Diffuse Supernova Neutrino Background at Water Cherenkov Detectors

II EU Workshop on Water Cherenkov Experiments for Precision Physics
(WCD-2025)
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Rudolph Rogly - CNRS / École Polytechnique

Diffuse Supernova Neutrino Background

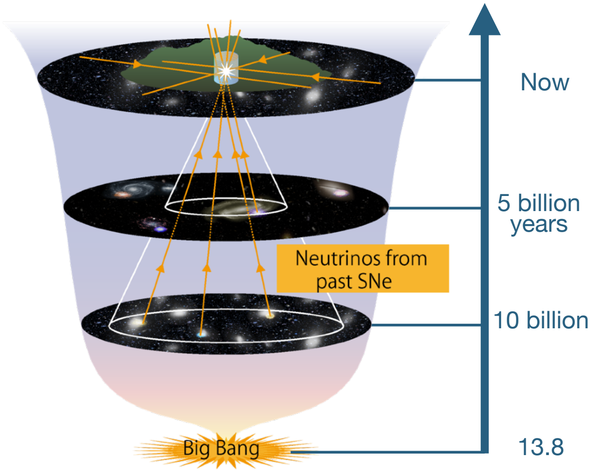
Core-Collapse Supernova (CCSN)

- Death of **massive stars** ($M \gtrsim 8\,M_\odot$), where ~99% of the energy (~10^{59} MeV) is released via the emission of neutrinos and antineutrinos of all flavors (~**10 MeV/ν**).

- Supernova neutrinos first detected in 1987 (Kamiokande II, IMB et Baksan), from SN1987A in the Large Magellanic Cloud.

- … but transient events every once in a while in the galaxy: **~1-3/century**.

❖ The **Diffuse Supernova Neutrino Background** is the integrated flux of supernova neutrinos originating from all CCSN events in the history of the universe → steady probe to study supernova neutrinos.



DSNB flux prediction

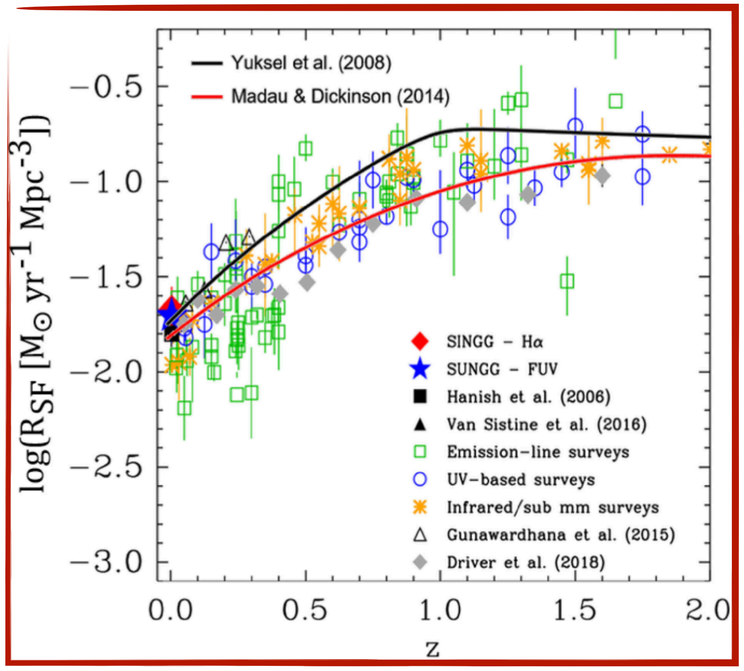
- DSNB flux is given by:

SN neutrino emission spectrum

$$\Phi(E_\nu) = c \int_z \sum_s R_{\mathrm{SN}}(z,s) \sum_{\nu_\beta, \bar{\nu}_\beta} F_\beta(E_\nu(1+z), s) \frac{\mathrm{d}z}{H(z)}$$

Redshift-dependent SN rate

Universe expansion



Star formation rate as a function of redshift[1]

[1] *S. Ando et al., Proc. Jpn. Acad., Ser. B, Phys. 99 (2023) 10*

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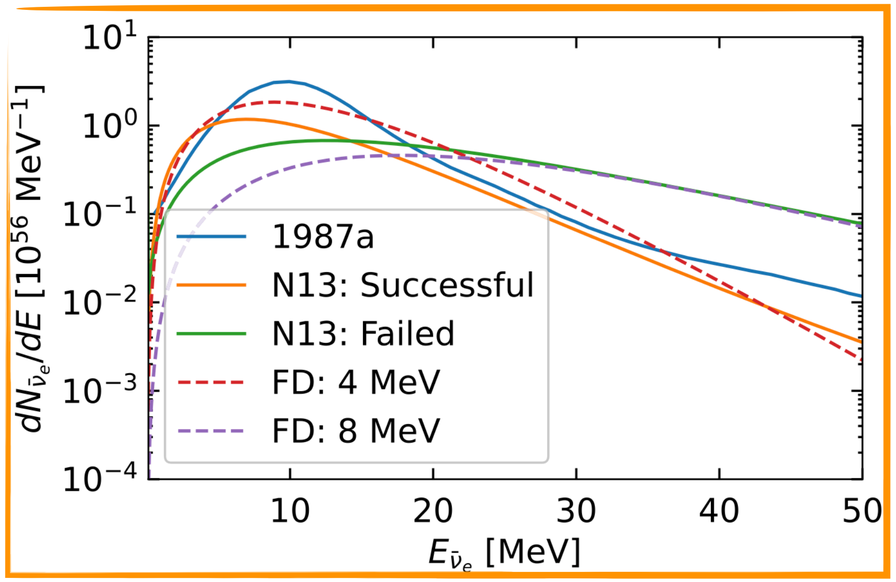
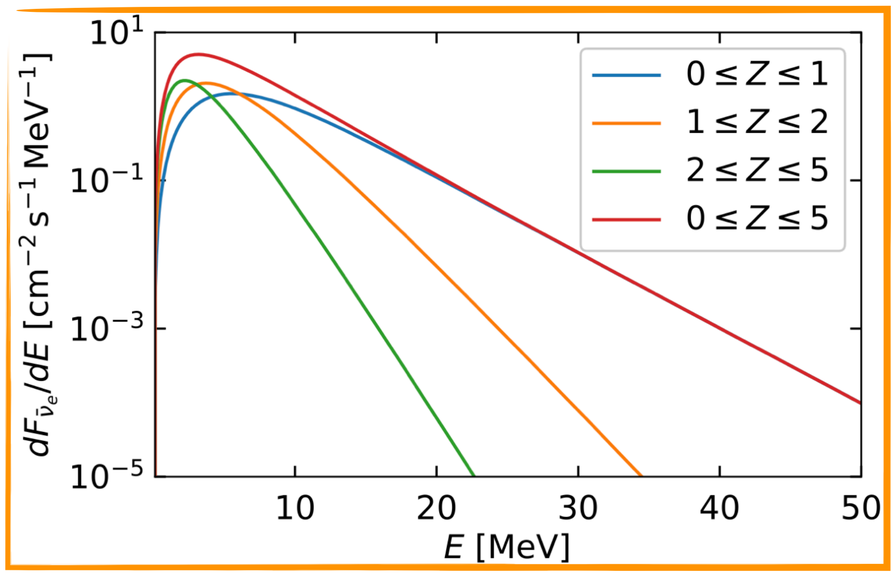


Example model of neutrino spectrum for successful & failed supernovae[1]



Redshitft-dependent neutrino spectrum[1]

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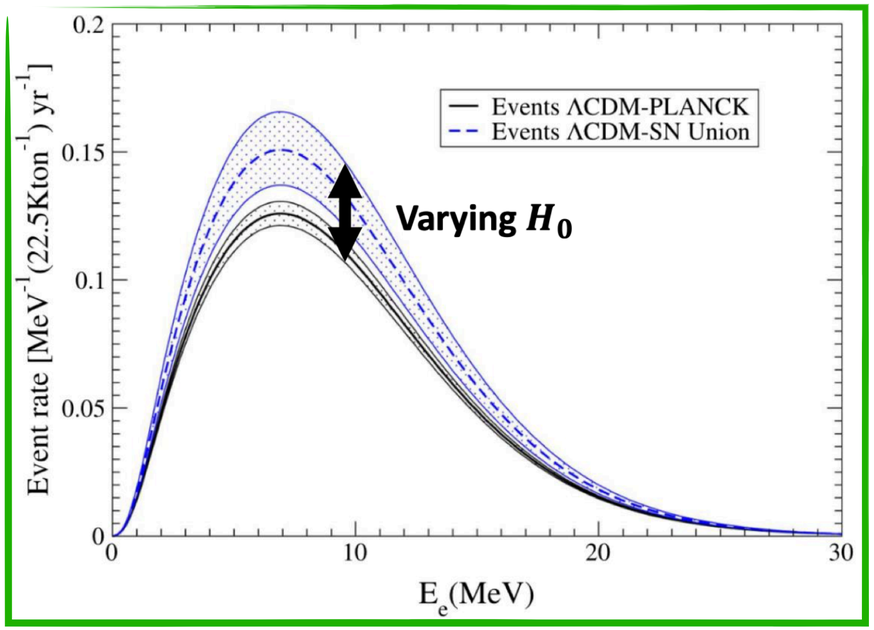

Expected DSNB event rate for different values of Hubble constant[2]

[2] *J. Barranco et al., J. Phys. G* ***45*** *(2018) 055201*

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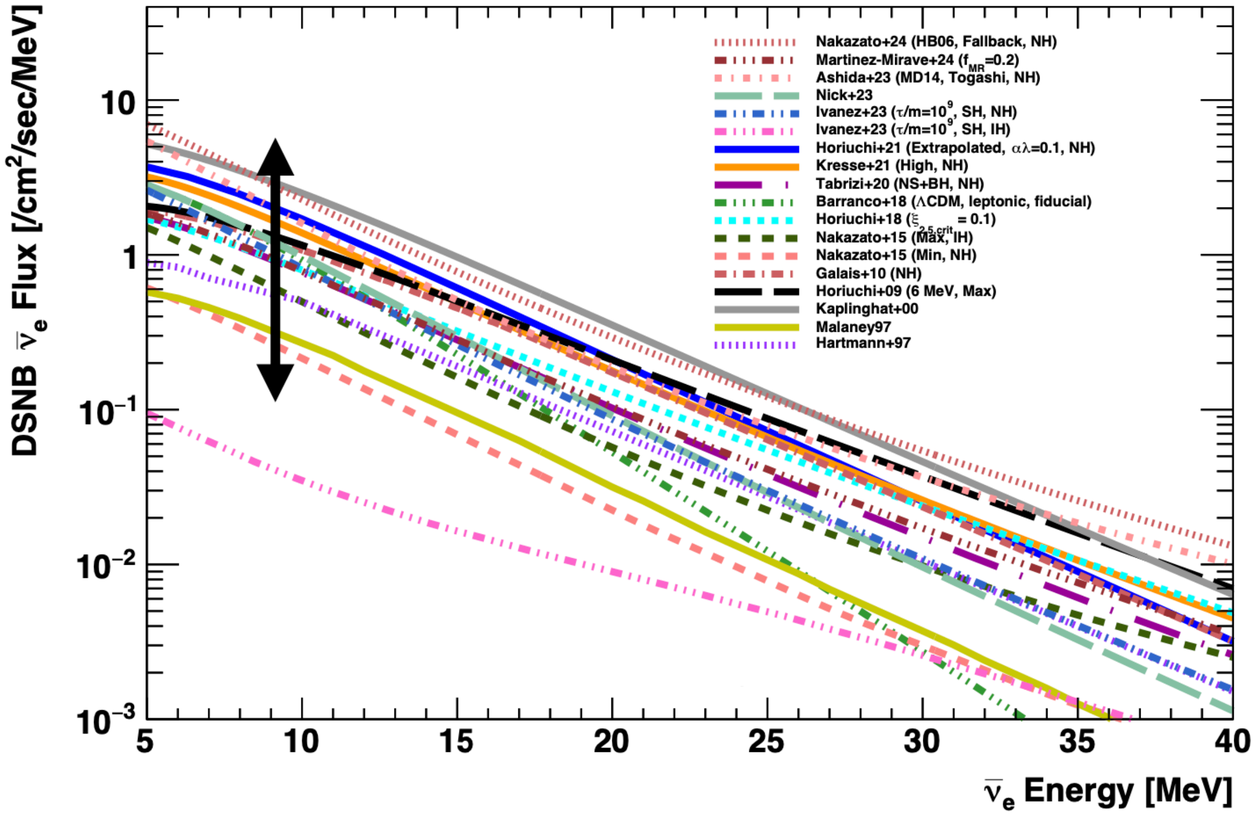
Redshift-dependent SN rate

Universe expansion

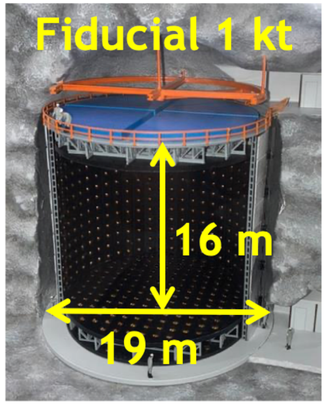
Rich phenomenology, e.g.:

- Star formation rate,
- Black hole fraction,
- Neutrino oscillation in stars,
- Exotic neutrino properties e.g. neutrino decay,
- Supernova explosion mechanism,
- History of the universe.



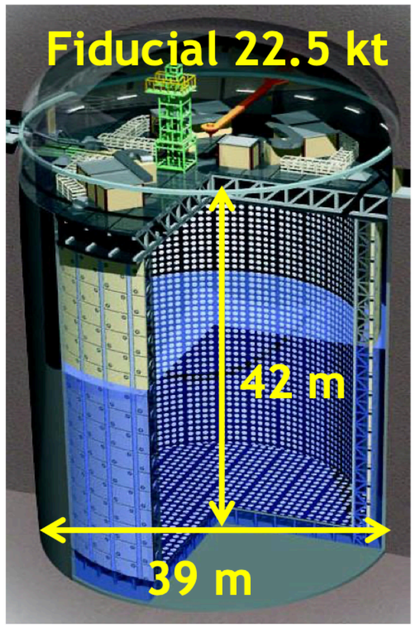
Supernova neutrinos and the Kamiokande saga

Kamiokande
(1983-1996)



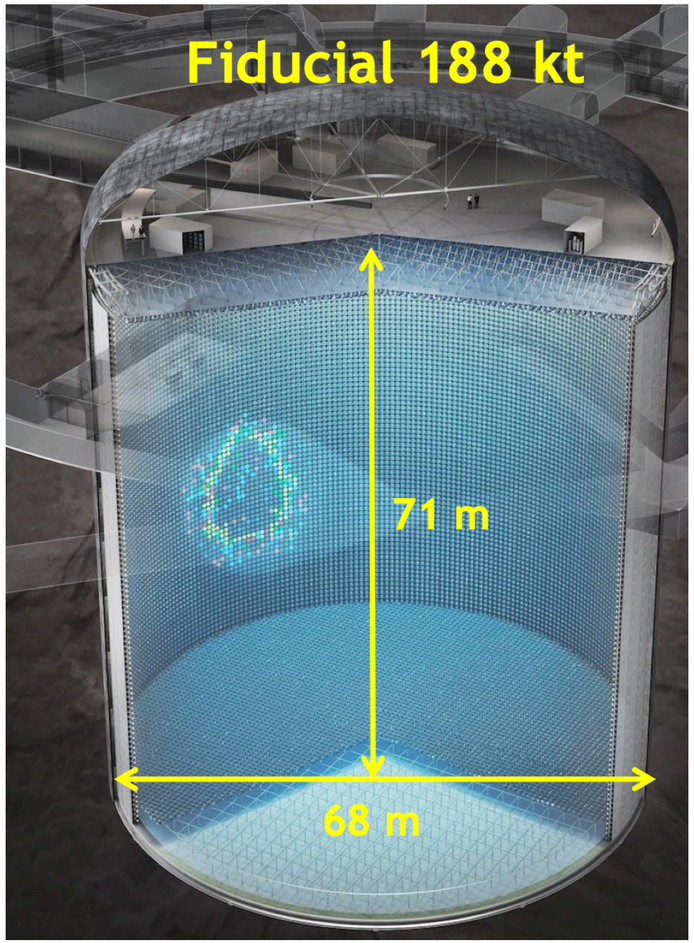
First detection of supernova burst neutrinos (SN1987A)

Super-Kamiokande
(1996-)



First hints / evidence of diffuse supernova neutrino background ?

Hyper-Kamiokande
(2028-)



First constraints on DSNB spectral shape ?

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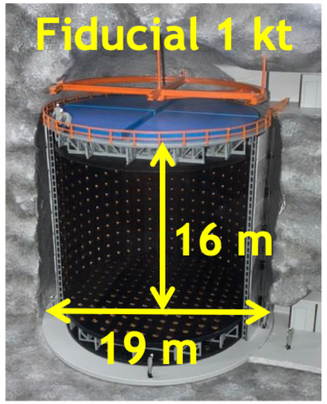

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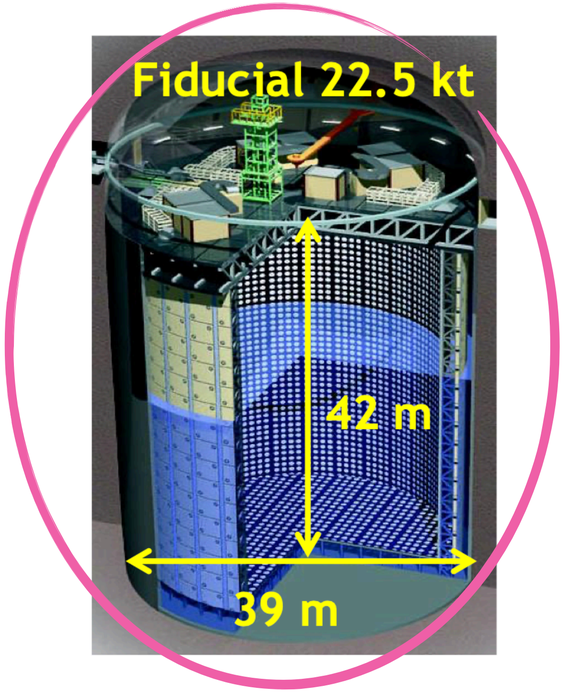

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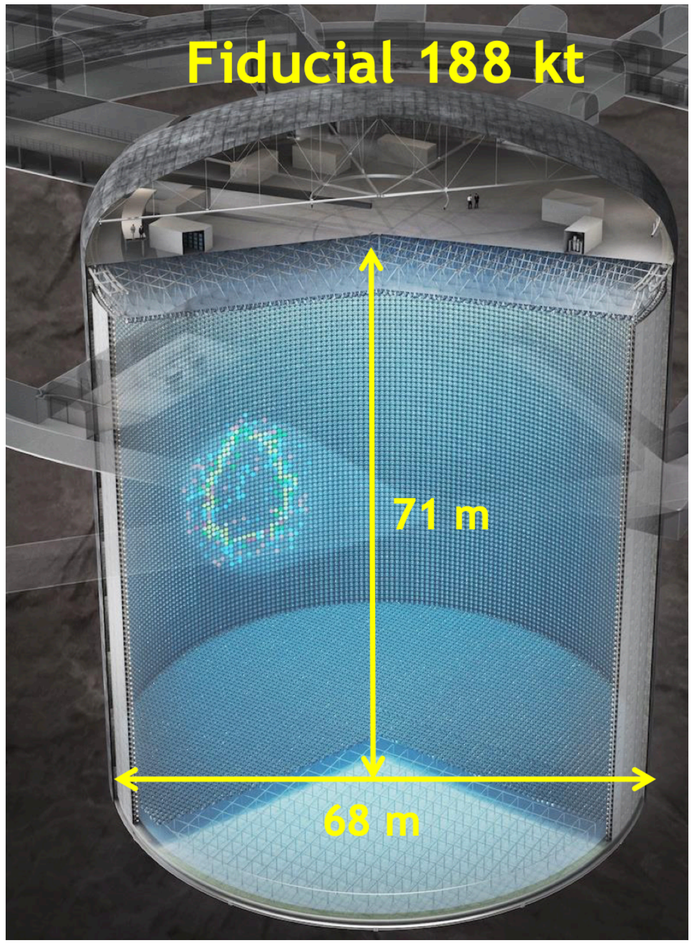

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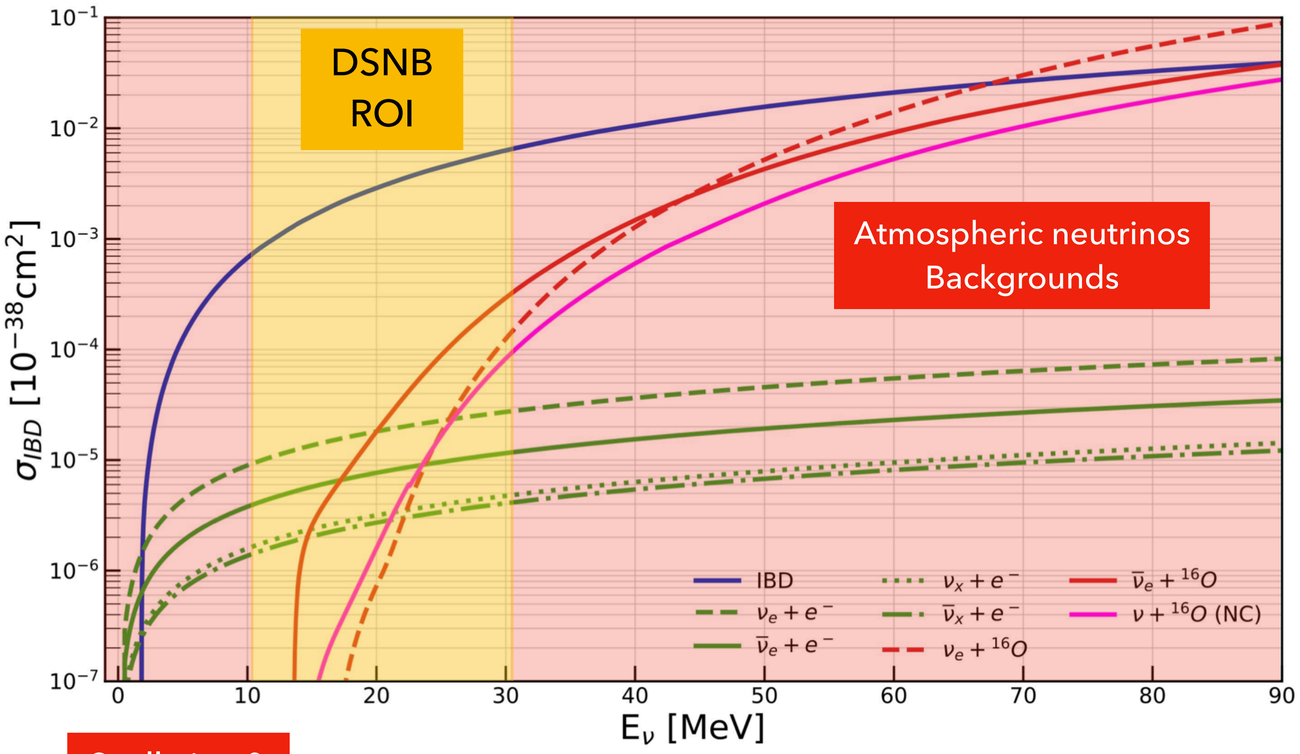
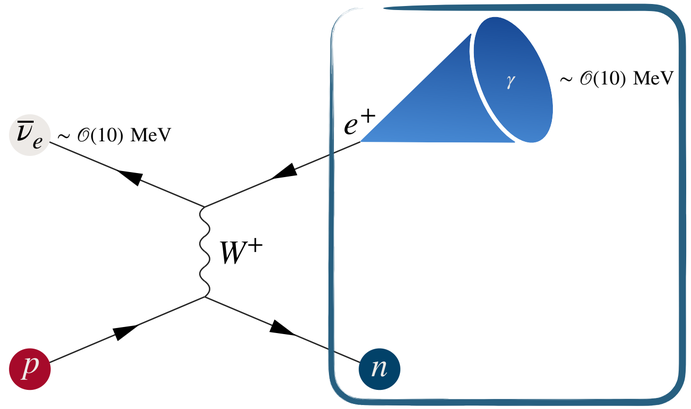
DSNB events at SK

- SK sensitive to the electronic antineutrino part of the DSNB via the Inverse Beta Decay channel:





DSNB dual signature from IBD interaction

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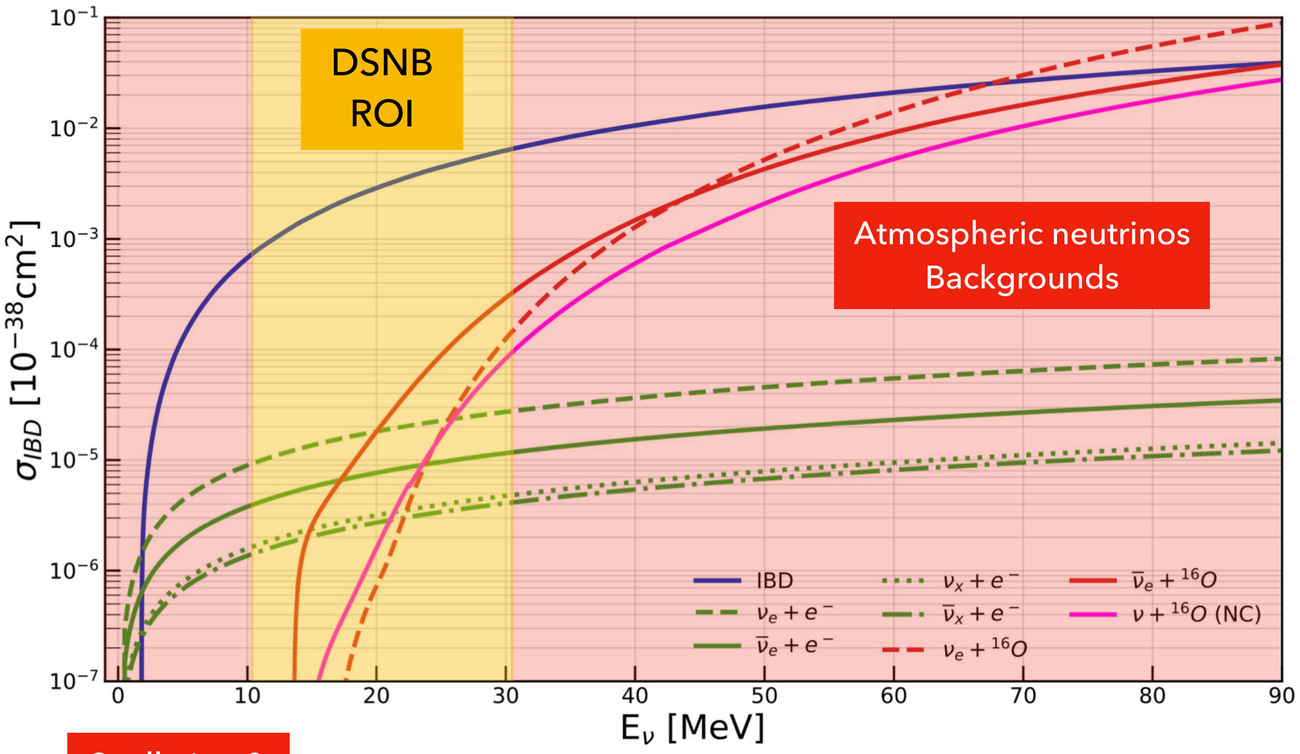
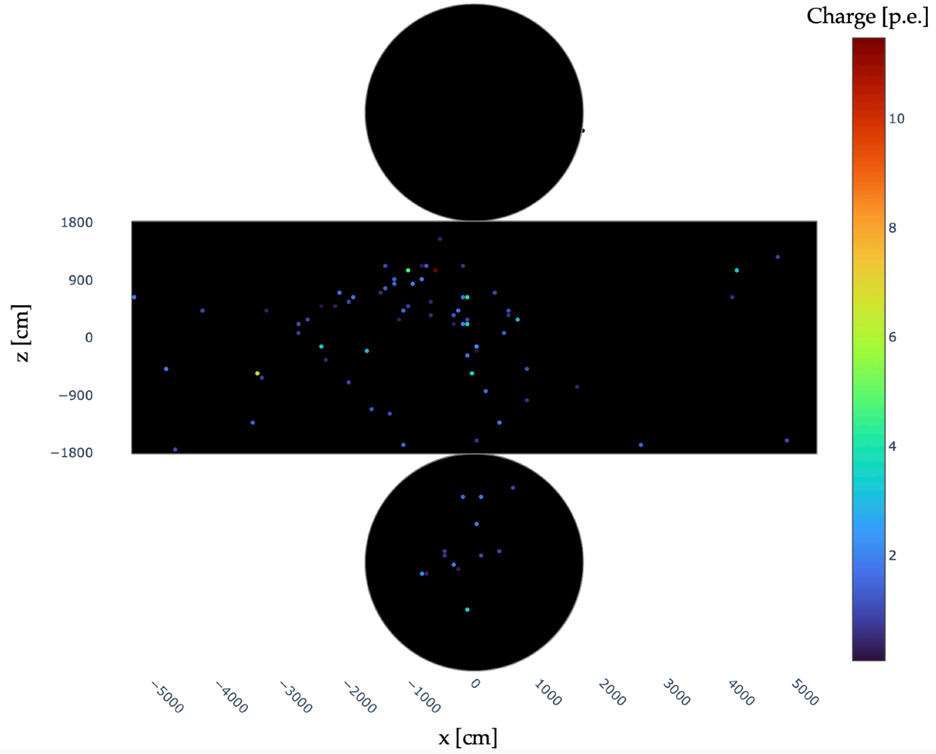
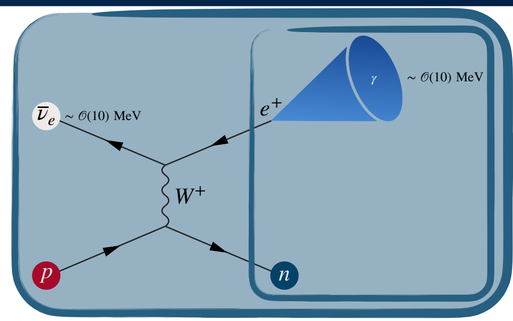




Event display of a simulated 10 MeV positron (without dark noise hits)

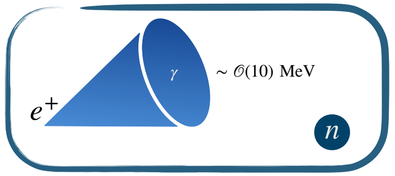
Background events

➡ Observables: e^+ rec. energy E_{e+}, rec. Cherenkov angle θ_C and number of tagged neutrons n

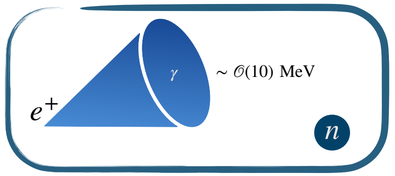


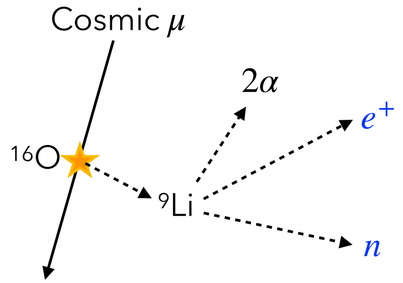
DSNB event

- Reactor $\bar{\nu}_e$:
  - **Irreducible and a dominant background** below ~10 MeV.

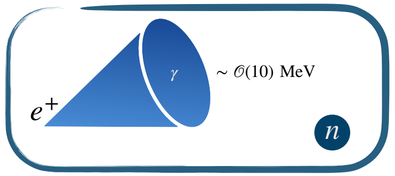


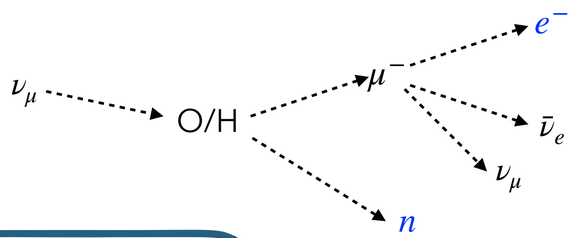
- Spallation-induced:
  - From cosmic muons going through SK (**~2 Hz**) : **dominant background in the low energy end** of the analysis window.



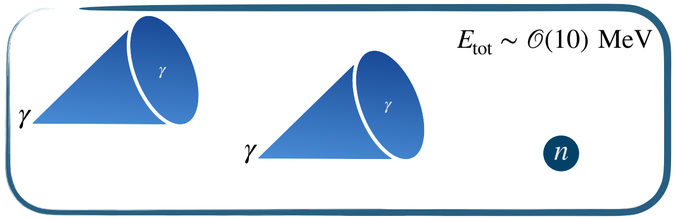


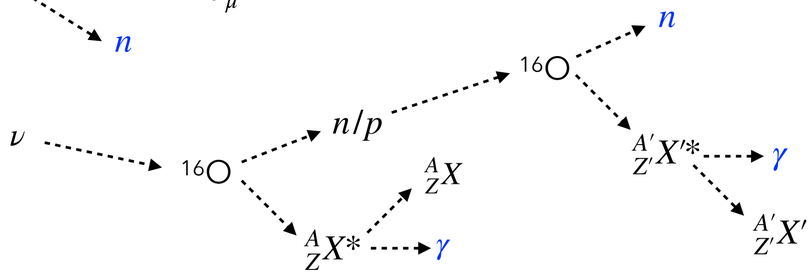
- Atmospheric ν - Charged-Current (CC)





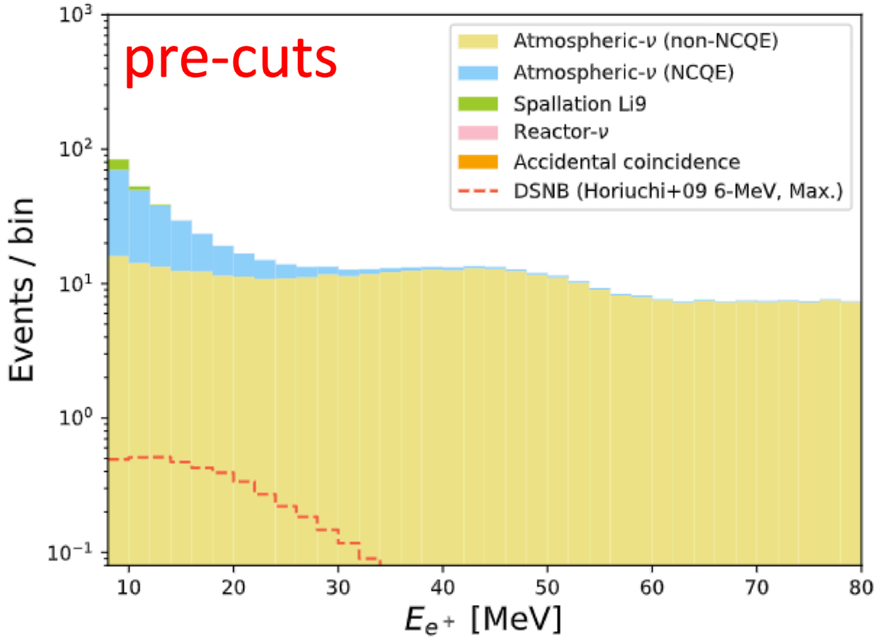
- Atmospheric ν - Neutral-Current (NC)





Prompt positron selection

Set of cuts applied on **ancillary observables** to bring the S/B closer to 1:



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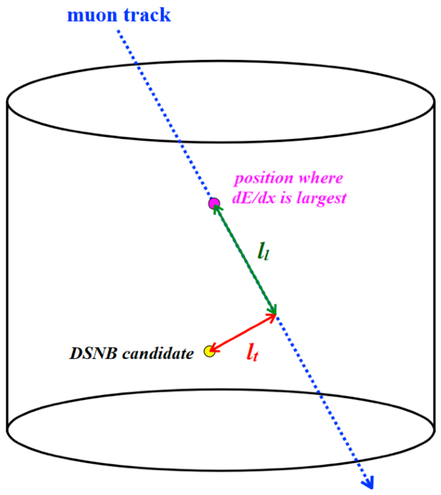
Set of cuts applied on **ancillary observables** to bring the S/B closer to 1:

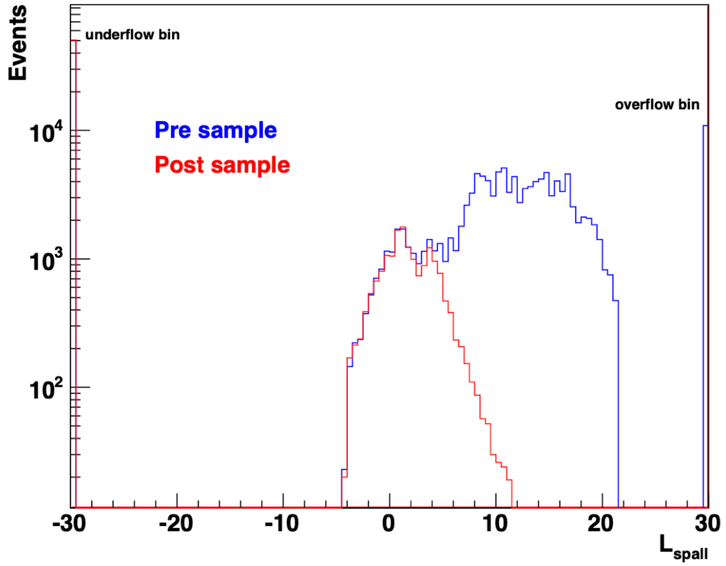
- *Spallation event reduction*

  ➡ Muon track observables based cuts, neutron cloud cuts, box cuts.

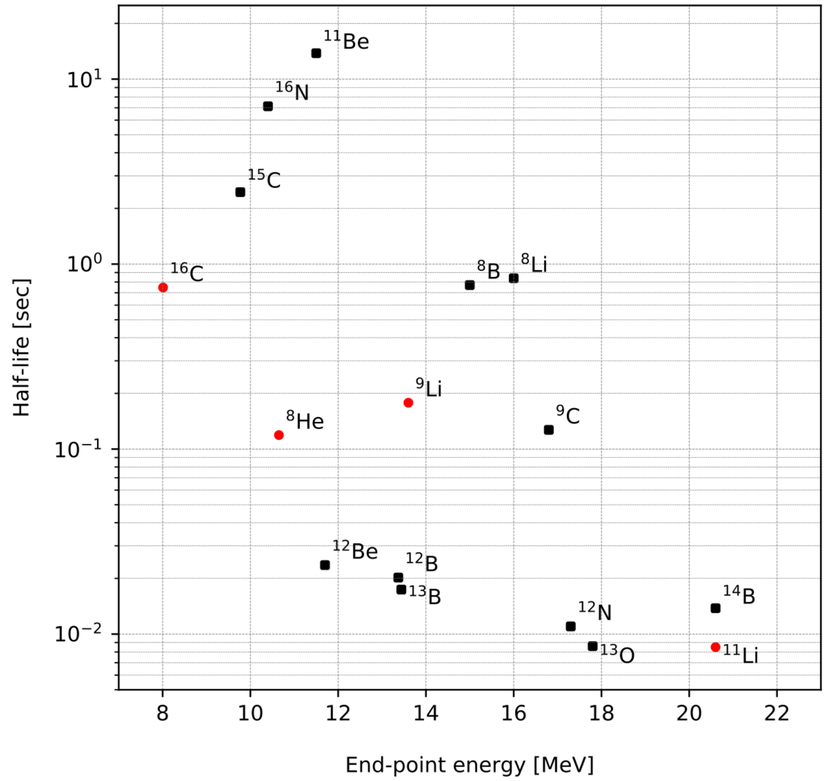
  ➡ Retain > 60% signal, with O(1%) background acceptance.



Muon track observables



Spallation log-likelihood ratio



*Spallation-induced β-decay isotopes, **w.** and **w/o.** neutron production*

Prompt positron selection

Set of cuts applied on **ancillary observables** to bring the S/B closer to 1:

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  ➡ Cuts on observables encompassing the « fuzziness » of the Cherenkov ring for μ/π rejection, decay electron cut, and **newly introduced single-cone likeness** (aka **MSG**) cut to remove multi-cone events.

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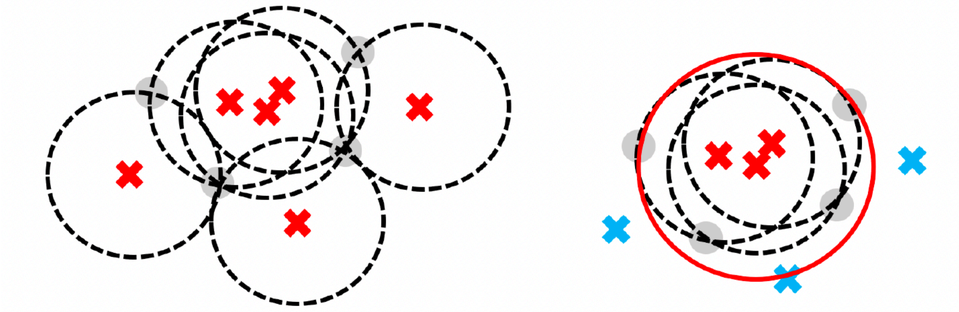
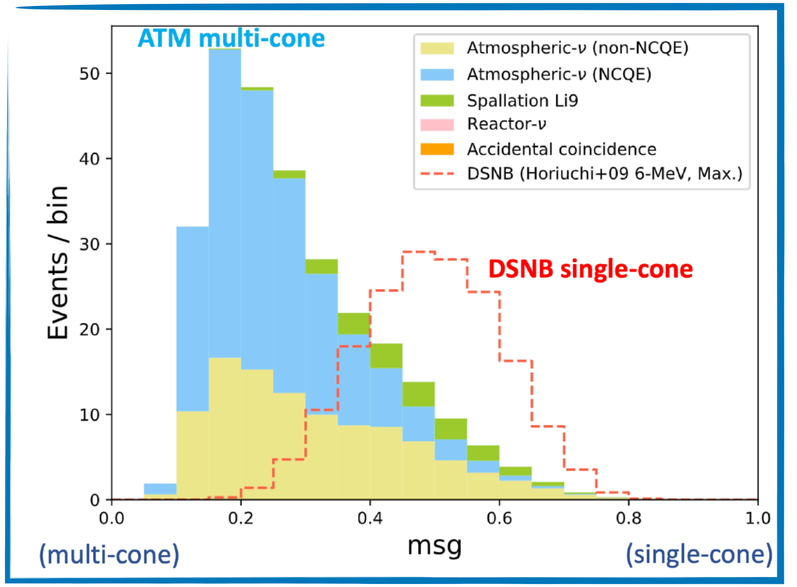
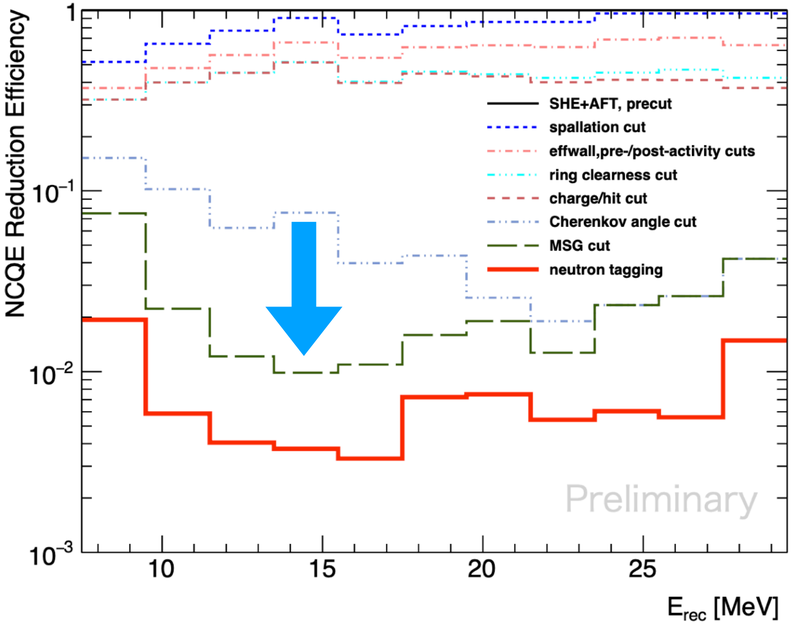


(b) Identify all candidate cones for pairs of PMTs hit.

(c) Find largest candidate cluster (red crosses) within a cone of 50° opening angle.

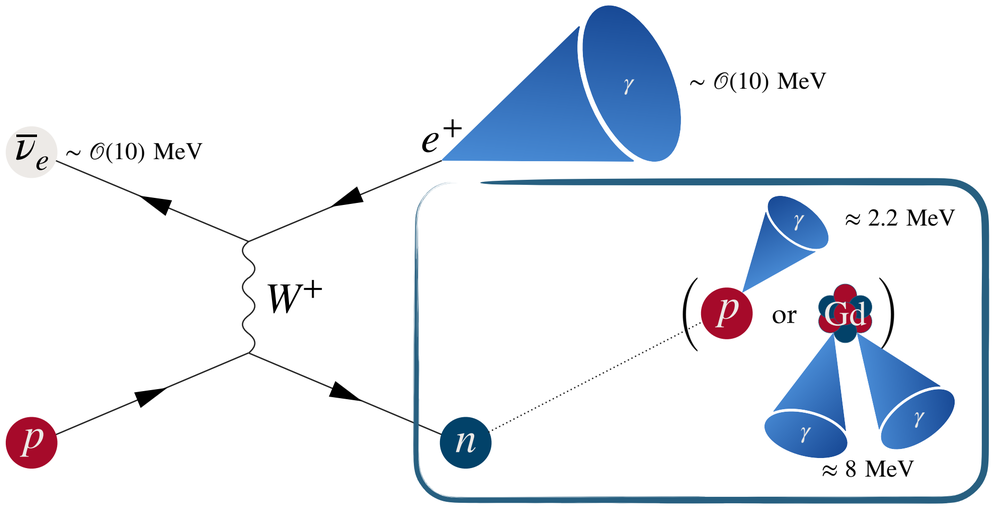
A.D. Santos, PhD thesis





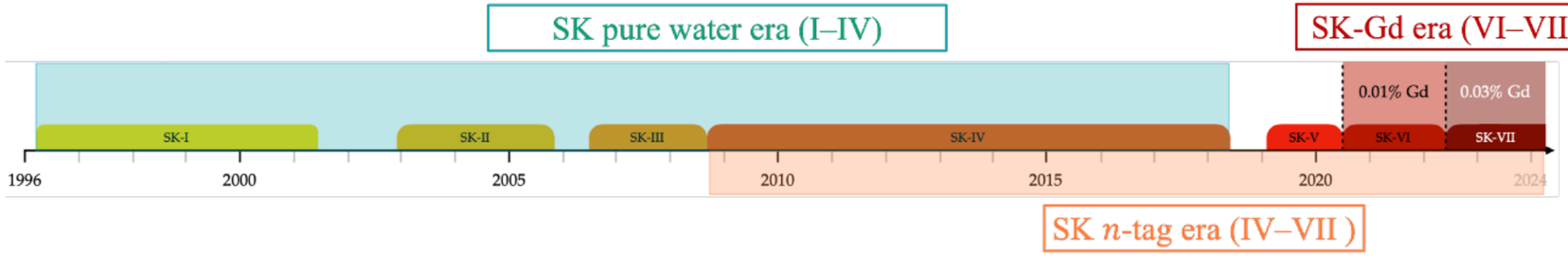
Delayed neutron selection

- Increasing Gd-loading since 2020 allows to enhance neutron tagging capability.



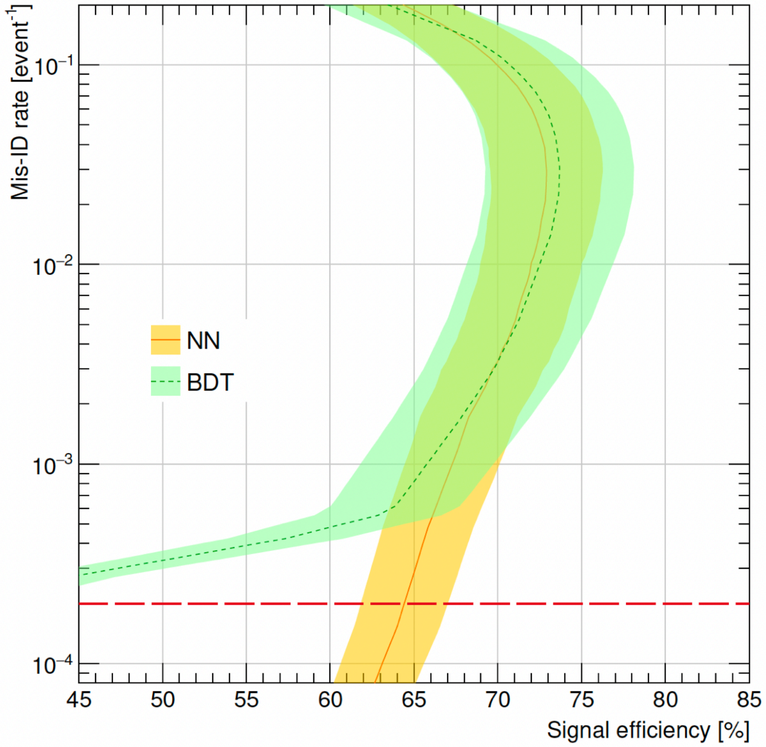
Neutron capture delayed signal

	SK-IV (pure water)	SK-VI (0.01% Gd)	SK-VII (0.03% Gd)
n-capture on Gd	0 %	50 %	75 %
Time constant	~210 μs	~115 μs	~65 μs



Delayed neutron selection

- 2 ML-based approaches developed to leverage full capability of SK-Gd detector, with mistag rate ~ O(0.01%).
  - ➡ *Boosted Decision Tree*, with 22 variables as inputs encompassing delayed signal photo-statistics, space-time clustering, characteristic reconstructed distances.
  - ➡ *Neural Network*, with 12 variables as inputs encoding the hit pattern and the energy.



Neutron tagging ROC curve (SK-VII)

	SK-IV (pure water)	SK-VI (0.01% Gd)	SK-VII (0.03% Gd)
n-capture on Gd	0 %	50 %	75 %
Time constant	~210 µs	~115 µs	~65 µs
n-detection efficiency	~25%	~40%	~60%

Overall selection

Set of cuts applied on **ancillary observables** to bring the S/B closer to 1:

- *Spallation event reduction*
  - ➡ Muon track based cuts, neutron cloud cuts, box cuts.
  - ➡ Retain > 60% signal, with O(1%) background acceptance.
- *Atmospheric event reduction*
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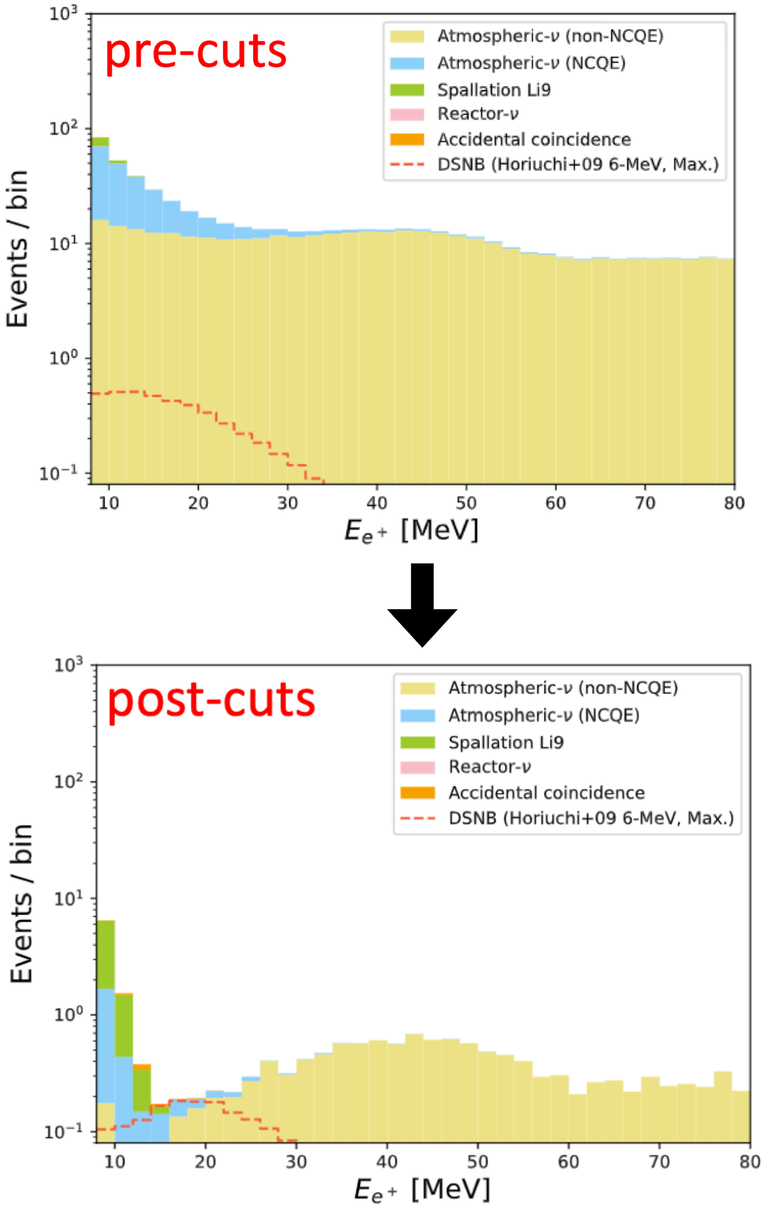
- *Neutron tagging*



Discovery analysis - DSNB Model-dependent spectral fit

Principle

- **Shape-driven** analysis: Fit DSNB + 5 background contents to the data,

via Extended Likelihood Maximization framework.

- Define 3 Cherenkov angle (θ_C) regions:
  - ➡ *Low* θ_C: Mostly μ/π events,
  - ➡ *High* θ_C: Mostly **NC** multi-cone events,
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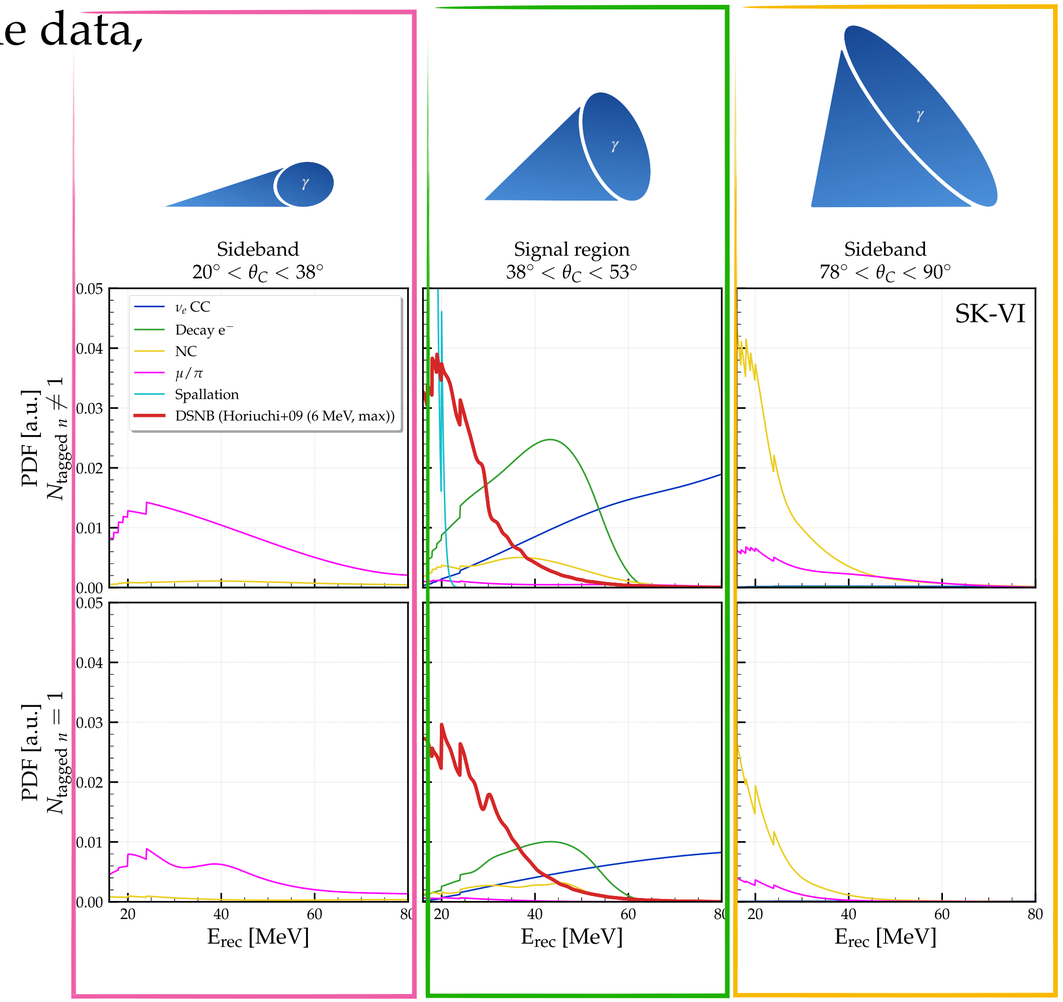

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- Define 2 $N_{\text{tagged } n}$-dependent region:
  - ➡ **Non IBD-like** events ($N_{\text{tagged } n} \neq 1$)
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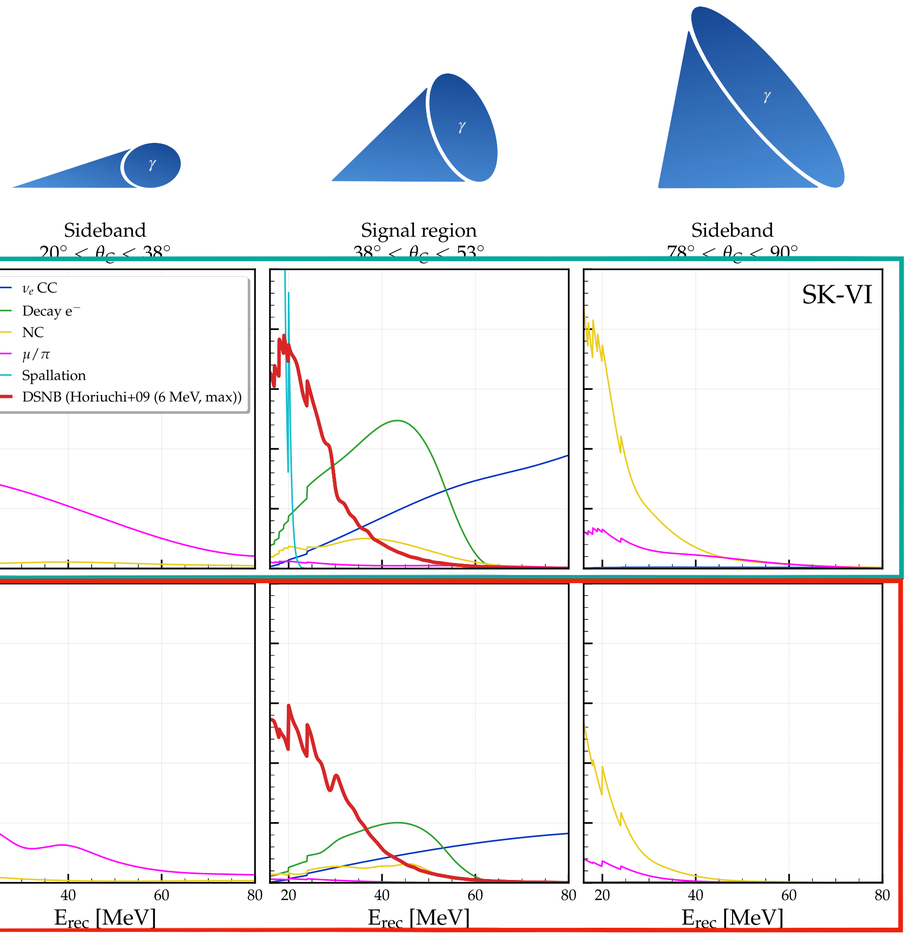

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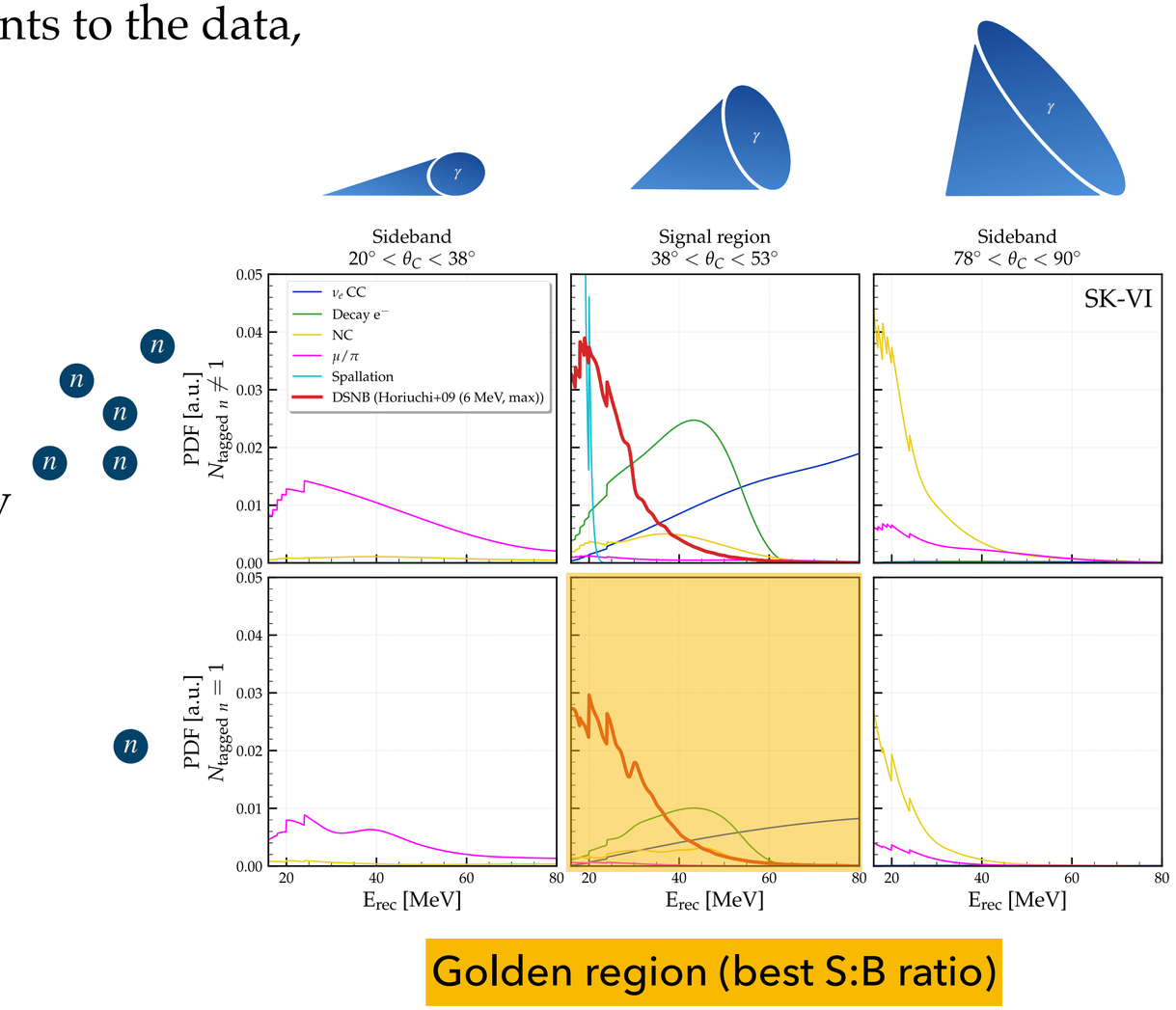

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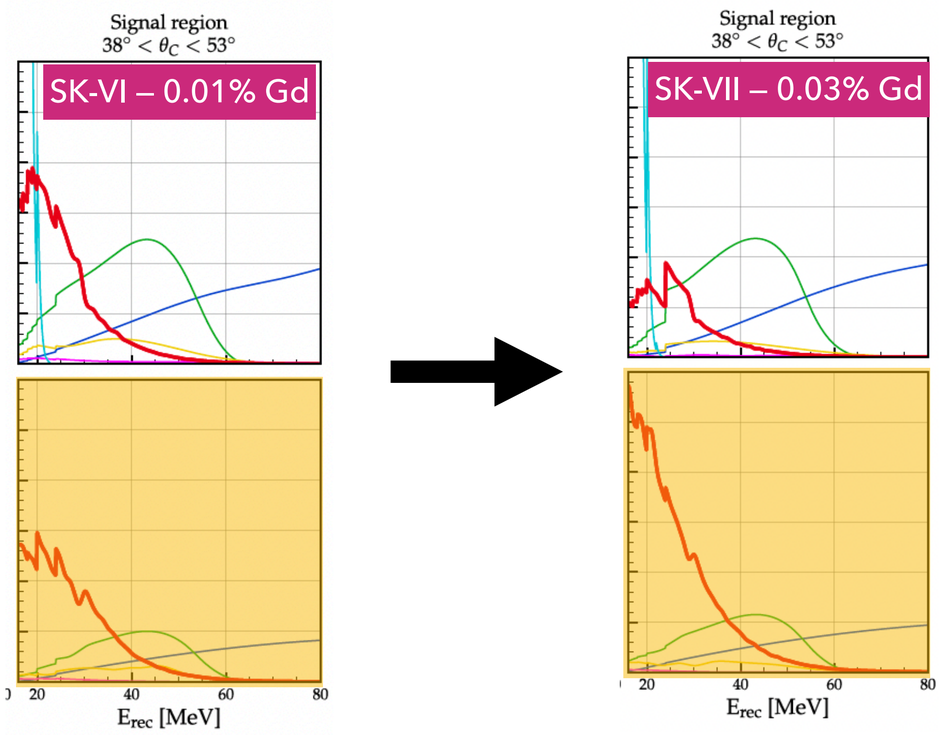


Gd-loading enrich the golden region in DSNB signal.

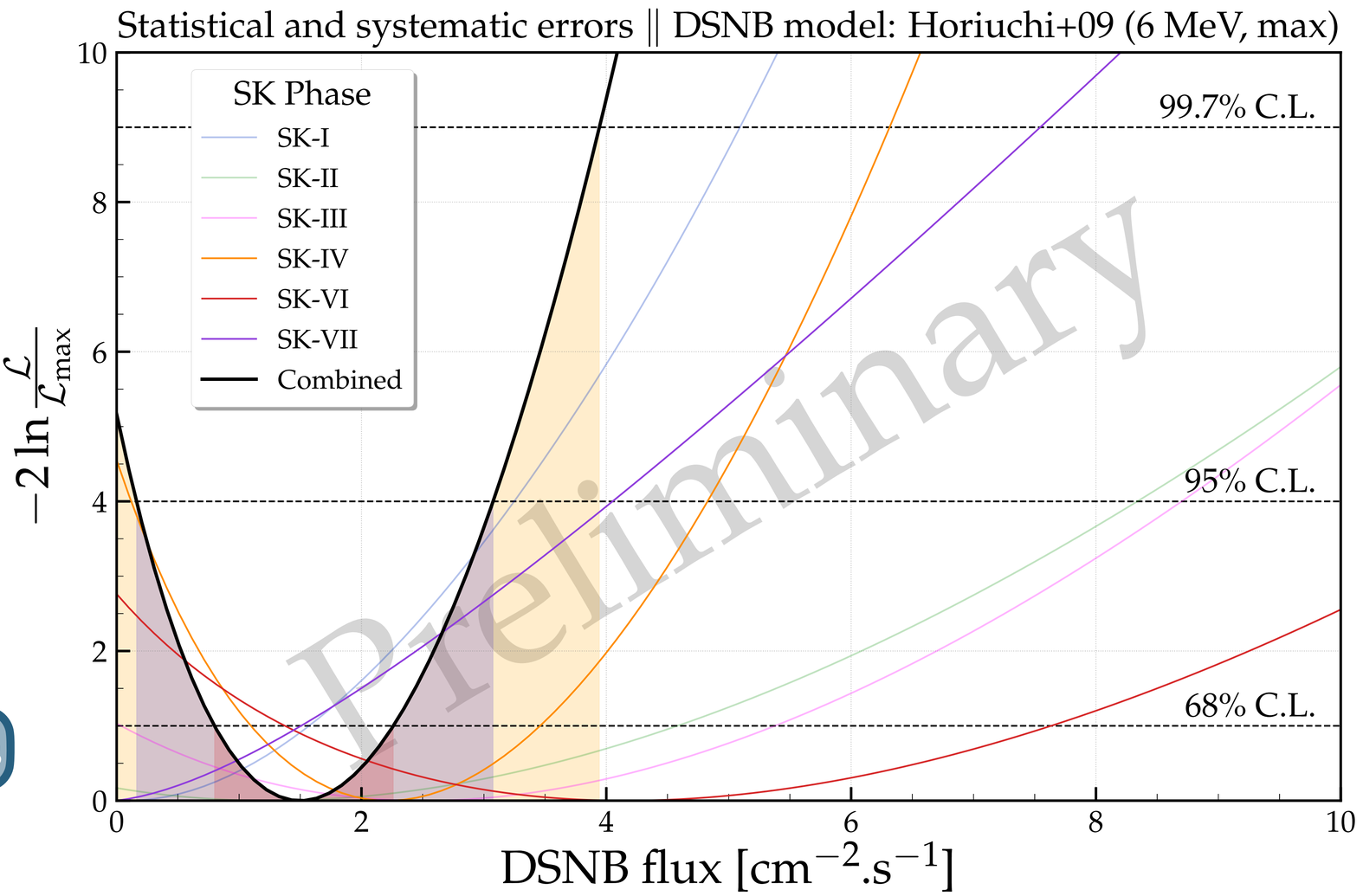
Discovery analysis - DSNB Model-dependent spectral fit

Likelihood ratio test

Combined Results

DSNB (Horiuchi+09)
Best fit rate $2.9\,\text{events}\cdot\text{year}^{-1}$
Best fit flux $1.4\,\text{cm}^{-2}\cdot\text{s}^{-1} > 17.3\,\text{MeV}$

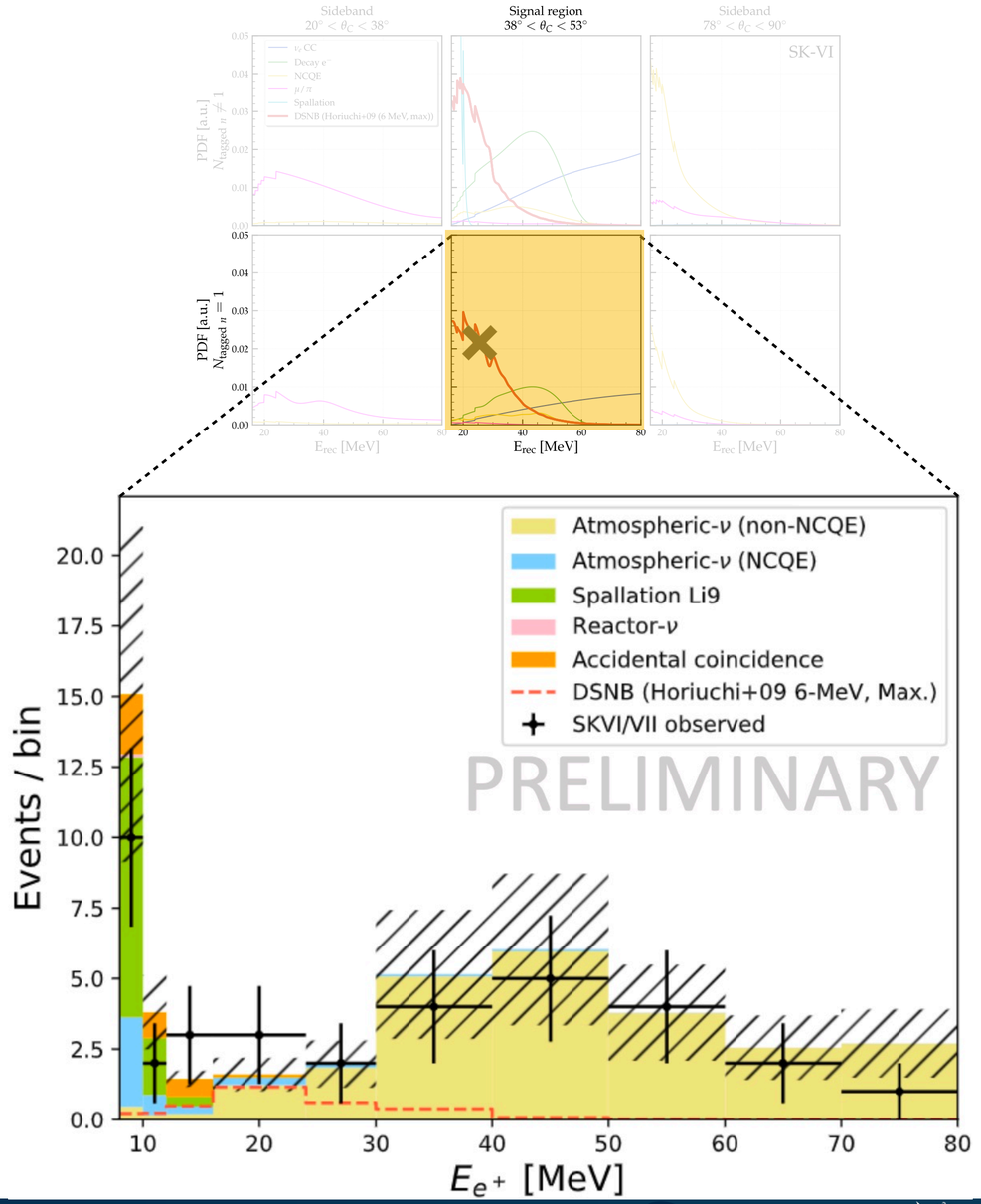
Combined (stat. + sys.) $\approx 2.3\,\sigma$ excess



DSNB Model-independent Binned Analysis

Principle

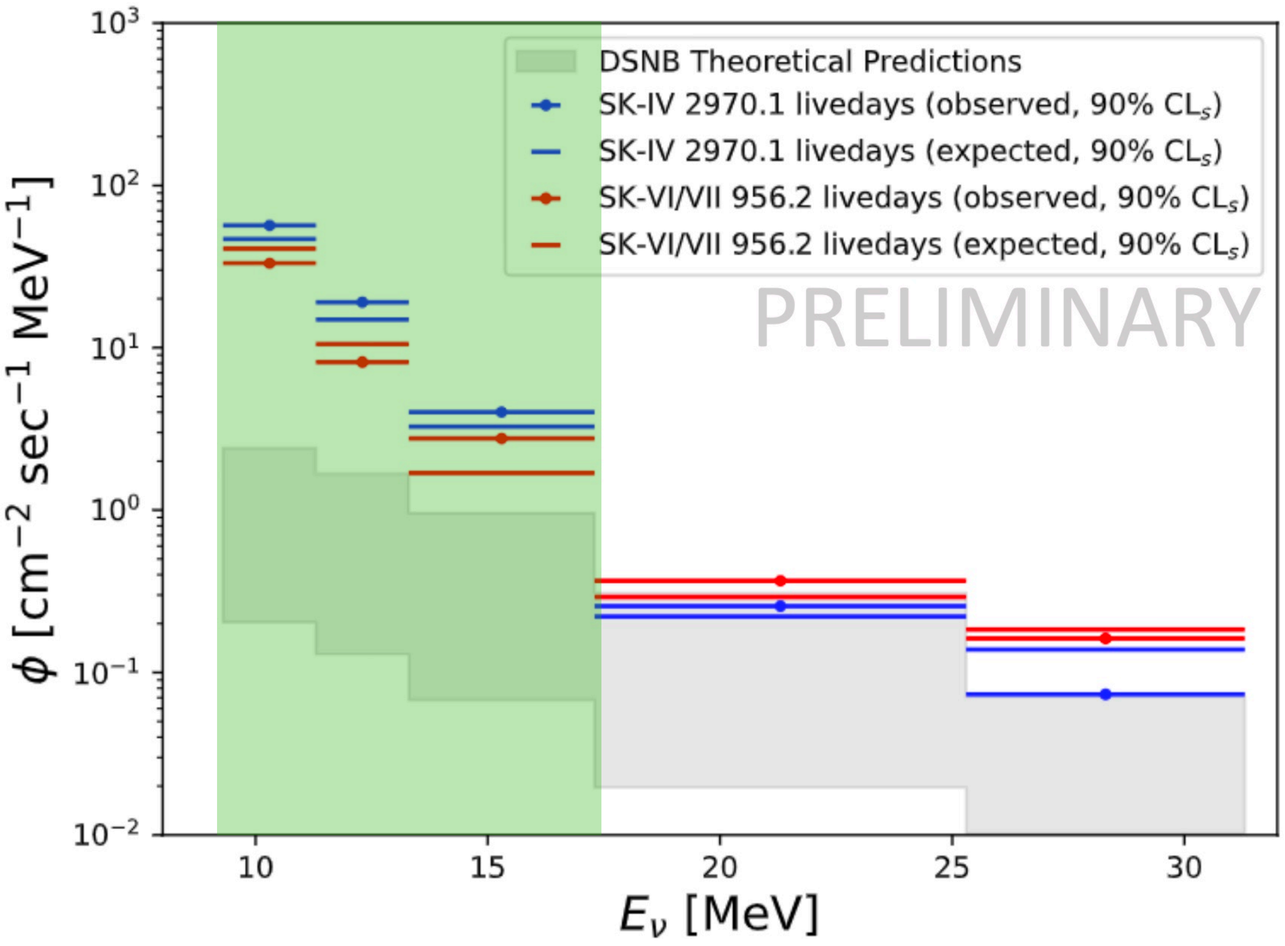
- No input DSNB model in this analysis.
- Predicted background fluxes, instead of inferring them from fit.
- In the golden region, look at the excess per bin observed wrt. background-only prediction.
- CLs approach to derive bin-by-bin upper limits.



DSNB Model-independent Binned Analysis

Upper Limits

- Poor sensitivity in the very low energy region (not probed by spectral analysis), mostly due to overwhelming spallation-induced background.
- … yet SK-Gd (VI-VII) limits in those bins already better than SK-pure water (IV) despite ~3 less stats → courtesy of **enhanced mitigation of spallation-induced accidental events owing to *decreased neutron mistag rate* thanks to Gd-loading**.



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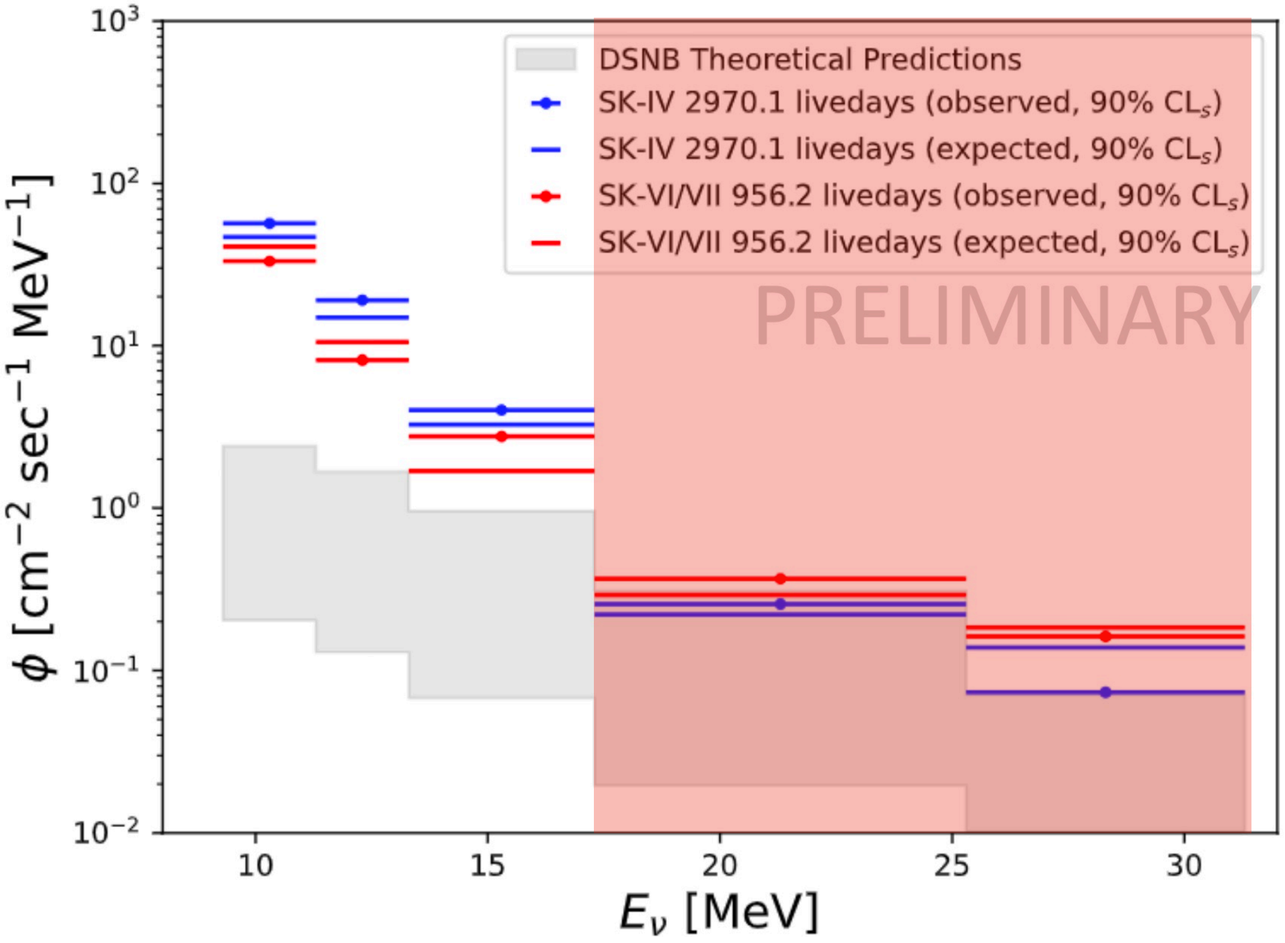
- … yet SK-Gd (VI-VII) limits in those bins already better than SK-pure water (IV) despite ~3 less stats → courtesy of **enhanced mitigation of spallation-induced accidental events owing to *decreased neutron mistag rate* thanks to Gd-loading**.
- In the intermediate energy region (common with spectral analysis), **upper limits approach the range of DSNB predictions.**

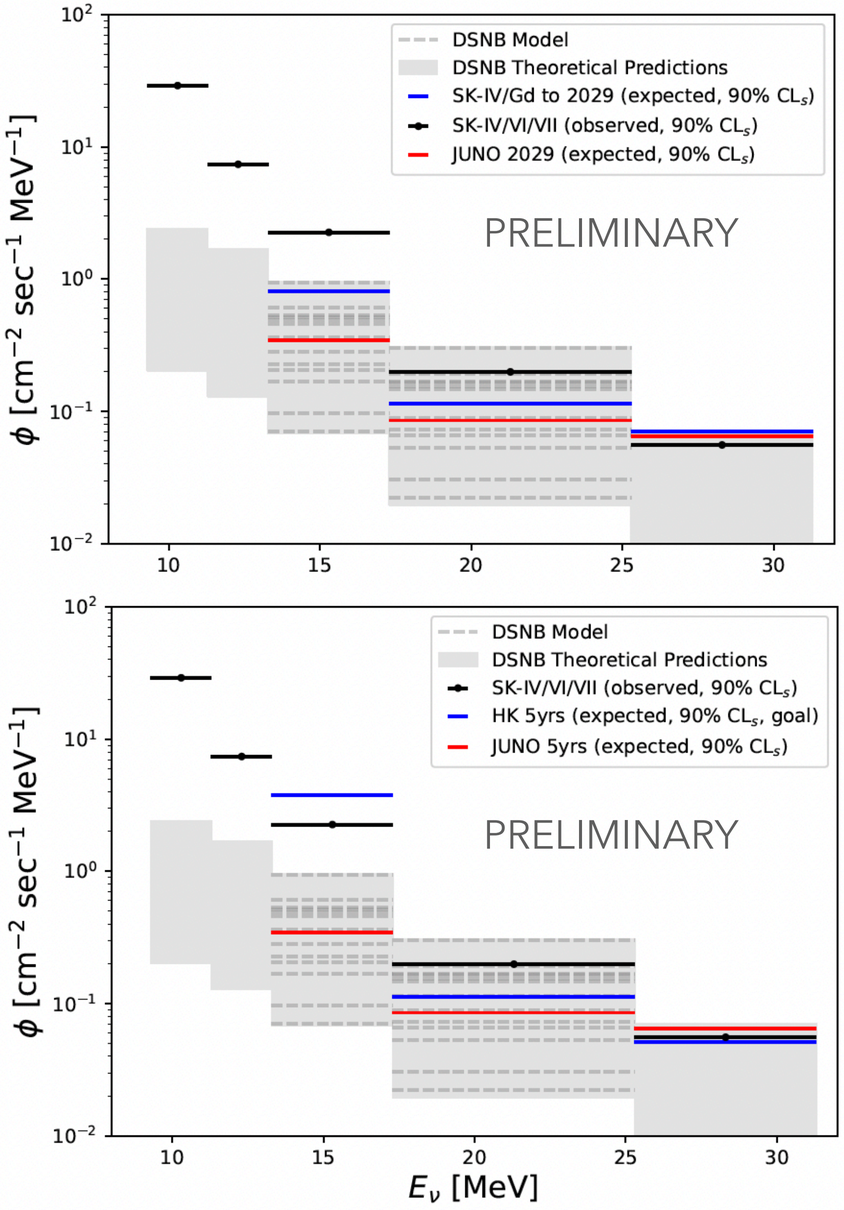


Paper soon-to-be released for the analysis of SK-Gd data.

DSNB Model-independent Binned Analysis

Projected sensitivity

- **Prospective work** by A.D. Santos [PhD thesis]: used information from HK and JUNO design reports to estimate sensitivities.
- As expected, **JUNO highly competitive at low energy** due to enhanced neutron tagging owing to LS light yield.
- **At high energy**, Water Cherenkov detectors (SK-Gd and HK) **bring similar or even better constraints**.



Conclusion

- DSNB is an exciting probe to study supernovae and neutrino properties.

- The Gd-era of the SK experiment went successful in improving the sensitivity to the DSNB signal.

  ➡ Rejection of the background-only hypothesis at the 2.3σ level across all SK phases.

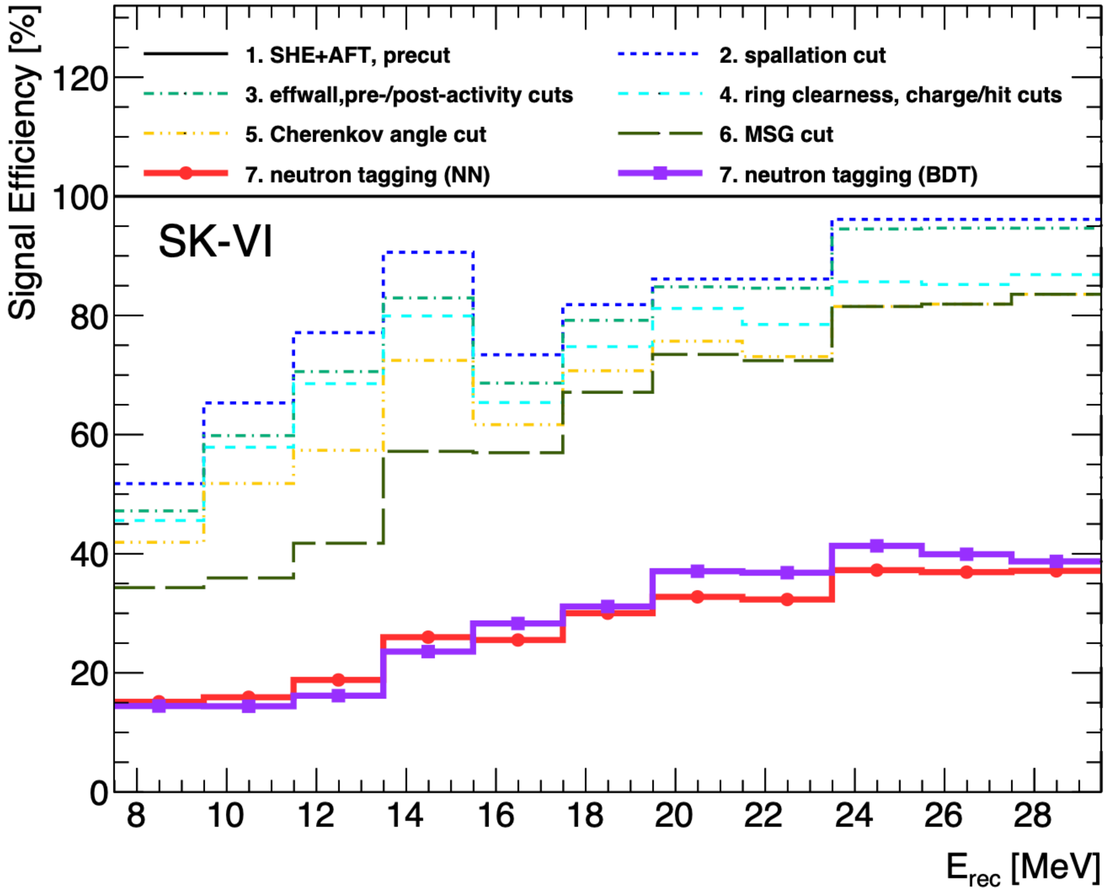
  ➡ Stringent upper limits, for neutrino energy > 17.3 MeV approaching the range of predictions.

- Looking forward to approaching evidence for DSNB in the upcoming years with SK-Gd, HK and JUNO !

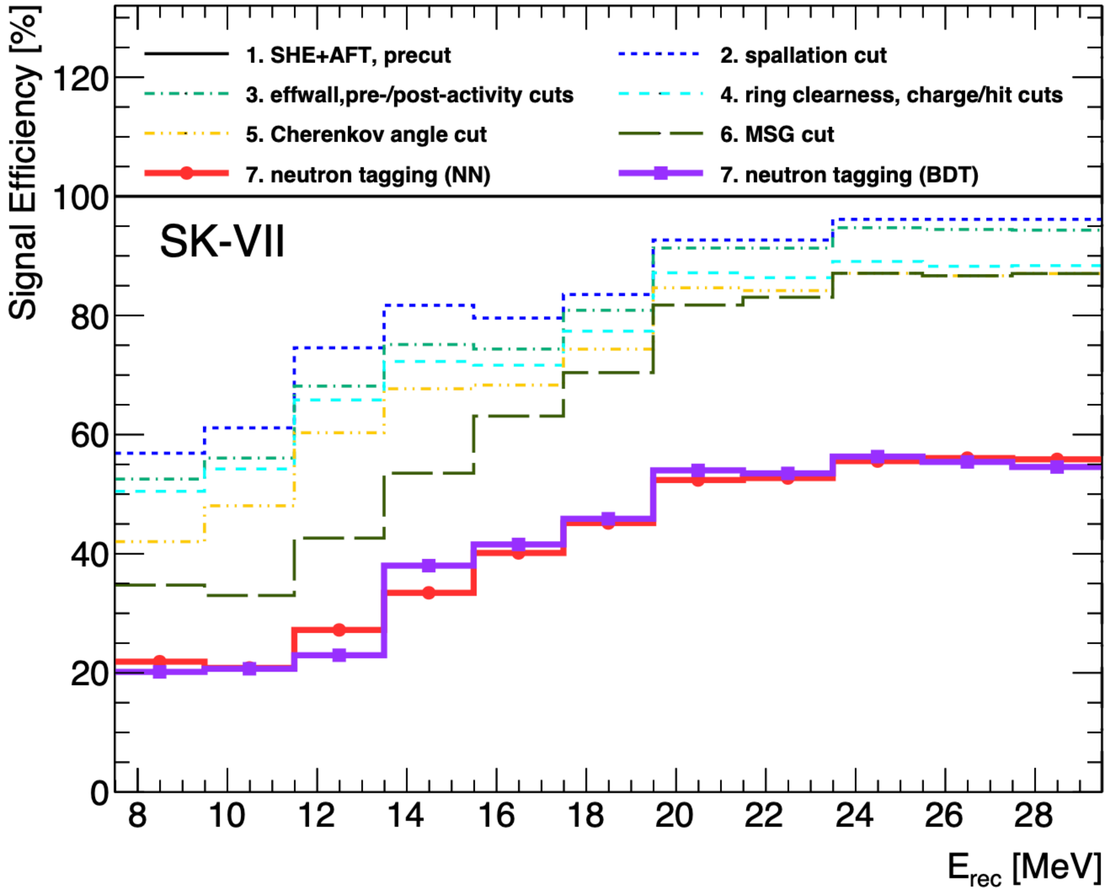
Backup

DSNB signal efficiency

SK-VI

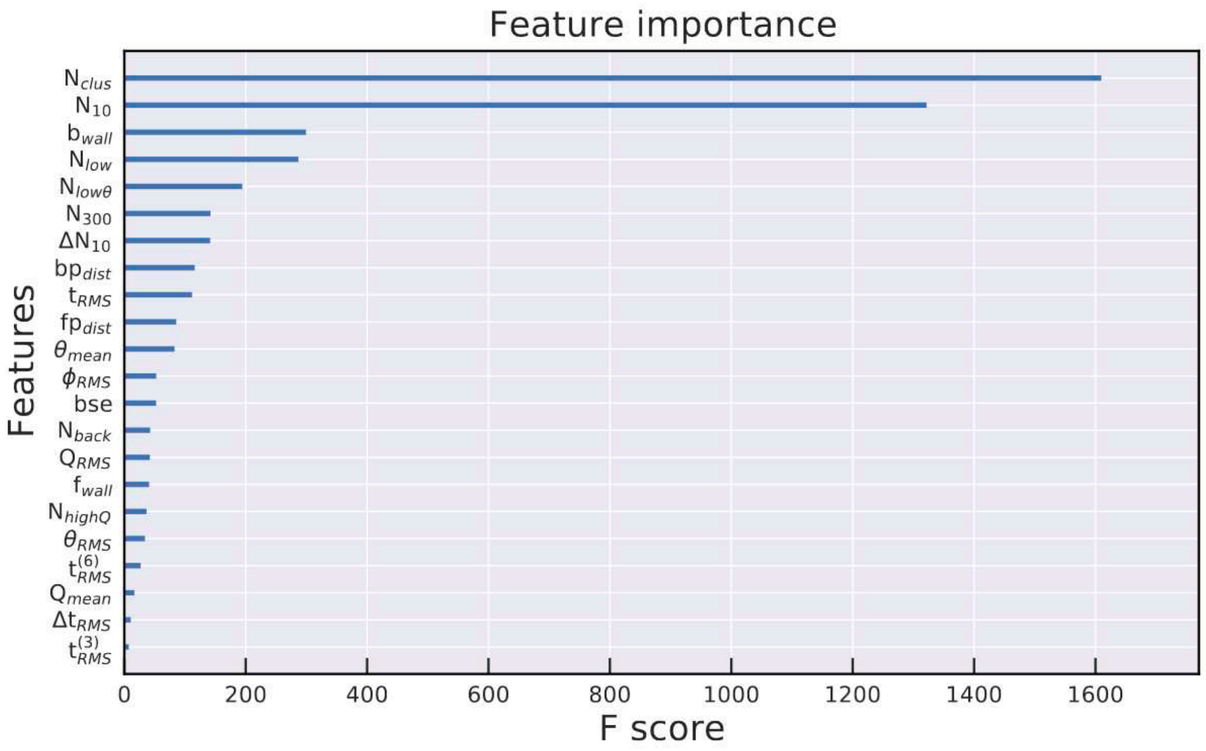


SK-VII

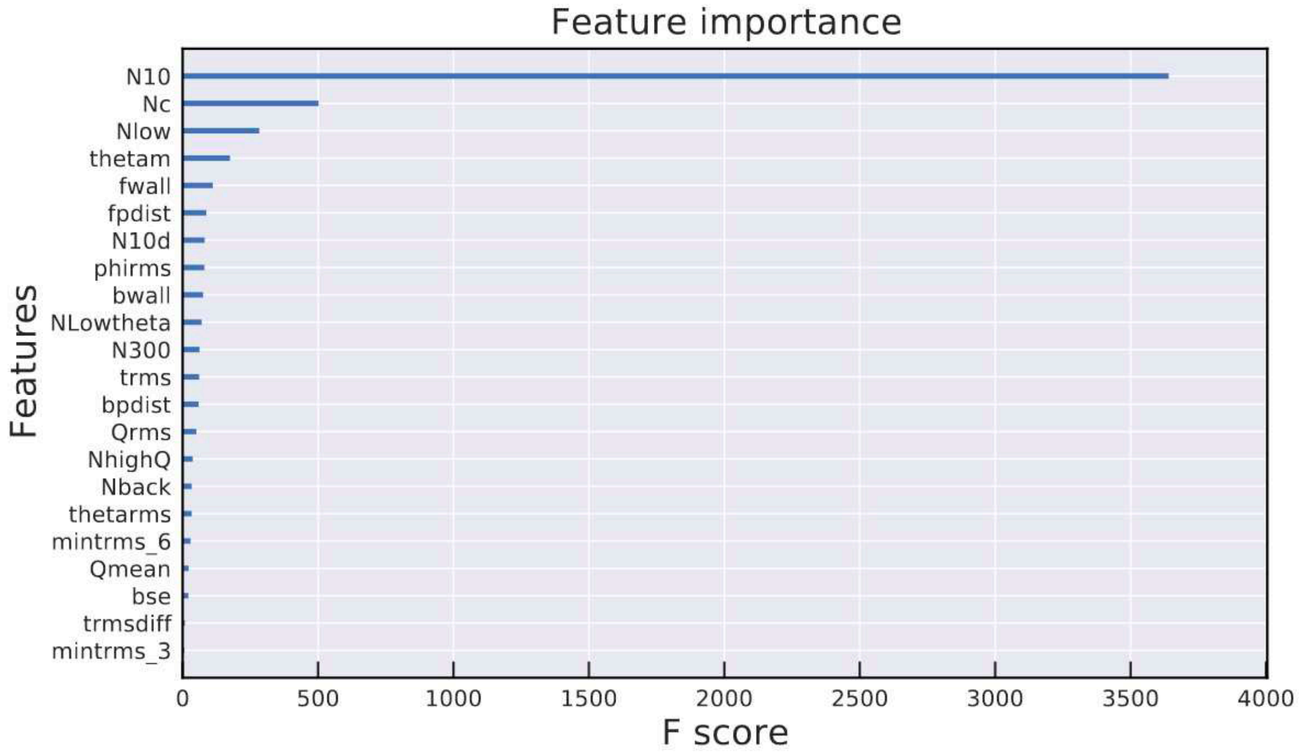


BDT features importance

SK-IV



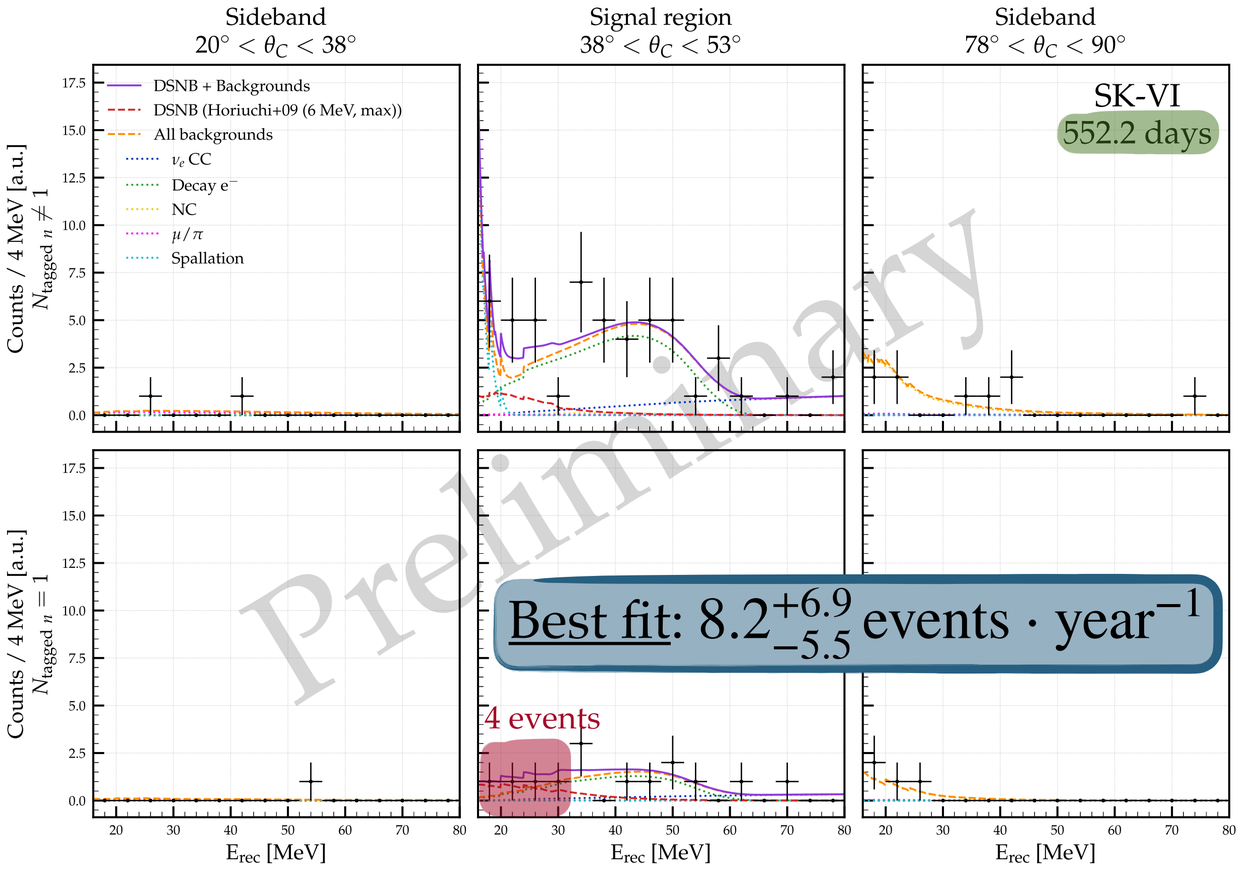
SK-VI



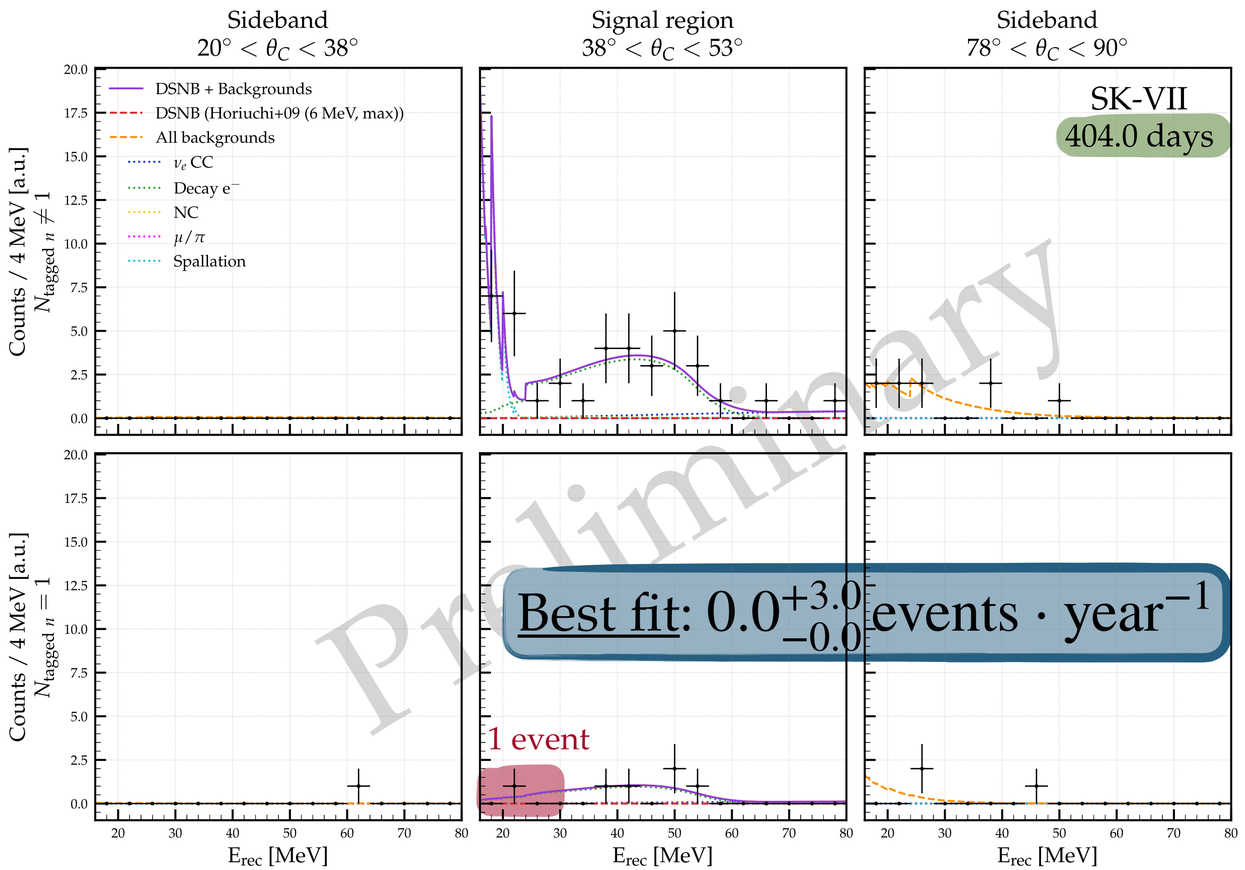
Discovery analysis - DSNB Model-dependent spectral fit

Fitted spectra

SK-VI

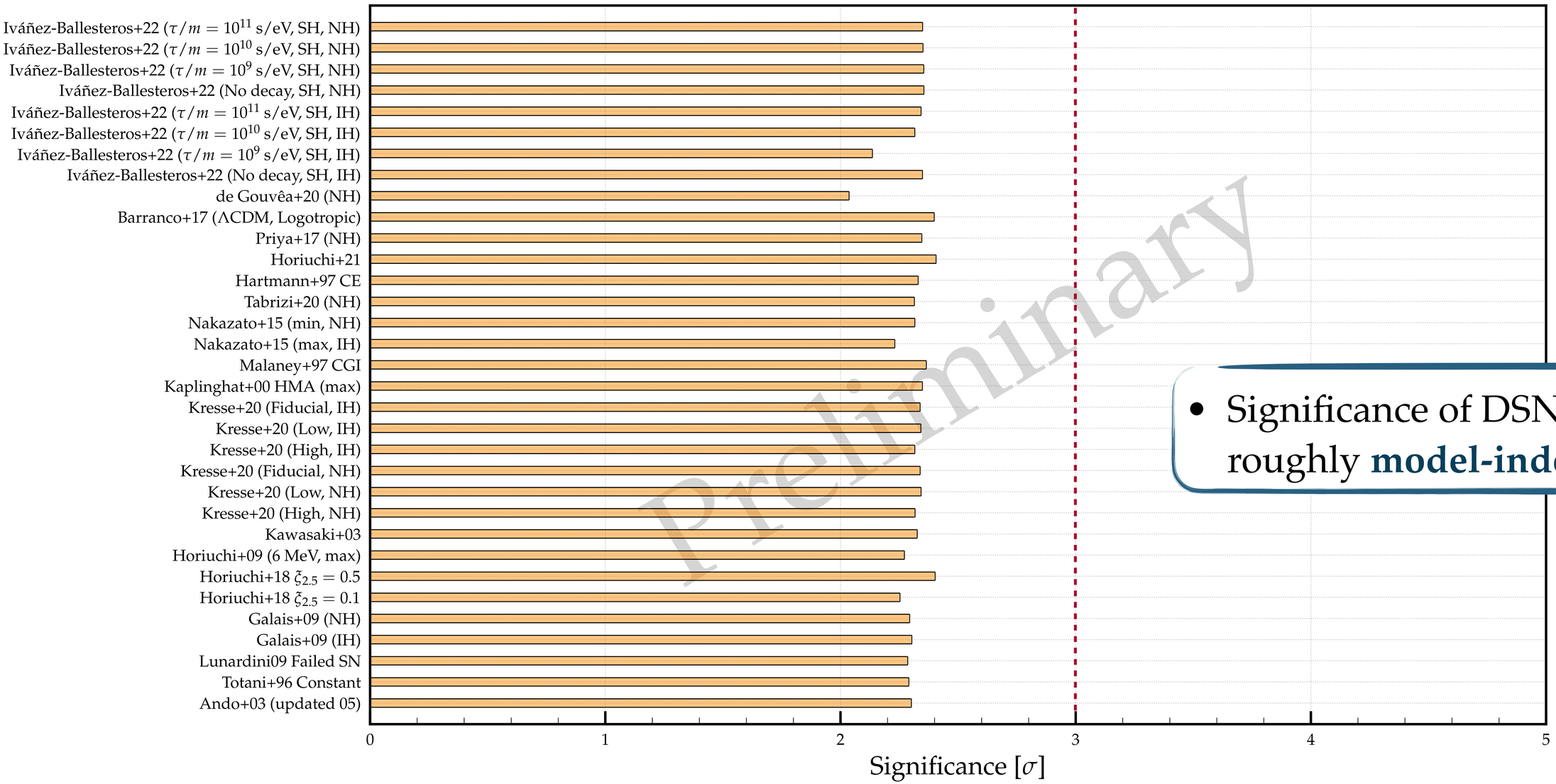


SK-VII



Analysis - DSNB Model-dependent spectral fit

Background-only hypothesis rejection



- Significance of DSNB signal is roughly **model-independent.**