Towards probing the diffuse supernova neutrino background in all flavors

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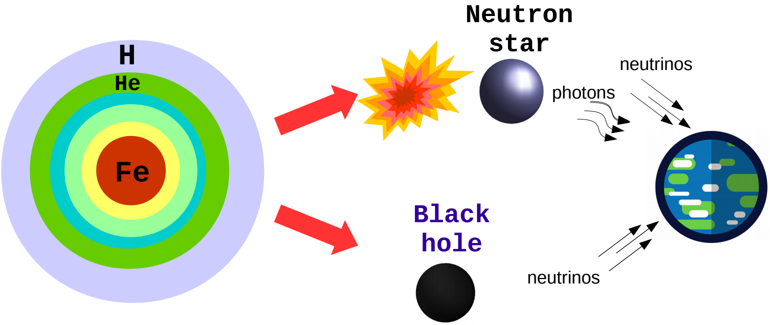
New Directions in Neutrino Flavor Evolution in Astrophysical Systems, INT

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

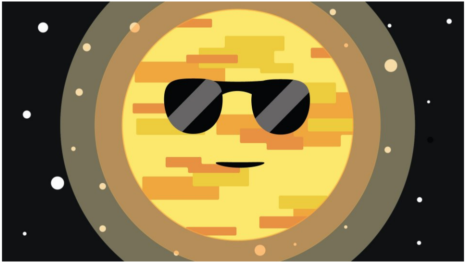
- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (DUNE, SK, XENON & LZ...)

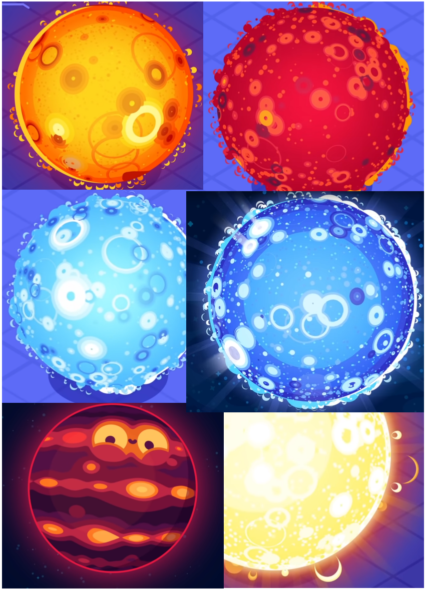
What can we learn with a variety of detectors?

- 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), **A. M. 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

cosmological supernovae rate

fraction of black-hole-forming progenitors

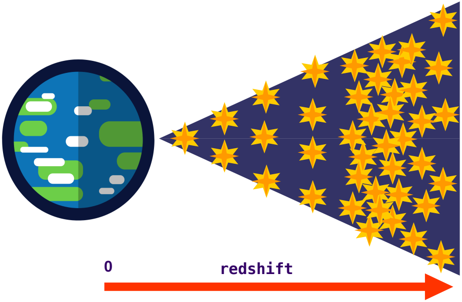
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\mathrm{SN}}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\mathrm{CC-SN}}F_{\nu_\beta,\mathrm{CC-SN}}(E',M) + f_{\mathrm{BH-SN}}F_{\nu_\beta,\mathrm{BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

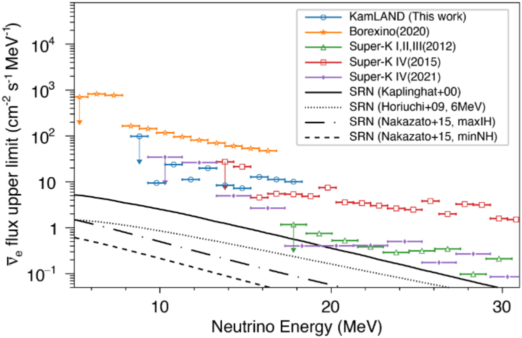
- $R_{\mathrm{SN}}, f_{\mathrm{BH-SN}}$
- neutrino mass ordering
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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)

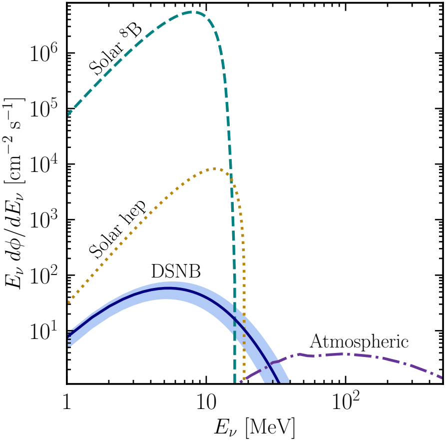


DSNB limits:

- $\bar{\nu}_e \approx 3\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3$ 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 $E_\nu \in [22.9, 36.9\ \mathrm{MeV}]$ 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

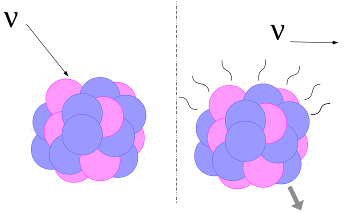


DSNB modeling:
Møller, **Suliga**, Tamborra, Denton (2018)

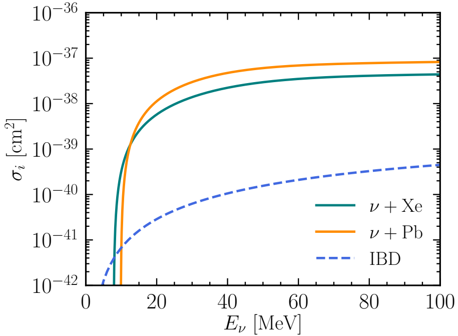
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

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

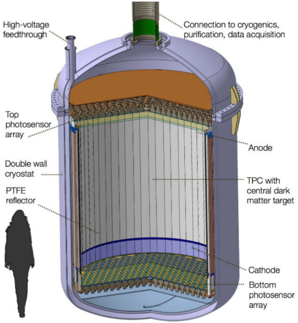
$$\frac{d\sigma_{\mathrm{SM}}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q), \;\; Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

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

D. Z. Freedman

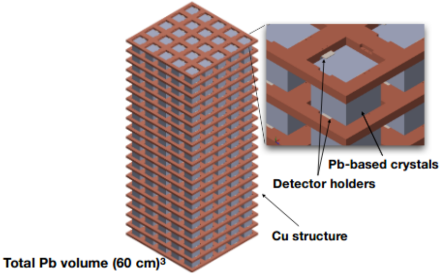
Future generation CEνNS detectors

DARWIN (arXiv: 1606.07001)



fiducial volume: 40 ton
target material: Xe
threshold: 1 keV
efficiency: XENON1T - 100%

RES-NOVA (arXiv: 2004.06936)

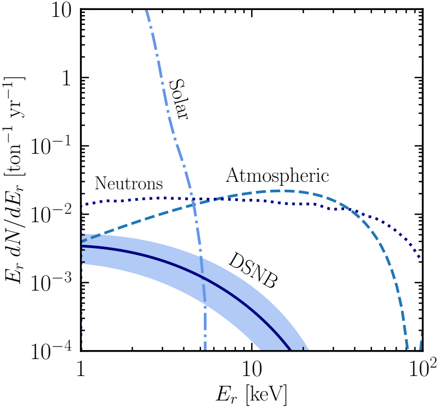


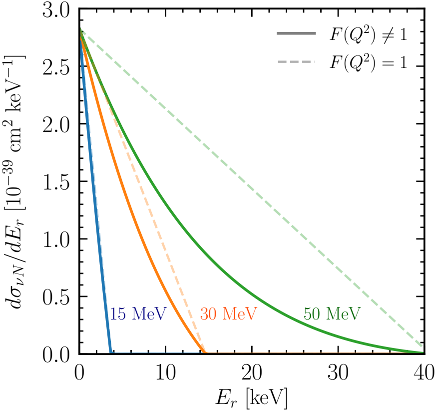
fiducial volume: 2.4 - 456 ton
target material: Pb
threshold: 1 keV
efficiency: 100%

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



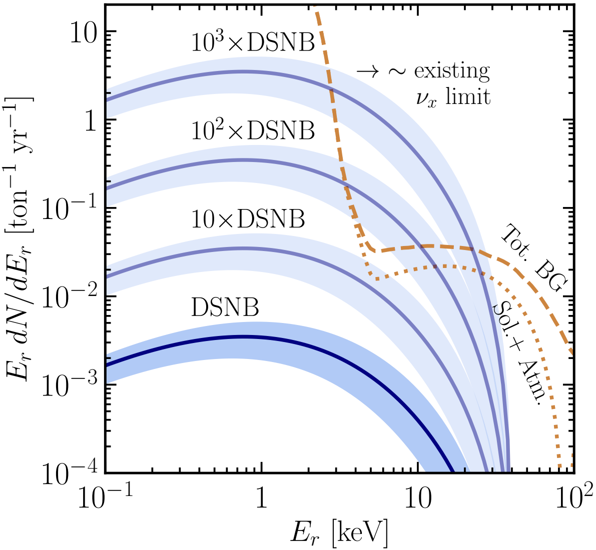


- The potential energy window displayed by the bare fluxes disapears
- Reason: Low energy recolis are most probable for all neutrino energies
- Detection of the x-flavor DSNB seems out of reach, BUT...

L. E. Strigari (2009)

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

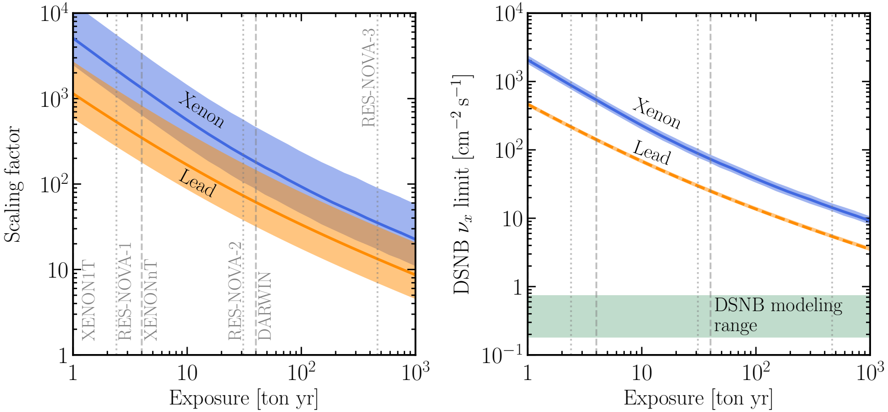
YES: Scaled event rate in the xenon-based detector



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

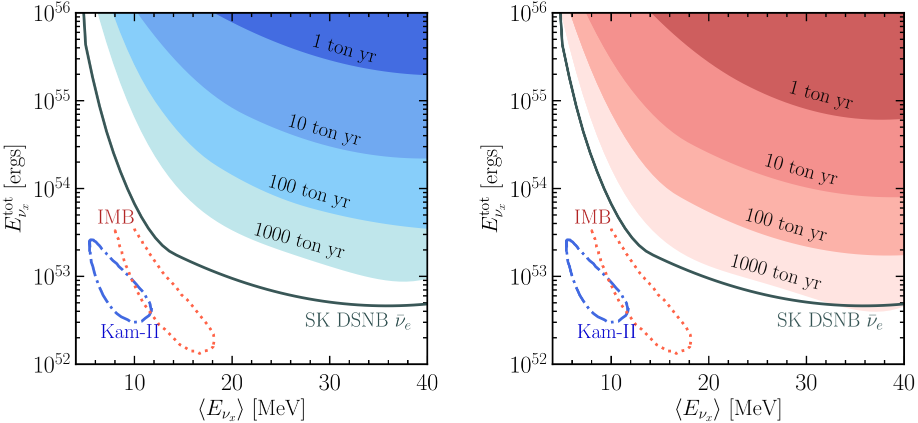
Sensitivity bounds on the x-flavor DSNB

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 $\gtrsim 100$

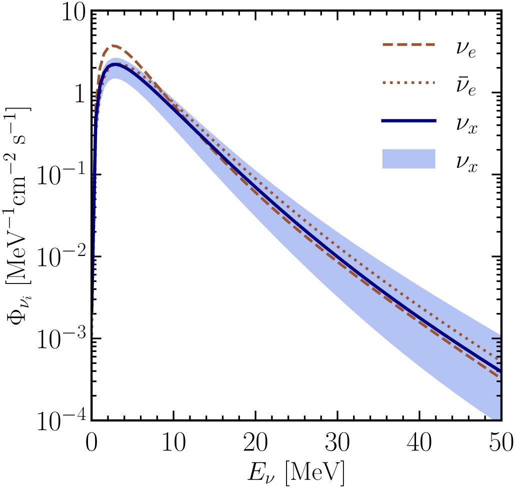
Improved limits on the x-flavor DSNB

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

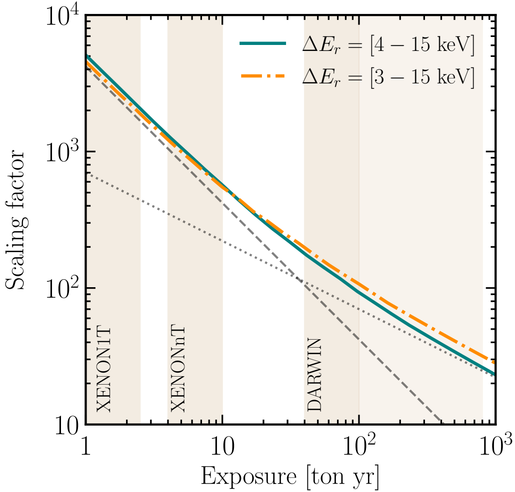
Thank you for the attention!

Backup slides

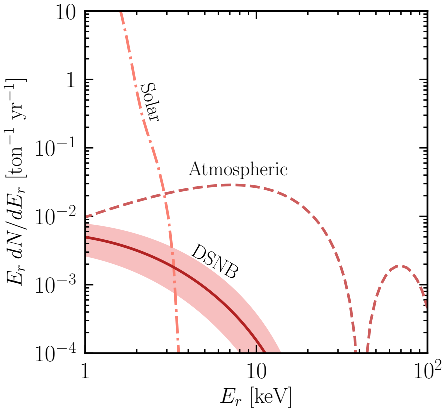
DSNB variability

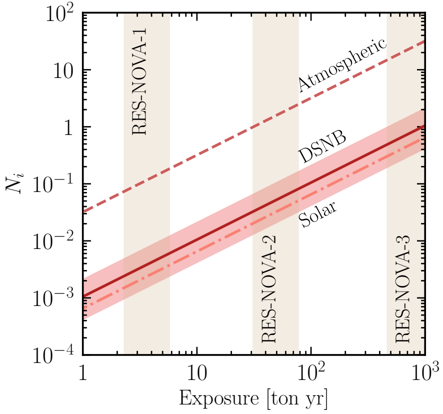


Sensitivity of the limits to a detection window

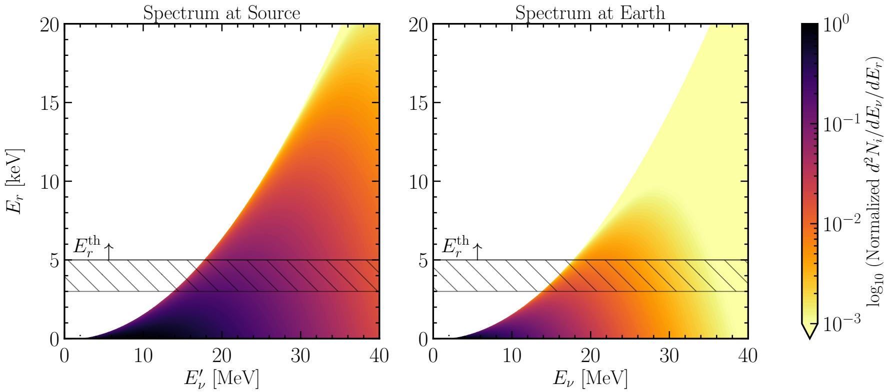


Event rate: lead detector



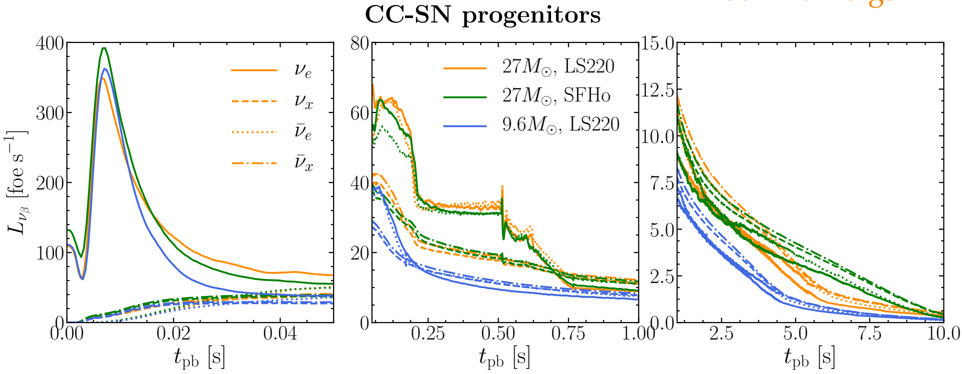


Which part of the spectrum are CEνNS detectors sensitive to?



Core-collapse supernovae

1 foe = 10^{51} ergs



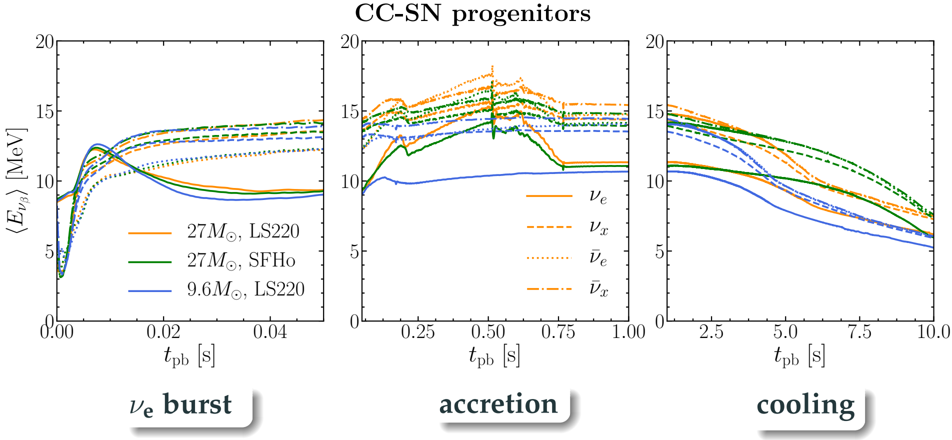
ν_e **burst** | **accretion** | **cooling**

CC-SN

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

Garching core-collapse supernova archive

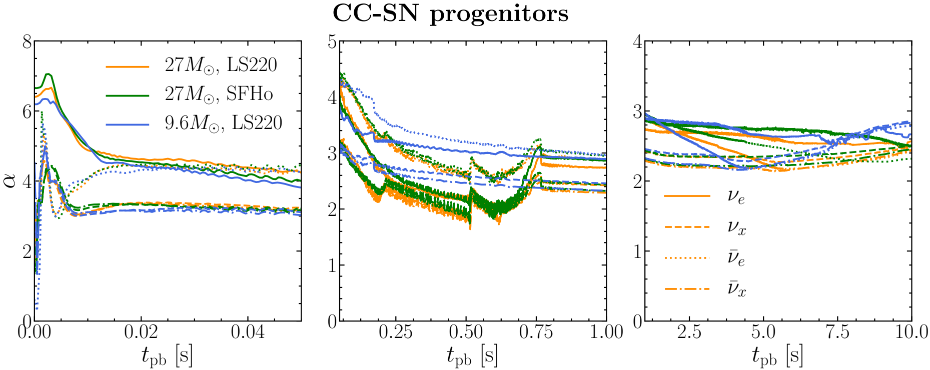
Progenitor stars forming neutron stars



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

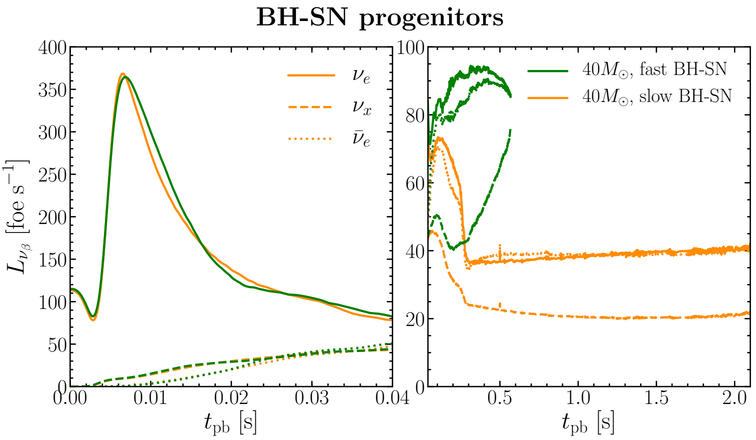


ν_{e} **burst**

accretion

cooling

Failed Supernovae



ν_e **burst**

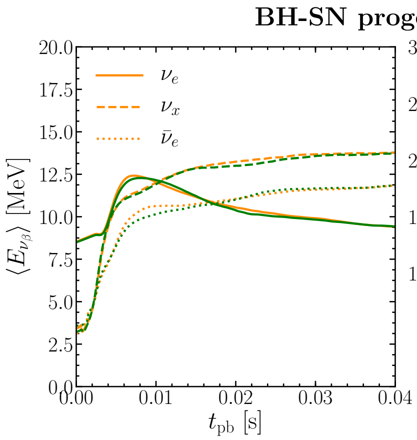
accretion

BH-SN

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

Garching core-collapse supernova archive

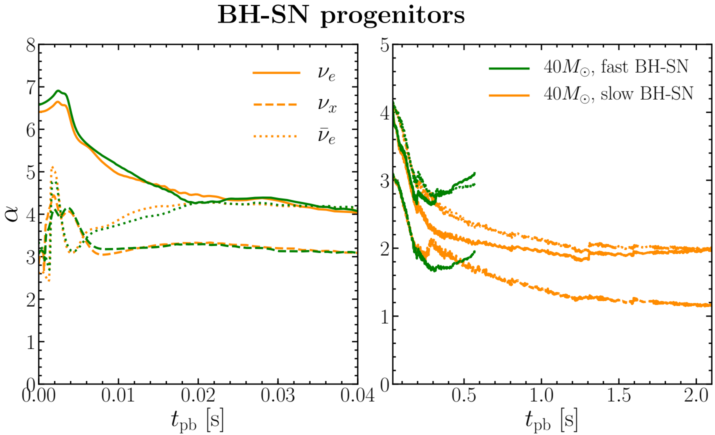
Progenitor stars forming black holes



ν_e **burst**

accretion

Progenitor stars forming black holes



ν_e **burst**

accretion

Neutrino fluxes

Neutrino energy distribution

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

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

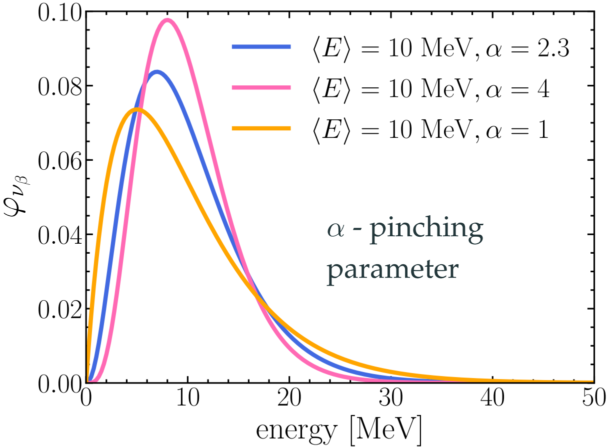
Pinching parameter

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

Keil et al., arXiv:0208035

Neutrino fluxes

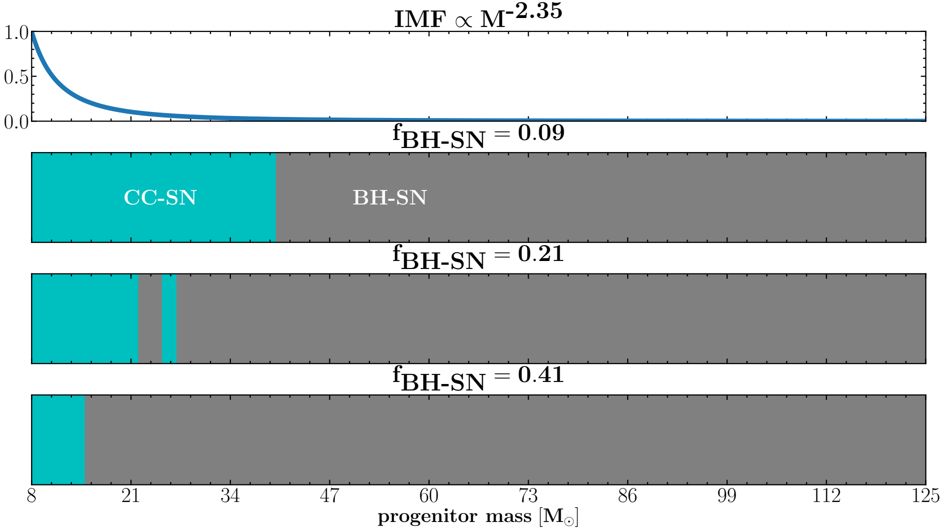
Neutrino energy distribution



Differential neutrino flux

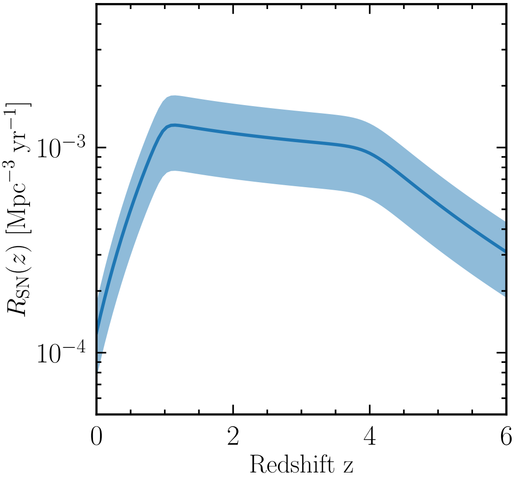
$$f^0_{\nu_\beta}(E, t_{\text{pb}}) = \frac{L_{\nu_\beta}(t_{\text{pb}})}{4\pi r^2} \frac{\varphi_{\nu_\beta}(E, t_{\text{pb}})}{\langle E_{\nu_\beta}(t_{\text{pb}}) \rangle} = \frac{F^0_{\nu_\beta}(E, t_{\text{pb}})}{4\pi r^2}$$

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)