Towards Probing the Diffuse Supernova Neutrino Background in All Flavors

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Phys.Rev.D 105 (2022)
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Dark Matter and Neutrino Forum,
INPAC/TDLI of Shanghai Jiao Tong University
Feb. 22/23, 2022

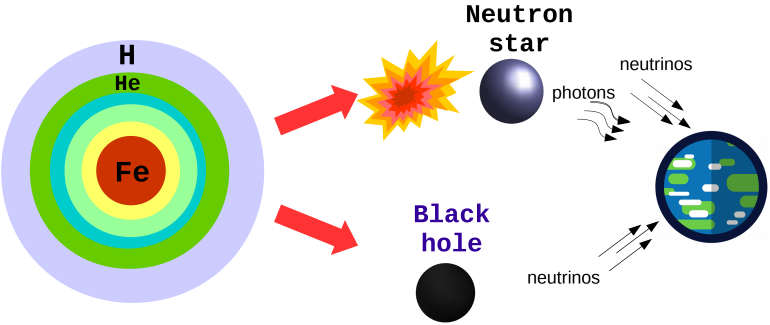
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Neutrinos and 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 (+ GW) can reveal the deep interior conditions
- only they (+ GW) are emitted from the collapse to a black hole



Earth image: Kurzgesagt

Why core-collapse supernovae are good physics probes?

Advantages

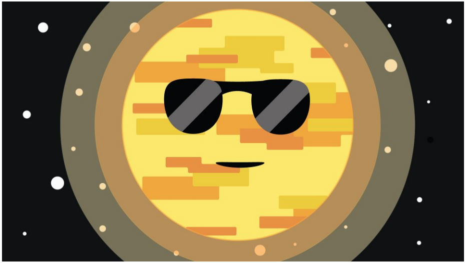
- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (SK, JUNO, XENON, PandaX...)

What can we learn with a variety of detectors?

- explosion mechanism — H. Bethe & J. Wilson (1985), T. Fischer et al. (2011)...
- yields of heavy elements — S. Woosley et al. (1994), S. Curtis et al. (2018)...
- compact object formation — M. Warren et al. (2019), S. Li, J. F. Beacom et al. (2020)...
- neutrino mixing — H. Duan et al. (2010), I. Tamborra & S. Shalgar (2020)...
- non-standard physics — A. de Gouvêa et al. (2019), **Suliga** et al. (2020)...

Why focus only on a single rare event?

Single event vs. multiple events

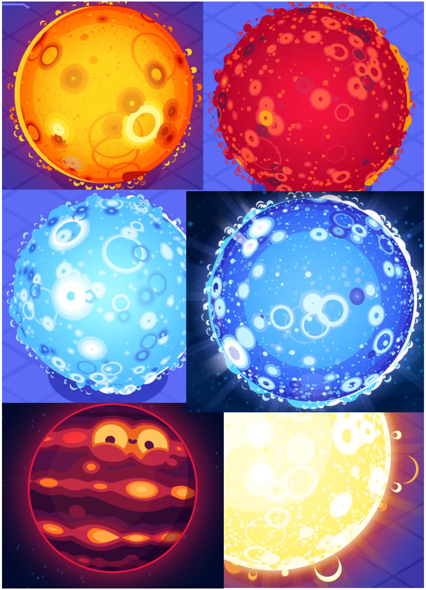


Single galactic SN event

- rare event
- precise infromation about one star

Multiple SN events (larger distances)

- cumulation of events
- uncovering any surprises



Images: Kurzgesagt

Diffuse supernova neutrino background

cosmological supernovae rate

fraction of black-hole-forming progenitors

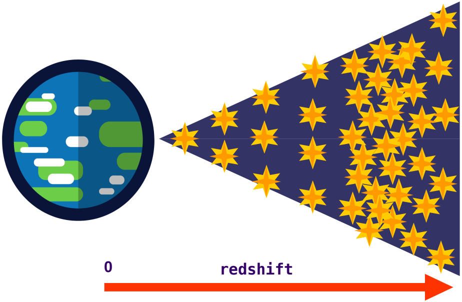
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,\rm CC-SN}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,\rm BH-SN}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

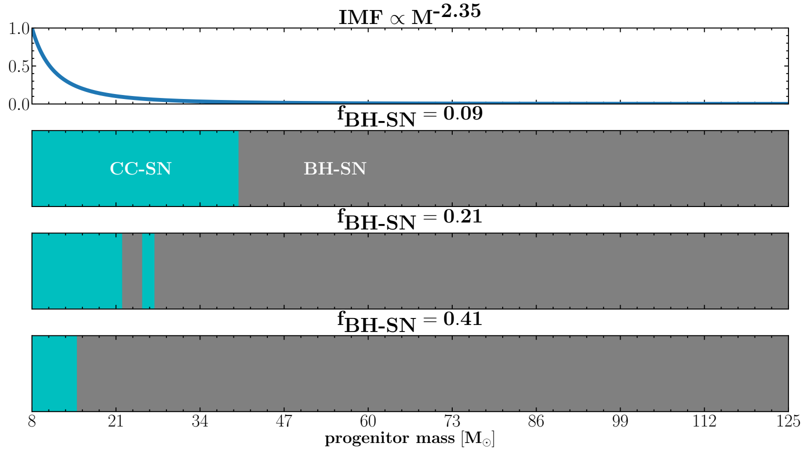
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino mass ordering
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010), Lunardini, Tamborra (2012), Møller, **Suliga** et al. (2018), Kresse et al. (2020)...

Astrophysical uncertainties

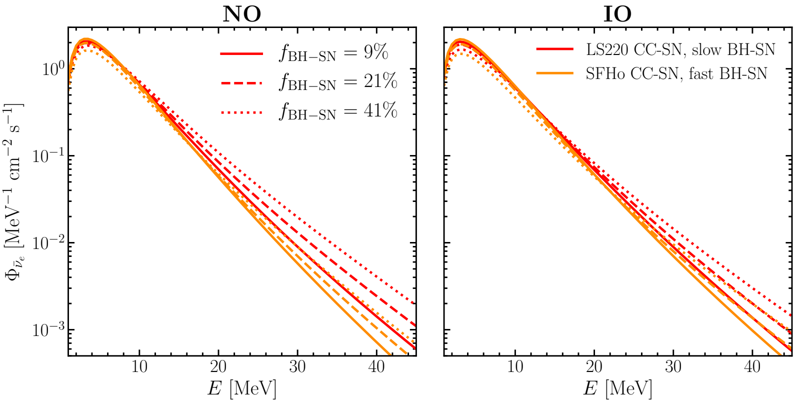
The fraction of black-hole-forming progenitors



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

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

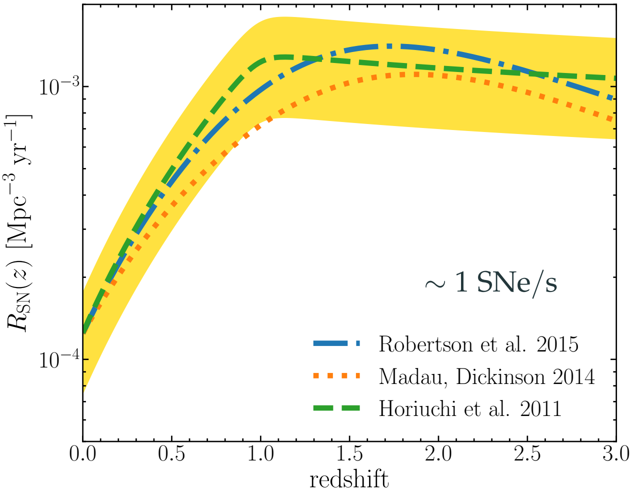
The fraction of black-hole-forming progenitors



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, **Suliga** et al. (2018), Nakazato et al. (2018) Kresse et al. (2020), ...

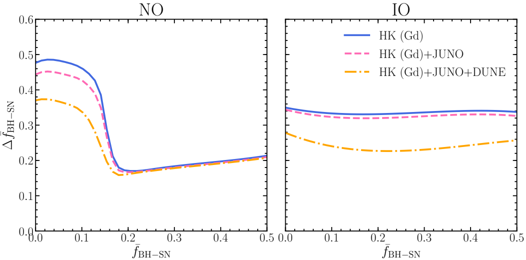
Cosmological supernovae rate



The supernovae rate influences the normalization of the DSNB.

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

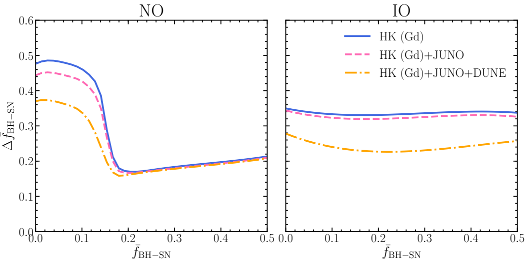
Expected 1σ uncertainty: fraction of BH forming progenitors



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

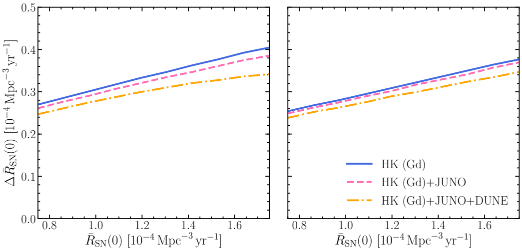
Møller, **Suliga**, Tamborra, Denton (2018)

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, **Suliga**, Tamborra, Denton (2018)

BSM scenarios affecting DSNB

Active neutrinos are massive and masses are not identical

- SM decays are loop supressed
- lifetimes $\gg$ age of the Universe

If neutrinos have interactions BSM they can decay faster

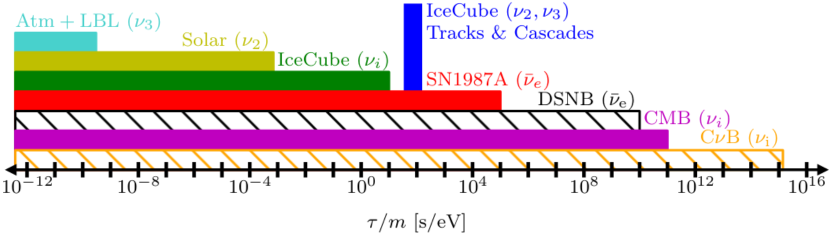
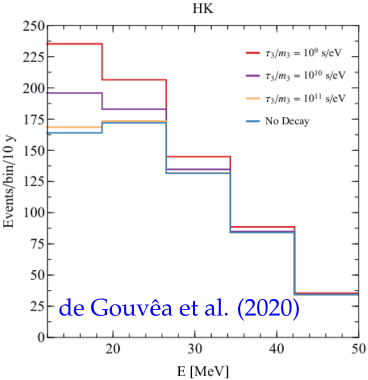
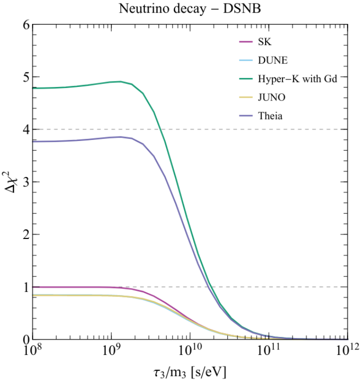


Figure credit: Abdullahi, Denton (2020)

Neutrino decay: impact on DSNB



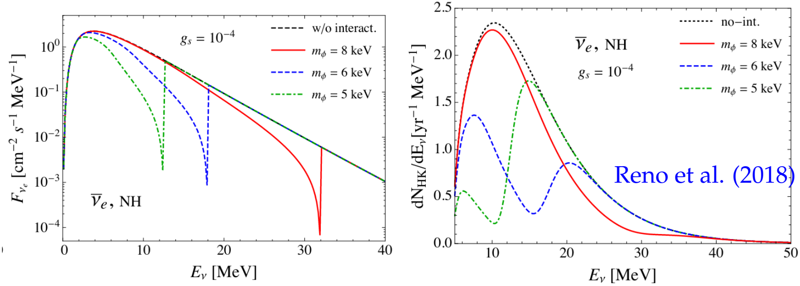


Exact detector features depend on

- Mass ordering
- Dirac vs Majorana nature
- details of the BSM model

Ando et al. 2003, Ando et al. 2003, Fogli et al. 2004, de Gouvêa et al. 2020

Secret neutrino interactions: impact on DSNB



Reno et al. (2018)

DSNB interactions with

- cosmic relic neutrinos

  Goldberg et al. (2005), Baker et al. (2007), Reno et al. (2018)

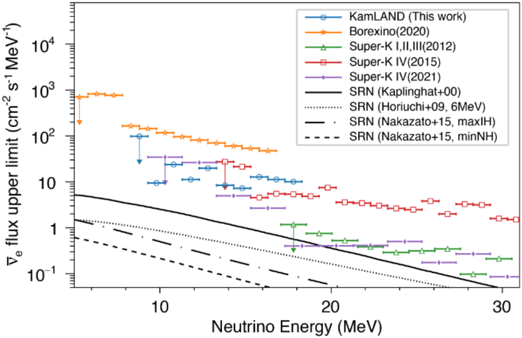
- dark matter Farzan, Palomares-Ruiz (2014)

result in spectral features in DSNB

Current limits on the DSNB

Diffuse supernova neutrino background: current limits

Abe et al. (2021)

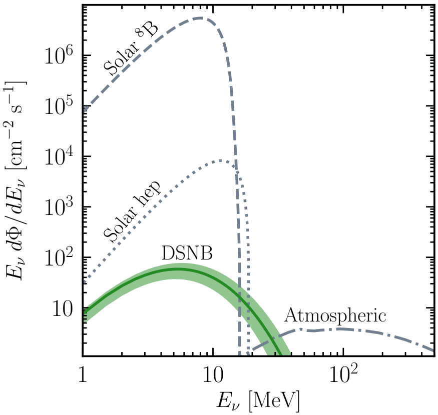


DSNB limits:

- $\bar{\nu}_e \approx 3\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3$ MeV Giampaolo et al. (2021), SK collab. (2021) soon detected by SK (Gd) Beacom, Vagins (2004) and JUNO JUNO collab. (2021)
- $\nu_e \approx 19\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu \,\epsilon\, [22.9, 36.9\ \mathrm{MeV}]$ Mastbaum et al. (2020) possibly detectable by DUNE Zhu et al. (2019)

Can we detect the x-flavor DSNB?

Can we detect the x-flavor DSNB? Maybe

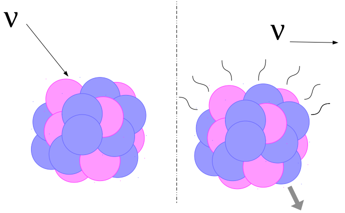


DSNB modeling:
Møller, **Suliga**, Tamborra, Denton (2018)

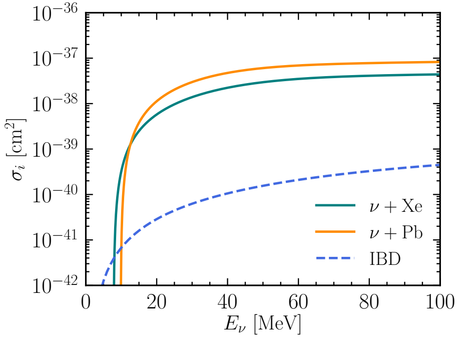
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750$ cm^{-2} s^{-1} for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

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

Maybe: Coherent elastic neutrino-nucleus scatterings (CEνNS)



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



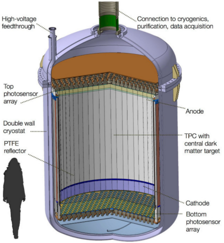
Cross section

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

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

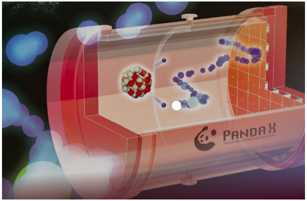
Freedman (1974)

XENONnT, DARWIN



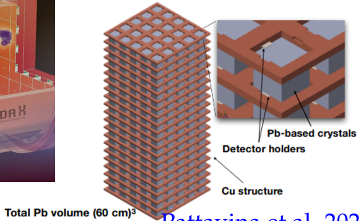
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

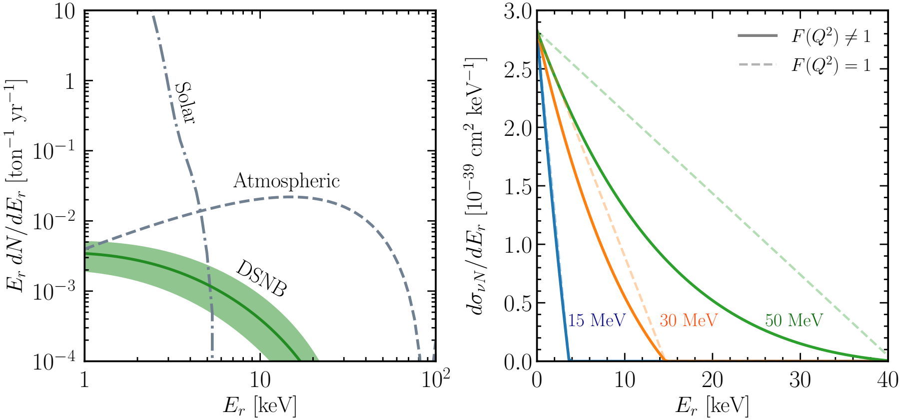
thresholds: $\mathcal{O}(1)$ keV

efficiency: $\sim$ 80-100%

Scattering rate

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

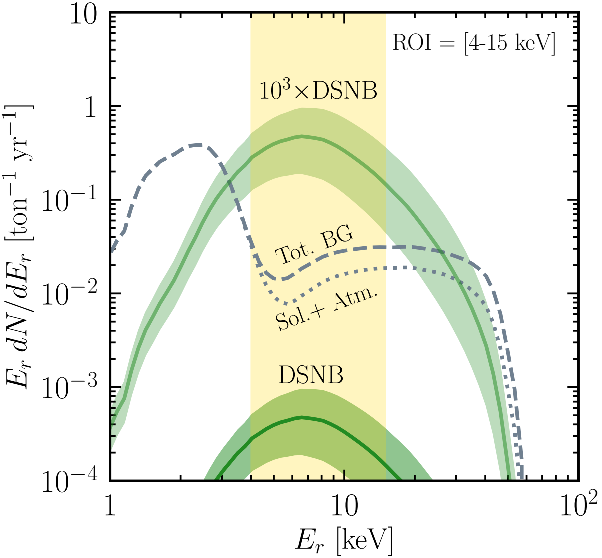
Event rate in the xenon-based detector



- 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?

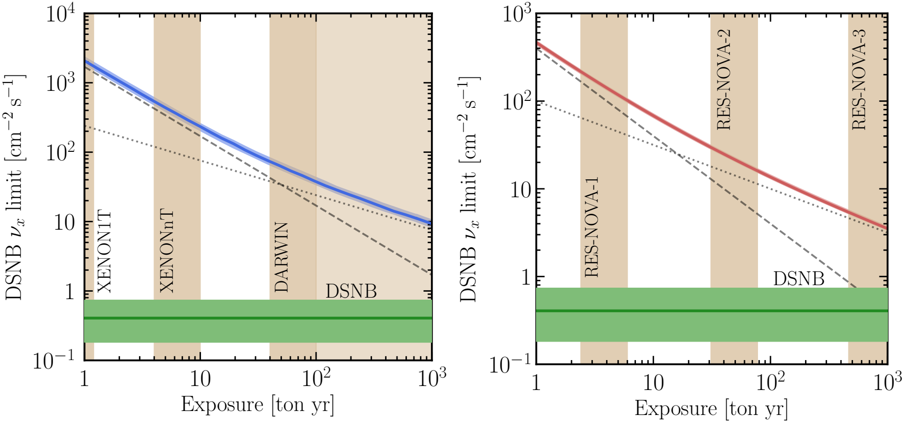
YES: Scaled event rate in the xenon-based detector



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

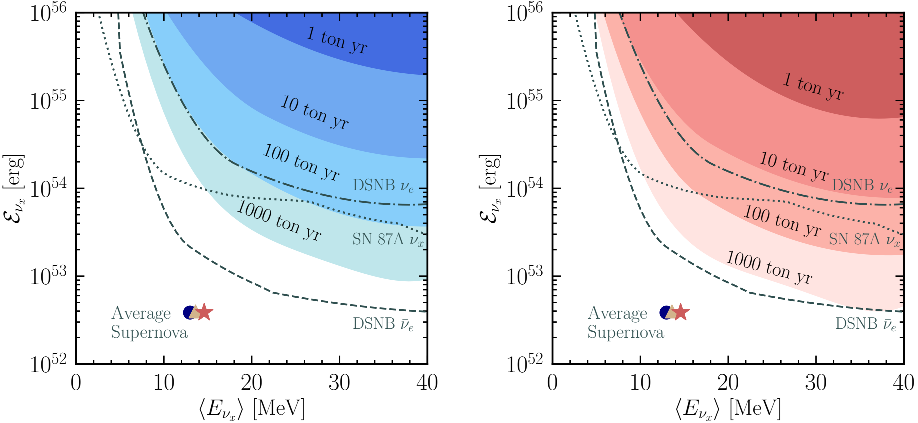
Sensitivity bounds on the x-flavor DSNB

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 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

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!