

Determining supernova unknowns with the diffuse supernova neutrino background

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with K. Møller, I. Tamborra, P. B. Denton

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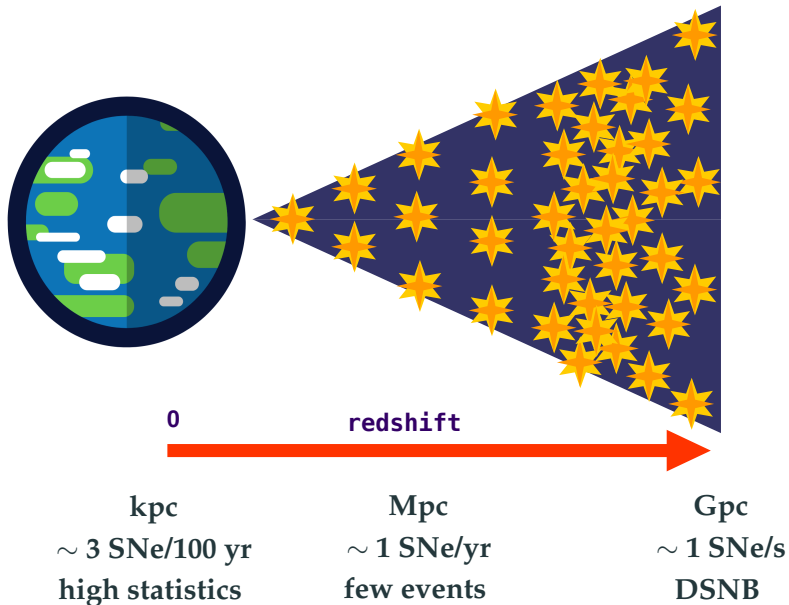
Niels Bohr Institute,
University of Copenhagen



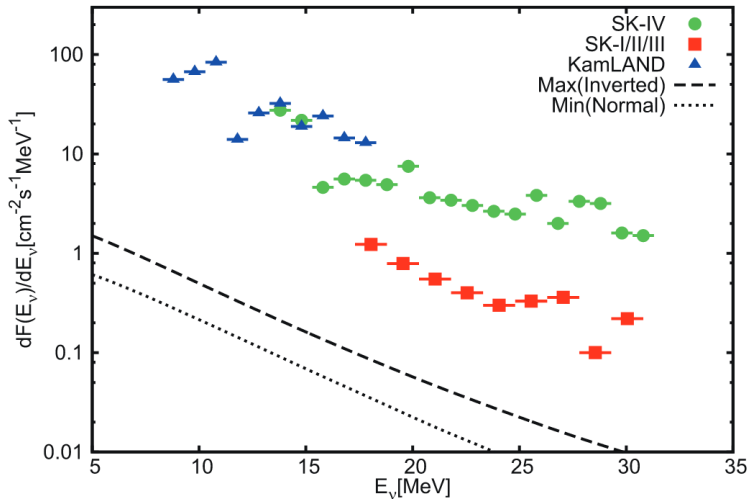
ECT*, Trento

- ① Neutrino emission from the core-collapse supernovae
- ② Diffuse supernova neutrino background
- ③ The DSNB detection and measurement
- ④ Conclusions

Diffuse supernova neutrino background



Inevitable detection within next 10-15 years

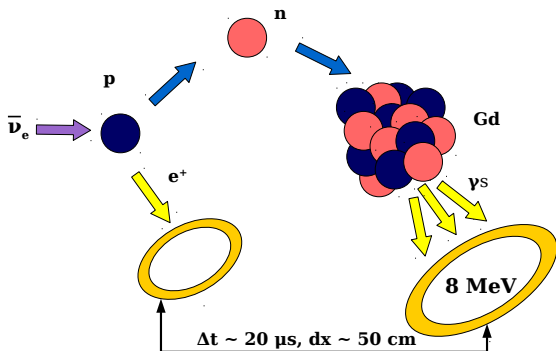


Super Kamiokande (Gd, 2020) $\sim 3 \sigma$ within 10 yrs

Gadolinium sulfate enrichment

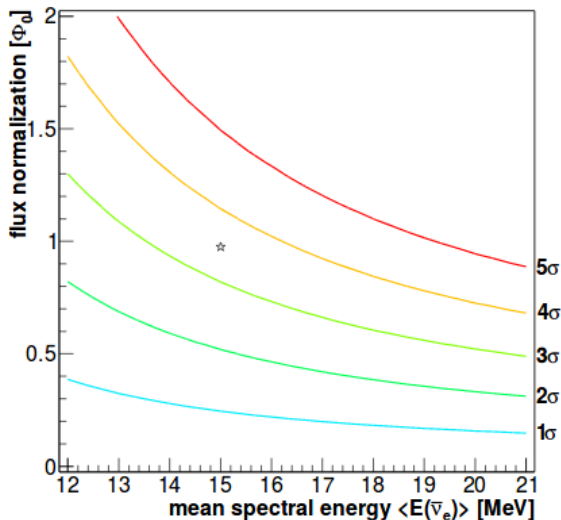
Neutron tagging in Gd-enriched water Cherenkov detectors

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



Inevitable detection within next 10-15 years

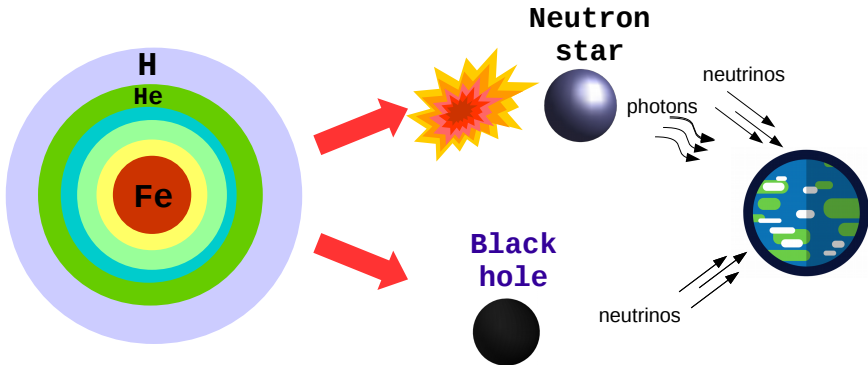
JUNO (2021) $\sim 3\sigma$ within 10 yrs



Core-collapse supernovae

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)

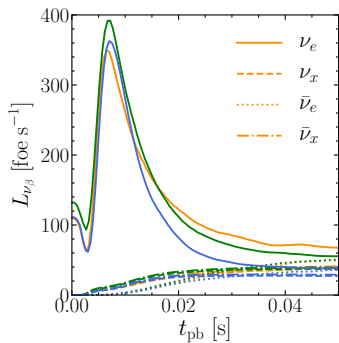


Neutrino emission from the core-collapse supernovae

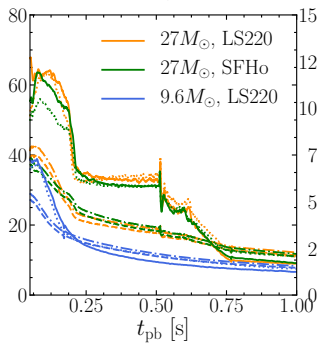
Core-collapse supernovae

1 foe = 10^{51} ergs

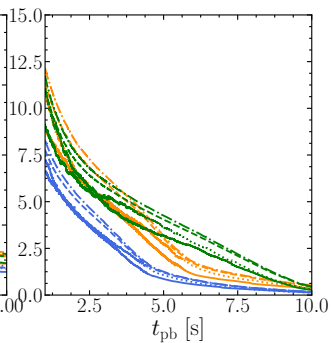
CC-SN progenitors



ν_e burst



accretion



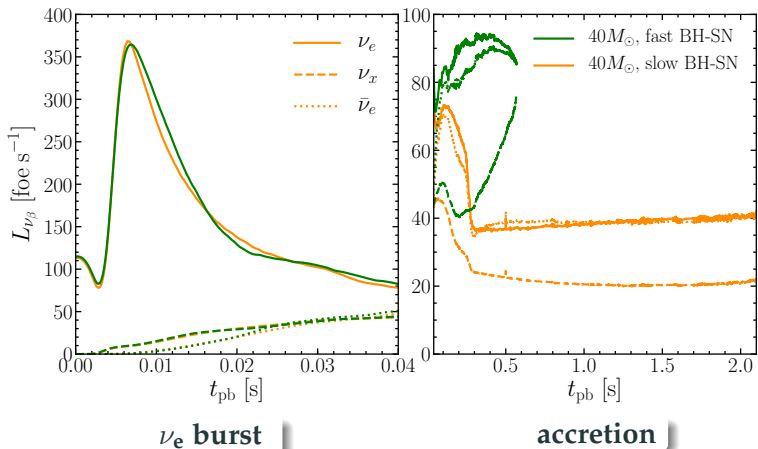
cooling

CC-SN

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

Failed Supernovae

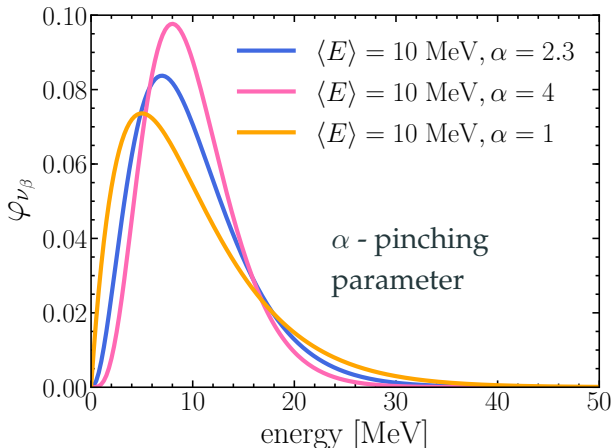
BH-SN progenitors



BH-SN

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

Neutrino energy distribution



Differential neutrino flux

$$f_{\nu\beta}^0(E, t_{\text{pb}}) = \frac{L_{\nu\beta}(t_{\text{pb}})}{4\pi r^2} \frac{\varphi_{\nu\beta}(E, t_{\text{pb}})}{\langle E_{\nu\beta}(t_{\text{pb}}) \rangle} = \frac{F_{\nu\beta}^0(E, t_{\text{pb}})}{4\pi r^2}$$

Equation of motion for supernova neutrinos

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

vacuum

matter

**neutrino -
neutrino**

$$H = U^\dagger \text{diag}(m_1^2, m_2^2, m_3^2)U + \text{diag}(V_{CC}, 0, 0) + \int d^3p' (\rho - \bar{\rho})(1 - v' \cdot v)$$

Equation of motion for supernova neutrinos

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

vacuum

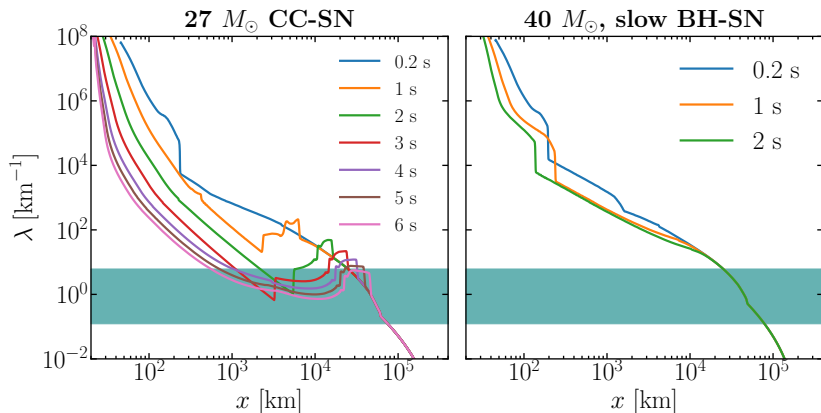
matter

**neutrino -
neutrino**

$$H = U^\dagger \text{diag}(m_1^2, m_2^2, m_3^2)U + \text{diag}(V_{CC}, 0, 0) + \int d^3p' (\rho - \bar{\rho})(1 - v' \cdot v)$$

Matter potentials

Snapshots of matter potentials

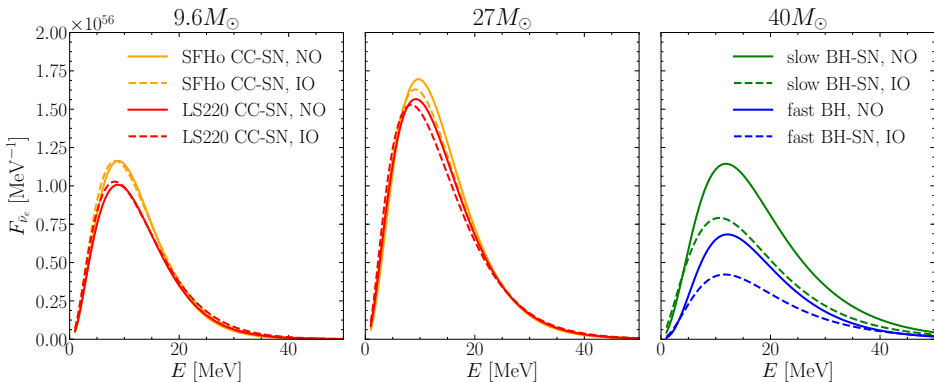


Resonance potential

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

Wolfenstein, Phys. Rev. D 17, 2369, Dighe and Smirnov, arXiv:9907423

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)

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

cosmological supernovae rate (points to $R_{\text{SN}}(z, M)$)

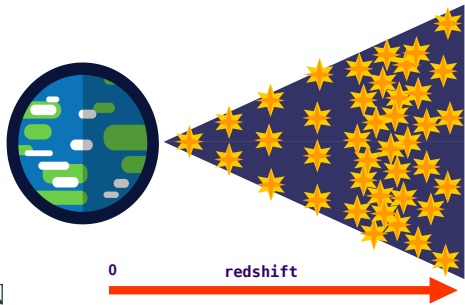
fraction of black-hole-forming progenitors (points to $f_{\text{BH-SN}}$)

fraction of neutron-star-forming progenitors (points to $f_{\text{CC-SN}}$)

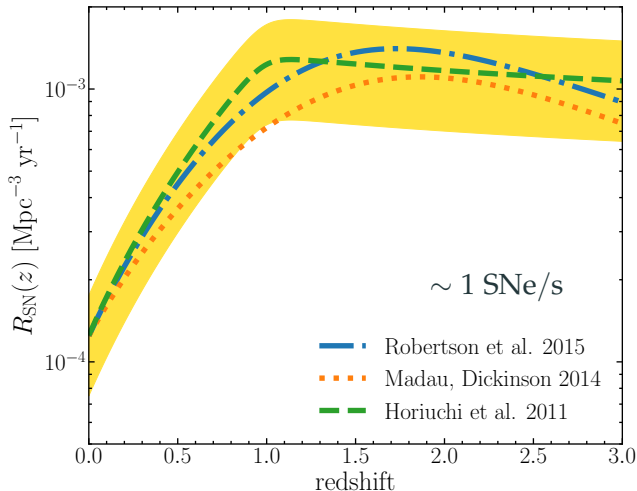
oscillated neutrino flux
 $E' = (1+z)E$ (points to $F_{\nu\beta, \text{BH-SN}}(E', M)$)

The DSNB is sensitive to:

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

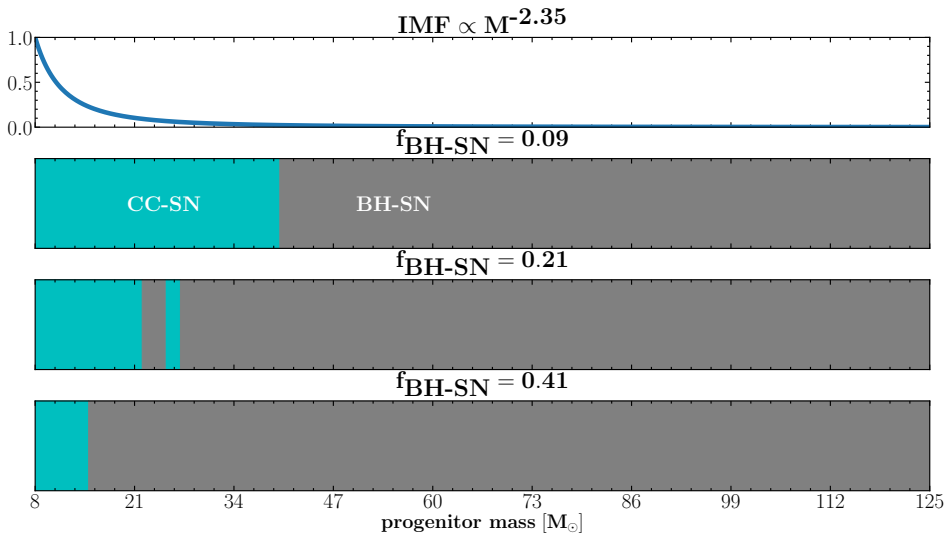


Cosmological supernovae rate



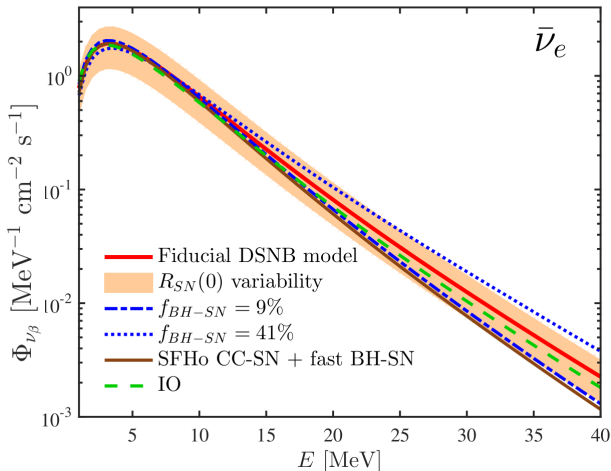
The supernovae rate influences the normalization of the DSNB.

Fraction of BH-forming progenitors



Ertl et al. [arXiv:1503.07522](https://arxiv.org/abs/1503.07522), Sukhbold et al. [arXiv:1510.04643](https://arxiv.org/abs/1510.04643),
Adams et al. [arXiv:1610.02402](https://arxiv.org/abs/1610.02402), Heger et al. [arXiv:0112059](https://arxiv.org/abs/0112059)

Diffuse supernova neutrino background

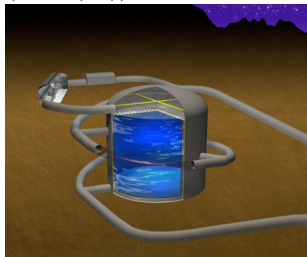


Fiducial DSNB model: $R_{SN}(0) = 1.25 \times 10^{-4} \text{ Mpc}^{-3} \text{ yr}^{-1}$, $f_{BH-SN} = 0.21$,
equation of state = LS220, mass accretion rate = slow

The DSNB detection and measurement

Future generation neutrino detectors

Hyper-Kamiokande
(2026(8?))



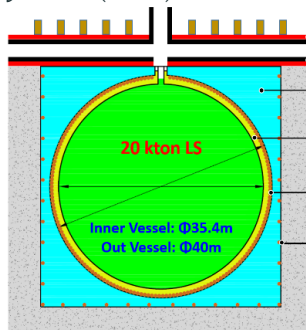
fiducial volume

2×187 kton

main detection channel



JUNO (2021)



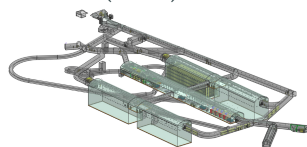
fiducial volume

17 kton

main detection channel



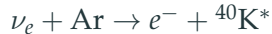
DUNE (2027)



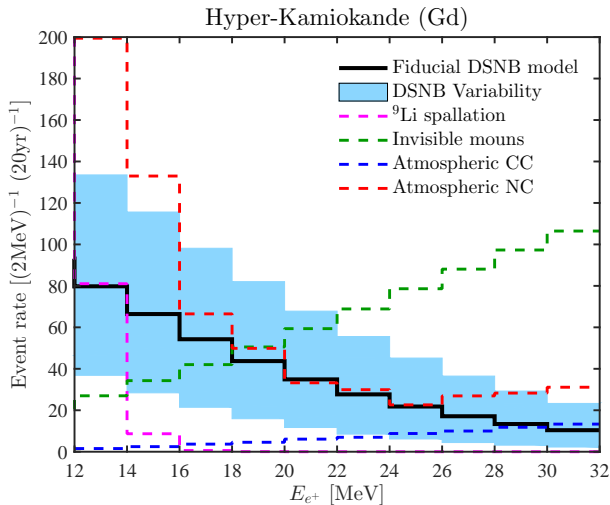
fiducial volume

4×10 kton

main detection channel



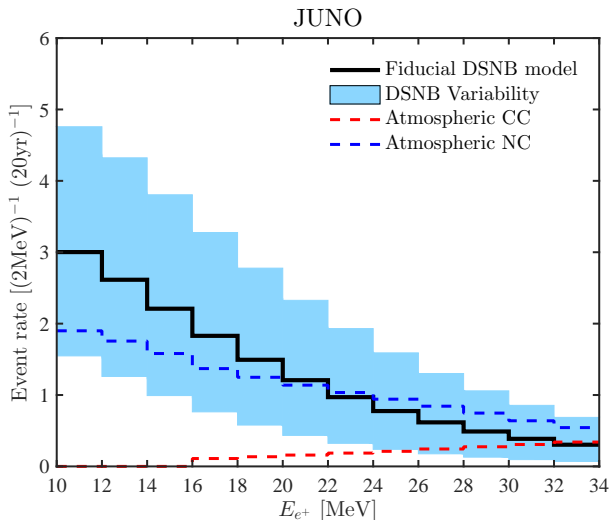
The DSNB event rates



Detectability prospects for 20 yrs

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

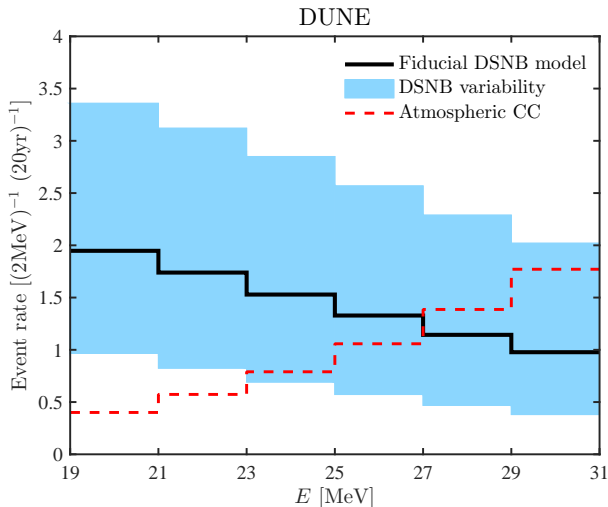
The DSNB event rates



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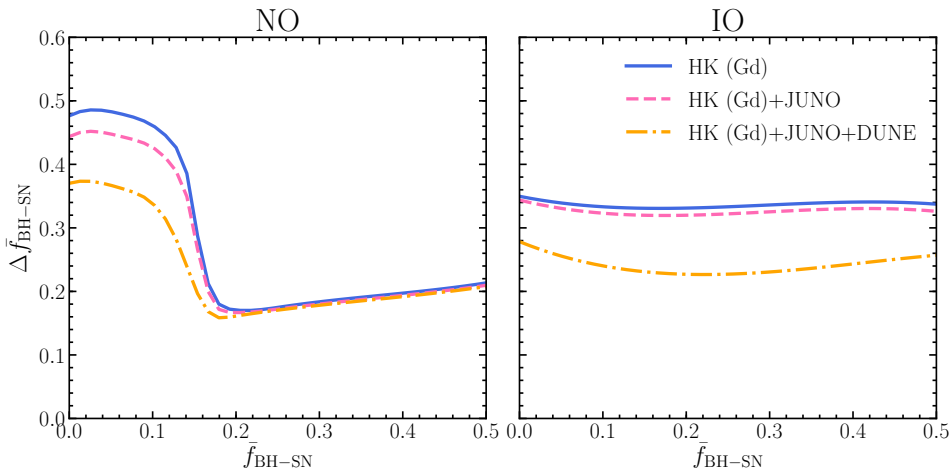
The DSNB event rates



Detectability prospects for 20 yrs

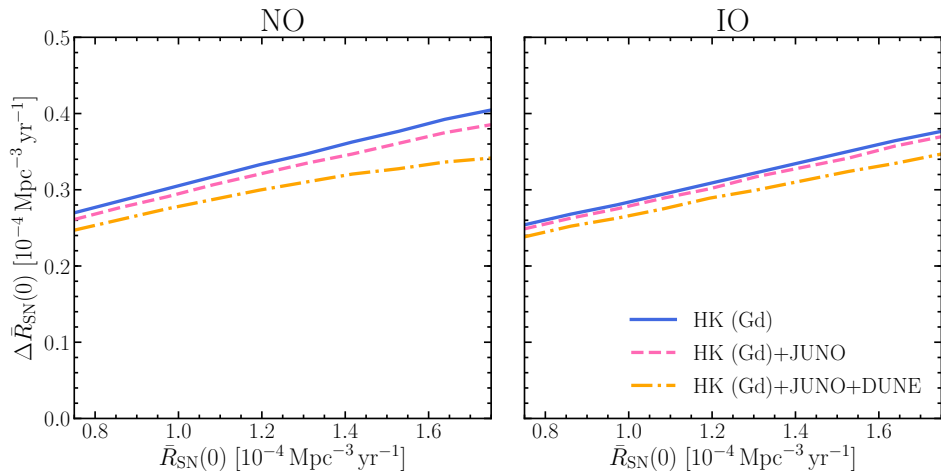
- HK (Gd) with NC: $\sim 10 \sigma$
- HK (Gd) w/o NC: $\sim 12.5 \sigma$
- JUNO: $\sim 3.4 \sigma$
- DUNE: $\sim 2.8 \sigma$

Expected 1σ uncertainty: fraction of BH forming progenitors



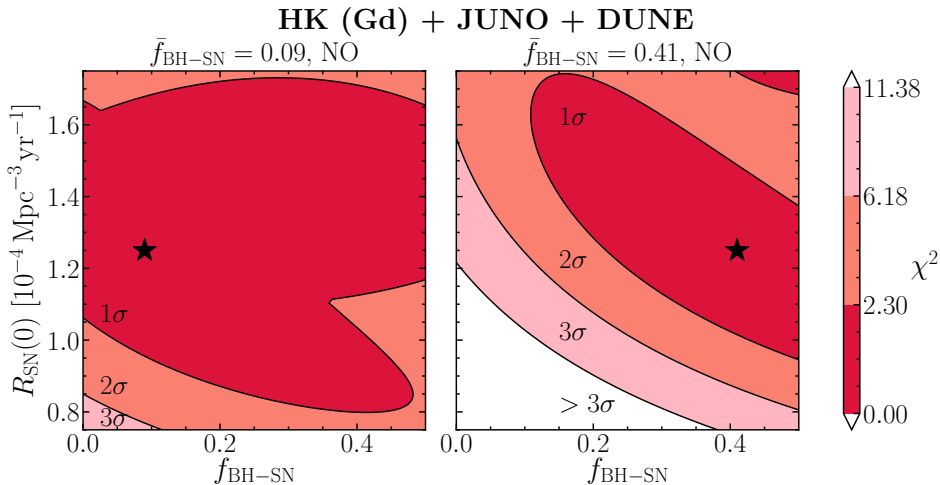
- The high uncertainty comes from $f_{\text{BH-SN}}$ -mass accretion rate degeneracy
- DUNE is sensitive to neutrinos \rightarrow helps to reduce the uncertainty

Expected 1σ uncertainty: local supernova rate



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

Determining the supernovae unknowns with DSNB



Conclusions

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- 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 weak discriminating power of the neutrino mass ordering

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Thank you!

Backup slides

Neutrino energy distribution

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

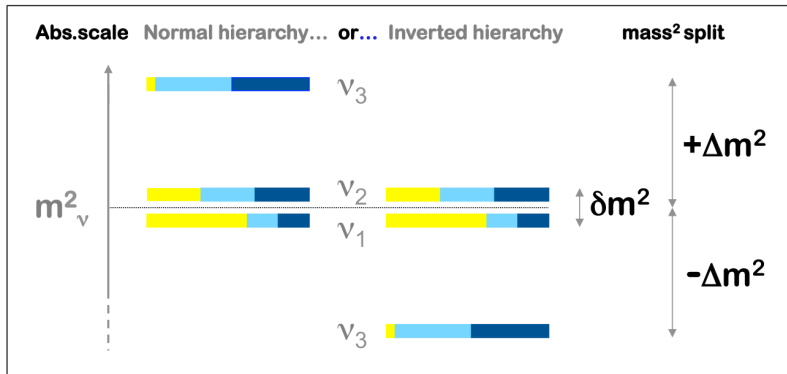
$$\text{normalization } 1/\xi_{\nu\beta}(t_{\text{pb}}) = \int dE \varphi_{\nu\beta}(E, t_{\text{pb}})$$

Pinching parameter

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

Neutrino mass ordering

e μ τ



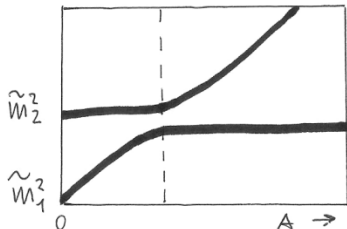
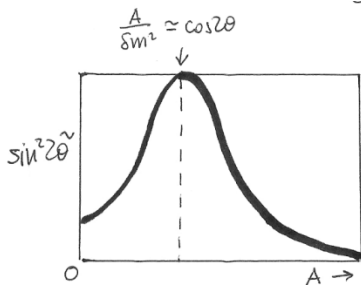
Effective mixing parameters

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

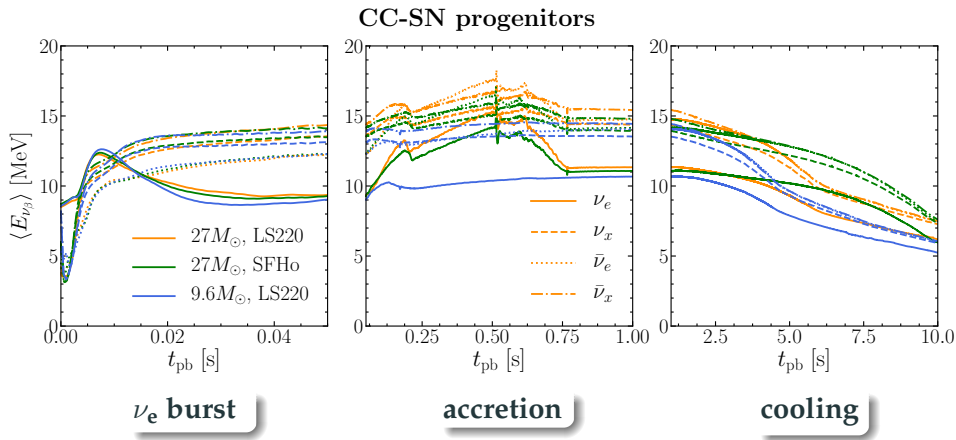
$$\cos 2\tilde{\theta} = \frac{\cos^2 2\theta - \frac{A}{\Delta m^2}}{\sqrt{(\cos 2\theta - \frac{A}{\Delta m^2})^2 + \sin^2 2\theta}}$$

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

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



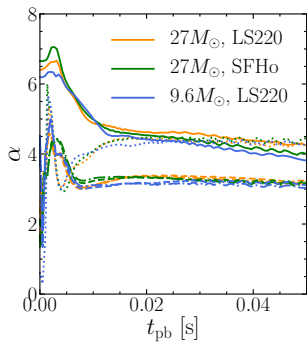
Progenitor stars forming neutron stars



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

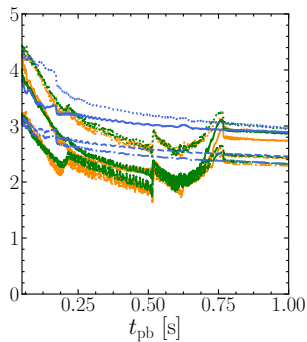
Late times $\langle E_{\nu_e} \rangle < \langle E_{\nu_x} \rangle < \langle E_{\bar{\nu}_e} \rangle$

Progenitor stars forming neutron stars

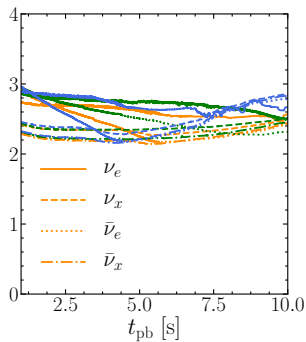


ν_e burst

CC-SN progenitors



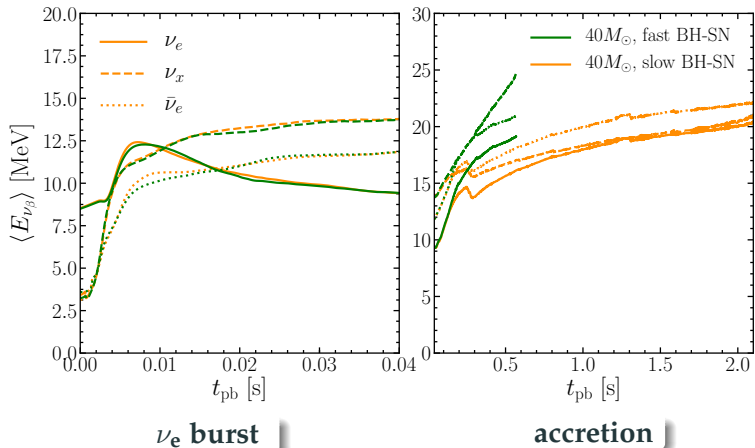
accretion



cooling

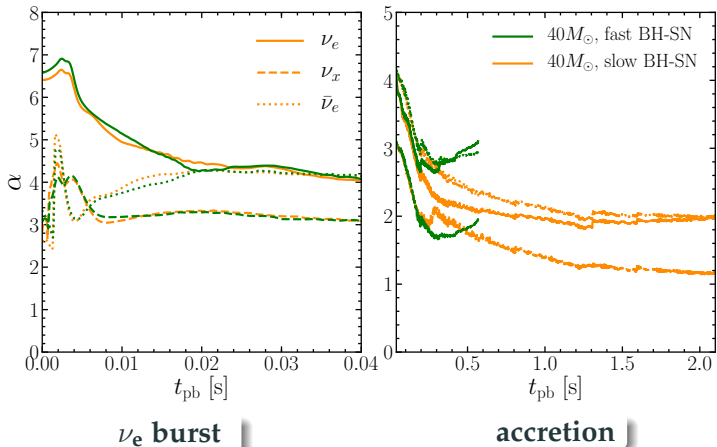
Progenitor stars forming black holes

BH-SN progenitors

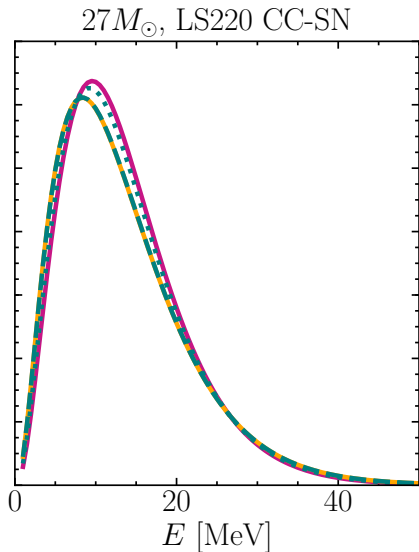
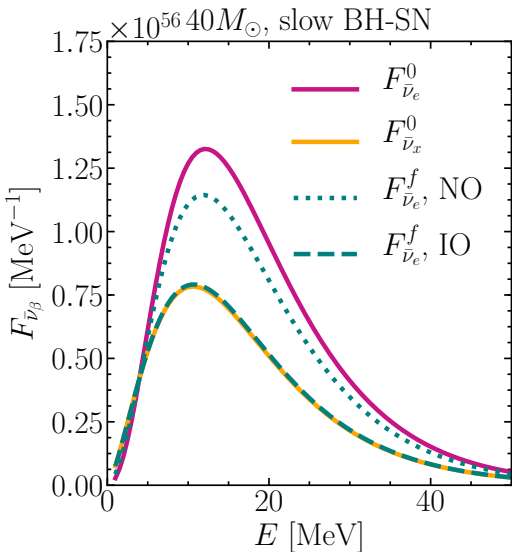


Progenitor stars forming black holes

BH-SN progenitors



Time-integrated neutrino fluxes



Neutrino energy distribution

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

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Pinching parameter

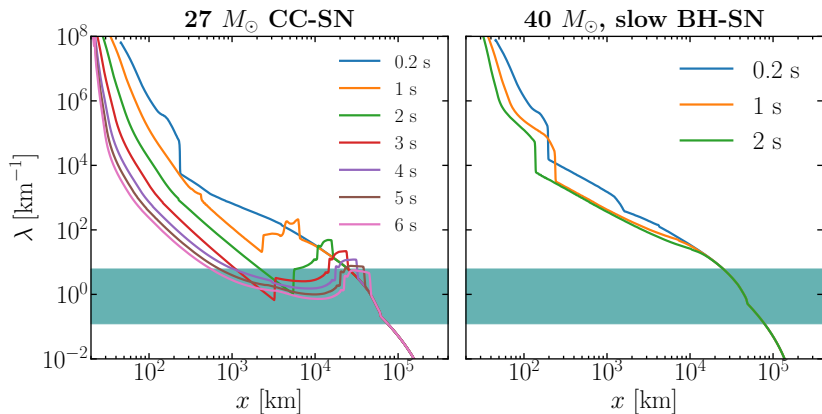
$$\alpha_{\beta}(t_{\text{pb}}) = \frac{\langle E_{\nu\beta}(t_{\text{pb}})^2 \rangle - 2\langle E_{\nu\beta}(t_{\text{pb}}) \rangle^2}{\langle E_{\nu\beta}(t_{\text{pb}}) \rangle^2 - \langle E_{\nu\beta}(t_{\text{pb}})^2 \rangle}.$$

Differential neutrino flux

$$f_{\nu\beta}^0(E, t_{\text{pb}}) = \frac{L_{\nu\beta}(t_{\text{pb}})}{4\pi r^2} \frac{\varphi_{\nu\beta}(E, t_{\text{pb}})}{\langle E_{\nu\beta}(t_{\text{pb}}) \rangle} = \frac{F_{\nu\beta}^0(E, t_{\text{pb}})}{4\pi r^2}$$

Mater potentials

Snapshots of matter potentials

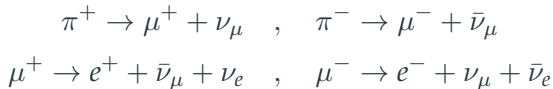


resonance potential

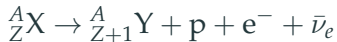
$$\lambda_{\text{res}} = \frac{\cos 2\theta_{13} \Delta m^2}{2E} = 2.538 \cos 2\theta_{13} \left(\frac{\Delta m^2}{\text{eV}^2} \right) \left(\frac{\text{GeV}}{E} \right) [\text{km}^{-1}]$$

Main sources of backgrounds

cosmic rays interactions with atmosphere



reactor antineutrinos

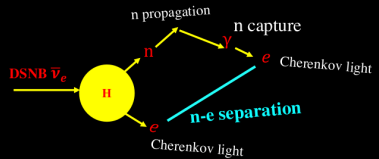
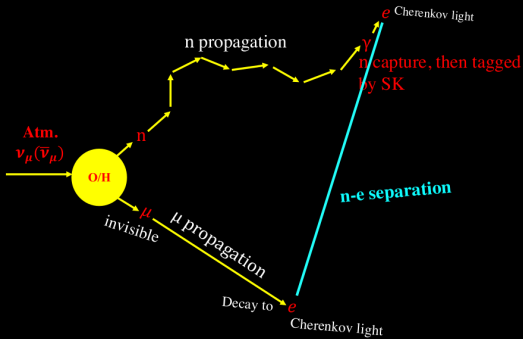


neutrinos from the Sun

proton - proton chain reactions, i.e.,



n-e separation: definition



Assumed uncertainties:

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

Pull terms: $\chi_{\text{BG}}^2 = \left(\frac{x}{\Delta_{\text{BG}}}\right)^2,$
 $\chi_{R_{\text{SN}}(0)}^2 = \left(\frac{R_{\text{SN}}(0) - \bar{R}_{\text{SN}}(0)}{\Delta_{R_{\text{SN}}(0)}}\right)^2$

Combined likelihood analysis

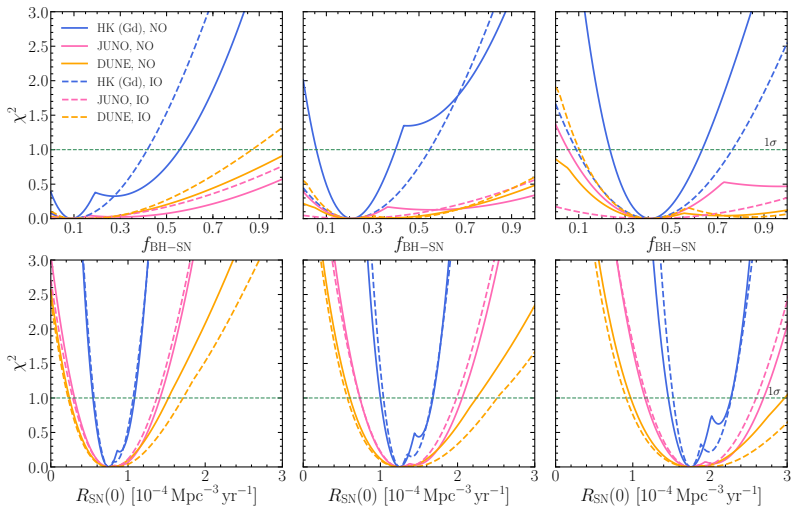
Significance test

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

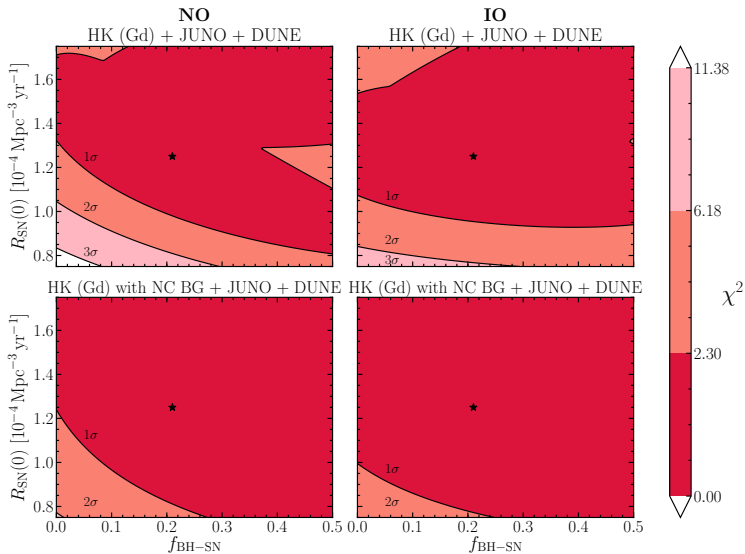
The set of parameters to be marginalized over:

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

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



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



Sources of background

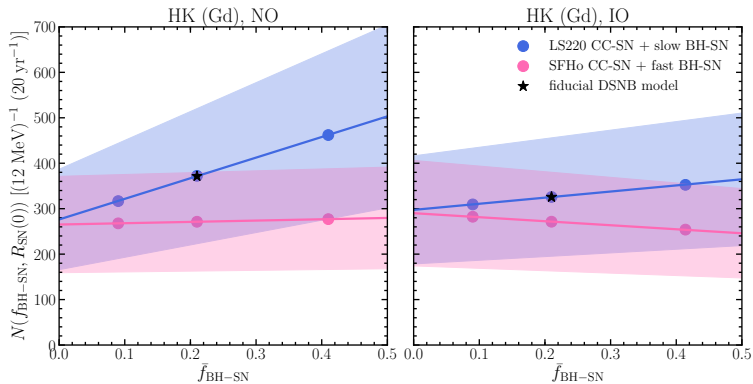
	atmospheric BG				solar ν_e	reactor $\bar{\nu}_e$
	invisible μ	spallation	NC	$\nu_e/\bar{\nu}_e$		
HK (Gd)	Yes	Yes	Yes	Yes	No	Yes
JUNO	No	No	Yes	Yes	No	Yes
DUNE	No	No	No	Yes	Yes	No

Yes - sets lower limit for the DSNB detection window

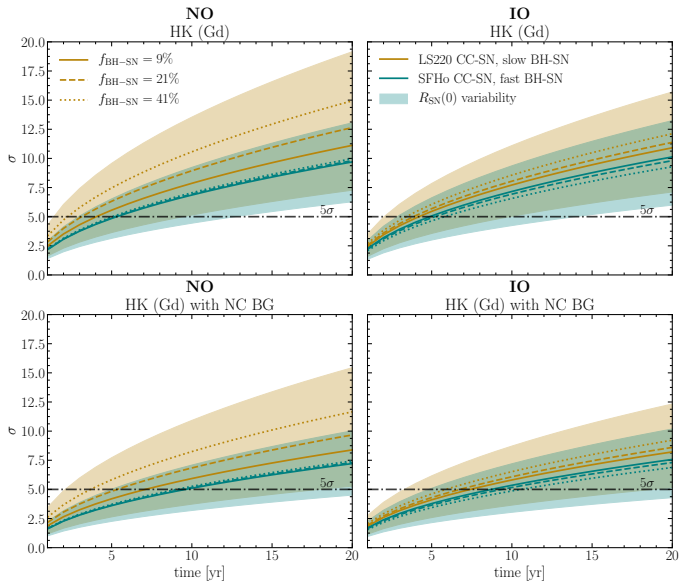
Yes - sets upper limit for the DSNB detection window

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

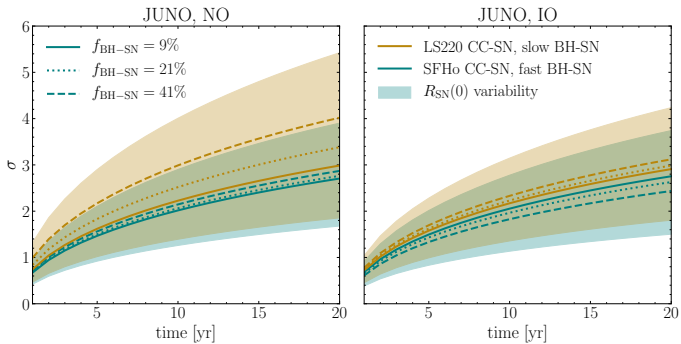
Number of events in HK (Gd) energy window



Detection significance HK (Gd)



Detection significance JUNO



Detection significance DUNE

