



Supernova Neutrinos Uncover Neutrino Properties and Decode New Physics

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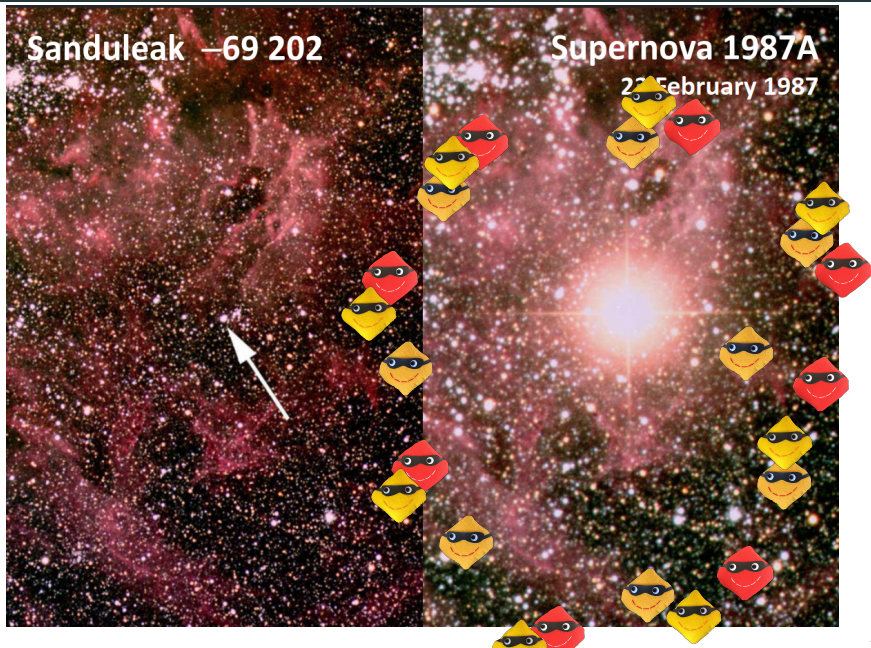
PPC 2026, September 2, 2026



Why is studying astrophysical neutrinos crucial?



Neutrinos from SN 1987A



Hints about nature of SN 1987A from light



Hubble (2017)



JWST (2023)

- Neutron star remnant

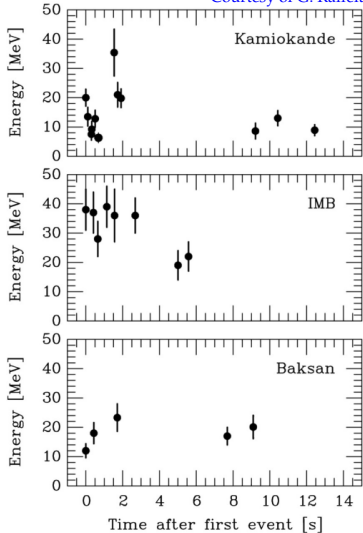
Fransson et al. (2024)

- 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

Benefits to the field of neutrino physics and astrophysics

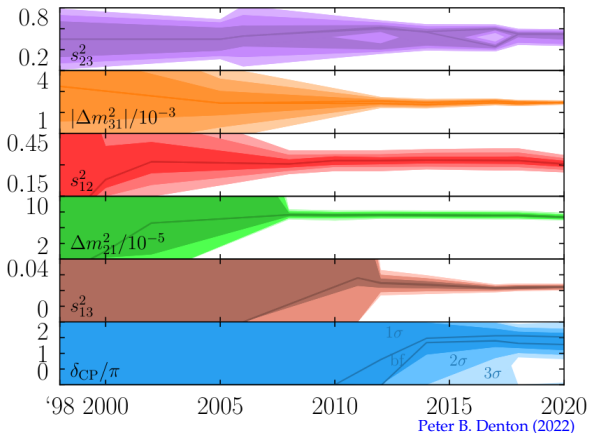
Towards Precise Neutrino Properties Measurements

We know now:

- large mixing angles
- non-zero masses

Remaining questions

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



Fermions

Quarks	u _{up}	c _{charm}	t _{top}	γ _{photon}	H _{Higgs boson}
	d _{down}	s _{strange}	b _{bottom}	g _{gluon}	
	ν _e _{electron neutrino}	ν _μ _{muon neutrino}	ν _τ _{tau neutrino}	Z _{Z boson}	
Leptons	e _{electron}	μ _{muon}	τ _{tau}	W _{W boson}	

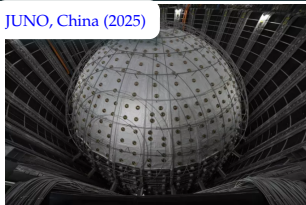
Force carriers

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

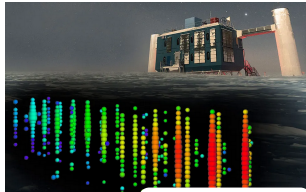
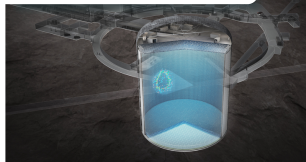
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} \text{beam, atmospheric} & \text{beam, reactor} & \text{solar, reactor} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

JUNO, China (2025)

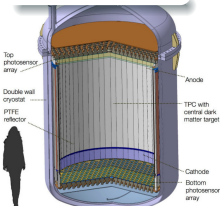


Hyper-Kamiokande, Japan (2027)



IceCube, South Pole

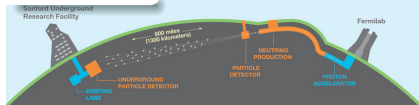
XLZD, DARWIN (20XX)



Rubin Observatory, Chile (2025)



DUNE, USA (2030)



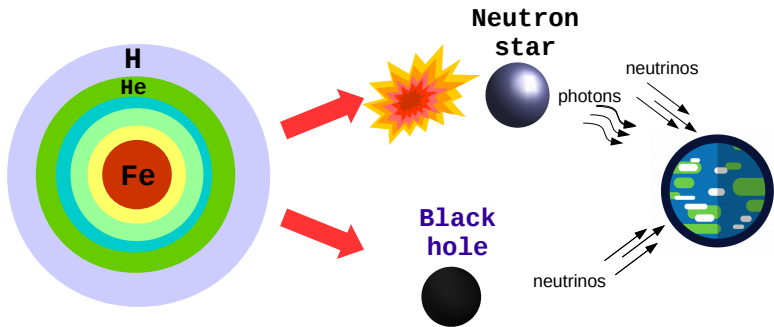
- Many new experiments coming online soon
- variety of approaches → superb sensitivity

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

Why are neutrinos important for a core-collapse supernova?

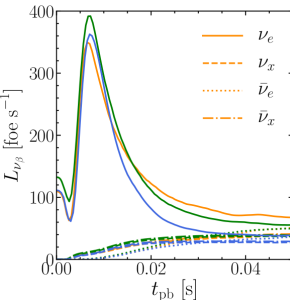
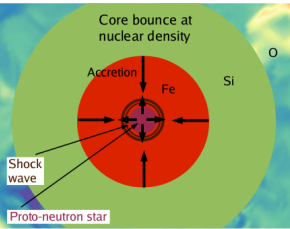
Neutrinos:

- $\sim 10^{58}$ 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

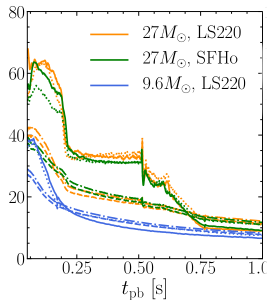
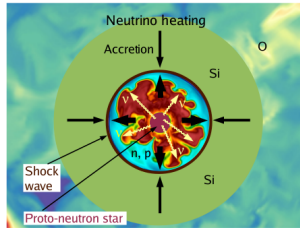


Different Phases of Supernova Explosion

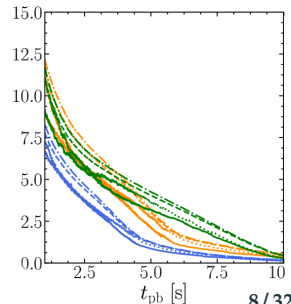
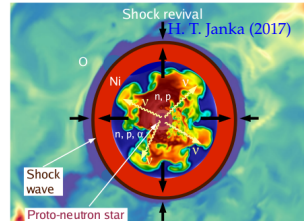
- Infall phase,
 ν_e burst ~ 40 ms



- Accretion phase,
 ~ 100 ms



- Cooling phase,
 ~ 10 s



**How astrophysical feedback affects
the bounds on new physics?**

LNV neutrino self-interactions in supernova explosion?

In collaboration with P. Cheong, G. Fuller, J. Froustey,
L. Graf, K. Kherer, S. Shalgar, O. Scholer

PRL 134 (2025) 24, 24

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.

Lepton number violating neutrino self-interactions

Motivation - to be taken with a grain of salt:

- lepton number conservation - accidental symmetry
- 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), ...

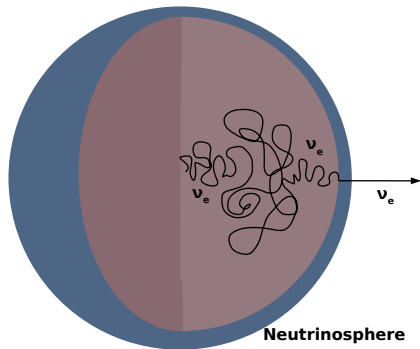
New Interaction Lagrangian

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

Probability of the New Interaction

$$\sigma_{\nu\text{SI}} \approx \frac{G_{\nu\text{SI}}^2}{8\pi} E_\nu^1 E_\nu^2 (1 - \cos \theta)$$

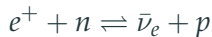
Neutrino Trapping and β -equilibrium



Neutrino trapping $\text{CE}\nu\text{NS}$



β -equilibrium



Implementation:

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

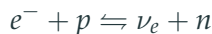
$$\nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau, \quad \nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_x, \bar{\nu}_x, \quad \nu_e \rightleftharpoons \nu_e, \bar{\nu}_e$$

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



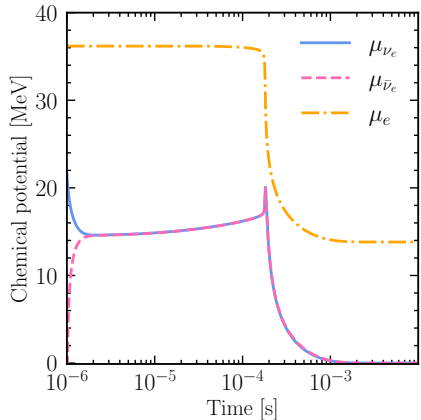
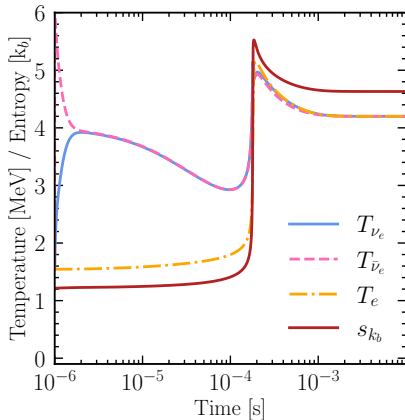
$$\frac{dY_e}{dt} = R_{\nu_e} - R_{\bar{\nu}_e} - R_{e^-} + R_{e^+} , \quad e^+ + n \rightleftharpoons \bar{\nu}_e + p$$

Temperature and chemical potential evolution for leptons

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

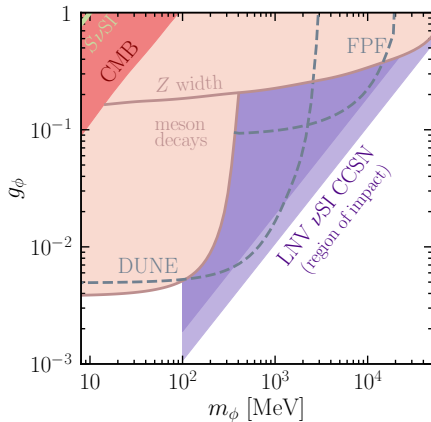
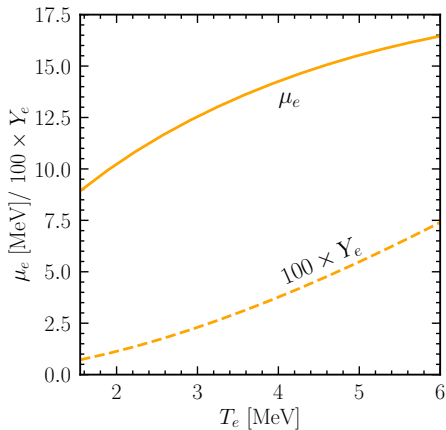
$$\frac{d\mu_i}{dt} = \left(\frac{\partial \rho_i}{\partial T_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial T_i} \frac{d\rho_i}{dt} \right) / \left(\frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial T_i} - \frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i} \right)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

Evolution of Thermodynamical Quantities



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

New β -equilibrium with LNV ν SI



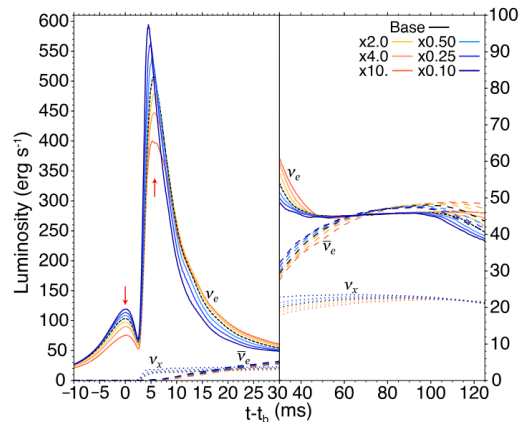
- regardless of the final T_e the new equilibrium has a very low Y_e
 $\mu_e = \delta m_{np} - T_e \ln \left(\frac{Y_e}{1-Y_e} \right)$, with $Y_e = \frac{1}{\pi^2 \rho} \int_0^\infty dp_e p_e^2 f_e(E_e, T_e, \mu_e)$
- complementarity with future accelerator-based experiments
- multi-flavor neutrino burst? 1st order phase transition [2510.23713?](#)

Can we detect non-standard neutrino-quark interactions in supernova neutrino signal?

In collaboration with A. Beatty and V. Takhistov

Phys.Rev.D Lett. 114 (2026) 2, L021301

Pre-neutronization burst



Neutrino trapping

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

β-equilibrium

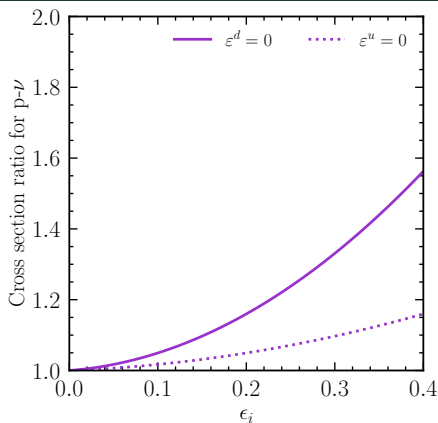
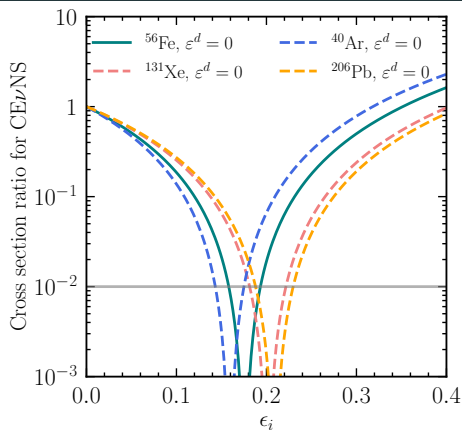
$$e^- + p \rightleftharpoons \nu_e + n$$

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

Sullivan et al. (2016)

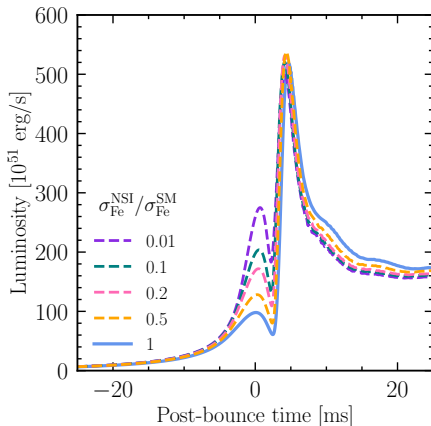
- ~40 supernova-ready stars within 1 kpc
- best-known Betelgeuse at ~ 0.2 kpc

NSI interactions: Cross section changes



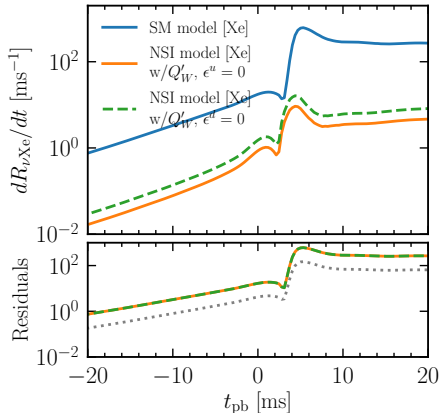
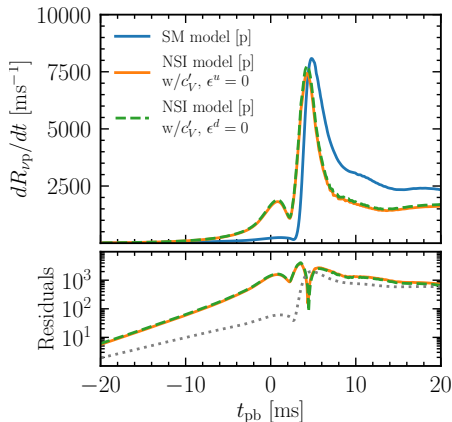
- Extreme changes for $\text{CE}\nu\text{NS}$
- Moderate changes for ν -p scattering

Changes in the neutrino signal: GR1D simulations



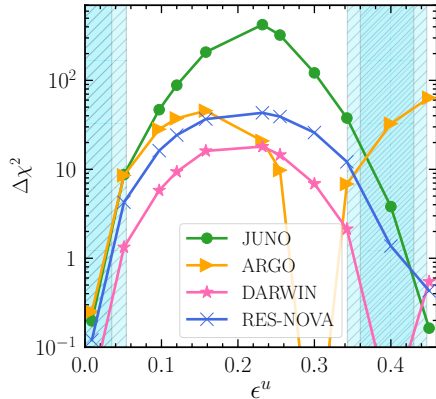
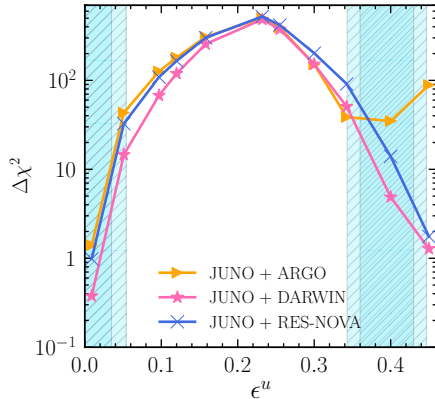
- Significant change in the luminosity pre-bounce
- Pre-bounce - heavy nuclei in the core
- Post-bounce - nucleons in the core

Rates in JUNO and DM detectors for the Betelgeuse



- JUNO - event rate changed significantly for the infall signal
- DARWIN - rate changed significantly always
- approximately opposite detector effects

Sensitivity limits on NSI from Supernova Neutrinos



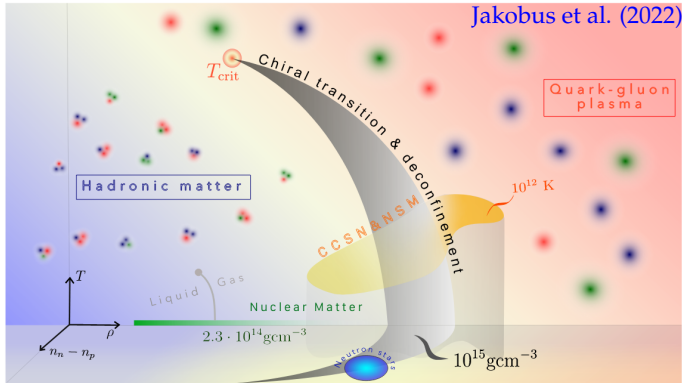
- Combined observation in two detectors $\rightarrow$ better limits
- Driven by the opposite effects in DM and ν detectors
- Sensitivity comparable to the CE ν NS terrestrial experiments

Can we detect neutrinos from QCD phase transition in supernova?

In collaboration with T. Pitik, D. Heimsoth, B. Balantekin

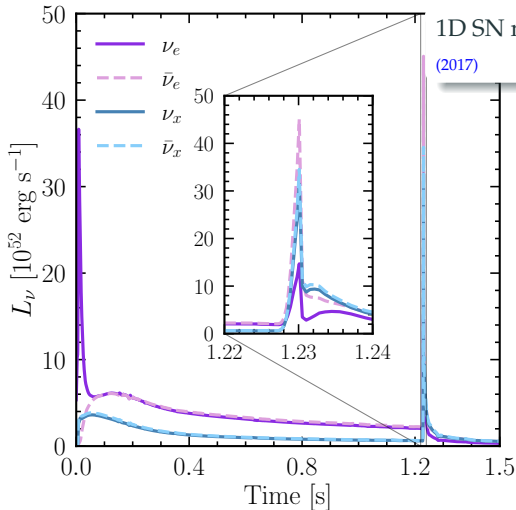
Phys.Rev.D 106 (2022) 10, 103007

QCD phase diagram



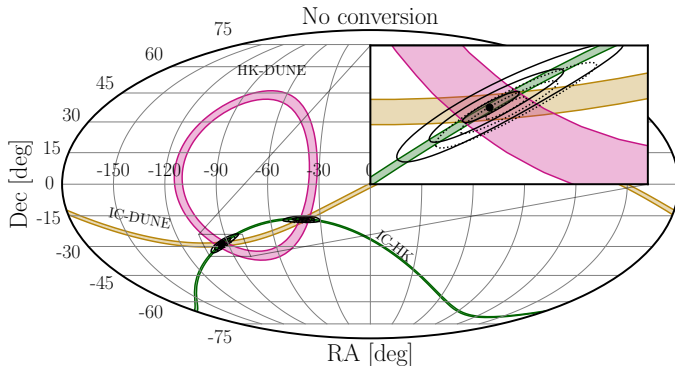
- Does the CCSN contain non-leptonic degrees of freedom other than neutrons and protons?
- How to identify the presence of quark matter in astrophysical objects?

Neutrino Emission properties from the QHPT CCSN



- second sharp neutrino burts dominated by $\bar{\nu}_e$
- non-exploding models can explode

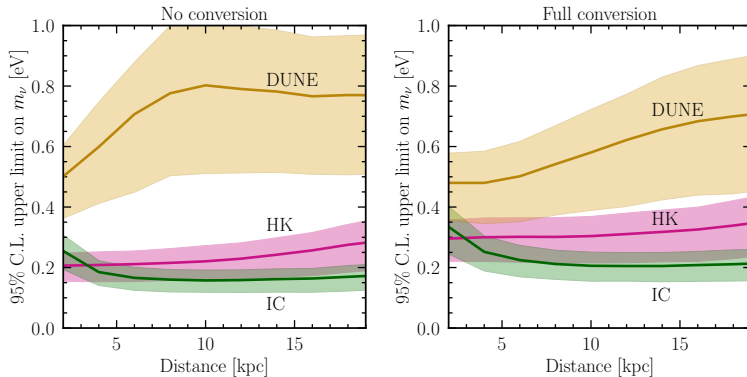
Determination of the supernova localization



- improvement by 4.5-10 times compared to neutronization burst
- comparable results for black hole forming supernovae
- not far off from elastic scattering on electrons

Sensitivity to the absolute neutrino mass

$$\Delta t \approx 5.15 \left(\frac{D}{10 \text{ kpc}} \right) \left(\frac{m_\nu}{1 \text{ eV}} \right)^2 \left(\frac{10 \text{ MeV}}{E_\nu} \right)^2 \text{ ms}$$



- up to $\sim 10\times$ improvement compared to neutronization burst
- more stringent limits than from the laboratory experiments (0.4 eV)

Diffuse supernova neutrino background

Why focus only on a single rare event?

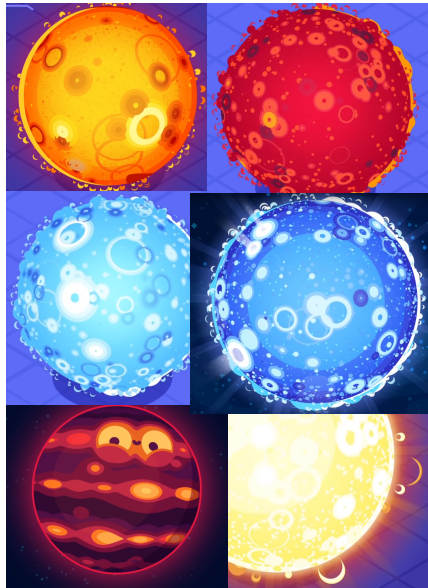


Single galactic SN event

- rare event
- precise information about one star

Multiple SN events (larger distances)

- accumulation of events
- will detect in coming years



Diffuse supernova neutrino background

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

cosmological supernovae rate (points to $R_{\text{SN}}(z, M)$)

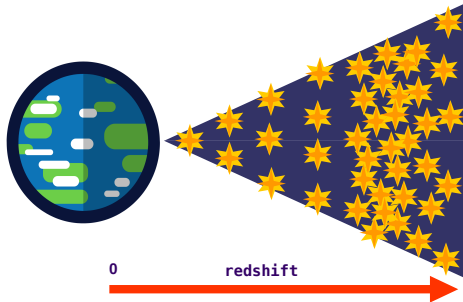
fraction of black-hole-forming progenitors (points to $f_{\text{BH-SN}}$)

fraction of neutron-star-forming progenitors (points to $f_{\text{CC-SN}}$)

neutrino flux from a single star (points to $F_{\nu_\beta, \text{CC-SN}}(E', M)$ and $F_{\nu_\beta, \text{BH-SN}}(E', M)$)

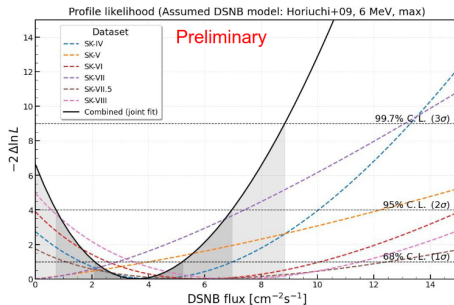
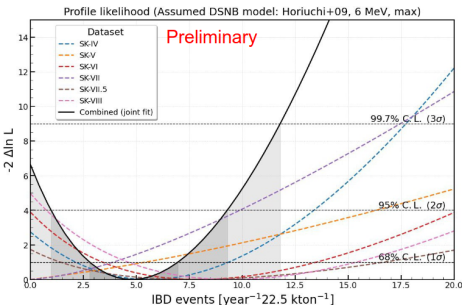
The DSNB is sensitive to:

- $R_{\text{SN}}, f_{\text{BH-SN}}$
- 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), ...

Profile likelihood curves



Joint fit significance = 2.6σ

99.5% CL

Under the null DSNB hypothesis, the one-sided p-value is 5×10^{-3} .

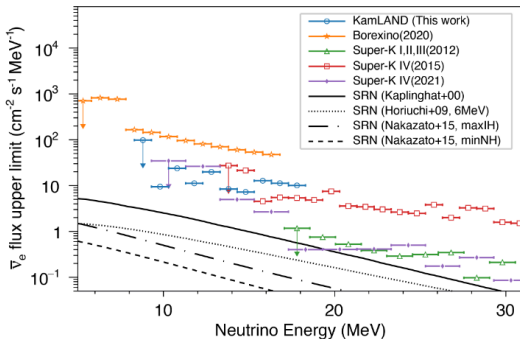
(Note that the per-phase curves are from the individual phase fits.)

35

Slide credit: Hiroyuki Sekiya talk at Neutrino 2026

Diffuse supernova neutrino background: current limits

SK collab. (2021)



DSNB limits:

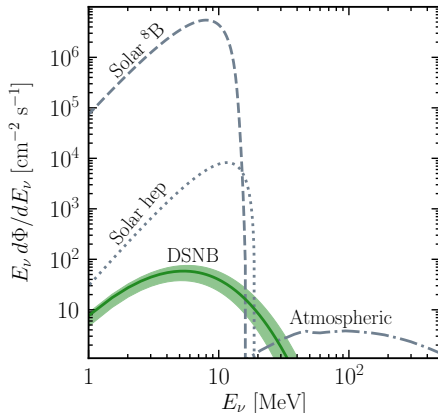
- $\bar{\nu}_e \approx$ SK-Gd hint of 2.6σ
soon detected by SK (Gd) [Beacom, Vagins \(2004\)](#) and [JUNO JUNO collab. \(2021\)](#)
- $\nu_e \approx 19 \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu \in [22.9, 36.9 \text{ MeV}]$ [SNO collab. \(2020\)](#)
possibly detectable by DUNE [Møller, AMS, et al. \(2018\)](#), [Zhu et al. \(2019\)](#)
- $\nu_x ??$

Towards diffuse supernova neutrino background in all flavors

In collaboration with J. Beacom, I. Tamborra

Phys.Rev.D 105 (2022) 4, 043008

Can we detect the x -flavor DSNB? Maybe

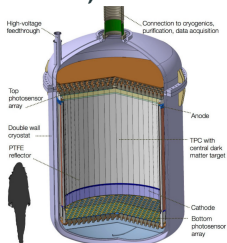


DSNB modeling:
Møller, AMS, et al.
(2018)

- Flavor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750 \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu > 19.3$ MeV [Lunardini, Peres \(2008\)](#)

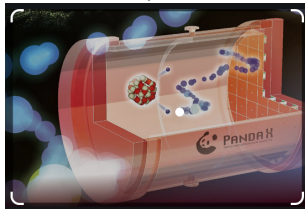
Current and future CE ν NS detectors

XENONnT, DARWIN



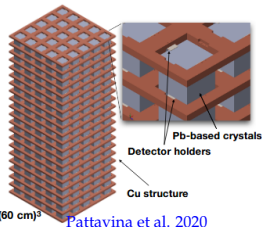
Aalbers et al. 2016

PandaX-4T, PandaX-xT



Menget et al. 2021

RES-NOVA



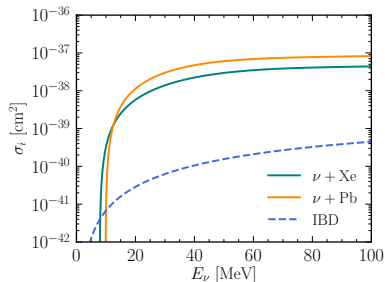
Pattavina et al. 2020

fiducial volumes: $\mathcal{O}(10)$ ton

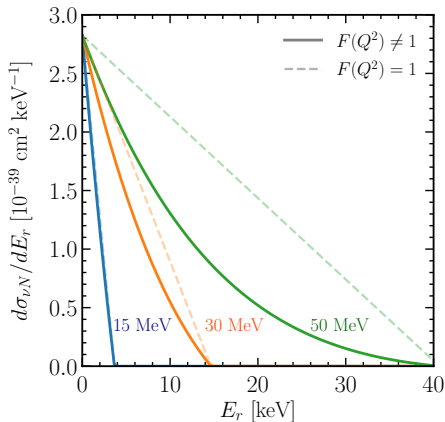
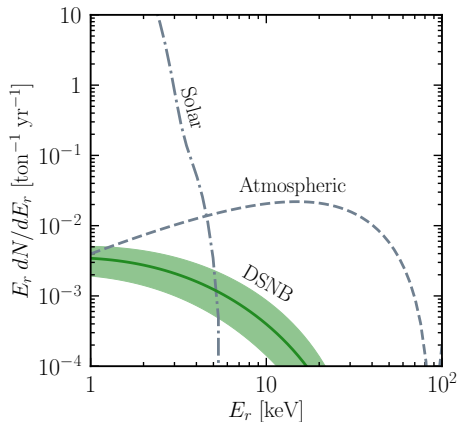
target materials: Xe, Pb

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

efficiency: ~ 80 -100%

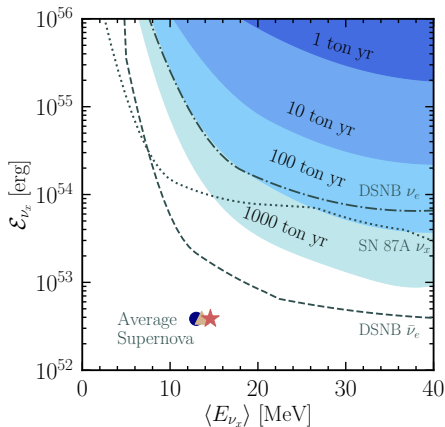
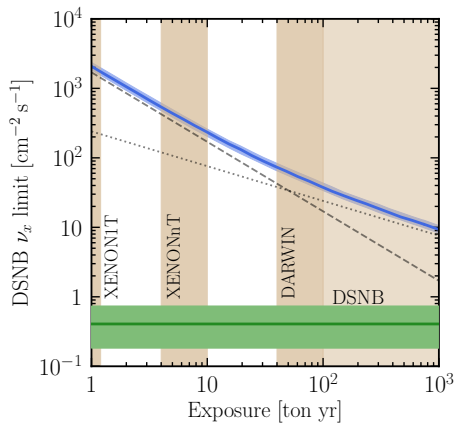


Event rate in the xenon-based detector



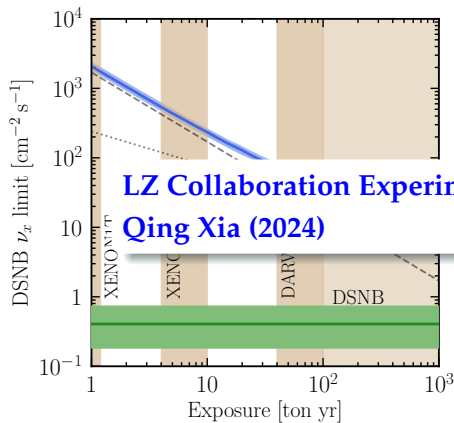
- The potential energy window displayed by the bare fluxes disappears
- Reason: Low energy recoils are most probable for all neutrino energies
- Detection of the x -flavor DSNB seems out of reach, BUT...

Can we improve the χ -flavor DSNB limits? Yes!

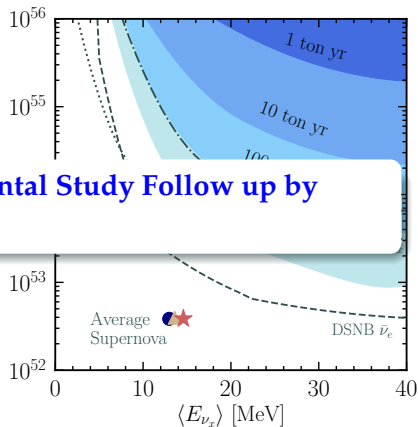


- XENON1T, PandaX-4T: limits comparable to the SK ν_x DSNB limit
- Potential handle on the normalization and mean energy of the SN ν_x
- 1000 ton yr: limits comparable with current SK limit on $\bar{\nu}_e$ DSNB
- RES-NOVA prediction in backup slides

Can we improve the χ -flavor DSNB limits? Yes!



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



- XENON1T, PandaX-4T: limits comparable to the SK ν_x DSNB limit
- 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
- RES-NOVA prediction in backup slides

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

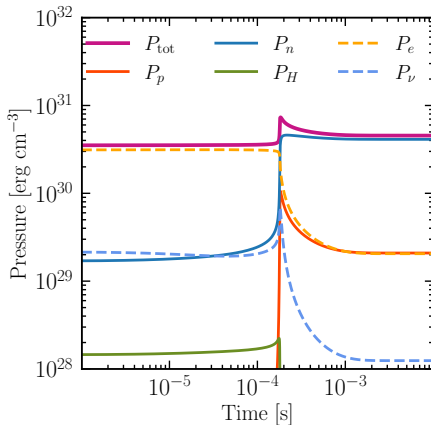
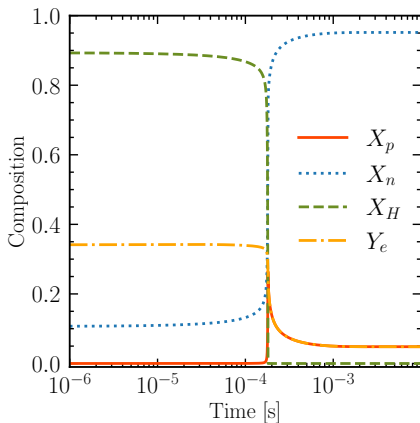
- brings us closer to fully understanding the physics inside the sources
- help us to probe potential new physics scenarios

Exciting times ahead

Thank you for the attention!

Backup

Composition and Pressure Support of the Core



- s_{k_b} - entropy generation shifts composition towards no heavy nuclei

$$X_H \propto s_{k_b}^{1-\langle A \rangle} n_p^Z n_n^N \exp(E_b/T_e)$$
- enhanced deleptonization changes the pressure support of the core

Fast LNV ν SI - Approximate Evolution

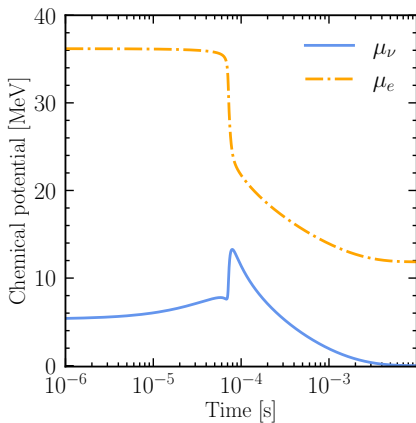
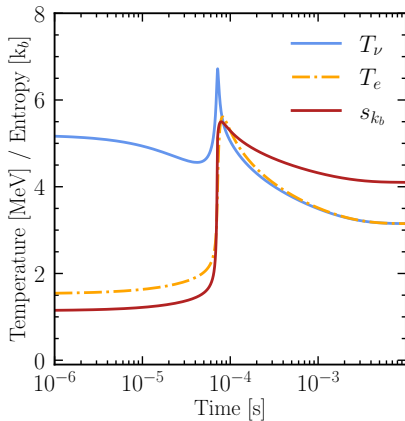
LNV ν SI timescale much faster than weak timescale $\rightarrow$
a single ν species evolution

$$\begin{aligned}\sum_{\alpha} \left(\frac{dn_{\nu\alpha}}{dt} + \frac{dn_{\bar{\nu}\alpha}}{dt} \right) &= \frac{\delta n_{\nu}}{\delta t} && \text{sum over charged-current} \\ \sum_{\alpha} \left(\frac{d\rho_{\nu\alpha}}{dt} + \frac{d\rho_{\bar{\nu}\alpha}}{dt} \right) &= \frac{\delta \rho_{\nu}}{\delta t} && \text{weak interactions}\end{aligned}$$

$$\frac{dT_{\nu}}{dt} = \frac{\frac{\partial \rho_{\nu}}{\partial \mu_{\nu}} \frac{\delta n_{\nu}}{\delta t} - \frac{\partial n_{\nu}}{\partial \mu_{\nu}} \frac{\delta \rho_{\nu}}{\delta t}}{2N_F \left(\frac{\partial n_{\nu}}{\partial T_{\nu}} \frac{\partial \rho_{\nu}}{\partial \mu_{\nu}} - \frac{\partial n_{\nu}}{\partial \mu_{\nu}} \frac{\partial \rho_{\nu}}{\partial T_{\nu}} \right)}$$

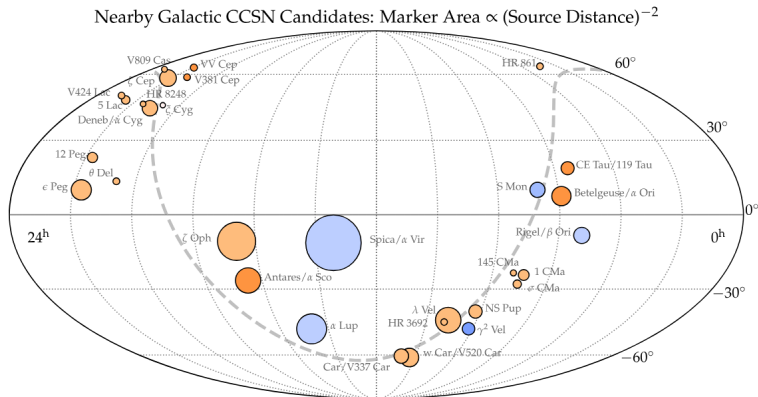
$$\frac{d\mu_{\nu}}{dt} = \frac{\frac{\partial \rho_{\nu}}{\partial T_{\nu}} \frac{\delta n_{\nu}}{\delta t} - \frac{\partial n_{\nu}}{\partial T_{\nu}} \frac{\delta \rho_{\nu}}{\delta t}}{2N_F \left(\frac{\partial n_{\nu}}{\partial \mu_{\nu}} \frac{\partial \rho_{\nu}}{\partial T_{\nu}} - \frac{\partial n_{\nu}}{\partial T_{\nu}} \frac{\partial \rho_{\nu}}{\partial \mu_{\nu}} \right)}$$

All flavors LNV ν SI



- new interactions quickly equilibrates all 6 neutrino seas
- temperature and entropy increase

Supernova-ready supergiant stars within ~ 1 kpc of Earth



- ~ 40 supernova-ready stars within 1 kpc
- best-known Betelgeuse at ~ 0.2 kpc

Non-standard neutrino-quark interactions

New Interaction Lagrangian

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\varepsilon_{\alpha\alpha}^{fV}(\bar{\nu}_{\alpha L}\gamma^\rho\nu_{\alpha L})(\bar{f}\gamma_\rho f)$$

$$\varepsilon^{u(d)} = \varepsilon_{ee}^{u(d)V} = \varepsilon_{\mu\mu}^{u(d)V} = \varepsilon_{\tau\tau}^{u(d)V}$$

New Cross Sections

1. Coherent Elastic Neutrino-Nucleus Scattering

$$\frac{d\sigma_{\nu X}}{dE_r} \approx \frac{G_F^2 m_X}{4\pi} Q_W^2 \left(1 - \frac{m_X E_r}{2E_\nu^2}\right) F^2(Q), \quad Q_W = [N - Z(1 - 4\sin^2(\theta_W))]$$

$$\text{with NSI } Q_W \rightarrow Q'_W = Q_W + Q_W^{\text{NSI}}$$

$$Q_W^{\text{NSI}} = -2[Z(2\varepsilon^u + \varepsilon^d) + N(\varepsilon^u + 2\varepsilon^d)]$$

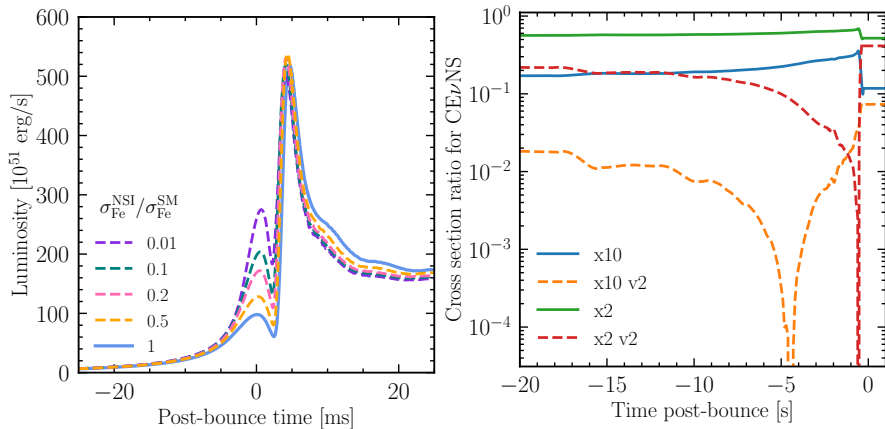
2. Elastic Neutrino-Proton Scattering

$$\frac{d\sigma_{\nu p}}{dE_p} \simeq \frac{G_F^2 m_p^2}{2\pi E_\nu^2} (BE_\nu^2 + C(E_\nu - E_p)^2 + Dm_p E_p)$$

$$B = (c_V + c_A)^2, C = (c_V - c_A)^2, D = (c_V^2 + c_A^2)$$

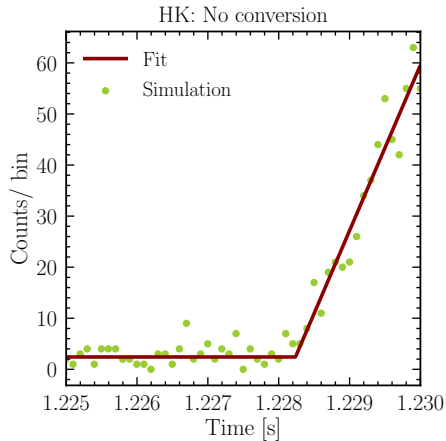
$$\text{with NSI } c_V \rightarrow c'_V = c_V + \varepsilon^p$$

Changes in the neutrino signal: GR1D simulations



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

Timing the Neutrino Signal



Detectors	No conversion	Full conversion
B_{ij} [ms]		
IC-HK	-0.32 ± 0.10	-0.32 ± 0.10
IC-DUNE	-0.11 ± 0.48	-0.27 ± 0.20
HK-DUNE	0.22 ± 0.50	0.05 ± 0.22
$\delta(\theta_{ij})$ (min, max) [deg]		
IC-HK	(0.30, 5.00)	(0.29, 4.90)
IC-DUNE	(1.00, 10.67)	(0.41, 6.90)
HK-DUNE	(2.27, 12.85)	(1.00, 8.54)
95% C.L. upper limit on m_ν [eV]		
IC	$0.16^{+0.03}_{-0.04}$	$0.21^{+0.05}_{-0.05}$
HK	$0.22^{+0.05}_{-0.06}$	$0.30^{+0.07}_{-0.09}$
DUNE	$0.80^{+0.21}_{-0.29}$	$0.58^{+0.14}_{-0.19}$

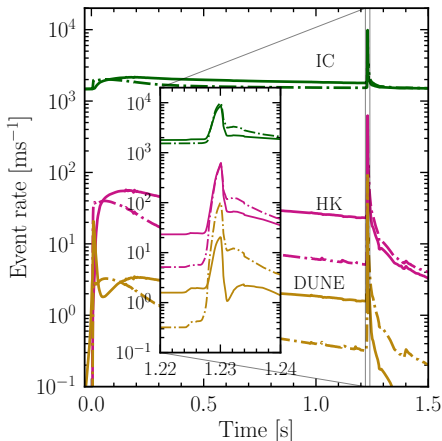
$$R_{\text{exp}} = \begin{cases} R_*, & \text{if } t < t_0 \\ R_* + a(t - t_0), & \text{otherwise} \end{cases},$$

$$\Delta t_{ij}^{\text{true}} = \frac{(\mathbf{r}_i - \mathbf{r}_j) \cdot \mathbf{n}}{c} = \frac{D_{ij} \cos \theta}{c}$$

$$\Delta t_{ij}^{\text{measured}} = \Delta t_{ij}^{\text{true}} + B_{ij}$$

Fit: Halzen and Raffelt (2009)

Neutrino Event Rates

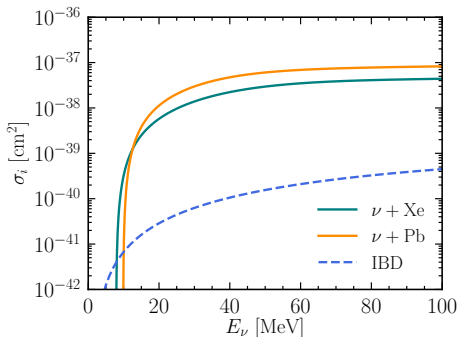
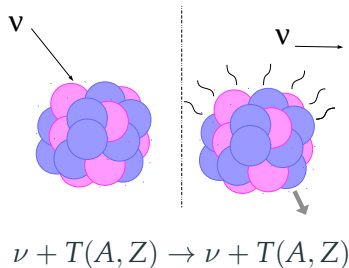


Impact of neutrino conversions

- Event rate in the antineutrino detectors comparable for both conversion scenarios
- Event rate in the neutrino detector larger for the full conversion case

$$R(t) = N_t \int_{E_{\nu}^{\min}}^{\infty} dE_{\nu} \int_{E_{\text{th}}}^{E_{\max}} dE \varepsilon \sigma_i(E, E_{\nu}) F_{\nu\beta}(E_{\nu}, t)$$

Maybe: Coherent elastic neutrino-nucleus scatterings (CE ν NS)



Cross section

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

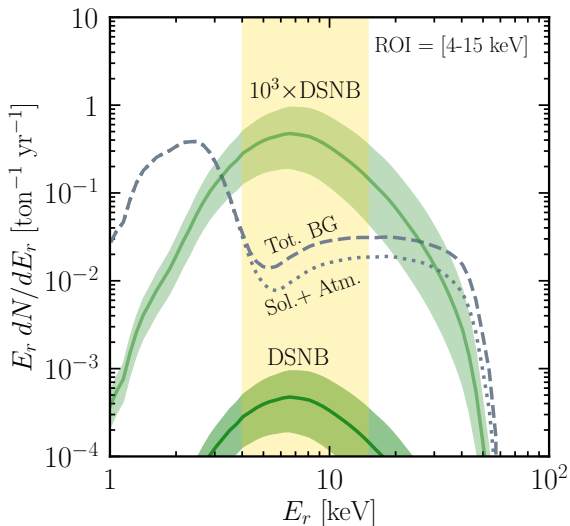
- coherently enhanced by the square of the neutron number
- flavor insensitive
- coherent up to ~ 50 MeV

Cross section:

Theory: [Freedman \(1974\)](#),

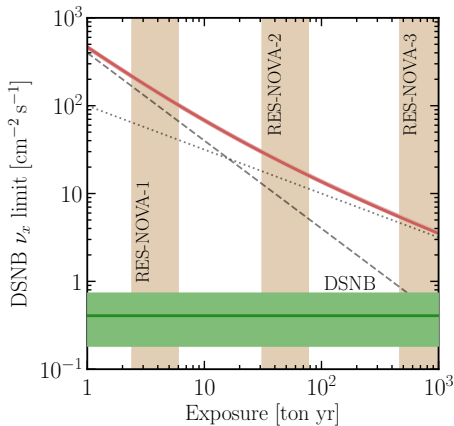
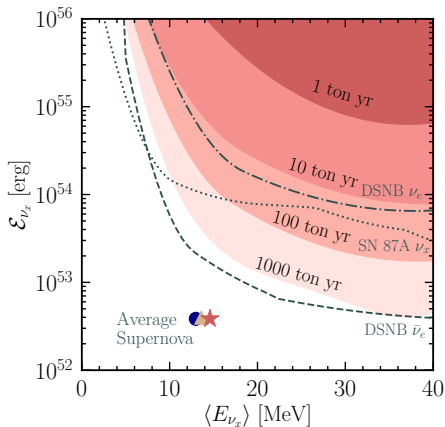
Measured: [COHERENT \(2017\)](#)

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



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

ES-NOVA: Sensitivity bounds on the x-flavor DSNB



- Simple DSNB: all supernovae emit the same Fermi-Dirac ν_x spectrum
- Constant energy window: limits can improve $\mathcal{O}(10\%)$ for wider window
small exposures and narrower windows at large exposures

Limits from SN1987A on ν_x

