Supernova Neutrinos Uncover Neutrino Properties and Decode New Physics

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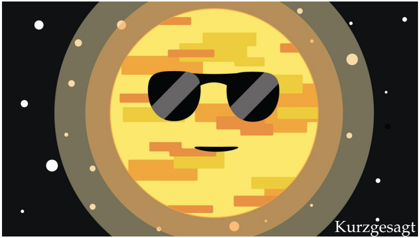
NNN 2025, October 1, 2025

Why is studying astrophysical neutrinos crucial?

Established track record of neutrino discoveries: solar ν



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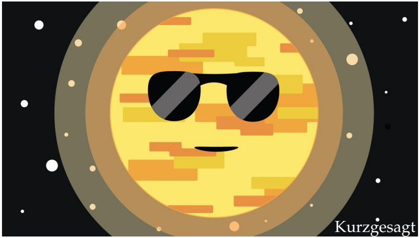

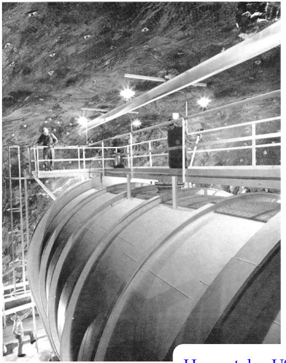

Homestake, USA

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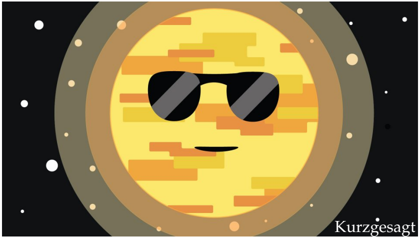

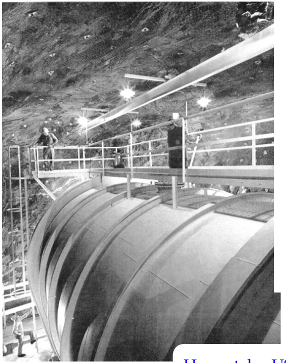

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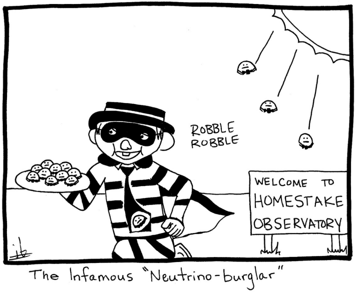

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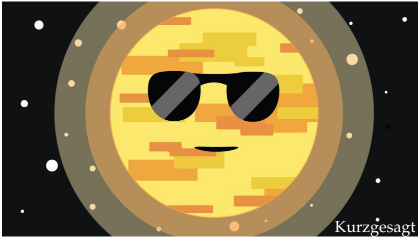
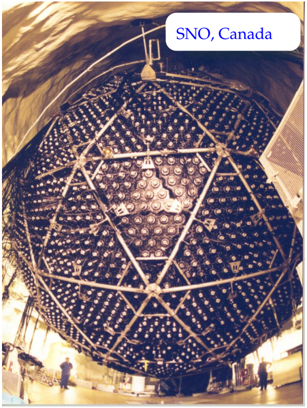
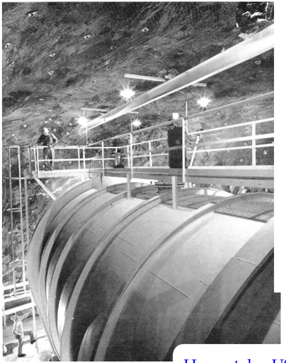


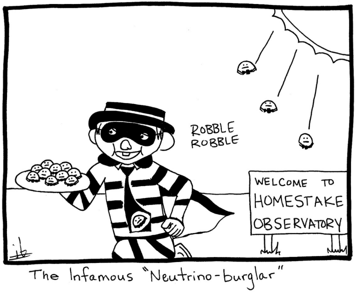
Kurzgesagt



SNO, Canada



Homestake, USA



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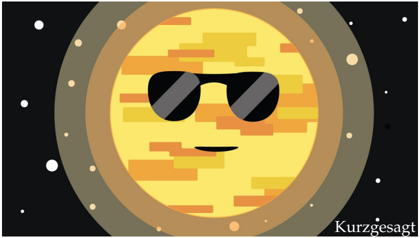
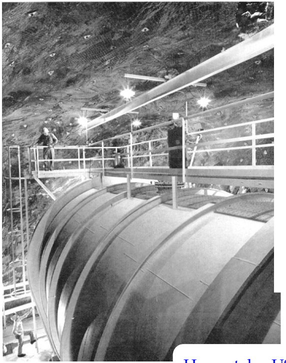
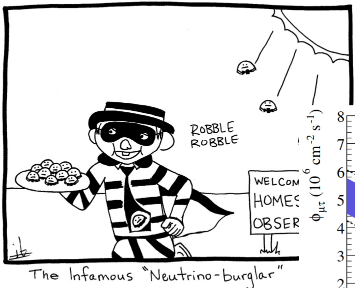
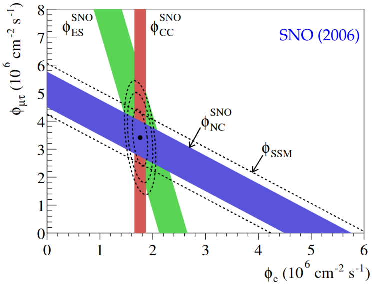
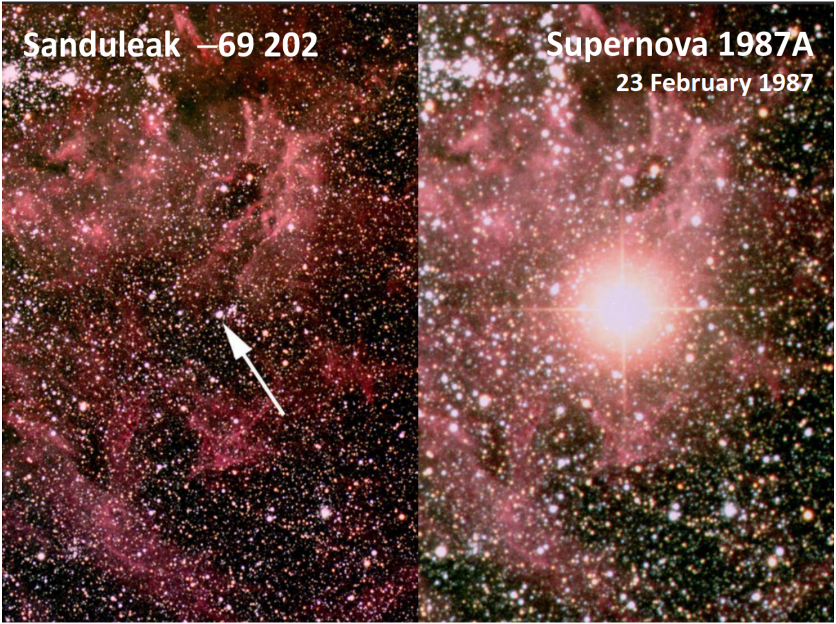




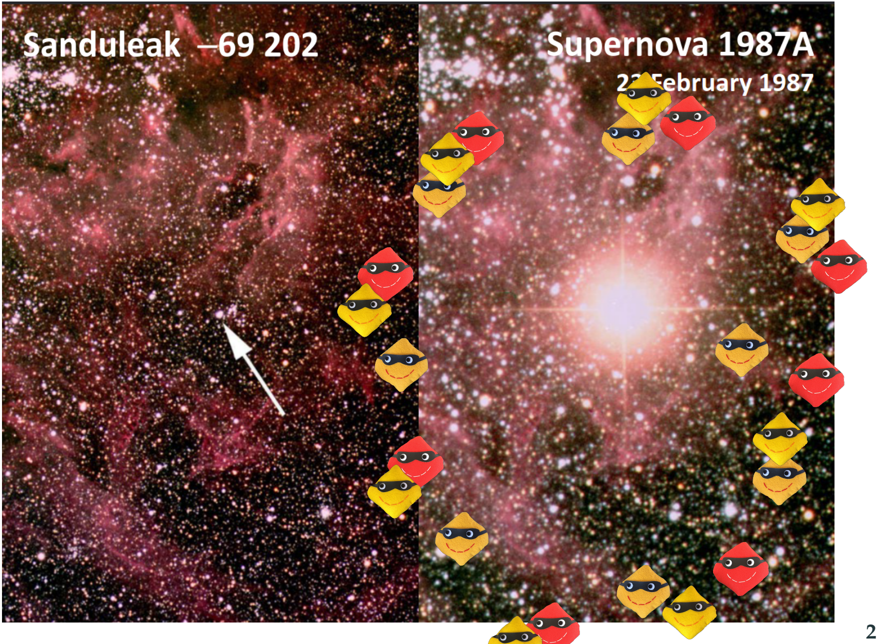




Established track record of neutrino discoveries: SN 1987A



Established track record of neutrino discoveries: SN 1987A



Established track record of neutrino discoveries: SN 1987A

Hubble (2017)

JWST (2023)

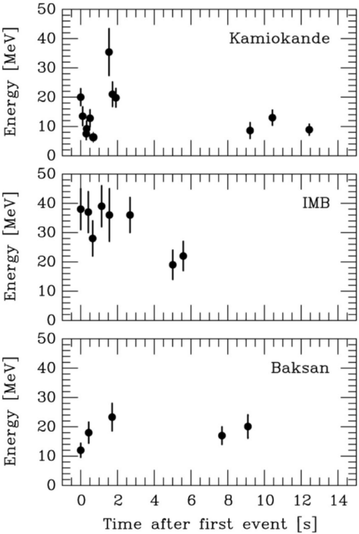
- Neutron star remnant

  Fransson et al. (2024)

- Binary system

  Morris & Podsiadlowski (2007), (2009)

Established track record of neutrino discoveries: SN 1987A



Courtesy of G. Raffelt

- Neutrino detection from SN 1987A:
  - confirmed the core-collapse scenario
  - 99% of the energy emitted in neutrinos
  - best limit at the time on the ν mass

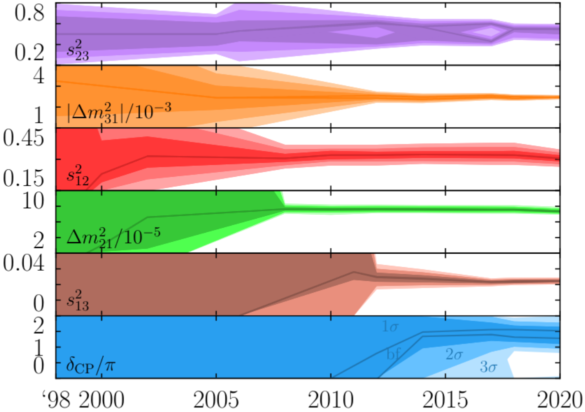
Towards Precise Neutrino Properties Measurements

We known now:

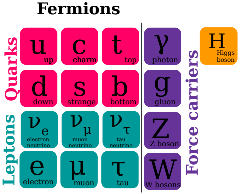
- large mixing angles
- non-zero masses

Remaining questions

- Majorana vs Dirac
- absolute masses
- degree of CP violation



Snowmass Neutrino Frontier Report (2022)

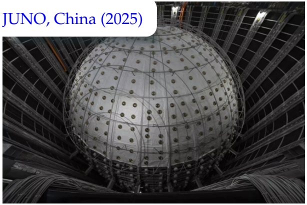


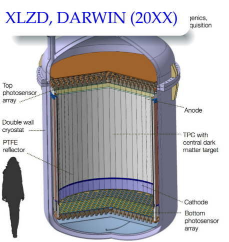
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

beam, atmospheric | **beam, reactor** | **solar, reactor**

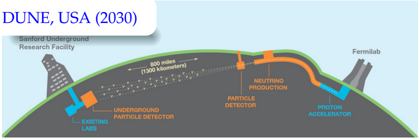
$$U = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix} \begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{bmatrix} \begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}$$

How to achieve full picture of neutrinos? All hands on deck!

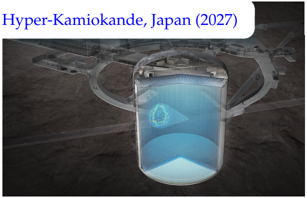

JUNO, China (2025)



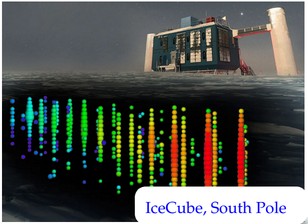
XLZD, DARWIN (20XX)



DUNE, USA (2030)


Hyper-Kamiokande, Japan (2027)


Rubin Observatory, Chile (2025)


IceCube, South Pole

- Many new experiments comimg online soon
- variety of approaches $\rightarrow$ superb sensitivity

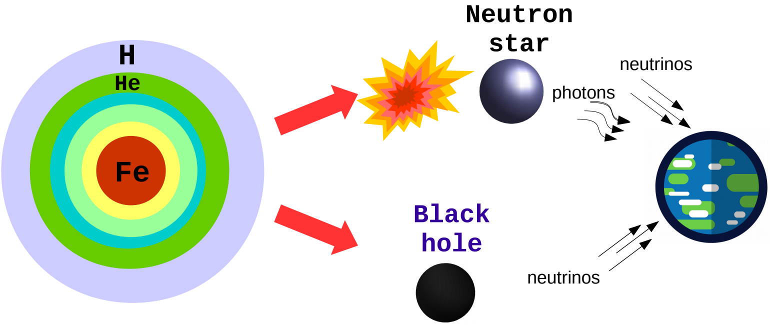
- Complementarity with:
  - reactor and accelerator searches
  - electromagnetic surveys
  - other astrophysical messengers

Neutrinos from Core-collapse Supernovae

Why are neutrinos important for a core-collapse supernova?

Neutrinos:

- $\sim 10^{58}$ of them emitted from a single core collapse
- only they can reveal the deep interior conditions
- only particles detectable from the collapse to a black hole



Why core-collapse supernovae are good physics probes?

Advantages

- extreme physical conditions not accessible on Earth
- within the reach of existing and upcoming detectors

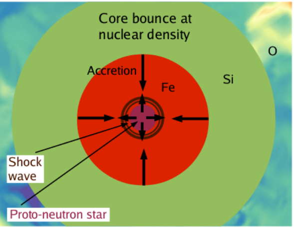
What can we learn with a variety of detectors?

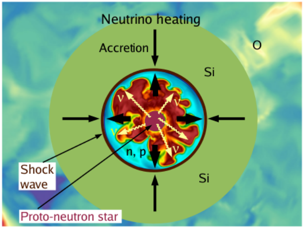
- explosion mechanism — Bethe & Wilson (1985), **AMS** et al. (2022)...
- nucleosynthesis — Woosley et al. (1994), Surman & McLaughlin (2003)...
- compact object formation — Warren et al. (2019), Li, Beacom et al. (2020)...
- neutrino mixing — Balantekin & Fuller (2013), Siwach, **AMS**, Balantekin (2022)...
- non-standard physics — **AMS** et al. (2020), **AMS**, Tamborra (2020) ...

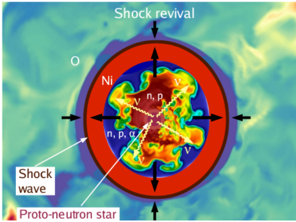
Neutrinos from Supernovae as Probes of New Physics

- Infall phase, ν_e burst ~ 40 ms
- Accretion phase, ~ 100 ms
- Cooling phase, ~ 10 s

H. T. Janka (2017)



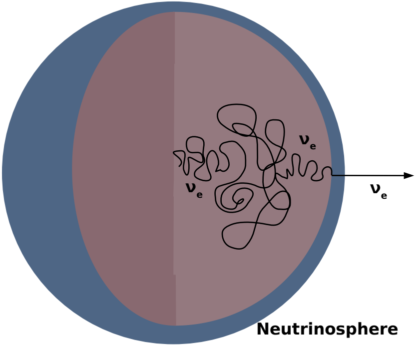




New neutrino physics affects the core-collapse supernovae:

- change diffusion time $\rightarrow$ possible change in the star's fate
- changed diffusion time $\rightarrow$ changed duration of the neutrino signal
- new cooling channel $\rightarrow$ affects explosion probability
- new distinct feature in the neutrino signal

Lepton number violating neutrino self-interactions



Neutrino trapping

$$A(N,Z) + \nu \rightleftharpoons A(N,Z) + \nu$$

β-equilibrium

$$e^- + p \rightleftharpoons \nu_e + n$$

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

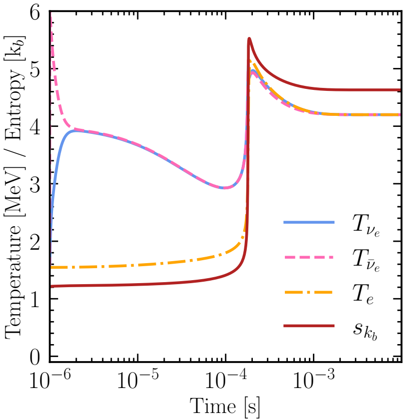
Implementation:

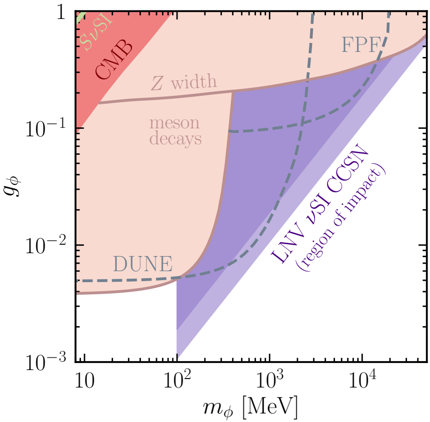
Thermalize the population of ν and $\bar{\nu}$ once $\rho \sim 10^{11} - 10^{12}\text{g cm}^{-3}$

$\nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau,$ $\quad \nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_x, \bar{\nu}_x,$ $\quad \nu_e \rightleftharpoons \nu_e, \bar{\nu}_e$

AMS et al. (2024), (PRL)

New β-equilibrium with LNV νSI

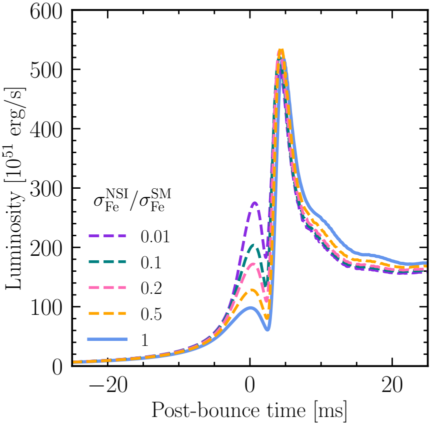


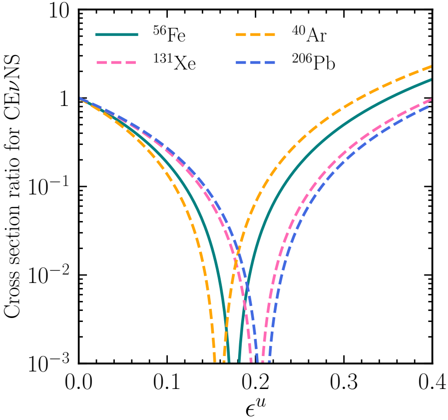


- new interactions quickly equilbrate ν_e and $\bar{\nu}_e$ seas
- enhanced ν_e and e^- captures heat up the matter
- complementarity with future accelerator-based experiments

AMS et al. (2024), (PRL)

Nonstandard neutrino-quark interactions

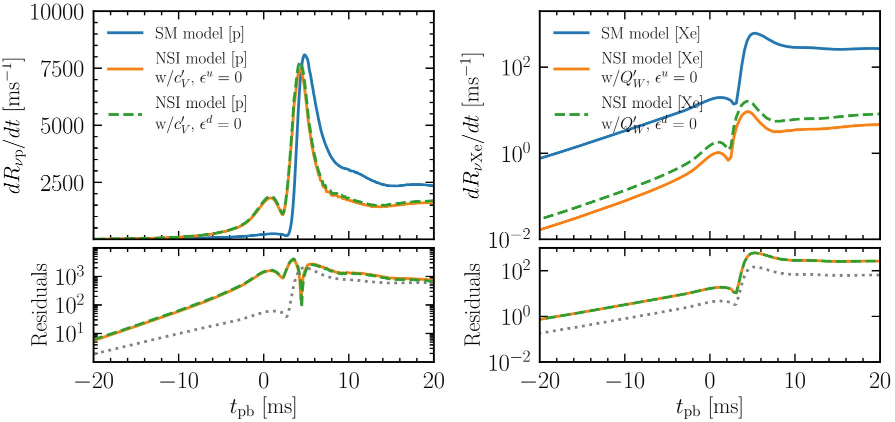




- Significant change in the luminosity core pre-bounce
- Pre-bounce: heavy nuclei in the core
- Post-bounce: nucleons in the core

Beatty, **AMS**, Takhistov (2025), (arXiv: 2509.07856)

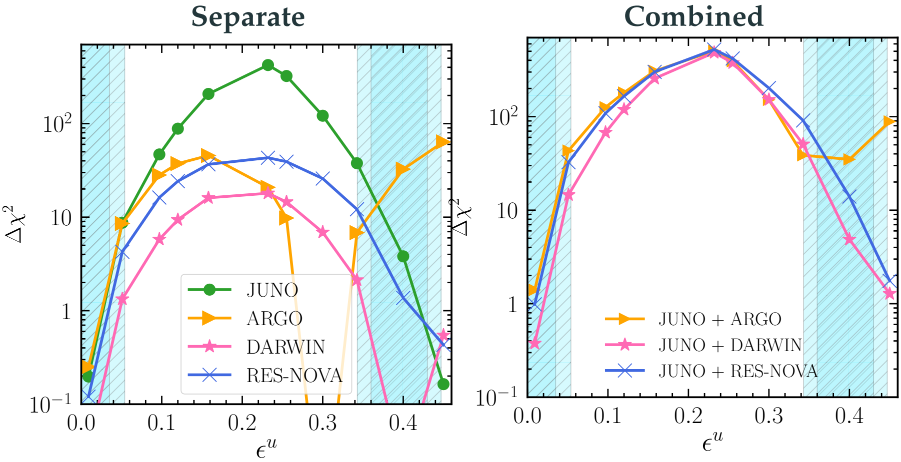
Rates in JUNO and DM detectors for the Betelgeuse



- JUNO: rate changed the most during the infall signal
- DARWIN: rate changed always
- opposite effects → minimized degeneracies

Beatty, **AMS**, Takhistov (2025), (arXiv: 2509.07856)

Sensitivity for constraining nonstandard interactions

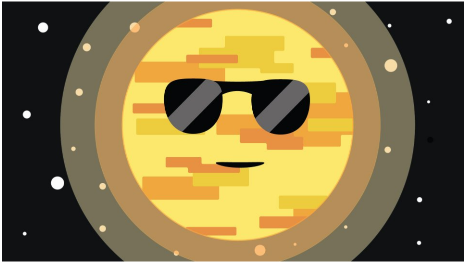


- Combined two-detector $\chi^2 \sim$ always better than a single detector
- Possibility to rule out completly the degenerate with SM NSI

Beatty, **AMS**, Takhistov (2025), (arXiv: 2509.07856)

Diffuse supernova neutrino background

Why focus only on a single rare event?

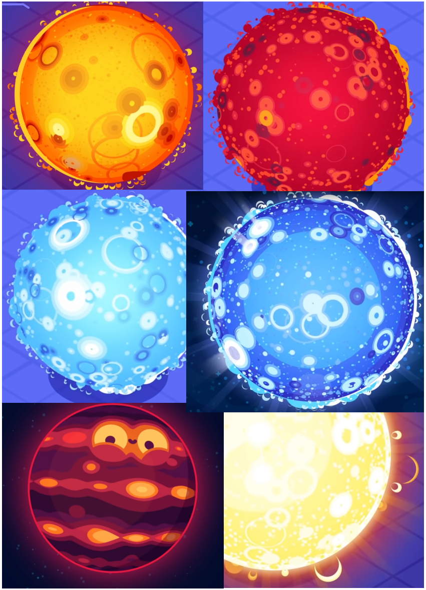


Single galactic SN event

- rare event
- precise infromation about one star

Multiple SN events (larger distances)

- accumulation of events
- will detect in coming years



Images: Kurzgesagt

Diffuse supernova neutrino background

cosmological supernovae rate

fraction of black-hole-forming progenitors

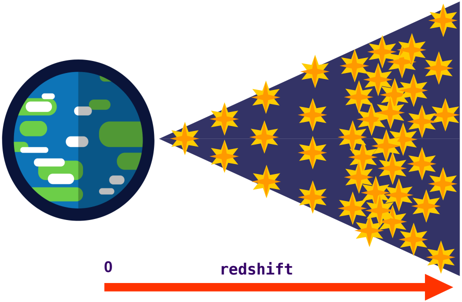
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,{\rm CC-SN}}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,{\rm BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

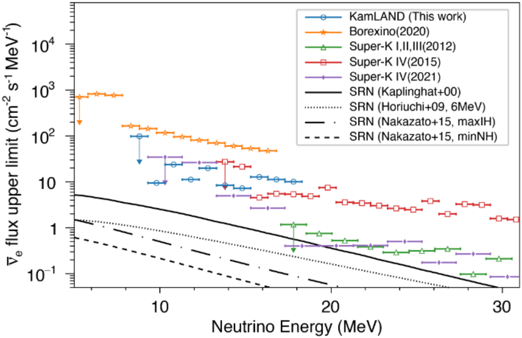
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010),..
Recent reviews: Kresse et al. (2020), **AMS** (2022), Ando et al. (2023), ...

Diffuse supernova neutrino background: current limits

SK collab. (2021)

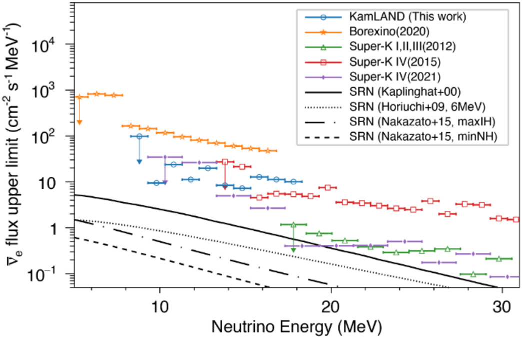


DSNB limits:

- $\bar{\nu}_e \approx 2.7\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3$ MeV SK collab. (2021), SK collab. (2023)
  soon detected by SK (Gd) Beacom, Vagins (2004) and JUNO JUNO collab. (2021)
- $\nu_e \approx 19\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu \in [22.9, 36.9\ \mathrm{MeV}]$ SNO collab. (2020)
  possibly detectable by DUNE Møller, **AMS**, et al. (2018), Zhu et al. (2019)
- $\nu_x \approx 750\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

Diffuse supernova neutrino background: current limits

SK collab. (2021)



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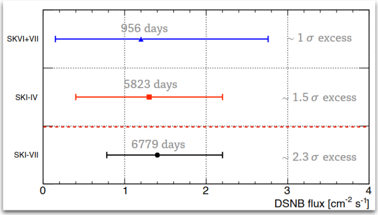
  possibly detectable by DUNE Møller, **AMS**, et al. (2018), Zhu et al. (2019)
- $\nu_x \lesssim 100\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV **AMS**, Beacom, Tamborra (2021)

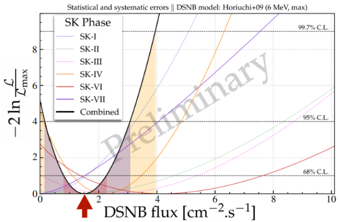
Tension from zero assumption

Spectral-fitting analysis

Spectrum fitting analysis to extract significance

- Total 6779 days of SK (5823 d pure-water and 956 d Gd-water) combined
- Analysis threshold: $E_\nu > 17.3$ MeV
- Suppress uncertainty of background prediction by fitting both $N_n=1$, $N_n \neq 1$





Best fit: 1.4

(Rogly, poster 79)

Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is $\mathbf{1.4^{+0.8}_{-0.6}}$ **cm^{-2} s^{-1}** for $E_\nu > 17.3$ MeV

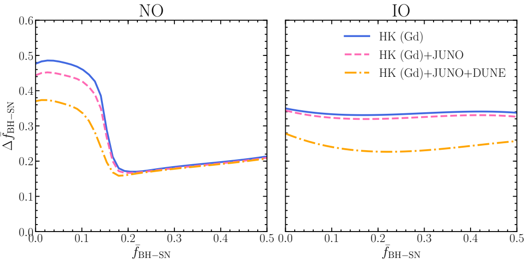
➡ **exhibit ~2.3 σ excess!!**

17

Slide credit: Masayuki Harada talk at Neutrino 2024

How to probe astrophysical parameters with DSNB?

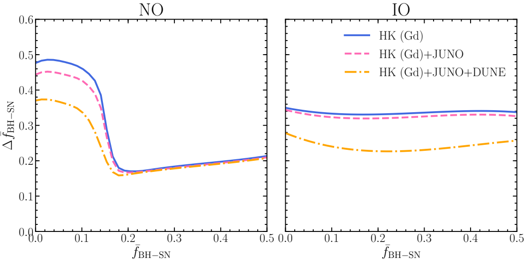
Expected 1σ uncertainty: fraction of BH forming progenitors



- The high uncertainty comes from $f_{\rm BH-SN}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos $\rightarrow$ helps to reduce the uncertainty

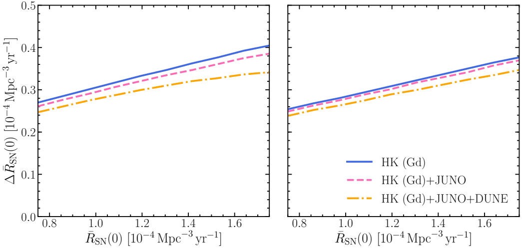
Møller, **AMS**, Tamborra, Denton (2018), (JCAP)

Expected 1σ uncertainty: local supernova rate



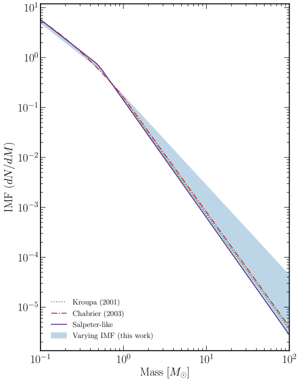
- The high uncertainty comes from $f_{\mathrm{BH-SN}}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos → helps to reduce the uncertainty

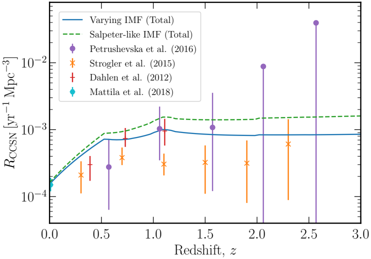
- Relative error of 20%-33% independent of the mass ordering.

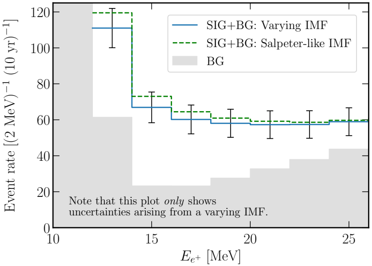


Møller, **AMS**, Tamborra, Denton (2018), (JCAP)

Varying Initial Mass Function







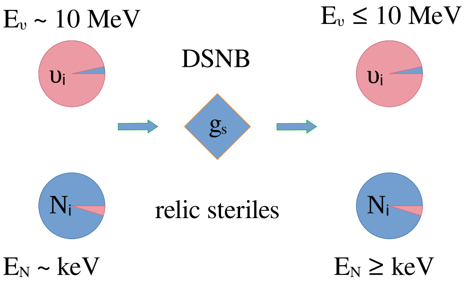
- larger fraction of stars may evolve to black holes at high redshift
- changed rate of the core-collapse supernovae

Ziegler, Edwards, **AMS**, Tamborra, Horiuchi, Ando, Freese (2022), (MNRAS)

How to probe new physics with DSNB?

Do keV-mass Sterile Neutrinos Have Self-Interactions?

Balantekin, Fuller, Ray, **AMS** (2023), (PRD)



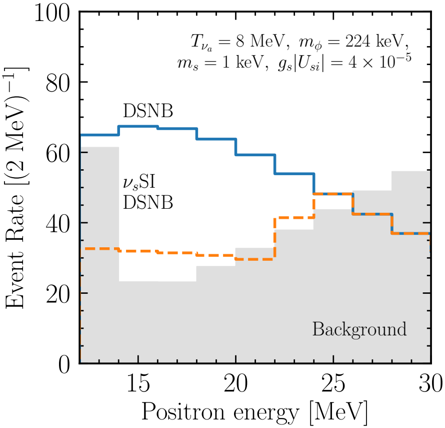
Resonant interaction for sterile neutrinos

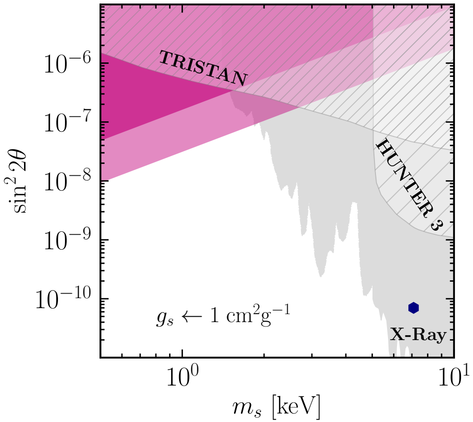
$$\mathcal{L}^{\phi} = g_s \phi \nu_s \nu_s$$

$$\sigma(E_\nu) = \frac{g_s^4}{4\pi} \frac{s}{(s - m_\phi^2)^2 + m_\phi^4 \Gamma_\phi^2} \approx \frac{\pi g_s^2}{m_\phi^2} E_\nu \delta(E_R - E_\nu), \text{ where } E_R = m_\phi^2 / 2m_s$$

- sterile component in the DSNB ν_i interacts with the mostly sterile relic background of N_i

bigger parameter space for keV serile neutrino dark matter with self-interactions:
Maria D. Astros and S. Vogl (2023), T. Bringmann et al. (2022)



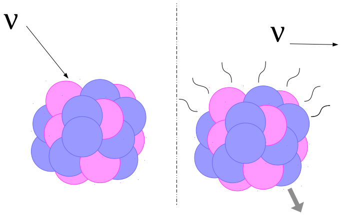


- Sterile neutrino self-interactions may result in features in DSNB
- Overalap with the TRISTAN experiment paramater space
- Reduction of the astrophysical uncertainties helps but not by a lot

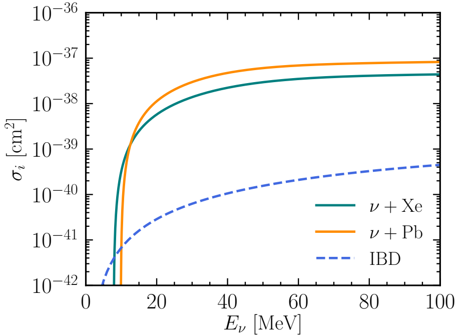
Balantekin, Fuller, Ray, **AMS** (2023), (PRD)

Can we detect the non-electron flavor DSNB?

Maybe: Coherent elastic neutrino-nucleus scatterings (CEνNS)



$$\nu + T(A,Z) \to \nu + T(A,Z)$$



Cross section

$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q),\ \ Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

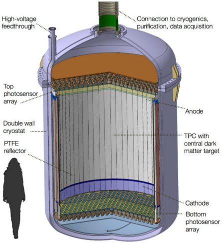
- coherently enhanced by the square of the neutron number
- flavor insensitive
- coherent up to ~ 50 MeV

AMS, Beacom, Tamborra (2022), (PRD)

Cross section:
Theory: Freedman (1974),
Measured: COHERENT (2017)

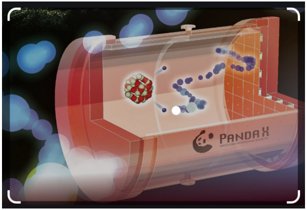
Current and future CEνNS detectors

XENONnT, DARWIN



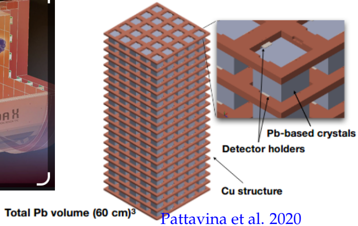
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

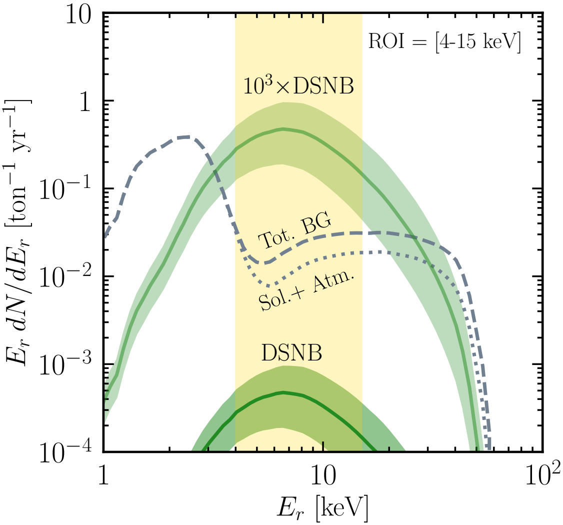
thresholds: $\mathcal{O}(1)$ keV

efficiency: $\sim$ 80-100%

Scattering rate

$$\frac{dR_{\nu N}}{dE_r dt} = N_T \, \epsilon(E_r) \int dE_\nu \, \frac{d\sigma_{\nu N}}{dE_r} \, \psi(E_\nu, t) \, \Theta(E_r^{\max} - E_r), \quad E_r^{\max} = \frac{2E_\nu^2}{m_T + 2E_\nu}$$

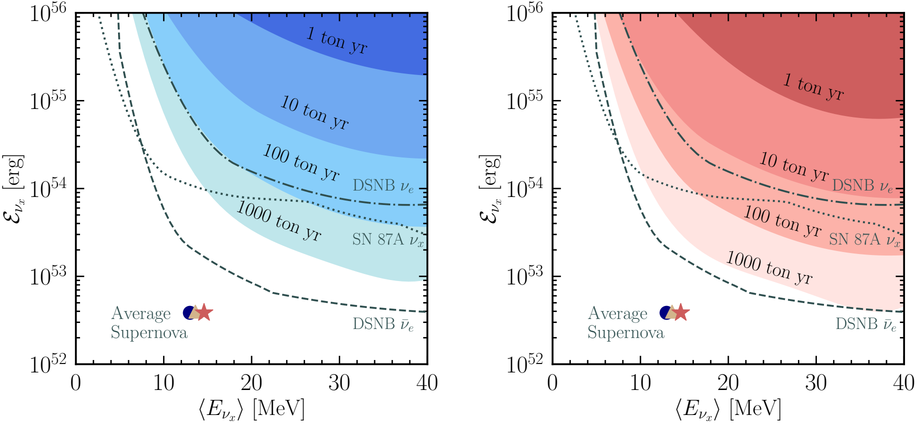
Can we improve the limits on the x-flavor DSNB? Yes



- Potential for an imporevement by $\gtrsim 1-2$ orders of magnitude

AMS, Beacom, Tamborra (2022), (PRD)

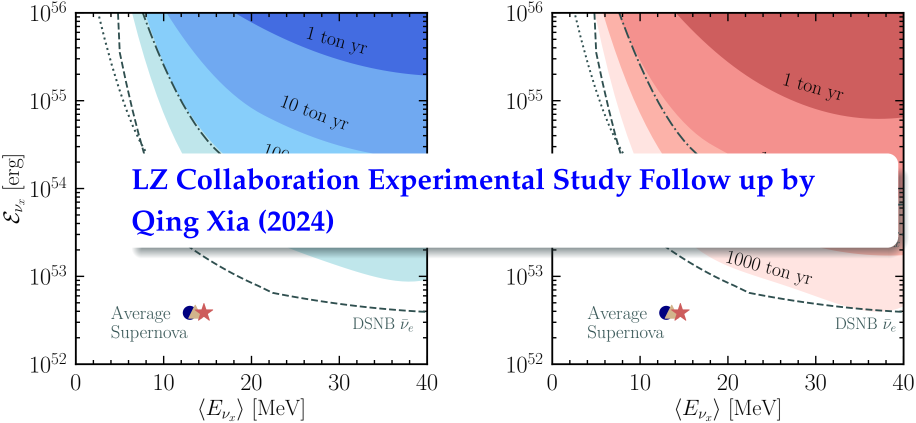
Sensitivity bounds on the x-flavor DSNB



- Simple DSNB: all supernovae emit the same Fermi-Dirac ν_x spectrum
- Potential handle on the normalization and mean energy of the SN ν_x
- 1000 ton yr: limits comparable with current SK limit on $\bar{\nu}_e$ DSNB

AMS, Beacom, Tamborra (2022), (PRD)

Sensitivity bounds on the x-flavor DSNB



LZ Collaboration Experimental Study Follow up by Qing Xia (2024)

- Simple DSNB: all supernovae emit the same Fermi-Dirac ν_x spectrum
- Potential handle on the normalization and mean energy of the SN ν_x
- 1000 ton yr: limits comparable with current SK limit on $\bar{\nu}_e$ DSNB

AMS, Beacom, Tamborra (2022), (PRD)

Conclusions

Core-collapse supernovae

- can serve as powerful testing grounds in constraining standard and new physics
- reliable limits, only when the sources are accurately modeled

Detection of astrophysical neutrino fluxes

- brings us closer to fully understanding the physics inside the sources
- help us to probe potential new physics scenarios

Exciting times ahead

Thank you for the attention!

Backup

Modeling secret neutrino interactions in DSNB

Balantekin, Fuller, Ray, **AMS** (2023)

Modified DSNB flux

$$\phi_\alpha(E_\nu) \simeq \sum_{i=1}^{3} |U_{\alpha i}|^2 \int_0^{z_{\rm max}} dz \, \frac{P_i(E_\nu, z)}{H(z)} \times \, R_{\rm SN}(z) \, F_{\rm SN}^i \left(E_\nu(1+z)\right)$$

Probability of interaction

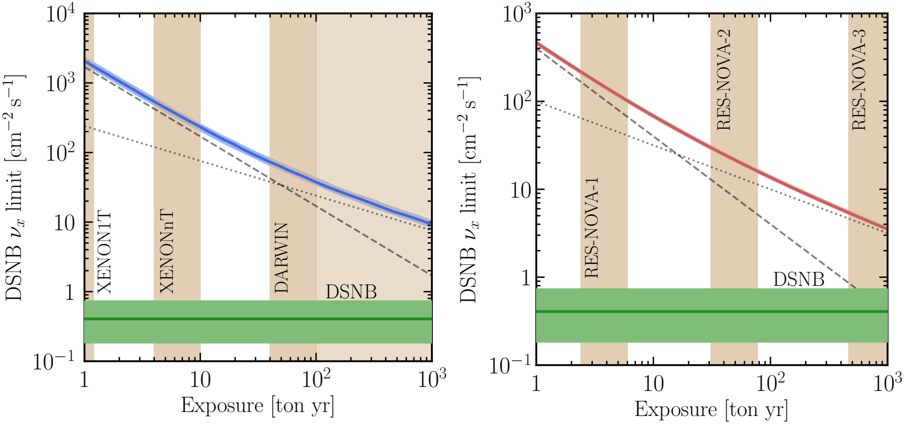
$$P_i(E_\nu, z) = e^{-\tau_i(E_\nu, z)}$$

$$\tau_i(E_\nu, z) \simeq \tau_R \Theta(z - z_R) = \frac{\Gamma_R(z_R)}{(1+z_R)H(z_R)} \Theta(z - z_R)$$

where $z_R = E_R/E_\nu - 1$,
interaction rate $\Gamma_R(z_R) \simeq |U_{si}|^2 n_{\nu_s}(z_R)\sigma_R$,
and sterile neutrino number density $n_{\nu_s}(z_R) = n_{\nu_s}(1+z_R)^3$

smilar studies for active neutrino self-interactions and eV-mass sterile neutrinos:
Goldberg et al. (2005), Baker et al. (2007), Farzan, Palomares-Ruiz (2014), Reno et al. (2018), Creque-Sarbinowski et al. (2021)

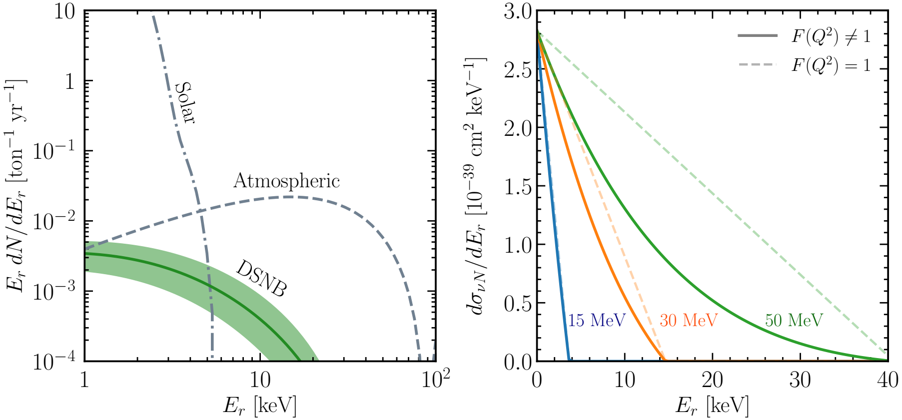
Sensitivity bounds on the normalization of the x-flavor DSNB



- XENON1T, PandaX-4T: limits comparable to the SK ν_x DSNB limit
- Constant energy window: limits can improve $\mathcal{O}(10\%)$ for wider windows at small exposures and narrower windows at large exposures

AMS, Beacom, Tamborra (2022)

Event rate in the xenon-based detector



- The potential energy window displayed by the bare fluxes disapears
- Reason: Low energy recolis are most probable for all neutrino energies
- Detection of the x-flavor DSNB seems out of reach, BUT...

AMS, Beacom, Tamborra (2022)

Do Neutrinos Have Self-Interactions?

IL NUOVO CIMENTO Vol. XXXIII, N. 5 1° Settembre 1964

Do Neutrinos Interact between Themselves?

Z. Bialynicka-Birula
Institute of Physics, Polish Academy of Sciences - Warsaw

(ricevuto il 26 Giugno 1964)

1. – Introduction.

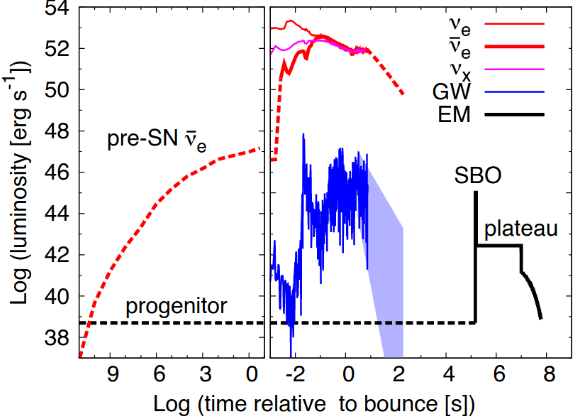
The neutrino is the only elementary particle, which, according to our present knowledge, does not take part in other than weak and gravitational interactions. Its role in nature is not yet fully understood and its interaction properties are only partially known.

The purpose of this note is to answer the following question: Do the present experimental data allow for the existence of interactions between neutrinos much stronger than their weak interactions? The answer to this question is positive. It turns out that such interactions even if they were 10^6 times stronger than weak interactions could not be detected with the present experimental accuracy.

Zofia Białynicka-Birula (1964)

Core-Collapse Supernova Light Curve

Nakamura et al. (2016)



Static, Homogenous and Isotropic Boltzmann Equation

Boltzmann Equation

$$\frac{df_\nu}{dt} = (1 - f_\nu) j_\nu - f_\nu \chi_\nu \ ,$$

Electron fraction evolution - weak rates

$$e^- + p \leftrightharpoons \nu_e + n$$

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

$$\frac{dY_e}{dt} = R_{\nu_e} - R_{\bar{\nu}_e} - R_{e^-} + R_{e^+} \ ,$$

Temperature and chemical potential evolution for leptons

$$\frac{dT_i}{dt} = \left(\frac{\partial \rho_i}{\partial \mu_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial \mu_i} \frac{d\rho_i}{dt} \right) / \left(\frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i} - \frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial T_i} \right) \ ,$$

$$\frac{d\mu_i}{dt} = \left(\frac{\partial \rho_i}{\partial T_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial T_i} \frac{d\rho_i}{dt} \right) / \left(\frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial T_i} - \frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i} \right) \ .$$

Lepton number violating neutrino self-interactions

Motivation - to be taken with a grain of salt:

- lepton number conservation - accidental symetry
- potential cosmological hints

  Barenboim et al. (2019), Song, Gonzalez-Garcia, Salvado (2018), ..

- strong impact on core-collapse supernova

  Kolb et al. (1982), Fuller et al. (1988), Farzan et al. (2018), **AMS**, Tamborra (2020), ...

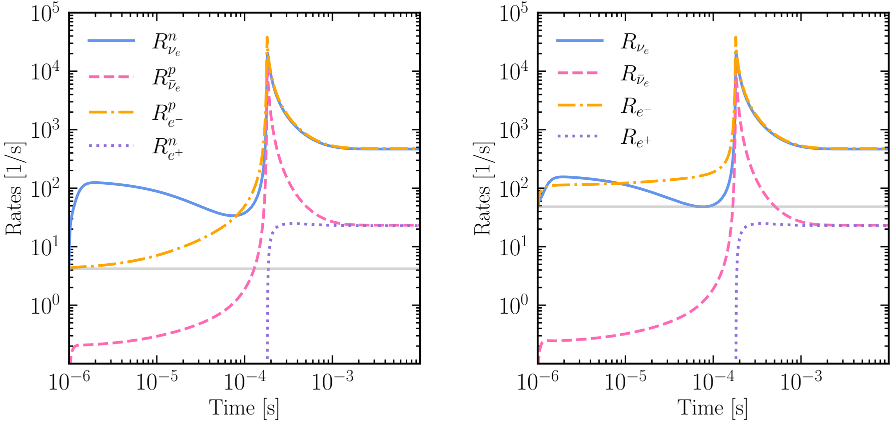
New Interaction Lagrangian

$$\mathcal{L}^{\phi} = g_{\phi,\alpha\beta}\,\phi\,\overline{\nu_{L,\alpha}}\,\nu^{c}_{L,\beta}$$

Probability of the New Interaction

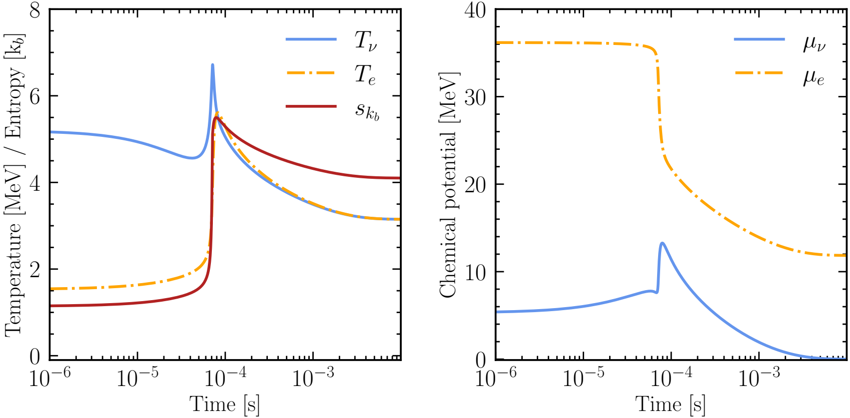
$$\sigma_{\nu\mathrm{SI}} \approx \frac{G^2_{\nu\mathrm{SI}}}{8\pi} E^1_\nu E^2_\nu (1-\cos\theta)$$

Weak reaction rates



- initial increase in $\nu_e + n$, $\nu_e + A$ and $e^- + A$
- enhanced ν_e and e^- captures heat up the matter
- similar results for all flavors equilibration

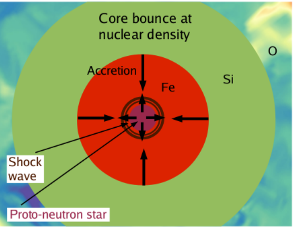
Evolution of Thermodynamical Quantities

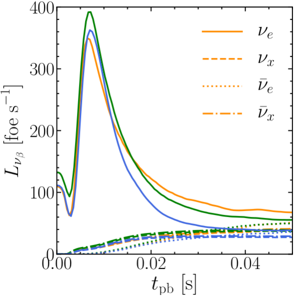


- the same qualitative results for all six flavor equilibration

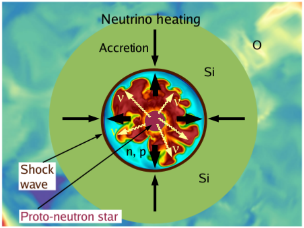
Different Phases of Supernova Explosion

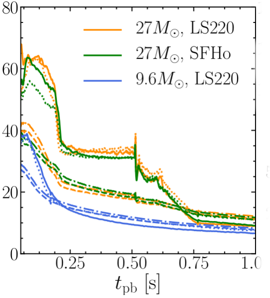
- Infall phase,
  ν_e burst ~ 40 ms



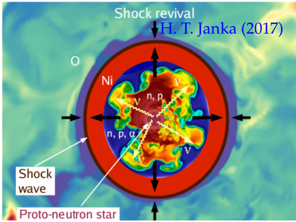


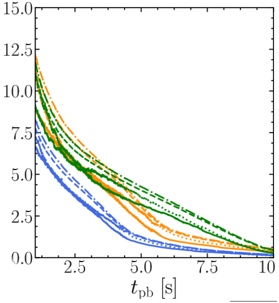
- Accretion phase,
  ~ 100 ms



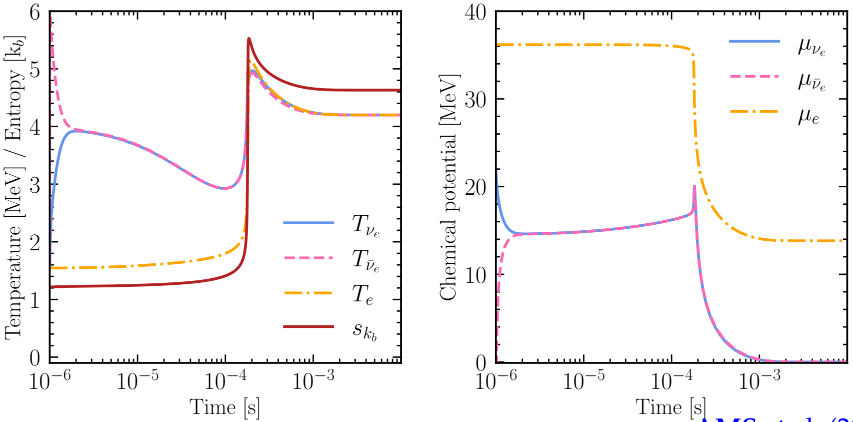


- Cooling phase,
  ~ 10 s





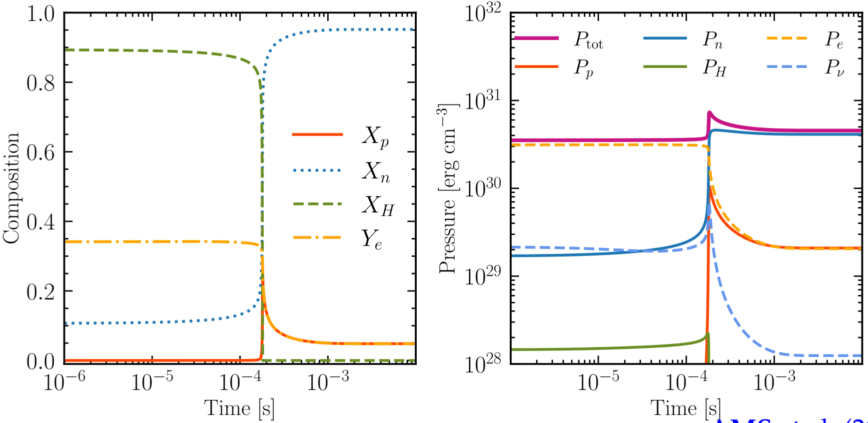
Evolution of Thermodynamical Quantities



AMS et al. (2024)

- new interactions quickly equilbrate ν_e and $\bar{\nu}_e$ seas
- enhanced ν_e and e^- captures heat up the matter
- similar results for all flavors equilibration

Composition and Pressure Support of the Core



AMS et al. (2024)

- s_{k_b} - entropy generation shifts composition towards no heavy nuclei
  $X_H \propto s_{k_\mathrm{B}}^{1-\langle A\rangle} n_p^Z n_n^N \exp(E_b/T_e)$
- enhanced deleptonization changes the pressure support of the core

Partial Derivatives for the Fermi-Dirac distributions

The partial derivatives for the Fermi-Dirac distributions are given by EscuderoAbenza (2020)

$$\frac{\partial n}{\partial T} = \frac{g}{2\pi^2} \int_m^\infty dE\, E \sqrt{E^2 - m^2}\, \frac{(E-\mu)}{4T^2} \cosh^{-2}\left(\frac{E-\mu}{2T}\right)\,, \quad (1a)$$

$$\frac{\partial \rho}{\partial T} = \frac{g}{2\pi^2} \int_m^\infty dE\, E^2 \sqrt{E^2 - m^2}\, \frac{(E-\mu)}{4T^2} \cosh^{-2}\left(\frac{E-\mu}{2T}\right)\,, \quad (1b)$$

$$\frac{\partial n}{\partial \mu} = \frac{g}{2\pi^2} \int_m^\infty dE\, E \sqrt{E^2 - m^2} \left[2T \cosh\left(\frac{E-\mu}{T}\right) + 2T\right]^{-1}\,, \quad (1c)$$

$$\frac{\partial \rho}{\partial \mu} = \frac{g}{2\pi^2} \int_m^\infty dE\, E^2 \sqrt{E^2 - m^2} \left[2T \cosh\left(\frac{E-\mu}{T}\right) + 2T\right]^{-1} \quad (1d)$$

Astrophysical neutrino fluxes

Supernova neutrinos

• large flux for Galactic SN

• transient event

Solar neutrinos

$^8\text{B} \to {}^8\text{Be}^* + e^+ + \nu_e$

$^3\text{He} + p \to {}^4\text{He} + e^+ + \nu_e$

• neutrino energies up to ~15 MeV

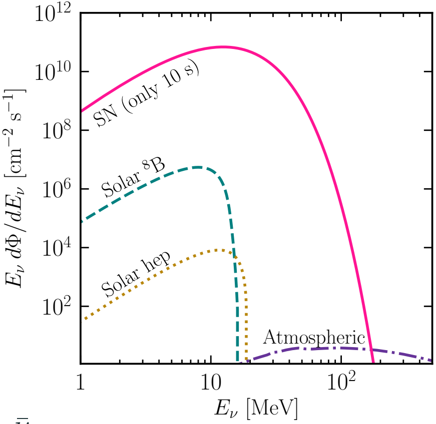
Atmospheric neutrinos

$\pi^+ \to \mu^+ + \nu_\mu$ and $\pi^- \to \mu^- + \bar{\nu}_\mu$

$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ and $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

• the highest neutrino energies among the considered sources

• small normalization



fluxes: E. Vitagliano et al. (2019), M. Honda et al. (2011), J. L. Newstead et al. (2020)

Astrophysical uncertainties affecting the DSNB

- Neutrino Flux from an "Average Supernova"

  Lunardini (2009), Horiuchi et al. (2018), Kresse et al. (2018), ...

- Cosmological Supernovae Rate

  Beacom (2010), Horiuchi et al. (2011), Ando et al. (2023), Ekanger et al. (2024)...

- Initial Mass Function

  Ziegler, Edwards, **AMS**, Tamborra, Horiuchi, Ando, Freese (2022)

- Fraction of Black-Hole-Forming Progenitors

  Lunardini (2009), Lien et al. (2010), Keehn & Lunardini (2012), Priya & Lunardini (2017),

  Møller, **AMS**, Tamborra, Denton (2018), Horiuchi et al. (2018), Kresse et al. (2018), ...

- Binary Interactions

  Horiuchi, Kinugawa, Takiwaki, Takahashi (2021)

  Sanduleak and Betelgeuse in binary systems? Morris & Podsiadlowski (2007), (2009), Goldberg et al (2024), MacLeod et al (2024)

Non exhaustive list of references