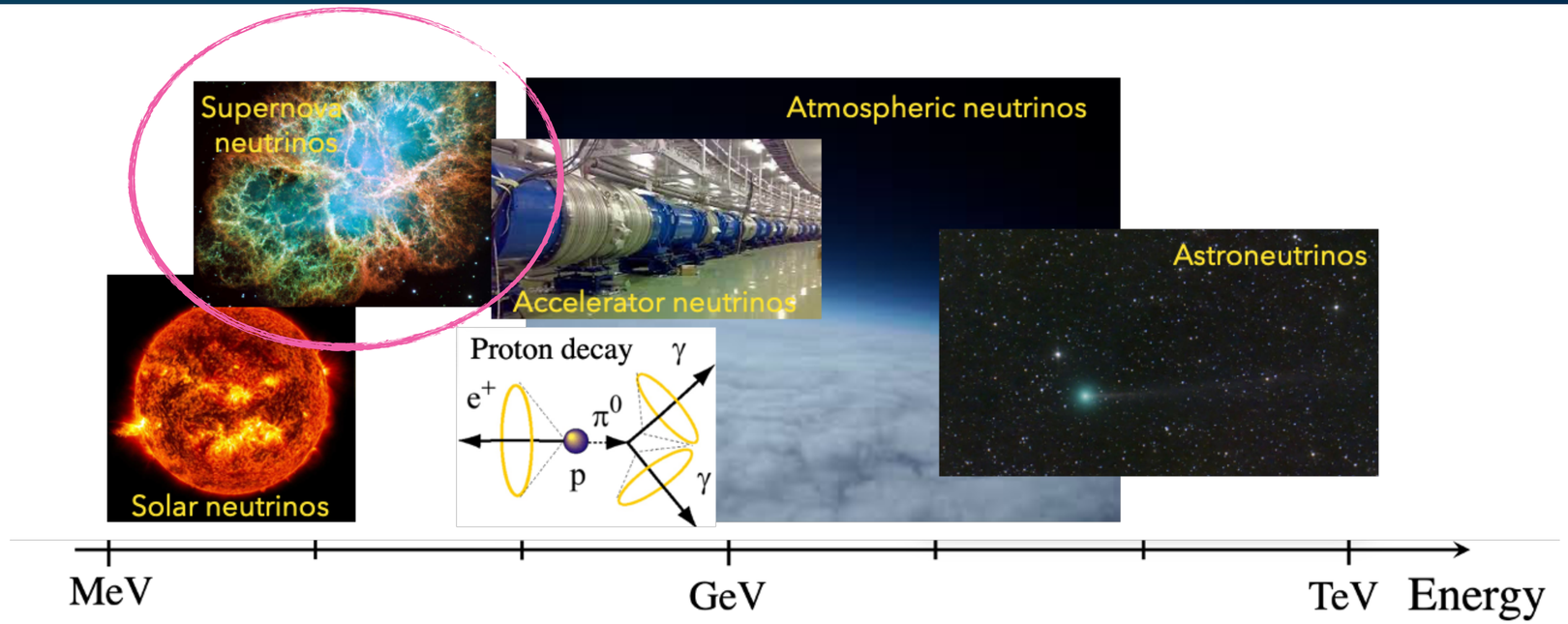
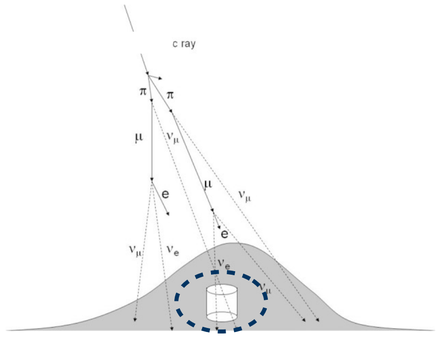
Latest results of the DSNB search at Super-Kamiokande

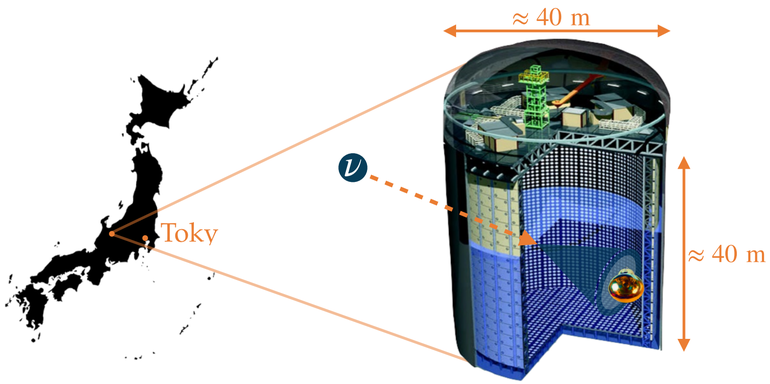
Rudolph Rogly - Laboratoire Leprince-Ringuet (CNRS/École Polytechnique)

EPS-HEP Conference — *July 07-11, 2025*

The Super-Kamiokande experiment







- Super-Kamiokande is a multi-purpose Cherenkov-based experiment with:
  - ➡ Reconstruction of vertex, direction, energy of impinging particles.
  - ➡ Multi-channel read-out of the Cherenkov signal of interacting particles, with **~11k PMTs**.
  - ➡ **Wide energy range** (from MeV to TeV) and **various sources** (e.g. human-made, astrophysical…).

Diffuse Supernova Neutrino Background

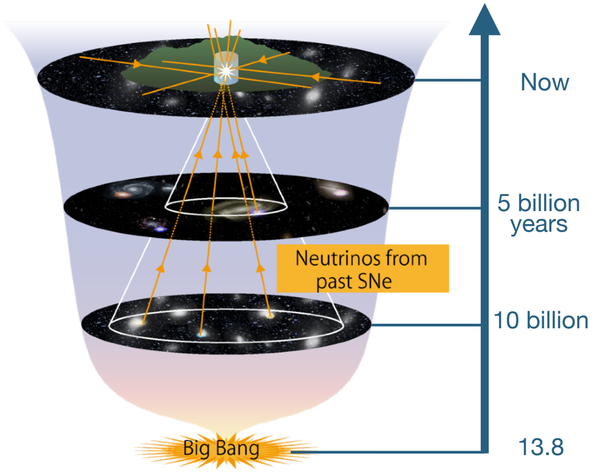
Core-Collapse Supernova (CCSN)

- 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**.

➡ Study the integrated flux of supernova neutrinos originating from all CCSN events in the history of the universe, so-called **Diffuse Supernova Neutrino Background**.



DSNB flux prediction

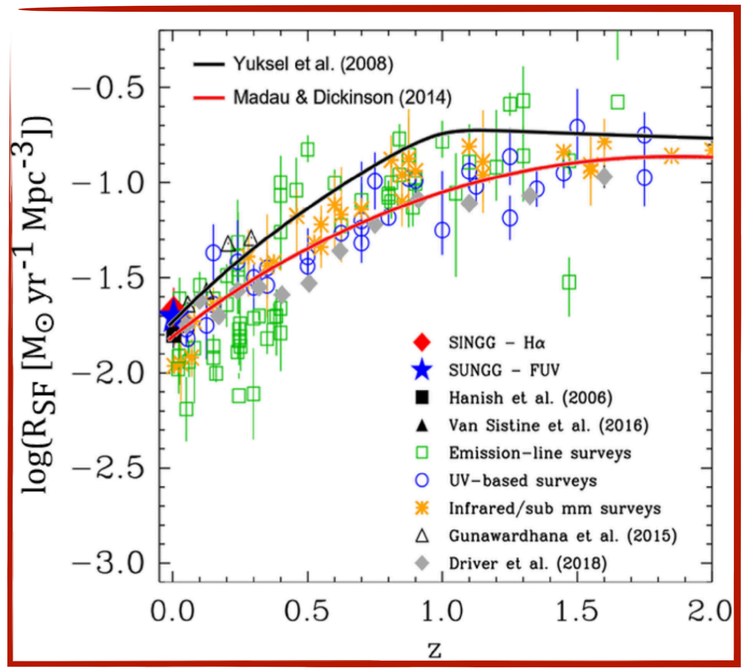
- DSNB flux is given by:

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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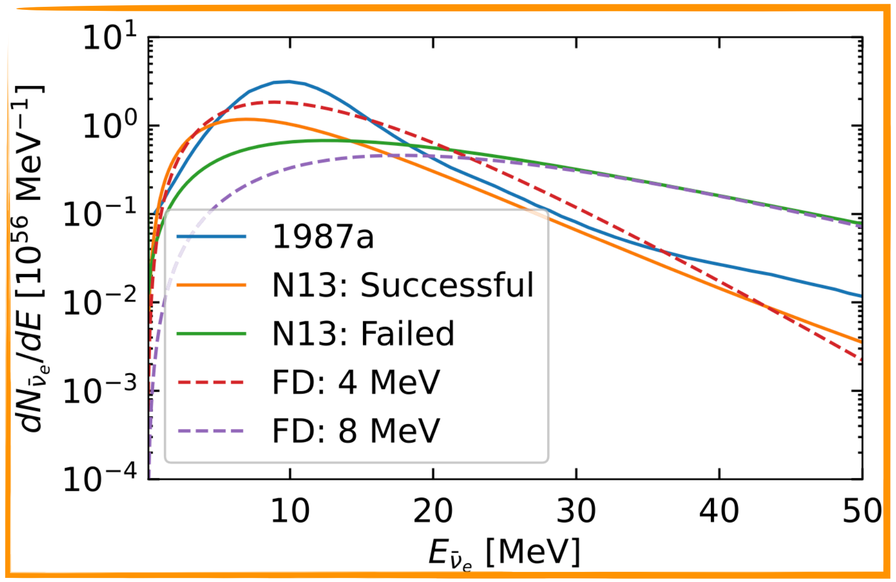
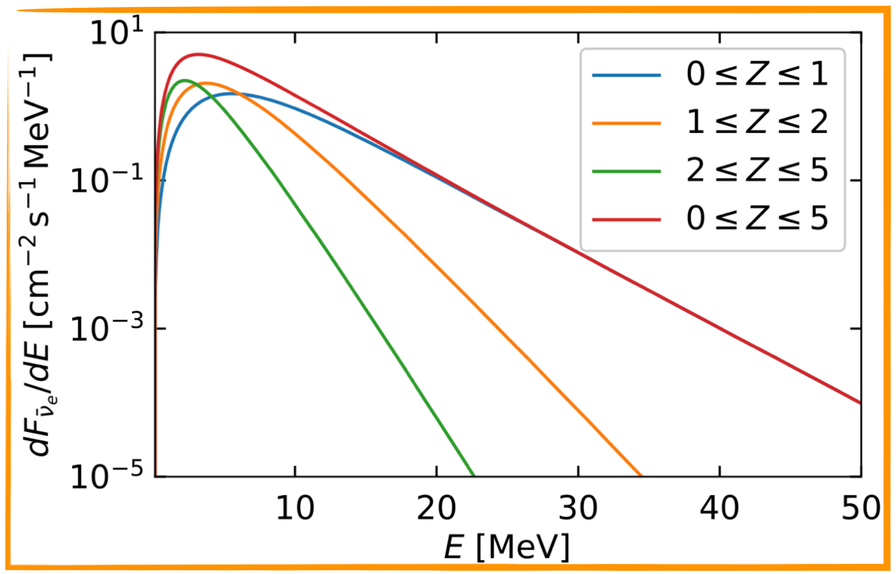


Example model of neutrino spectrum for successful & failed supernovae[1]



Redshitft-dependent neutrino spectrum[1]

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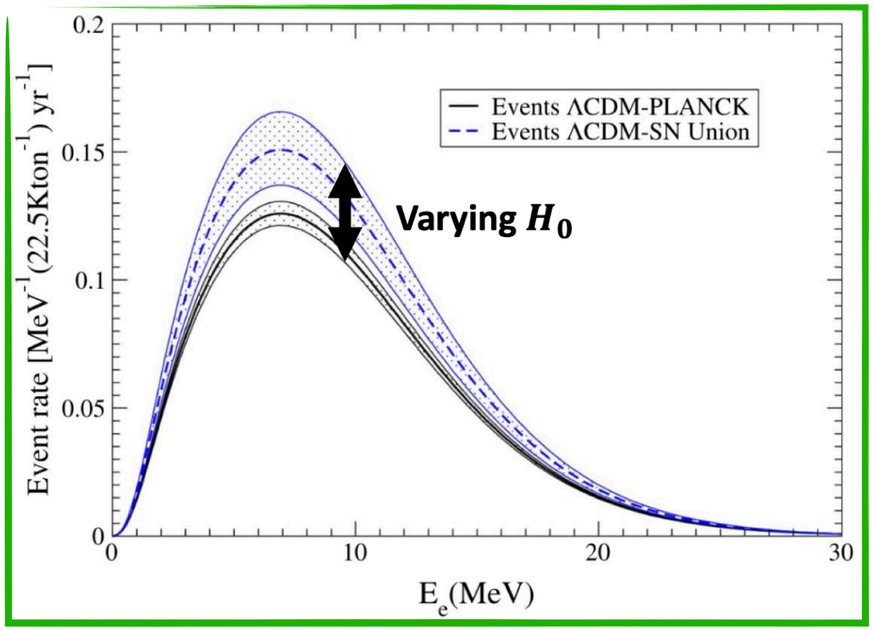

Expected DSNB event rate for different values of Hubble constant[2]

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

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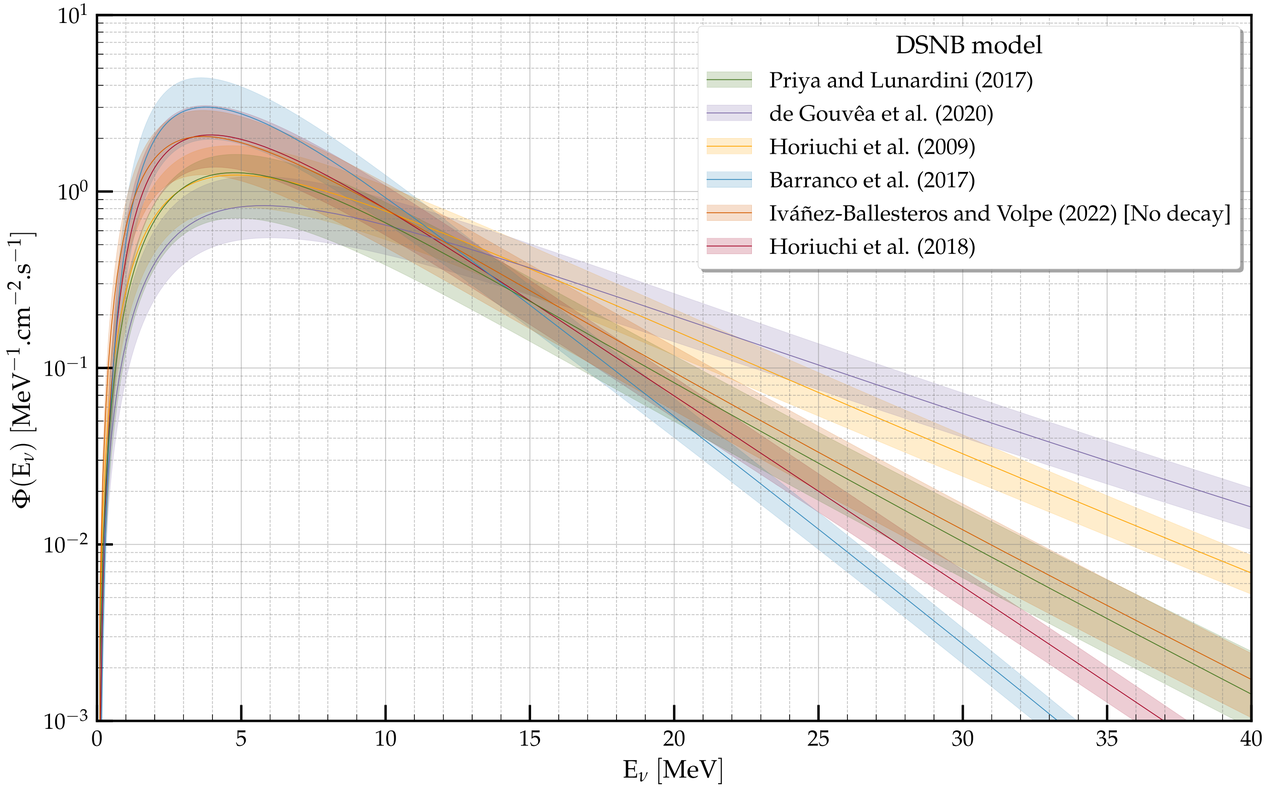
Redshift-dependent SN rate

Universe expansion

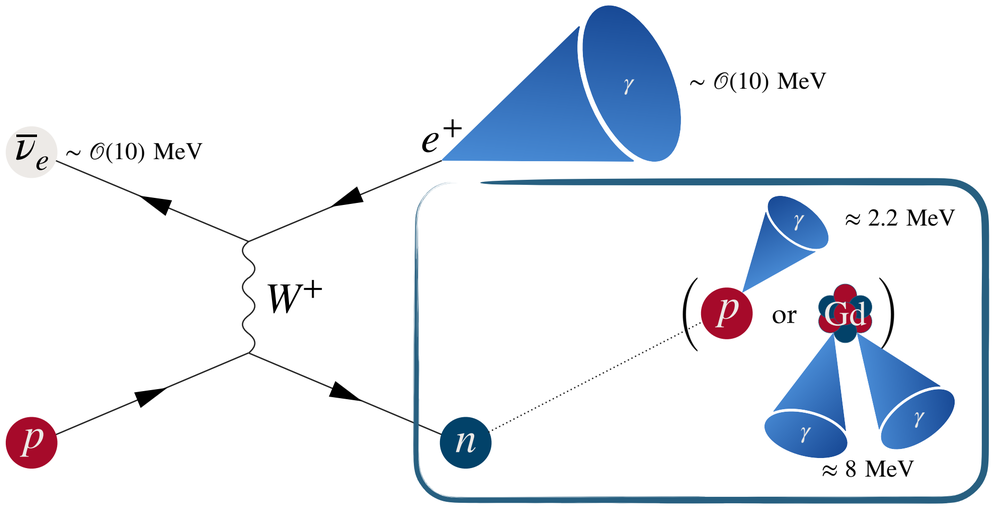
Rich phenomenology, e.g.:

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



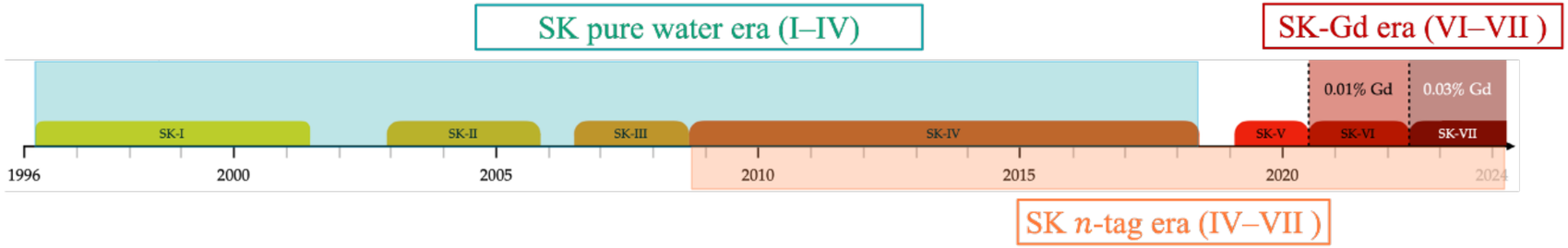
DSNB events at SK

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



Neutron capture delayed signal

Phys. Rev. D 104, 122002, 2021



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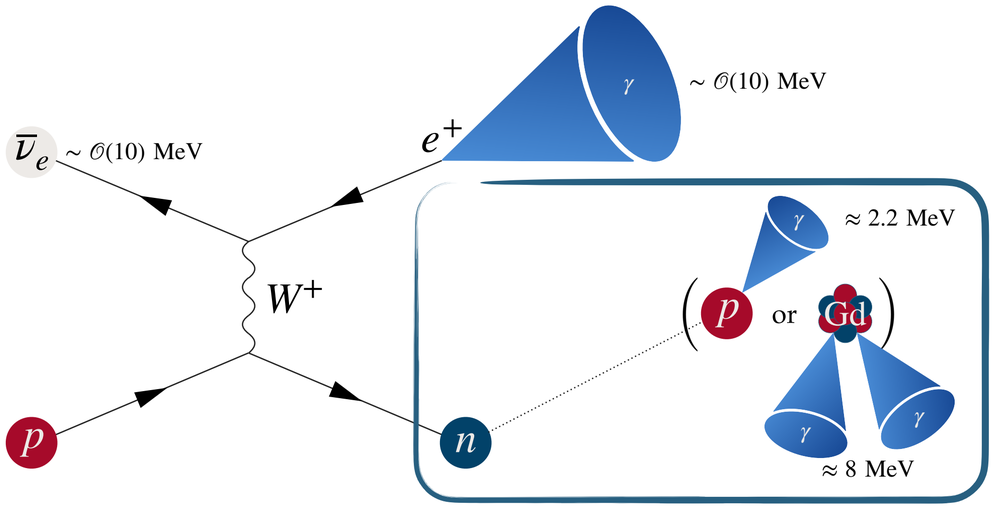

Neutron capture delayed signal

	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

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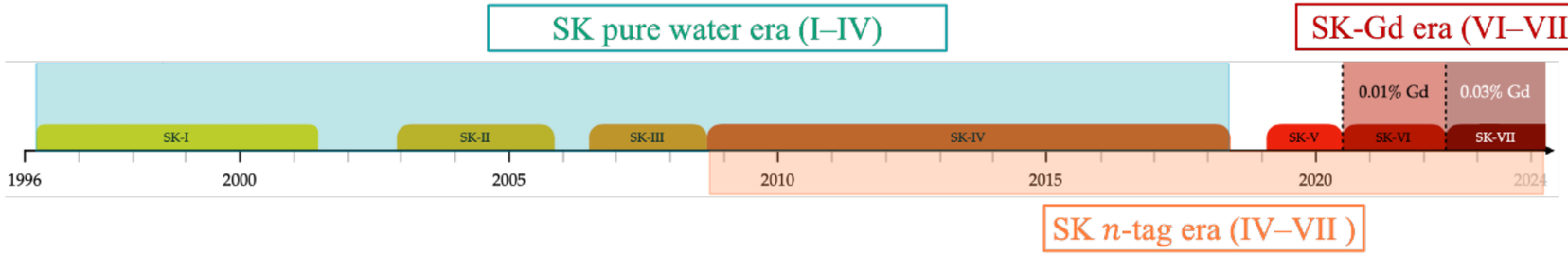

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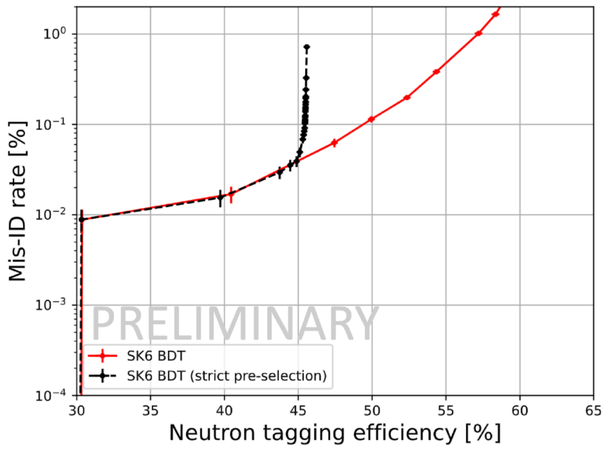

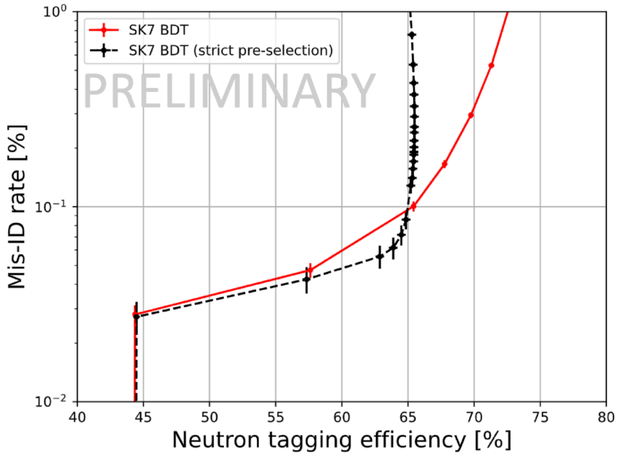

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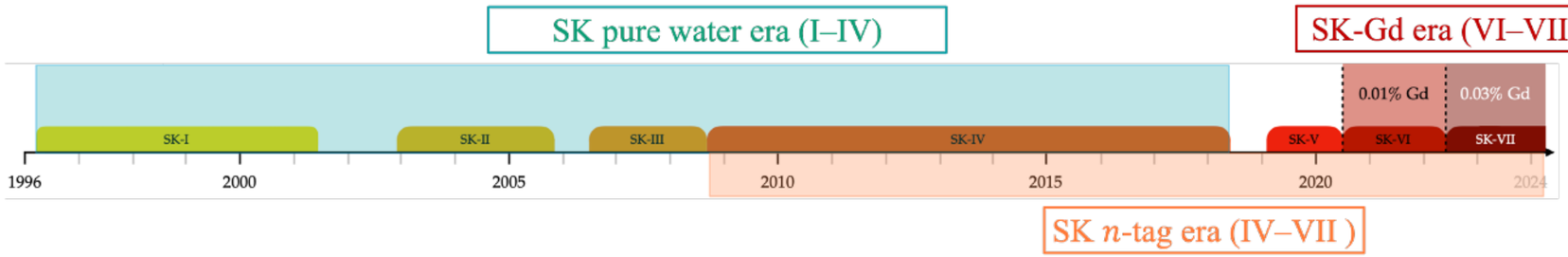
n-capture on Gd	0 %	50 %	75 %
Time constant	~210 μs	~115 μs	~65 μs
n-detection efficiency	~25%	~40%	~60%

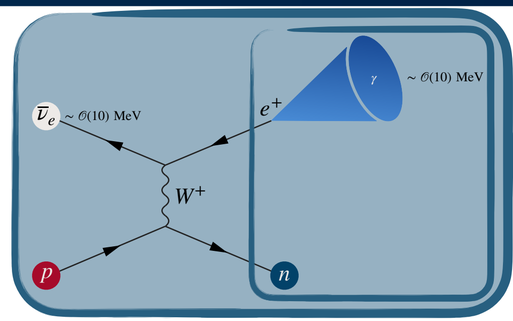
Phys. Rev. D 104, 122002, 2021



Two neutron-tagging algorithms:
Boosted Decision Tree & Neural Network

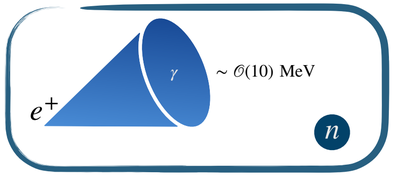
Background events at SK

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

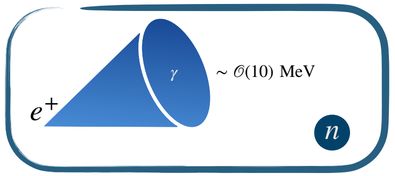


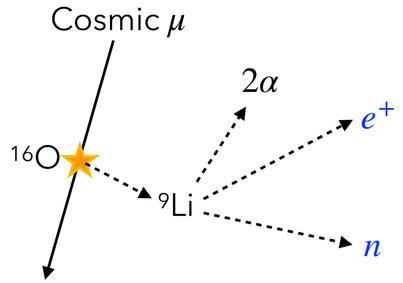
DSNB event

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

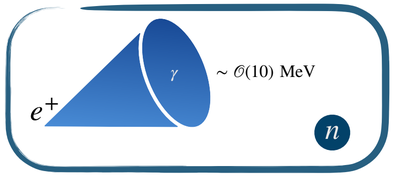


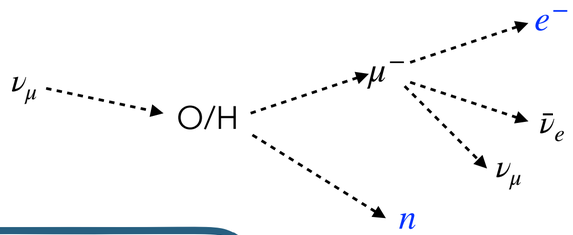
- Spallation-induced:
  - From cosmic muons going through SK (**~2 Hz**) : **dominant background in the low energy end** of the analysis window.



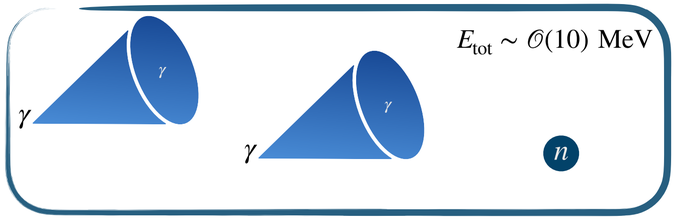


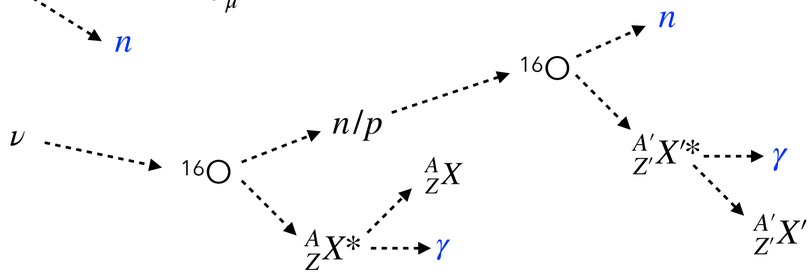
- Atmospheric ν - Charged-Current (CC)





- Atmospheric ν - Neutral-Current (NC)

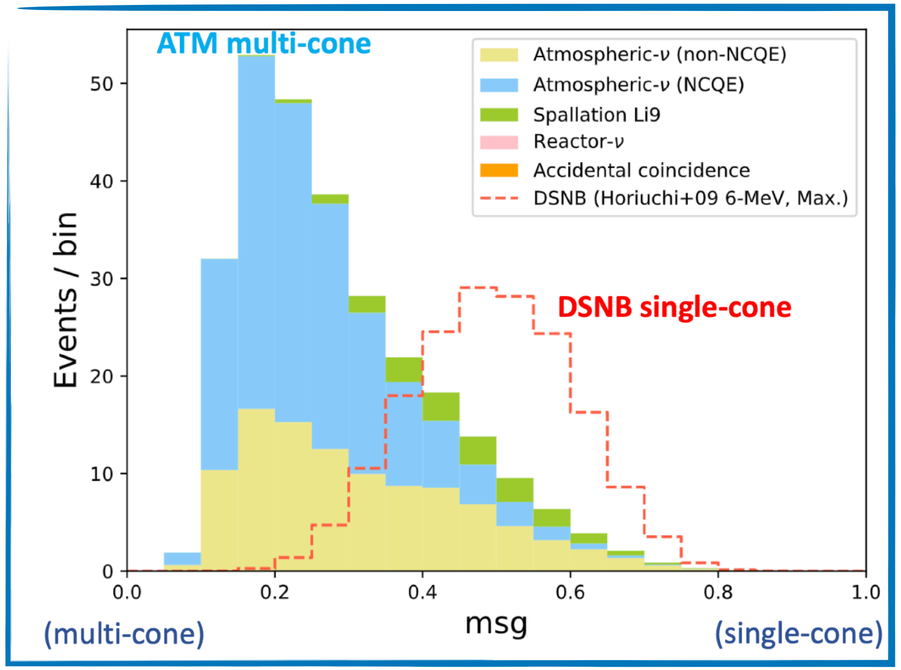




Data reduction

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

- *1st reduction cuts:* Noise reduction, data quality, fiducial volume cuts in particular.
- *2nd reduction cuts:* Target spallation events, neutron clouds, i.e. events correlated in space & time with a parent cosmic ray muon.
- *3rd reduction cuts:* Target atmospheric neutrino background events: e.g. pion-likeness cut, decay electron cut, and **newly introduced single-cone likeness** (aka **MSG**) cut to remove multi-cone events.



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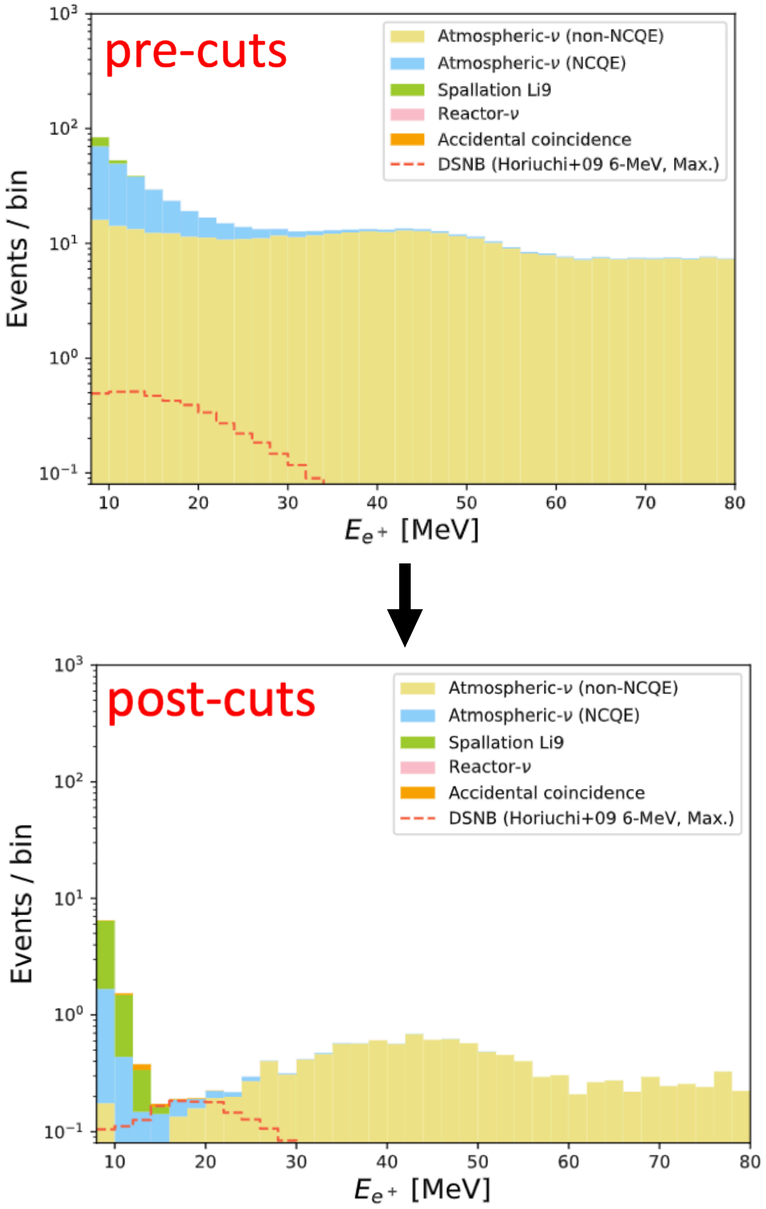


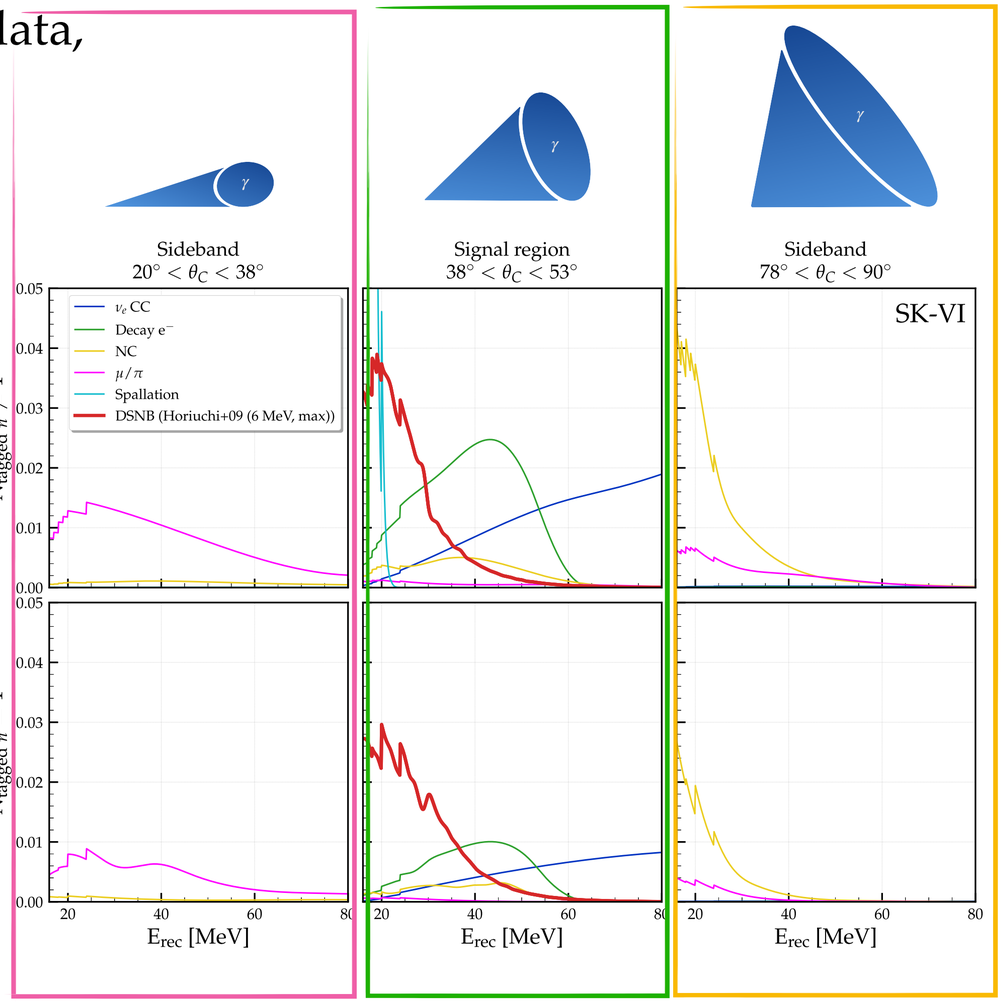
DSNB analysis - Model-dependent spectral fit

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,
  - ➡ *Medium* θ_C: **Signal** & **backgrounds** (spallation, decay electrons, NCQE multi-cone events, atmospheric ν_e).



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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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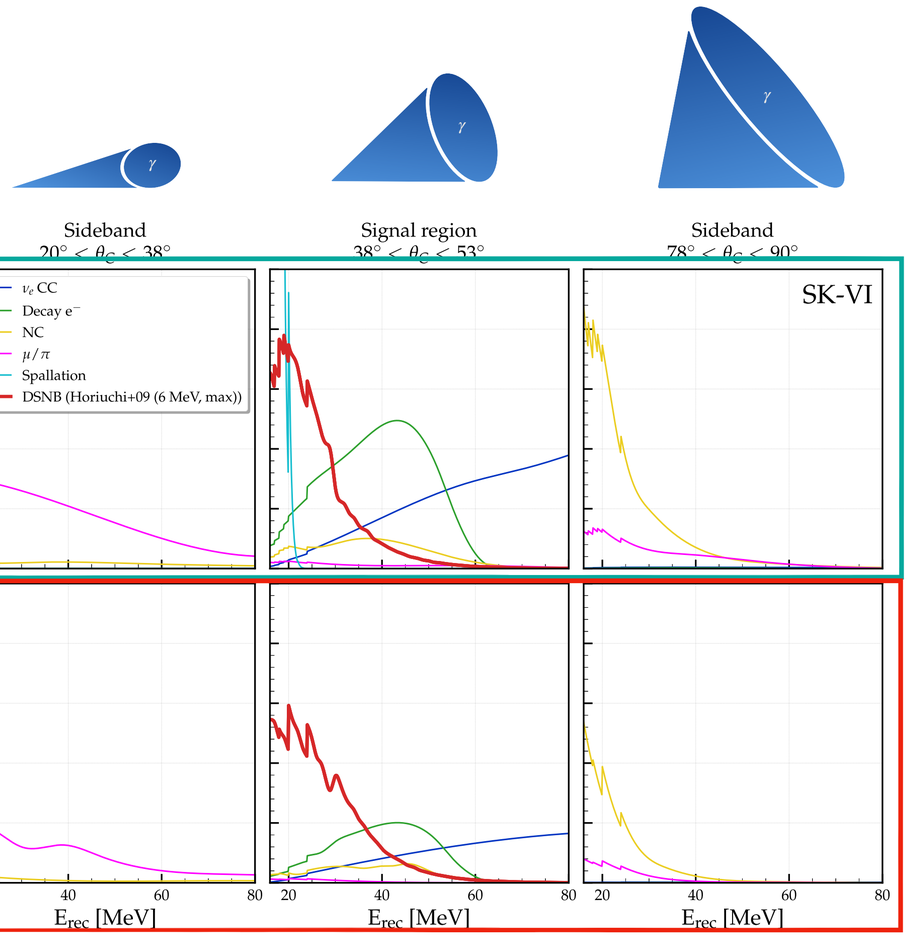

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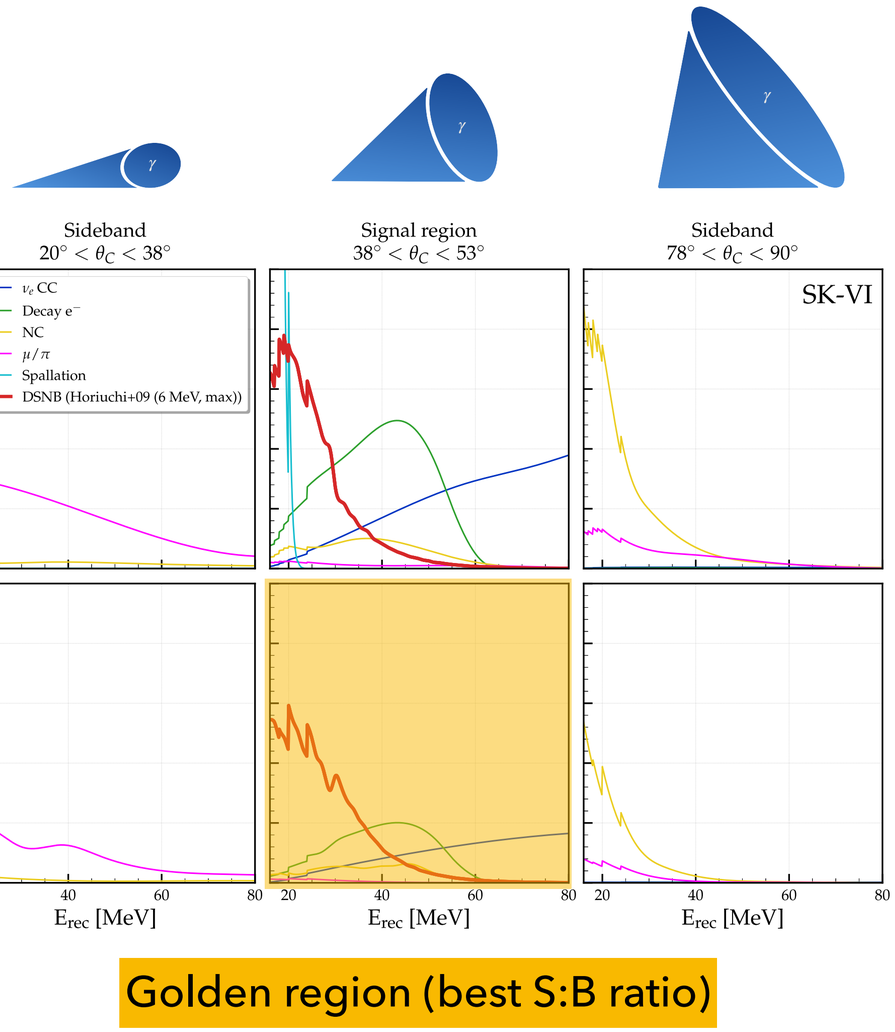

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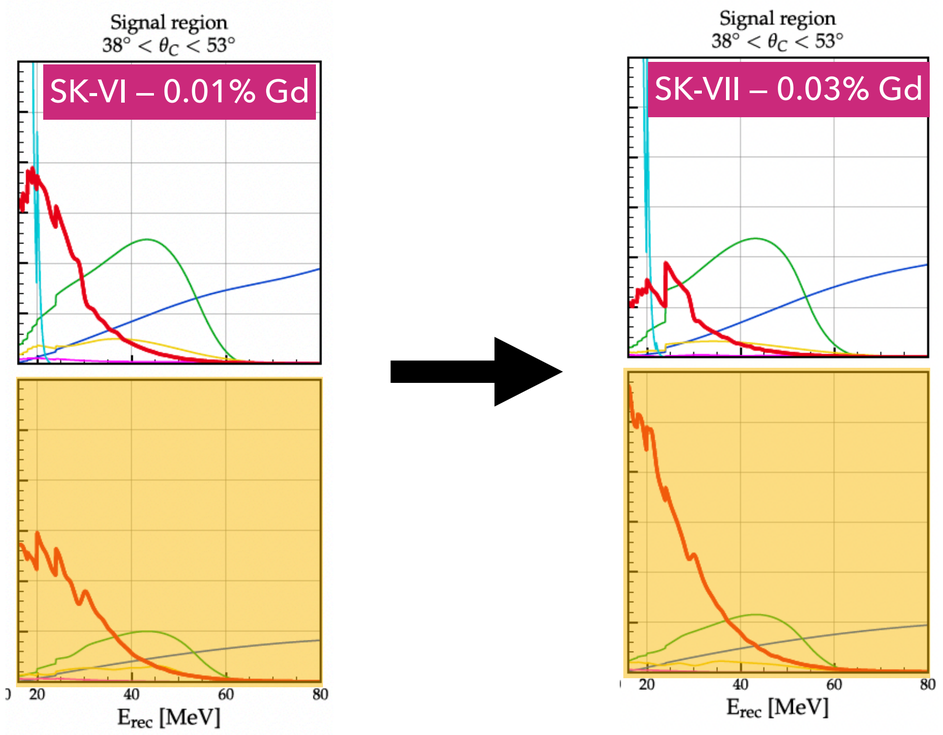
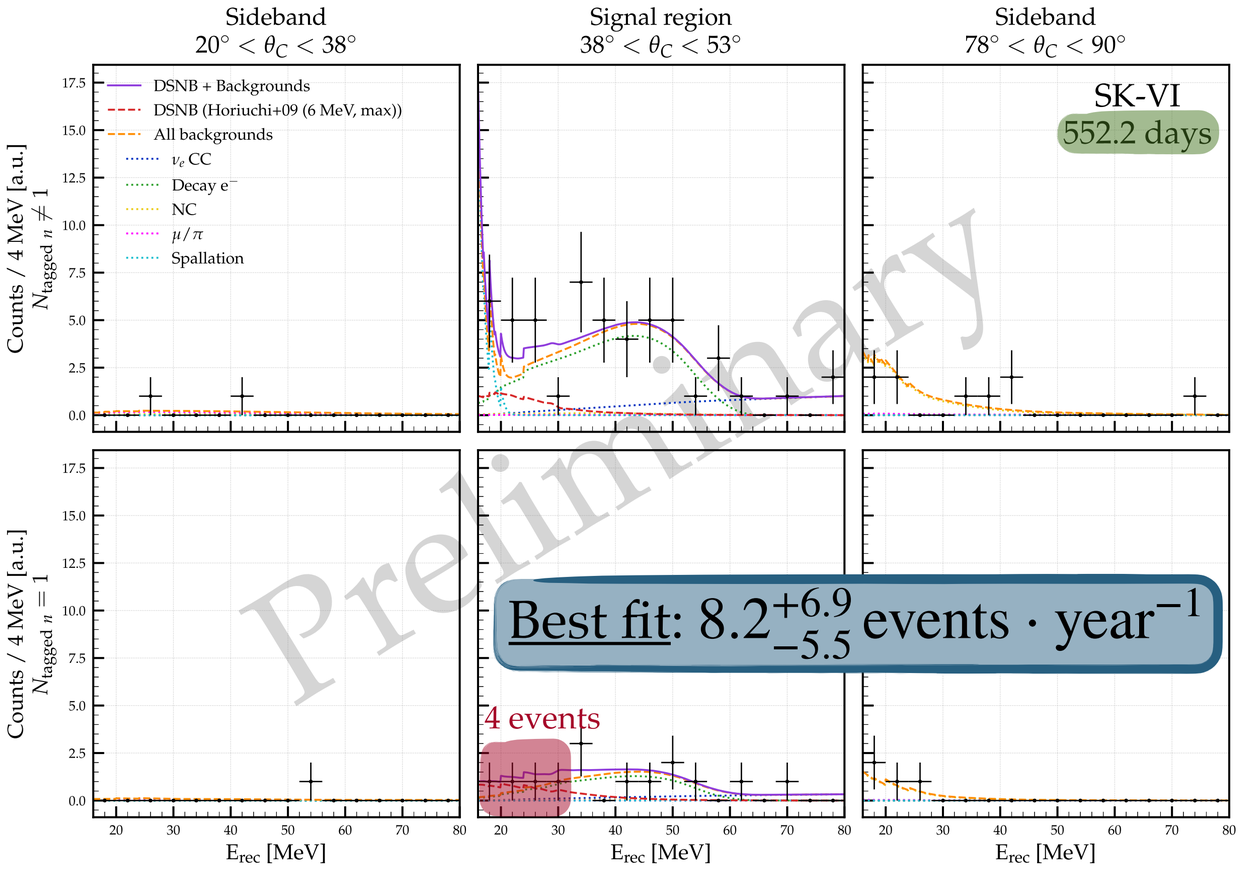


Gd-loading enrich the golden region in DSNB signal.

DSNB analysis - Model-dependent spectral fit results

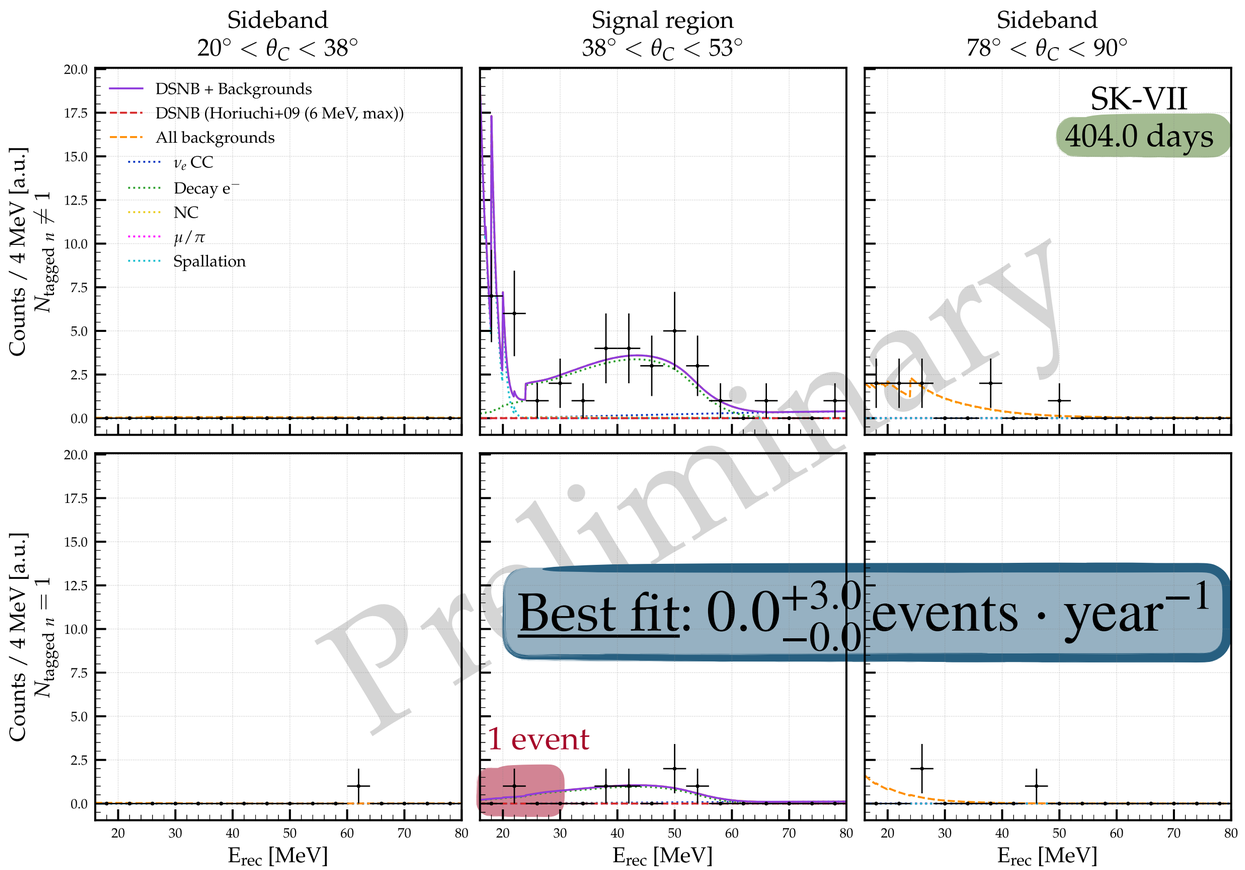
Fitted spectra

SK-VI



Best fit: $8.2^{+6.9}_{-5.5}$ events · year^{-1}

SK-VII



Best fit: $0.0^{+3.0}_{-0.0}$ events · year^{-1}

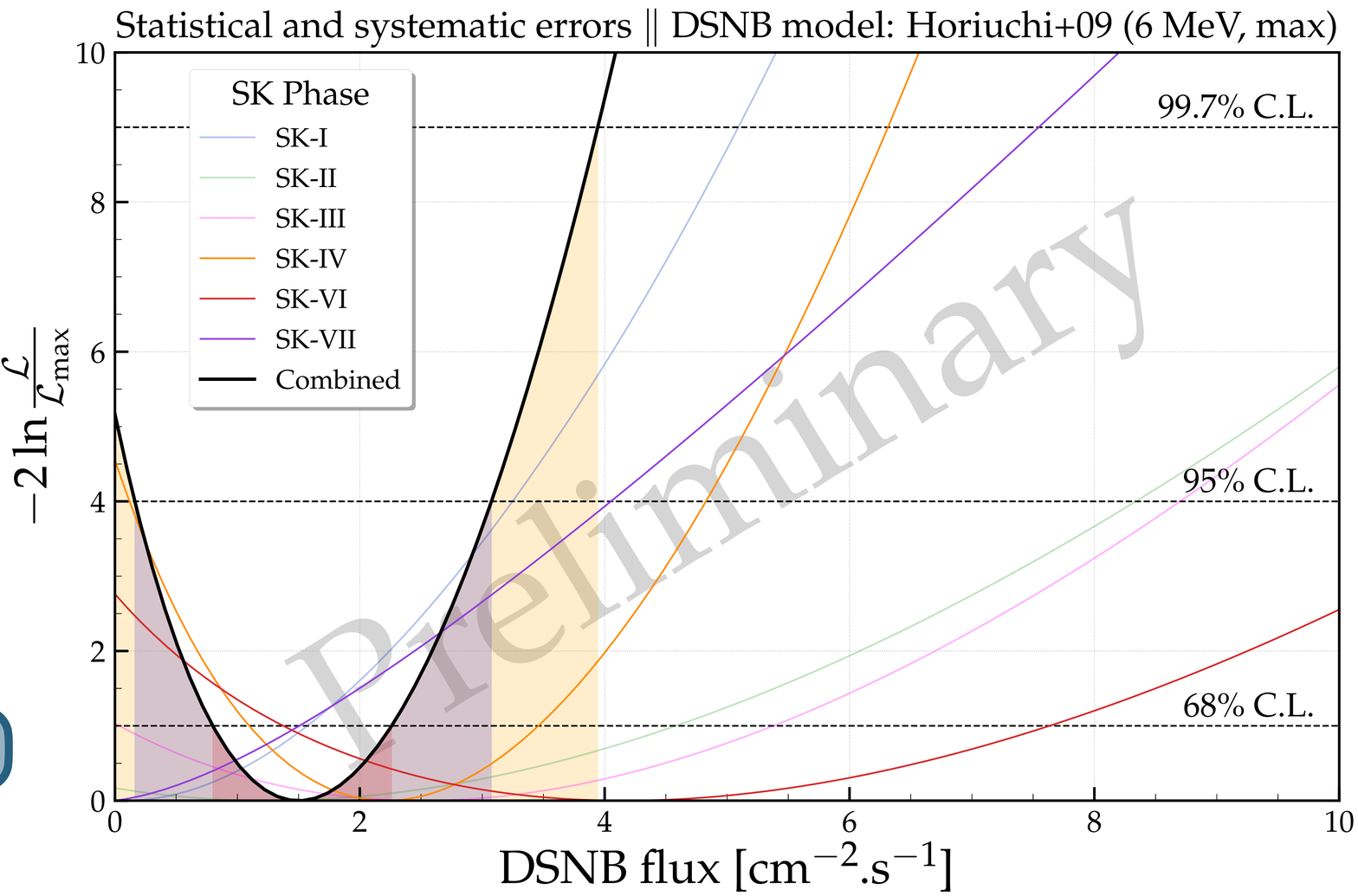
DSNB analysis - Model-dependent spectral fit results

Likelihood ratio test

Combined Results

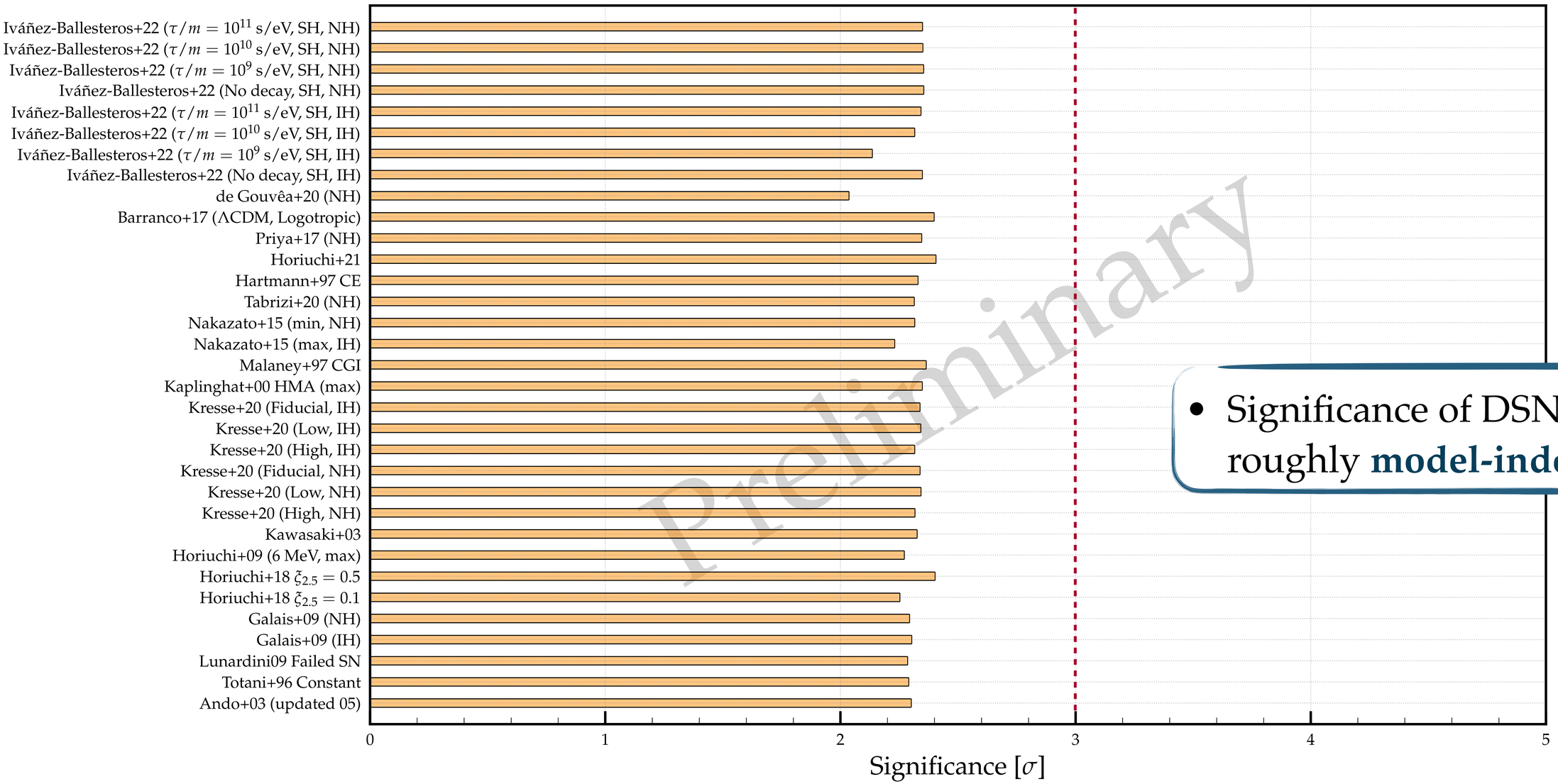
DSNB (Horiuchi+09)
Best fit rate $2.9\,\text{events}\cdot\text{year}^{-1}$
Best fit flux $1.4\,\text{cm}^{-2}\cdot\text{s}^{-1} > 17.3\,\text{MeV}$

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



DSNB analysis - Model-dependent spectral fit results

Background-only hypothesis rejection

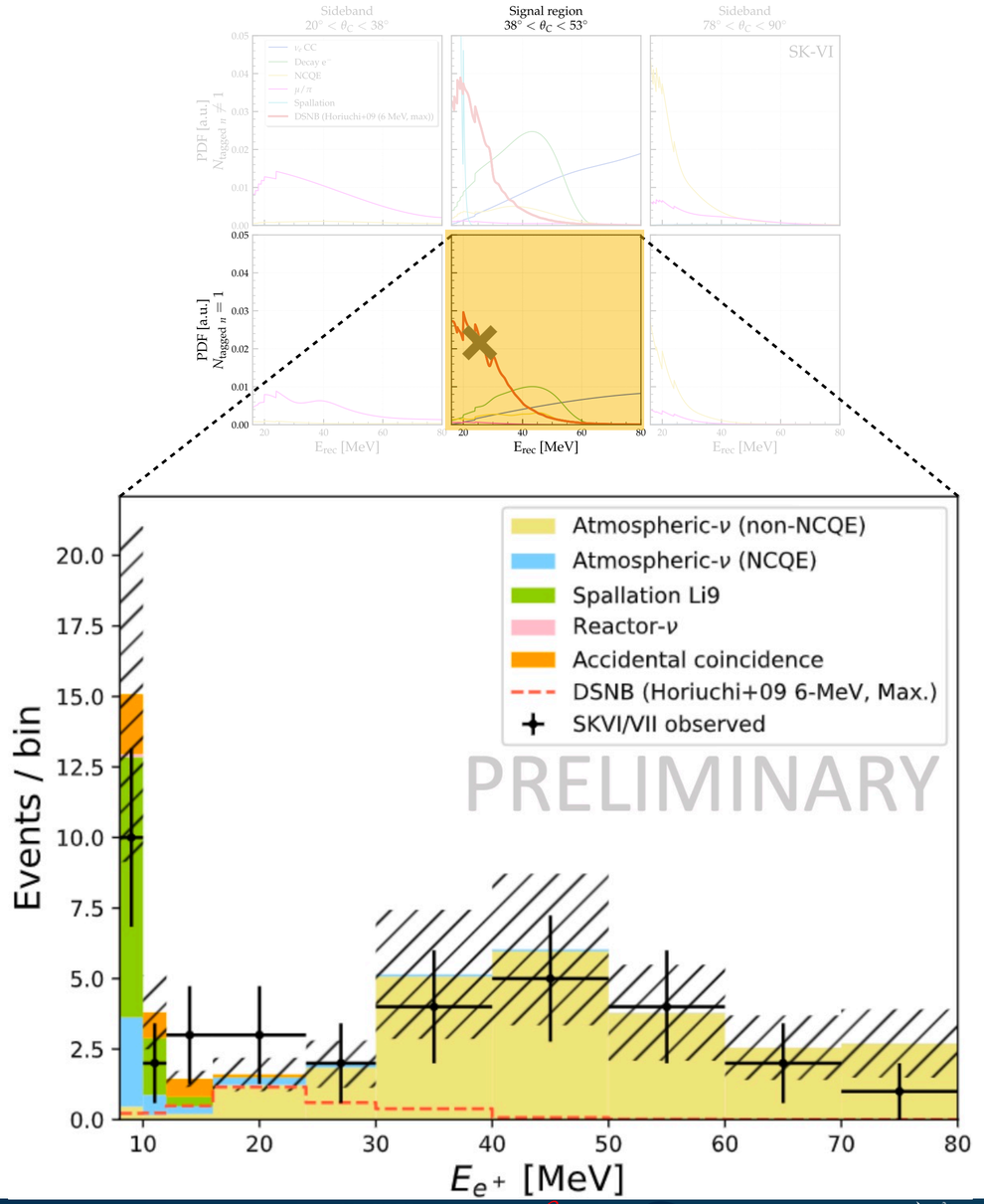


- Significance of DSNB signal is roughly **model-independent.**

DSNB analysis - Model-independent Binned Analysis

Principle

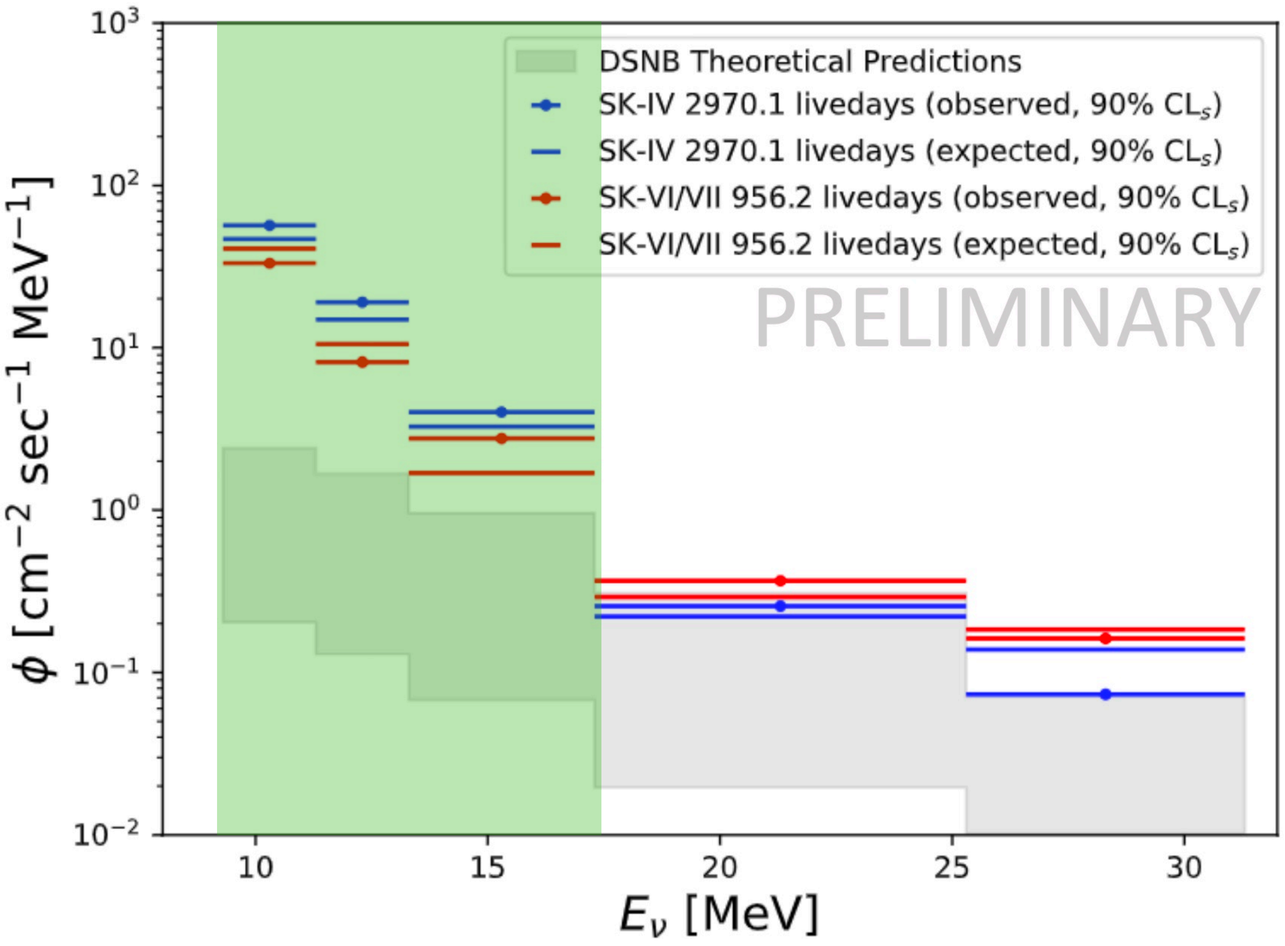
- No input DSNB model in this analysis.
- Predicted background fluxes, instead of inferring them from fit.
- In the golden region, look at the excess per bin observed wrt. background-only prediction.
- CLs approach to derive bin-by-bin upper limits.



DSNB analysis - Model-independent Binned Analysis results

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



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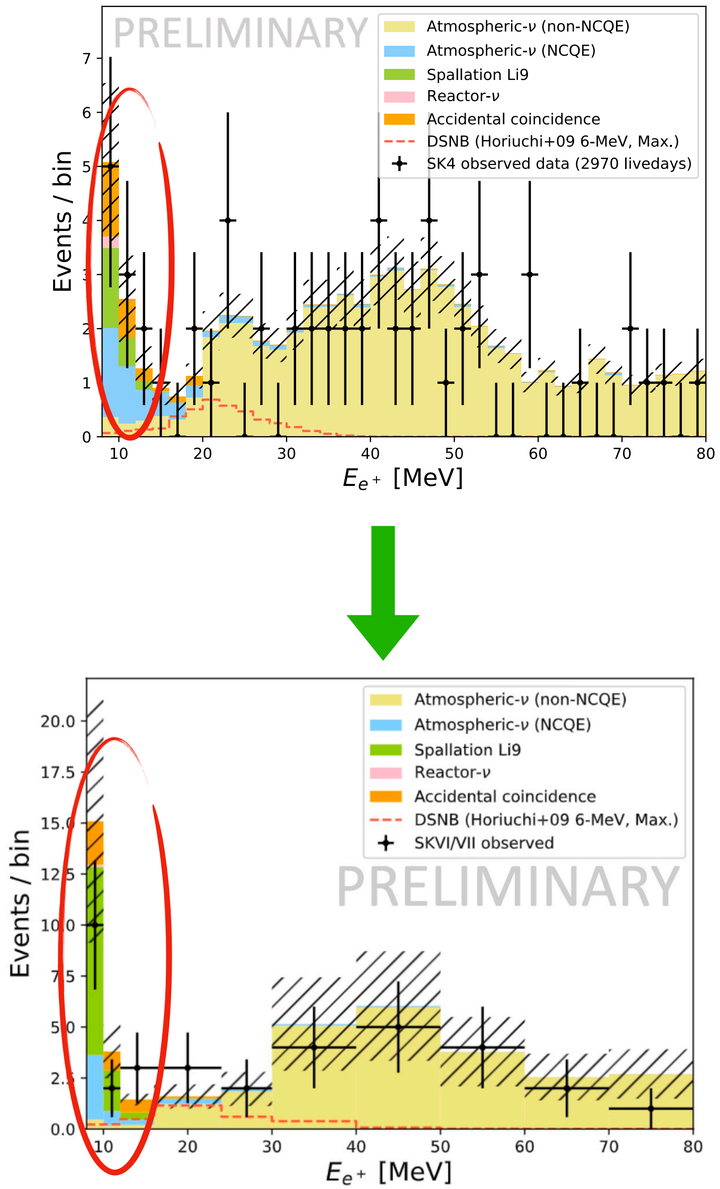

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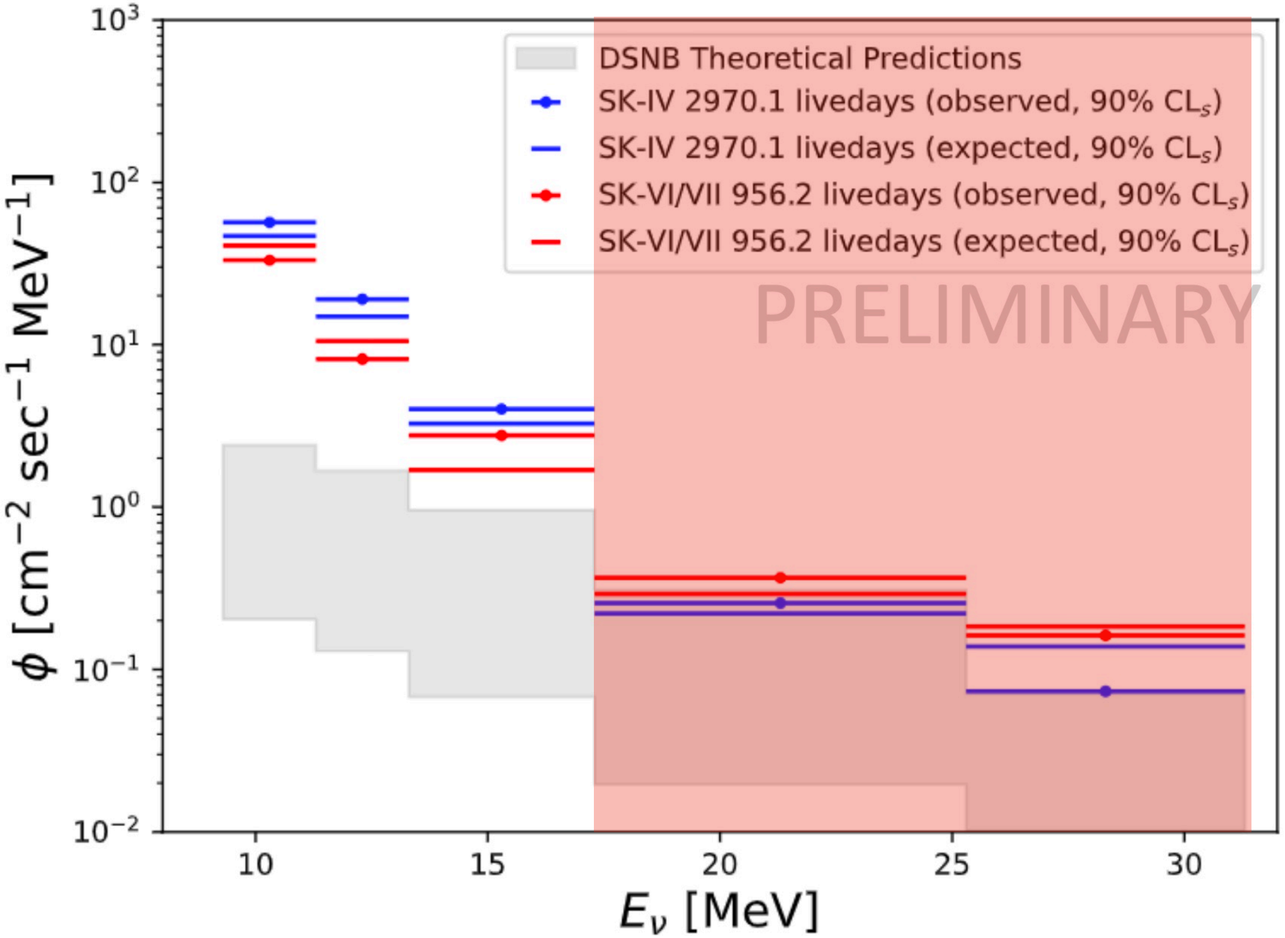
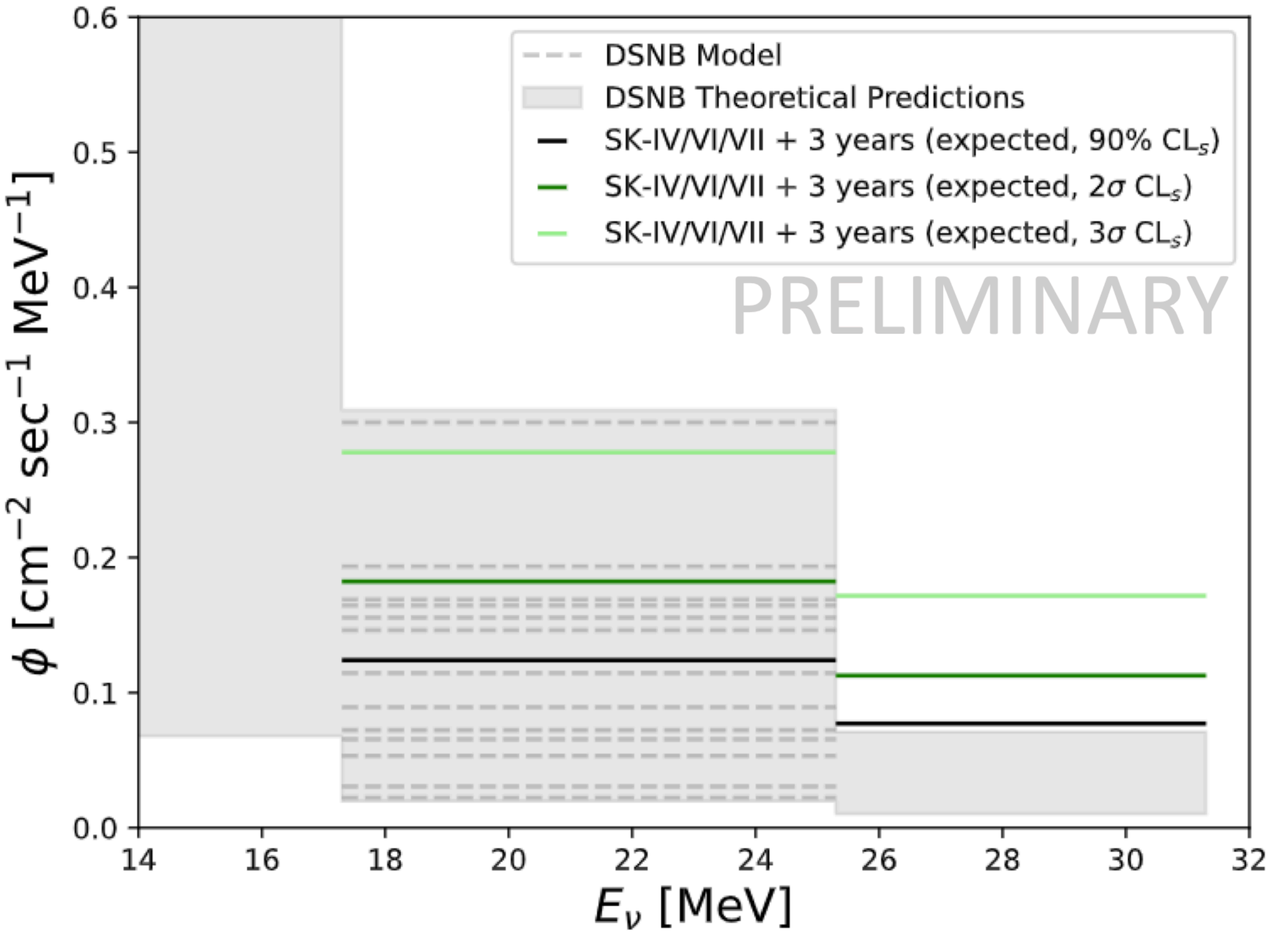
- In the intermediate energy region (common with spectral analysis), **upper limits approach the range of DSNB predictions.**



DSNB analysis - Model-independent Binned Analysis results

Projected sensitivity

- 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**.
- In the intermediate energy region (common with spectral analysis), **upper limits approach the range of DSNB predictions.**



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.

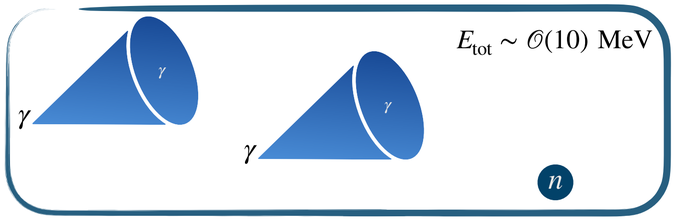
  ➡ Stringent upper limits, for neutrino energy > 17.3 MeV approaching the range of predictions.

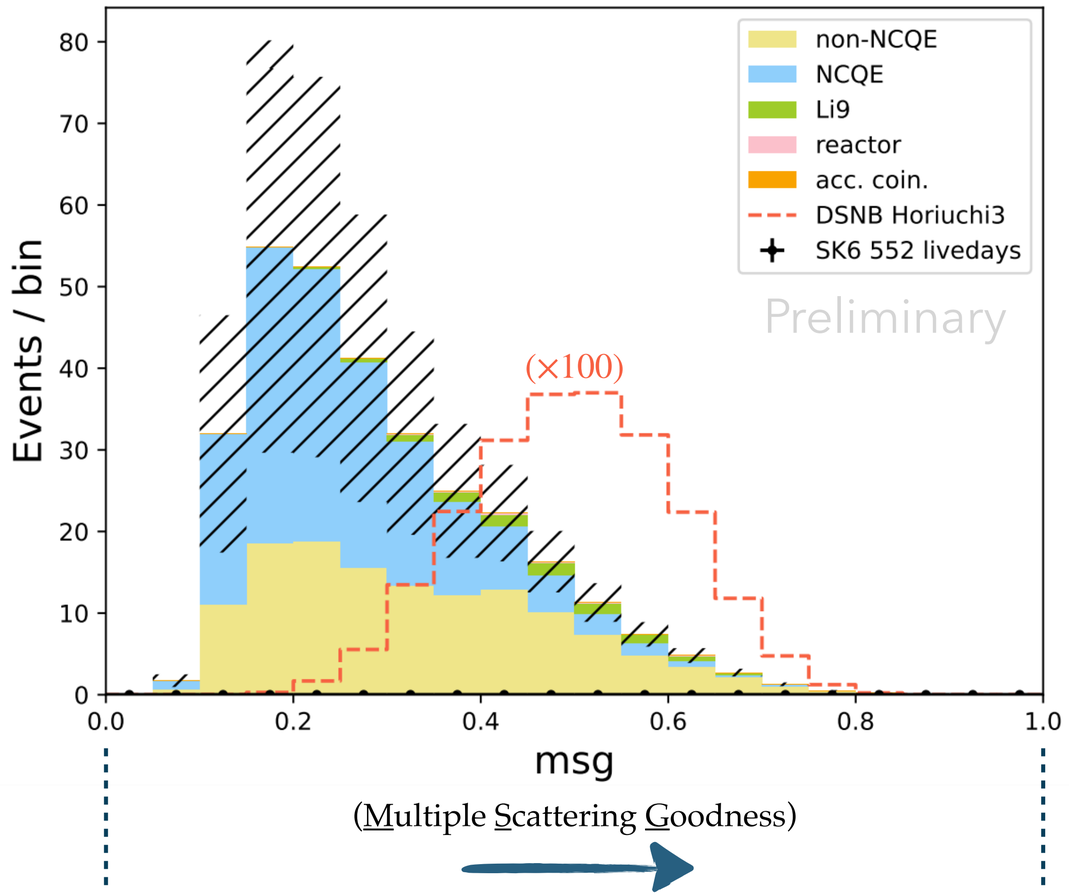
- Looking forward to approaching evidence for DSNB in the upcoming years!

Backup

MSG Cut

DSNB / NC events separation

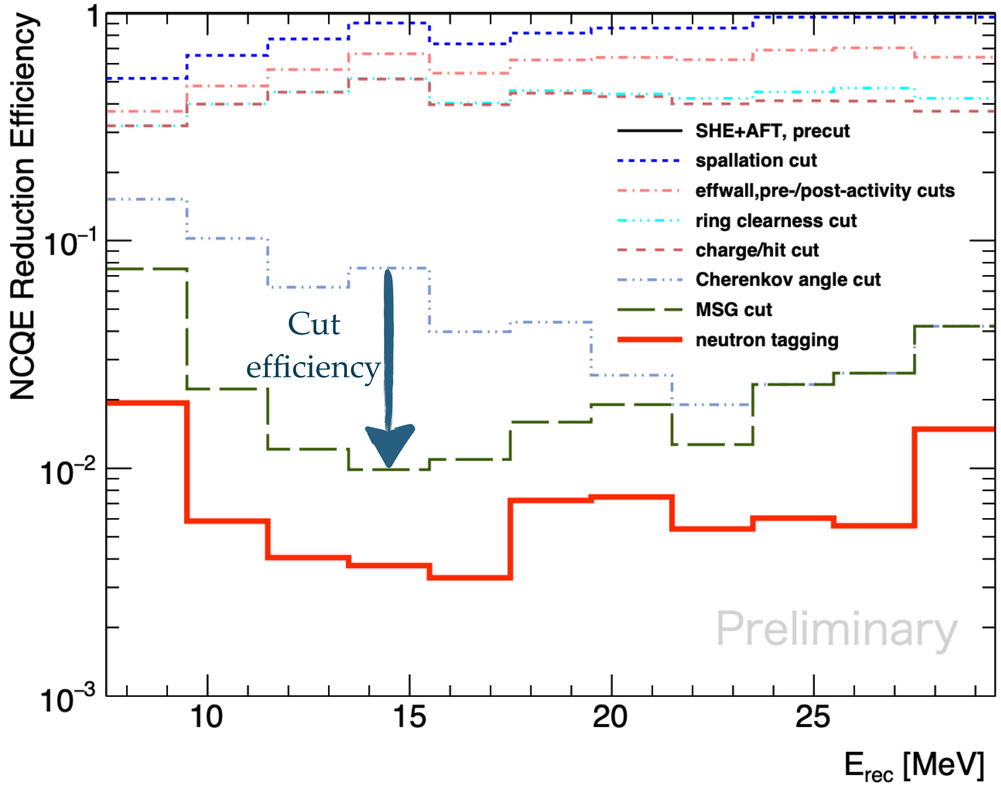




(Multiple Scattering Goodness)

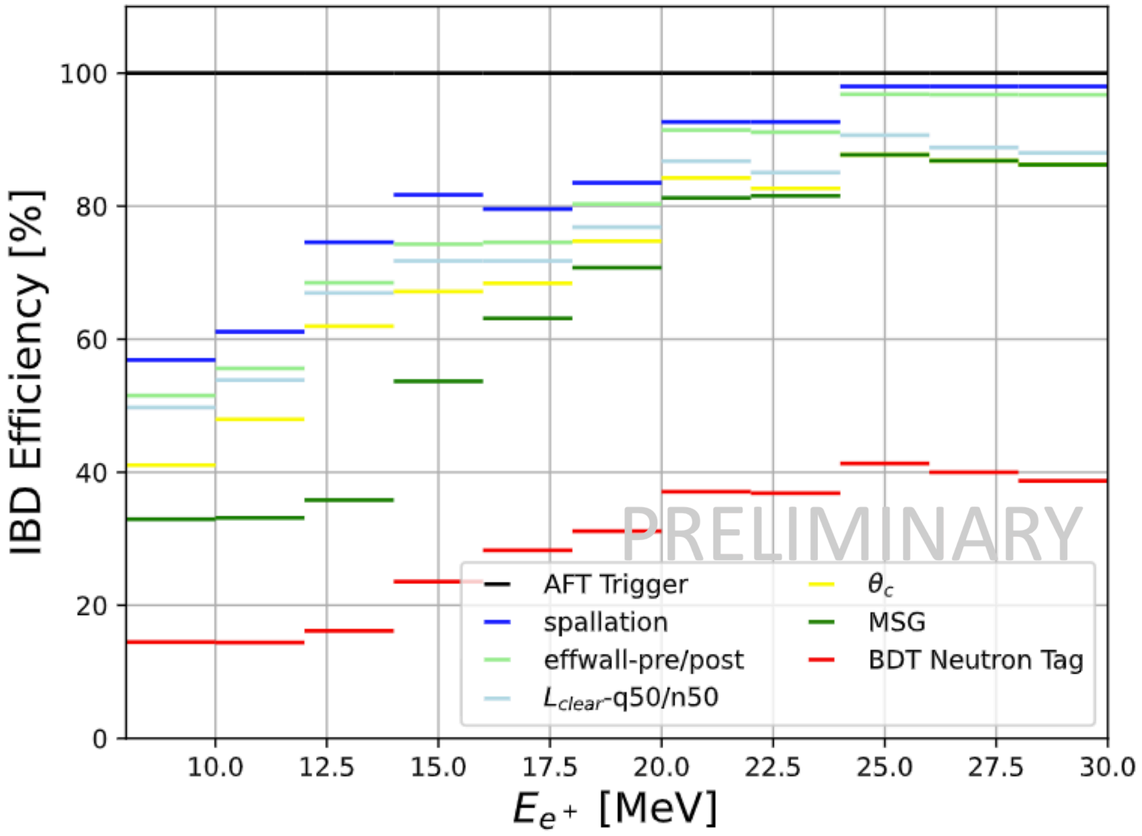
Consisting of several cones

Consisting of a single cone

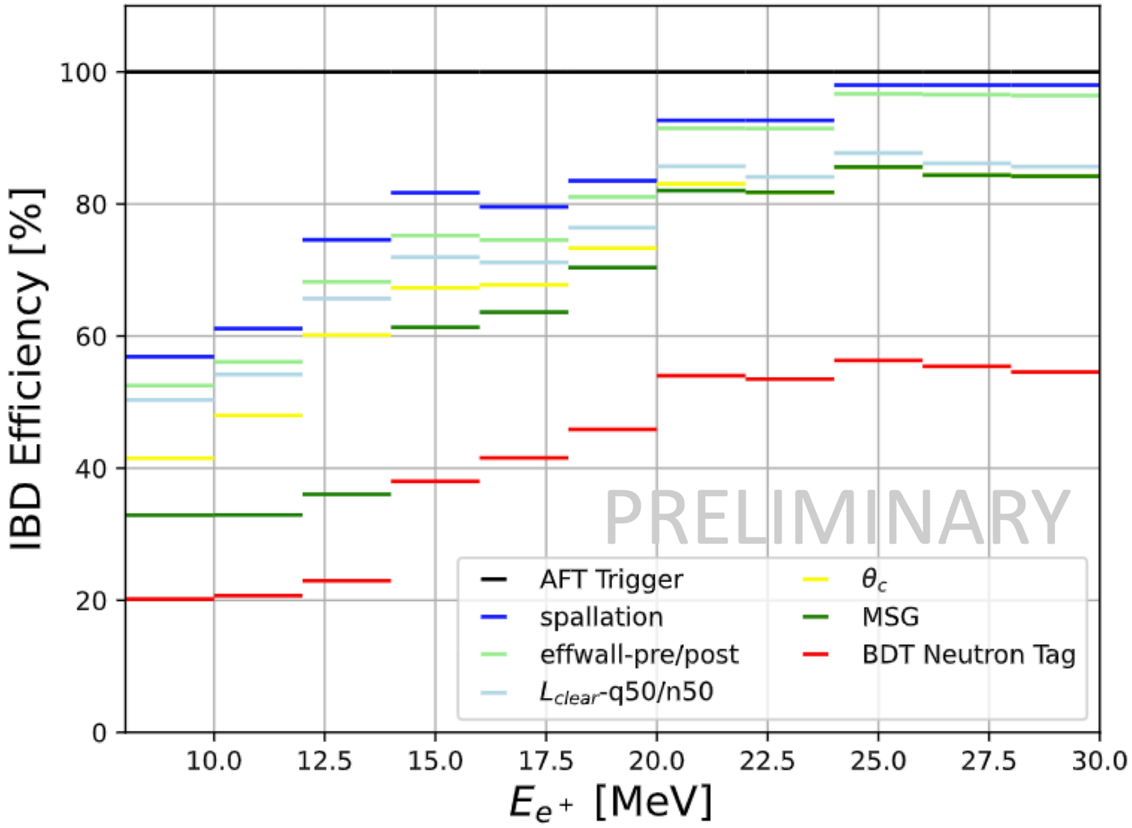


DSNB signal efficiency

SK-VI



SK-VII



DSNB analysis - Model-dependent spectral fit results

CL intervals