Strategies for detecting low-energy neutrino fluxes

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FERMILAB
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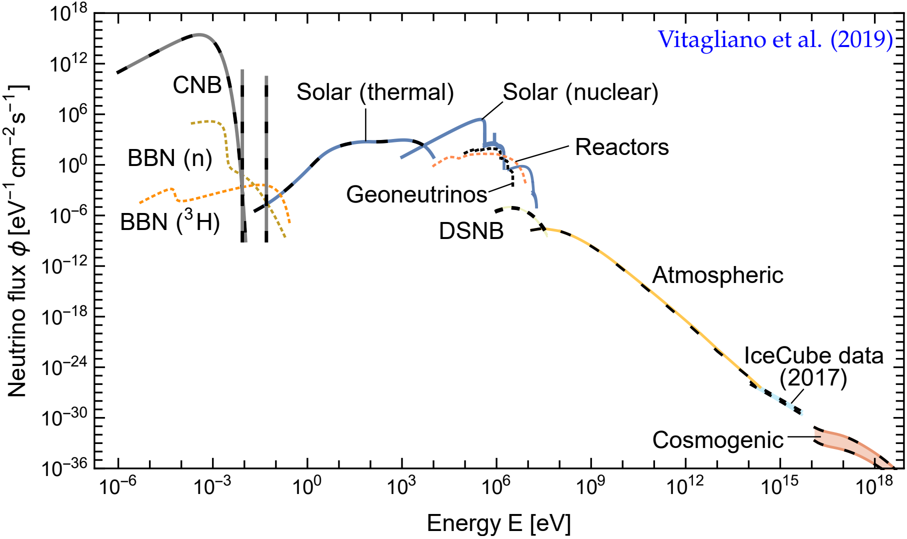
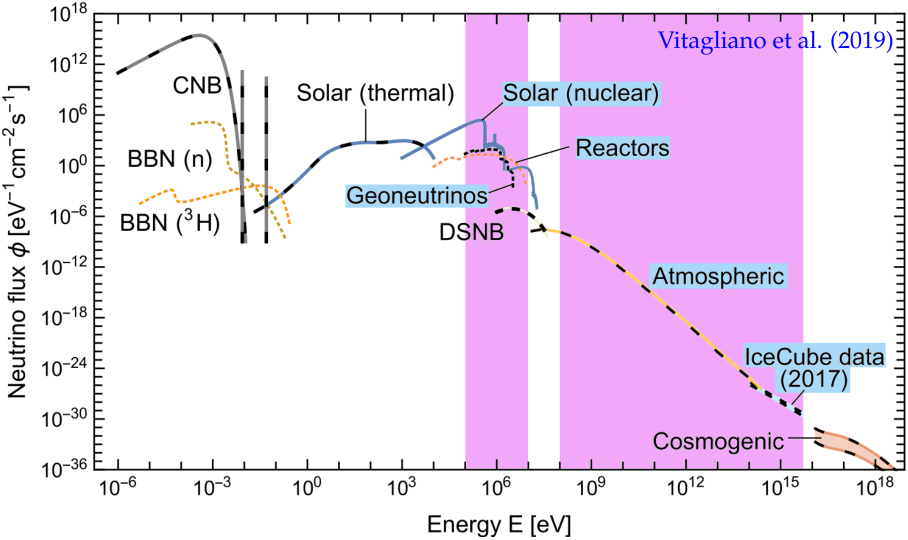
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

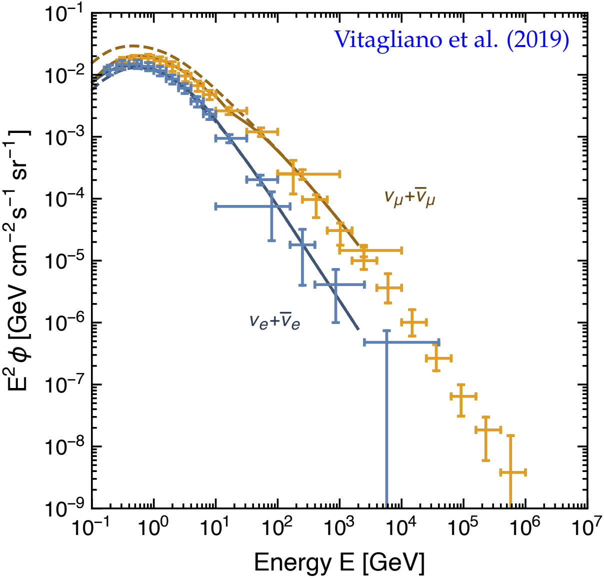
Grand Unified Neutrino Spectrum



Grand Unified Neutrino Spectrum - Detected Fluxes



Atmospheric neutrino measurements



Data points from:

- Super-Kamiokande (SK)
  SK Collaboration (2015)
- Ice-Cube (IC)
  IC Collaboration (2015)

No measurements below 100 MeV

Why it is important to measure low-energy atmospheric neutrinos?

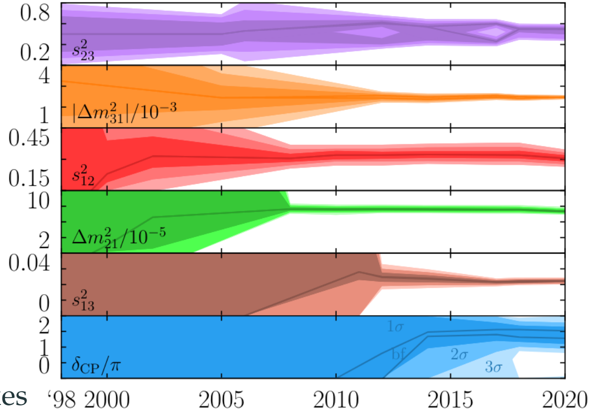
Towards precise neutrino mixing measurements

Past measurements

- large mixing angles
- non-zero masses

Remaining questions

- Majorana vs Dirac
- absolute masses
- degree of CP violation
- some low-energy ν fluxes

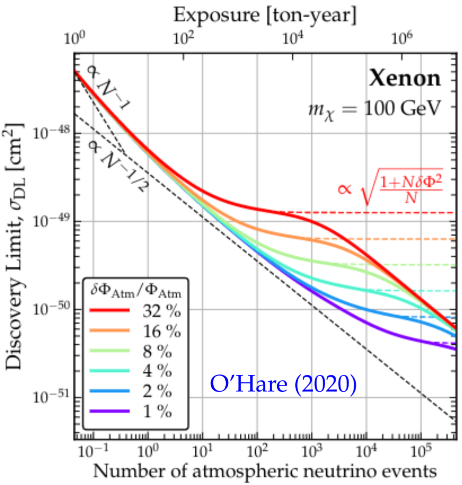


Snowmass Neutrino Frontier Report

How to achieve it? All hands on deck

- Many new experiments comimg online soon, DUNE, JUNO, HK, DARWIN-LZ...
- variety of approaches → superb sensitivity

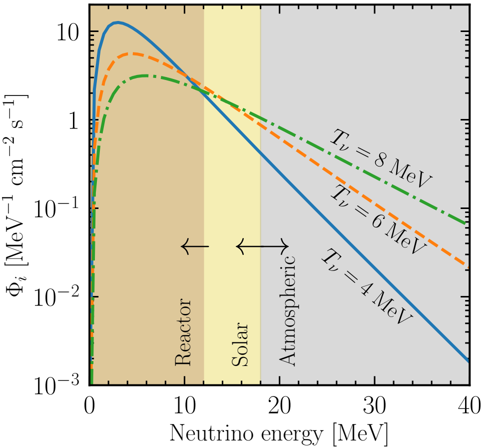
Direct Dark Matter Detection Experiments - Neutrino Fog



- neutrino floor/fog → barrier for dark matter direct detection experiments Vergados & Ejiri (2008), Strigari (2009), Baudis et al. (2013), ...
- mitigating uncertainties in the atmopsheric neutrinos helps the discovery limits

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 atmopsheric neutrinos helps the discovery limits

Distinctive nuclear signatures of low-energy atmospheric neutrinos

In collaboration with J. Beacom

Phys.Rev.D 108 (2023) 4, 043035

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-oscilated flavor ratio

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

Sources of uncertainty

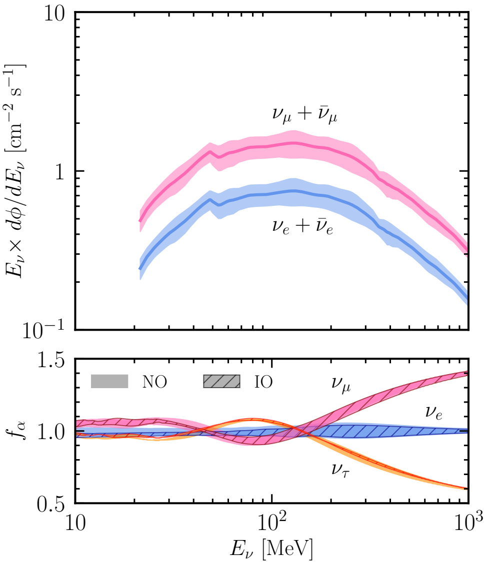
solar wind modulations

Earth's geomagnetic field

Oscilated flavor ratio

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

Past measurements: energies > 100 MeV



Neutrino flux: Zhuang (2021)

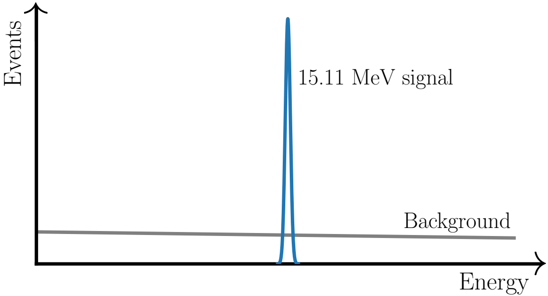
Mixing: NuCraft

Distinctive nuclear channels

Neutral current channels

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

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



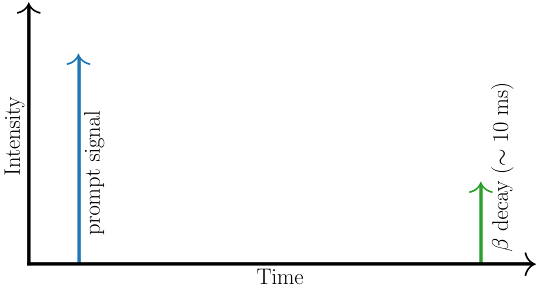
- instantaneous decay of ${}^{12}\mathrm{C}^*$
- emission of a monoenergetic γ

Distinctive nuclear channels

Charged current channels: ν_e

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

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



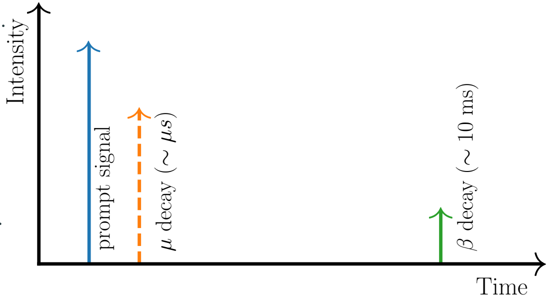
- coincidence detection of e^+ and e^-
- difference in ${}^{12}\mathrm{B}_{\mathrm{g.s.}}$ and ${}^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes $\rightarrow$ ν_e vs. $\bar{\nu}_e$ distinction

Distinctive nuclear channels

Charged current channels: ν_μ

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

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

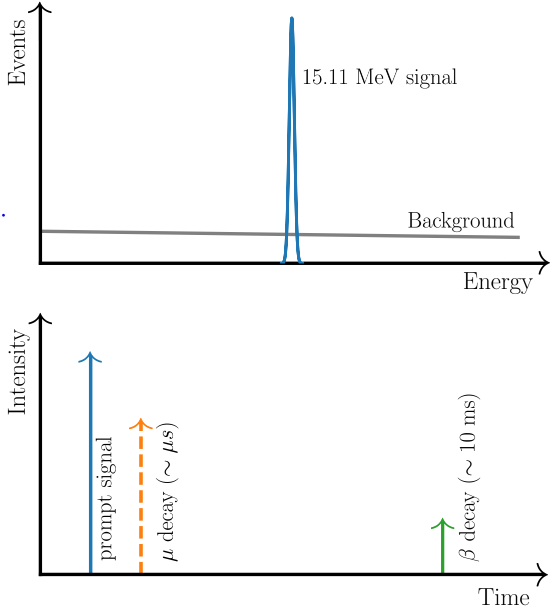


- coincidence detection of μ, its decay e and β-decay e
- difference in ${}^{12}\mathrm{B}_{\mathrm{g.s.}}$ and ${}^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes $\to$ ν_μ vs. $\bar{\nu}_\mu$ distinction
- triple vs. double coincidence detection $\to$ ν_e vs. ν_μ distinction

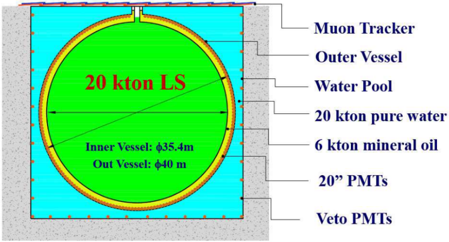
Distinctive nuclear channels

Also suggested for supernova neutrino detection

Fukugita et al. (1988), Cadonati et al. (2000), Laha et al. (2014), Lu et al. (2016)



The Jiangmen Underground Neutrino Observatory (JUNO)

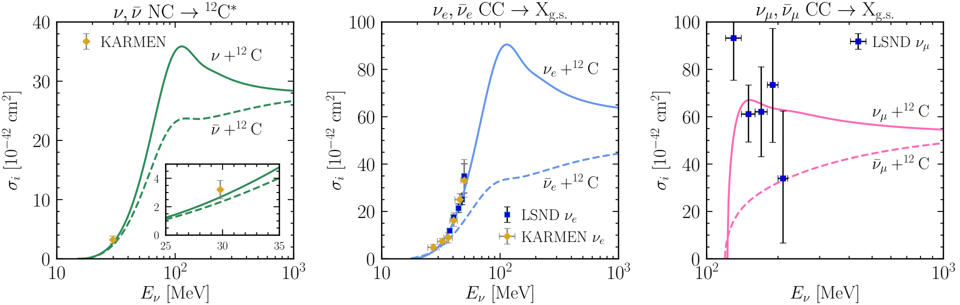


- large-scale carbon-based liquid scintilator detector
- soon operational ($\sim$ 2024)
- excelent energy resolution $\lesssim 3\%$
- excelent spatial resolution $\lesssim 10$ cm
- low backgrounds in the considerd channels

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

JUNO collabortation (2015), Sitsi (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)

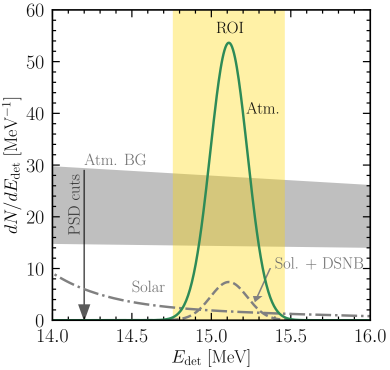
Atmospheric neutrino detection in JUNO

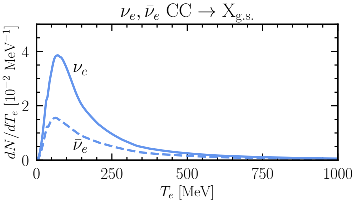
NC channel detection: single events

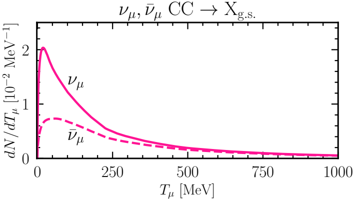
Irredicible BG: solar and DSNB ν

Reducible BG: atm. ν - p scattering

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







CC channel detection: coincidence events

Irredicible BG: accidental coincidences

Rate per 85 kton yr: $\sim$0.0004

esentially background free channels

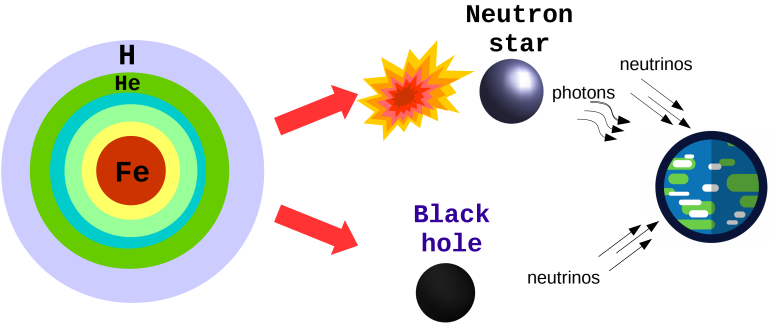
Conclusions

- high statistic era of neutrino physics $\rightarrow$ exploring all the available channels
- potentially first measurement of the sub-100 MeV atmospheric neutrino flux
- potentially first measurement of the exclusive ^{12}C cross sections for $\bar{\nu}$
- helps high-precision measurements of the mixing parameters and neutrino fluxes
- exclusive nuclear channels $\rightarrow$ clean observables
- similar channels exist for C and different nuclei?
- helps DSNB and WIMP studies

Why are neutrinos important for a core-collapse supernova?

Neutrinos:

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



Earth image: Kurzgesagt

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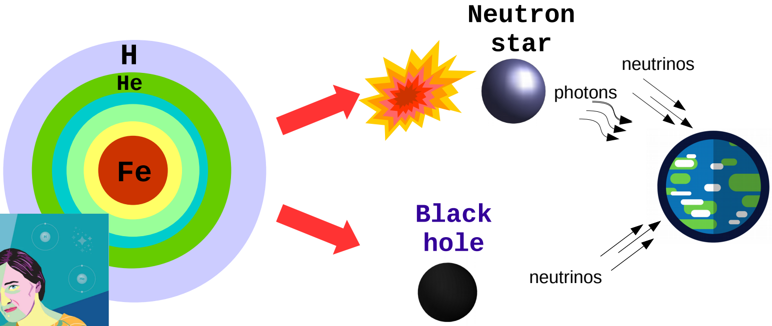


Earth image: Kurzgesagt

Why core-collapse supernovae are good physics probes?

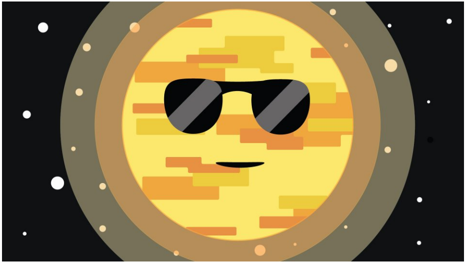
Advantages

- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (SK, JUNO, XENON, PandaX...)

What can we learn with a variety of detectors?

- explosion mechanism — Bethe & Wilson (1985), Fischer et al. (2011)...
- yields of heavy elements — Woosley et al. (1994), Surman & McLaughlin (2003)...
- compact object formation — Warren et al. (2019), Li, Beacom et al. (2020)...
- neutrino flavor evolution — Balantekin & Fuller (2013), Tamborra & Shalgar (2020)...
- non-standard physics — McLaughlin et al. (1999), de Gouvêa et al. (2019) ...

Why focus only on a single rare event?

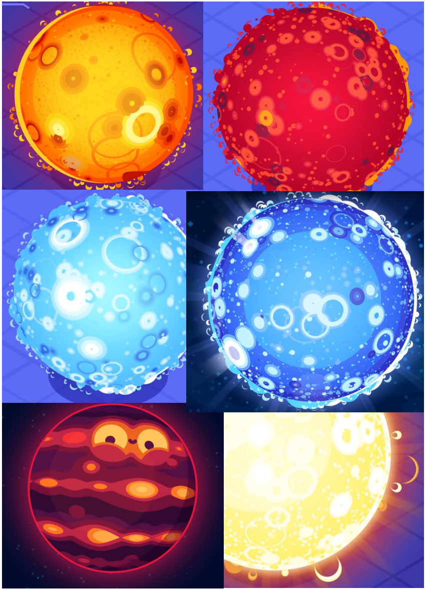


Single galactic SN event

- 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

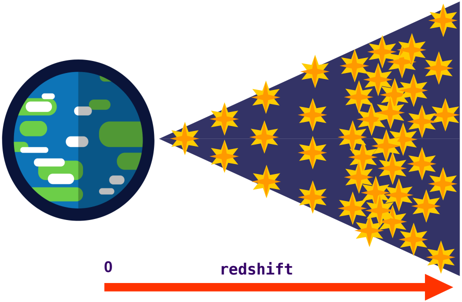
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,{\rm CC-SN}}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,{\rm BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

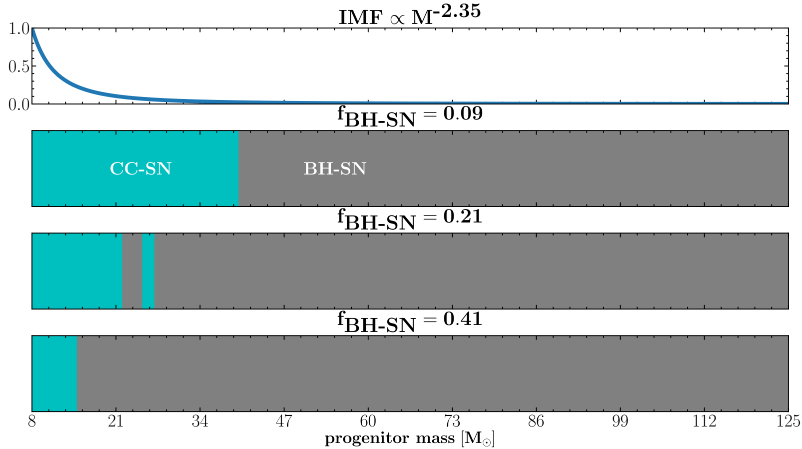
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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), ...

Astrophysical uncertainties

The fraction of black-hole-forming progenitors

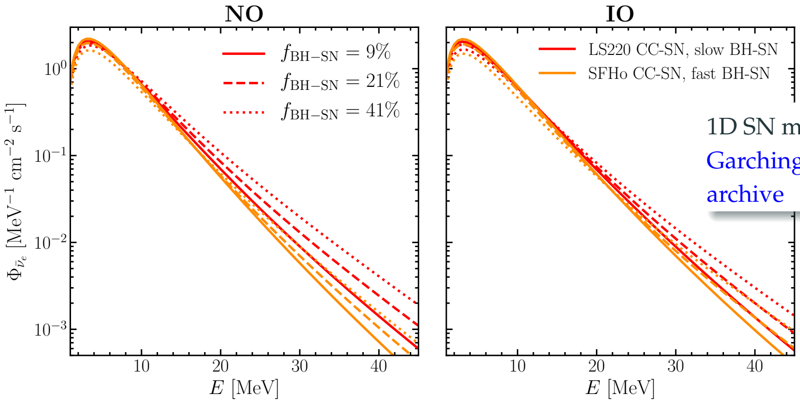


Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV.

C. Lunardini (2009)

Ertl et al. 2015, Sukhbold et al.2015, Adams et al. 2016, Heger et al. 2001, Kochanek et al. 2001, Basinger et al. 2020, ...

The fraction of black-hole-forming progenitors



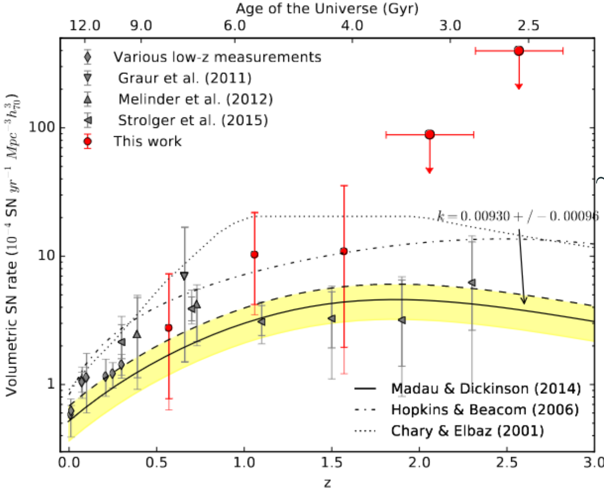
1D SN models
Garching group archive

Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV.

Lunardini (2009), Keehn, Lunardini (2010), Lunardini, Tamborra (2012), Priya, Lunardini (2017), Møller, **AMS** et al. (2018), Nakazato et al. (2018) Kresse et al. (2020), ...

Cosmological supernovae rate

Petrushevska et al (2016)



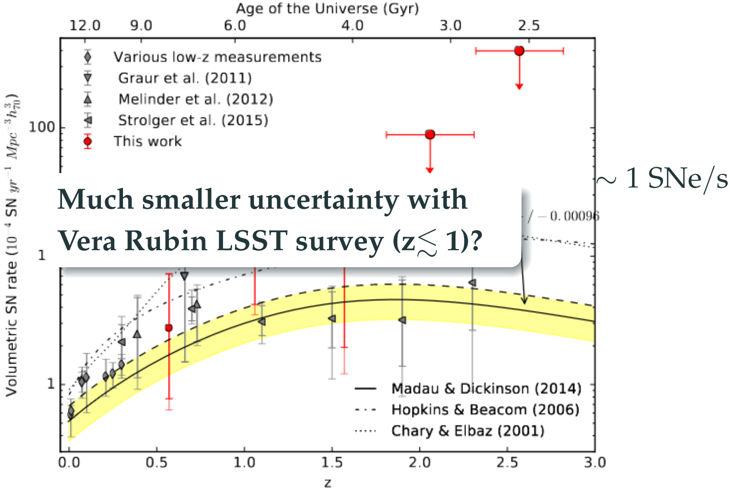
~ 1 SNe/s

The supernovae rate influences the normalization of the DSNB.

Ando, Sato (2004), Beacom (2010), Horiuchi et al. (2011), Møller, **AMS**, Tamborra, Denton (2018), Nakazato et al. (2018), ...

Cosmological supernovae rate

Petrushevska et al (2016)



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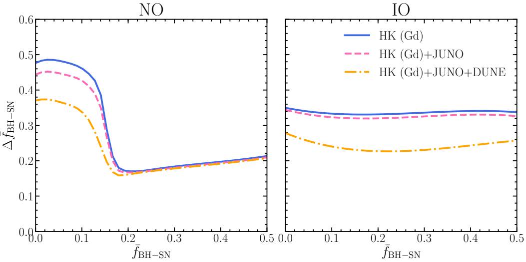
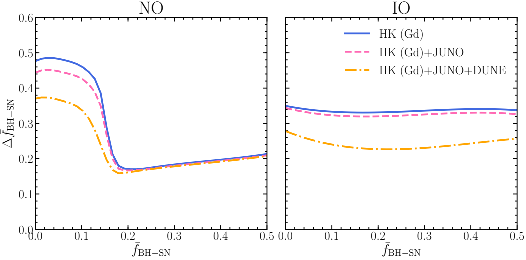
Expected 1σ uncertainty: fraction of BH forming progenitors



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

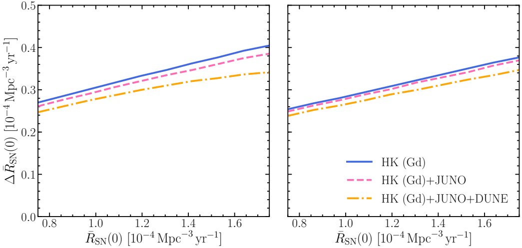
Møller, **AMS**, Tamborra, Denton (2018)

Expected 1σ uncertainty: local supernova rate



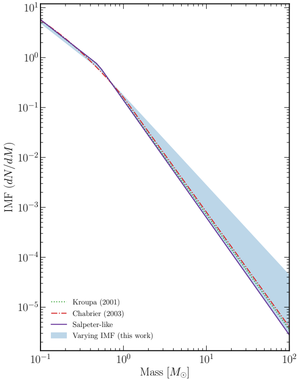
- The high uncertainty comes from $f_{\mathrm{BH-SN}}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos $\rightarrow$ helps to reduce the uncertainty

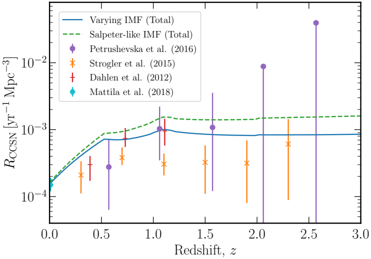
- Relative error of 20%-33% independent of the mass ordering.

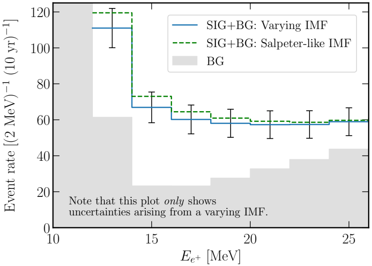


Møller, **AMS**, Tamborra, Denton (2018)

Varying Initial Mass Function







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

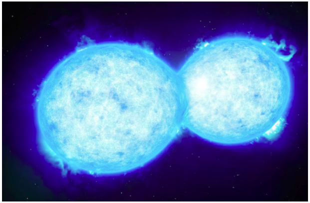
Ziegler, Edwards, **AMS**, Tamborra, Horiuchi, Ando, Freese (2022)

Binary interactions

Majority of massive stars have stellar companions and experience binary interactions Sana et al. 2012, Zapartas et al. 2020

Mass transfer

Mergers



Images: iflscience, Wiki

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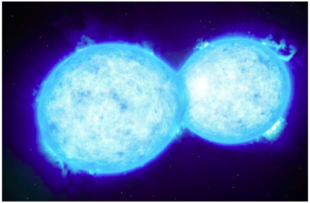
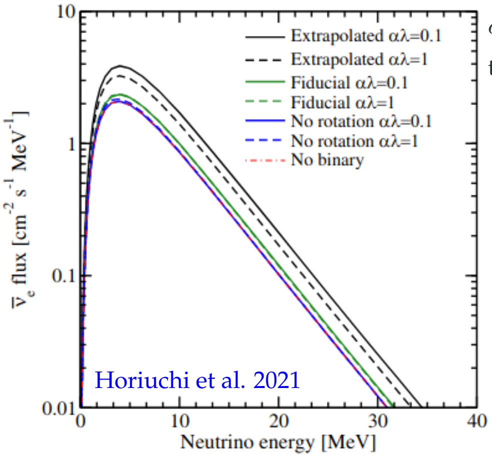


Effects on the stellar population Horiuchi et al. 2021

- change in mass due to mass transfer
- reduced progenitor counts
- increased progenitor counts

Images: iflscience, Wiki

Binary interactions: impact on DSNB



$\alpha\lambda$ - measure how hard it is to unbind the envelope

- enhancement $\leqslant 75\%$ compared to estimate w/o binary considerations
- core mass increases due to rotational effects
- more studies needed

Astrophysical uncertainties affecting the DSNB

- Neutrino Flux from an "Average Supernova"

  Lunardini (2009), Lunardini & Tamborra (2012), Horiuchi et al. (2018), Kresse et al. (2018), ...

- Cosmological Supernovae Rate

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

- 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), ...

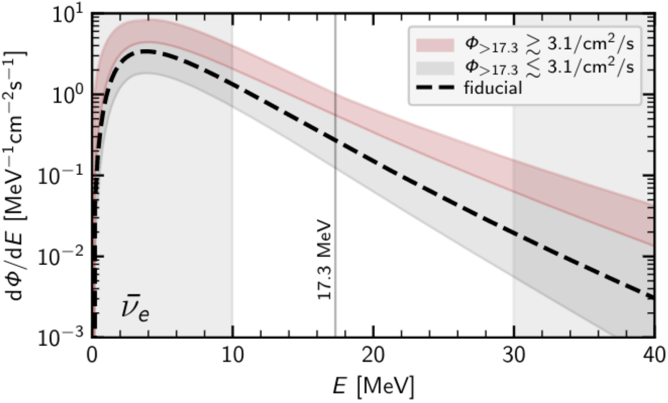
- Binary Interactions

  Horiuchi, Kinugawa, Takiwaki, Takahashi (2021)

Non exhaustive list of references

Astrophysical uncertainties affecting the DSNB

Kresse et al. (2020)



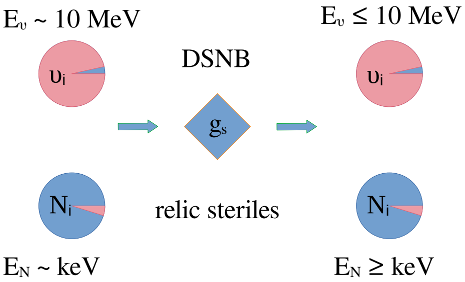
- models with the extreme combinations of parameters are disfavoured
  - large emission from black-hole-forming collapses and their fraction

Probing self-interacting sterile neutrino dark matter with the DSNB

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

Phys.Rev.D in 108 (2023) 12, 123011

KeV-mass sterile neutrino 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

Modified DSNB flux

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

Probability of interaction

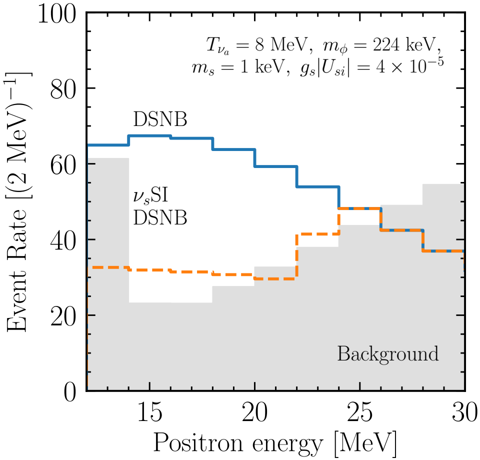
$$P_i(E_\nu, z) = e^{-\tau_i(E_\nu, z)}$$

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

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

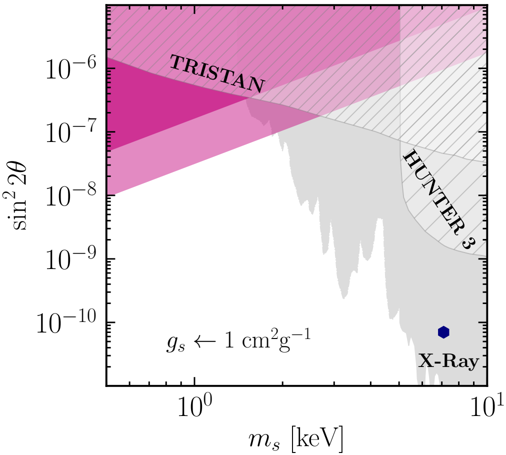
smilar studies for active neutrino self-interactions and eV-mass sterile neutrinos:
Goldberg et al. (2005), Baker et al. (2007), Farzan, Palomares-Ruiz (2014), Reno et al. (2018), Creque-Sarbinowski et al. (2021)

Secret neutrino interactions: DSNB



- **Sterile neutrino self-interactions may result in features in DSNB**

Sensitivity limits



- **Overalap with the TRISTAN experiment paramater space**
- **Reduction of the astrophysical uncertainties helps but not by a lot**

Conclusions

- Diffuse supernova neutrino background may soon be detected
- Flux encodes infformation about whole supernova population
- Sterile neutrino self-interactions can imprint dips in the flux
- Testable parameter space overalaps with TRISTAN
- **Dips in the DSNB may point to rich dark sector**

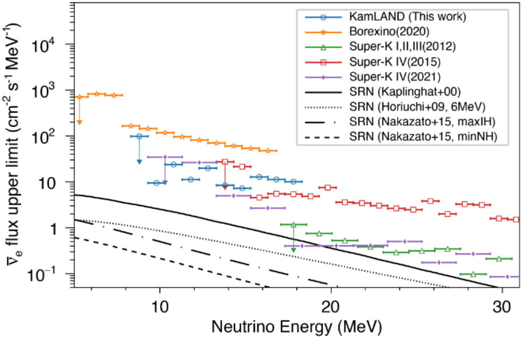
Towards probing the DSNB in all flavors

In collaboration with J. Beacom, and I. Tamborra

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

Diffuse supernova neutrino background: current limits

SK collab. (2021)



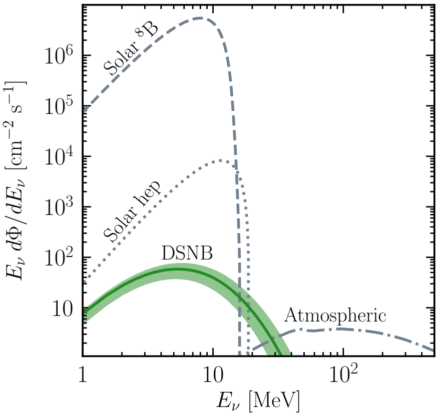
DSNB limits:

- $\bar{\nu}_e \approx 3$ cm^{-2} 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)
- $\nu_e \approx 19$ cm^{-2} s^{-1} for $E_\nu \in [22.9, 36.9$ MeV$]$ SNO collab. (2020)

  possibly detectable by DUNE Møller, **AMS**, Tamborra, Denton (2018), Zhu et al. (2019)

Can we detect the x-flavor DSNB? Maybe

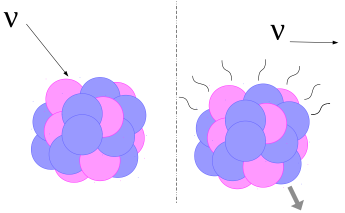


DSNB modeling:
Møller, **AMS**, Tamborra, Denton (2018)

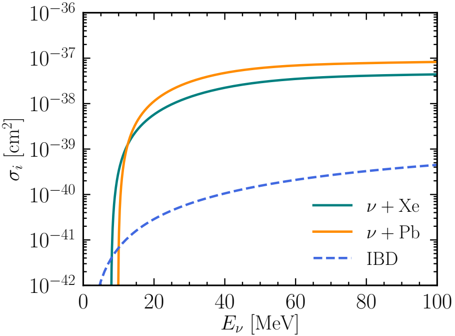
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750$ cm^{-2} s^{-1} for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

Vitagliano et al. (2019), Honda et al. (2011), Newstead et al. (2020)

Maybe: Coherent elastic neutrino-nucleus scatterings (CEνNS)



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



Cross section

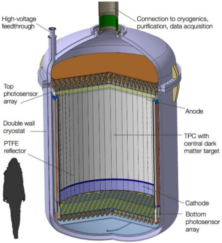
$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q),\ \ Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

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

Freedman (1974), Strigari (2009)

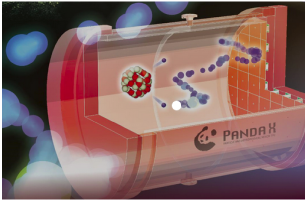
Current and future CEνNS detectors

XENONnT, DARWIN



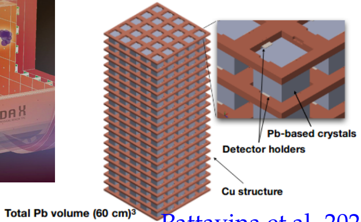
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

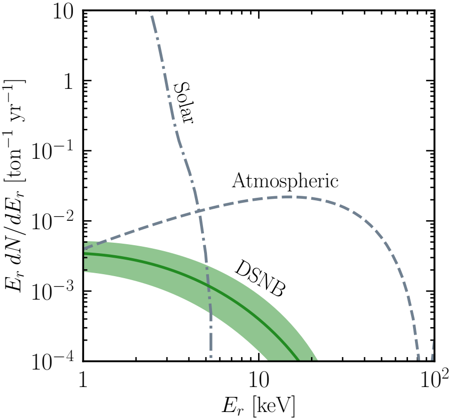
thresholds: $\mathcal{O}(1)$ keV

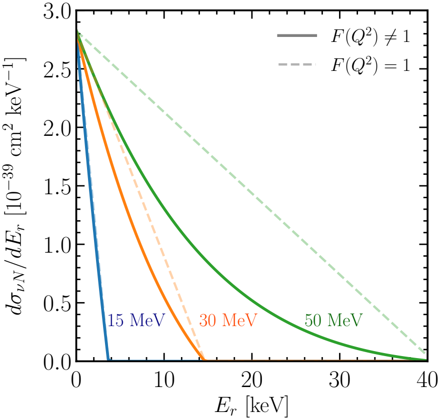
efficiency: $\sim$ 80-100%

Scattering rate

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

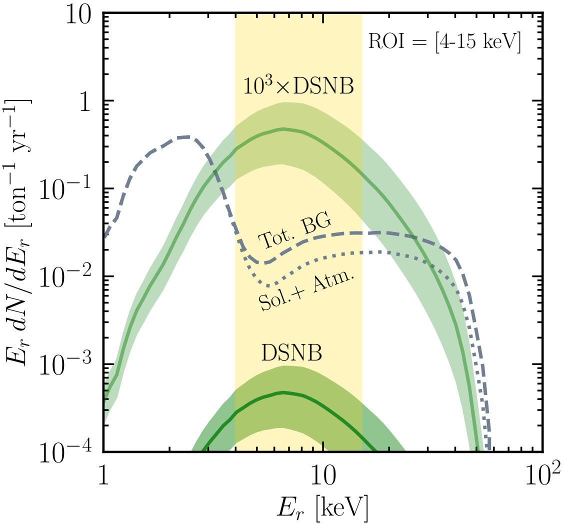
Event rate in the xenon-based detector





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

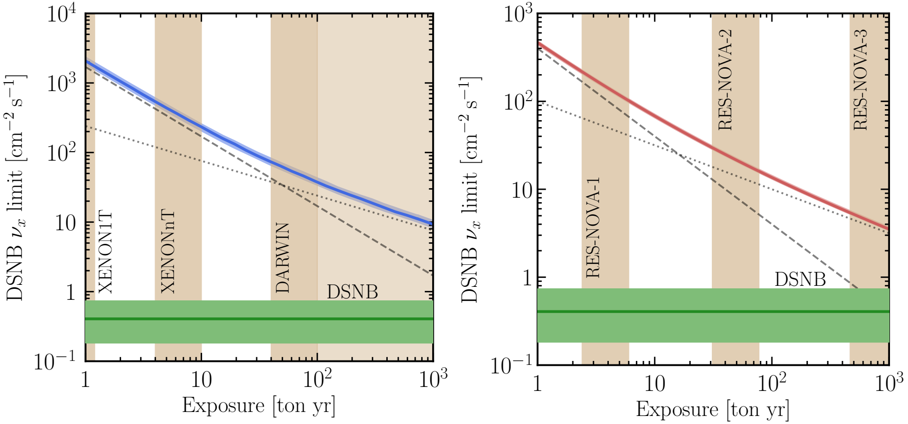
Can we improve the limits on the x-flavor DSNB? Yes



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

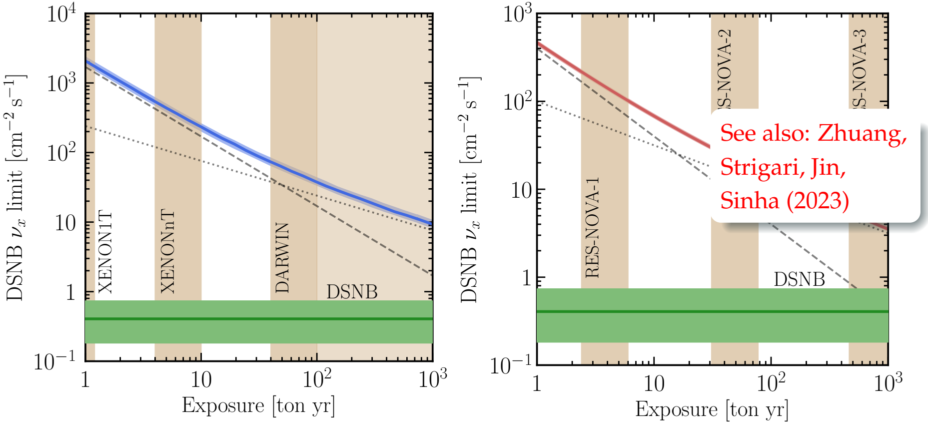
AMS, Beacom, Tamborra (2022)

Sensitivity bounds on the normalization of the x-flavor DSNB



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

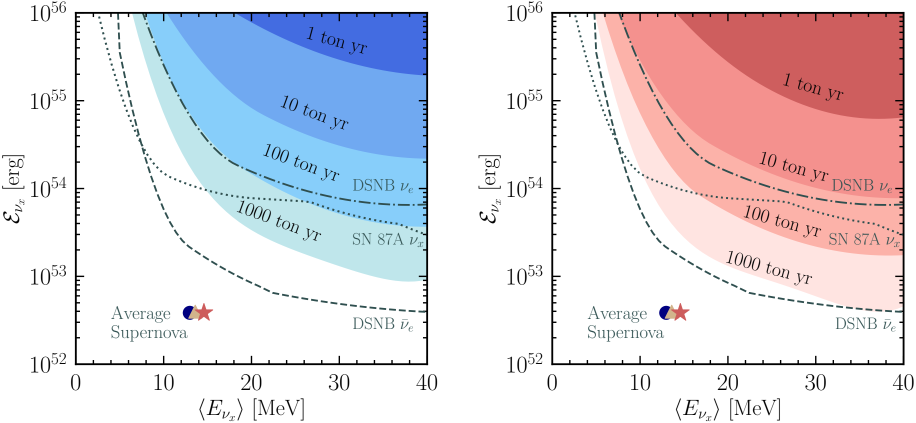
Sensitivity bounds on the normalization of the x-flavor DSNB



See also: Zhuang, Strigari, Jin, Sinha (2023)

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

Sensitivity bounds on the x-flavor DSNB



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

Conclusions

Diffuse supernova neutrino background

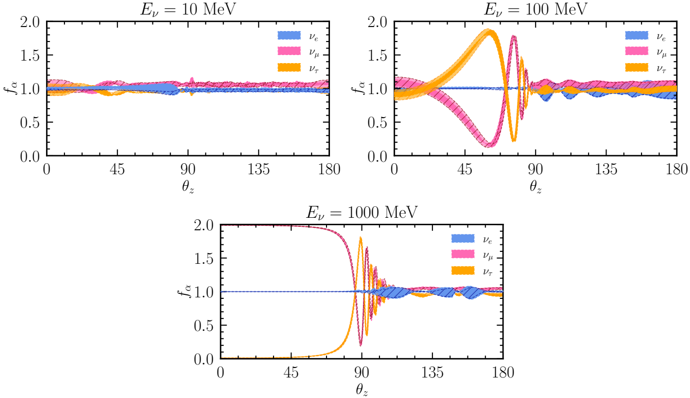
- $\bar{\nu}_e$: soon to be detected by SK + Gd, JUNO
- ν_e: posssibly detectable by DUNE
- ν_x:
  - XENON1T, PandaX-4T yield similar limits to the one from SK
  - CEνNS detectors can improve the existing limits $\gtrsim 100$

Improved limits on the *x*-flavor DSNB

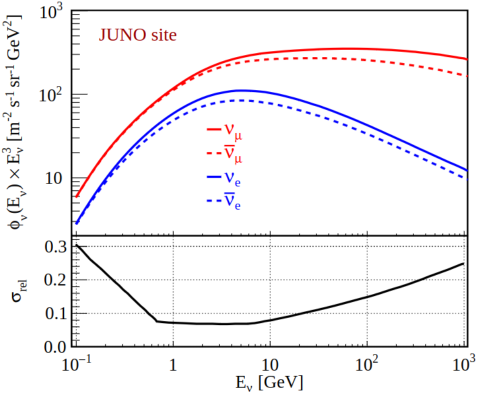
- help us to rule out potential non-standard scenarios
- bring us closer to understaning the supernova physics

Thank you for the attention!

Atmospheric neutrino oscillations



Relative uncertainty of atmospheric neutrinos



Cheng et al. (2022)

EPT cross sections

$$\sigma(E_\nu) = \frac{3G_F^2}{2\pi} F_A^2 (E_\nu')^2 I \,, \quad \sigma(E_\nu) = \frac{3G_F^2}{\pi} \cos\theta_C^2 F_A^2 E_e p_e I \mathcal{F}^{\pm}(Z, E_e) \,, \tag{1}$$

$$I = \frac{1}{2}\int_{-1}^{1} dz f(\mathbf{q}^2) \left(A + B + C\right) \,, \tag{2}$$

$$f(\mathbf{q}^2) = \left(\frac{F_A(q)}{F_A}\right)^2 = \left(1 - \frac{1-\rho}{6(b|\mathbf{q}|)^2}\right)^2 \exp\left(-\frac{(b|\mathbf{q}|)^2}{2}\right) \,, \tag{3}$$

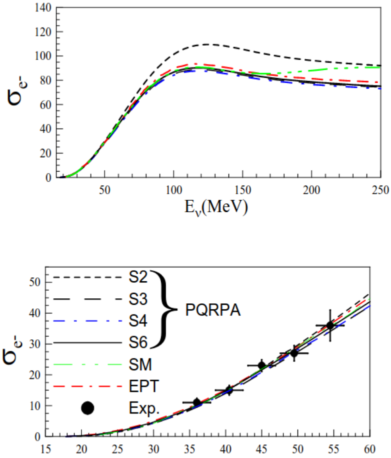
$$A = 1 - \frac{z}{3} \pm \frac{4}{3}(E_\nu + E_\nu')(1 - 2\sin^2\theta_W)(1-z)\,\frac{F_M}{F_A} \,, \tag{4}$$

$$B = \frac{2}{3}\left(E_\nu' E_\nu (1 - z^2) + (1-z)\mathbf{q}^2\right)(1 - 2\sin^2\theta_W)^2 \left(\frac{F_M}{F_A}\right)^2 \,, \tag{5}$$

$$C = -\frac{2}{3}\Delta M (1+z)\frac{F_T}{F_A} + \frac{1}{3}(1+z)\mathbf{q}^2 \left(\frac{F_M}{F_A}\right)^2 \,. \tag{6}$$

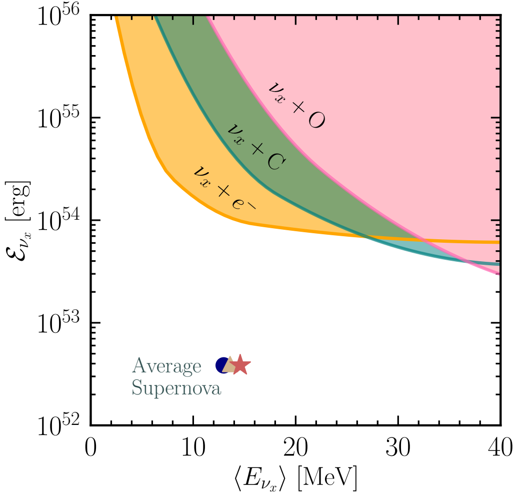
Fukugita et al. (1988)

CQRPA cross sections

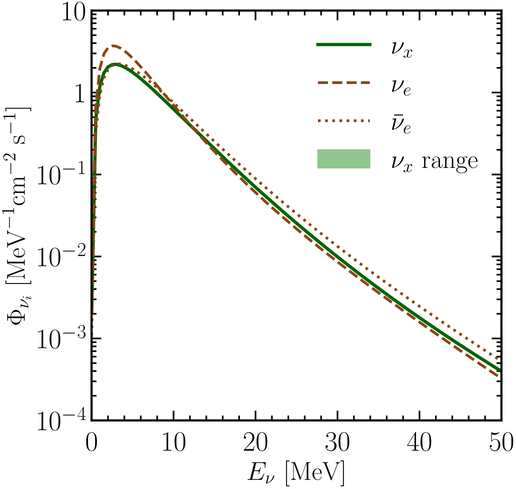


Samana et al. (2010)

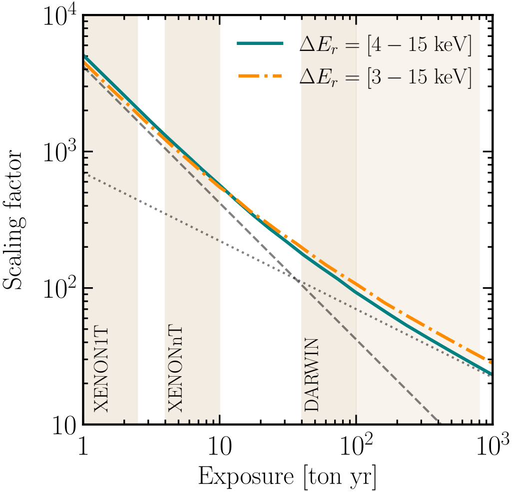
Limits from the SN 1987A



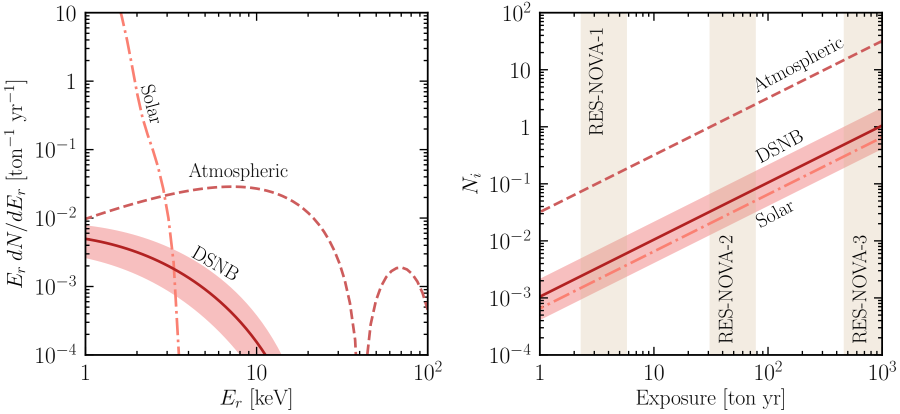
DSNB variability



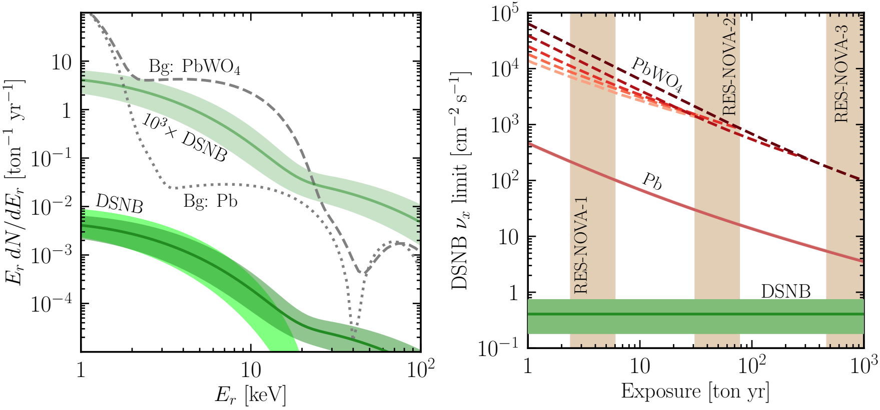
Sensitivity of the limits to a detection window



Event rate: lead detector



Event rate: lead crystals detector



Which part of the spectrum are CEνNS detectors sensitive to?