Towards Probing the Diffuse Supernova Neutrino Background in All Flavors

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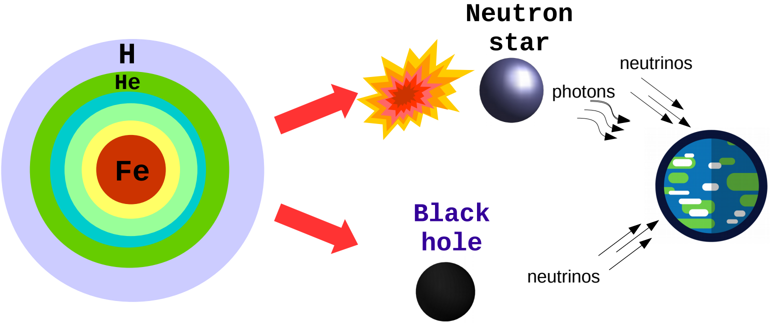
PHYSICS FRONTIER CENTER

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 core-collapse supernovae are good physics probes?

Advantages

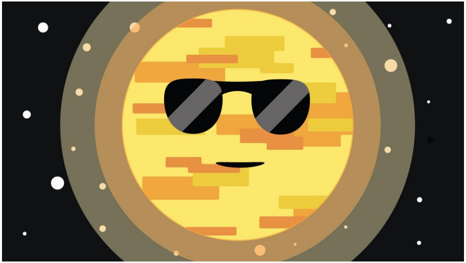
- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (DUNE, SK, XENON & LZ...)

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

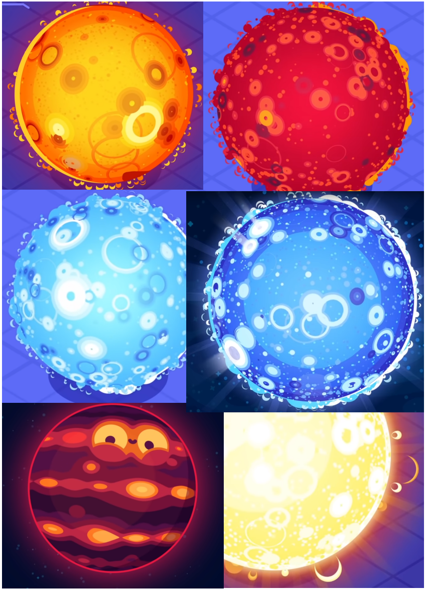


Single galactic SN event

- 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

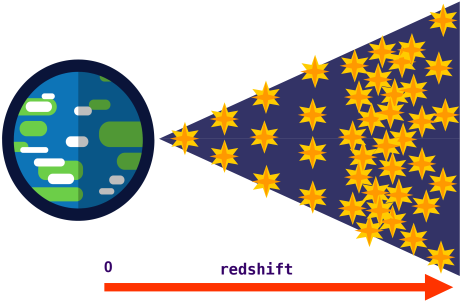
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\mathrm{SN}}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\mathrm{CC-SN}}F_{\nu_\beta,\mathrm{CC-SN}}(E',M) + f_{\mathrm{BH-SN}}F_{\nu_\beta,\mathrm{BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

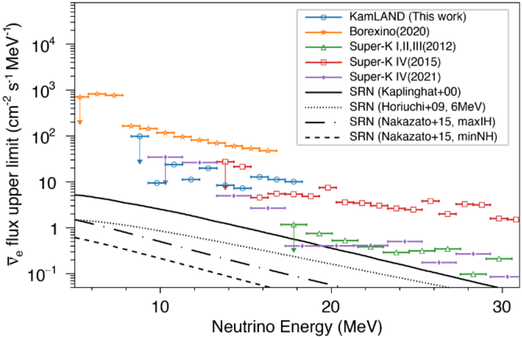
The DSNB is sensitive to:

- $R_{\mathrm{SN}}, f_{\mathrm{BH-SN}}$
- 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)...

Diffuse supernova neutrino background: current limits



Abe et al. (2021)

DSNB limits:

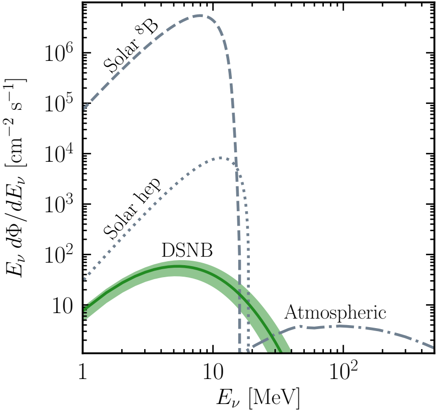
- $\bar{\nu}_e \approx 3\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3\ \mathrm{MeV}$ Giampaolo et al. (2021)

  soon will be detected by SK + Gd Beacom, Vagins (2004)
- $\nu_e \approx 19\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ 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

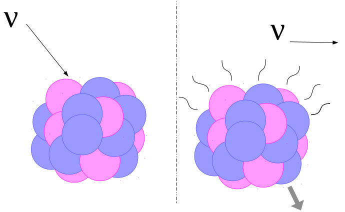


DSNB modeling:
Møller, **Suliga**, Tamborra, Denton (2018)

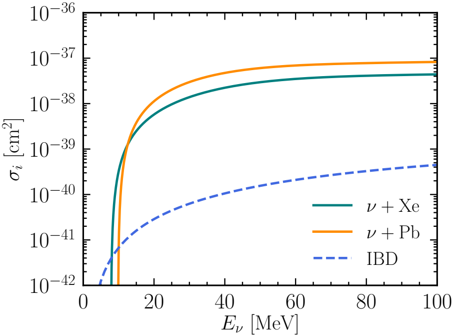
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750 \text{ cm}^{-2} \text{ s}^{-1}$ for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

E. Vitagliano et al. (2019), M. Honda et al. (2011), J. L. Newstead et al. (2020)

Maybe: Coherent elastic neutrino-nucleus scatterings (CEνNS)



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



Cross section

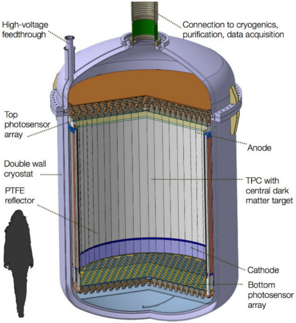
$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q),\ \ Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

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

D. Z. Freedman

Future generation CEνNS detectors

DARWIN (arXiv: 1606.07001)



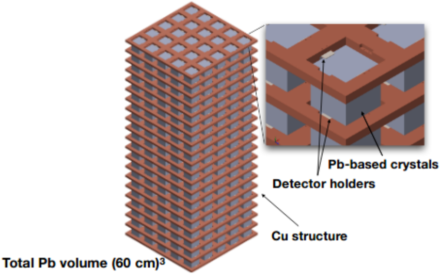
fiducial volume: 40 ton

target material: Xe

threshold: 1 keV

efficiency: XENON1T - 100%

RES-NOVA (arXiv: 2004.06936)



fiducial volume: 2.4 - 456 ton

target material: Pb

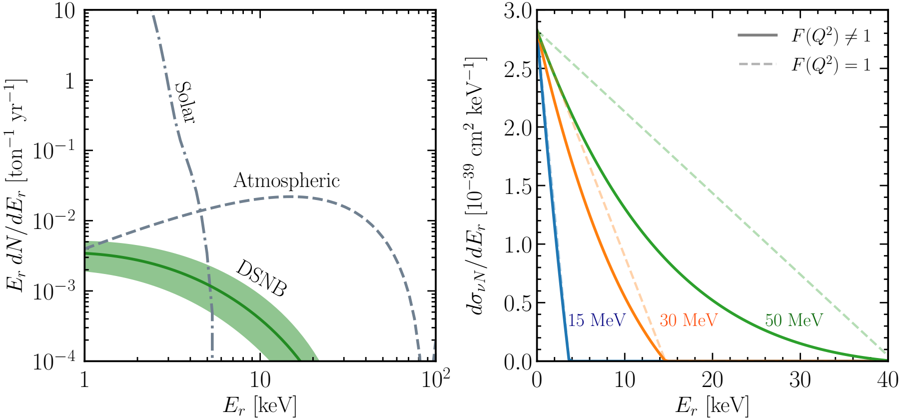
threshold: 1 keV

efficiency: 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

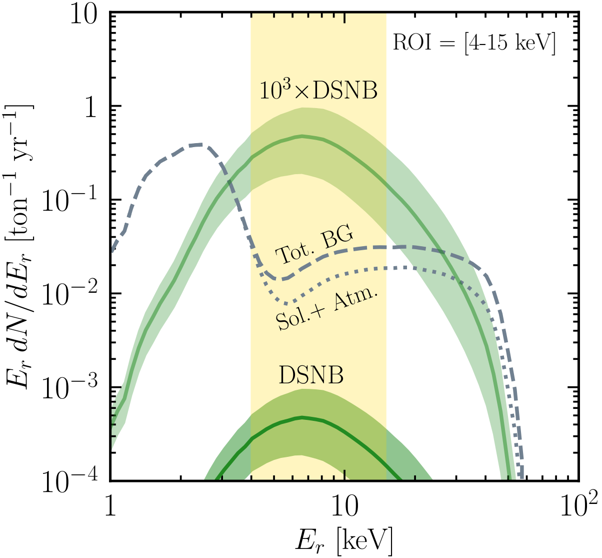


- The potential energy window displayed by the bare fluxes disapears
- Reason: Low energy recolis are most probable for all neutrino energies
- Detection of the *x*-flavor DSNB seems out of reach, BUT...

L. E. Strigari (2009)

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

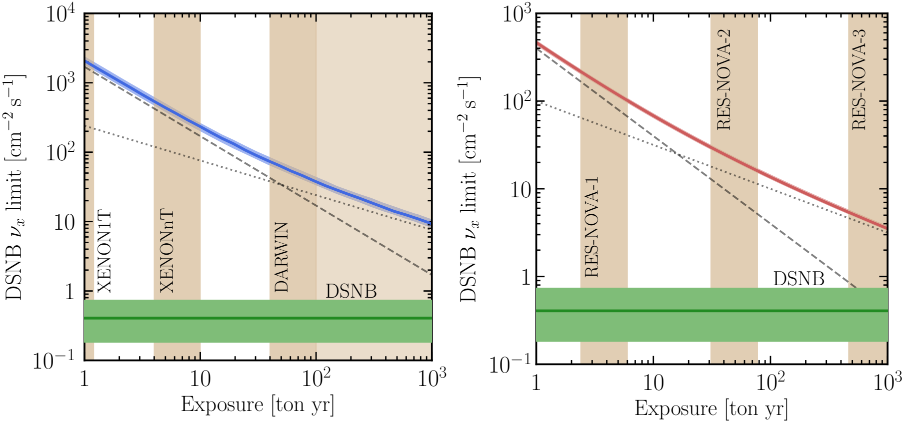
YES: Scaled event rate in the xenon-based detector



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

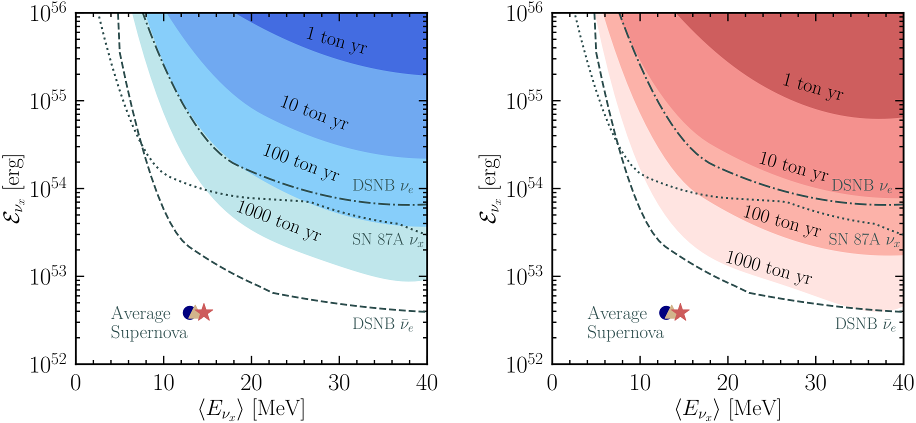
Sensitivity bounds on the x-flavor DSNB

Sensitivity bounds on the normalization of the x-flavor DSNB



- XENON1T, RES-NOVA-1: 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
- ν_e: posssibly detectable by DUNE
- ν_x:
  - XENON1T yields a comparable limit to the existing one from SK
  - CEνNS detectors can improve the existing limits $\gtrsim 100$

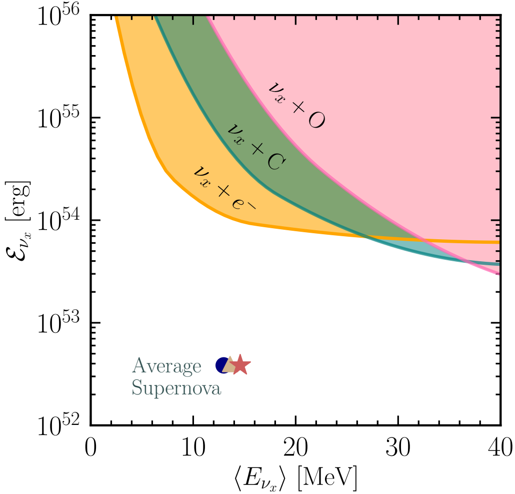
Improved limits on the *x*-flavor DSNB

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

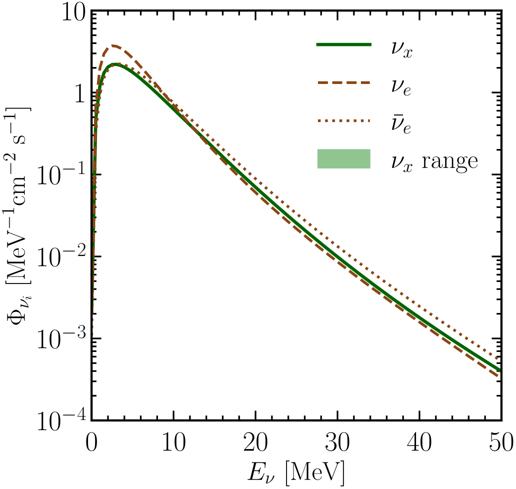
Thank you for the attention!

Backup slides

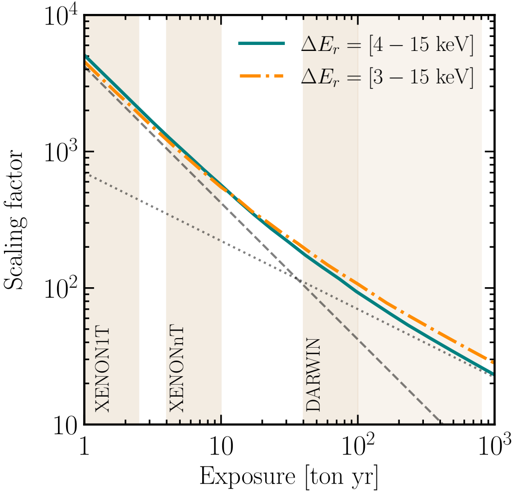
Limits from the SN 1987A



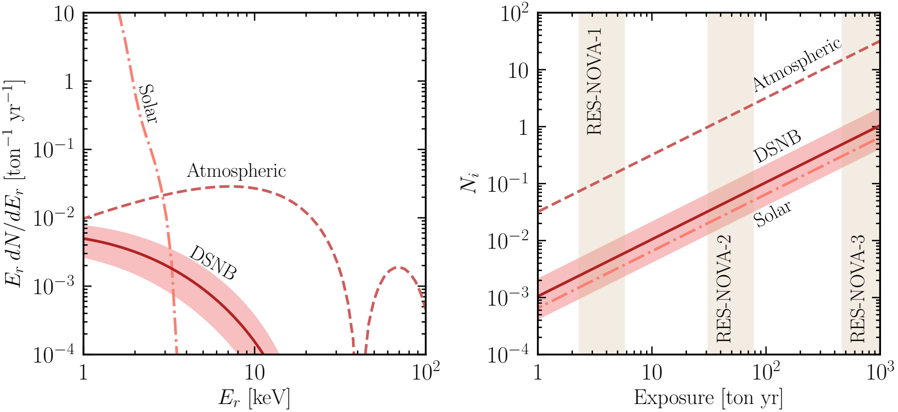
DSNB variability



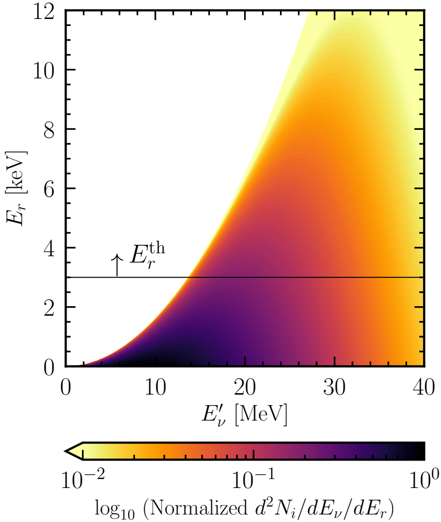
Sensitivity of the limits to a detection window



Event rate: lead detector

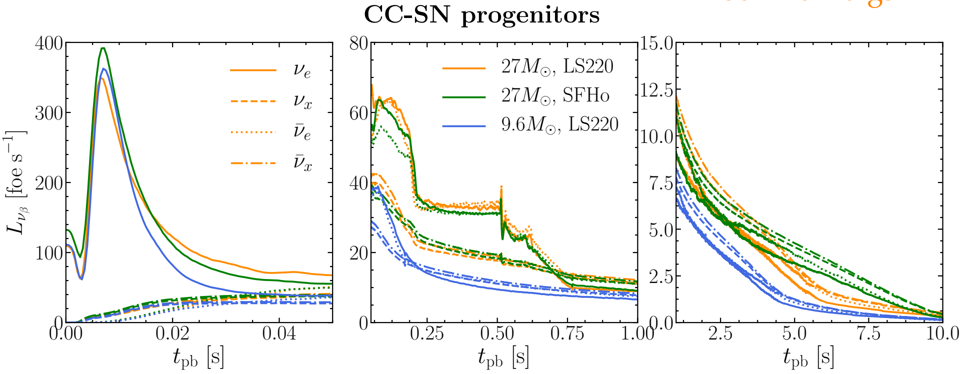


Which part of the spectrum are CEνNS detectors sensitive to?



Core-collapse supernovae

1 foe = 10^{51} ergs



ν_e burst

accretion

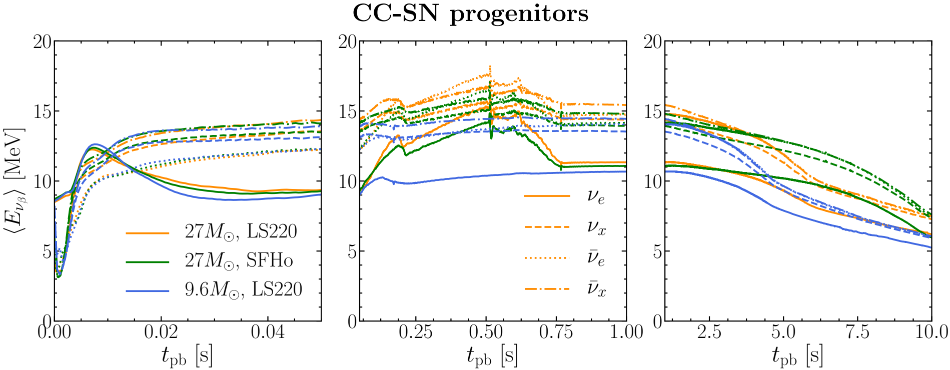
cooling

CC-SN

equation of state = LS220 or SFHo, mass = 9.6 $M_\odot$ or 27 $M_\odot$

Garching core-collapse supernova archive

Progenitor stars forming neutron stars



$\nu_{\rm e}$ burst

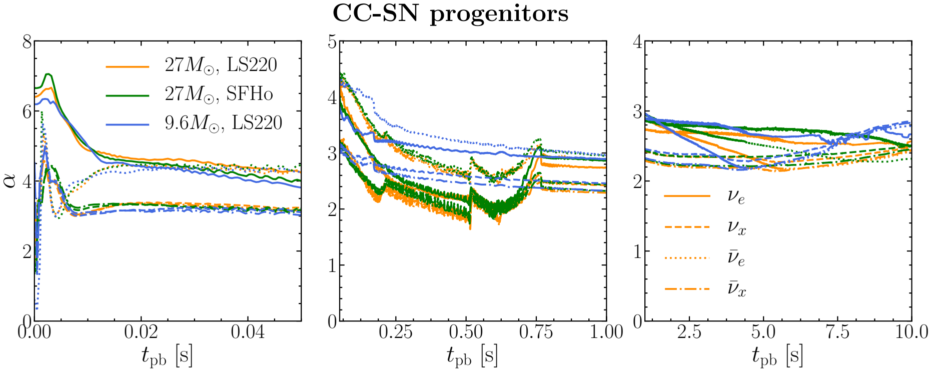
accretion

cooling

Early times$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$,

Late times $\langle E_{\nu_e} \rangle < \langle E_{\nu_x} \rangle < \langle E_{\bar{\nu}_e} \rangle$

Progenitor stars forming neutron stars

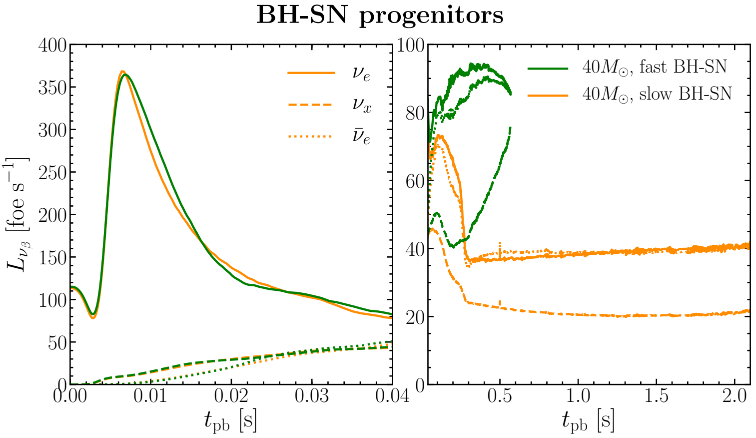


ν_e burst

accretion

cooling

Failed Supernovae



ν_e burst

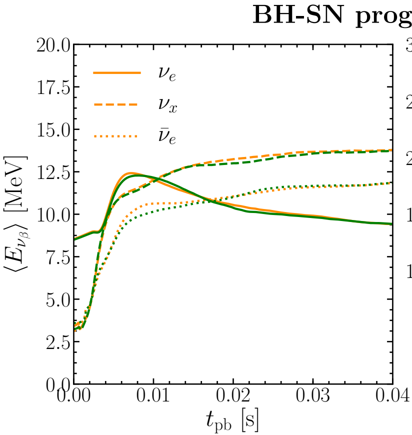
accretion

BH-SN

equation of state = LS220, mass = 40 $M_\odot$, $t_{\rm BH}$ = 0.57 s or 2.1 s

Garching core-collapse supernova archive

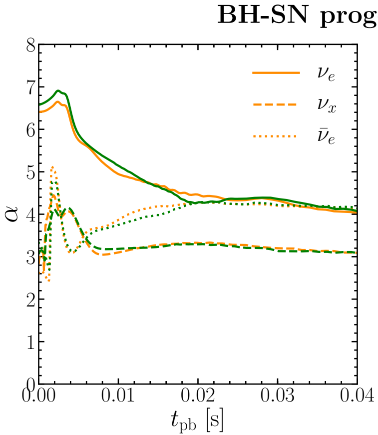
Progenitor stars forming black holes

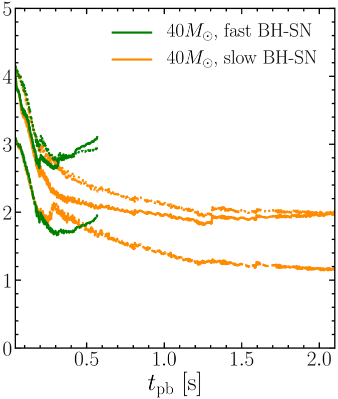


ν_e burst

accretion

Progenitor stars forming black holes





ν_e burst

accretion

Neutrino fluxes

Neutrino energy distribution

$$\varphi_{\nu_\beta}(E, t_{\text{pb}}) = \xi_{\nu_\beta}(t_{\text{pb}}) \left(\frac{E}{\langle E_{\nu_\beta}(t_{\text{pb}}) \rangle} \right)^{\alpha_\beta(t_{\text{pb}})} e^{-\frac{E(\alpha_\beta(t_{\text{pb}})+1)}{\langle E_{\nu_\beta}(t_{\text{pb}}) \rangle}}$$

normalization $1/\xi_{\nu_\beta}(t_{\text{pb}}) = \int dE \varphi_{\nu_\beta}(E, t_{\text{pb}})$

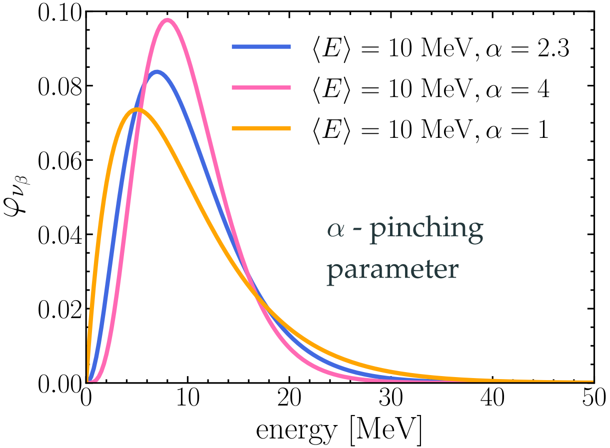
Pinching parameter

$$\alpha_\beta(t_{\text{pb}}) = \frac{\langle E_{\nu_\beta}(t_{\text{pb}})^2 \rangle - 2\langle E_{\nu_\beta}(t_{\text{pb}}) \rangle^2}{\langle E_{\nu_\beta}(t_{\text{pb}}) \rangle^2 - \langle E_{\nu_\beta}(t_{\text{pb}})^2 \rangle}.$$

Keil et al., arXiv:0208035

Neutrino fluxes

Neutrino energy distribution

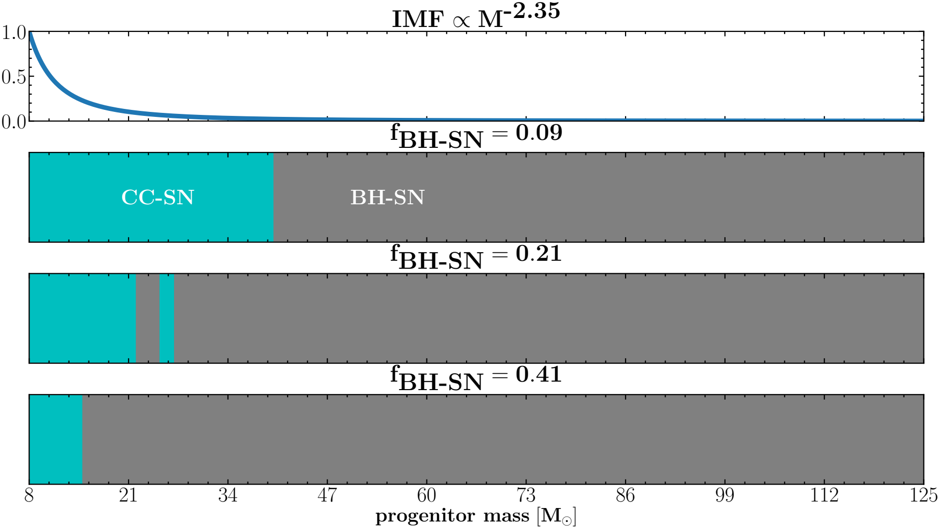


α - pinching parameter

Differential neutrino flux

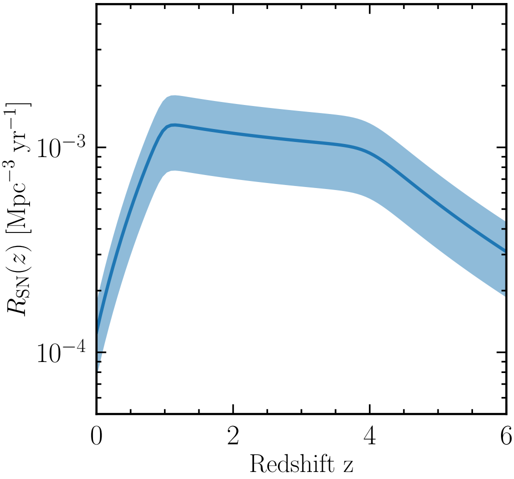
$$f^0_{\nu_\beta}(E, t_{\rm pb}) = \frac{L_{\nu_\beta}(t_{\rm pb})}{4\pi r^2} \frac{\varphi_{\nu_\beta}(E, t_{\rm pb})}{\langle E_{\nu_\beta}(t_{\rm pb}) \rangle} = \frac{F^0_{\nu_\beta}(E, t_{\rm pb})}{4\pi r^2}$$

Fraction of BH-forming progenitors



Ertl et al. arXiv:1503.07522, Sukhbold et al. arXiv:1510.04643, Adams et al. arXiv:1610.02402, Heger et al. arXiv:0112059

Core-collapse supernova rate



Yüksel et al. (2008)