Determining supernova unknowns with the diffuse supernova neutrino background

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Overview

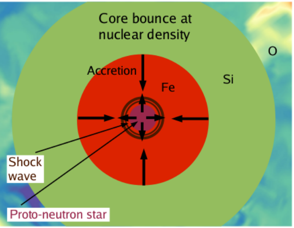
1. Core-collapse supernovae
2. Neutrino emission from the core-collapse supernovae
3. Neutrino oscillations
4. Time-integrated neutrino fluxes
5. Diffuse supernova neutrino background
6. The DSNB event rate at future generation neutrino detectors
7. Combined likelihood analysis
8. Conclusions

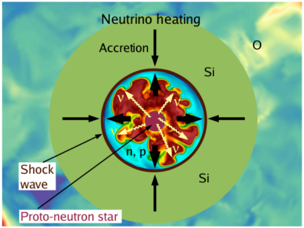
Core-collapse supernovae

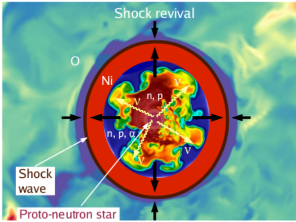
What is a core-collapse supernova?

Different phases of a core-collapse supernova explosion

- Neutronization phase, ν_e burst ~ 40 ms
- Accretion phase, ~ 100 ms
- Cooling phase, ~ 10 s



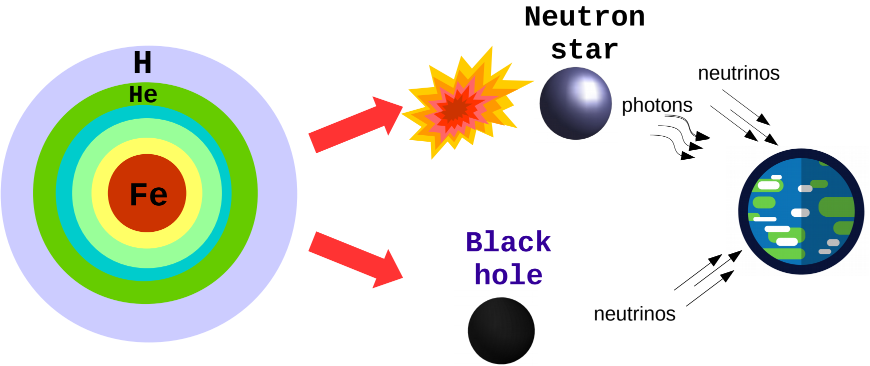




H. T. Janka, arXiv:1702.08713

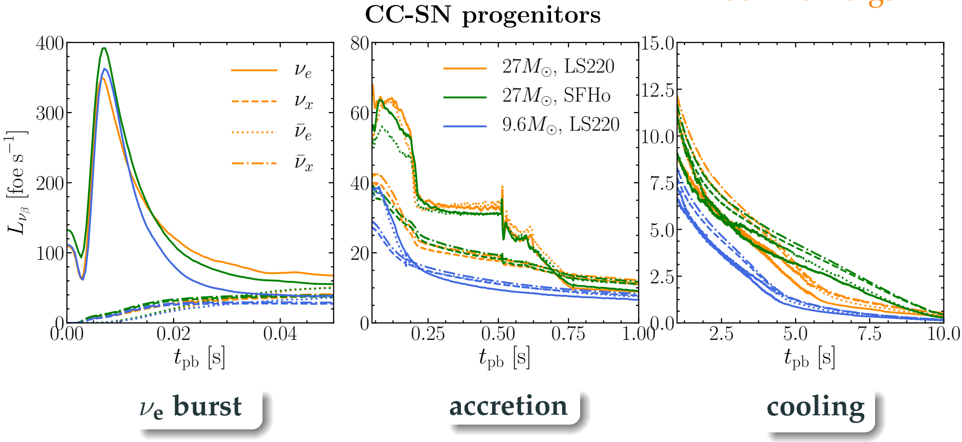
Neutrinos:

- play a crucial role in the explosion mechanism
- can reveal the interior conditions of a collapsing star
- are the only messengers from the collapse to a black hole (+ GW)



Neutrino emission from the core-collapse supernovae

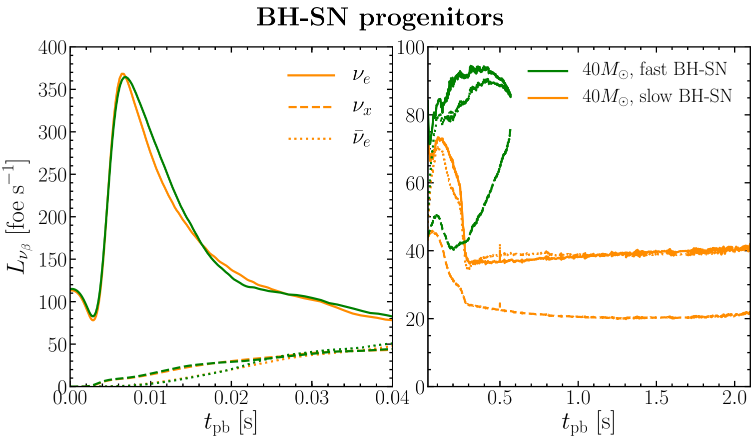
1 foe = 10^{51} ergs



CC-SN

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

Garching core-collapse supernova archive



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

Neutrino fluxes

Neutrino energy distribution

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

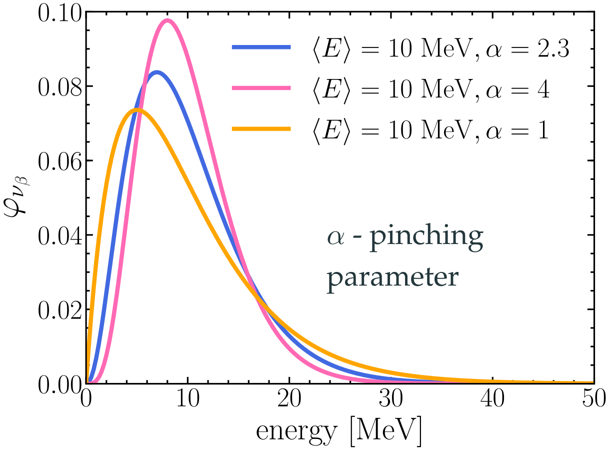
$$\text{normalization } 1/\xi_{\nu_\beta}(t_{\rm pb}) = \int dE \varphi_{\nu_\beta}(E, t_{\rm pb})$$

Pinching parameter

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

Keil et al., arXiv:0208035

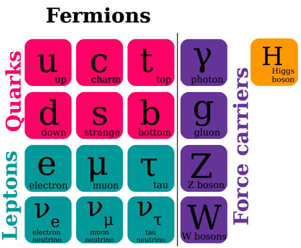
Neutrino energy distribution



Differential neutrino flux

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

Neutrino oscillations

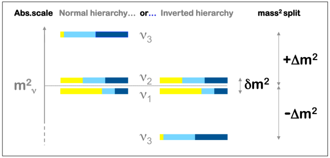


flavor basis **mass basis**

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

e μ τ

E. Lisi



atmospheric **beam, reactor** **solar, reactor**

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

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

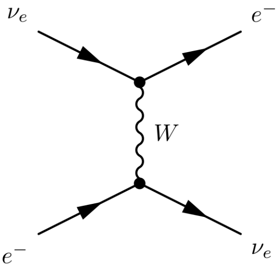
P in MNS, MNS in PMNS

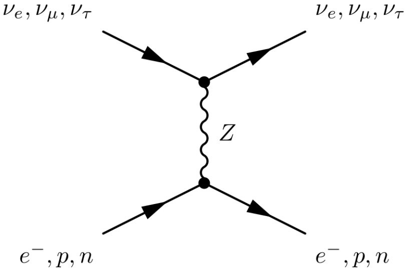
Neutrino oscillations in matter

$$P(\nu_e \to \nu_\mu) = \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta\tilde{m}^2 L}{4E}$$

$V_{CC} \propto N_e$

- $V_{CC} \to 0$, vacuum oscillations
- $V_{CC} \to \infty$, suppression of oscillations
- $V_{CC} = \frac{\Delta m^2}{2E} \cos 2\theta$, resonance enhancement of oscillations





"Fundamentals of Neutrino Physics and Astrophysics", C. Giunti and C. W. Kim

Density matrix evolution

$$\frac{d}{dx}\rho = -i[H,\rho],$$

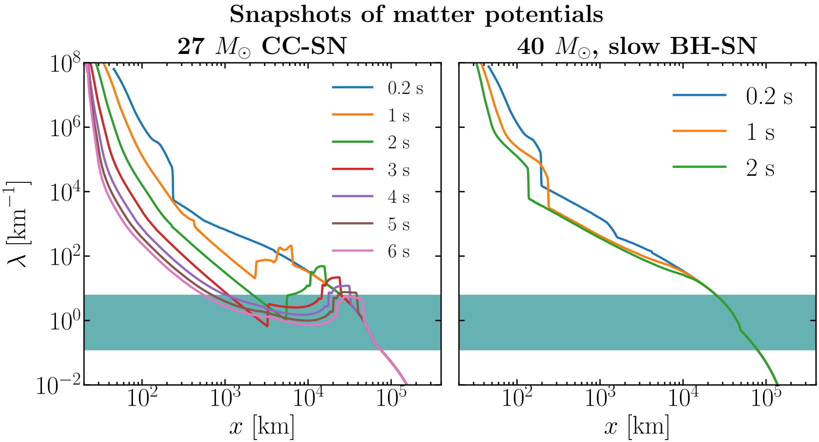
$$H = \overbrace{U^\dagger diag(m_1^2, m_2^2, m_3^2)U}^{\textbf{vacuum}} + \overbrace{diag(V_{CC}, 0, 0)}^{\textbf{matter}}$$

$$\rho = |\psi\rangle\langle\psi| = \begin{bmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{bmatrix}$$

Initial condition for very dense medium

$$\rho = \begin{bmatrix} n_e & 0 & 0 \\ 0 & n_\mu & 0 \\ 0 & 0 & n_\tau \end{bmatrix}, \quad n_\alpha = F_\alpha^0/(F_e^0 + F_\mu^0 + F_\tau^0)$$

Mater potentials



Resonance potential

$$\lambda_{res} = \frac{\cos 2\theta_{13} \Delta m^2}{2E} \approx \cos 2\theta_{13} \left(\frac{\Delta m^2}{\text{eV}^2}\right)\left(\frac{\text{GeV}}{E}\right) \ [\text{km}^{-1}]$$

Adiabatic oscillations

Assumptions

- slowly changing matter profile
- oscillations can follow the change of matter

Fluxes arriving at the Earth

$$F_\alpha = \sum_i |U_{\alpha i}|^2 F_i$$

NO

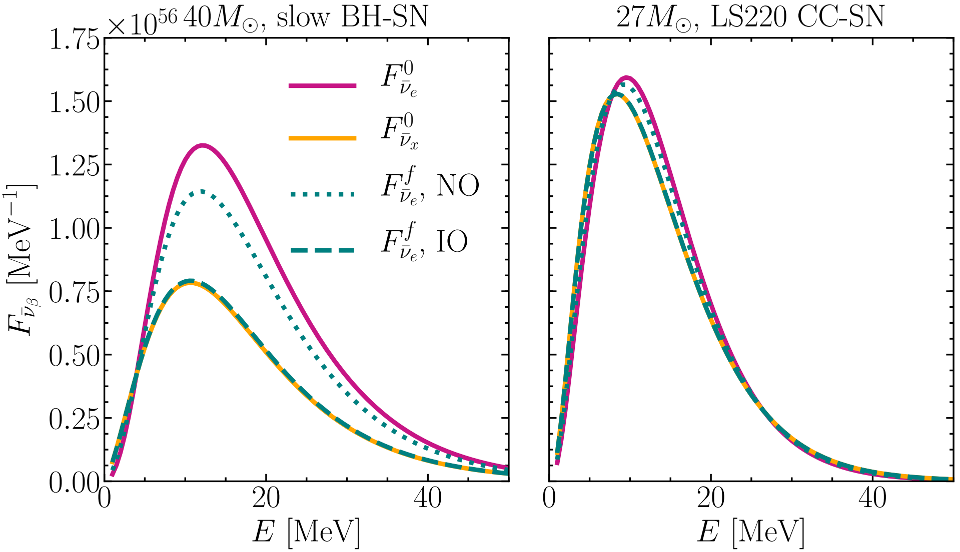
$$F_{\bar{\nu}_e} = \underbrace{\cos^2\theta_{12}}_{\sim 0.71} \underbrace{\cos^2\theta_{13}}_{\sim 0.98} \left(F^0_{\bar{\nu}_e} - F^0_{\bar{\nu}_x}\right) + F^0_{\bar{\nu}_x} \approx \cos^2\theta_{12} \left(F^0_{\bar{\nu}_e} - F^0_{\bar{\nu}_x}\right) + F_{\bar{\nu}^0_x}$$

IO

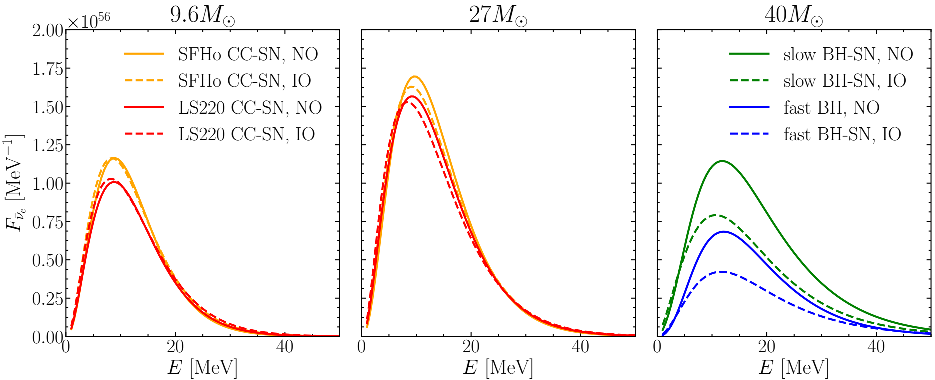
$$F_{\bar{\nu}_e} = \underbrace{\sin^2\theta_{13}}_{\sim 0.02} F^0_{\bar{\nu}_e} + \cos^2\theta_{13} F^0_{\bar{\nu}_x} \approx F^0_{\bar{\nu}_x}$$

Time-integrated neutrino fluxes

Time-integrated neutrino fluxes



Time-integrated neutrino fluxes



	CC-SN	BH-SN
high-energy neutrinos	fewer	more
distinguish progenitor	no	yes
distinguish mass ordering	no	yes

Diffuse supernova neutrino background

Diffuse supernova neutrino background (DSNB)

cosmological supernovae rate

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int_{8M_\odot}^{125M_\odot} dM \int_0^{z_{\max}} dz \frac{R_{\mathrm{SN}}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

$$\times \left[f_{\mathrm{CC-SN}} F_{\nu_\beta,\mathrm{CC-SN}}(E',M) + f_{\mathrm{BH-SN}} F_{\nu_\beta,\mathrm{BH-SN}}(E',M)\right]$$

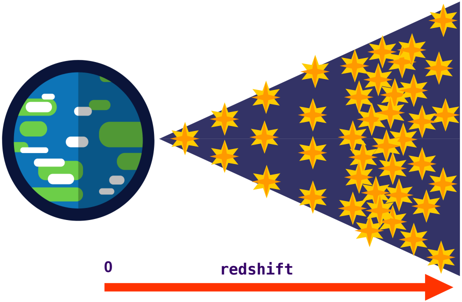
fraction of neutron-star-forming progenitors

fraction of black-hole-forming progenitors

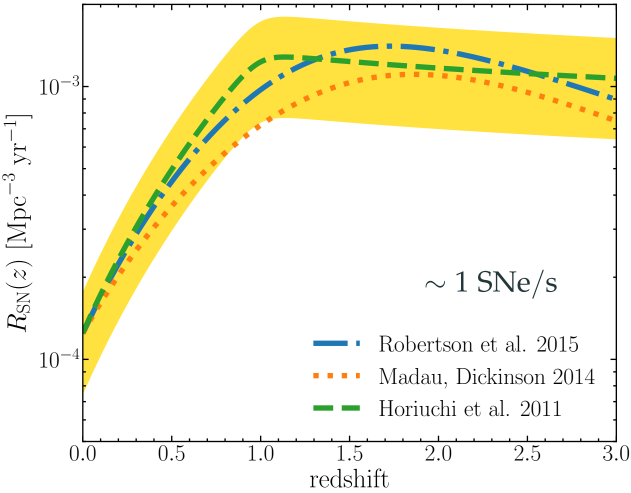
oscillated neutrino flux
E′ = (1+z)E

The DSNB is sensitive to:

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

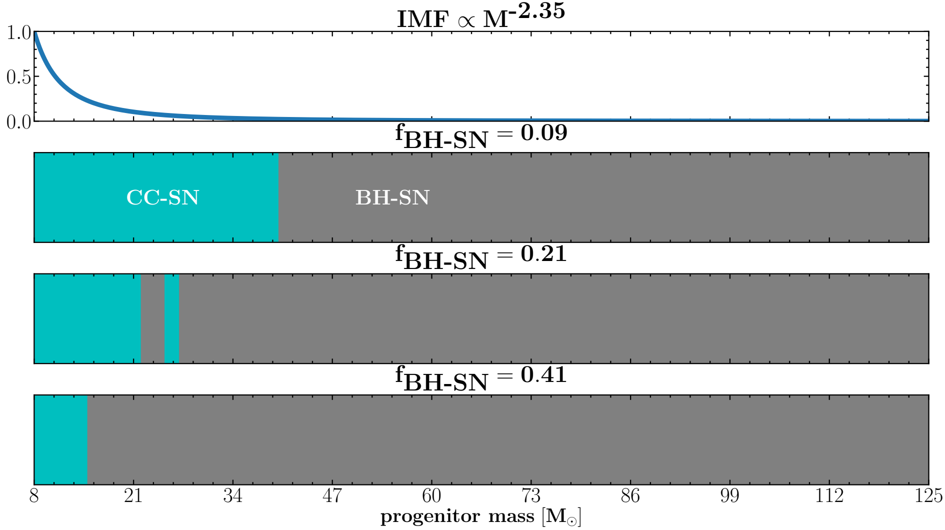


Cosmological supernovae rate

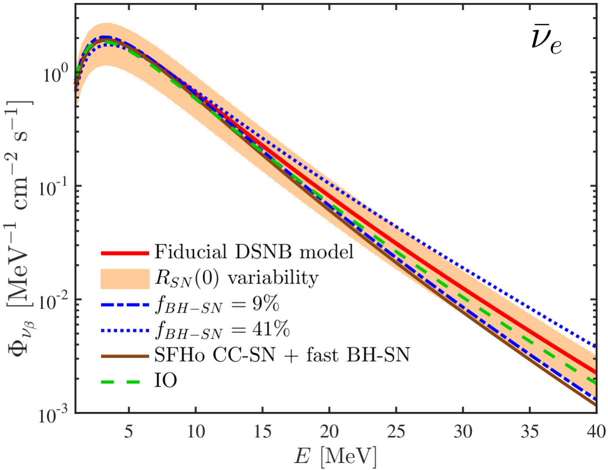


The supernovae rate influences the normalization of the DSNB.

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

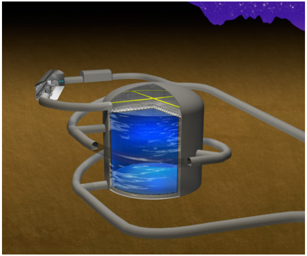


Fiducial DSNB model: $R_{\rm SN}(0) = 1.25 \times 10^{-4}$ Mpc^{-3} yr^{-1}, $f_{\rm BH-SN} = 0.21$, equation of state = LS220, mass accretion rate = slow

The DSNB event rate at future generation neutrino detectors

Future generation neutrino detectors

Hyper-Kamiokande (2025)



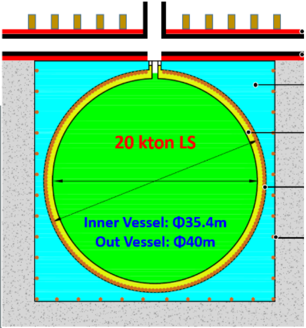
fiducial volume

2×187 kton

main detection channel

$\bar{\nu}_e + \mathrm{p} \rightarrow e^+ + \mathrm{n}$

JUNO (2021)



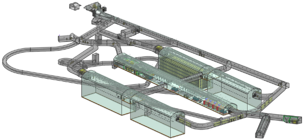
fiducial volume

17 kton

main detection channel

$\bar{\nu}_e + \mathrm{p} \rightarrow e^+ + \mathrm{n}$

DUNE (2027)



fiducial volume

4×10 kton

main detection channel

$\nu_e + \mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

Super-Kamiokande + gadolinium

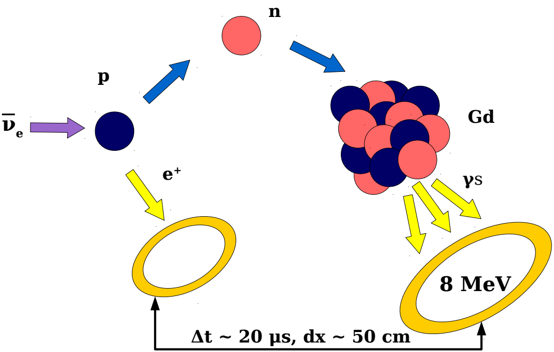
3 σ detection in 10 yrs

HK Design Report, JUNO Conceptual Design Report, DUNE science

Gadolinium sulfate enrichment

Neutron tagging in Gd-enriched water Cherenkov detectors

- concidence detection of positron and neutron
- high cross section for neutron capture ~4900 barn
- elimination of spallation background
- reduction of invisible muon background



J. Beacom and M. R. Vagins, arXiv:0309300

$$R = \int \Phi\, \sigma\, N_t\, f$$

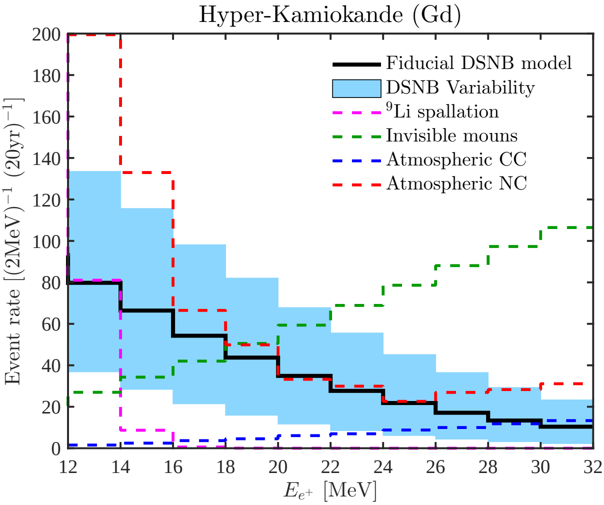
flux

cross section

number of targets

detector efficiency

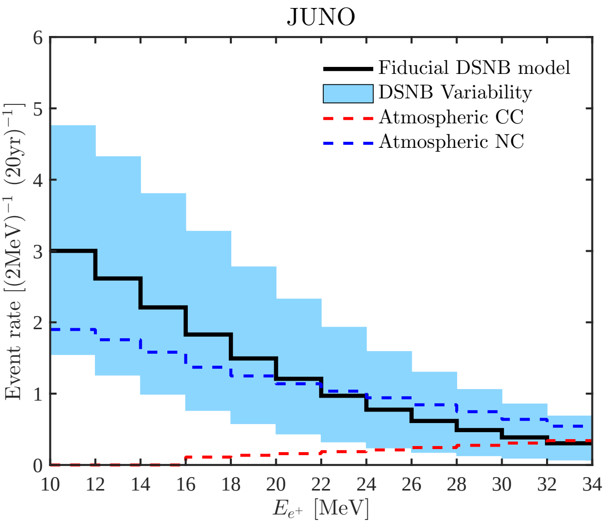
The DSNB event rates



Detectability prospects for 20 yrs

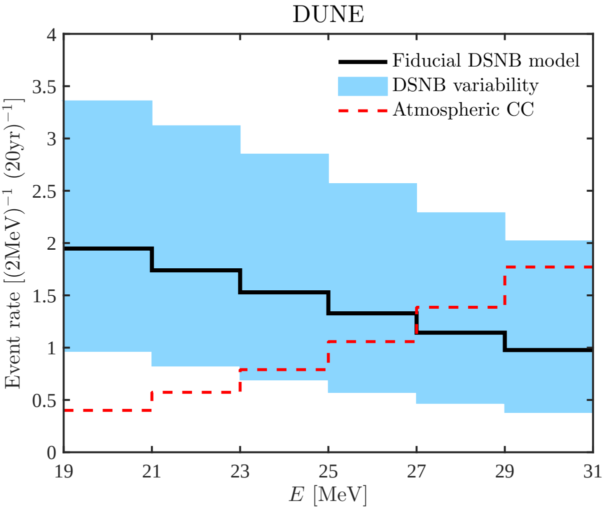
- HK (Gd) with NC: $\sim 10\ \sigma$
- HK (Gd) w/o NC: $\sim 12.5\ \sigma$

The DSNB event rates



Detectability prospects for 20 yrs

- HK (Gd) with NC: $\sim 10\ \sigma$
- HK (Gd) w/o NC: $\sim 12.5\ \sigma$
- JUNO: $\sim 3.4\ \sigma$



Detectability prospects for 20 yrs

- HK (Gd) with NC: $\sim 10\ \sigma$
- HK (Gd) w/o NC: $\sim 12.5\ \sigma$
- JUNO: $\sim 3.4\ \sigma$
- DUNE: $\sim 2.8\ \sigma$

Combined likelihood analysis

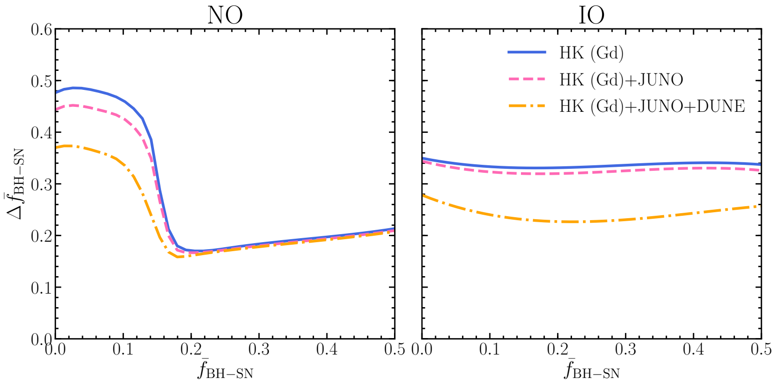
Significance test

$$\chi^2 = \min_A \left(\sum_j \chi^2_{A,j} + \chi^2_{\mathrm{HK}} + \chi^2_{\mathrm{JUNO}} + \chi^2_{\mathrm{DUNE}} \right)$$

The set of parameters to be marginalized over:

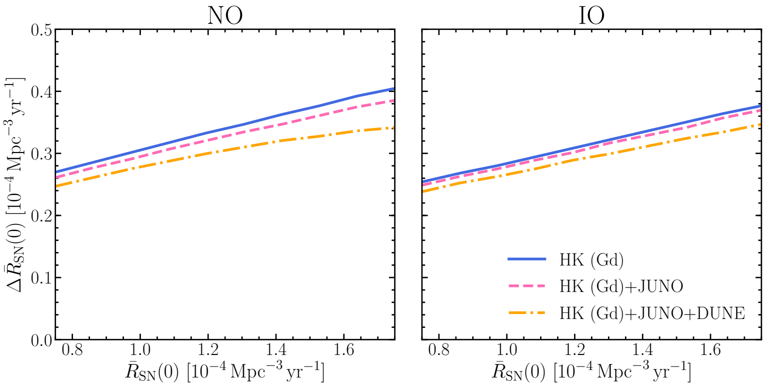
- $f_{\mathrm{BH-SN}}$, $\Delta_{f_{\mathrm{BH-SN}}} = 0.2$
- $R_{\mathrm{SN}}(0)$, $\Delta_{R_{\mathrm{SN}}(0)} = 0.25 \times 10^{-4}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$
- background normalization uncertainty, $\Delta_{\mathrm{BG}} = 20\%$
- liquid argon cross section uncertainty, $\Delta\sigma_{\mathrm{LAr}} = 15\%$
- mass accretion rate - equation of state uncertainty

Expected 1σ uncertainty: fraction of BH forming progenitors



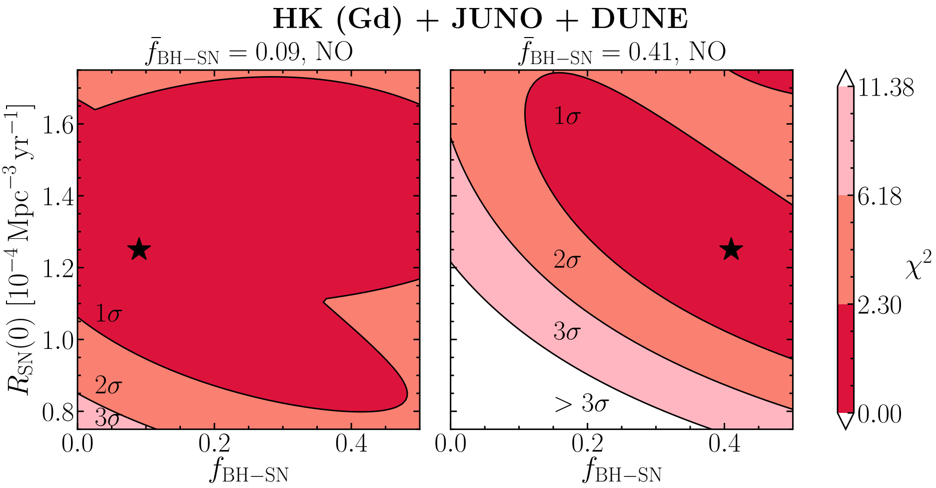
- The high uncertainty comes from $f_{\rm BH-SN}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos → helps to reduce the uncertainty

Expected 1σ uncertainty: local supernova rate



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

Determining the supernovae unknowns with DSNB



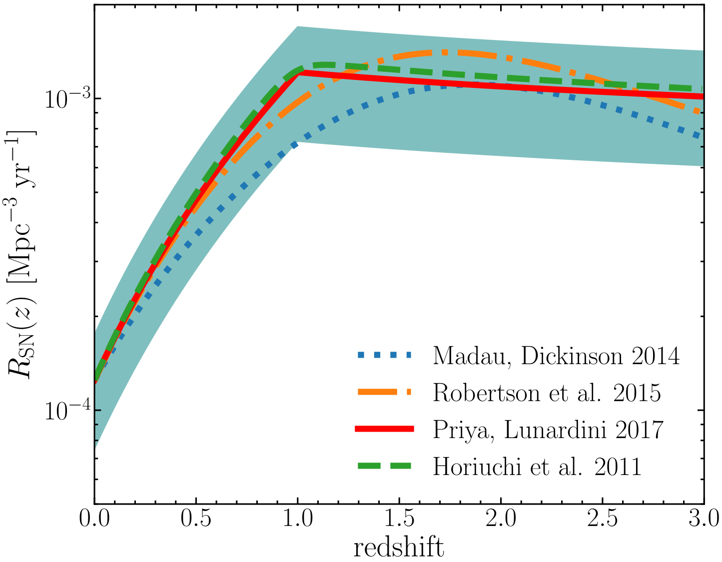
Conclusions

Conclusions

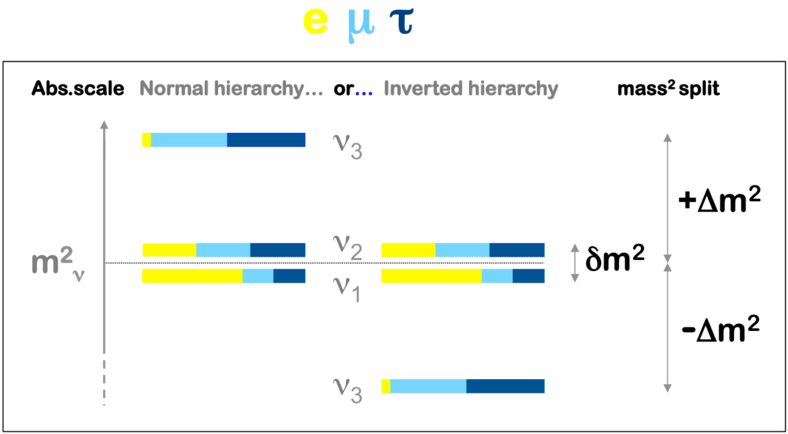
- Future neutrino detectors will detect and measure the DSNB
- The DSNB
  - is sensitive to the fraction of BH forming progenitors
  - is sensitive to the local supernovae rate
  - shows no discriminating power of the mass accretion rate

Backup slides

Star formation rate shape



Neutrino mass ordering



E. Lisi

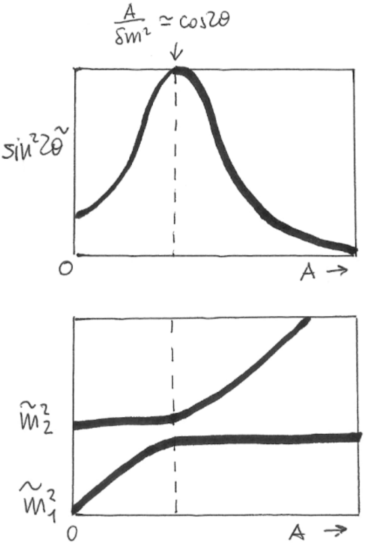
Effective mixing parameters

$$\sin 2\tilde{\theta} = \frac{\sin 2\theta}{\sqrt{(\cos 2\theta - \frac{A}{\Delta m^2})^2 + \sin^2 2\theta}},$$

$$\cos 2\tilde{\theta} = \frac{\cos^2 2\theta - \frac{A}{\Delta m^2}}{\sqrt{(\cos 2\theta - \frac{A}{\Delta m^2})^2 + \sin^2 2\theta}}$$

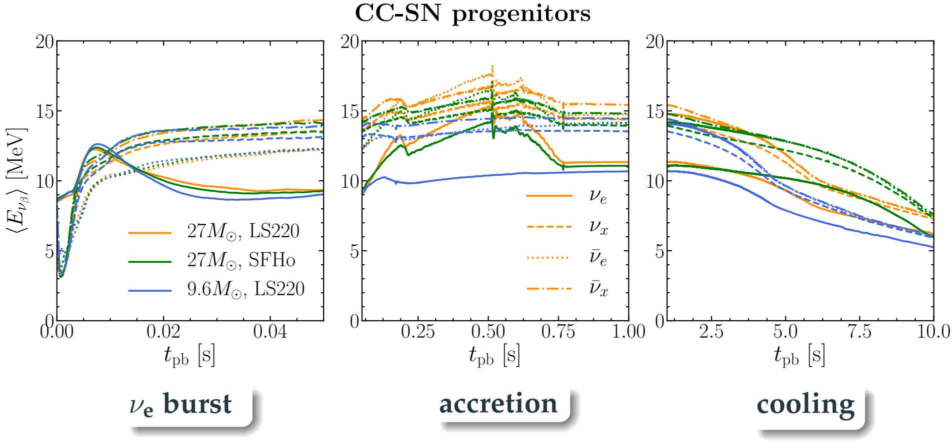
$$\Delta \tilde{m}^2 = \Delta m^2 \frac{\sin 2\theta}{\sin 2\tilde{\theta}}$$

$$A = 2\sqrt{2} G_F N_e E$$



E. Lisi

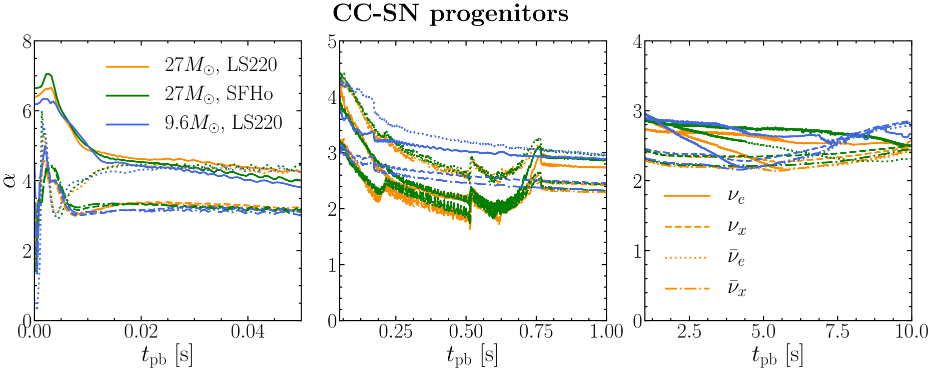
Progenitor stars forming neutron stars



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

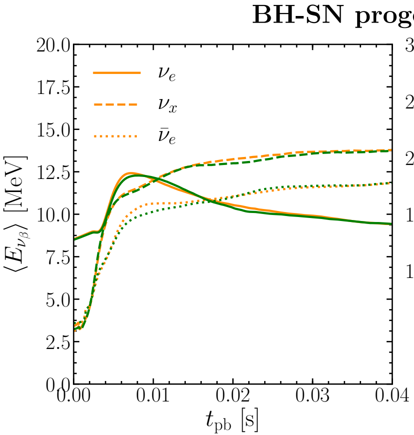


ν_e **burst**

accretion

cooling

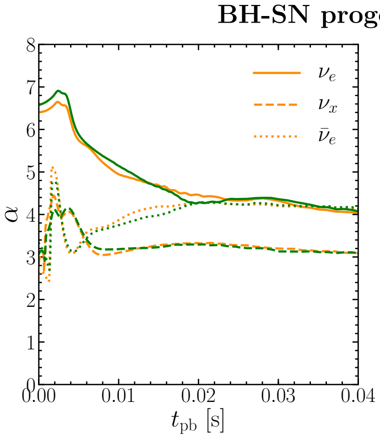
Progenitor stars forming black holes



ν_e **burst**

accretion

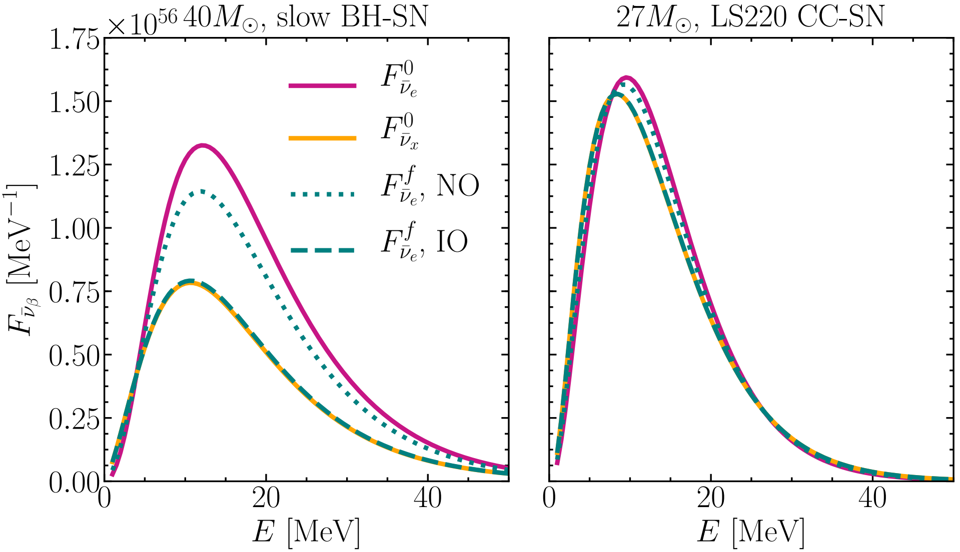
Progenitor stars forming black holes



ν_e **burst**

accretion

Time-integrated neutrino fluxes



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

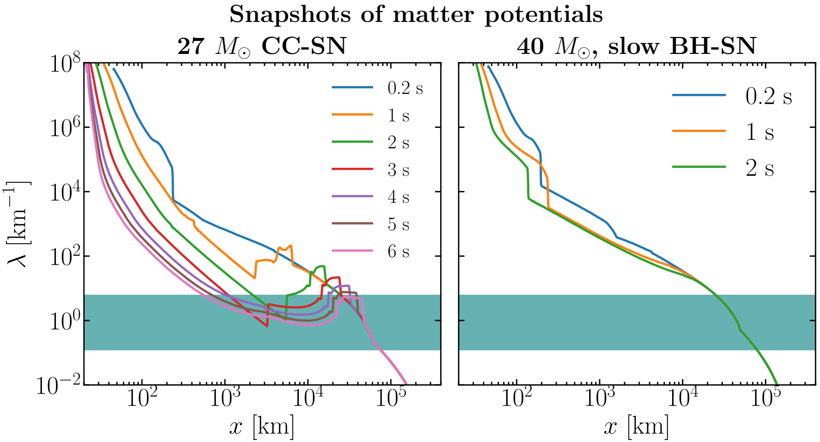
Pinching parameter

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

Differential neutrino flux

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

Mater potentials



resonance potential

$$\lambda_{res} = \frac{\cos 2\theta_{13} \Delta m^2}{2E} = 2.538 \ \cos 2\theta_{13} \ \left(\frac{\Delta m^2}{eV^2}\right)\left(\frac{GeV}{E}\right) \ [\text{km}^{-1}]$$

Main sources of backgrounds

cosmic rays interactions with atmosphere

$$\pi^+ \to \mu^+ + \nu_\mu \quad , \quad \pi^- \to \mu^- + \bar{\nu}_\mu$$

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e \quad , \quad \mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

reactor antineutrinos

$$^{A}_{Z}\mathrm{X} \to {}^{A}_{Z+1}\mathrm{Y} + \mathrm{p} + \mathrm{e}^- + \bar{\nu}_e$$

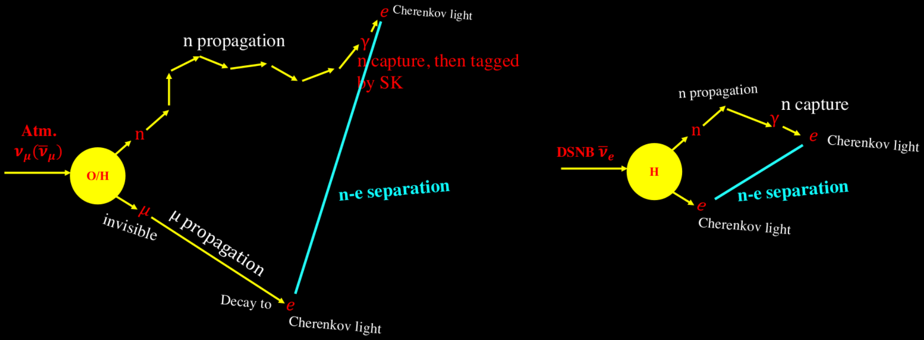
neutrinos from the Sun

proton - proton chain reactions, i.e.,

$$\mathrm{p} + \mathrm{p} \to {}^{2}\mathrm{He} + \mathrm{e}^+ + \nu_e \quad , \quad \mathrm{p} + \mathrm{e}^- + \mathrm{p} \to {}^{2}\mathrm{He} + \nu_e$$

$$^{3}\mathrm{H} + \mathrm{p} \to {}^{4}\mathrm{He} + \mathrm{e}^+ + \nu_e \quad , \quad {}^{7}\mathrm{Be} + \mathrm{e}^- \to {}^{7}\mathrm{Li} + \nu_e$$

n-e separation: definition



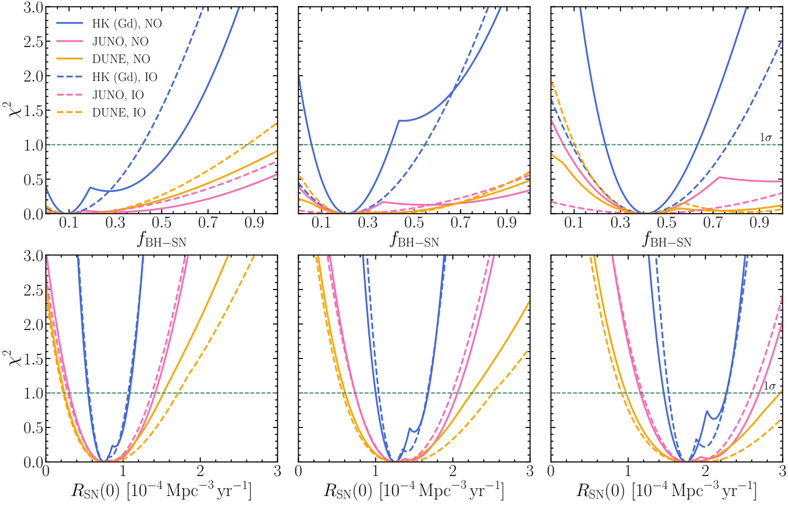
Assumed uncertainties:

- $\Delta_{R_{\rm SN}(0)} = 0.25 \times 10^{-4}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$
- $\Delta_{f_{\rm BH-SN}} = 0.2$
- $\Delta_{\rm BG} = 20\%$
- $\Delta\sigma_{\rm LAr} = 15\%$

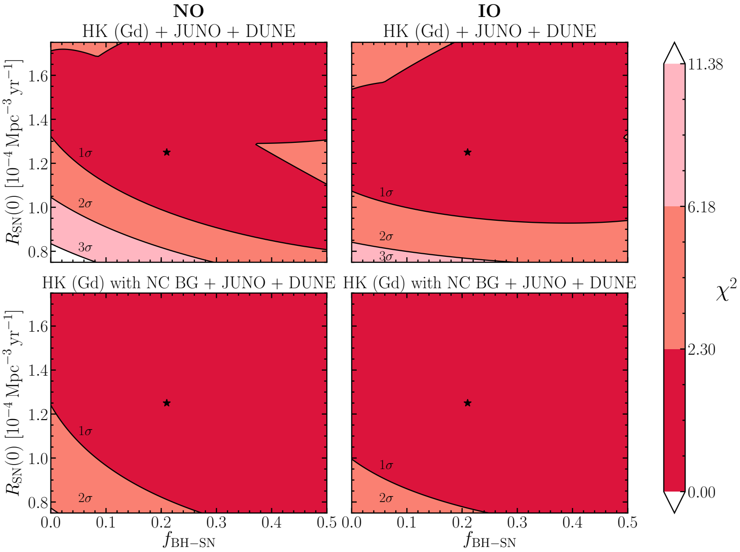
Pull terms: $\chi^2_{\rm BG} = \left(\frac{x}{\Delta_{\rm BG}}\right)^2$,

$\chi^2_{\rm R_{SN}(0)} = \left(\frac{R_{\rm SN}(0) - \bar{R}_{\rm SN}(0)}{\Delta_{R_{\rm SN}(0)}}\right)^2$

Expected 1D χ^2 as a function of $f_{\mathrm{BH-SN}}$ and $R_{\mathrm{SN}}(0)$



χ^2 for the fraction of BH forming progenitors - local supernova rate plane



Sources of background

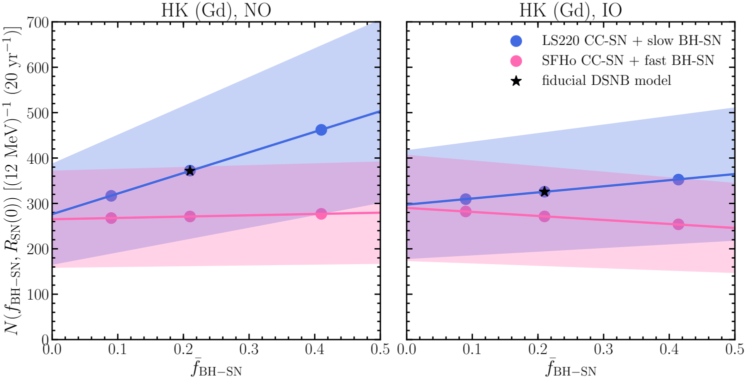
	atmospheric BG				solar ν_e	reactor $\bar{\nu}_e$
	invisible μ	spallation	NC	$\nu_e/\bar{\nu}_e$		
HK (Gd)	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**
JUNO	**No**	**No**	**Yes**	**Yes**	**No**	**Yes**
DUNE	**No**	**No**	**No**	**Yes**	**Yes**	**No**

Yes - sets lower limit for the DSNB detection window

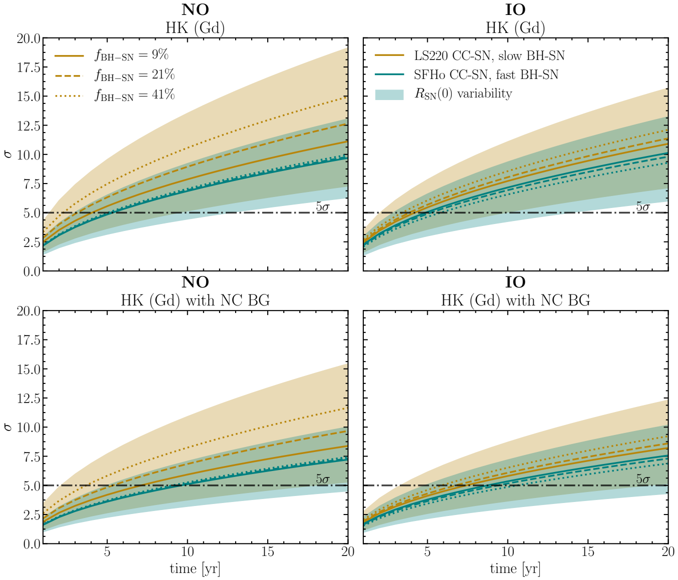
Yes - sets upper limit for the DSNB detection window

Yes - doesn't set limit for the DSNB detection window

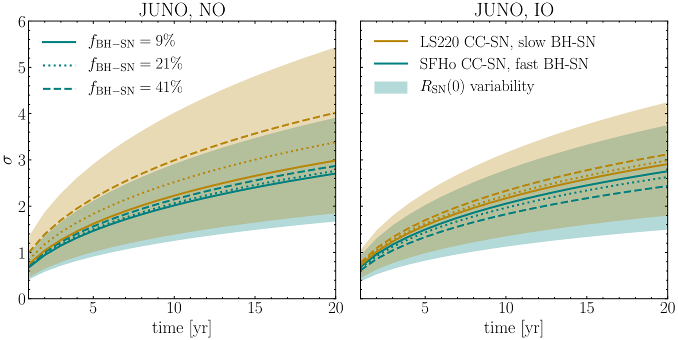
Number of events in HK (Gd) energy window



Detection significance HK (Gd)



Detection significance JUNO



Detection significance DUNE