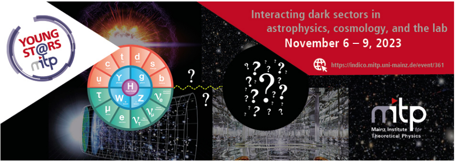
Probing self-interacting sterile neutrino dark matter with the diffuse supernova neutrino background



Anna M. Suliga

University of California, Berkeley
University of California, San Diego

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

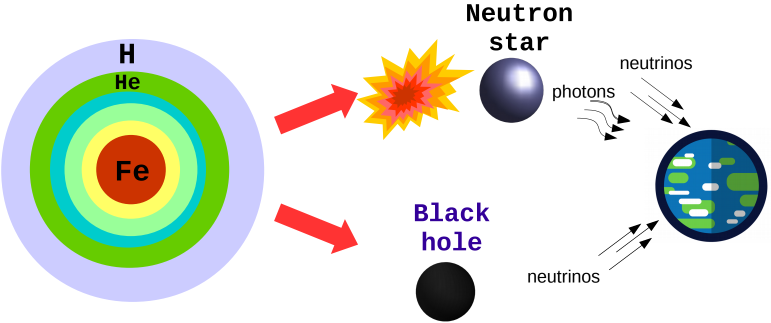
MITP, November 8, 2023

N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER
NSF

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

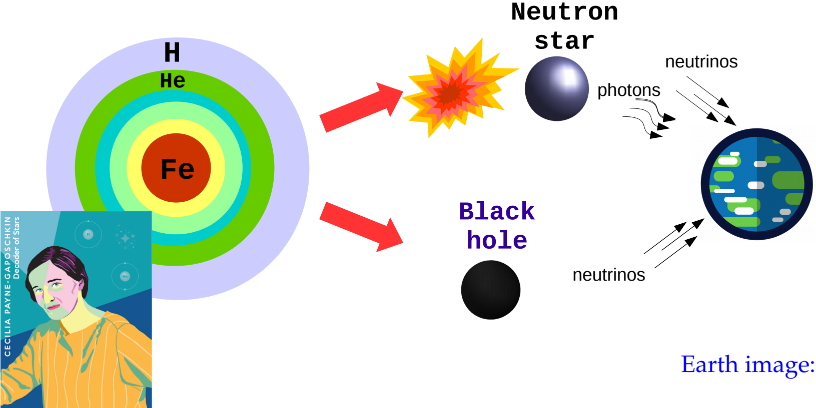


Earth image: Kurzgesagt

Why 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?

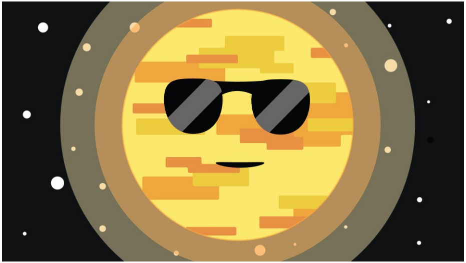
Advantages

- 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	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?

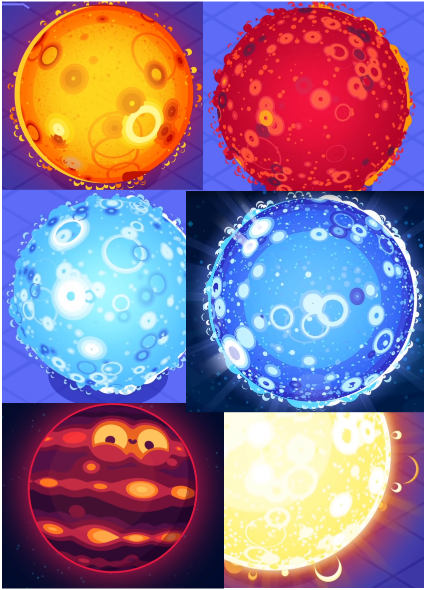


Single galactic SN event

- 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 (DSNB)

cosmological supernovae rate

fraction of black-hole-forming progenitors

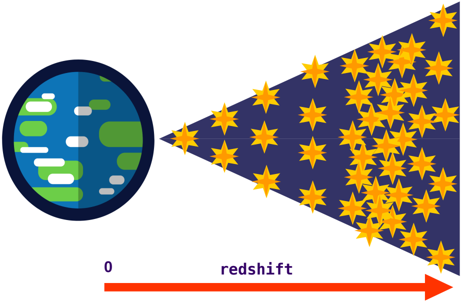
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,{\rm CC-SN}}(E',M)+f_{\rm BH-SN}F_{\nu_\beta,{\rm BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

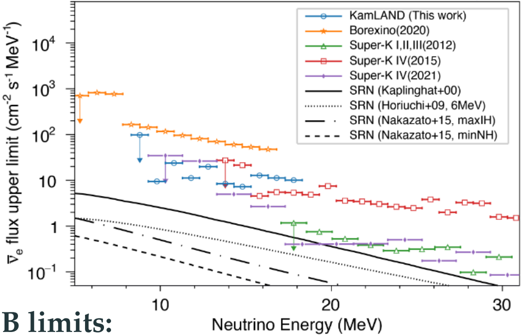
- $R_{\rm SN}$, $f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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)



SK with 0.01 Gd: ∼same limits with ∼ 5x shorter exposure SK collab. (2023)

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 $E_\nu \in [22.9, 36.9\ \mathrm{MeV}]$ SNO collab. (2020)

  possibly detectable by DUNE Møller, **AMS**, Tamborra, Denton (2018), Zhu et al. (2019)
- $\nu_x \approx 750\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV SK Lunardini, Pestes (2008)

  much better limits with DARWIN Strigari (2009), **AMS**, Beacom, Tamborra (2021)

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), ...

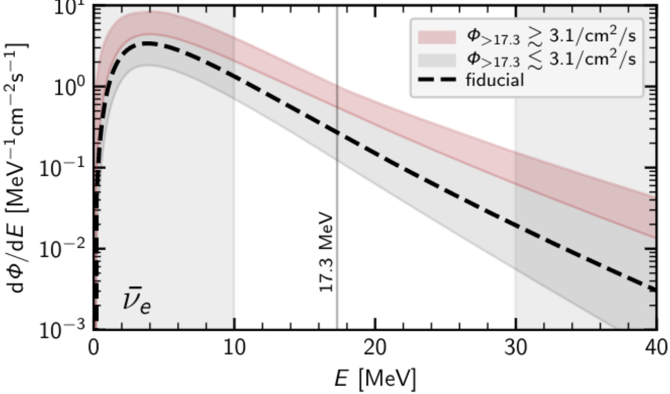
- Binary Interactions

  Horiuchi, Kinugawa, Takiwaki, Takahashi (2021)

Non exhaustive list of references

Astrophysical uncertainties affecting the DSNB

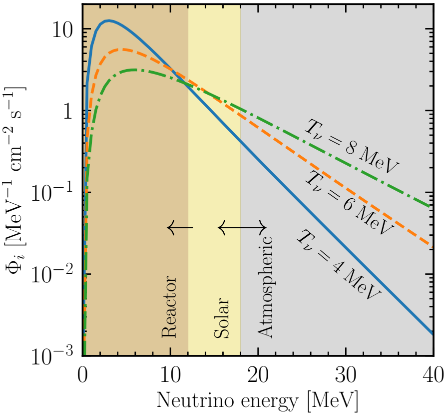
Kresse et al. (2020)



- 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”

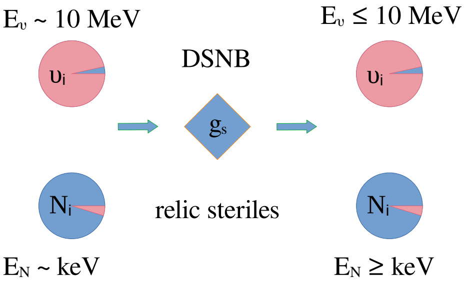
AMS (2022)



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

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

KeV-mass sterile neutrino self-interactions



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

Modeling secret neutrino interactions in DSNB

Modified DSNB flux

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

Probability of interaction

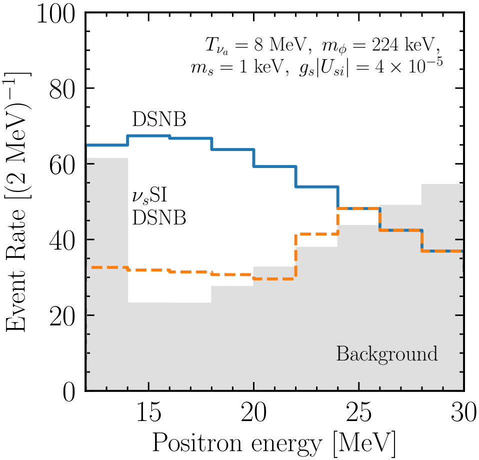
$$P_i(E_\nu, z) = e^{-\tau_i(E_\nu, z)}$$

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

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 $n_{\nu_s}(z_R) = n_{\nu_s}(1+z_R)^3$

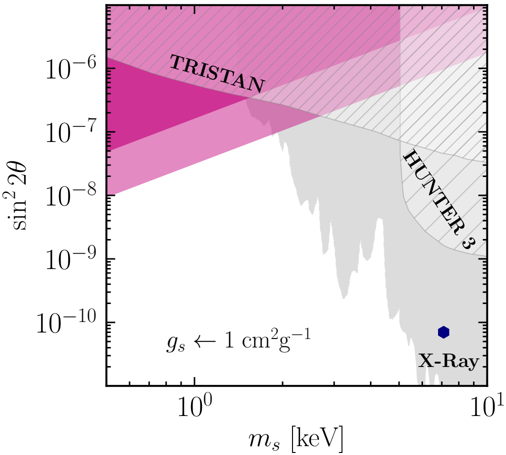
smilar studies for active neutrino self-interactions and eV-mass sterile neutrinos:
Goldberg et al. (2005), Baker et al. (2007), Farzan, Palomares-Ruiz (2014), Reno et al. (2018), Creque-Sarbinowski et al. (2021)

Secret neutrino interactions: DSNB



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

Sensitivity limits



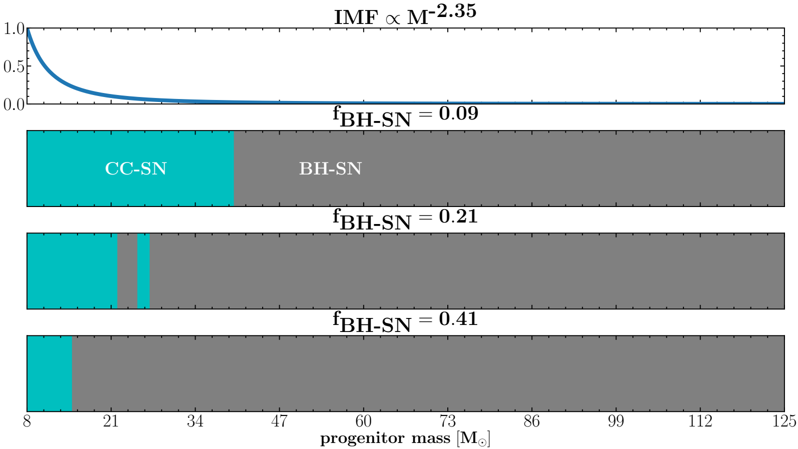
- **Overalap with the TRISTAN experiment paramater space**
- **Reduction of the astrophysical uncertainties helps but not by a lot**

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**

Thank you for the attention!

The fraction of black-hole-forming progenitors

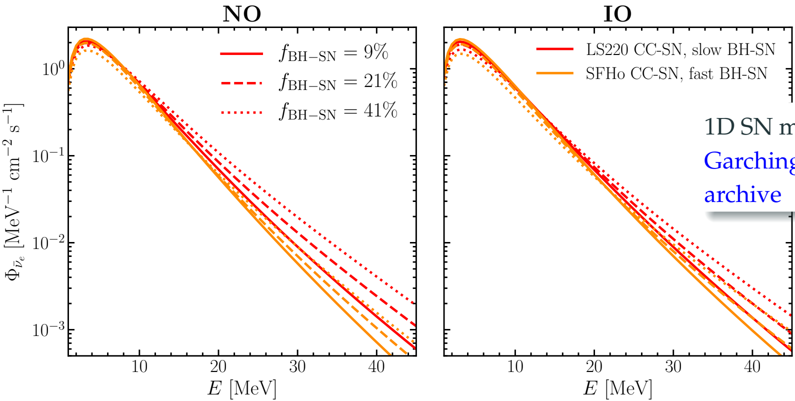


Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV.

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, ...

The fraction of black-hole-forming progenitors

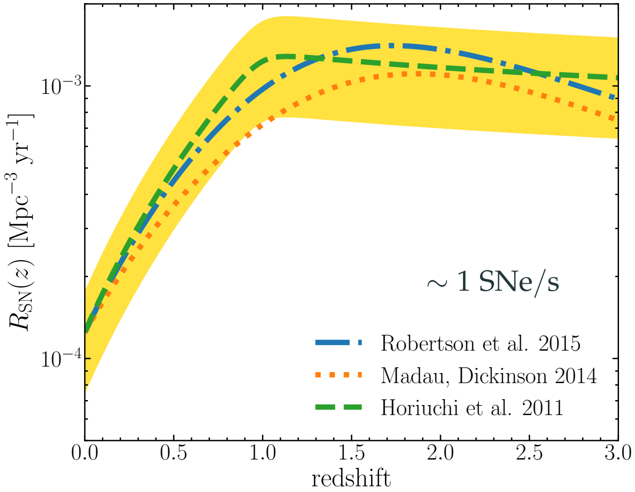


1D SN models
Garching group archive

Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above $\sim$ 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), ...

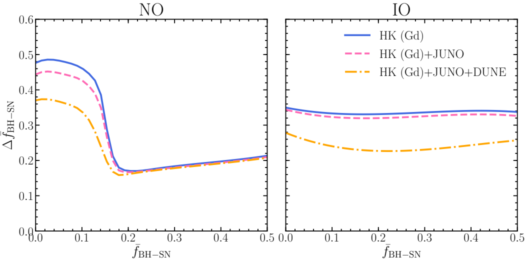
Cosmological supernovae rate



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), ...

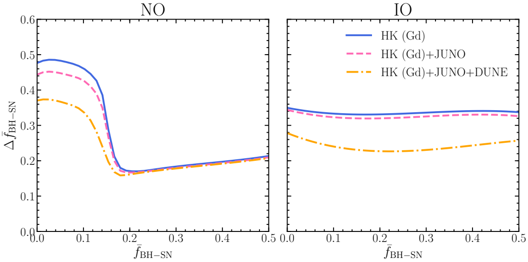
Expected 1σ uncertainty: fraction of BH forming progenitors



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

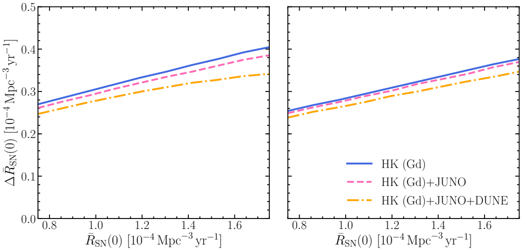
Møller, **AMS**, Tamborra, Denton (2018)

Expected 1σ uncertainty: local supernova rate



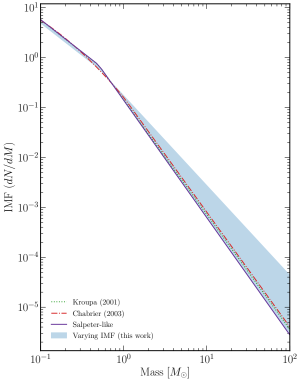
- The high uncertainty comes from $f_{\rm BH-SN}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos → helps to reduce the uncertainty

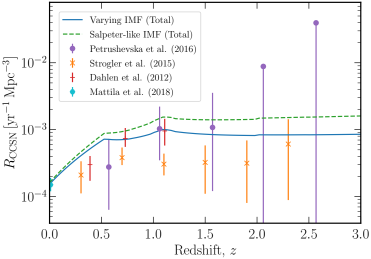
- Relative error of 20%-33% independent of the mass ordering.

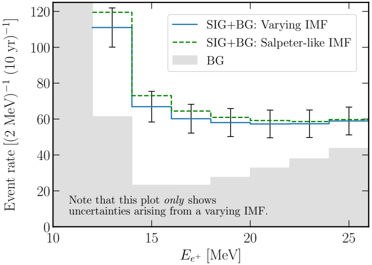


Møller, **AMS**, Tamborra, Denton (2018)

Varying Initial Mass Function







Note that this plot *only* shows uncertainties arising from a varying IMF.

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

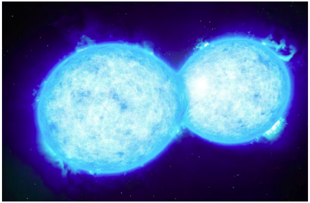
Ziegler, Edwards, **AMS**, Tamborra, Horiuchi, Ando, Freese (2022)

Binary interactions

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

Mass transfer

Mergers



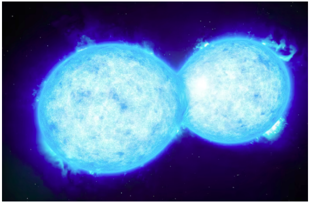
Images: iflscience, Wiki

Binary interactions

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

Mass transfer

Mergers

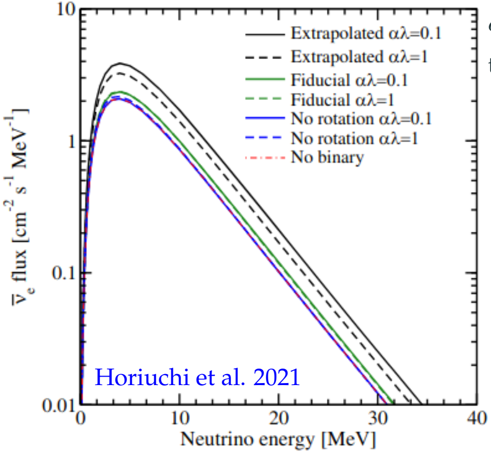


Effects on the stellar population Horiuchi et al. 2021

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

Images: iflscience, Wiki

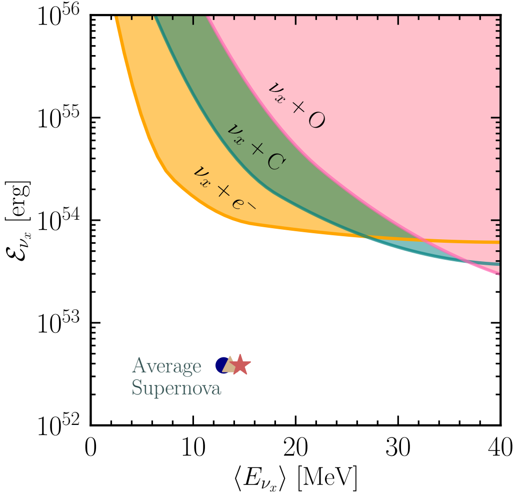
Binary interactions: impact on DSNB



$\alpha\lambda$ - 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

Limits from the SN 1987A



AMS, Beacom, Tamborra (2022)