Determining supernova unknowns with the diffuse supernova neutrino background

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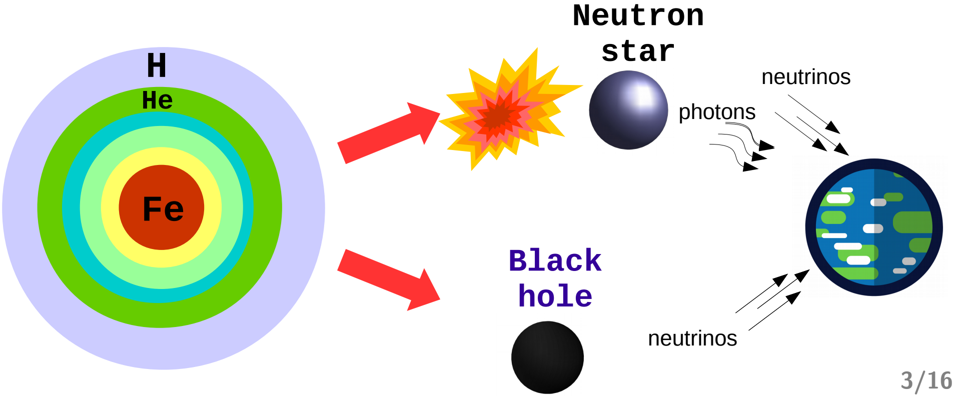
Overview

1. Core-collapse supernovae
2. Neutrino emission properties from core-collapse progenitor stars
3. Diffuse supernova neutrino background
4. The DSNB event rate at future generation neutrino detectors
5. Combined likelihood analysis
6. Conclusions

Core-collapse supernovae

Neutrinos:

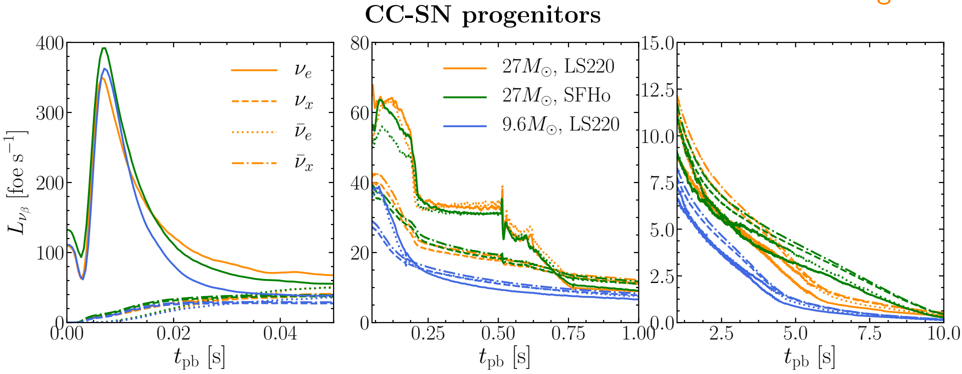
- play a crucial role in the explosion mechanism
- can reveal the interior conditions of a collapsing star
- are the only messengers from the collapse to a black hole (+ GW)



Neutrino emission properties from core-collapse progenitor stars

Progenitor stars forming neutron stars

1 foe = 10^{51} ergs



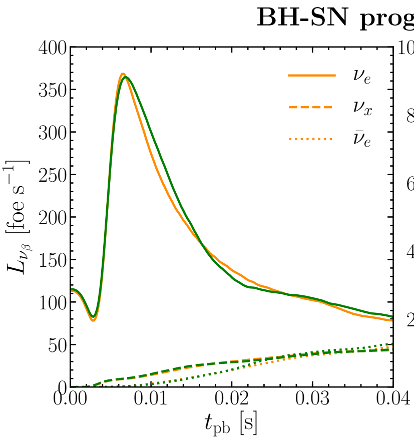
ν_e **burst** | **accretion** | **cooling**

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 black holes



ν_e **burst**

accretion

BH-SN

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

Diffuse supernova neutrino background

Diffuse supernova neutrino background

cosmological supernovae rate

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0} \int_{8M_\odot}^{125M_\odot} dM \int_0^{z_{\max}} dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$
$$\times \left[f_{\rm CC-SN} F_{\nu_\beta,{\rm CC-SN}}(E',M) + f_{\rm BH-SN} F_{\nu_\beta,{\rm BH-SN}}(E',M) \right]$$

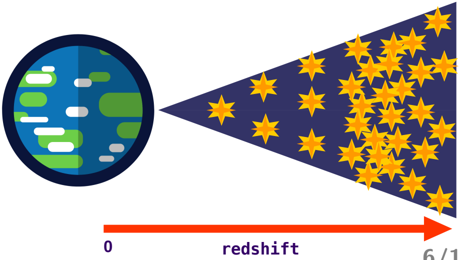
fraction of neutron-star-forming progenitors

fraction of black-hole-forming progenitors

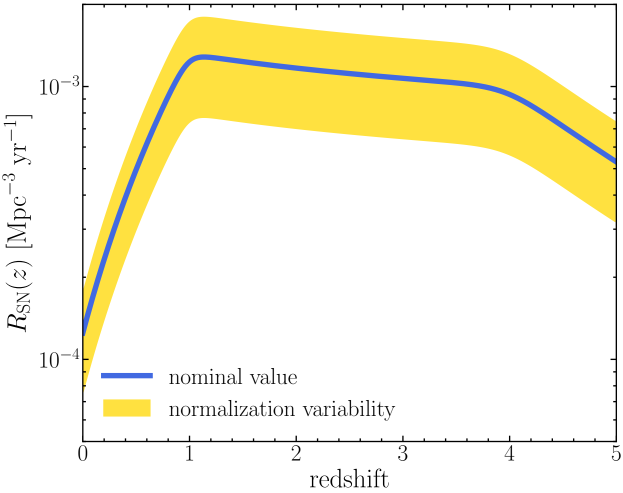
oscillated neutrino flux
E' = (1+z)E

The DSNB is sensitive to:

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



Cosmological supernovae rate

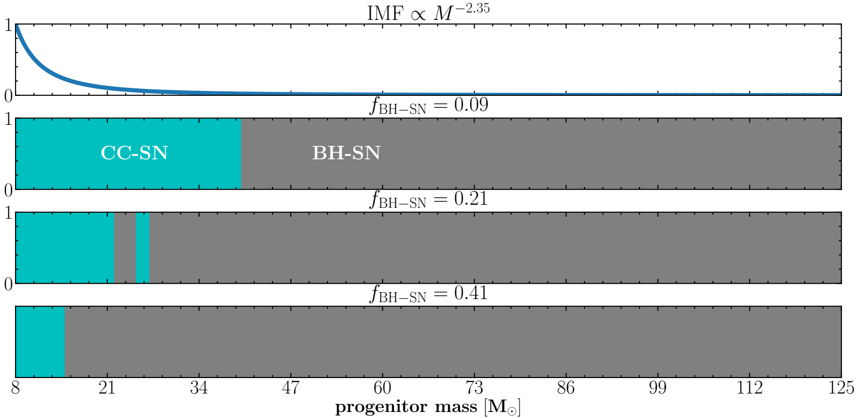


$\sim 10^8/\text{yr}$

The supernovae rate influences the normalization of the DSNB.

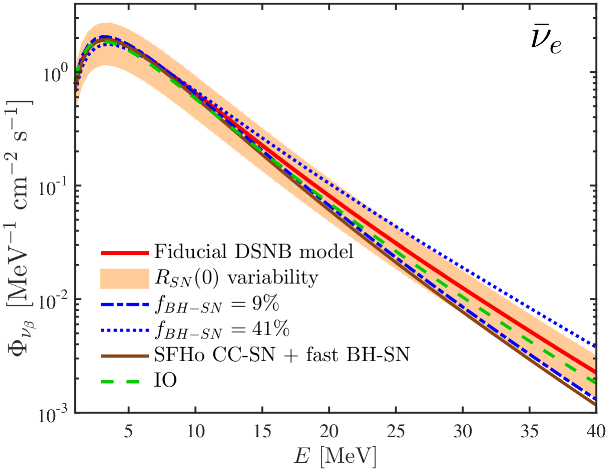
arXiv:1102.1977

Fraction of BH-forming progenitors



Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above $\sim$ 15 MeV.

arXiv:1503.07522, arXiv:1510.04643, arXiv:1411.1761

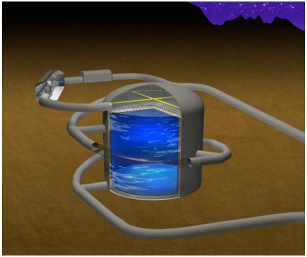


Fiducial DSNB model: $R_{\rm SN}(0) = 1.25 \times 10^{-4}$ Mpc^{-3} yr^{-1}, $f_{\rm BH-SN} = 0.21$, equation of state = LS220, mass accretion rate = slow

The DSNB event rate at future generation neutrino detectors

Future generation neutrino detectors

Hyper-Kamiokande (2025)



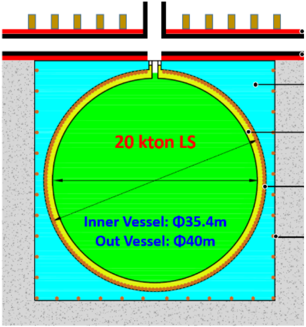
fiducial volume

2×187 kton

main detection channel

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

JUNO (2020)



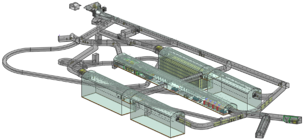
fiducial volume

17 kton

main detection channel

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

DUNE (2027)



fiducial volume

4×10 kton

main detection channel

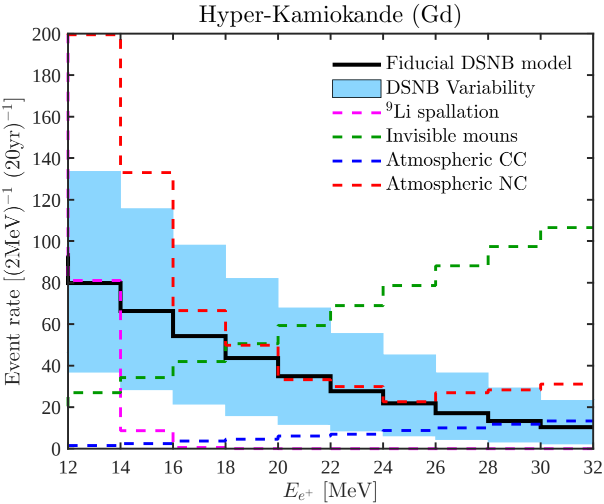
$\nu_e + \mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$

Super-Kamiokande
+ gadolinium

3 σ detection in 10 yrs

HK Design Report, JUNO Conceptual Design Report, DUNE science

The DSNB event rates

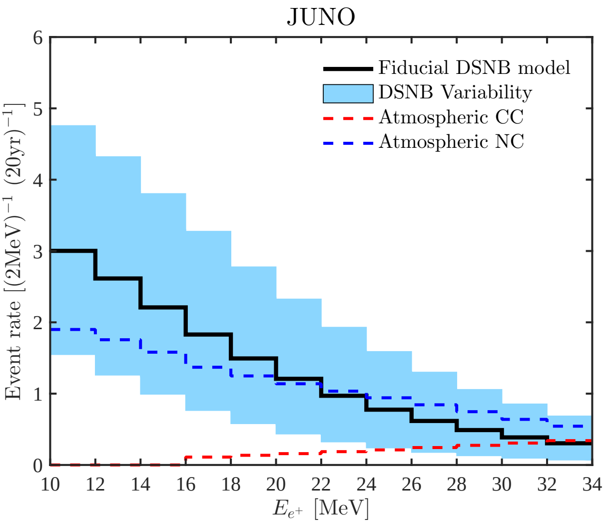


Detectability prospects for 20 yrs

- HK (Gd) with NC: 10 σ [4.8 - 15]
- HK (Gd) w/o NC: 12.5 σ [6.2 - 18]

arXiv:1805.04163, H. Kunxian - PhD thesis, arXiv:1507.05613, arXiv:0408031

The DSNB event rates



Detectability prospects for 20 yrs

- HK (Gd) with NC: 10 σ [4.8 - 15]
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- JUNO: 3.4 σ [1.6-5.4]

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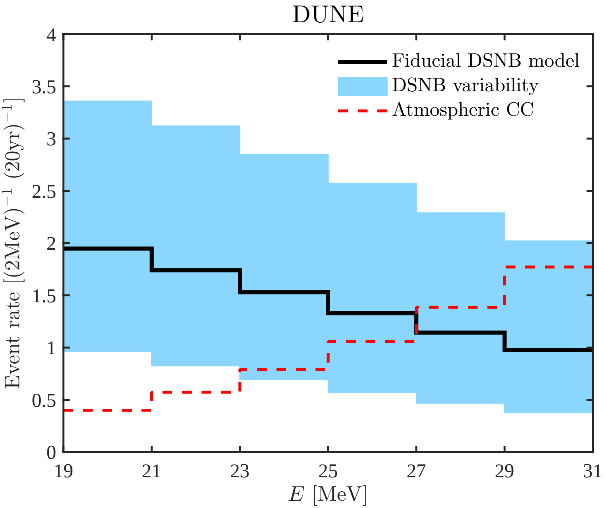


Detectability prospects for 20 yrs

- HK (Gd) with NC: 10 σ [4.8 - 15]
- HK (Gd) w/o NC: 12.5 σ [6.2 - 18]
- JUNO: 3.4 σ [1.6-5.4]
- DUNE: 2.8 σ [1.6-4]

arXiv:1805.04163, H. Kunxian - PhD thesis, arXiv:1507.05613, arXiv:0408031

Combined likelihood analysis

Combined likelihood analysis

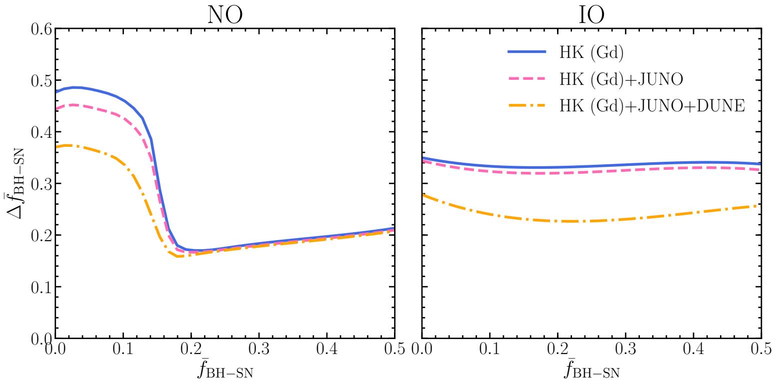
Significance test

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

The set of parameters to be marginalized over:

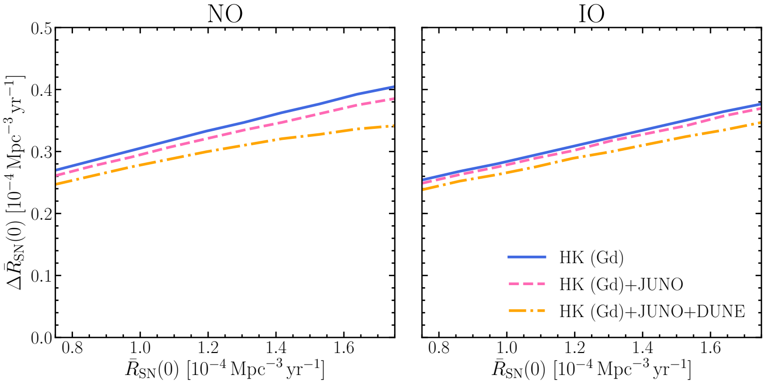
- $f_{\mathrm{BH-SN}}$
- $R_{\mathrm{SN}}(0)$
- background normalization uncertainty
- liquid argon cross section uncertainty
- mass accretion rate - equation of state uncertainty

Expected 1σ uncertainty: fraction of BH forming progenitors



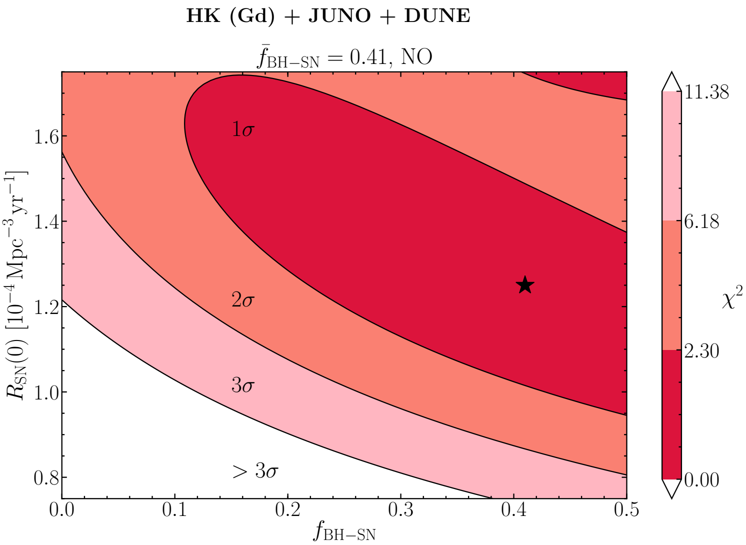
- High uncertainty comes from $f_{\mathrm{BH-SN}}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos $\rightarrow$ helps to reduce the uncertainty

Expected 1σ uncertainty: local supernova rate



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

2D χ^2



HK (Gd) + JUNO + DUNE
$\bar{f}_{\mathrm{BH-SN}} = 0.41$, NO
1σ
2σ
3σ
> 3σ
1.6
1.4
1.2
1.0
0.8
$R_{\mathrm{SN}}(0)$ [10^{-4} Mpc^{-3} yr^{-1}]
0.0
0.1
0.2
0.3
0.4
0.5
$f_{\mathrm{BH-SN}}$
11.38
6.18
2.30
0.00
χ^2

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
  - measurement = an independent check for EM and GW surveys