Strong Supernova 1987A Constraints on Bosons Decaying to Neutrinos

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האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

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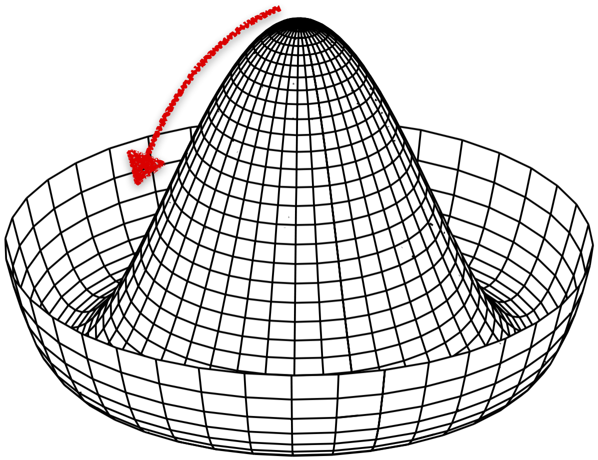
Sub-GeV particles are abundantly produced in supernovae

Strong novel constraints obtained recently

(Coupling to photons, charged leptons etc.)

Today: neutrino couplings

Particles with a neutrino coupling



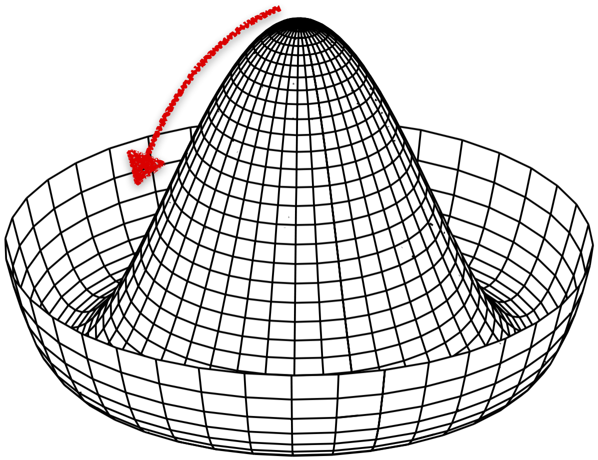
Many BSM particles have coupling to neutrinos:

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

Interesting for a huge number of reasons:

- **Neutrinos might be the portal to the dark sector** (see e.g. Kelly et al. 2020)
- 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 by depositing energy back in the mantle

Particles with a neutrino coupling



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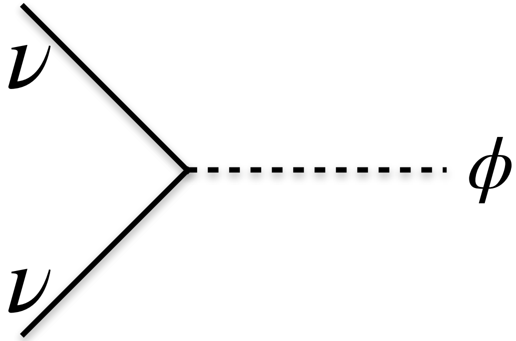
To simplify things, we will assume an extremely simple case: (pseudo)scalars coupling diagonally to all neutrino flavors

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



Particles with a neutrino coupling

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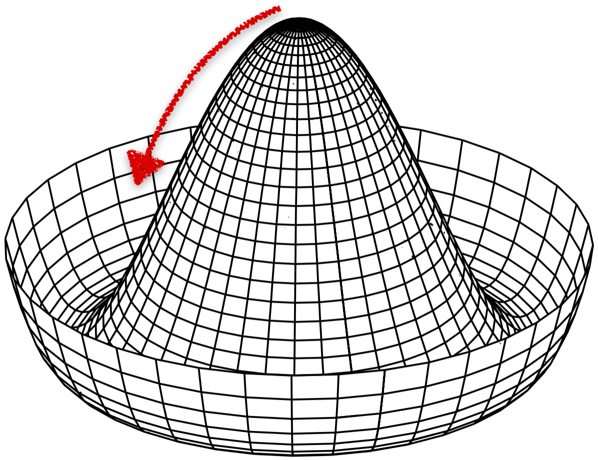

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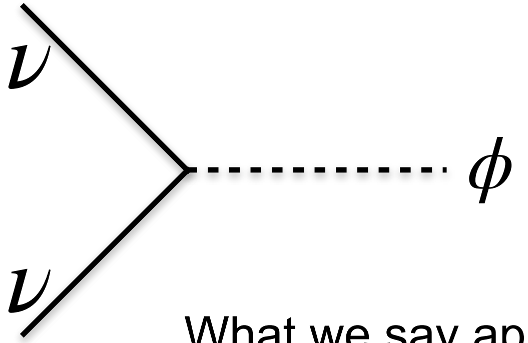
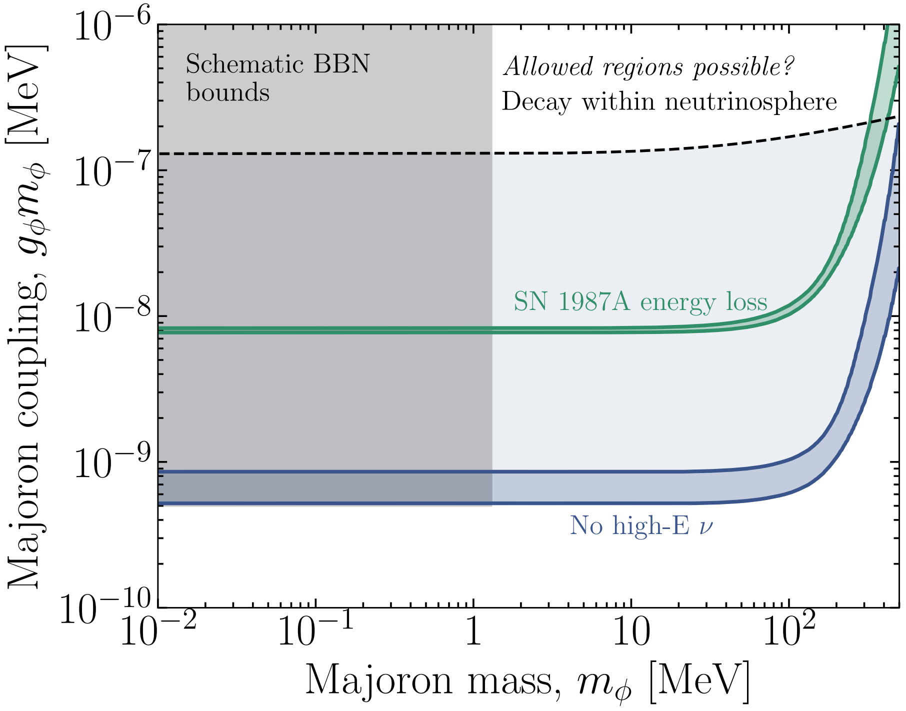


What we say applies also to the other cases

Take home messages

- Particle physics: best bounds on new feebly interacting particles for "heavy" bosons from decay to neutrinos
- Astrophysics: rule-out decaying bosons as supernova explosions catalyzers
- Cosmology: strongly constraining DM mediators



Credit: Anglo-Australian Observatory

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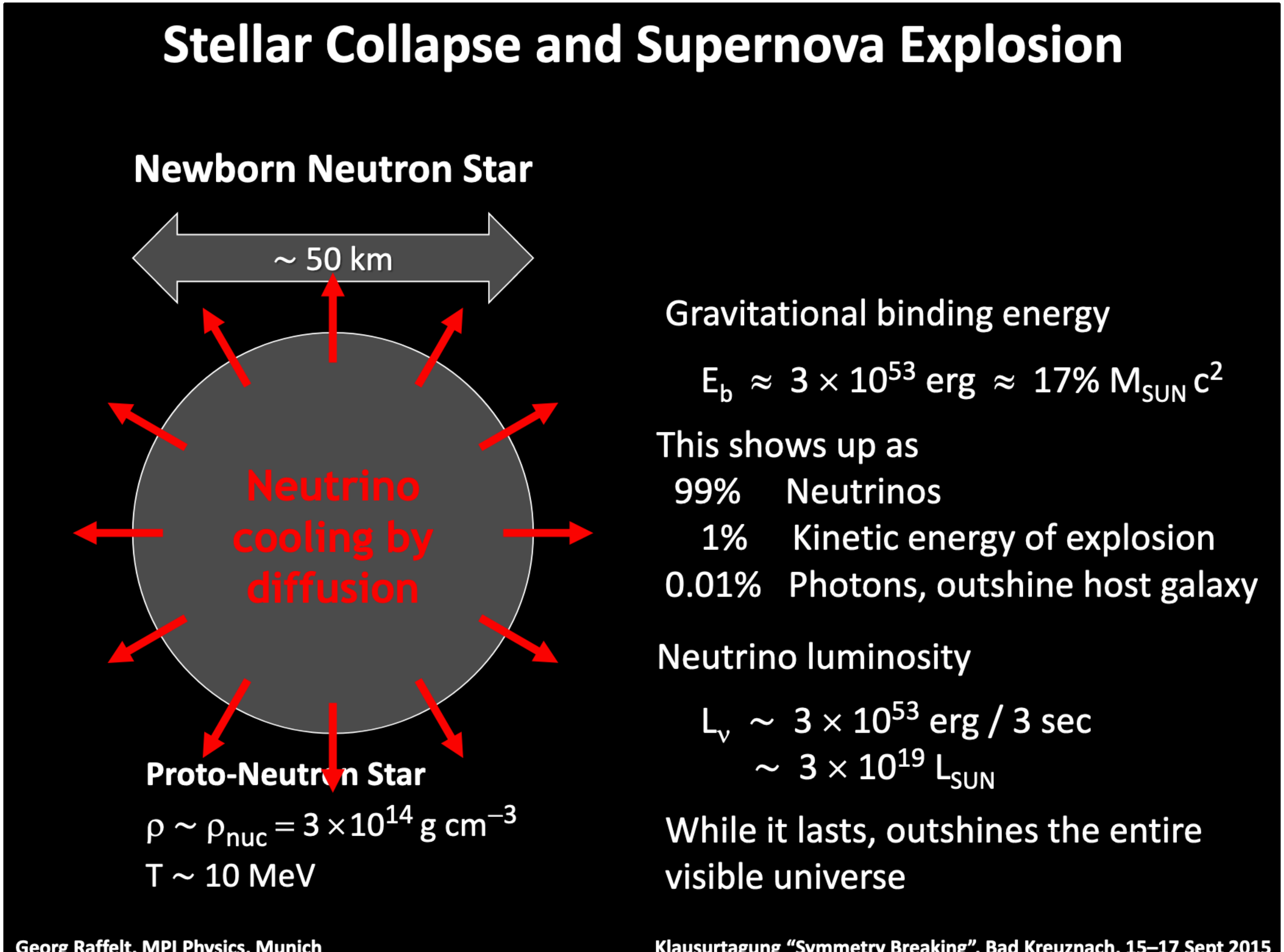
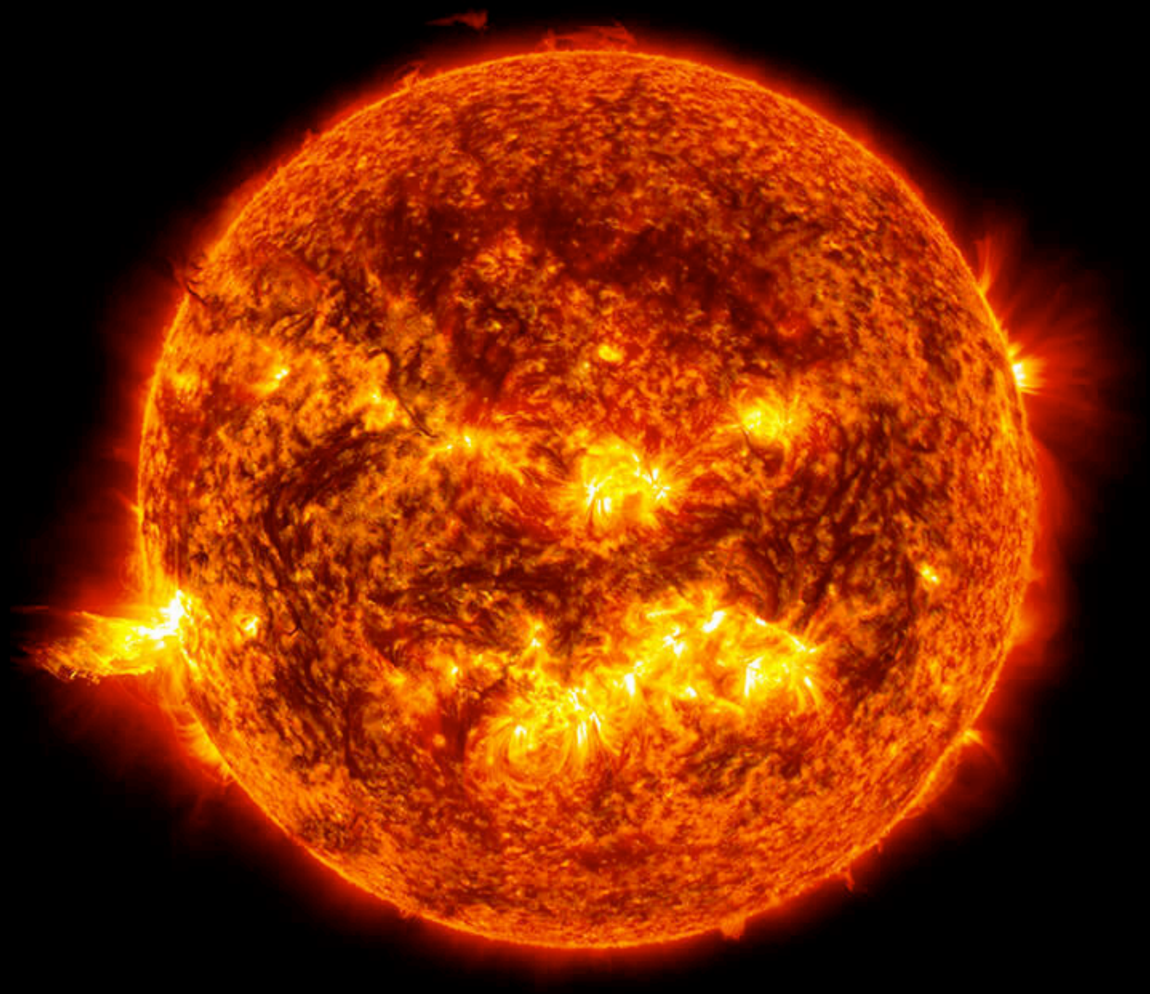
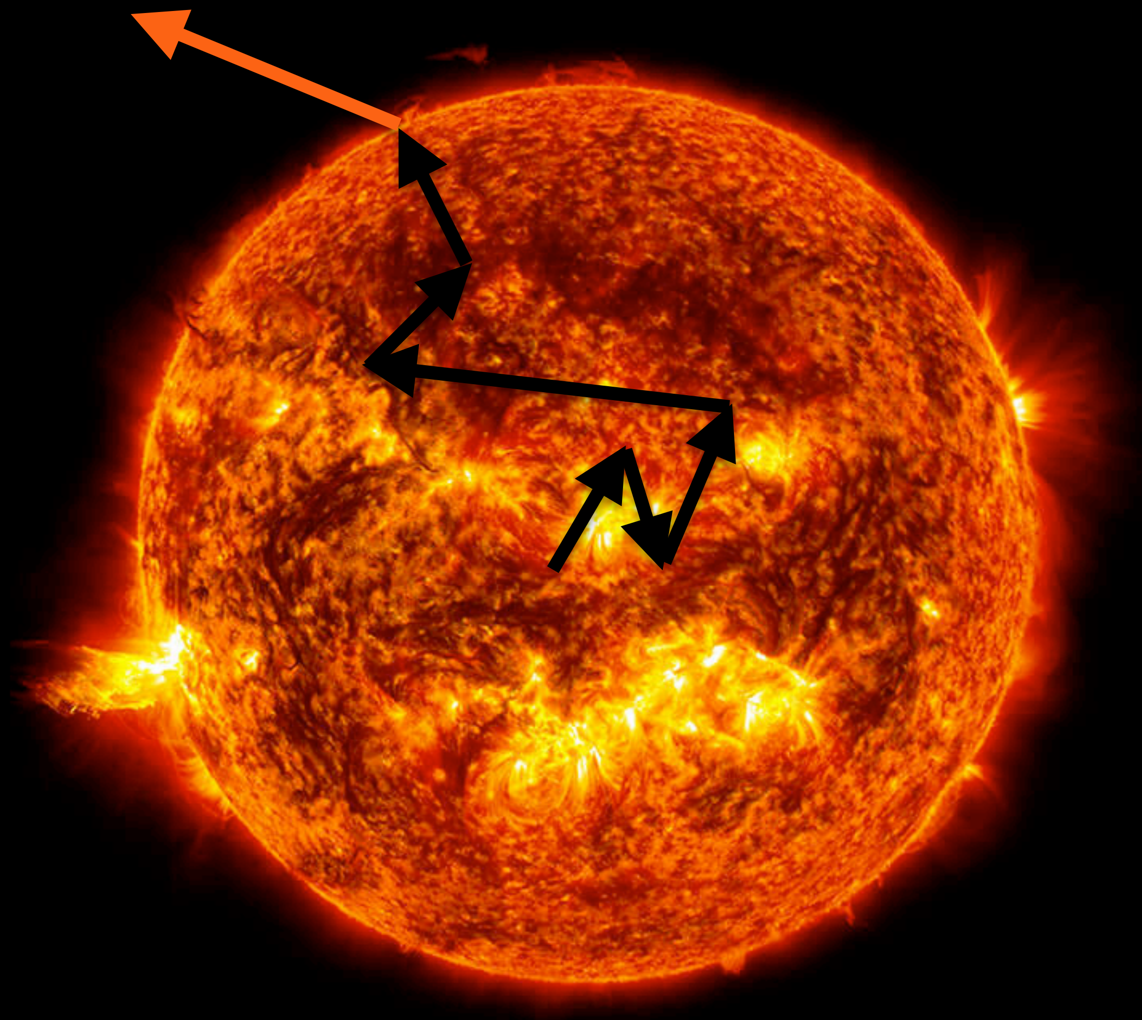
Stellar collapse





Credit: NASA



Credit: NASA

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:

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

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

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

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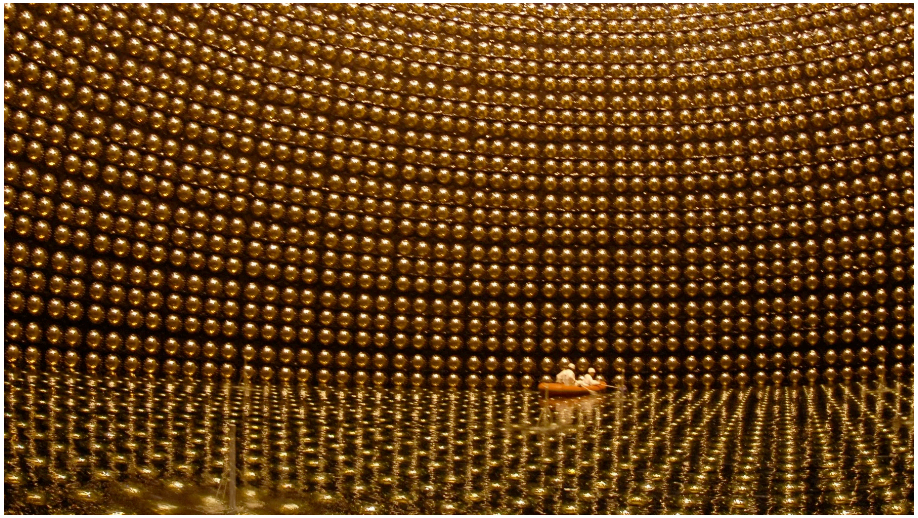
Therefore: $0.5 \times 10^{53}\,\text{erg}$ for each neutrino species, with energies $\mathcal{O}(10\,\text{MeV})$ and a signal of $\mathcal{O}(1 - 10\,\text{s})$

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)

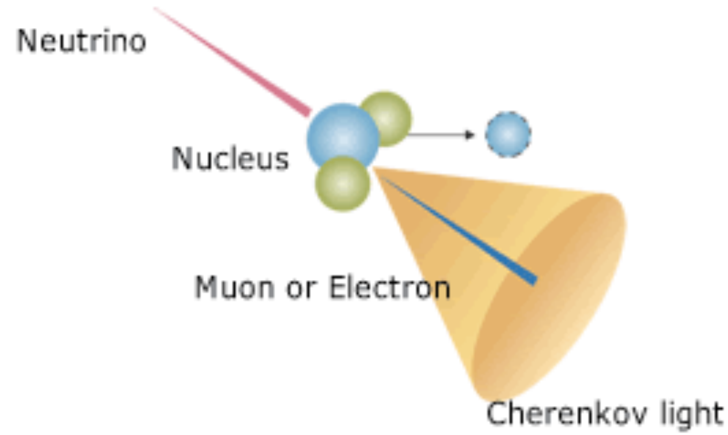


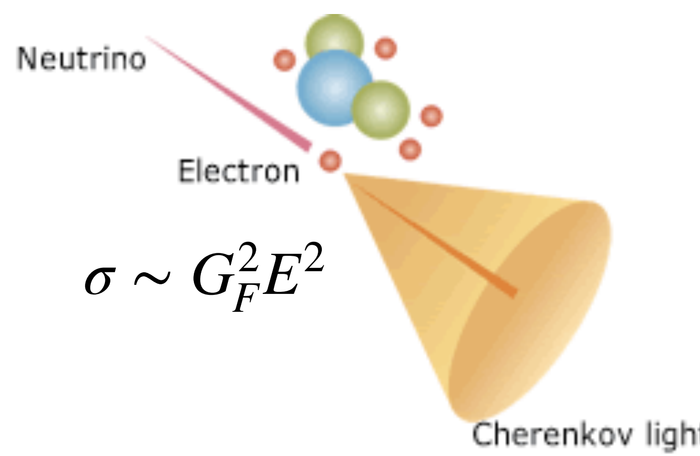
Credit: Super-Kamiokande

Cherenkov detectors

The idea of Cherenkov detectors is extremely simple:

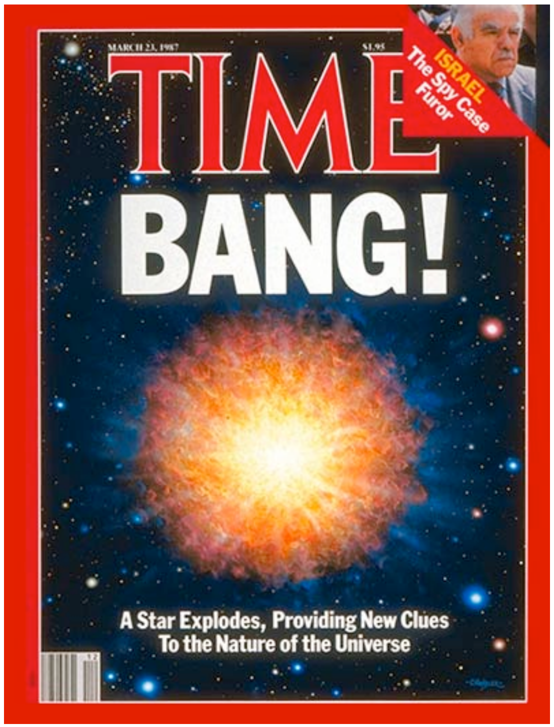
- Take a huge tank of water
- Neutrinos travel in the detector, until they interact with a nucleus (or electrons)
- Inverse Beta Decay (IBD), namely $\bar{\nu}_e + p \rightarrow e^+ + n$
- Charged particles emits Cherenkov radiation, since it is faster than the speed of light in the medium

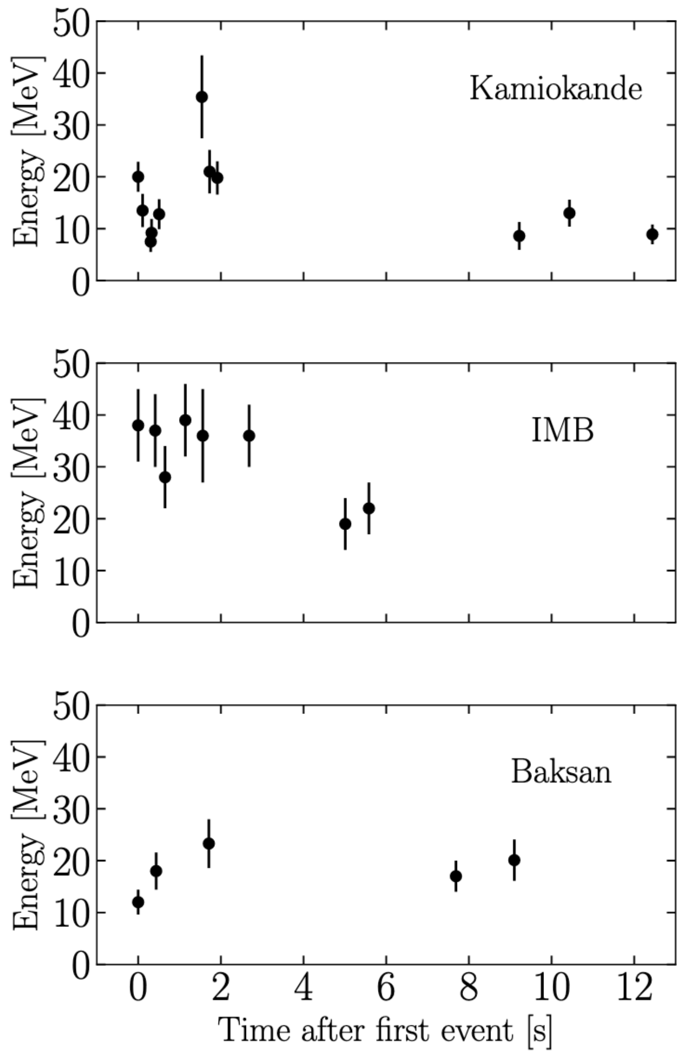




$$\sigma \sim G_F^2 E^2$$

SN 1987A Neutrino Observations

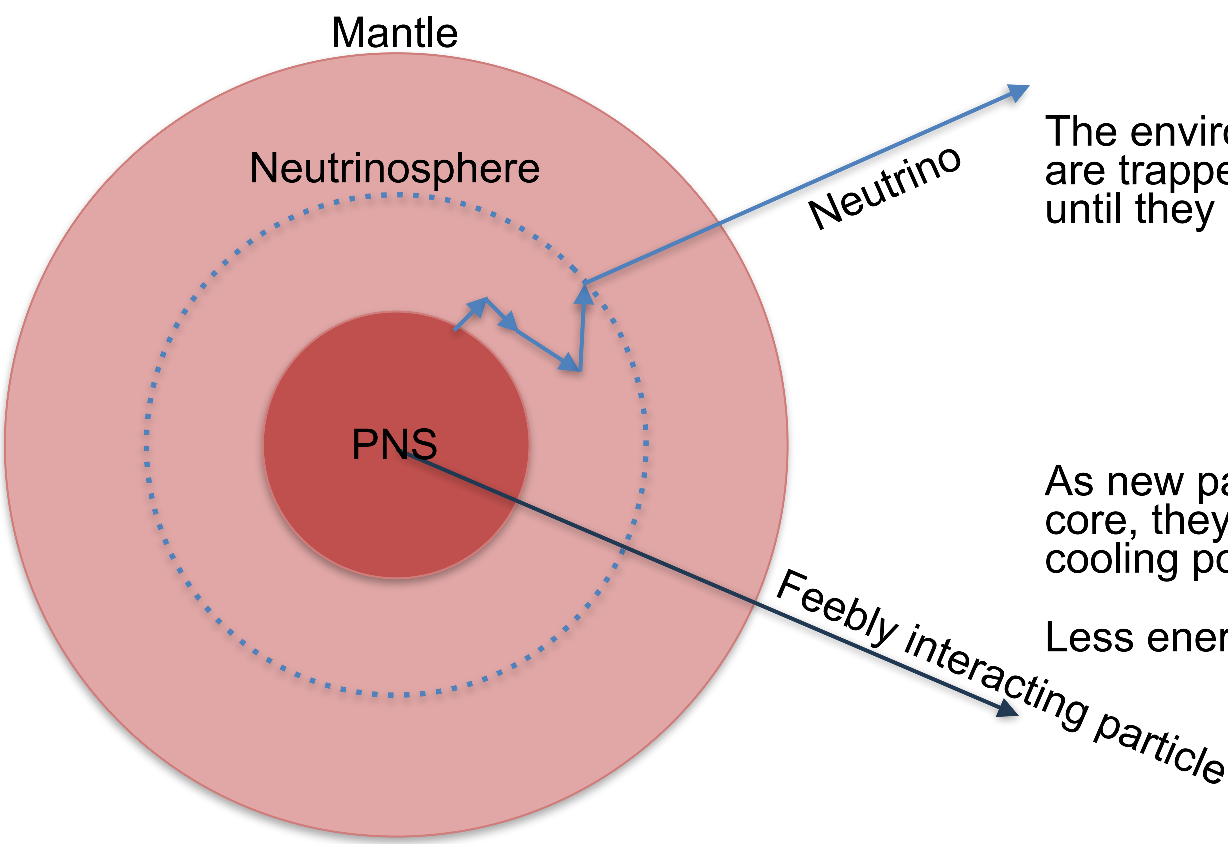




2002: Koshiba
2015: Kajita
(was a fresh PhD in 1987!)

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

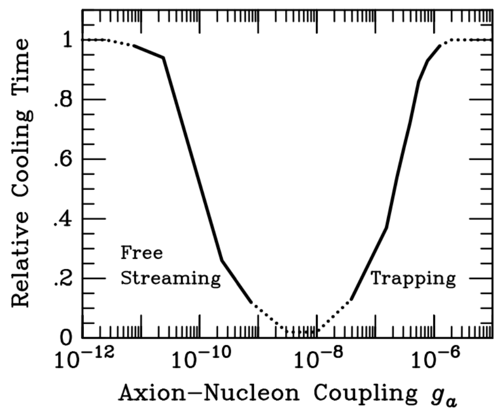


Fig. 13.1. Relative duration of neutrino cooling of a SN core as a function of the axion-nucleon Yukawa coupling g_a. In the free-streaming limit axions are emitted from the entire volume of the protoneutron star, in the trapping limit from the "axion sphere" at about unit optical depth. The solid line 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)

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

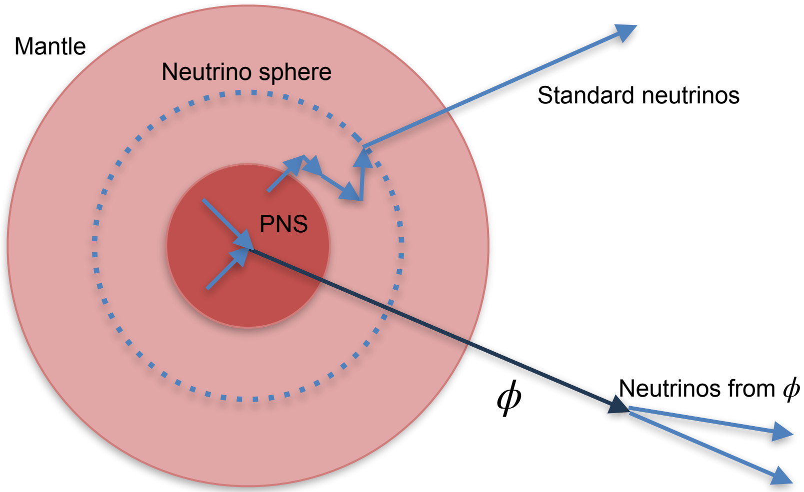
Computed at $T = 30\,\mathrm{MeV}$ and $\rho = 3\times 10^{14}\,\mathrm{g\,cm^{-3}}$

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



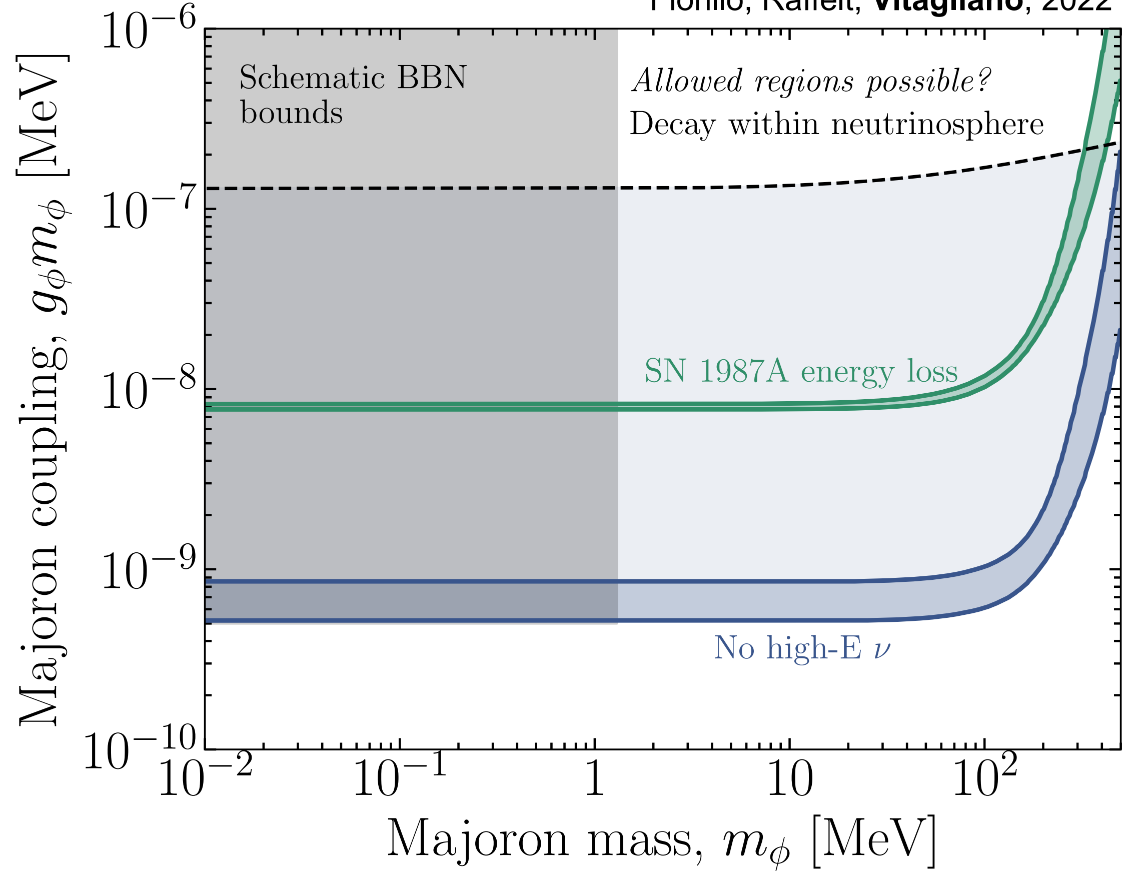
Therefore $\dfrac{n_\nu^{\phi\,\mathrm{decay}}}{n_\nu^{\mathrm{standard}}} \sim \dfrac{E_\nu^{\mathrm{standard}}}{E_\nu^{\phi\,\mathrm{decay}}}$

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

Fiorillo, Raffelt, **Vitagliano**, 2022

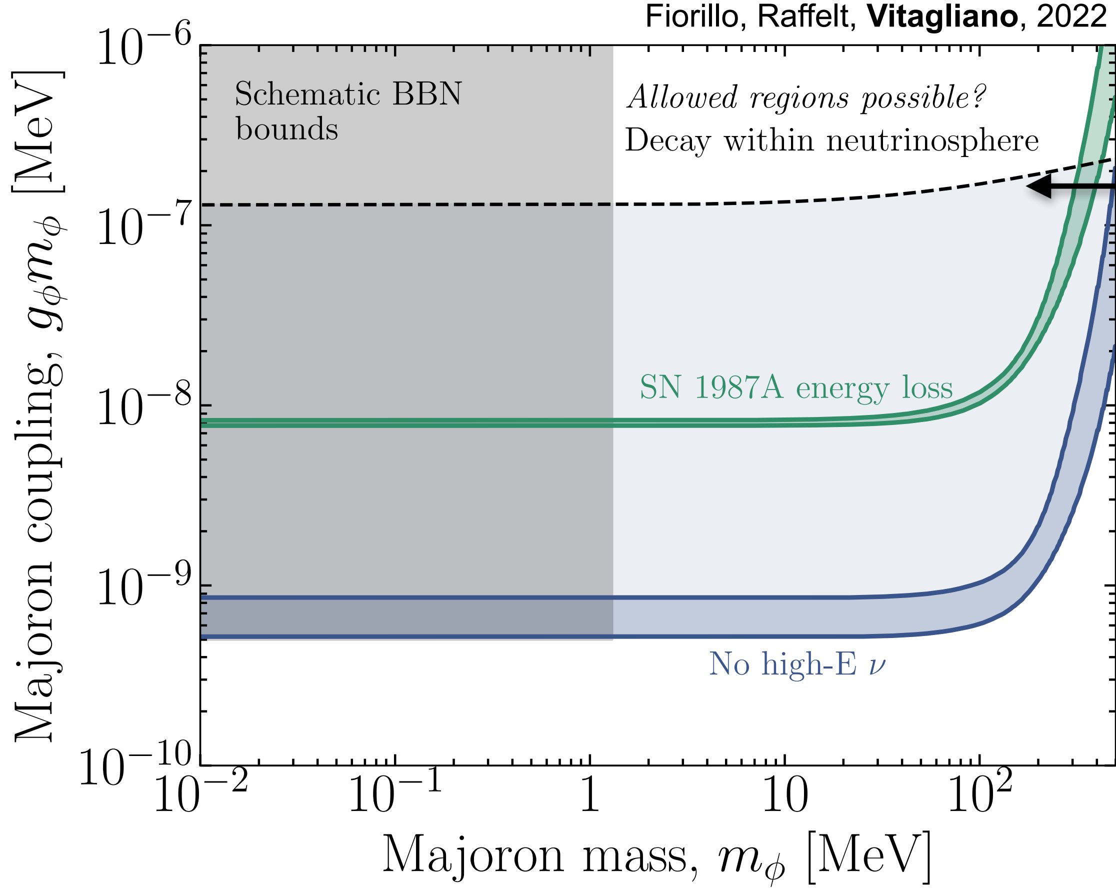


Not strongly dependent on the Supernova model

New bounds from decay to neutrinos

Brand new!

Fiorillo, Raffelt, **Vitagliano**, 2022



$\lambda \simeq R_{NS}$

Think twice before using modified luminosity criterion for trapping

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

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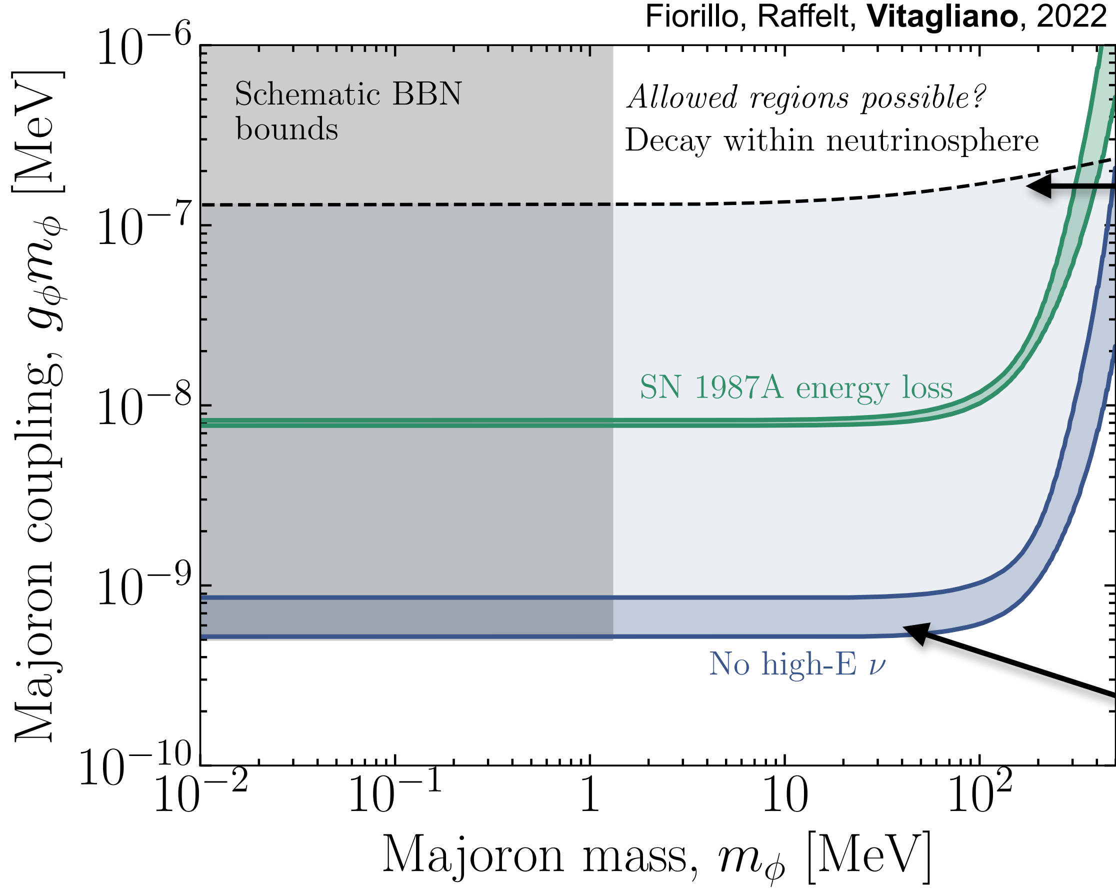

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Maximum allowed luminosity 1/100 of cooling bounds

Not strongly dependent on the Supernova model

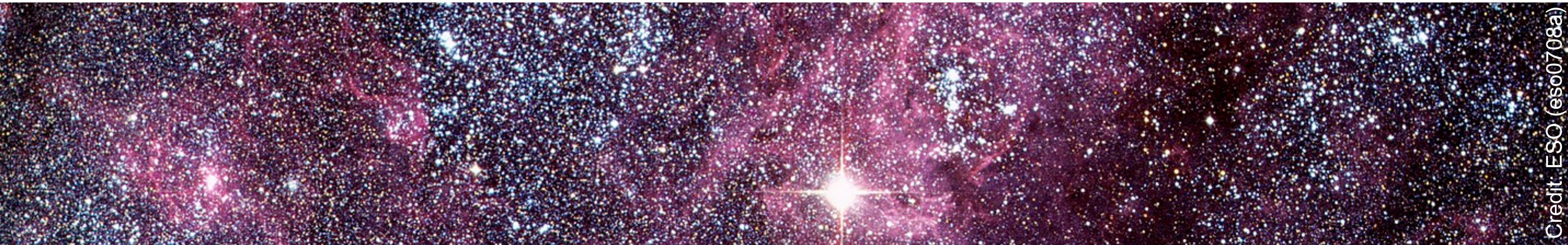
Conclusions

Conclusions

- Majoron-like bosons copiously produced in supernova cores
- They have 100-MeV range energies and decay back to neutrinos
- An additional high-energy neutrino source from supernovae—and **we did not see it**

Results:

- Particle physics: best bounds on new feeble interacting particles for "heavy" bosons decaying to neutrinos
- Astrophysics: rule-out decaying bosons as supernova explosions catalyzers
- Cosmology: strongly constraining DM mediators



Thank you

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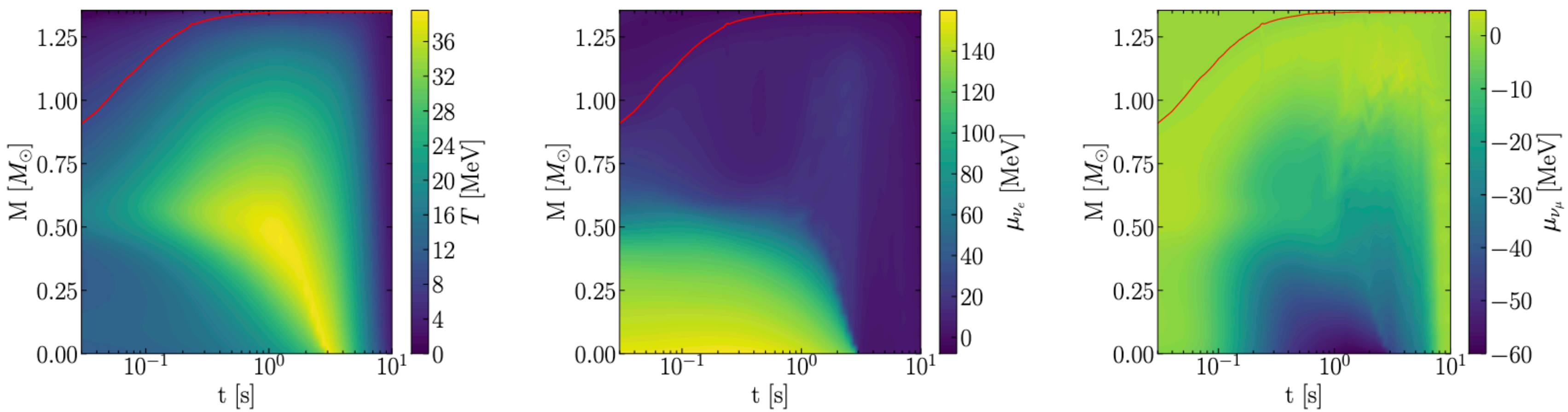
Deleptonization and cooling

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 $M_\odot$.

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

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

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

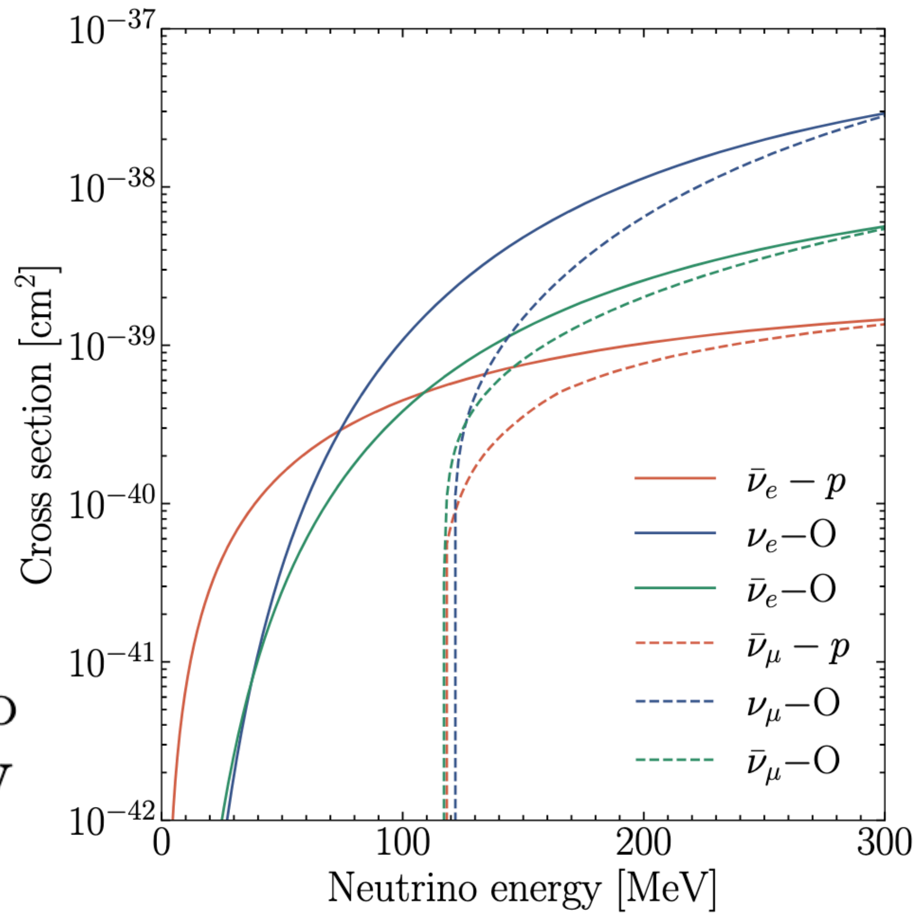
$$E_{e^-} = E_\nu - Q_{\nu_e \text{O}}$$

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

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

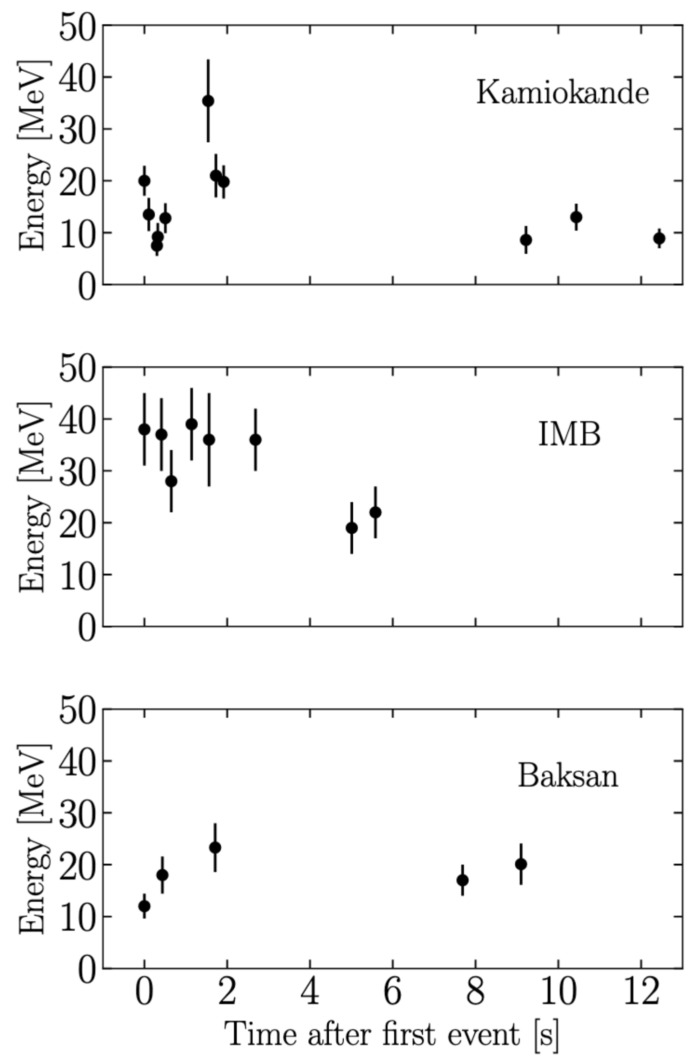
$$E_{e^+} = E_{\bar{\nu}} - Q_{\bar{\nu}_e \text{O}}$$

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

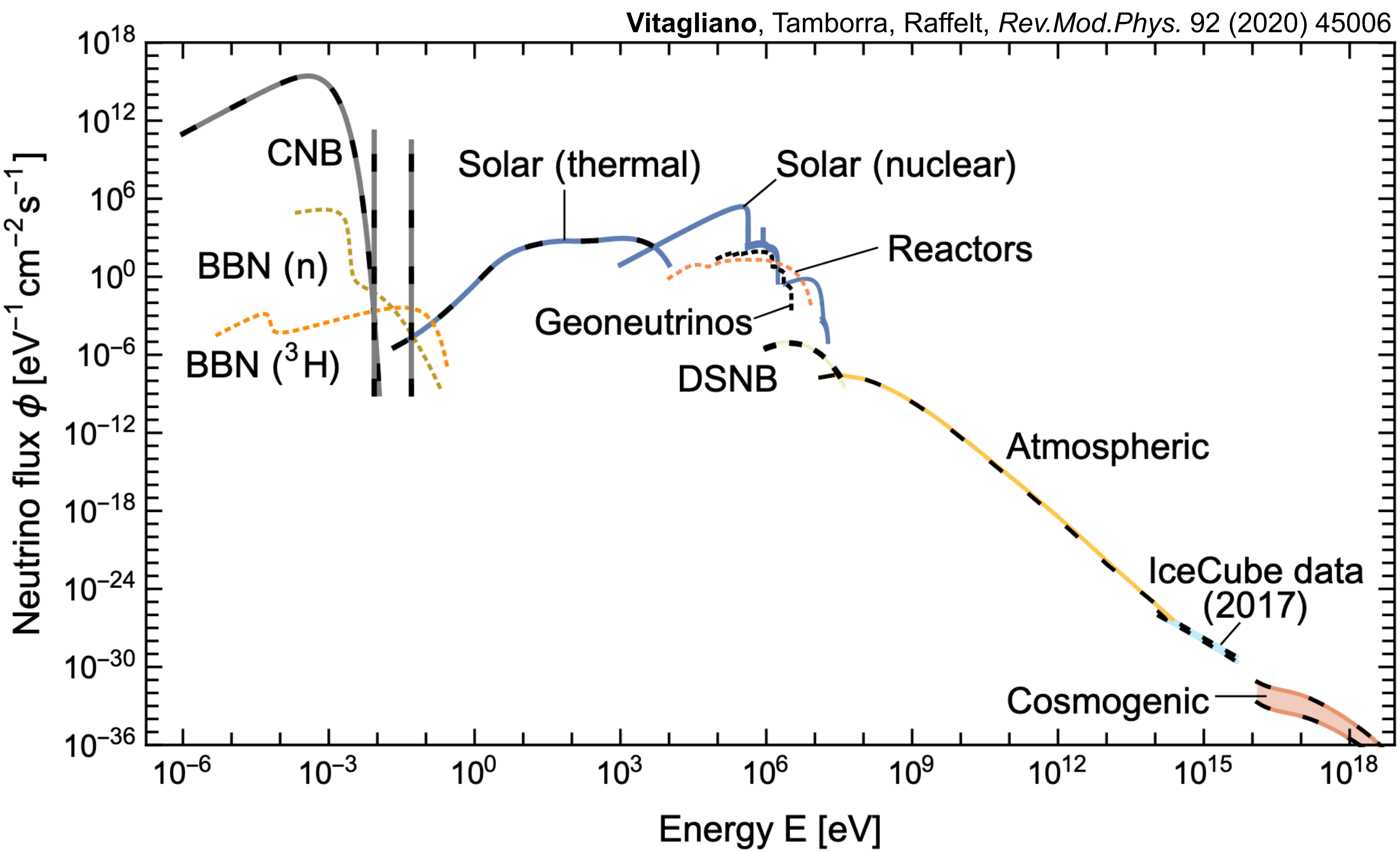


SN 1987A Neutrino Observations

- 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)

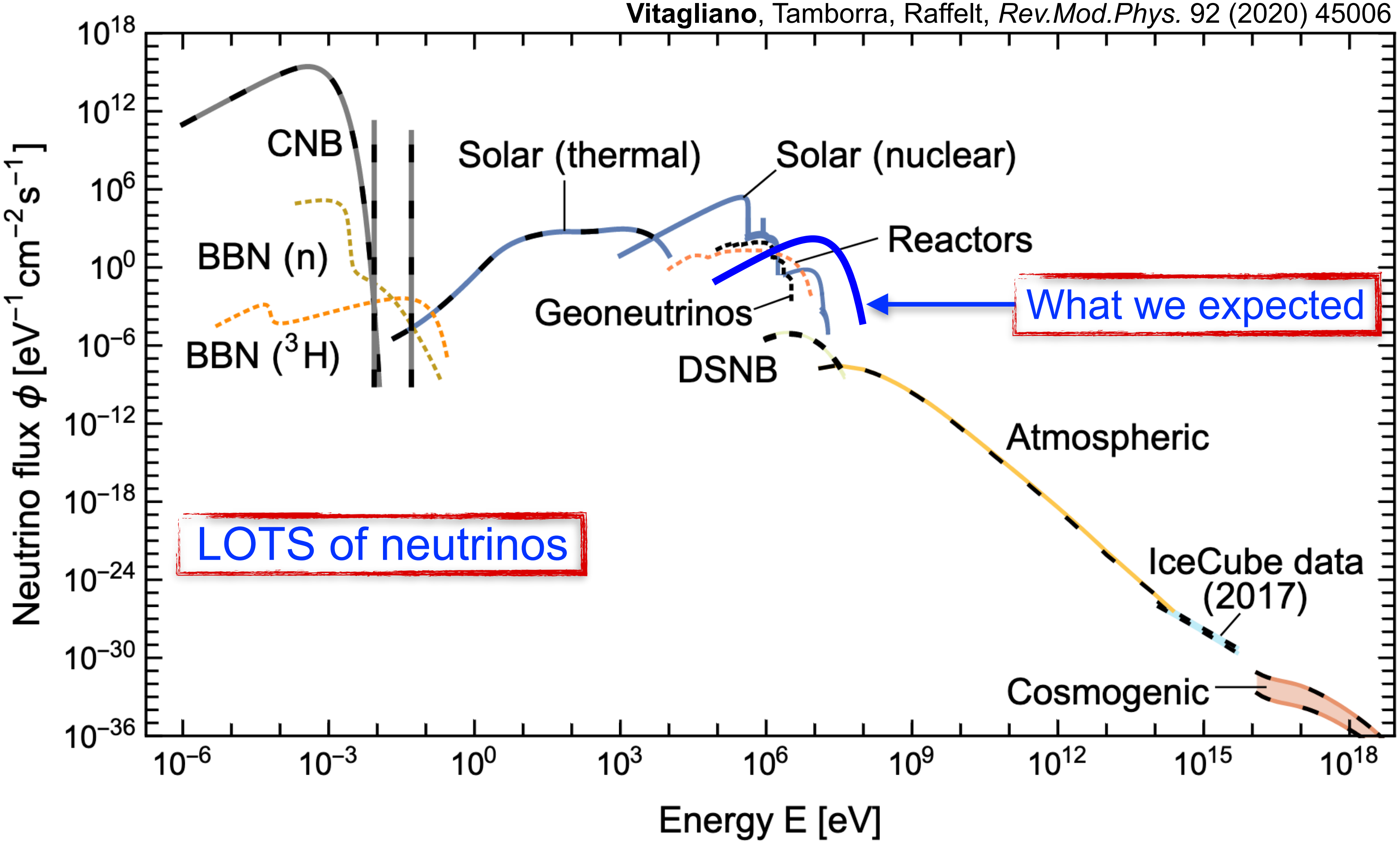


Grand unified neutrino spectrum at Earth



Grand unified neutrino spectrum at Earth

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



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