Towards Probing the Diffuse Supernova Neutrino Background in All Flavors

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Phys.Rev.D 105 043008 (2022)
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UCSD-SDSU Seminars
April 29, 2022

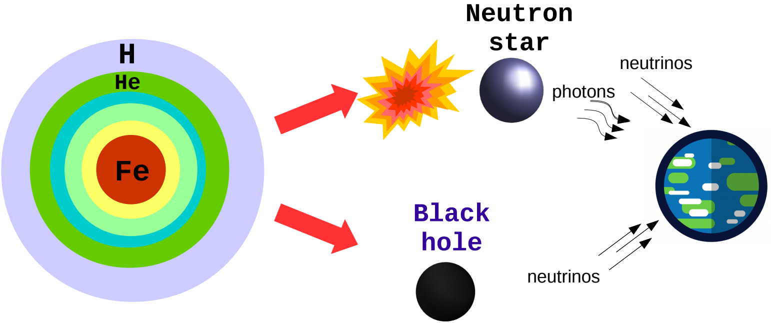
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

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

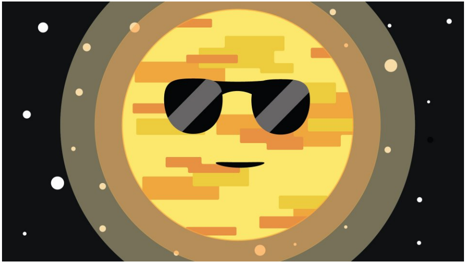
- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (SK, JUNO, XENON, PandaX...)

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

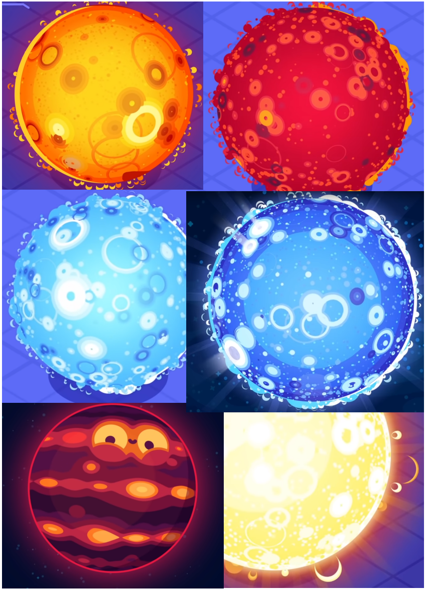


Single galactic SN event

- rare event
- precise infromation about one star

Multiple SN events (larger distances)

- accumulation of events
- will detect in coming years



Images: Kurzgesagt

Diffuse supernova neutrino background

cosmological supernovae rate

fraction of black-hole-forming progenitors

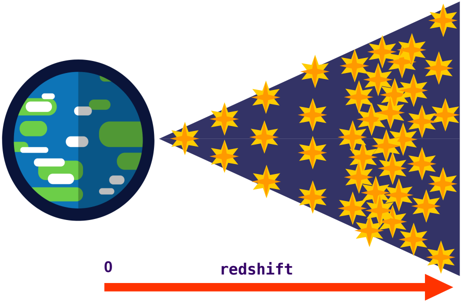
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\mathrm{SN}}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}} \left[f_{\mathrm{CC-SN}}F_{\nu_\beta,\mathrm{CC-SN}}(E',M) + f_{\mathrm{BH-SN}}F_{\nu_\beta,\mathrm{BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

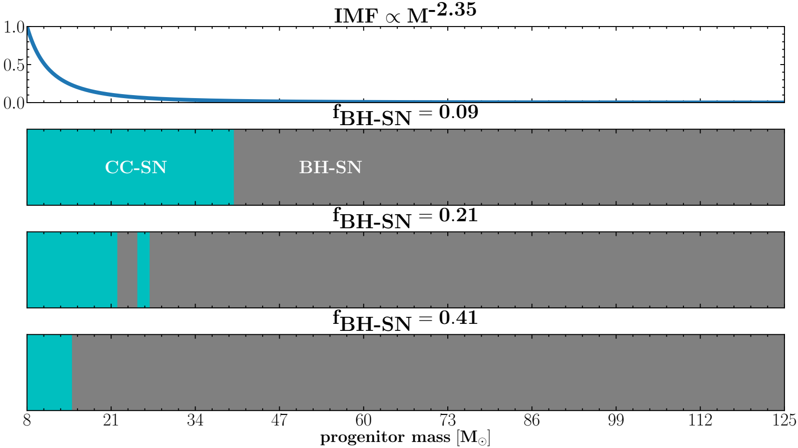
- $R_{\mathrm{SN}}, f_{\mathrm{BH-SN}}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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

Astrophysical uncertainties

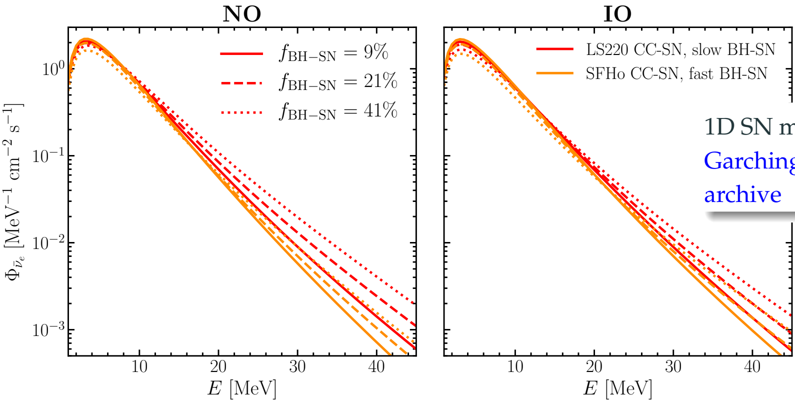
The fraction of black-hole-forming progenitors



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

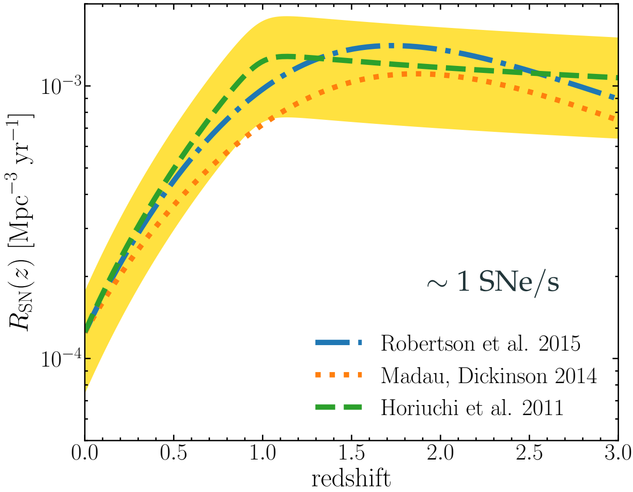


1D SN models
Garching group archive

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

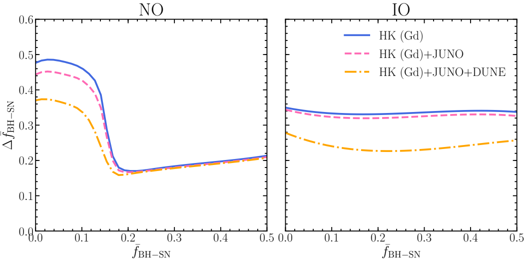
Cosmological supernovae rate



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), ...

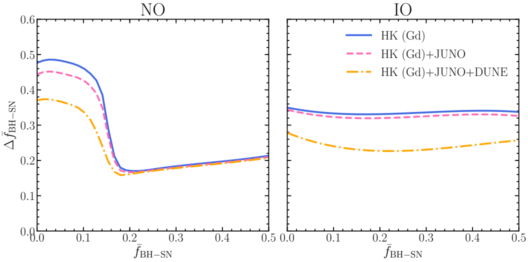
Expected 1σ uncertainty: fraction of BH forming progenitors



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

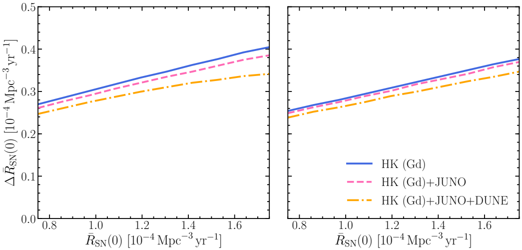
Møller, **Suliga**, Tamborra, Denton (2018)

Expected 1σ uncertainty: local supernova rate



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

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



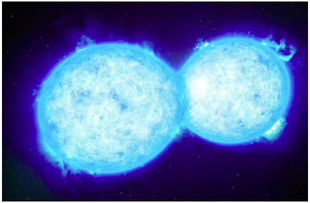
Møller, **Suliga**, Tamborra, Denton (2018)

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

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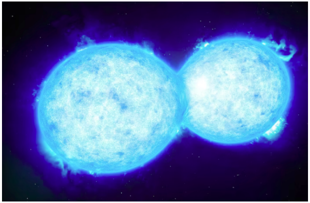
Mass transfer

Mergers

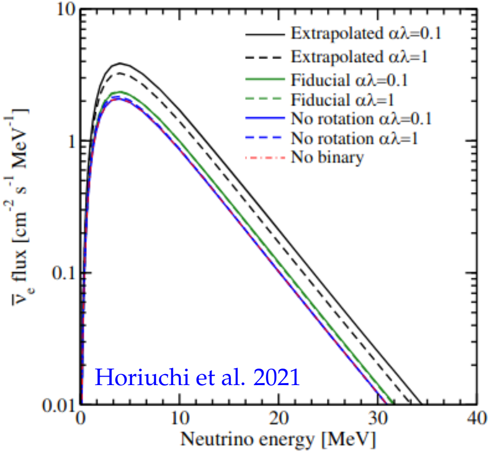


Effects on the stellar population Horiuchi et al. 2021

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

Images: iflscience, Wiki

Binary interactions: impact on DSNB



Horiuchi et al. 2021

$\alpha\lambda$ - 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

BSM scenarios affecting DSNB

Neutrino decay

Active neutrinos are massive and masses are not identical

- SM decays are loop supressed
- lifetimes ≫ age of the Universe

If neutrinos have BSM interactions they can decay faster

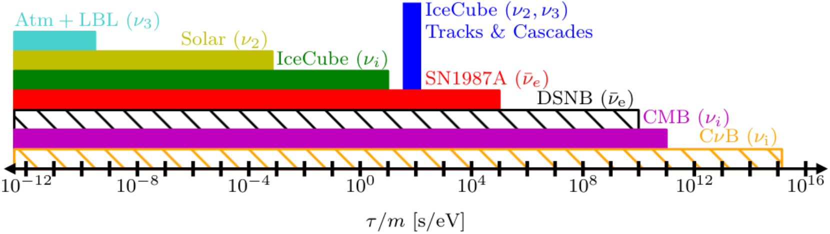
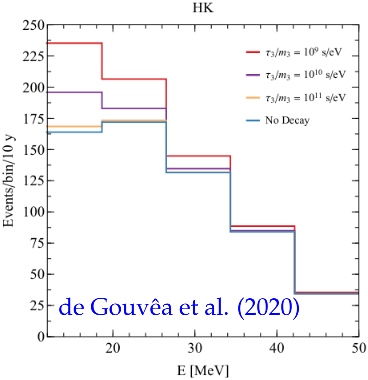
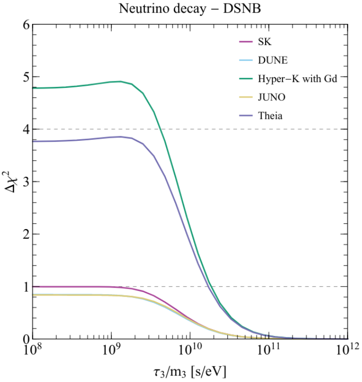


Figure credit: Abdullahi, Denton (2020)

Neutrino decay: impact on DSNB



de Gouvêa et al. (2020)

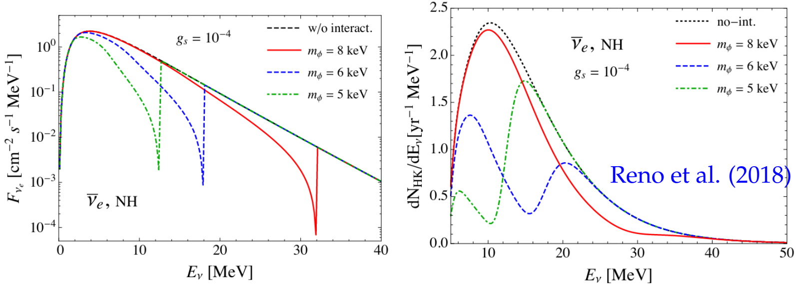


Exact detector features depend on

- 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

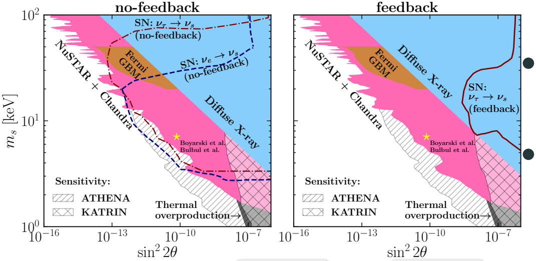
  Goldberg et al. (2005), Baker et al. (2007), Reno et al. (2018)

- dark matter Farzan, Palomares-Ruiz (2014)

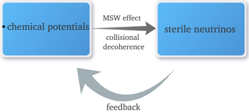
result in spectral features in DSNB

BSM impacting neutrinos inside CCSN

KeV sterile neutrinos



- The inclusion of feedback: reduction of the excluded region
- CC-SNe cannot exclude any region the DM parameter space


- chemical potentials

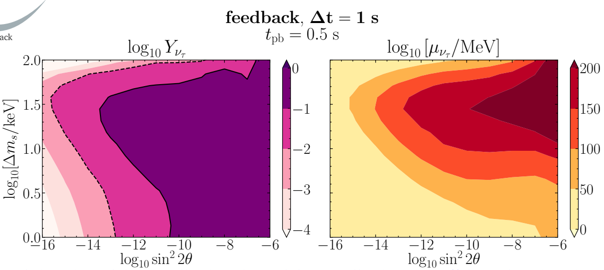
MSW effect

collisional decoherence

sterile neutrinos

feedback

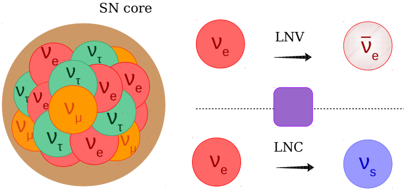
- The inclusion of feedback: growth of asymmetries
- Neutrino spectrum affected

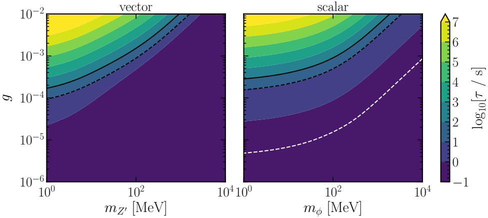

feedback, $\boldsymbol{\Delta t = 1}$ **s**

$t_{\rm pb} = 0.5$ s

Raffelt & Sigl (1992), Shi & Sigl (1994), Nunokawa et al. (1997), Hidaka & Fuller (2006), Hidaka & Fuller (2007), Raffelt & Zhou (2011), Warren et al. (2014), Argüelles et al. (2016), **Suliga et al. (2019)**, Syvolap et al. (2019), **Suliga et al. (2020)**

Non-standard coherent scattering in the supernova core





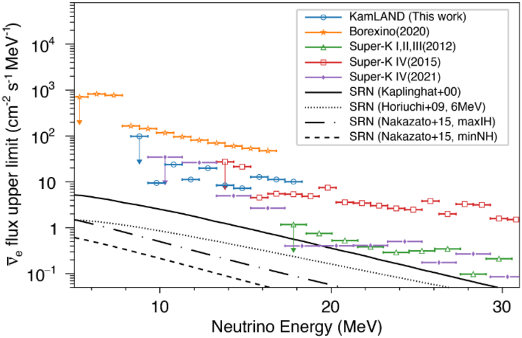
- prolonged diffusion time → possible change in the star's fate
- prolonged diffusion time → changed duration of the neutrino signal
- LNC scalar mediator → new cooling channel due to ν_R

Kolb & Turner (1987), Fuller et al. (1988) Farzan et al.(2018), Heurtier & Zhang (2016), Shalgar et al. (2019), **Suliga** & Tamborra (2020), Reddy Zhou & et al.(2021)

Current limits on the DSNB

Diffuse supernova neutrino background: current limits

Abe et al. (2021)

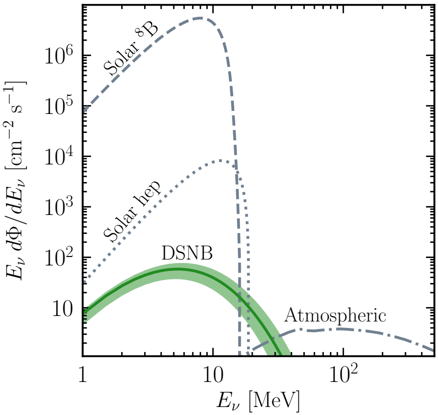


DSNB limits:

- $\bar{\nu}_e \approx 3 \text{ cm}^{-2}\text{ s}^{-1}$ 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)
- $\nu_e \approx 19 \text{ cm}^{-2}\text{ s}^{-1}$ for $E_\nu \,\epsilon\, [22.9, 36.9 \text{ MeV}]$ 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

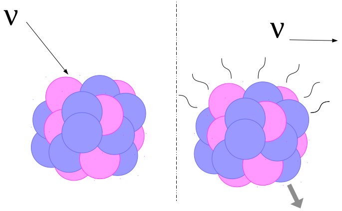


DSNB modeling: Møller, **Suliga**, Tamborra, Denton (2018)

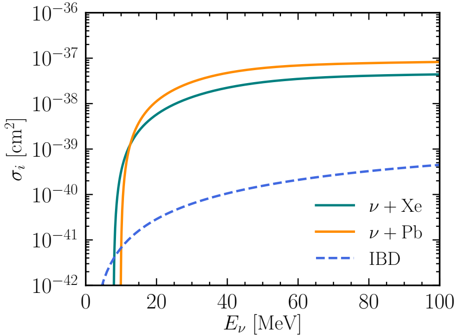
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750$ cm^{-2} s^{-1} for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

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

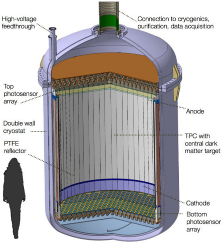
$$\frac{d\sigma_{\mathrm{SM}}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q), \;\; Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

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

Freedman (1974)

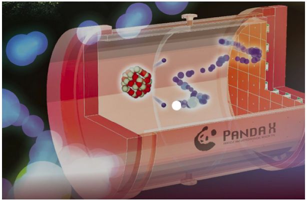
Current and future CEνNS detectors

XENONnT, DARWIN



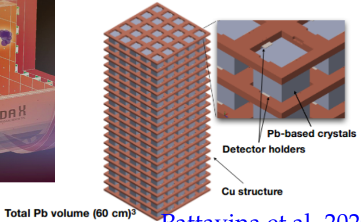
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

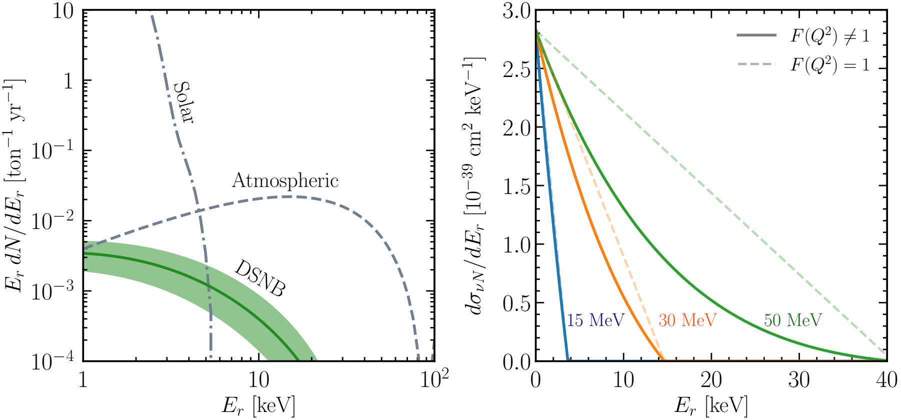
thresholds: $\mathcal{O}(1)$ keV

efficiency: $\sim$ 80-100%

Scattering rate

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

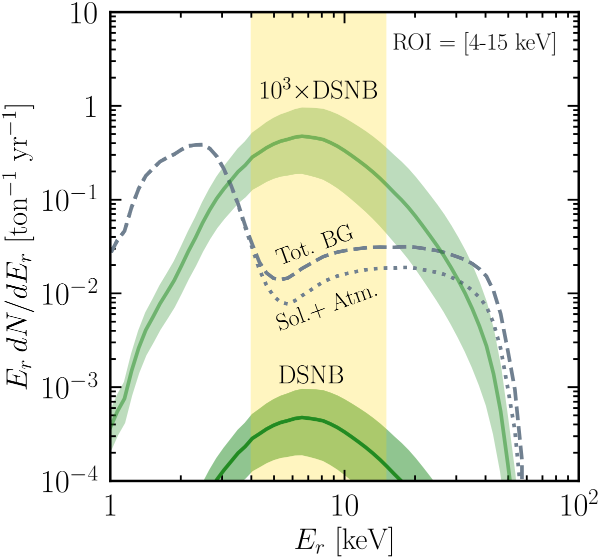
Event rate in the xenon-based detector



- 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?

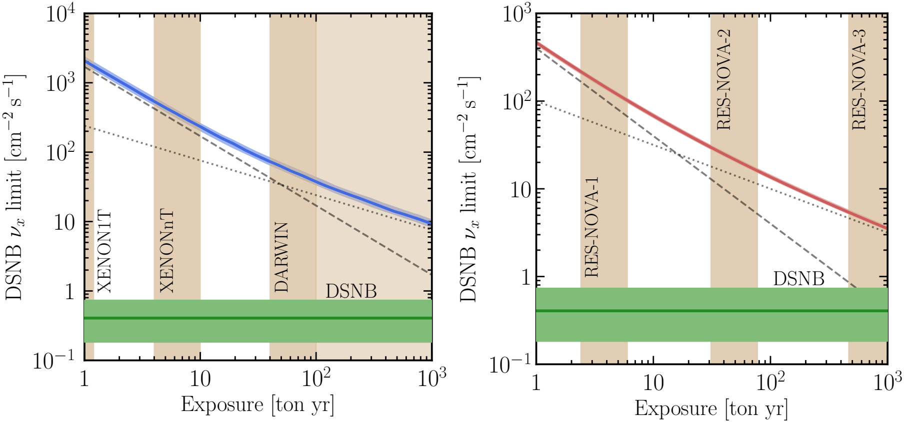
YES: Scaled event rate in the xenon-based detector



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

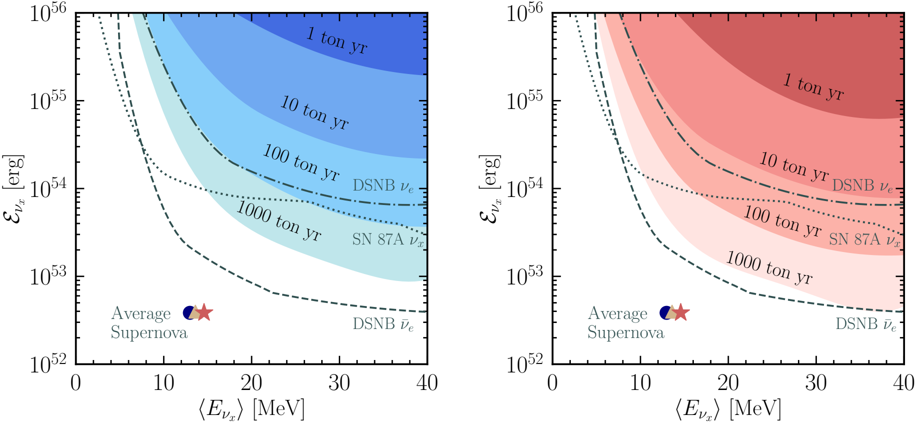
Sensitivity bounds on the x-flavor DSNB

Sensitivity bounds on the normalization of the x-flavor DSNB



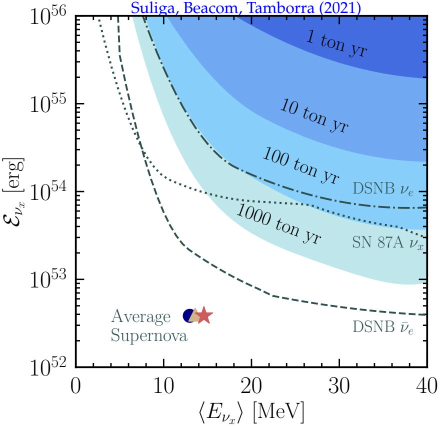
- XENON1T, PandaX-4T: limits comparable to the SK ν_x DSNB limit
- Constant energy window: limits can improve $\mathcal{O}(10\%)$ for wider windows at small exposures and narrower windows at large exposures

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

Diffuse supernova neutrino background (DSNB)



- $\bar{\nu}_e$: soon to be detected by SK + Gd, JUNO
- ν_e: posssibly detectable by DUNE
- ν_x: CEνNS detectors can improve the existing limits to almost $\bar{\nu}_e$ level

Detection of all flavors required to

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

Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010), Horiuchi et al. (2011), Lunardini, Tamborra (2012), Møller, Suliga, Tamborra, Denton (2018), Nakazato et al. (2018), Kresse et al. (2020) ...

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 $\gtrsim 100$

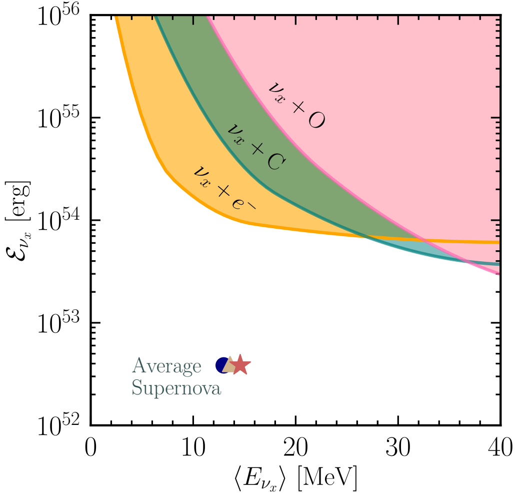
Improved limits on the *x*-flavor DSNB

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

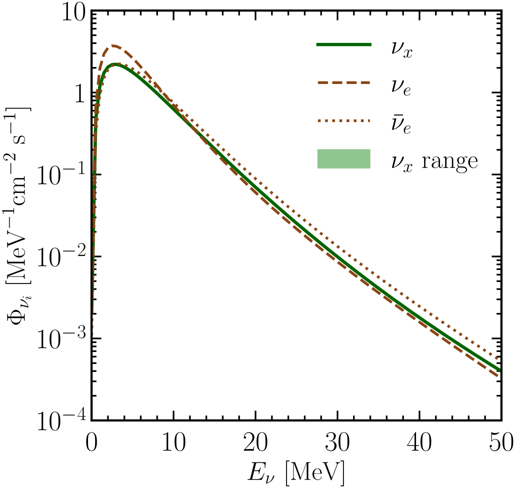
Thank you for the attention!

Backup slides

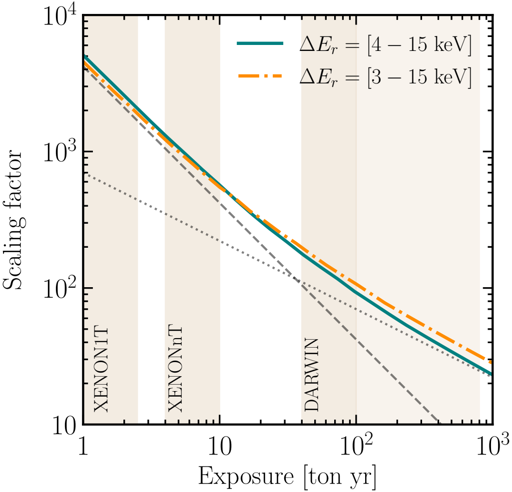
Limits from the SN 1987A



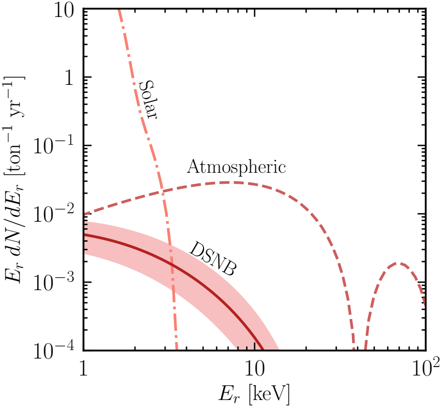
DSNB variability

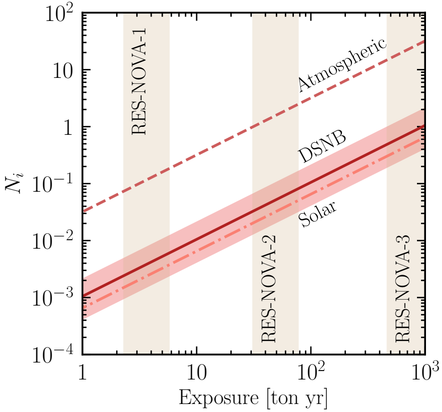


Sensitivity of the limits to a detection window

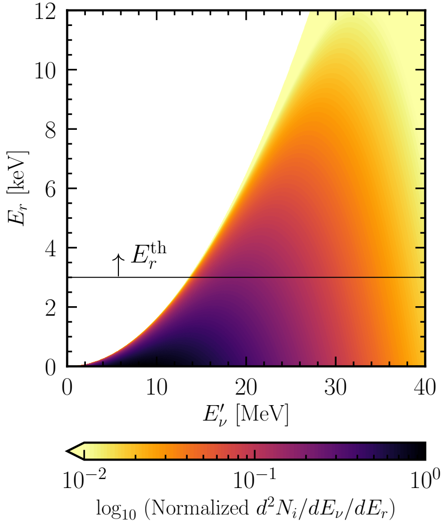


Event rate: lead detector



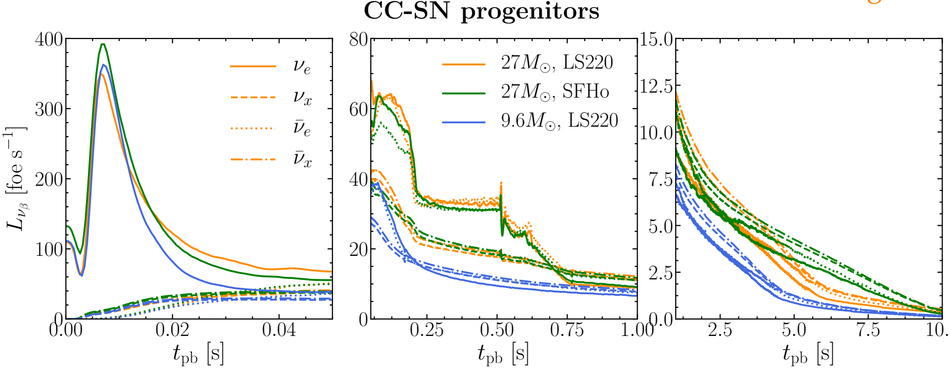


Which part of the spectrum are CEνNS detectors sensitive to?



Core-collapse supernovae

1 foe = 10^{51} ergs



ν_e burst

accretion

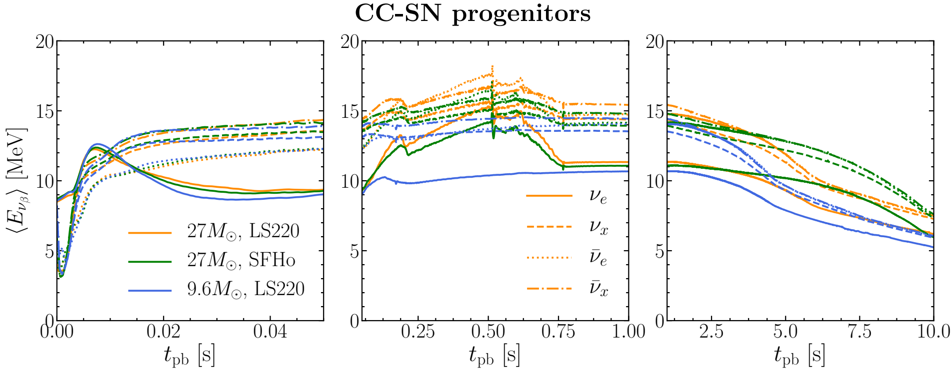
cooling

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



ν_e burst

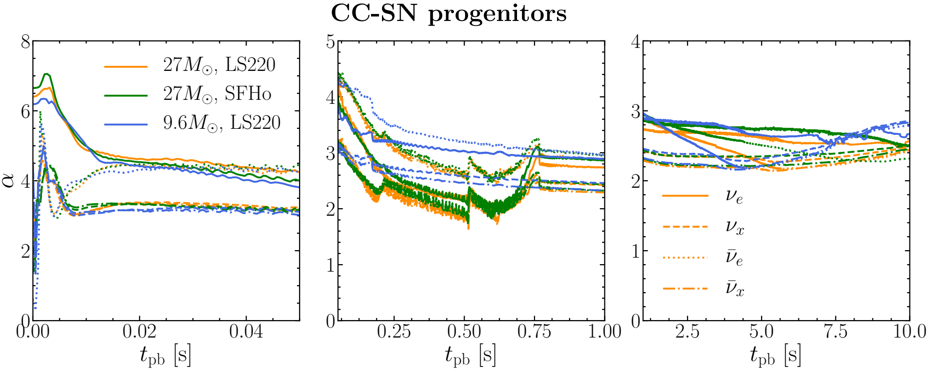
accretion

cooling

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

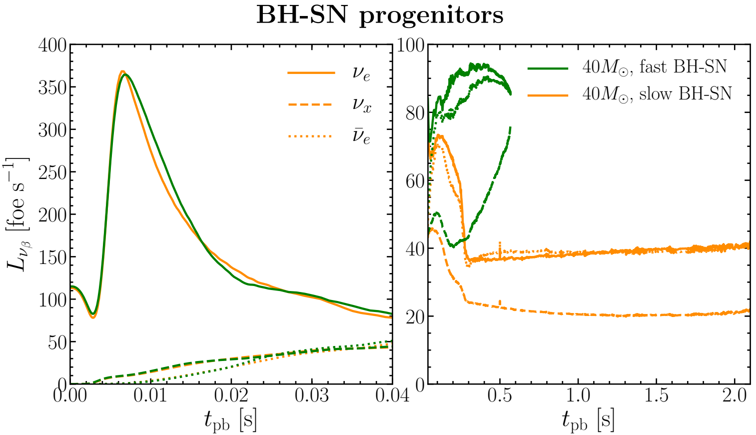
Late times $\langle E_{\nu_e} \rangle < \langle E_{\nu_x} \rangle < \langle E_{\bar{\nu}_e} \rangle$

Progenitor stars forming neutron stars



ν_e burst **accretion** **cooling**

Failed Supernovae



ν_e **burst**

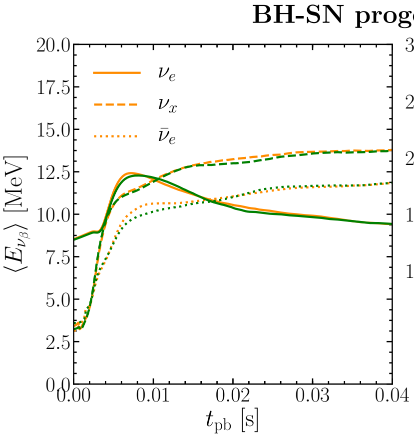
accretion

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

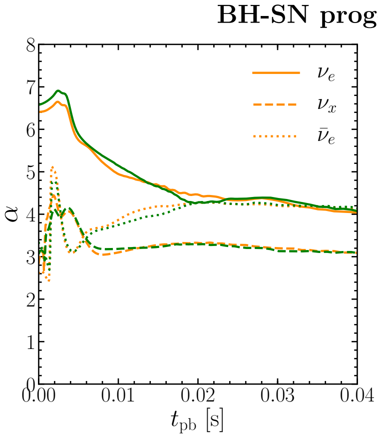
Progenitor stars forming black holes

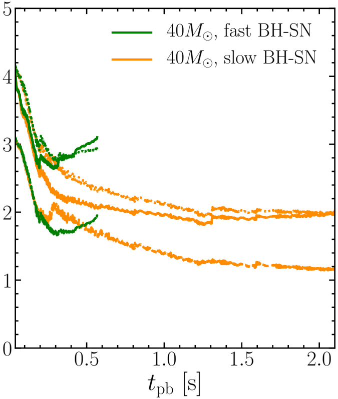


ν_e burst

accretion

Progenitor stars forming black holes





ν_e burst

accretion

Neutrino fluxes

Neutrino energy distribution

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

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

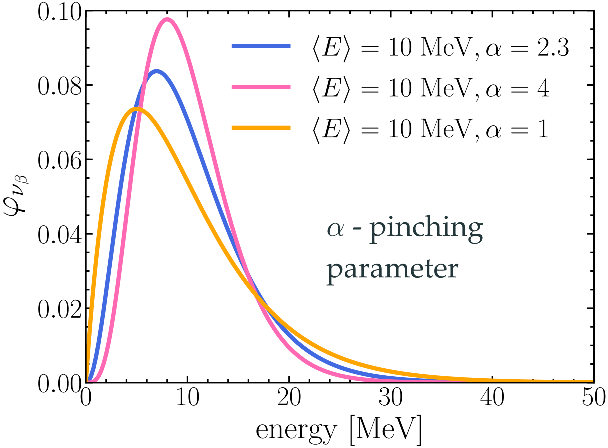
Pinching parameter

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

Keil et al., arXiv:0208035

Neutrino fluxes

Neutrino energy distribution

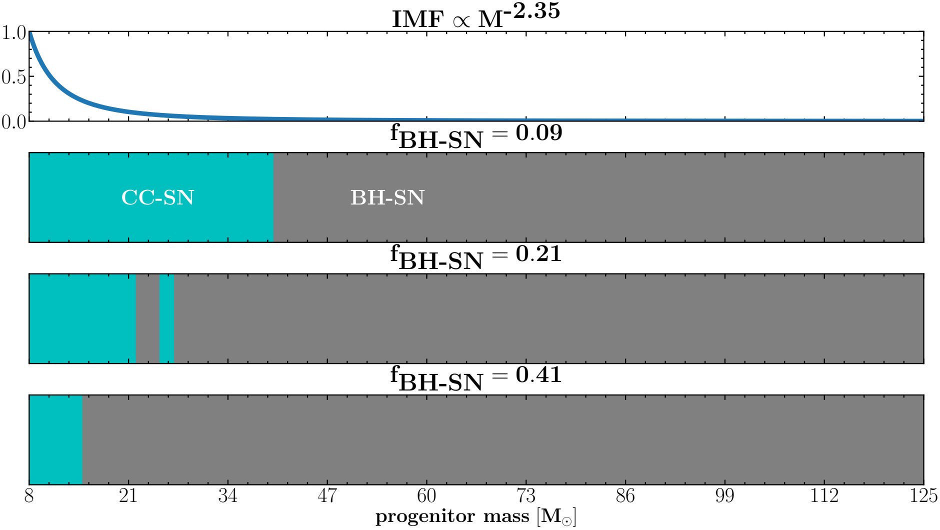


α - pinching parameter

Differential neutrino flux

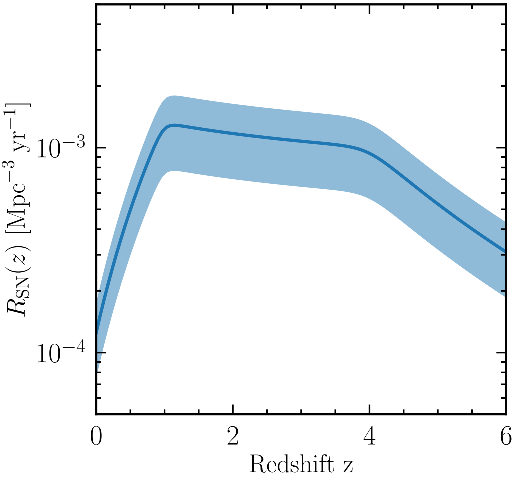
$$f^0_{\nu_\beta}(E, t_{\rm pb}) = \frac{L_{\nu_\beta}(t_{\rm pb})}{4\pi r^2} \frac{\varphi_{\nu_\beta}(E, t_{\rm pb})}{\langle E_{\nu_\beta}(t_{\rm pb}) \rangle} = \frac{F^0_{\nu_\beta}(E, t_{\rm pb})}{4\pi r^2}$$

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)