DSNB search in the Gd-loaded Super-Kamiokande detector

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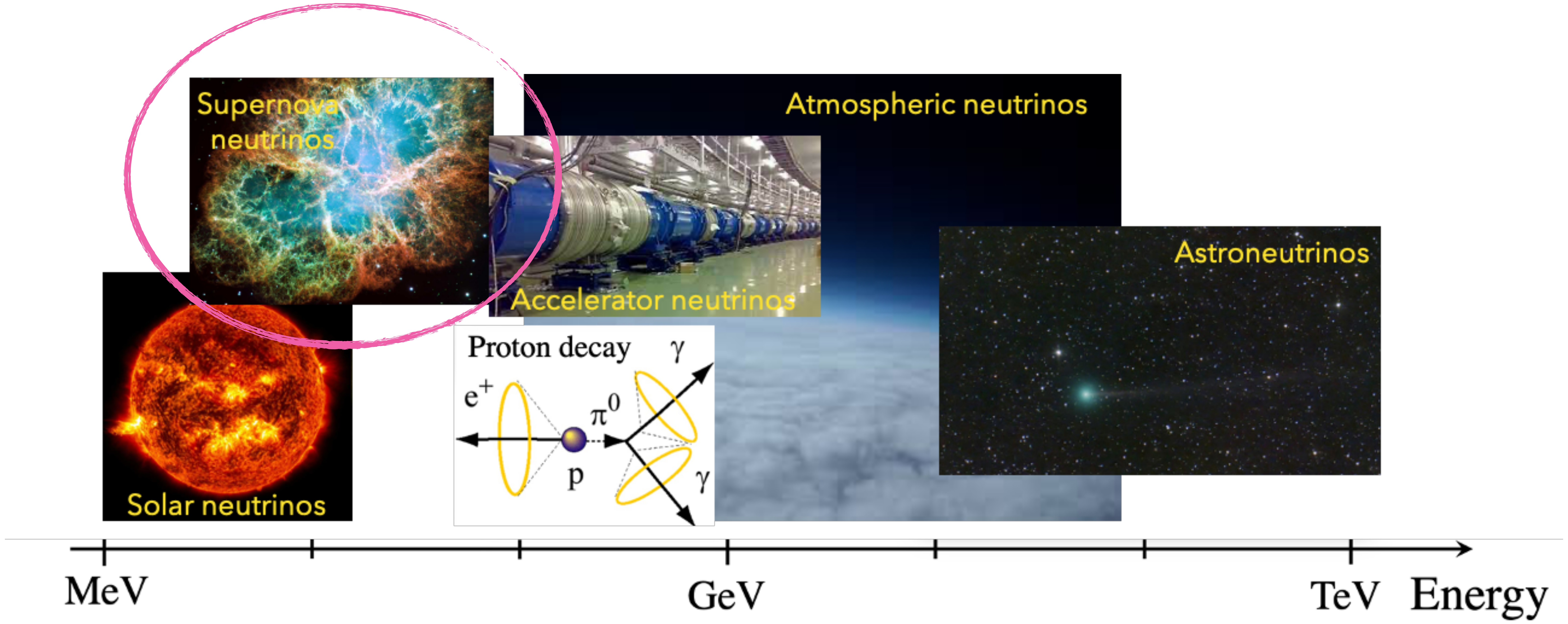
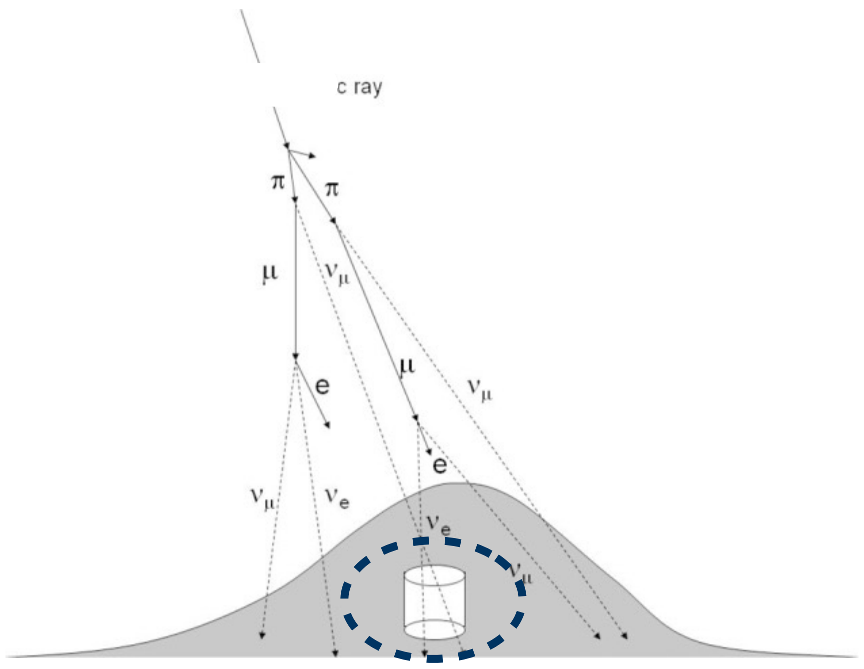
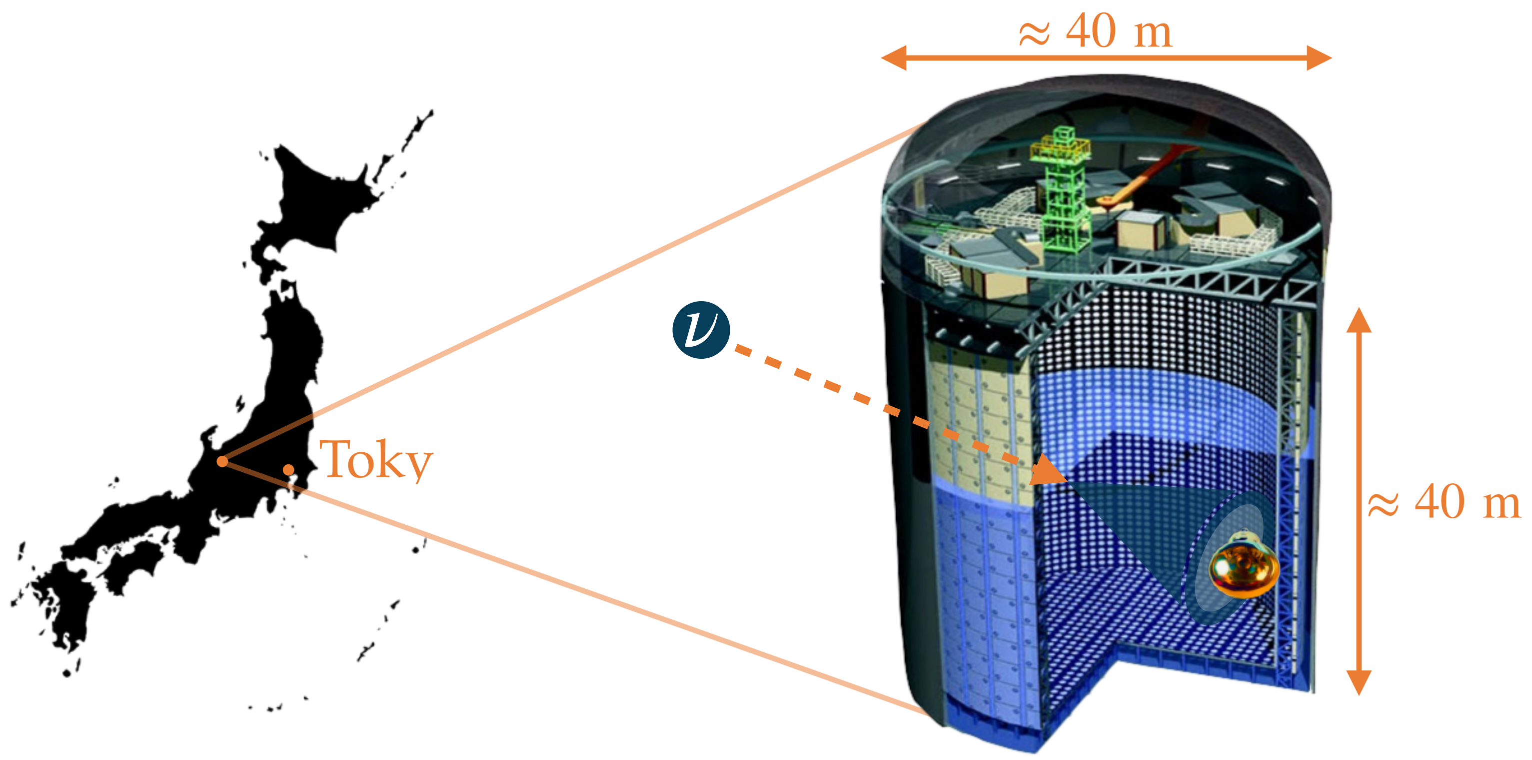
Applied Antineutrino Physics Workshop 2024

The Super-Kamiokande experiment



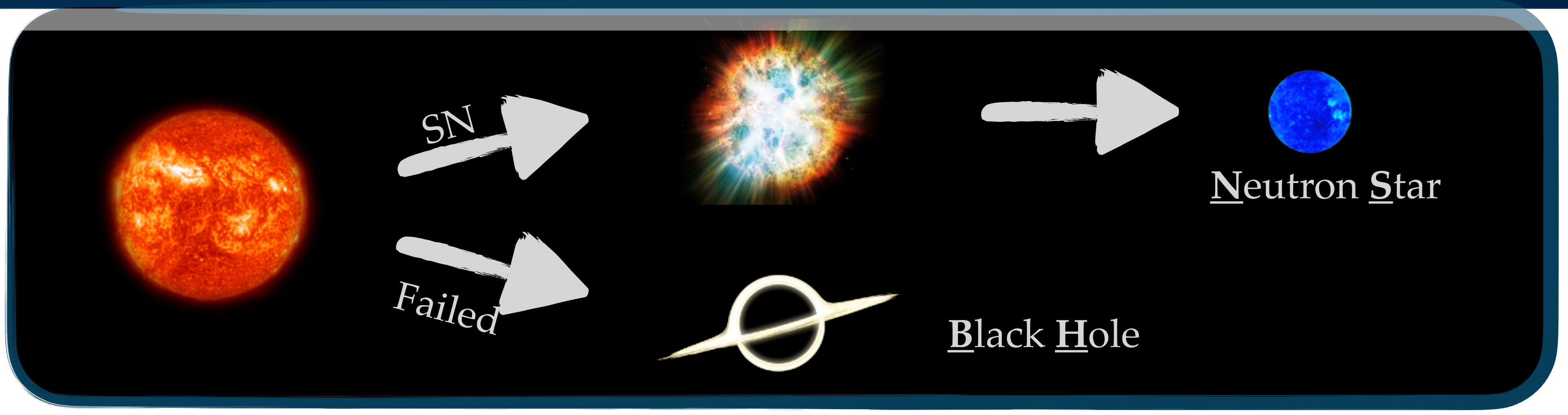




- Super-Kamiokande is a multi-purpose Cherenkov-based experiment with:
  - ➡ Reconstruction of vertex, direction, energy of impinging particles.
  - ➡ Multi-channel read-out of the Cherenkov signal of interacting particles, with **~11k PMTs**.
  - ➡ **Wide energy range** (from MeV to TeV) and **various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

Diffuse Supernova Neutrino Background

Core-Collapse Supernova (CCSN)

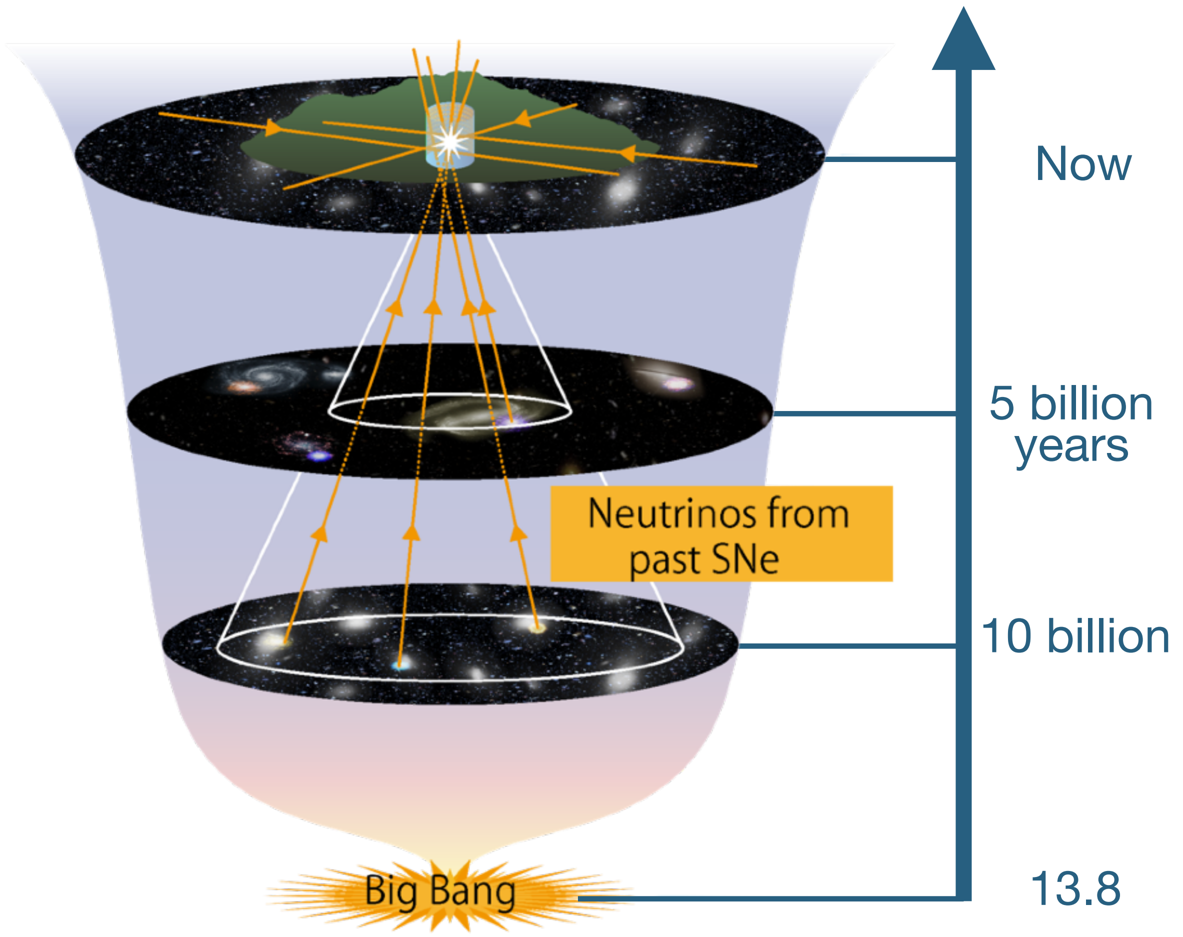


- Death of **massive stars** ($M \gtrsim 8\,\mathrm{M}_\odot$), where ~99% of the energy (~10^{59} MeV) is released via the emission of neutrinos and antineutrinos of all flavors (~**10 MeV/ν**).

- 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

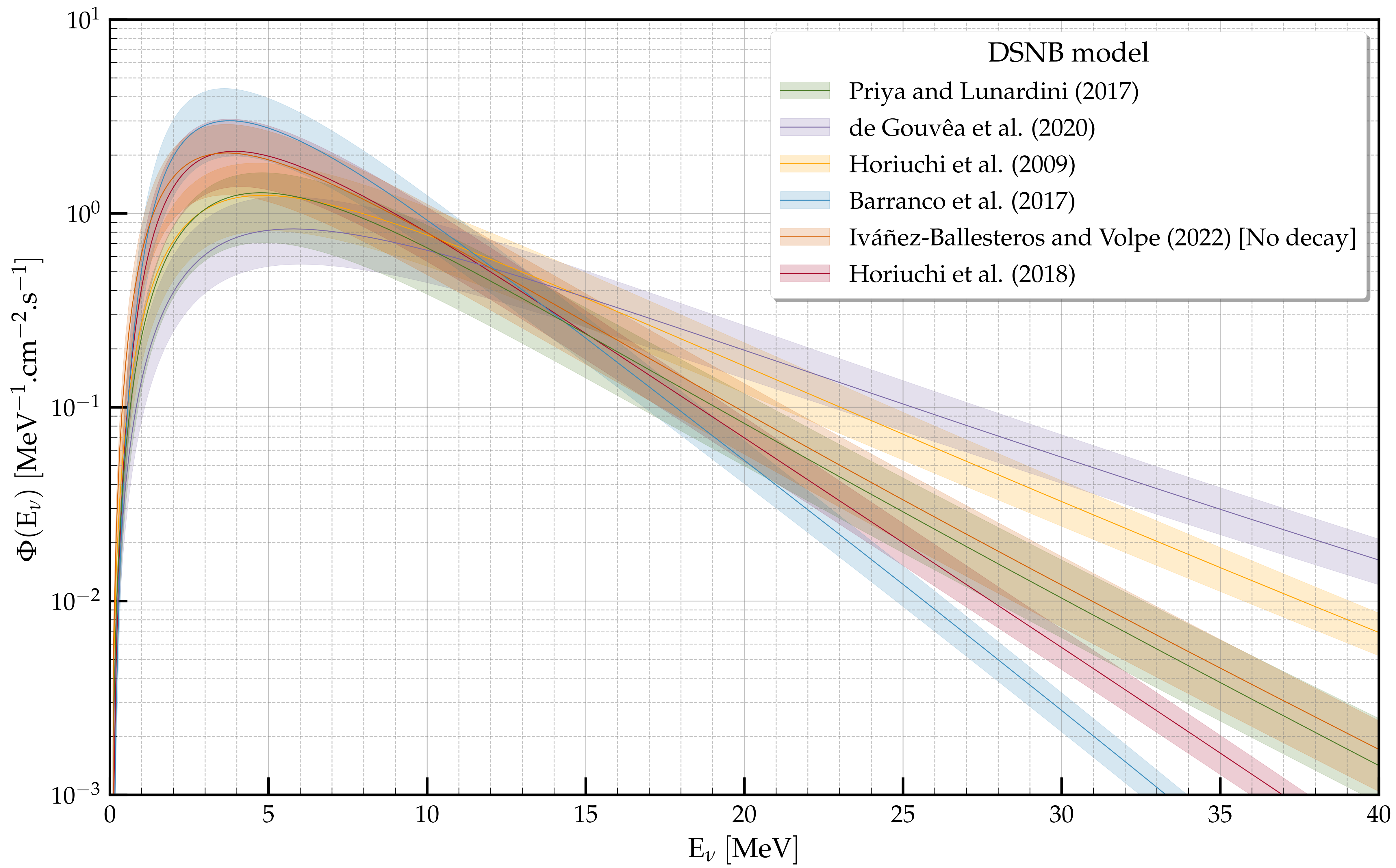
$$\Phi(E_\nu) = c \int_z \sum_s R_{SN}(z,s) \sum_{\nu_\beta, \bar{\nu}_\beta} F_{\overset{(-)}{\nu}_\beta}(E_\nu(1+z), s) \frac{dz}{H(z)}$$

Redshift-dependent SN rate

Universe expansion

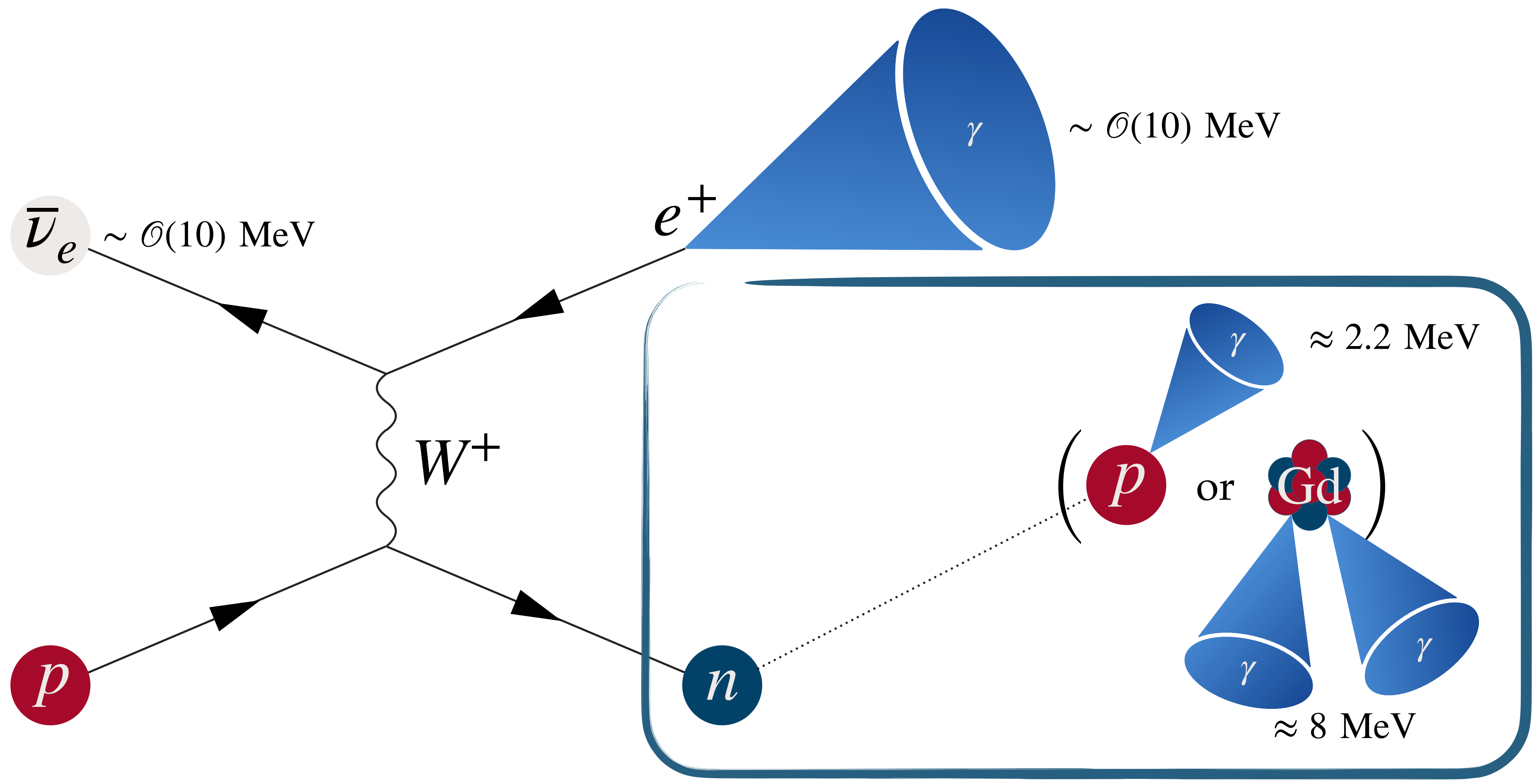
Rich phenomenology:

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

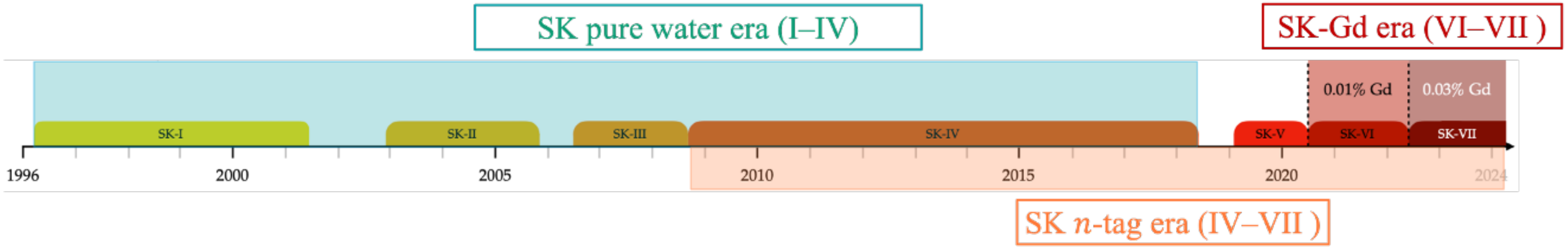


DSNB events at SK

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



Neutron capture delayed signal



DSNB events at SK

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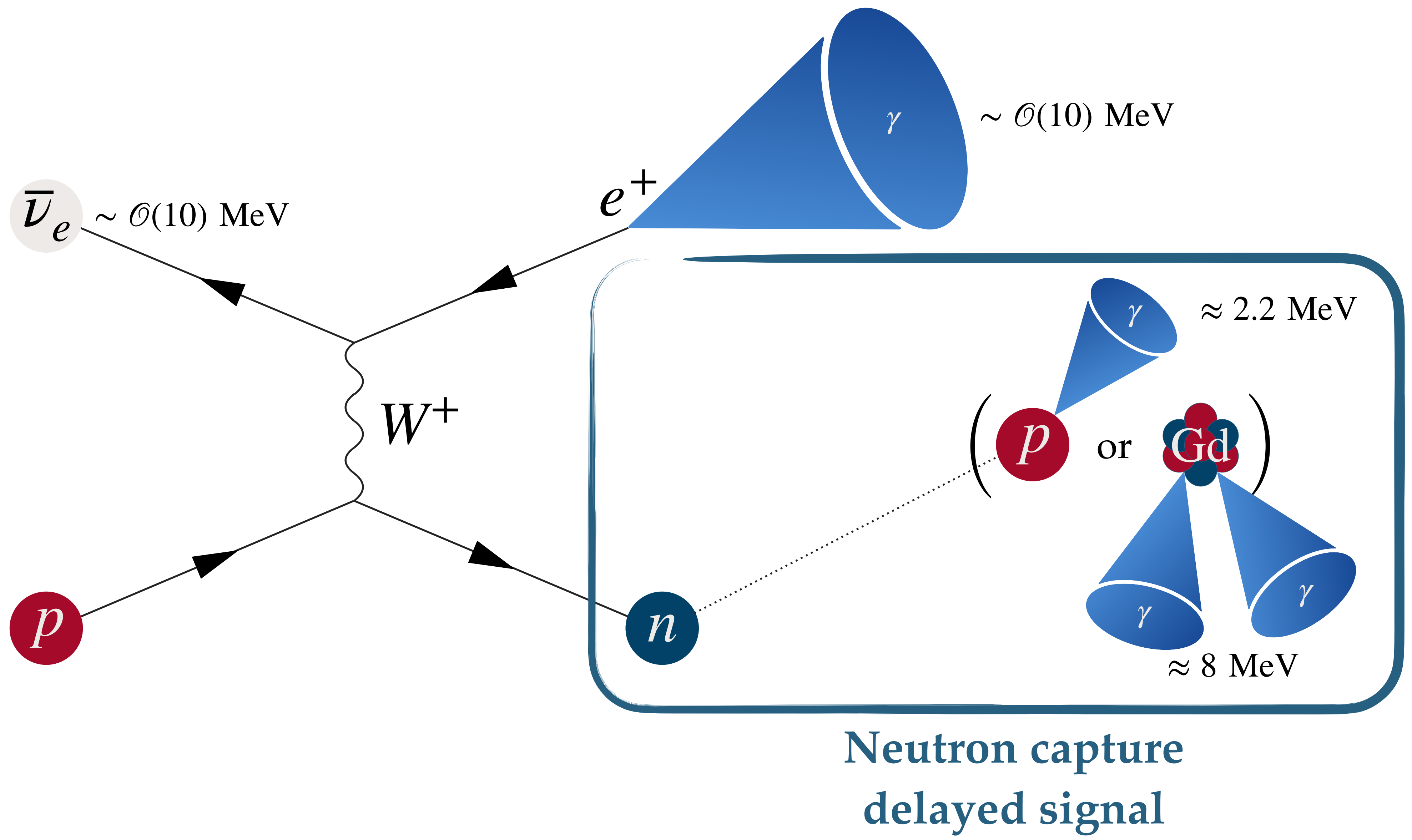
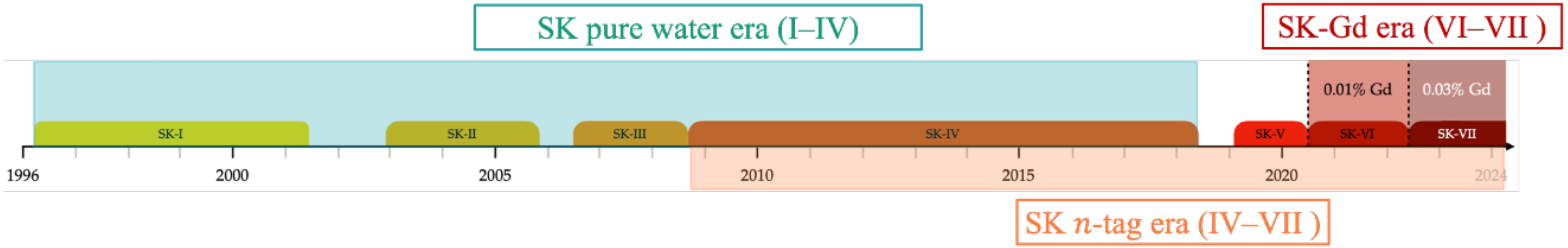


	SK-IV (pure water)	SK-VI (0.01% Gd)	SK-VII (0.03% Gd)
n-capture on Gd	0 %	50 %	75 %
Time constant	~210 μs	~115 μs	~65 μs



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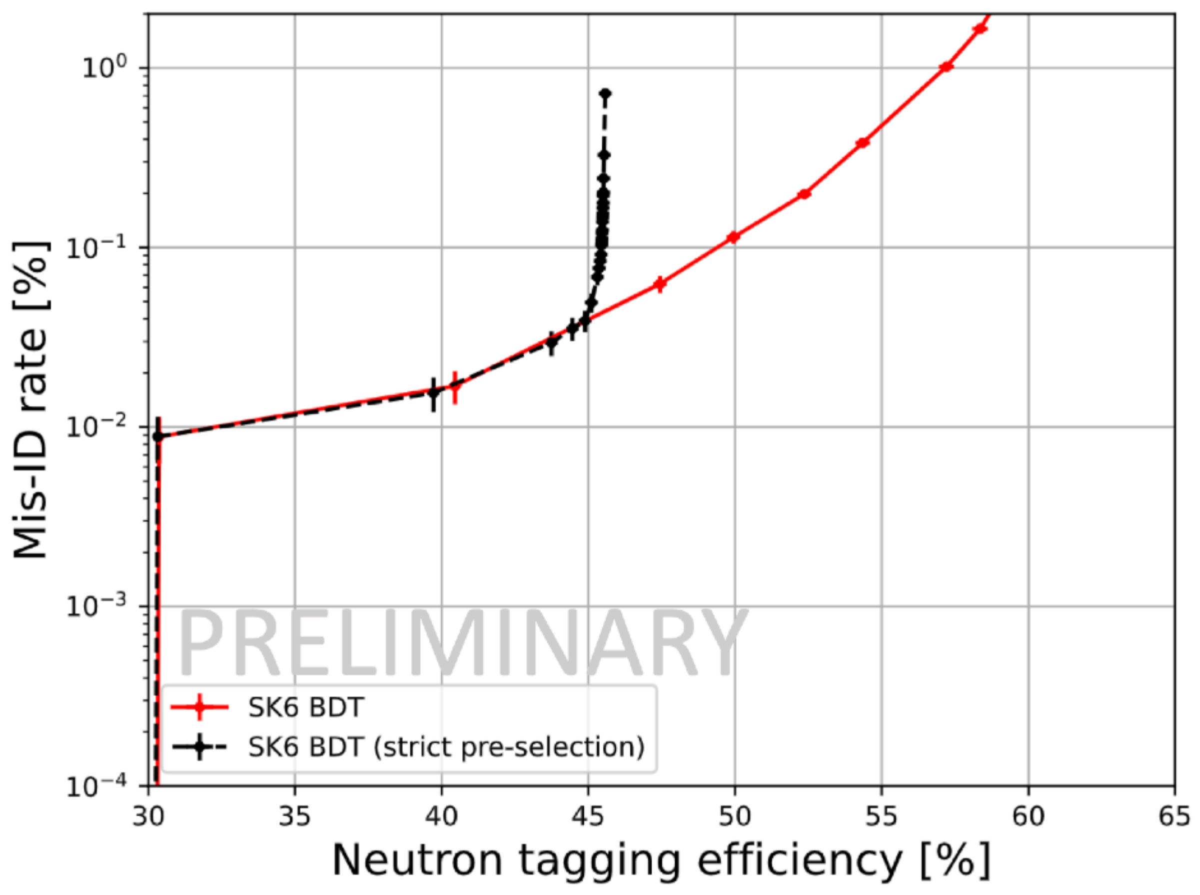
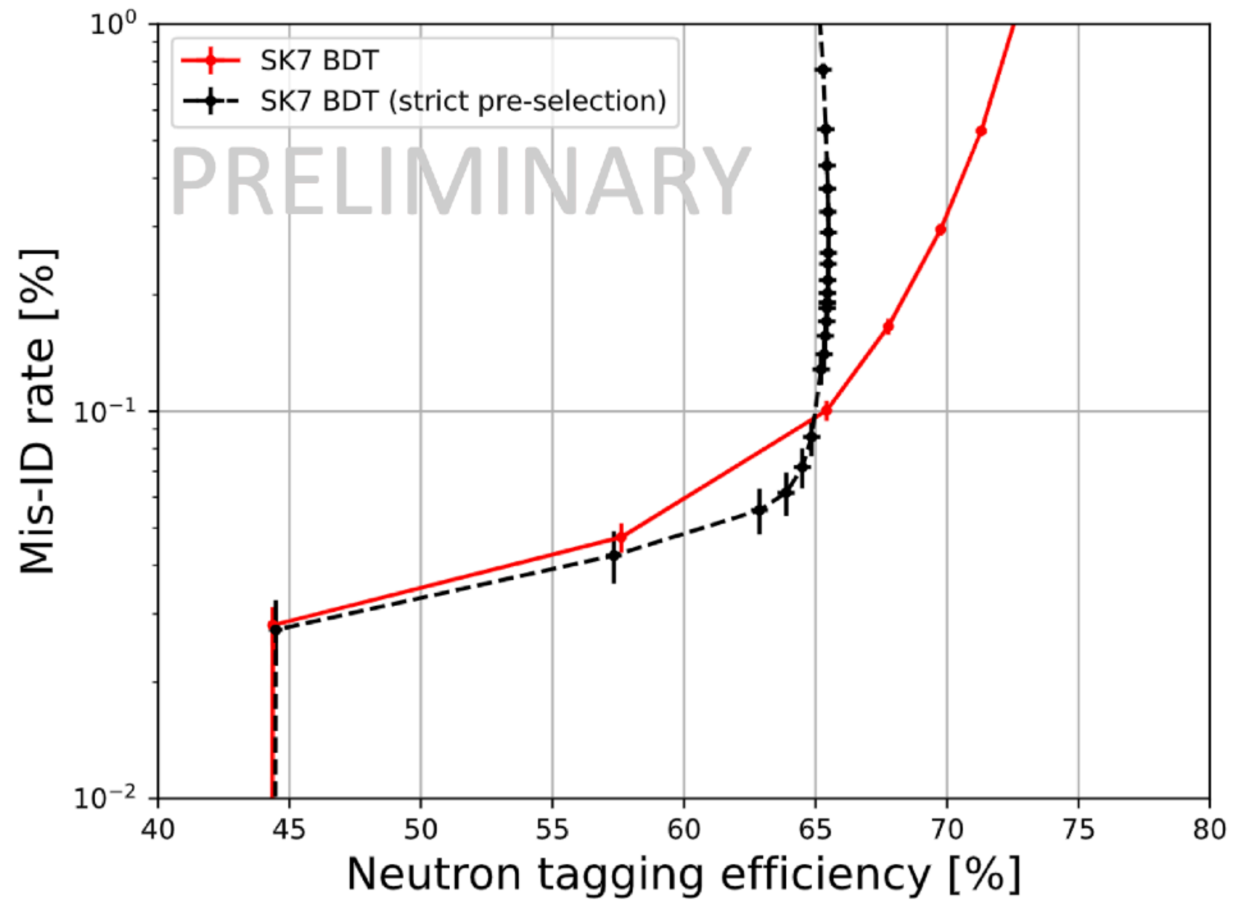
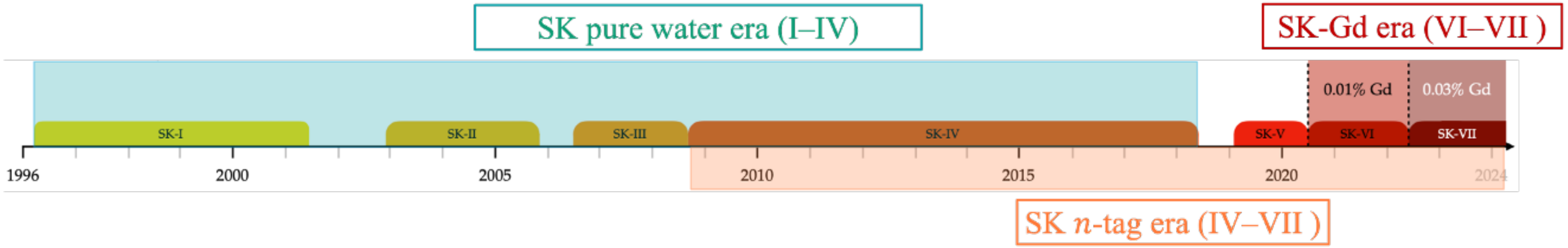




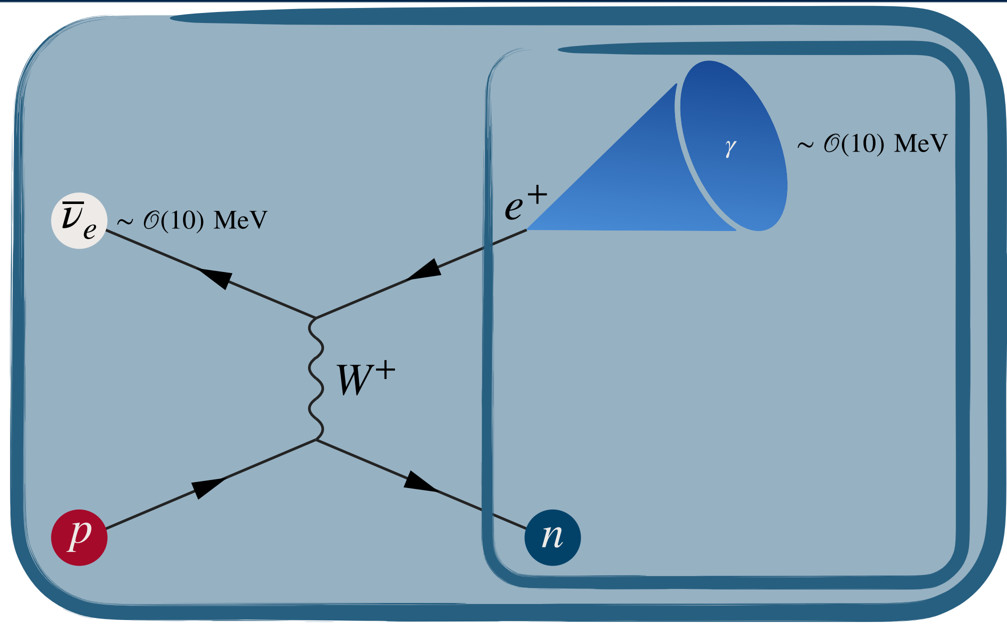
	SK-IV (pure water)	SK-VI (0.01% Gd)	SK-VII (0.03% Gd)
n-capture on Gd	0 %	50 %	75 %
Time constant	~210 μs	~115 μs	~65 μs
n-detection efficiency	~25%	~40%	~60%

Two neutron-tagging algorithms:
BDT & Neural Net



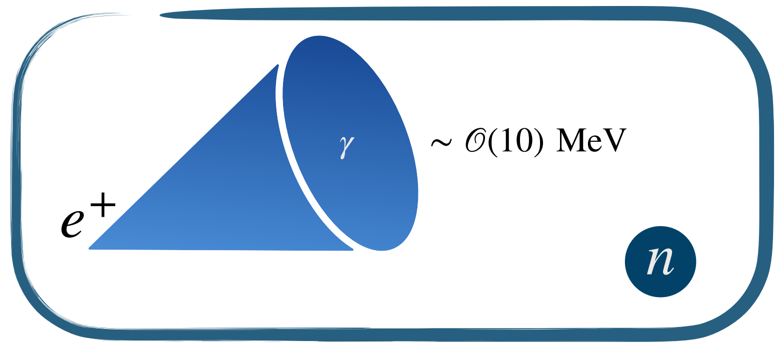
Background events at SK

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

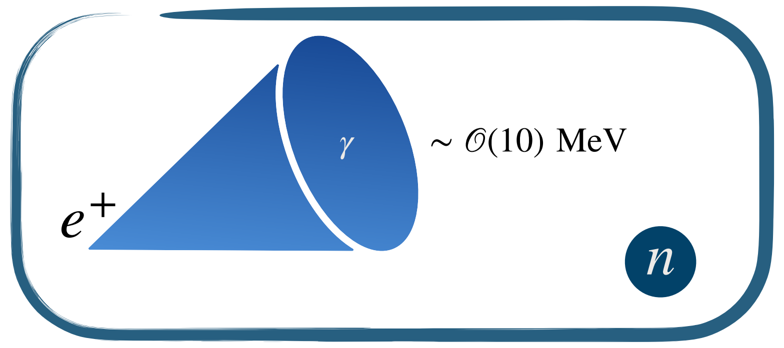


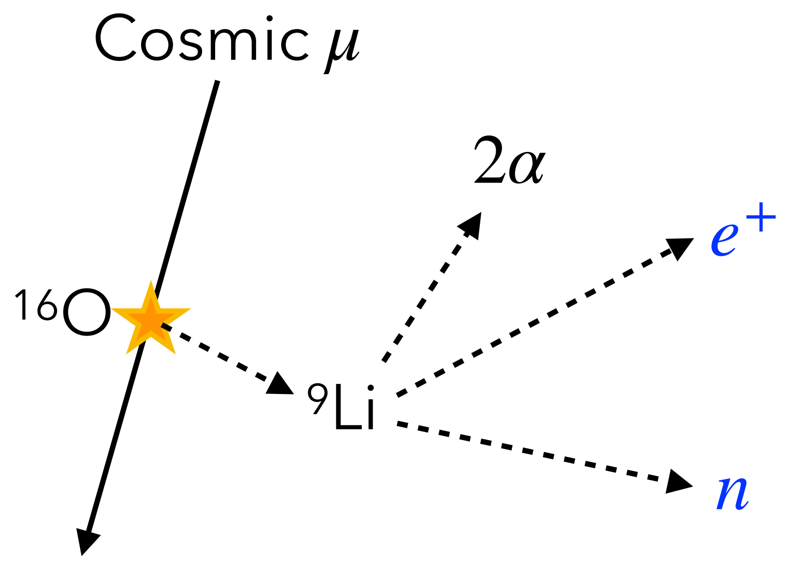
DSNB event

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

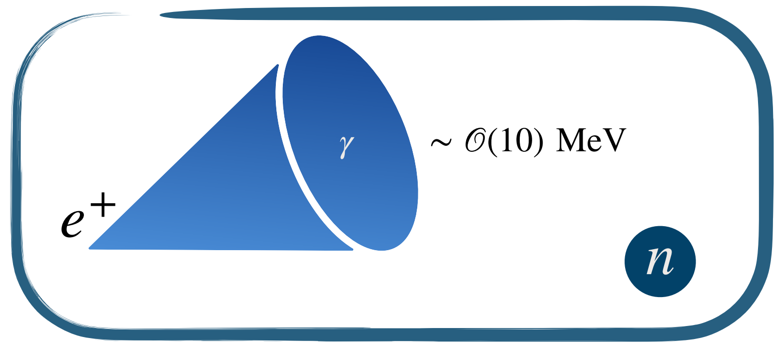


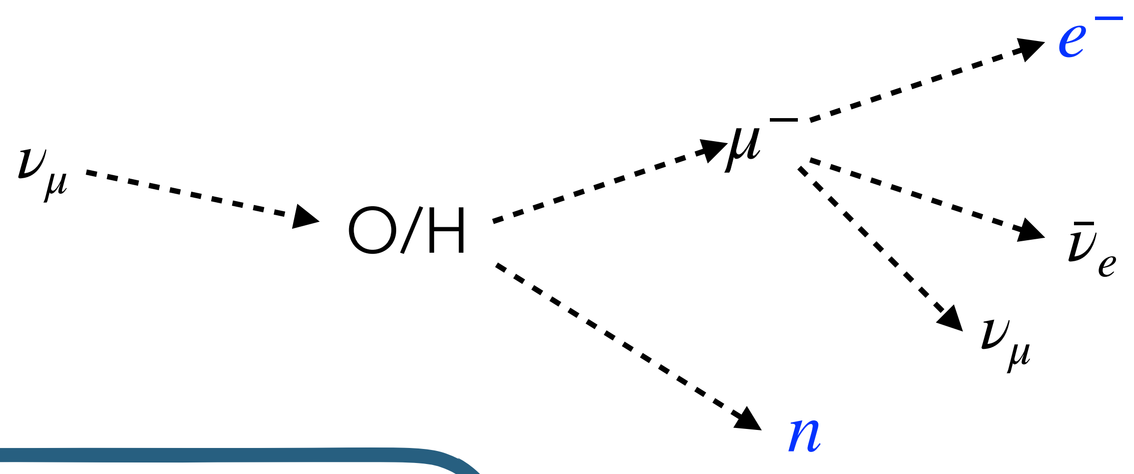
- Spallation-induced:
  - From cosmic muons going through SK (**~2 Hz**) : **dominant background in the low energy end** of the analysis window.



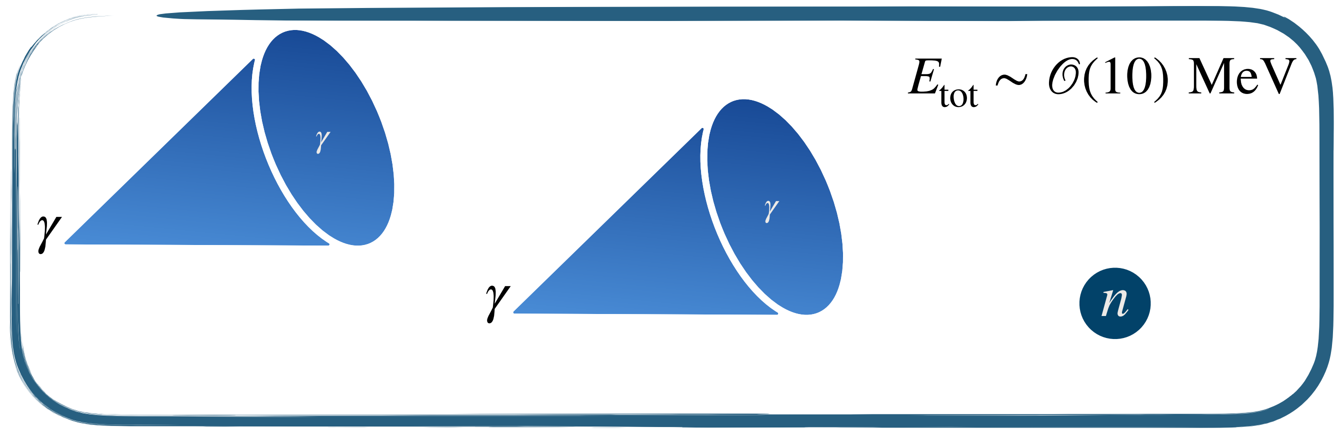


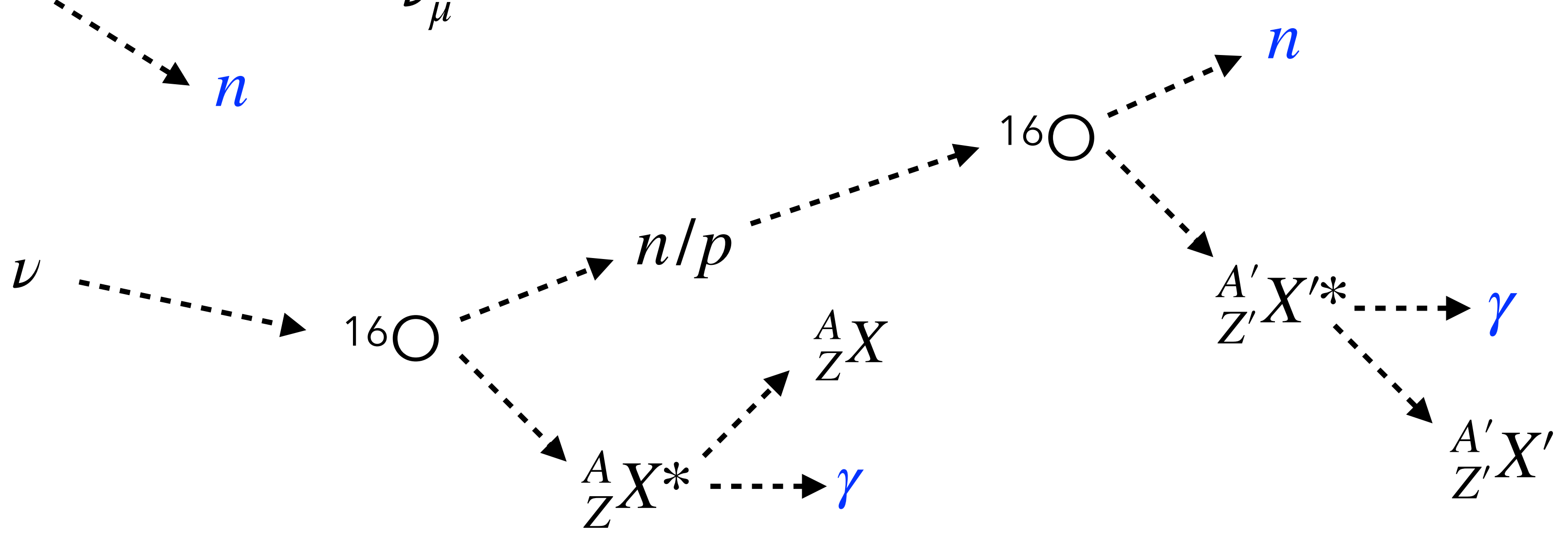
- Atmospheric ν - Charged-Current (CC)





- Atmospheric ν - Neutral-Current (NC)

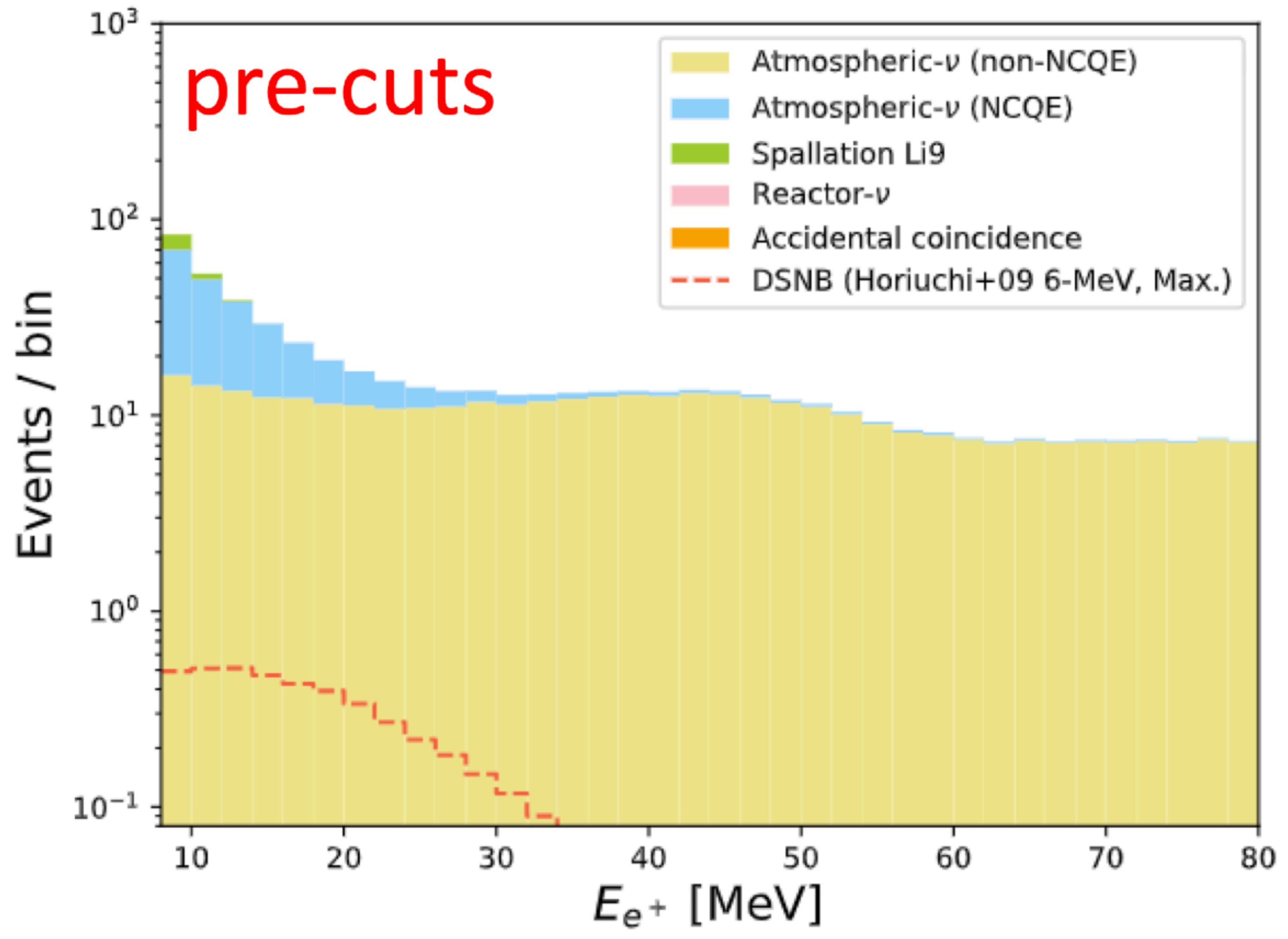


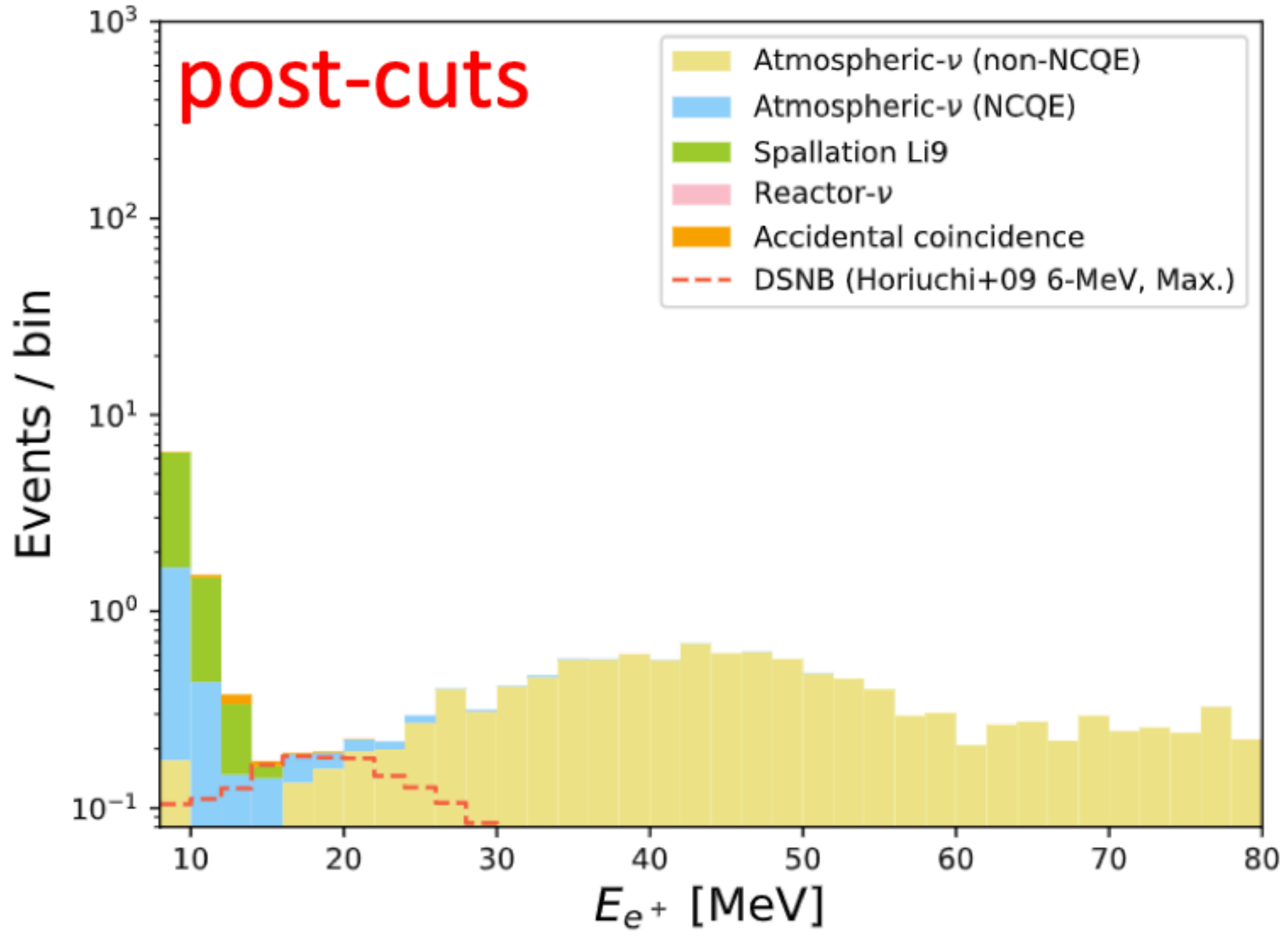


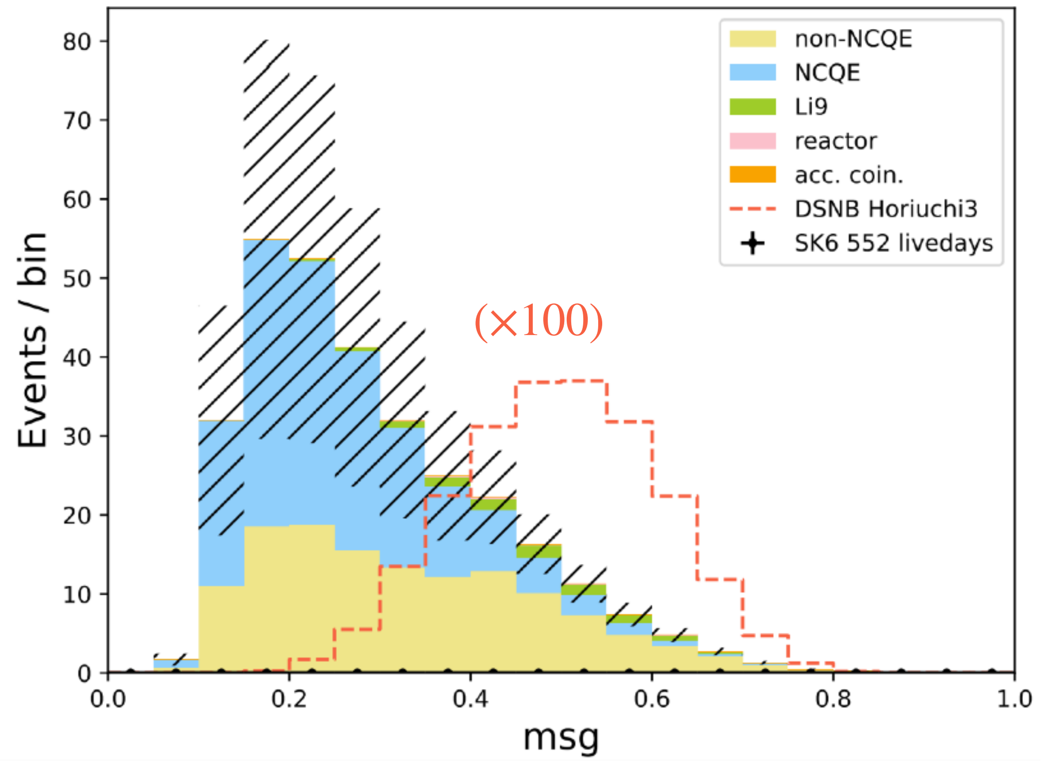
Data reduction

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

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







DSNB analysis - Spectral Fit

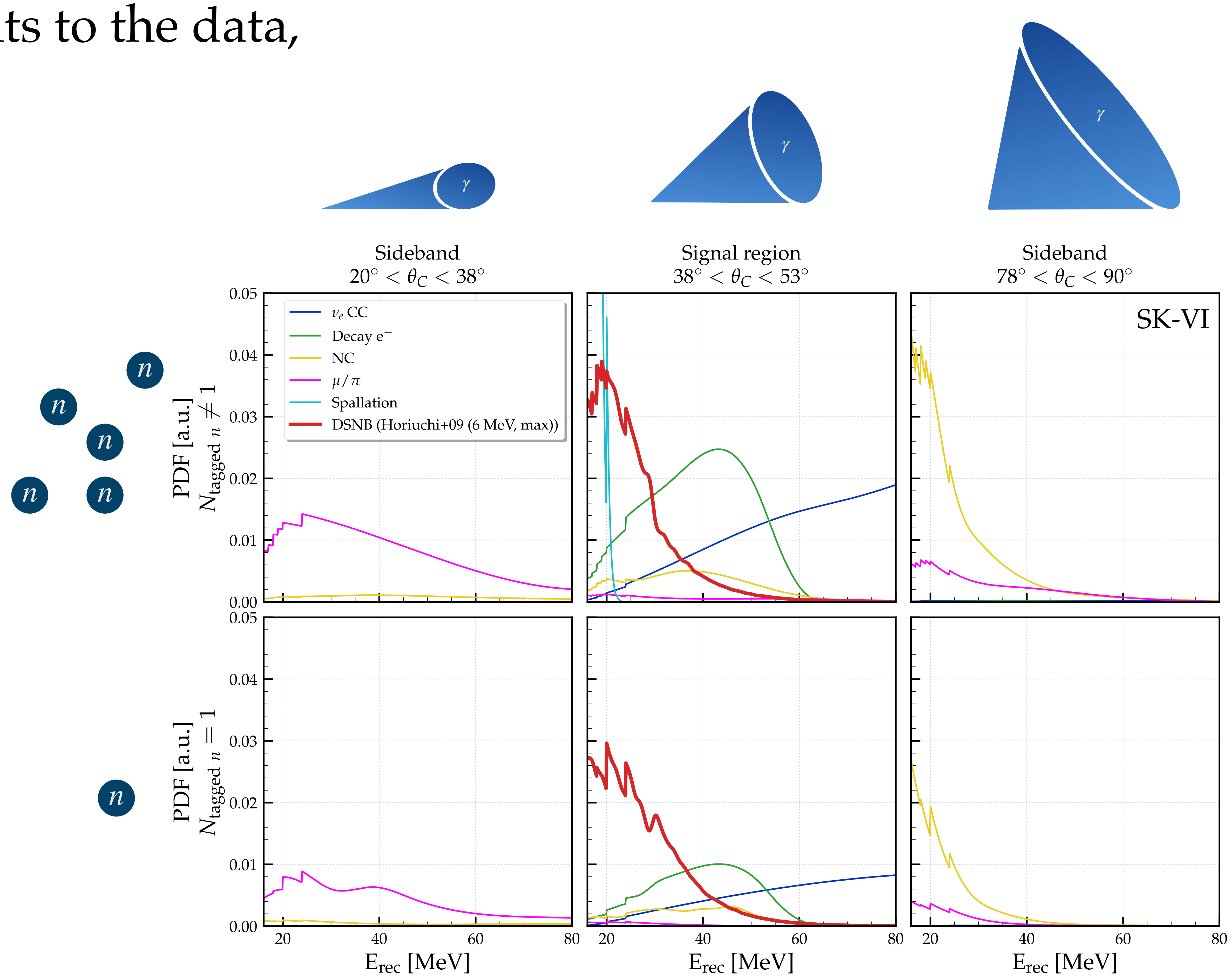
Principle

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

via Extended Maximum Likelihood Framework.

- Define 3 Cherenkov angle (θ_C) regions
  - *Low* θ_C: Mostly **CC** events
  - *High* θ_C: Mostly **NC** events
  - *Medium* θ_C: **Signal** & **backgrounds** (**CC** & **Spallation** events)

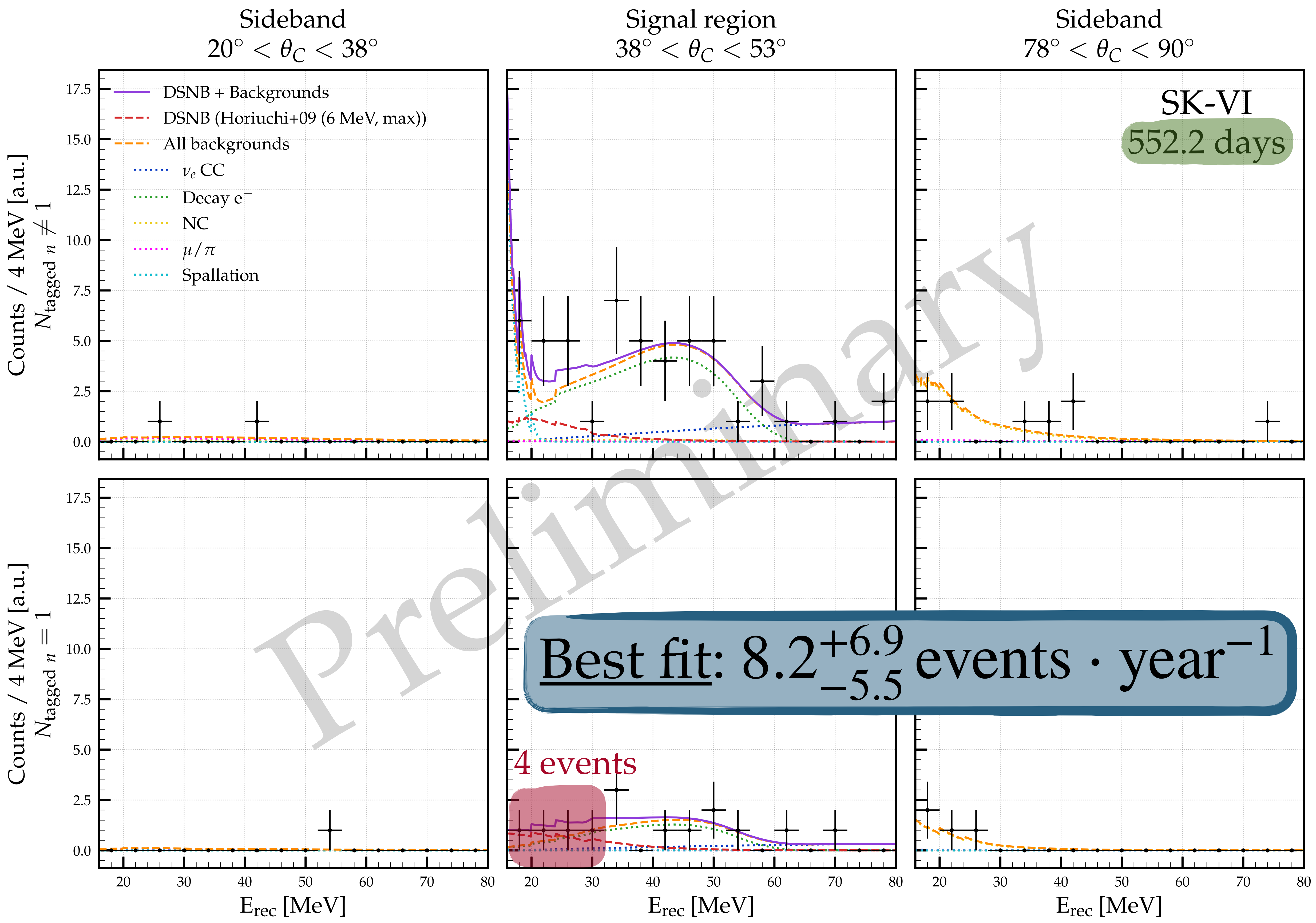
- Define 2 $N_{\text{tagged } n}$-dependent region:
  - **IBD-like** events ($N_{\text{tagged } n} = 1$)
  - **Non IBD-like** events ($N_{\text{tagged } n} \neq 1$)



DSNB analysis - Spectral Fit results

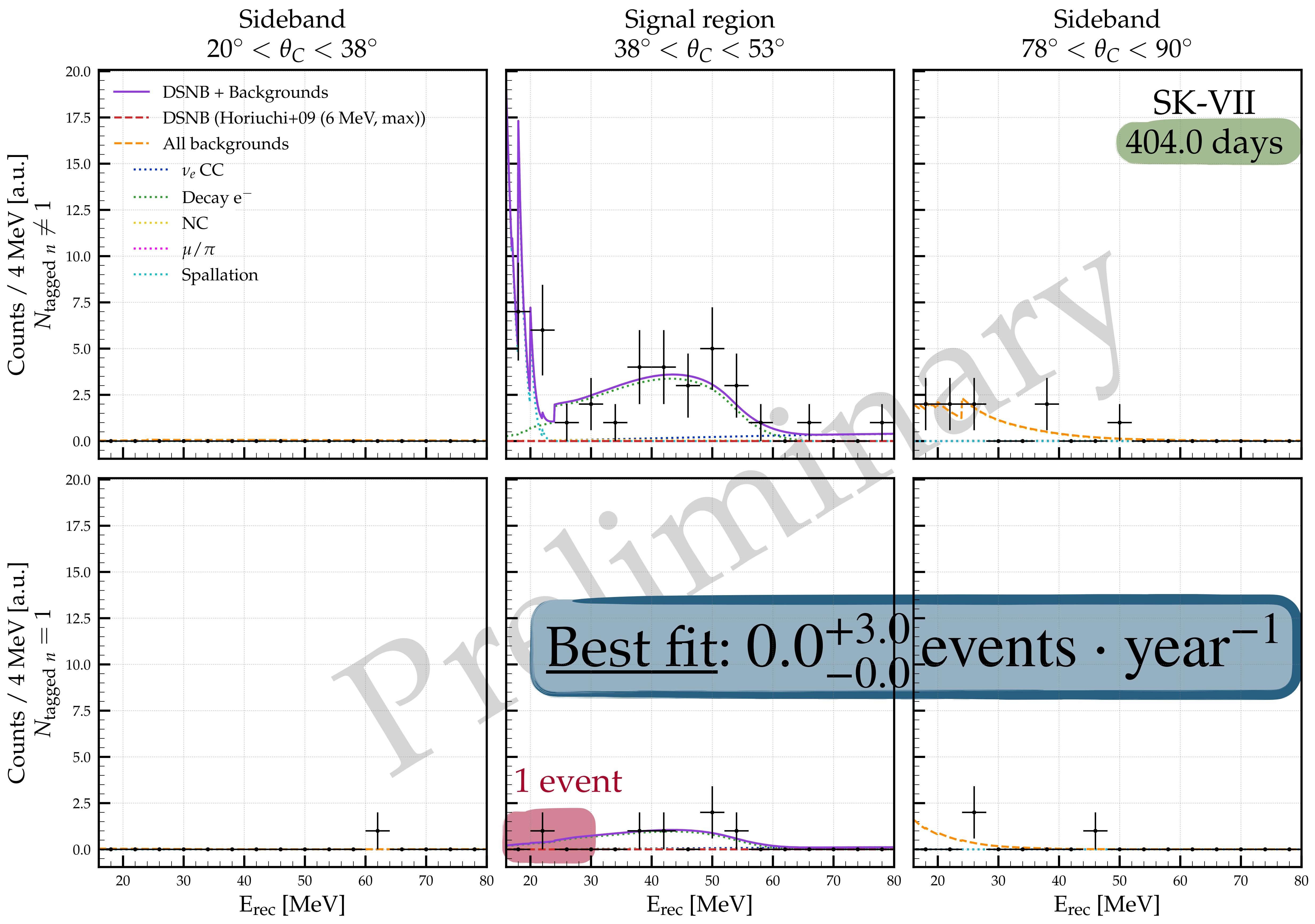
Fitted spectra

SK-VI



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

SK-VII



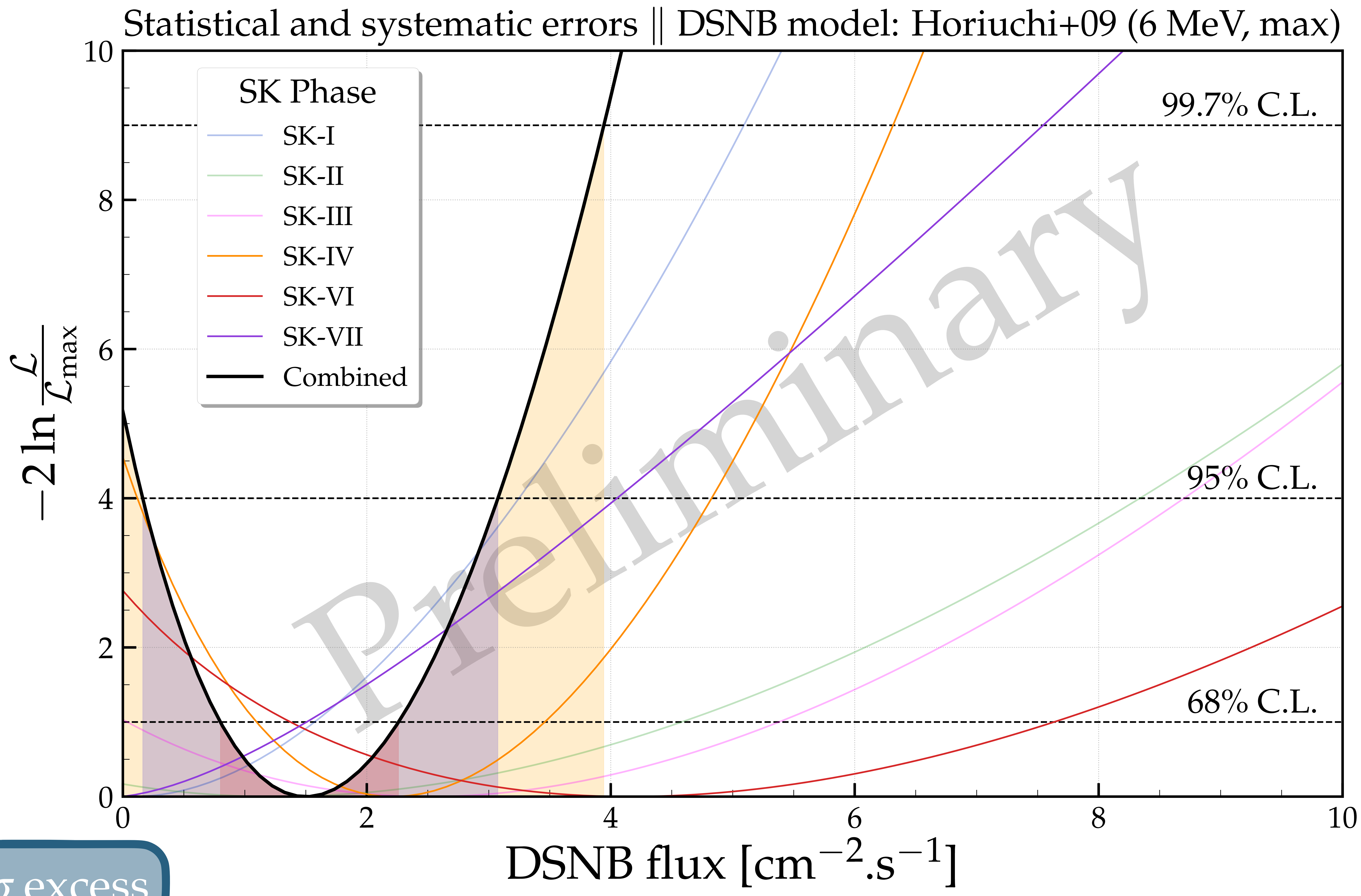
Best fit: $0.0^{+3.0}_{-0.0}$ events · year^{-1}

DSNB analysis - Spectral Fit results

Likelihoods

Combined Results

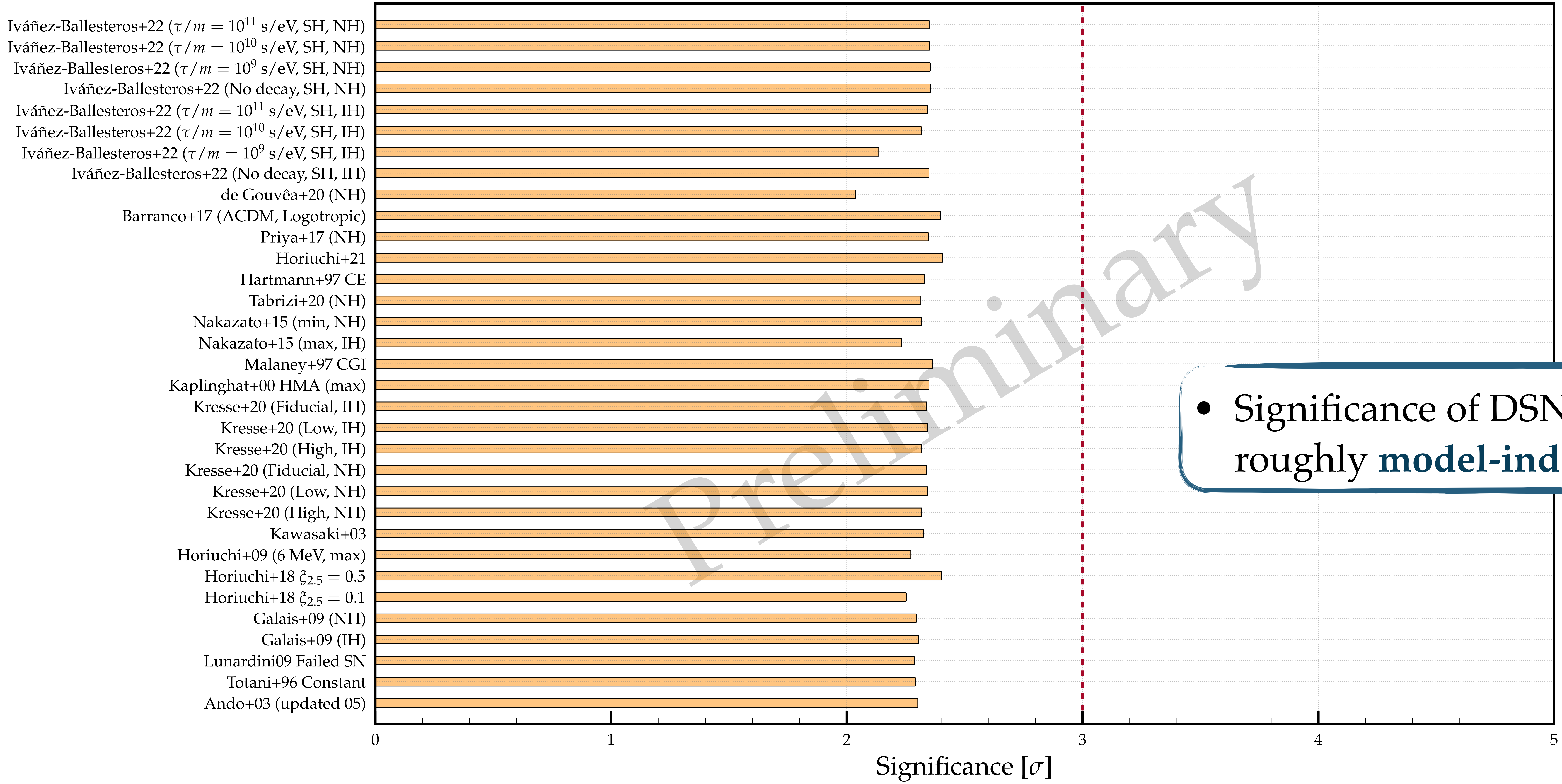
DSNB (Horiuchi+09)
Best fit rate 2.9 events $\cdot$ year^{-1}
90% C.L. upper limit (rate) 5.0 events $\cdot$ year^{-1}
Best fit flux $1.4\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1} > 17.3\,\mathrm{MeV}$
90% C.L. upper limit (flux) $2.5\,\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1} > 17.3\,\mathrm{MeV}$



- Combined (stat. + sys.) ≈ 2.3 σ excess

DSNB analysis - Spectral Fit results

Significances

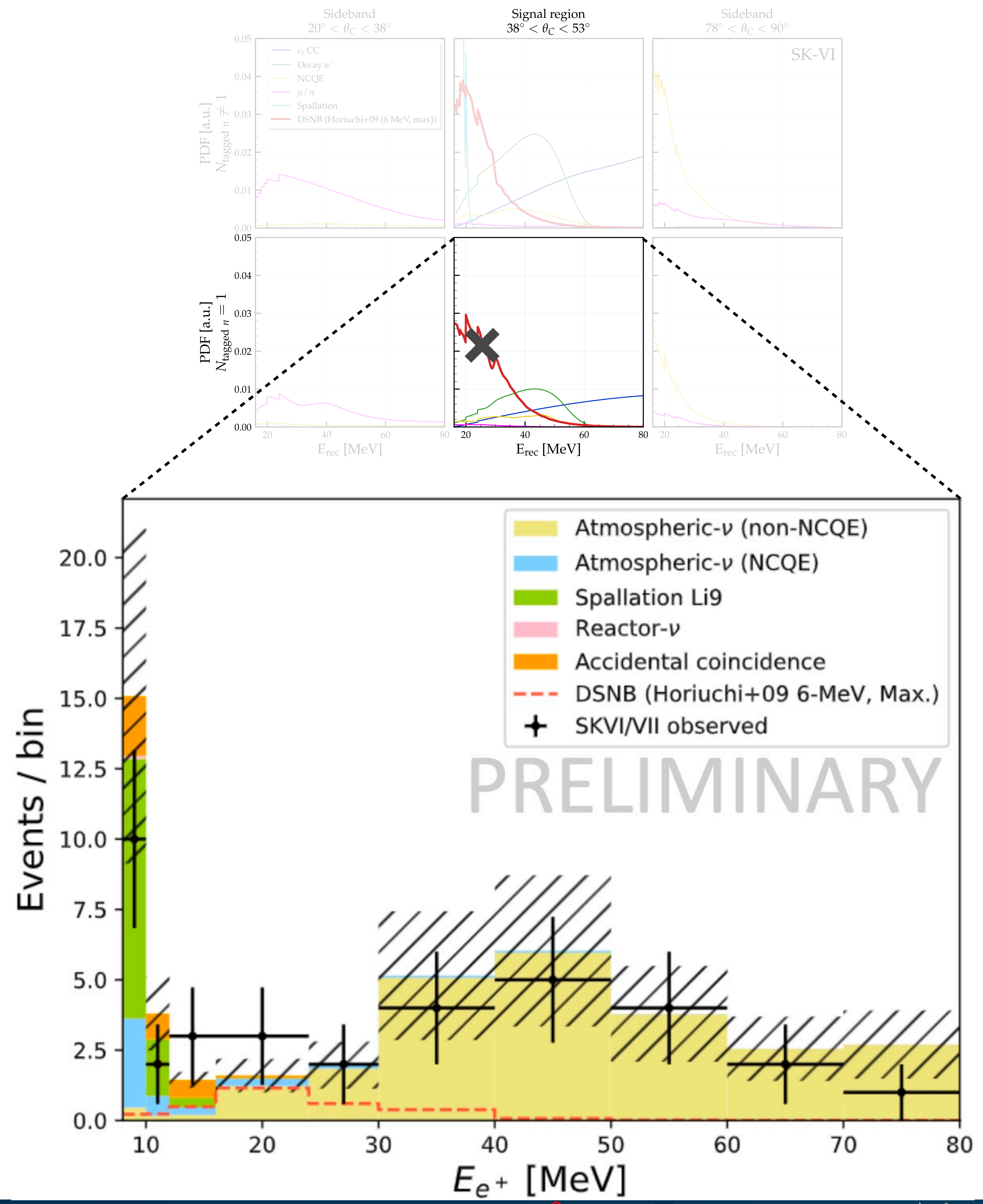


- Significance of DSNB signal is roughly **model-independent.**

DSNB analysis - Binned Analysis

Principle

- No input DSNB model in this analysis.
- Look at the excess per bin observed wrt. background prediction in the signal region (medium θ_C & $N_{\text{tagged } n} = 1$).
- CLs approach to derive bin-by-bin upper limits.

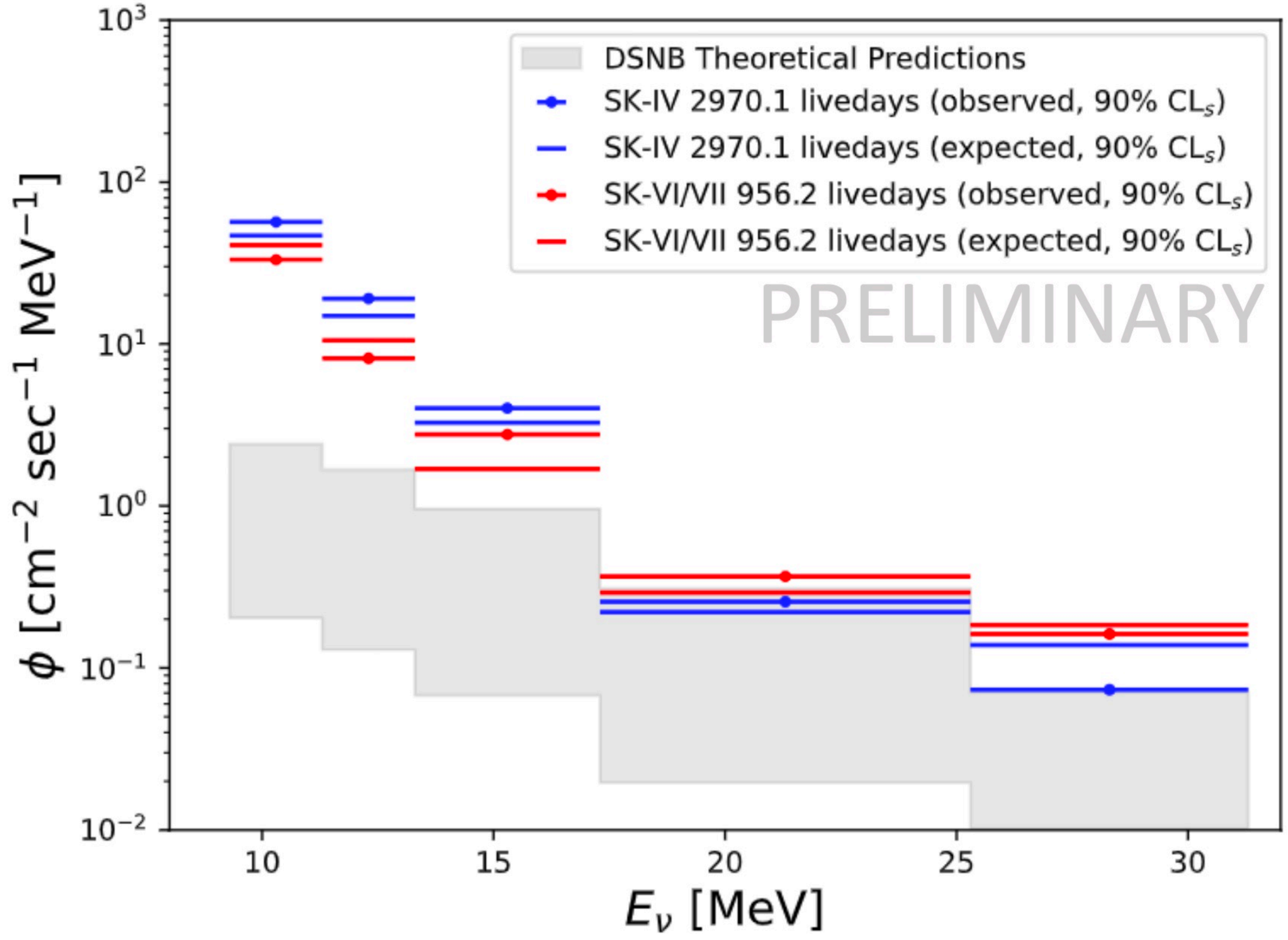


DSNB analysis - Binned Analysis results

Upper Limits

- Poor sensitivity in the very low energy region, mostly due to spallation-induced background.

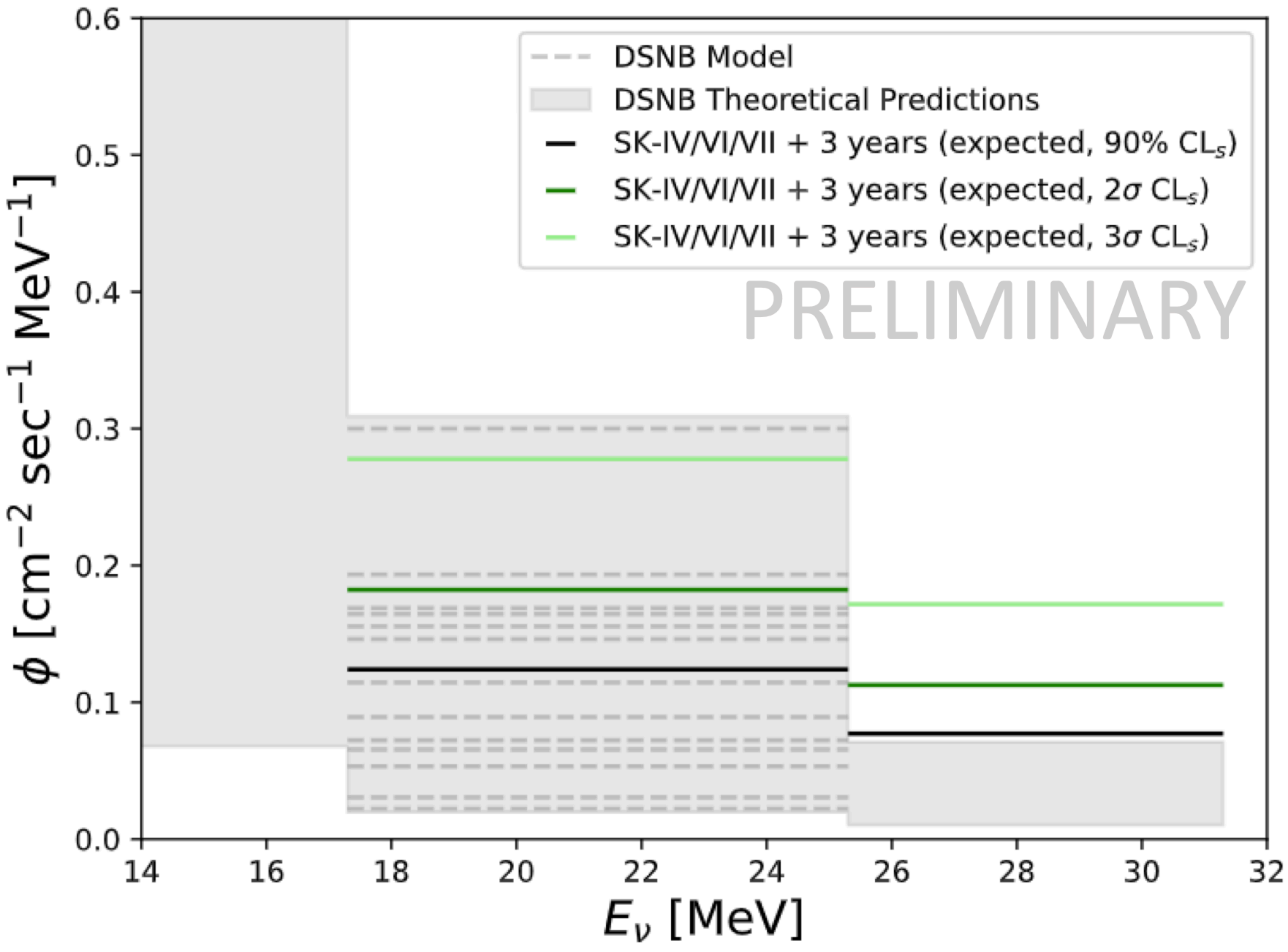
- From 17.3 MeV in neutrino energy (16 MeV in positron energy), upper limits approach the range of DSNB predictions.



DSNB analysis - Binned Analysis results

Upper Limits

- Poor sensitivity in the very low energy region, mostly due to spallation-induced background.
- From 17.3 MeV in neutrino energy (16 MeV in positron energy), upper limits approach the range of DSNB predictions.
- Sensitivity studies on the total SK-Gd era show potential to constrain the models with the upcoming data.



Conclusion

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

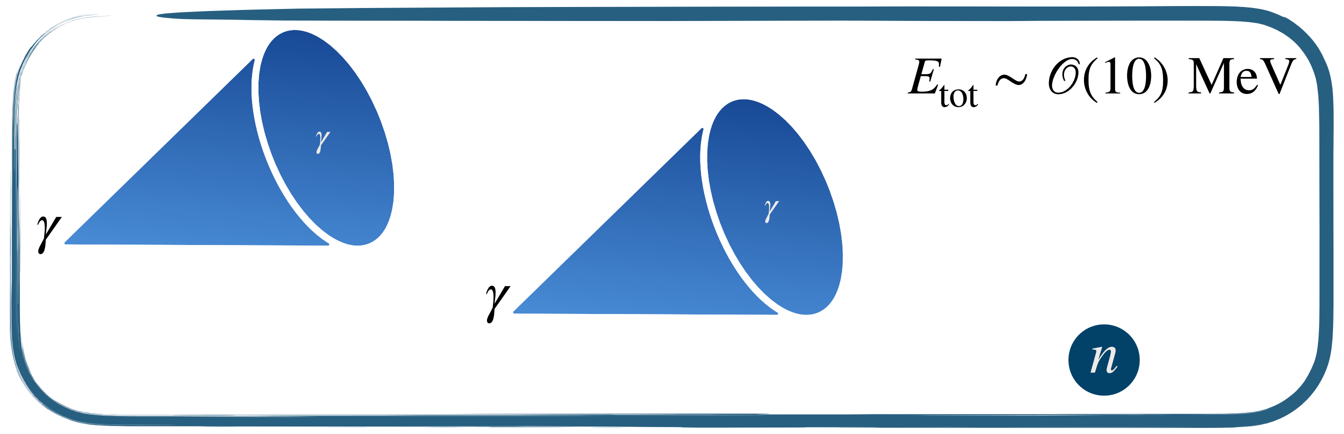
- The Gd-era of the SK experiment went successful in improving the sensitivity to the DSNB signal.
  - ➡ Rejection of the background-only hypothesis at the 2.3σ level across all SK phases.
  - ➡ Stringent upper limits, for neutrino energy > 17.3 MeV approaching the range of predictions.

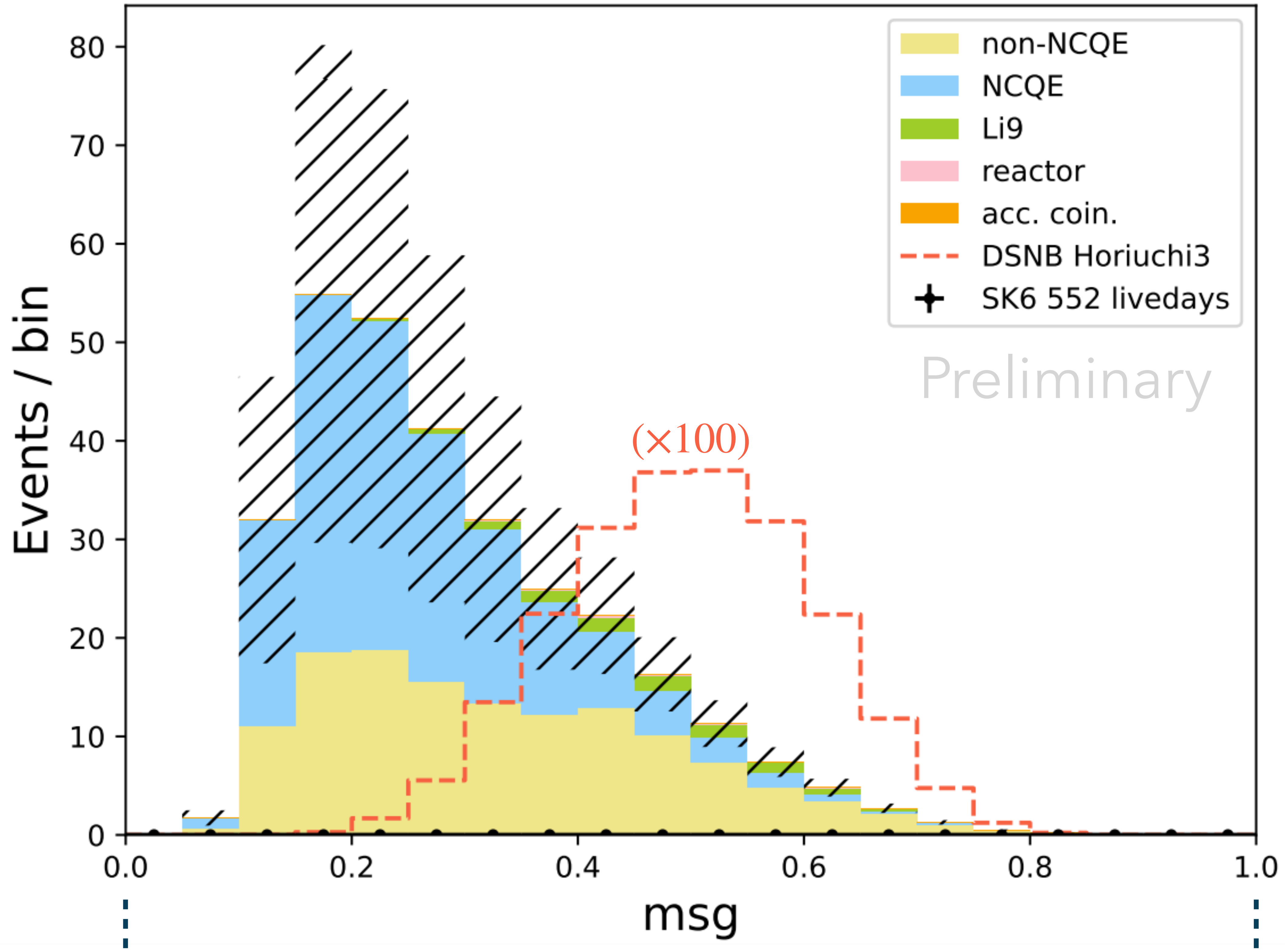
- Looking forward to approaching evidence for DSNB in the upcoming years!

Backup

MSG Cut

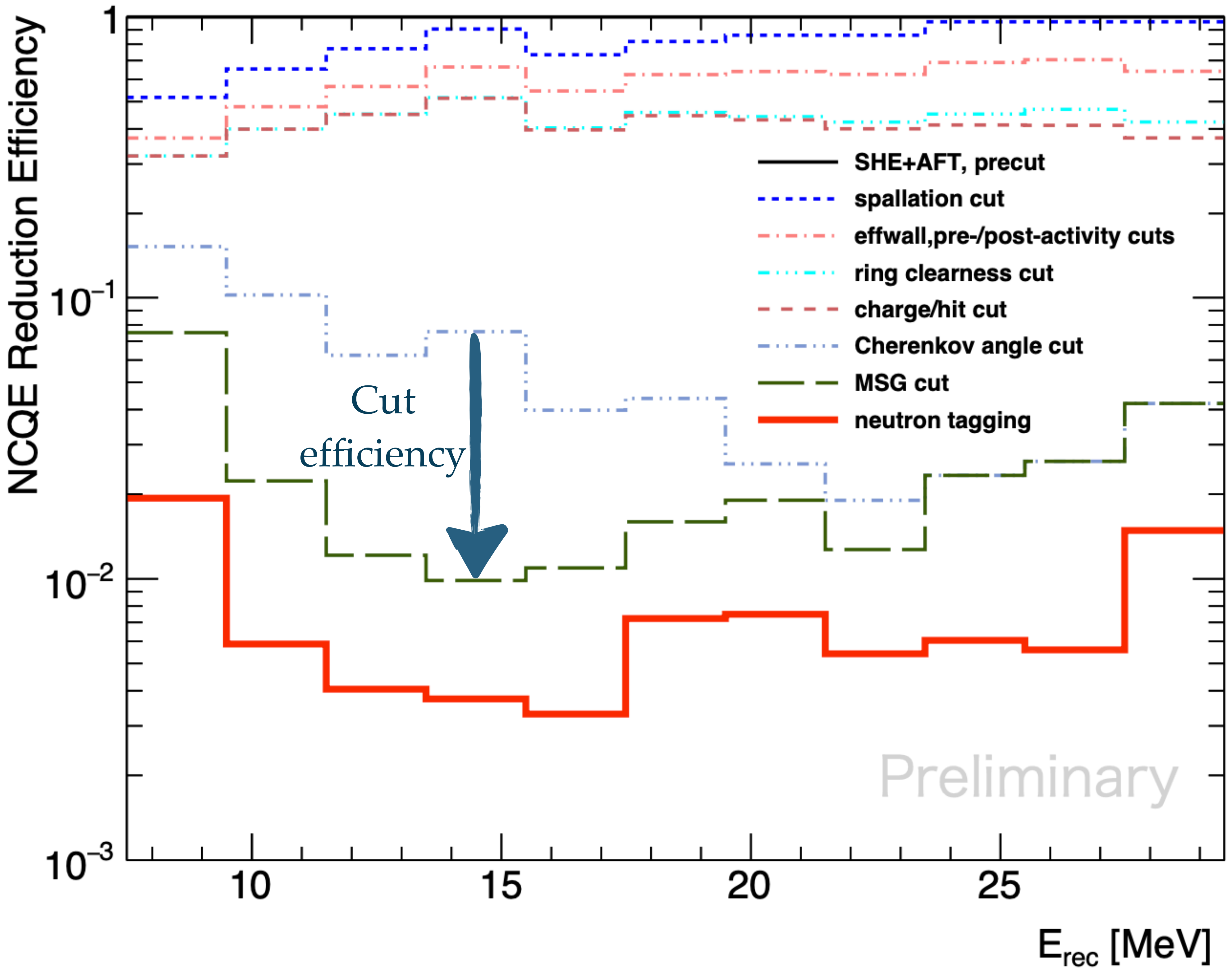
DSNB / NC events separation





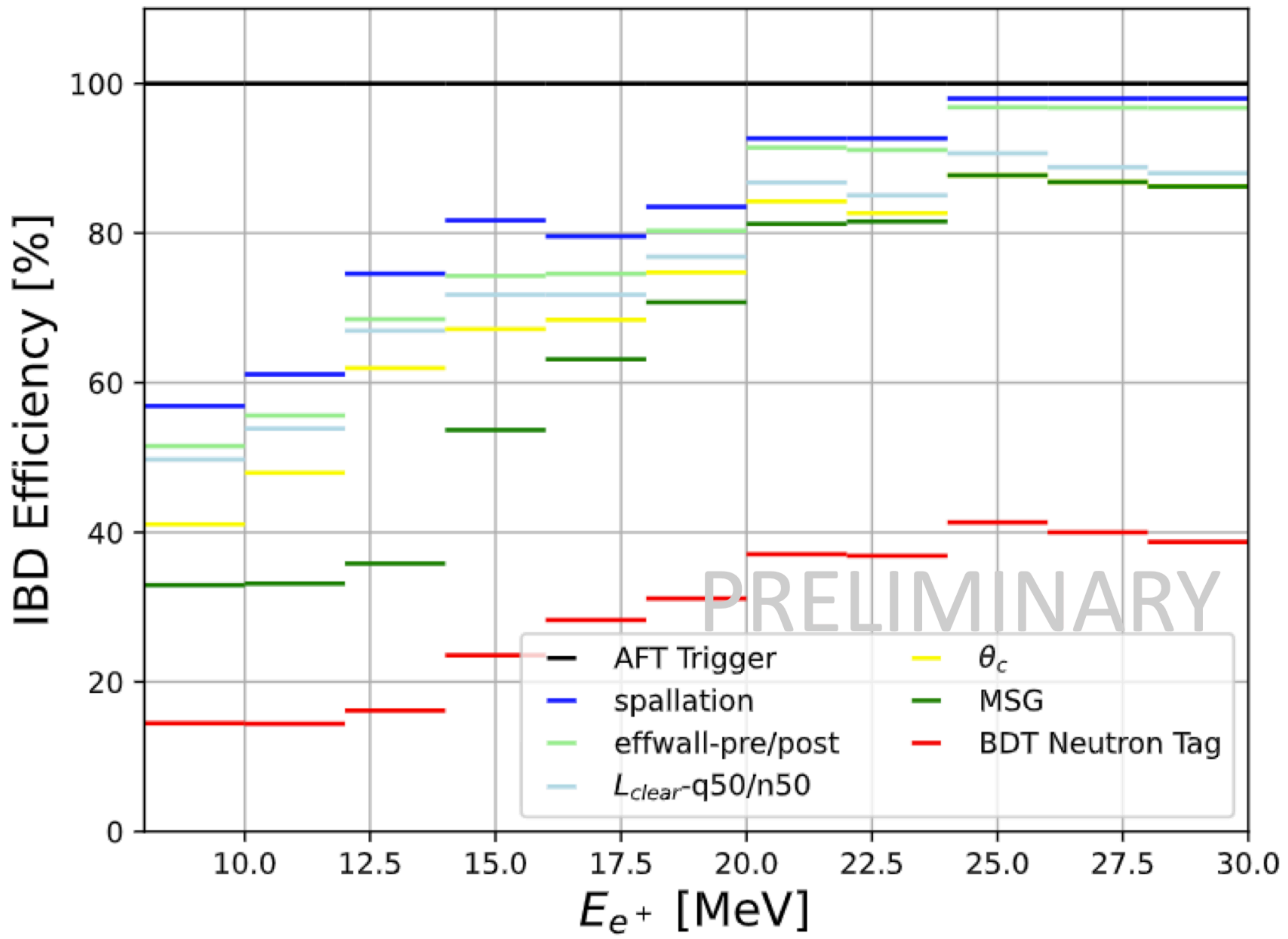
(Multiple Scattering Goodness)

Consisting of several cones → Consisting of a single cone



DSNB signal efficiency

SK-VI



SK-VII