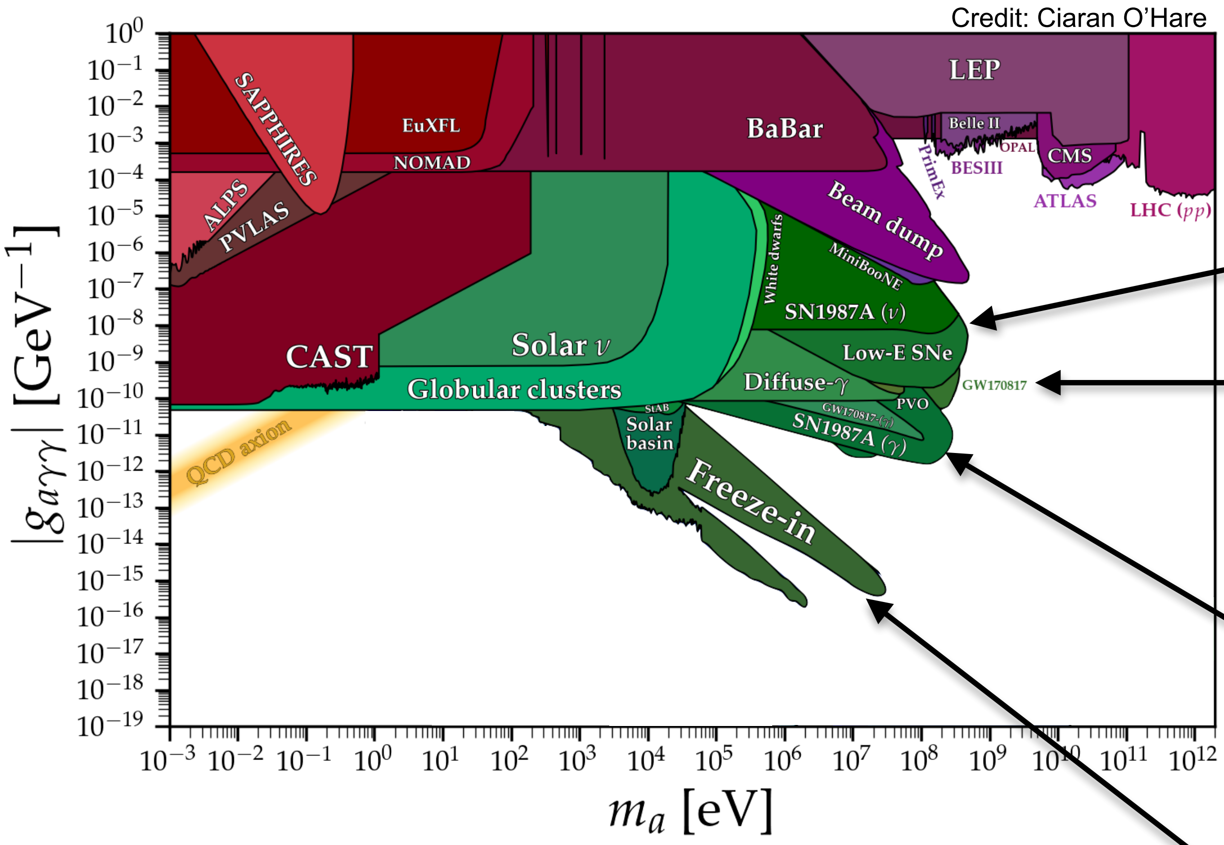
Heats up the mantle of low-energy SNe
(see Caputo, Raffelt, Janka, **Vitagliano**, *Phys.Rev.Lett.* 128 (2022) 22, 221103)

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
(see Langhoff, Outmezguine, Rodd *Phys.Rev.Lett.* 129 (2022) 24, 241101)

Axion-like particles with photon coupling



Credit: Ciaran O'Hare

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

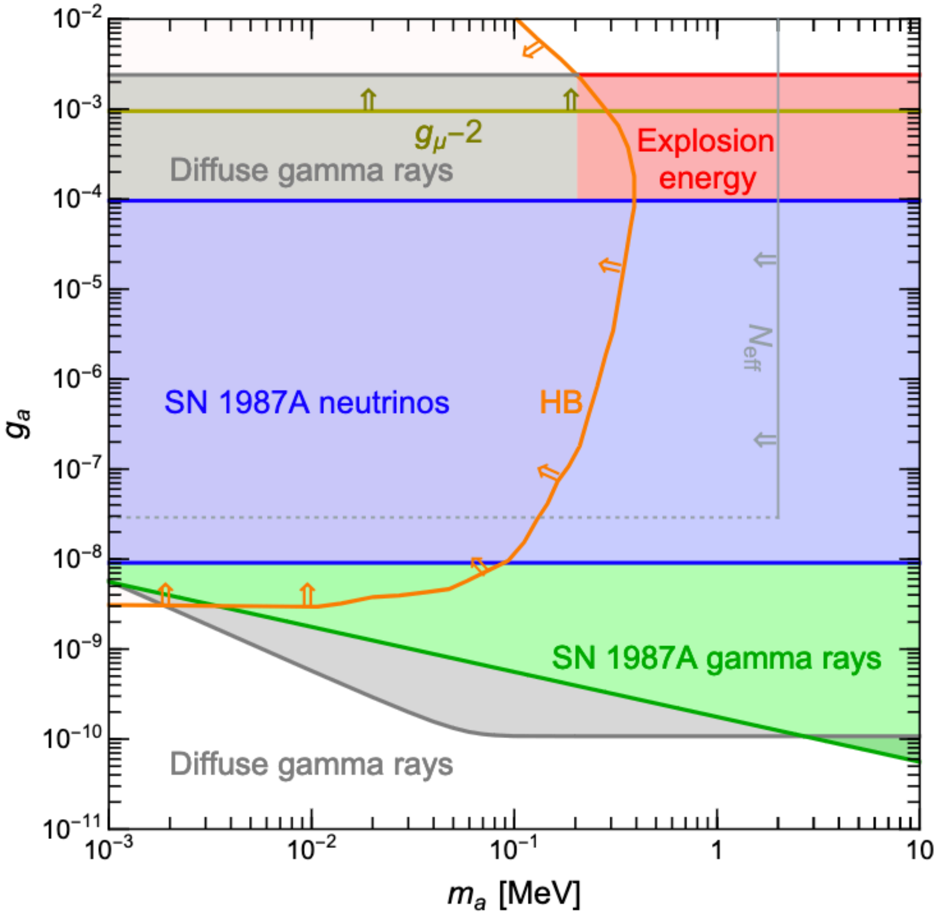
(see Langhoff, Outmezguine, Rodd *Phys.Rev.Lett.* 129 (2022) 24, 241101)

Resonant production and subsequent decay for some specific couplings and masses

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

New bounds on photon, charged lepton, neutrino coupling

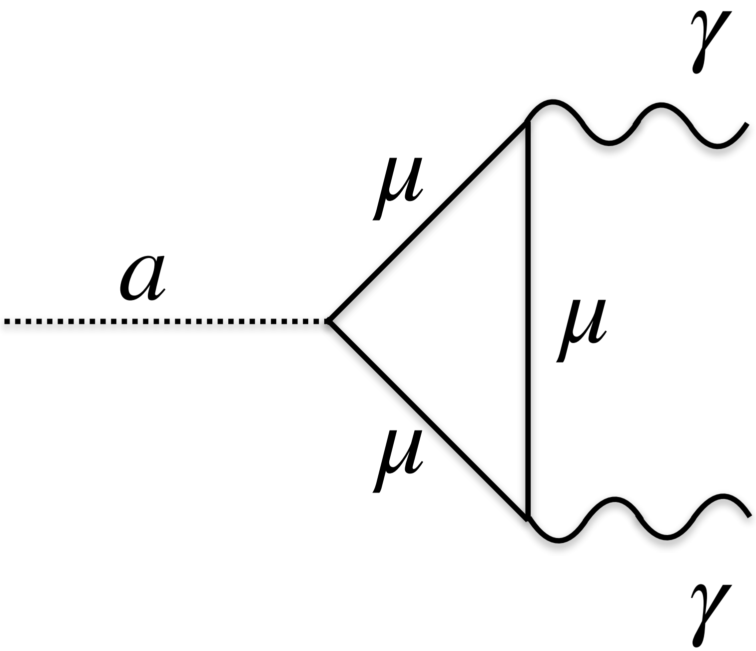
Leptonic couplings: example with muons



Caputo, Raffelt, **Vitagliano**, *Phys.Rev.D* 105 (2022) 3, 035022

Editors' Suggestion

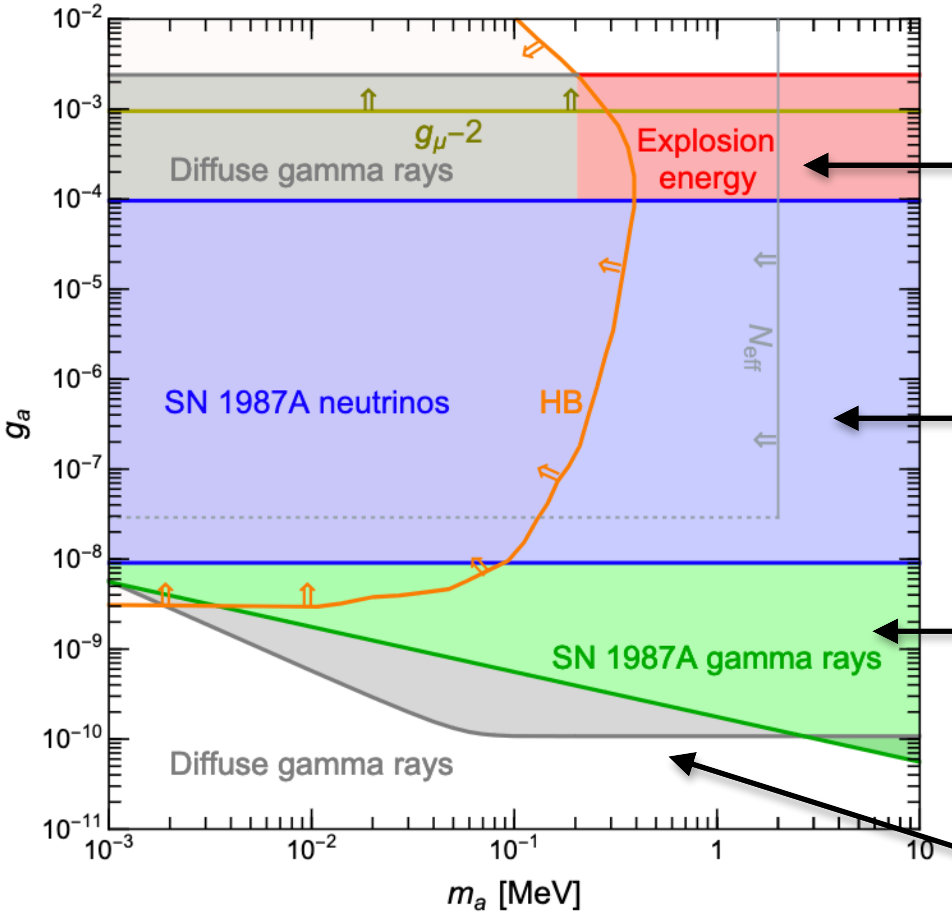
$$\mathscr{L}_{\text{loop}} \sim a\frac{G_{a\gamma}}{4}F\tilde{F}$$



See also Ferreira et al. *JCAP* 11 (2022) 057 for the electron coupling

Leptonic couplings: example with muons

Editors' Suggestion



Caputo, Raffelt, **Vitagliano**, *Phys.Rev.D* 105 (2022) 3, 035022

Heats up the mantle of the SN

Cooling bound

Gamma-ray from SN 1987A at SMM

Diffuse gamma-ray background from past SNe

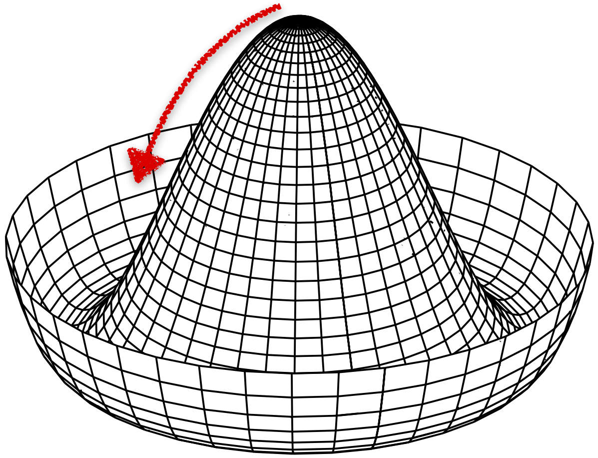
See also Ferreira et al. *JCAP* 11 (2022) 057 for the electron coupling

New bounds on photon, charged lepton, neutrino coupling

Majoron (mass generation for neutrinos)

Many BSM particles have coupling to neutrinos:

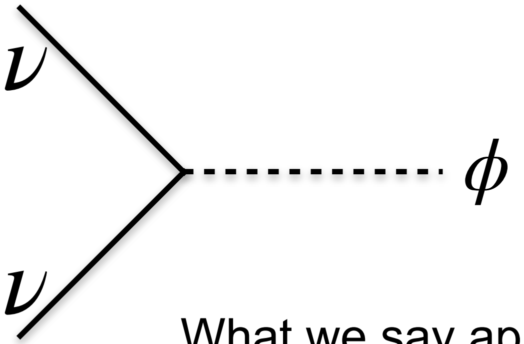
- gauge bosons from $U(1)_{L_\mu - L_\tau}$, $U(1)_{B-L}\cdots$ symmetries
- Scalar and pseudo scalars, e.g. Majorons related to the neutrino mass generation



Fiorillo, Raffelt, **Vitagliano**, *Phys.Rev.Lett.* 131 (2023) 2, 021001

To simplify things, we will assume an extremely simple case: (pseudo)scalars coupling diagonally to all neutrino flavors

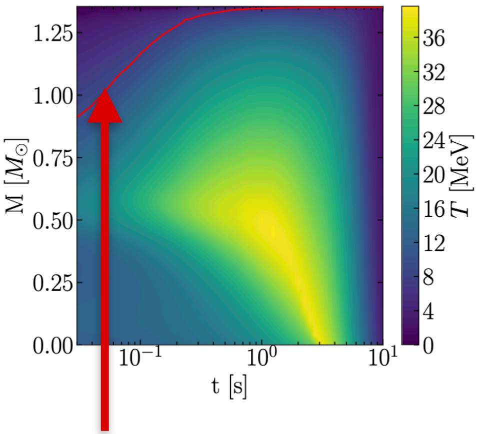
$$\mathscr{L}_{\rm int} = -\frac{g}{2}\phi\psi_\nu^T\sigma_2\psi_\nu + \text{h.c.}$$



What we say applies also to the other cases

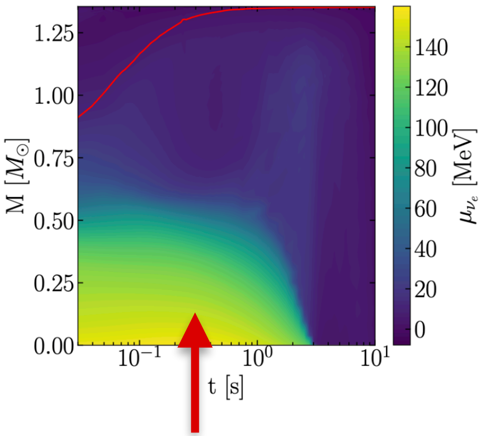
High-energy neutrinos from SN 1987A

Looking for high-energy events (100 MeV) at Cherenkov detectors in 1987, IMB and Kamiokande II



Neutrinos escape at the neutrino sphere,

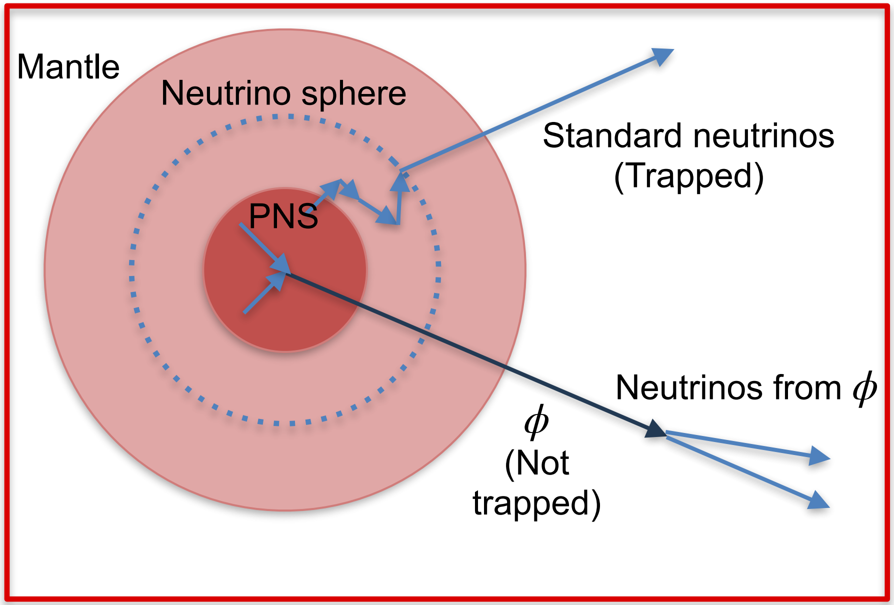
$E_\nu \sim 10\,\mathrm{MeV}$



Majorons produced in the core,

$E_\phi \sim \mu_\nu \sim 100\,\mathrm{MeV}$

then decay back to high-energy neutrinos



Mantle

Neutrino sphere

PNS

Standard neutrinos (Trapped)

Neutrinos from ϕ

ϕ (Not trapped)

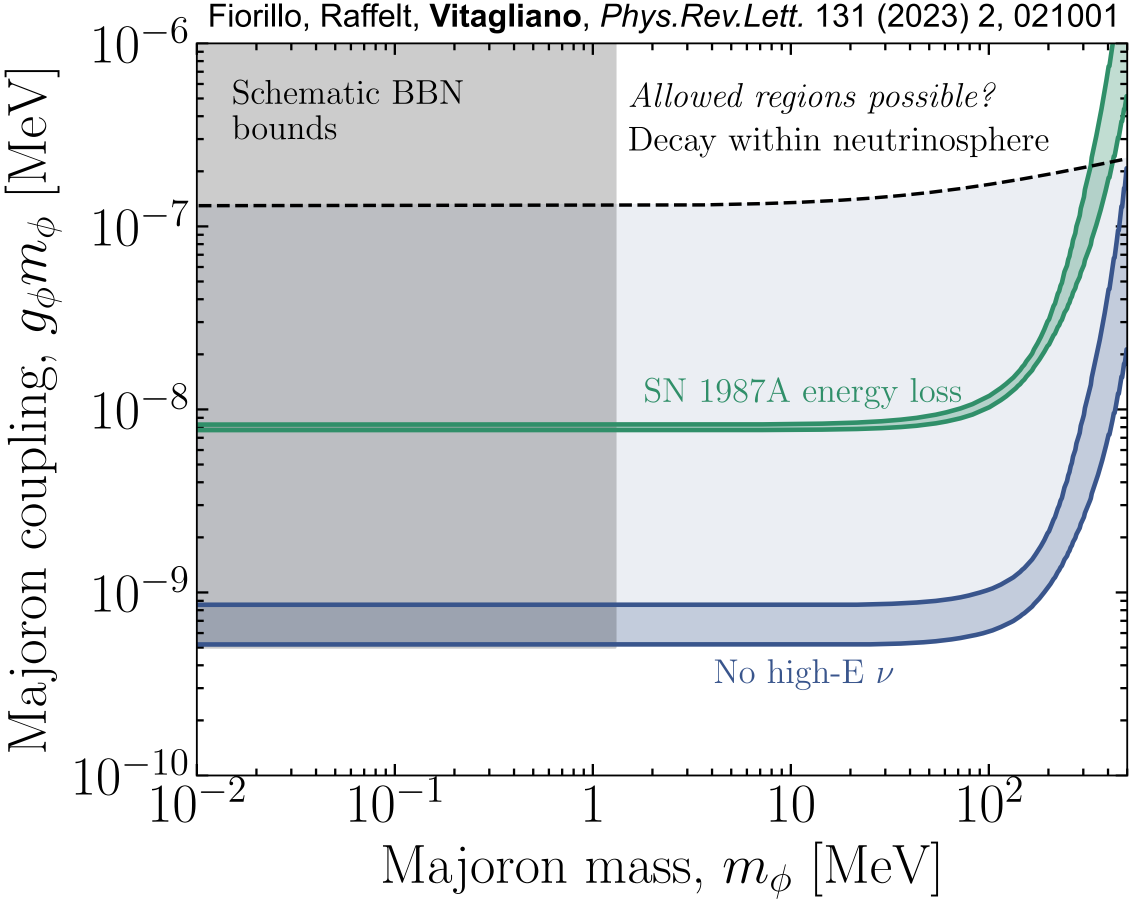
Fiorillo, Raffelt, **Vitagliano**, *Phys.Rev.Lett.* 131 (2023) 2, 021001

The cross section in the detector is $\sigma_{\nu N} \simeq G_F^2 E_\nu^2$, much larger for high-energy neutrinos from ϕ decay

New bounds from decay to neutrinos

Brand new! 2022

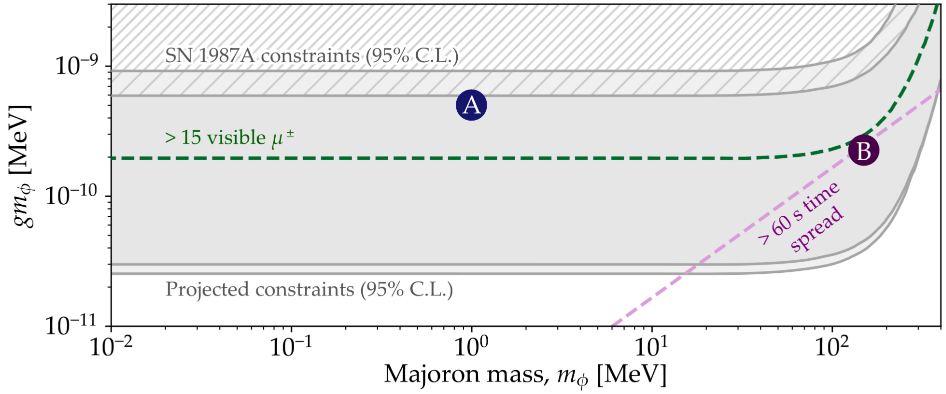
Fiorillo, Raffelt, **Vitagliano**, *Phys.Rev.Lett.* 131 (2023) 2, 021001

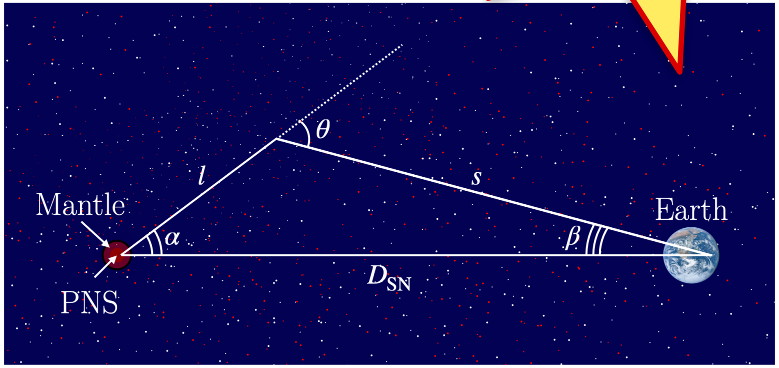


See also our new results in Fiorillo, Raffelt, **Vitagliano** *Phys.Rev.Lett*. 132 (2024) 2, 021002

Learning from the next galactic SN

Brand new! 2024

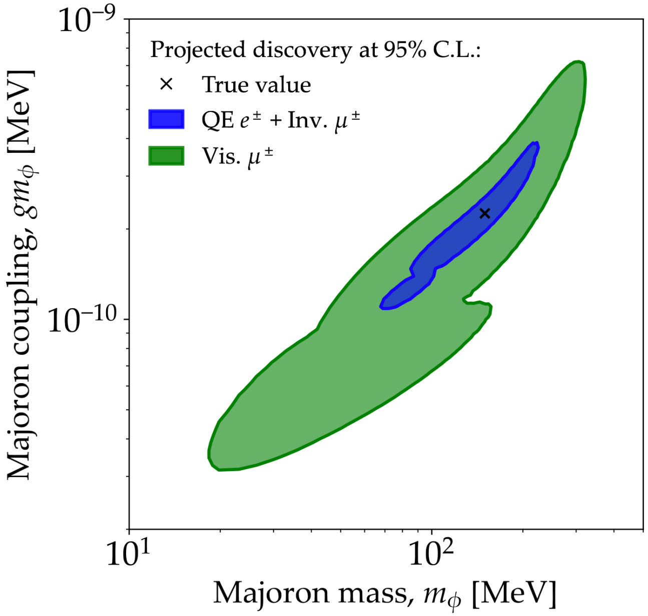




Telalovic, Fiorillo, Martínez-Miravé, **Vitagliano**, Bustamante
e-Print: 2406.15506 [hep-ph]

- A new observable: time spread of neutrinos at neutrino and dark matter detectors from the next galactic SN (useful **only** when combined with the spectrum)
- Worst case scenario: HyperK will improve bounds by orders of magnitude
- Best case scenario: we could be able to reconstruct mass and couplings to different flavors if a high-energy neutrino flux is observed

(**see also Kensuke Akita poster**)

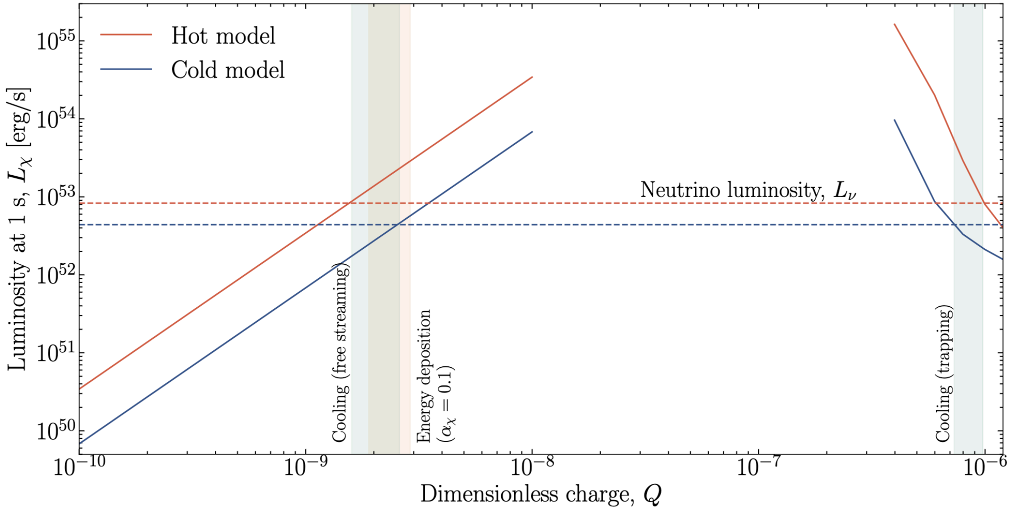


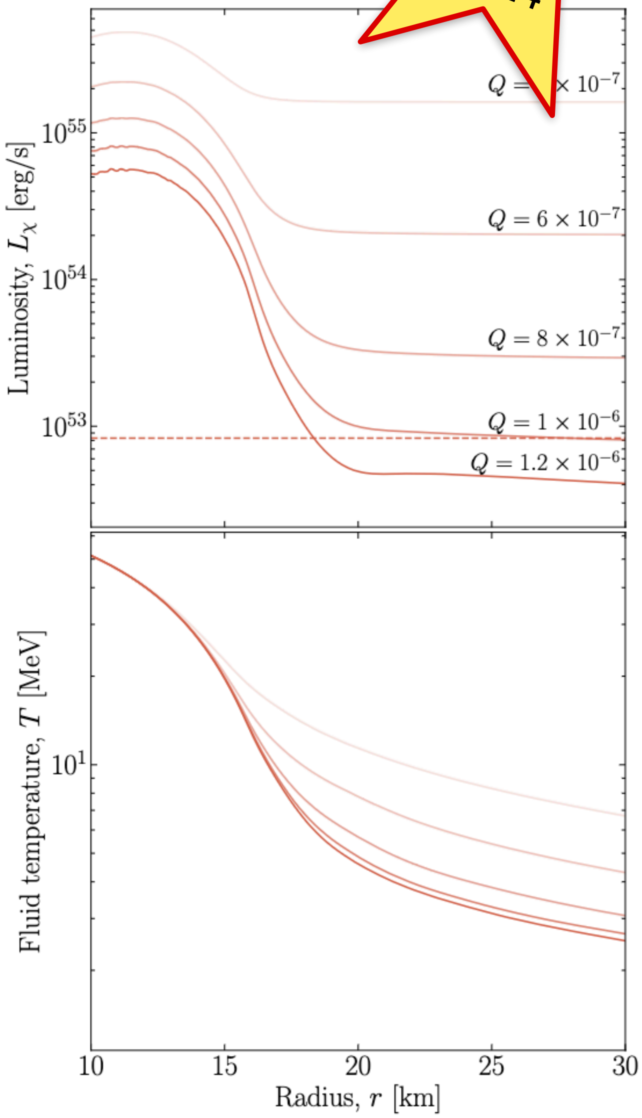
New bounds on millicharged particles

Self-interacting particles

Brand new! 2024

Fiorillo & **Vitagliano**, e-Print: 2404.07714 [hep-ph]





Be careful with self-interacting DM models!

- Because of self-interactions, they form a fluid upon exiting the SN
- Use **fluid-dynamics** to describe the evolution of the outgoing flux, kinetic theory not appropriate
- Millicharged particles coupling constraints moved by one order of magnitude compared to Chang, Essig, Mcdermott (*JHEP* 01 (2017) 107)
- Can also deposit energy (**new bounds from low-energy SNe**)

Self-interacting particles

Brand new!
2024

Fiorillo & **Vitagliano**, e-Print: 2404.07714 [hep-ph]

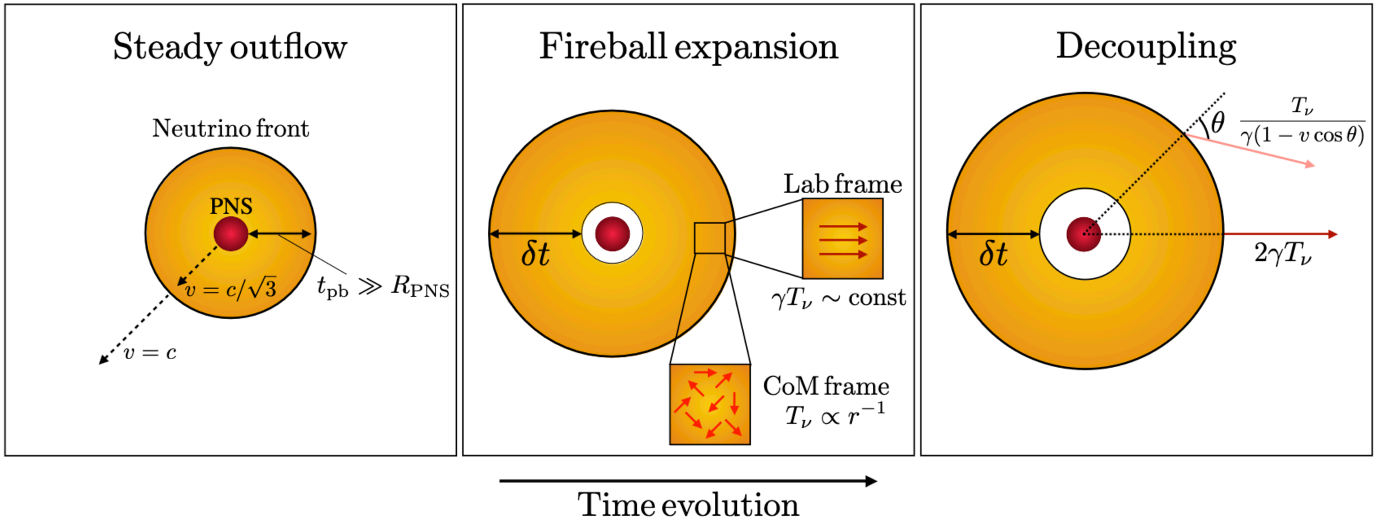
(A similar story applies to self interacting neutrinos)

Brand new!
2023

Editors' Suggestion

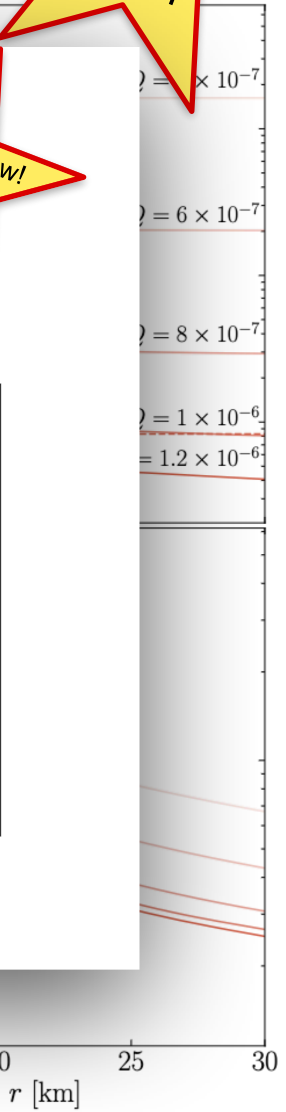
Fiorillo, Raffelt, **Vitagliano**, *Phys.Rev.D* 109 (2024) 2, 023017

Fiorillo, Raffelt, **Vitagliano**, *Phys.Rev.Lett.* 132 (2024) 2, 021002



107)

- Can also deposit energy (**new bounds from low-energy SNe**)



Conclusions

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

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

Ongoing

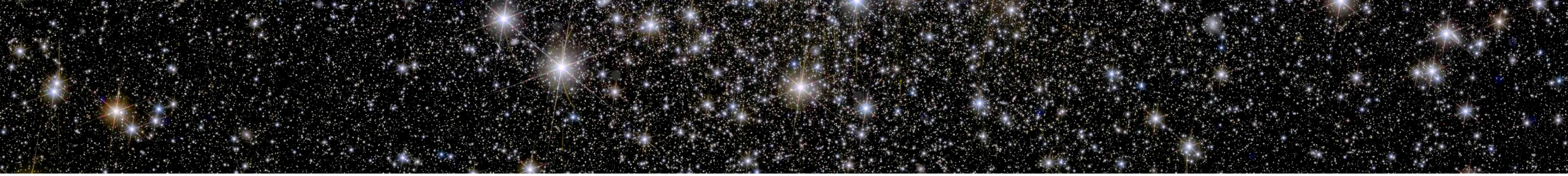
- Robustness of SN 1987A QCD axion bounds
- QCD axion bounds from cooling Neutron Stars
- Trapping regime

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

Thank you

NOW HIRING POSTDOCS!

This project has received funding/support from the European Research Council (ERC) under the European Union's Horizon Europe research and innovation program (grant agreement No. 101040019)



inνisibles ^{16} Workshop

Orto Botanico Padova 12-16 September 2016

Some extra physics with other couplings!

QCD axion bounds (dating back to the 80s)

- Raffelt, Lect. Notes Phys. 741 (2008) 51 [hep-ph/0611350]
  Burst duration calibrated by early numerical studies
  "Generic" emission rates inspired by OPE rates
  $f_a \gtrsim 4\times 10^8\,\mathrm{GeV}$ and $m_a \lesssim 16\,\mathrm{meV}$ (KSVZ, based on proton coupling)

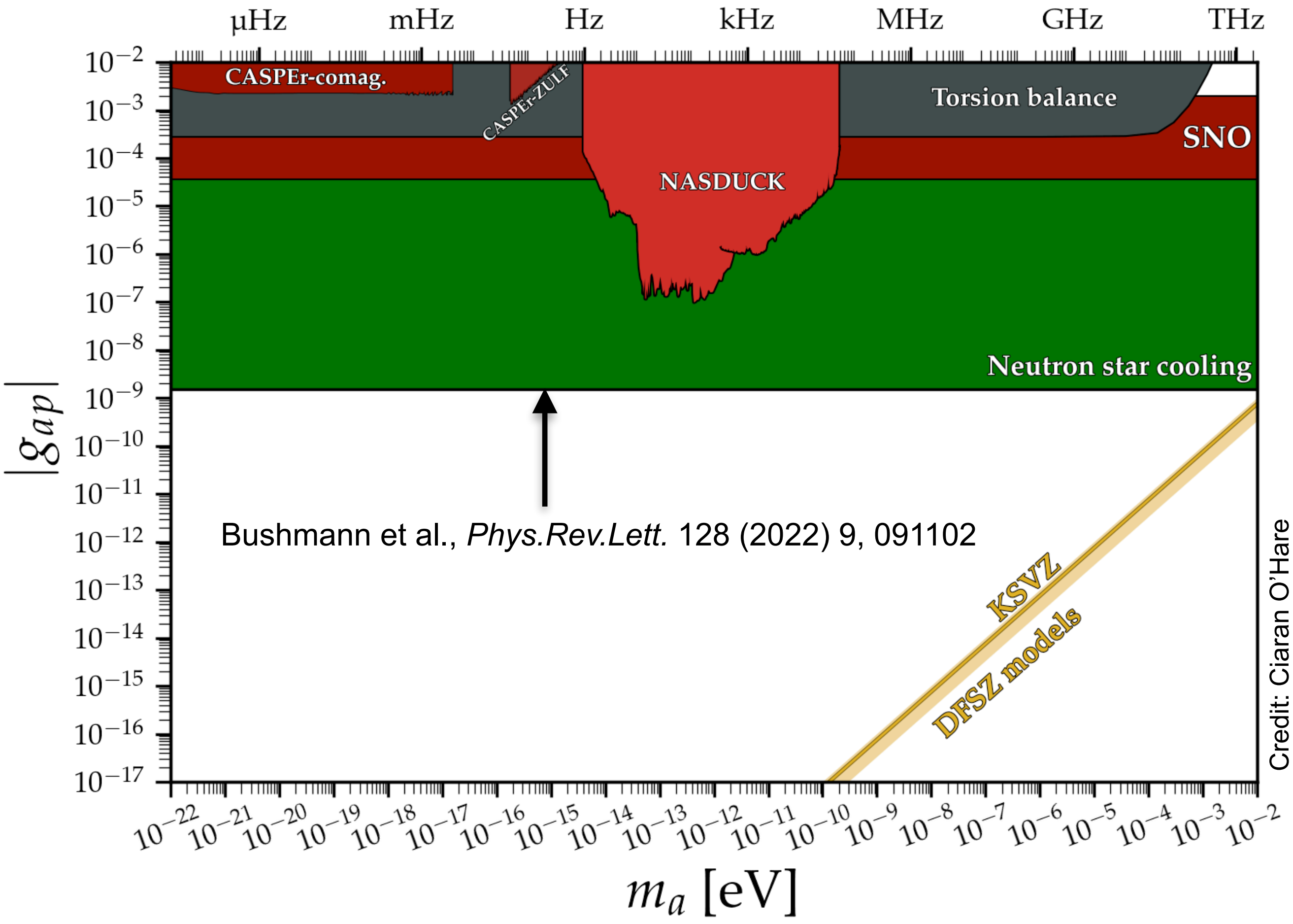
- Chang, Essig & McDermott, JHEP 1809 (2018) 051 [1803.00993]
  Various correction factors to emission rates, specific SN core models
  $f_a \gtrsim 1\times 10^8\,\mathrm{GeV}$ and $m_a \lesssim 60\,\mathrm{meV}$ (KSVZ, based on proton coupling)

- Carenza, Fischer, Giannotti, Guo, Martínez-Pinedo & Mirizzi,
  JCAP 10 (2019) 016 & Erratum [1906.11844v3]
  Beyond OPE emission rates, specific SN core models: similar to Chang et al.
  $f_a \gtrsim 4\times 10^8\,\mathrm{GeV}$ and $m_a \lesssim 16\,\mathrm{meV}$ (KSVZ, based on proton coupling)

- Carenza, Fore, Giannotti, Mirizzi & Reddy [arXiv:2010.02943]
  Including thermal pions $\pi^- + p \to n + a$ (factor 3 larger emission)
  $f_a \gtrsim 5\times 10^8\,\mathrm{GeV}$ and $m_a \lesssim 11\,\mathrm{meV}$ (KSVZ, based on proton coupling)

- Bar, Blum & D'Amico, Is there a supernova bound on axions? [1907.05020]
  Alternative picture of SN explosion (thermonuclear event)
  Observed signal not PNS cooling. SN1987A neutron star (or pulsar) not yet found.
  (but see "NS 1987A in SN 1987A", Page et al. arXiv:2004.06078)

Are SN bounds competitive?

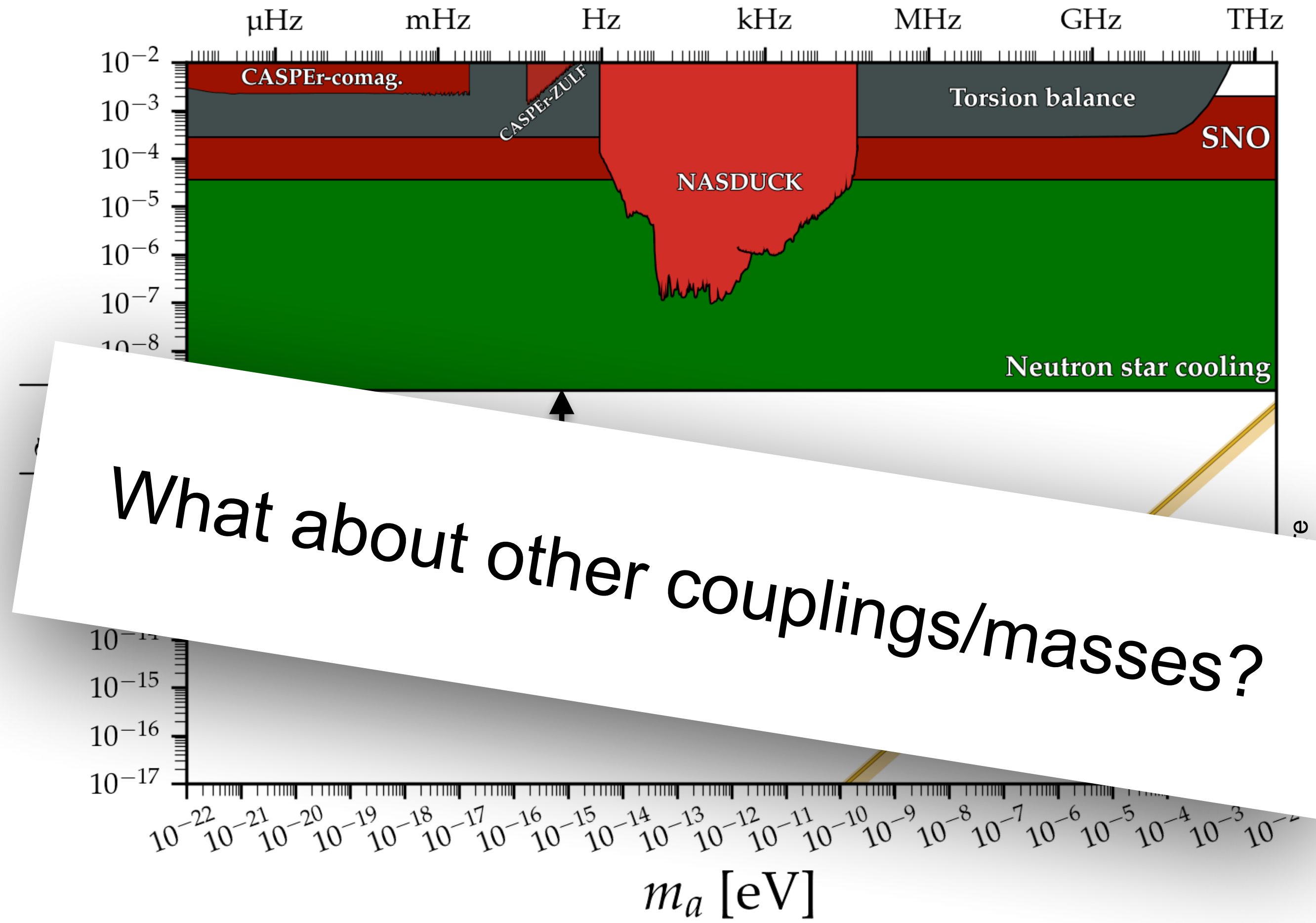


Bushmann et al., *Phys.Rev.Lett.* 128 (2022) 9, 091102

Credit: Ciaran O'Hare

(Complementary to neutron star cooling observations for hadronic couplings)

Are SN bounds competitive?



What about other couplings/masses?

(Complementary to neutron star cooling observations for hadronic couplings)

Trapping in SNe

Trapping regime (axions)

What happens for MFP $\lesssim R_{\mathrm{PNS}}$? Trapping regime is notoriously complicated

Two examples: **axions** and majorons

1987
- Trapping well known since early days and treated as the emission from a Stefan-Boltzmann sphere (Turner, Phys.Rev.Lett. 60 (1988) 1797, see also Burrows et al. *Phys.Rev.D* 42 (1990) 3297-3309)

2018
- More recently, Chang, Essig, Mcdermott (*JHEP* 09 (2018) 051) introduced a modified luminosity criterion (MLC) to account for opacity

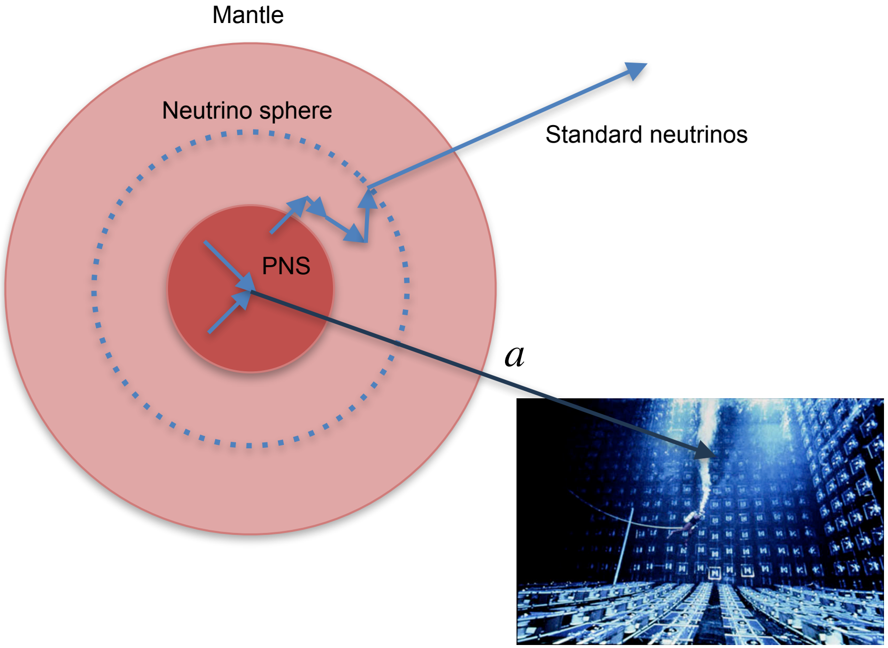
2019
- This criterion has been applied also to axion-photon couplings (Carenza et al., *JCAP* 10 (2019) 10, 016), finding two different results for SB emission and MLC. Why?

2022
- One need to account for angle averages! SB and MLC equivalent for axions with photon couplings as shown in Caputo, Raffelt, **Vitagliano** (*JCAP* 08 (2022) 08, 045)

Trapping regime (axions)

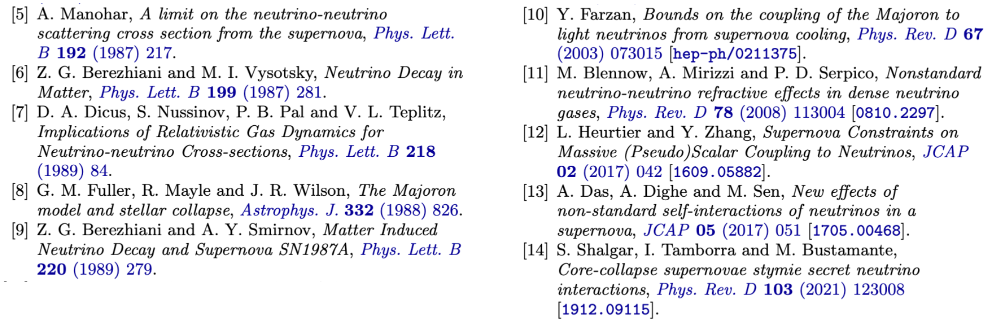
Further in the trapping regime: detecting QCD axions from SN 1987A in the detector

- Proposed already by Engel, Seckel and Hayes (Phys.Rev. Lett. 65 (1990) 960)
- Recently revisited by Lella et al. (2306.01048)
- Problem: when MFP $\simeq R_{\rm PNS}$, SN profiles should be modified
- Solution: use stars that have larger MFP! Ongoing work on neutron stars (Bottaro, Caputo, Fiorillo, **Vitagliano**)



Trapping regime (Majoron)

Trapping regime is notoriously complicated also for neutrino secret interactions. Claimed strong sensitivities. Is it true?



[5] A. Manohar, *A limit on the neutrino-neutrino scattering cross section from the supernova*, *Phys. Lett. B* **192** (1987) 217.

[6] Z. G. Berezhiani and M. I. Vysotsky, *Neutrino Decay in Matter*, *Phys. Lett. B* **199** (1987) 281.

[7] D. A. Dicus, S. Nussinov, P. B. Pal and V. L. Teplitz, *Implications of Relativistic Gas Dynamics for Neutrino-neutrino Cross-sections*, *Phys. Lett. B* **218** (1989) 84.

[8] G. M. Fuller, R. Mayle and J. R. Wilson, *The Majoron model and stellar collapse*, *Astrophys. J.* **332** (1988) 826.

[9] Z. G. Berezhiani and A. Y. Smirnov, *Matter Induced Neutrino Decay and Supernova SN1987A*, *Phys. Lett. B* **220** (1989) 279.

[10] Y. Farzan, *Bounds on the coupling of the Majoron to light neutrinos from supernova cooling*, *Phys. Rev. D* **67** (2003) 073015 [`hep-ph/0211375`].

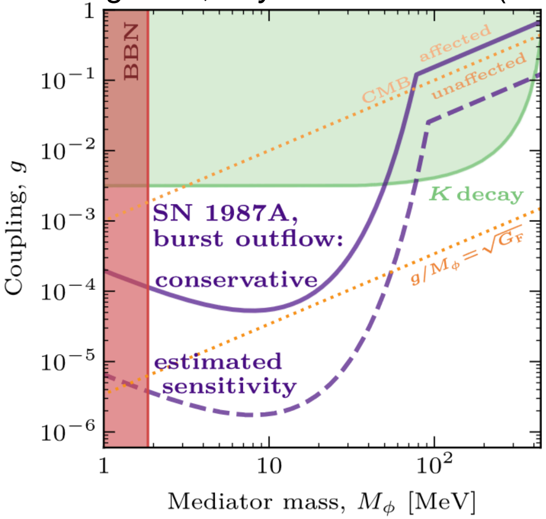
[11] M. Blennow, A. Mirizzi and P. D. Serpico, *Nonstandard neutrino-neutrino refractive effects in dense neutrino gases*, *Phys. Rev. D* **78** (2008) 113004 [`0810.2297`].

[12] L. Heurtier and Y. Zhang, *Supernova Constraints on Massive (Pseudo)Scalar Coupling to Neutrinos*, *JCAP* **02** (2017) 042 [`1609.05882`].

[13] A. Das, A. Dighe and M. Sen, *New effects of non-standard self-interactions of neutrinos in a supernova*, *JCAP* **05** (2017) 051 [`1705.00468`].

[14] S. Shalgar, I. Tamborra and M. Bustamante, *Core-collapse supernovae stymie secret neutrino interactions*, *Phys. Rev. D* **103** (2021) 123008 [`1912.09115`].

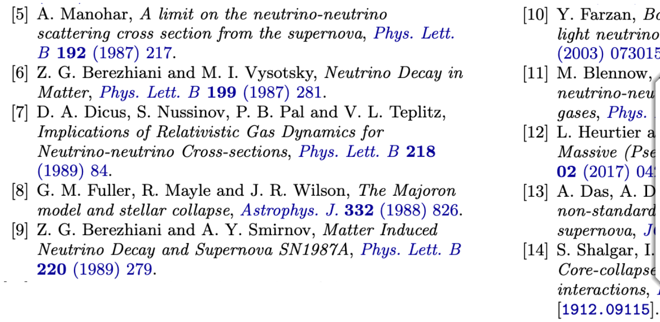
Chang et al., *Phys.Rev.Lett.* 131 (2023) 7, 071002



Trapping regime (Majoron)

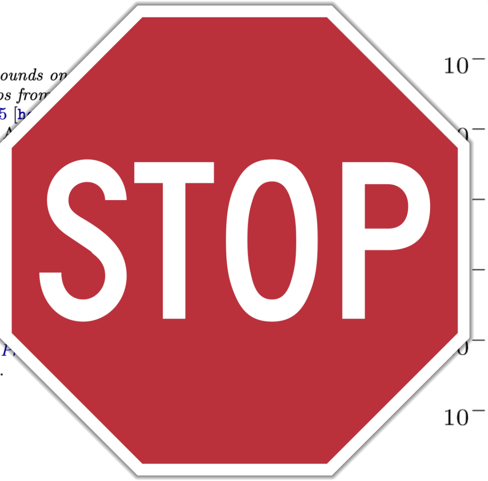
Trapping regime is notoriously complicated also for neutrino secret interactions. Claimed strong sensitivities. Is it true?

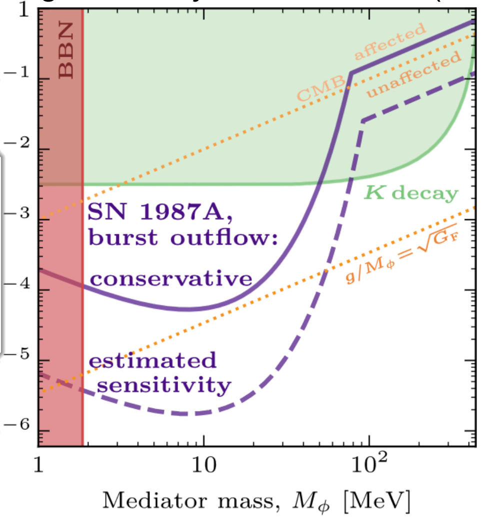
Chang et al., *Phys.Rev.Lett.* 131 (2023) 7, 071002



[5] A. Manohar, *A limit on the neutrino-neutrino scattering cross section from the supernova*, *Phys. Lett. B* **192** (1987) 217.
[6] Z. G. Berezhiani and M. I. Vysotsky, *Neutrino Decay in Matter*, *Phys. Lett. B* **199** (1987) 281.
[7] D. A. Dicus, S. Nussinov, P. B. Pal and V. L. Teplitz, *Implications of Relativistic Gas Dynamics for Neutrino-neutrino Cross-sections*, *Phys. Lett. B* **218** (1989) 84.
[8] G. M. Fuller, R. Mayle and J. R. Wilson, *The Majoron model and stellar collapse*, *Astrophys. J.* **332** (1988) 826.
[9] Z. G. Berezhiani and A. Y. Smirnov, *Matter Induced Neutrino Decay and Supernova SN1987A*, *Phys. Lett. B* **220** (1989) 279.

[10] Y. Farzan, *Bounds on light neutrinos from* (2003) 073015 [h
[11] M. Blennow, *neutrino-neu gases*, *Phys.*
[12] L. Heurtier a *Massive (Pse* **02** (2017) 04
[13] A. Das, A. D *non-standard supernova*, *J*
[14] S. Shalgar, I. *Core-collapse interactions*, *P* [1912.09115].

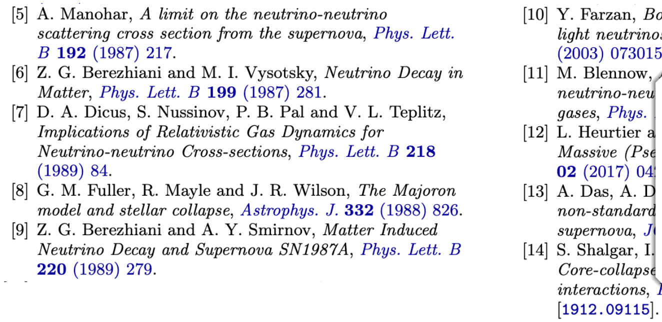




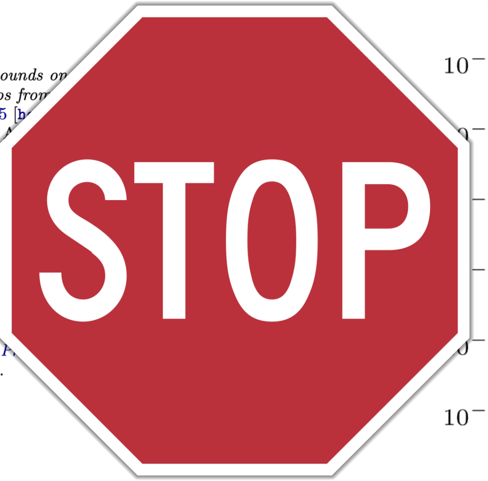
Trapping regime (Majoron)

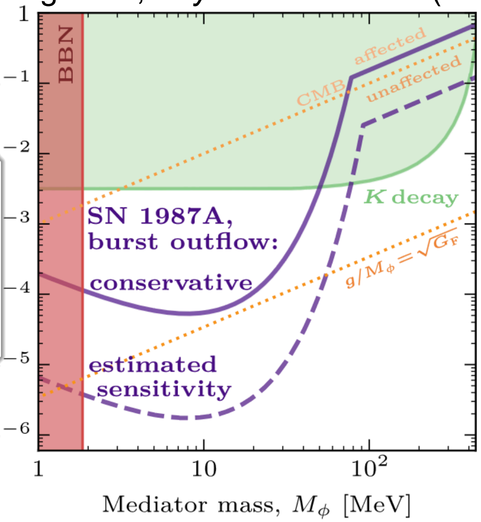
Trapping regime is notoriously complicated also for neutrino secret interactions. Claimed strong sensitivities. Is it true?

Chang et al., *Phys.Rev.Lett.* 131 (2023) 7, 071002



[5] A. Manohar, *A limit on the neutrino-neutrino scattering cross section from the supernova*, *Phys. Lett. B* **192** (1987) 217.
[6] Z. G. Berezhiani and M. I. Vysotsky, *Neutrino Decay in Matter*, *Phys. Lett. B* **199** (1987) 281.
[7] D. A. Dicus, S. Nussinov, P. B. Pal and V. L. Teplitz, *Implications of Relativistic Gas Dynamics for Neutrino-neutrino Cross-sections*, *Phys. Lett. B* **218** (1989) 84.
[8] G. M. Fuller, R. Mayle and J. R. Wilson, *The Majoron model and stellar collapse*, *Astrophys. J.* **332** (1988) 826.
[9] Z. G. Berezhiani and A. Y. Smirnov, *Matter Induced Neutrino Decay and Supernova SN1987A*, *Phys. Lett. B* **220** (1989) 279.
[10] Y. Farzan, *Bounds on*
light neutrinos from
(2003) 073015 [h
[11] M. Blennow, A
neutrino-neu
gases, *Phys.*
[12] L. Heurtier a
Massive (Pse
02 (2017) 04
[13] A. Das, A. D
non-standard
supernova, *J*
[14] S. Shalgar, I.
Core-collapse
interactions, *P*
[1912.09115].

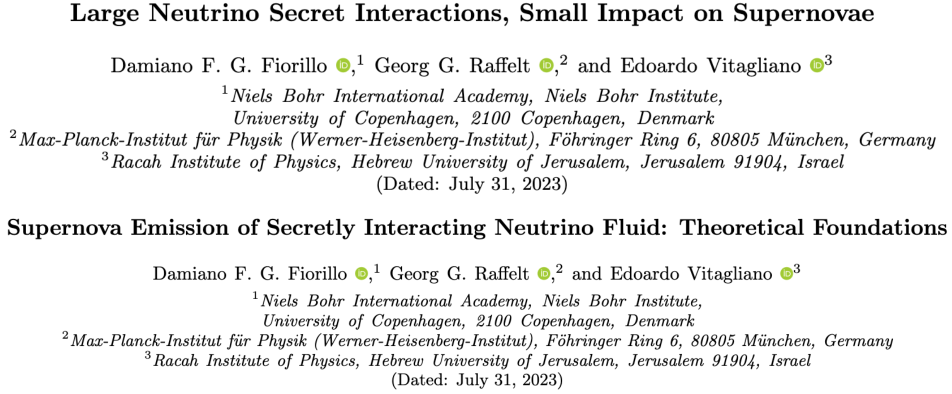




Editors' Suggestion

Small effects on the neutrino signal when solving all steps in the development of the neutrino fluid

Fiorillo, Raffelt, **Vitagliano**, *Phys.Rev.Lett.* 132 (2024) 2, 021002

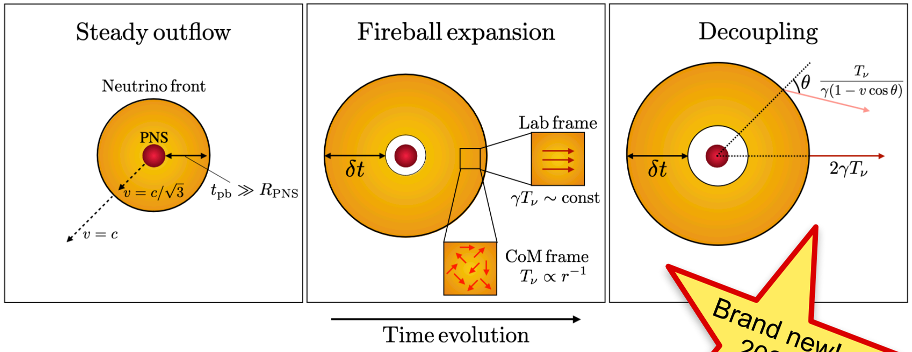


Large Neutrino Secret Interactions, Small Impact on Supernovae

Damiano F. G. Fiorillo,[1] Georg G. Raffelt,[2] and Edoardo Vitagliano[3]
[1] *Niels Bohr International Academy, Niels Bohr Institute,*
University of Copenhagen, 2100 Copenhagen, Denmark
[2] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*
[3] *Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel*
(Dated: July 31, 2023)

Supernova Emission of Secretly Interacting Neutrino Fluid: Theoretical Foundations

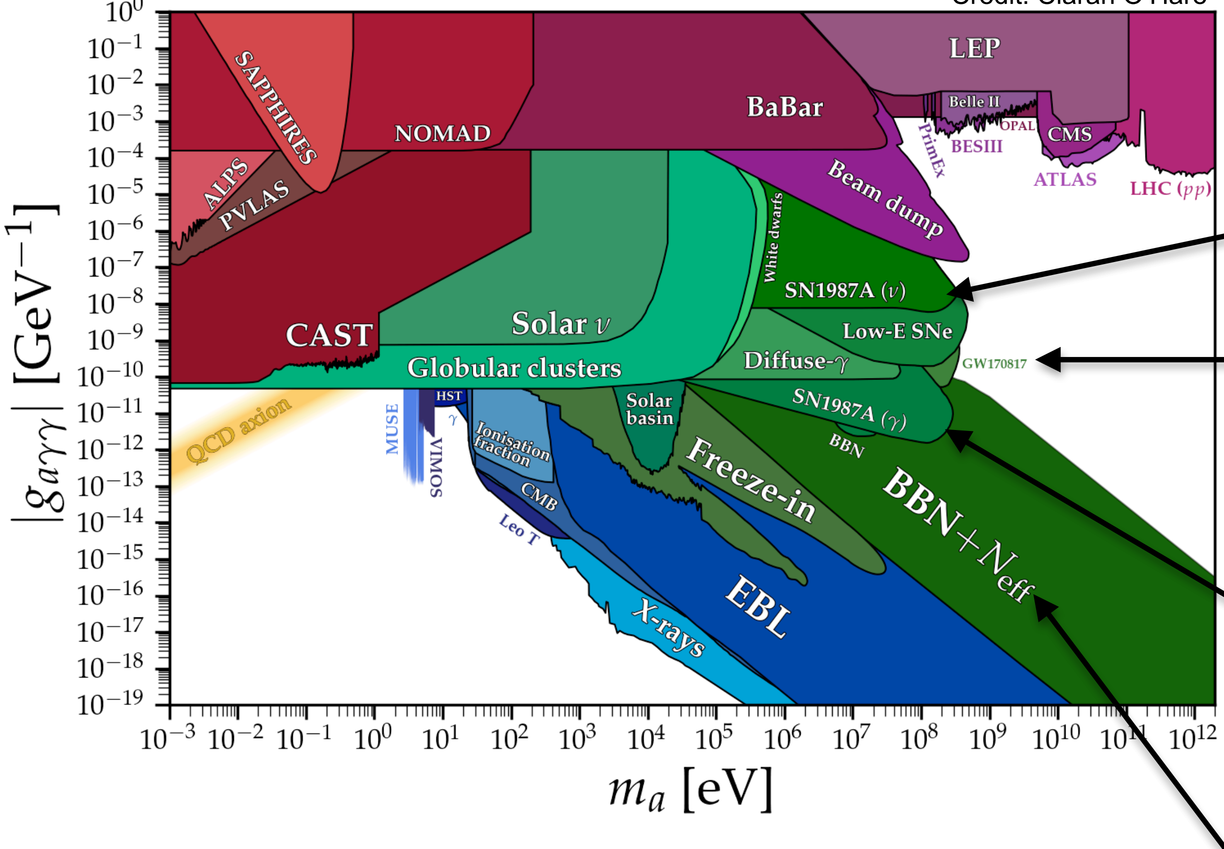
Damiano F. G. Fiorillo,[1] Georg G. Raffelt,[2] and Edoardo Vitagliano[3]
[1] *Niels Bohr International Academy, Niels Bohr Institute,*
University of Copenhagen, 2100 Copenhagen, Denmark
[2] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*
[3] *Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel*
(Dated: July 31, 2023)



Brand new! 2023

Axion-like particles with photon coupling

Credit: Ciaran O'Hare



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)

Goes away for low $T_{\rm RH}$

(see Langhoff, Outmezguine, Rodd *Phys.Rev.Lett.* 129 (2022) 24, 241101)