New Neutrino Interactions and Core-Collapse Supernovae

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New York University

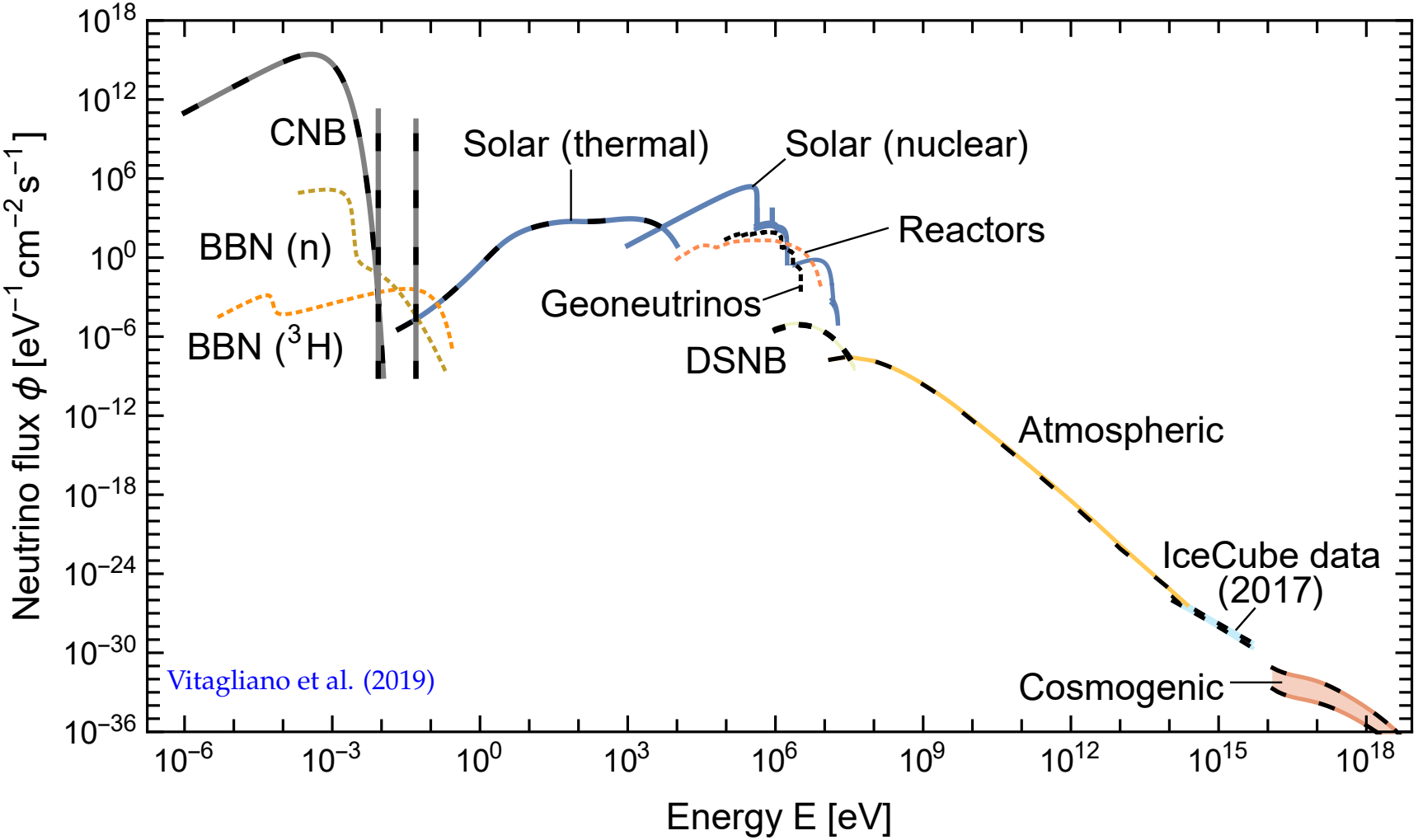
CCAPP seminar, December 9, 2025

NYU

Overview

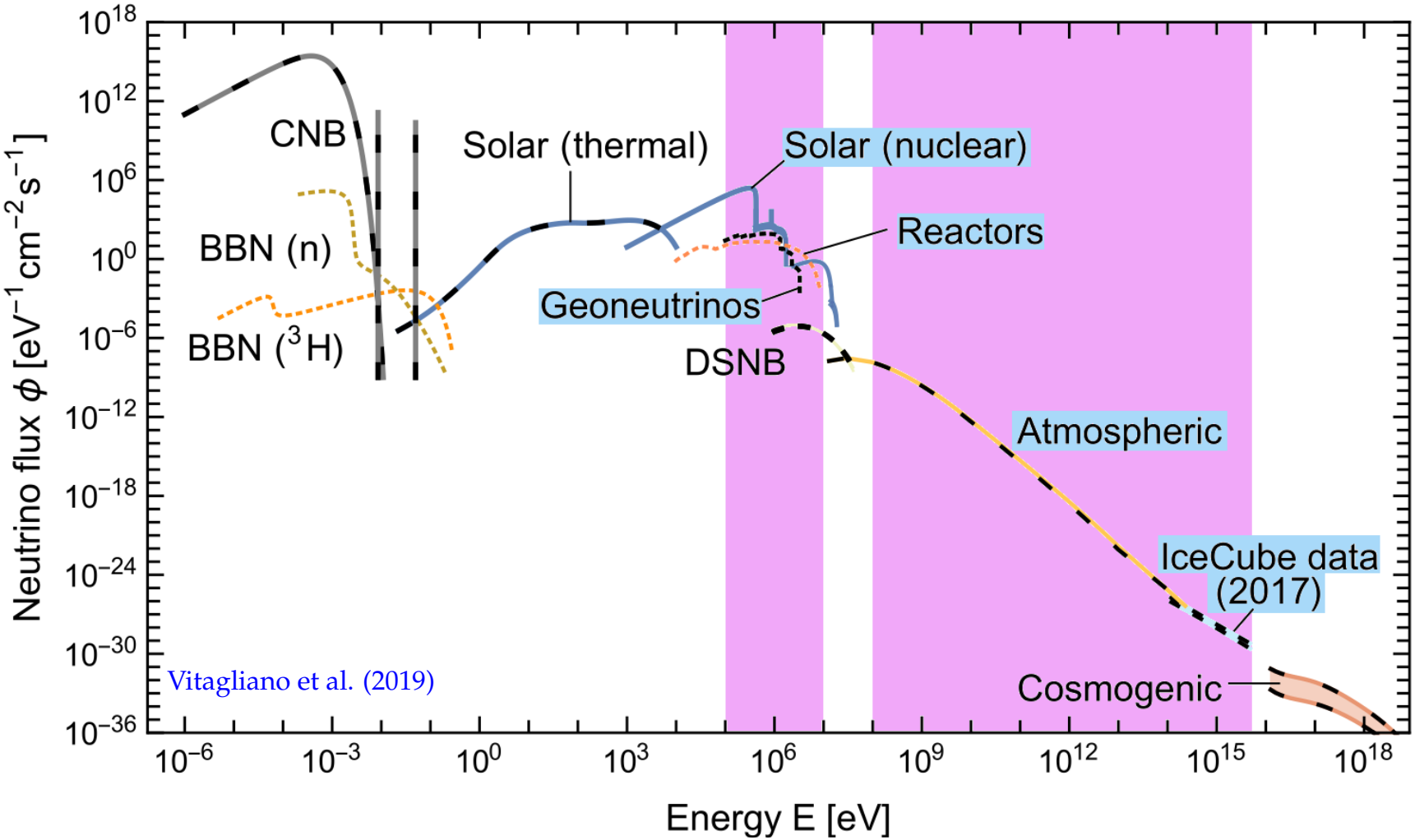
- Why is studying astrophysical neutrinos crucial?
- Core-collapse Supernovae as New Physics Probes
- Diffuse Supernova Neutrino Background
- Low-energy Atmospheric Neutrinos
- Summary and Outlook

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?

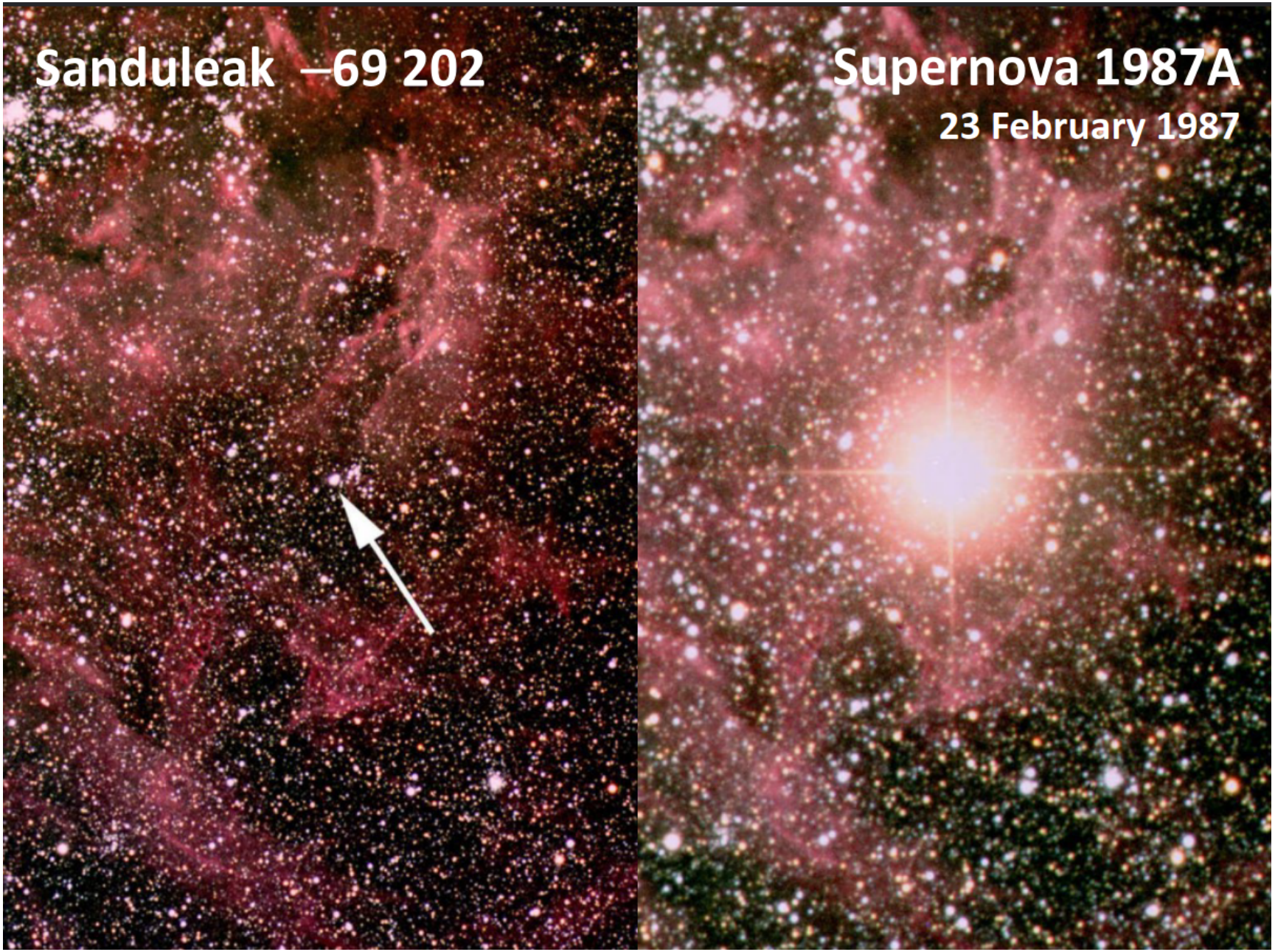
Benefits to the field of neutrino physics

- 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

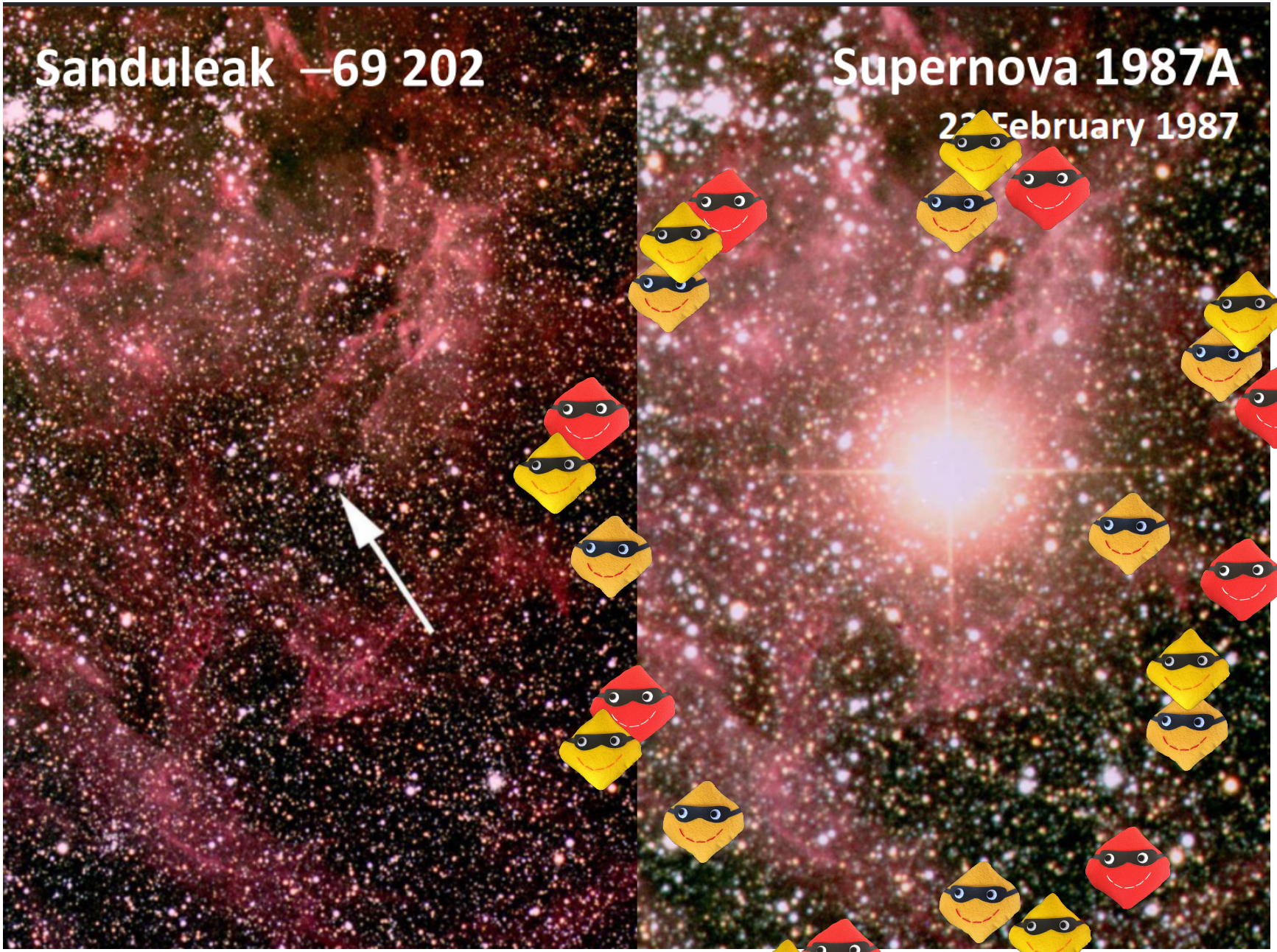
Benefits to the field of multimessenger astrophysics

- 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)

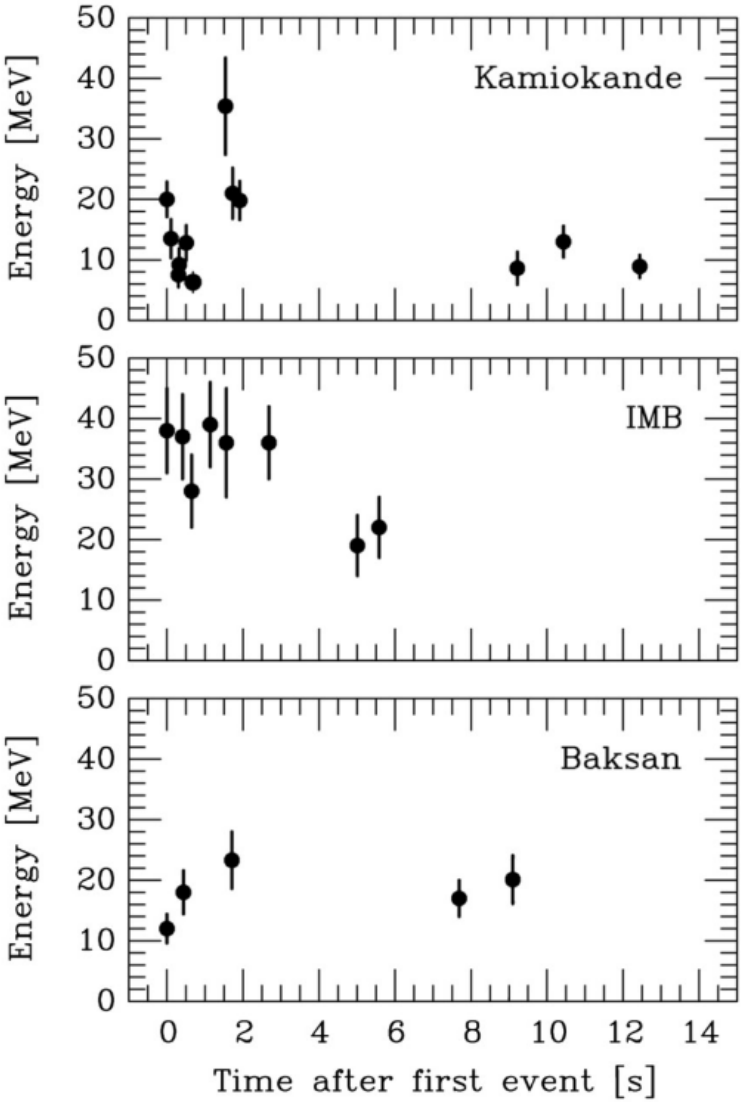
- Neutron star remnant

  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

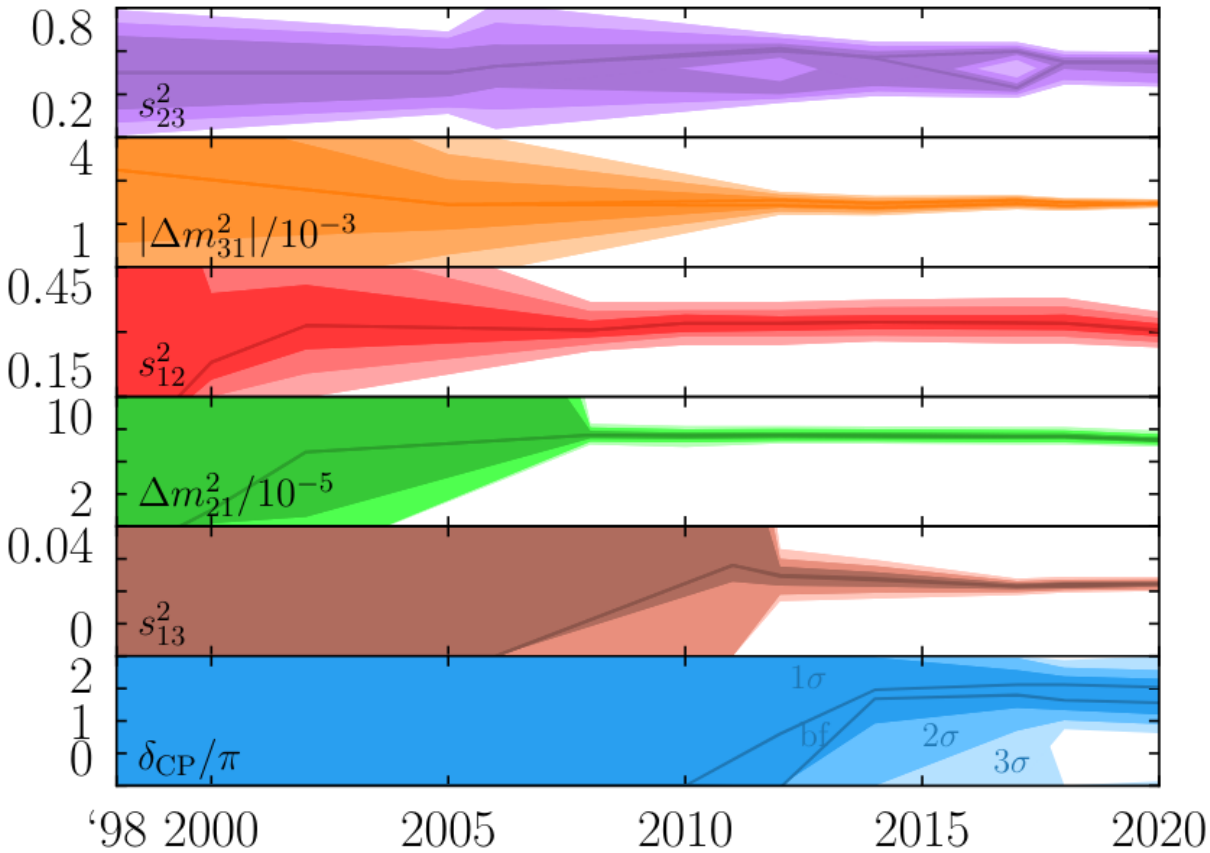
Towards Precise Neutrino Properties Measurements

We known now:

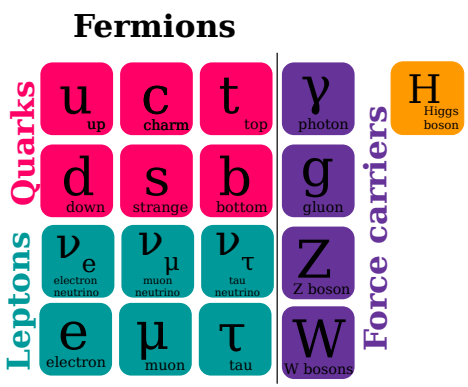
- large mixing angles
- non-zero masses

Remaining questions

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



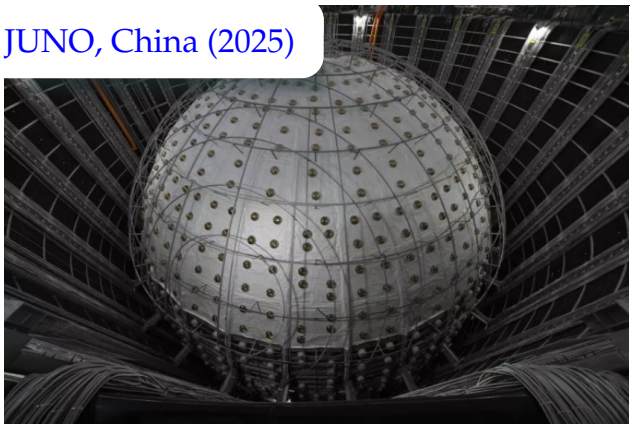
Snowmass Neutrino Frontier Report (2022)



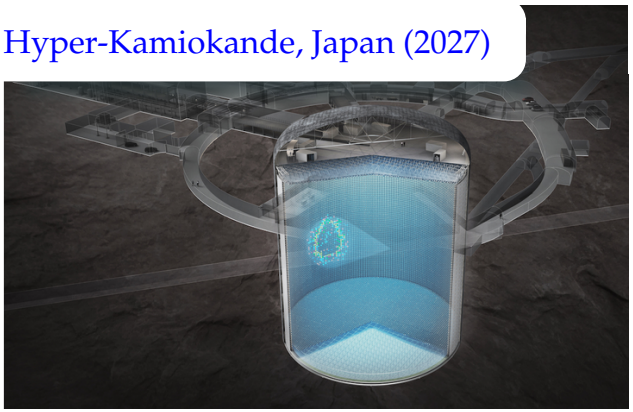
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} \qquad U = \underbrace{\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}}_{\text{beam, atmospheric}} \underbrace{\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{bmatrix}}_{\text{beam, reactor}} \underbrace{\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}}_{\text{solar, reactor}}$$

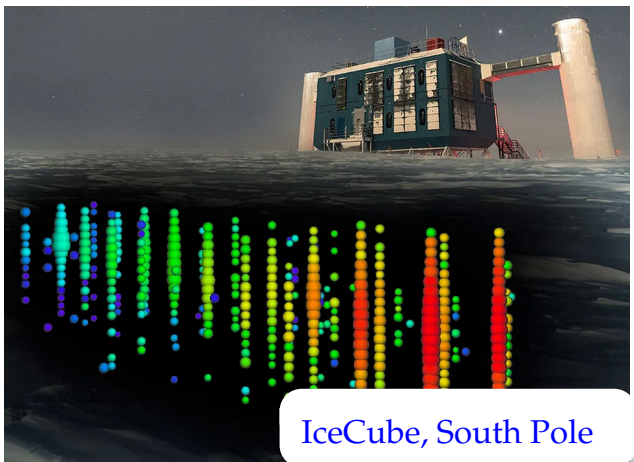
How to achieve full picture of neutrinos? All hands on deck!

JUNO, China (2025)



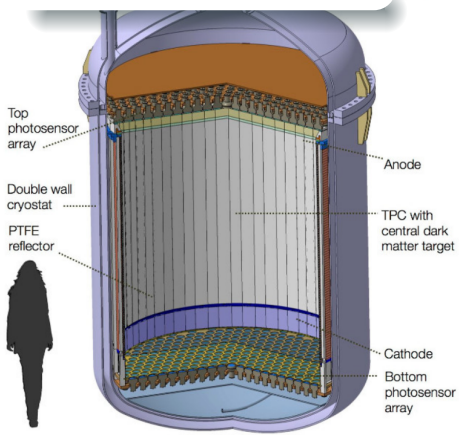
Hyper-Kamiokande, Japan (2027)



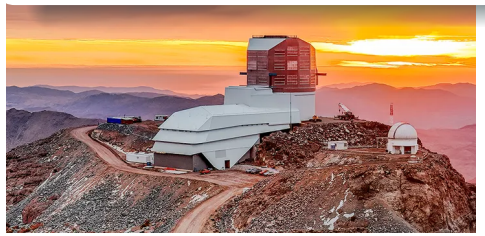


IceCube, South Pole

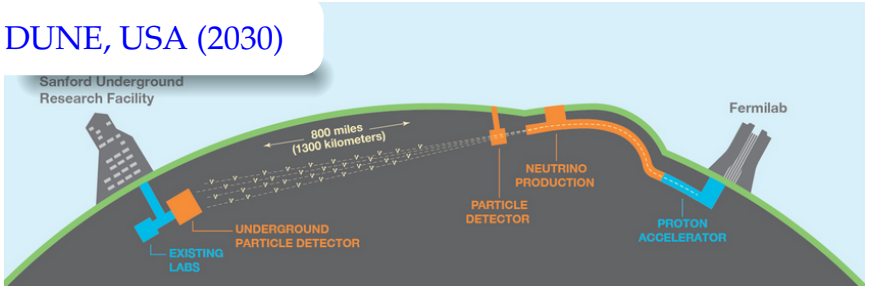
XLZD, DARWIN (20XX)



Rubin Observatory, Chile (2025)



DUNE, USA (2030)



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

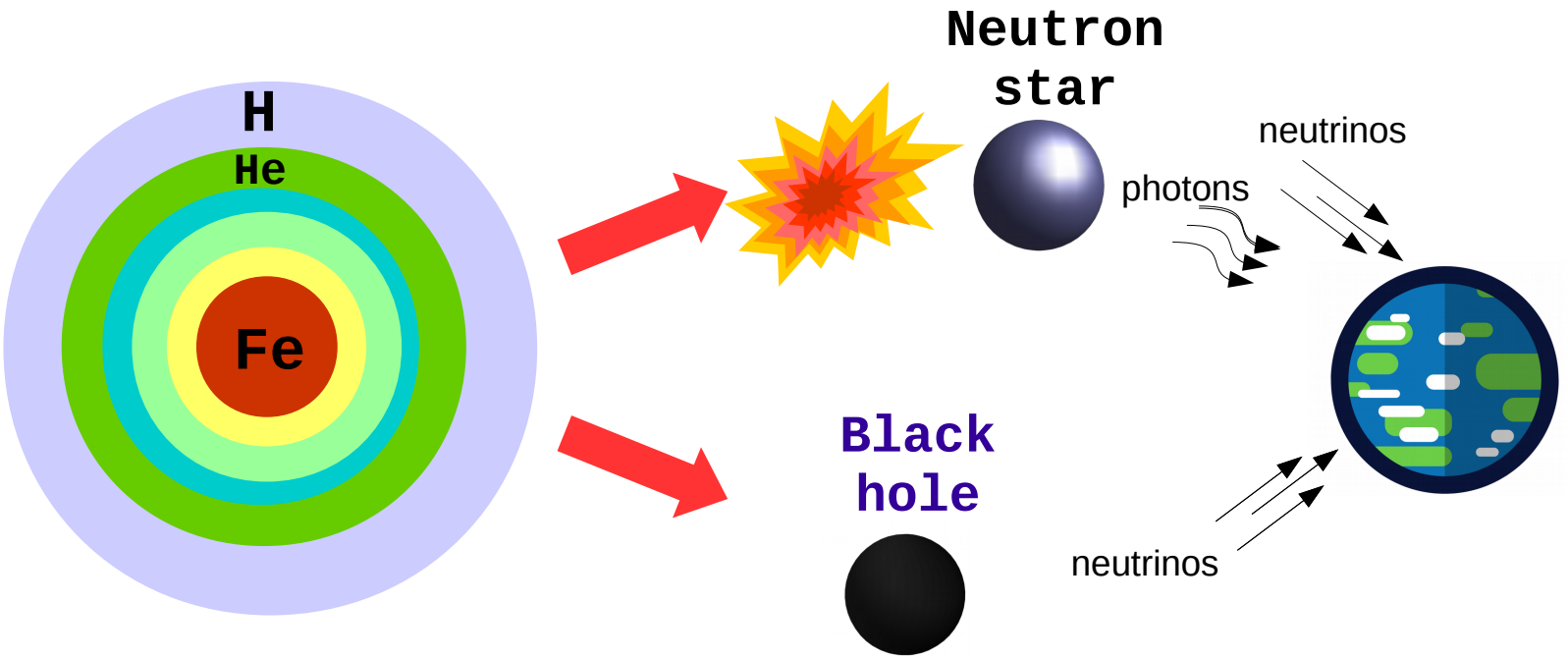
- Complementarity with:
  - reactor and accelerator searches
  - electromagnetic surveys
  - other astrophysical messengers

Neutrinos from Core-collapse Supernovae

Why are neutrinos important for a core-collapse supernova?

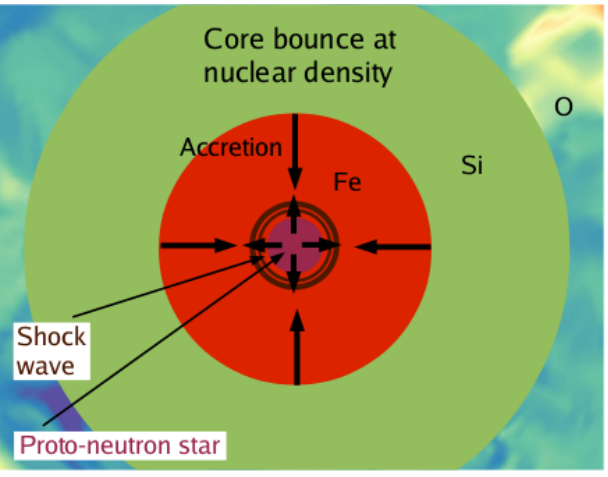
Neutrinos:

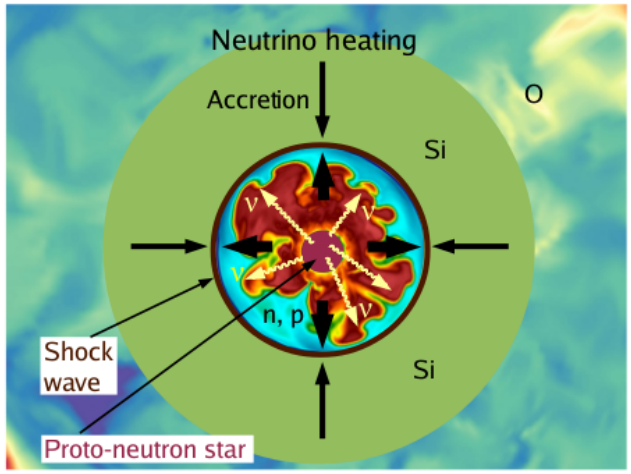
- $\sim 10^{58}$ of them emitted from a single core collapse
- only they can reveal the deep interior conditions
- only particles detectable from the collapse to a black hole

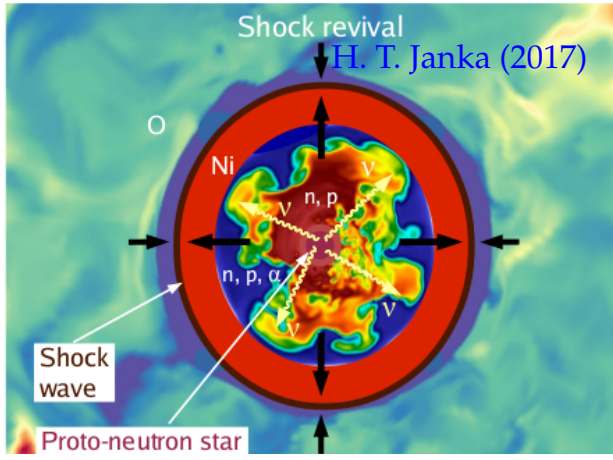


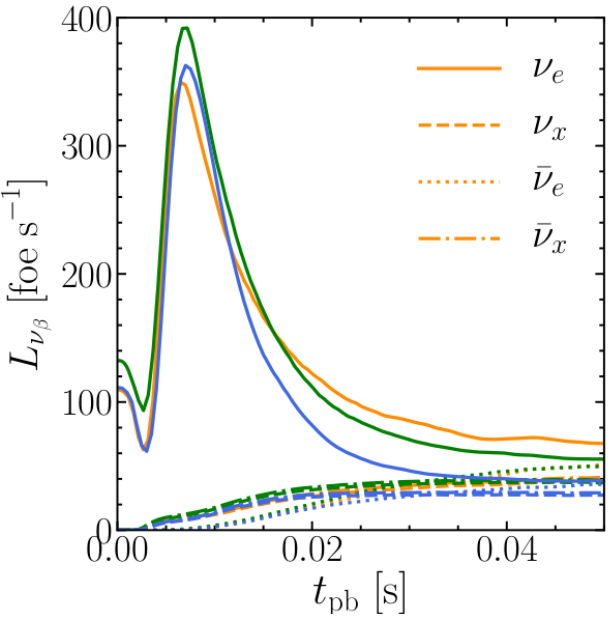
Different Phases of Supernova Explosion

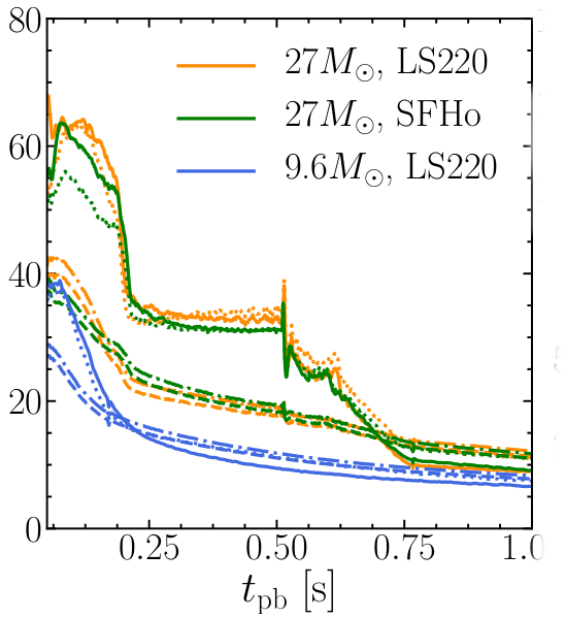
- Infall phase,
  ν_e burst $\sim$ 40 ms
- Accretion phase,
  $\sim$ 100 ms
- Cooling phase,
  $\sim$ 10 s

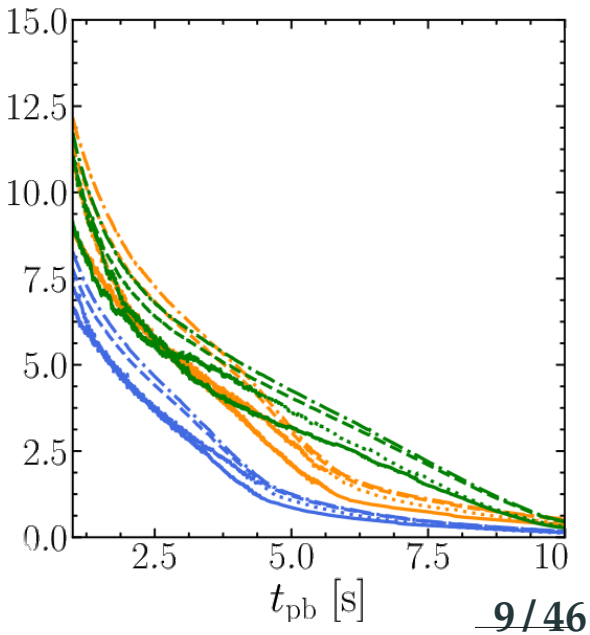












Why core-collapse supernovae are good physics probes?

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?

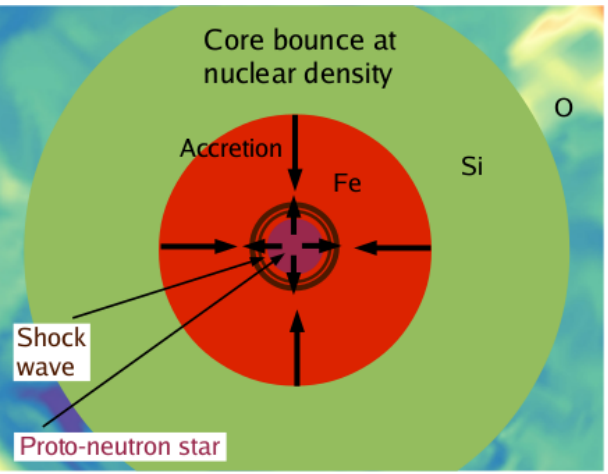
- explosion mechanism — Bethe & Wilson (1985), **AMS** et al. (2022)...
- nucleosynthesis — Woosley et al. (1994), Surman & McLaughlin (2003)...
- compact object formation — Warren et al. (2019), Li, Beacom et al. (2020)...
- neutrino mixing — Balantekin & Fuller (2013), Siwach, **AMS**, Balantekin (2022)...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

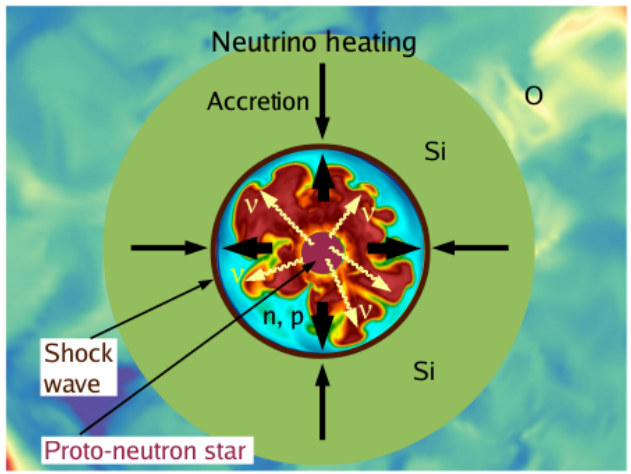
Neutrinos from Supernovae as Probes of New Physics

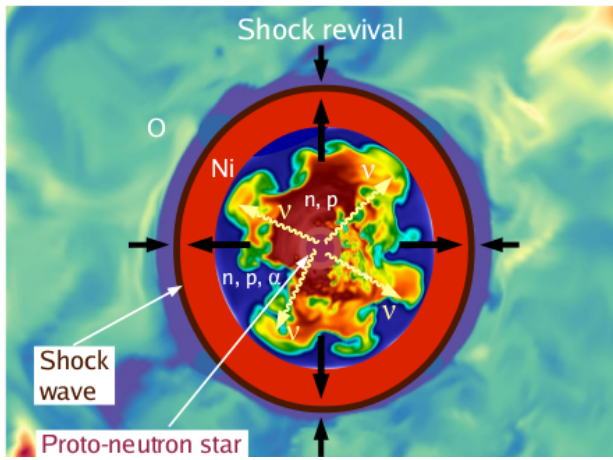
Different Phases of Supernova Explosion

- Infall phase,
  ν_e burst $\sim$ 40 ms
- Accretion phase,
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- Cooling phase,
  $\sim$ 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.

Zofia Białynicka-Birula (1964)

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), ...

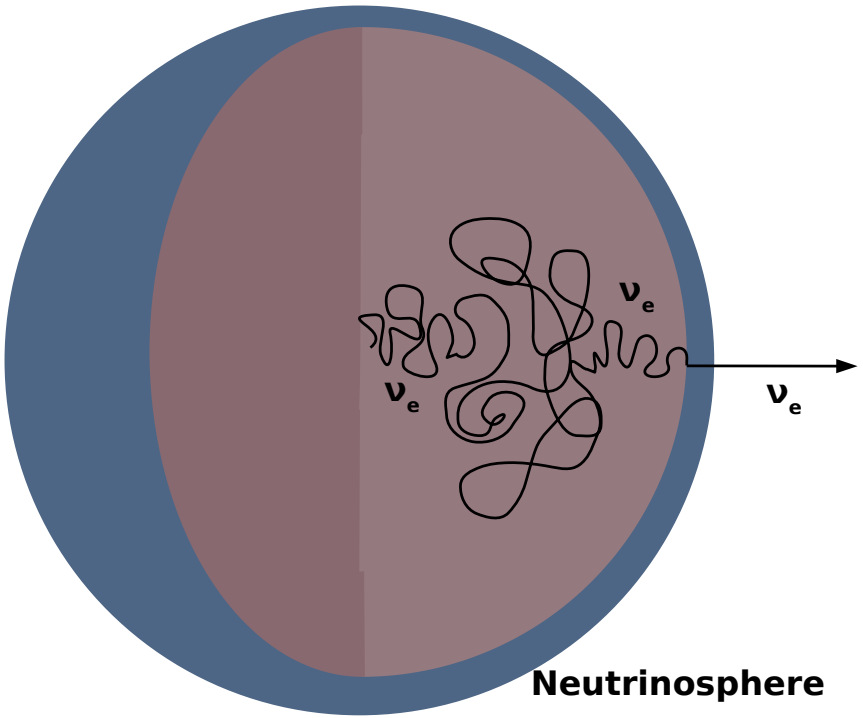
New Interaction Lagrangian

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

Probability of the New Interaction

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

Neutrino Trapping and $\beta-$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 $\rho \sim 10^{11} - 10^{12}$g cm^{-3}

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

LNV νSI in supernovae illustrated by cats

Without LNV νSI



Pics credit: Tony Zhou who was courageously cat sitting Aurora and Beetle

LNV νSI in supernovae illustrated by cats

With LNV νSI



Pics credit: Tony Zhou who was courageously cat sitting Aurora and Beetle

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

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

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

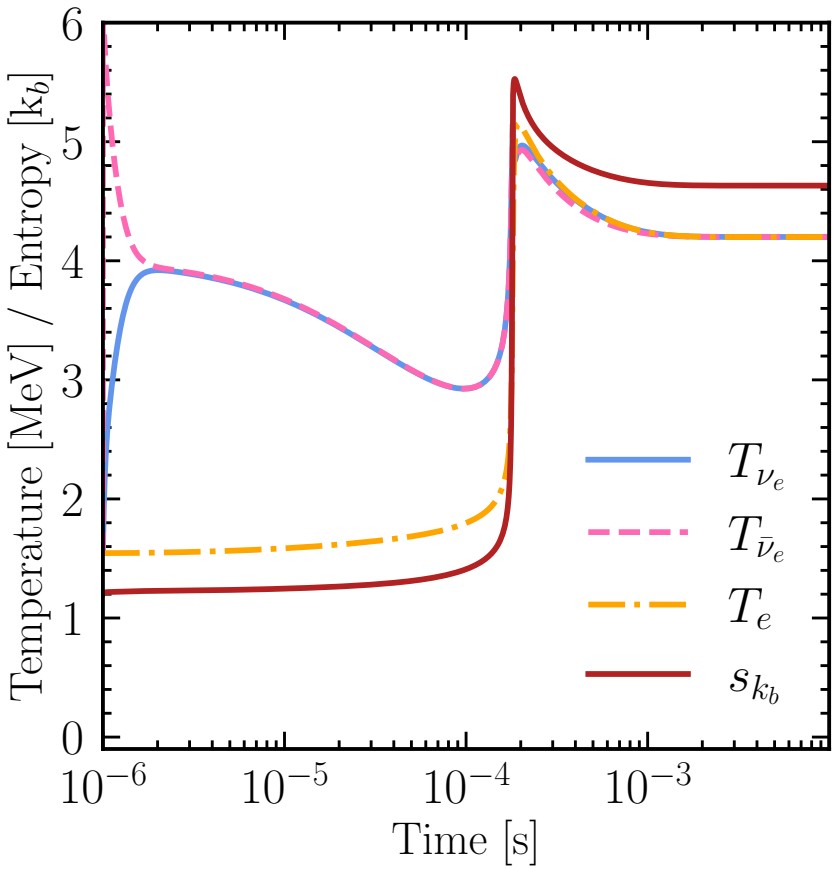
Temperature and chemical potential evolution for leptons

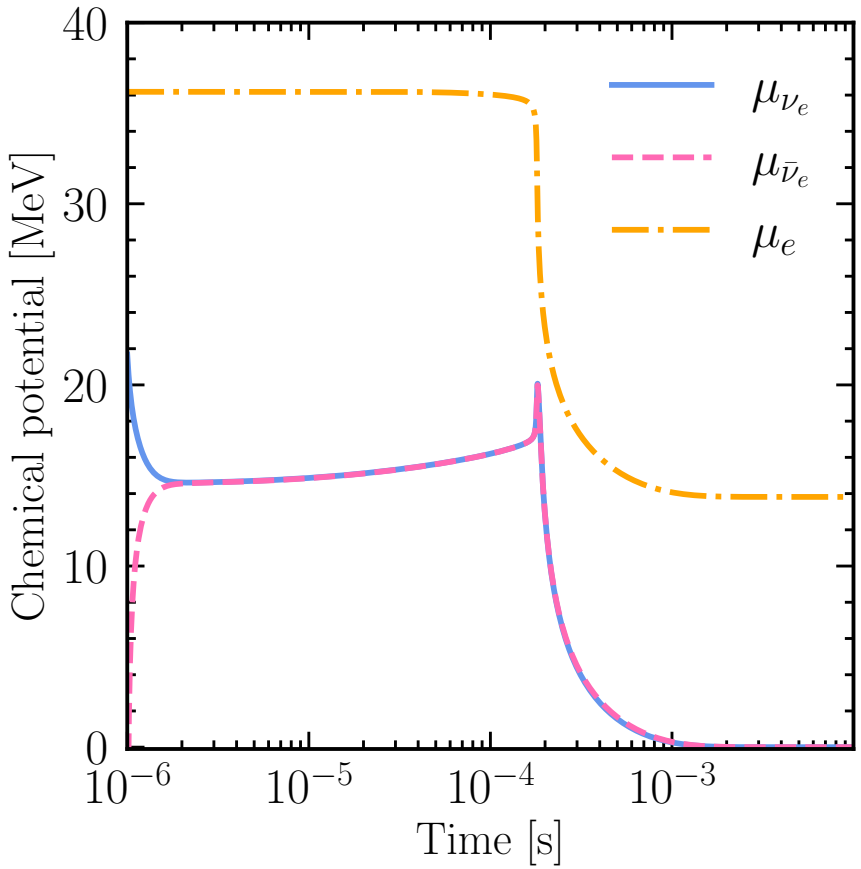
$$\frac{dT_i}{dt} = \left(\frac{\partial \rho_i}{\partial \mu_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial \mu_i} \frac{d\rho_i}{dt} \right) \Big/ \left(\frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i} - \frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial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

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

+**BBAL** (1979) EOS

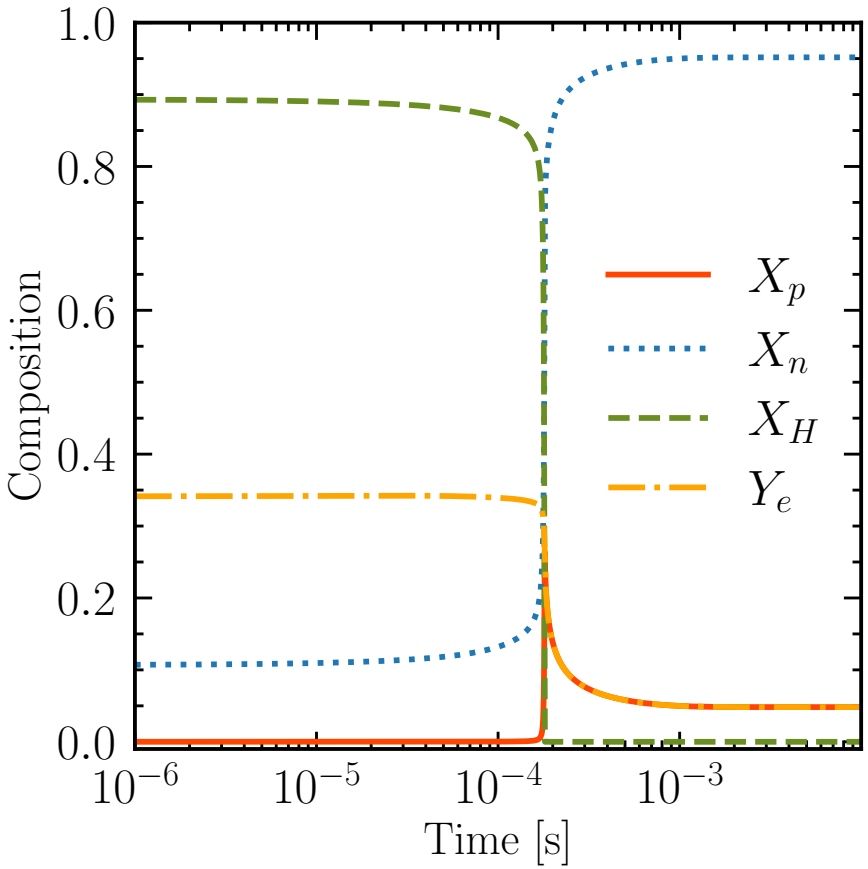
Evolution of Thermodynamical Quantities

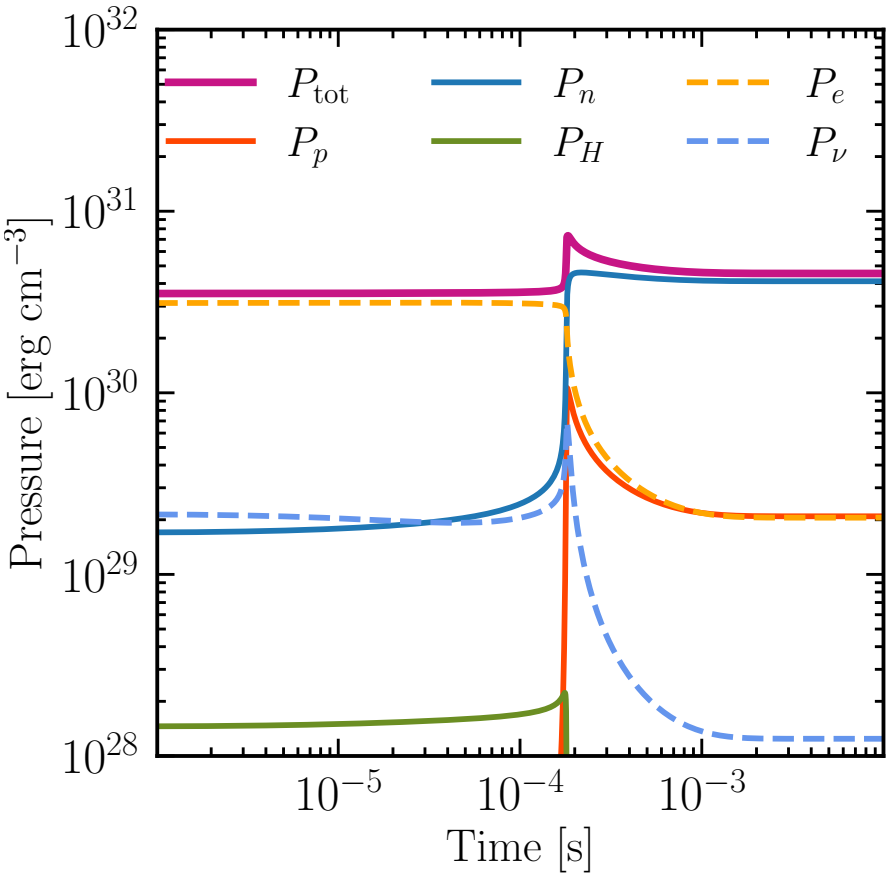




- new interactions quickly equilbrate ν_e and $\bar{\nu}_e$ seas
- enhanced ν_e and e^- captures heat up the matter
- similar results for all flavors equilibration

Composition and Pressure Support of the Core





- 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 νSI - Approximate Evolution

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

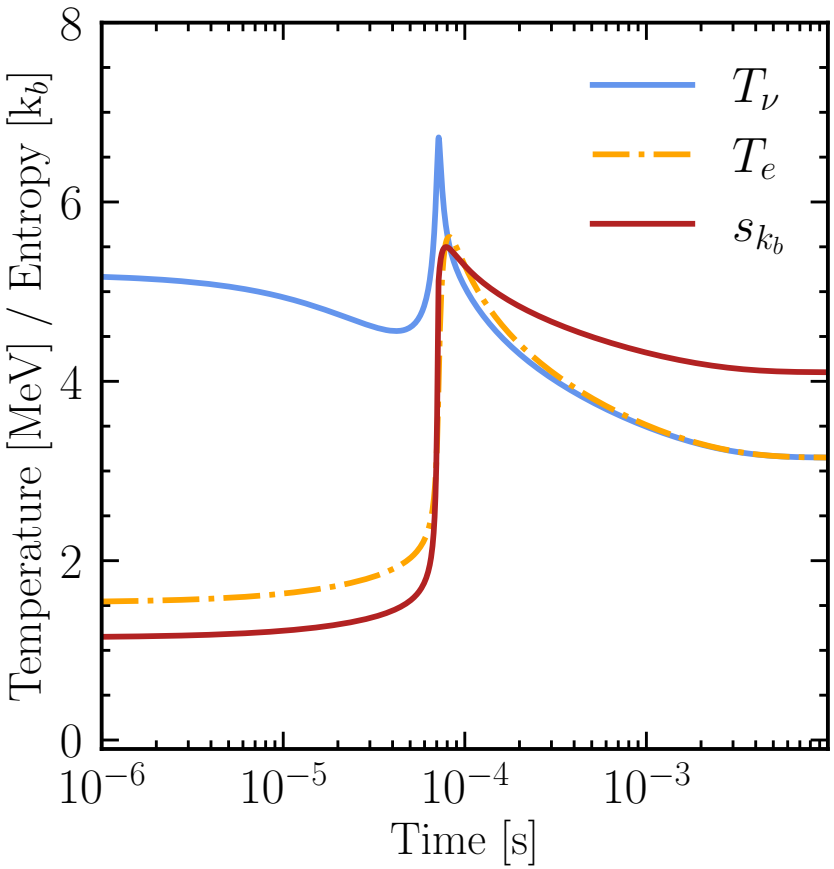
$$\sum_\alpha \left(\frac{dn_{\nu_\alpha}}{dt} + \frac{dn_{\bar{\nu}_\alpha}}{dt} \right) = \frac{\delta n_\nu}{\delta t}$$
$$\sum_\alpha \left(\frac{d\rho_{\nu_\alpha}}{dt} + \frac{d\rho_{\bar{\nu}_\alpha}}{dt} \right) = \frac{\delta \rho_\nu}{\delta t}$$

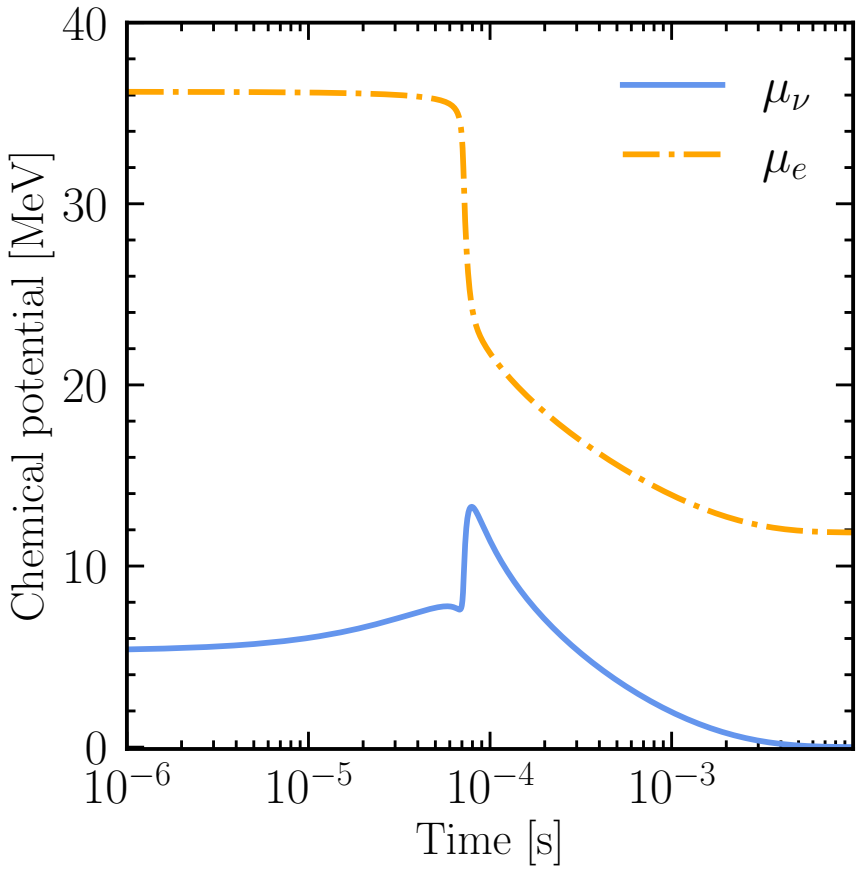
sum over charged-current weak interactions

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

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

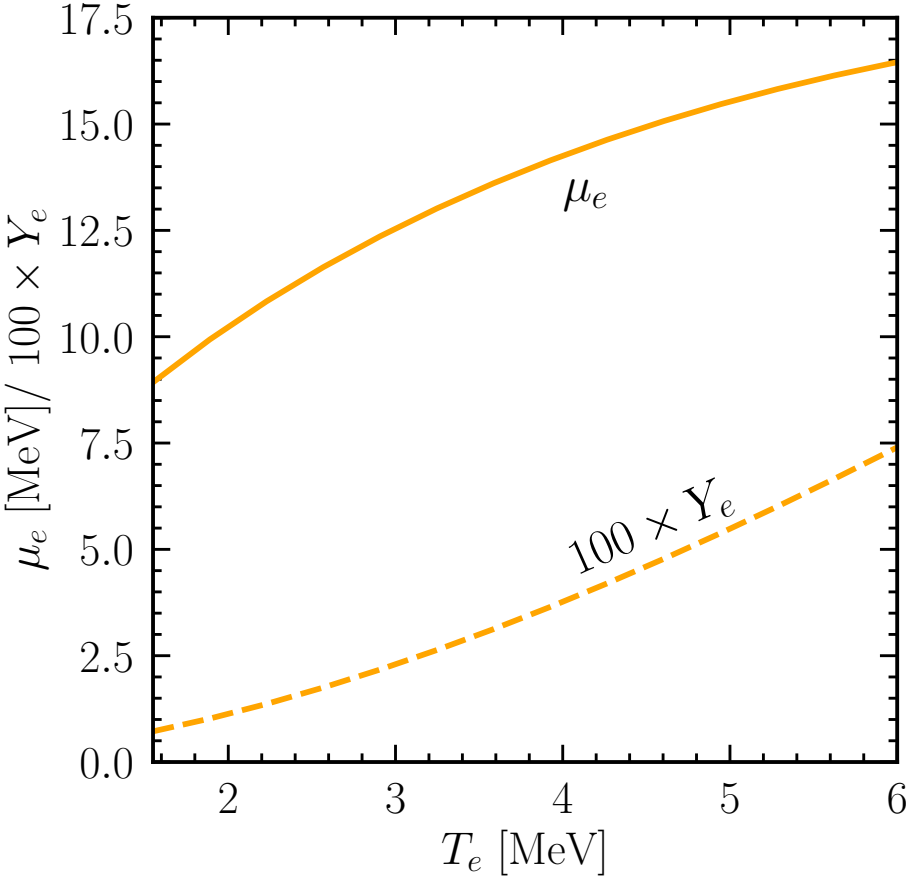
All flavors LNV νSI

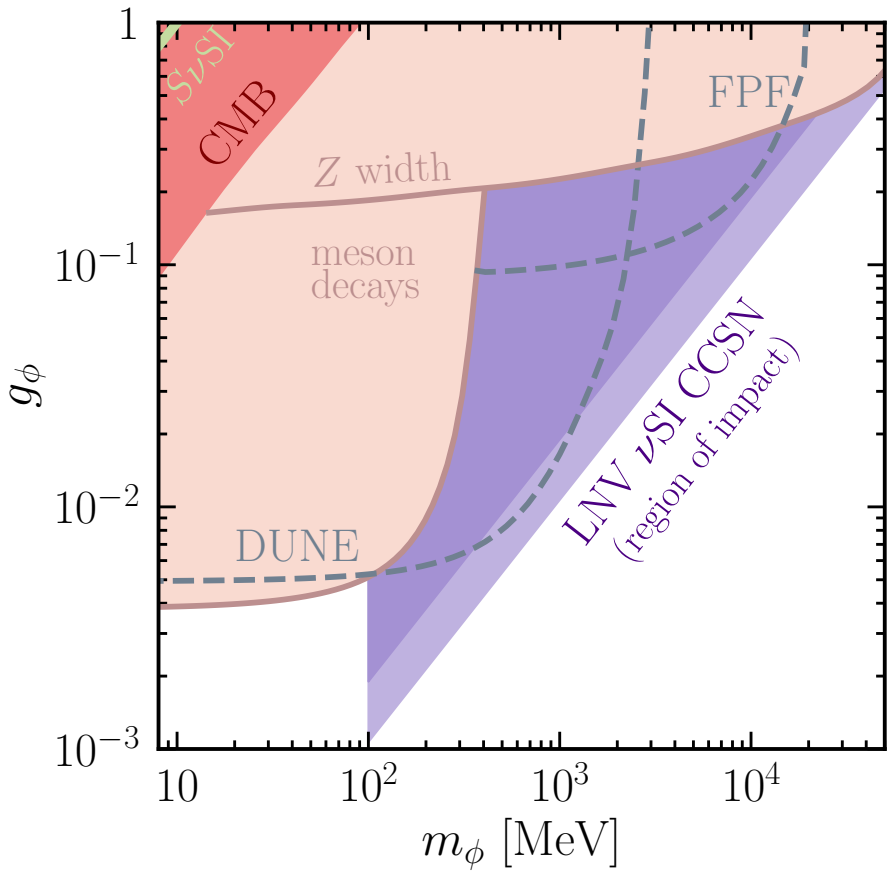




- new interactions quickly equilbrates all 6 neutrino seas
- temperature and entropy increase

New β-equilibrium with LNV νSI





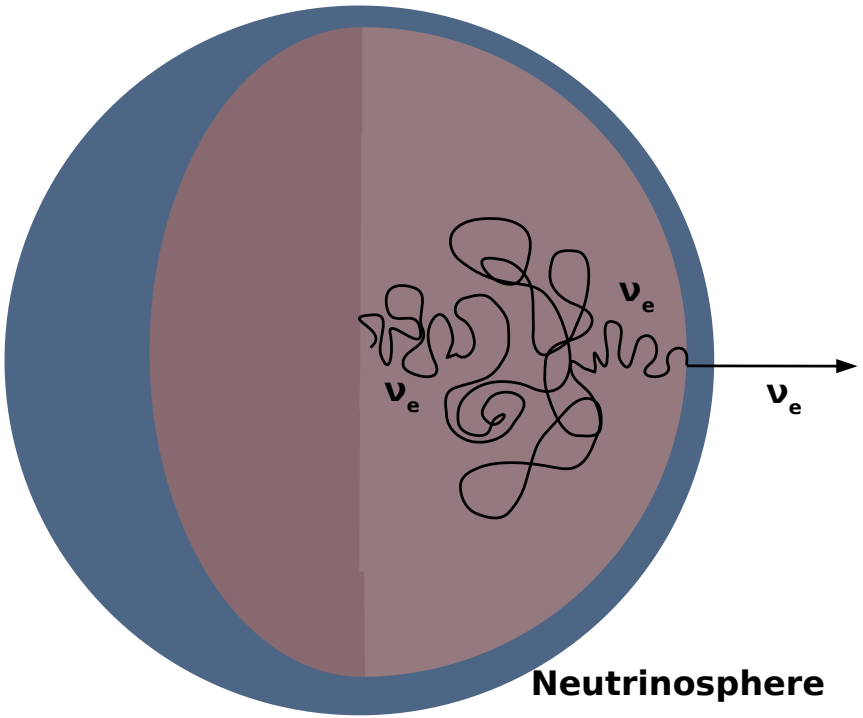
- regardless of the final T_e the new equilibrium has a very low Y_e
  $\mu_e = \delta m_{np} - T_e \ln\left(\frac{Y_e}{1-Y_e}\right)$, with $Y_e = \frac{1}{\pi^2 \rho} \int_0^\infty dp_e \, p_e^2 \, f_e(E_e, T_e, \mu_e)$
- complementarity with future accelerator-based experiments
- multi-flavor neutrino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

arXiv: 2509.07856

Neutrino Trapping and $\beta-$equilibrium



Neutrino trapping

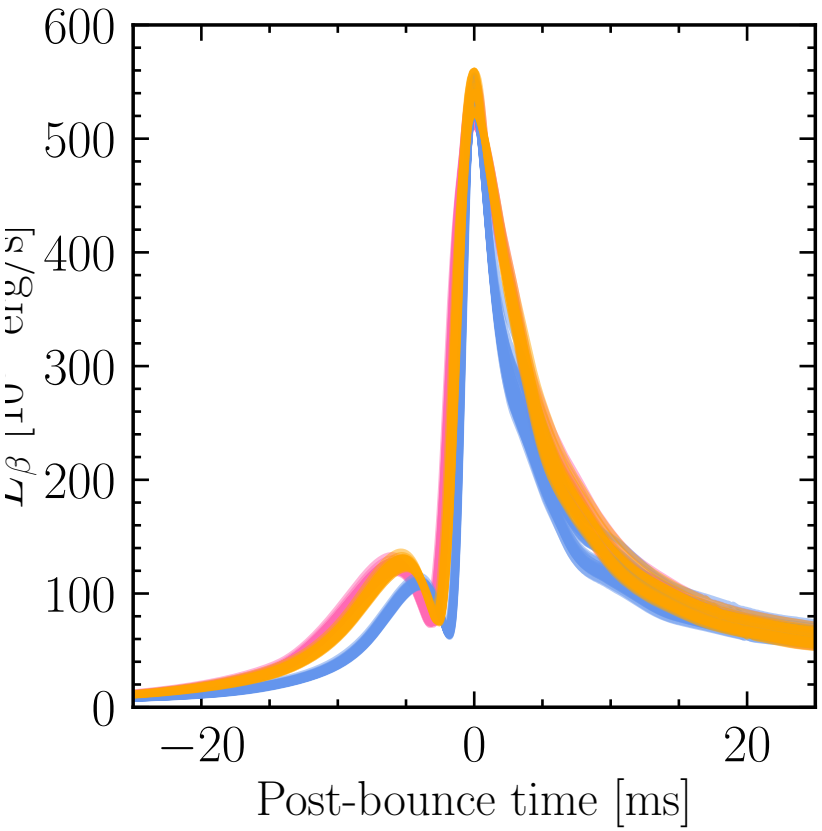
$$A(N,Z) + \nu \rightarrow A(N,Z) + \nu$$

β-equilibrium

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Neutrino Trapping and $\beta-$equilibrium



Neutrino trapping

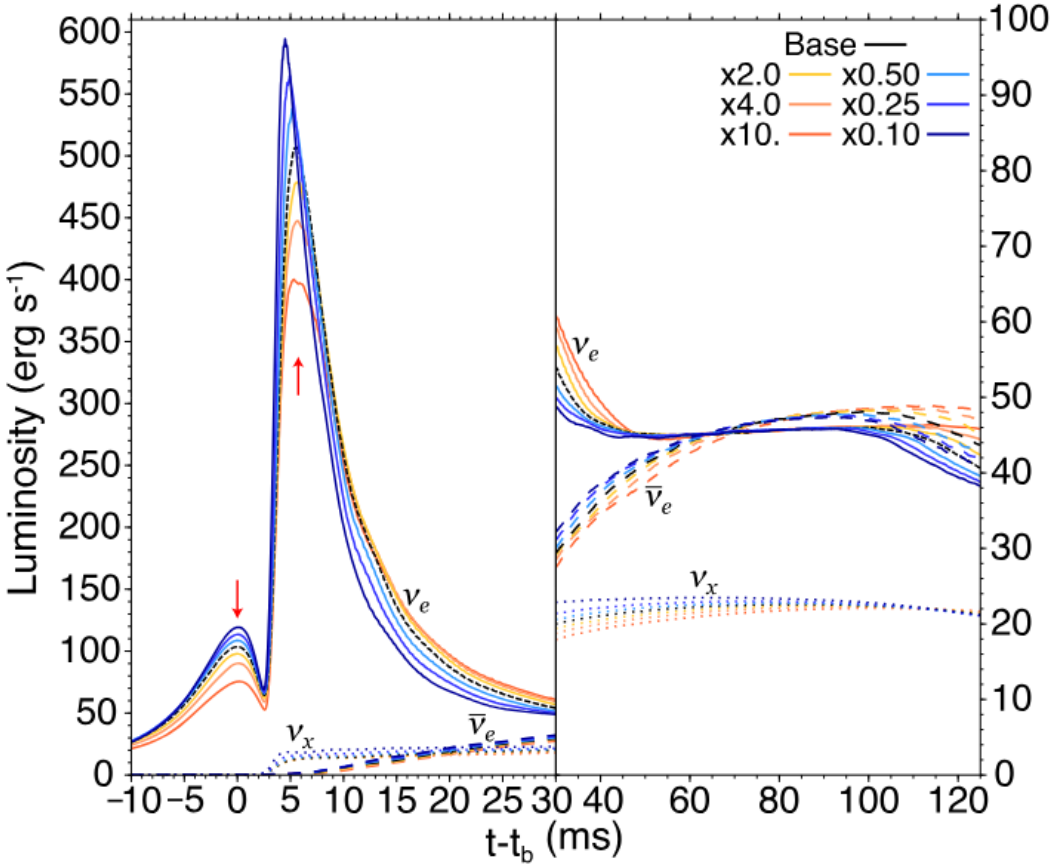
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Neutrino Trapping and $\beta-$equilibrium



Sullivan et al. (2016)

Neutrino trapping

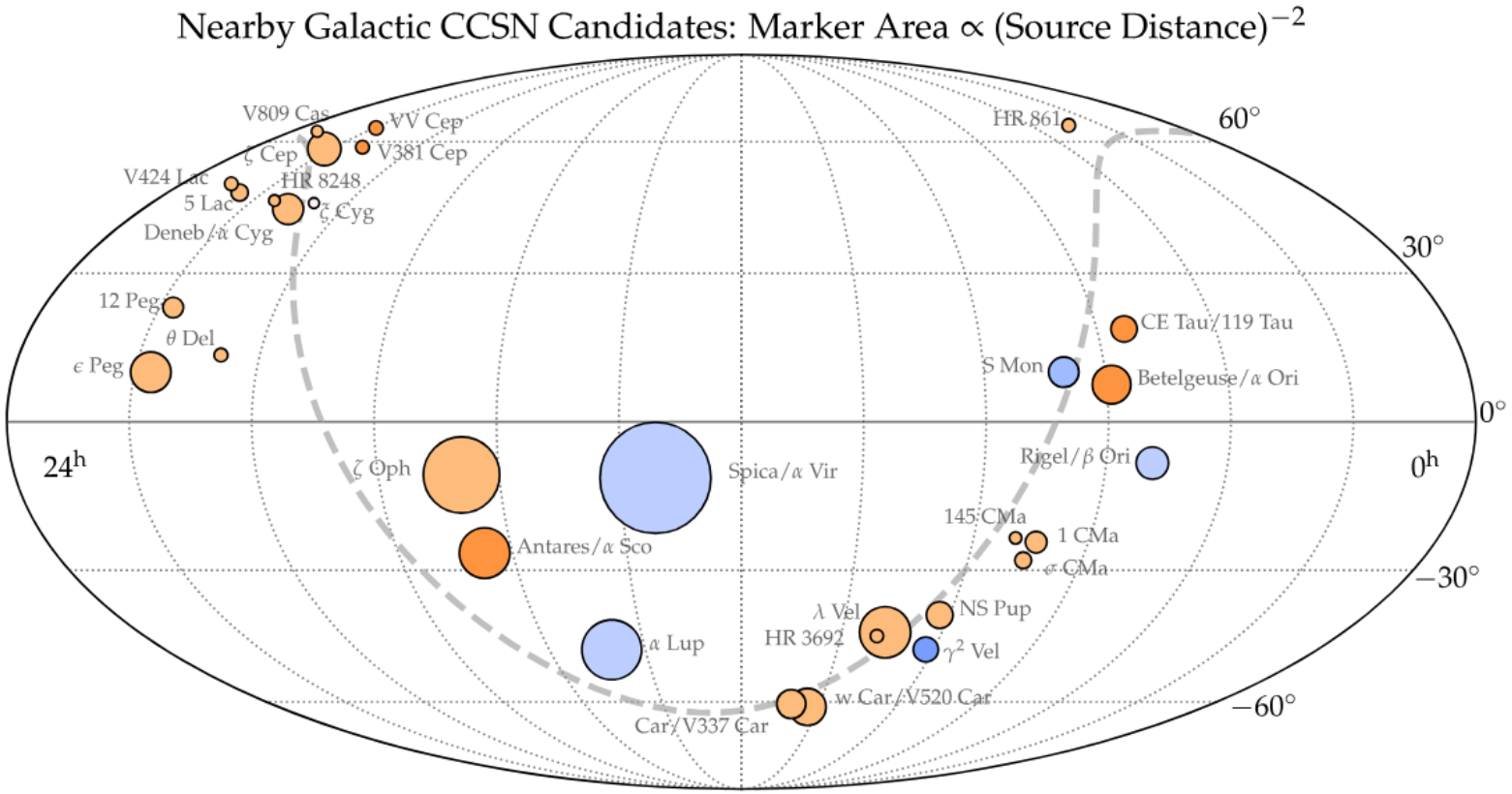
$$A(N,Z) + \nu \rightarrow A(N,Z) + \nu$$

β-equilibrium

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

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

Supernova-ready supergiant stars within ∼1 kpc of Earth



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

SNEWS 2.0 (2021)

Non-standard neutrino-quark interactions

New Interaction Lagrangian

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

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

New Cross Sections

1. Coherent Elastic Neutrino-Nucleus Scattering

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

with NSI $Q_W \to Q'_W = Q_W + Q_W^{\mathrm{NSI}}$

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

2. Elastic Neutrino-Proton Scattering

$$\frac{d\sigma_{\nu \mathrm{p}}}{dE_{\mathrm{p}}} \simeq \frac{G_{\mathrm{F}}^2 m_{\mathrm{p}}^2}{2\pi E_\nu^2}\left(BE_\nu^2 + C(E_\nu - E_{\mathrm{p}})^2 + Dm_{\mathrm{p}}E_{\mathrm{p}}\right)$$

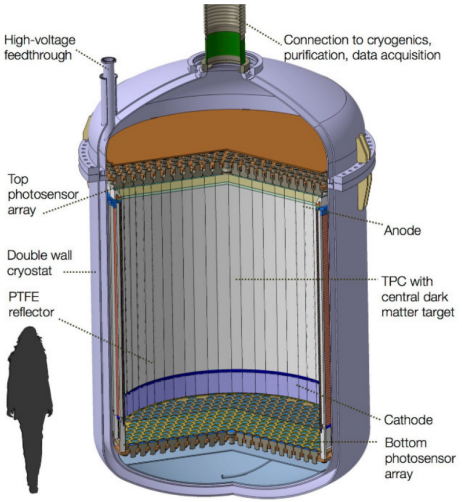
$$B = (c_V + c_A)^2, C = (c_V - c_A)^2, D = (c_V^2 + c_A^2)$$

with NSI $c_V \to c'_V = c_V + \varepsilon^p$

D. Z. Freedman (1973), L. Wolfenstein (1977), B. Dev et al. (2016), Huang et al. (2021)

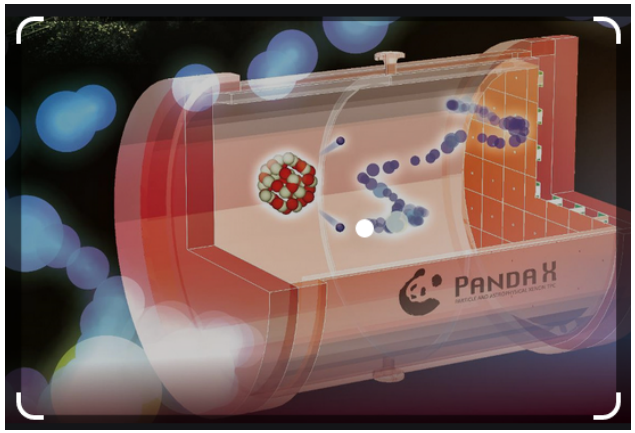
Current and future large CEνNS detectors

XENONnT, DARWIN



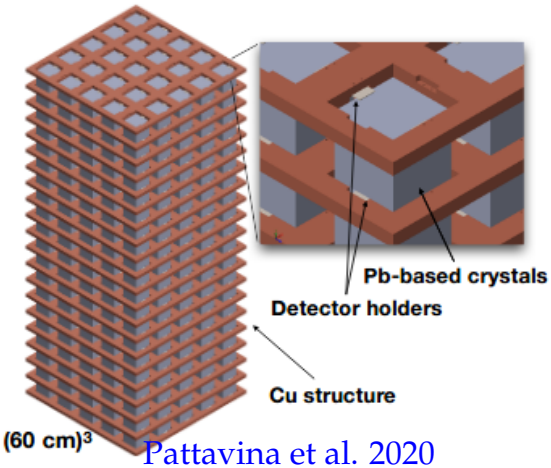
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb, Ar

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

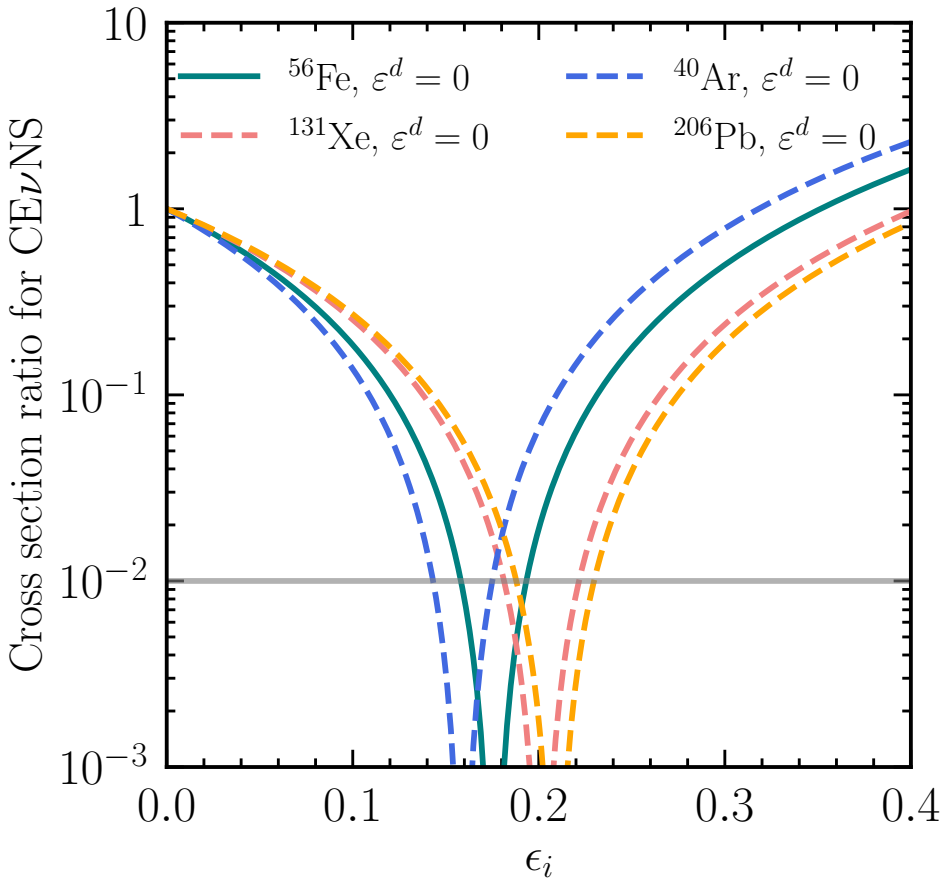
efficiency: $\sim$ 80-100%

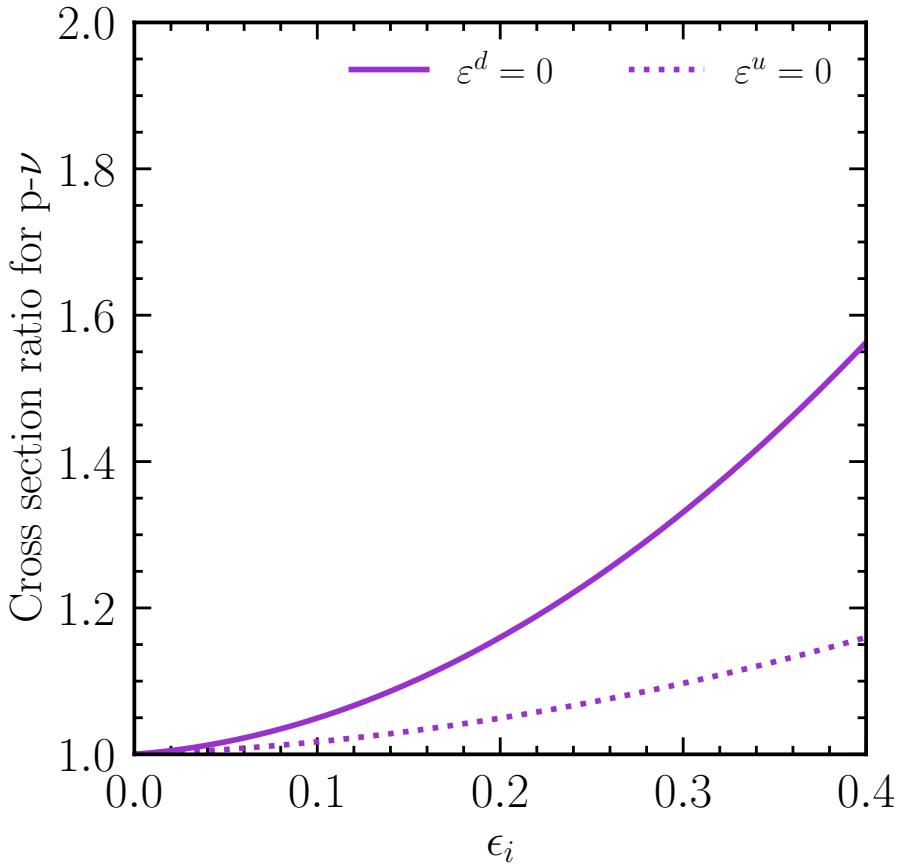
Already very close to detecting solar neutrinos!

PandaX-4T 2.64σ

XENONnT 4.5σ

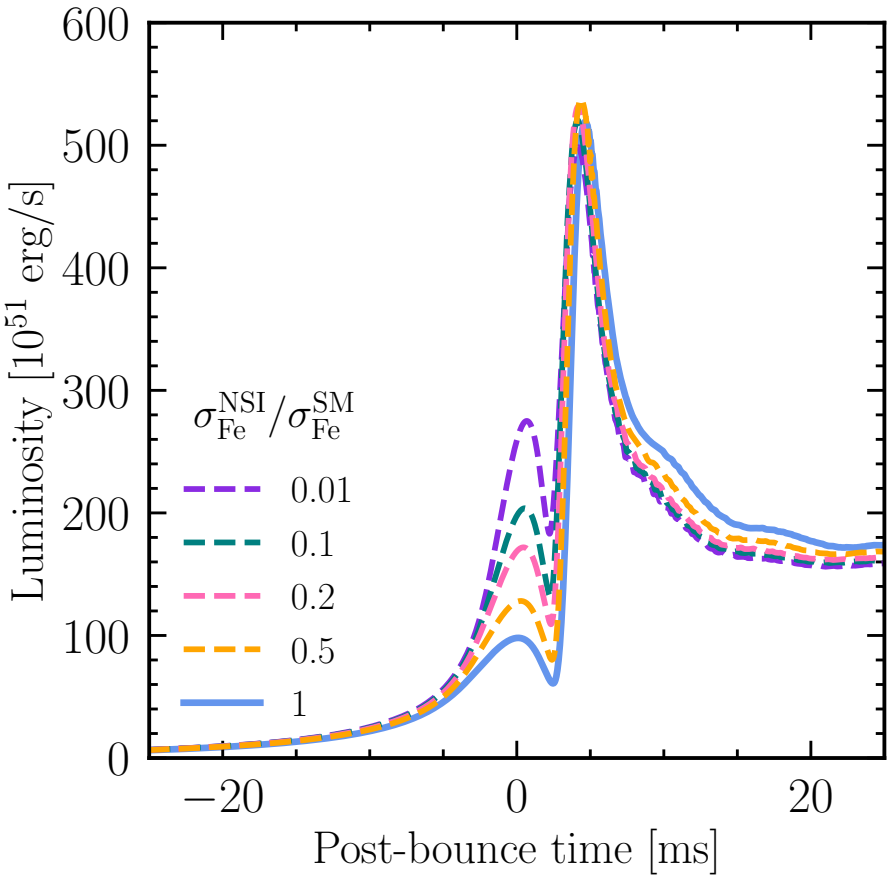
Cross-Section Changes

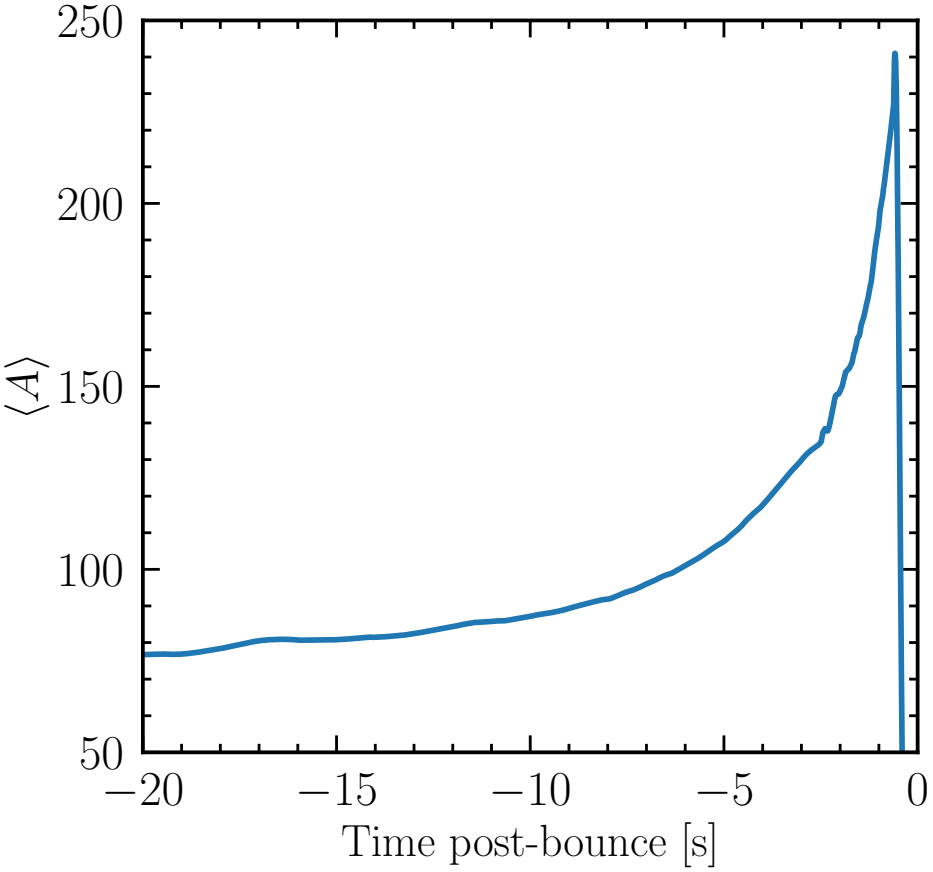




- Extreme changes for CEνNS
- Moderate changes for ν-p scattering

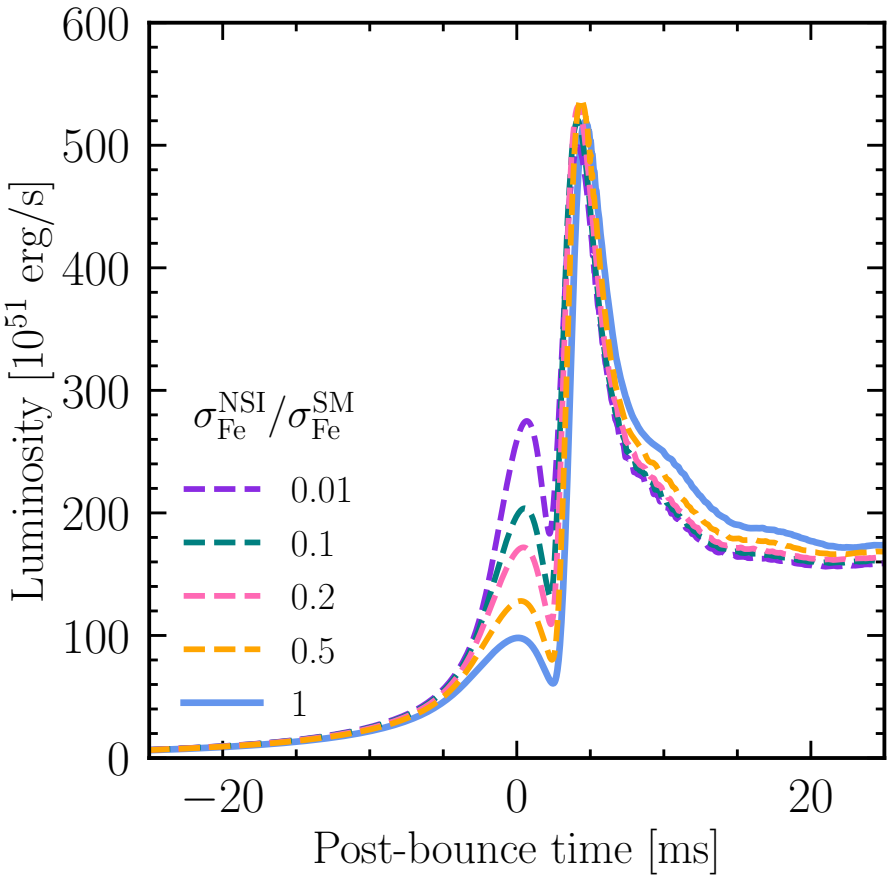
Changes in the neutrino signal: GR1D simulations

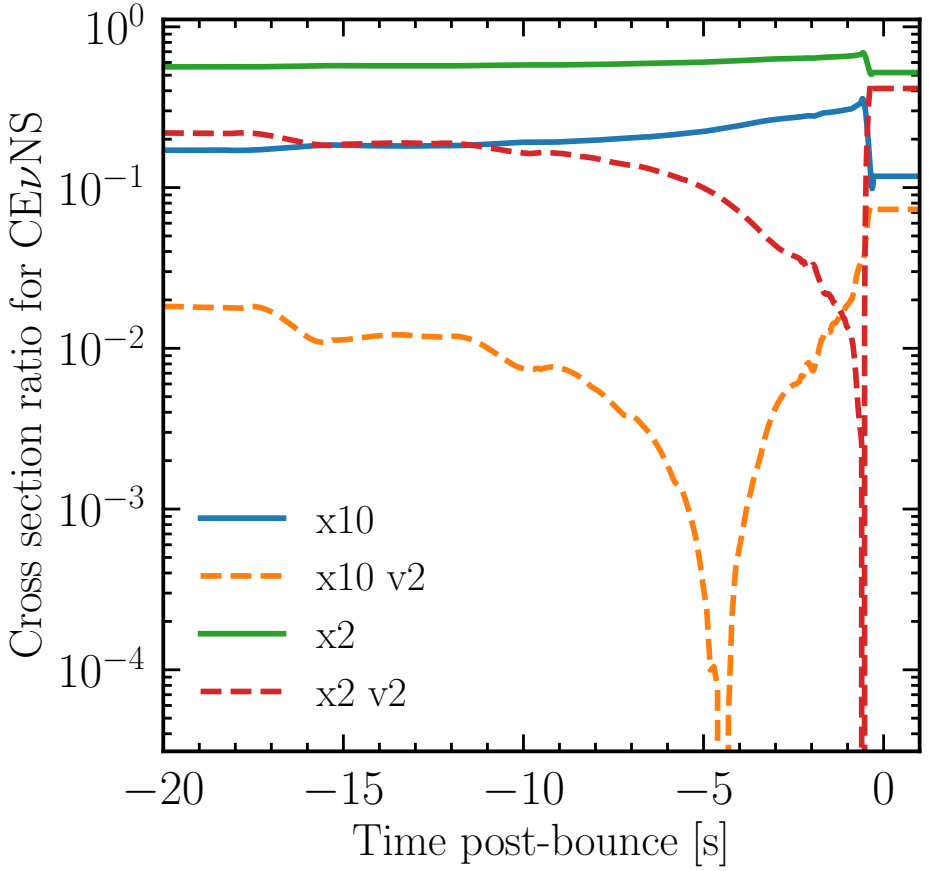




- Significant change in the luminosity pre-bounce
- Pre-bounce - heavy nuclei in the core
- Post-bounce - nucleons in the core

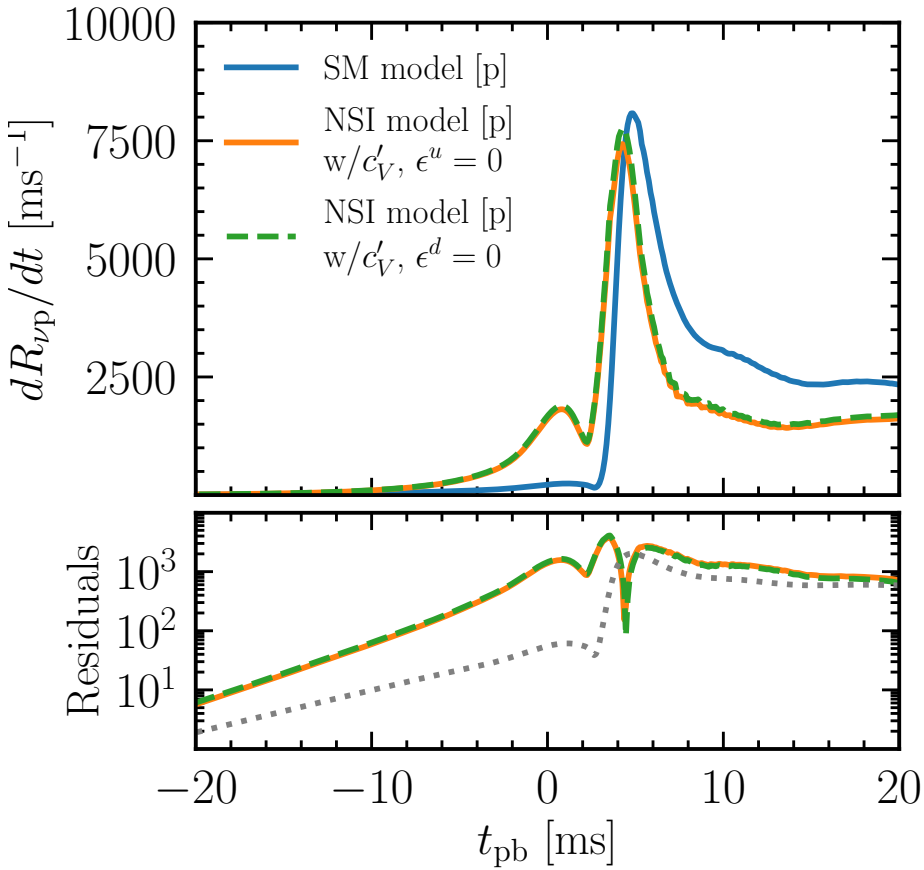
Changes in the neutrino signal: GR1D simulations

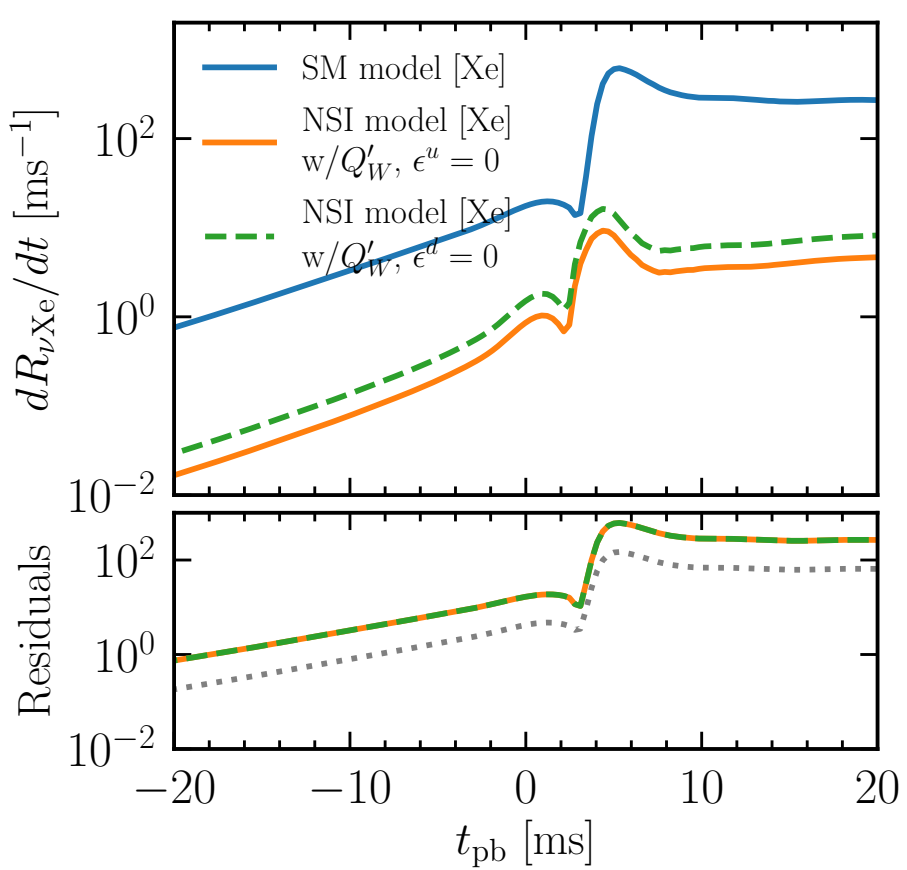




- Significant change in the luminosity pre-bounce
- Pre-bounce - heavy nuclei in the core
- Post-bounce - nucleons in the core

Rates in JUNO and DM detectors for the Betelgeuse

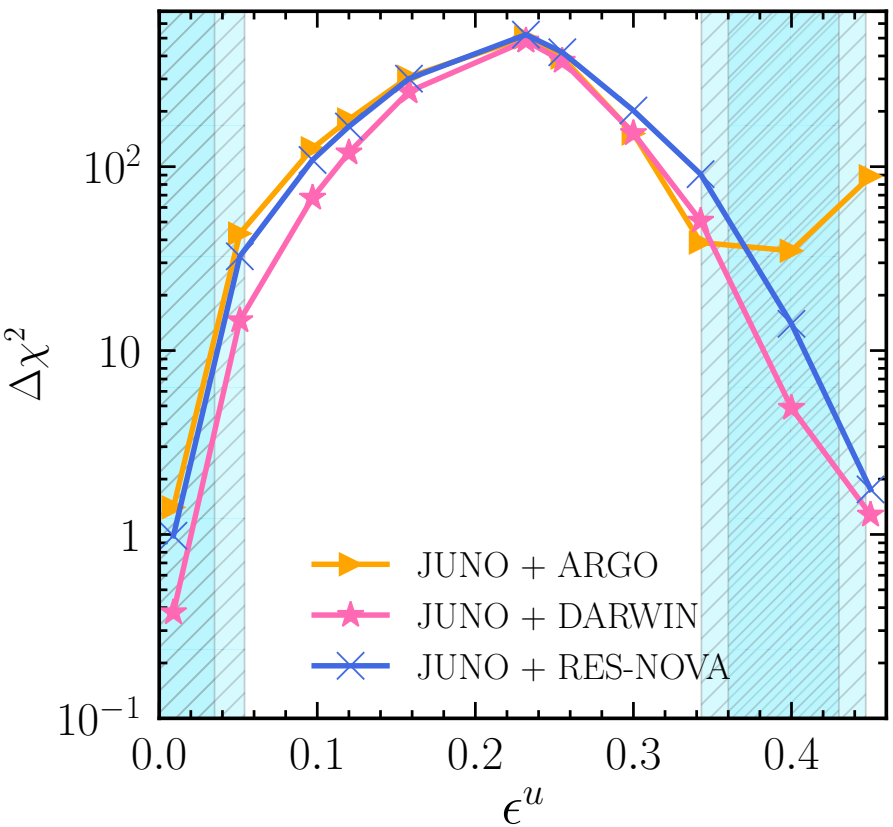


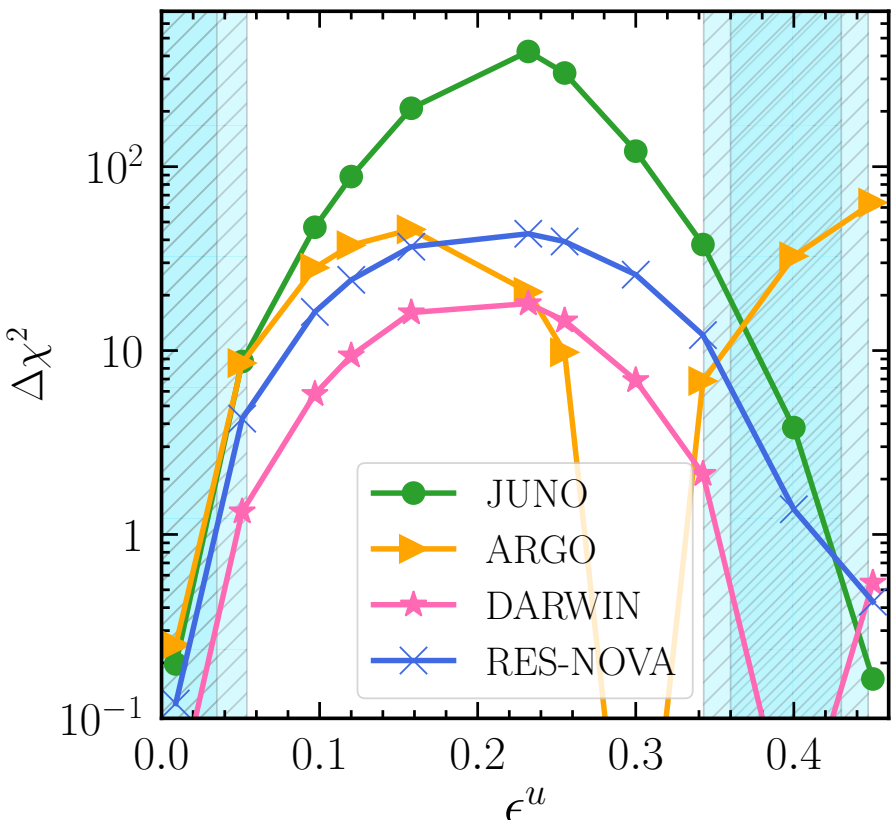


- JUNO - rate changed for the infall signal
- DARWIN - rate changed always
- approximately opposite effects

Statistical Analysis

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





Diffuse supernova neutrino background

Why focus only on a single rare event?

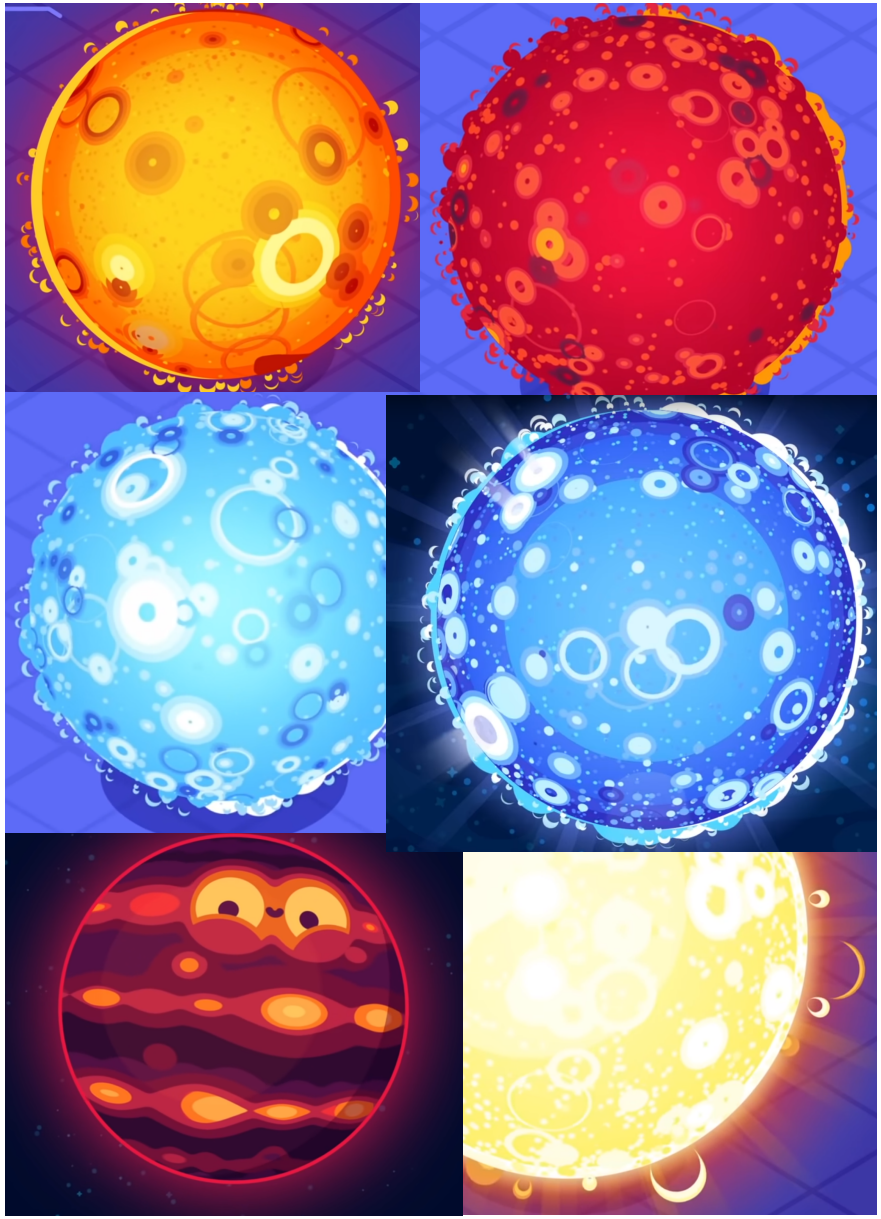


Single galactic SN event

- rare event
- precise 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

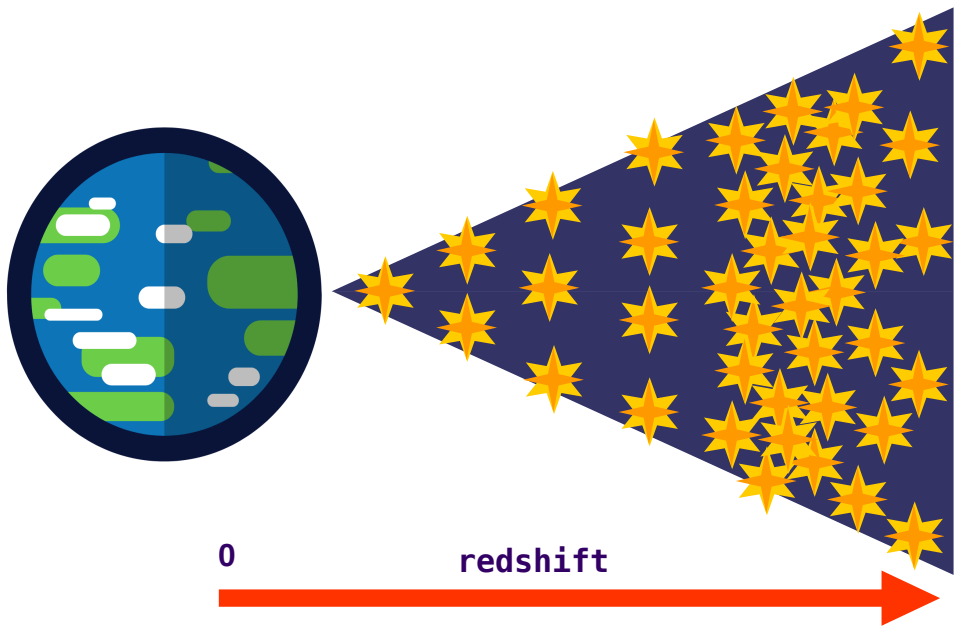
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}} \left[f_{\rm CC-SN}F_{\nu_\beta,\rm CC-SN}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,\rm BH-SN}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

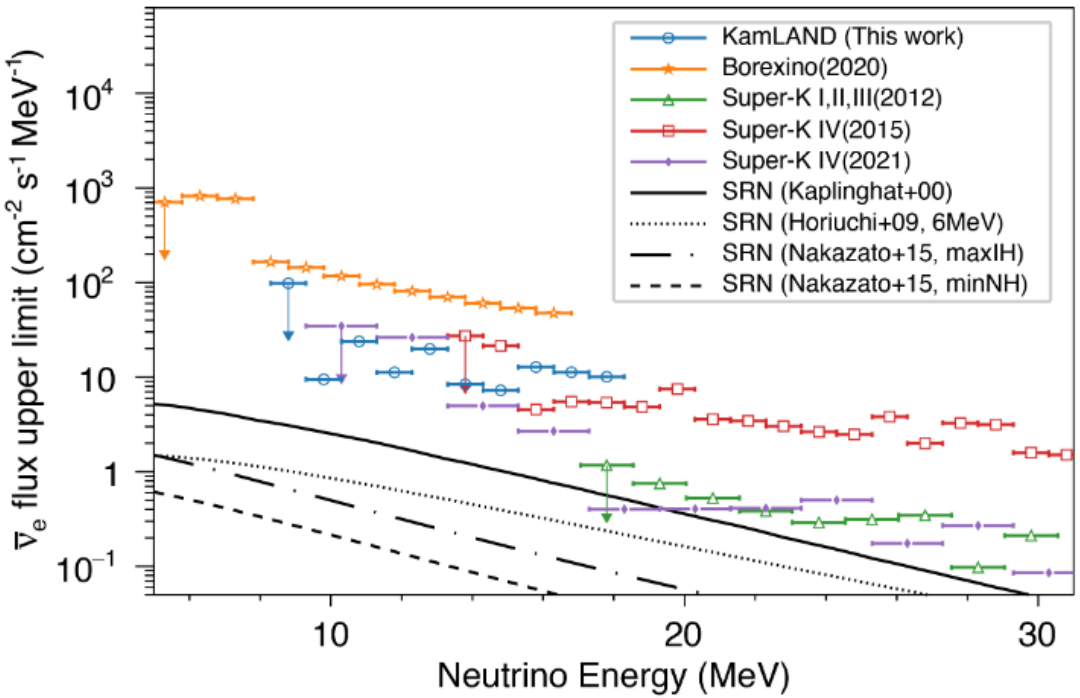
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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:

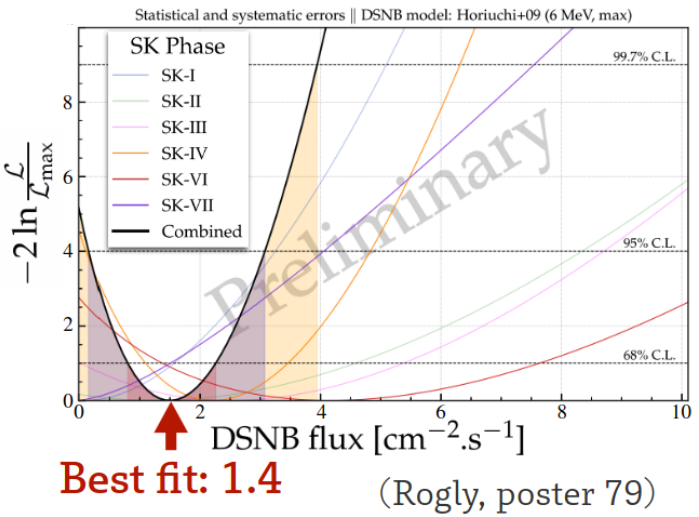
- $\bar{\nu}_e \approx 2.7\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3$ MeV SK collab. (2021), SK collab. (2023)
  soon detected by SK (Gd) Beacom, Vagins (2004) and JUNO JUNO collab. (2021)
- $\nu_e \approx 19\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu\ \epsilon\ [22.9, 36.9\ \mathrm{MeV}]$ SNO collab. (2020)
  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

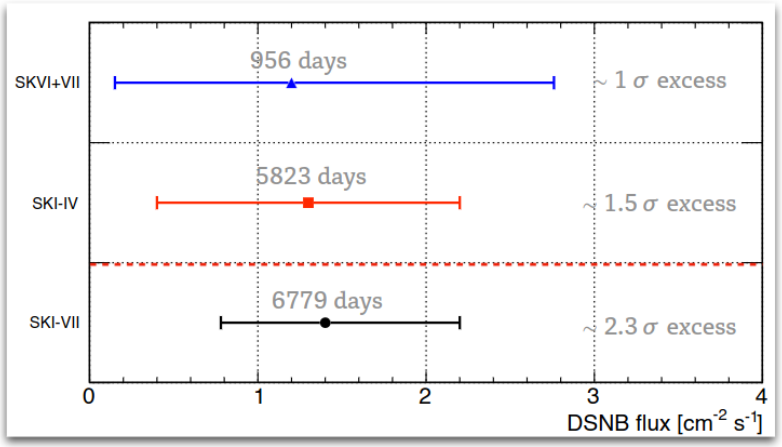
Spectrum fitting analysis to extract significance

- 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

Recent SK paper with Gd only results: ~1.2σ 2511.02222

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

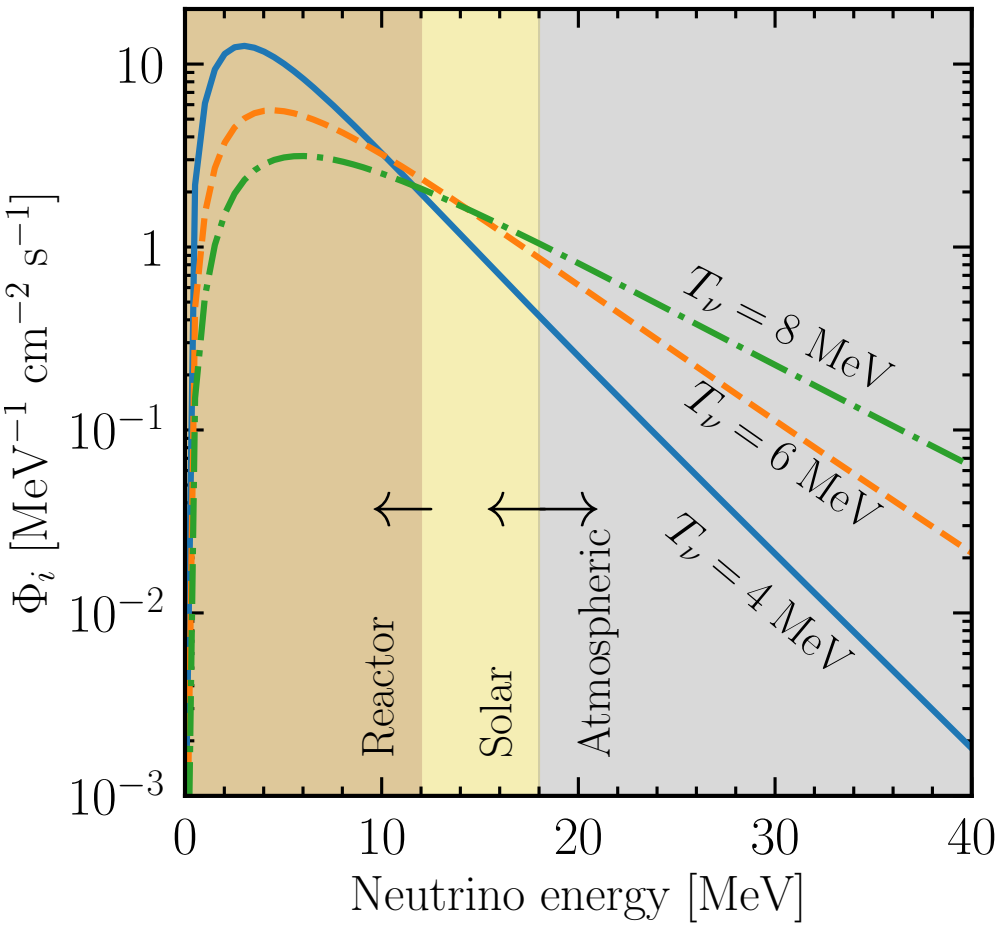
Why and how to measure low-energy atmospheric neutrinos?

In collaboration with J. F. Beacom

PRD 108 (2023) 4, 043035

Diffuse Supernova Neutrino Background (DSNB)

AMS (2022)

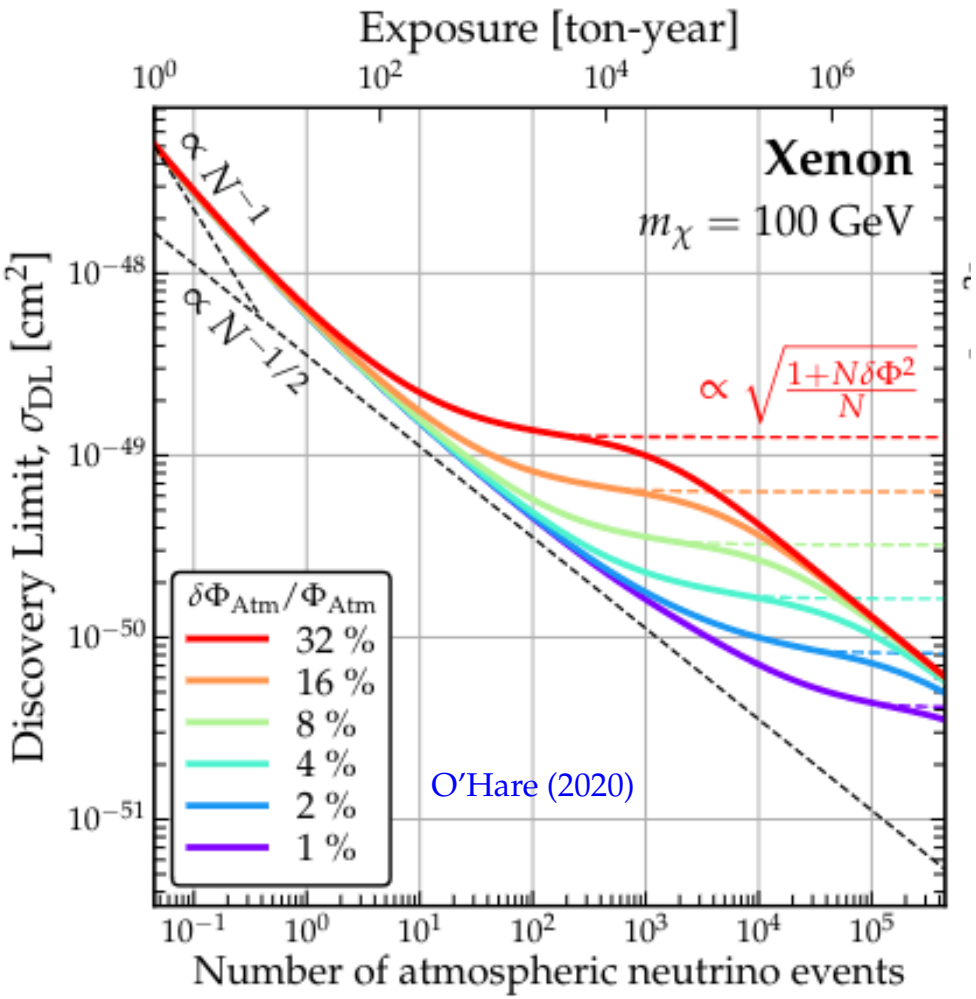


- DSNB →
  isotropic and stationary
  guaranteed neutrino flux

  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

Primary production channels

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

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

Non-oscillated flavor ratio

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

Sources of uncertainty

solar wind modulations

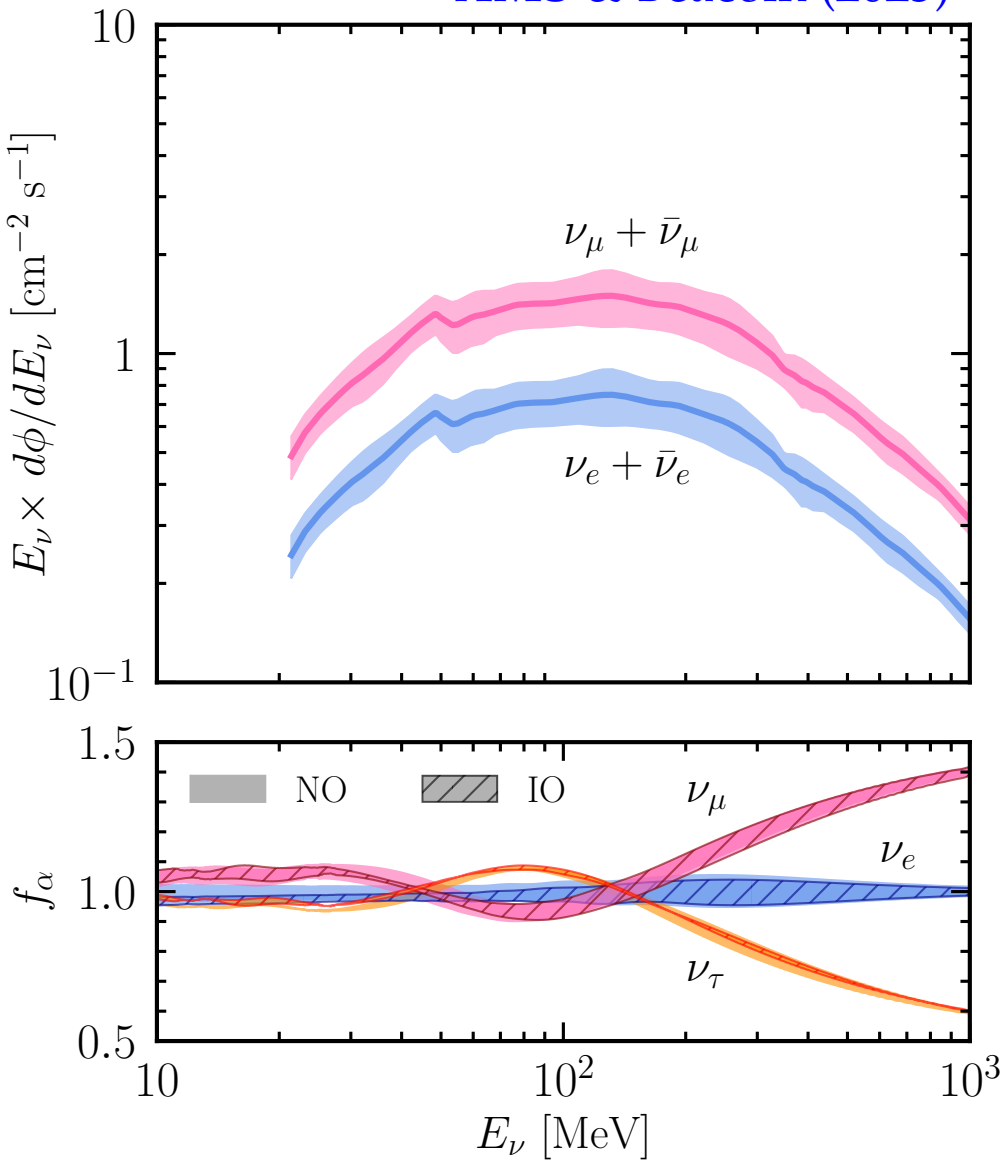
Earth's geomagnetic field

Oscillated flavor ratio

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

Past measurements: energies $>$ 100 MeV

AMS & Beacom (2023)



Neutrino flux: Zhuang (2021)

Mixing: NuCraft

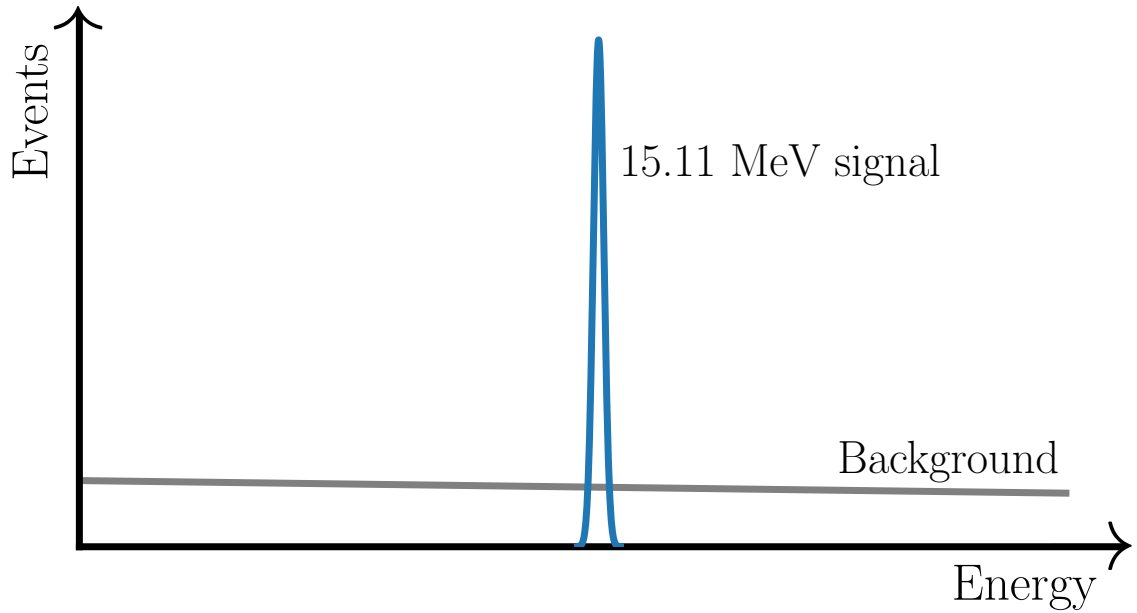
Distinctive nuclear channels in JUNO

AMS & Beacom (2023)

Neutral current channels

$$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$$
$${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma,$$

$$\bar{\nu} + {}^{12}\mathrm{C} \to \bar{\nu} + {}^{12}\mathrm{C}^*$$
$${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma,$$



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

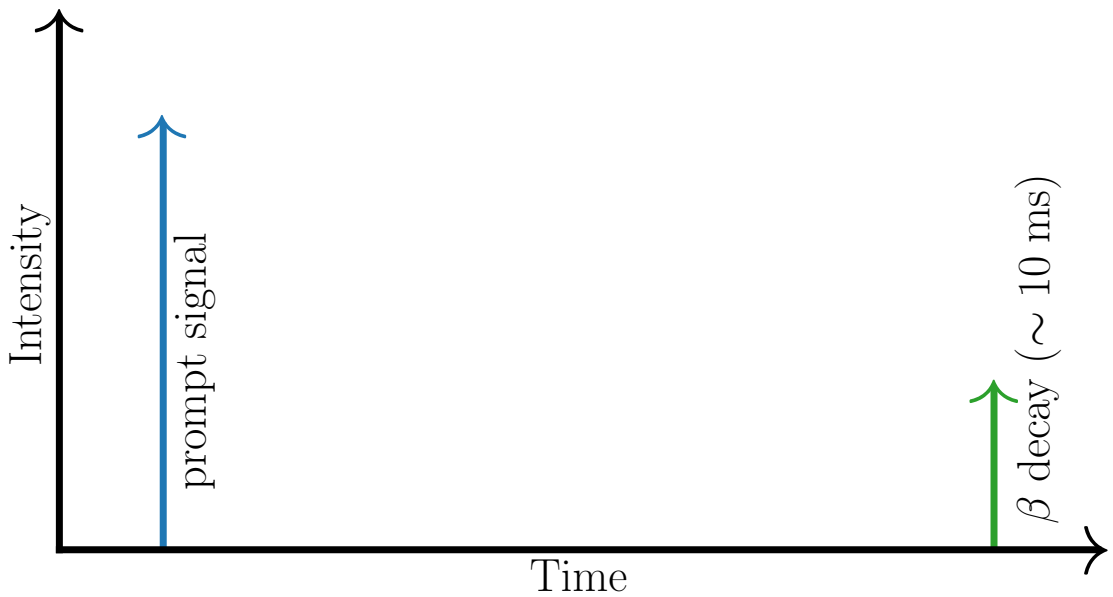
Distinctive nuclear channels in JUNO

AMS & Beacom (2023)

Charged current channels: ν_e

$$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e,$$

$$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{B}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e.$$



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

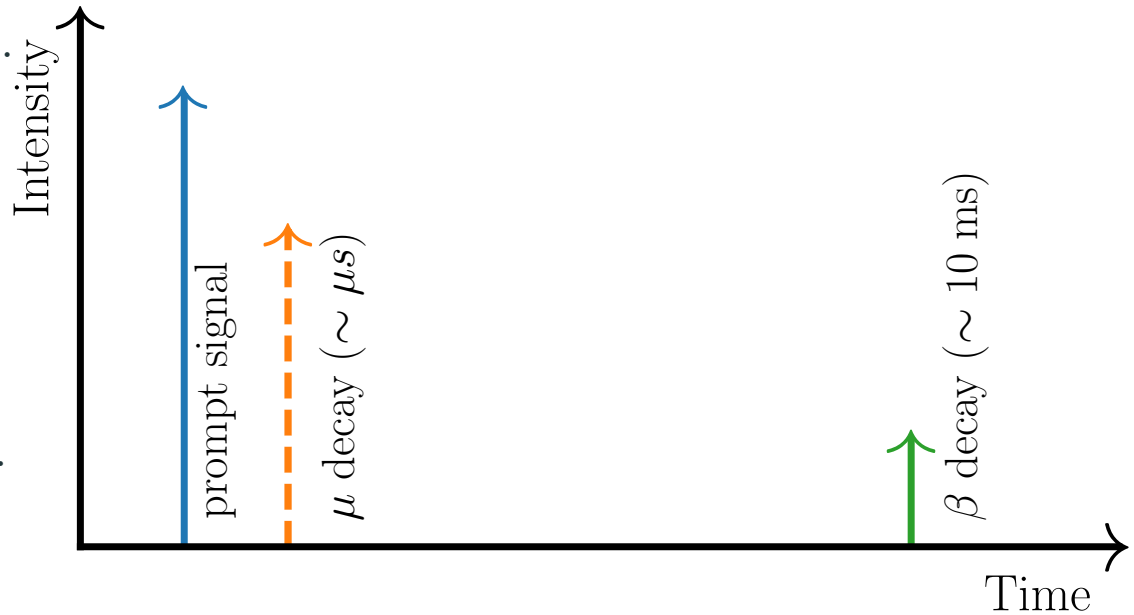
Distinctive nuclear channels in JUNO

AMS & Beacom (2023)

Charged current channels: ν_μ

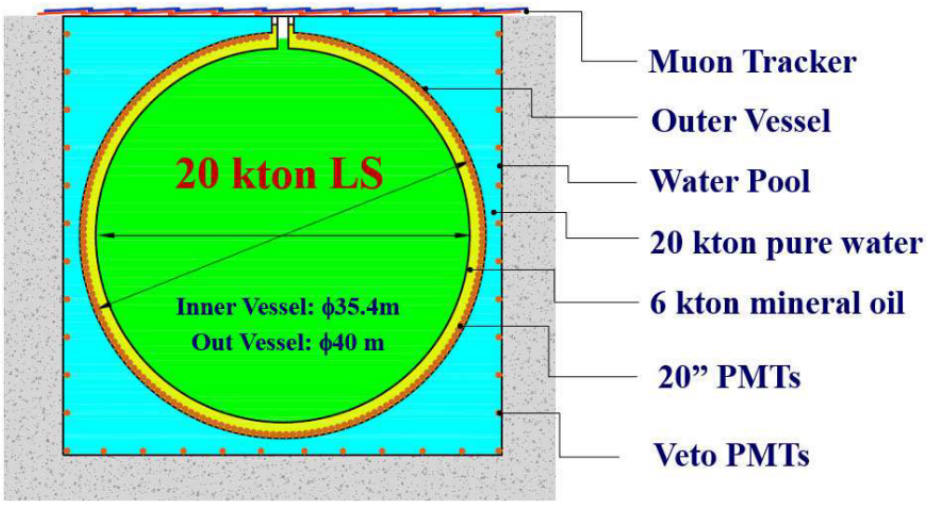
$$\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu,$$

$$\bar{\nu}_\mu + {}^{12}\mathrm{C} \to \mu^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{B}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu.$$



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

The Jiangmen Underground Neutrino Observatory (JUNO)

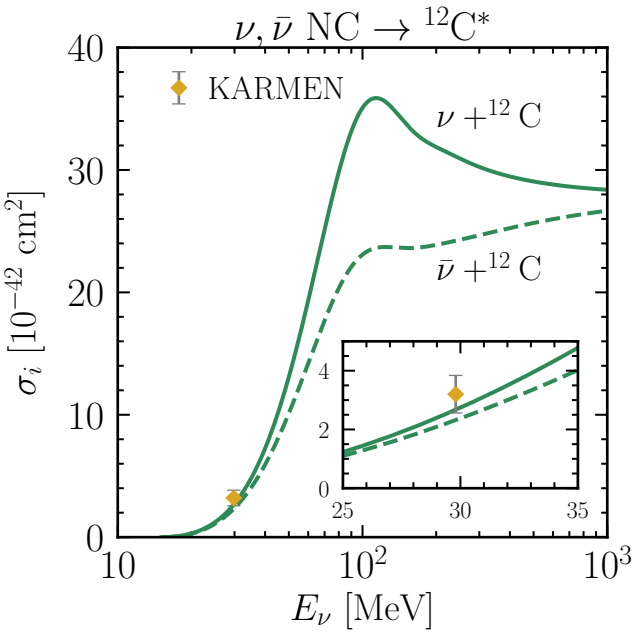


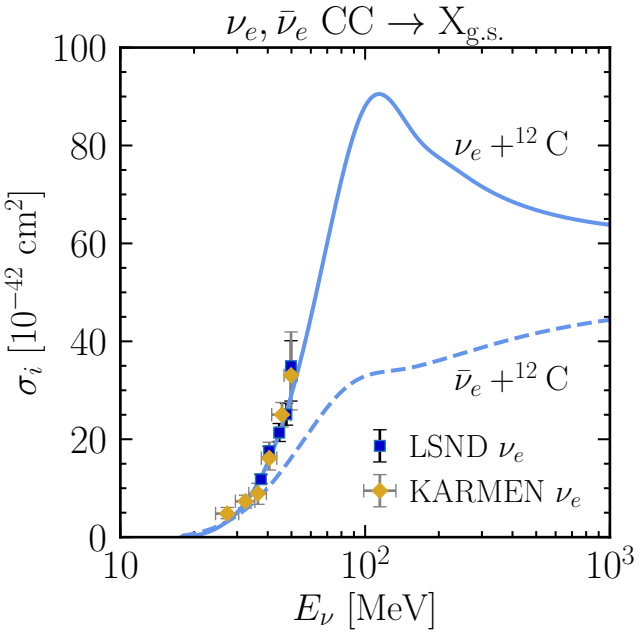


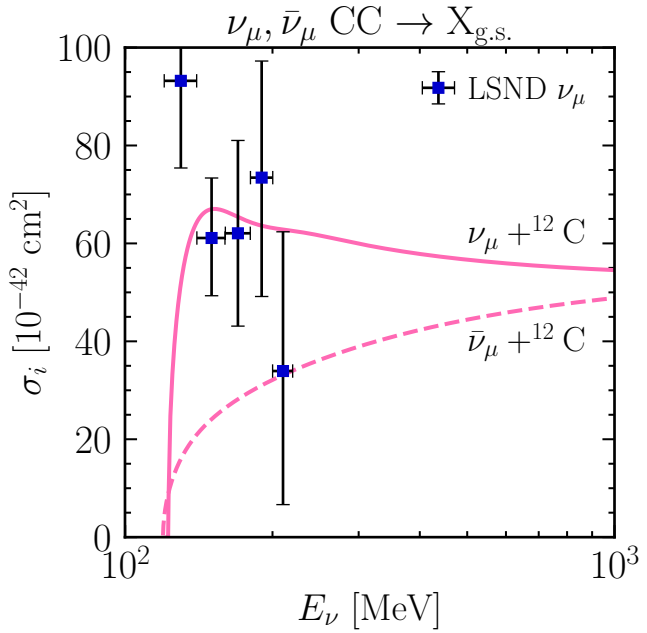
- large-scale carbon-based liquid scintilator detector
- already operational!
- excellent energy resolution $\lesssim 3\%$
- excellent spatial resolution $\lesssim 10$ cm
- low backgrounds in the considerd channels

JUNO inclusive studies: Cheng et al. (2020), Cheng et al. (2020), JUNO Collaboration (2022)

Cross section: elementary particle treatment (EPT)







- superallowed transitions from 0^+ to 1^+ states in A=12 triad
- the exclusive ν - ^{12}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

Fukugita et al. (1988), Pourkaviani & Mintz (1990), Kubodera & Nozawa (1993), Engel et al. (1996), Kolbe (1996), Samana et al. (2010)

Atmospheric neutrino detection in JUNO

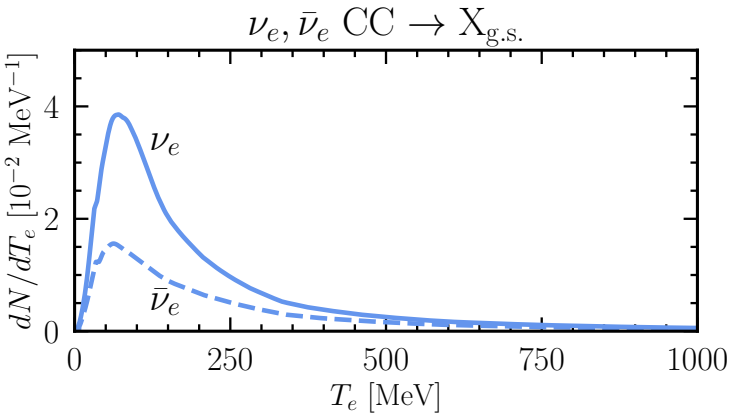
NC channel detection: single events

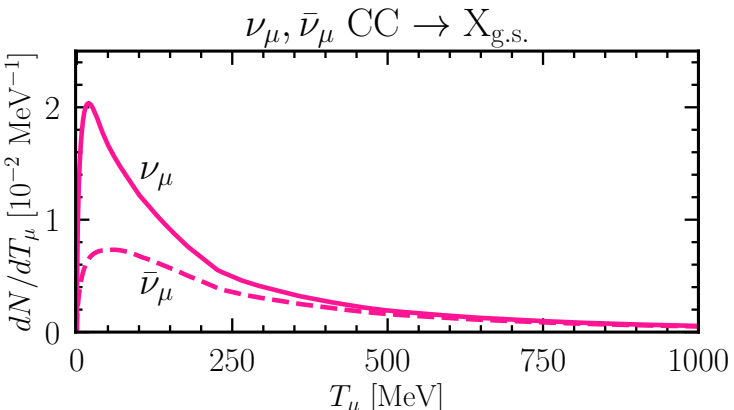
Irreducible BG: solar and DSNB ν

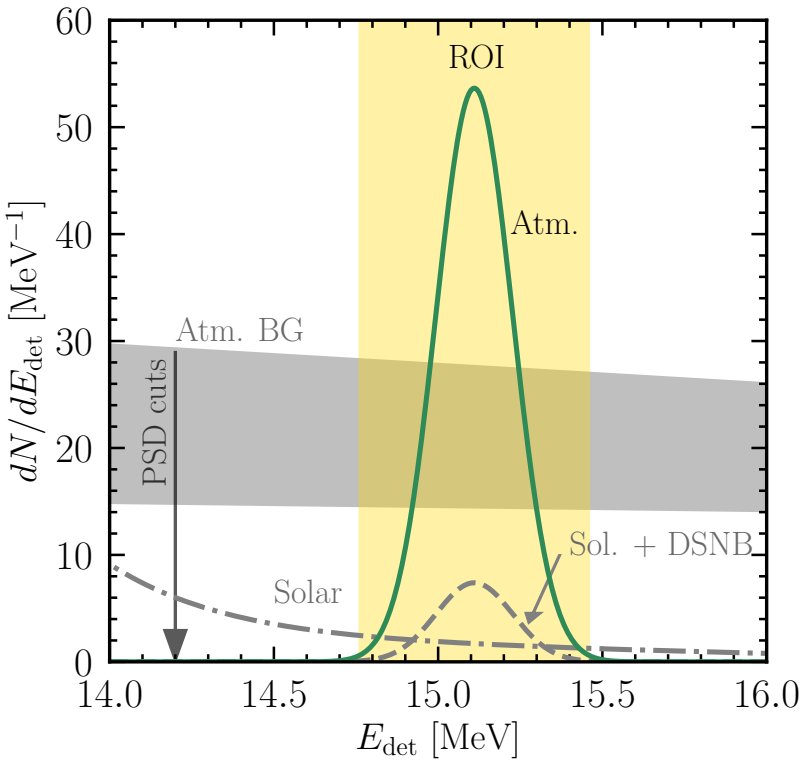
Reducible BG: atm. ν - p scattering

85 kton yr exposure → 25(40)%

uncertainty of the atmospheric ν rate







CC channel detection: coincidence events

Irreducible BG: accidental coincidences

Rate per 85 kton yr: ∼0.0004

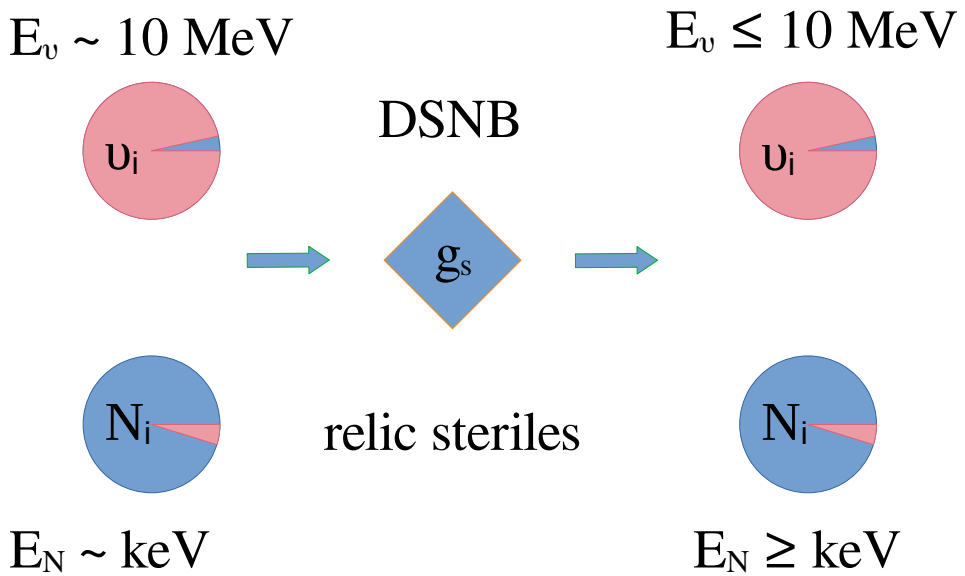
essentially background free channels

How to probe new physics in DSNB with large uncertainties?

In collaboration with A. B. Balantekin, G. Fuller, A. Ray,

PRD 108 (2023) 12, 123011

Do KeV-mass Sterile Neutrinos Have Self-Interactions?



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)

Modeling secret neutrino interactions in DSNB

Modified DSNB flux

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

Probability of interaction

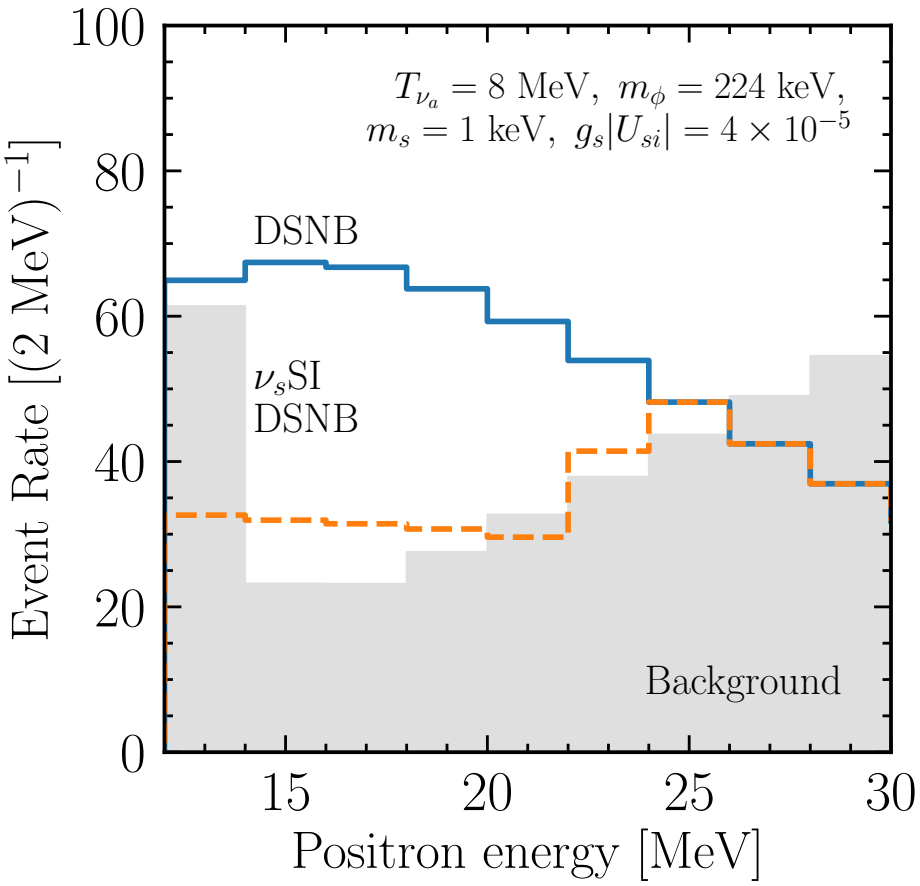
$$P_i(E_\nu, z) = e^{-\tau_i(E_\nu, z)}$$

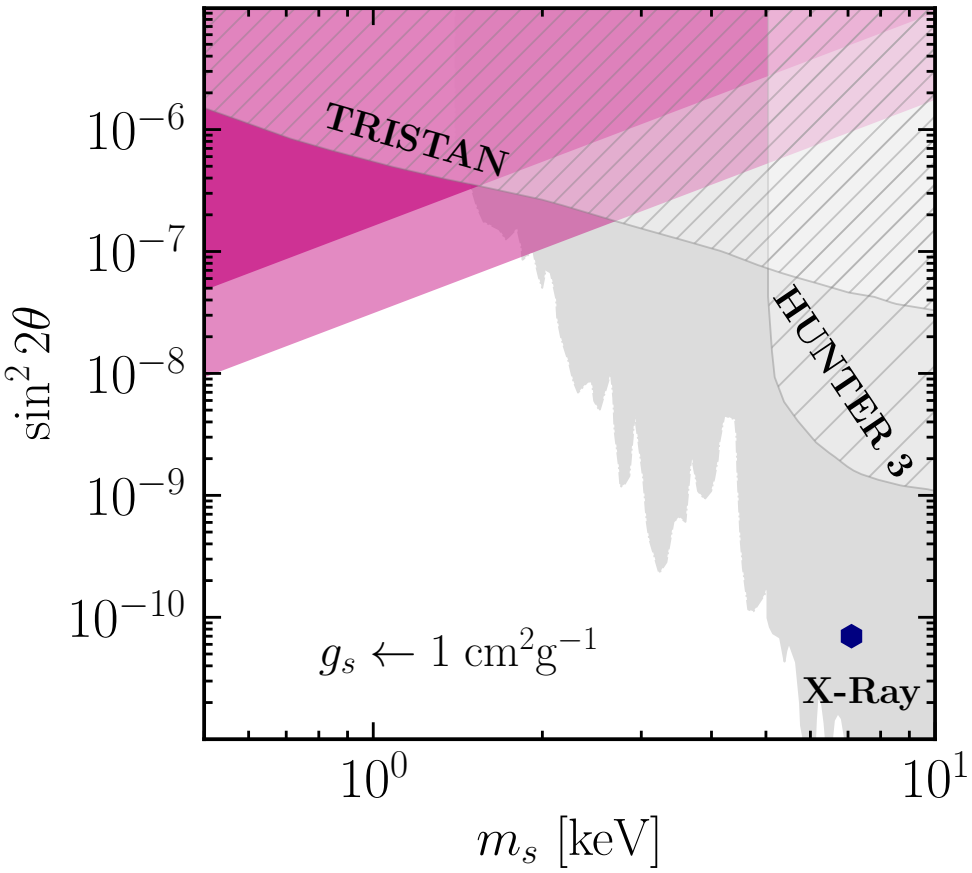
$$\tau_i(E_\nu, z) \backsimeq \tau_R \Theta(z - z_R) = \frac{\Gamma_R(z_R)}{(1+z_R)H(z_R)} \Theta(z - z_R)$$

where $z_R = E_R/E_\nu - 1$,
interaction rate $\Gamma_R(z_R) \backsimeq |U_{si}|^2 n_{\nu_s}(z_R)\sigma_R$,
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)

Secret neutrino interactions: DSNB





- 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

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

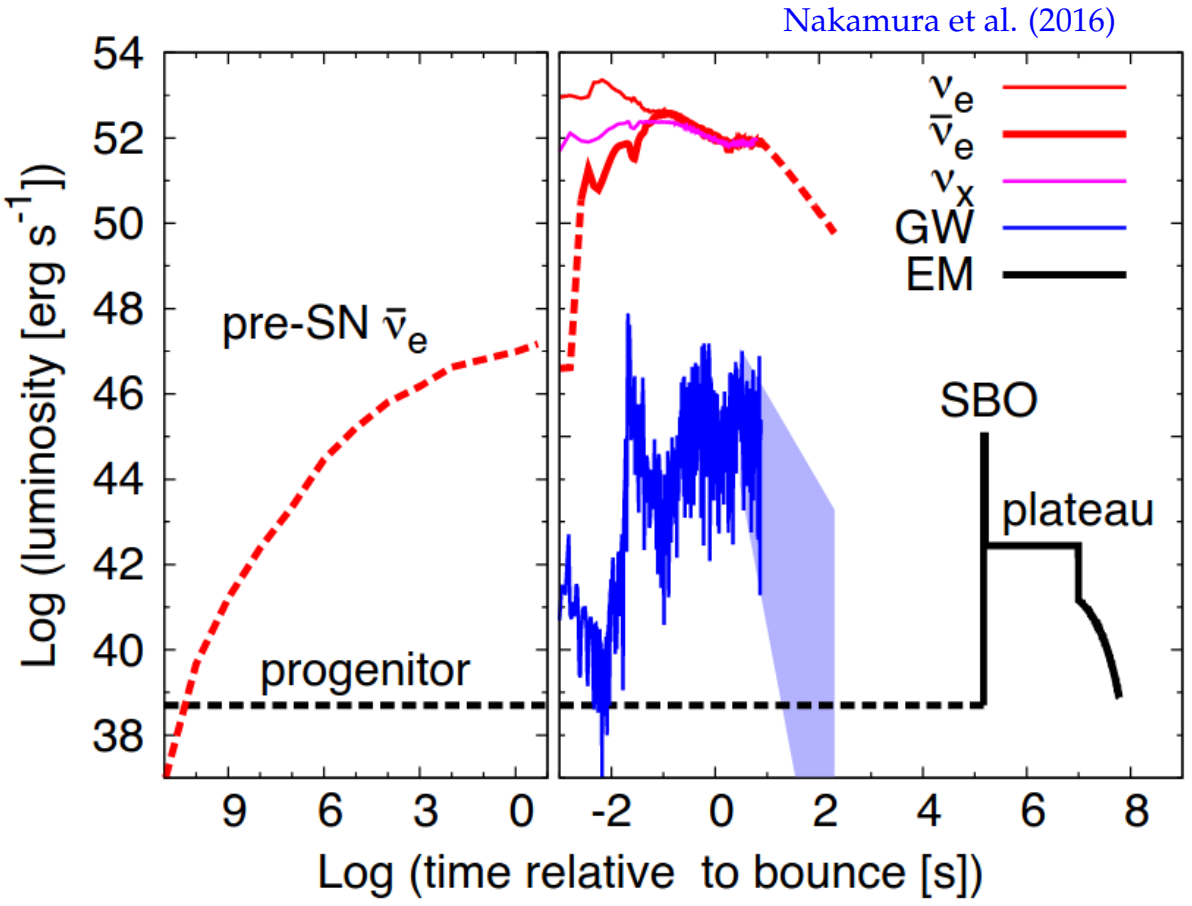
- brings us closer to fully understanding the physics inside the sources
- help us to probe potential new physics scenarios

Exciting times ahead

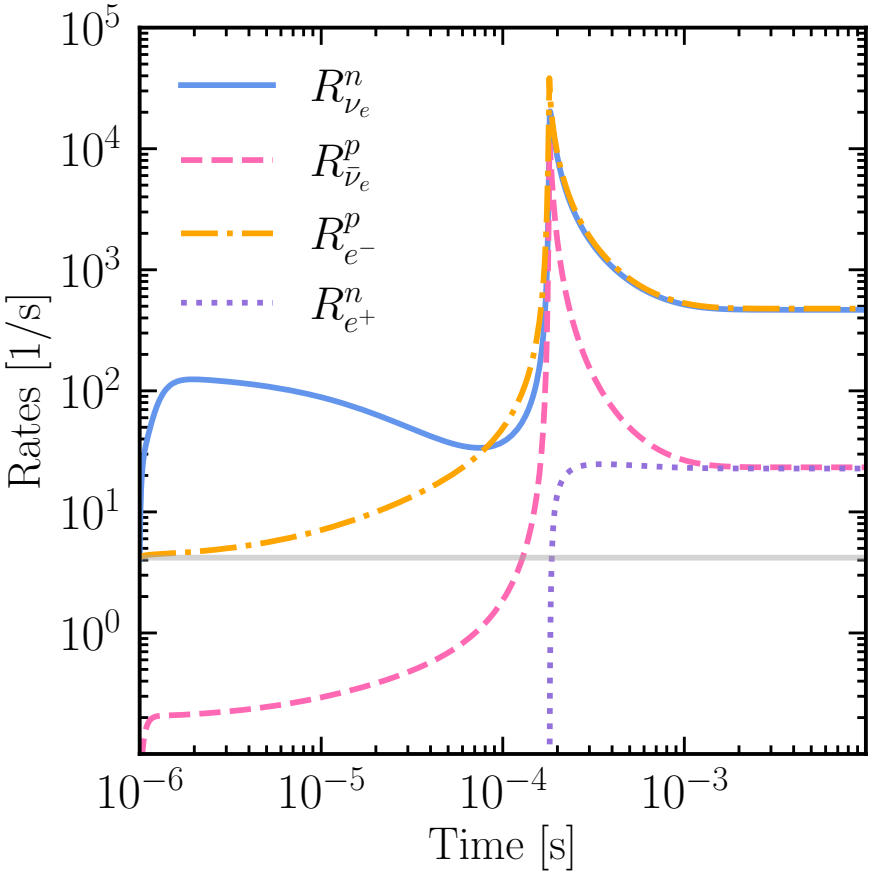
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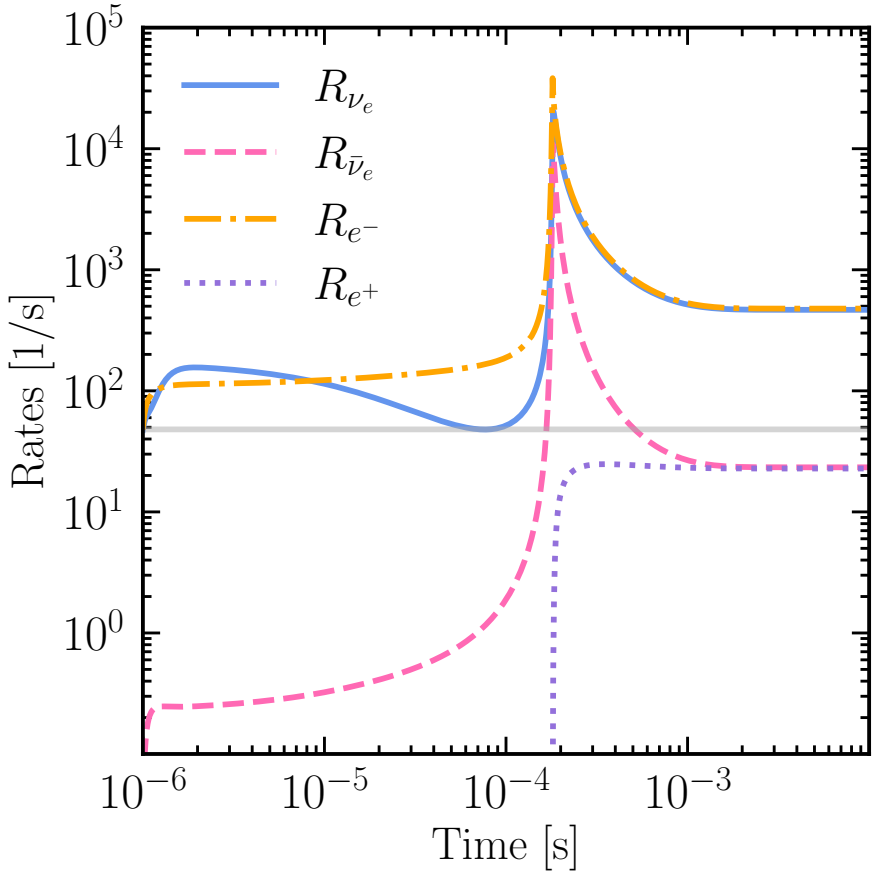
Backup

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)

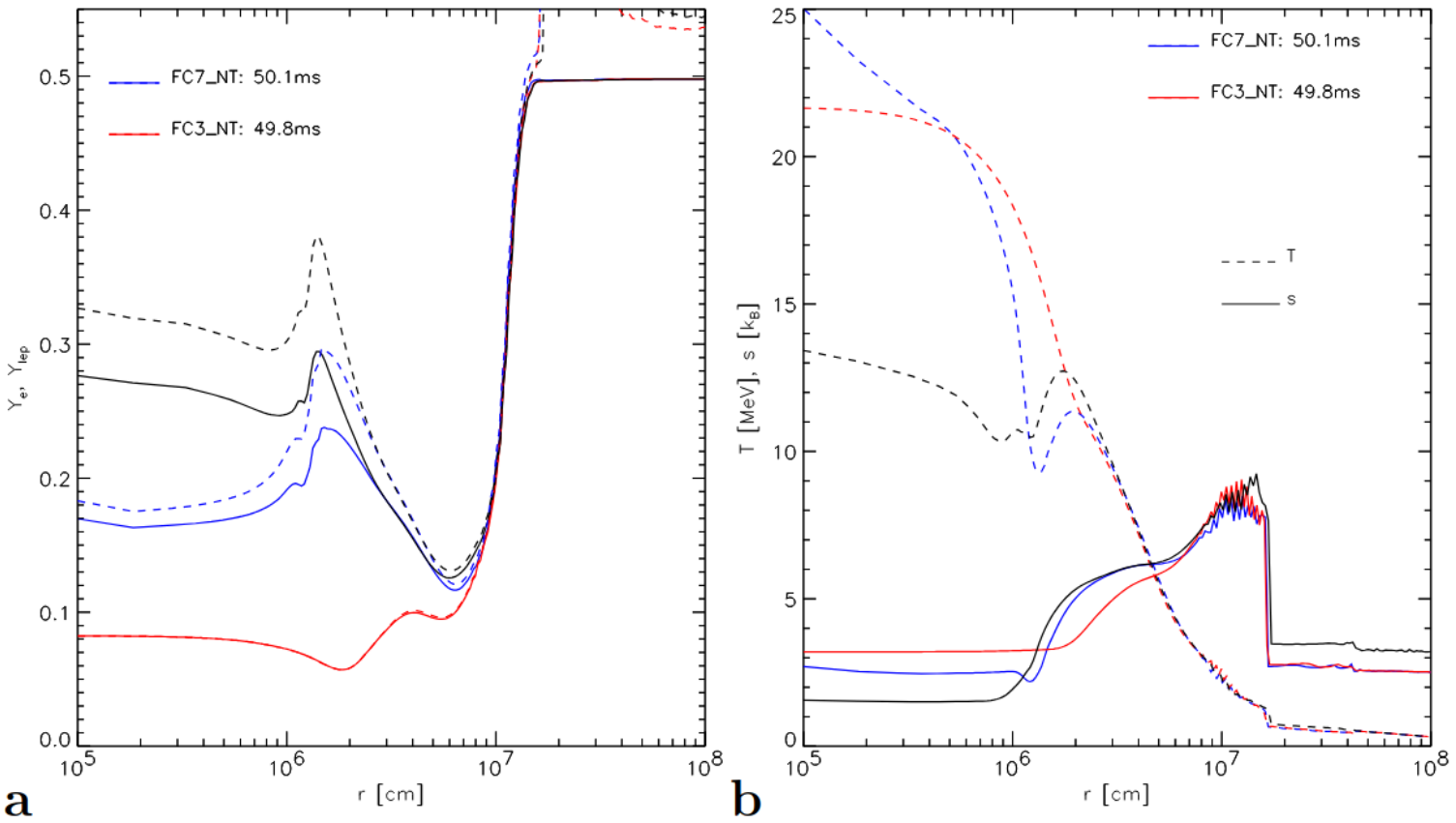
$$\frac{\partial n}{\partial T} = \frac{g}{2\pi^2}\int_m^\infty dE\, E\sqrt{E^2-m^2}\,\frac{(E-\mu)}{4T^2}\cosh^{-2}\left(\frac{E-\mu}{2T}\right), \quad (2a)$$

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

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

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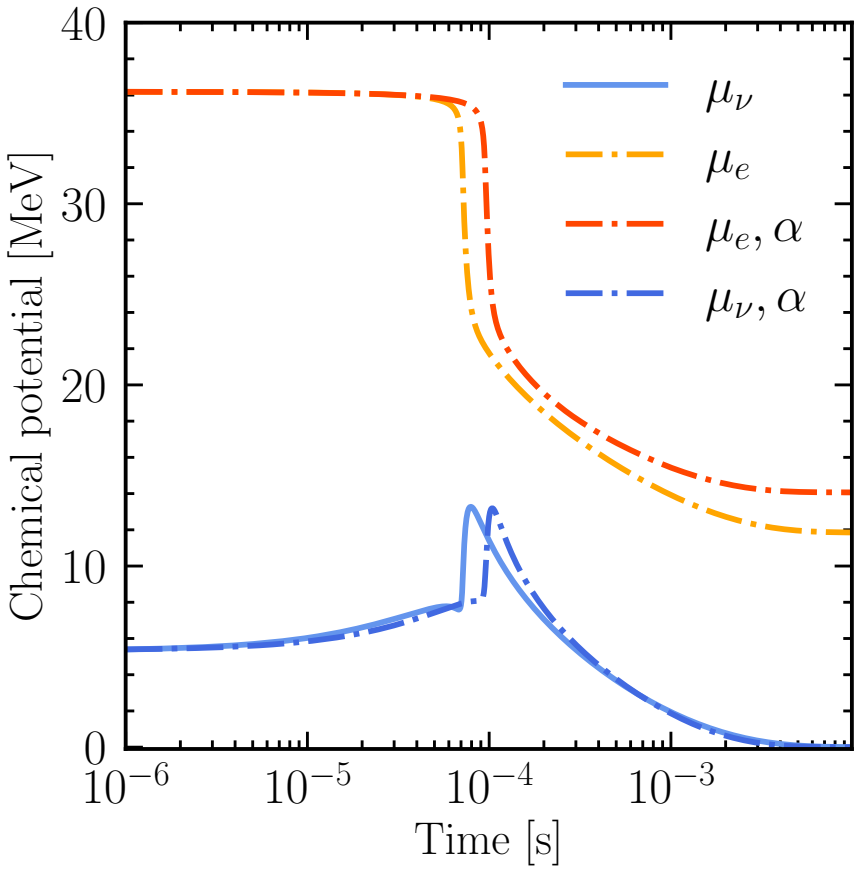
Proxy "Internal Deleptonization"

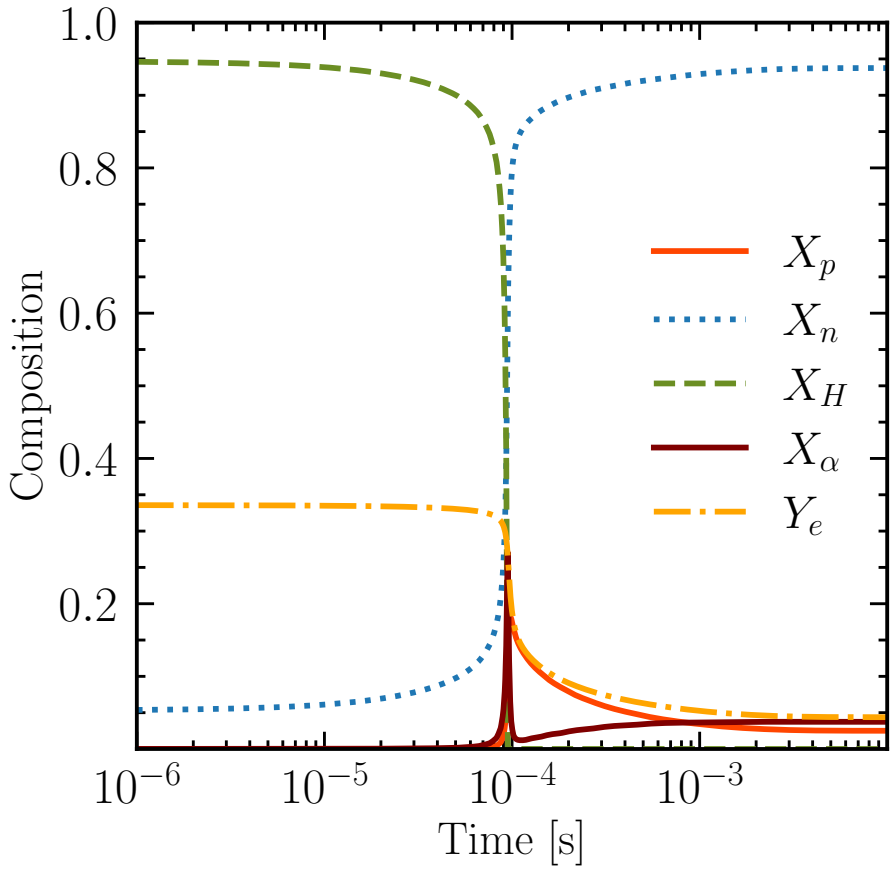


$$\nu_e + N \leftrightarrow \bar{\nu}_e + N$$

M. Rampp et al. (2002)

LS 220 Equation of State: impact of α particles





Astrophysical neutrino fluxes

Supernova neutrinos

- large flux for Galactic SN
- transient event

Solar neutrinos

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

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

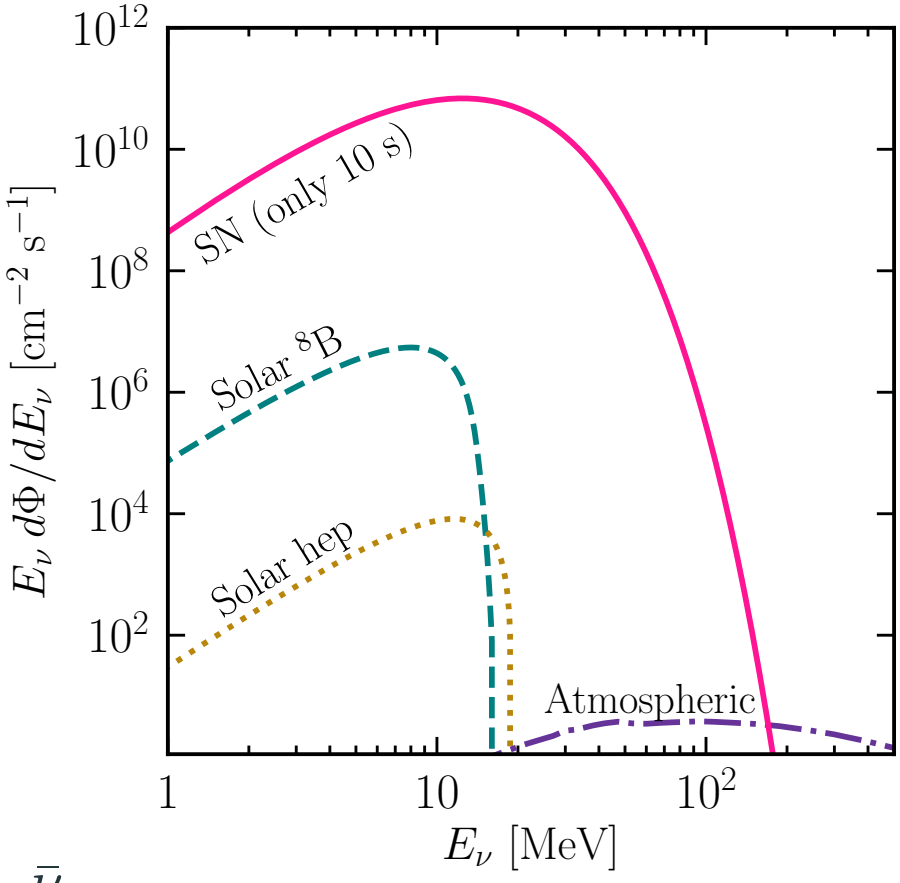
- neutrino energies up to ∼15 MeV

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)

Non-standard coherent neutrino-nucleus scatterings

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

new vector mediator

Z'

new scalar mediator

ϕ

Lagrangian terms

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

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

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

D. G. Cerdeno et al. (2016), Y. Farzan et al.(2018), D. Aristizabal Sierra et al. (2019)

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Cross sections

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

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

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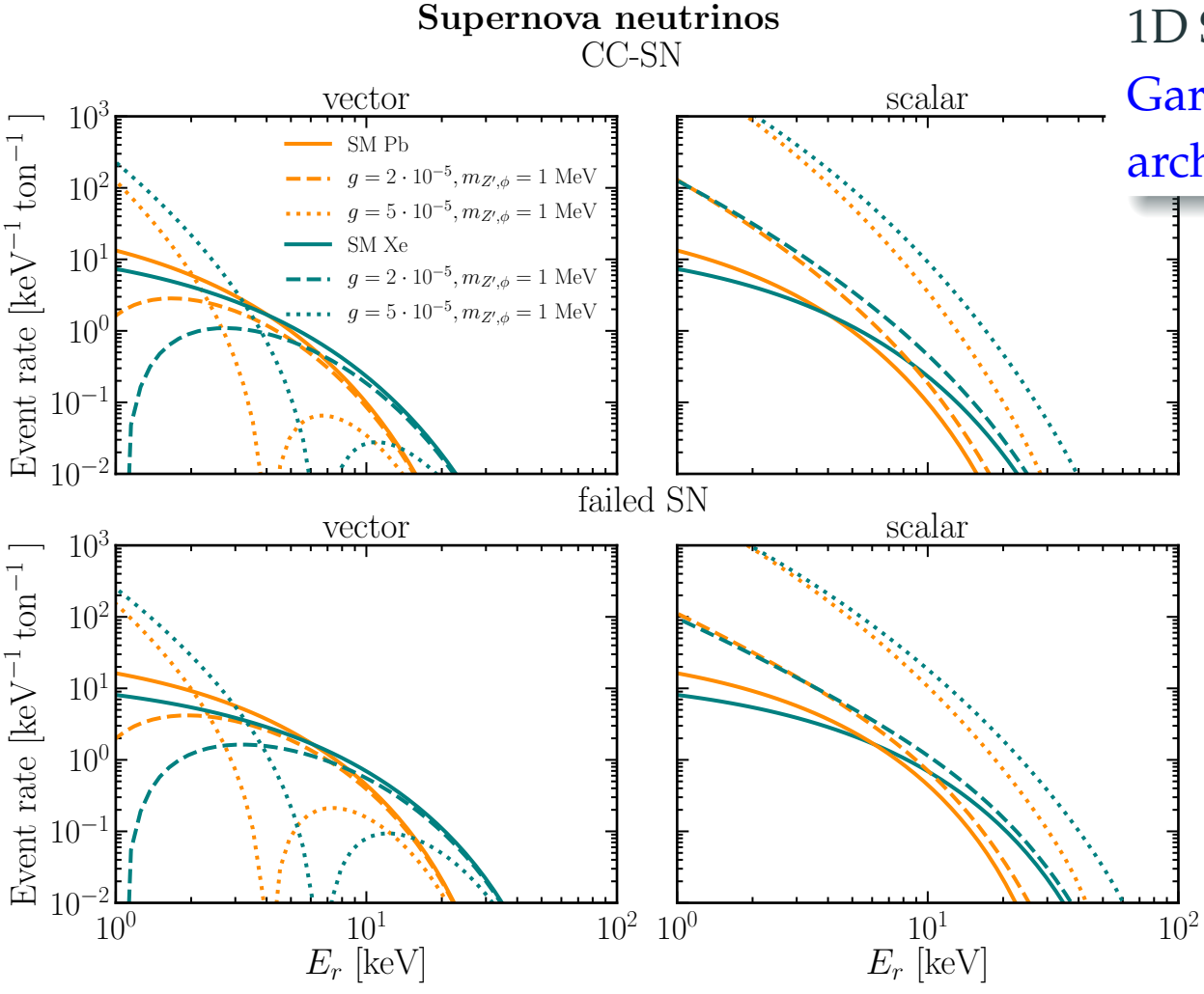
$$\xi = -\frac{Q_w}{2} + \frac{g_{\nu,Z'} Q'_w}{\sqrt{2} G_F (2 m_T E_r + m^2_{Z'})}$$

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

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

D. G. Cerdeno et al. (2016), Y. Farzan et al.(2018), D. Aristizabal Sierra et al. (2019)

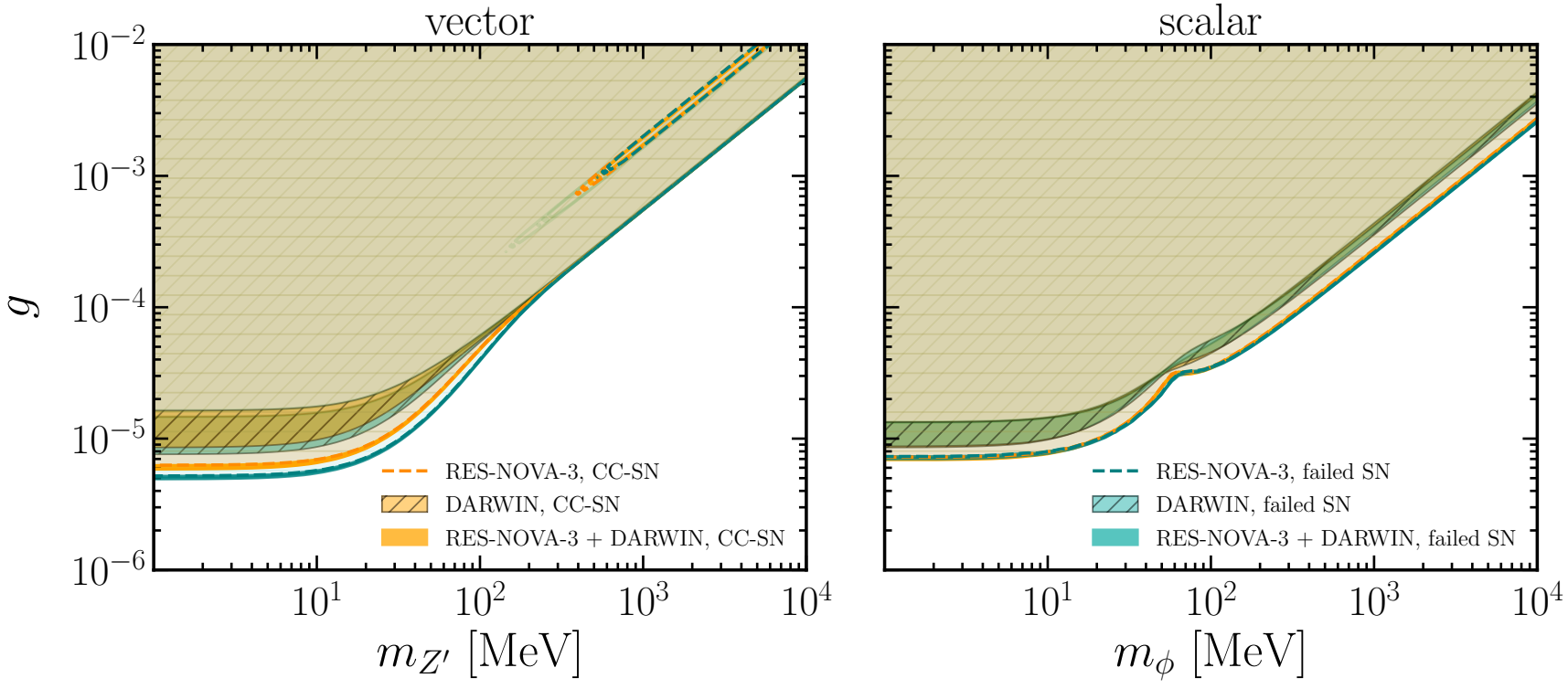
Event rates for supernova neutrinos



1D SN models
Garching group archive

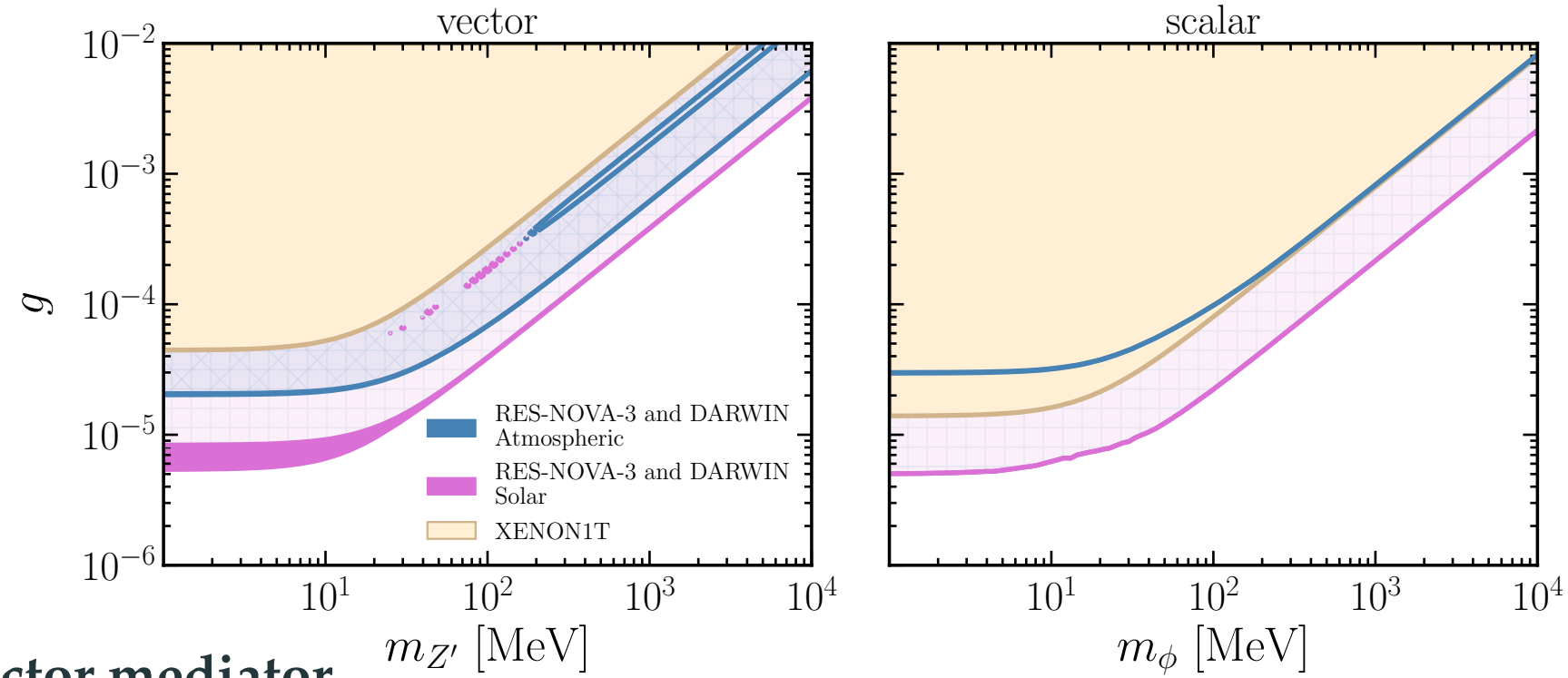
- Failed SN: hotter neutrino spectrum → longer recoil spectrum
- Heavier target: higher number of events but shorter recoil spectrum

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



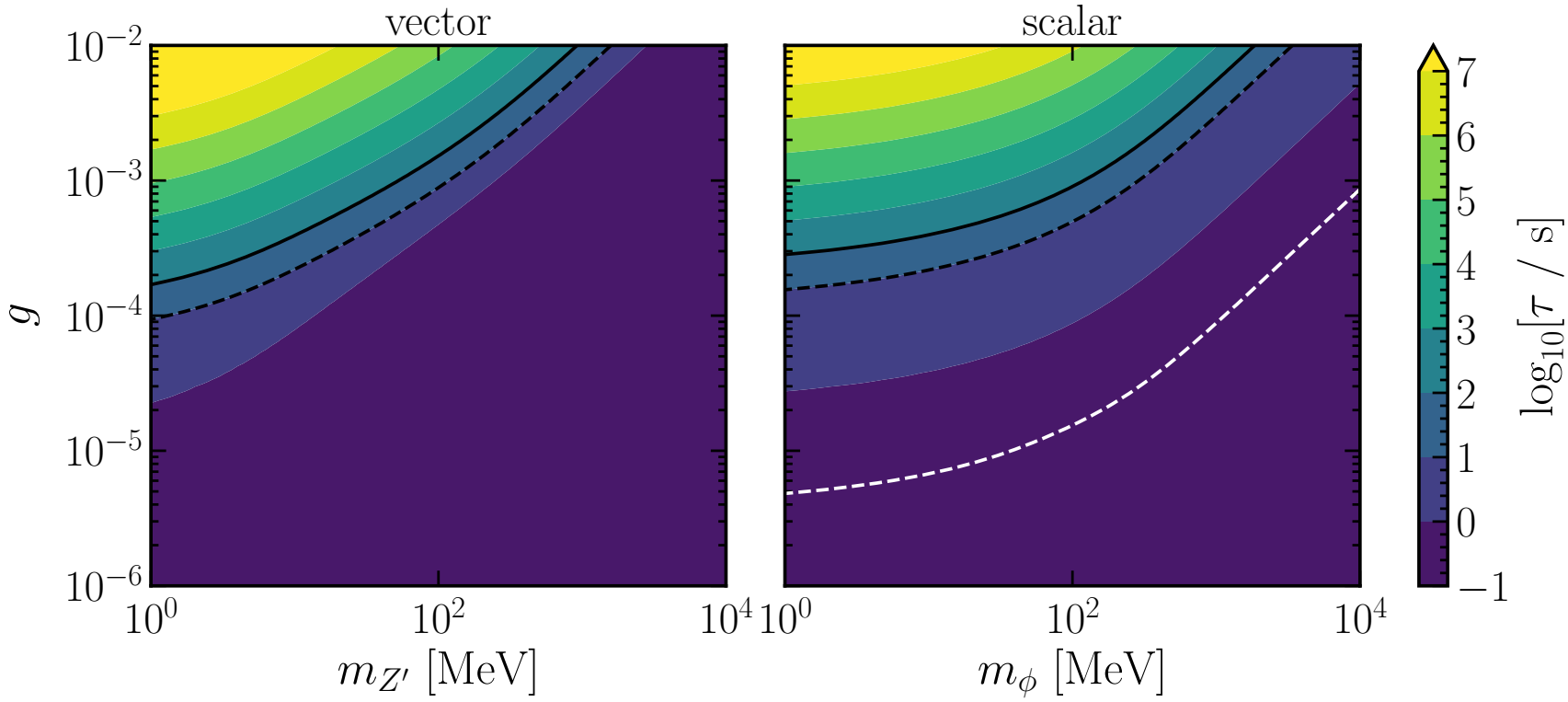
Vector mediator

- 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

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

- diffusion time

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

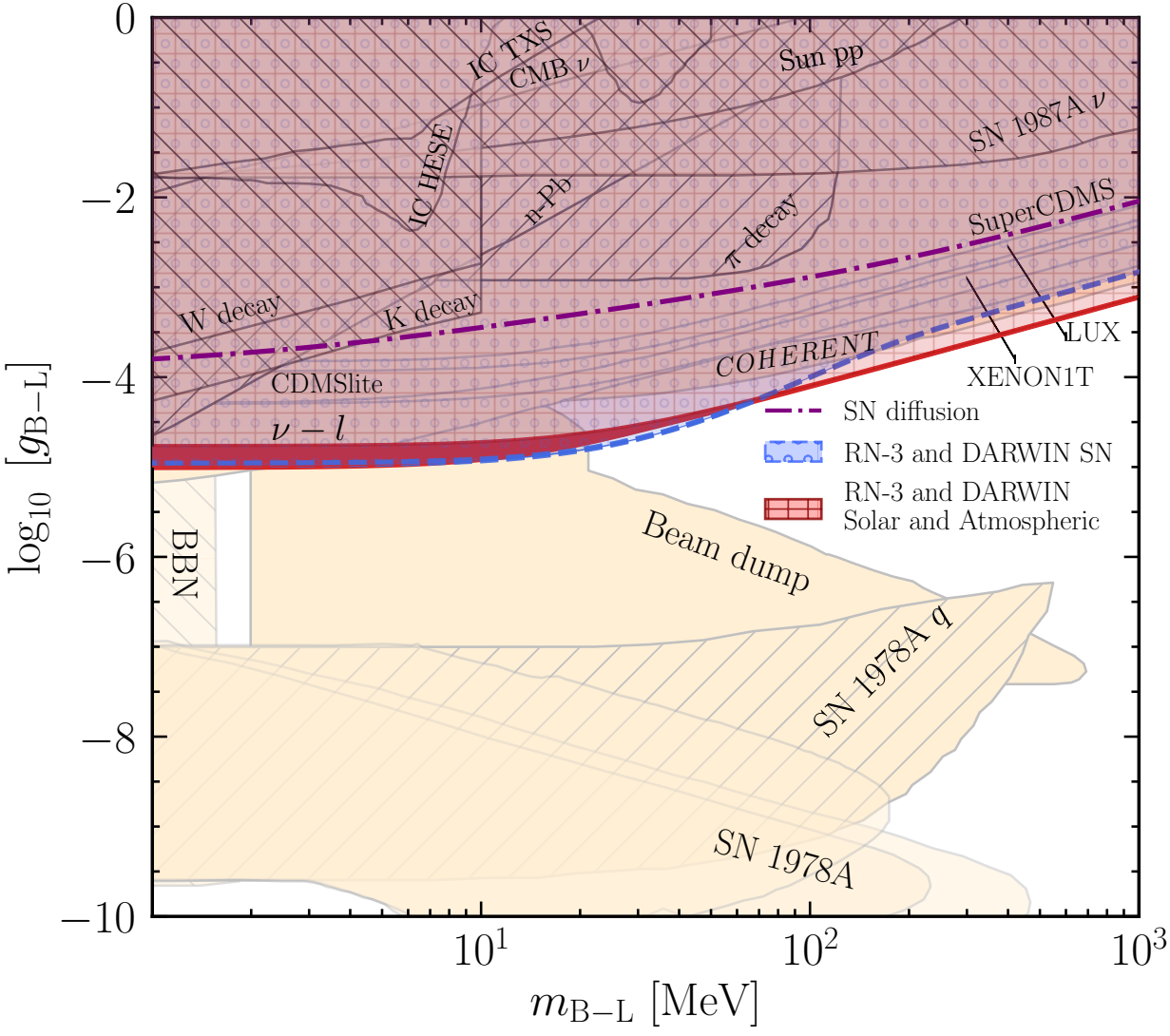
- number of scatters

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

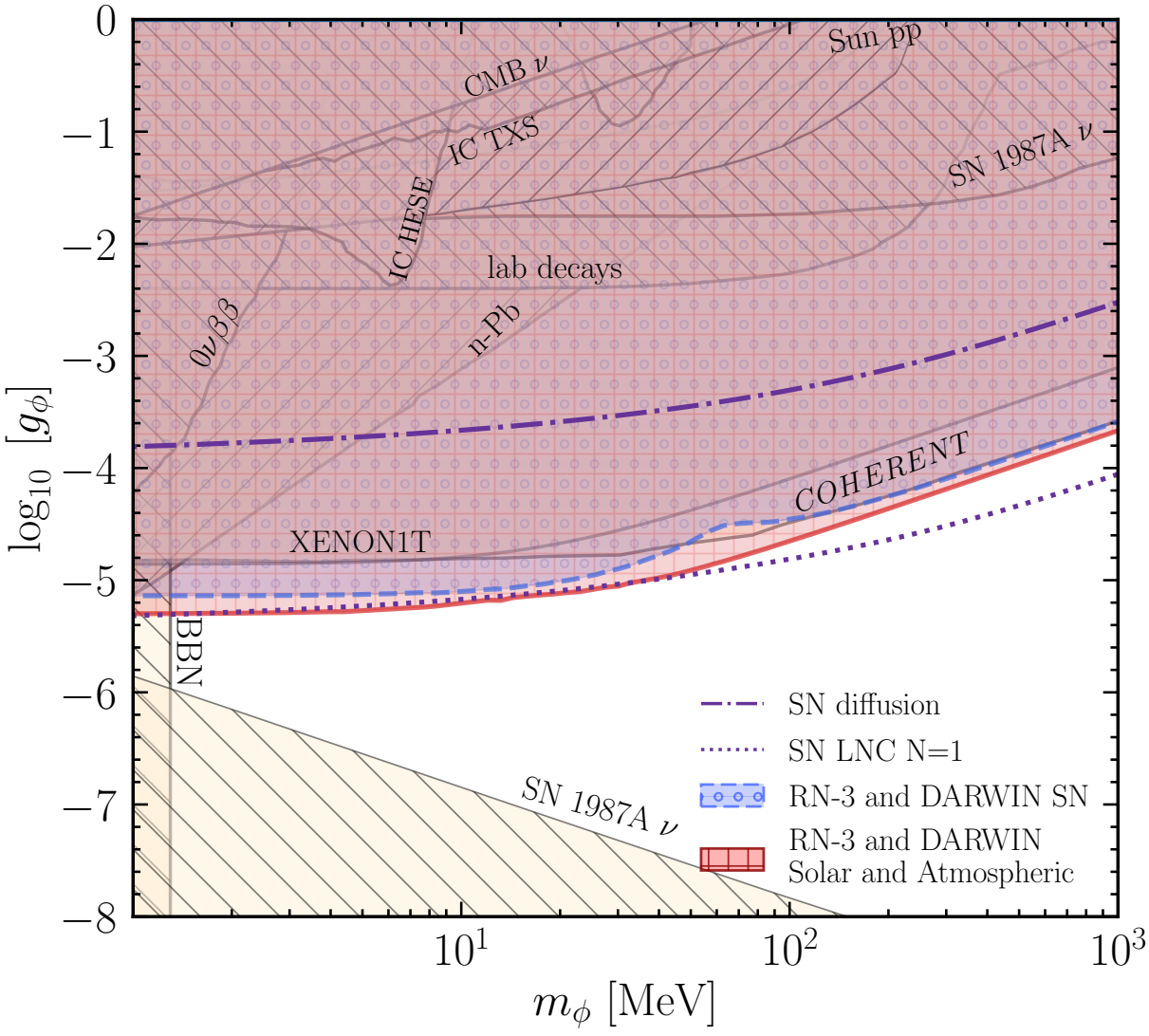
$R_1 = 10$ km

$R_2 = 40$ km

Comparison of limits from specific new physics models



Comparison of limits from specific new physics models



Limits from SN1987A on ν_x

