The Diffuse Supernova Neutrino Background at Super-Kamiokande: latest results and future prospects

AstroDark-2021

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Laboratoire Leprince-Ringuet - École Polytechnique

In this talk

The DSNB search with Super-Kamiokande

Latest analysis results using SK-I-II-III-IV data

The future: SK-Gd

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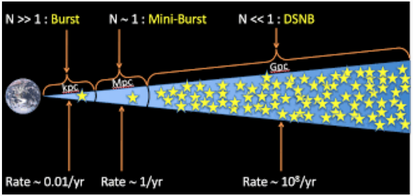
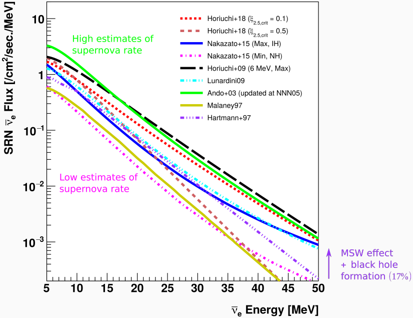
Neutrino flux from all distant core-collapse supernovae



J. Beacom

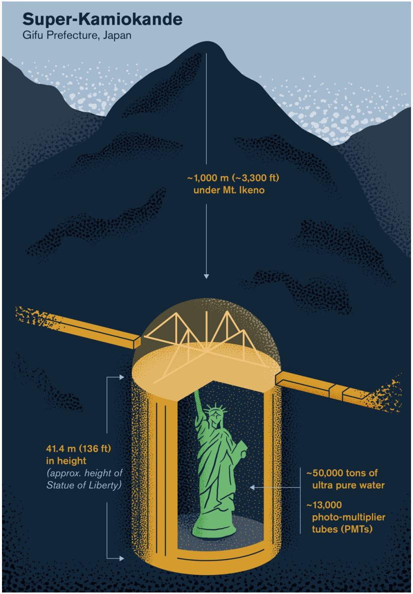
2-3 galactic supernovae/century
1 SN/s in the observable Universe



Y. Ashida

- Detection and characterization would allow for the study of aggregate properties of core-collapse supernovae, while probing the history of the universe and neutrino properties
- All flavors of neutrinos produced during CC SN, reaching Earth redshifted
- Expected signal is $\sim$10s of MeVs and has so far proved elusive

A 50-kton water Cherenkov detector in Japan's Kamioka mine



- Located under Mt. Ikeno in Gifu Prefecture, Japan
- Shielded from cosmic ray activity by $\sim$1 km of rock
- Inner Detector: 11129 PMTs
- Resolution: 50cm, 3 ns
- Energy coverage: 4 MeV $\leftrightarrow$ $\sim$TeV
- Water constantly recirculated and purified
- SK phases I-V: ultrapure water
- SK phases VI+ (starting summer 2020): water doped with Gadolinium sulfate, enhancing the signature of a neutron in the detector

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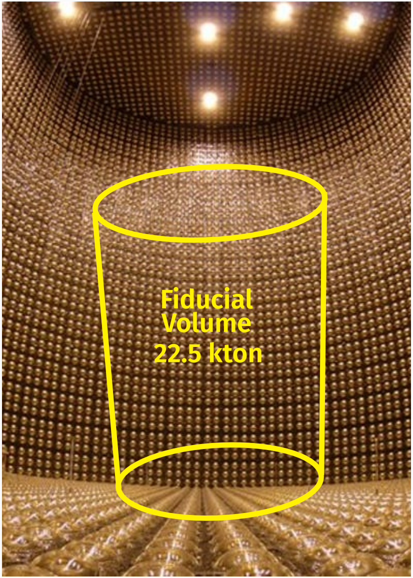

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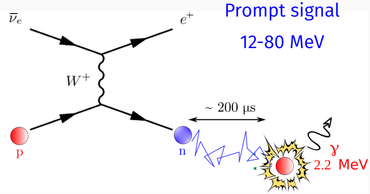
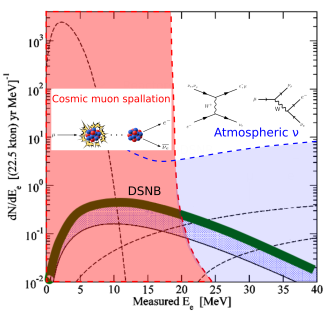
Detection of DSNB $\overline{\nu}_e$ via Inverse Beta Decay (IBD) in water

- 5-20 events/year
  Energy range: 12-80 MeV
- Need extremely powerful algorithms to characterize spallation and atmospheric backgrounds and **identify the neutrons**
- Current analysis: uses runs from the **SK-IV** data-taking era (Sep 2008-May 2018)
- Reconstruction separates into:
  1. Prompt event (e^+) vertex reconstruction
  2. Delayed event (n) tagging



Weak delayed signal



[Beacom and Vagins, Phys. Rev. Lett., 93:171101, 2004]

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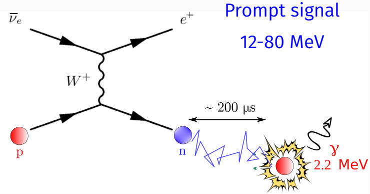

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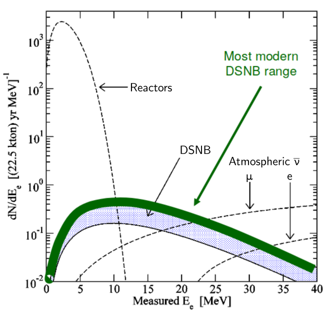

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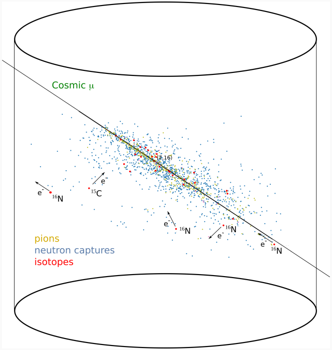
Radioactive spallation backgrounds

Radioactivity induced by cosmic muon spallation in water



[FLUKA simulation, A. Coffani]

- One spallation muon every two minutes
- Needs to be reduced by $\mathcal{O}(10^4)$
- Main signatures
  - $> 99\%$ β decays: $A \rightarrow e^{\pm} + \nu$
  - $< 1\%$ IBD-like (^{9}Li): $A \rightarrow e^{\pm} + n$
- Isotopes' half-lives up to 13 s
  $\Rightarrow$ correlations over large time scales
- No simulation in WC detectors ready at time of analysis

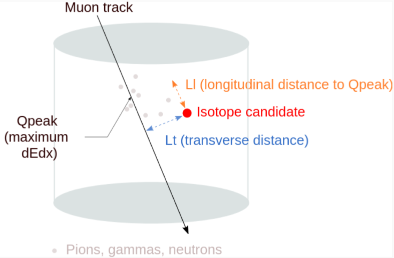
Reduction strategy:

- Identify isotope clusters and neutrons from muon showers
- Investigate correlations between muons and candidate events

Spallation backgrounds reduction

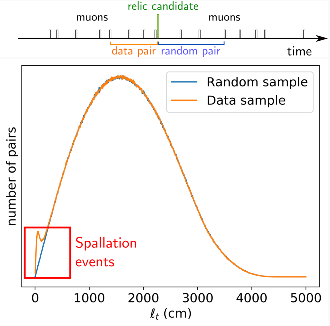
Pair each candidate event with muons up to 30 s before
Investigate correlations using a likelihood analysis

Observables

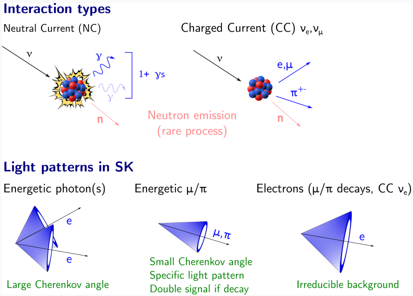


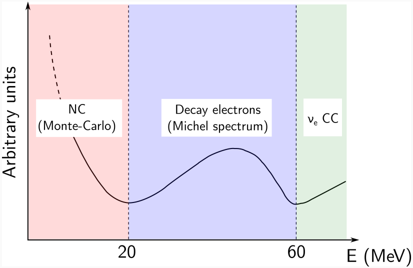
- Δt, L_t, L_l: distance and time difference
- resQ: charge deposited by the muon in addition to minimum ionization

Extracting distributions



Atmospheric neutrino backgrounds

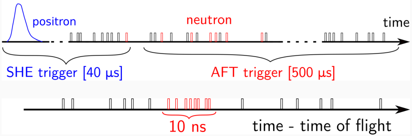




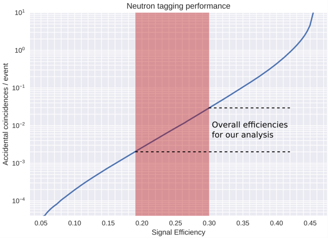
Estimating normalization and spectral shapes:

- $\mathcal{O}$(100%) uncertainties on rates and spectral shapes below 100 MeV except for decay electrons (measured Michel spectrum from stopping muons).
- Strategies: Use T2K to estimate cross-sections and efficiencies (NC backgrounds), or use sidebands in energy and Cherenkov angle. [Y. Ashida, Ph D. thesis (2019)]

A faint neutron capture signal amid a sea of low-energy background



- **2.2 MeV neutron capture** signal extremely weak; easily lost among abundant low-energy backgrounds (4 kHz PMT noise, radioactivity, flasher events...): vertex not readily reconstructed
- **Wide trigger scheme** (540 μs time window), makes detection of neutron captures in water ($\tau_{\text{CAP}} \sim 200\mu$s) feasible.
- Up to $\mathcal{O}(10^4)$ reduction required after candidate selection



- Maximally exploit correlations with well-reconstructed primary vertex
- Use a BDT (a Machine Learning method) to classify neutron candidates, achieving ∼20%-30% overall efficiency

⋆ Gd has recently been dissolved inside the tank, producing **brighter, 8 MeV capture signals**. Efficiency is expected to increase to >80% for future analyses.

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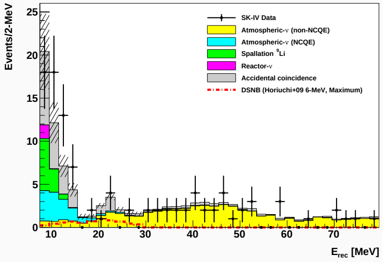
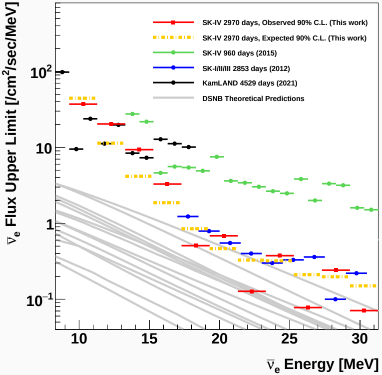
Binned, model-independent analysis





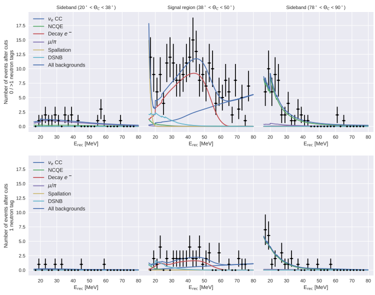
- Bin-by-bin cut optimization and limit extraction
- SK-IV is the first data perdiod where neutron tagging is possible, allowing to lower the energy threshold down to E_{ν}=9.3 MeV

Unbinned, model-dependent spectral fit

- Fit the spectral shapes of remaining background contributions and various DSNB models to the data
- Simultaneous unbinned extended maximum likelihood fit in 6 regions:

	Cherenkov angle		
Neutrons	$[20, 38]^\circ$	$[38, 50]^\circ$	$[78, 90]^\circ$
0 or >1	μ/π	Signal	NC
1	μ/π	Signal	NC

- Results are combined with fits from previous SK data periods



- **Neutron tagging defines cleaner, more sensitive 1-neutron signal region.** With the introduction of Gd in the tank, a much larger fraction of our signal will be contained in the clean signal region.

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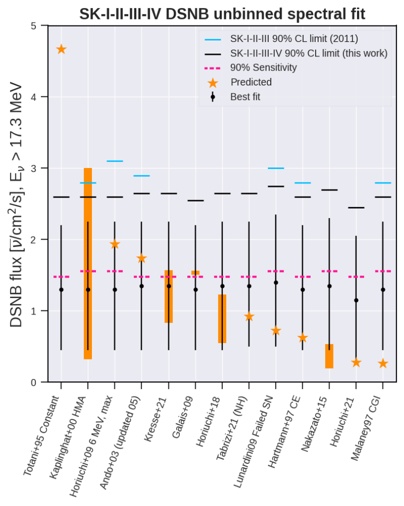

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Summary of results

- Combined SK-I-II-III-IV analysis complete, using roughly double the livetime of previous (SK-I-II-III) 2007 analysis
- **Model-independent differential upper limits** are placed down to $E_\nu = 9.3$ MeV, obtaining the current tightest sensitivities for $E_\nu > 11.3$ MeV. The latest 2021 KAMLAND results reach tighter sensitivities for $E_\nu < 11.3$ MeV
- Model-dependent **spectral fits** performed on the data after reduction cuts, reaching a combined 90% SK-I-II-III-IV flux sensitivity of 1.5 $\overline{\nu}_e$ cm^{-2}·sec^{-1}. A 1.5σ excess leads to a best-fit of $1.30^{+0.90}_{-0.85}$ and an **observed upper limit of 2.6 $\overline{\nu}_e$ cm^{-2}·sec^{-1}.**
- The most optimistic models still excluded, by wider margins (Totani+96, upper range of Kaplinghat+00)
- Sensitivity is now comparable to predictions for more realistic models (e.g. Ando+03, Horiuchi+09, Galais+09, Kresse+20)

$\rightarrow$ Pre-print available at `arxiv.org/abs/2109.11174`

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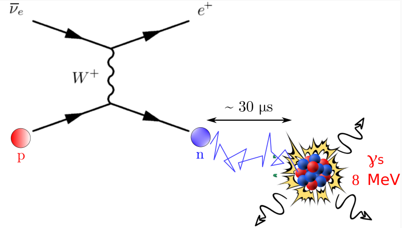
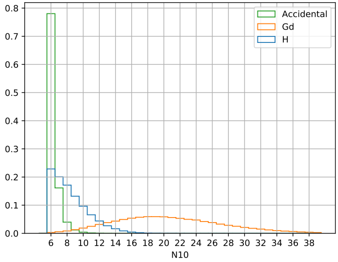
The SK-Gd project

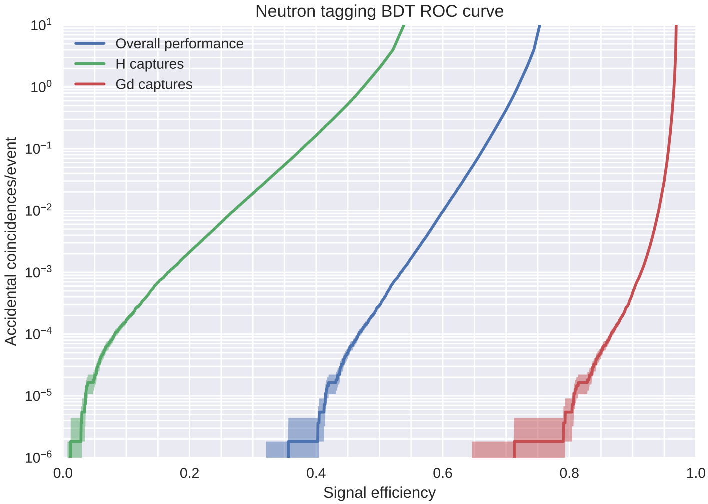
- Since 2020 SK has started dissolving Gd sulfate in the tank to enhance the neutron capture signal
- n capture on Gd is faster ($\tau \sim 30\mu$s) and brighter ($\sim$8 MeV total photon energy)
- Current Gd concentration: 0.01% (50% neutrons captured on Gd)
- 2022 target concentration: 0.03% (75% neutrons captured on Gd)
- Ultimate target concentration: 0.1% (90% neutrons captured on Gd)

	Efficiency (%) H	Efficiency (%) Gd
N10 > 5	59	99.5
dt∈[1-535]	54.4	96.7





Neutron tagging BDT (still unoptimized)



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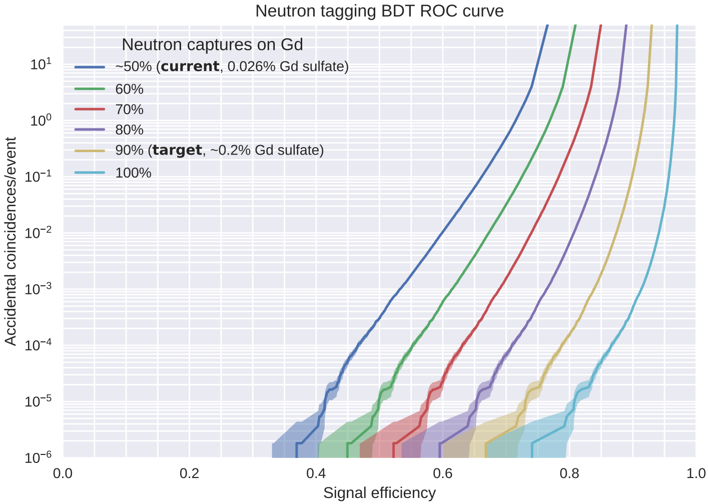
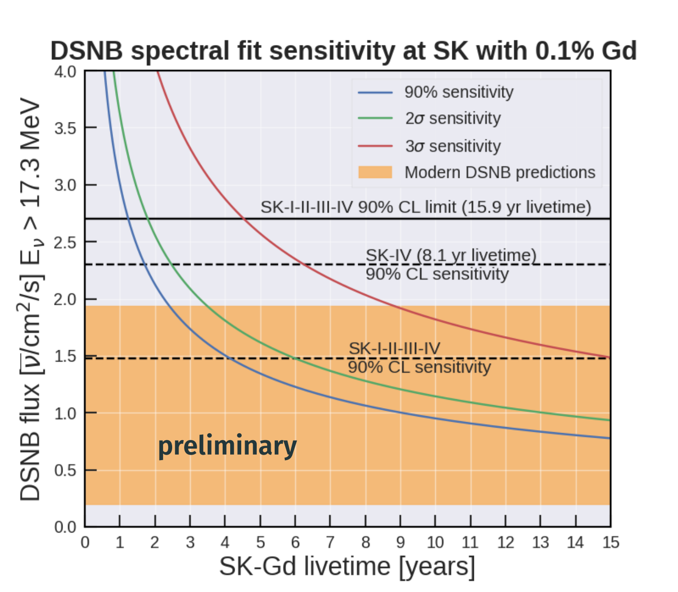


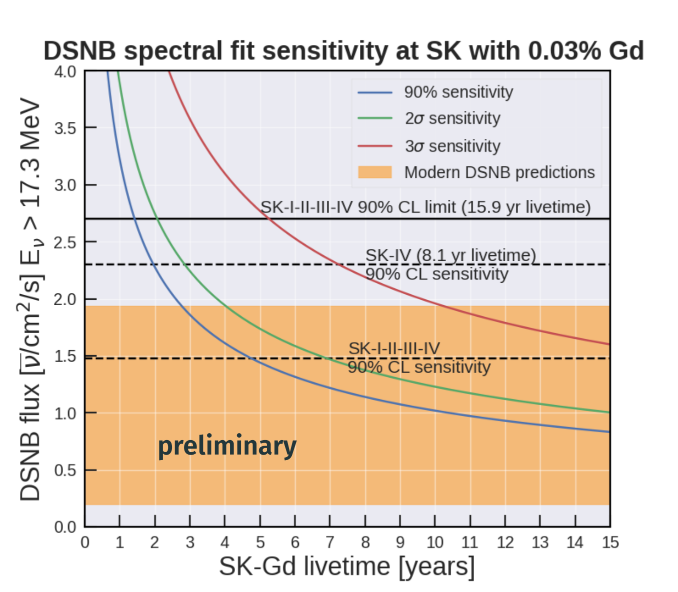
Sensitivity projection study

- Project SK-Gd performance for future DSNB spectral fit searches
- Assume atmospheric background PDFs after cuts are the same as in SK-IV
- Reweight PDFs according to ntag efficiency at desired Gd concentration
- Starting with a pure-background hypothesis, study expected exclusion power

Sensitivity projection: nominal 0.1% Gd concentration

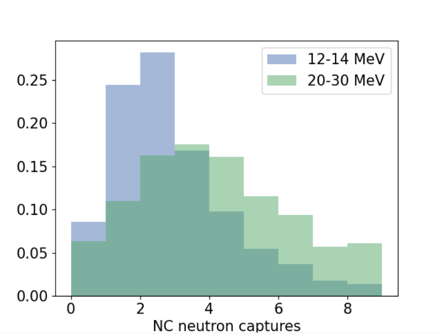


Sensitivity projection: 0.03% Gd concentration



Atmospheric neutrino background neutron multiplicity

- Sensitivity to the DSNB with Gd limited by neutron-producing atmospheric backgrounds in the signal region
- **Important neutron multiplicity observed for all atmospheric categories**
- In particular, **neutral current backgrounds are the most problematic**, as they frequently produce neutrons, and their spectrum peaks at low energies, as does the DSNB spectrum.



Outlook

- Analysis of the full SKIV dataset complete, integrating neutron tagging for the first time. To be fully capitalized on with SK-Gd.
- SK-Gd project set to increase neutron tagging efficiency 3-4 fold, and preliminary study shows DSNB exclusion sensitivity set to improve 4-fold
- Neutron tagging still far from optimized: performance improvements possible
- For further gains in sensitivity, need better characterization of atmospheric backgrounds.

→ At the prompt level: to what extent can we characterize and remove neutral current backgrounds?

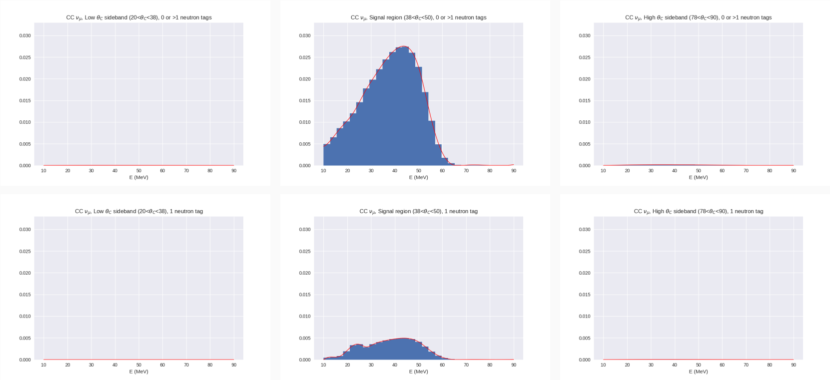
→ At the delayed level: to what extent can we differentiate neutron capture signals from atmospheric interactions?

- Looking further ahead: the larger statistics afforded by Hyper-K, as well as combined efforts with other neutrino observatories, will allow for more precise characterization of the DSNB

Backup

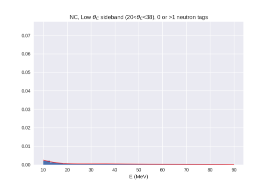
Decay e PDF

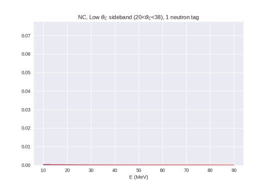
(20 < θ_C < 38) (38 < θ_C < 50) (78 < θ_C < 90)



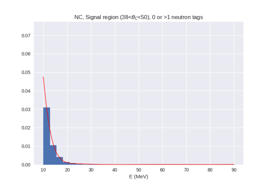
NC PDF

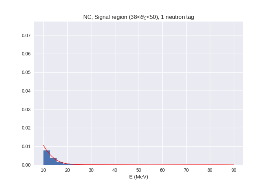
$(20 < \theta_C < 38)$



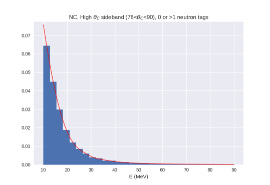


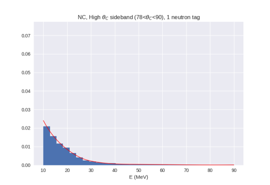
$(38 < \theta_C < 50)$





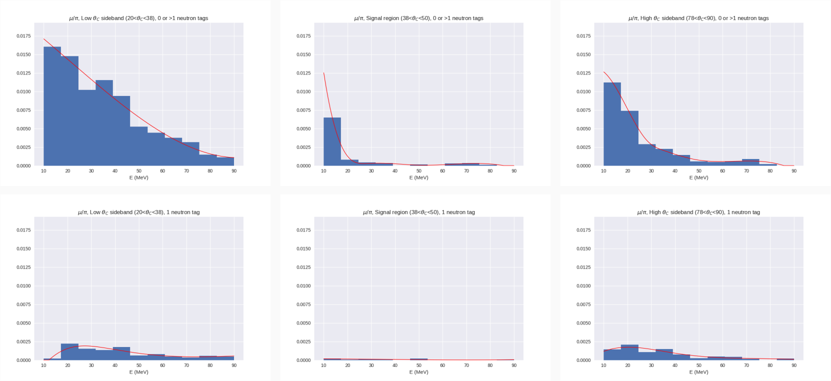
$(78 < \theta_C < 90)$



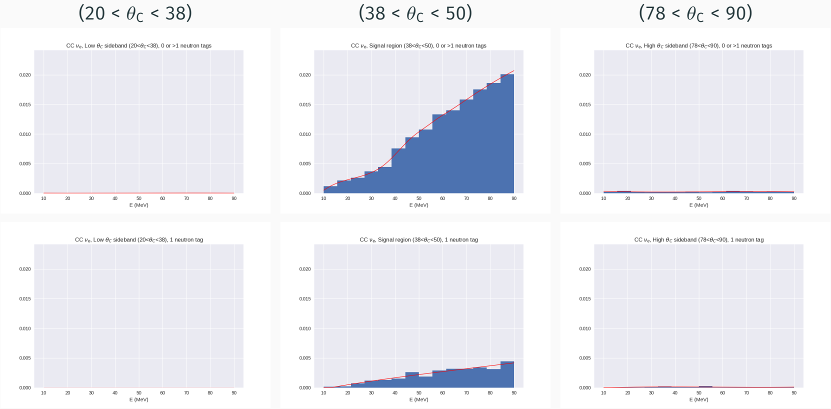


CC μ/π PDF

$(20 < \theta_C < 38)$ $(38 < \theta_C < 50)$ $(78 < \theta_C < 90)$



CC ν_e PDF



(20 < θ_C < 38)
(38 < θ_C < 50)
(78 < θ_C < 90)
CC ν_e, Low θ_C sideband (20<θ_C<38), 0 or >1 neutron tags
CC ν_e, Signal region (38<θ_C<50), 0 or >1 neutron tags
CC ν_e, High θ_C sideband (78<θ_C<90), 0 or >1 neutron tags
CC ν_e, Low θ_C sideband (20<θ_C<38), 1 neutron tag
CC ν_e, Signal region (38<θ_C<50), 1 neutron tag
CC ν_e, High θ_C sideband (78<θ_C<90), 1 neutron tag
E (MeV)

Atmospheric CC ν_e spectral shape uncertainty

$$\mathrm{PDF}_\mathrm{new} = \mathrm{PDF}_\mathrm{old} \times \mathrm{N} \left[1 + \frac{0.5\epsilon(\mathrm{E} - 16\ \mathrm{MeV})}{74\ \mathrm{MeV}}\right] \tag{1}$$

$$\mathcal{L}' = \int_{-1}^{3} \mathcal{L}(\epsilon)\mathrm{G}(\epsilon)\,\mathrm{d}\epsilon. \tag{2}$$

With asymmetric Gaussian function $\mathrm{G}(\epsilon)$

Atmospheric NC relative normalization uncertainty

$$\begin{aligned}
\text{PDF'}^{\text{NC}}_{\text{med}} &= \text{PDF}^{\text{NC}}_{\text{med}} \times (1 + \epsilon) \\
\text{PDF'}^{\text{NC}}_{\text{high}} &= \text{PDF}^{\text{NC}}_{\text{high}} \times (1 - \text{f}_{\text{high}}\epsilon) \\
\text{PDF'}^{\text{NC}}_{\text{low}} &= \text{PDF}^{\text{NC}}_{\text{low}} \times (1 - \text{f}_{\text{low}}\epsilon)
\end{aligned} \tag{3}$$

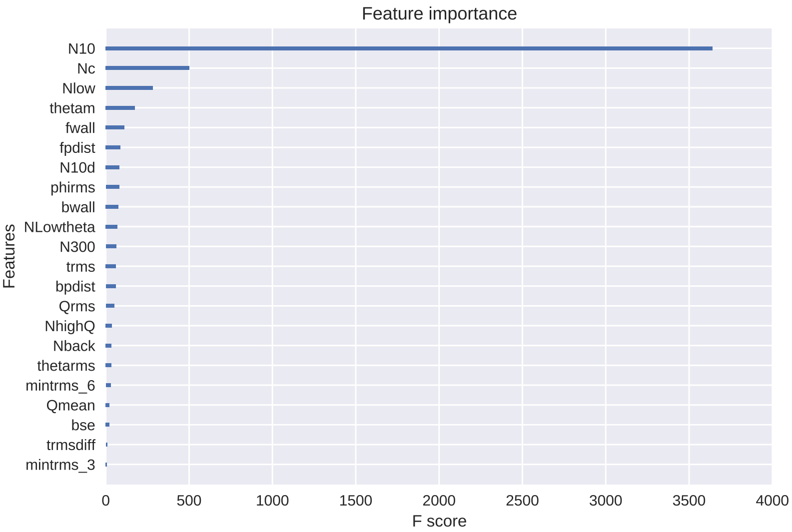
where

$$\begin{aligned}
\text{f}_{\text{high}} &= \frac{\int \text{PDF}^{\text{NC}}_{\text{med}} \int \text{PDF}^{\text{NC}}_{\text{high}}}{(\int \text{PDF}^{\text{NC}}_{\text{high}})^2 + (\int \text{PDF}^{\text{NC}}_{\text{low}})^2} \\
\text{f}_{\text{low}} &= \frac{\int \text{PDF}^{\text{NC}}_{\text{med}} \int \text{PDF}^{\text{NC}}_{\text{low}}}{(\int \text{PDF}^{\text{NC}}_{\text{high}})^2 + (\int \text{PDF}^{\text{NC}}_{\text{low}})^2}
\end{aligned} \tag{4}$$

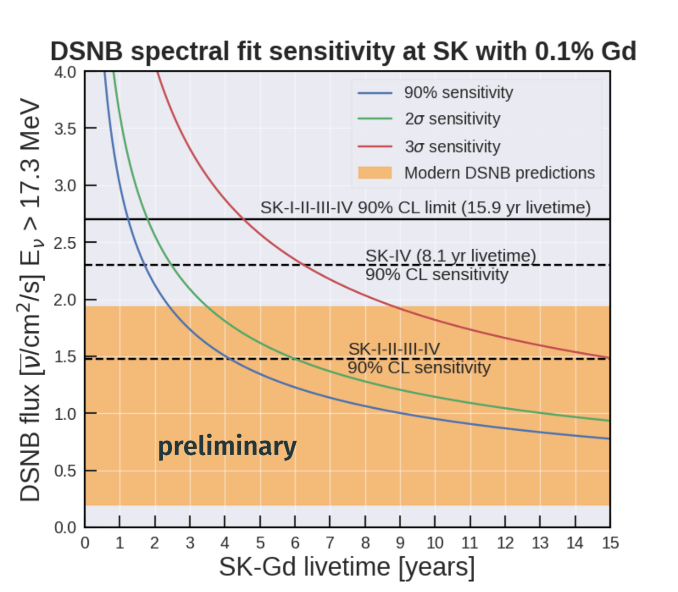
SK-I-II-III-IV DSNB flux limits ($\overline{\nu}$ cm^{-2}s^{-1} E_ν > 17.3 MeV)

	Best fit		90% CL limit					Pred.
Model	**SK4**	**All**	**SK1**	**SK2**	**SK3**	**SK4**	**All**	
Totani+95 Constant	$2.5^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.3	7.0	4.5	2.6	4.67
Kaplinghat+00 HMA (max)	$2.6^{+1.5}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.7	7.1	4.7	2.6	3.00
Horiuchi+09 6 MeV, max	$2.6^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.4	6.0	7.0	4.6	2.6	1.94
Ando+03 (updated 05)	$2.7^{+1.5}_{-1.4}$	$1.4^{+0.9}_{-0.9}$	2.3	6.6	7.2	4.7	2.7	1.74
Kresse+21 (High, NO)	$2.7^{+1.5}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.3	6.7	7.2	4.7	2.7	1.57
Galais+09 (NO)	$2.5^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.3	7.0	4.5	2.6	1.56
Galais+09 (IO)	$2.6^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.4	7.0	4.5	2.6	1.50
Horiuchi+18 $\xi_{2.5} = 0.1$	$2.6^{+1.4}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.4	6.1	7.1	4.6	2.7	1.23
Kresse+21 (High, IO)	$2.7^{+1.5}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.3	6.7	7.1	4.7	2.7	1.21
Tabrizi+21 (NO)	$2.7^{+1.5}_{-1.3}$	$1.4^{+0.9}_{-0.9}$	2.4	6.6	7.1	4.7	2.7	0.92
Lunardini09 Failed SN	$2.8^{+1.5}_{-1.4}$	$1.4^{+0.9}_{-0.9}$	2.4	6.8	7.3	4.8	2.8	0.73
Hartmann+97 CE	$2.6^{+1.4}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.5	7.1	4.6	2.6	0.63
Nakazato+15 (max, IO)	$2.7^{+1.5}_{-1.4}$	$1.4^{+1.0}_{-0.9}$	2.4	6.5	7.2	4.8	2.7	0.53
Horiuchi+21	$2.1^{+1.3}_{-1.2}$	$1.2^{+0.9}_{-0.9}$	3.4	4.3	5.9	3.9	2.5	0.28
Malaney97 CGI	$2.7^{+1.5}_{-1.3}$	$1.3^{+0.9}_{-0.9}$	2.3	6.8	7.1	4.7	2.6	0.26
Nakazato+15 (min, NO)	$2.8^{+1.5}_{-1.4}$	$1.4^{+1.0}_{-0.9}$	2.3	6.8	7.2	4.8	2.7	0.19

BDT trained on 0.01% Gd: Feature importance



Sensitivity projection: nominal 0.1% Gd, 12 MeV threshold



Sensitivity projection: nominal 0.1% Gd, 16 MeV threshold