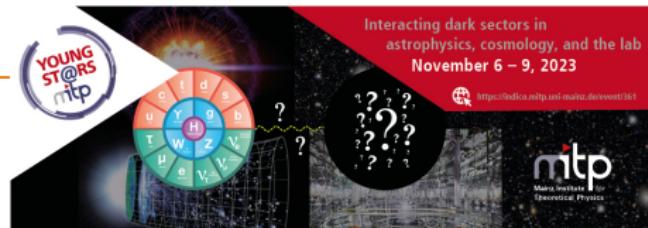


Probing self-interacting sterile neutrino dark matter with the diffuse supernova neutrino background

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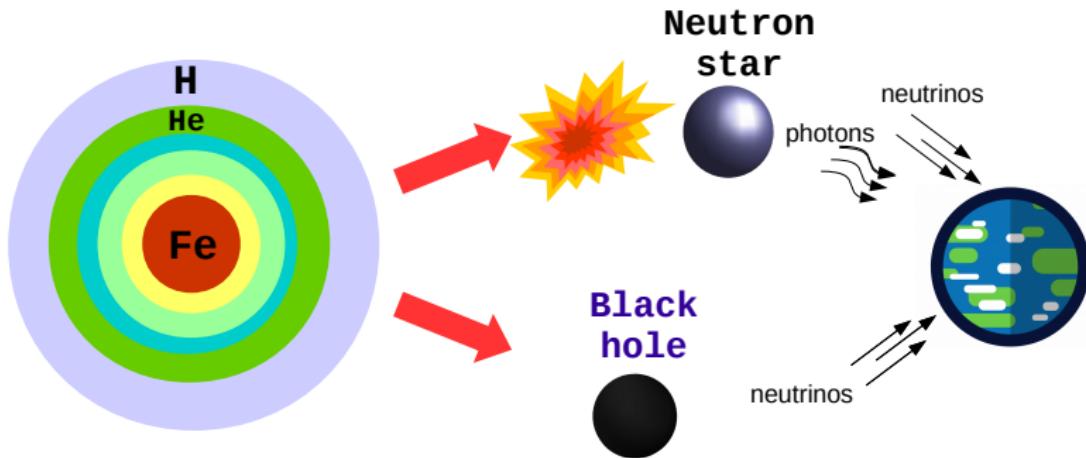
arXiv: 2310.07145, with B. Balantekin, G. Fuller, and A. Ray

MITP, November 8, 2023

Why are neutrinos important for a core-collapse supernova?

Neutrinos:

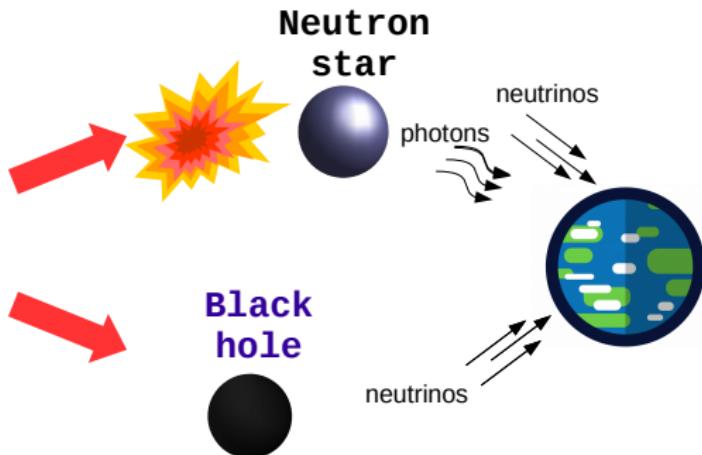
- $\sim 10^{58}$ of them emitted from a single core collapse
- only they (+ GW) can reveal the deep interior conditions
- only they (+ GW) are emitted from the collapse to a black hole



Why are neutrinos important for a core-collapse supernova?

Neutrinos:

- $\sim 10^{58}$ of them emitted from a single core collapse
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- 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?

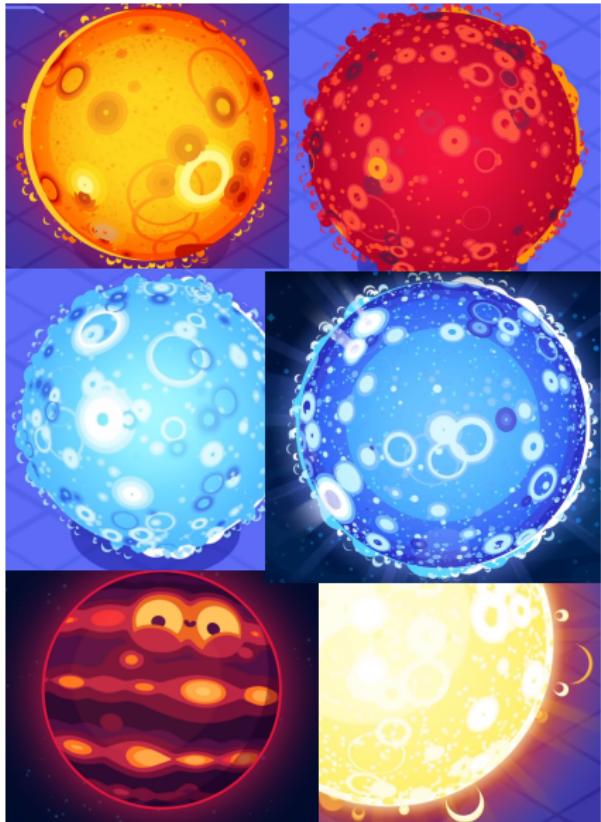
- explosion mechanism
[Bethe & Wilson \(1985\)](#),
[Fischer et al. \(2011\)](#)...
- yields of heavy elements
[Woosley et al. \(1994\)](#),
[Surman & McLaughlin \(2003\)](#)...
- compact object formation
[Warren et al. \(2019\)](#),
[Li, Beacom et al. \(2020\)](#)...
- neutrino flavor evolution
[Balantekin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

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 (DSNB)

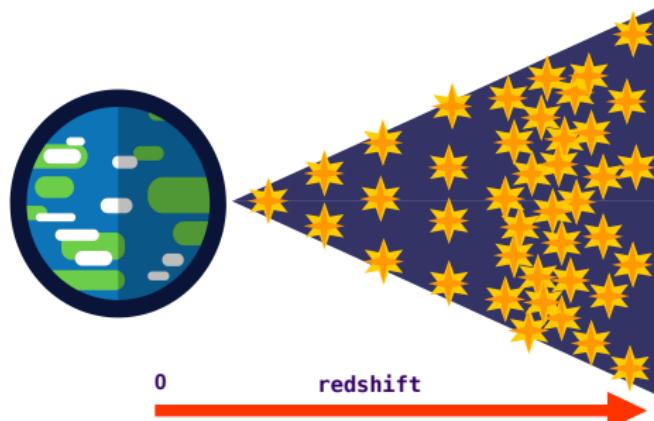
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0} \int dM \int dz \frac{R_{\text{SN}}(z, M)}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}} [f_{\text{CC-SN}} F_{\nu_\beta, \text{CC-SN}}(E', M) + f_{\text{BH-SN}} F_{\nu_\beta, \text{BH-SN}}(E', M)]$$

Diagram illustrating the components of the DSNB formula:

- cosmological supernovae rate**: Red arrow pointing to the term $\frac{R_{\text{SN}}(z, M)}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}}$.
- fraction of black-hole-forming progenitors**: Blue arrow pointing to the term $f_{\text{BH-SN}}$.
- neutrino flux from a single star**: Red arrow pointing to the term $F_{\nu_\beta, \text{CC-SN}}(E', M)$ or $F_{\nu_\beta, \text{BH-SN}}(E', M)$.
- fraction of neutron-star-forming progenitors**: Red arrow pointing to the term $f_{\text{CC-SN}}$.

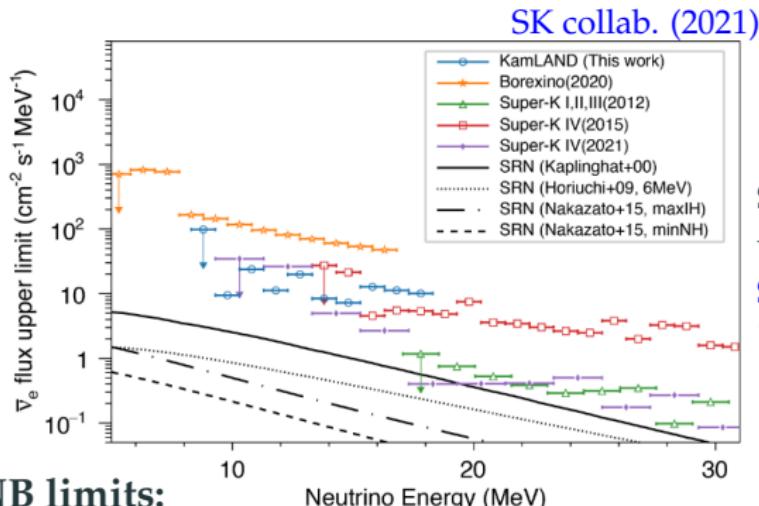
The DSNB is sensitive to:

- $R_{\text{SN}}, f_{\text{BH-SN}}$
- 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 with 0.01 Gd: ~same limits
with ~ 5 x shorter exposure

SK collab. (2023)

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, Tamborra, Denton (2018), Zhu et al. (2019)
- $\nu_x \approx 750 \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu > 19.3 \text{ MeV}$ SK Lunardini, Pestes (2008)
much better limits with DARWIN Strigari (2009), AMS, Beacom, Tamborra (2021)

Neutrinos

Fermions

Leptons	Quarks			Force carriers	
	u up	c charm	t top	γ photon	H Higgs boson
	d down	s strange	b bottom	g gluon	
e electron	μ muon	τ tau		Z Z boson	
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino		W W bosons	

Neutrino flavor and mass states

flavor basis mass basis

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

atmospheric

**beam,
reactor**

**solar,
reactor**

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

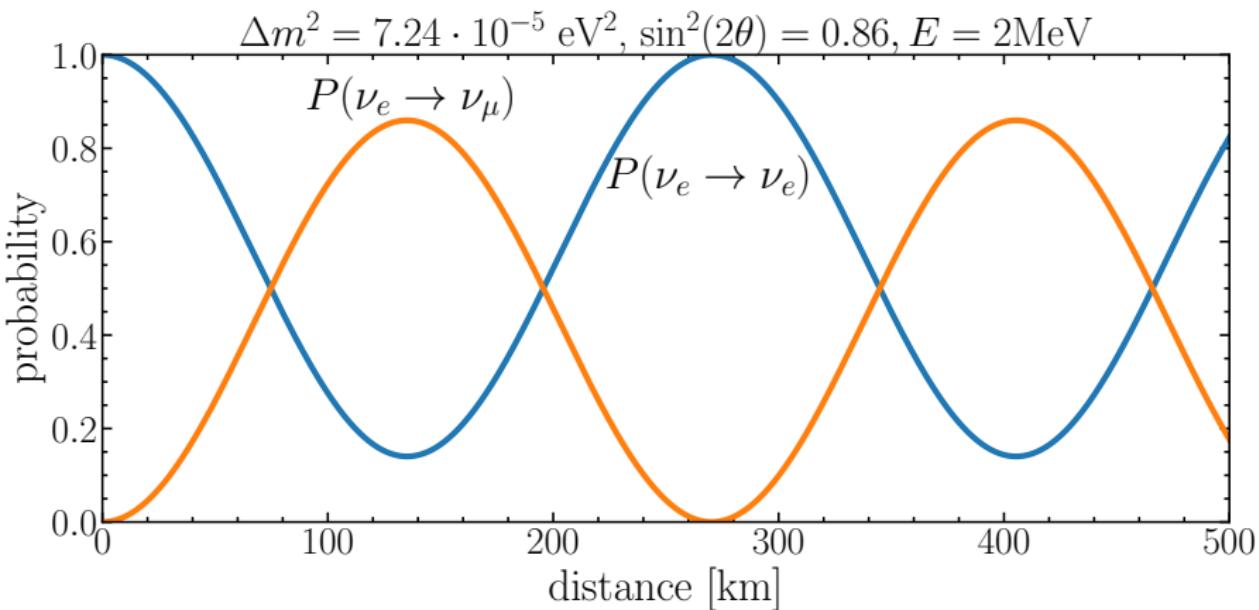
$$c_{ij} = \cos(\theta_{ij}), s_{ij} = \sin \theta_{ij}, \delta_{CP}$$

Neutrino oscillations in vacuum

2ν mixing = easy dependence on

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

- mixing angle
- mass squared difference



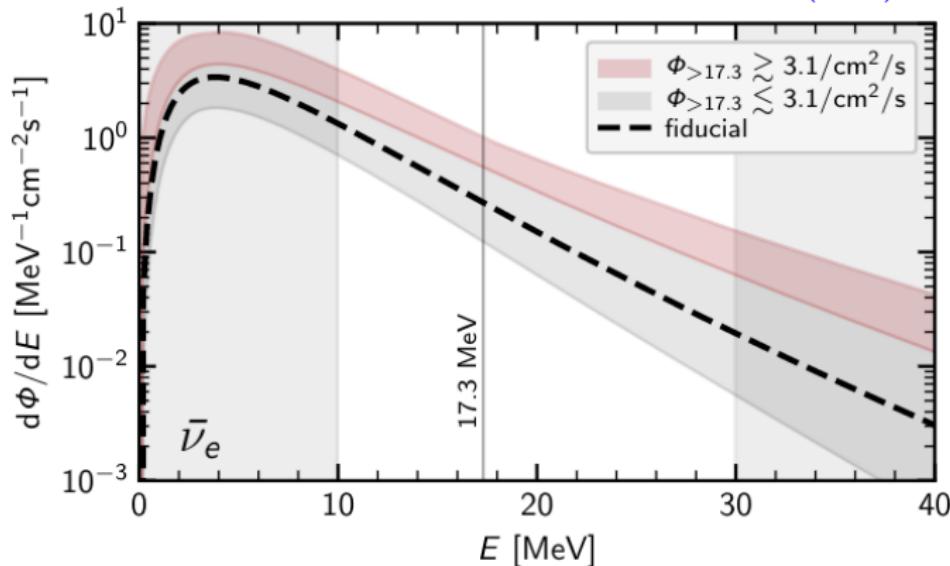
Astrophysical uncertainties affecting the DSNB

- 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

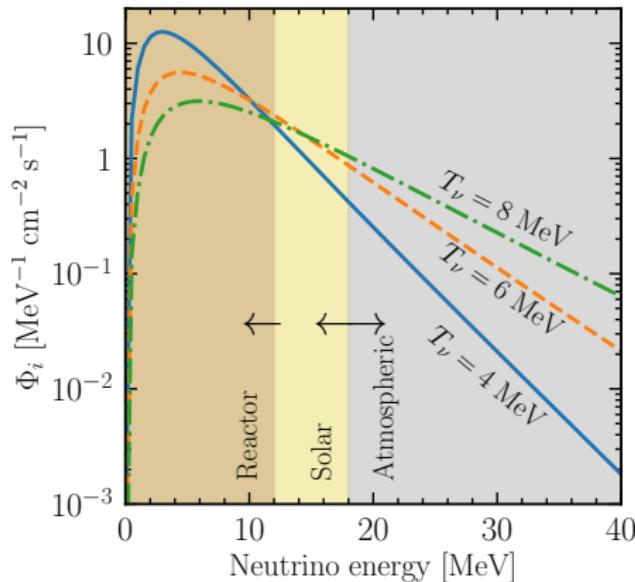
Kresse et al. (2020)



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

Neutrino Flux from an "Average Supernova"

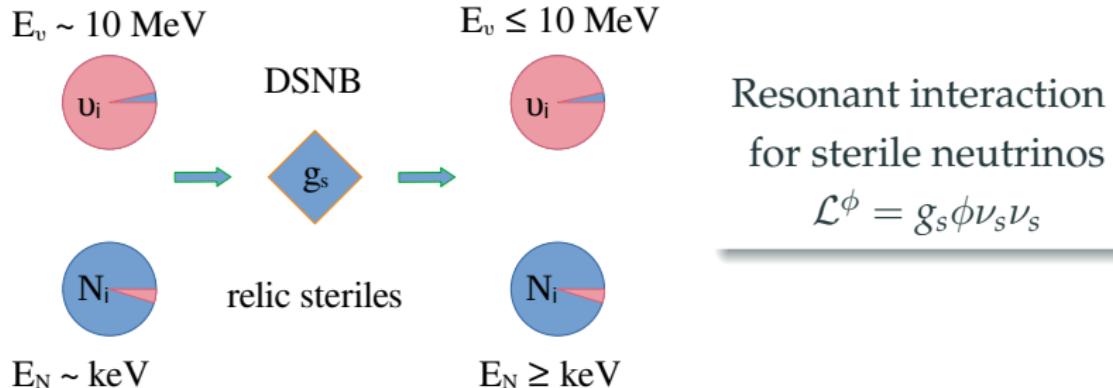
AMS (2022)



$$F_{\text{SN}}(E_\nu) = \frac{E_{\text{tot}}}{6} \frac{120}{7\pi^4} \frac{E_\nu^2}{T_\nu^4} \frac{1}{\exp(E_\nu/T_\nu) + 1},$$

**What types of new physics can be
probed with DSNB given the
astrophysical uncertainties?**

KeV-mass sterile neutrino self-interactions



$$\sigma(E_\nu) = \frac{g_s^4}{4\pi} \frac{s}{(s - m_\phi^2)^2 + m_\phi^4 \Gamma_\phi^2} \approx \frac{\pi g_s^2}{m_\phi^2} E_\nu \delta(E_R - E_\nu), \text{ where } E_R = m_\phi^2 / 2m_s$$

- sterile component in the DSNB ν_i interacts with the mostly sterile relic background of N_i

Modeling secret neutrino interactions in DSNB

Modified DSNB flux

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

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 $z_R = E_R/E_\nu - 1$,

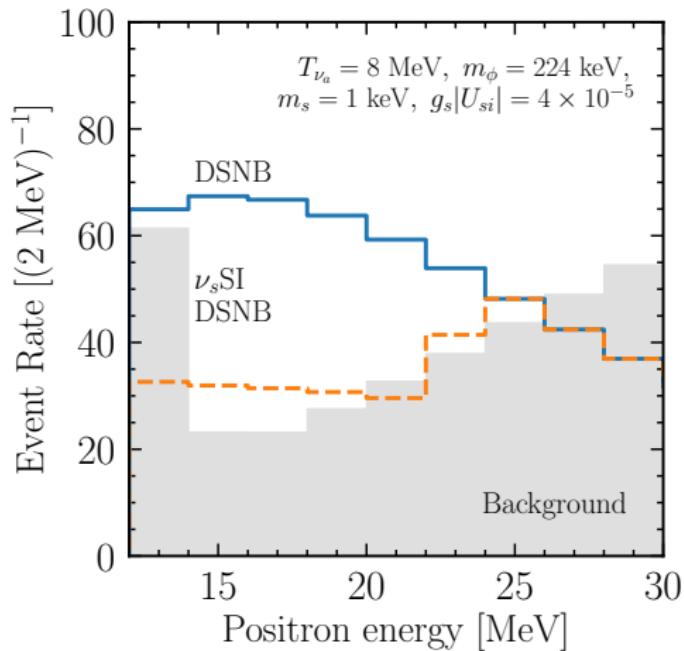
interaction rate $\Gamma_R(z_R) \simeq |U_{si}|^2 n_{\nu_s}(z_R) \sigma_R$,

and sterile neutrino number density $n_{\nu_s}(z_R) = n_{\nu_s}(1 + z_R)^3$

similar studies for active neutrino self-interactions and eV-mass sterile neutrinos:

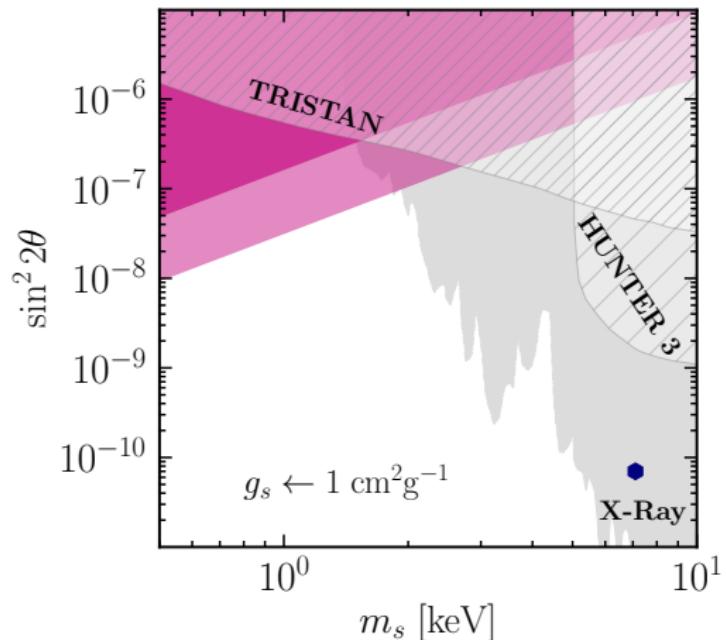
Goldberg et al. (2005), Baker et al. (2007), Farzan, Palomares-Ruiz (2014), Reno et al. (2018), Creque-Sarbinowski et al. (2021) **13/16**

Secret neutrino interactions: DSNB



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

Sensitivity limits



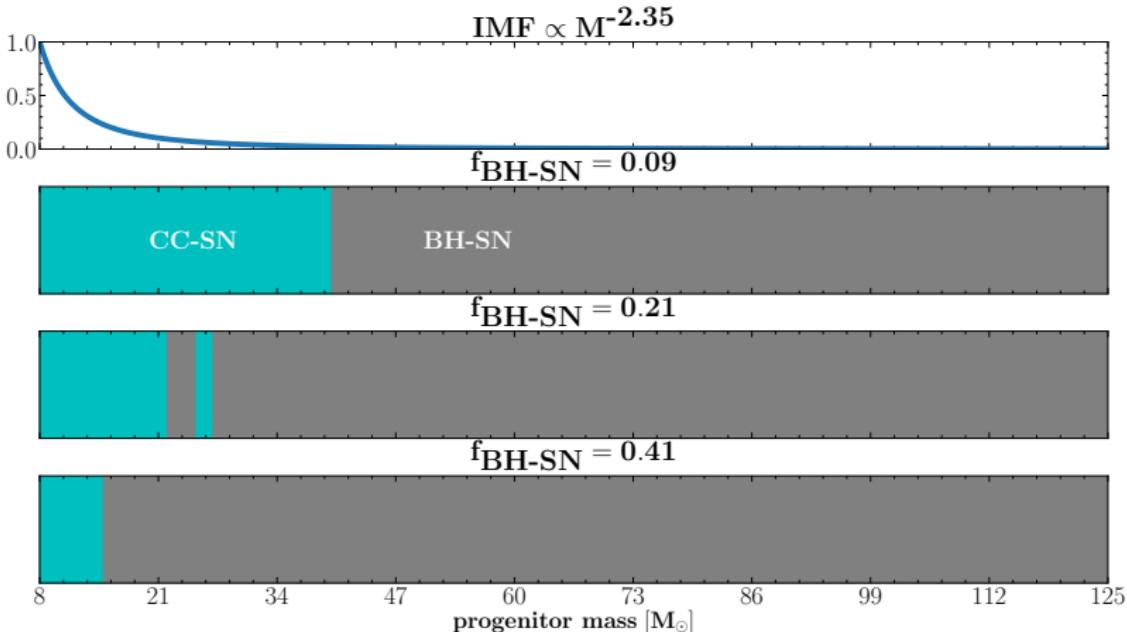
- Overlap with the TRISTAN experiment parameter space
- Reduction of the astrophysical uncertainties helps but not by a lot

Conclusions

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

Thank you for the attention!

The fraction of black-hole-forming progenitors

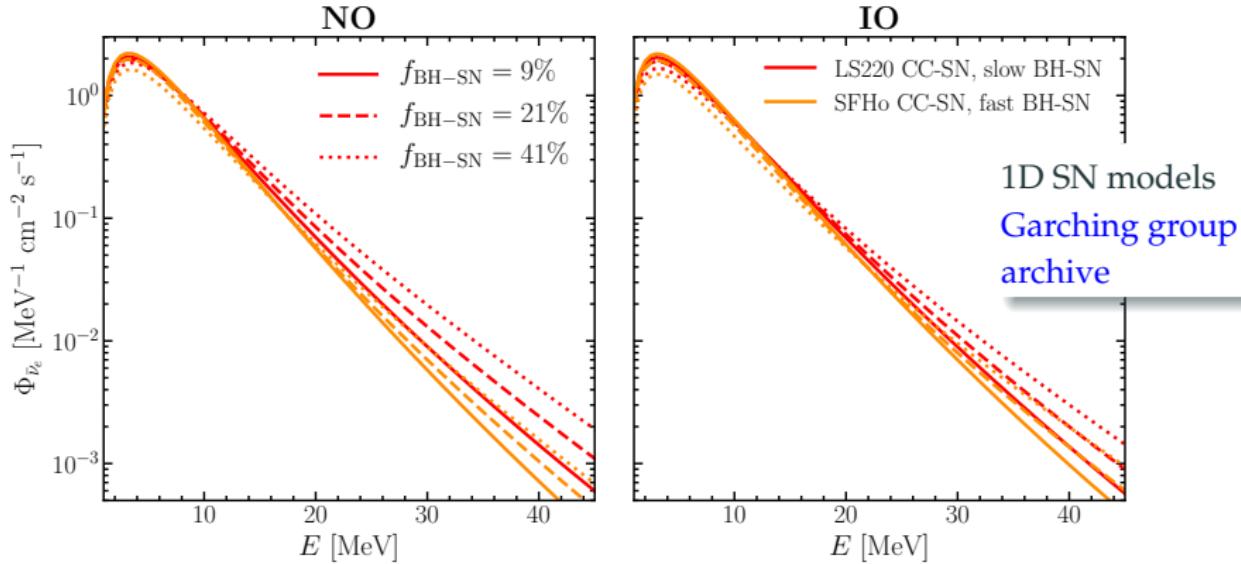


Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV.

C. Lunardini (2009)

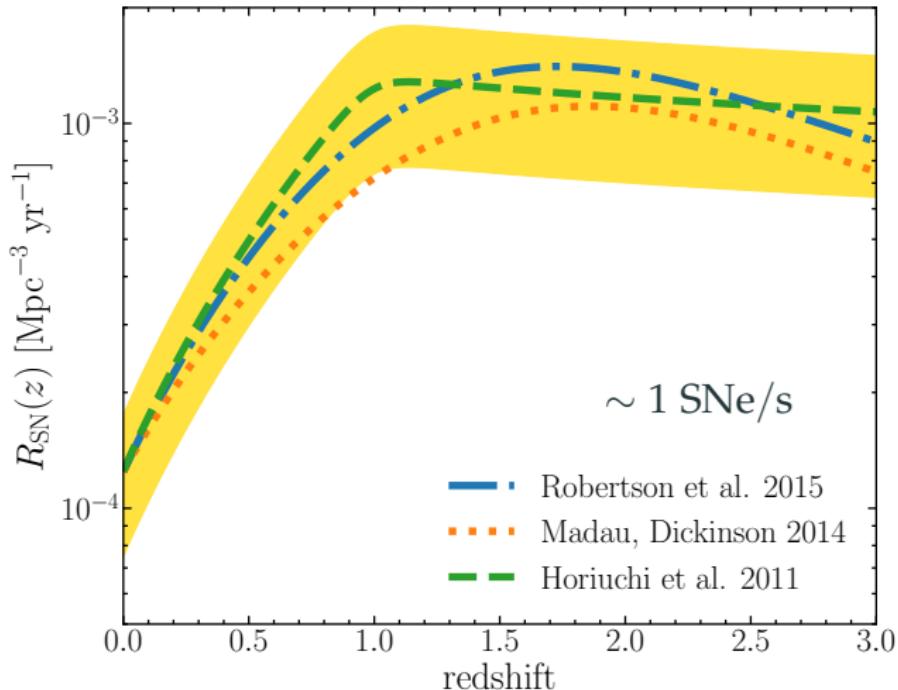
Ertl et al. 2015, Sukhbold et al. 2015, Adams et al. 2016, Heger et al. 2001,
Kochanek et al. 2001, Basinger et al. 2020, ...

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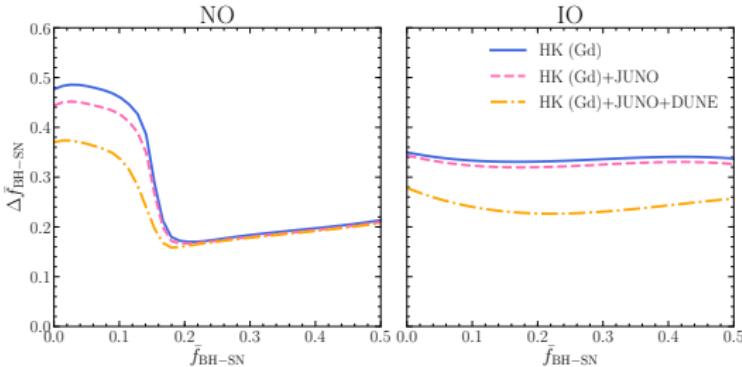
Cosmological supernovae rate



The supernovae rate influences the normalization of the DSNB.

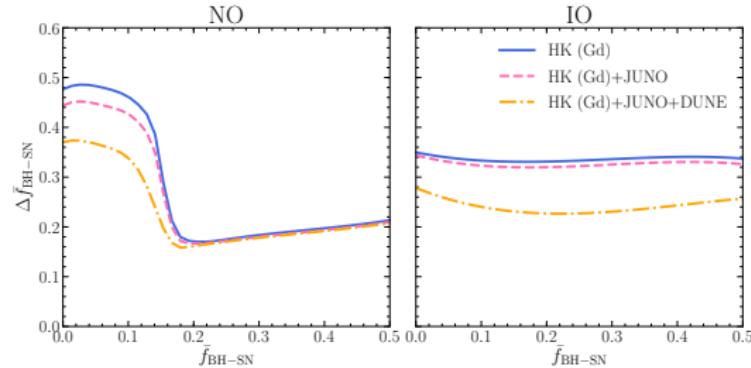
Ando, Sato (2004), Beacom (2010), Horiuchi et al. (2011), Møller, AMS, Tamborra, Denton (2018), Nakazato et al. (2018), ...

Expected 1σ uncertainty: fraction of BH forming progenitors



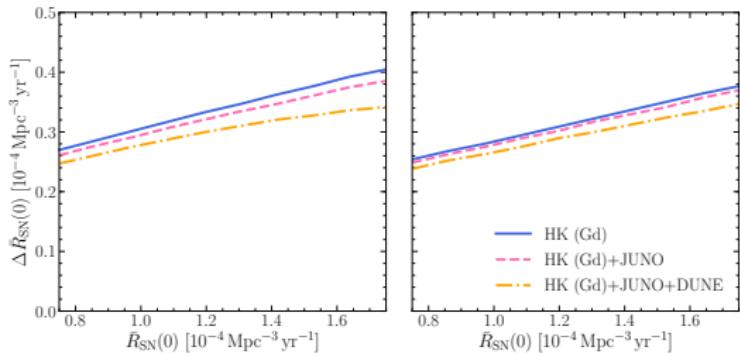
- The high uncertainty comes from $f_{\text{BH-SN}}$ -mass accretion rate degeneracy
- DUNE is sensitive to neutrinos → helps to reduce the uncertainty

Expected 1σ uncertainty: local supernova rate

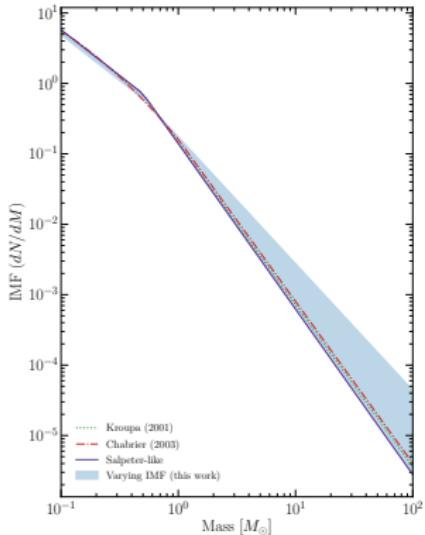


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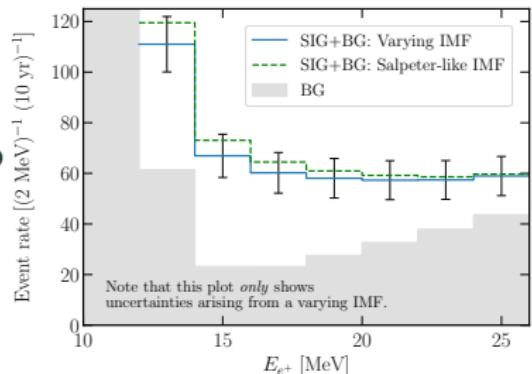
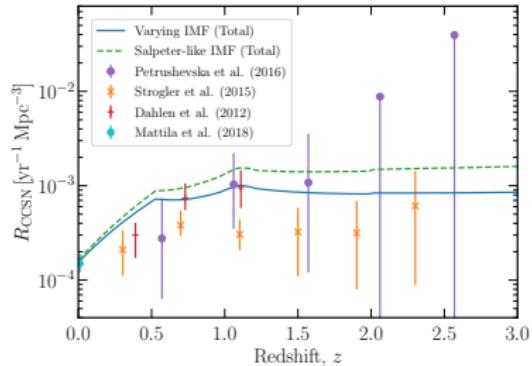
- Relative error of 20%-33% independent of the mass ordering.



Varying Initial Mass Function



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



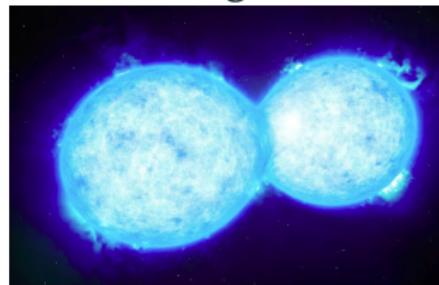
Binary interactions

**Majority of massive stars have stellar companions
and experience binary interactions** [Sana et al. 2012](#), [Zapartas et al. 2020](#)

Mass transfer



Mergers



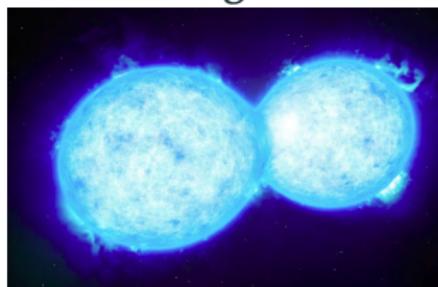
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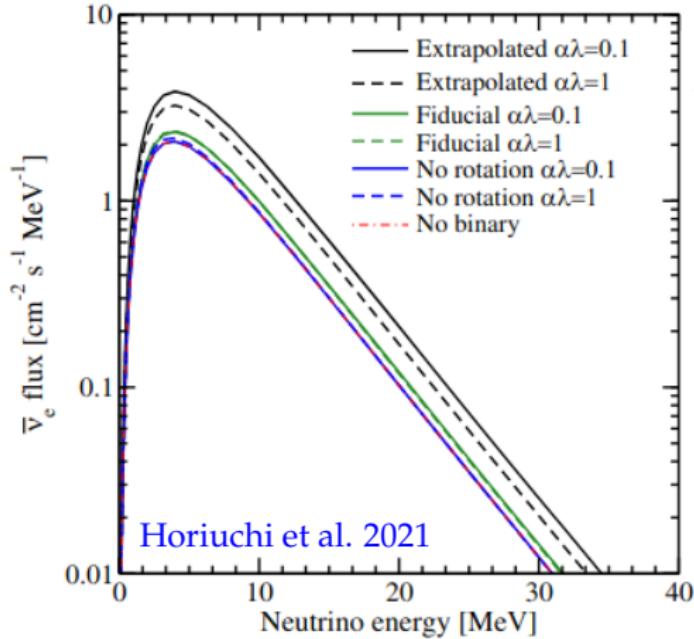


Effects on the stellar population [Horiuchi et al. 2021](#)

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

Limits from the SN 1987A

