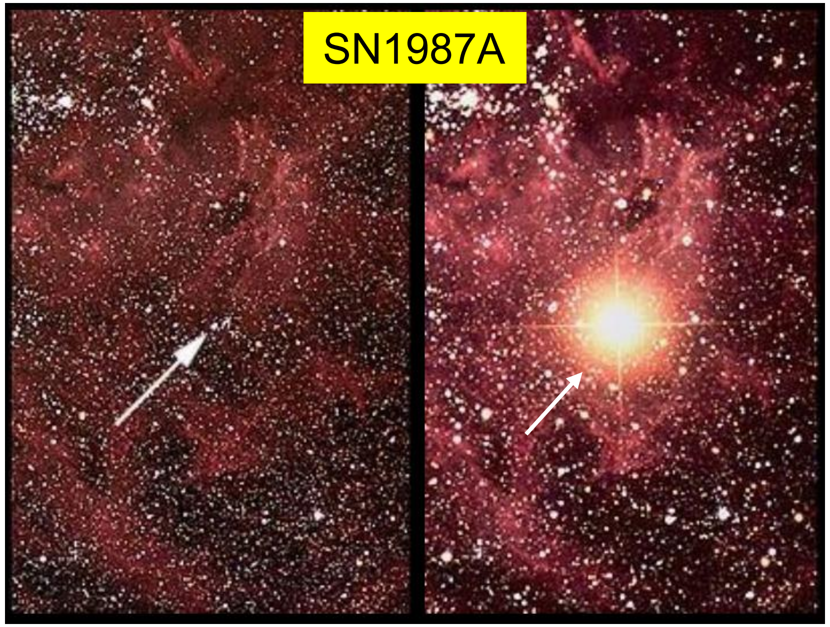
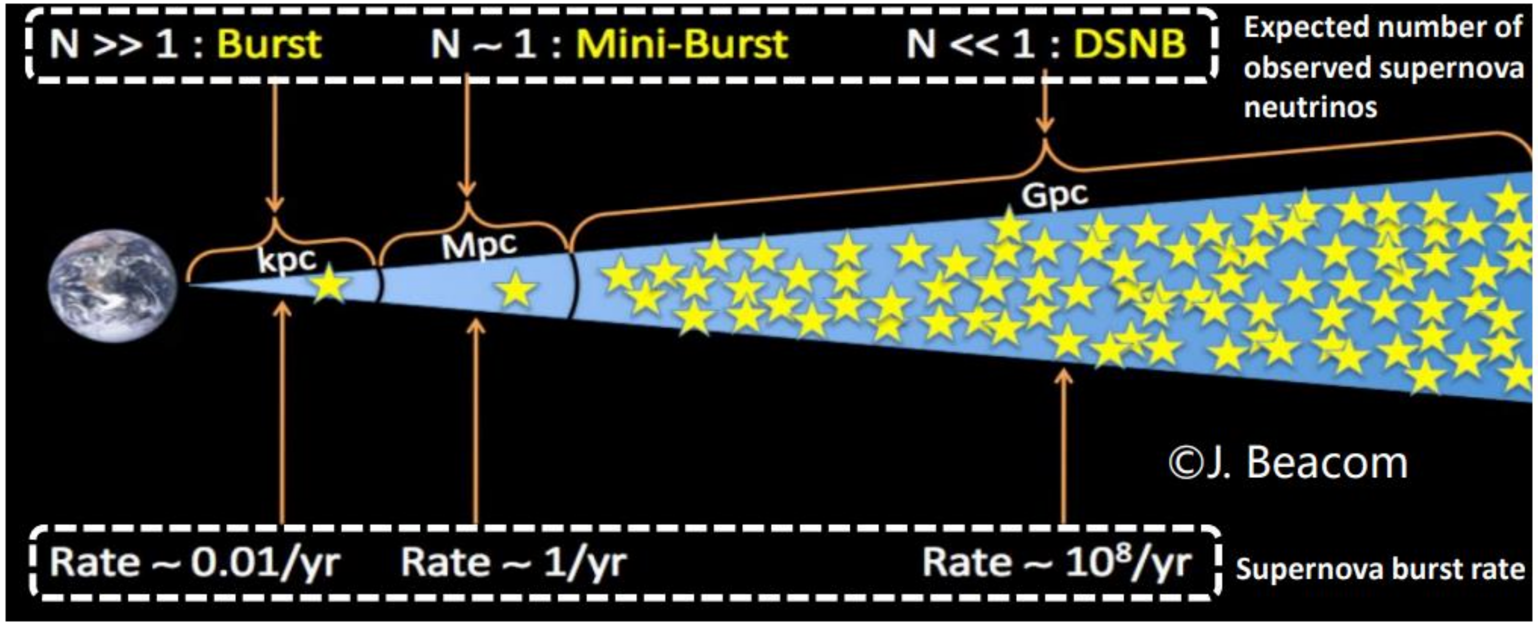
Prospects of Detecting Diffuse Supernova Neutrino Background at JUNO

Gaosong Li, Institute of High Energy Physics, CAS
on behalf of the JUNO collaboration
June 11 @ WIN 2025, Brighton

Diffuse Supernova Neutrino Background (DSNB)





- Neutrino emission from SN1987A observed
- Nearby SN is rare
- A diffused flux of neutrinos from all the past supernovae is predicted
- Valuable information on SN explosion and star formation history

DSNB flux modeling

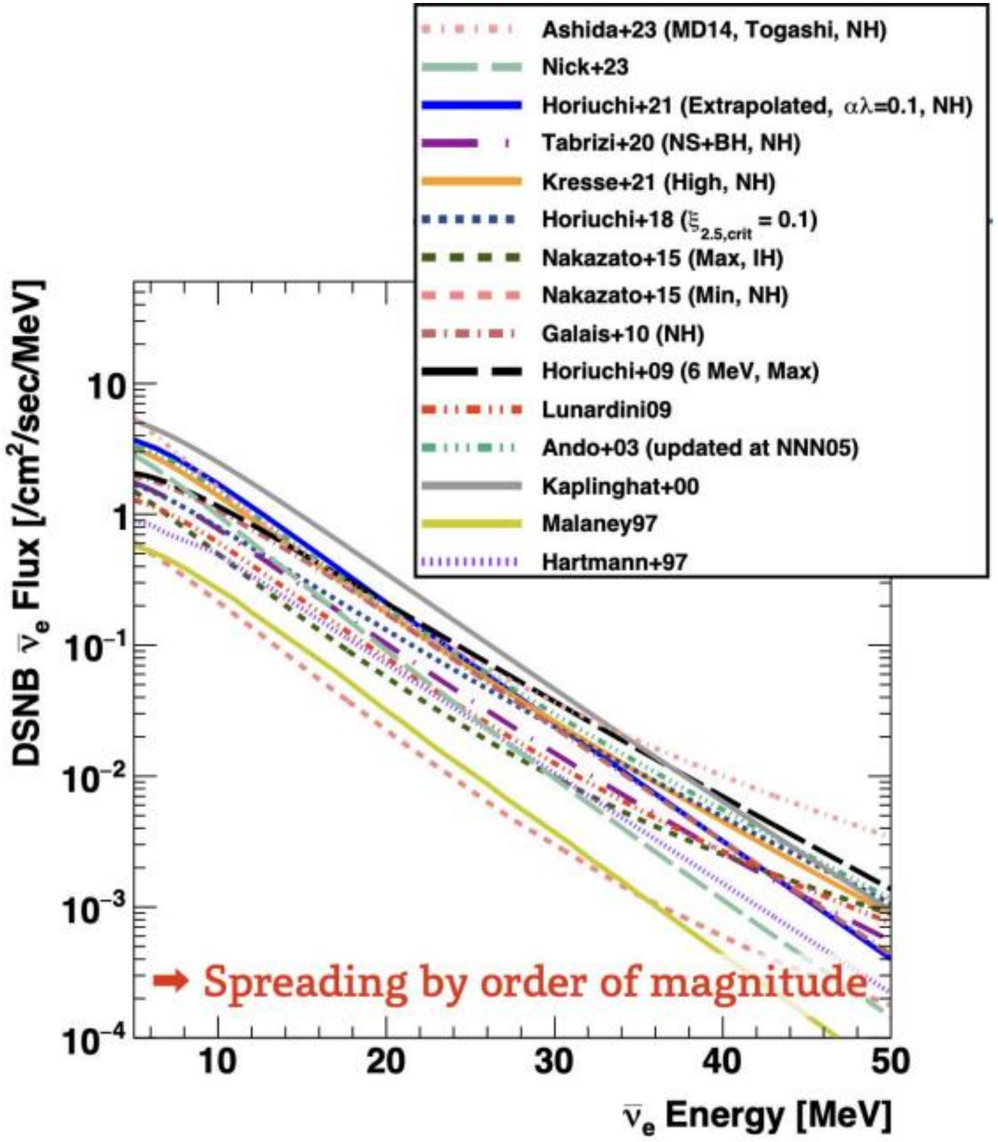
Supernova rate
- Star formation rate
- Initial mass function

Cosmological time integral

$$\frac{d\phi}{dE_\nu} = \int_0^{z_{\max}} R_{\rm SN}(z) \frac{dN(E'_\nu)}{dE'_\nu}(1+z) \left|\frac{c\,dt}{dz}\right| dz$$

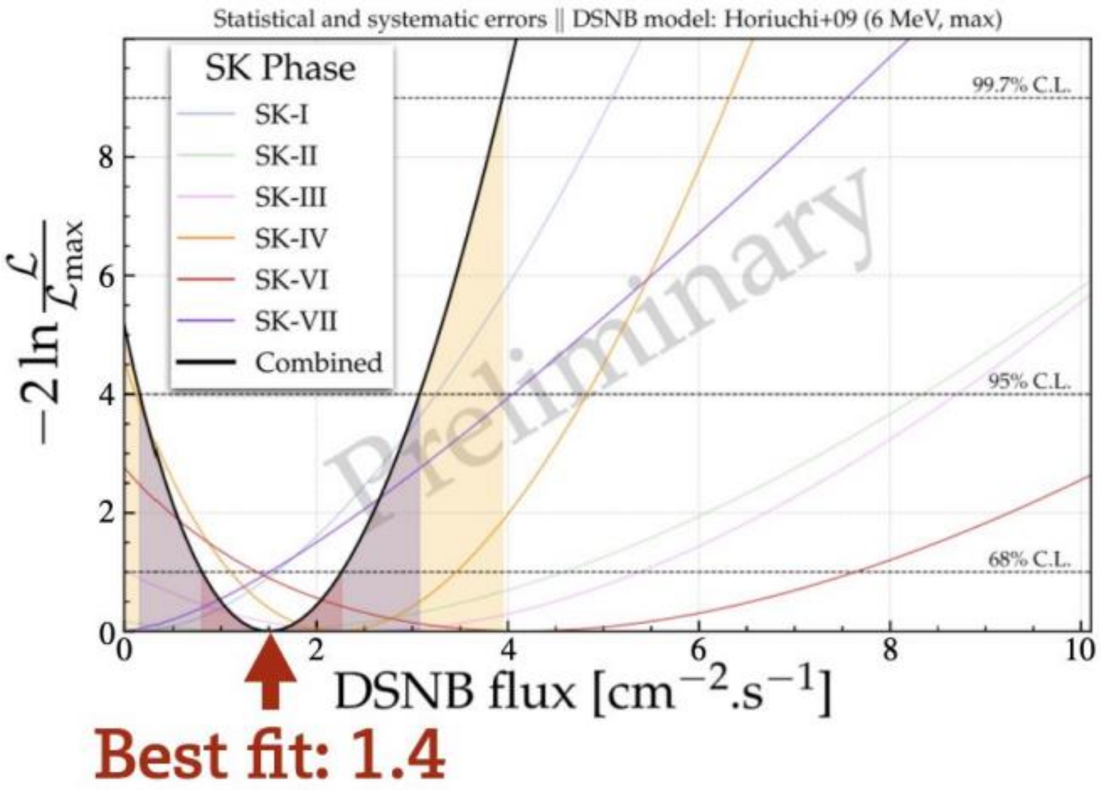
Neutrino emission
- CCSN neutrino spectrum
- Oscillation inside the star
- Black hole formation rate
- NSI …

Current Landscape



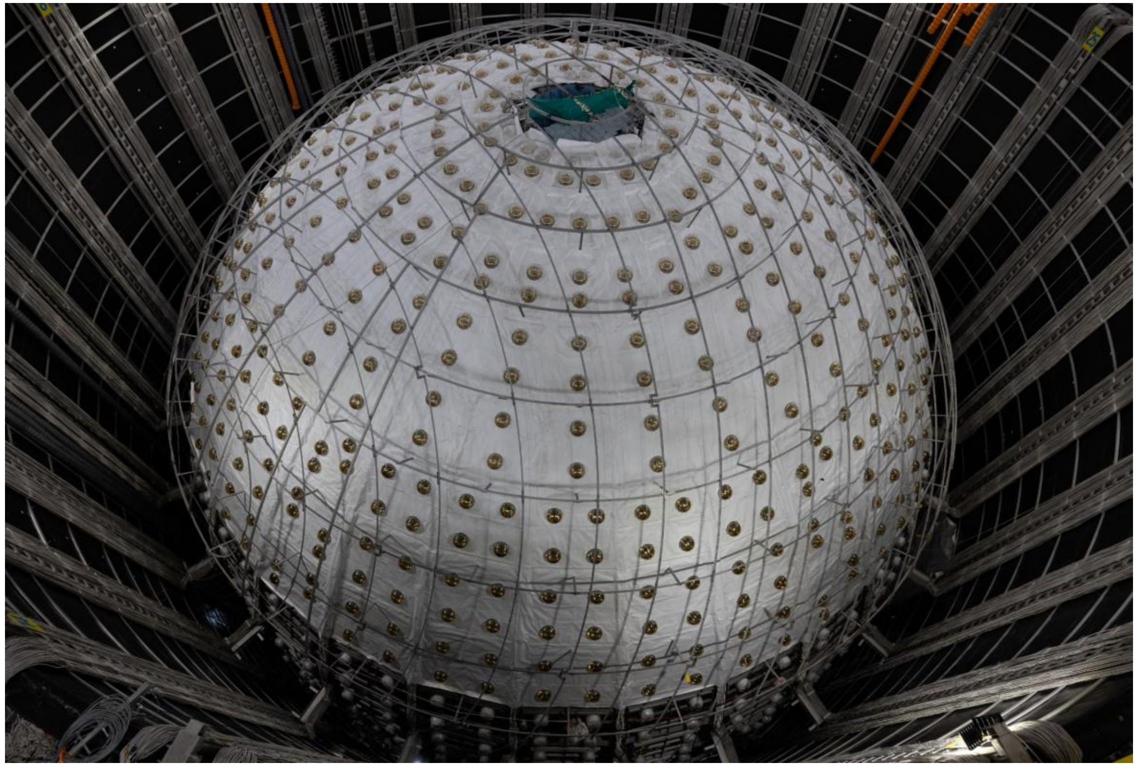
Modern model predictions spreads by an order of magnitude

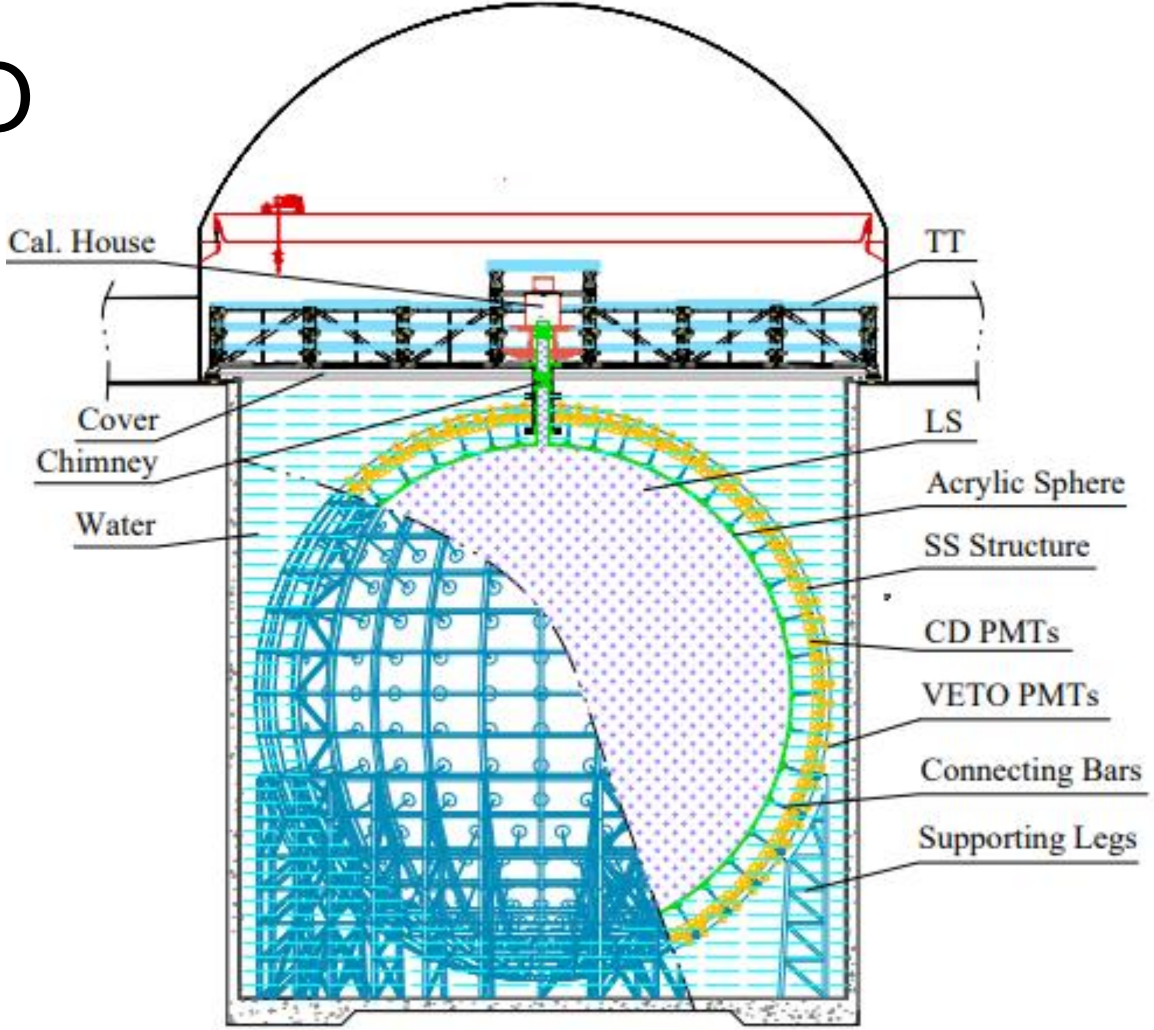
M. Harada, Neutrino 2024



- Detection channel: **inverse beta decay**
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Large x-sec and delayed-coincidence signal
- SK-Gd phase loading Gd to improve n-tag efficiency
- Best data search from SK, 2.3σ excess over background

JUNO

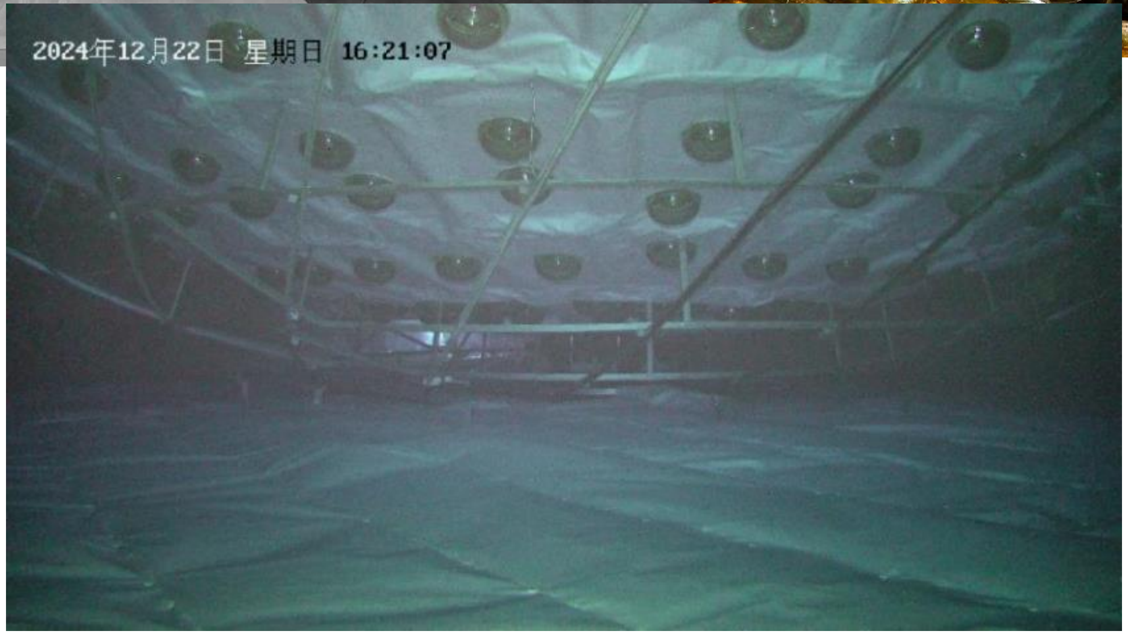




- 20 kton LS detector, designed for NMO determination with reactor $\overline{\nu_e}$
- Huge target mass and excellent neutron tagging ability
- Great potential to detect DSNB

JUNO is filling LS now

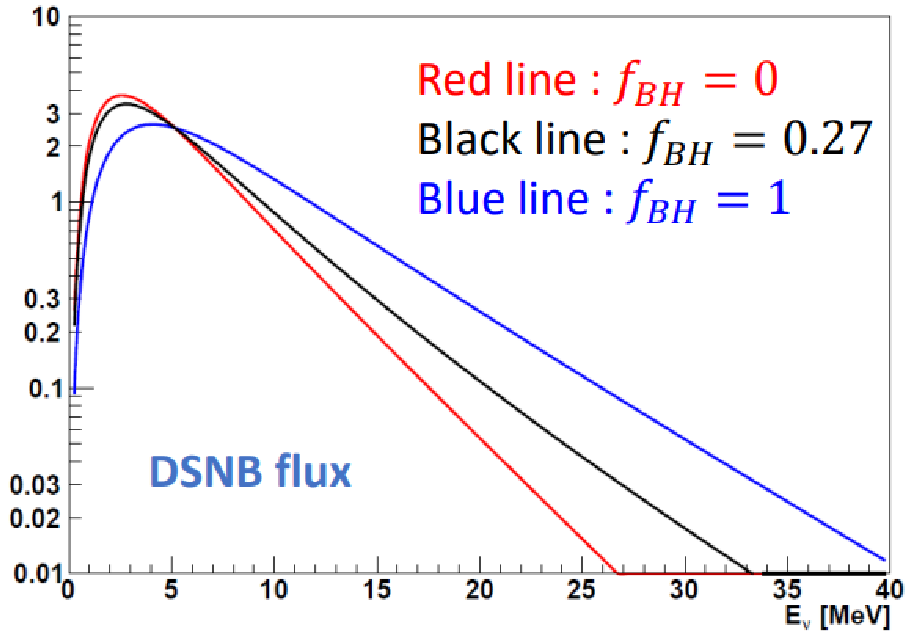
M. Grassi's talk on Thursday



DSNB signal prediction at JUNO

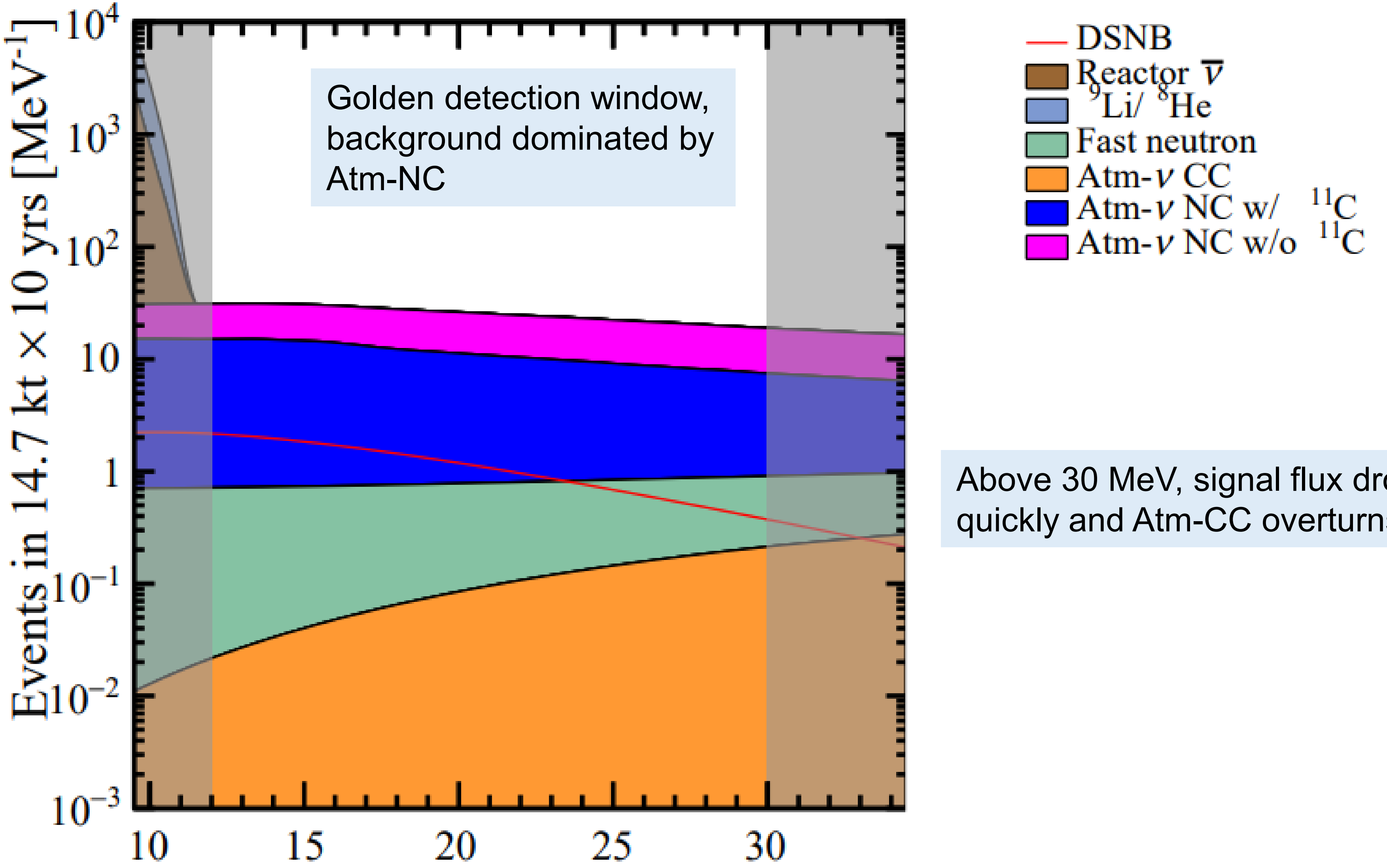
- Spectrum parameterized with three parameters
  - Supernova rate $R_{SN}(0)$
  - Average energy of SN neutrinos $<E_\nu>$
  - Fraction of black hole f_{BH}

$$\frac{d\phi}{dE_\nu} = \int_0^{z_{\max}} R_{\mathrm{SN}}(z) \frac{dN\left(E'_\nu\right)}{dE'_\nu}(1+z)\left|\frac{cdt}{dz}\right| dz$$



→ A couple signal events per year at JUNO with a typical model prediction

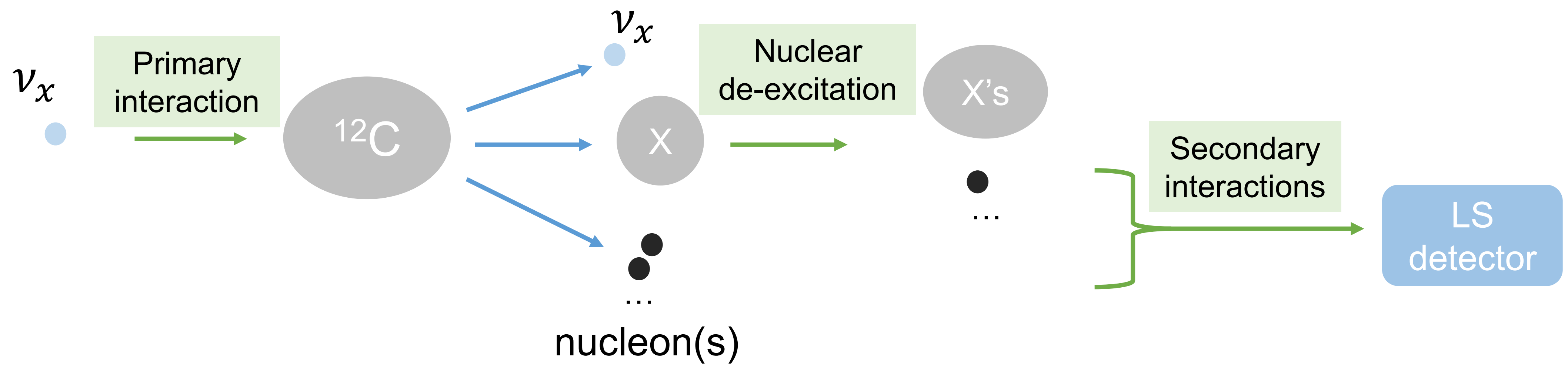
Background



Below 12 MeV, dominated by reactor neutrinos and ^{9}Li/^{8}He

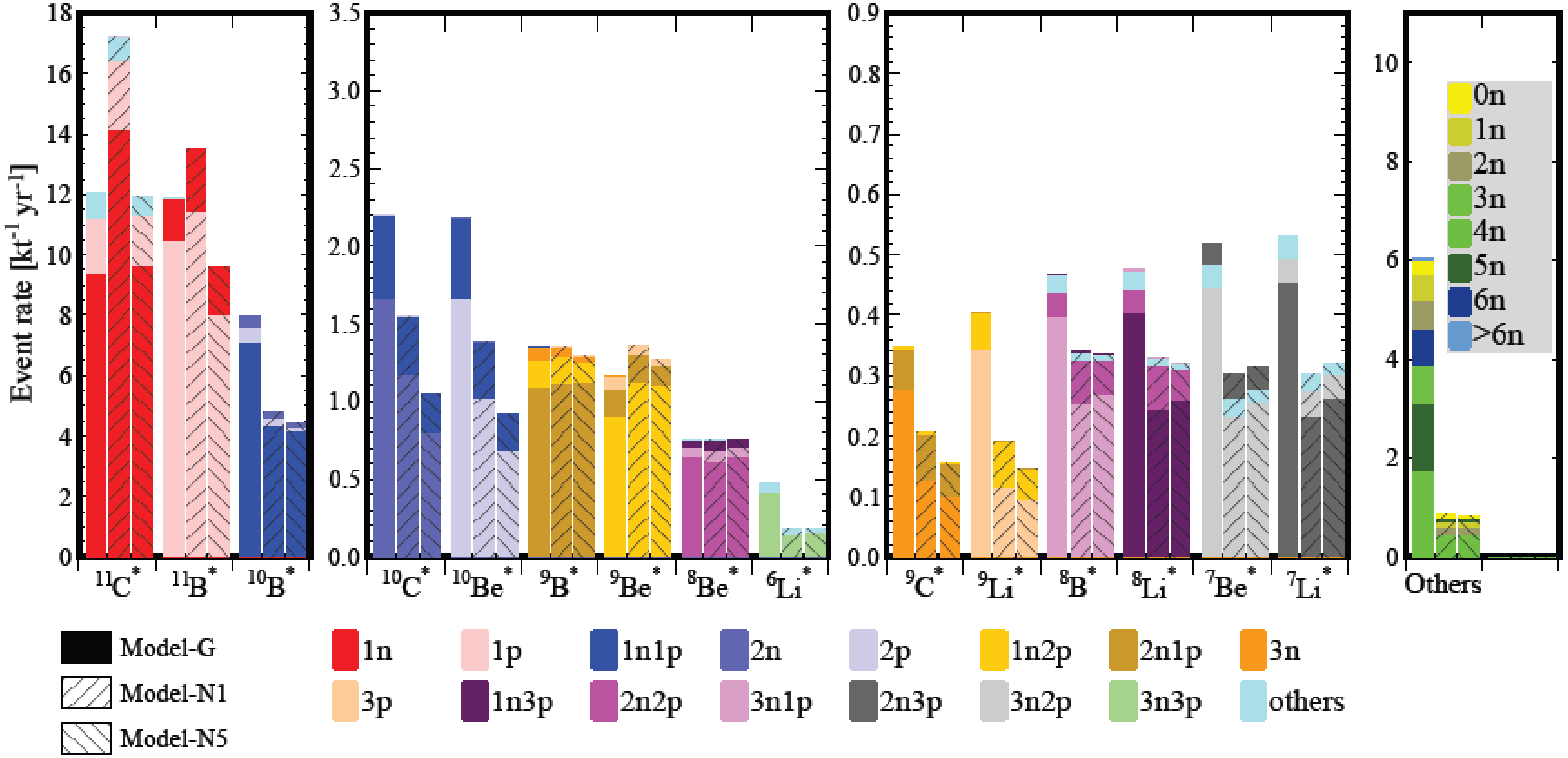
Above 30 MeV, signal flux drops quickly and Atm-CC overturns

The dominant background: Atm-ν NC



- Neutron production in final states → background to DSNB
  - Primary interaction: Atm-ν NC interaction with ^{12}C generates neutrons
  - De-excitation: unstable nuclei de-excitation, could also produce neutrons
  - Secondary interaction: final state particles interaction with LS, further change particle types

Primary ν-nucleus interaction



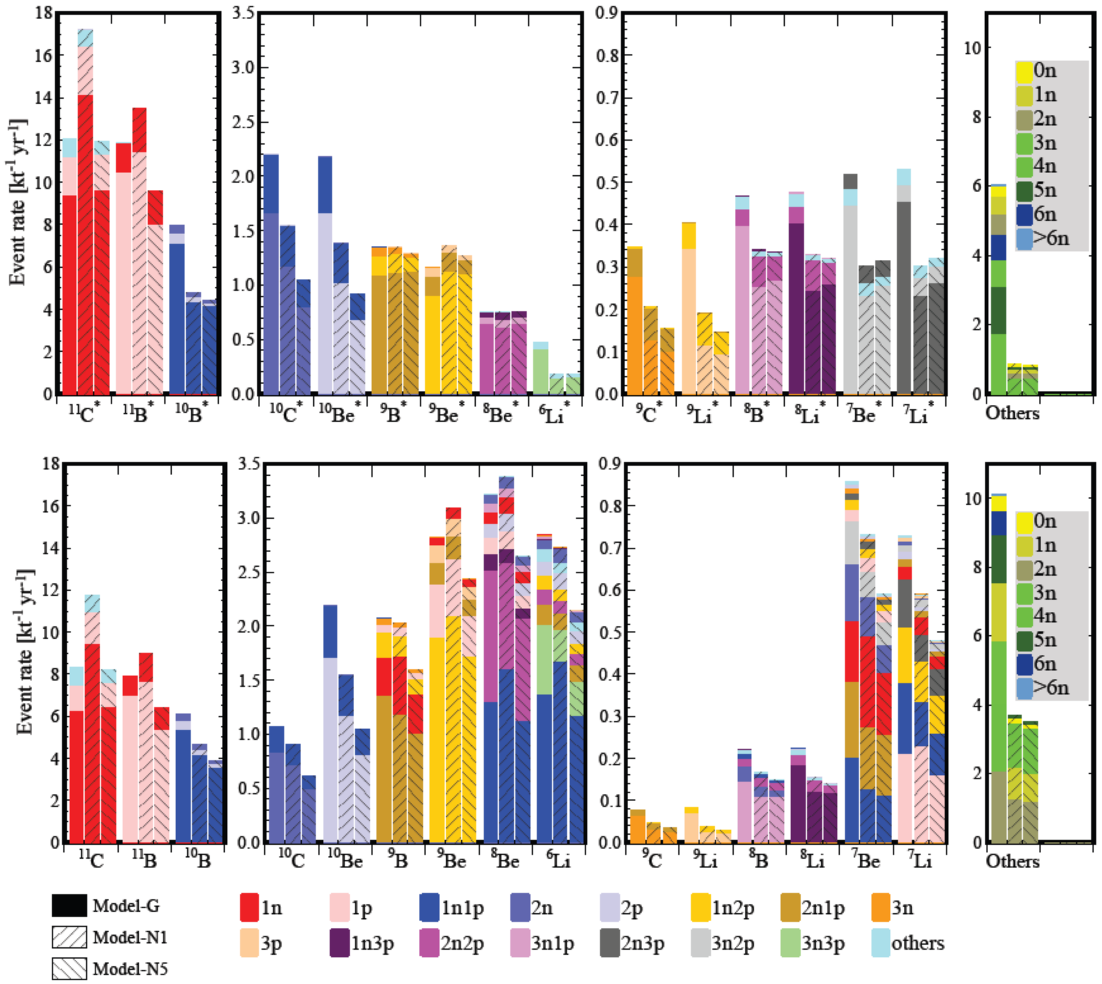
- Main ν-int models like GENIE and NuWro were used to evaluate primary interaction uncertainties
- ^{11}C, ^{11}B dominates the event rate
  - Isotope yield decreases as more nucleons are kicked out

Phys. Rev. D 103 (2021) 5, 053002

De-excitation effect

Before de-excitation

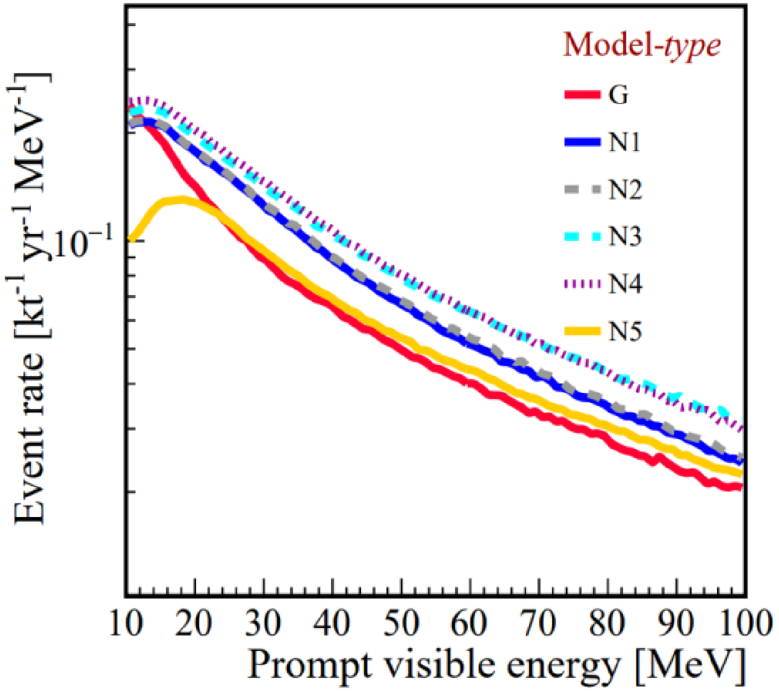
After de-excitation



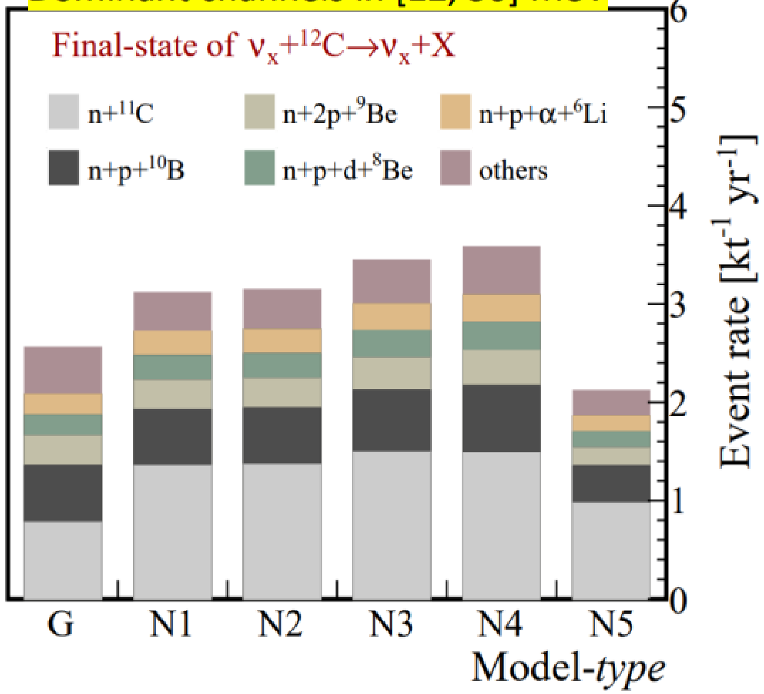
- De-excitation is handled in a statistical approach using TALYS
- De-excitation effect changes the final states distribution
  - More light nuclei after de-excitation
- Unstable final state nuclei, neutron multiplicity, et al are useful for tagging background

Expected NC rate

JUNO, *JCAP 10 (2022) 033*



Dominant channels in [12, 30] MeV

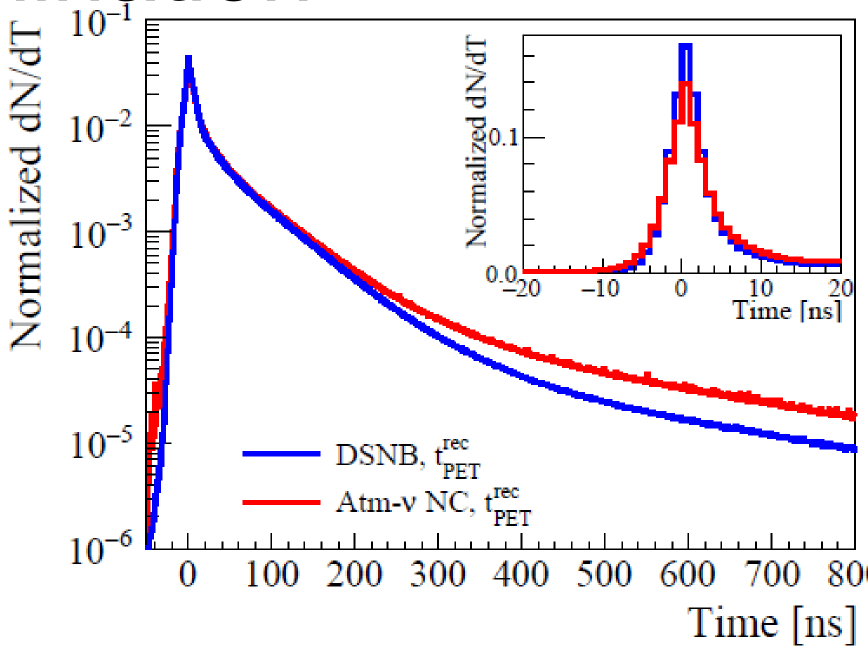


- After detector simulation, event rate of IBD-like NC events: 3.0±0.5 /kton/yr in [12, 30] MeV
- Uncertainty could be evaluated with *in-situ* measurement of exclusive final state nuclei
  - ^{11}C → triple coincidence
  - ~15% in 10 years

Phys. Rev. D 103 (2021) 5, 053002

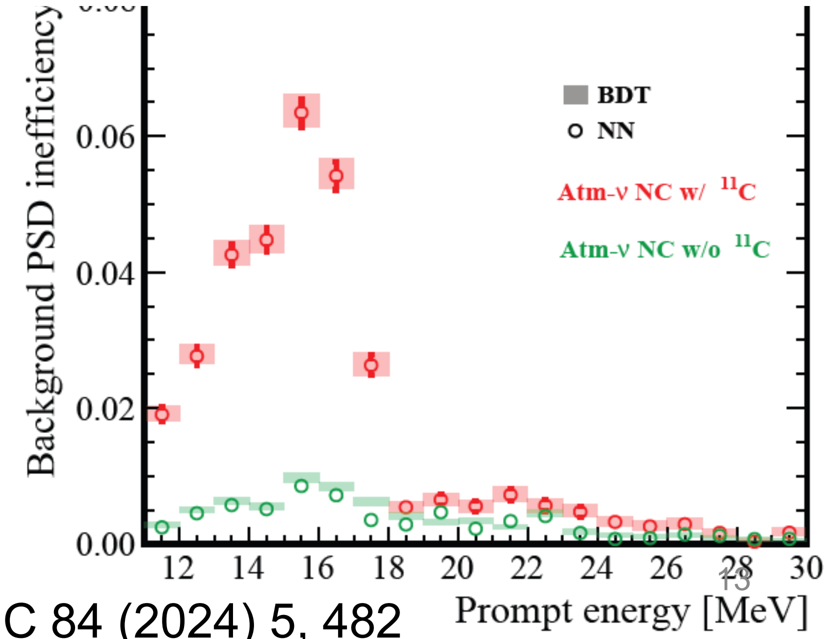
Pulse shape discrimination

Channel	Prompt signal	Raw: Rate [$\mathrm{yr}^{-1}\ \mathrm{kt}^{-1}$]	Raw: Fraction [%]	After IBD selection: Rate [$\mathrm{yr}^{-1}\ \mathrm{kt}^{-1}$]	After IBD selection: Fraction [%]
DSNB					
IBD	e^+	0.16	100	0.14	100
NC interactions of $\nu_x + {}^{12}\mathrm{C} \rightarrow \nu_x + \mathrm{X}$					
$n+{}^{11}\mathrm{C}$	n	2.73	28.4	0.78	30.4
$n+p+{}^{10}\mathrm{B}$	n, p, γ	3.02	31.3	0.58	22.5
$n+2p+{}^{9}\mathrm{Be}$	n, p, γ	0.81	8.45	0.30	11.8
$n+p+\alpha+{}^{6}\mathrm{Li}$	n, p, α, γ	0.67	6.93	0.21	8.30
$n+p+d+{}^{8}\mathrm{Be}$	n, p, d, γ	0.63	6.54	0.21	8.30
n+others	n, x	1.76	18.3	0.48	19.5
Total	n, x	9.63	100	2.56	100



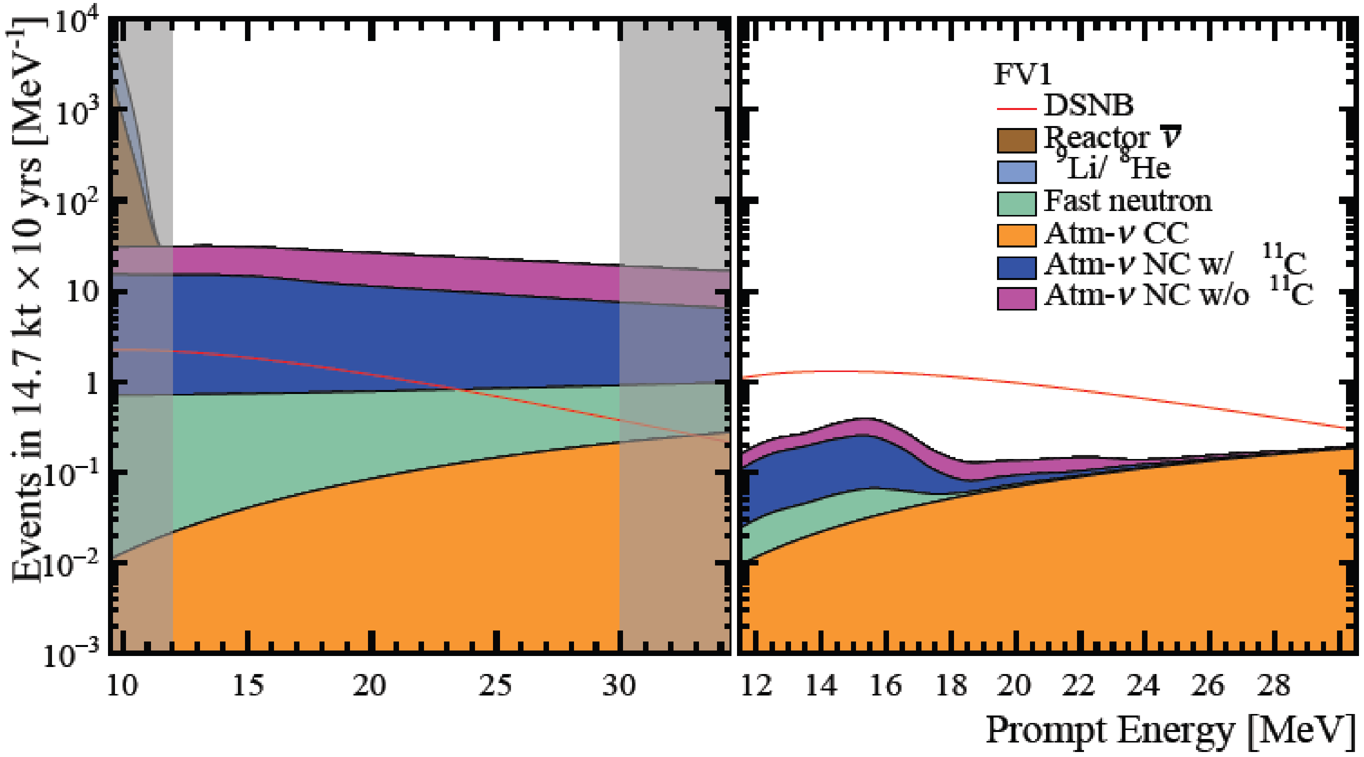
- LS scintillation time profile is used to distinguish n vs e
- Machine learning methods to separate S vs B with time profile shape
- PSD uncertainty evaluated by future data
  - Fast neutron, neutron sources, muon captures
- Energy dependent LS time profile ongoing

Exposure	1 yr	4 yr	10 yr
PSD uncertainty	30%	20%	10%



Eur. Phys. J. C 84 (2024) 5, 482

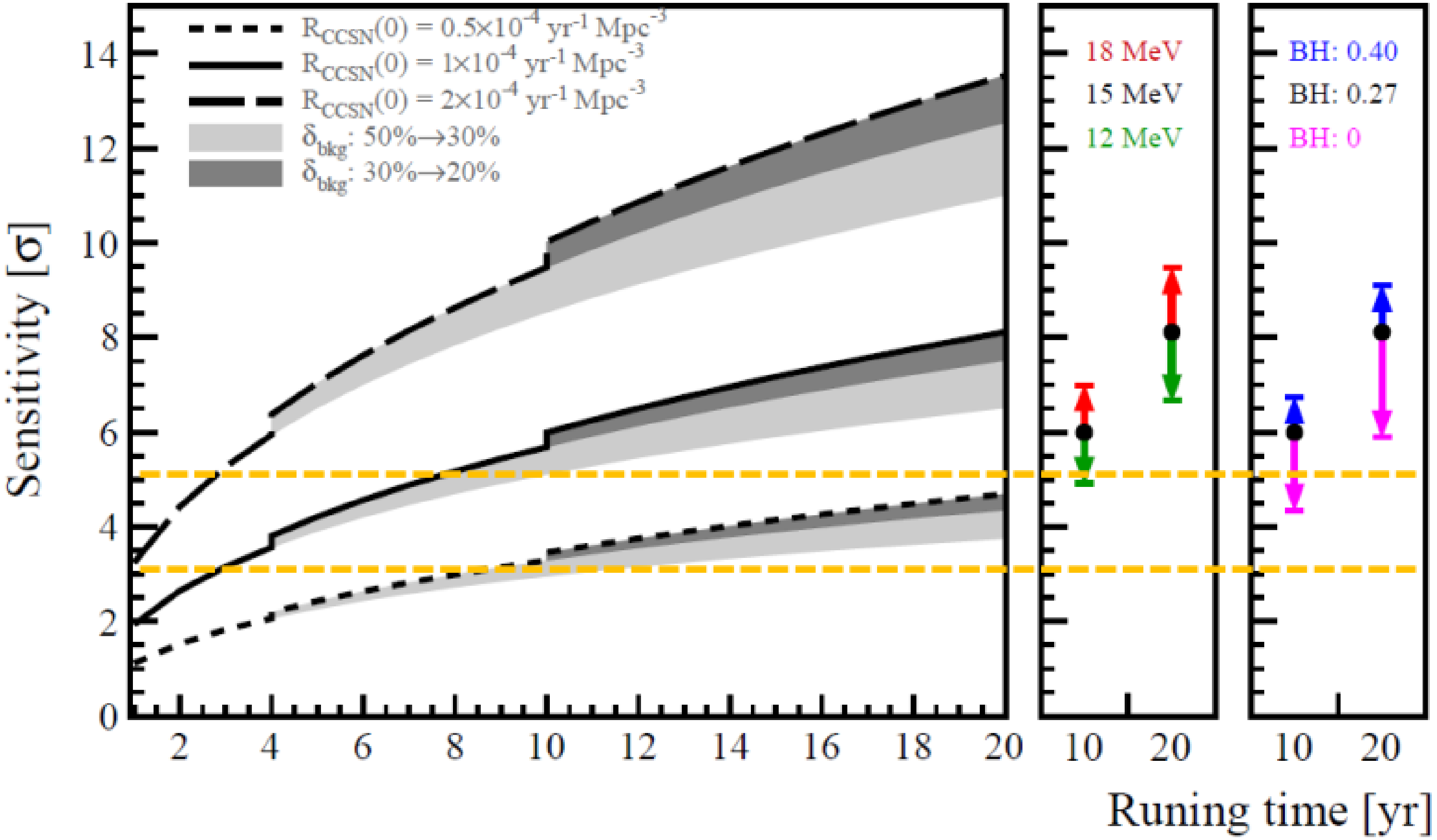
Background rate



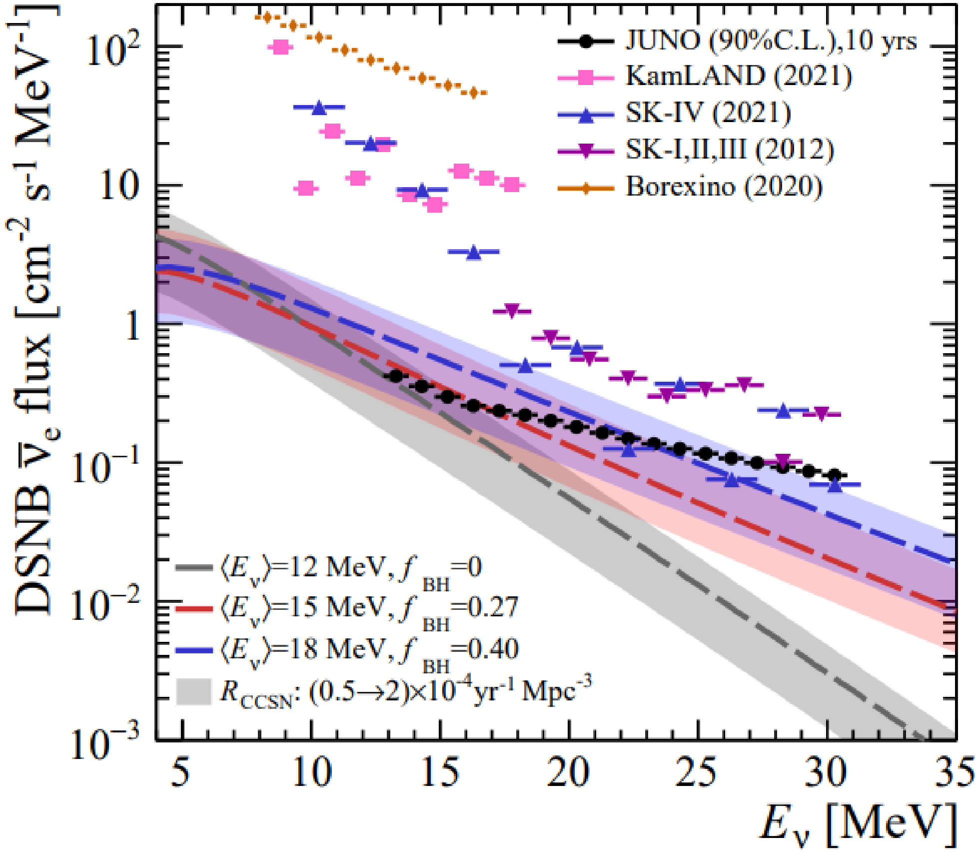
- PSD to suppress NC and fast neutron background
- Background significantly reduced, S/B: 0.05 → 4.8
- NC ^{11}C events suppressed by tagging with triple coincidence utilizing the decay signal of ^{11}C

DSNB sensitivity

Discovery sensitivity: >3σ/5.0σ in 3/10 yr



Model independent limit



JCAP 10 (2022) 033

Conclusion

- Detection of DSNB is very important
  - DSNB flux holds the information on supernova explosion, neutrino properties and the star formation history

- JUNO is designed resolve NMO with reactor $\bar{\nu}_e$ and well suited to detect DSNB
  - Great discovery potential, reaching 3σ/5.0σ in 3/10yr

- JUNO will finish detector filling soon. Looking forward to the discovery of DSNB flux in ~10 years together with SK-Gd.

- Stay tuned!

Bakcup

Models used

Models	Generator (version)	M_A for QE [GeV]	Nuclear model	Inclusion of $2p2h$	FSI model
		Models used in preceding papers			
Model-G1 (G)	GENIE (2.12.0)	0.99	BRRFG	×	hA
Model-N1	NuWro (17.10)	1.03	LFG	×	Ref. [43]
Model-N2	NuWro (17.10)	0.99	LFG	×	Ref. [43]
Model-N3	NuWro (17.10)	1.35	LFG	×	Ref. [43]
Model-N4	NuWro (17.10)	0.99	LFG	✓(TEM)	Ref. [43]
Model-N5	NuWro (17.10)	0.99	SF	×	Ref. [43]
		New models added in this work			
Model-G2	GENIE (3.0.6)	0.96	LFG	✓(EP)	hN2018
Model-G3	GENIE (3.0.6)	0.96	LFG	✓(EP)	hA2018
Model-G4	GENIE (3.0.6)	0.96	BRRFG	✓(EP)	hN2018
Model-N6	NuWro (19.02)	1.03	LFG	×	Ref. [43]
Model-N7	NuWro (19.02)	1.03	SF	×	Ref. [43]

BRRFG: relativistic Fermi gas model with "Bodek-Ritchie" modifications

LFG: local Fermi gas model

SF: spectral function

0.99 GeV: deuterium measurements

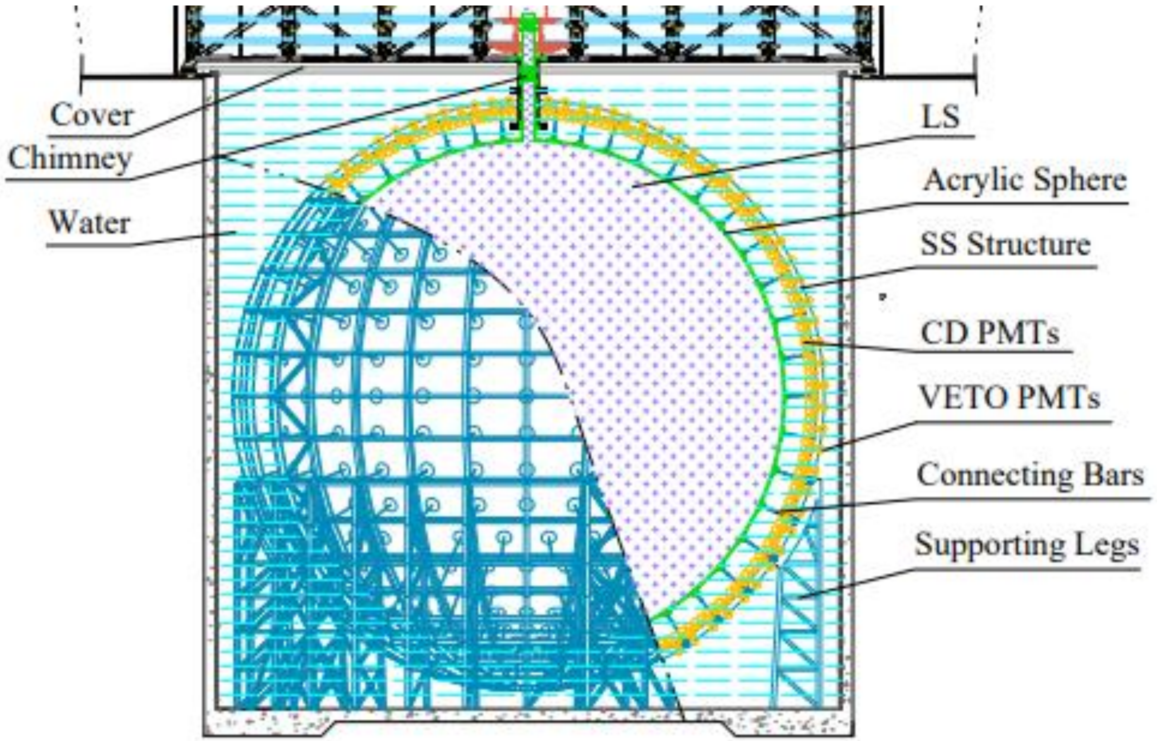
1.35 GeV: MiniBooNE neutrino QE data

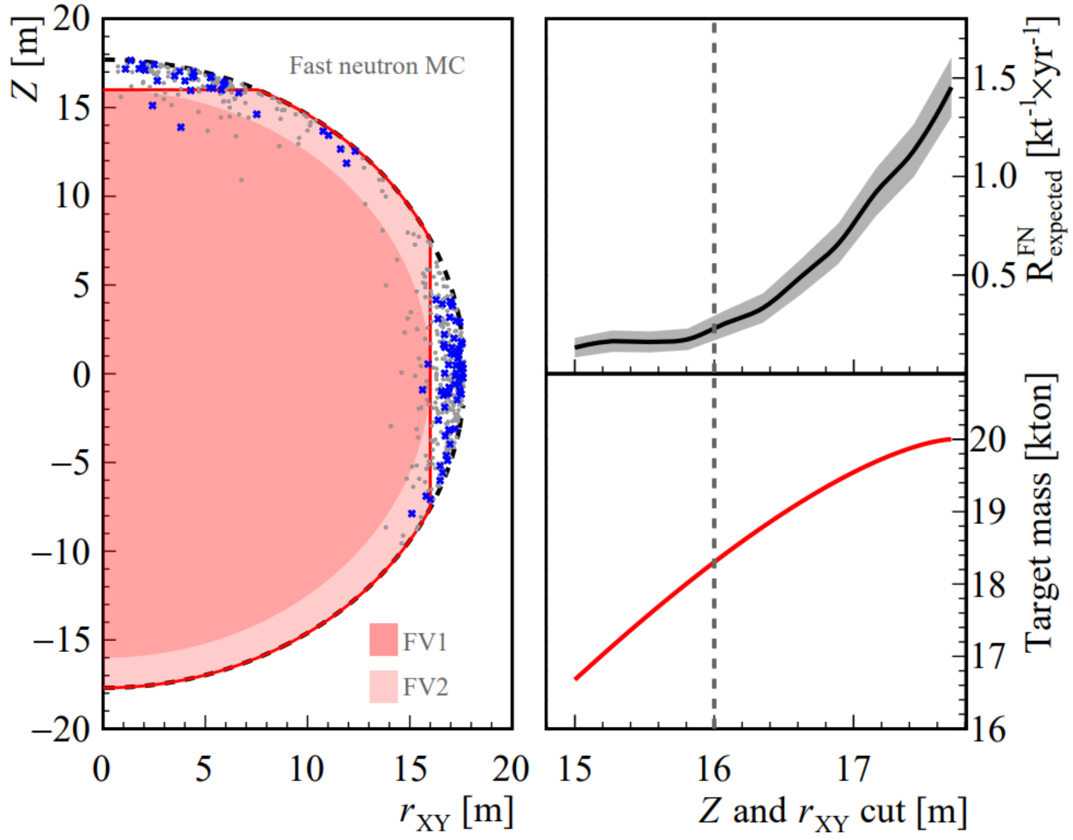
TEM: Transverse Enhancement model for *2p2h*

EP: Empirical model for *2p2h*

Ref.[43]: Phys. Rev. D 79, 053003 (2009)

Fast neutron





- Suppressed by fiducial volume cut
- PSD to further distinguish between n vs e/gamma