

Supernova Neutrinos Uncover Neutrino Properties and Decode New Physics

Anna M. Suliga

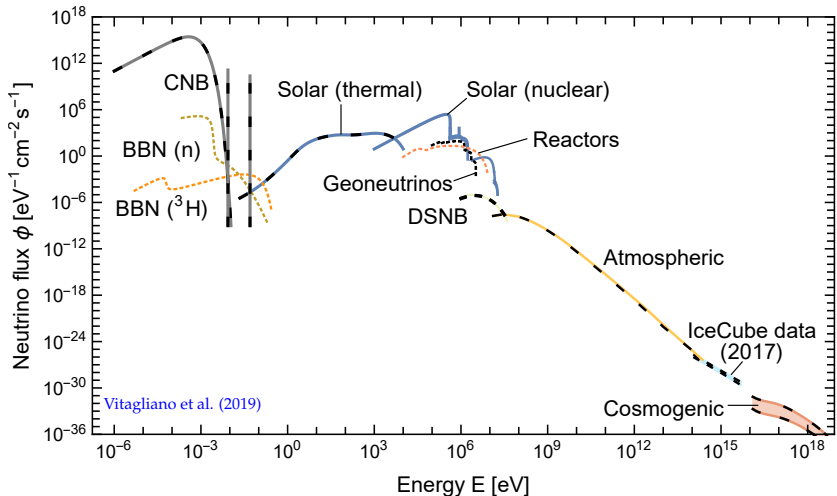
Neutrino Theory Network Fellow
New York University

BNL Lunch talk, October 17, 2025



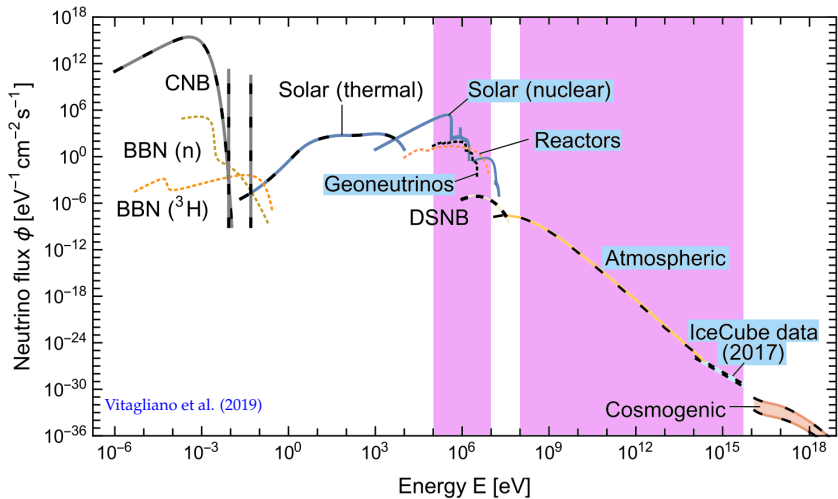
- Why is studying astrophysical neutrinos crucial?
- Core-collapse Supernovae as New Physics Probes
- Diffuse Supernova Neutrino Background
- Low-energy Atmospheric Neutrinos
- Summary and Outlook

Why is studying astrophysical neutrinos crucial?



Free neutrino sources spanning nearly 25 decades in energy

Established track record of neutrino discoveries



Significant progress, but still room for new discoveries

Why is studying astrophysical neutrinos crucial?

Benefits to the field of neutrino physics

- free sources spanning nearly 25 decades in energy
- established track record of neutrino discoveries
- test of physics in conditions not accessible on Earth
- complements terrestrial neutrino experimental efforts

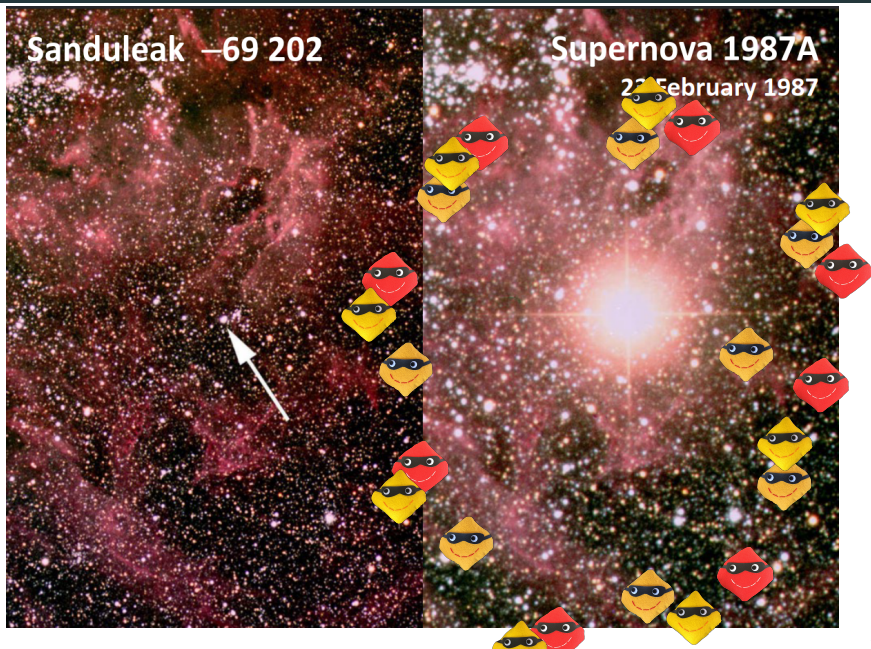
Benefits to the field of multimessenger astrophysics

- unveils physics of the sources
- experimentally and observationally timely

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)

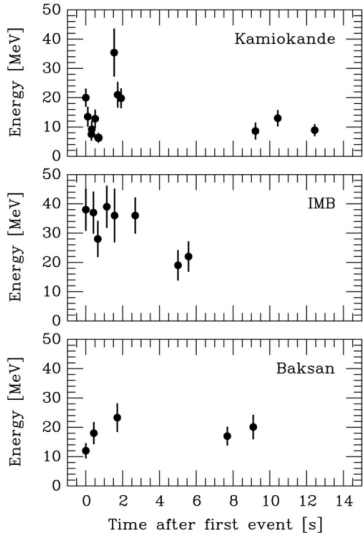
- Neutron star remnant

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

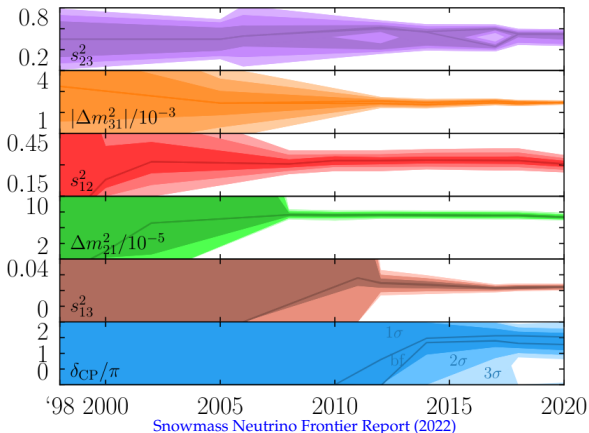
Towards Precise Neutrino Properties Measurements

We 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}	

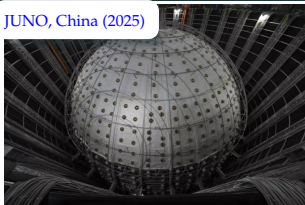
Force carriers

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

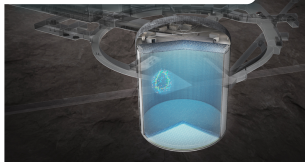
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

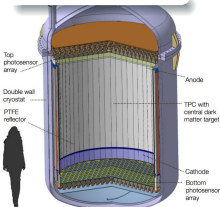
JUNO, China (2025)



Hyper-Kamiokande, Japan (2027)



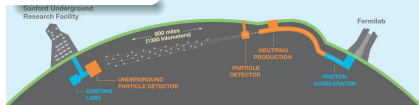
XLZD, DARWIN (20XX)



Rubin Observatory, Chile (2025)



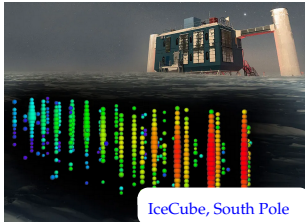
DUNE, USA (2030)



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

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

IceCube, South Pole

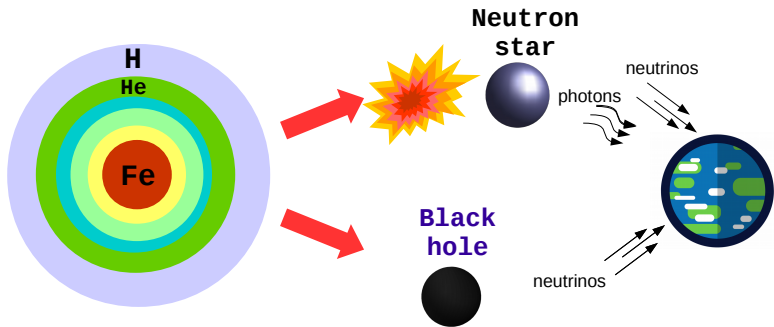


Neutrinos from Core-collapse Supernovae

Why are neutrinos important for a core-collapse supernova?

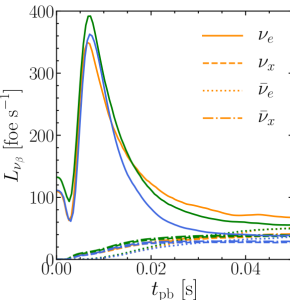
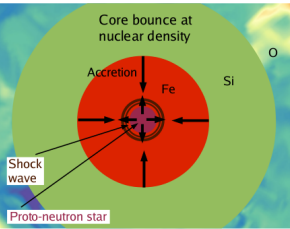
Neutrinos:

- $\sim 10^{58}$ 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

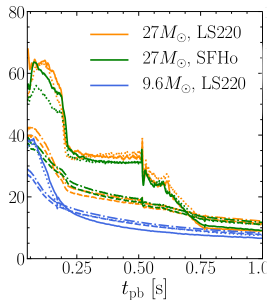
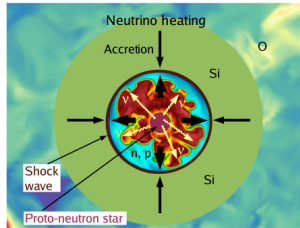


Different Phases of Supernova Explosion

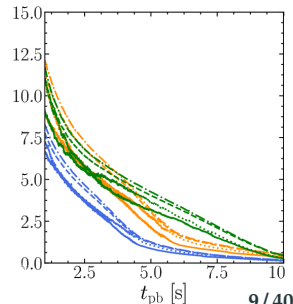
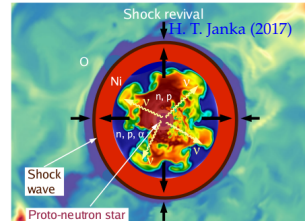
- Infall phase,
 ν_e burst ~ 40 ms



- Accretion phase,
 ~ 100 ms



- Cooling phase,
 ~ 10 s



Why core-collapse supernovae are good physics probes?

Advantages

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

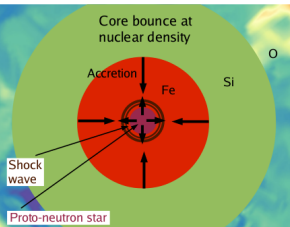
What can we learn with a variety of detectors?

- 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 \(2020\) ...](#)

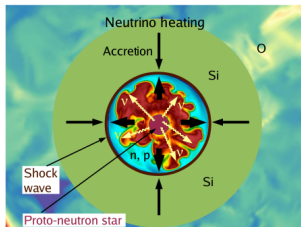
Neutrinos from Supernovae as Probes of New Physics

Different Phases of Supernova Explosion

- Infall phase,
 ν_e burst ~ 40 ms

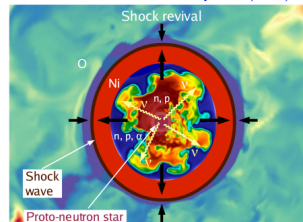


- Accretion phase,
 ~ 100 ms



- 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

astrophysical feedback often ignored

**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), ...

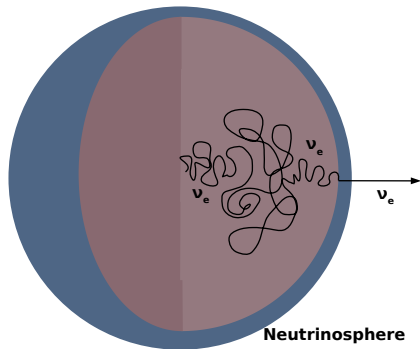
New Interaction Lagrangian

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

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

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

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 $\rho \sim 10^{11} - 10^{12} \text{ g cm}^{-3}$

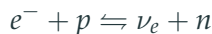
$$\nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau, \quad \nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_x, \bar{\nu}_x, \quad \nu_e \rightleftharpoons \nu_e, \bar{\nu}_e$$

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



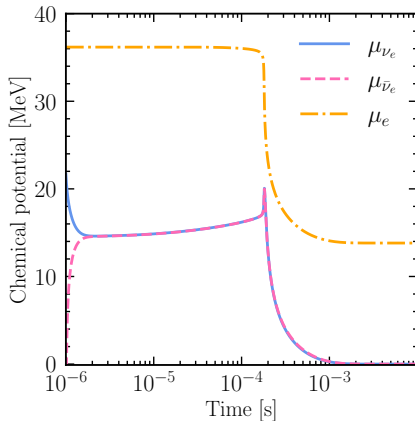
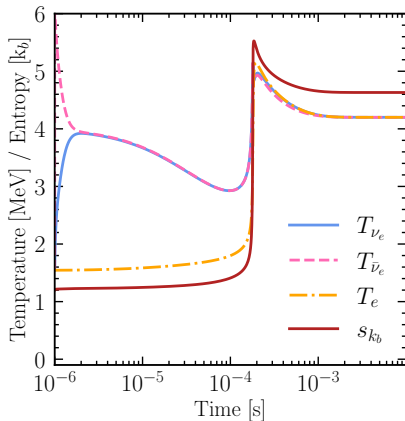
$$\frac{dY_e}{dt} = R_{\nu_e} - R_{\bar{\nu}_e} - R_{e^-} + R_{e^+} , \quad e^+ + n \rightleftharpoons \bar{\nu}_e + p$$

Temperature and chemical potential evolution for leptons

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

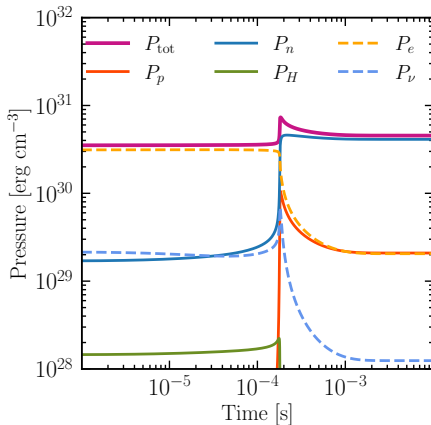
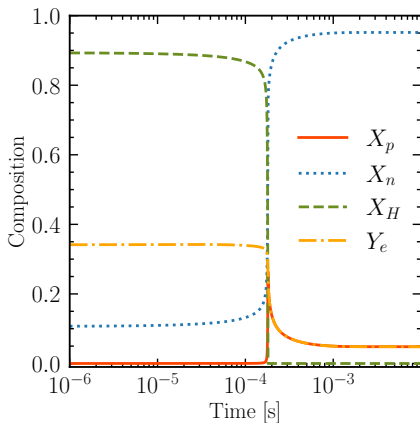
$$\frac{d\mu_i}{dt} = \left(\frac{\partial \rho_i}{\partial T_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial T_i} \frac{d\rho_i}{dt} \right) / \left(\frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial T_i} - \frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i} \right)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

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

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

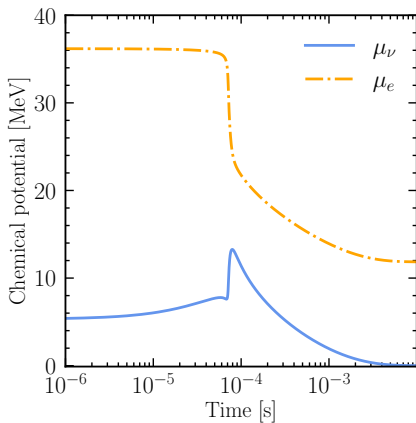
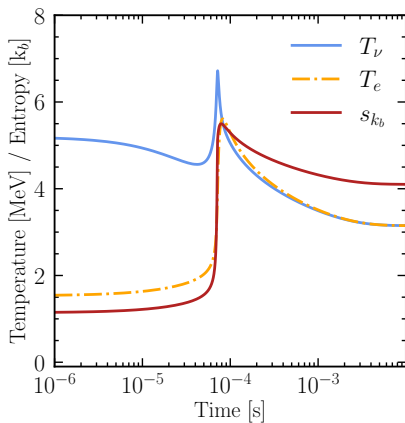
LNV ν SI timescale much faster than weak timescale $\rightarrow$
a single ν species evolution

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

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

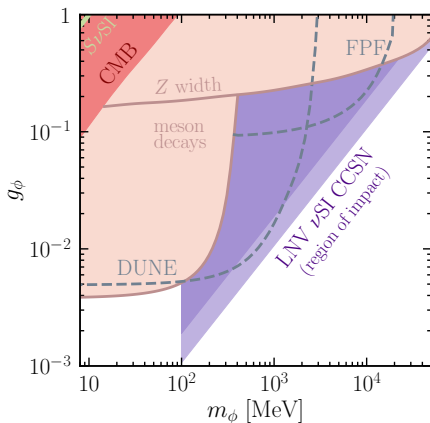
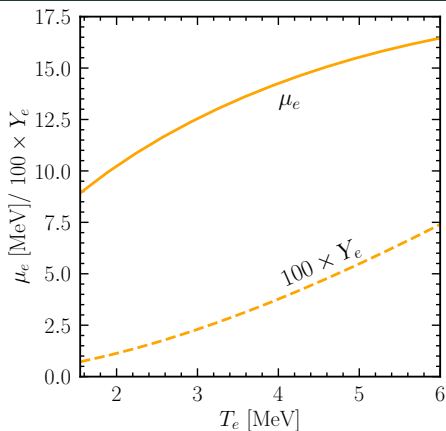
$$\frac{d\mu_{\nu}}{dt} = \frac{\frac{\partial \rho_{\nu}}{\partial T_{\nu}} \frac{\delta n_{\nu}}{\delta t} - \frac{\partial n_{\nu}}{\partial T_{\nu}} \frac{\delta \rho_{\nu}}{\delta t}}{2N_F \left(\frac{\partial n_{\nu}}{\partial \mu_{\nu}} \frac{\partial \rho_{\nu}}{\partial T_{\nu}} - \frac{\partial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

All flavors LNV ν SI



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

New β -equilibrium with LNV ν SI



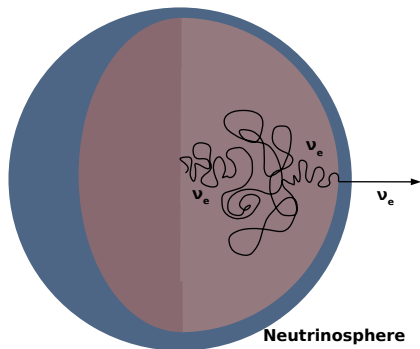
- regardless of the final T_e the new equilibrium has a very low Y_e
 $\mu_e = \delta m_{np} - T_e \ln \left(\frac{Y_e}{1-Y_e} \right)$, with $Y_e = \frac{1}{\pi^2 \rho} \int_0^\infty dp_e p_e^2 f_e(E_e, T_e, \mu_e)$
- complementarity with future accelerator-based experiments
- multi-flavor neutrino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

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

In collaboration with A. Beatty and V. Takhistov

arXiv: 2509.07856

Neutrino Trapping and β -equilibrium



Neutrino trapping

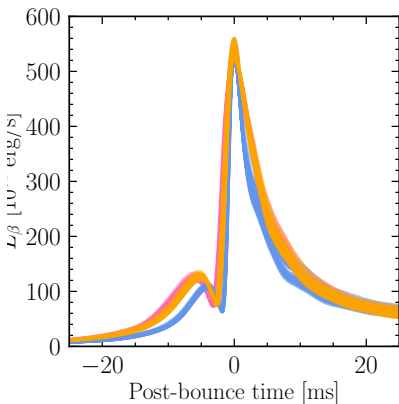
$$A(N, Z) + \nu \rightarrow A(N, Z) + \nu$$

β -equilibrium

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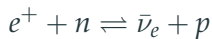
Neutrino Trapping and β -equilibrium



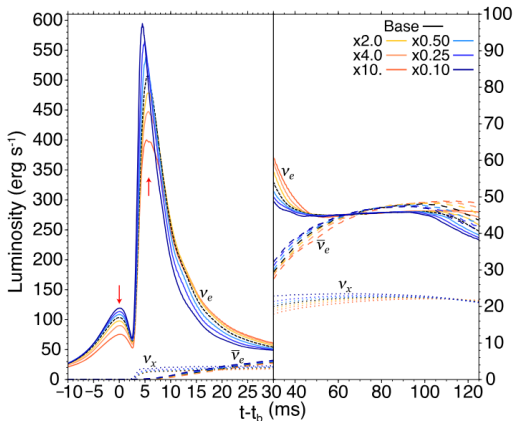
Neutrino trapping



β -equilibrium



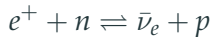
Neutrino Trapping and β -equilibrium



Neutrino trapping

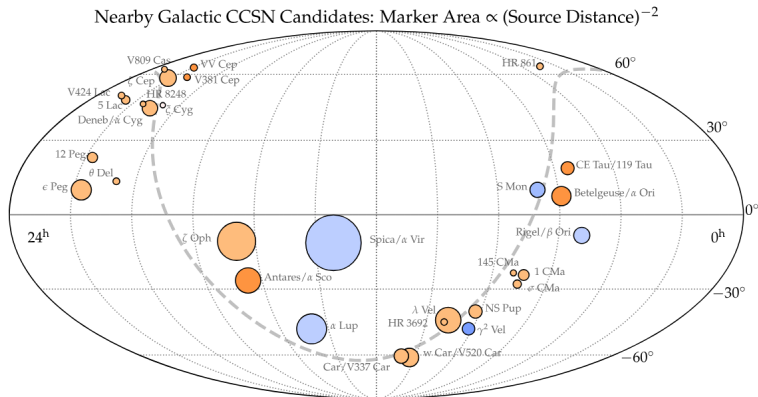


β -equilibrium



Sullivan et al. (2016)

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

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

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

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

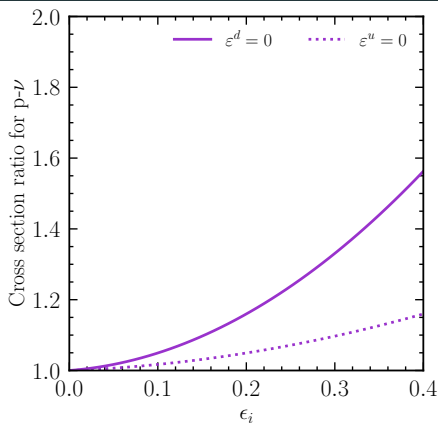
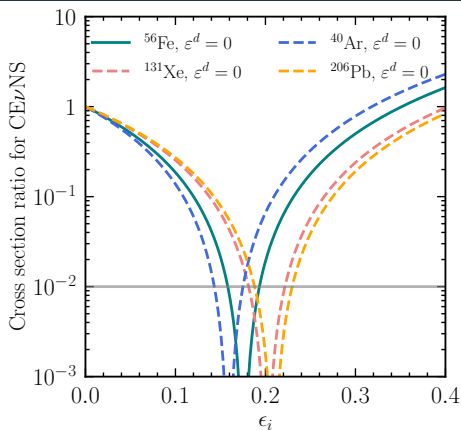
2. Elastic Neutrino-Proton Scattering

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

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

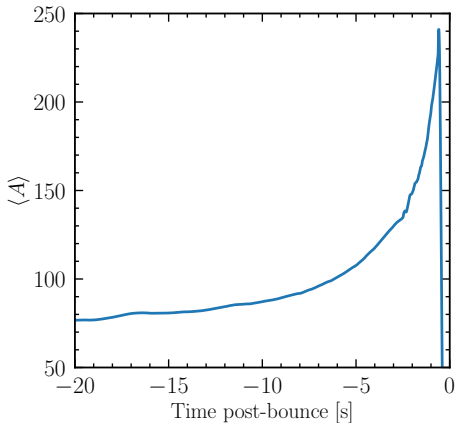
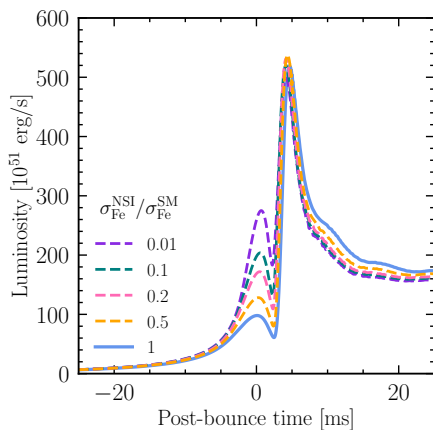
$$\text{with NSI } c_V \rightarrow c'_V = c_V + \varepsilon^p$$

Cross-Section Changes



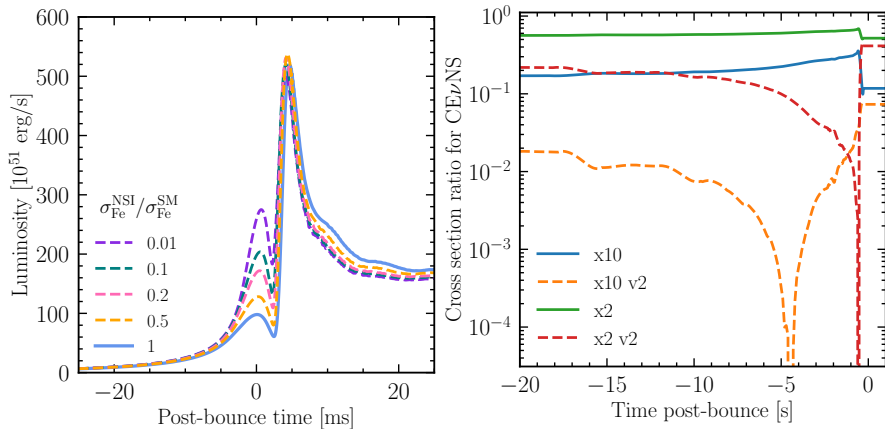
- Extreme changes for CE ν NS
- Moderate changes for ν -p scattering

Changes in the neutrino signal: GR1D simulations



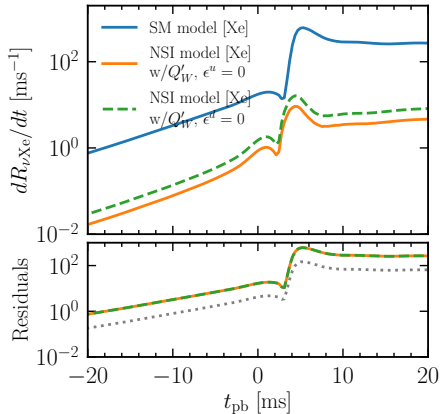
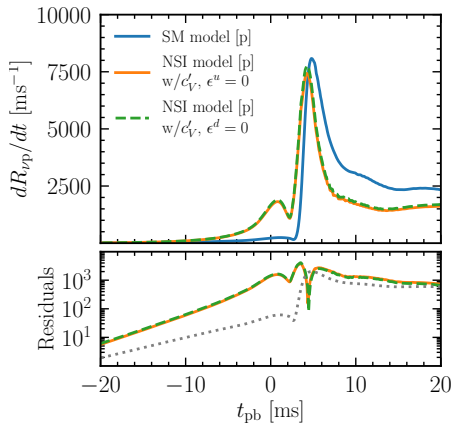
- Significant change in the luminosity pre-bounce
- Pre-bounce - heavy nuclei in the core
- Post-bounce - nucleons in the core

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

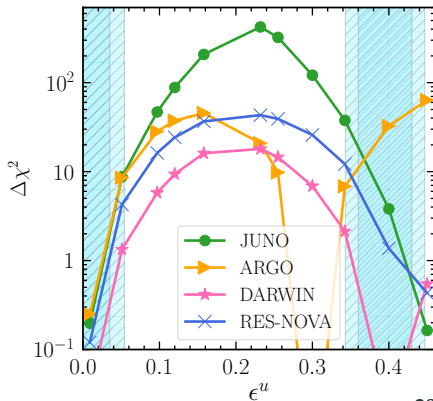
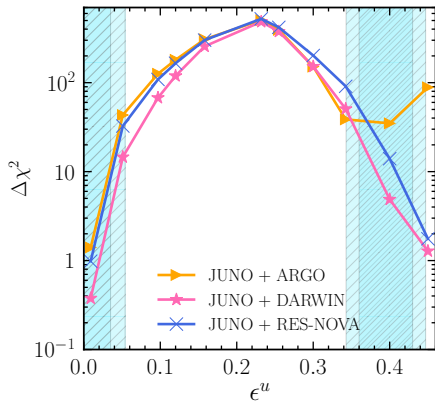
Rates in JUNO and DM detectors for the Betelgeuse



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

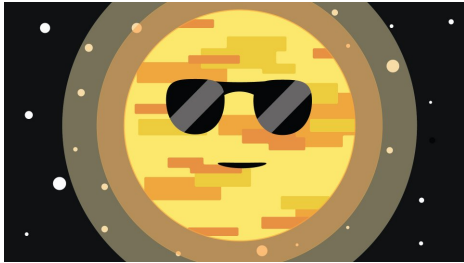
Statistical Analysis

$$\Delta\chi^2 = \min_{x,y,z} \left\{ \frac{(N_J^{\text{SM}}(1+x)(1+y) - N_J^{\text{NSI}})^2}{N_J^{\text{SM}}(1+x)(1+y)} + \frac{(N_{\text{DM}}^{\text{SM}}(1+x)(1+z) - N_{\text{DM}}^{\text{NSI}})^2}{N_{\text{DM}}^{\text{SM}}(1+x)(1+z)} + \left(\frac{x}{\sigma_x}\right)^2 + \left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{z}{\sigma_z}\right)^2 \right\}$$



Diffuse supernova neutrino background

Why focus only on a single rare event?

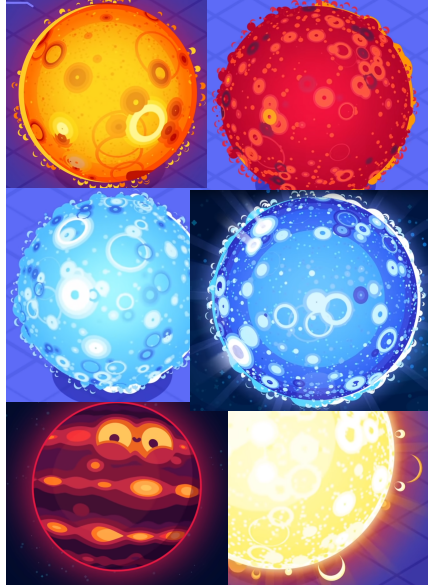


Single galactic SN event

- 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 $R_{\text{SN}}(z, M)$)

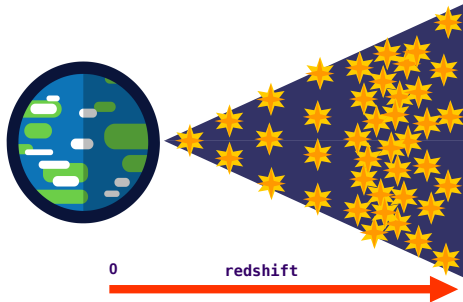
fraction of black-hole-forming progenitors (points to $f_{\text{BH-SN}}$)

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:

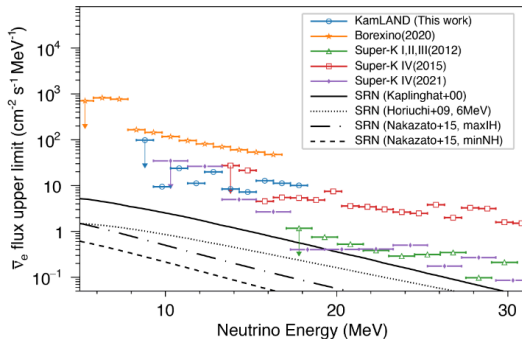
- $R_{\text{SN}}, f_{\text{BH-SN}}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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), ...

Diffuse supernova neutrino background: current limits

SK collab. (2021)



DSNB limits:

- $\bar{\nu}_e \approx 2.7 \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu > 17.3 \text{ MeV}$ SK collab. (2021), SK collab. (2023)
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)
- $\nu_x \lesssim 100 \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu > 19.3 \text{ MeV}$ AMS, Beacom, Tamborra (2021)

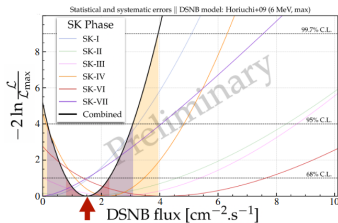
Tension from zero assumption

Spectral-fitting analysis

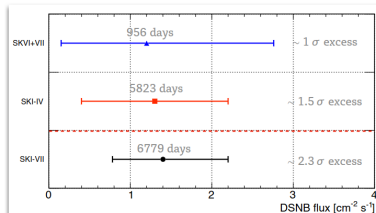


Spectrum fitting analysis to extract significance

- 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 $N_n=1$, $N_n \neq 1$



(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 $1.4^{+0.8}_{-0.6} \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu > 17.3$ MeV
- exhibit $\sim 2.3 \sigma$ excess!!

17

Slide credit: Masayuki Harada talk at Neutrino 2024

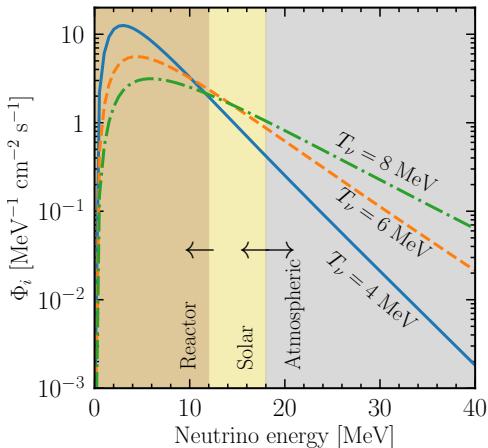
How to measure low-energy atmospheric neutrinos?

In collaboration with J. F. Beacom

PRD 108 (2023) 4, 043035

Diffuse Supernova Neutrino Background (DSNB)

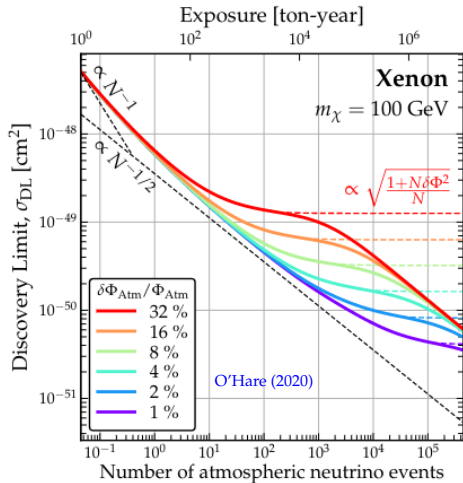
AMS (2022)



- DSNB $\rightarrow$
isotropic and stationary
guaranteed neutrino flux

[Guseinov \(1967\)](#), [Totani et al. \(2009\)](#), [Ando, Sato \(2004\)](#),
[Lunardini \(2009\)](#), [Beacom \(2010\)](#),...
- mitigating uncertainties in the
atmospheric neutrinos helps
the discovery limits

Direct Dark Matter Detection Experiments - Neutrino Fog



- neutrino floor/fog $\rightarrow$ barrier for dark matter direct detection experiments

Vergados & Ejiri (2008), Strigari (2009), Baudis et al. (2013), ...

- mitigating uncertainties in the atmospheric neutrinos helps the discovery limits

Low-energy Atmospheric Neutrino Flux

AMS & Beacom (2023)

Primary production channels

$$\pi^+ \rightarrow \mu^+ + \nu_\mu; \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu; \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

Non-oscillated flavor ratio

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

Sources of uncertainty

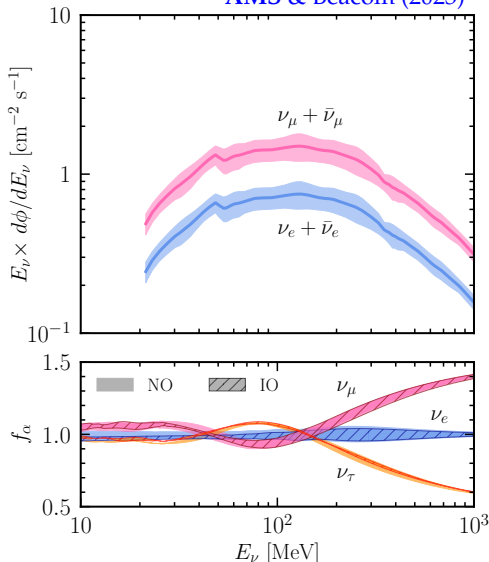
solar wind modulations

Earth's geomagnetic field

Oscillated flavor ratio

$$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$$

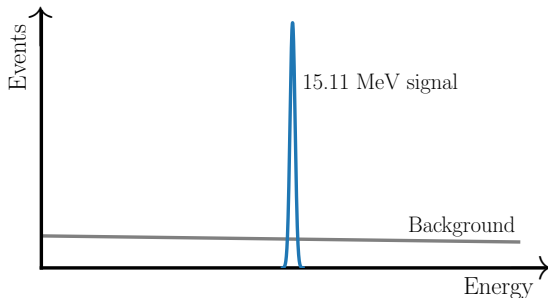
Past measurements: energies > 100 MeV



Neutrino flux: Zhuang (2021)

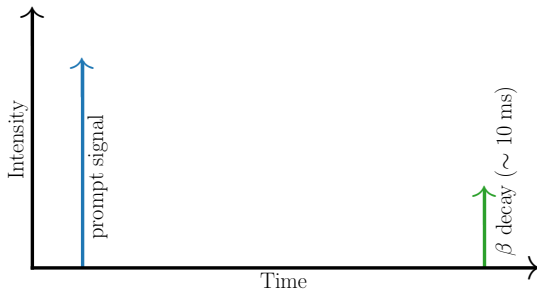
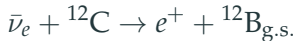
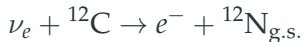
Mixing: NuCraft

Neutral current channels



- instantaneous decay of ${}^{12}\text{C}^*$
- emission of a monoenergetic γ

Charged current channels: ν_e

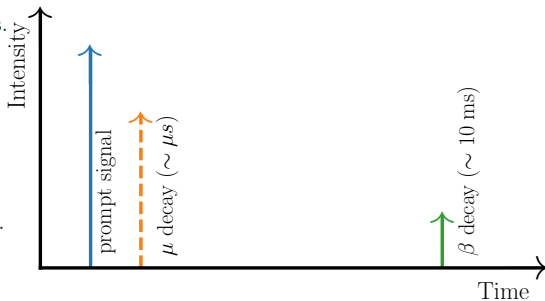
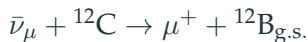
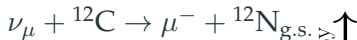


- coincidence detection of e^+ and e^-
- difference in ${}^{12}\text{B}_{\text{g.s.}}$ and ${}^{12}\text{N}_{\text{g.s.}}$ lifetimes $\rightarrow \nu_e$ vs. $\bar{\nu}_e$ distinction

Distinctive nuclear channels in JUNO

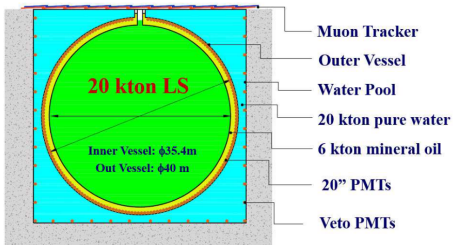
AMS & Beacom (2023)

Charged current channels: ν_μ



- coincidence detection of μ , its decay e and β -decay e
- difference in ${}^{12}\text{B}_{\text{g.s.}}$ and ${}^{12}\text{N}_{\text{g.s.}}$ lifetimes $\rightarrow \nu_\mu$ vs. $\bar{\nu}_\mu$ distinction
- triple vs. double coincidence detection $\rightarrow \nu_e$ vs. ν_μ distinction

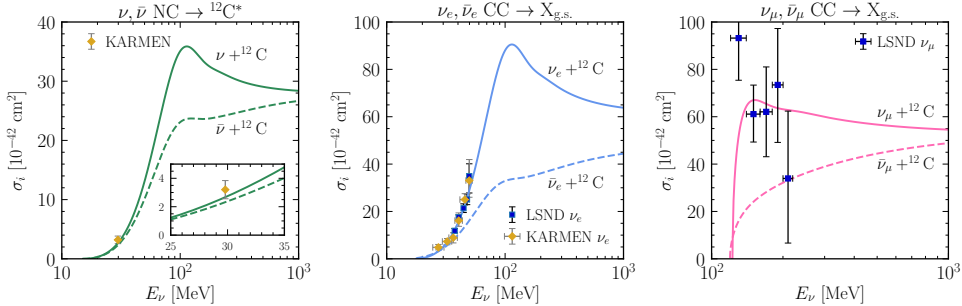
The Jiangmen Underground Neutrino Observatory (JUNO)



- large-scale carbon-based liquid scintillator detector
- already operational (~ 2025)
- excellent energy resolution $\lesssim 3\%$
- excellent spatial resolution $\lesssim 10\text{ cm}$
- low backgrounds in the considered channels

JUNO inclusive studies: [Cheng et al. \(2020\)](#), [Cheng et al. \(2020\)](#), JUNO Collaboration (2022)

Cross section: elementary particle treatment (EPT)



AMS & Beacom (2023)

- superallowed transitions from 0^+ to 1^+ states in A=12 triad
- the exclusive $\nu - {}^{12}\text{C}$ cross sections measured only at low energies
- experimental data agrees well with the EPT treatment
- 5-40% difference with respect to, e.g., RPA calculations

Atmospheric neutrino detection in JUNO

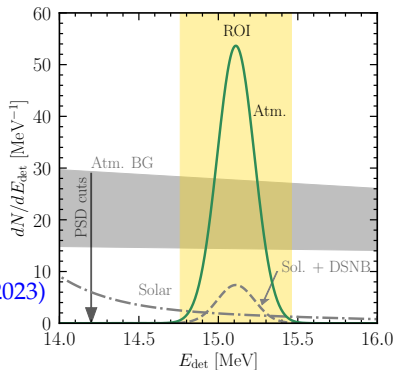
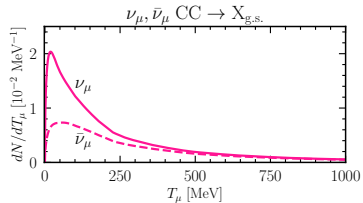
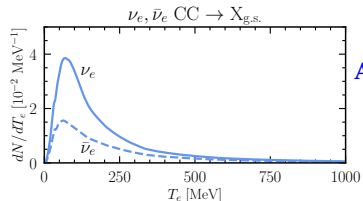
NC channel detection: single events

Irreducible BG: solar and DSNB ν

Reducible BG: atm. ν - p scattering

85 kton yr exposure $\rightarrow$ 25(40)%
uncertainty of the atmospheric ν rate

AMS & Beacom (2023)



CC channel detection: coincidence events

Irreducible BG: accidental coincidences

Rate per 85 kton yr: ~ 0.0004

essentially background free channels

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

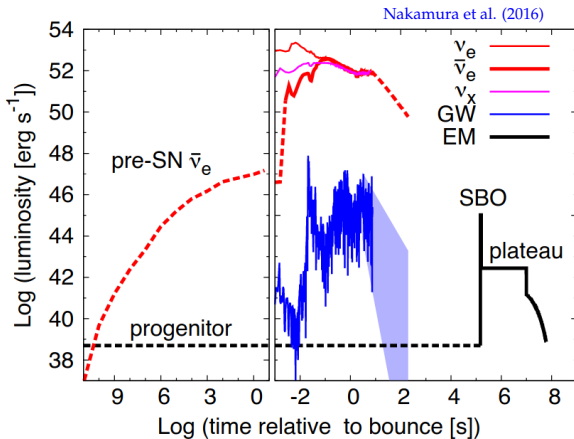
- brings us closer to fully understanding the physics inside the sources
- help us to probe potential new physics scenarios

Exciting times ahead

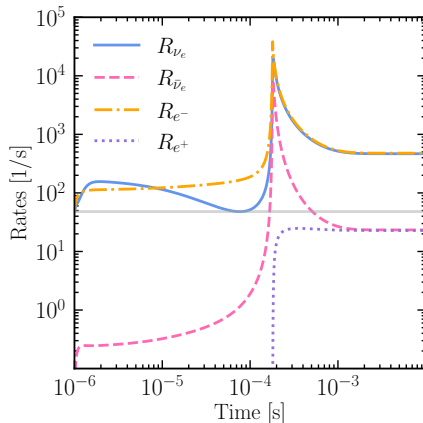
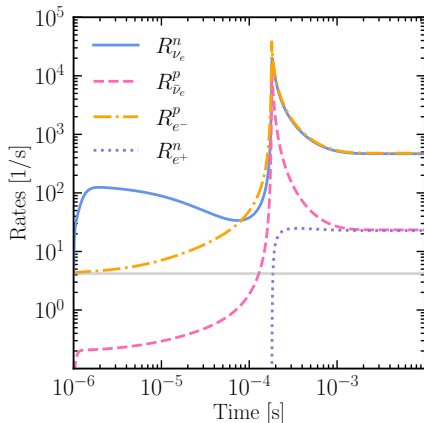
Thank you for the attention!

Backup

Core-Collapse Supernova Light Curve



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

Partial Derivatives for the Fermi-Dirac distributions

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

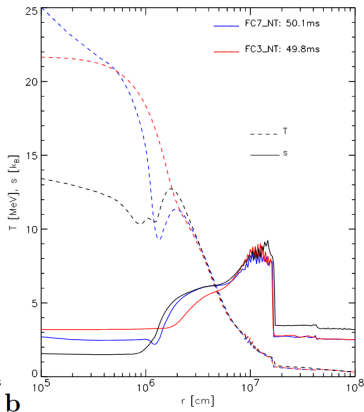
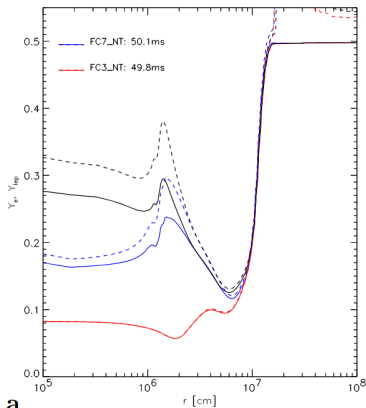
$$\frac{\partial n}{\partial T} = \frac{g}{2\pi^2} \int_m^\infty dE E \sqrt{E^2 - m^2} \frac{(E - \mu)}{4T^2} \cosh^{-2} \left(\frac{E - \mu}{2T} \right), \quad (2a)$$

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

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

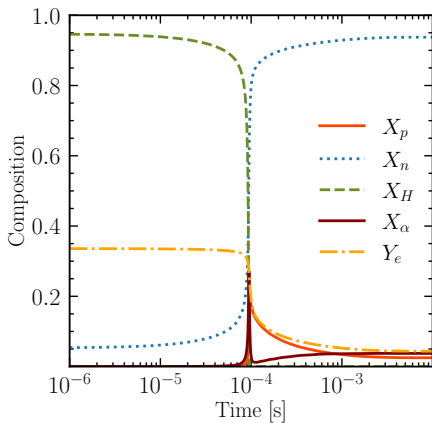
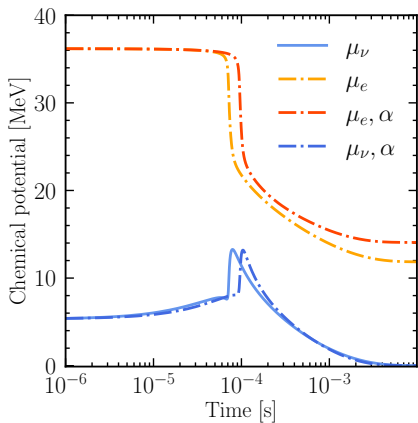
$$\frac{\partial \rho}{\partial \mu} = \frac{g}{2\pi^2} \int_m^\infty dE E^2 \sqrt{E^2 - m^2} \left[2T \cosh \left(\frac{E - \mu}{T} \right) + 2T \right]^{-1} \quad (2d)$$

Proxy "Internal Deleptonization"



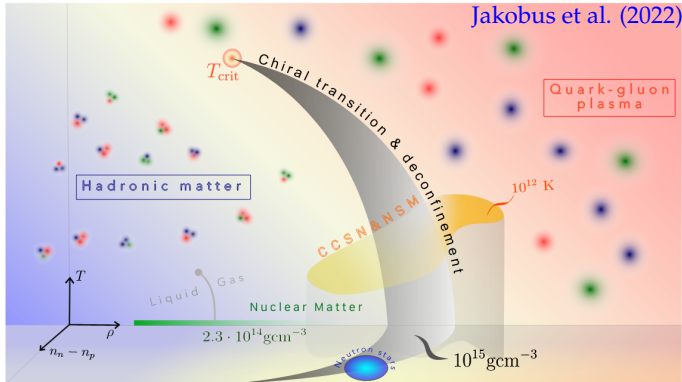
M. Rampp et al. (2002)

LS 220 Equation of State: impact of α particles



Exotic Supernovae as Probes of Neutrino Physics

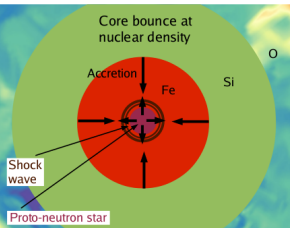
QCD phase diagram



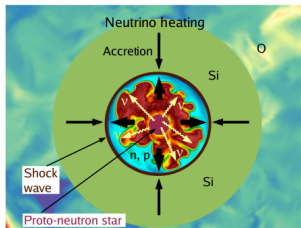
- Does the protocompact star contain non-leptonic degrees of freedom other than neutrons and protons?
- How to identify the presence of quark matter in astrophysical objects?

Different phases of core-collapse supernova explosion

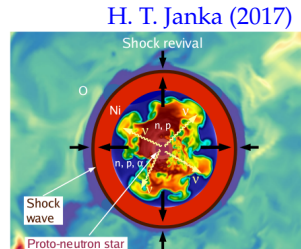
- Infall phase,
 ν_e burst ~ 40 ms



- Accretion phase,
 ~ 100 ms



- Cooling phase,
 ~ 10 s

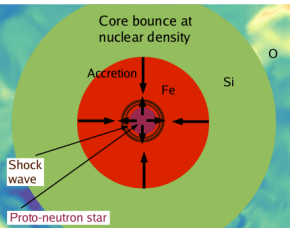


What drives the supernova supernova explosions?

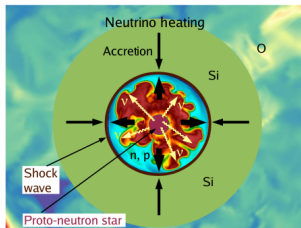
- neutrino heating Colgate & White (1966), Bethe & Wilson (1985)
- magneto-rotational mechanism LeBlanc and Wilson (1970), Takiwaki et al. (2009)
- particles beyond the Standard Model Fuller et al. (2008), AMS et al. (2020) ...
- phase transition to quark matter Sagert et al. (2008)...

Different phases of core-collapse supernova explosion

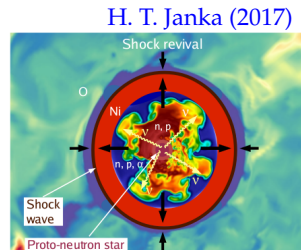
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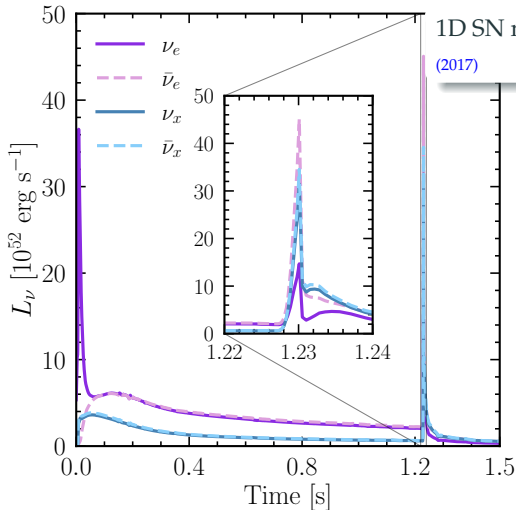
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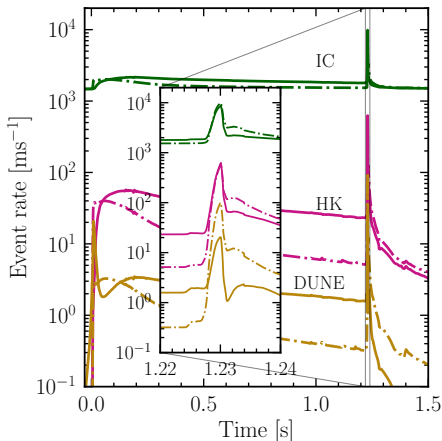
Neutrino Emission Properties from the QHPT CCSN



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

Pitik, Heimsoth, **AMS**, Balantekin (2023)

Neutrino Event Rates

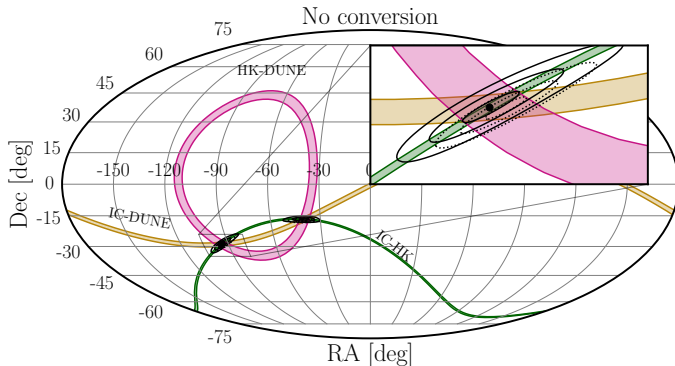


Impact of neutrino conversions

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

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

Determination of the Supernova Localization



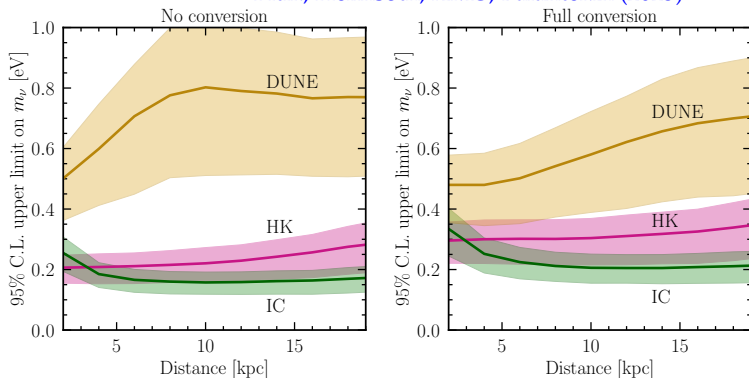
Pitik, Heimsoth, **AMS**, Balantekin (2023)

- 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

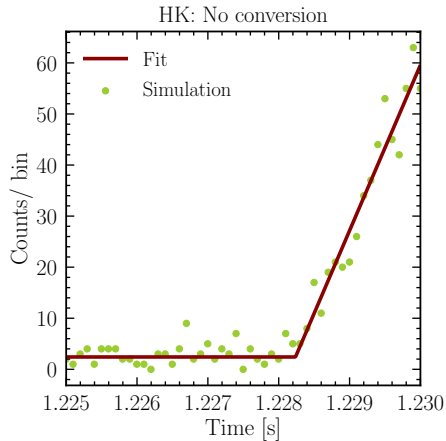
$$\Delta t \approx 5.15 \left(\frac{D}{10 \text{ kpc}} \right) \left(\frac{m_\nu}{1 \text{ eV}} \right)^2 \left(\frac{10 \text{ MeV}}{E_\nu} \right)^2 \text{ ms}$$

Pitik, Heimsoth, AMS, Balantekin (2023)



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

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)

Astrophysical neutrino fluxes

Supernova neutrinos

- large flux for Galactic SN
- transient event

Solar neutrinos

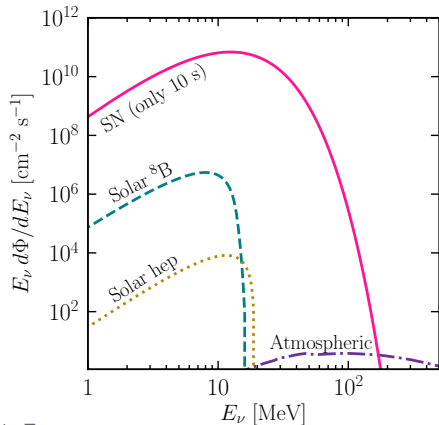


- neutrino energies up to ~ 15 MeV

Atmospheric neutrinos



- the highest neutrino energies among the considered sources
- small normalization



Non-standard coherent neutrino-nucleus scatterings

$$g = \sqrt{|g_{q,i}g_{\nu,i}|}, \quad g_{q,i}g_{\nu,i} > 0$$

new vector mediator

Z'

Lagrangian terms

$$\mathcal{L}^{Z'} = g_{\nu,Z'} Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{q} \gamma^\mu g_{q,Z'} q$$

new scalar mediator

ϕ

$$\mathcal{L}_{\text{LNC}}^\phi = g_{\nu,\phi} \phi \bar{\nu}_R \nu_L + \phi \bar{q} g_{q,\phi} q$$

$$\mathcal{L}_{\text{LNV}}^\phi = g_{\nu,\phi} \phi \bar{\nu}_L^c \nu_L + \phi \bar{q} g_{q,\phi} q$$

Non-standard coherent neutrino-nucleus scatterings

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$$\mathcal{L}_{\text{LNV}}^\phi = g_{\nu,\phi} \phi \bar{\nu}_L^c \nu_L + \phi \bar{q} g_{q,\phi} q$$

Cross sections

$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{G_F^2 m_T}{\pi} |\xi|^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q)$$

$$\xi = -\frac{Q_w}{2} + \frac{g_{\nu,Z'} Q'_w}{\sqrt{2} G_F (2m_T E_r + m_{Z'}^2)}$$

Non-standard coherent neutrino-nucleus scatterings

$$g = \sqrt{|g_{q,i}g_{\nu,i}|}, \quad g_{q,i}g_{\nu,i} > 0$$

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new scalar mediator

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Cross sections

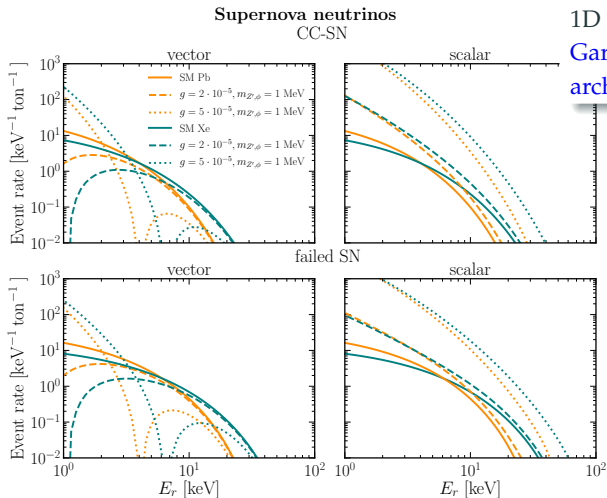
$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{G_F^2 m_T}{\pi} |\xi|^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q)$$

$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{d\sigma_{\text{SM}}}{dE_r} + \frac{d\sigma_\phi}{dE_r}$$

$$\xi = -\frac{Q_w}{2} + \frac{g_{\nu,Z'} Q'_w}{\sqrt{2} G_F (2m_T E_r + m_{Z'}^2)}$$

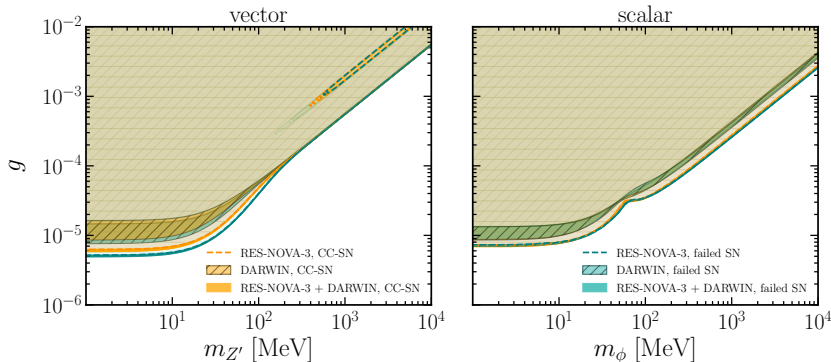
$$\frac{d\sigma_\phi}{dE_r} = \frac{(g_{\nu,\phi} g_{q,\phi} Q_s)^2}{2\pi (2E_r m_T + m_\phi^2)^2} \frac{m_T^2 E_r}{2E_\nu^2} F^2(Q)$$

Event rates for supernova neutrinos



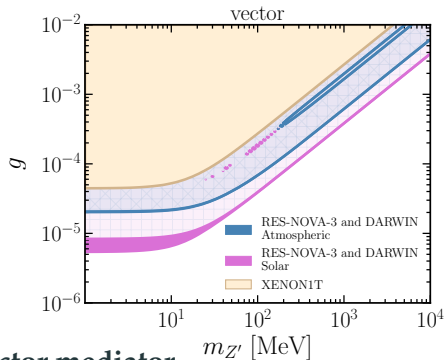
- Failed SN: hotter neutrino spectrum $\rightarrow$ longer recoil spectrum
- Heavier target: higher number of events but shorter recoil spectrum

Sensitivity bounds: supernova neutrinos



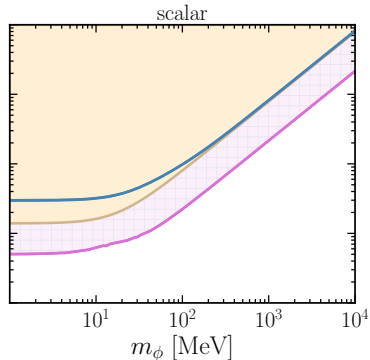
- failed SN: higher number of events $\rightarrow$ better constraints
- RES-NOVA-3 drives the limits due to higher volume
- vector mediator small unconstrained region due to the interference term
- limits on the vector mediator better for low mediator masses

Sensitivity bounds: solar and atmospheric neutrinos



Vector mediator

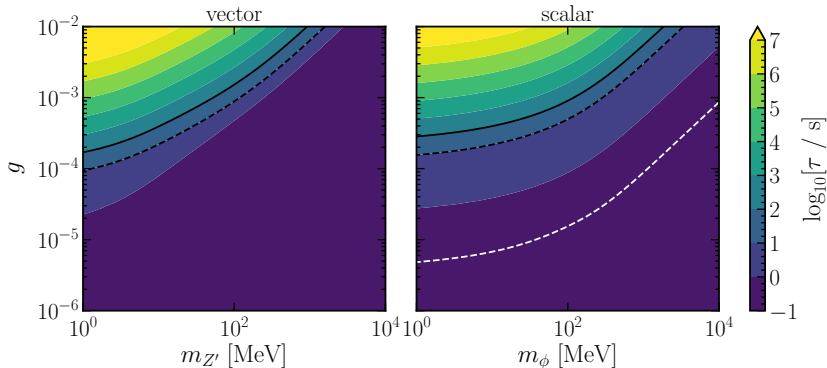
- Solar neutrinos: bounds driven by Xe based detector
- Atmospheric neutrinos: bounds driven by Pb detector



Scalar mediator

- Bounds driven by Pb detector

Non-standard coherent scattering in the supernova core



- mean-free path

$$\lambda_{\nu_\beta} = \sum_{\text{CC,NC}} \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta}) E_{\nu_\beta}^2}{n_t \int dE_{\nu_\beta} f(E_{\nu_\beta}) E_{\nu_\beta}^2 \sigma_i(E_{\nu_\beta})}$$

- number of scatters

$$N = \int_0^{R_2} \frac{2r}{\lambda(r)^2} dr$$

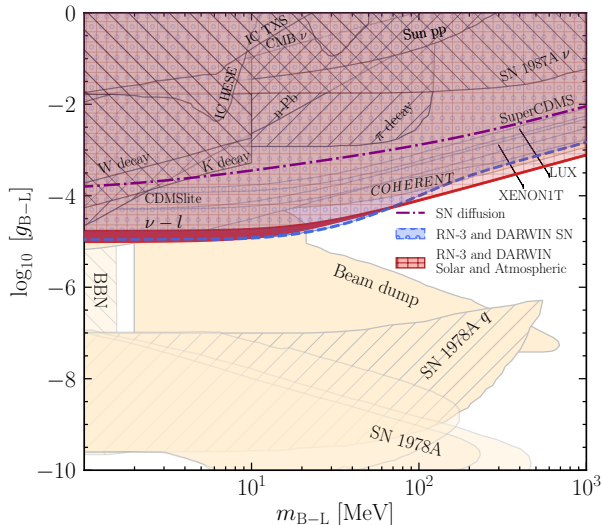
- diffusion time

$$\tau_{\nu_\beta} = \int_{R_1}^{R_2} dr \frac{r}{\lambda_{\nu_\beta}(r)}$$

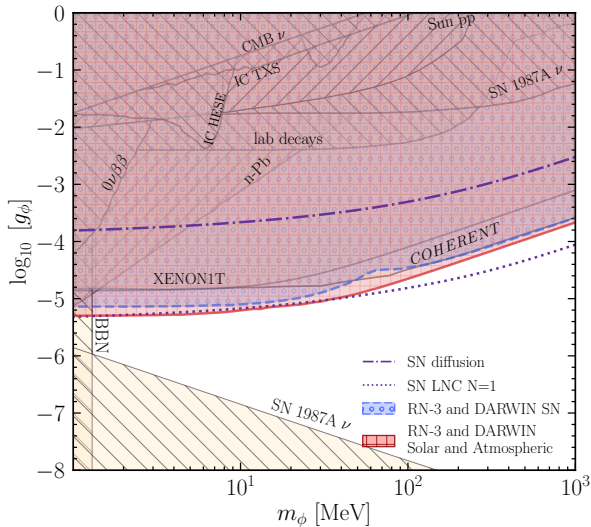
$$R_1 = 10 \text{ km}$$

$$R_2 = 40 \text{ km}$$

Comparison of limits from specific new physics models



Comparison of limits from specific new physics models



Limits from SN1987A on ν_x

