Latest results of the DSNB search at Super-Kamiokande

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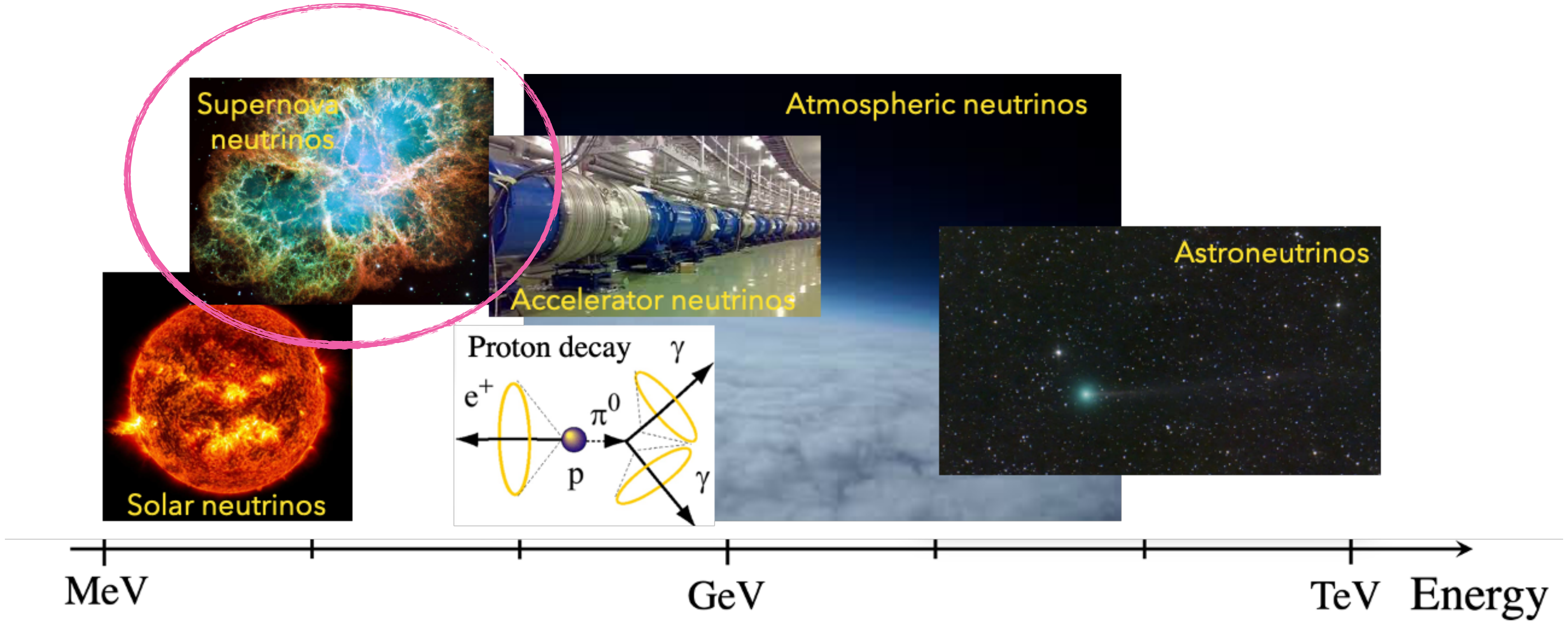
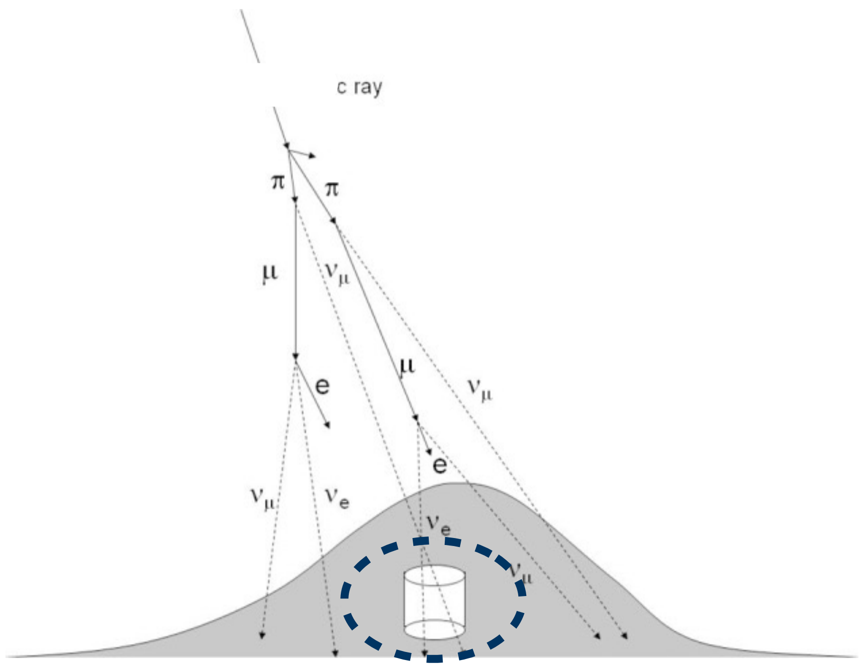
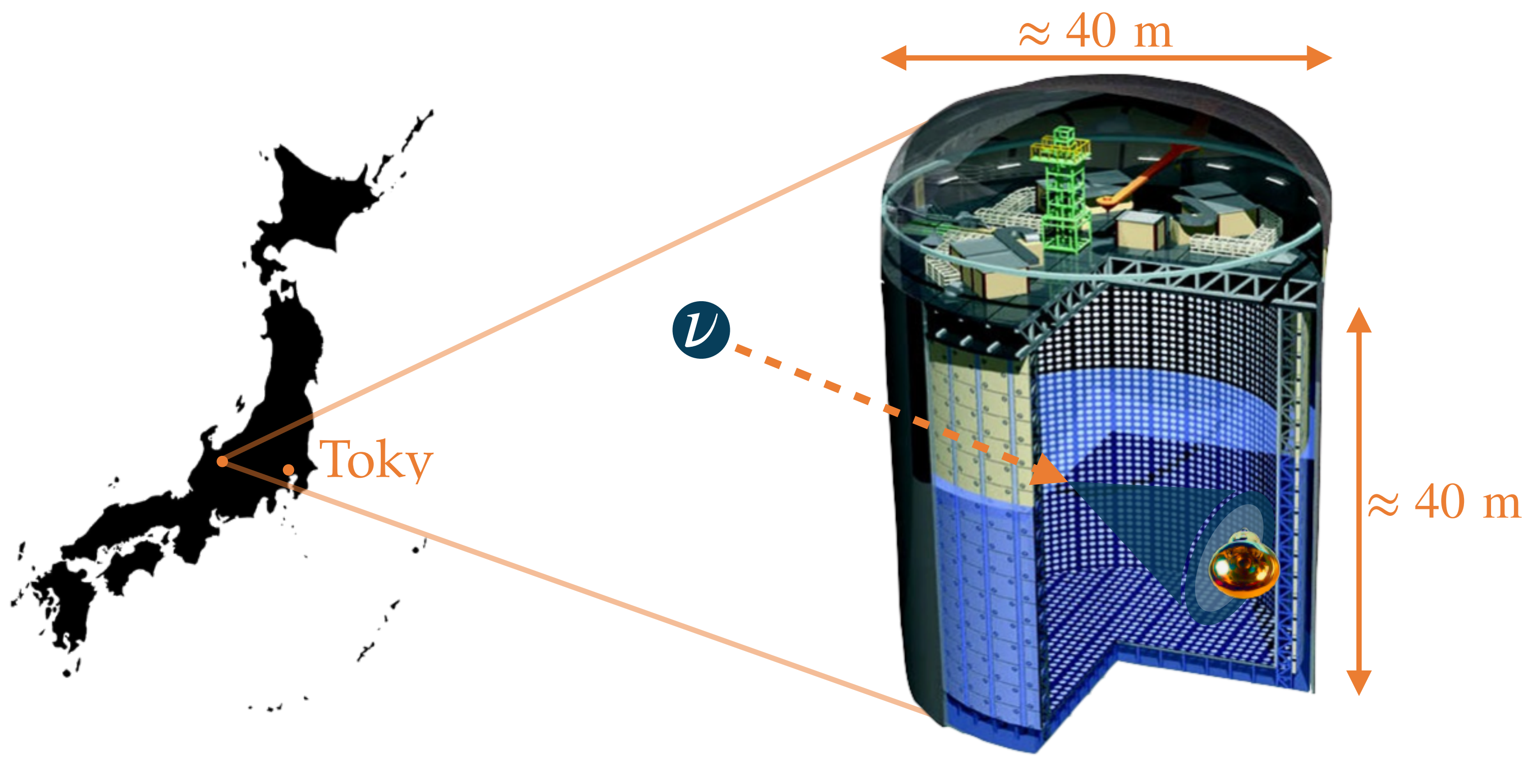
IRN Neutrino Meeting — *October 10th, 2024*

The Super-Kamiokande experiment



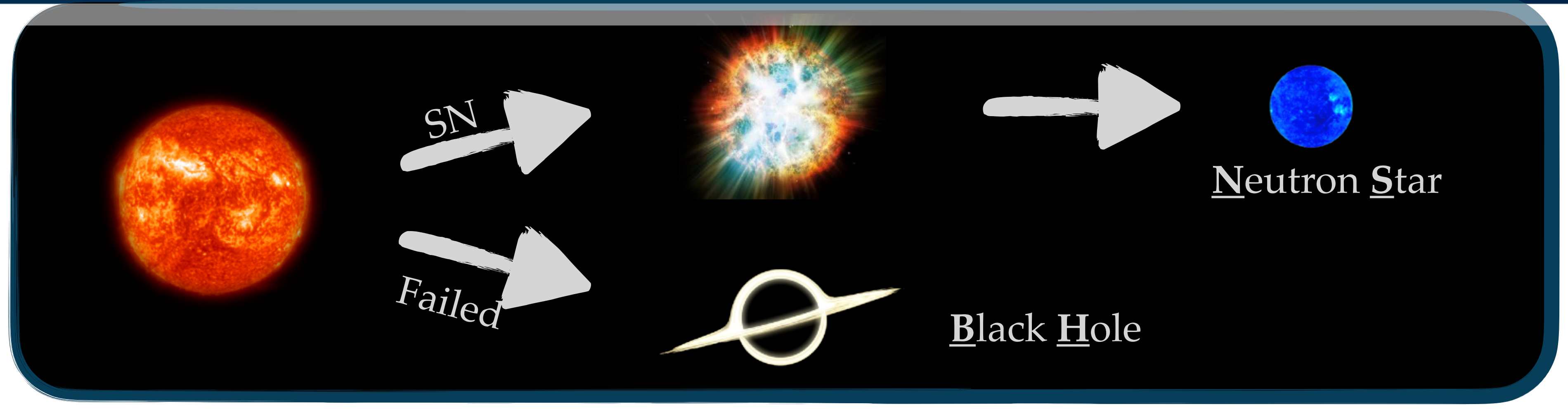




- Super-Kamiokande is a multi-purpose Cherenkov-based experiment with:
  - ➡ Real time measurement of vertex, direction, energy of impinging particles.
  - ➡ Multi-channel read-out of the Cherenkov signal of interacting particles, with **~11k PMTs**.
  - ➡ **Wide energy range** (from MeV to TeV) and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

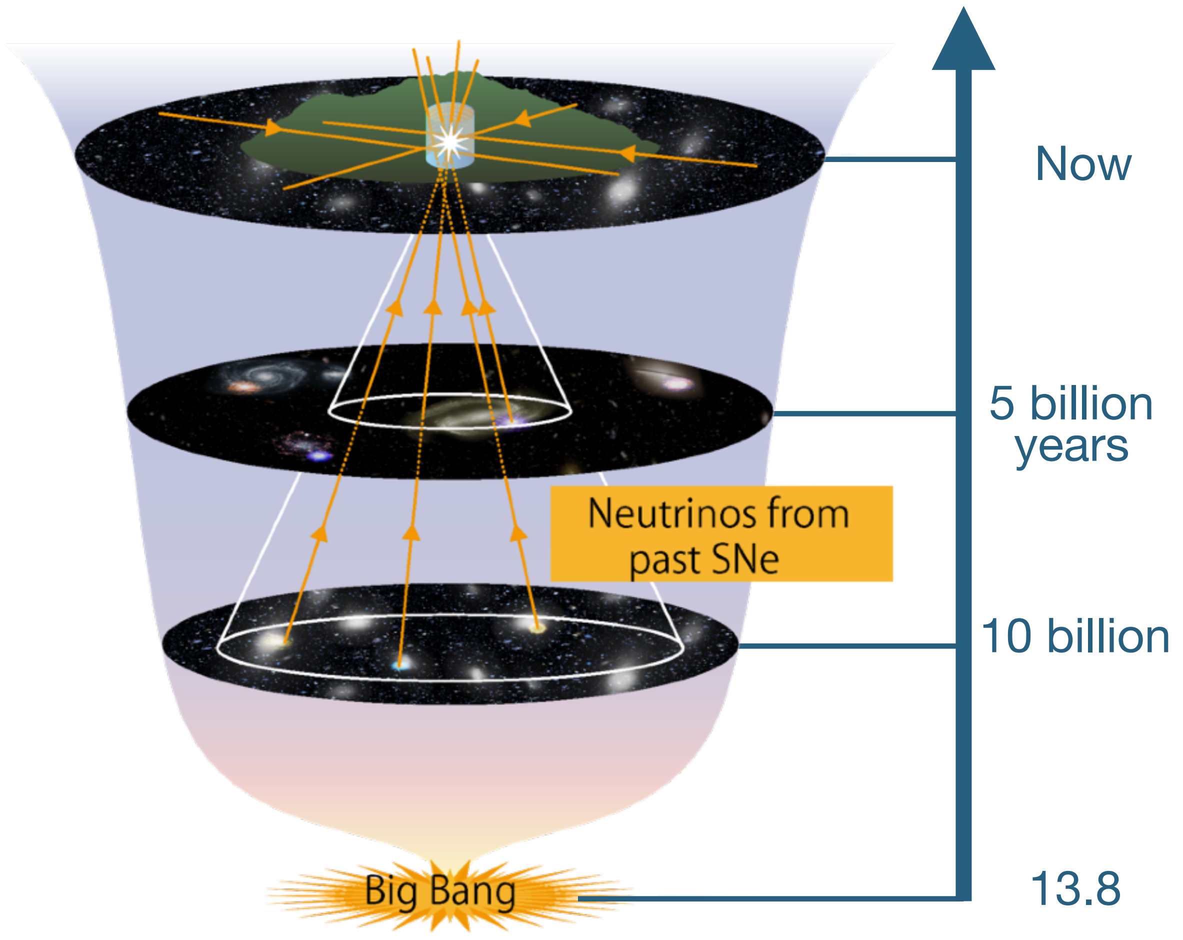
Diffuse Supernova Neutrino Background

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

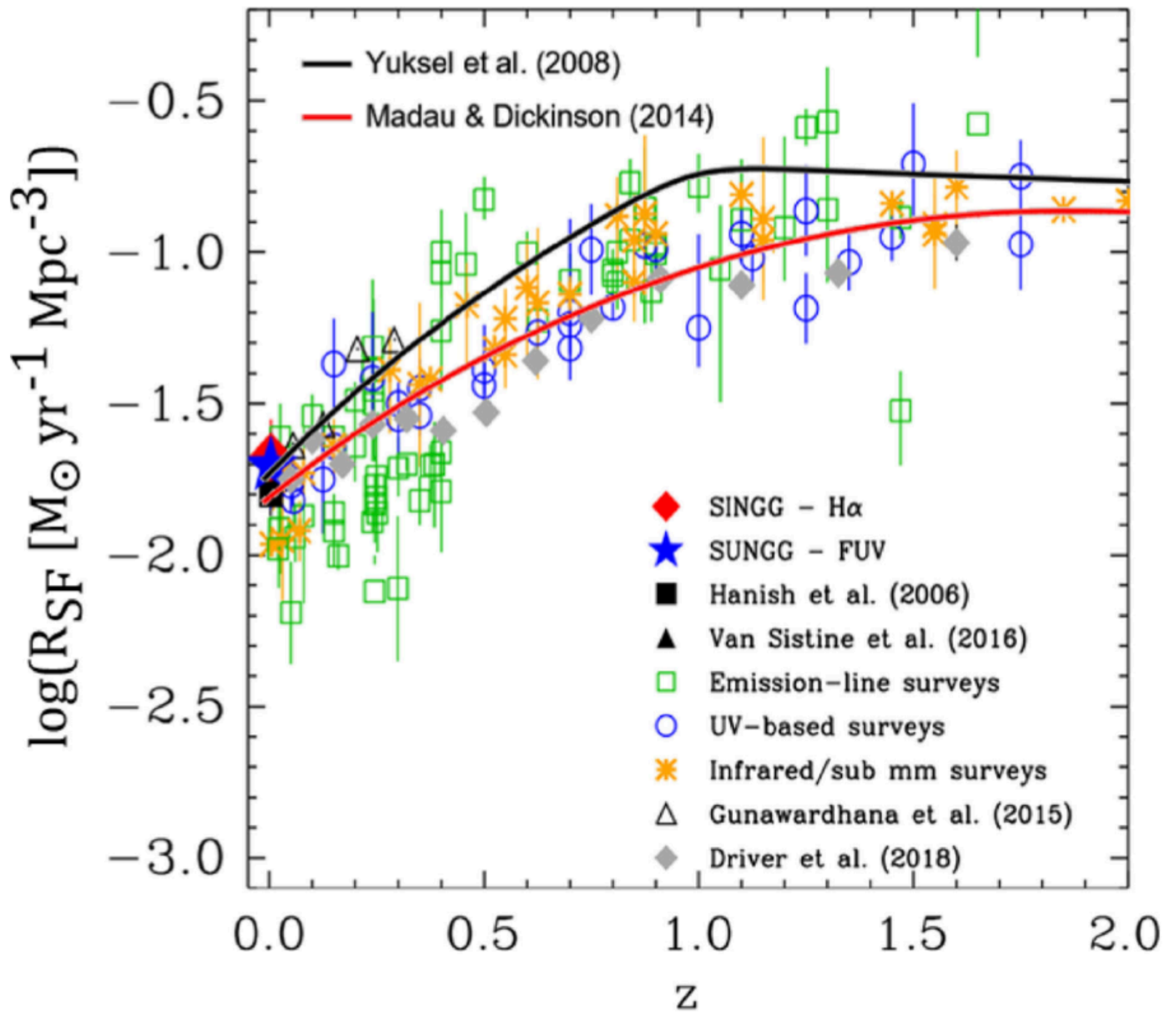
- DSNB flux is given by:

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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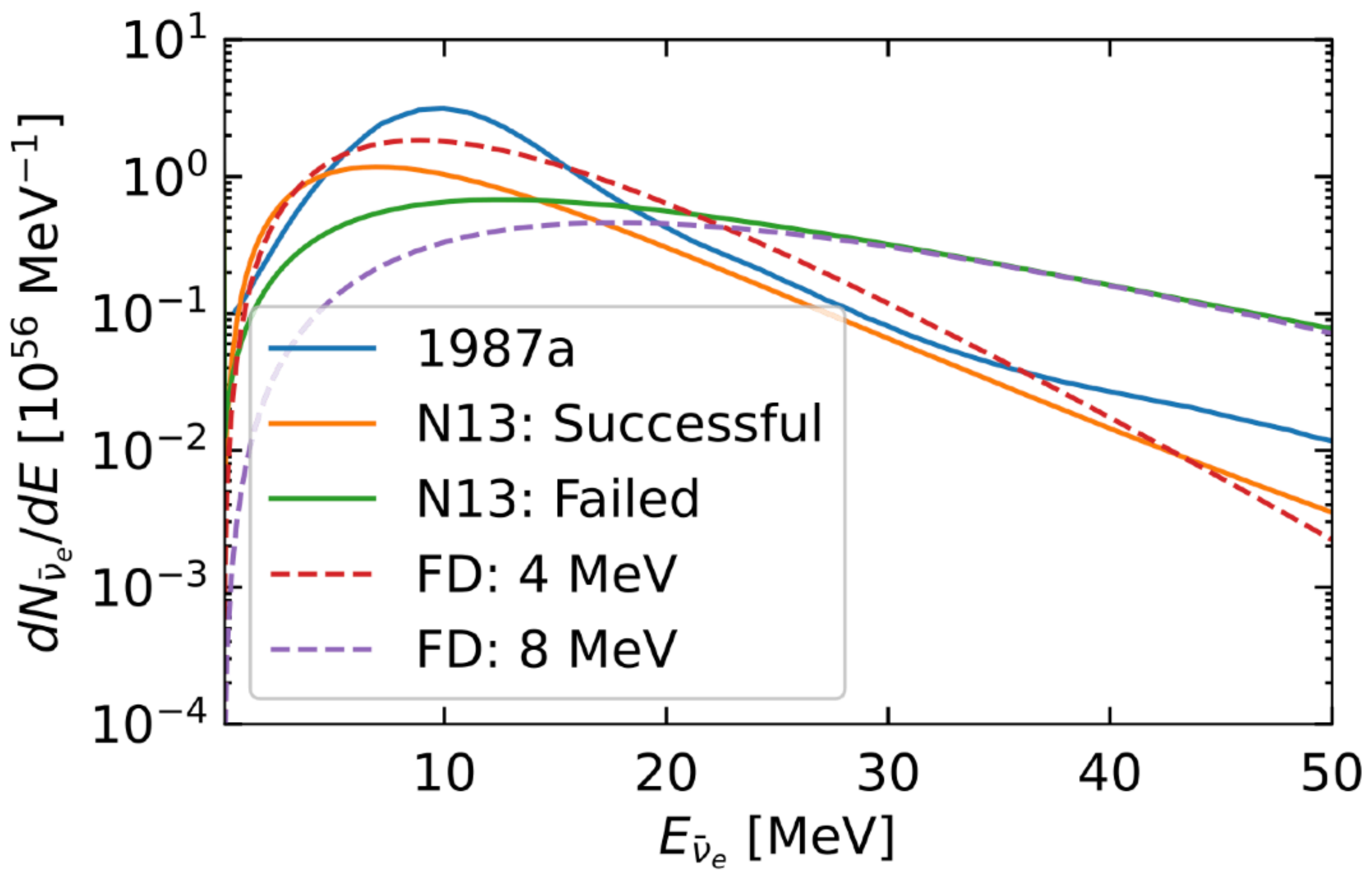
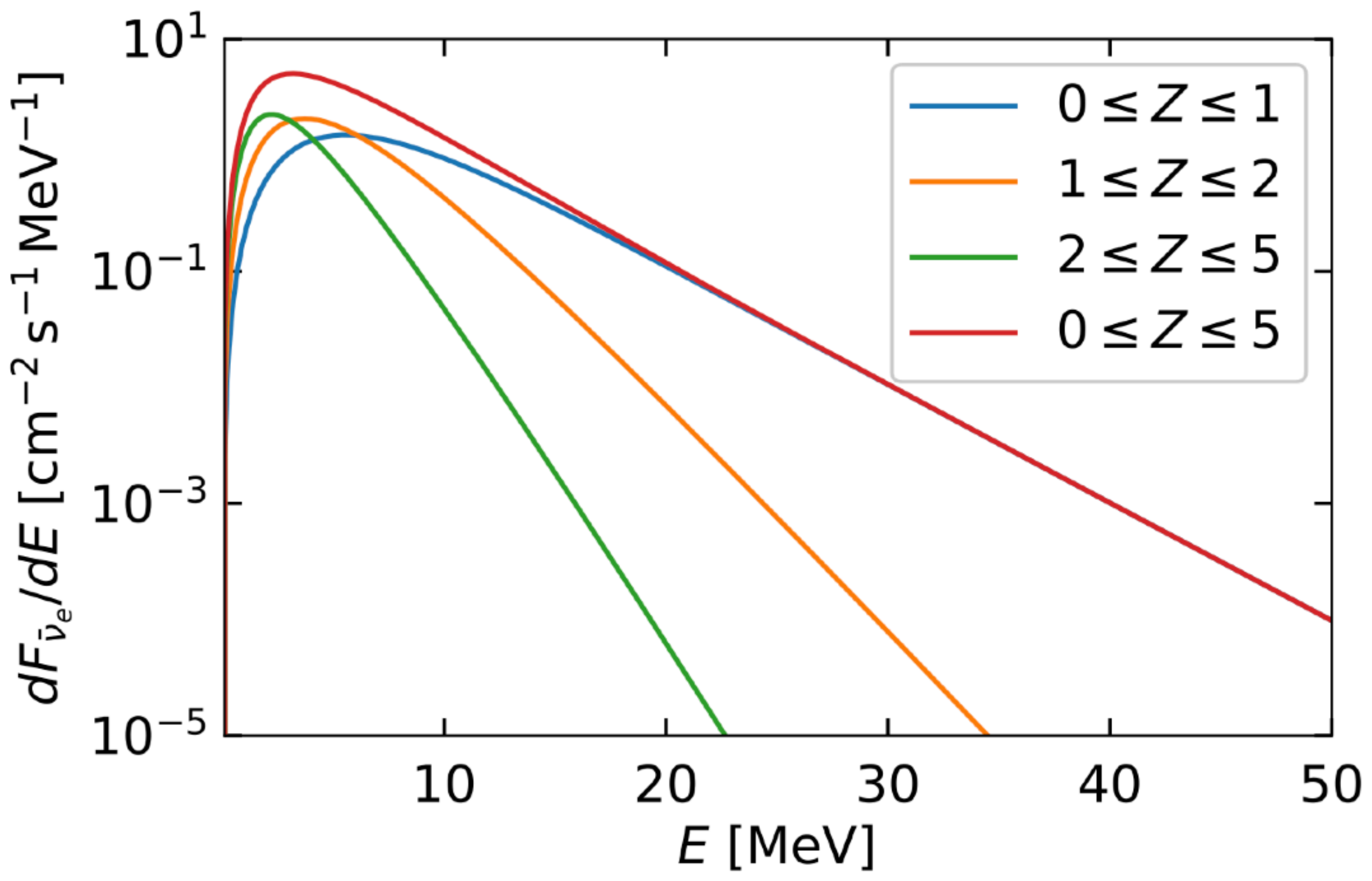


Example model of neutrino spectrum for successful & failed supernovae[1]



Redshitft-dependent neutrino spectrum[1]

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

DSNB flux prediction

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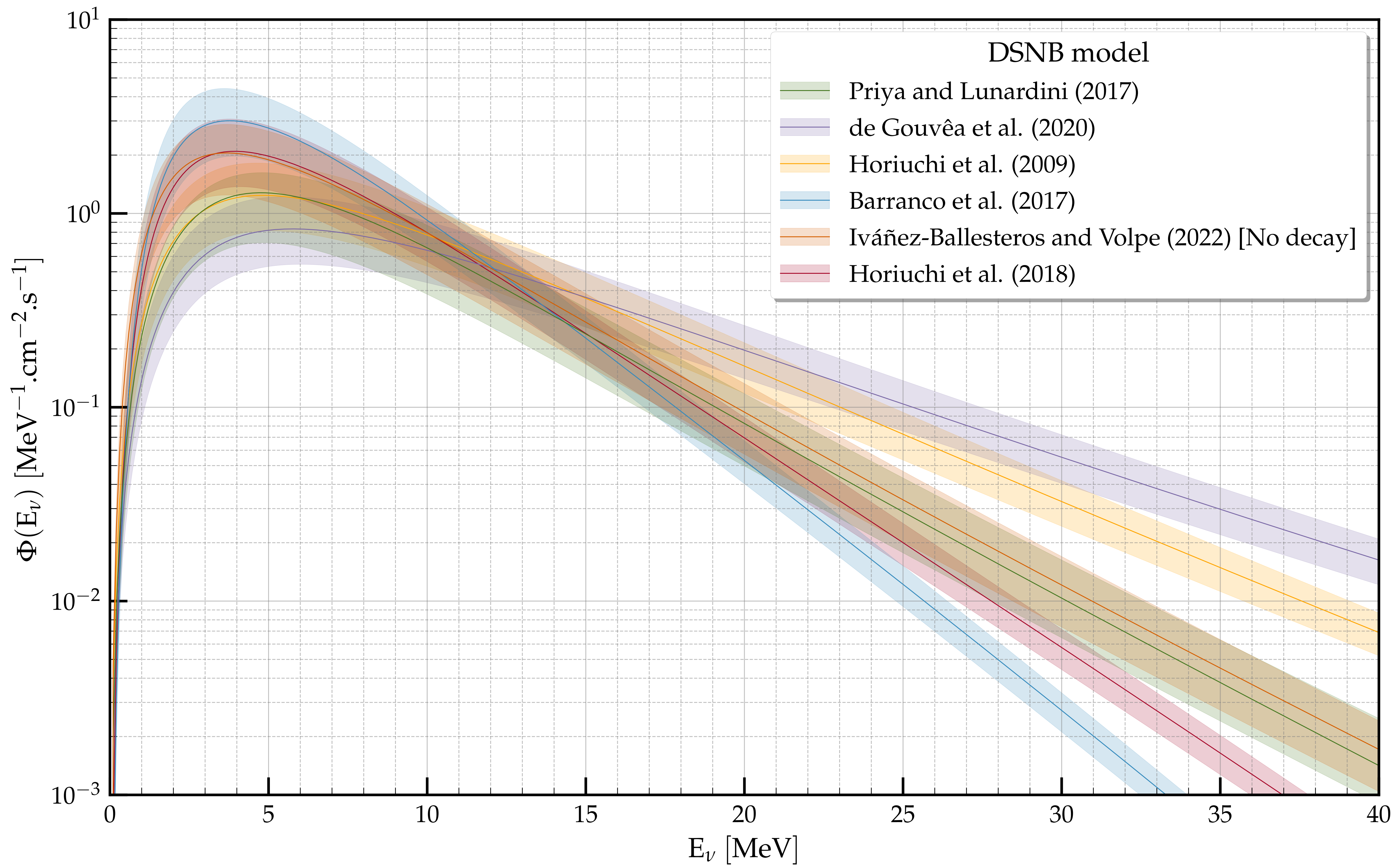
Redshift-dependent SN rate

Universe expansion

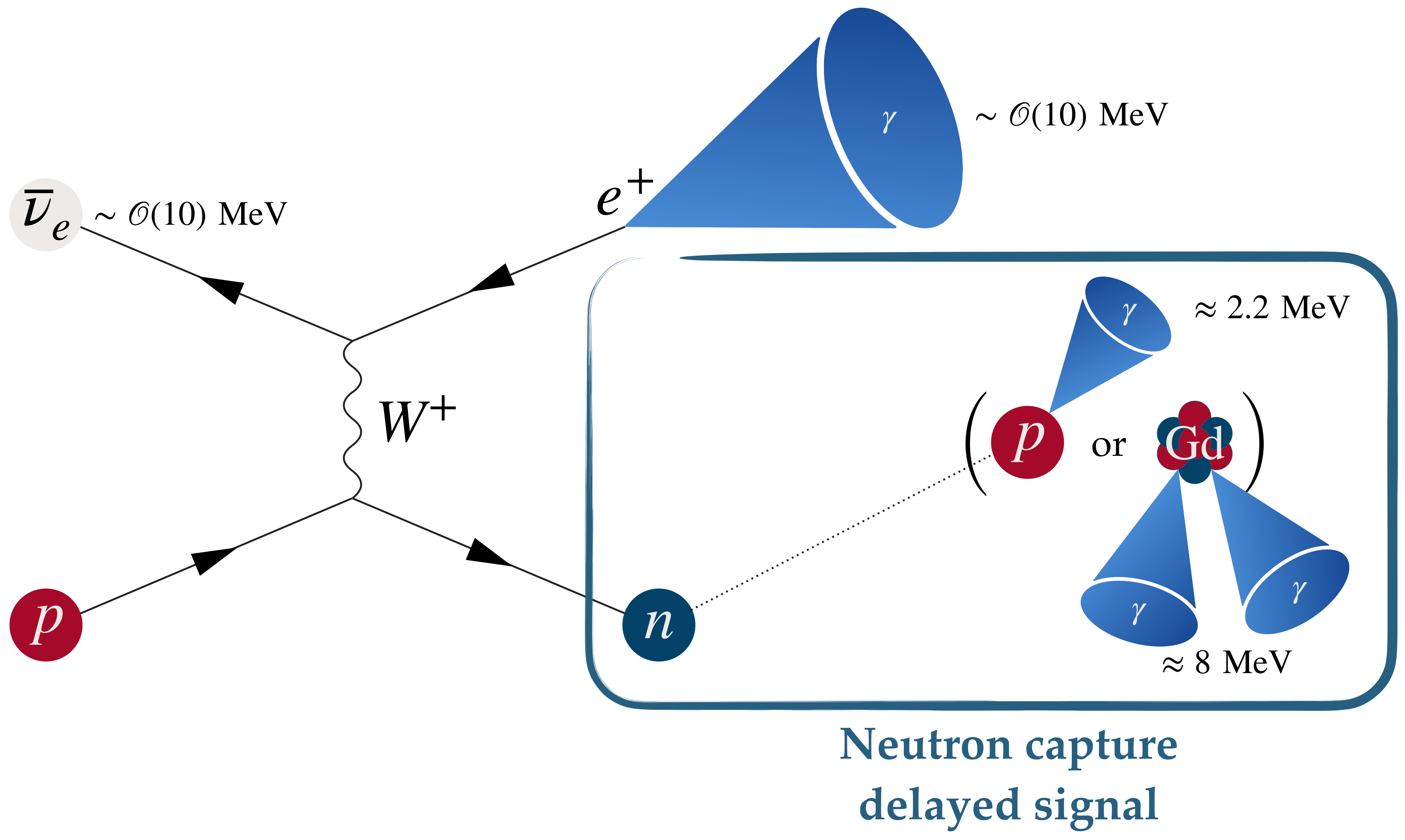
Rich phenomenology:

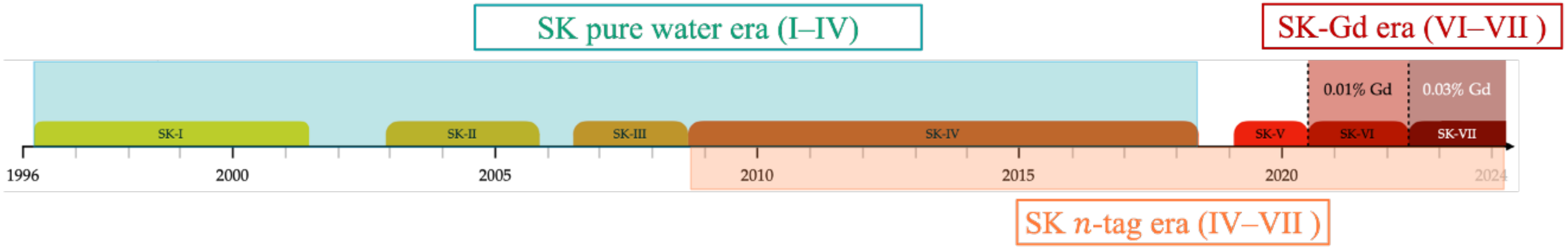
- Star formation rate,
- Black hole fraction,
- Neutrino oscillation in the stars,
- Exotic neutrino properties, e.g. neutrino decay,
- Supernova explosion mechanism,
- History of the universe.



DSNB events at SK

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





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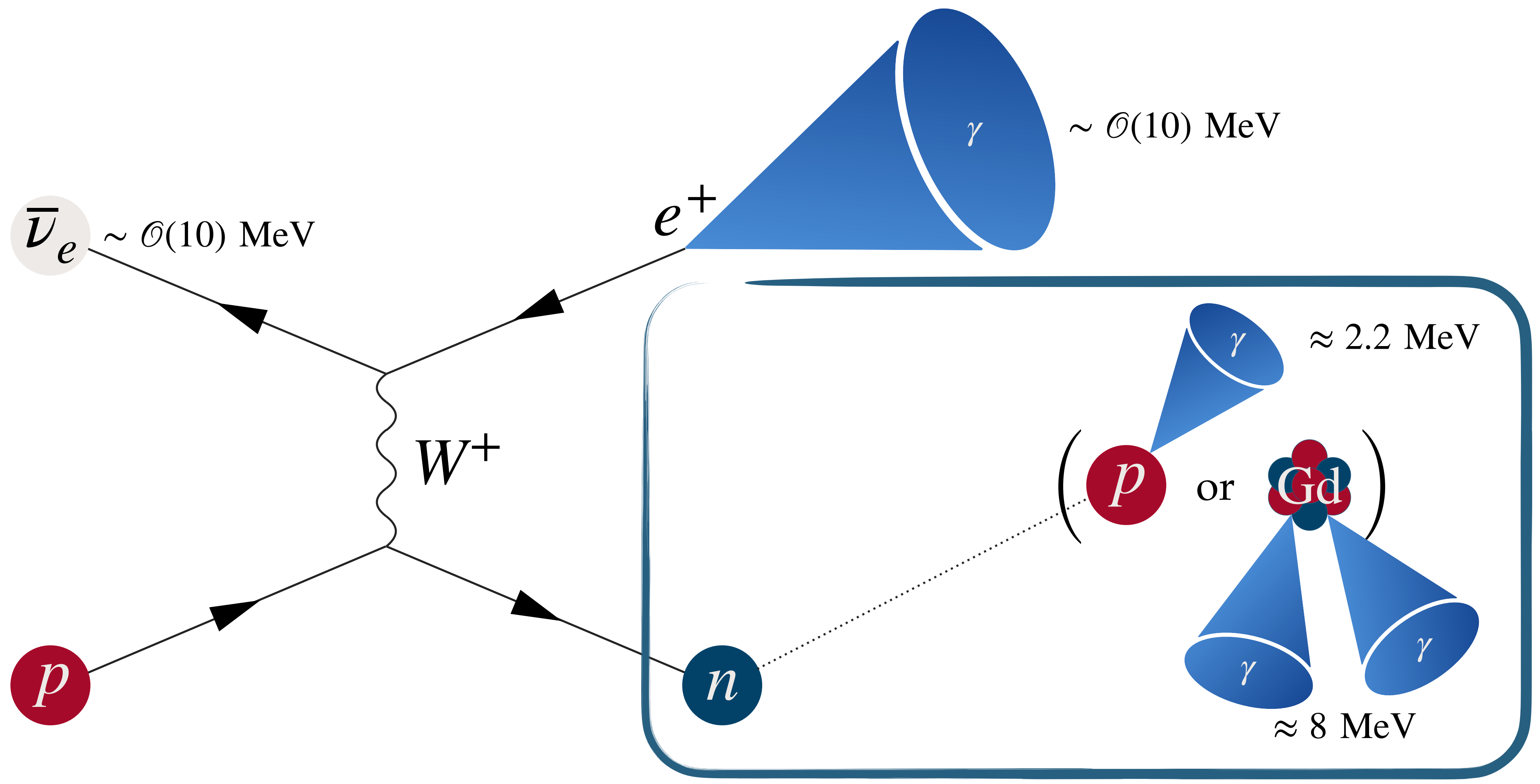
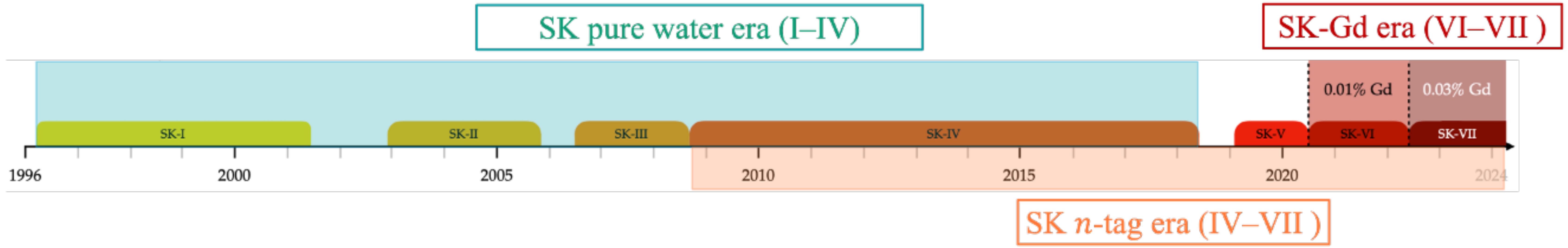


Neutron capture delayed signal

	SK-IV (pure water)	SK-VI (0.01% Gd)	SK-VII (0.03% Gd)
n-capture on Gd	0 %	50 %	75 %
Time constant	~205 μs	~115 μs	~65 μs
n-detection efficiency	~25%	~40%	~60%

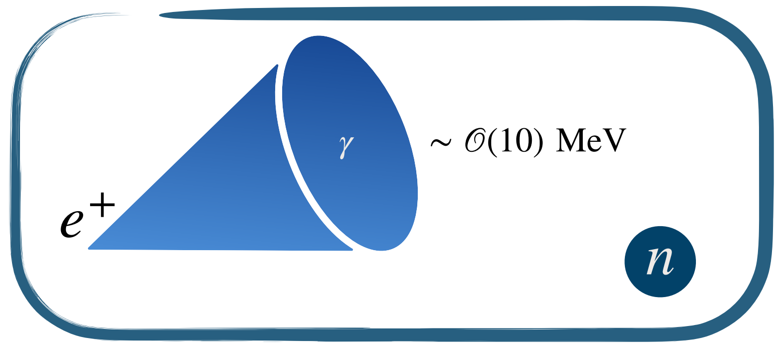
Two neutron-tagging algorithms: BDT & Neural Net



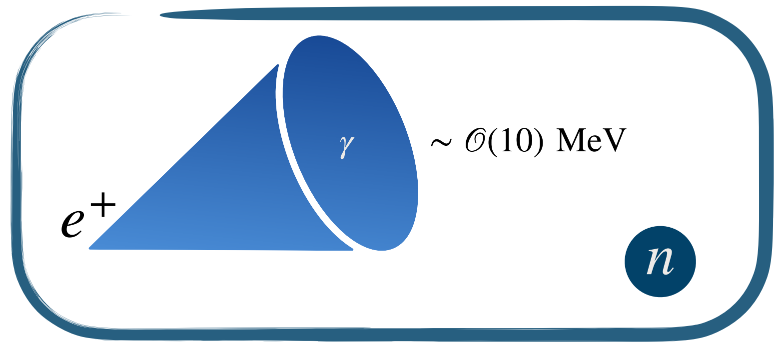
Background events at SK

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

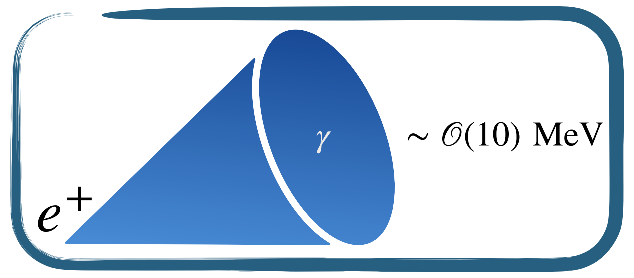
- Reactor:
  - **Irreducible**, $\sim 10^3$ times more than DSNB events below 10 MeV



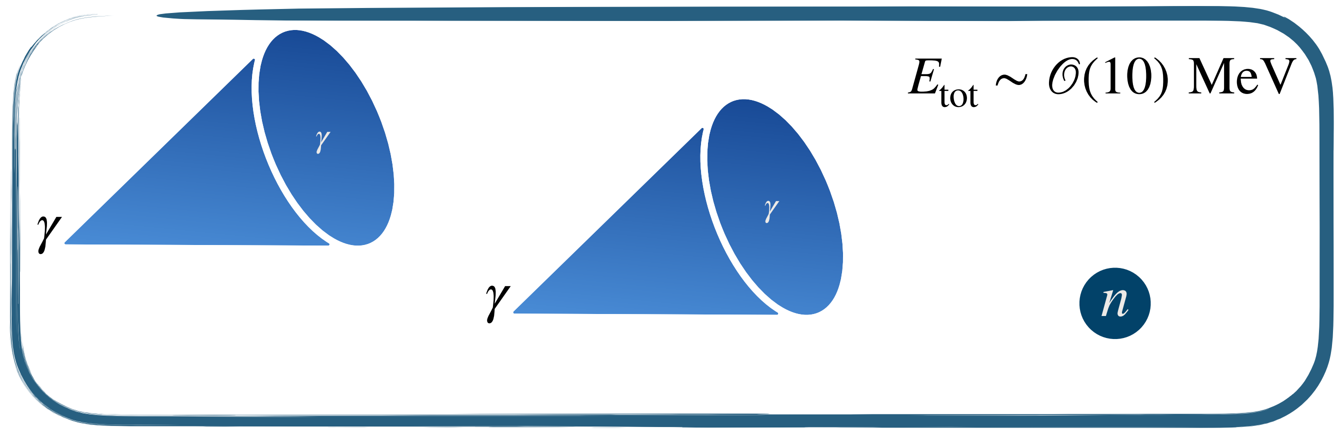
- Spallation:
  - Observables: E_{e^+}, θ_C and number of n



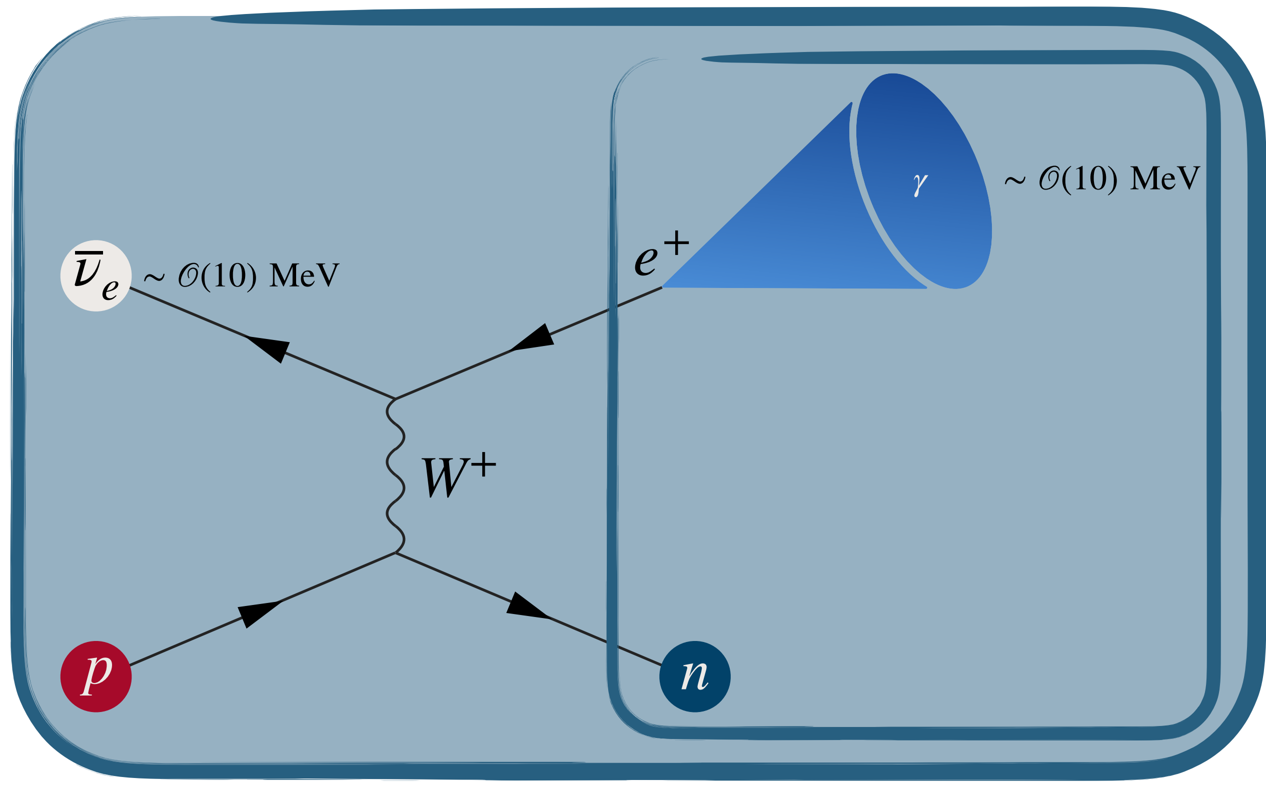
- Atmospheric ν - Charged-Current (CC):
  - Observables: E_{e^+} and θ_C



- Atmospheric ν - Neutral-Current (NC):
  - Observables: E_{e^+}, θ_C and number of n



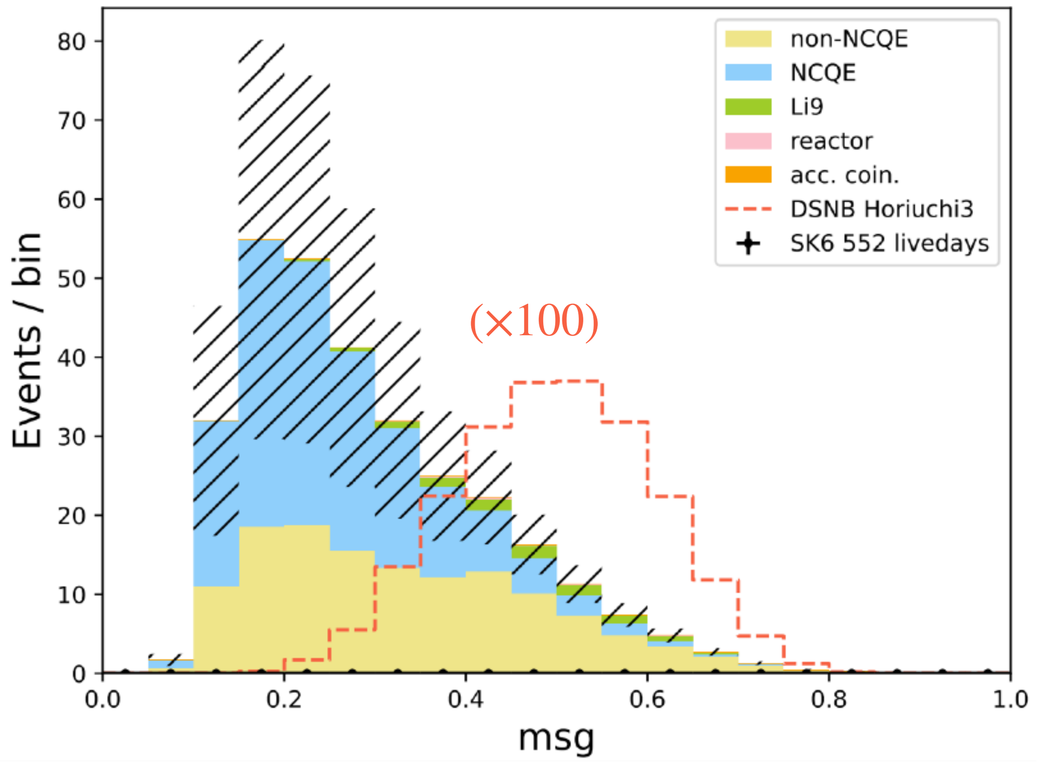
DSNB event

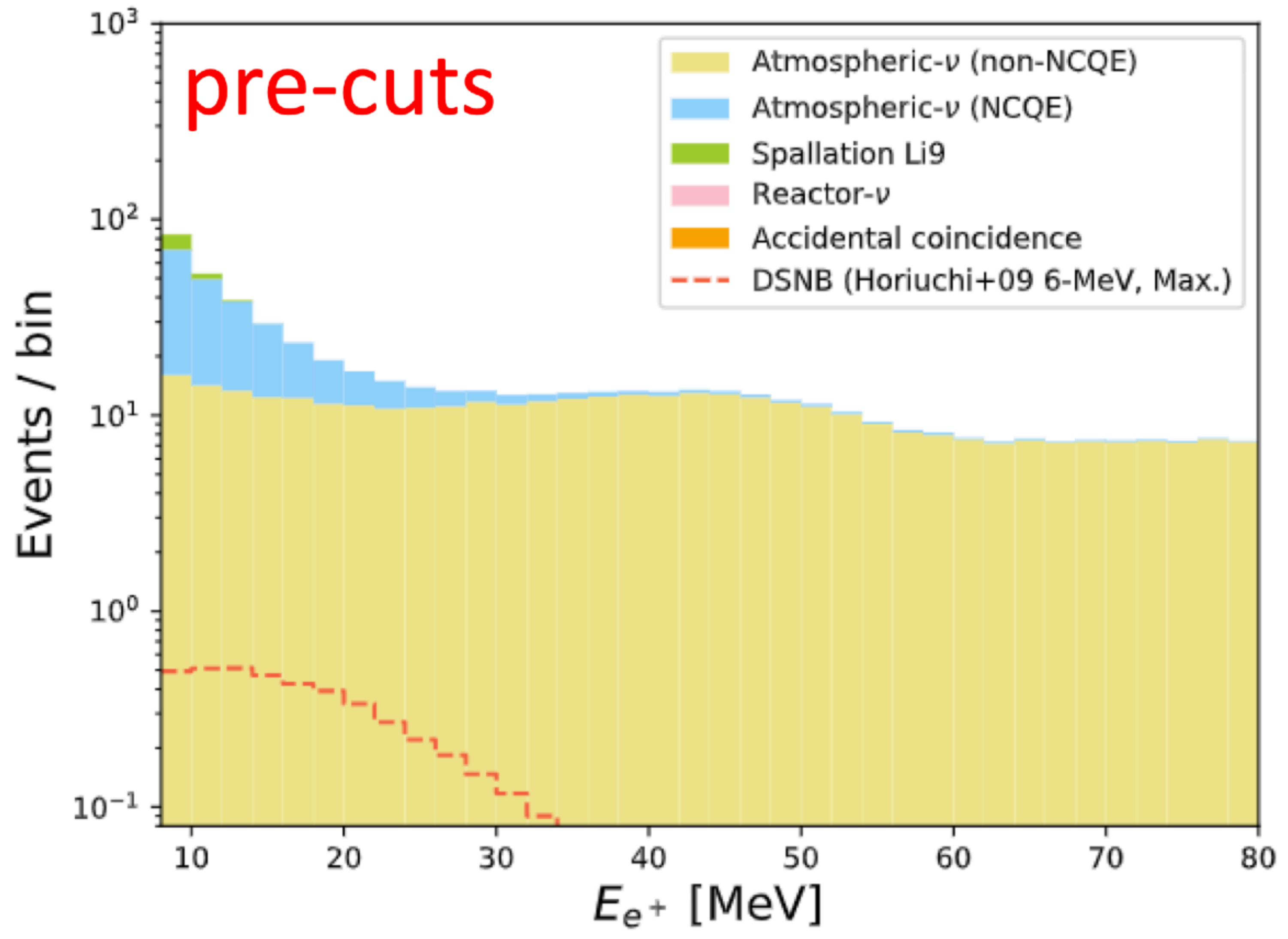


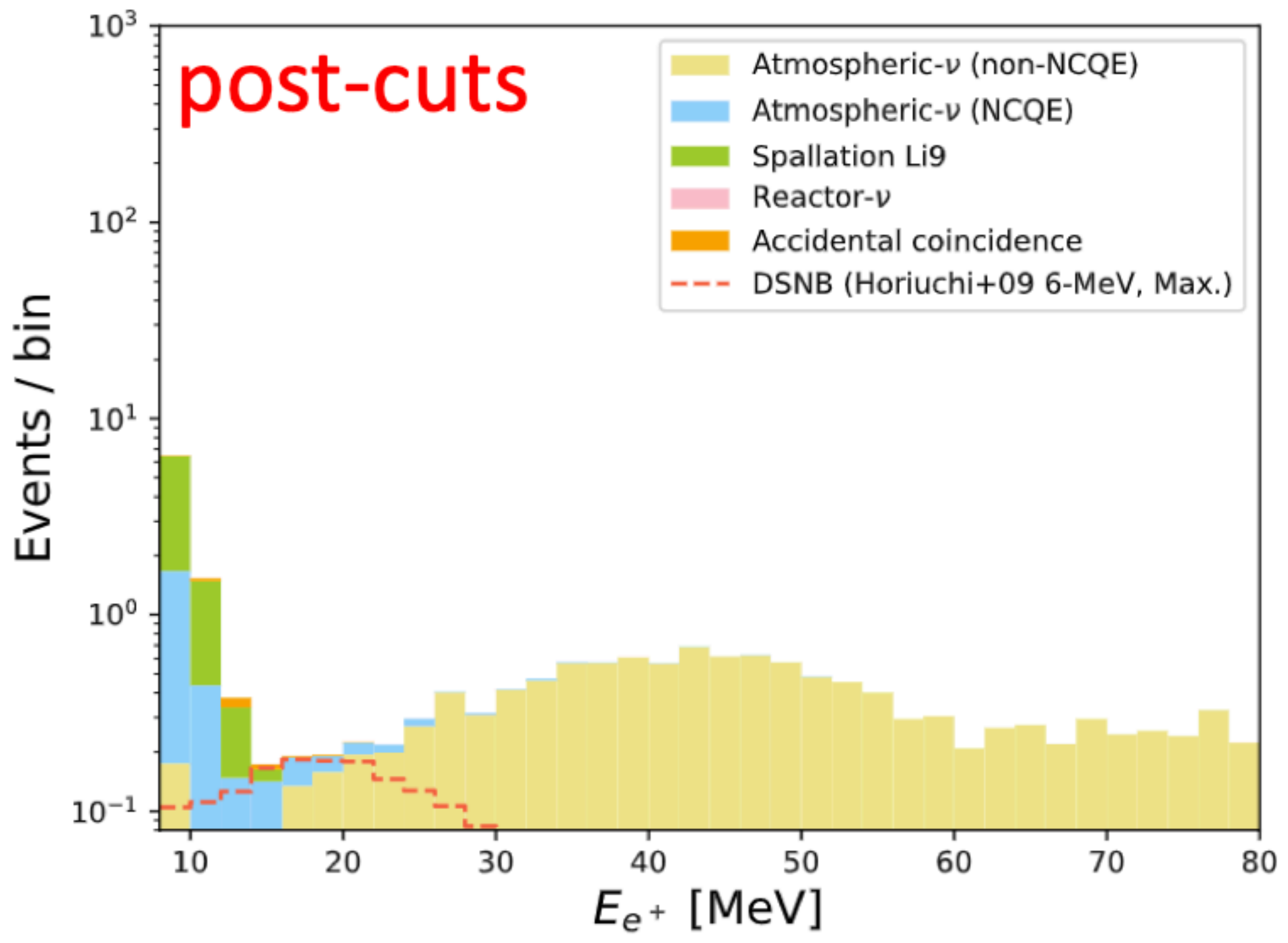
Data reduction

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, single-cone likeness cut (or **MSG cut**).







DSNB analysis - Spectral Fit

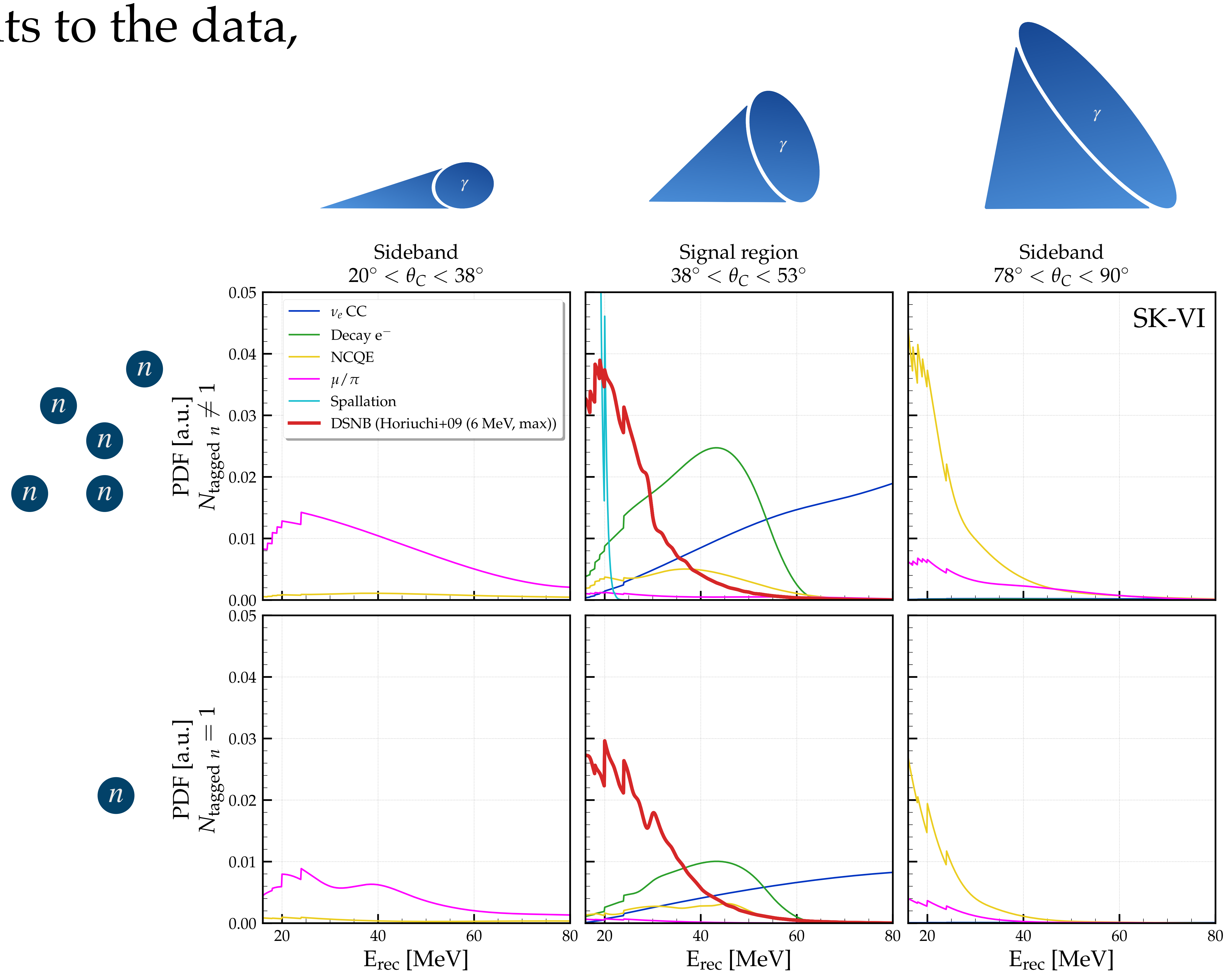
Principle

- **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 ($N_{\text{tagged } n} \neq 1$)



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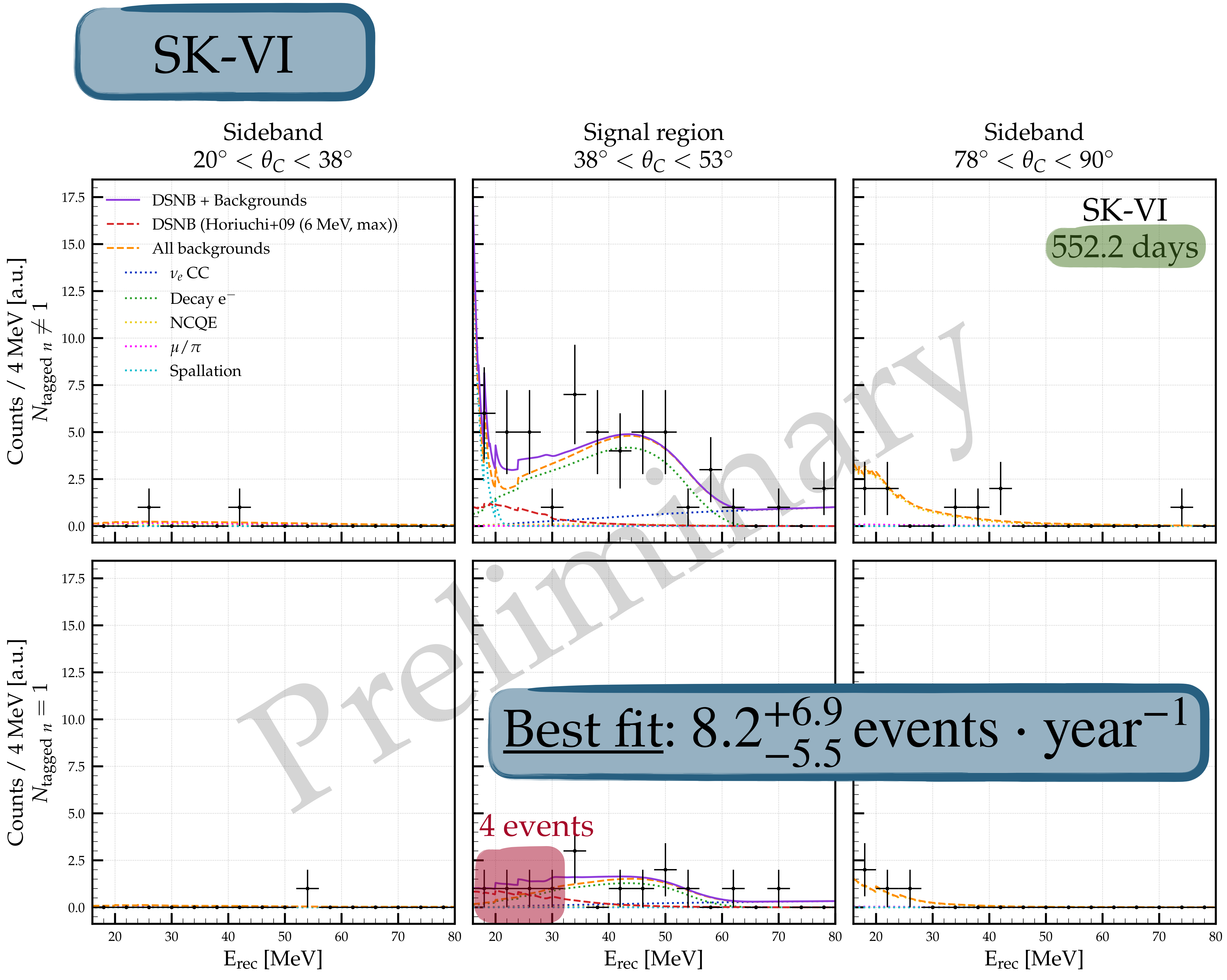
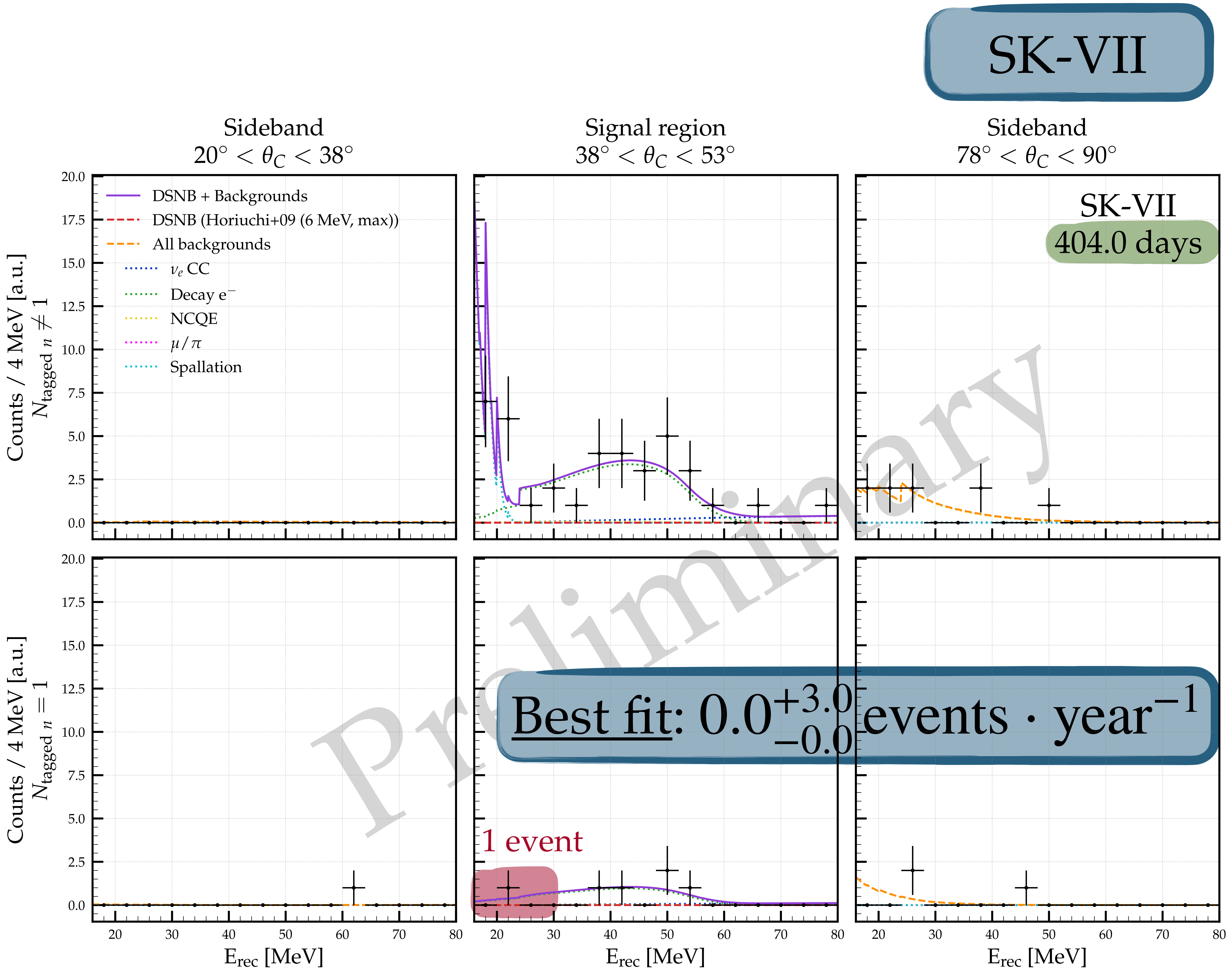
DSNB analysis - Spectral Fit results

Fitted spectra

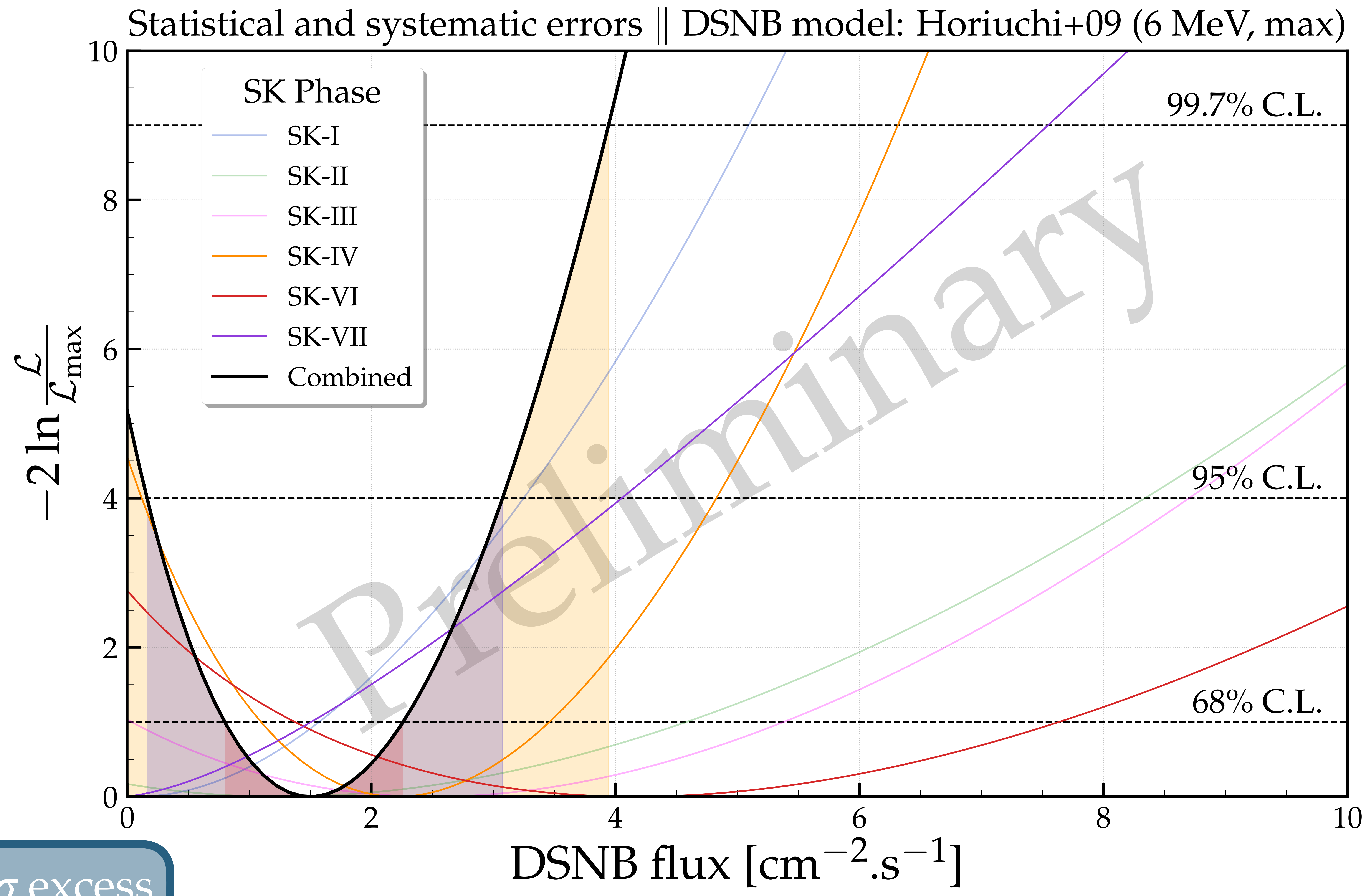




Likelihoods

Combined Results

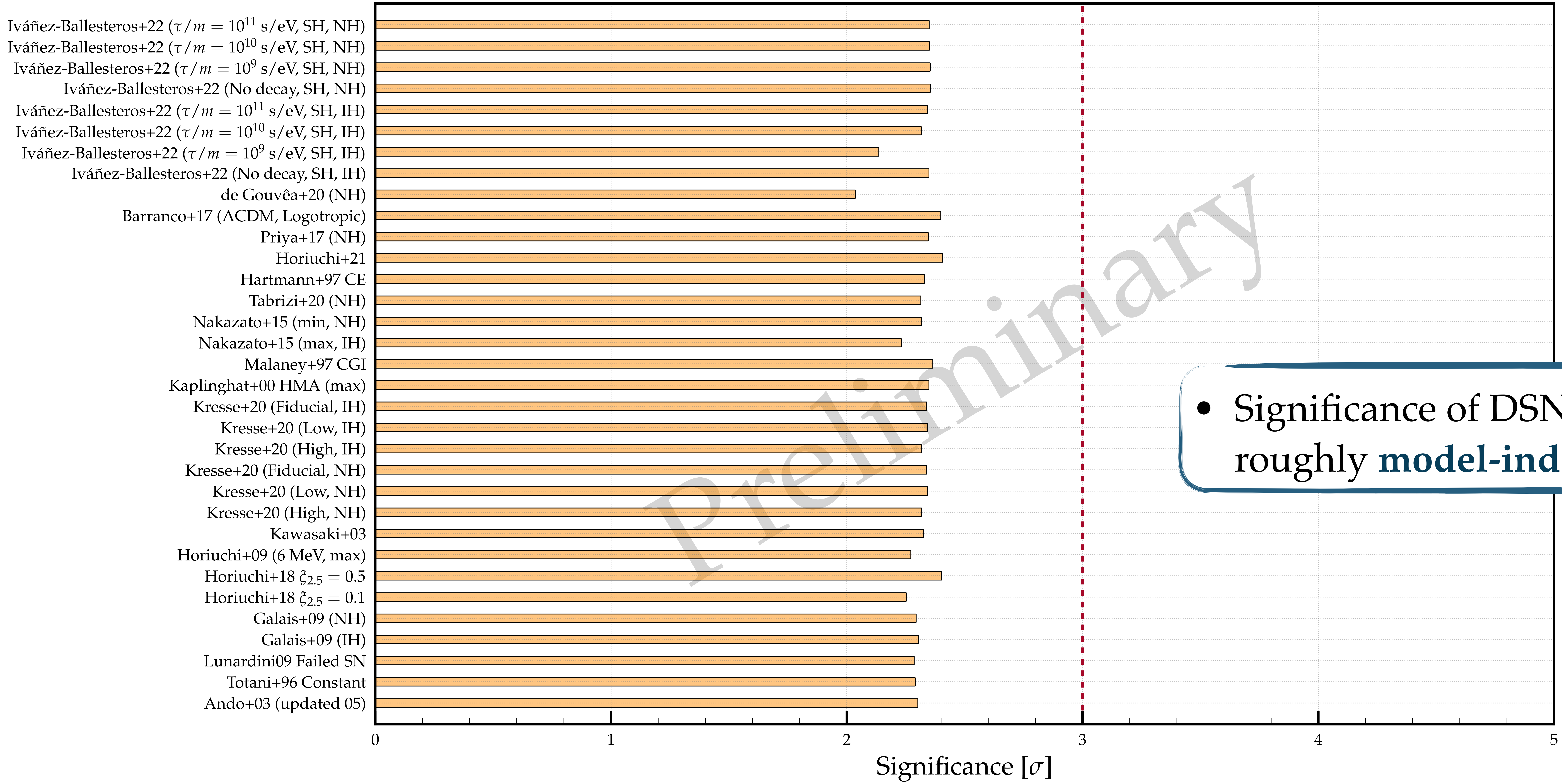
DSNB (Horiuchi+09)
Best fit rate $2.9\,\text{events} \cdot \text{year}^{-1}$
90% C.L. upper limit (rate) $5.0\,\text{events} \cdot \text{year}^{-1}$
Best fit flux $1.4\,\text{cm}^{-2} \cdot \text{s}^{-1} > 17.3\,\text{MeV}$
90% C.L. upper limit (flux) $2.5\,\text{cm}^{-2} \cdot \text{s}^{-1} > 17.3\,\text{MeV}$



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

DSNB analysis - Spectral Fit results

Significances

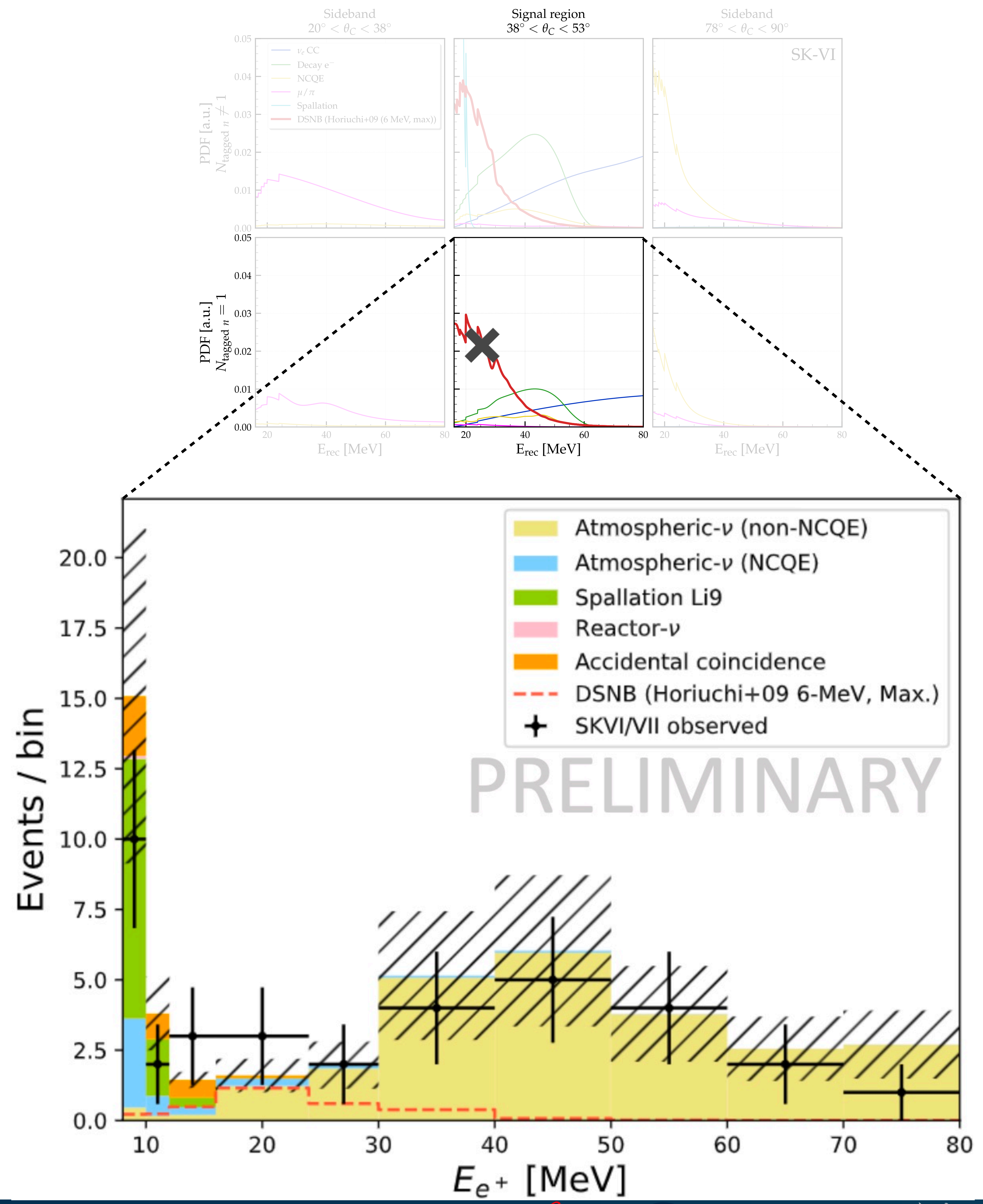


- Significance of DSNB signal is roughly **model-independent.**

DSNB analysis - Binned Analysis

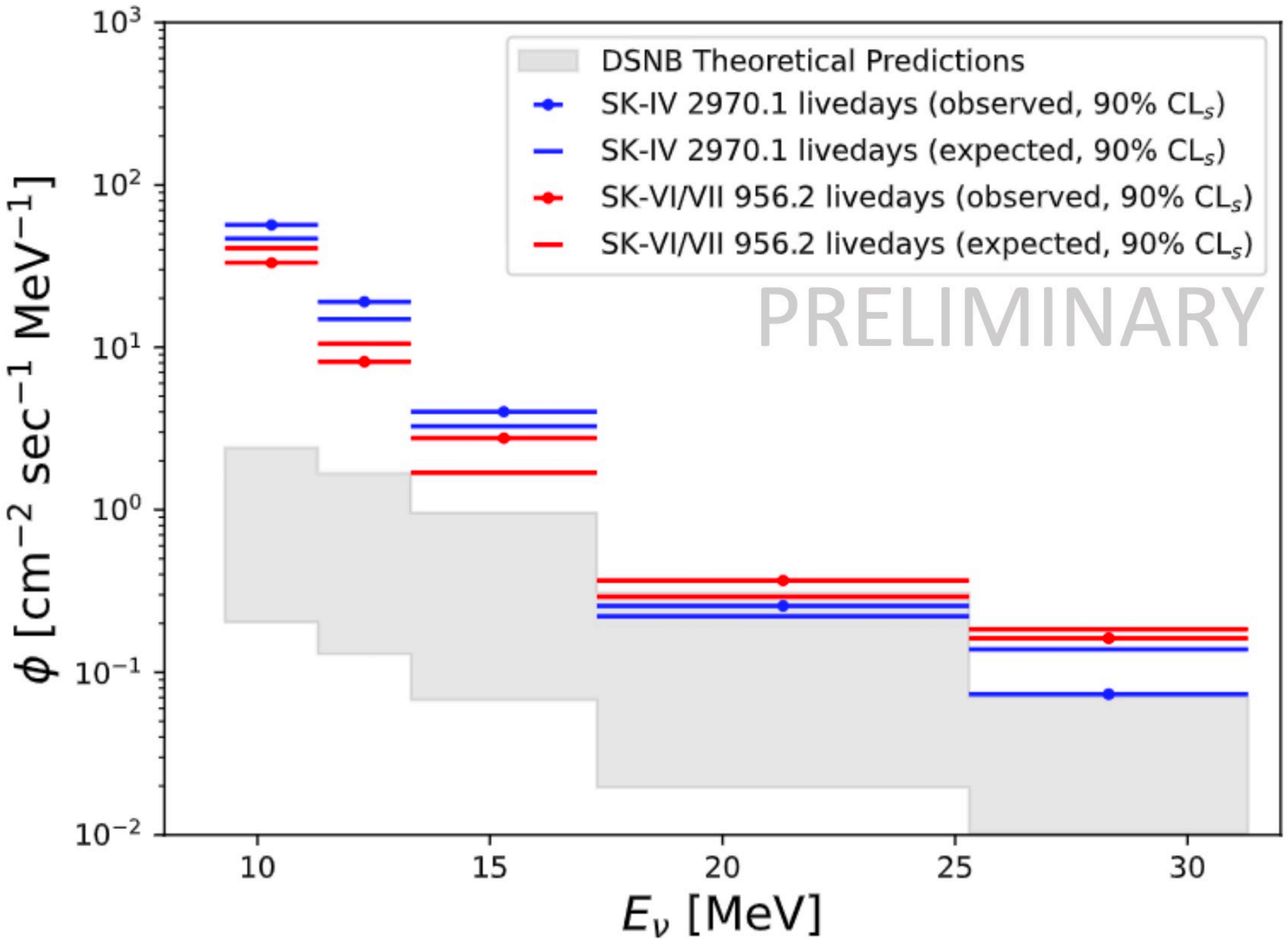
Principle

- 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.



Upper Limits

- Poor sensitivity in the very low energy region, mostly due to spallation background.
- From 17.3 MeV in neutrino energy (16 MeV in positron energy), upper limits approach the range of DSNB prediction.



Conclusion

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

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

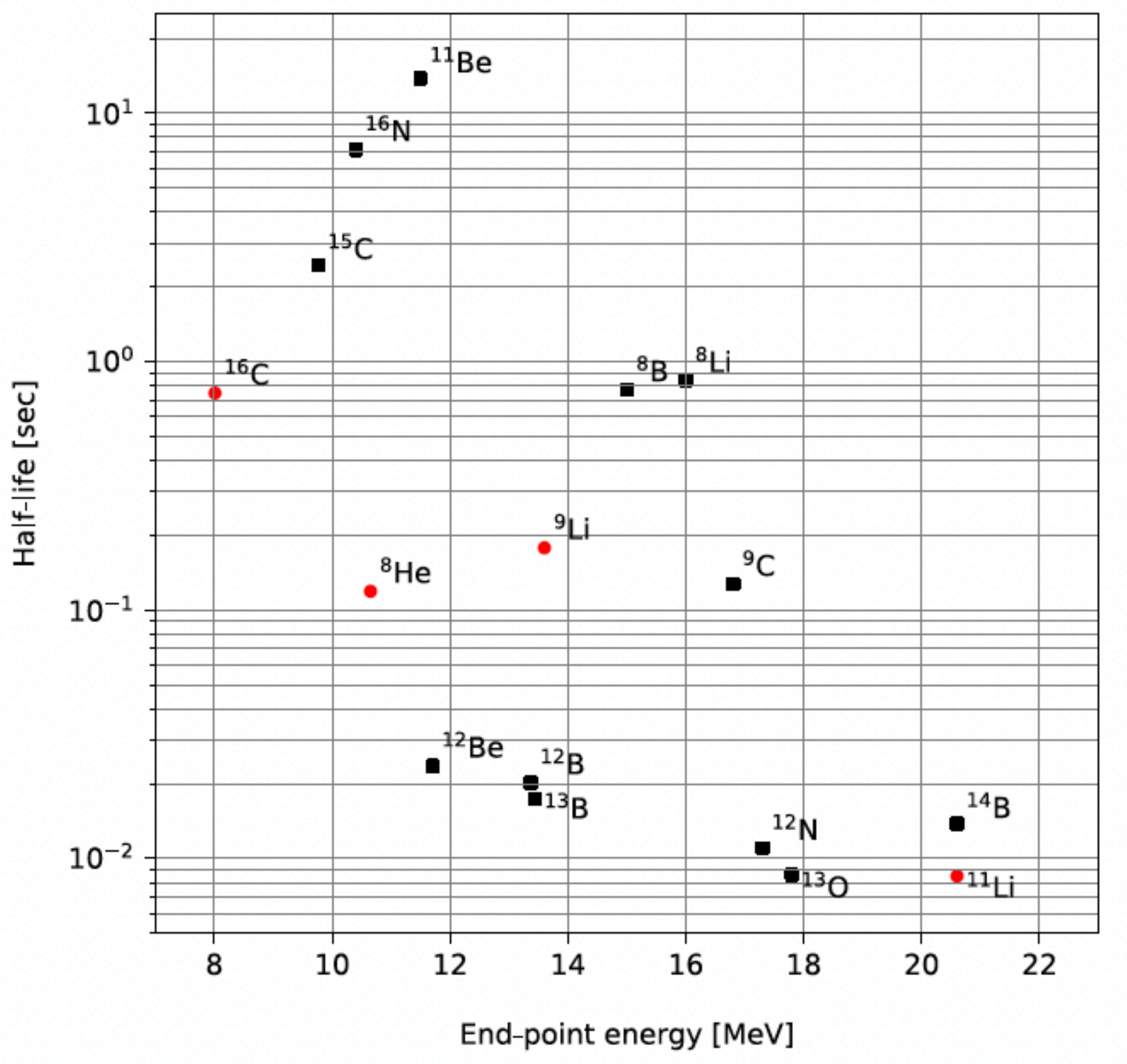
  ➡ Rejection of the background-only hypothesis at the 2.3σ level across all SK phases.

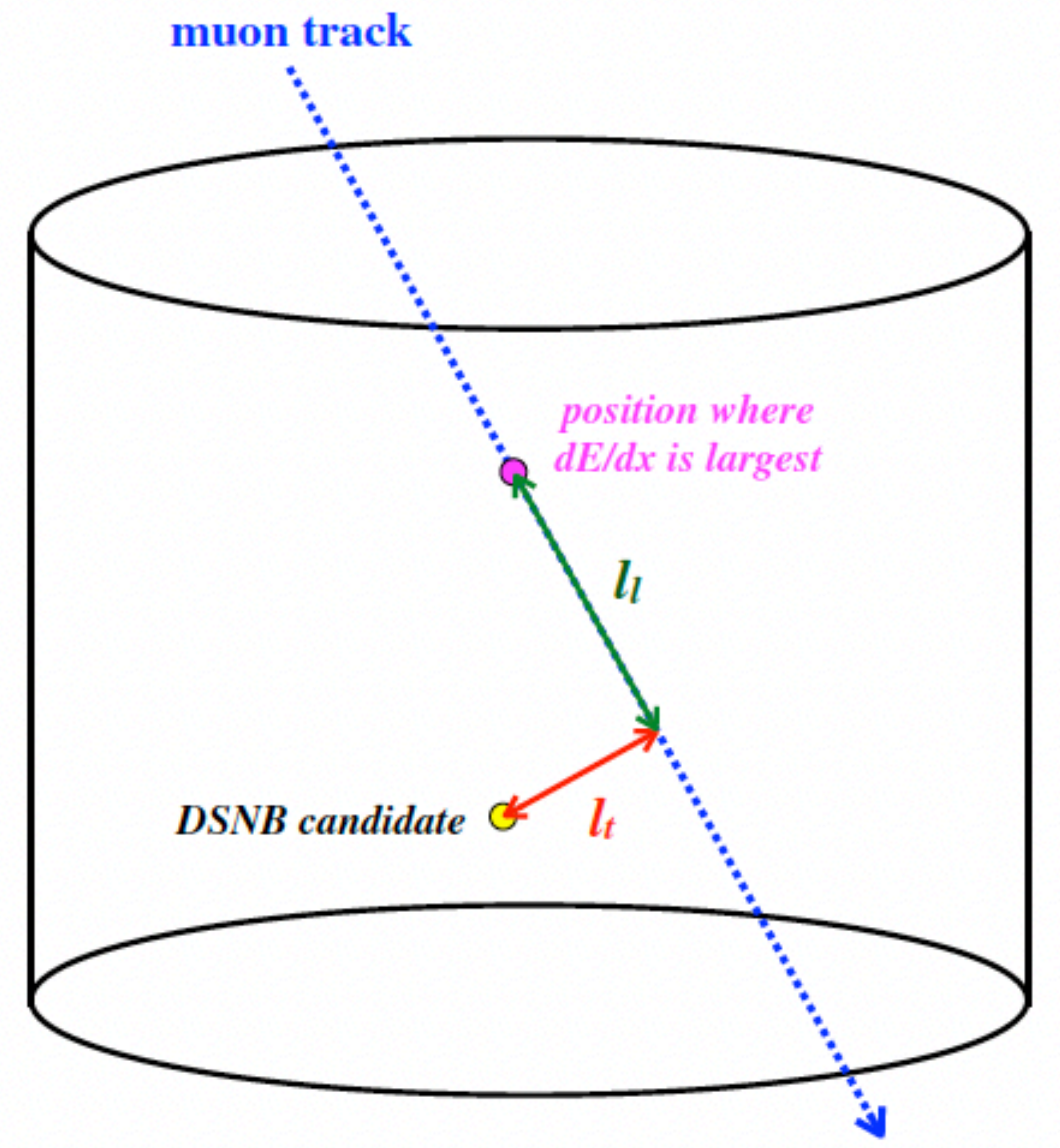
  ➡ Stringent upper limits, for neutrino energy > 17.3 MeV approaching the range of predictions.

- Looking forward to evidence for DSNB in the next decade!

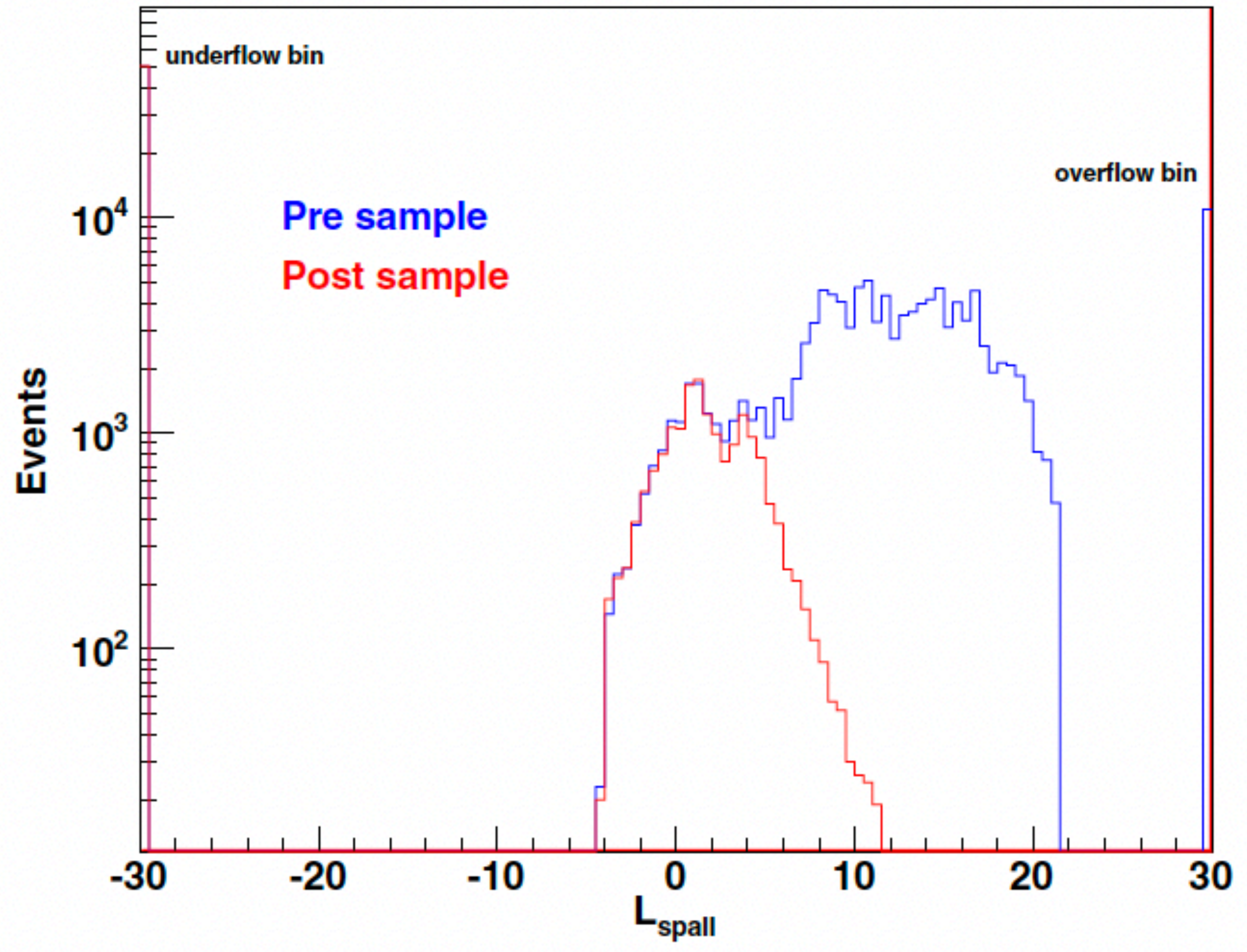
Backup

Spallation





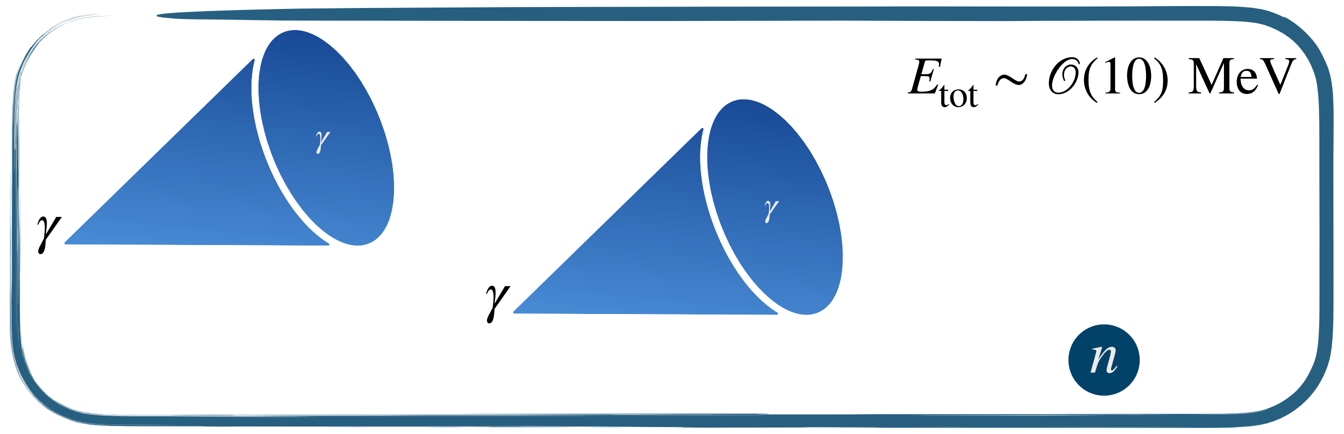
Scheme of spallation observables

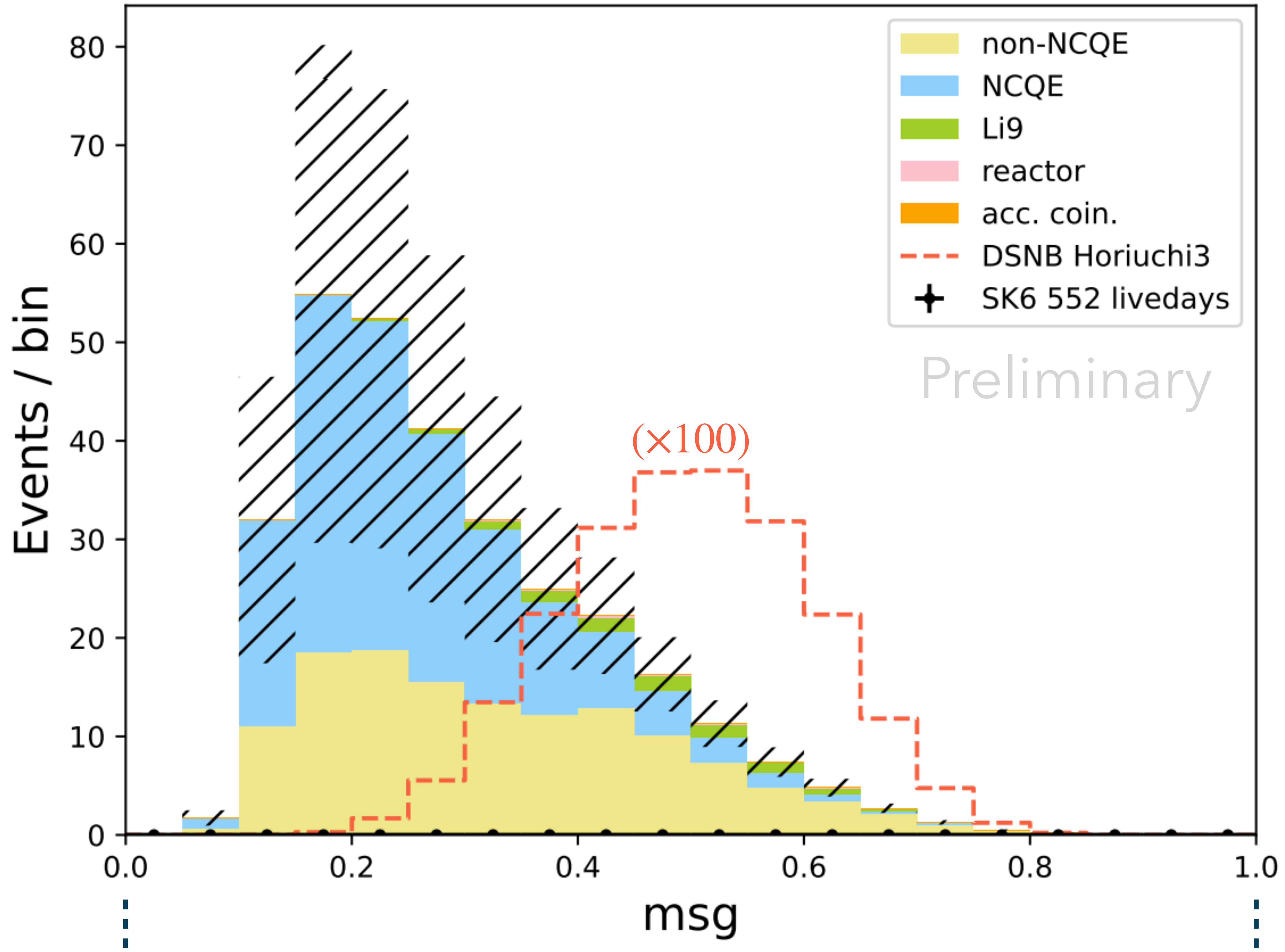


Log-likelihood ratio of spallation observables (single through-going muons).

MSG Cut

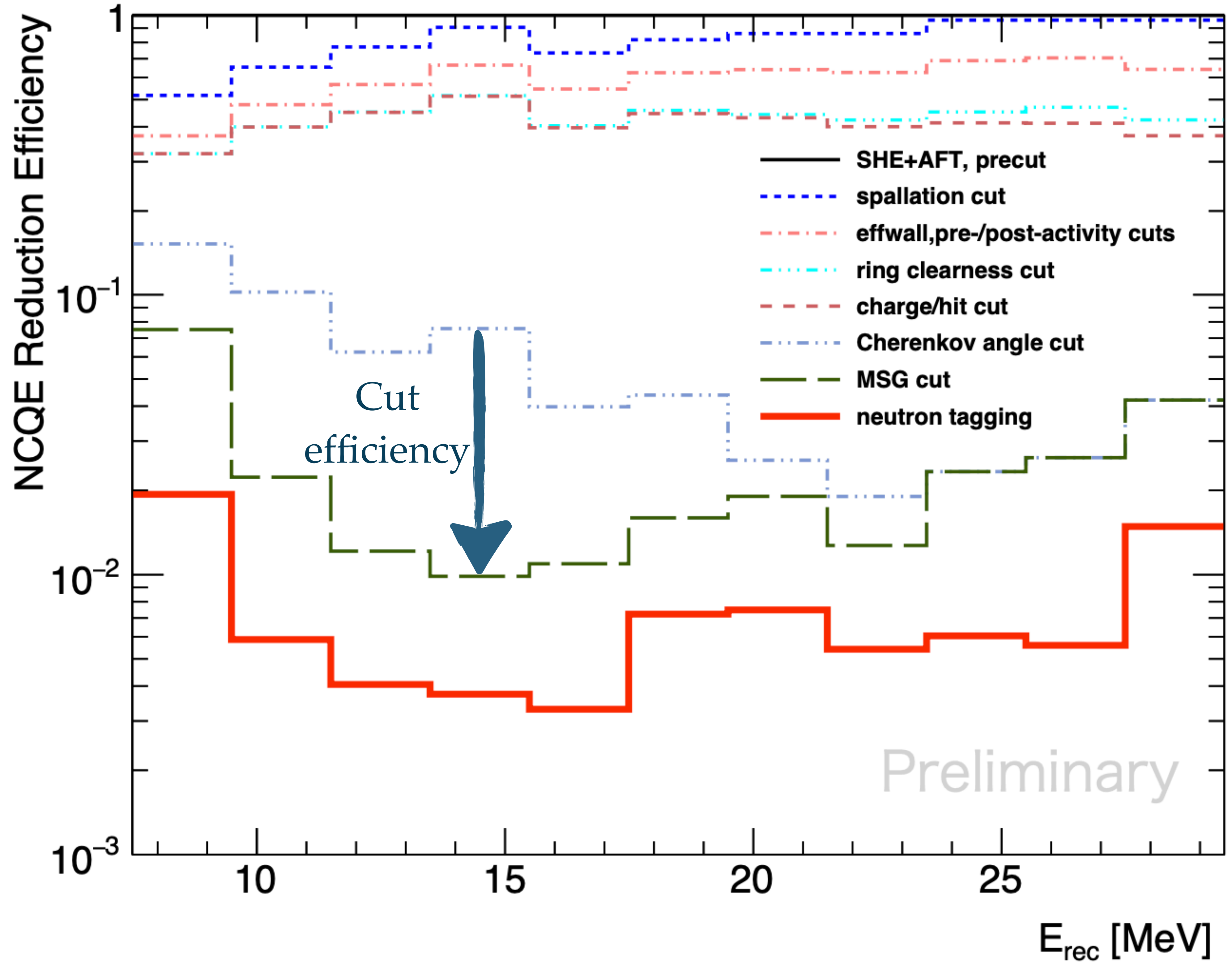
DSNB / NC events separation





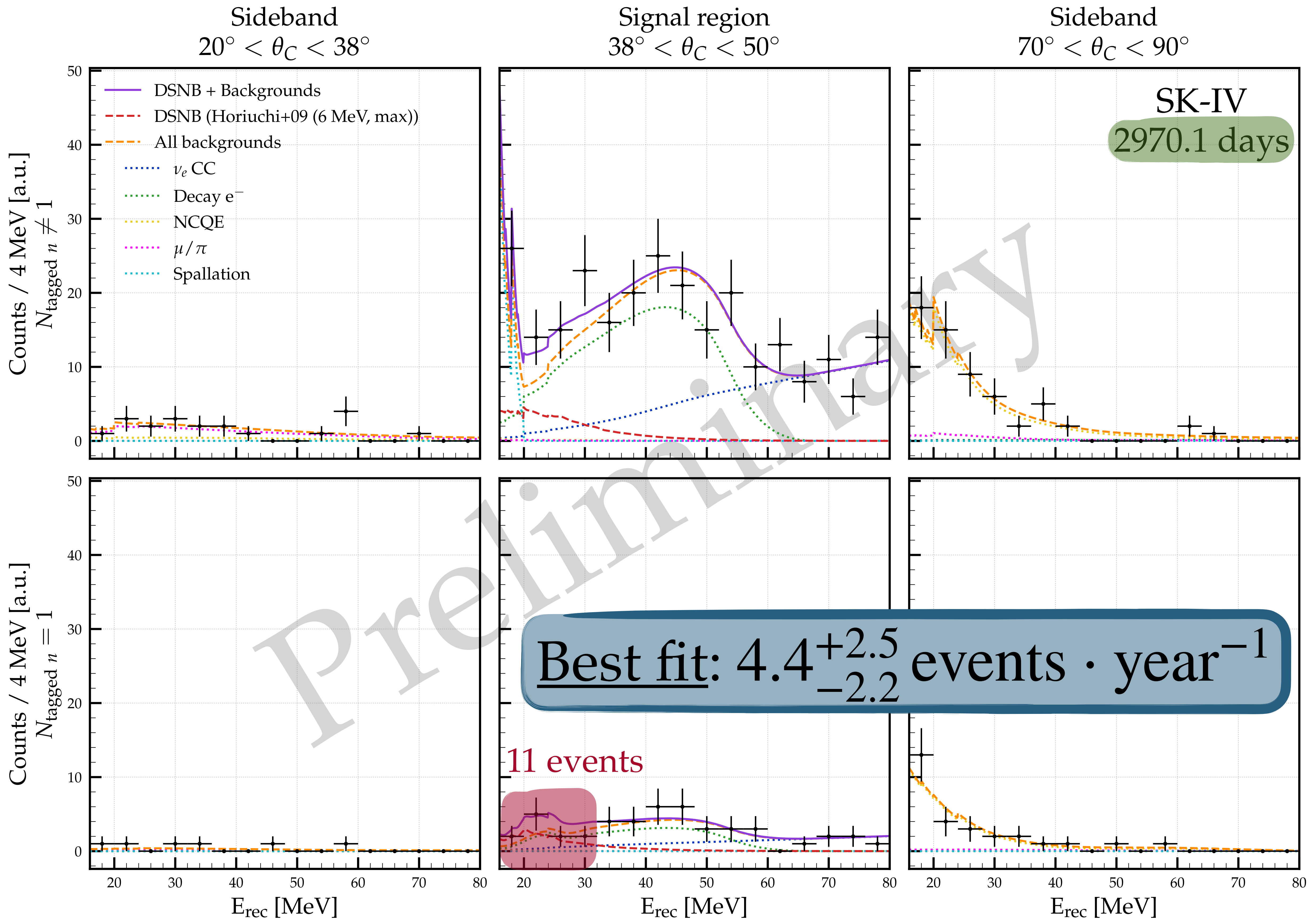
(Multiple Scattering Goodness)

Consisting of several cones → Consisting of a single cone



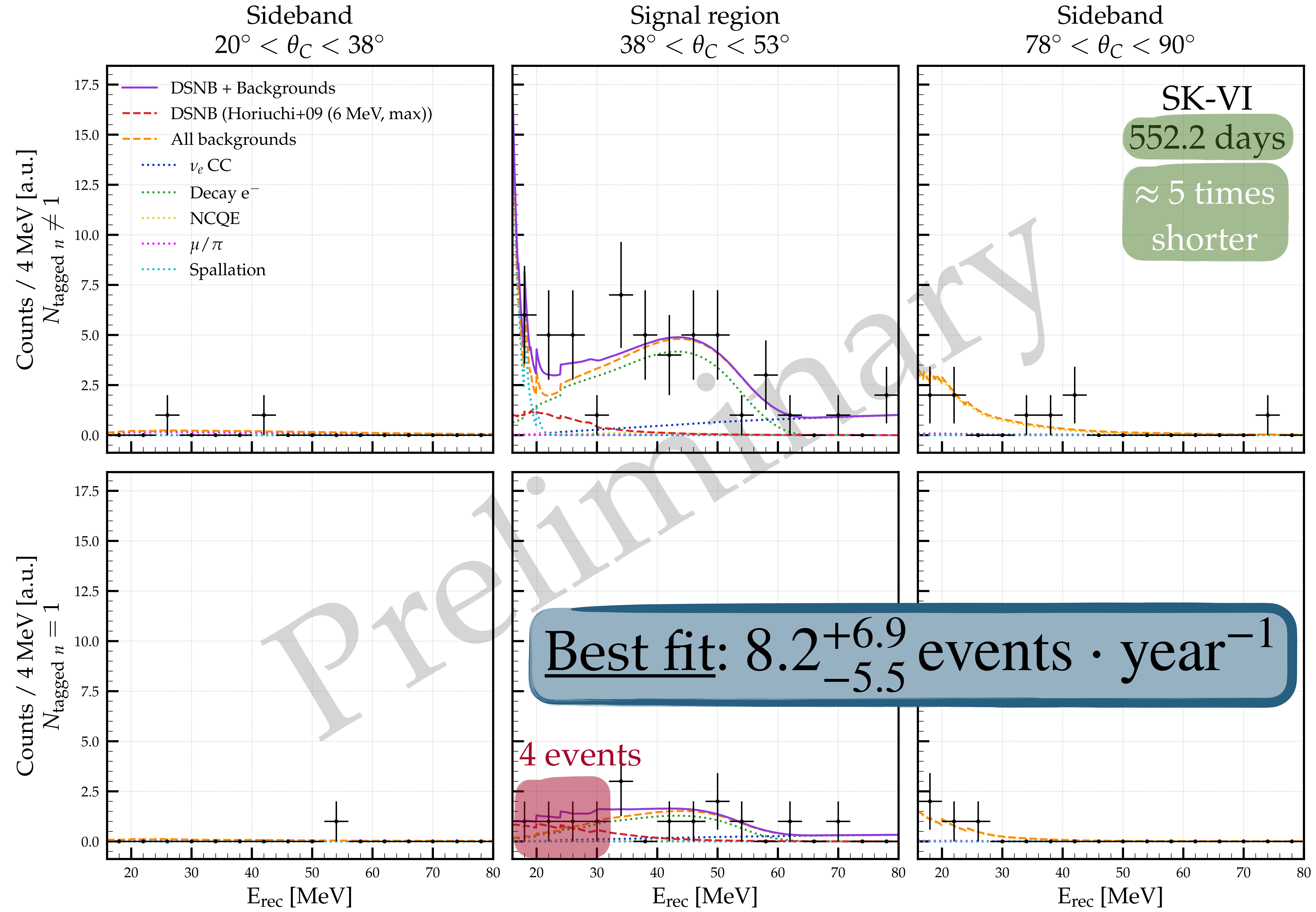
Fitted spectra

Water only



Best fit: $4.4^{+2.5}_{-2.2}$ events · year^{-1}

Water + Gd



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