Credit: ESO (eso0708a)

Stellar Probes of Feebly Interacting Particles, Circa 2023

1st General Meeting of COST Action COSMIC
WISPers (CA21106),
Bari, Italy
September 5, 2023

Edoardo Vitagliano
edoardo.vitagliano@mail.huji.ac.il
Hebrew University of Jerusalem

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM
erc
European Research Council
Established by the European Commission
cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY
COSMIC WISPERS
CA21106

Disclaimer

- Personal point of view
- Conflict of Interest
- Not a talk on latest bounds, focus on novel ideas
- We will not assume new particles to be necessarily DM

Take home messages

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

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

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

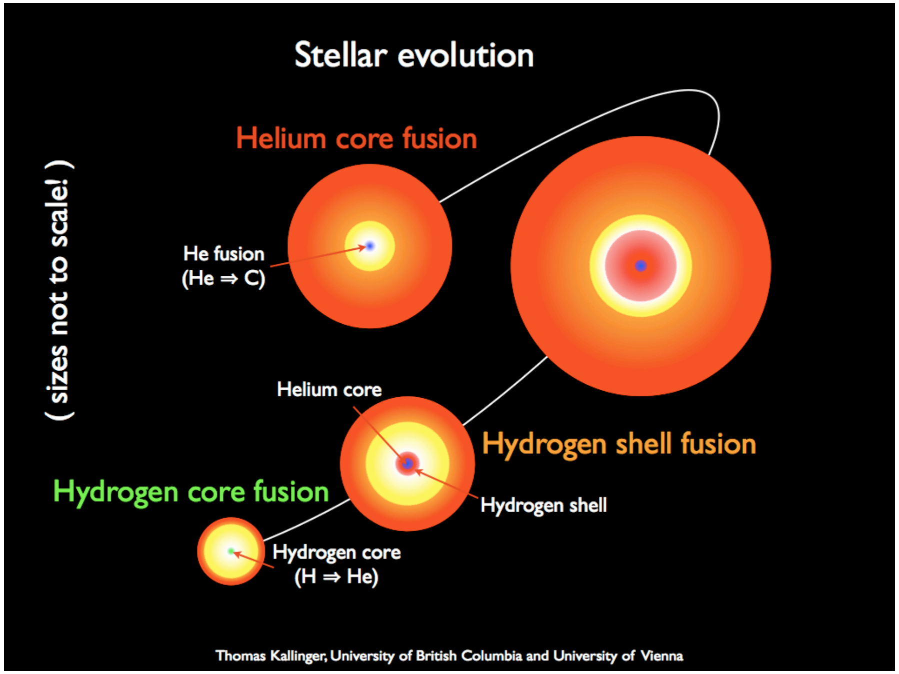
- Look for other observables in other cases—decays!
- Particle physics: best bounds on new feebly interacting particles for “heavy” bosons from decay to photon, charged leptons, or neutrinos
- Astrophysics: rule-out decaying bosons as supernova explosion or GRB catalyzers

An introduction: stellar bounds on new feebly interacting particles

Generic stars: self-regulation

Virial theorem

$$\langle E_{\text{kin}} \rangle = -\frac{1}{2}\langle E_{\text{grav}} \rangle$$



Thomas Kallinger, University of British Columbia and University of Vienna

Stars are in equilibrium

Star contraction

Larger temperature

Larger nuclear burning

Larger pressure

Expansion

Implies

And lose energy (cooling)

Loss of pressure

Contraction

Heating

Larger nuclear burning

Expansion

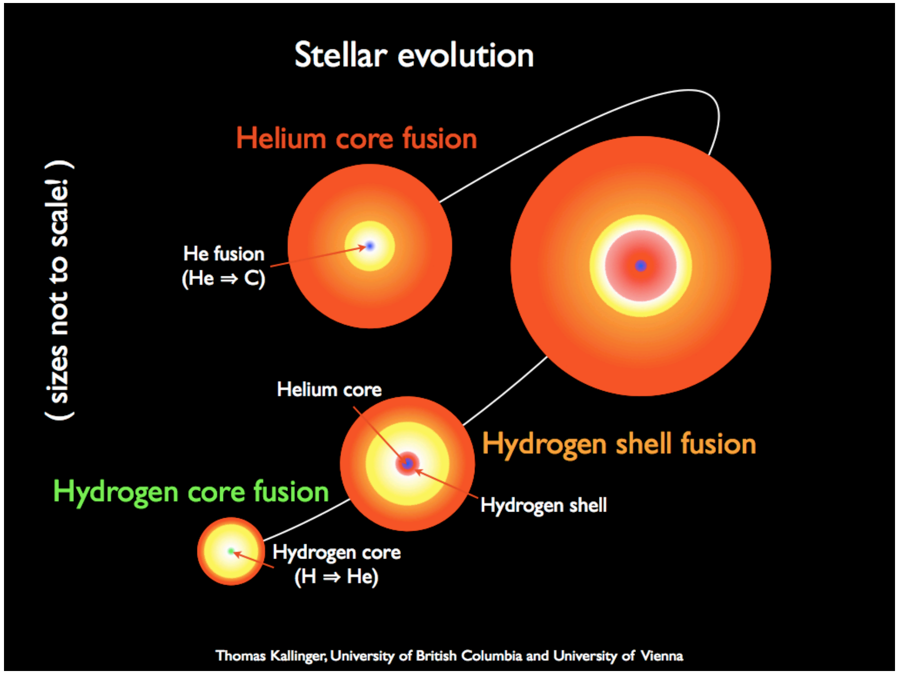
Implies

Negative specific heat capacity

Generic stars: self-regulation

Virial theorem

$$\langle E_{\text{kin}} \rangle = -\frac{1}{2} \langle E_{\text{grav}} \rangle$$



Stellar evolution

Thomas Kallinger, University of British Columbia and University of Vienna

Stars are in equilibrium

Star contraction
Larger temperature
Larger nuclear burning
Larger pressure
Expansion

Implies

And lose energy (cooling)

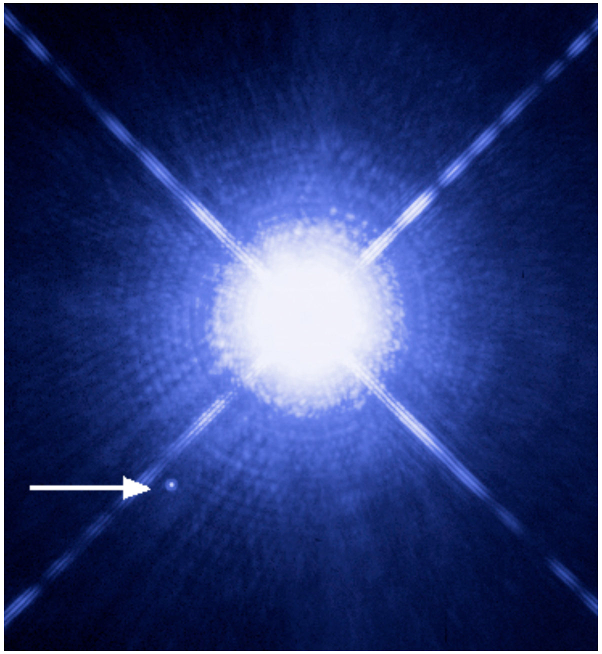
Loss of pressure
Contraction
Heating
Larger nuclear burning
Expansion

Implies

Negative specific heat capacity

If the mass is small…

If the mass is $M \lesssim 8M_{\odot}$, the star repeats the cycle and produces C and O



Sirius A and Sirius B Credit: HST

The equilibrium is guaranteed by electron degeneracy pressure, not by nuclear burning! The specific heat is positive (cooling implies a lower temperature)

Astrophysical bounds

Stars are factories of feebly interacting particles

How can we obtain bounds from astrophysics?

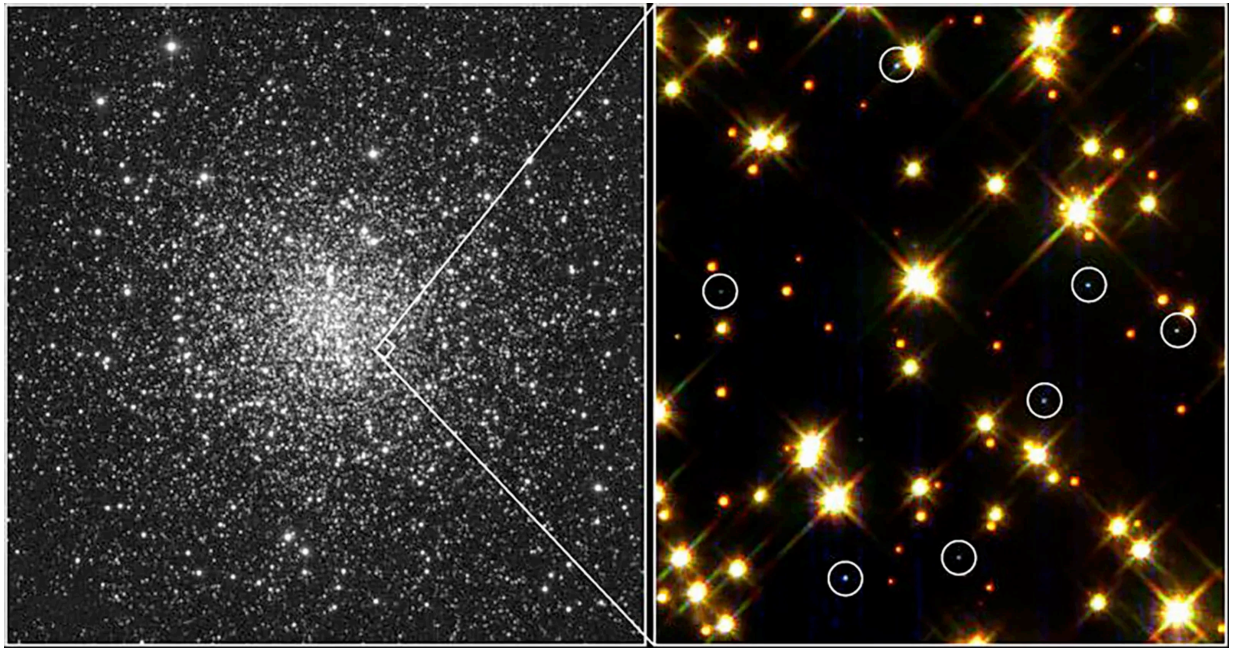
Astrophysical bounds

Stars are factories of feebly interacting particles

How can we obtain bounds from astrophysics?

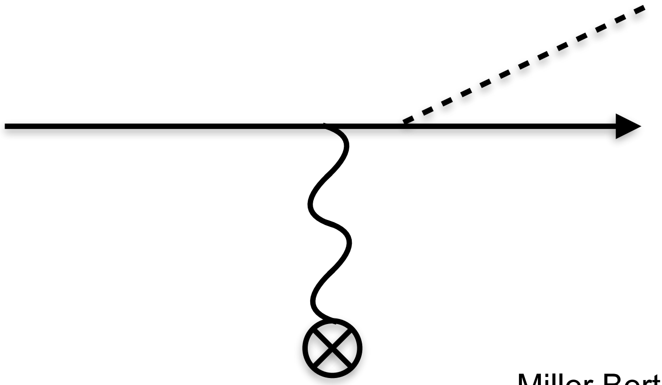
Example: white dwarfs for (pseudo)scalars with coupling to electrons

$$\mathscr{L}_{\text{int}} \sim g_{ae}\phi\bar{\psi}_e\psi_e = \frac{m_e}{v}\sin\theta\,\phi\bar{\psi}_e\psi_e$$



Credit: AURA/STScI/NASA/JPL

Energy loss bounds from white dwarfs

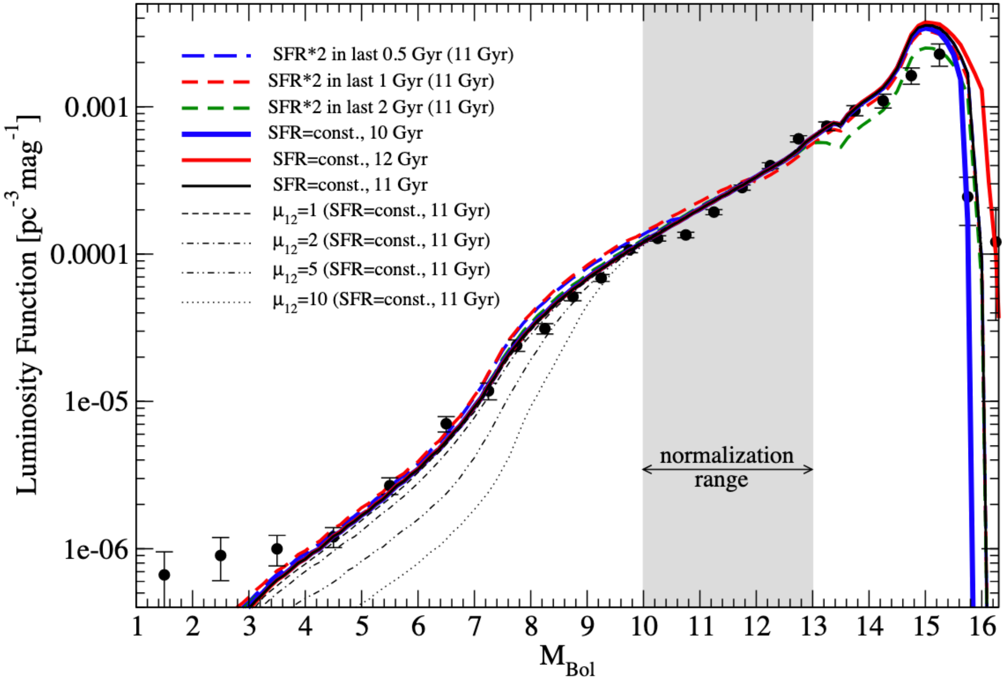


Axion bremsstrahlung dominates
See e.g. Raffelt (1986)

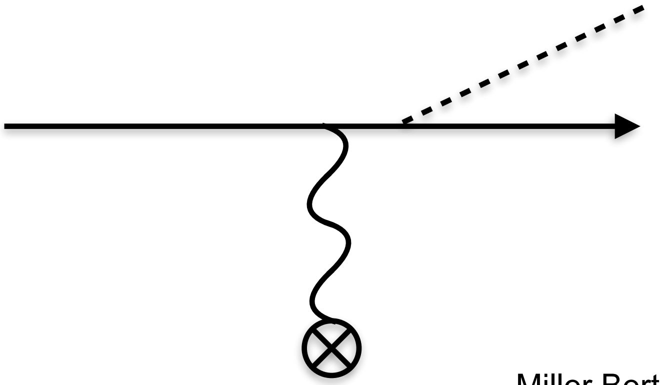
Same for scalars

- Simple systems: they just cool down, first through neutrino emission (plasmon decay), then photon emission

Miller Bertolami, Melendez, Althaus, Isern (2014)



Energy loss bounds from white dwarfs

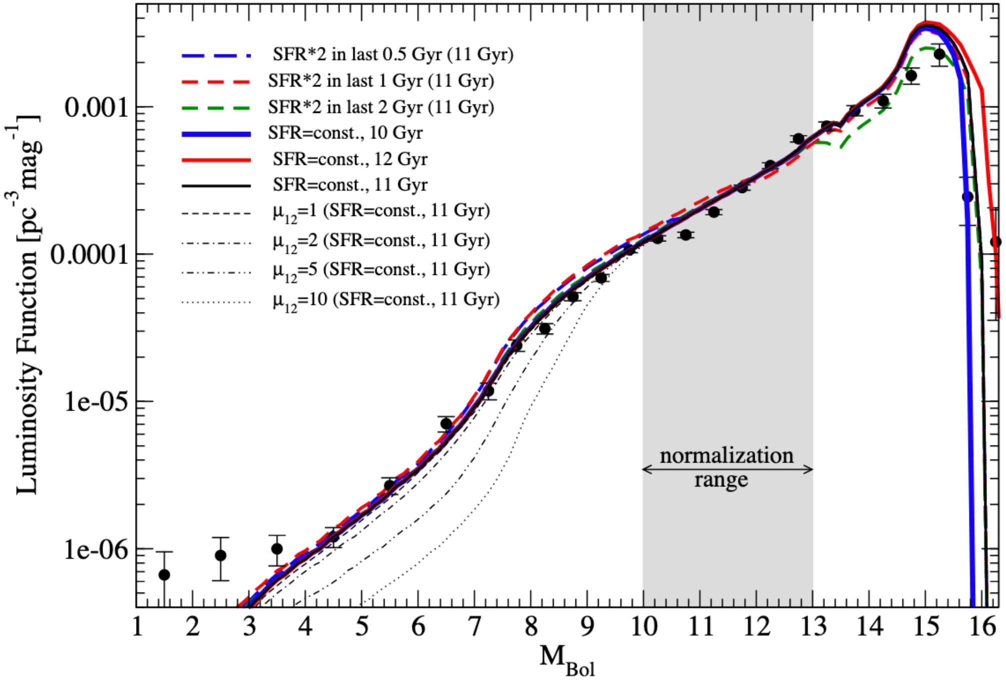


Axion bremsstrahlung dominates
See e.g. Raffelt (1986)

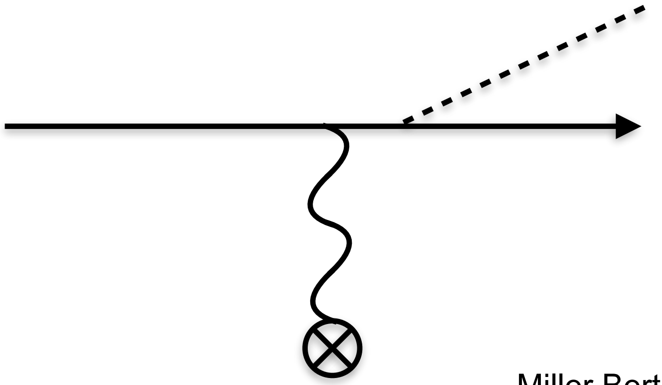
Same for scalars

- Simple systems: they just cool down, first through neutrino emission (plasmon decay), then photon emission
- Compute the additional energy loss Q due to particle emission (e.g. axions with electron coupling)

Miller Bertolami, Melendez, Althaus, Isern (2014)



Energy loss bounds from white dwarfs

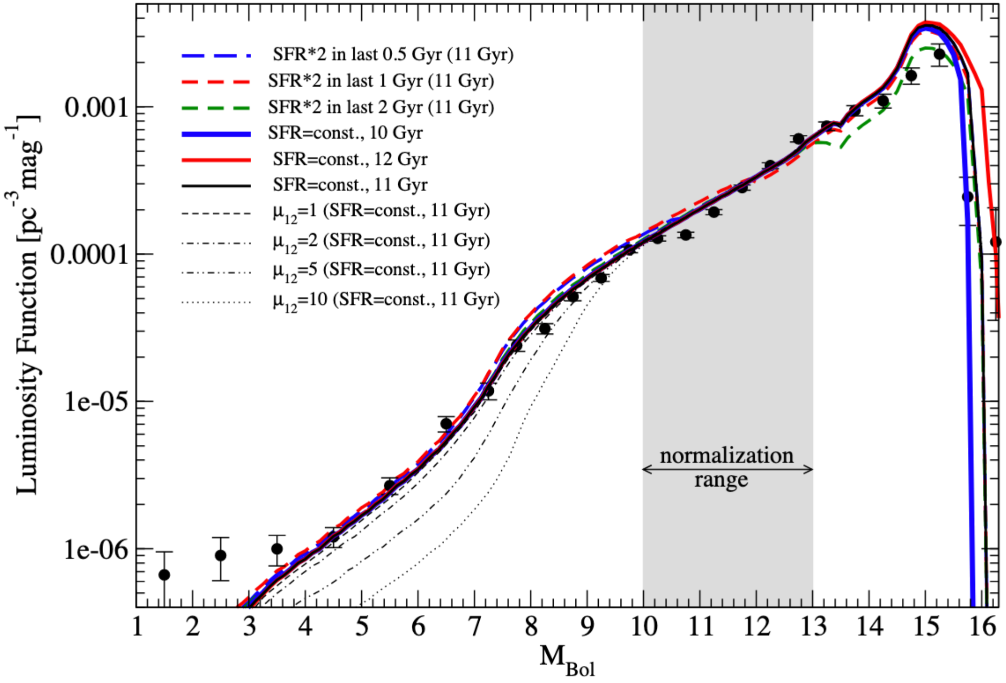


Axion bremsstrahlung dominates
See e.g. Raffelt (1986)

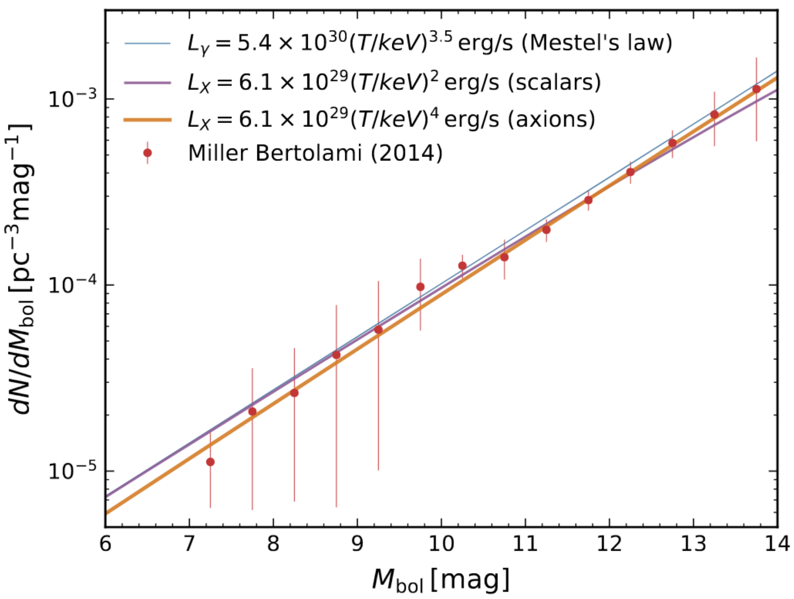
Same for scalars

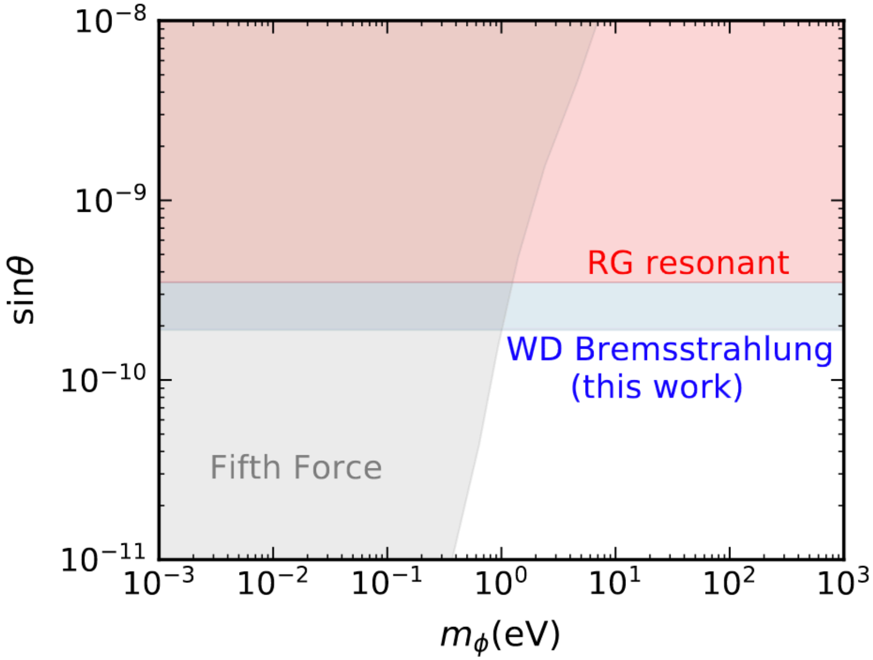
- Simple systems: they just cool down, first through neutrino emission (plasmon decay), then photon emission
- Compute the additional energy loss Q due to particle emission (e.g. axions with electron coupling)
- Check the effect on the white dwarf luminosity function (number of white dwarf stars with a given luminosity). This is determined by the rates at which these stars form and cool

Miller Bertolami, Melendez, Althaus, Isern (2014)



Energy loss bounds from white dwarfs





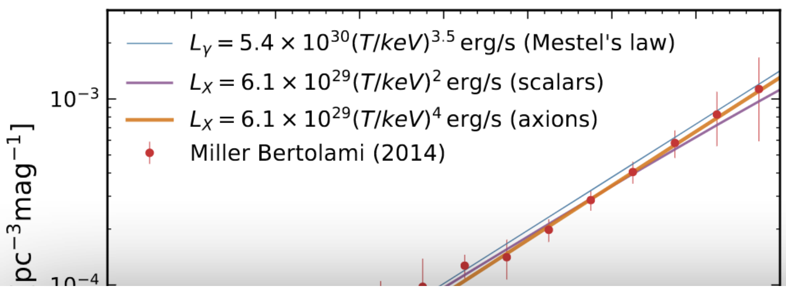
Bottaro, Caputo, Raffelt, **Vitagliano**, *JCAP 07 (2023) 071*

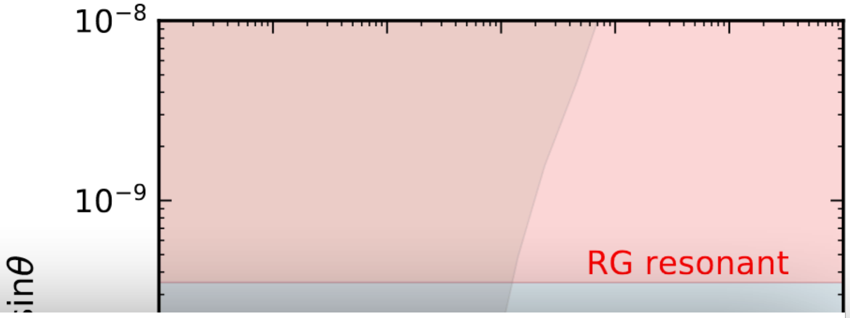
Fresh new bounds on scalar emission from WDs (dominant constraints in the eV-keV range)

Be careful with larger masses (Dolan et al. 2306.13335)

Brand new!

Energy loss bounds from white dwarfs





Take home lesson

- Identify system appropriate for the particle model you are interested in
- Compute the FIP emission
- Identify the **observable**

Fresh new bounds on scalar emission from WDs (dominant constraints in the eV-keV range)

Be careful with larger masses (Dolan et al. 2306.13335)

Brand new!

Other observables related to cooling

Many different observables depending on the particle model
(incomplete reference list)

- R and R_2 ratios (Horizontal Branch stars) Ayala et al. *Phys.Rev.Lett.* 113 (2014) 19, 191302, Dolan et al. *JCAP* 10 (2022) 096, Lucente et al. *Phys.Rev.Lett.* 129 (2022) 1, 011101
- RGB tip (Red Giants) Viaux et al. *Phys.Rev.Lett.* 111 (2013) 231301, Capozzi and Raffelt *Phys.Rev.D* 102 (2020) 8, 083007, Raffelt and Dearborn *Phys.Rev.D* 36 (1987) 2211, Raffelt and Weiss *Phys.Rev.D* 51 (1995) 1495-1498, Straniero et al. Astron.Astrophys. 644 (2020) A166
- Observed cooling of Magnificent Seven and Cas A (Neutron Stars) Buschmann et al *Phys.Rev.Lett.* 128 (2022) 9, 091102, Leinson *JCAP* 08 (2014) 031, Hamaguchi et al. *Phys.Rev.D* 98 (2018) 10, 103015
- Solar neutrinos Vinyoles et al. *JCAP* 10 (2015) 015
- General analysis of bounds Giannotti et al. *JCAP* 10 (2017) 010, Giannotti et al. *JCAP* 05 (2016) 057
- …

End of the introduction.
Time for exploding star pictures!

Credit: Anglo-Australian Observatory

Credit: Anglo-Australian Observatory

Supernova 1994D in the galaxy NGC 4526

Credit: ESO (ann11014a)

Astro bounds on heavy bosons

I. What did we expect from SN 1987A?

II. What did we see from SN 1987A?

III. New bounds on decaying bosons:
photon, charged lepton, neutrino couplings

Conclusions

What did we expect?

Stellar collapse

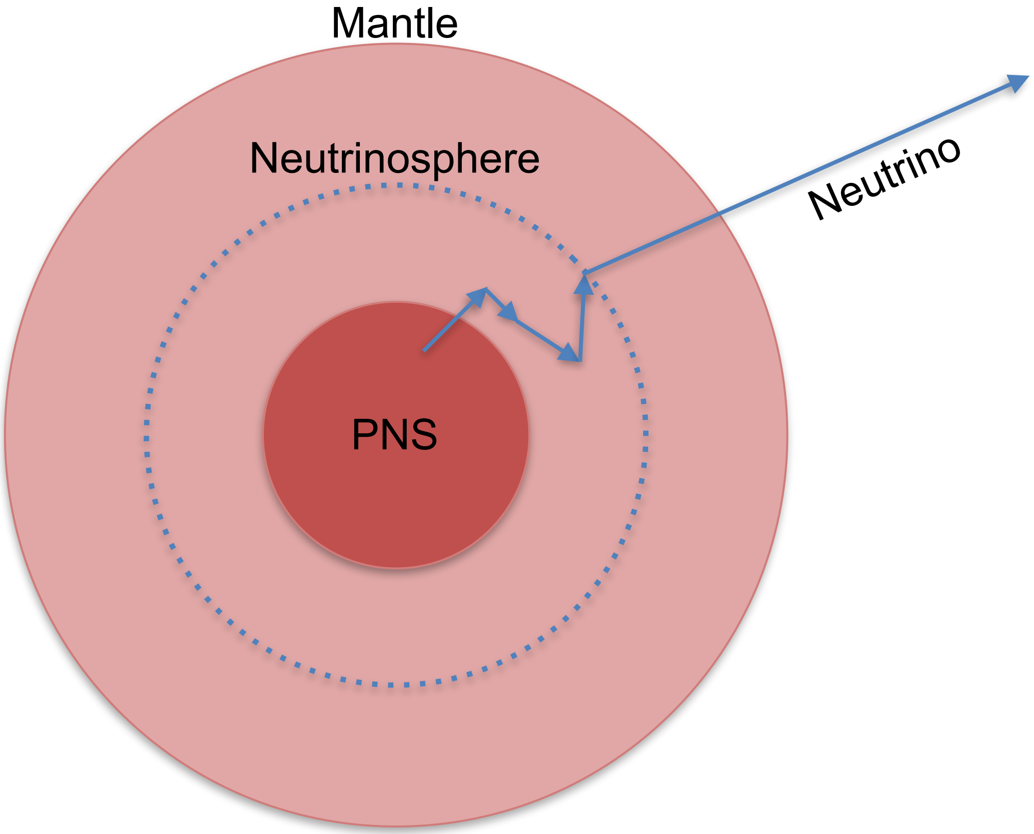
Protoneutron star, it has

- $T = \mathcal{O}(10\,\mathrm{MeV})$
- $\rho = 3 \times 10^{14}\mathrm{g/cm^3}$
- $R_{\mathrm{PNS}} = 20\,\mathrm{km}$

And produce many neutrinos,

- $L_\nu = 3 \times 10^{53}\mathrm{erg/3s}$
- Energy deposited: 1%

MASTER FIGURE



(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:

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

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

$$t_{\text{diff}} \simeq R^2/\lambda \simeq \mathcal{O}(1\text{s})$$

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:

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

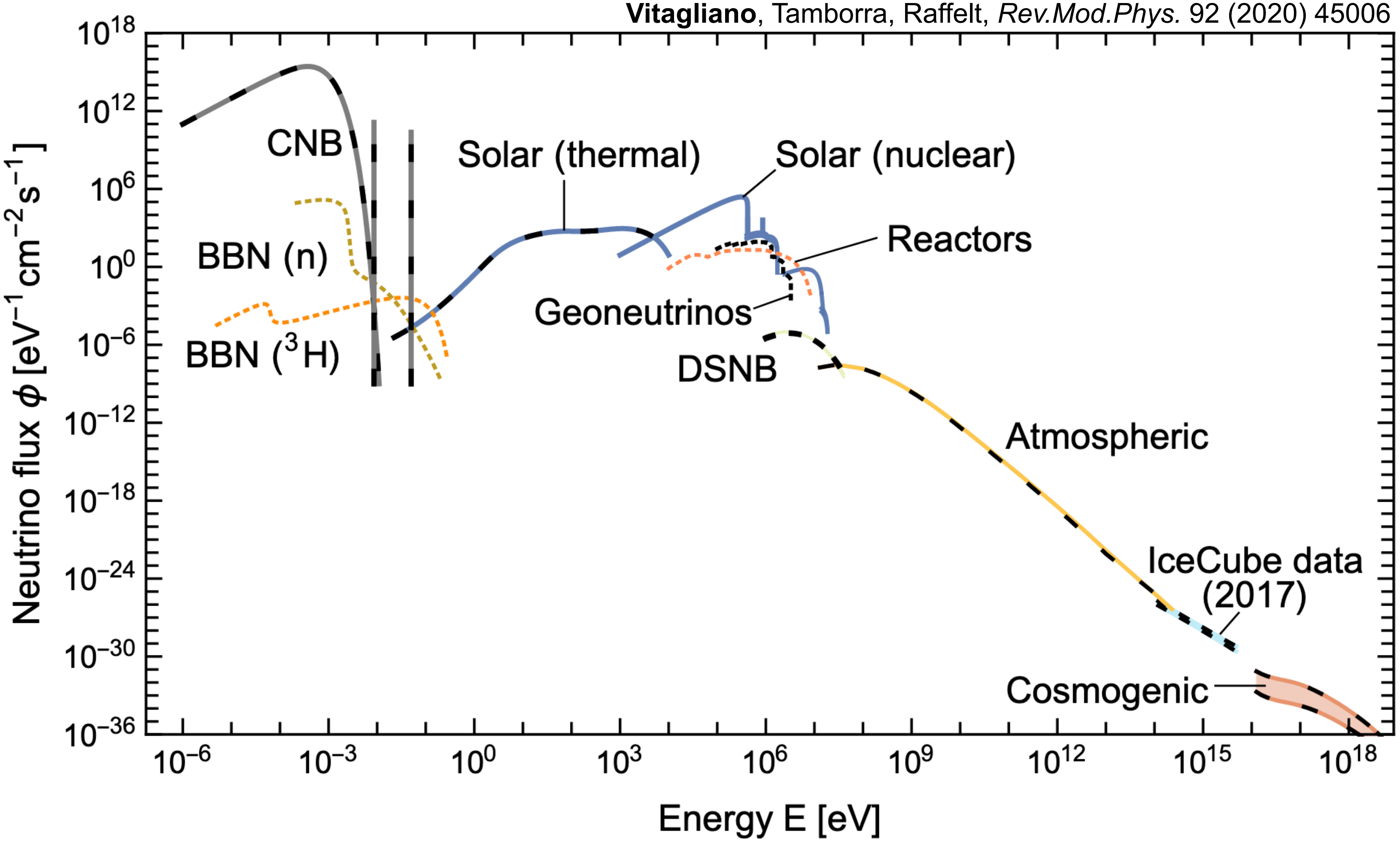
$$M \simeq 1.4M_\odot, R = 15\,\text{km} \rightarrow T = \frac{2}{3}\langle E_{\text{kin}}\rangle \simeq 17\,\text{MeV}$$

$$t_{\text{diff}} \simeq R^2/\lambda \simeq \mathcal{O}(1\text{s})$$

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

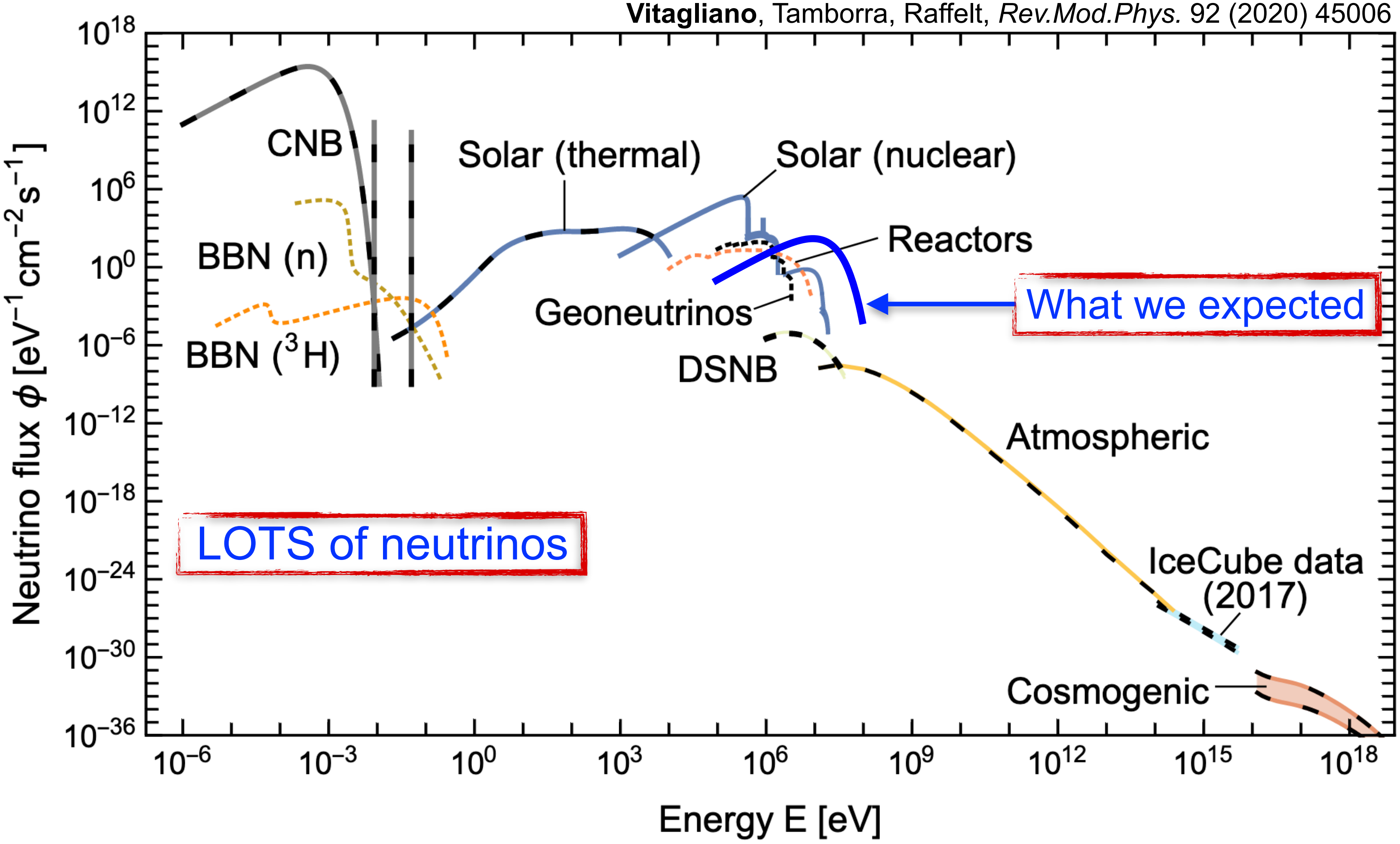
Grand unified neutrino spectrum at Earth

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

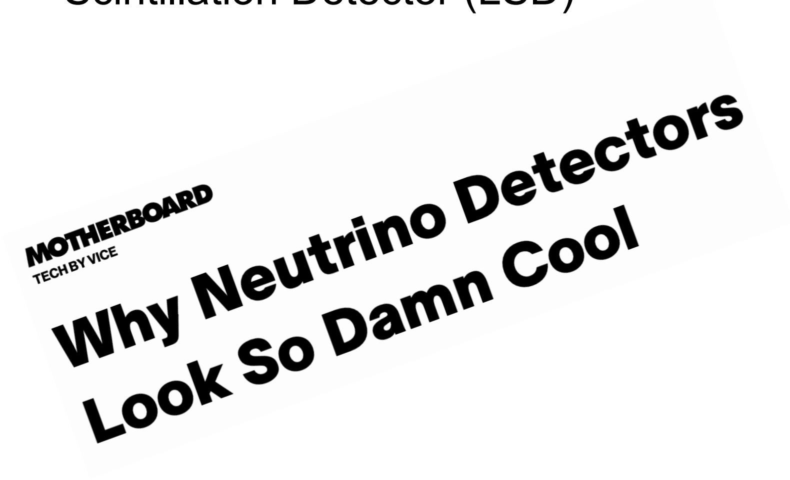
LOTS of neutrinos

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

What did we see?

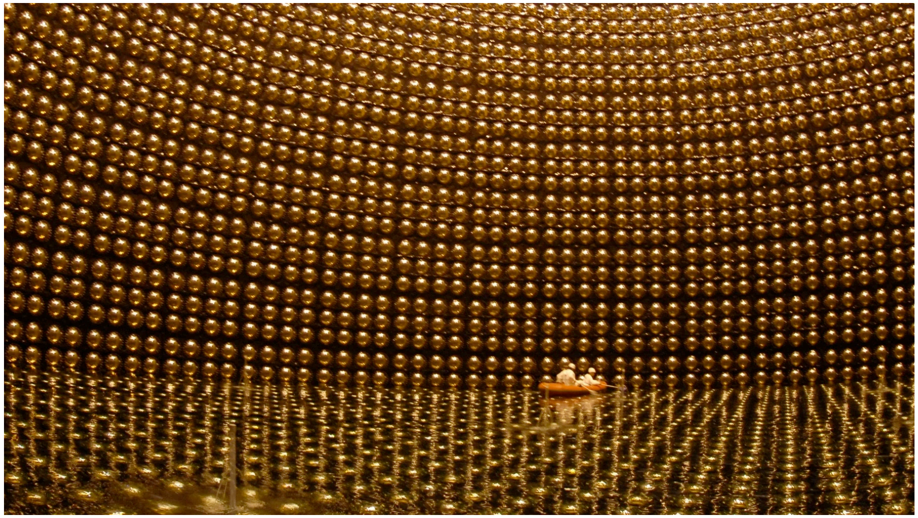
SN 1987A Neutrino Observations

- Discovered independently by Ian Shelton, Oscar Duhalde, and Albert Jones on February 23, 1987, and later targeted by searches in the entire electromagnetic spectrum. The first evidence for optical brightening was found at 10:38 UT (Universal Time) on plates taken by McNaught
- Many experiments available in 1987! CTIO 4-m also known as Victor Blanco, AngloAustralian, CFHT and soon Herschel, radio observations from Chris Cross at Fleurs, 1.4 GHz and Molonglo Observatory Synthesis Telescope at 800 MHz
- Most of all: 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)



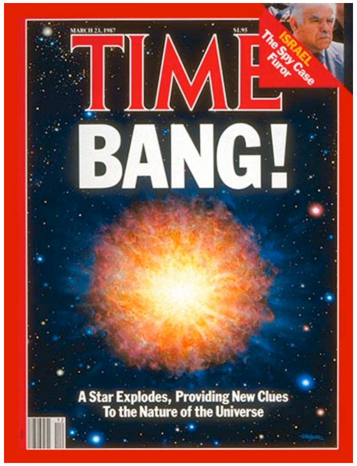
MOTHERBOARD
TECH BY VICE

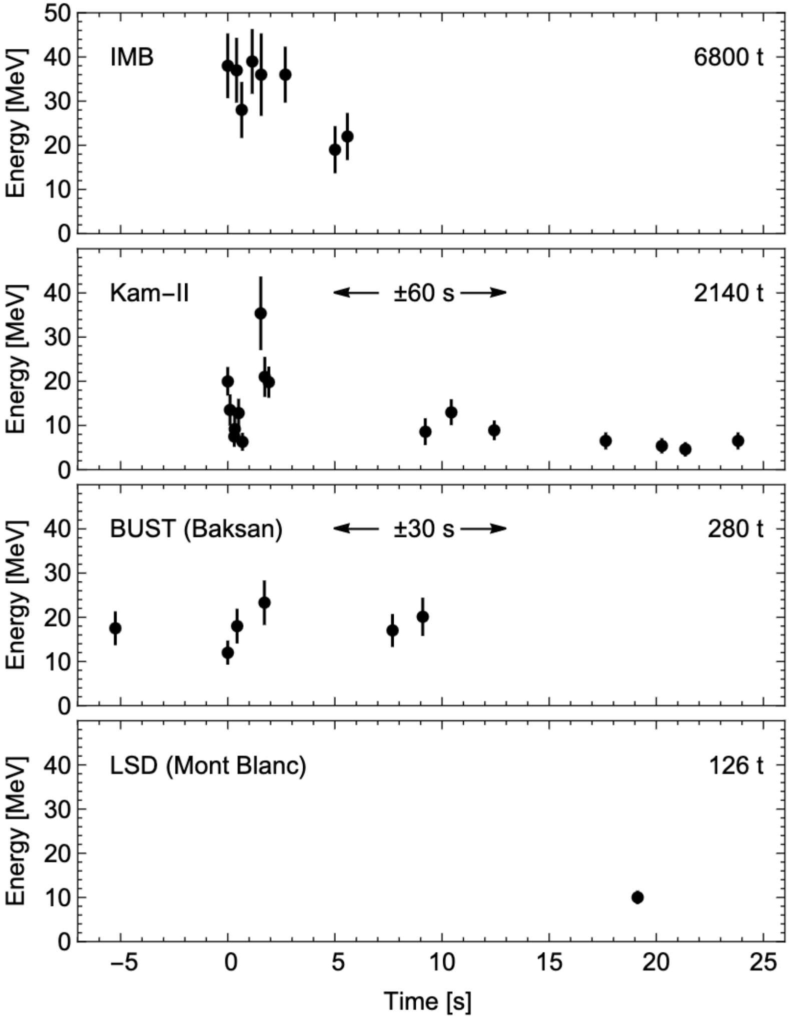
Why Neutrino Detectors Look So Damn Cool



Credit: Super-Kamiokande

SN 1987A Neutrino Observations





2002 Nobel prize to Masatoshi Koshiba (Kamiokande)

2015 Nobel prize winner Takaaki Kajita was a postdoc there

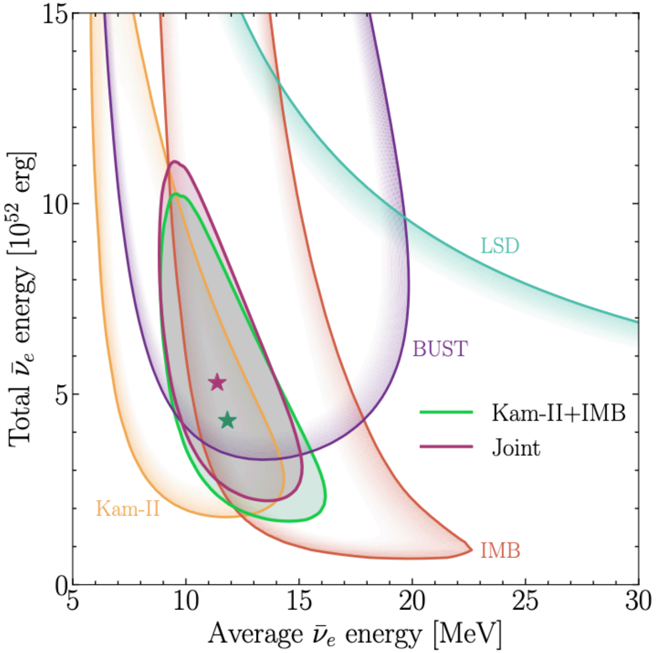
New comparisons to SN simulations from several groups

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

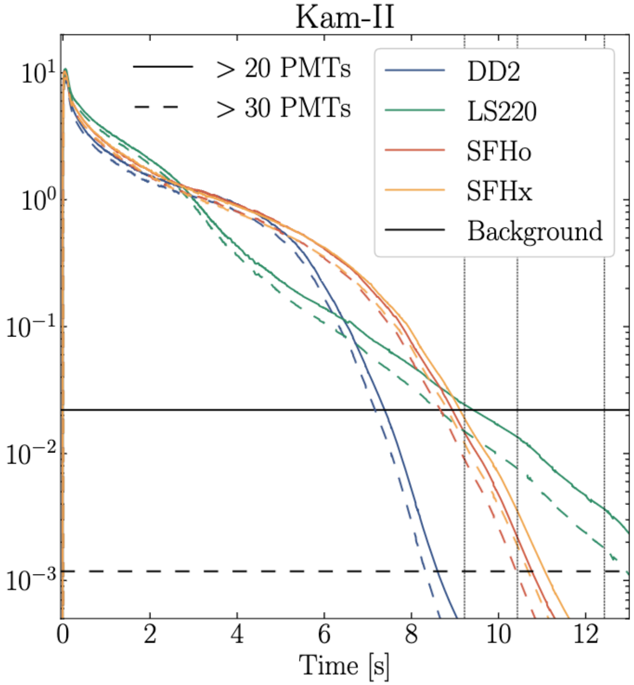
SN 1987A Neutrino Observations

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)



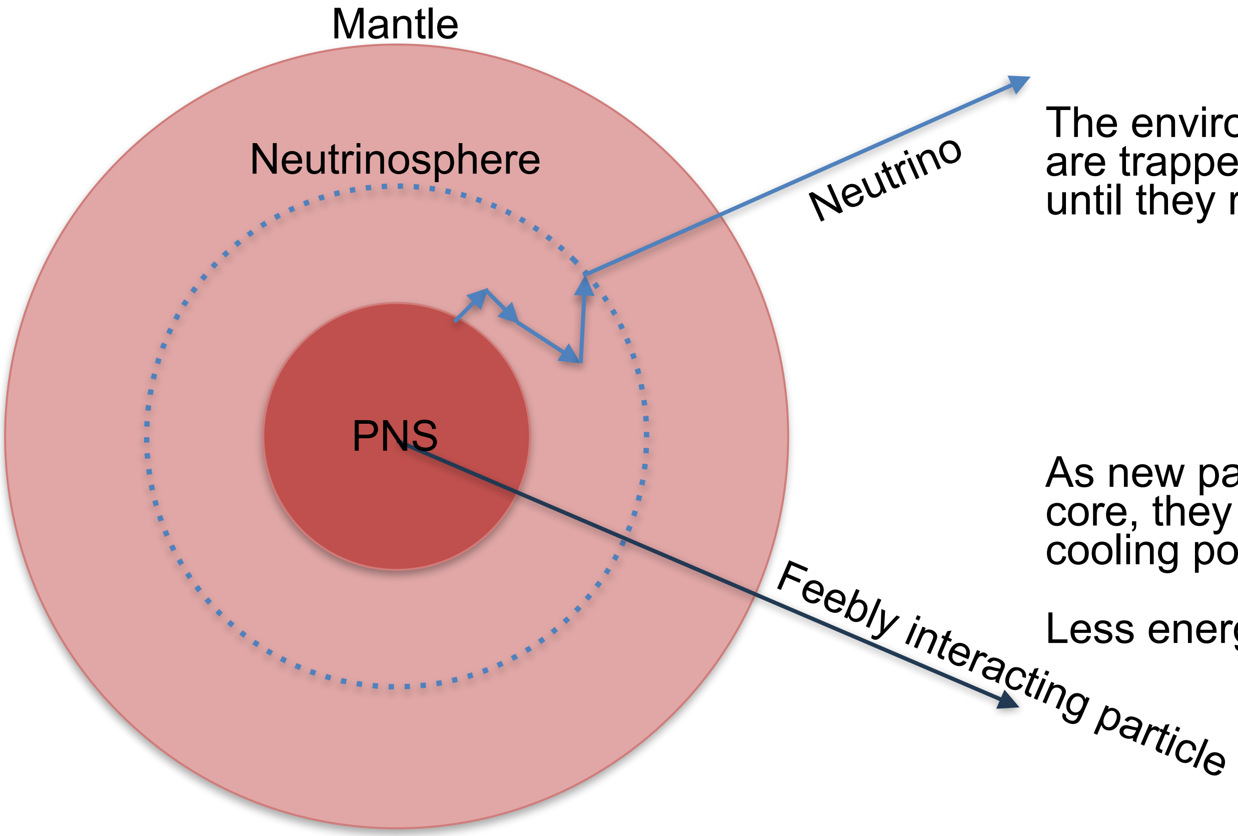
Fiorillo, Heinlein, Janka, Raffelt, **Vitagliano**, Bollig (2023)

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

What can we learn? (aka new bounds on decaying bosons)

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

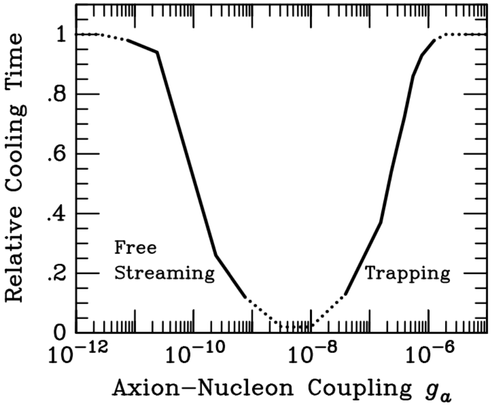


Fig. 13.1. Relative duration of neutrino cooling of a SN core as a function of the axion-nucleon Yukawa coupling g_a. In the free-streaming limit axions are emitted from the entire volume of the protoneutron star, in the trapping limit from the "axion sphere" at about unit optical depth. The solid line 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 $\rho = 3 \times 10^{14}\, \mathrm{g\, cm^{-3}}$

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)

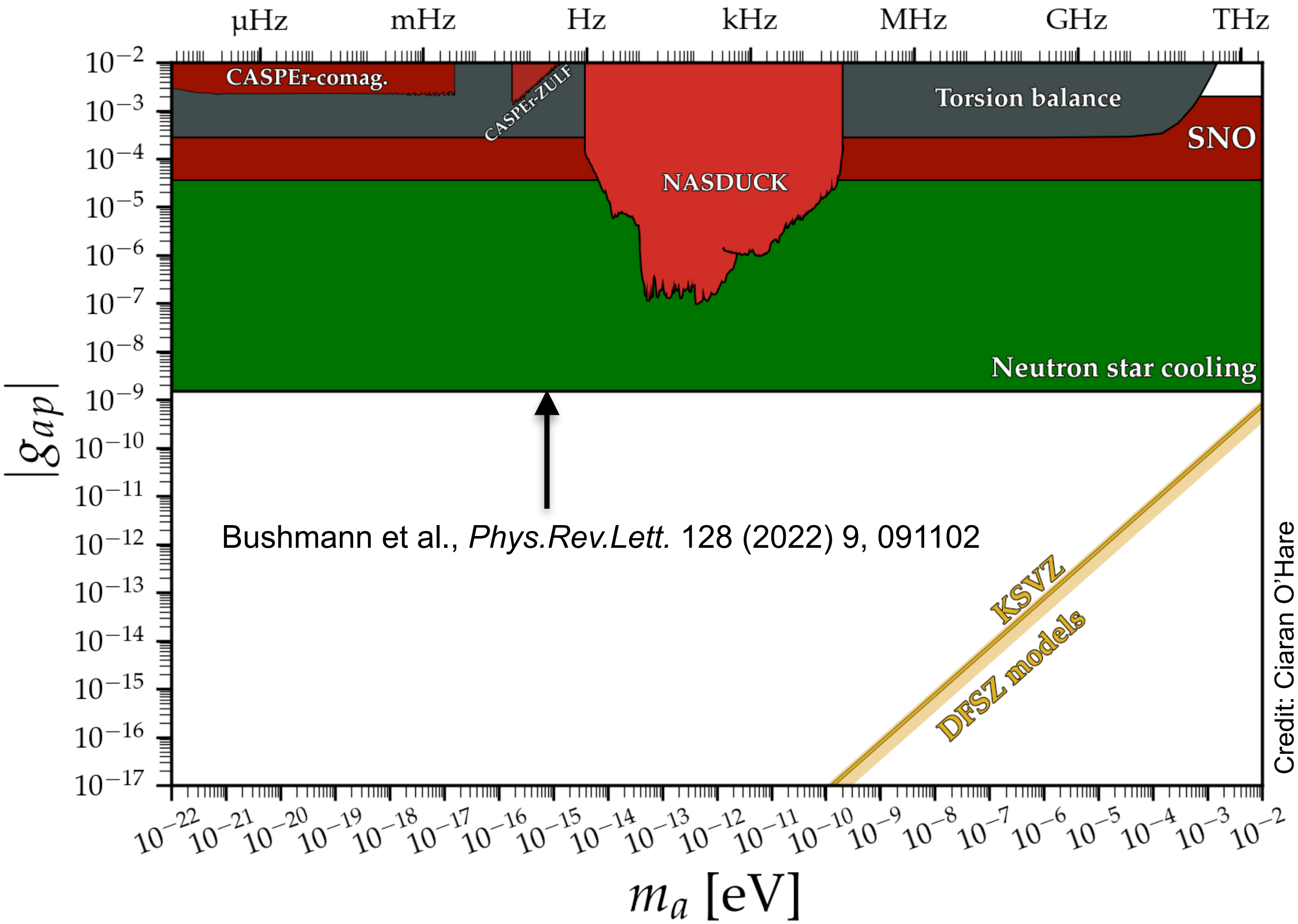
- Chang, Essig & McDermott, JHEP 1809 (2018) 051 [1803.00993]
  Various correction factors to emission rates, specific SN core models
  $f_a \gtrsim 1 \times 10^8\,\mathrm{GeV}$ and $m_a \lesssim 60\,\mathrm{meV}$ (KSVZ, based on proton coupling)

- 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 $\pi - + p \rightarrow n + a$ (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, viable?)
  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?

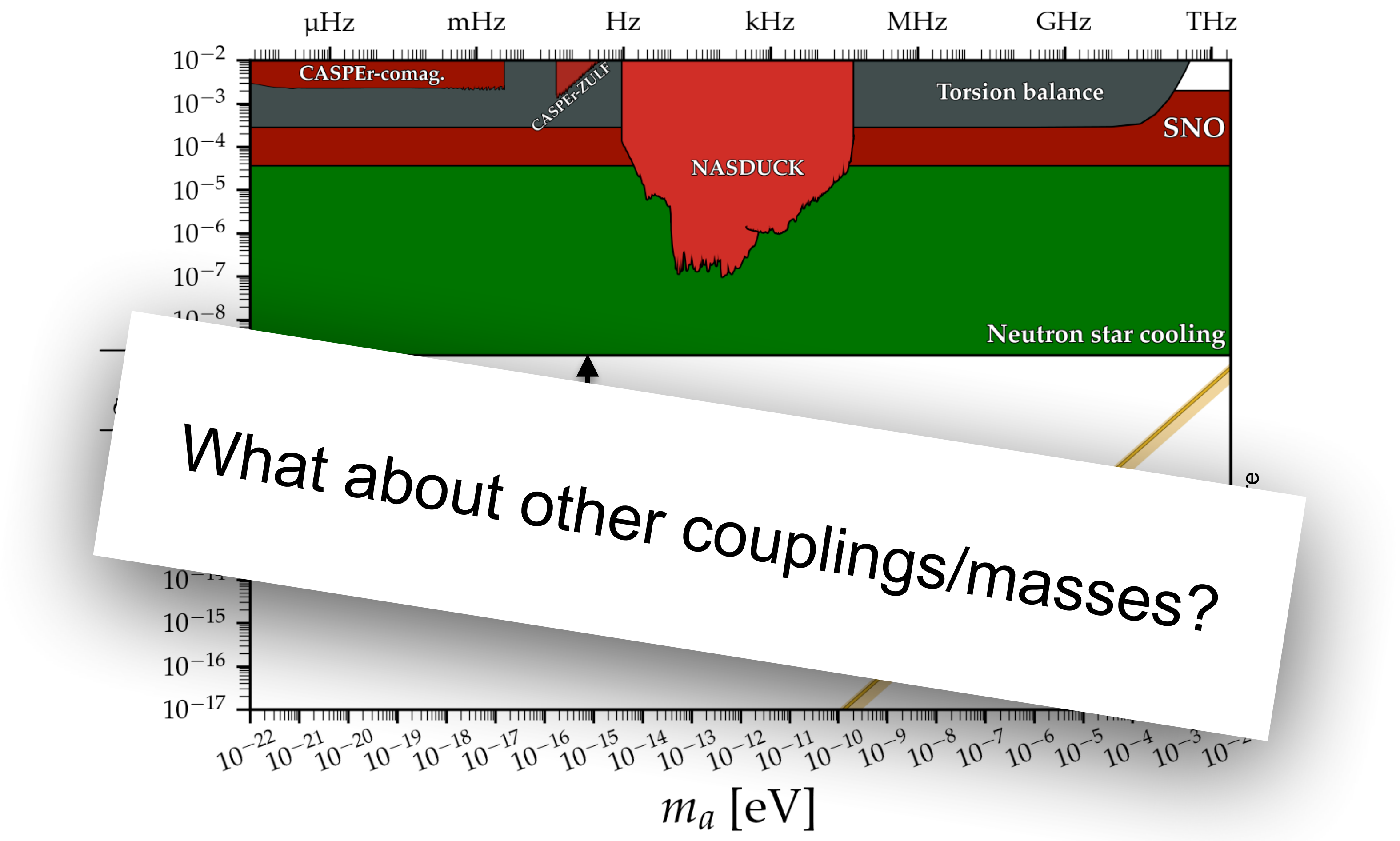


Bushmann et al., *Phys.Rev.Lett.* 128 (2022) 9, 091102

Credit: Ciaran O'Hare

(Complementary to neutron star cooling observations for hadronic couplings)

Are SN bounds competitive?



What about other couplings/masses?

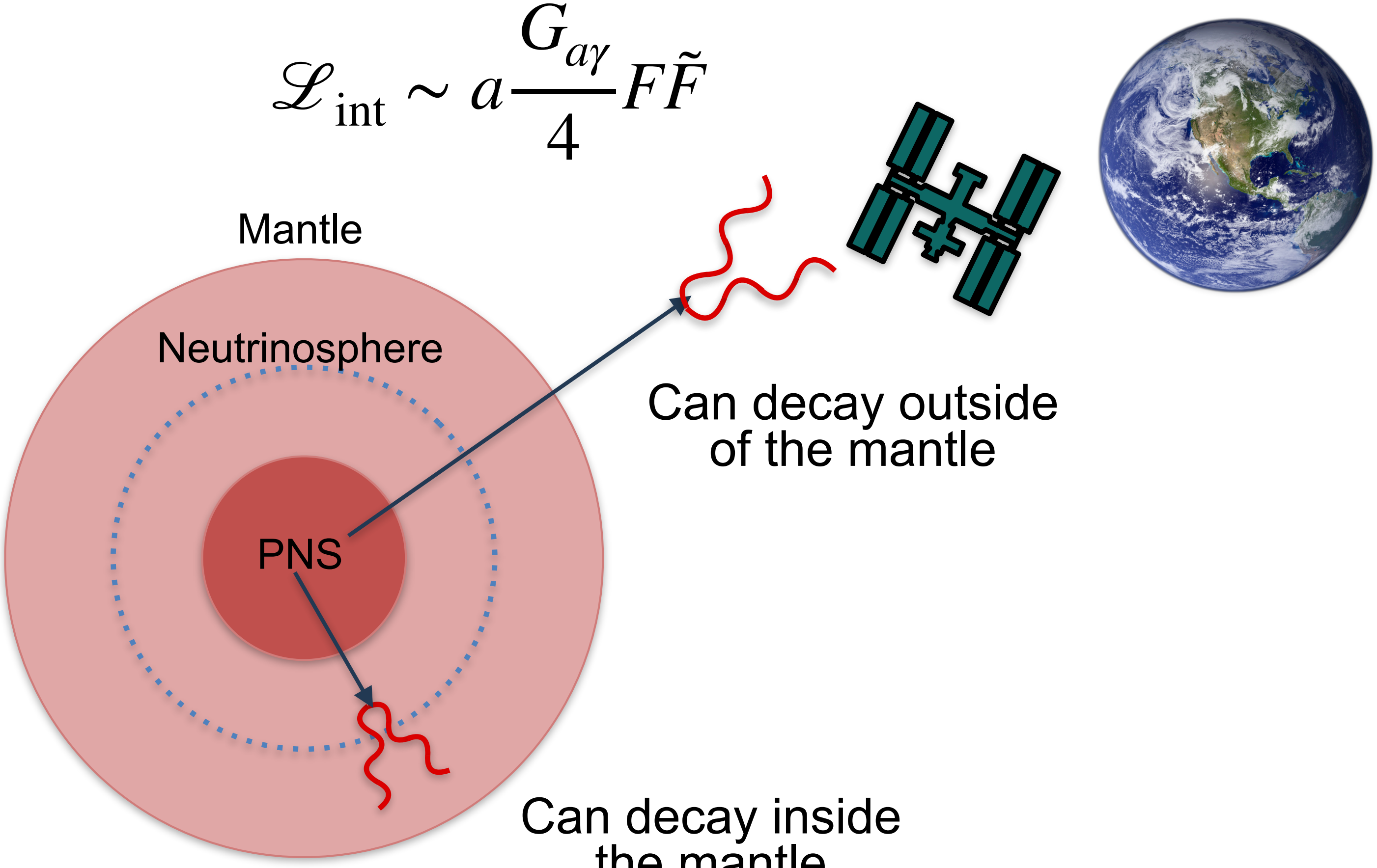
(Complementary to neutron star cooling observations for hadronic couplings)

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

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



Mantle

Neutrinosphere

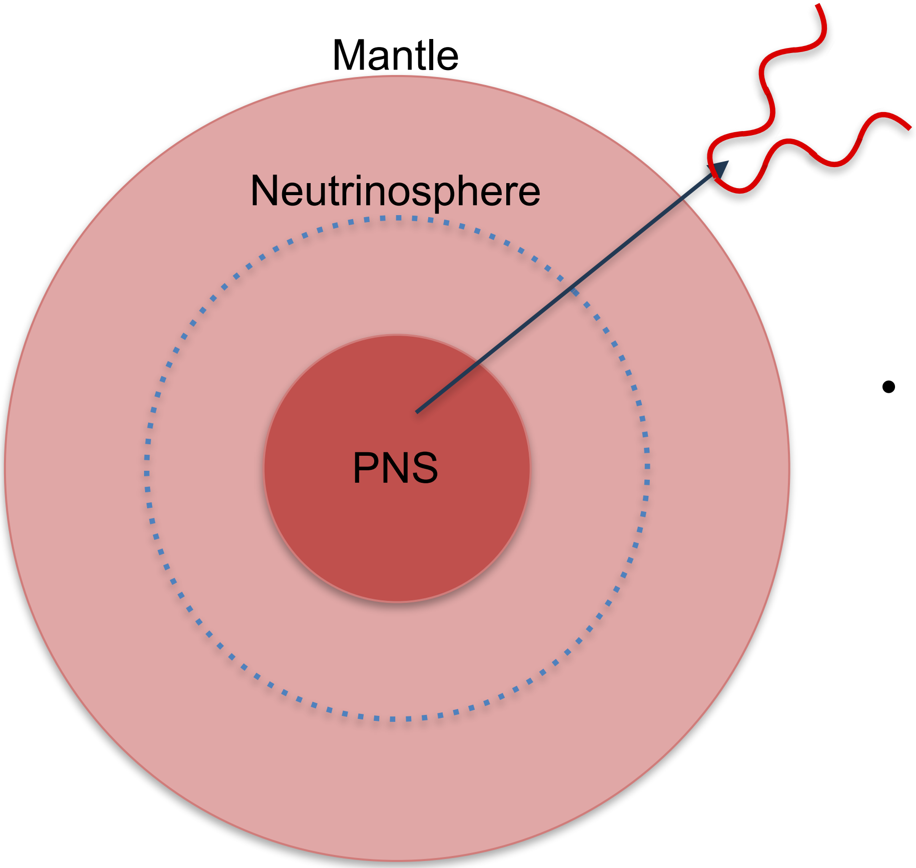
PNS

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

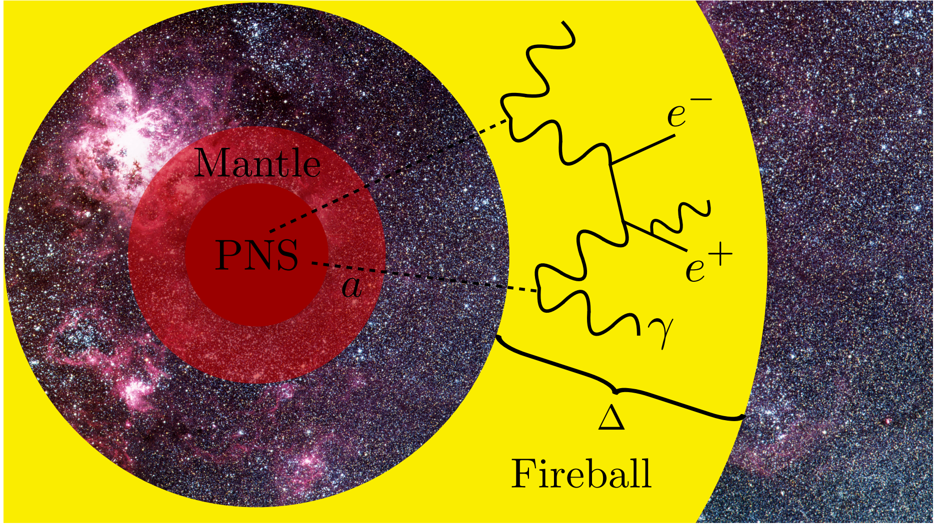
BUT…

Long lifetimes: fireball formation

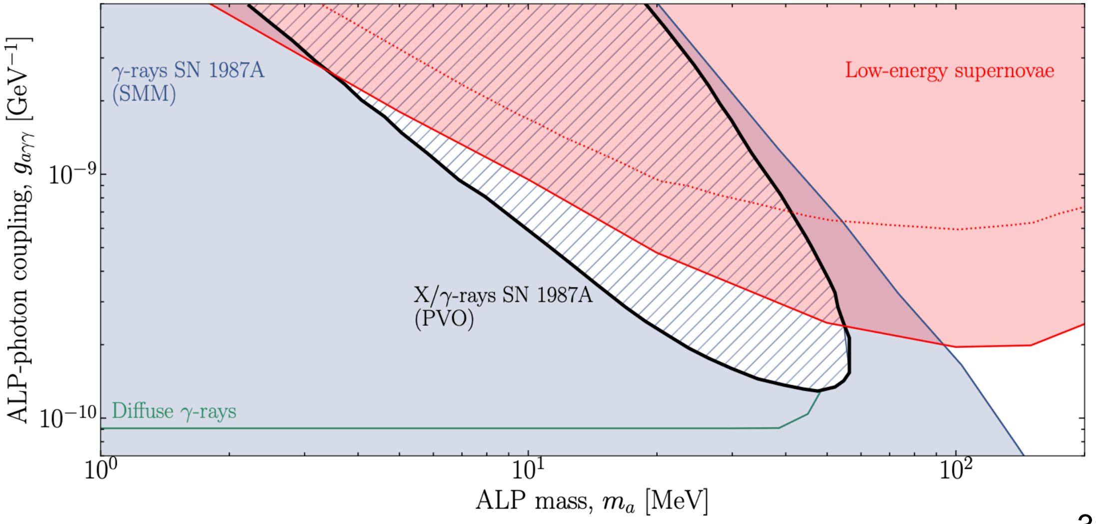
Brand new!

Editors' Suggestion

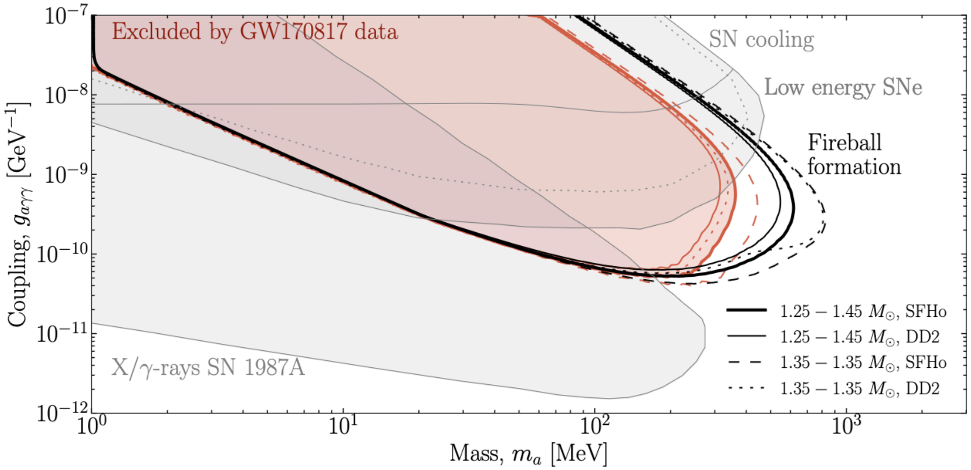
Diamond, Fiorillo, Marques-Tavares, **Vitagliano**, *Phys.Rev.D* 107 (2023) 10, 103029



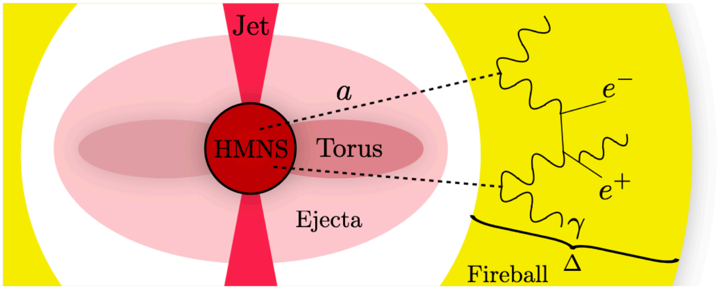
- The bounds from decay to gamma-ray do not apply everywhere!
- For a large region of masses and couplings, axions form a fireball
- The expected flux is at much smaller frequencies
- New bounds from Pioneer Venus Observatory

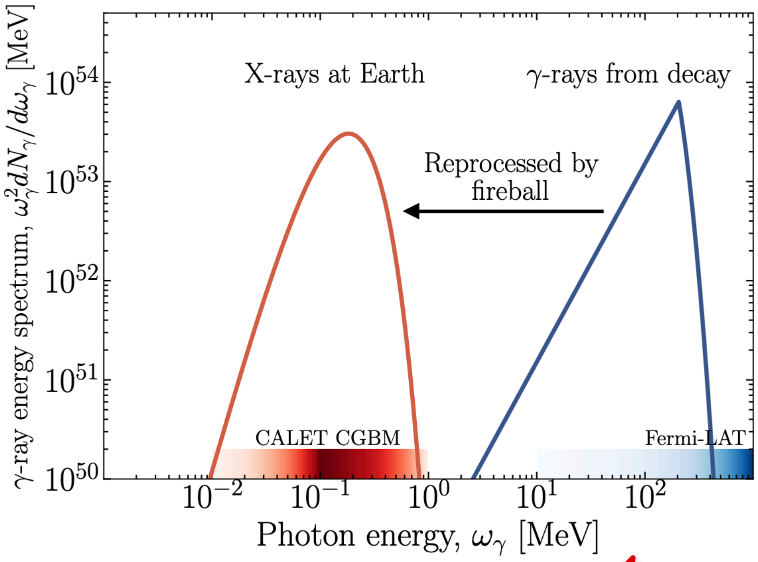


Bounds from GW170817



Diamond, Fiorillo, Marques-Tavares, Tamborra, **Vitagliano**, e-Print: 2305.10327

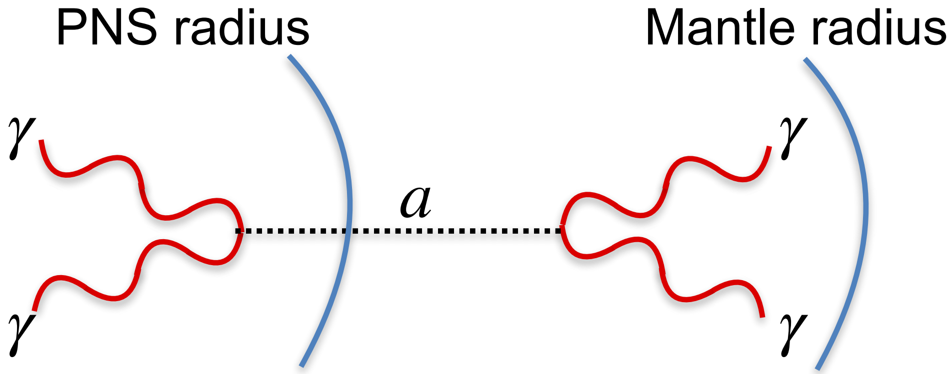




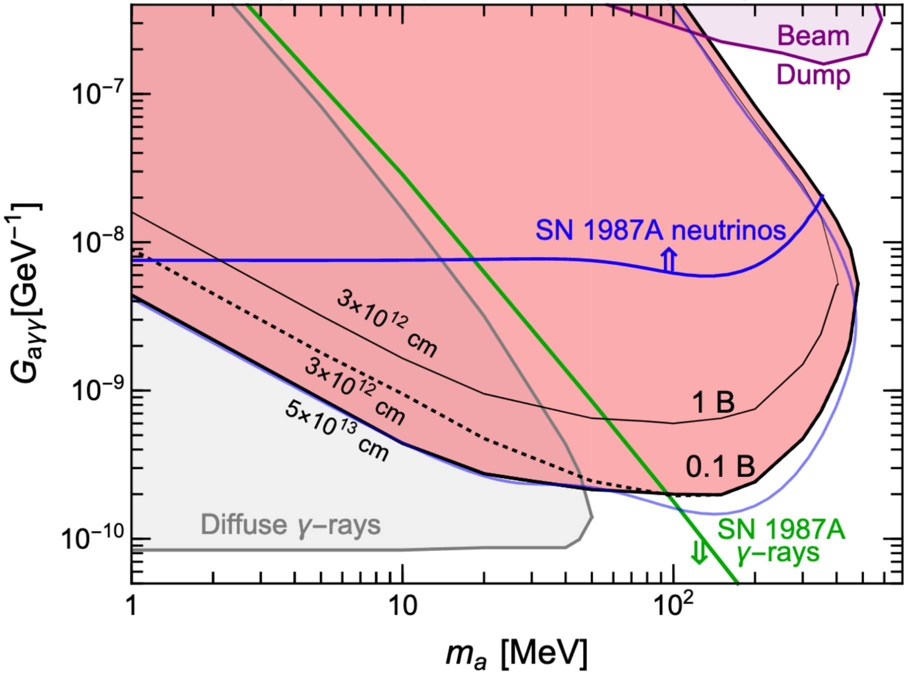
- Neutron star mergers produce a heavy mass NS remnant without a mantle!
- Huge temperature and densities
- Extremely sensitive measurements by X-ray detectors of GW 170817
- Fresh bounds on $m_a > 1\,\mathrm{MeV}$ axions

Brand new!

Short lifetimes: New bound from decay in the mantle

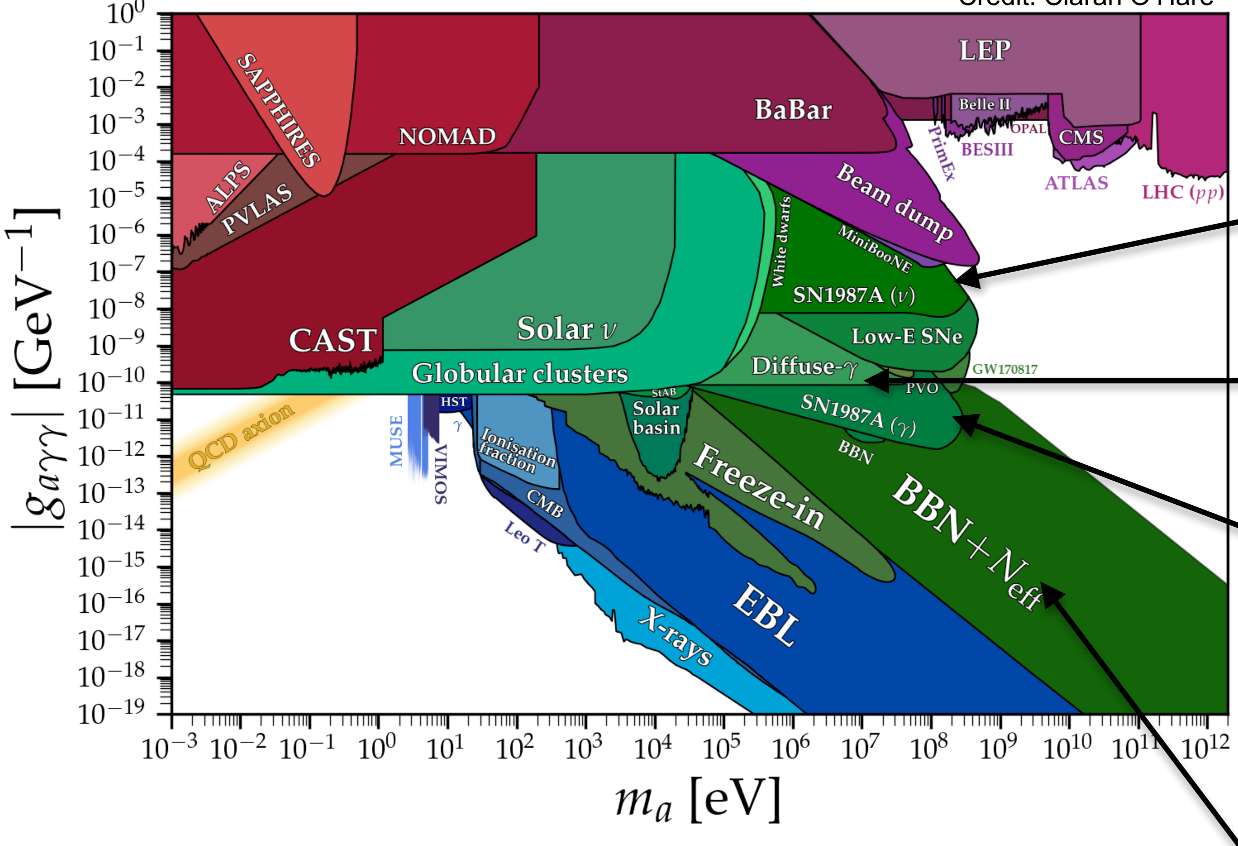


- Typical SN explosion energy 1-2 B
  $1\,\mathrm{B\ (bethe)} = 10^{51}\,\mathrm{erg}$
- Neutron star binding energy 200-400 B
- Some SNe have very small observed explosion energies < 0.1 B
- New restrictive limits from low-energy SNe



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)

Diffuse gamma-ray background from past SNe

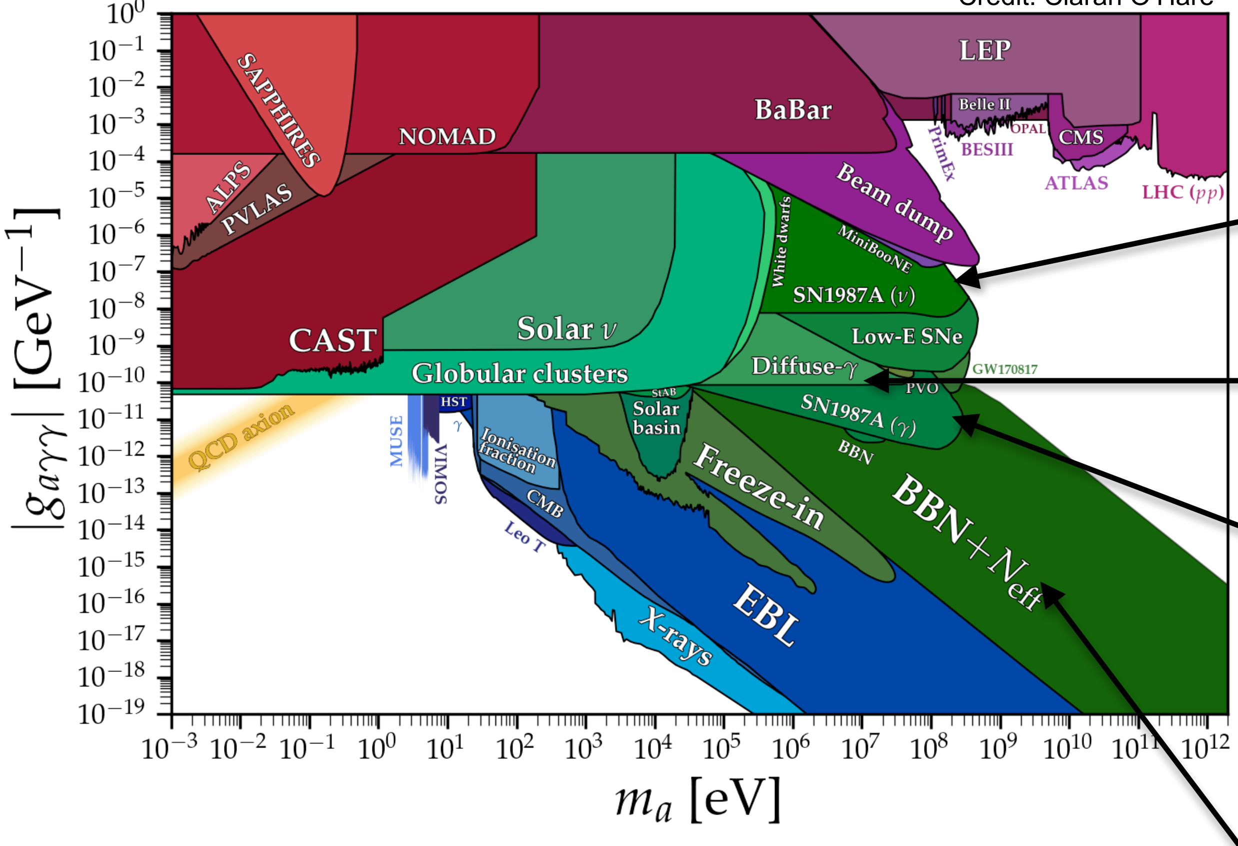
Gamma-ray from SN 1987A at SMM and PVO

(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)

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)

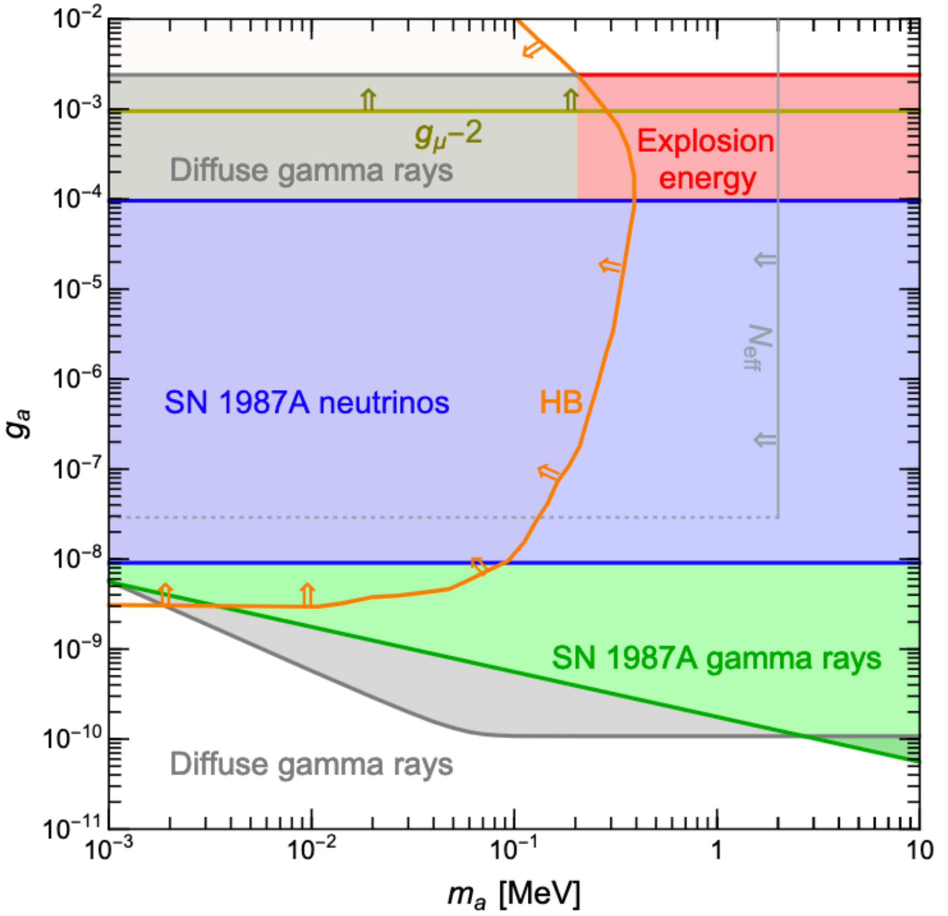
Diffuse gamma-ray background from past SNe

Gamma-ray from 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)

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

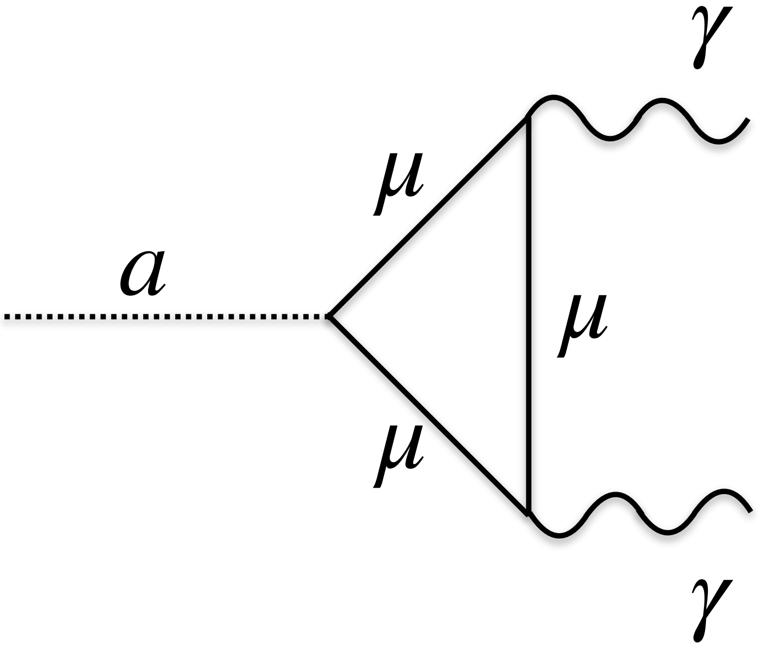
Leptonic couplings: example with muons



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

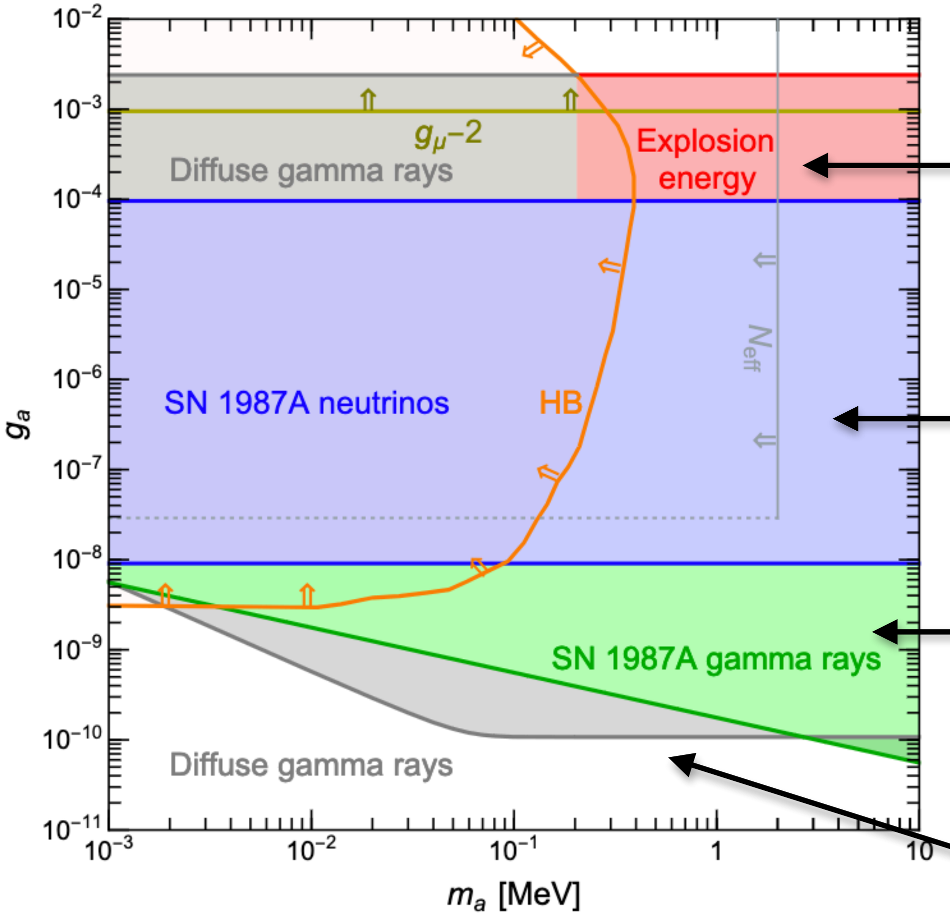
Editors' Suggestion

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



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

Leptonic couplings: example with muons



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

Editors' Suggestion

Heats up the mantle of the SN

Cooling bound

Gamma-ray from SN 1987A at SMM

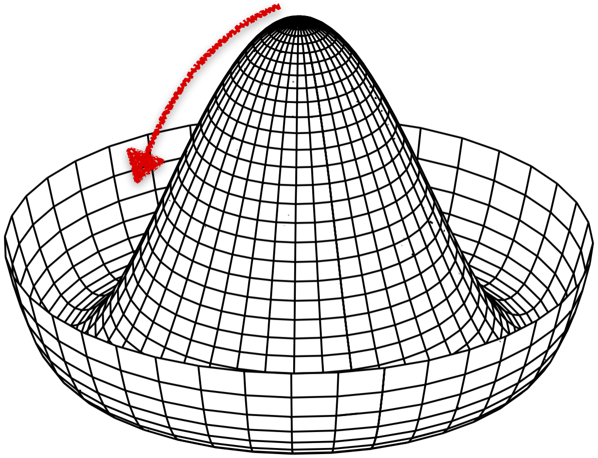
Diffuse gamma-ray background from past SNe

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

Particles with a neutrino coupling

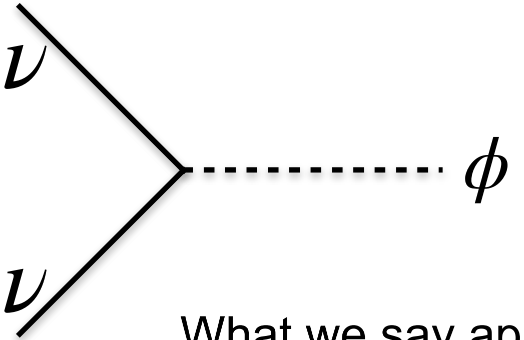
Many BSM particles have coupling to neutrinos:

- 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



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

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



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

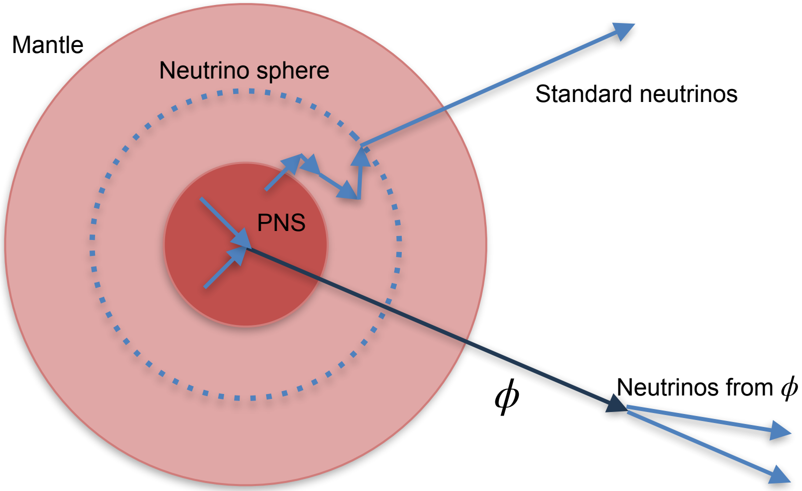
What we say applies also to the other cases

Is it the best bound we can get?

If we assume the free-streaming bound value for the coupling, $L_\phi = L_\nu$

Majoron produced in the core,
$E_\phi \sim \mu_\nu \sim 100\,\mathrm{MeV}$
then decay back to neutrinos

Neutrinos escape at the neutrino sphere so $E_\nu \sim 10\,\mathrm{MeV}$



Fiorillo, Raffelt, **Vitagliano**, 2022

Therefore $\dfrac{n_\nu^{\phi\,\mathrm{decay}}}{n_\nu^{\mathrm{standard}}} \sim \dfrac{E_\nu^{\mathrm{standard}}}{E_\nu^{\phi\,\mathrm{decay}}}$

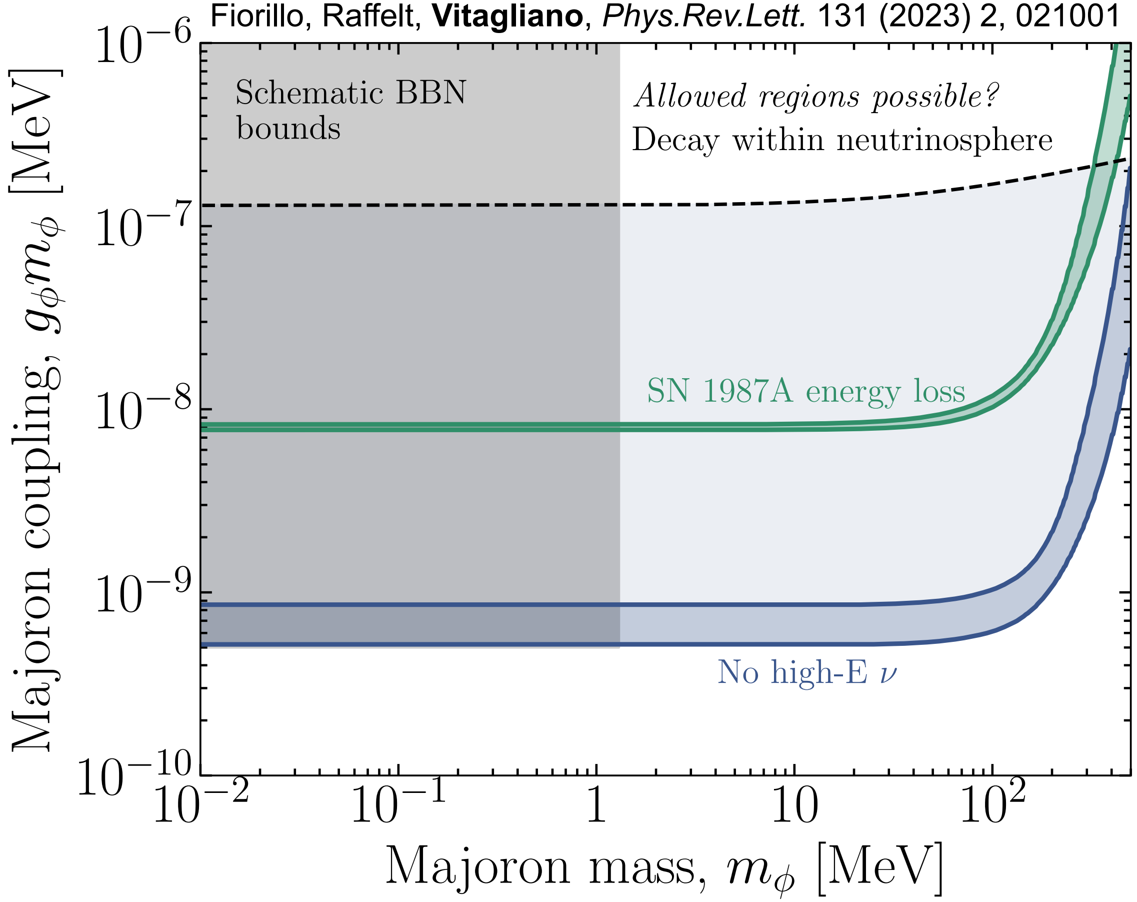
But the cross section in the detector grows like $\sigma \sim G_F^2 E^2$

We would have seen 10 times more events compared to the ones we saw!

New bounds from decay to neutrinos

Brand new!

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



Not strongly dependent on the Supernova model

(See also Akita, Im, Masud JHEP 12 (2022) 050 for an application to future galactic SNe)

Trapping regime (axions)

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

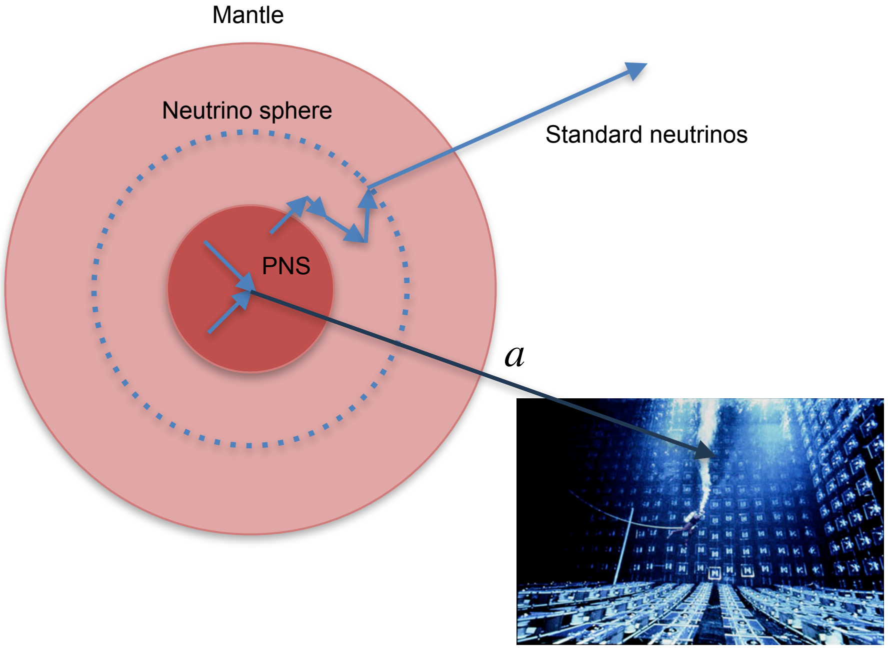
Two examples: **axions** and majorons

- 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 Modified luminosity criterion (MLC) to account for opacity Chang, Essig, Mcdermott (*JHEP* 09 (2018) 051)
- 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 Caputo, Raffelt, **Vitagliano** (*JCAP* 08 (2022) 08, 045)

Trapping regime (axions)

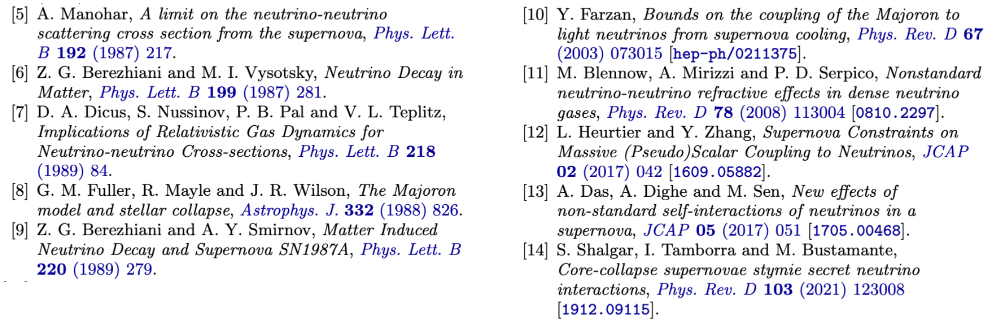
Further in the trapping regime: detecting QCD axions from SN 1987A in the detector

- 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**, to appear)



Trapping regime (NSI)

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`].

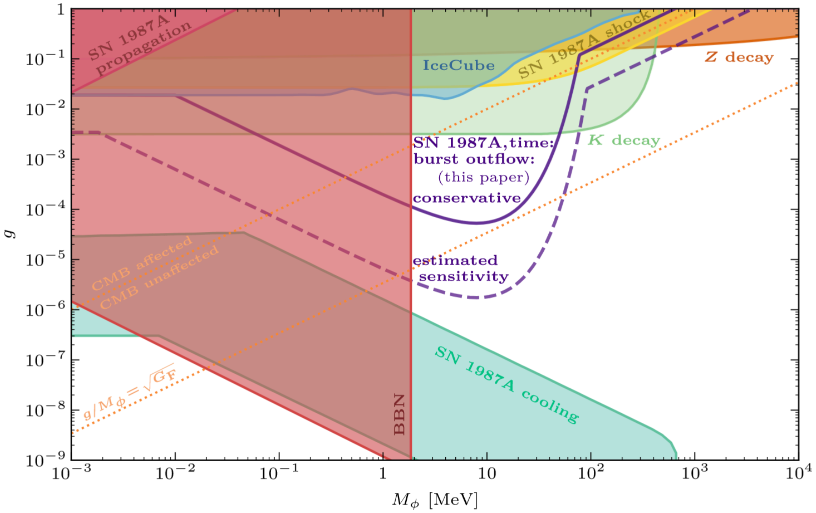
[11] M. Blennow, A. Mirizzi and P. D. Serpico, *Nonstandard neutrino-neutrino refractive effects in dense neutrino gases*, *Phys. Rev. D* **78** (2008) 113004 [`0810.2297`].

[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`].

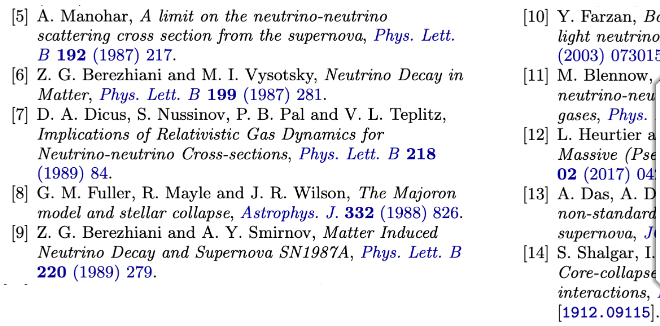
[14] S. Shalgar, I. Tamborra and M. Bustamante, *Core-collapse supernovae stymie secret neutrino interactions*, *Phys. Rev. D* **103** (2021) 123008 [`1912.09115`].

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



Trapping regime (NSI)

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*
light neutrinos from
(2003) 073015 [h

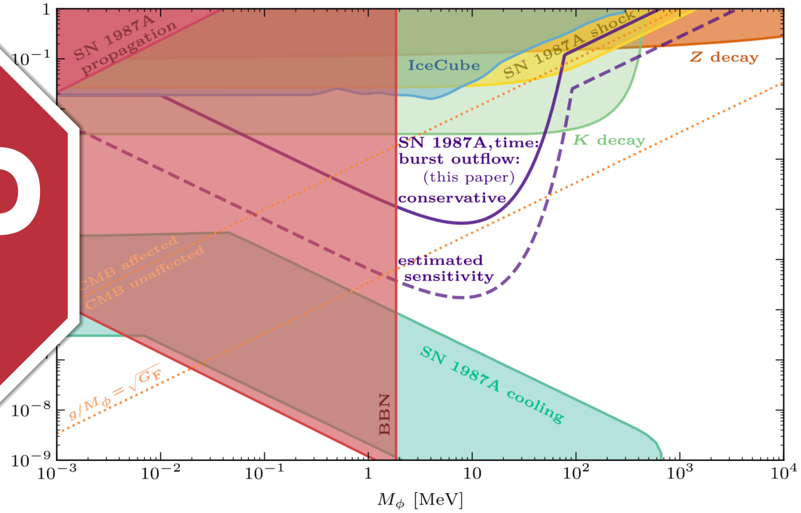
[11] M. Blennow, A
neutrino-neu
gases, *Phys.*

[12] L. Heurtier a
Massive (Pse
02 (2017) 04

[13] A. Das, A. D
non-standard
supernova, *J*

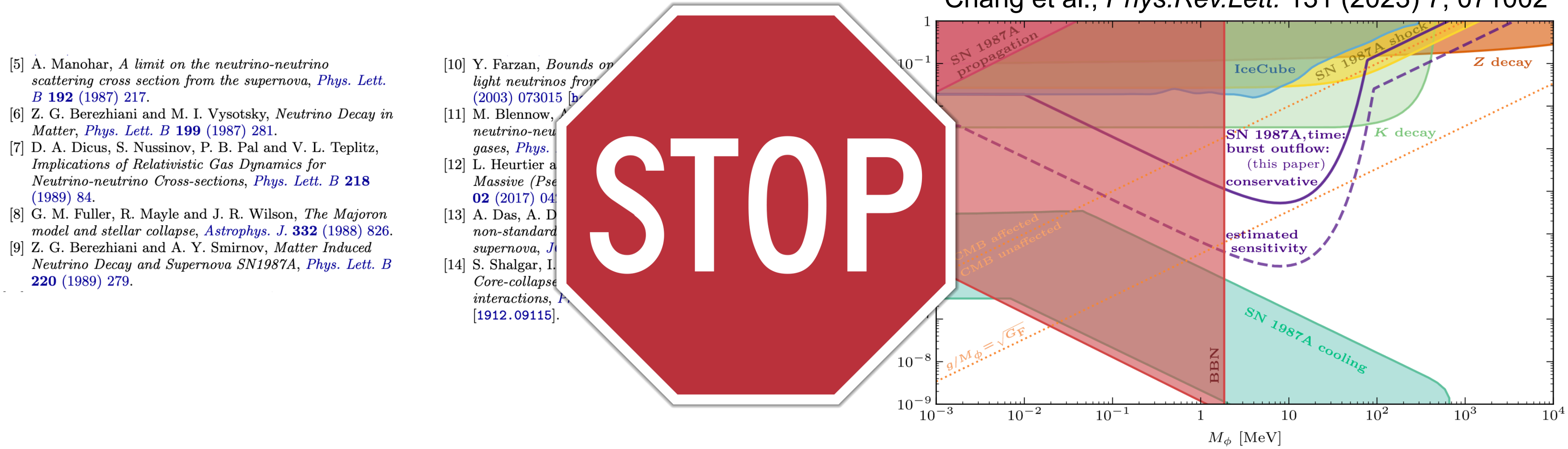
[14] S. Shalgar, I.
Core-collapse
interactions, *P*
[1912.09115].

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



Trapping regime (NSI)

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*
light neutrinos from
(2003) 073015 [h

[11] M. Blennow, A
neutrino-neu
gases, *Phys.*

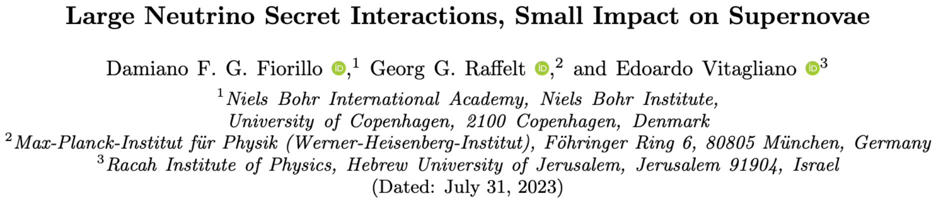
[12] L. Heurtier a
Massive (Pse
02 (2017) 04

[13] A. Das, A. D
non-standard
supernova, *J*

[14] S. Shalgar, I.
Core-collapse
interactions, *P*
[`1912.09115`].

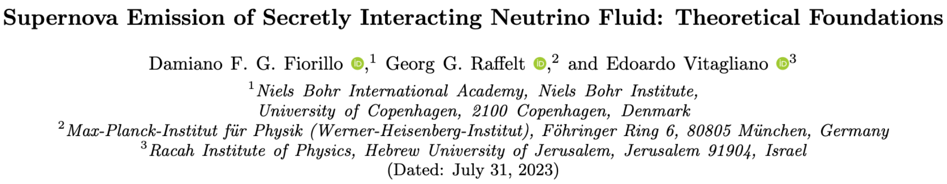
Chang et al., *Phys.Rev.Lett.* 131 (2023) 7, 071002

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



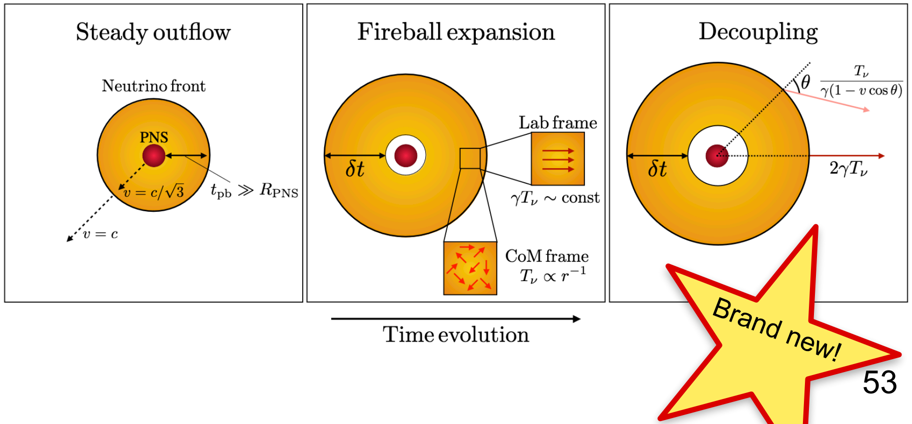
Large Neutrino Secret Interactions, Small Impact on Supernovae

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

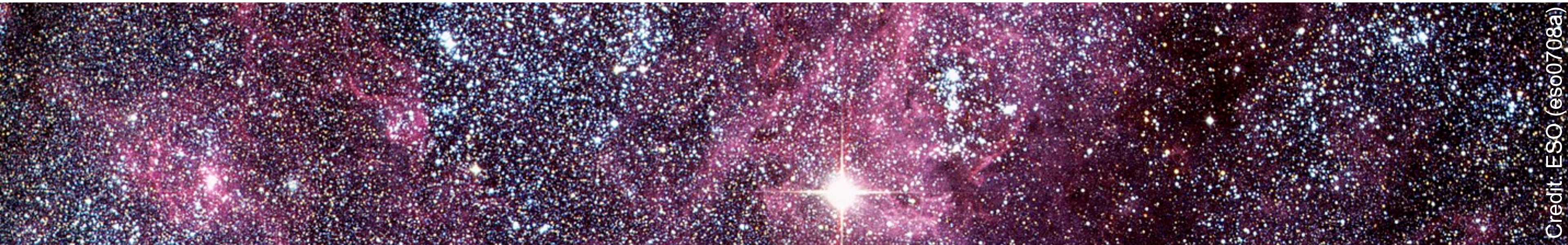
Damiano F. G. Fiorillo [1], Georg G. Raffelt [2] and Edoardo Vitagliano [3]
[1] *Niels Bohr International Academy, Niels Bohr Institute,*
University of Copenhagen, 2100 Copenhagen, Denmark
[2] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany*
[3]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



Conclusions

Conclusions

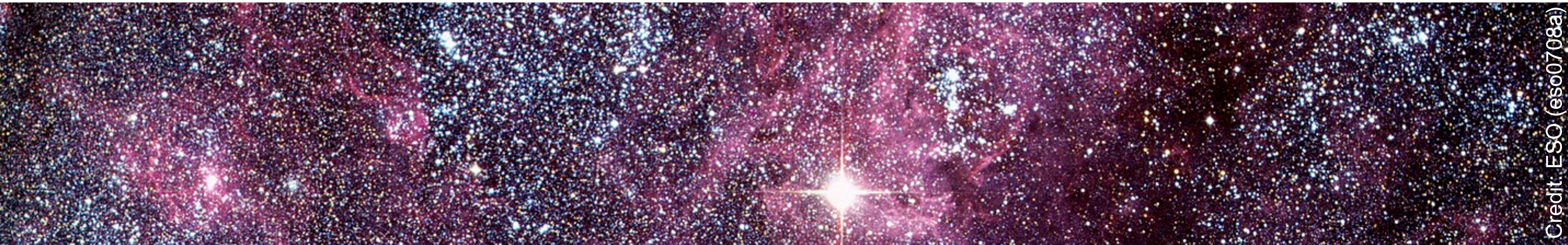
- Stellar bounds still the most constraining in large part of the parameter space
- Cooling bounds still useful for QCD axion hadronic couplings, look for other observables in other cases—decays
- Alternative astrophysical transients (e.g. NS mergers)
- Be careful when in the trapping regime
- Many missing topics from this review (magnetic WDs, light axions converting in galactic B fields, effects on NS magnetospheres, stellar basins…)



Credit: ESO (eso0708a)

Homeworks

- How sure we are of the hadronic coupling treatment?
- Astrophysical backreactions
- Other applications of the BSM fireball concept?
- Self-consistent treatment for strongly coupled particles
- Sterile neutrinos much more complicated
- There are decays also with hadronic couplings



Credit: ESO (eso0708a)

Thank you

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)

Backup

SN 1987A comparison with simulations