Supernova bounds on Feebly Interacting Particles

Kick-off Workshop of the COST Action (CA21106),
Laboratori Nazionali di Frascati (Rome), Italy
February 22, 2022

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Credit: Anglo-Australian Observatory

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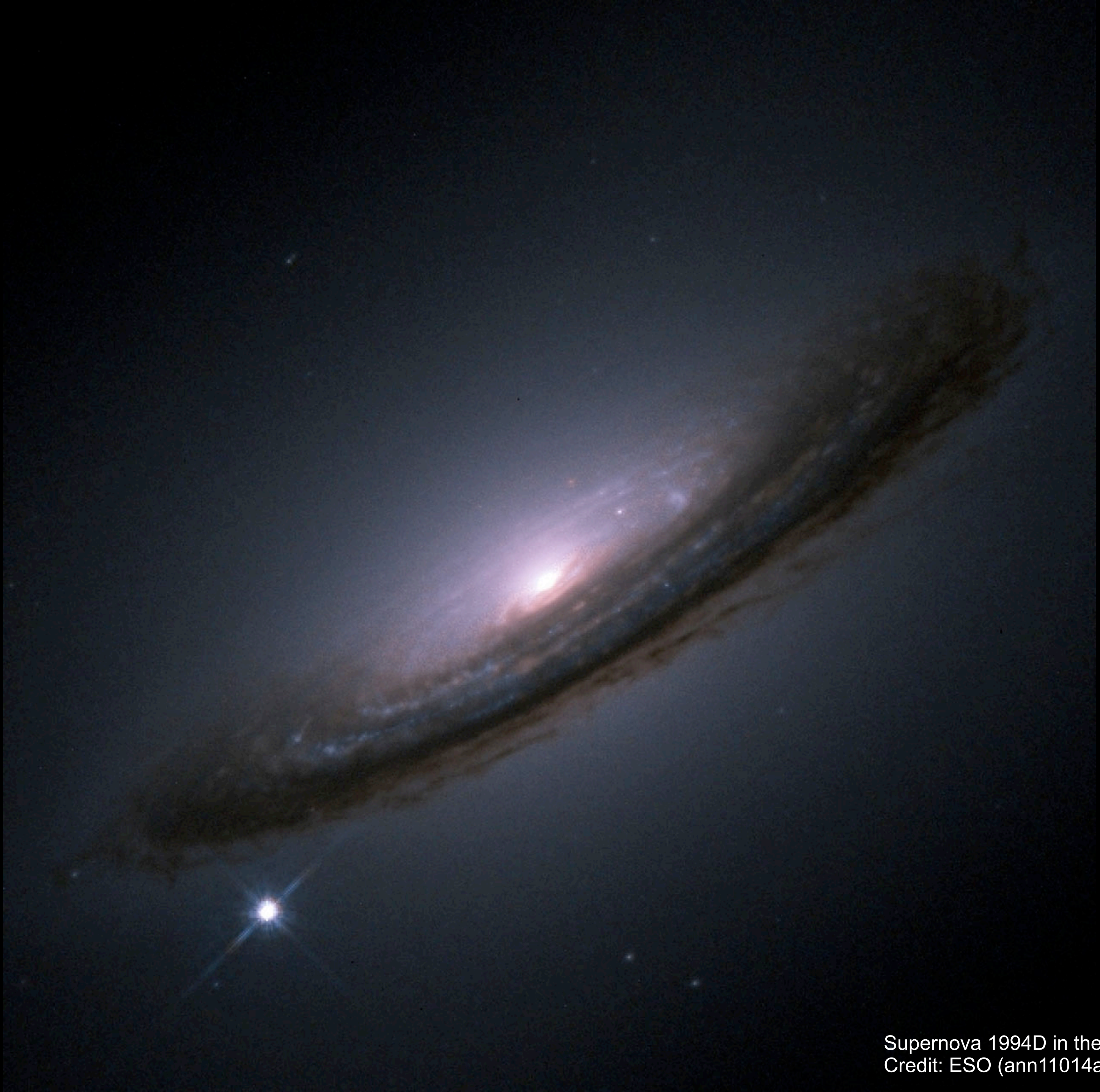


Supernova 1994D in the galaxy NGC 4526
Credit: ESO (ann11014a)

Take home messages

- Cooling bounds still useful for hadronic couplings, 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 explosions catalyzers
- Cosmology: strongly constraining DM mediators

Supernova bounds on decaying bosons

I. What did we expect from SN 1987A?

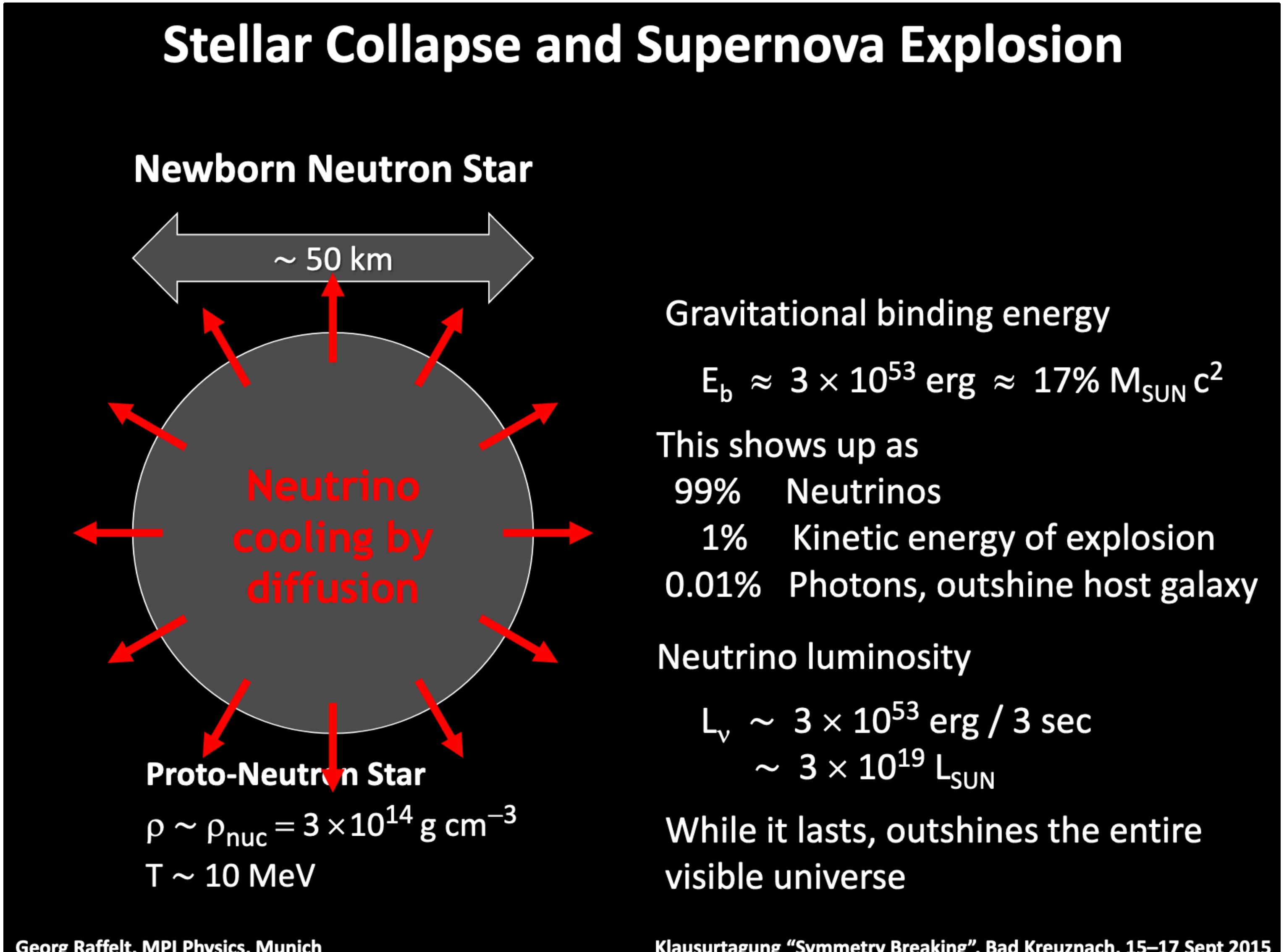
II. What did we see from SN 1987A?

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

Conclusions

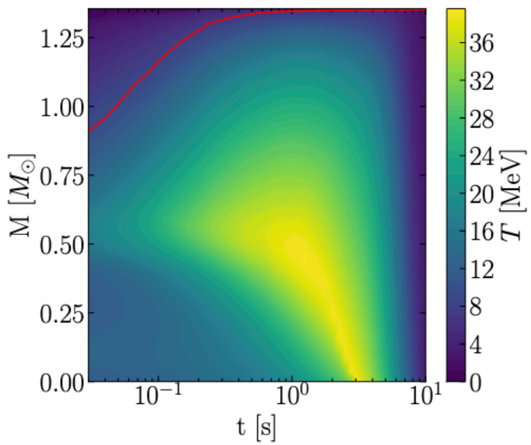
What did we expect?

Stellar collapse

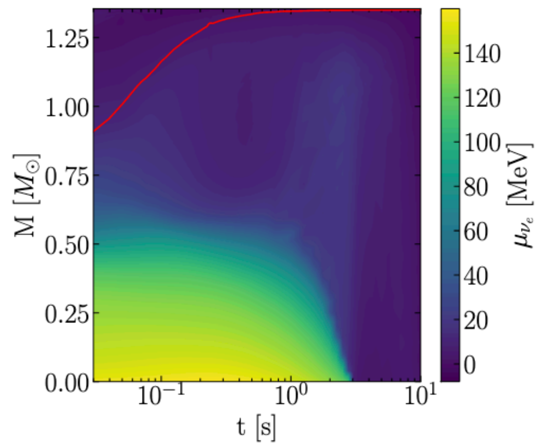


Deleptonization and cooling

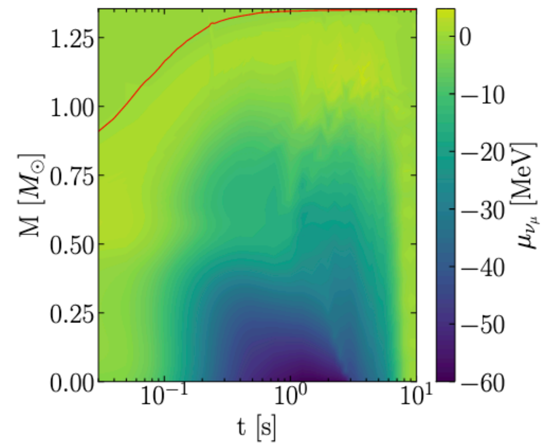
Garching 1D models SFHo-18.8 evolved with the
Prometheus Vertex code with six-species neutrino transport



The core heats up from the outside…



…as the core deleptonizes…



…and after the core heats up, muons can be produced

FIG. S4. Temperature (left), chemical potential of electron neutrinos (center), and chemical potential of muon neutrinos (right) as a function of post-bounce time and mass coordinate for the Garching "cold" model. The red line identifies the density 3×10^{12} g cm^{-3} and thus essentially the edge of the PNS. The final neutron-star mass is $1.351\ M_\odot$.

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:

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

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

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

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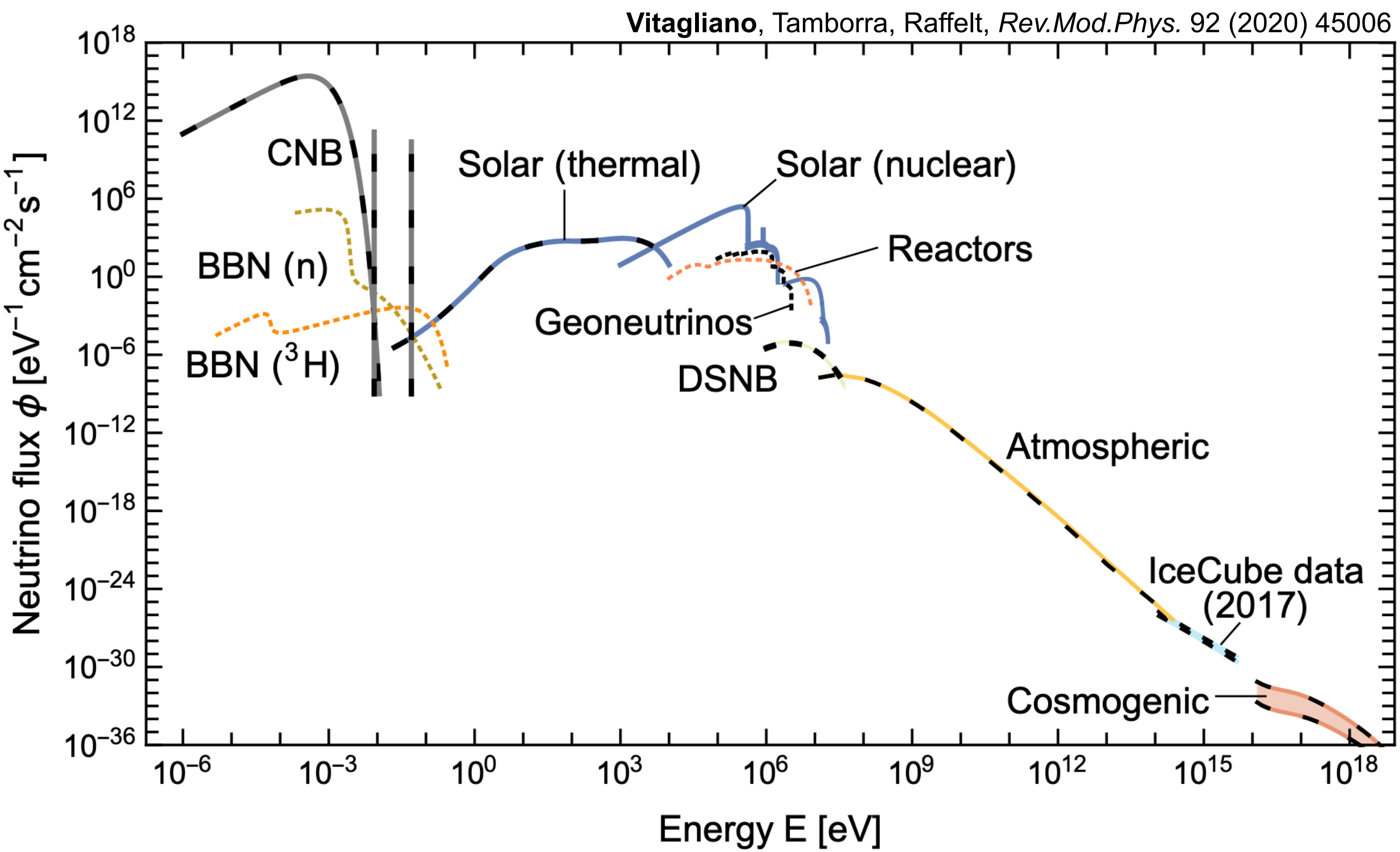
Therefore: $0.5 \times 10^{53}\,\text{erg}$ for each neutrino species, with energies $\mathcal{O}(10\,\text{MeV})$ and a signal of $\mathcal{O}(1-10\,\text{s})$

Grand unified neutrino spectrum at Earth



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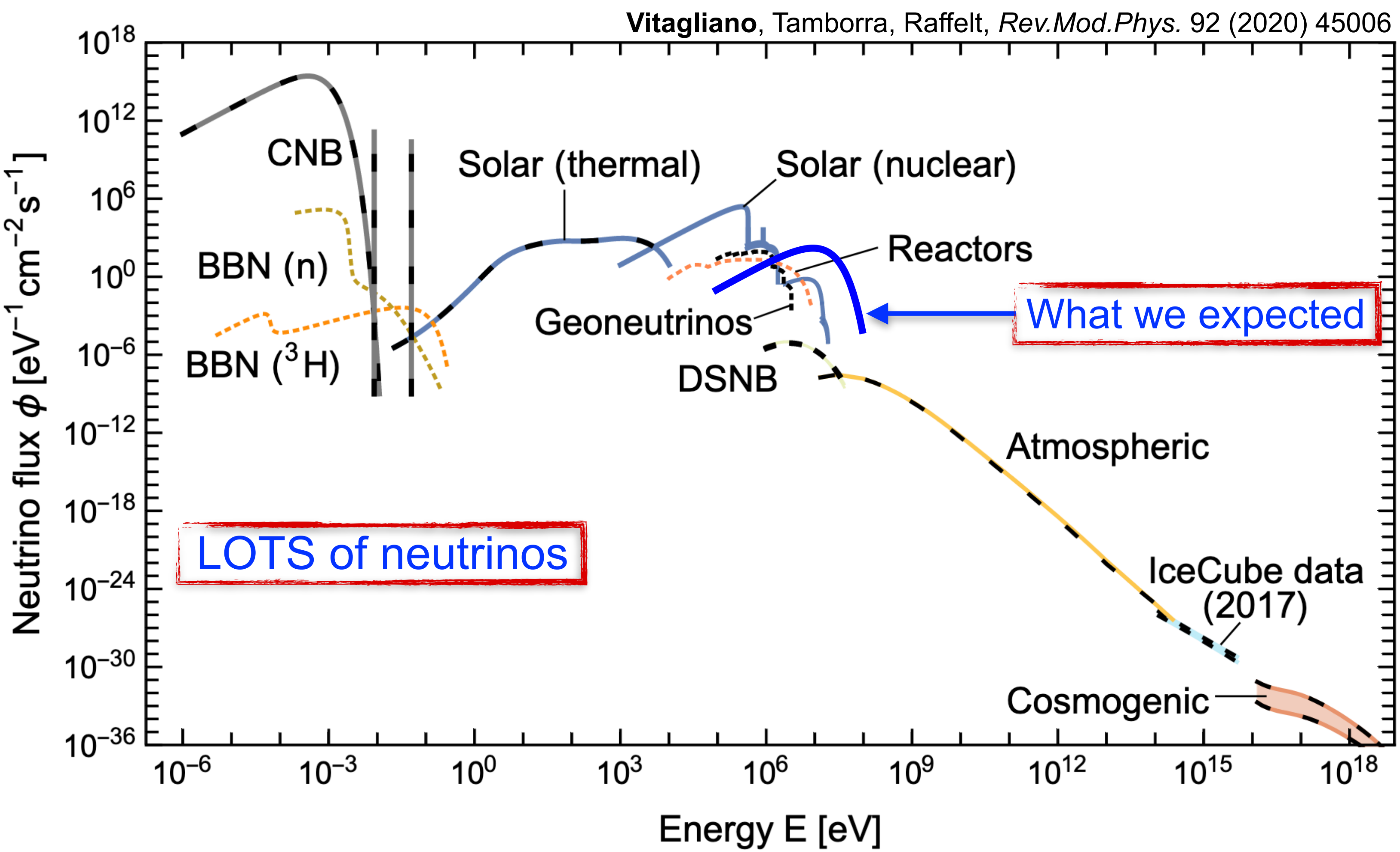


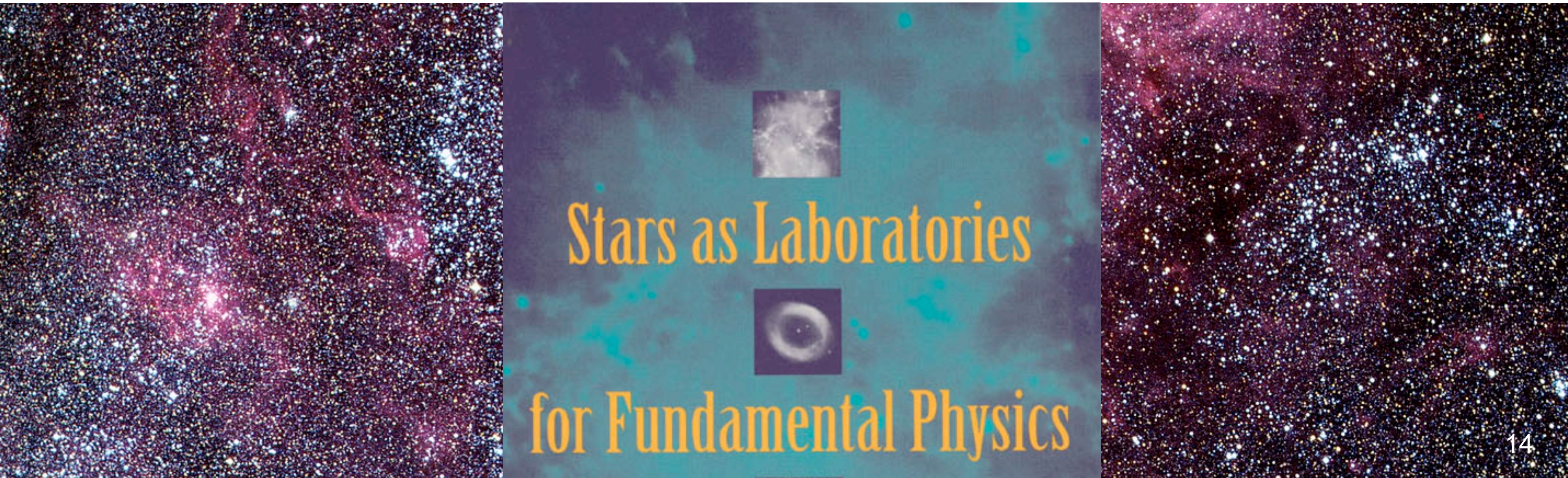
Tables available to produce your own GUNS plot on arXiv & supplemental material

Astrophysical bounds

From the previous discussion, it is clear that
SNe are factories of feebly interacting particles
How can we obtain bounds from astrophysics?

Take home lesson

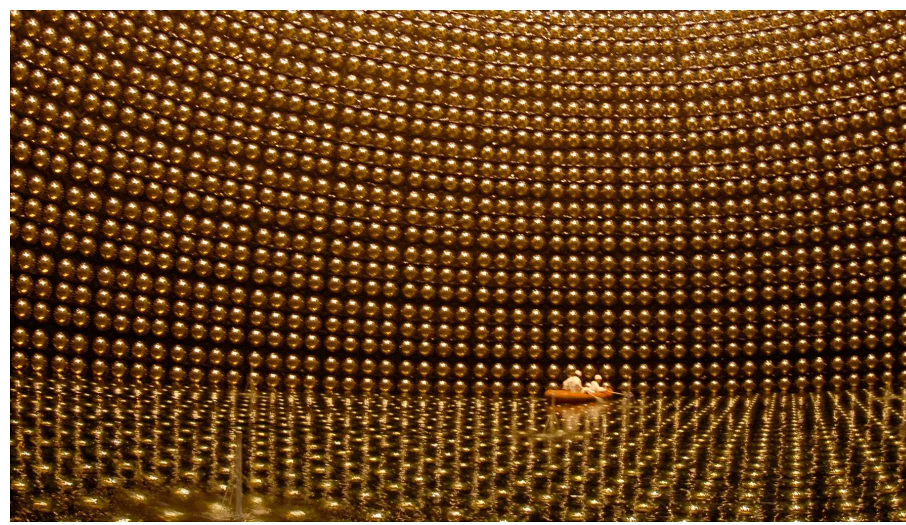
- Identify system appropriate for the particle model you are interested in
- Identify the **observable**



What did we see?

SN 1987A Neutrino Observations

- Discovered independently by Ian Shelton, Oscar Duhalde, and Albert Jones on February 23
- Gamma-ray observations from Gamma-Ray Spectrometer (GRS) on the Solar Maximum Mission (SMM)
- 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)

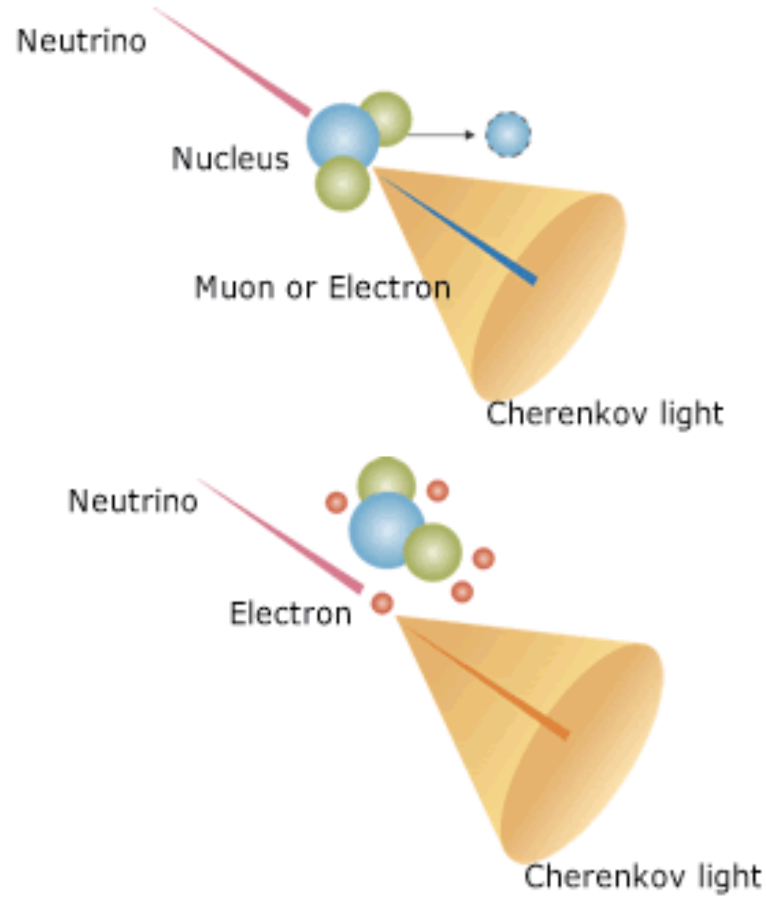


Credit: Super-Kamiokande

Cherenkov detectors

The idea of Cherenkov detectors is extremely simple:

- Take a huge tank of water
- Neutrinos travel in the detector, until they interact with a nucleus (or electrons)
- Inverse Beta Decay (IBD), namely $\bar{\nu}_e + p \rightarrow e^+ + n$
- Charged particles emits Cherenkov radiation, since it is faster than the speed of light in the medium



Neutrino cross sections

At low energies

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$E_e = E_\nu - Q_{\bar{\nu}_e p}$$

$$Q_{\bar{\nu}_e p} = 1.29 \text{ MeV}$$

At large energies

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + \mathrm{X}$$

$$X_{\nu_e} = {}^{16}F^*$$

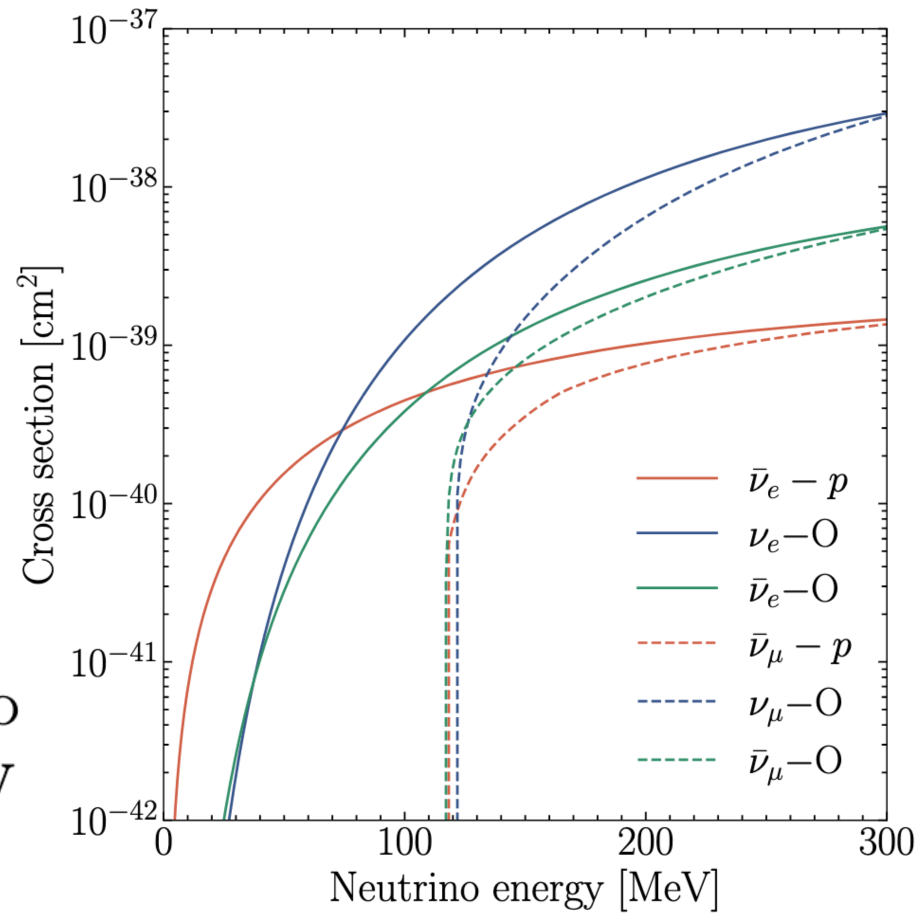
$$E_{e^-} = E_\nu - Q_{\nu_e \mathrm{O}}$$

$$Q_{\nu_e \mathrm{O}} = 15.4 \text{ MeV}$$

$$X_{\bar{\nu}_e} = {}^{16}N^*$$

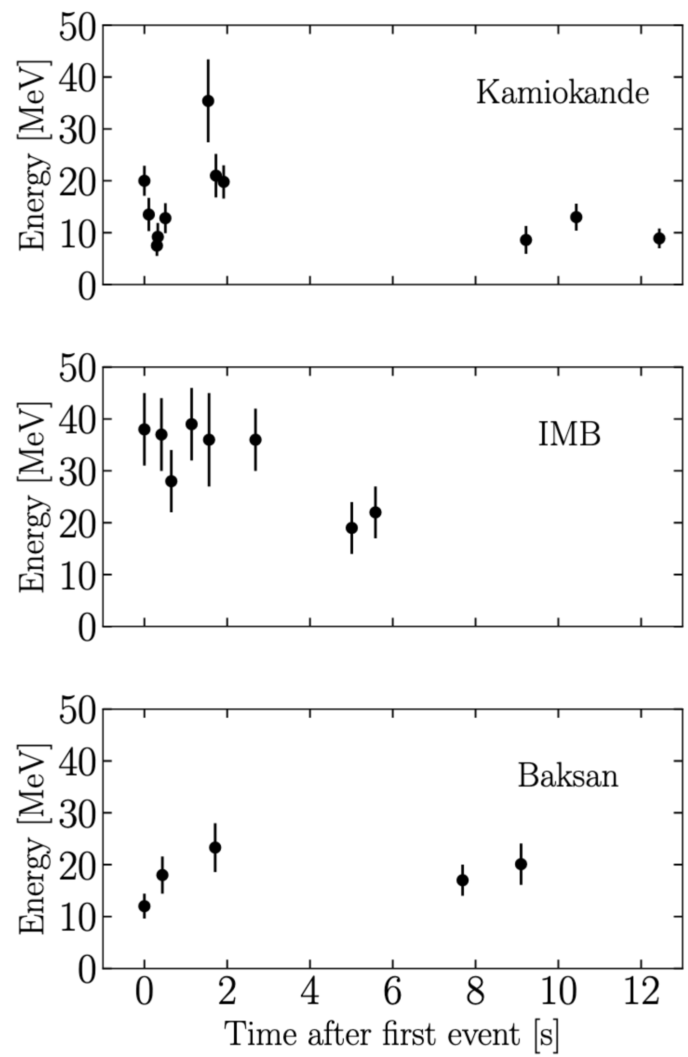
$$E_{e^+} = E_{\bar{\nu}} - Q_{\bar{\nu}_e \mathrm{O}}$$

$$Q_{\bar{\nu}_e \mathrm{O}} = 11.4 \text{ MeV}$$



SN 1987A Neutrino Observations

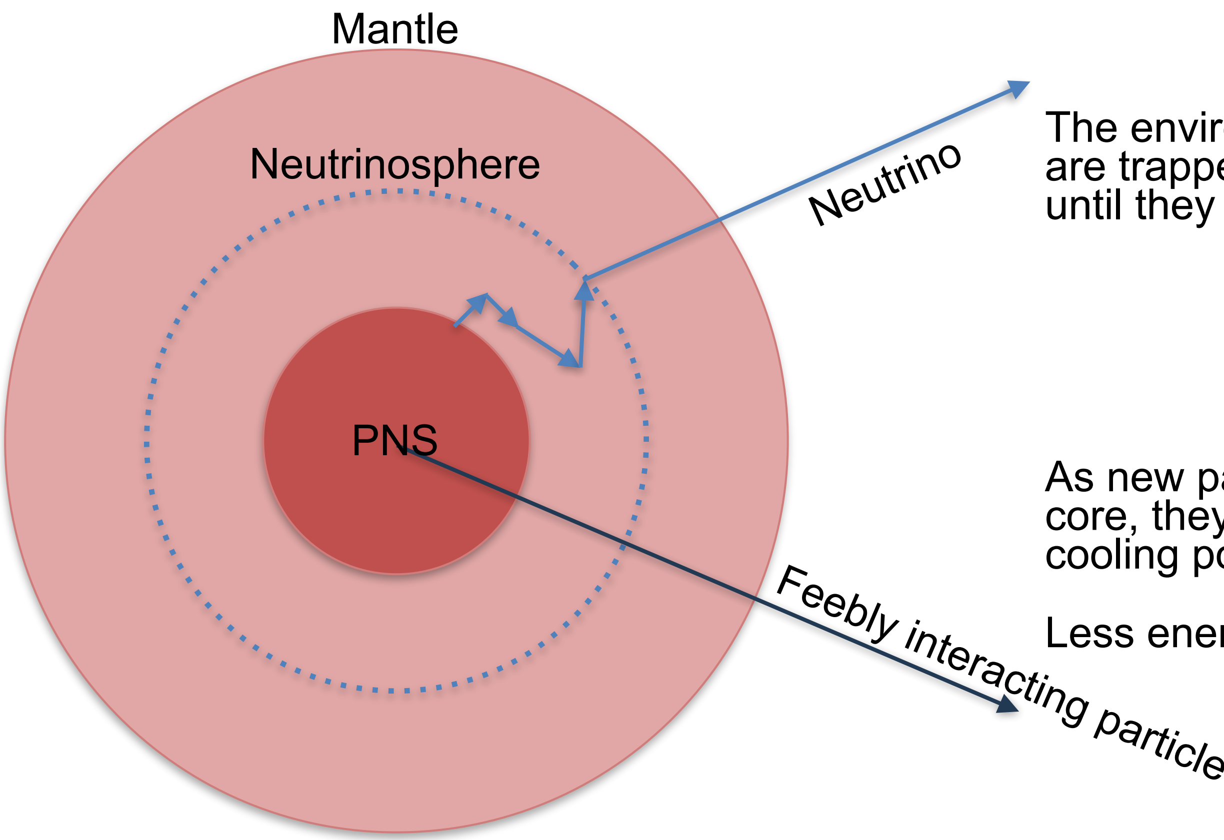
- First IMB event occurred at 7:35:41.374 Universal Time on 23 February 1987, corresponding to 3:35 am local time on a Monday very early morning
- SN 1987A signal consisted of 8 events and in addition 15 muons were recorded, a total of 23 triggers, amounting to 23 × 35 ms = 0.8 s dead time, or 13% of the SN signal duration of 6 s
- At Kamiokande II 4 muons were found in the 20 s interval preceding the SN 1987A burst, 12 events (with a gap)



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

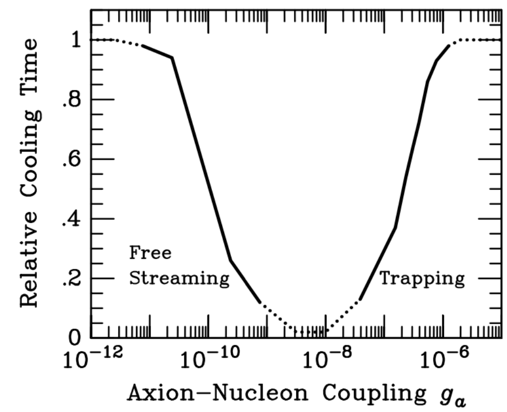


Fig. 13.1. Relative duration of neutrino cooling of a SN core as a function of the axion-nucleon Yukawa coupling g_a. In the free-streaming limit axions are emitted from the entire volume of the protoneutron star, in the trapping limit from the "axion sphere" at about unit optical depth. The solid line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

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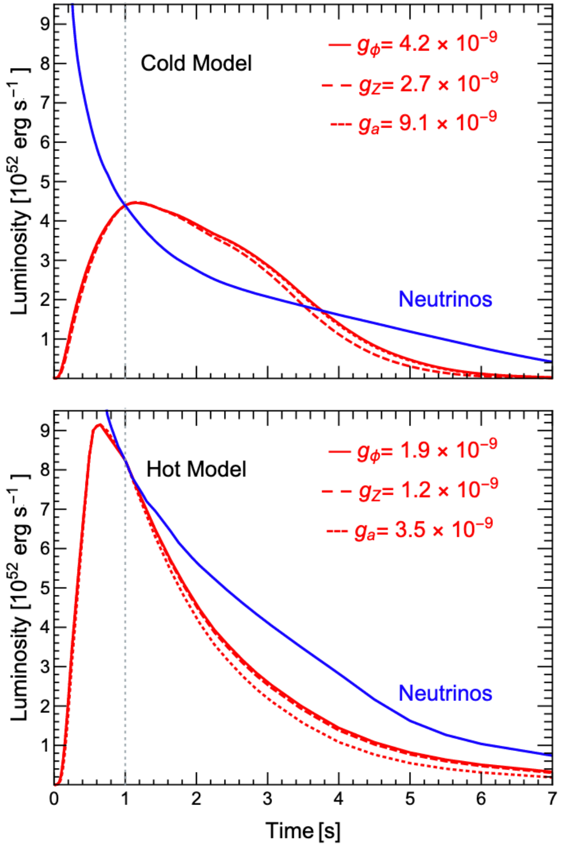
- This is the celebrated Raffelt criterion
- At $t_{\mathrm{post-bound}} = 1\,\mathrm{s}$ the luminosity of new particles and neutrinos is comparable
- Right: example of scalar-muon coupling (always compare L_ϕ with L_ν of your model if you use one!)

Caputo, Raffelt, **Vitagliano** (2021)



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)

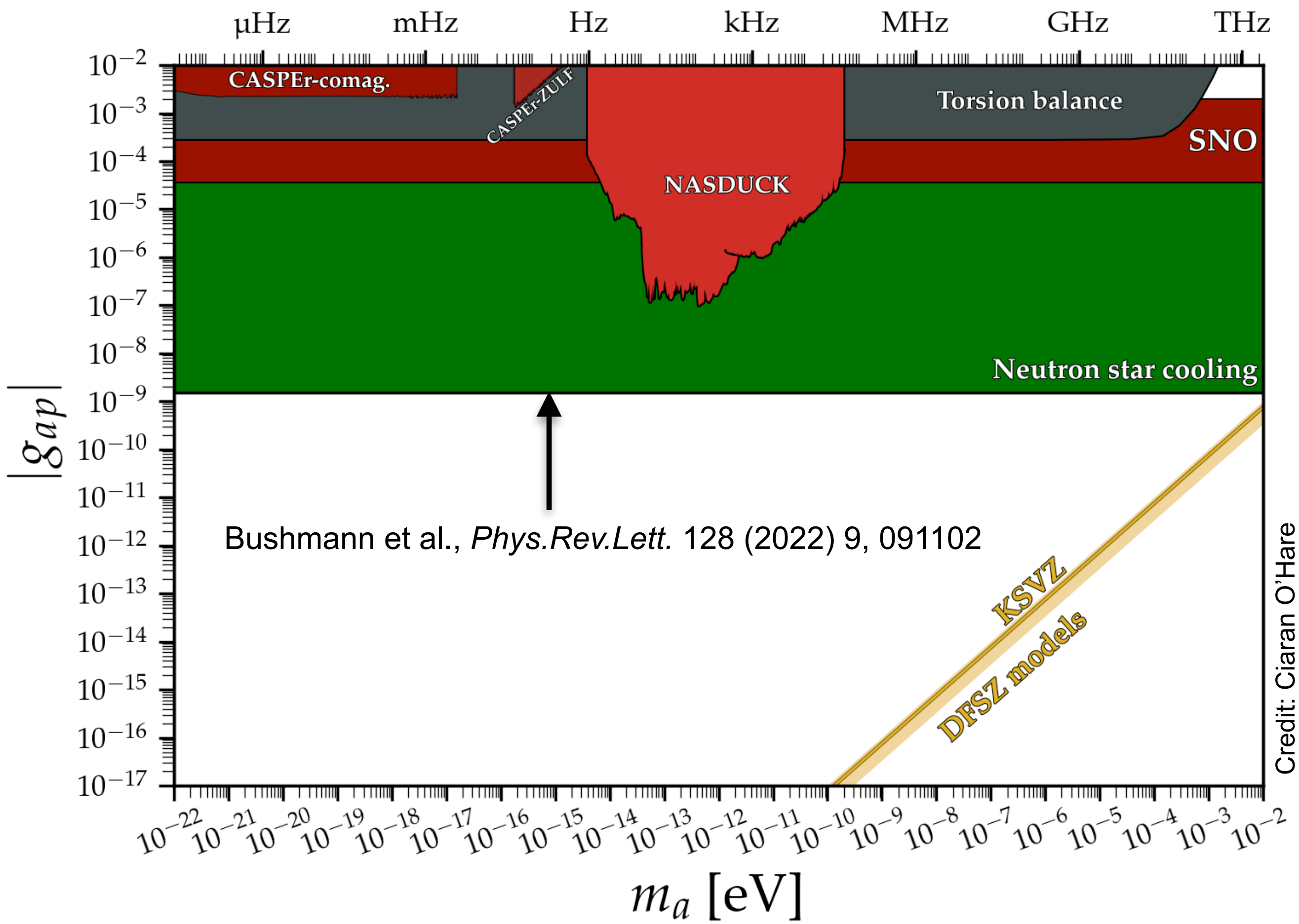
- Chang, Essig & McDermott, JHEP 1809 (2018) 051 [1803.00993]
  Various correction factors to emission rates, specific SN core models
  $f_a \gtrsim 1 \times 10^8\,\mathrm{GeV}$ and $m_a \lesssim 60\,\mathrm{meV}$ (KSVZ, based on proton coupling)

- 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)
  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?



(Complementary to neutron star cooling observations for hadronic couplings)

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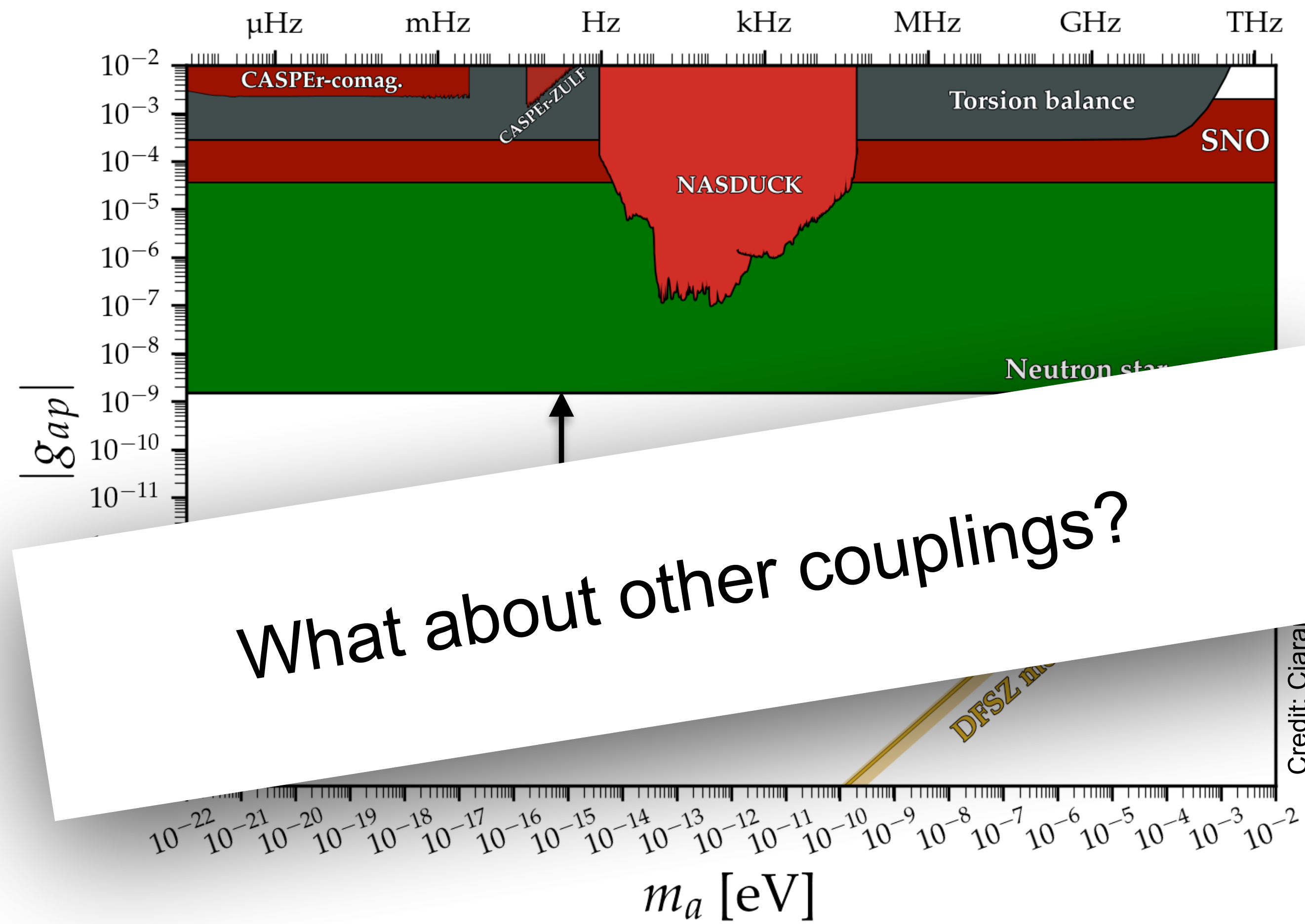


What about other couplings?

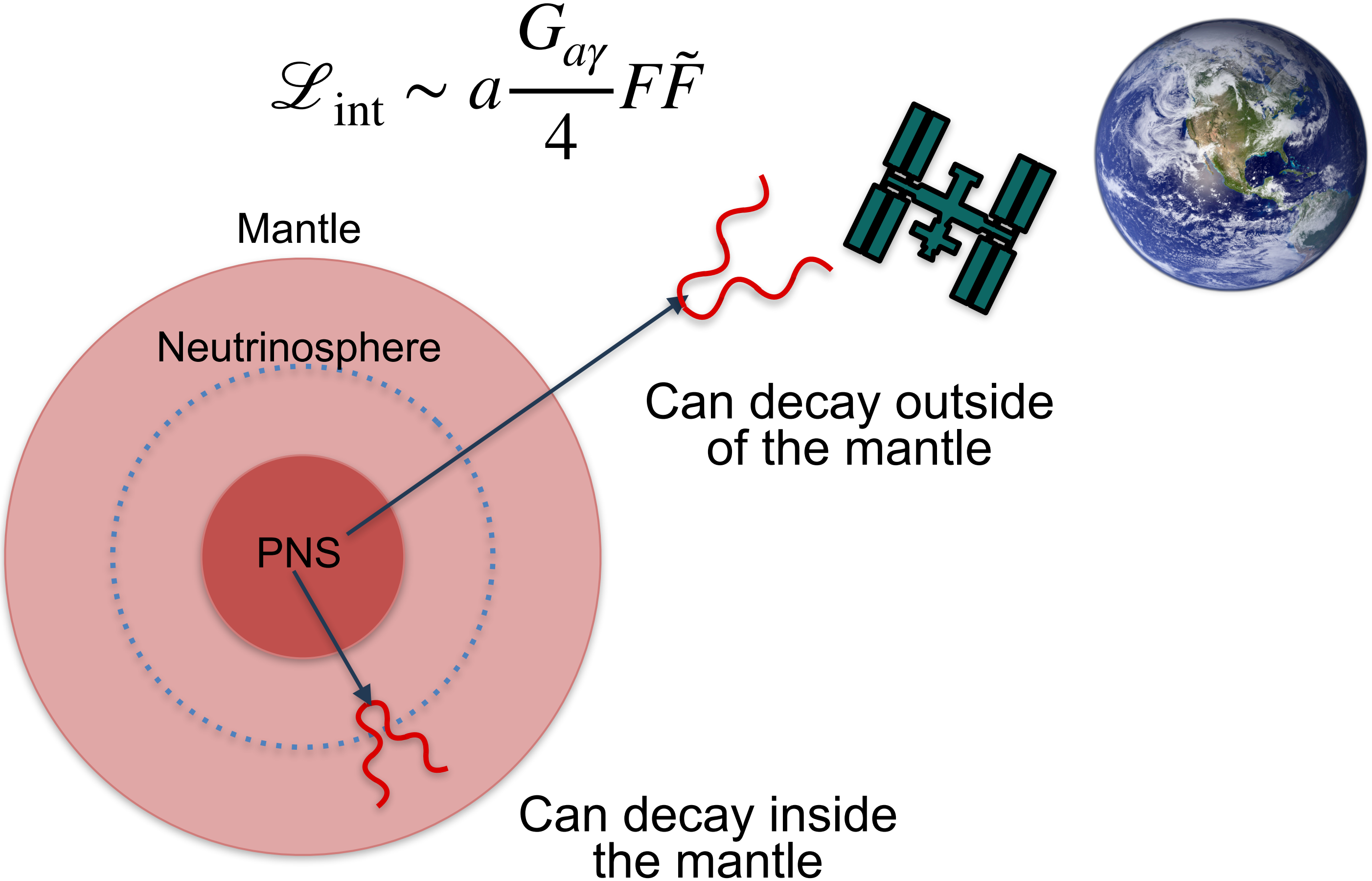
(Complementary to neutron star cooling observations for hadronic couplings)

Look for different observables

Supernovae 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

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



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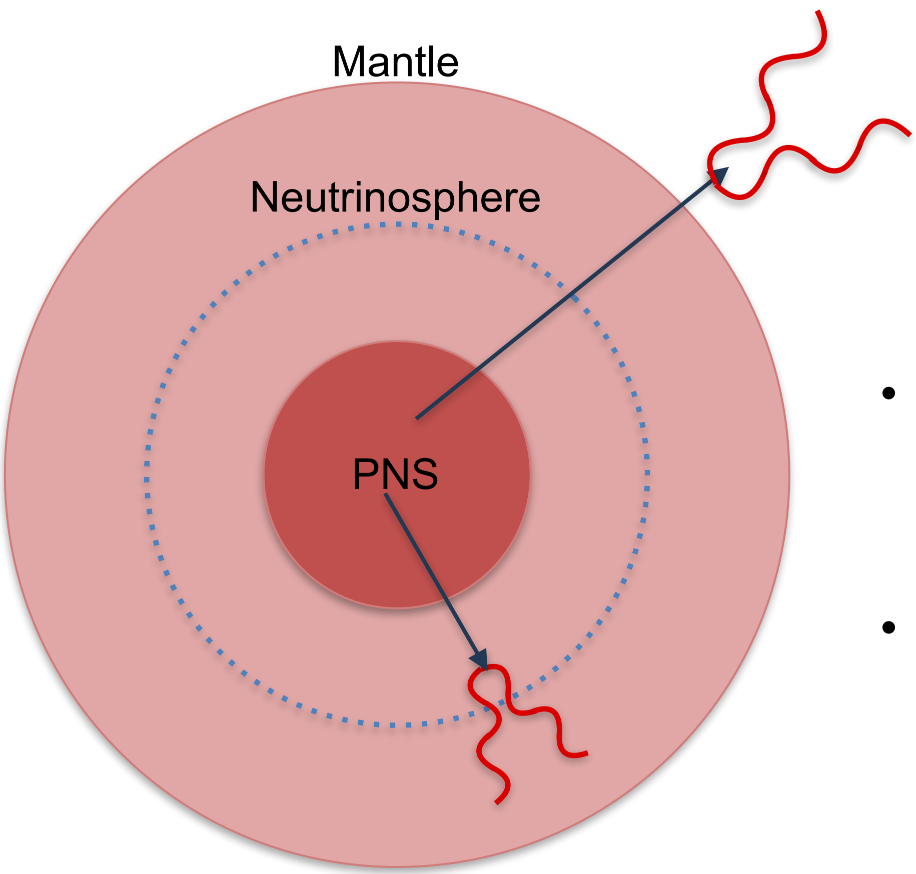


- **Gamma-ray decay** observed by the Gamma-Ray Spectrometer (GRS) on board the Solar Maximum Mission (SMM) satellite that operated 02/1980–12/1989

  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)

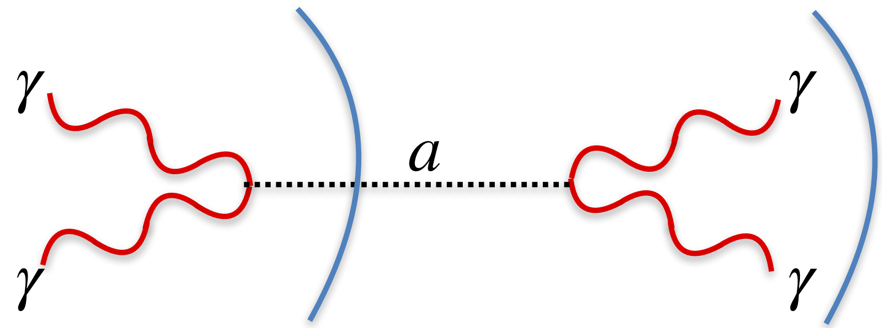
- They also create a **diffuse** from all the SNe in the history of the universe

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

- If the mean free path is short, they decay in the mantle and **light-up the SN**

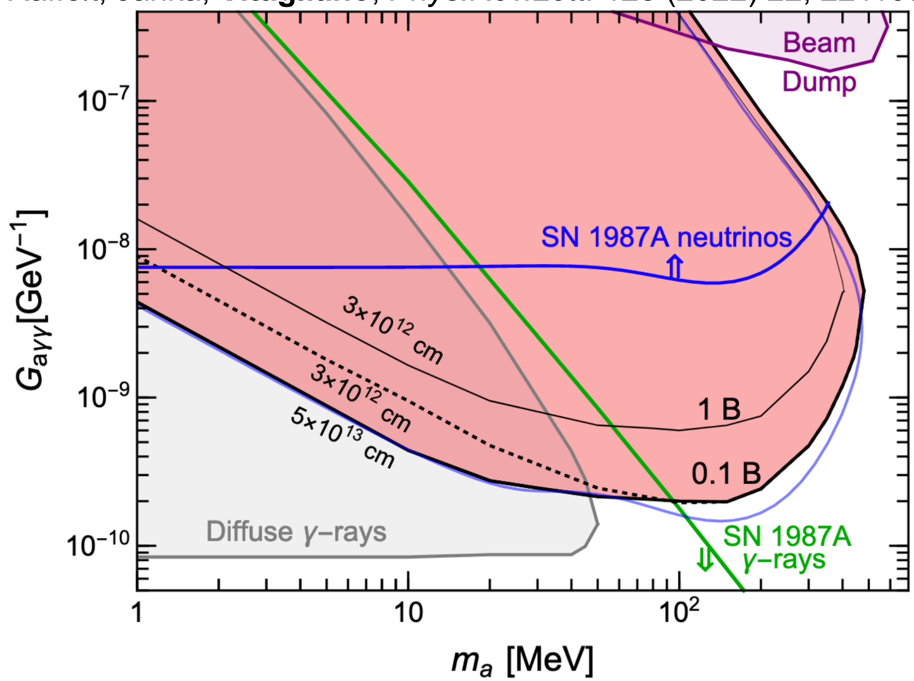
  Falk and Schramm, *Phys.Lett.B* 79 (1978) 511
  Caputo, Raffelt, Janka, **Vitagliano**, *Phys.Rev.Lett.* 128 (2022) 22, 221103

New bound from decay in the mantle

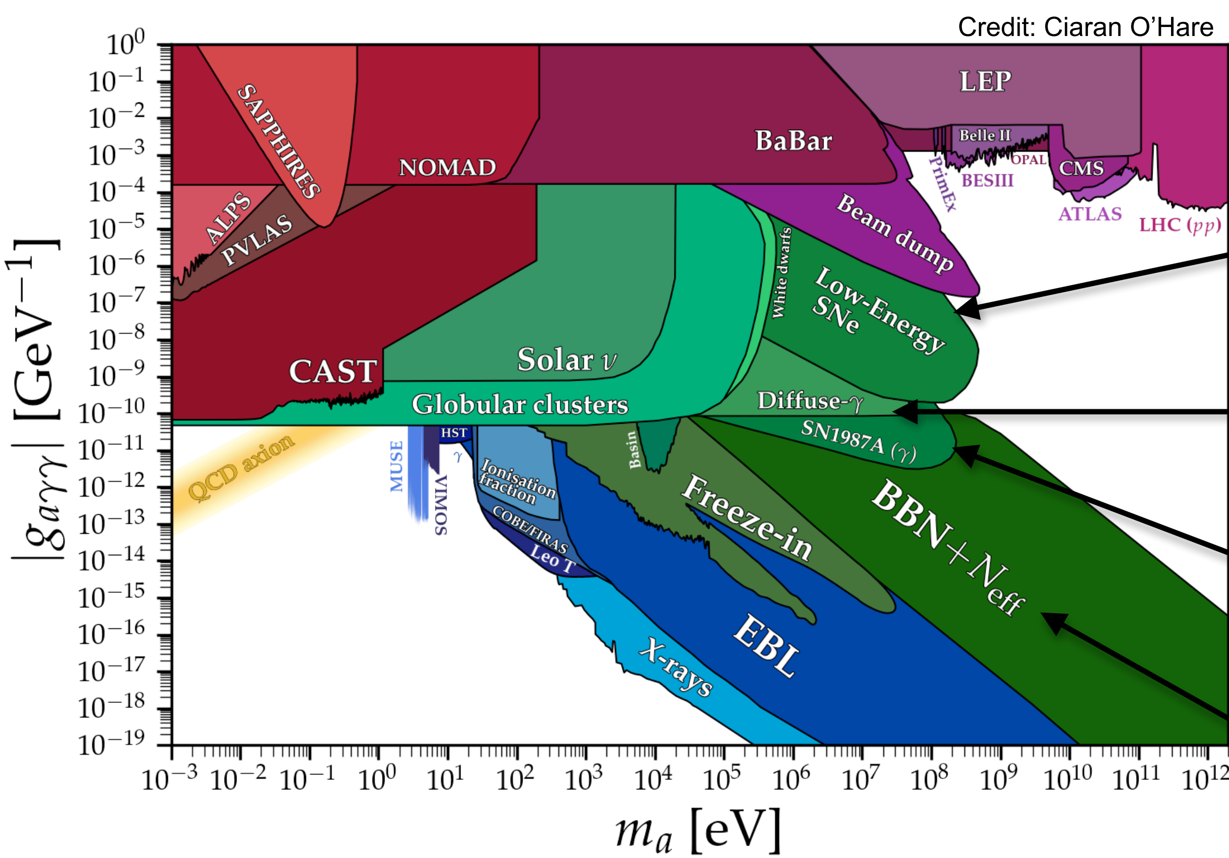


- Typical SN explosion energy 1-2 B
  $1\,\mathrm{B}\,(\mathrm{bethe}) = 10^{51}\,\mathrm{erg}$
- Neutron star binding energy 200-400 B
- Some SNe have very small observed explosion energies < 0.1 B
- New restrictive limits from low-energy SNe

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



Axion-like particles with photon coupling



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

Goes away for low T_{RH}
(see Langhoff, Outmezguine, Rodd *Phys.Rev.Lett.* 129 (2022) 24, 241101)

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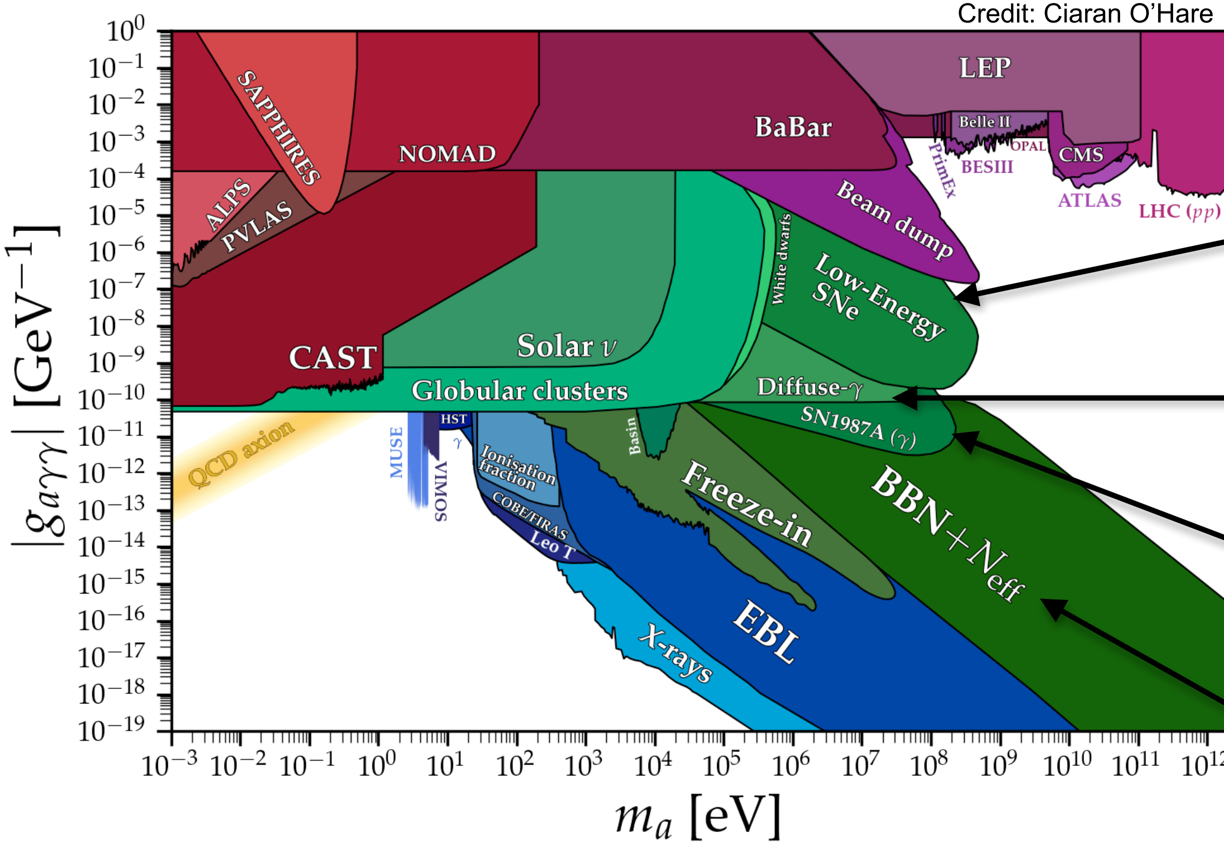

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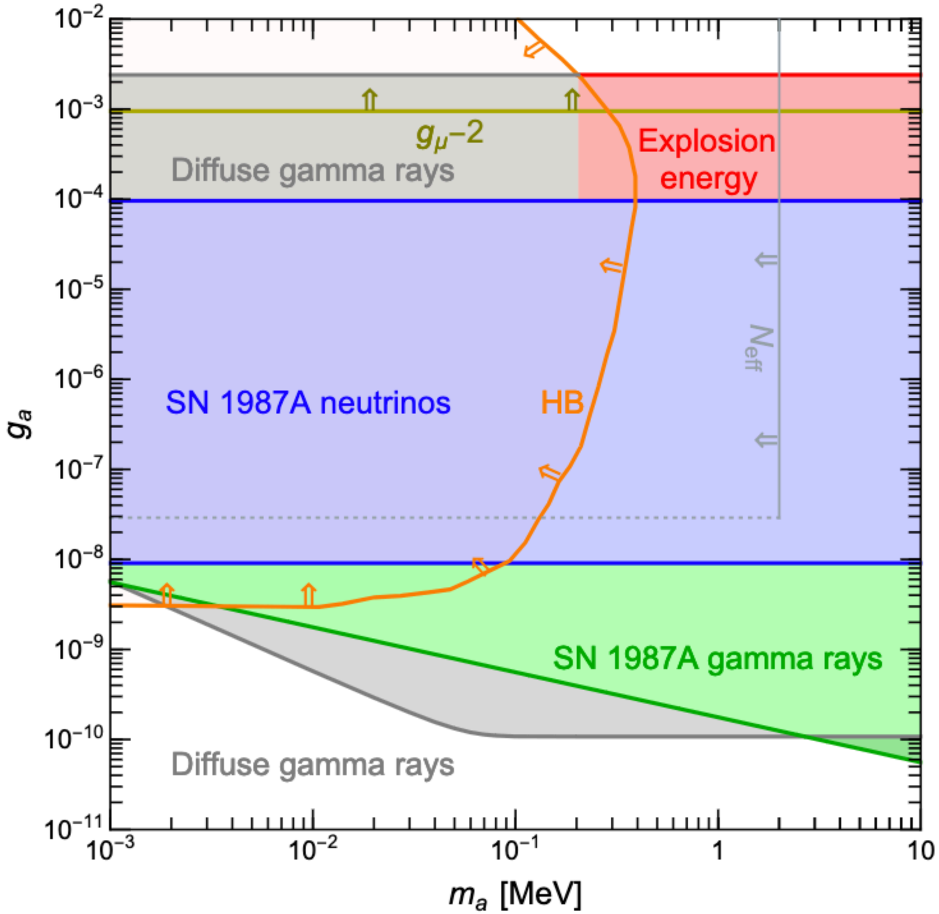
Goes away for low $T_{\rm RH}$
(see Langhoff, Outmezguine, Rodd *Phys.Rev.Lett.* 129 (2022) 24, 241101)

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

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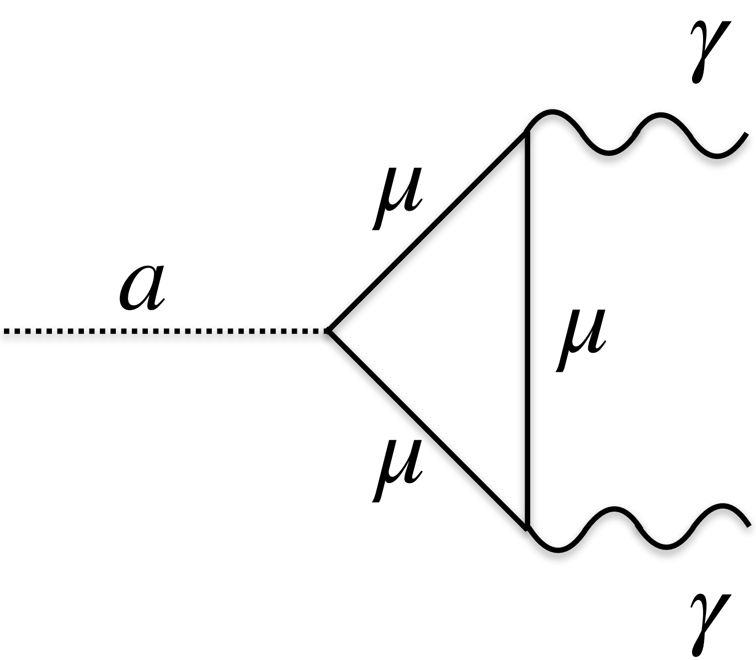
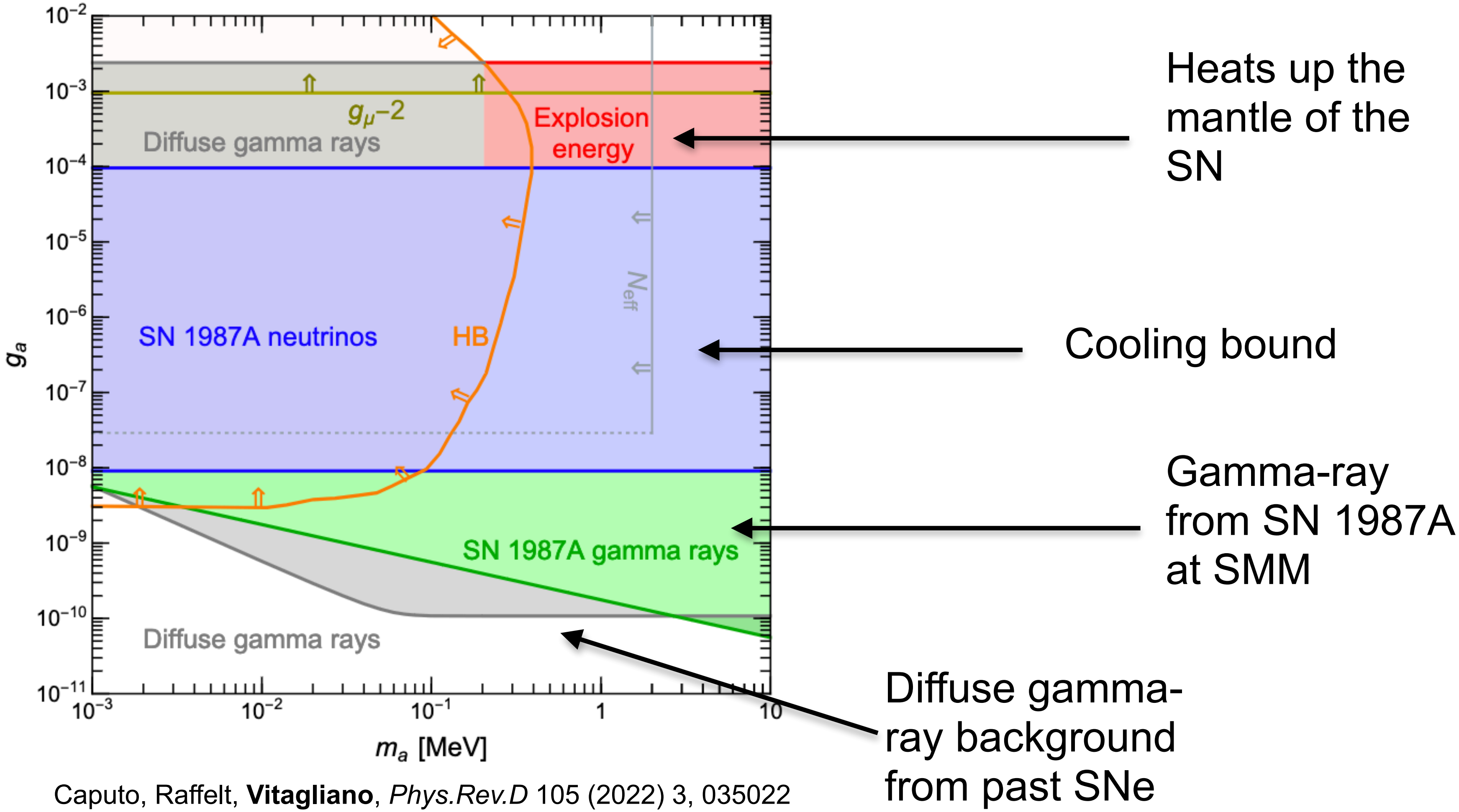


See also Ferreira et al. *JCAP* 11 (2022) 057 for the electron coupling

Leptonic couplings: example with muons



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

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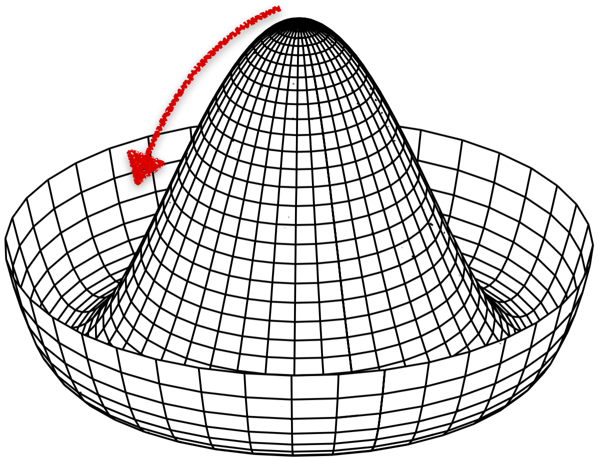
Neutrino couplings

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



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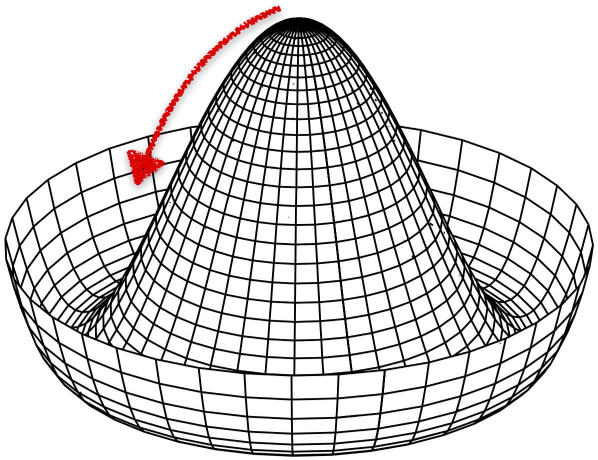

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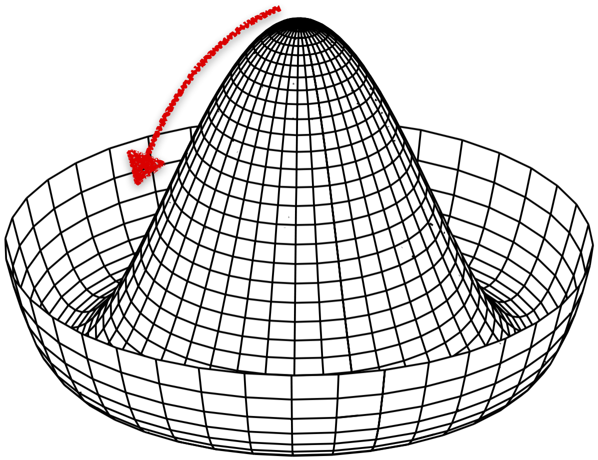
Interesting for a huge number of reasons:

- Neutrinos might be the portal to the dark sector
- Can be related to many puzzles, e.g. $g_\mu - 2$ (Caputo, Raffelt and Vitagliano 2021), Hubble tension (Escudero and Witte 2019)
- Neutrino secret interactions UV completion (Snowmass reports Argüelles et al. 2203.10811 and Barryman et al. 2203.01955)
- **Effect on the supernova explosion**: they could help the explosion depositing energy back in the mantle

Particles with a neutrino coupling



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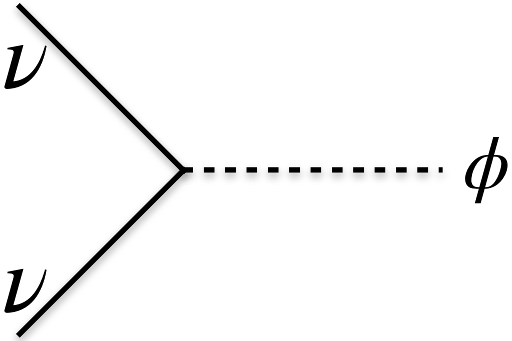
To simplify things, we will assume an extremely simple case: (pseudo)scalars coupling diagonally to all neutrino flavors

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



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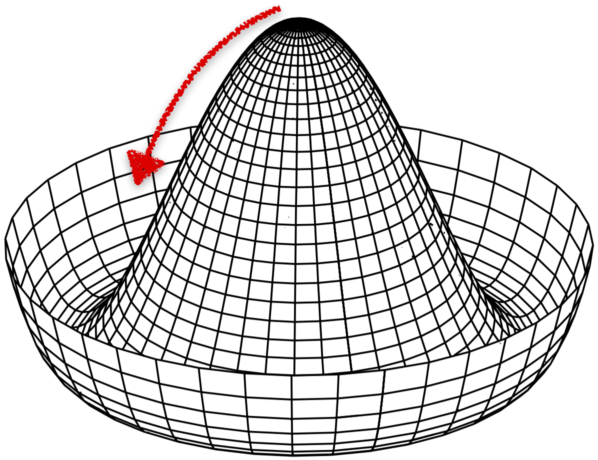

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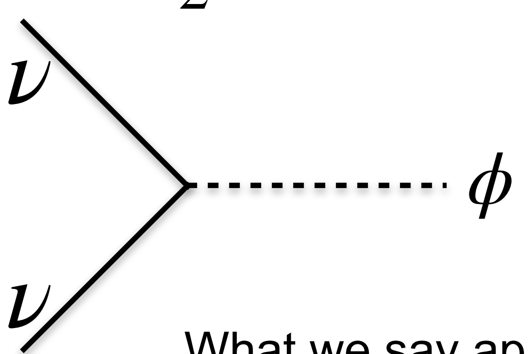


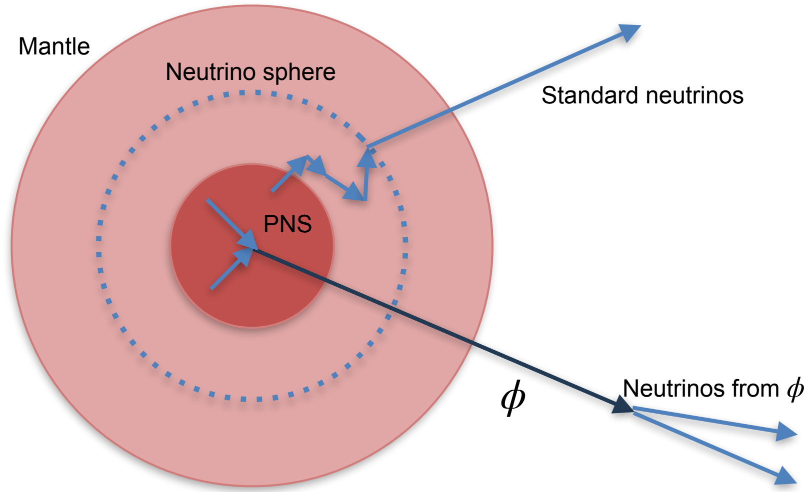
What we say applies also to the other cases

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



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

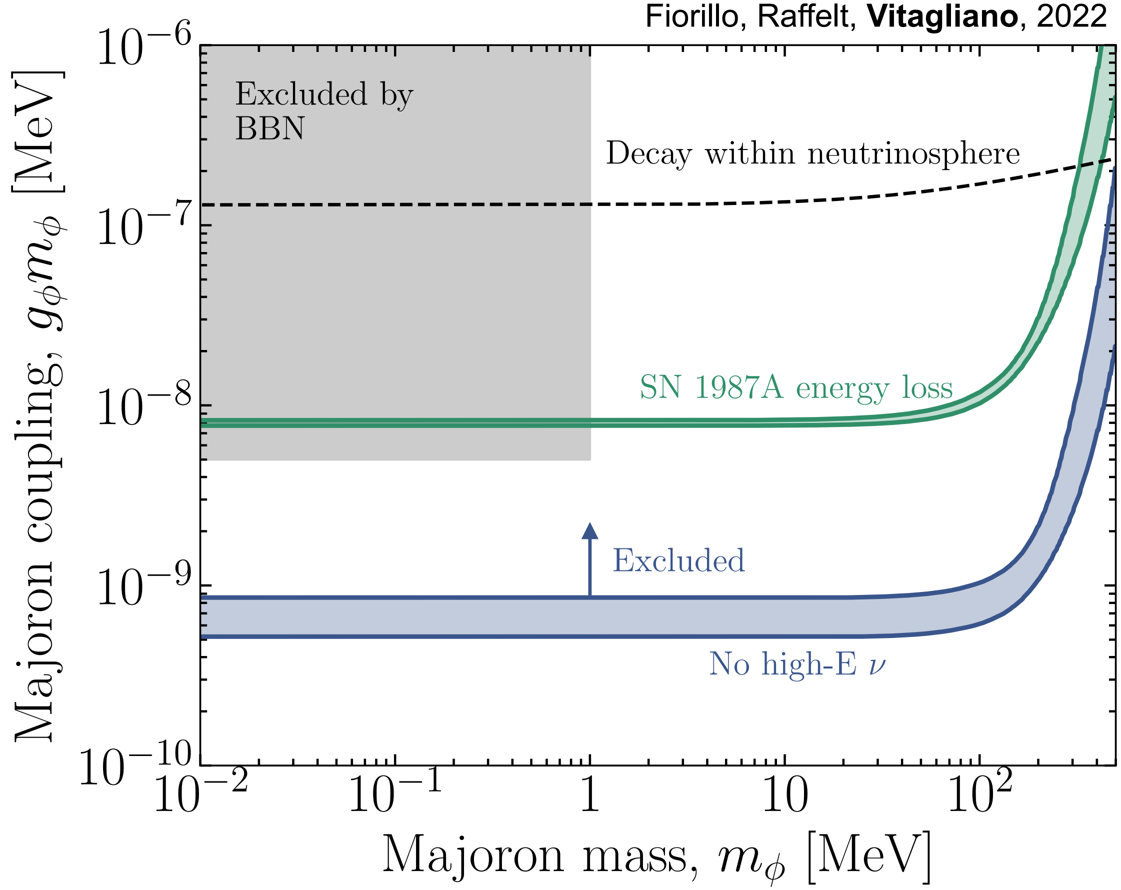
But the cross section in the detector grows like $\sigma \sim G_F^2 E^2$

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

New bounds from decay to neutrinos

Brand new!

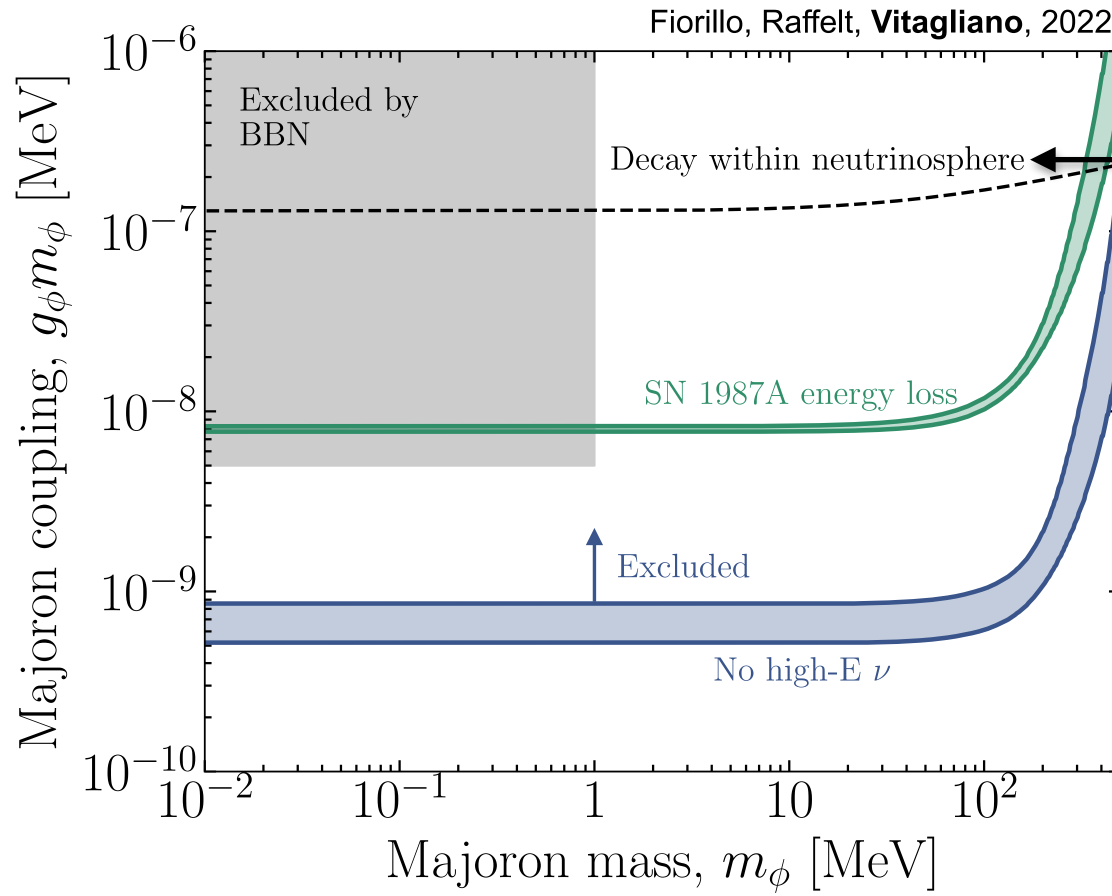
Fiorillo, Raffelt, **Vitagliano**, 2022



Not strongly dependent on the Supernova model

New bounds from decay to neutrinos

Brand new!



$\lambda \simeq R_{\rm NS}$

Think twice before using modified luminosity criterion for trapping

(See also Caputo, Raffelt, **Vitagliano**, *JCAP* 08 (2022) 08, 045)

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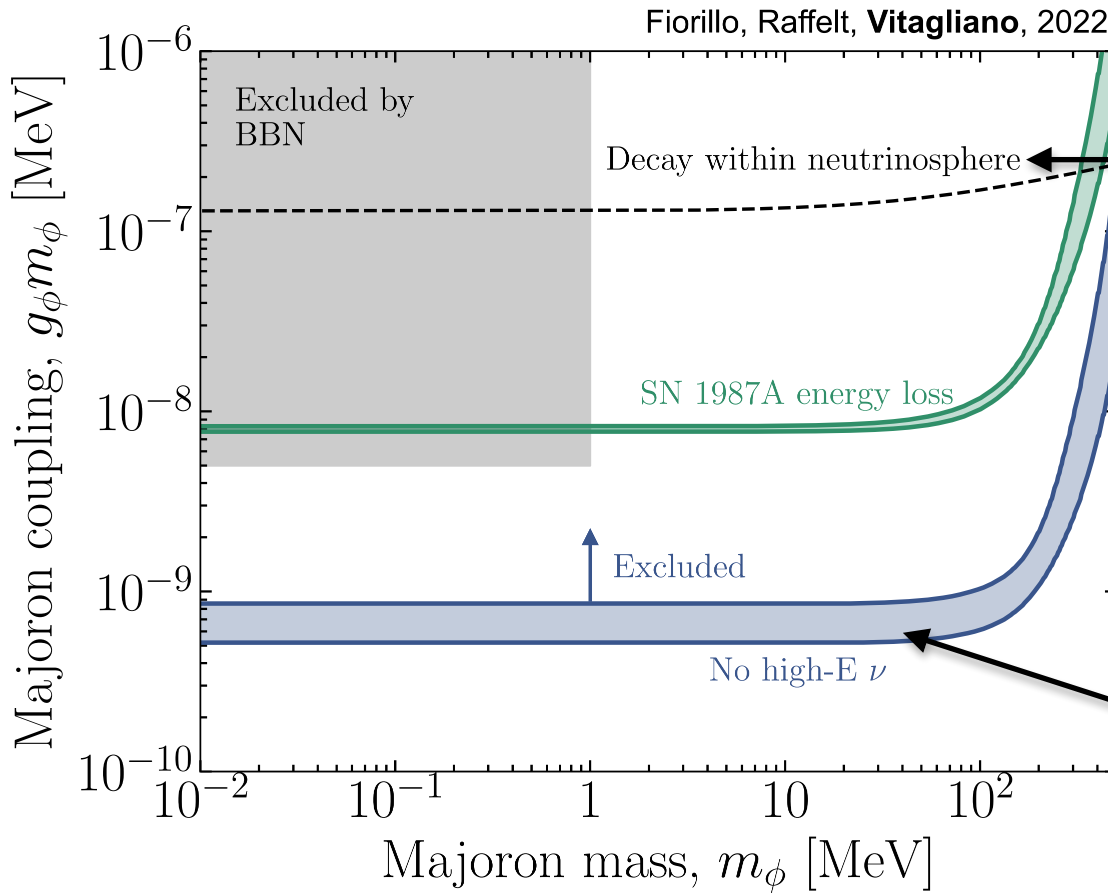


$\lambda \simeq R_{\rm NS}$

Think twice before using modified luminosity criterion for trapping

(See also Caputo, Raffelt, **Vitagliano**, *JCAP* 08 (2022) 08, 045)

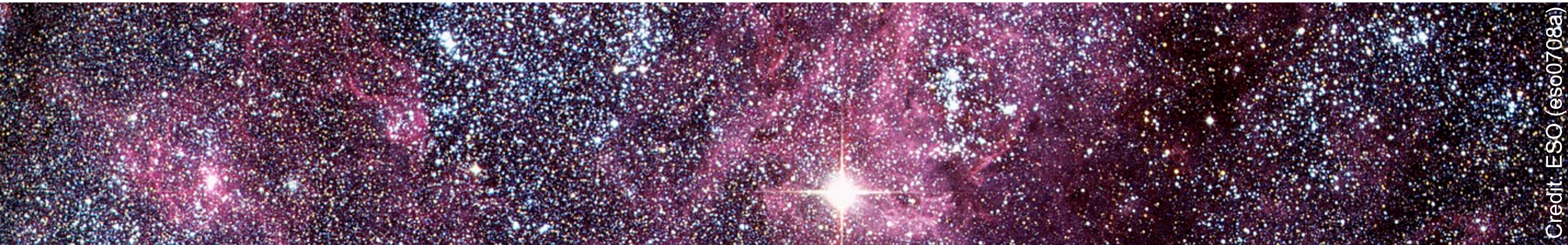
Maximum allowed luminosity 1/100 of cooling bounds

Not strongly dependent on the Supernova model

Conclusions

Conclusions

- Cooling bounds still useful for QCD axion hadronic couplings, look for other observables in other cases—decays!
- Particle physics: best bounds on new feeble interacting particles for “heavy” bosons from decay to photon, charged leptons, or neutrinos
- Astrophysics: rule-out decaying bosons as supernova explosions catalyzers
- Cosmology: strongly constraining DM mediators

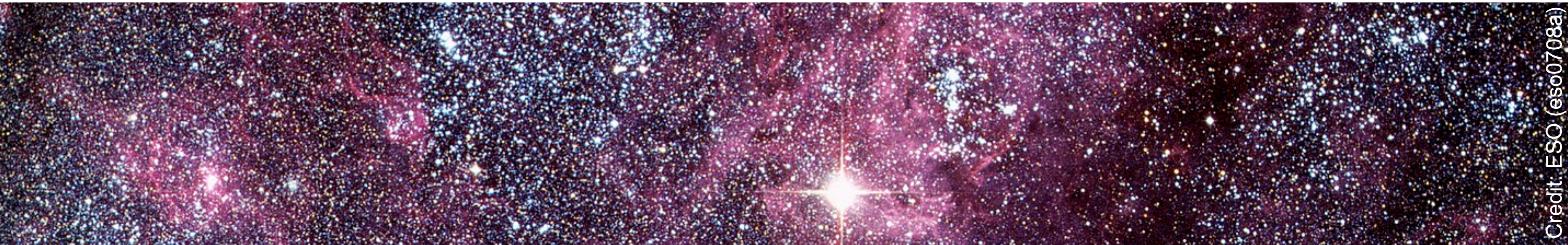


Homeworks

- How sure we are of the hadronic coupling treatment?
- Self-consistent simulations for strongly coupled particles
- Sterile neutrinos much more complicated
- There are decays also with hadronic couplings
- Other transients (e.g. Neutron star mergers)*
- Are we accounting correctly for the evolution of the outgoing γ flux…?**

* Hint #1: interesting
** Hint #2: we are not
Stay tuned!

Personal goal: NEW weakly(ish) slim(ish) interacting particle bounds from SNe



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)