# DSNB Search With SK

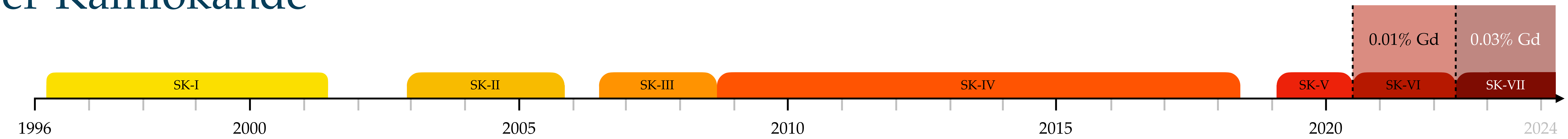
*Diffuse Supernova Neutrino Background*

Antoine Beauchêne - *February 2nd, 2024*

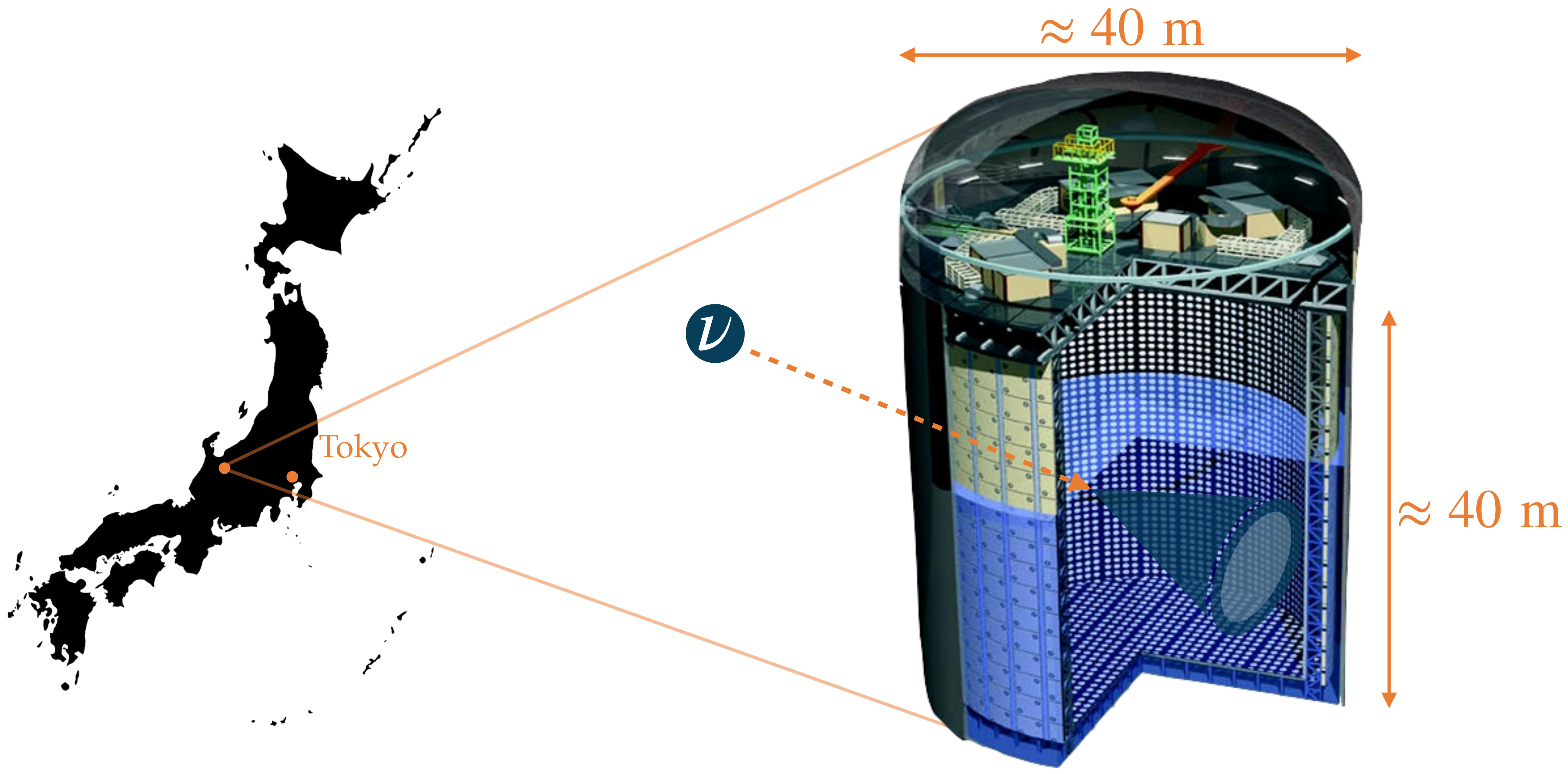
Biennale LLR 2024

# Introduction

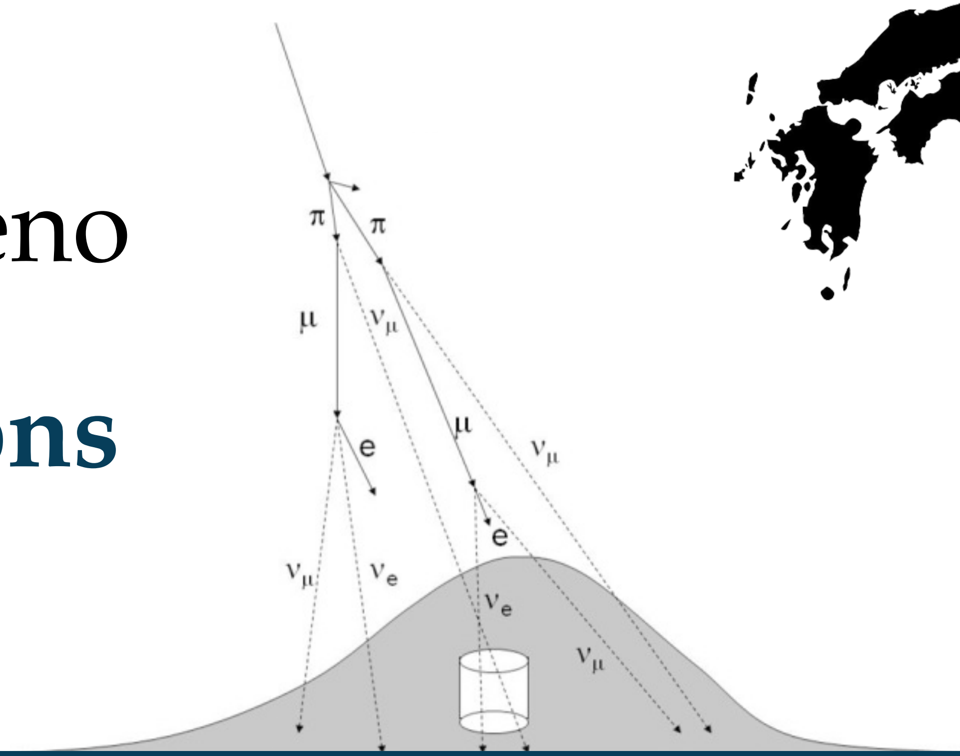
## Super-Kamiokande




- Water mass (**Fiducial mass**): 50 kton (**22.5 kton**)
- 11 129 PMTs in the inner detector
  - Diameter: 50 cm
  - Time resolution: $\sigma \approx 3.4$ ns
  - Photocathode coverage: 40%




- Located 1 km under Mt. Ikeno
  - **Shield from cosmic muons**



# Introduction

## Core-Collapse Supernova

- Death of **massive stars** ($M \gtrsim 8\,\mathrm{M}_\odot$) $\longrightarrow$ (CC)SN: Powerful source of $\nu$!
  - $\sim 10^{58}\,\nu$ in $\sim 10$ s
  - $\approx 99\%$ of the released energy $\longleftrightarrow \sim 10^{59}$ MeV

  } $\sim 10$ MeV$/\nu$
  - **All flavours** are generated: $\nu_e$, $\bar{\nu}_e$ and $\nu_x$ ($x \in \{\mu, \tau\}$)


- **Difficult to detect**: Flux decreases $\propto r^{-2}$ & Small cross section $\longrightarrow$ Sensitive only to galactic SNe. Rare events ($\sim$ 1 - 3/century)!!
- Only one detected: SN1987A (11 events with Kamiokande)

# Introduction

## Core-Collapse Supernova


- Death of **massive stars** ($M \gtrsim 8\,M_\odot$) $\longrightarrow$ (CC)SN: Powerful source of $\nu$!
  - $\sim 10^{58}\,\nu$ in $\sim 10$ s
  - $\approx 99\%$ of the released energy $\longleftrightarrow \sim 10^{59}$ MeV

  (both of the above) $\Big\} \sim 10$ MeV$/\nu$
  - All flavours are generated: $\nu_e$, $\bar{\nu}_e$ and $\nu_x$ ($x \in \{\mu, \tau\}$)






- **Difficult to detect**: Flux decreases $\propto r^{-2}$ & Small cross section $\longrightarrow$ Sensitive only to galactic SNe. Rare events ($\sim$ 1 - 3/century)!!
- Only one detected: SN1987A (11 events with Kamiokande)

# Introduction

## Core-Collapse Supernova

- Death of **massive stars** ($M \gtrsim 8\,M_\odot$) $\longrightarrow$ (CC)SN: Powerful source of $\nu$!
  - $\sim 10^{58}\ \nu$ in $\sim 10$ s
  - $\approx 99\%$ of the released energy $\longleftrightarrow \sim 10^{59}$ MeV
  
  $\Big\} \sim 10$ MeV$/\nu$
  - All flavours are generated: $\nu_e$, $\bar{\nu}_e$ and $\nu_x$ ($x \in \{\mu, \tau\}$)





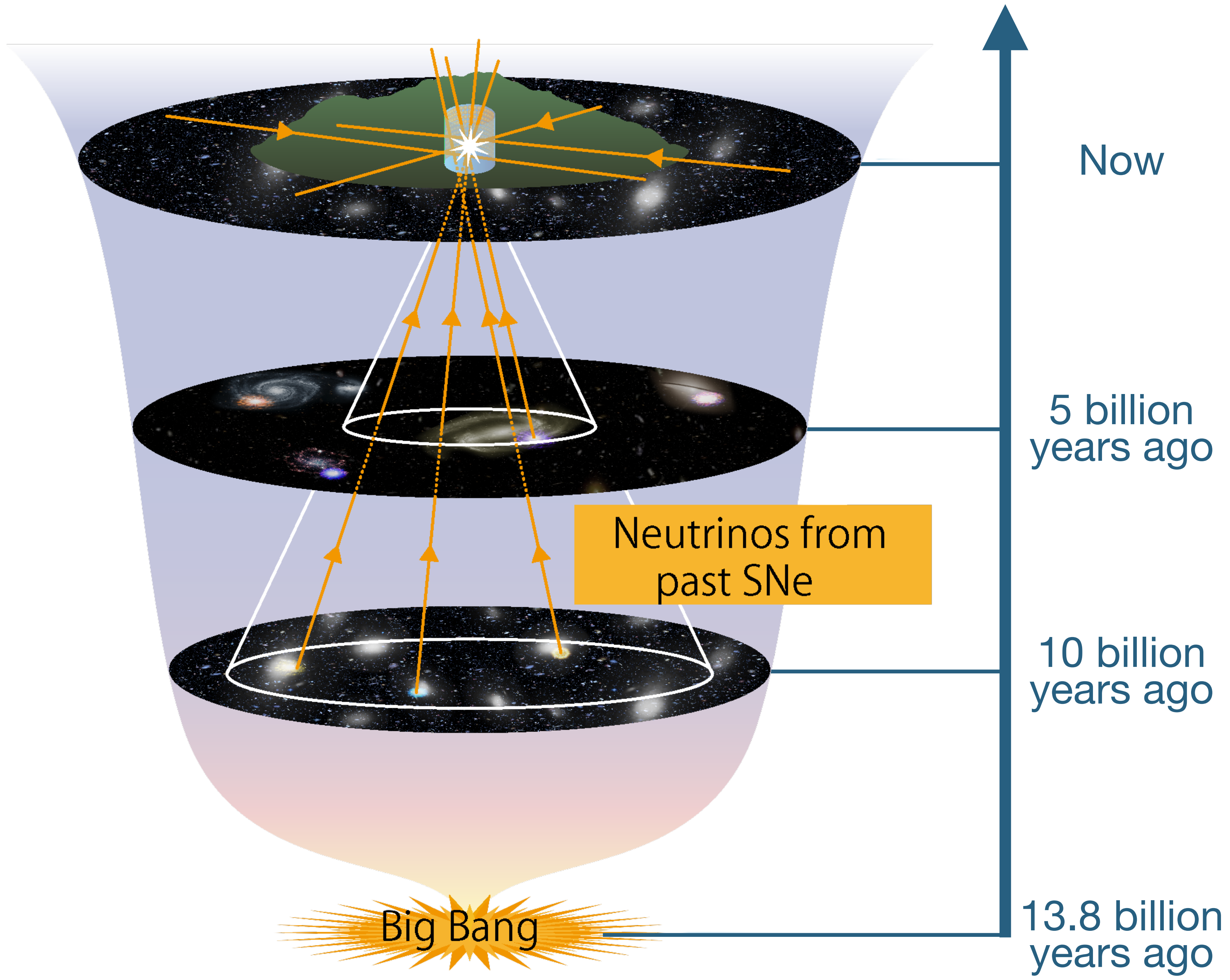


- Difficult to detect: Flux decreases $\propto r^{-2}$ & Small cross section $\longrightarrow$ Sensitive only to galactic SNe. Rare events ($\sim 1$ - $3/$century)!!
- Only one detected: SN1987A (11 events with Kamiokande)

# Diffuse Supernova Neutrino Background

- $\nu$ from **every SN in the observable Universe** since its beginning
  - Estimated SNe rate: $\sim 1$ SN/s
  - **Isotropic** and **time independent**

- Information about:
  - Star formation rate
  - Fraction of SNe forming BH
  - History of our Universe (cosmology)
  - Exotic neutrino properties (e.g. decay)



# DSNB in a Nutshell

## Description

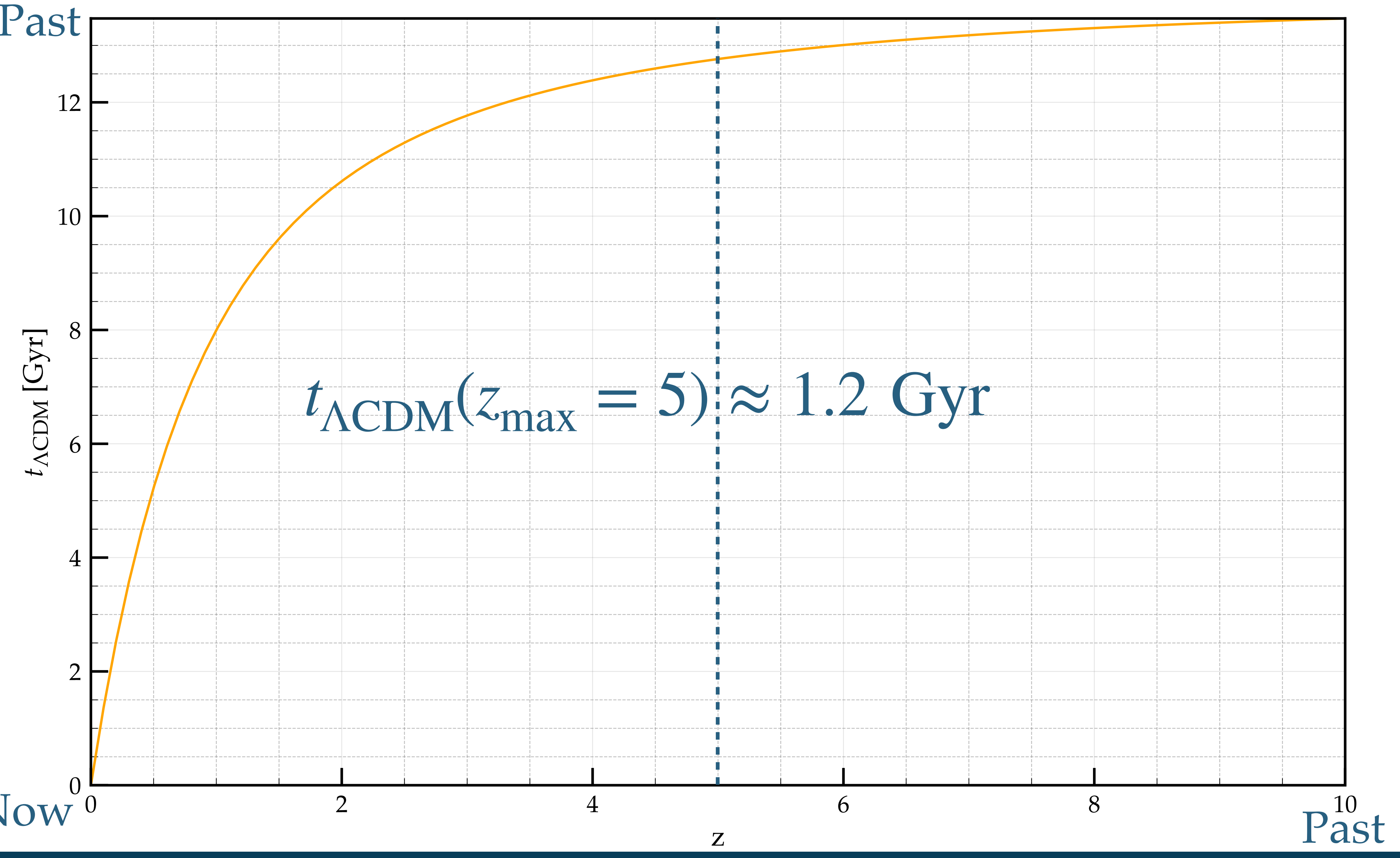
- DSNB flux: $$\Phi(E_\nu) = c \int_{z_0=0}^{z_{\max}} \sum_s R_{\mathrm{SN}}(z,s) \sum_{\nu_\beta,\bar{\nu}_\beta} F_\beta(E_\nu(1+z),s)\,\frac{\mathrm{d}z}{H(z)}$$

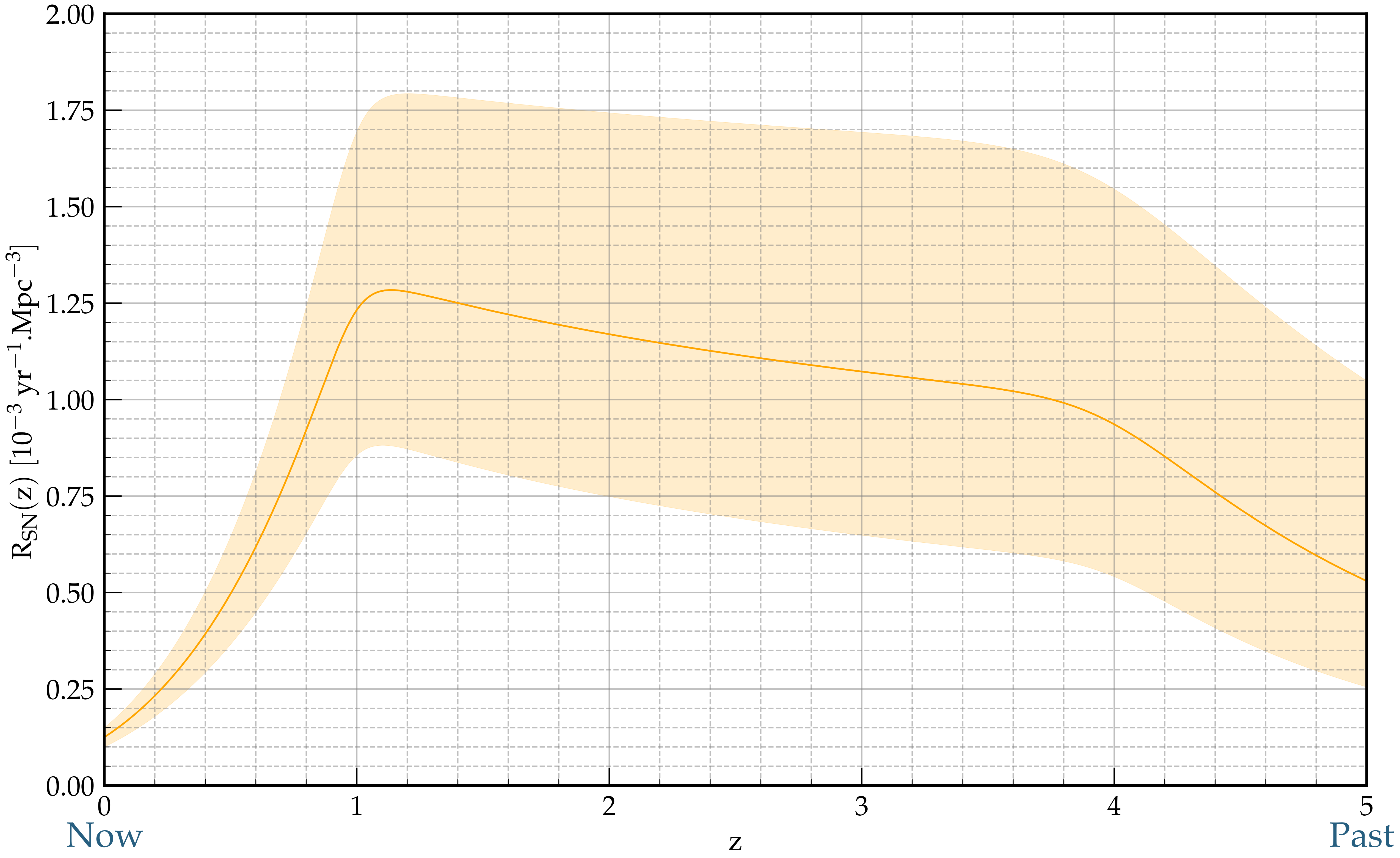
## Description

- DSNB flux: $$\Phi(E_\nu) = c \int_{z_0=0}^{z_{\max}} \sum_s R_{SN}(z,s) \sum_{\nu_\beta, \bar{\nu}_\beta} F_\beta(E_\nu(1+z), s) \frac{dz}{H(z)}$$

Redshift-dependent SN rate

- $R_{SN}(z) \propto R_{SF}(z)$ → Star Formation Rate



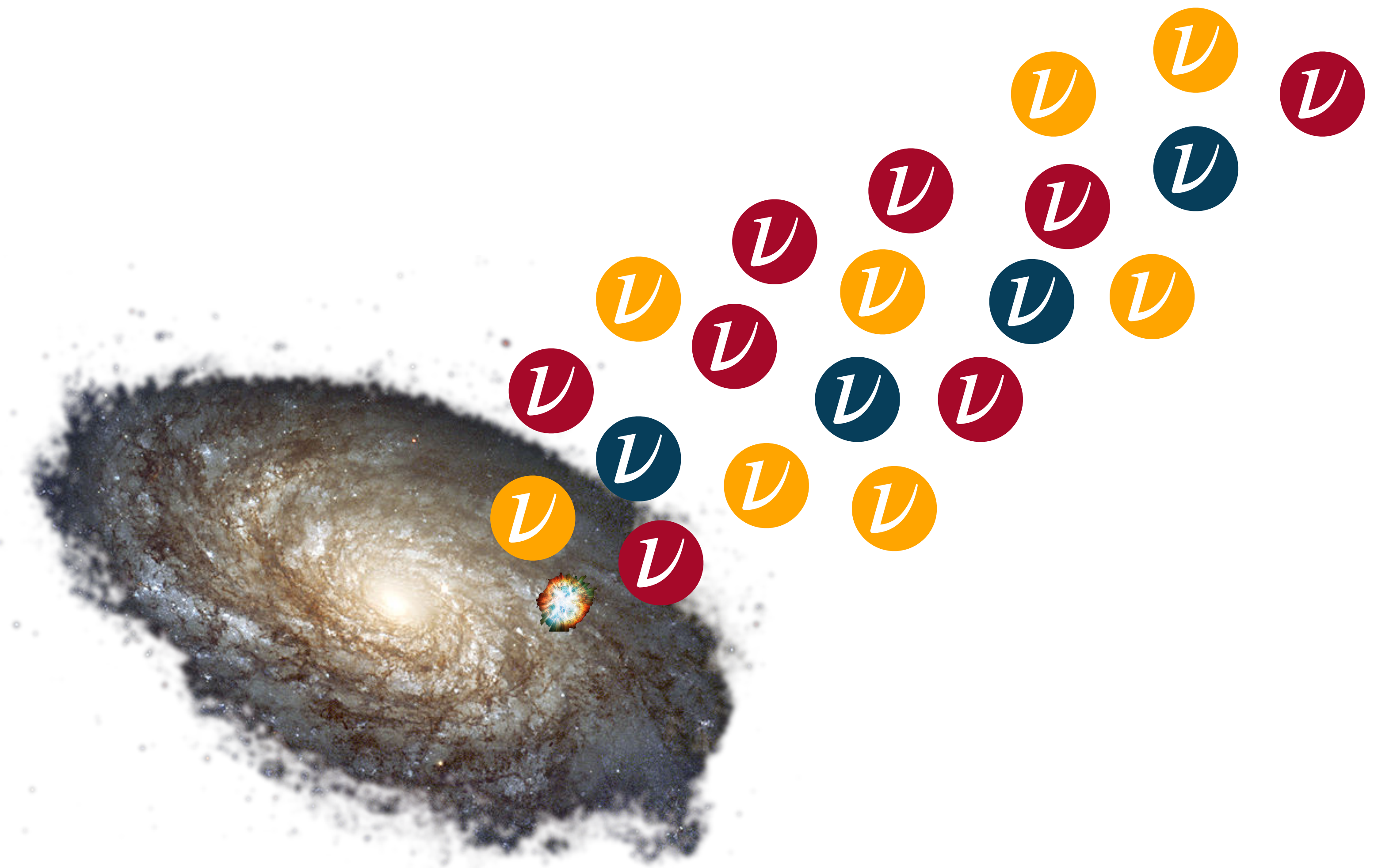
## Description

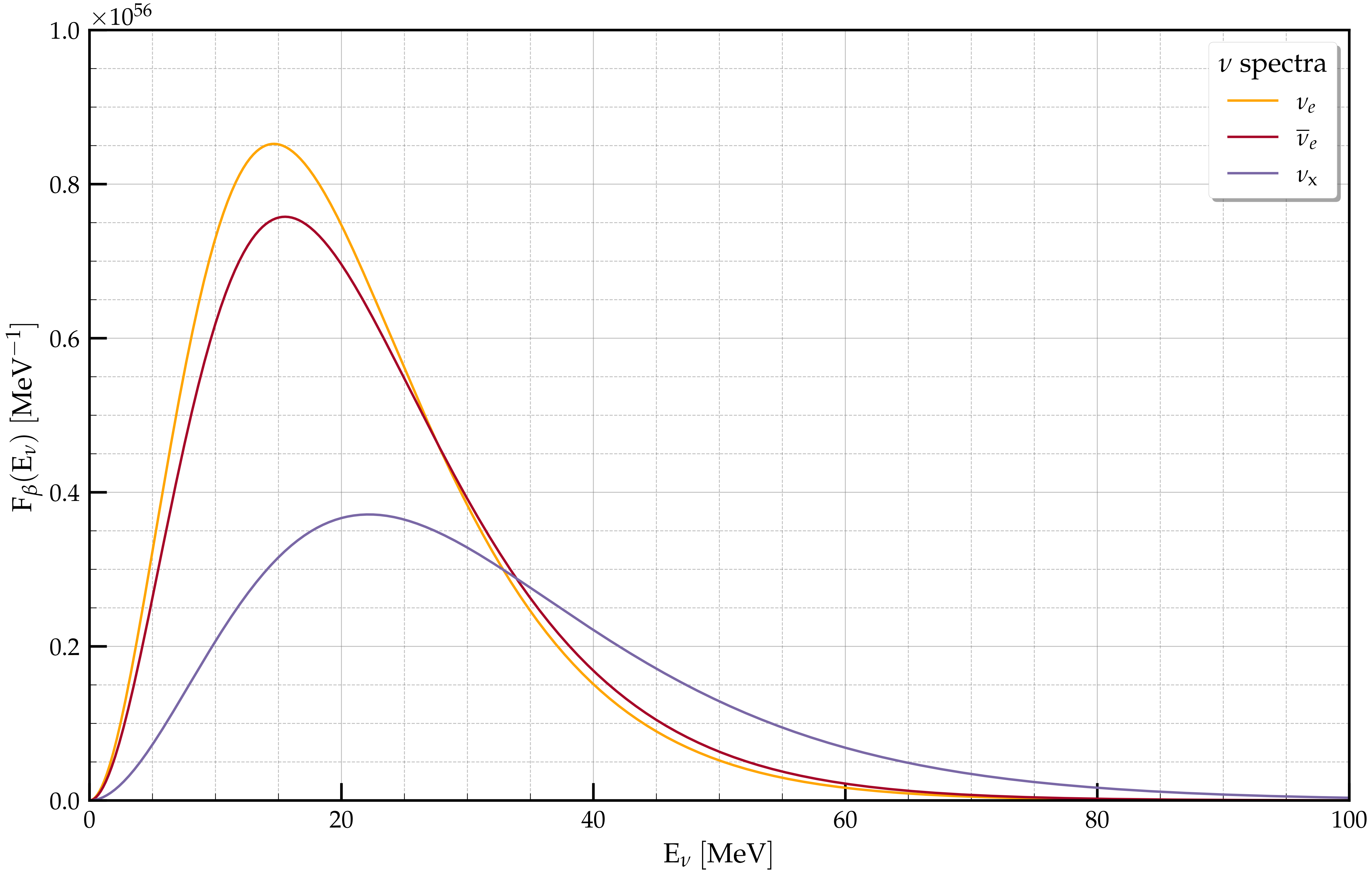
SN neutrino emission spectrum

- DSNB flux: $$\Phi(E_\nu) = c \int_{z_0=0}^{z_{\max}} \sum_s R_{\mathrm{SN}}(z,s) \sum_{\nu_\beta,\bar{\nu}_\beta} F_\beta(E_\nu(1+z),s) \frac{\mathrm{d}z}{H(z)}$$

Redshift-dependent SN rate

Fermi-Dirac distribution





# DSNB in a Nutshell

## Description

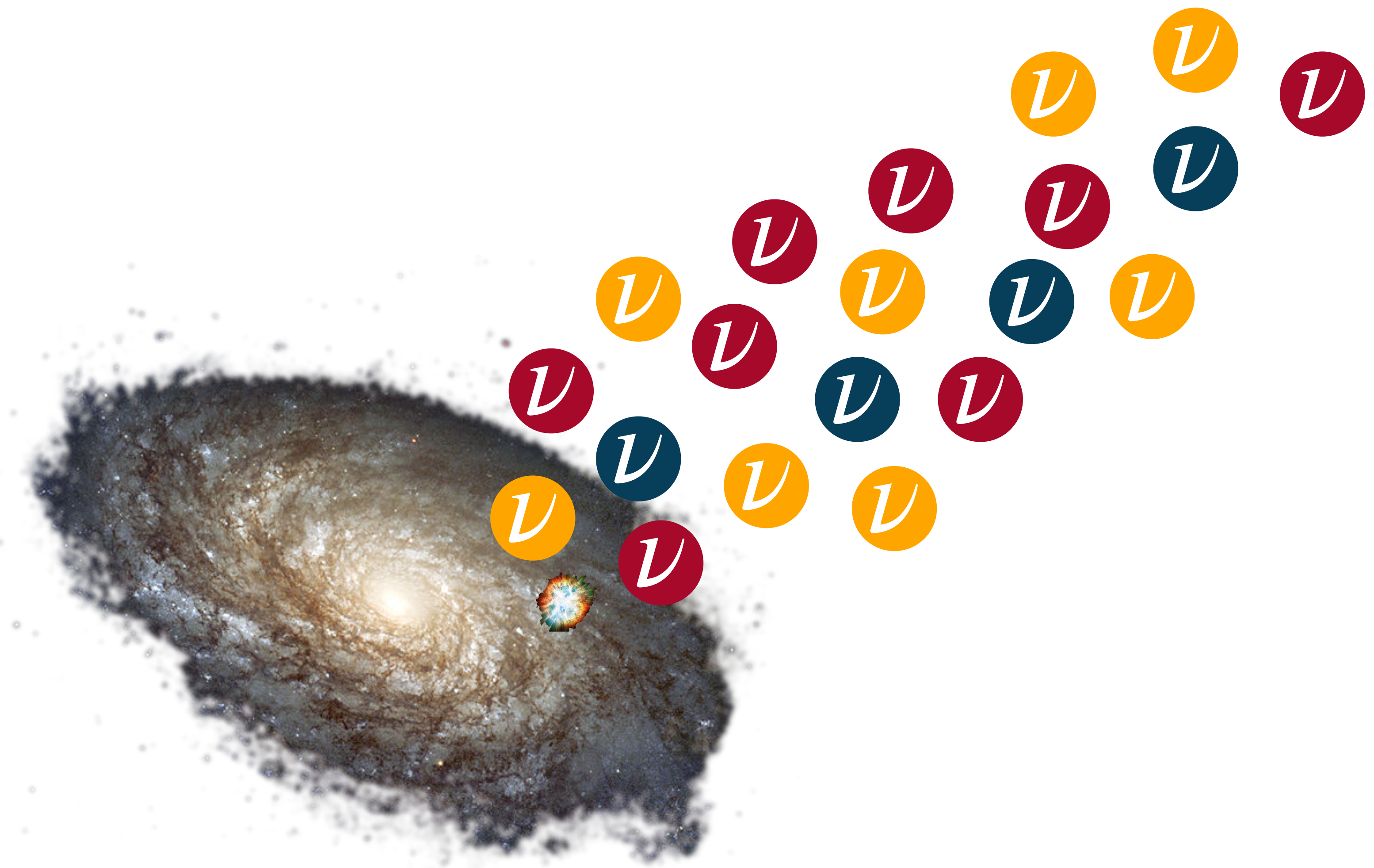
SN neutrino emission spectrum

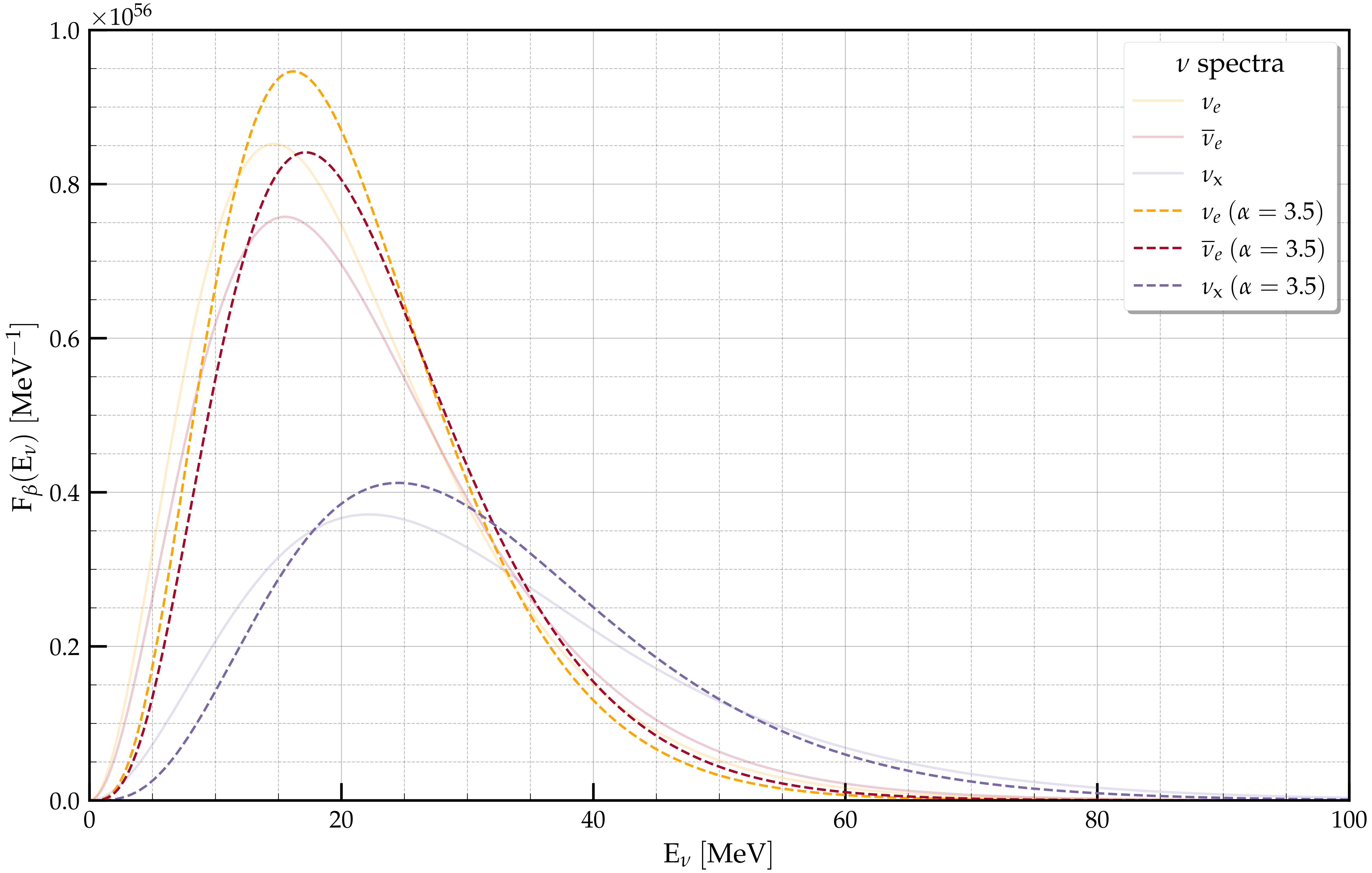
- DSNB flux: $$\Phi(E_\nu) = c \int_{z_0=0}^{z_{max}} \sum_s R_{SN}(z, s) \sum_{\nu_\beta, \bar{\nu}_\beta} F_\beta(E_\nu(1+z), s) \frac{dz}{H(z)}$$

Redshift-dependent SN rate

Pinched Fermi-Dirac distribution

- Better fit of spectra from simulations



# DSNB in a Nutshell

## Description

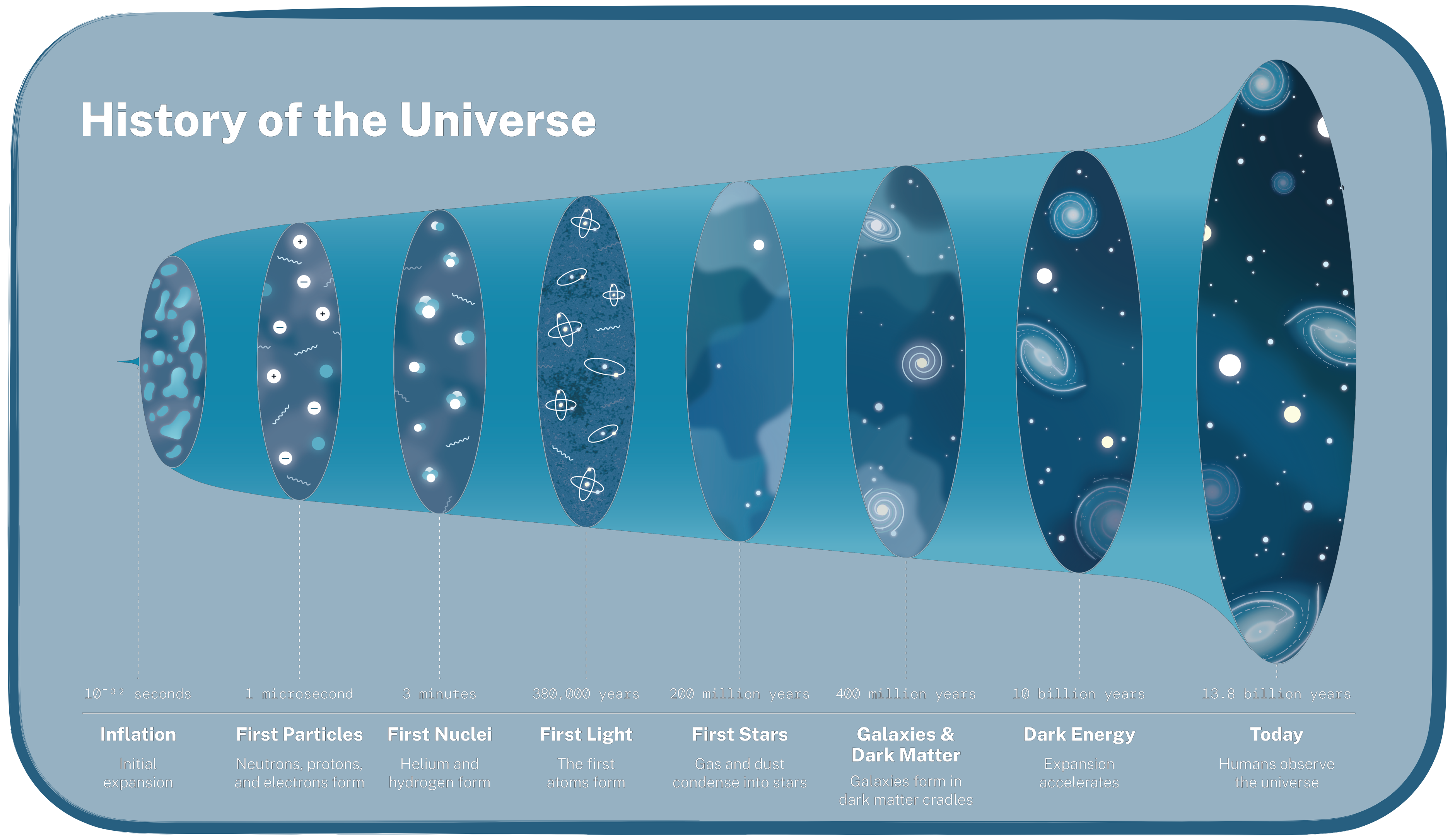
- <u>DSNB flux</u>: $$\Phi(E_\nu) = c \int_{z_0=0}^{z_{\max}} \sum_s R_{\mathrm{SN}}(z,s) \sum_{\nu_\beta,\bar{\nu}_\beta} F_\beta(E_\nu(1+z),s) \frac{\mathrm{d}z}{H(z)}$$

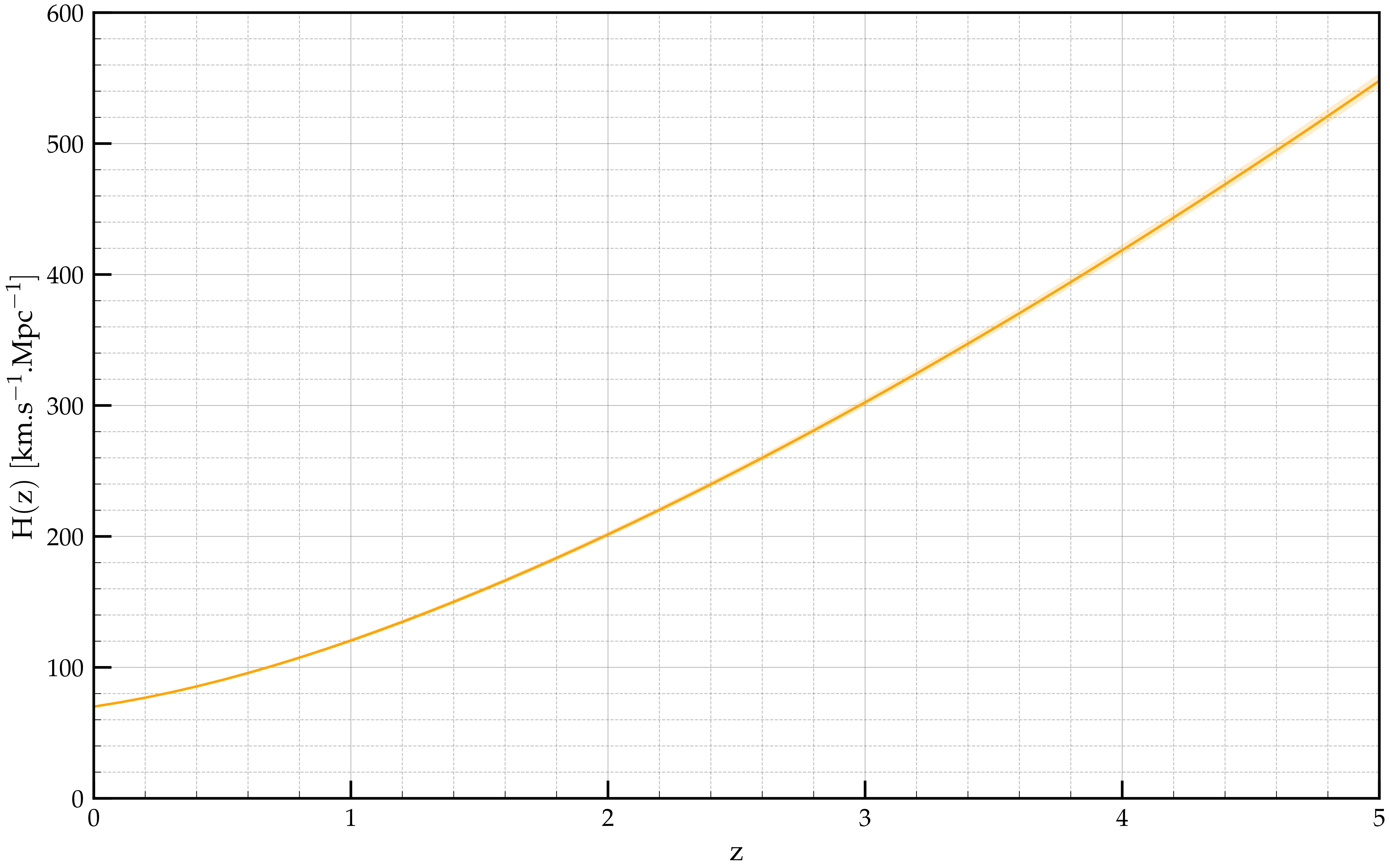
SN neutrino emission spectrum

Redshift-dependent SN rate

Universe expansion

<u>ΛCDM model</u>



# DSNB in a Nutshell

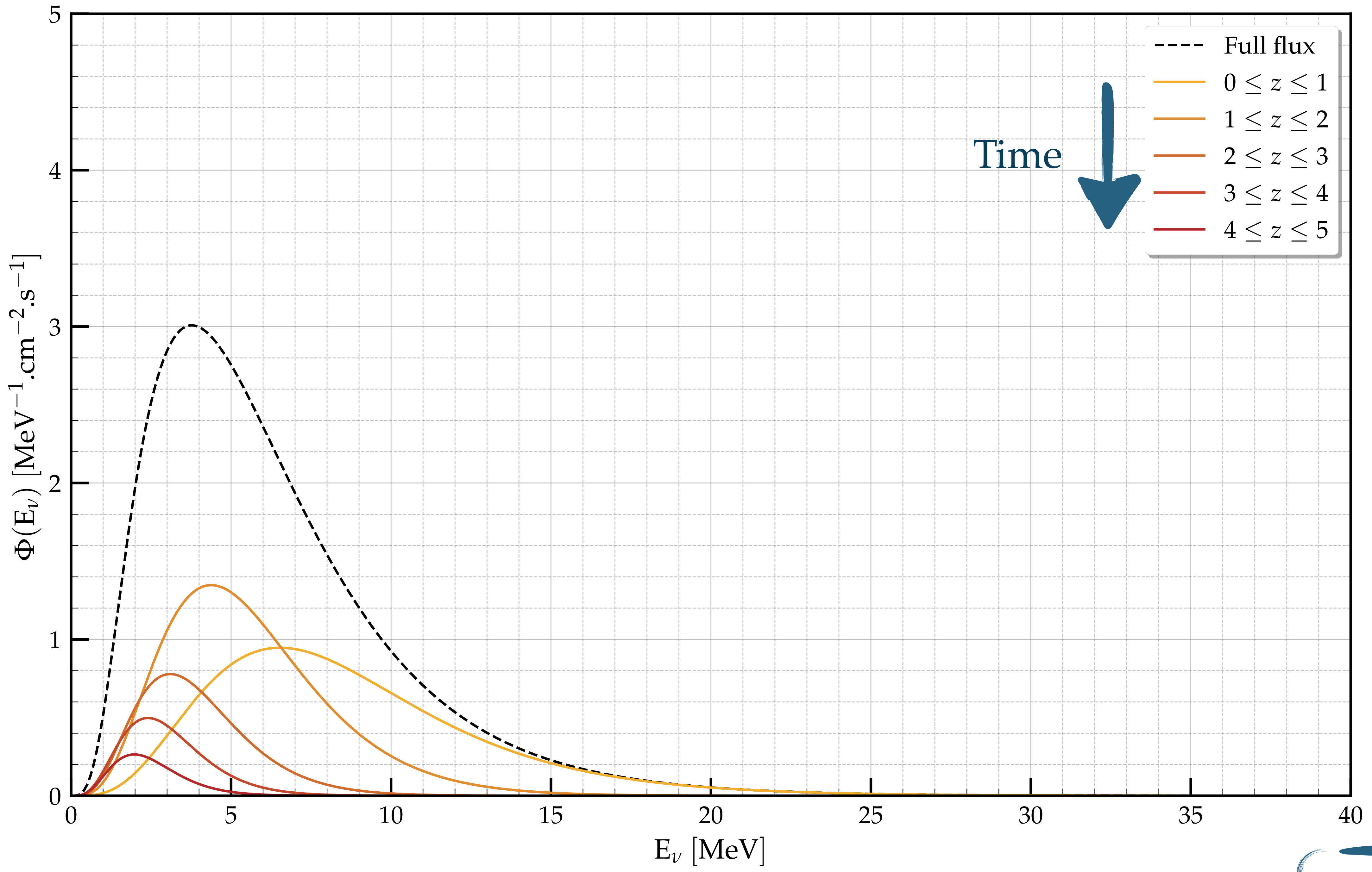
## Description

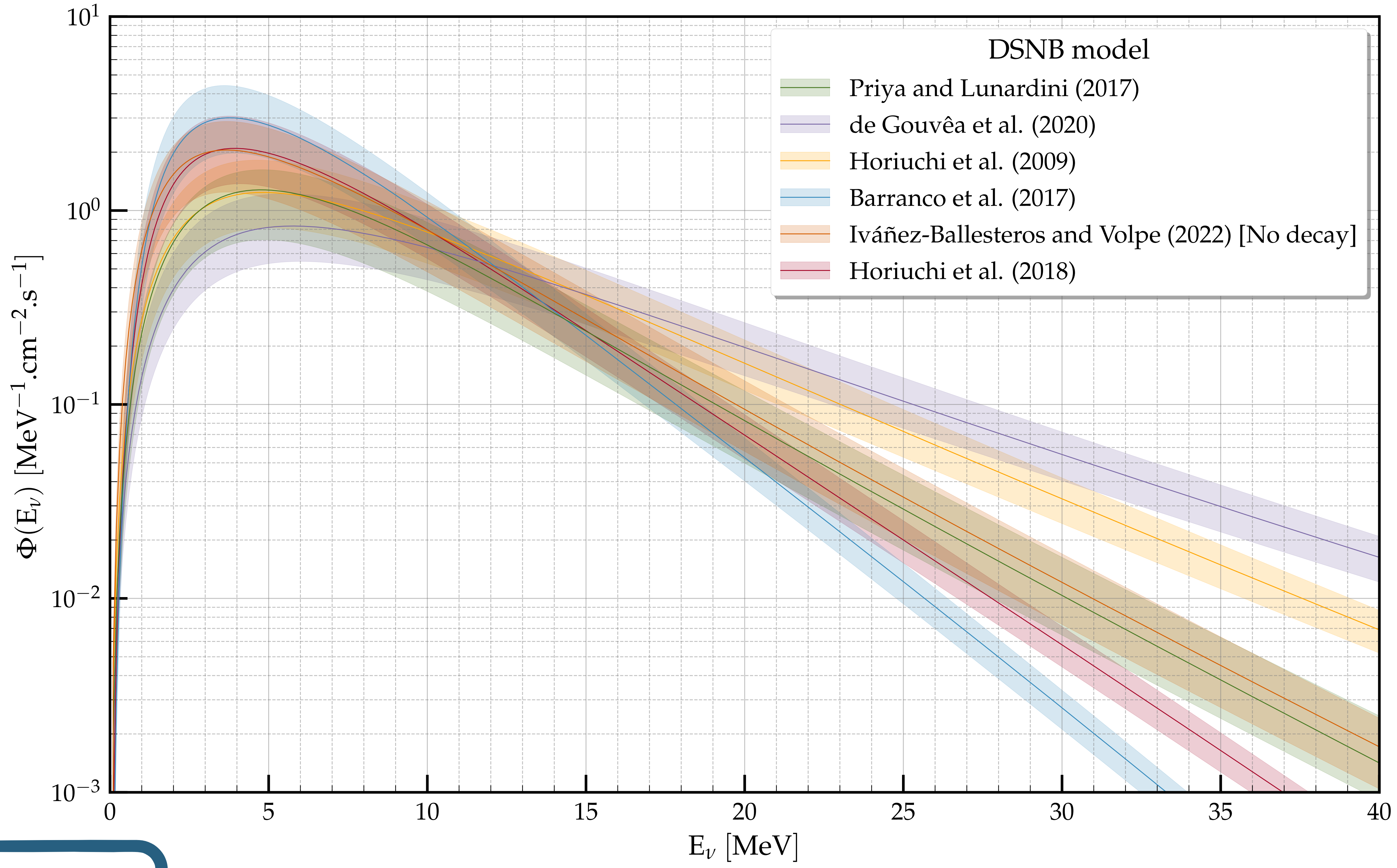
- DSNB flux: $$\Phi(E_\nu) = c \int_{z_0=0}^{z_{max}} \sum_s R_{SN}(z,s) \sum_{\nu_\beta, \bar{\nu}_\beta} F_\beta(E_\nu(1+z), s) \frac{dz}{H(z)}$$

SN neutrino emission spectrum

Redshift-dependent SN rate

Universe expansion

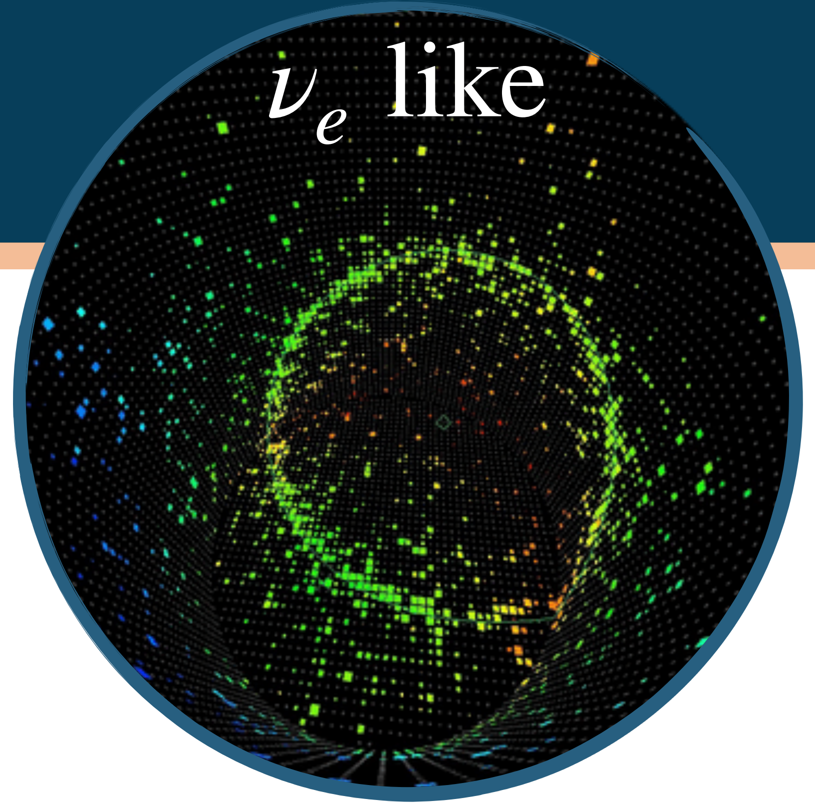



$z_{max} = 5$

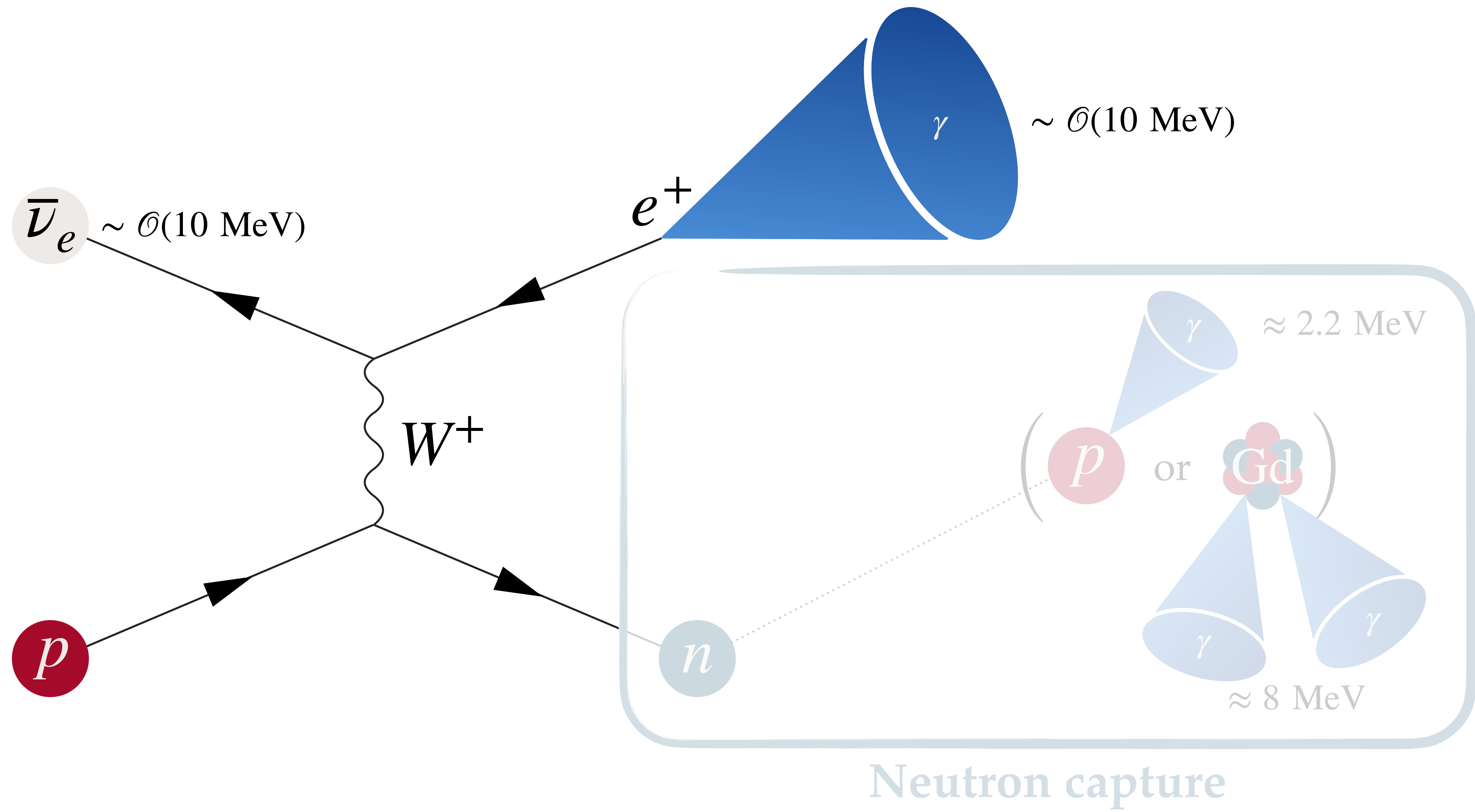
* $t_{\Lambda CDM}(z_{max} = 5) \approx 1.2$ Gyr

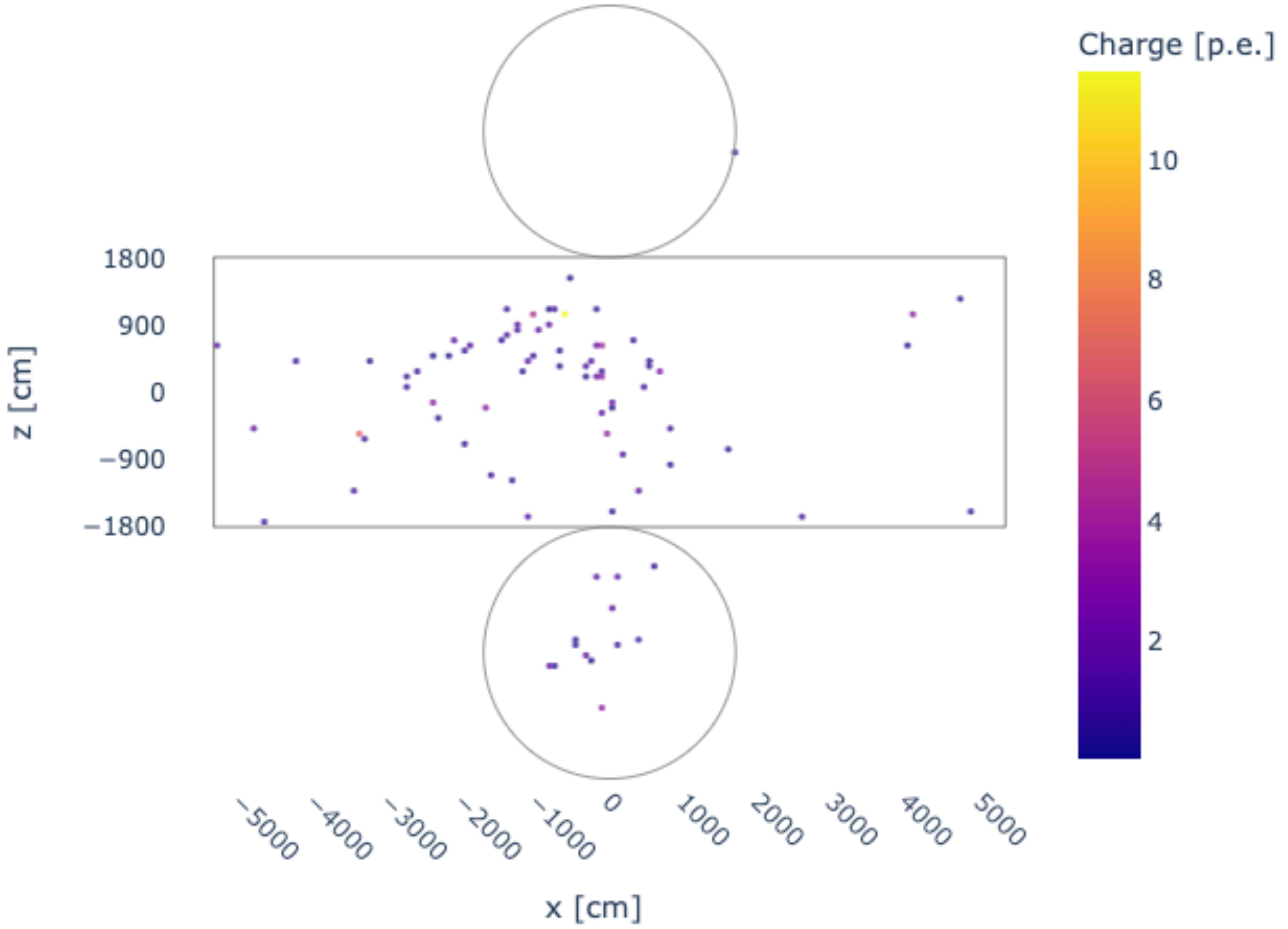
# Detection




## DSNB events

- Main detection channel: **I**nverse **B**eta **D**ecay

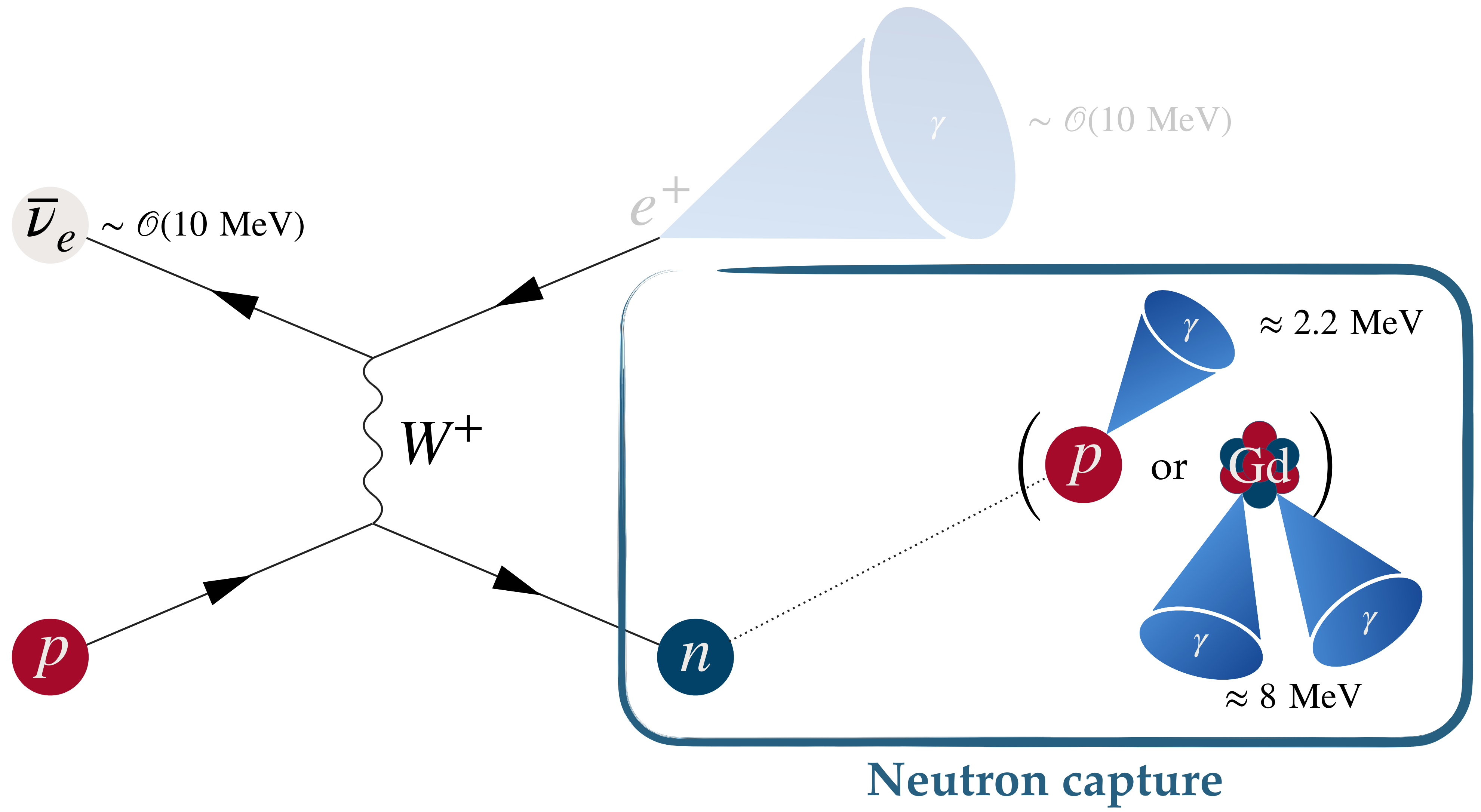


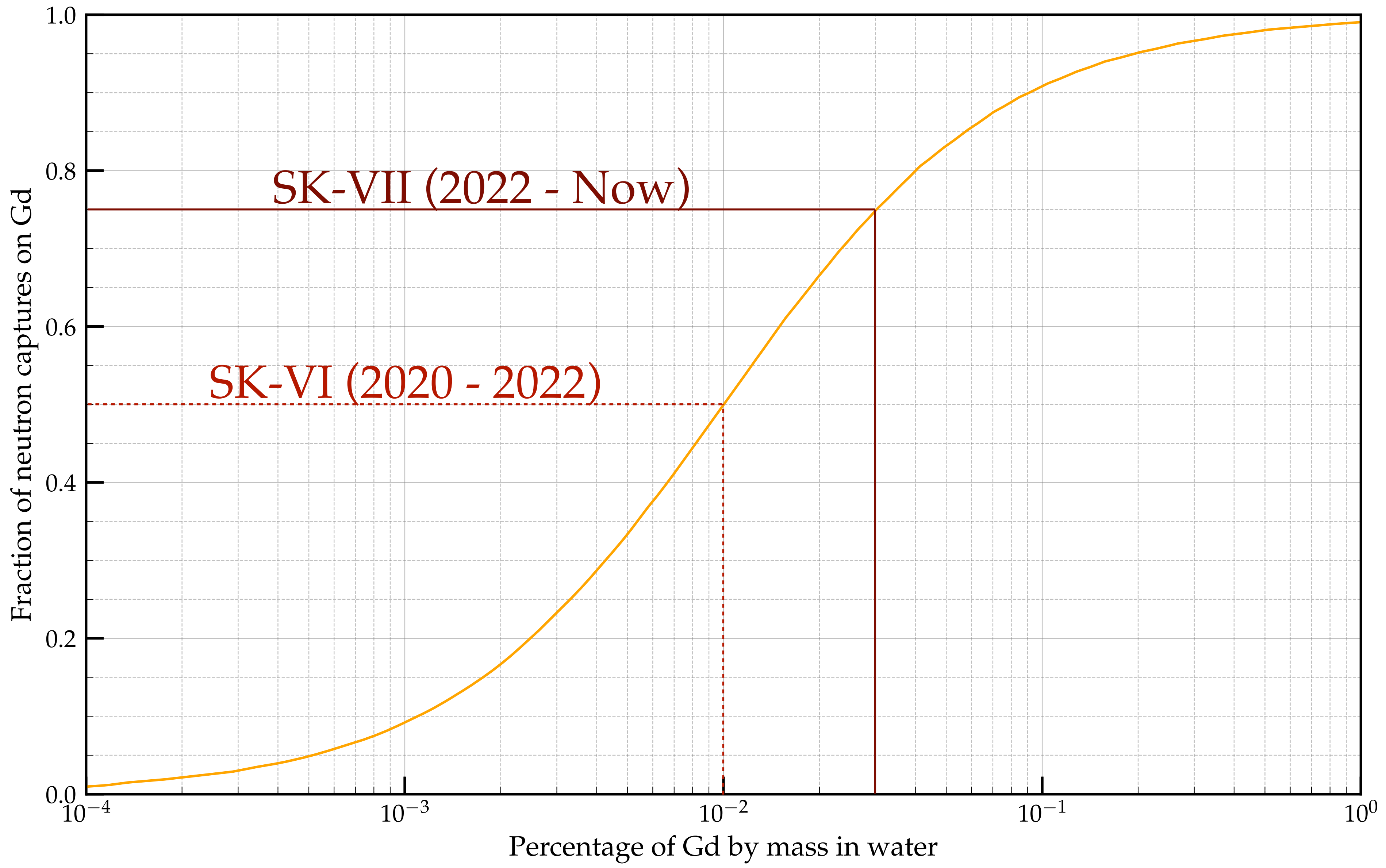




- Observables: $e^+$ energy $E_{e^+}$, Cherenkov angle $\theta_C$ and number of neutrons $n$

## DSNB events

- Main detection channel: **I**nverse **B**eta **D**ecay

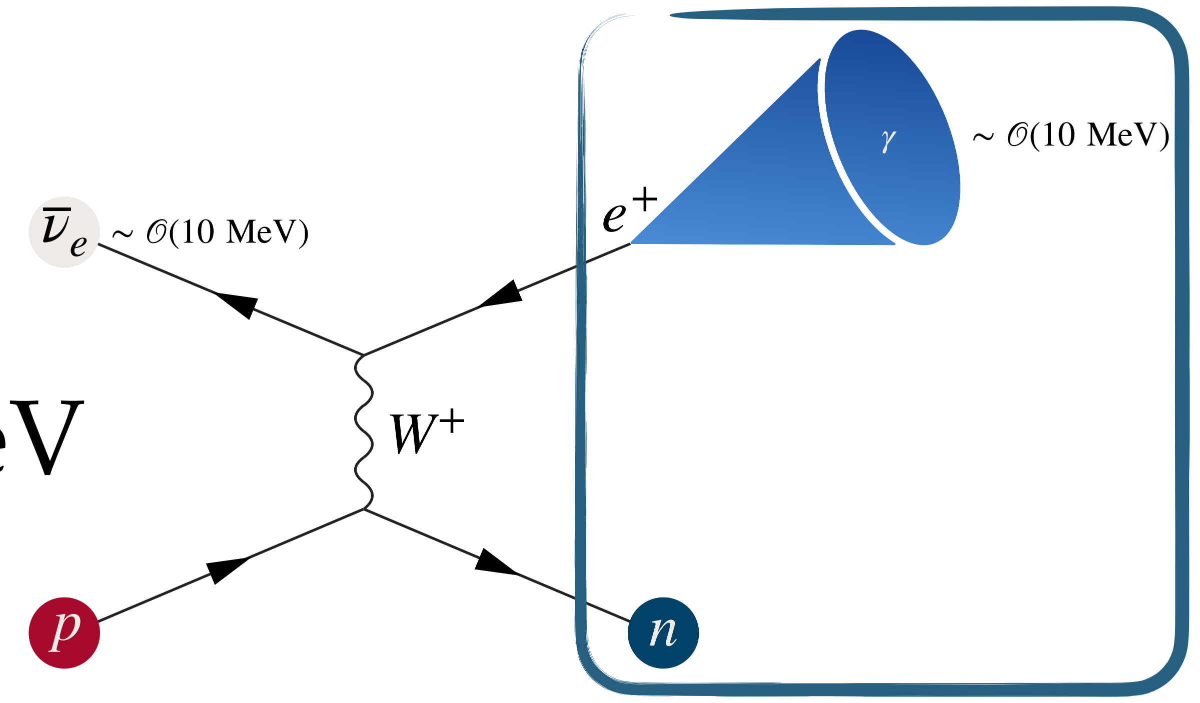


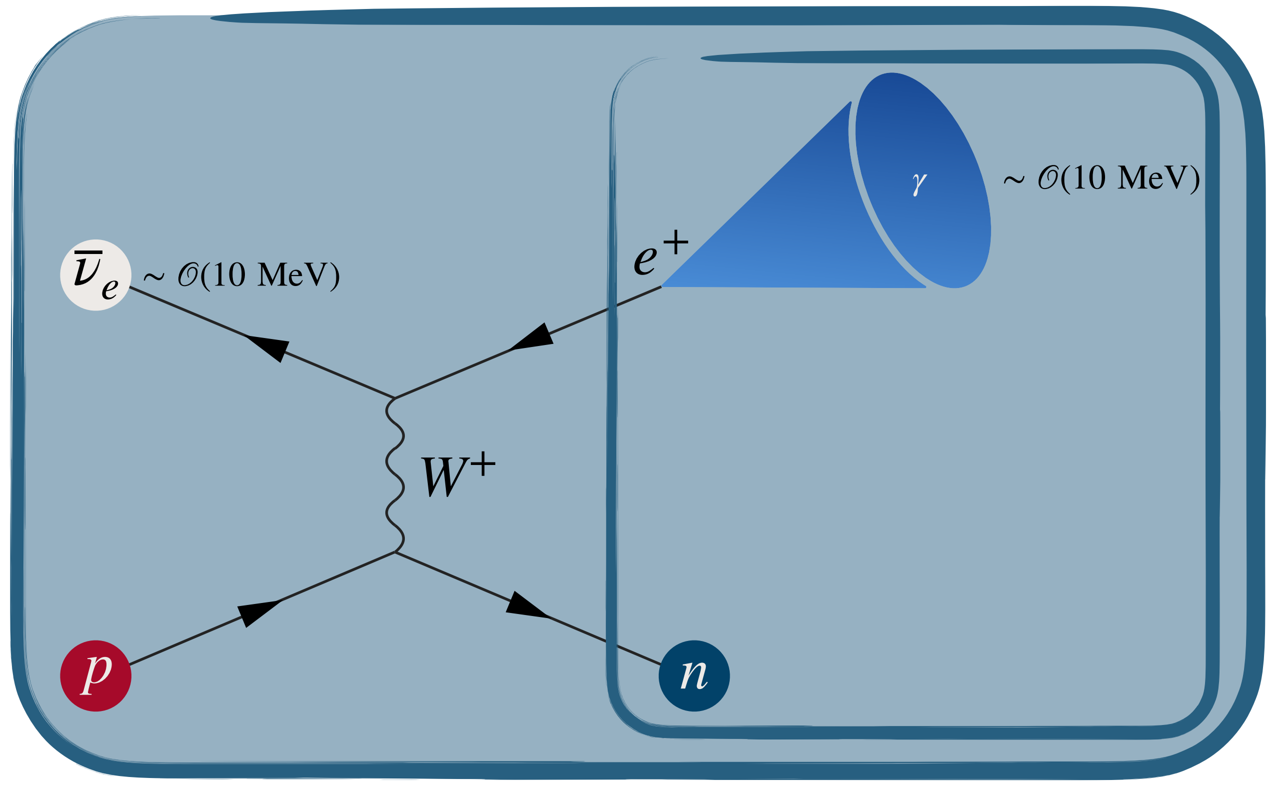

- Observables: $e^+$ energy $E_{e^+}$, Cherenkov angle $\theta_C$ and number of neutrons $n$

## Other events (Backgrounds)

- <u>Reactor</u>:
  - **Irreducible** because $\sim 10^3$ times more than DSNB events below 10 MeV




DSNB event



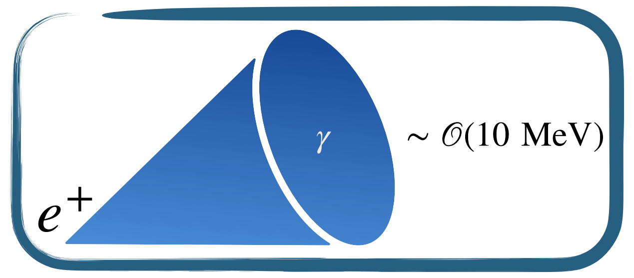
# Detection

## Other events (Backgrounds)

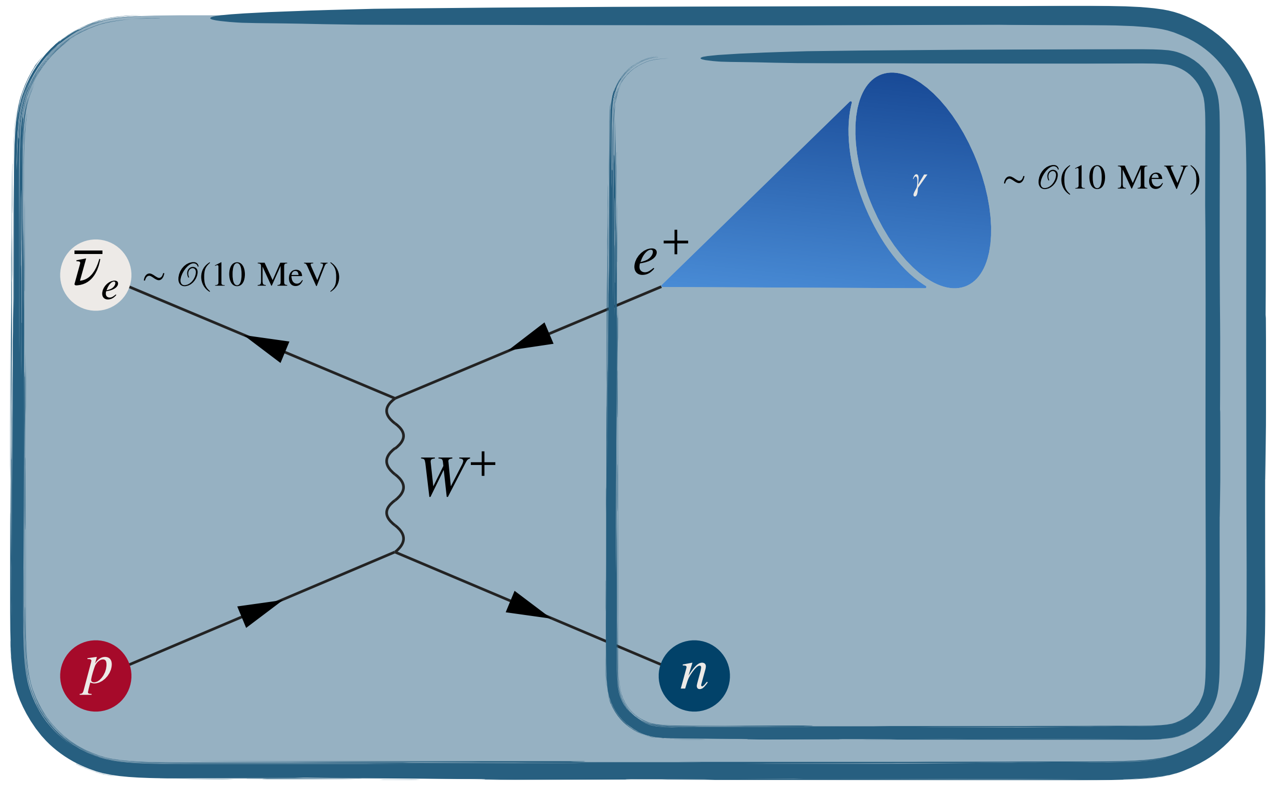
- Reactor:
  - **Irreducible** because $\sim 10^3$ times more than DSNB events below 10 MeV




- Charged-Current (CC):
  - Observables: $e^+$ energy $E_{e^+}$ and Cherenkov angle $\theta_C$




DSNB event



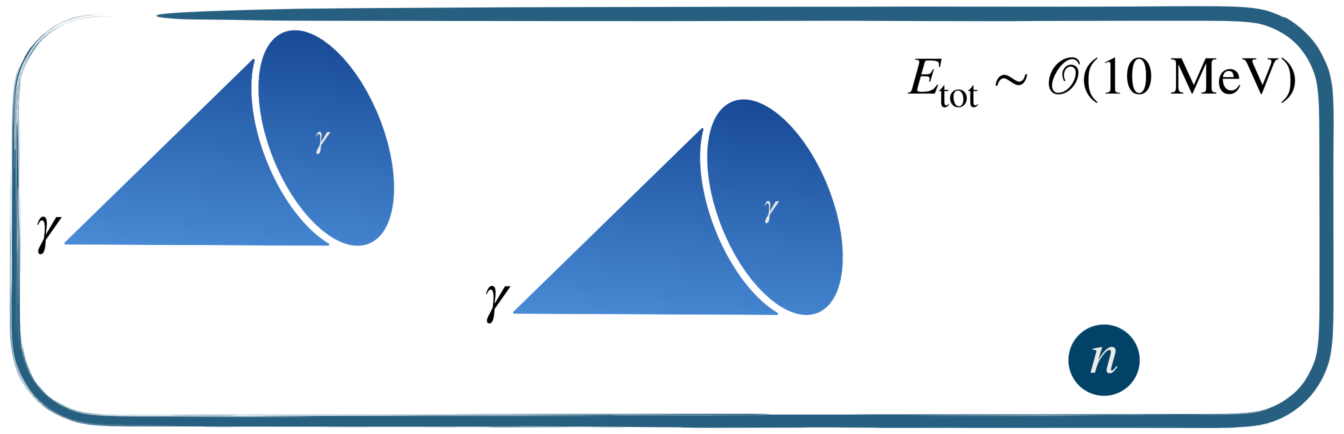
## Other events (Backgrounds)



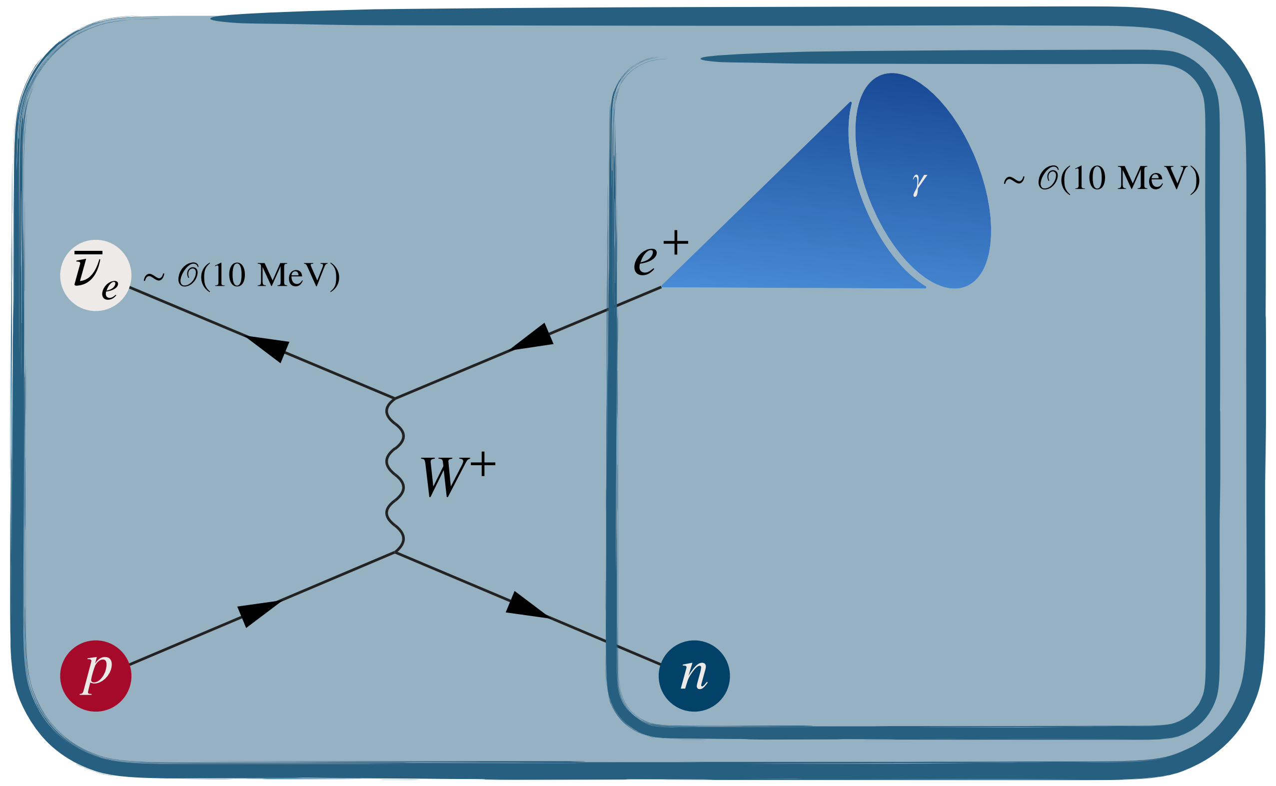

- Reactor:
  - **Irreducible** because $\sim 10^3$ times more than DSNB events below 10 MeV
- Charged-Current (CC):
  - Observables: $e^+$ energy $E_{e^+}$ and Cherenkov angle $\theta_C$




- Neutral-Current (NC):
  - Observables: $e^+$ energy $E_{e^+}$, Cherenkov angle $\theta_C$ and number of neutrons $n$




DSNB event



## Other events (Backgrounds)

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



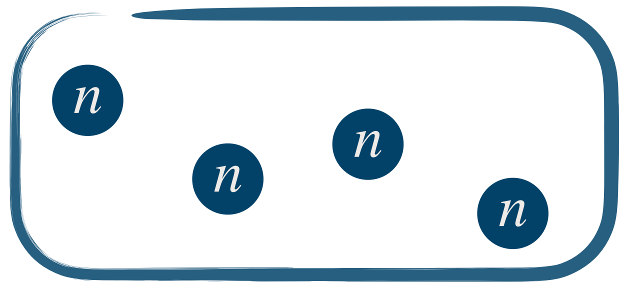

- Charged-Current (CC):
  - Observables: $e^+$ energy $E_{e^+}$ and Cherenkov angle $\theta_C$



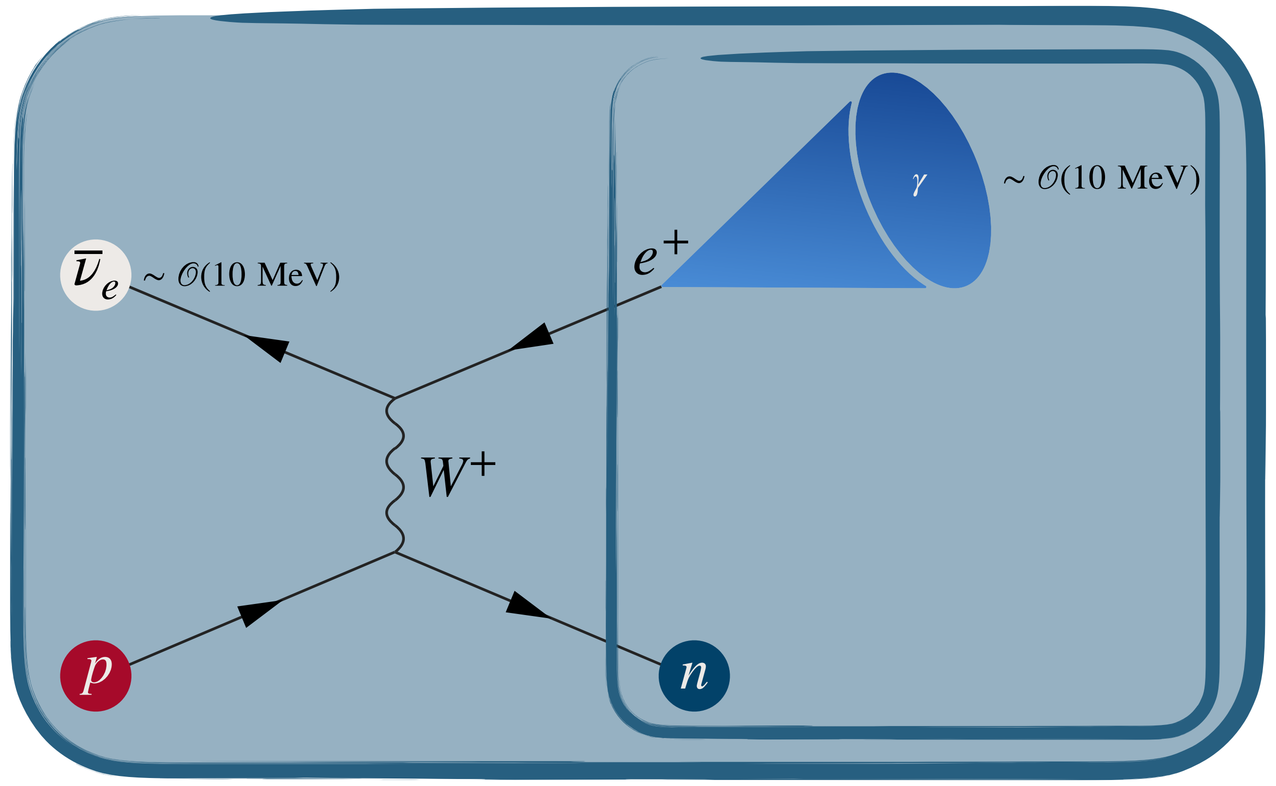

- Neutral-Current (NC):
  - Observables: $e^+$ energy $E_{e^+}$, Cherenkov angle $\theta_C$ and number of neutrons $n$




- Spallation:
  - Observables: Number of neutrons $n$

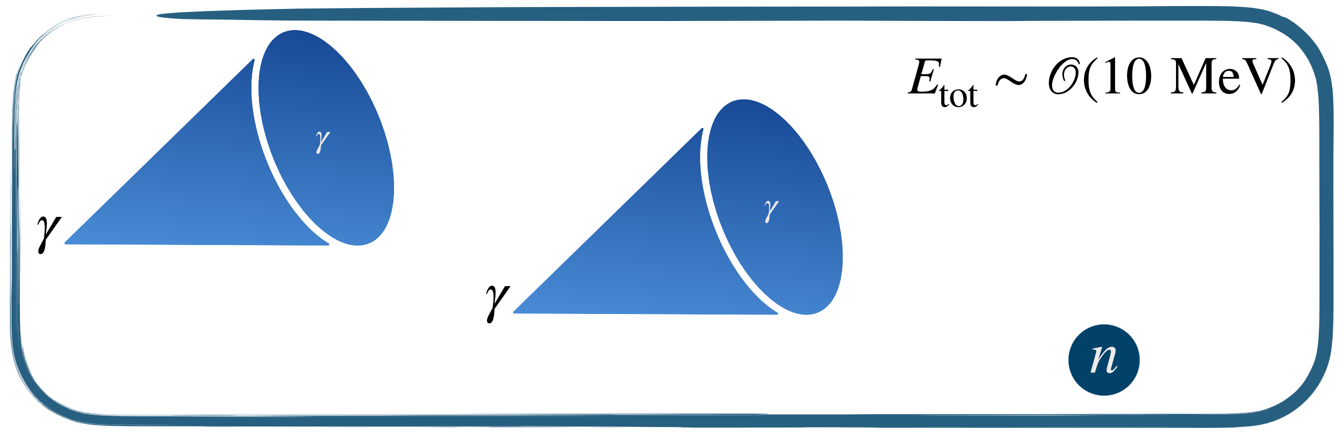


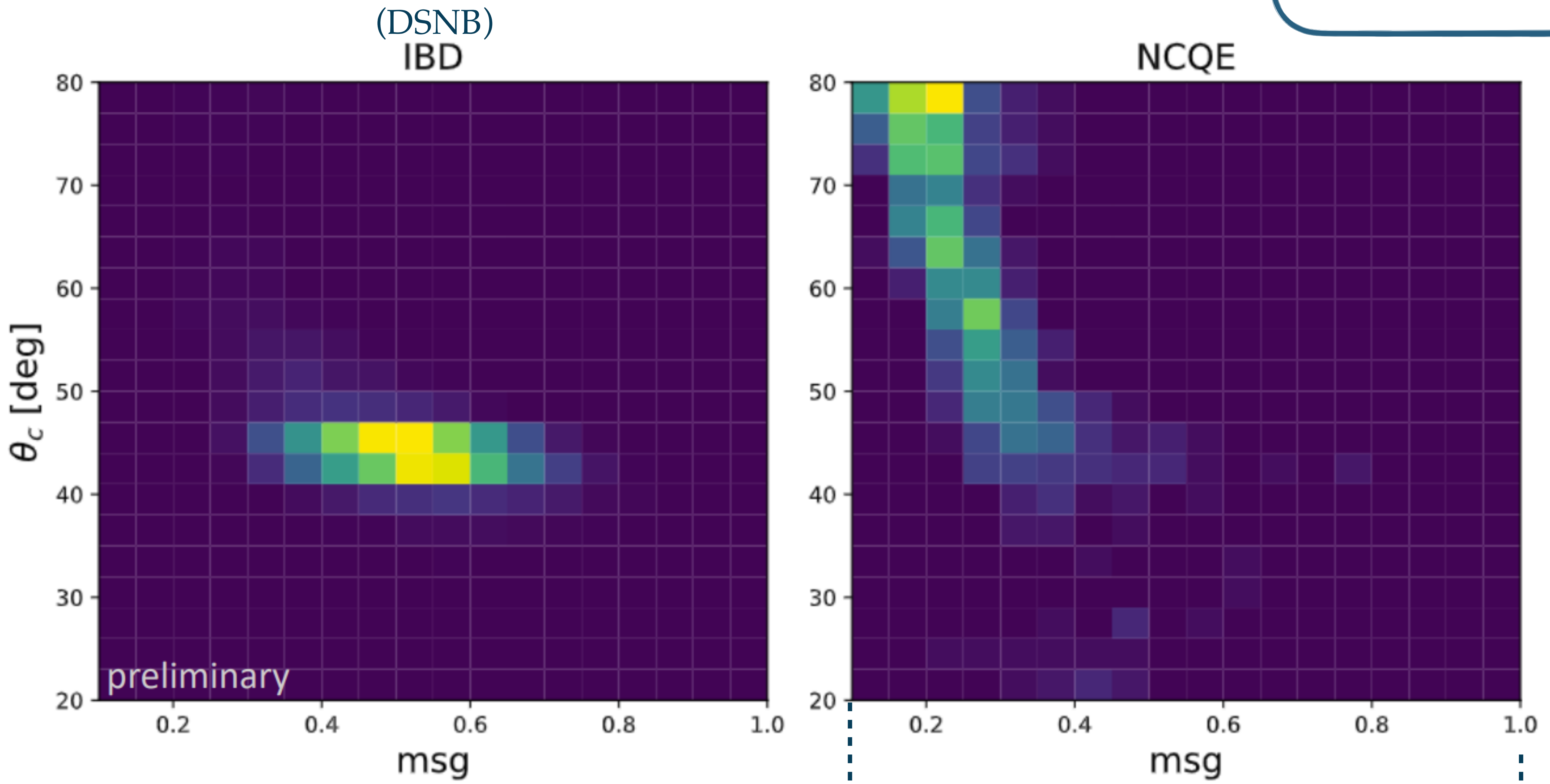

DSNB event



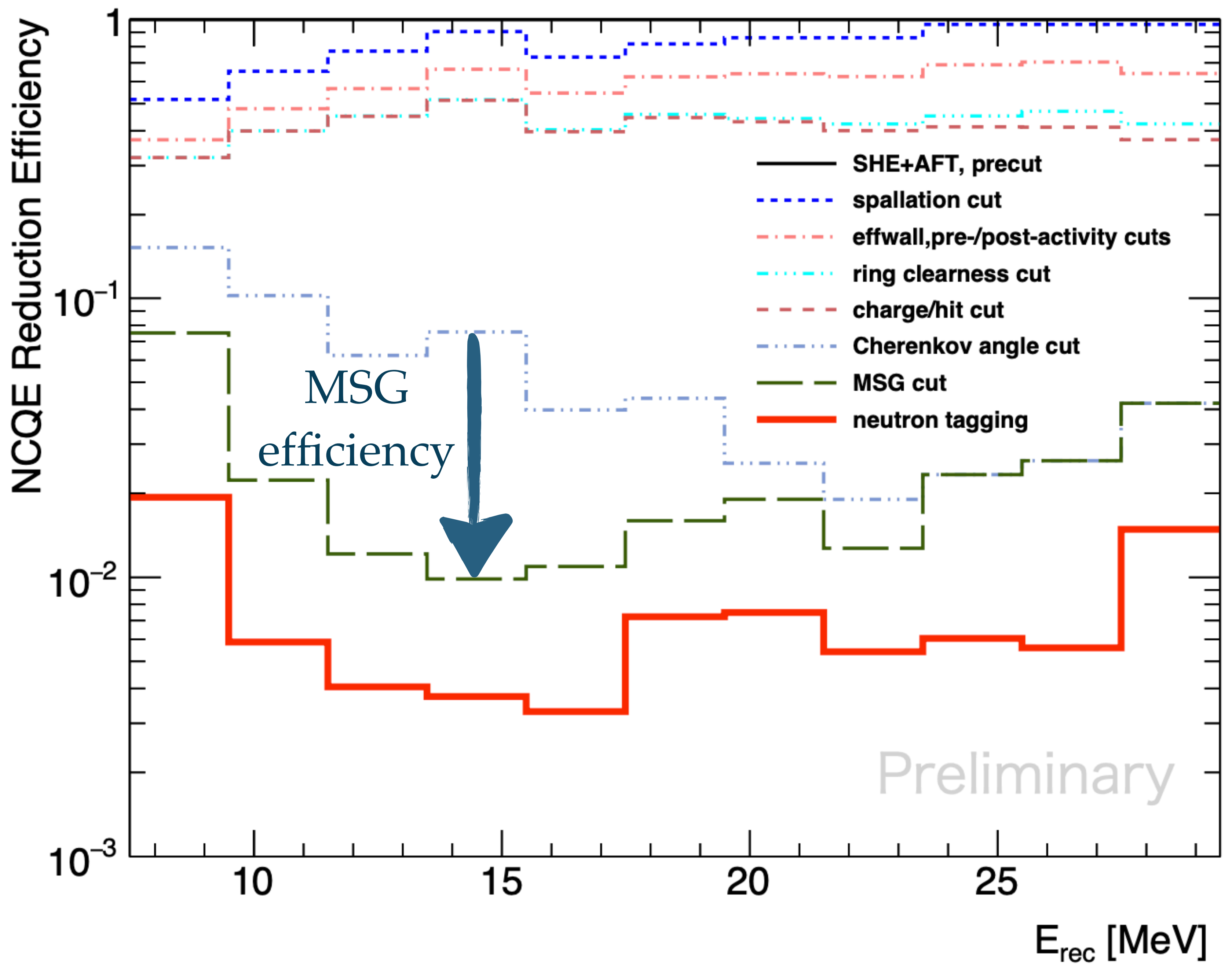
# MSG cut

## NCQE / DSNB events separation



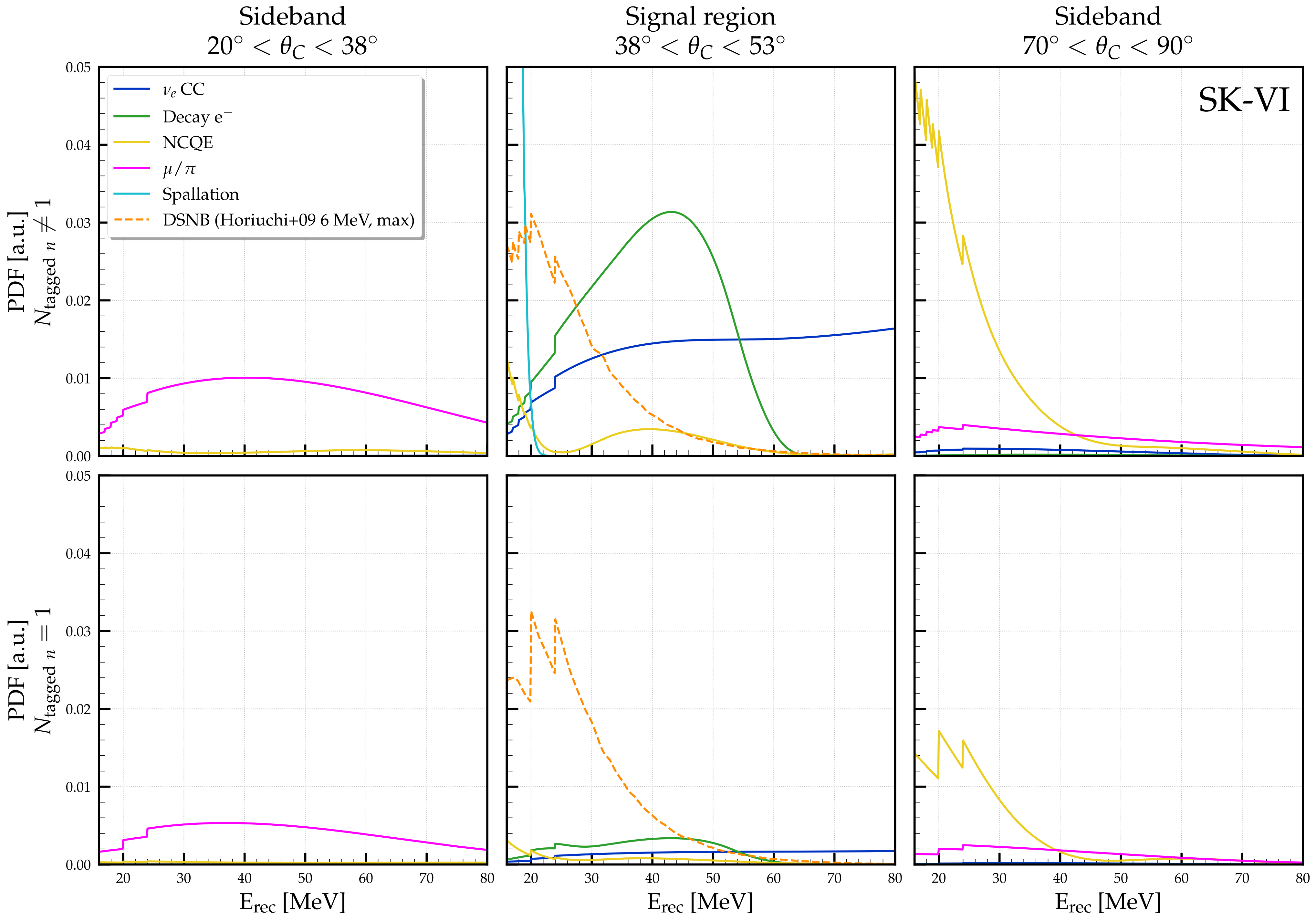

Consisting of several cones → Consisting of a single cone



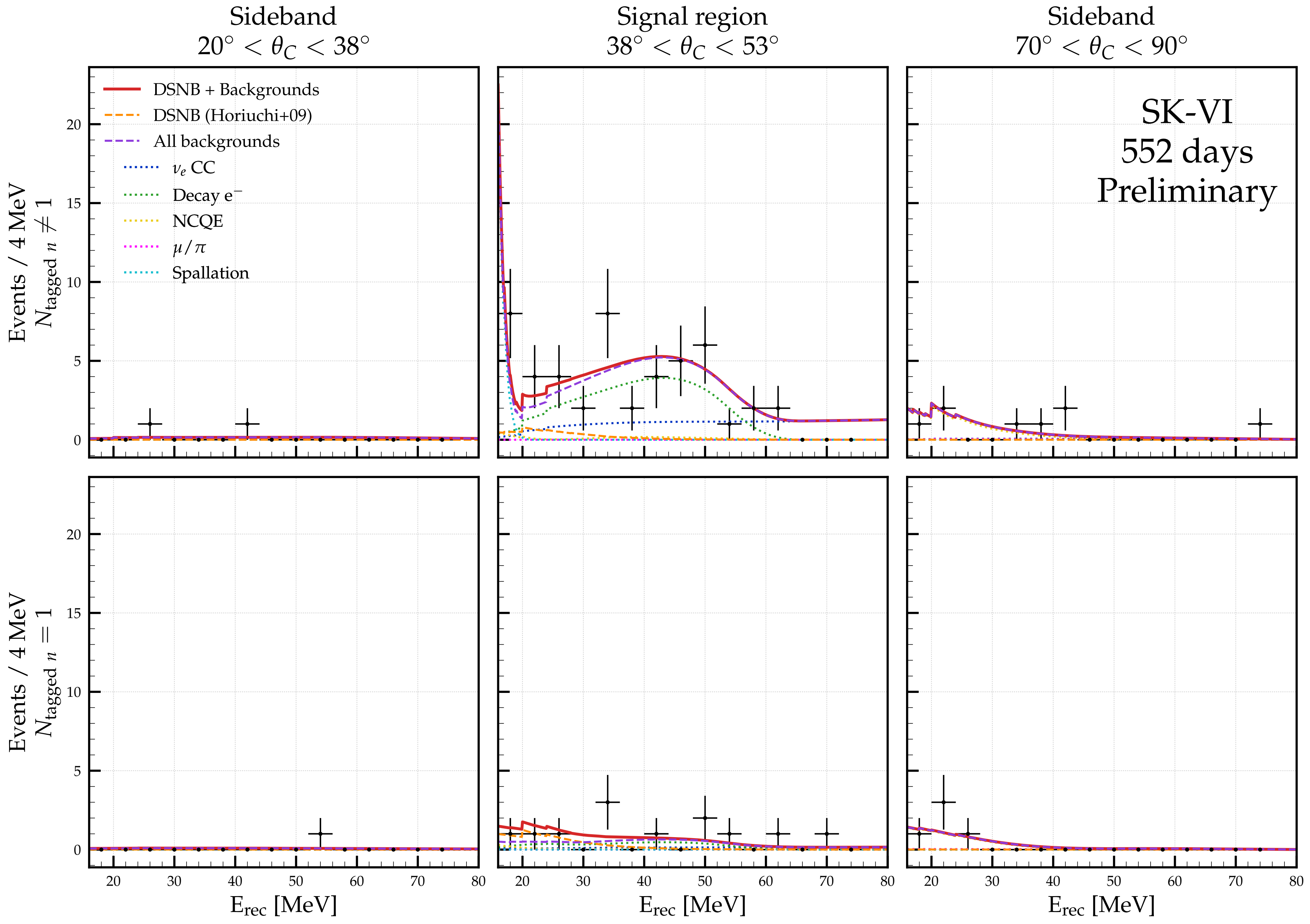

See Andrew's poster !!

## Principle

- **Unbinned** and **model-dependent** analysis: Fit DSNB + 5 background spectra to data




**Previous fitter**

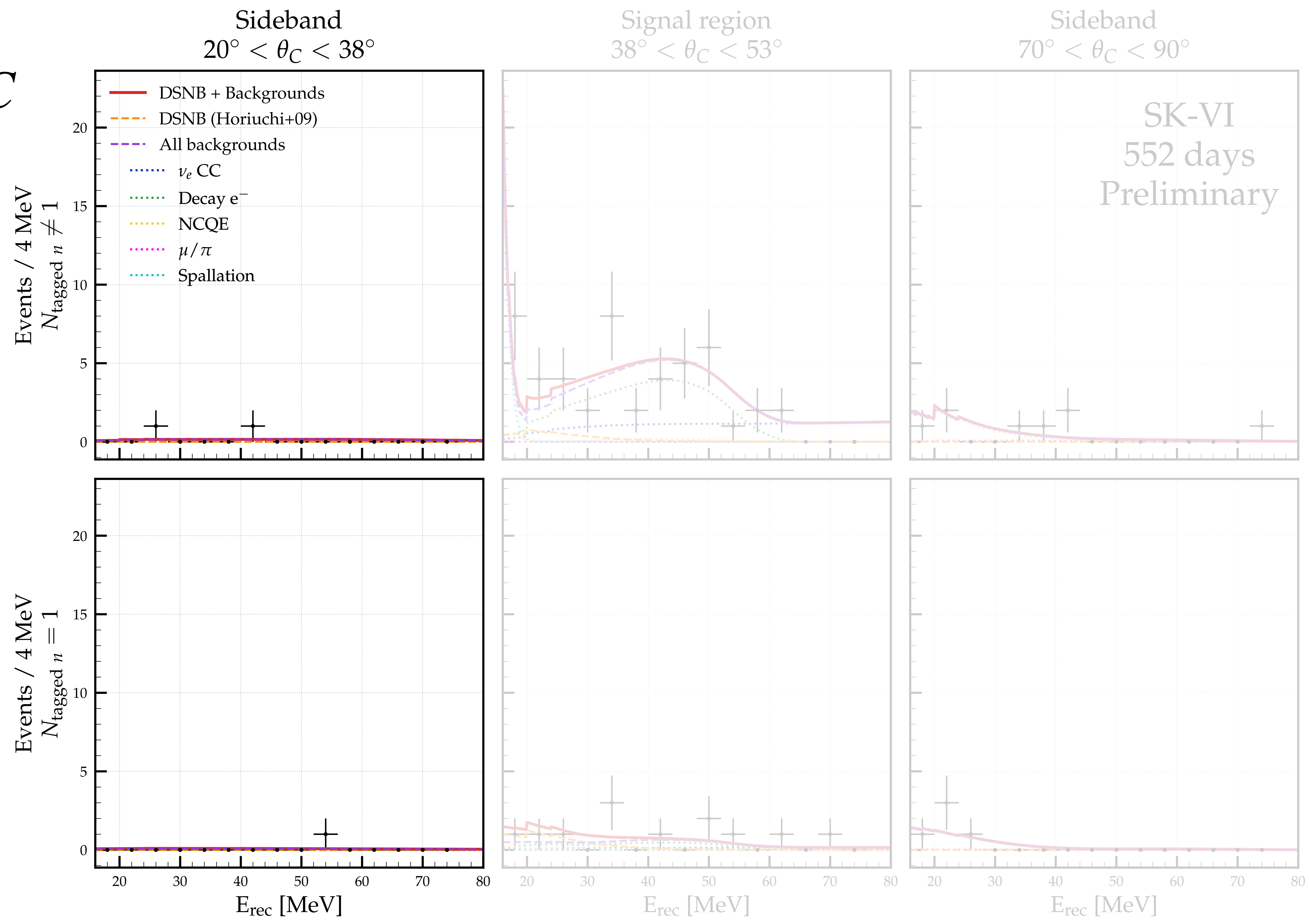


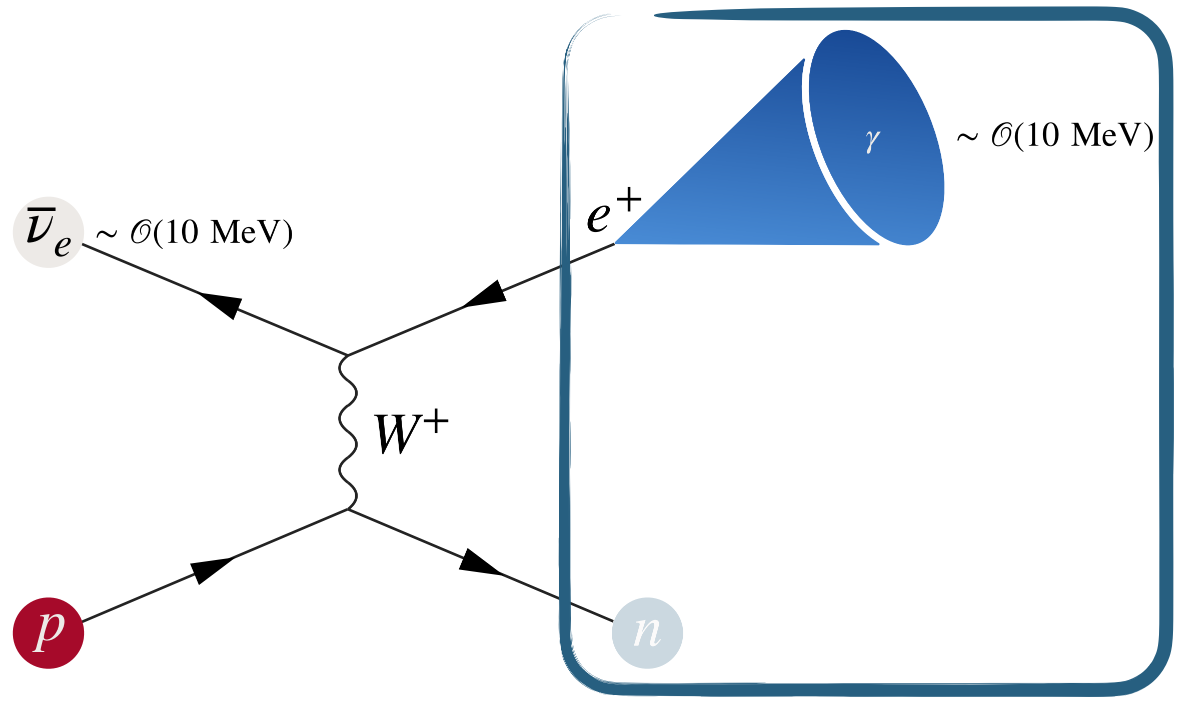
## Principle

- **Unbinned** and **model-dependent** analysis: Fit DSNB + 5 background spectra to data

- Define 3 regions depending on the Cherenkov angle $\theta_C$
  - Mostly **visible** $\mu/\pi$ events (in the final-state)

**Previous fitter**

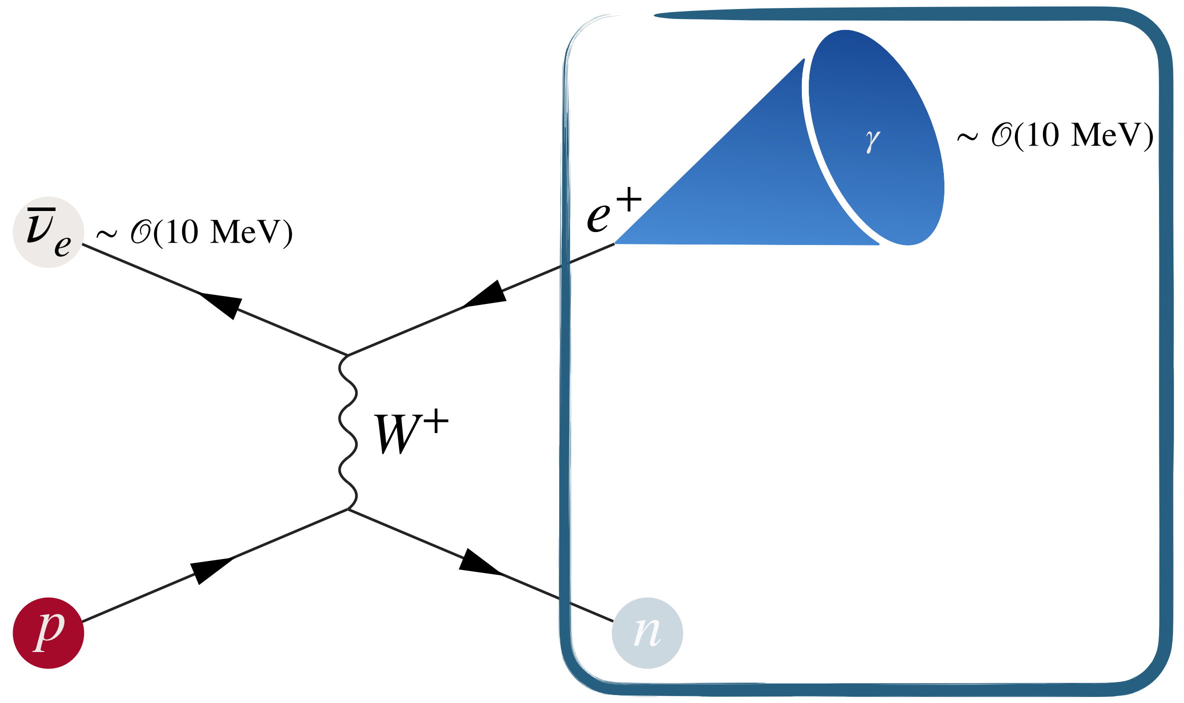


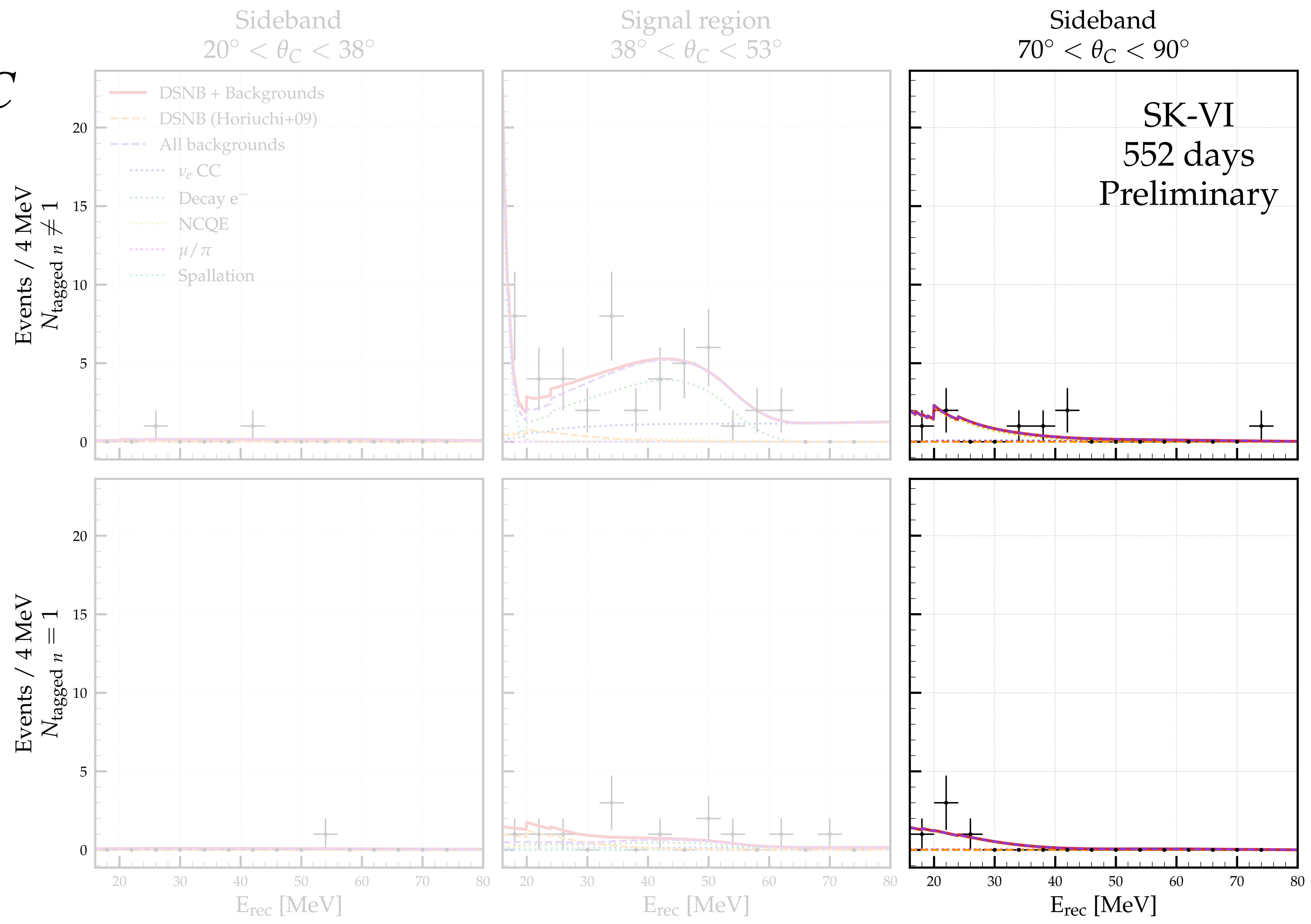
## Principle

- **Unbinned and model-dependent analysis**: Fit DSNB + 5 background spectra to data

- Define 3 regions depending on the Cherenkov angle $\theta_C$
  - Mostly **visible** $\mu/\pi$ events (in the final-state)
  - Mostly **NCQE** events with multiple final-state $\gamma$



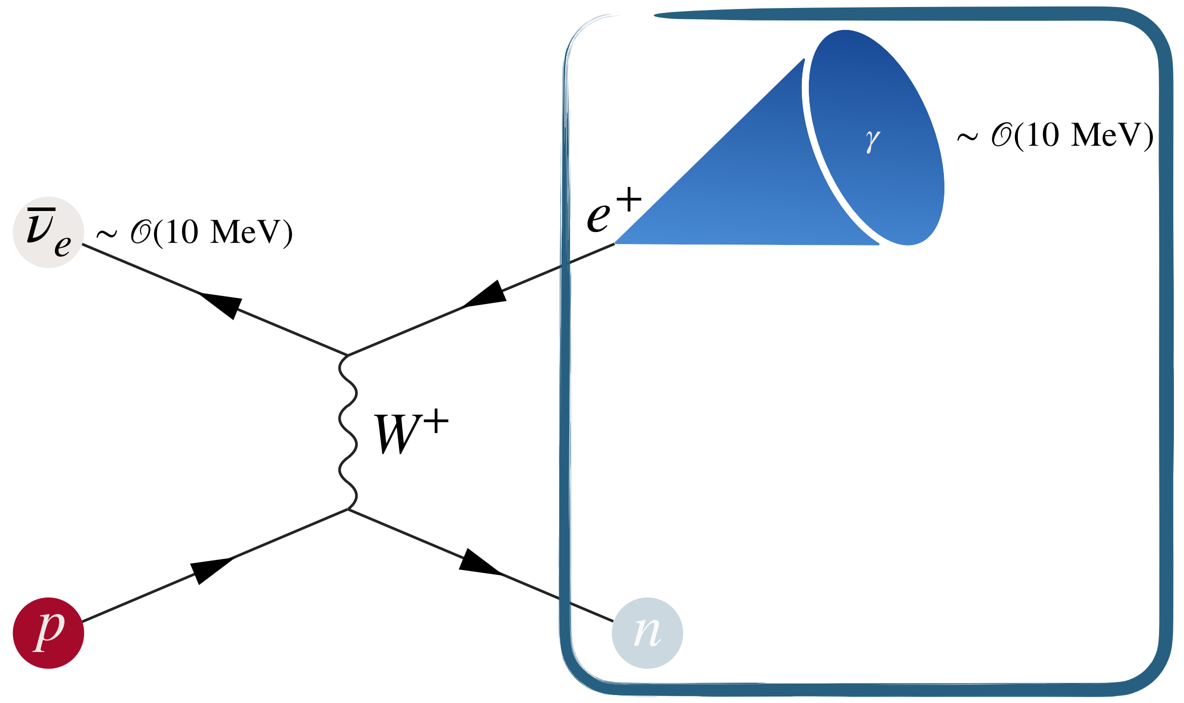

**Previous fitter**



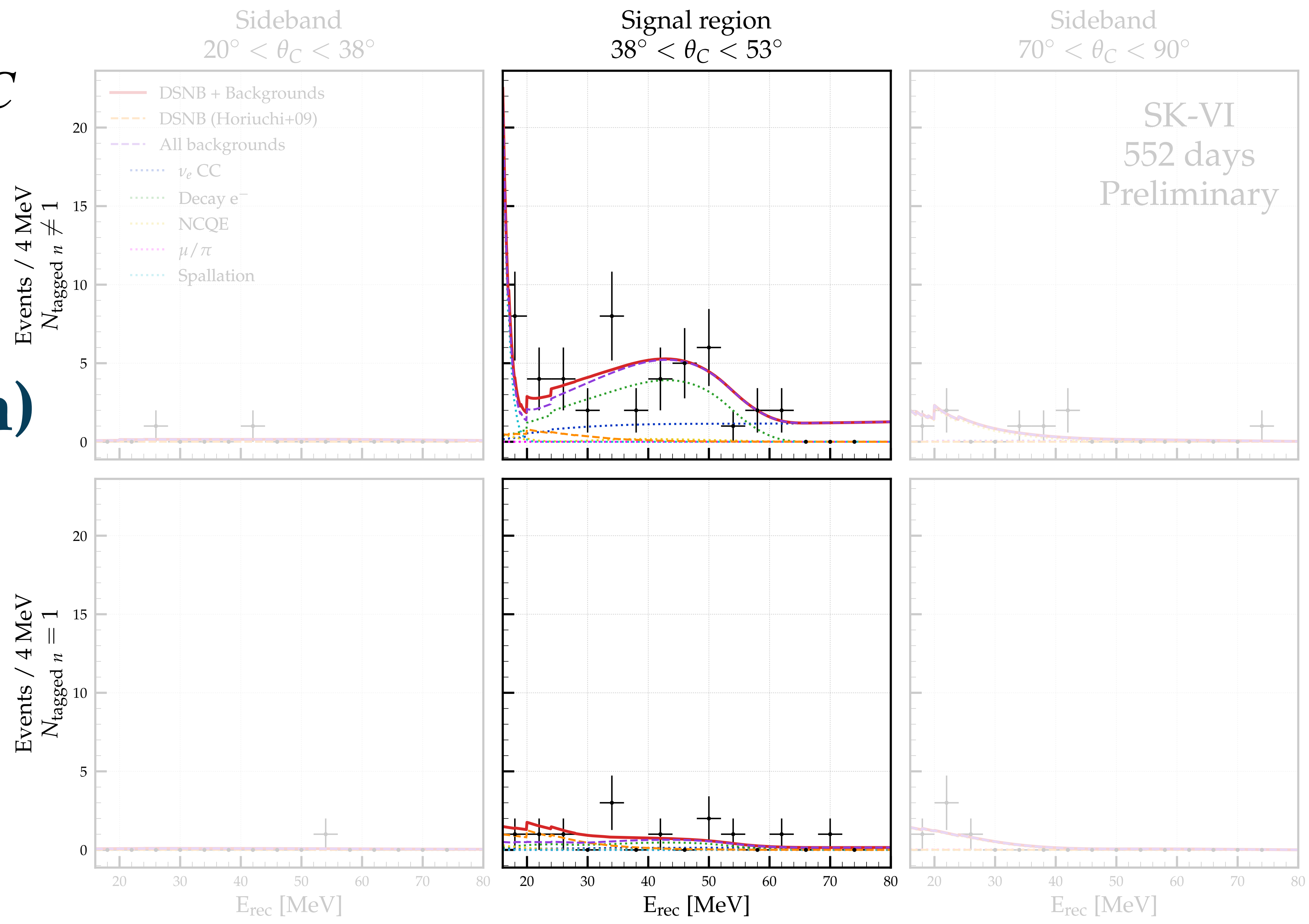
# Spectral Analysis

## Principle

- **Unbinned** and **model-dependent** analysis: Fit DSNB + 5 background spectra to data
- Define 3 regions depending on the Cherenkov angle $\theta_C$
  - Mostly **visible** $\mu/\pi$ events (in the final-state)
  - Mostly **NCQE** events with multiple final-state $\gamma$
  - **Signal** & **backgrounds** ($\nu_e$ **CC, Decay** $e^-$**, Spallation)**




**Previous fitter**

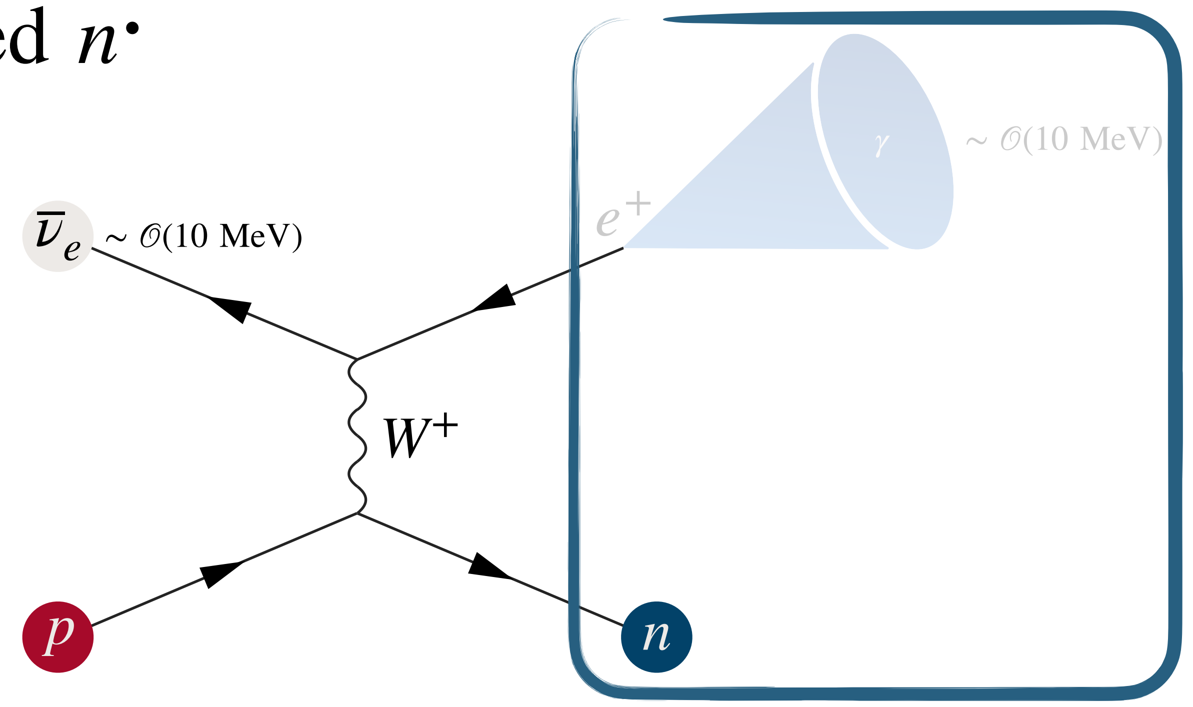


# Principle

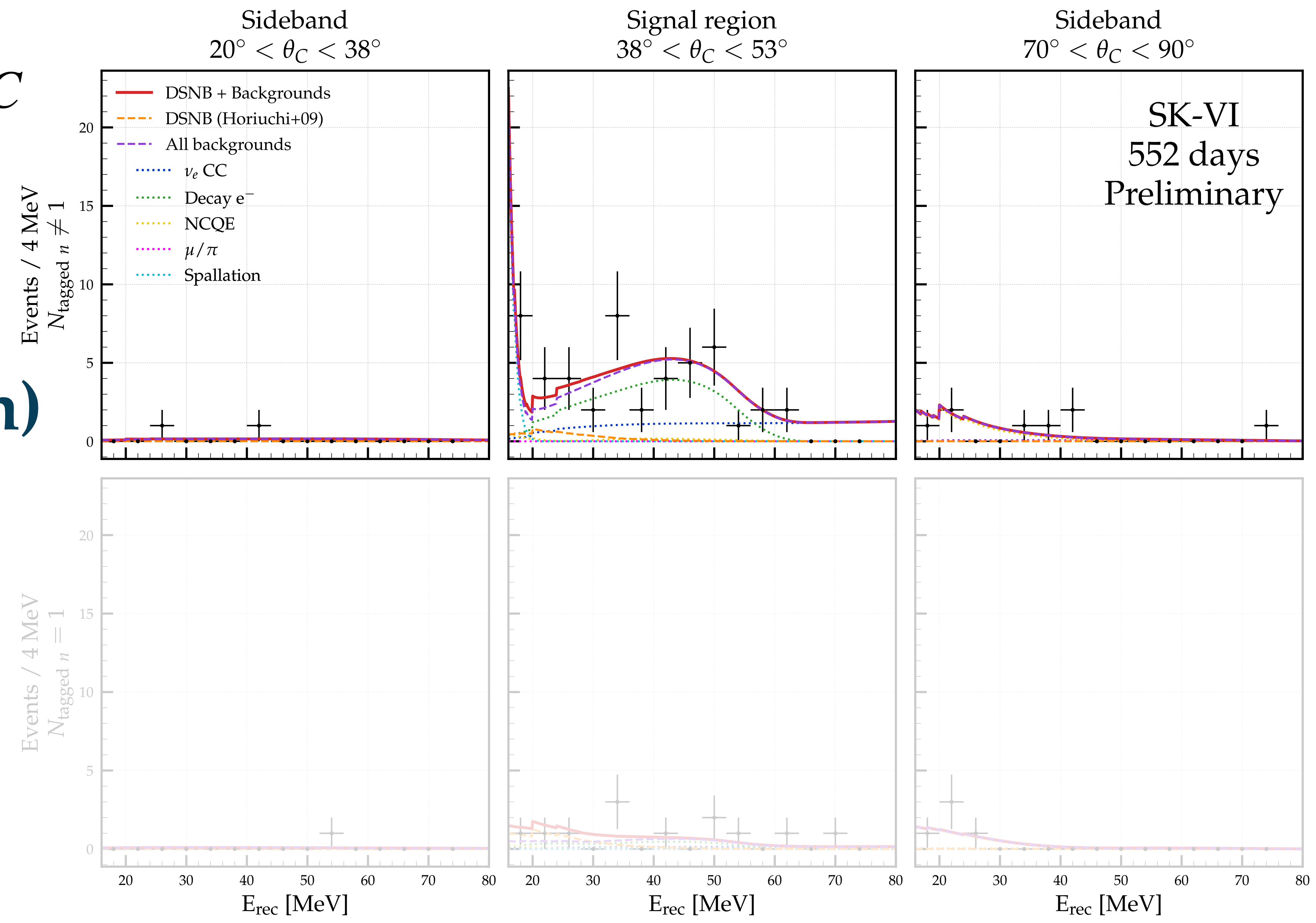
- **Unbinned and model-dependent analysis**: Fit DSNB + 5 background spectra to data

- Define 3 regions depending on the Cherenkov angle $\theta_C$
  - Mostly **visible $\mu/\pi$** events (in the final-state)
  - Mostly **NCQE** events with multiple final-state $\gamma$
  - **Signal** & **backgrounds ($\nu_e$ CC, Decay $e^-$, Spallation)**

- Separated according to $N_{\text{tagged } n}$:
  - **Non IBD-like** events




**Previous fitter**



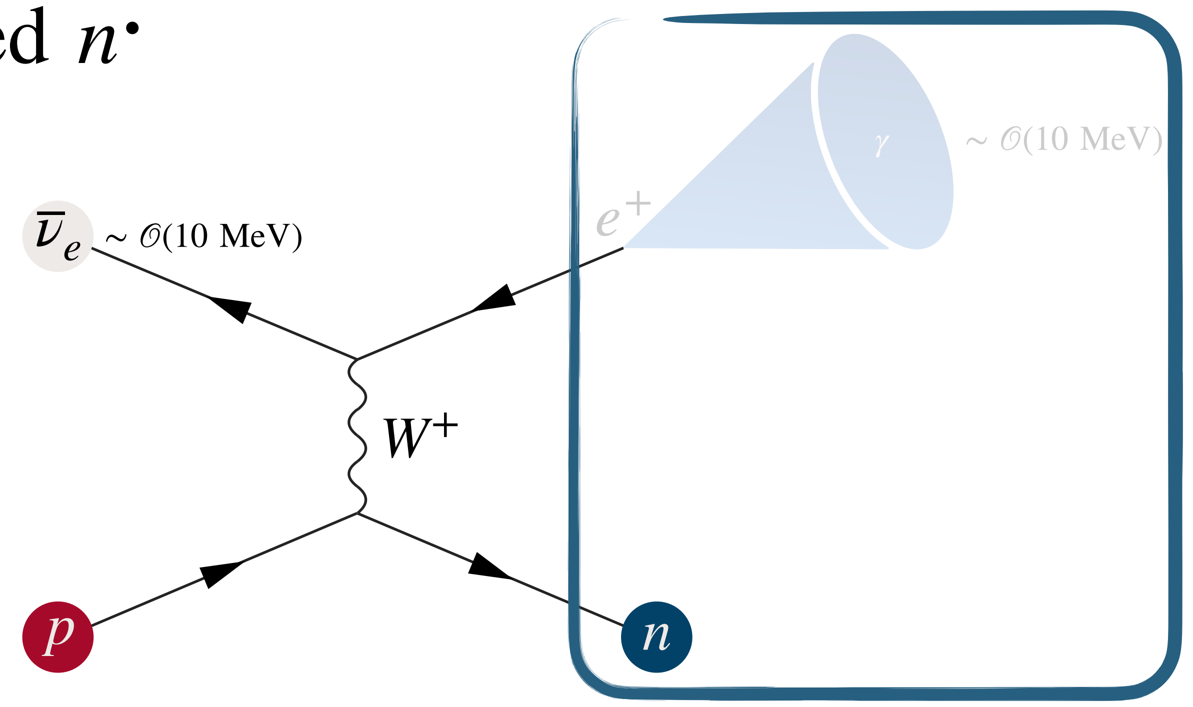
# Spectral Analysis

## Principle

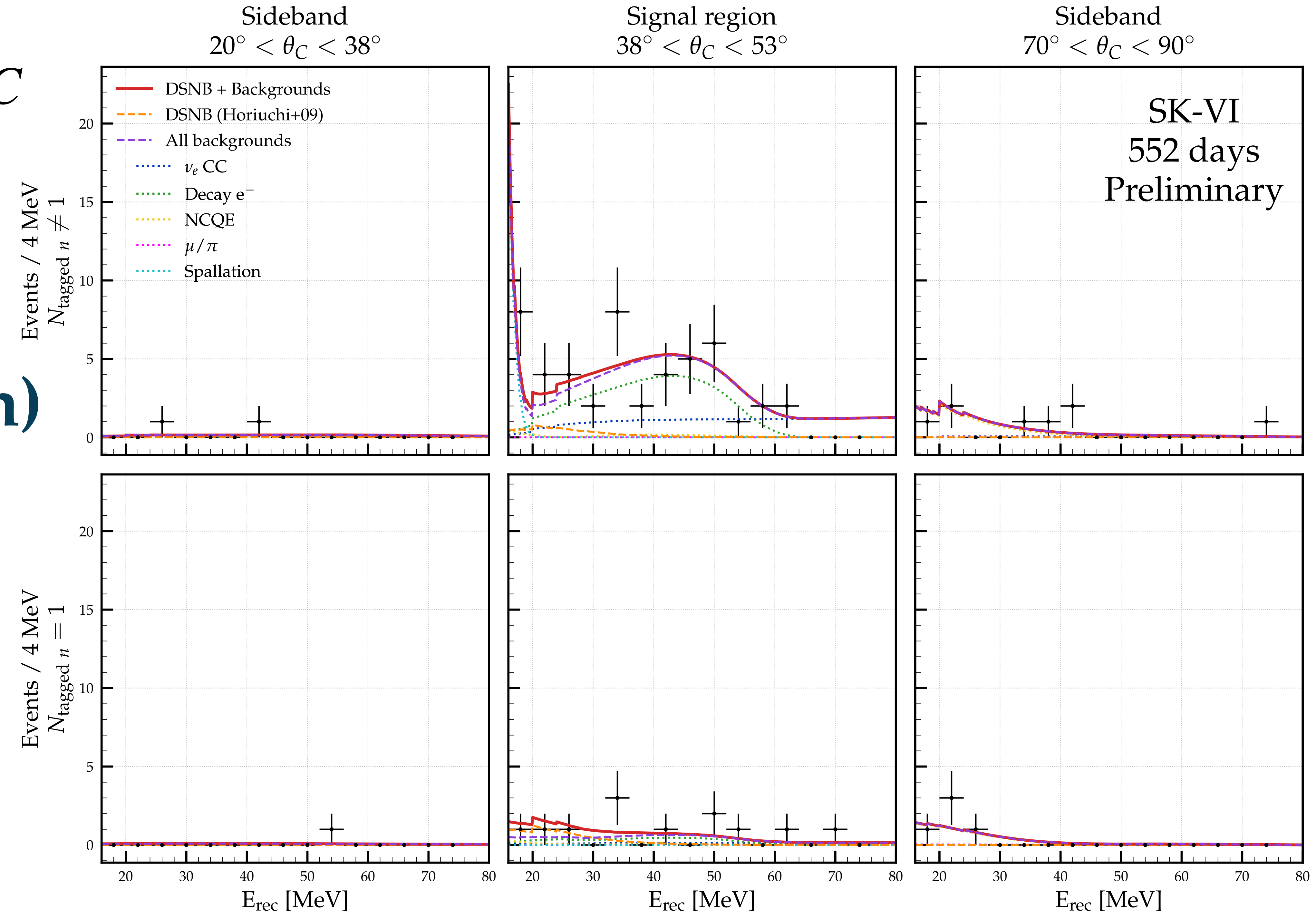
- **Unbinned** and **model-dependent** analysis: Fit DSNB + 5 background spectra to data

- Define 3 regions depending on the Cherenkov angle $\theta_C$
  - Mostly **visible $\mu/\pi$** events (in the final-state)
  - Mostly **NCQE** events with multiple final-state $\gamma$
  - **Signal** & **backgrounds ($\nu_e$ CC, Decay $e^-$, Spallation)**

- Separated according to $N_{\text{tagged } n}$:
  - **Non IBD-like** events
  - **IBD-like** events




**Previous fitter**



# Spectral Analysis

## Extended maximum likelihood fit

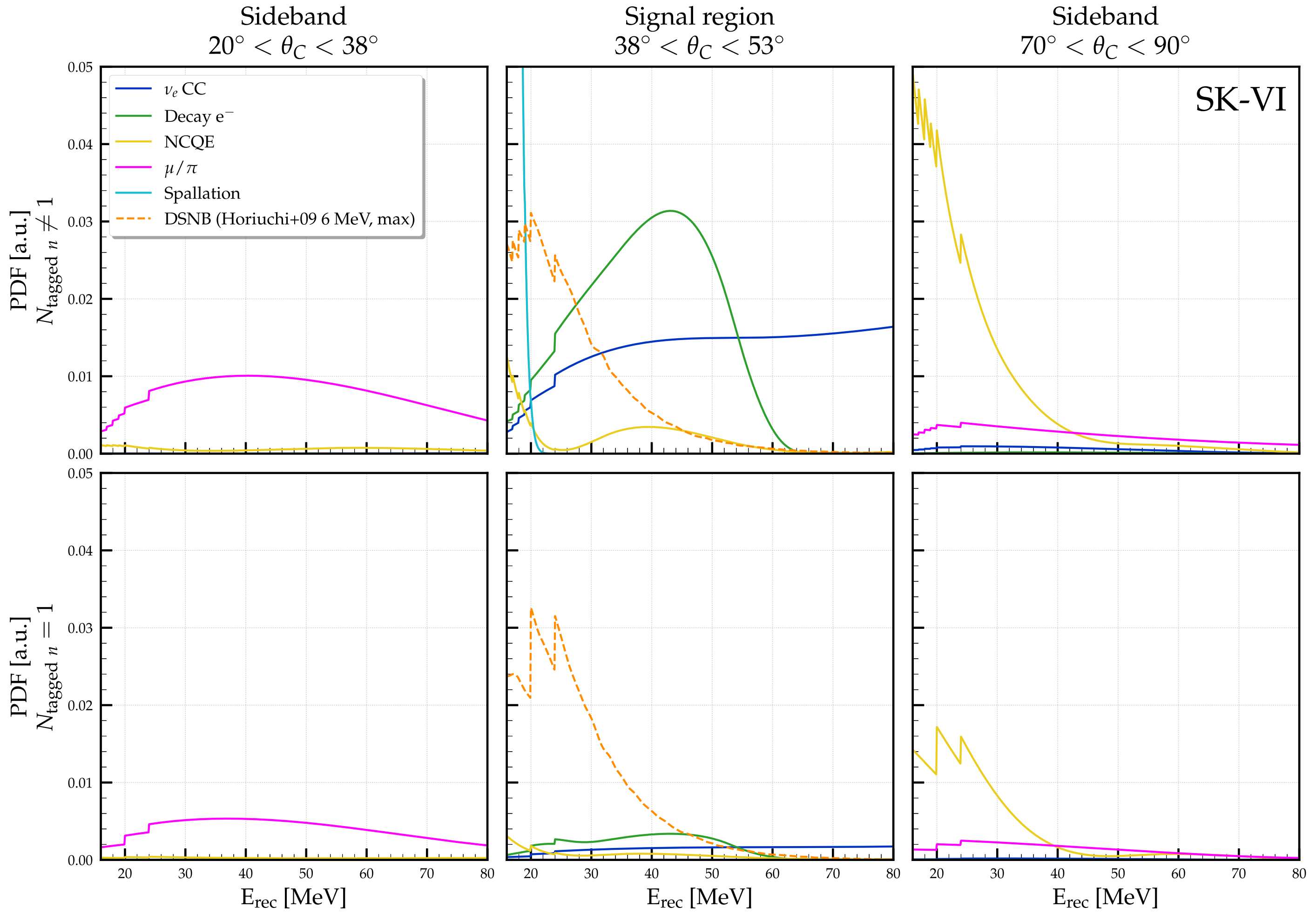
- Define $\mathrm{PDF}_j$ (spectral categories $j$)

Simultaneously on the 6 regions

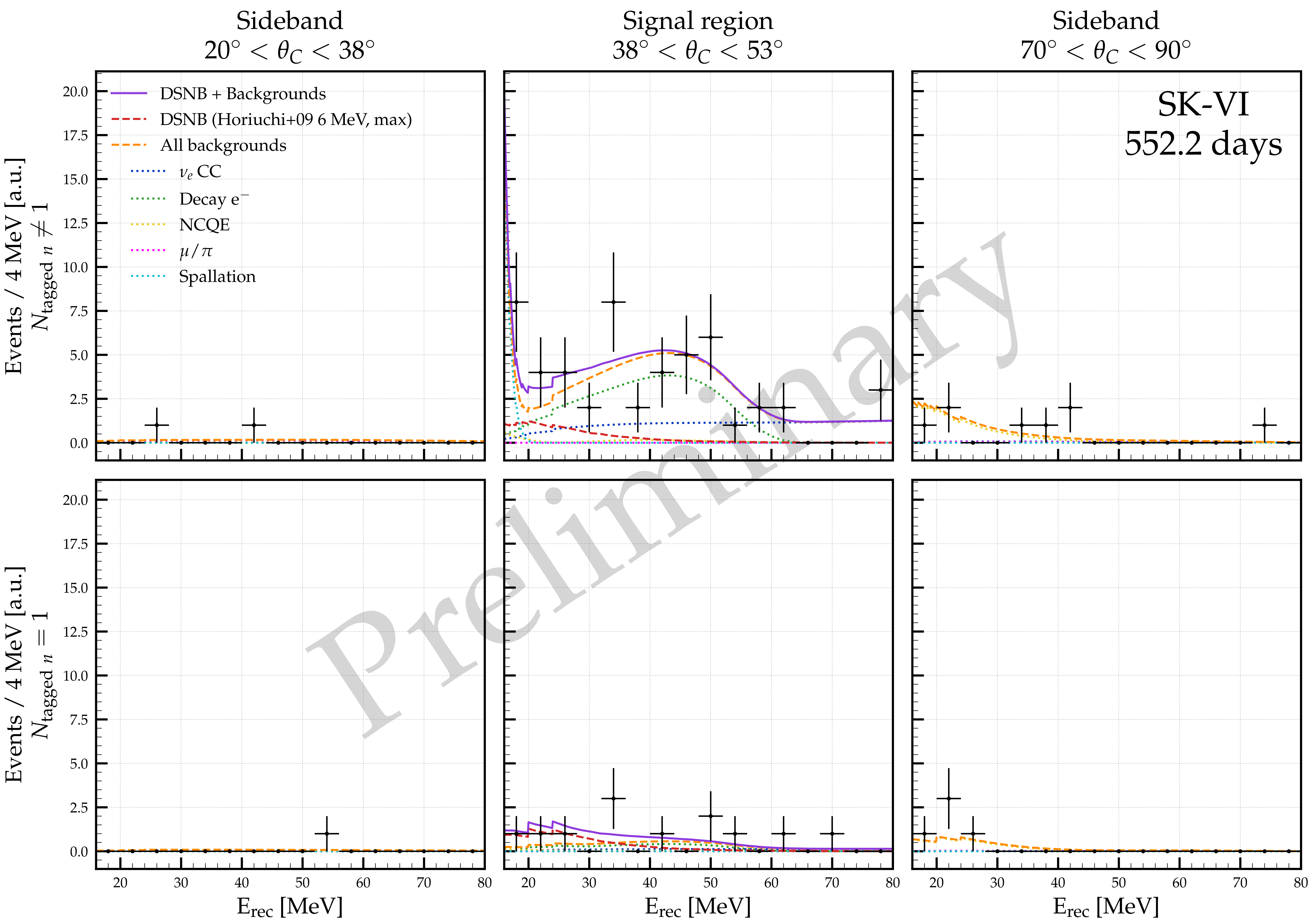
- We fit the number of observed events $N_j$ that maximizes the following likelihood:

$$\mathscr{L}(\vec{E}\,|\,N_s, \vec{N}_b) = e^{-\sum_{j\in s+b} N_j} \prod_{i=1}^{N_{\text{data}}} \sum_{j\in s+b} N_j \,\mathrm{PDF}_j(E^i\,|\,\theta_C^i, N^i_{\text{tagged } n})$$

- Background categories treated as **nuisance parameters**
- Systematic uncertainties with the spectral forms:
  - **Spectral distortions** of the PDFs



## Fitted spectra

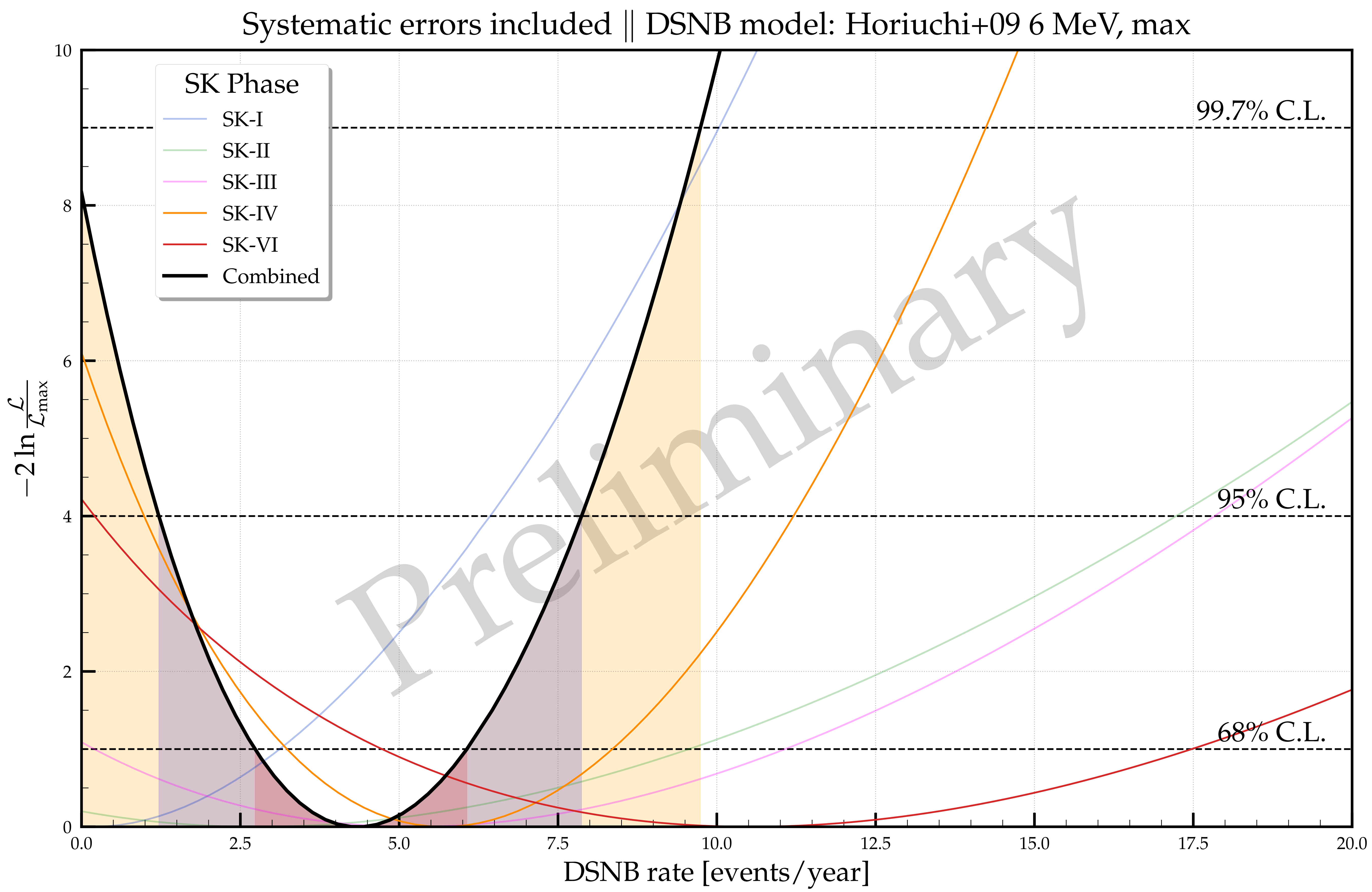


# Fit Results

## Likelihood for SK-VI

- Combined (stat. + sys.) ≈ 2.8 $\sigma$ excess
- Previous analysis:

  Combined (stat. + sys.) ≈ 2.1 $\sigma$ excess




- Need to improve phases combination
- Also improving reduction steps: e.g. MSG cut and neutron-tagging (BDT → GNN)

## Conclusion

- Close Supernovæ are really rare events
- Can study the DSNB to probe SN properties and other phenomenon

- Many background sources:
  - Worked on reducing the one from NCQE
  - Also improving neutron tagging algorithm

- Introduced a new Spectral Fitter:
  - Still in the process of validating it
  - Getting closer to $3\sigma$

See my poster and Rudolph's one !!

# Backup

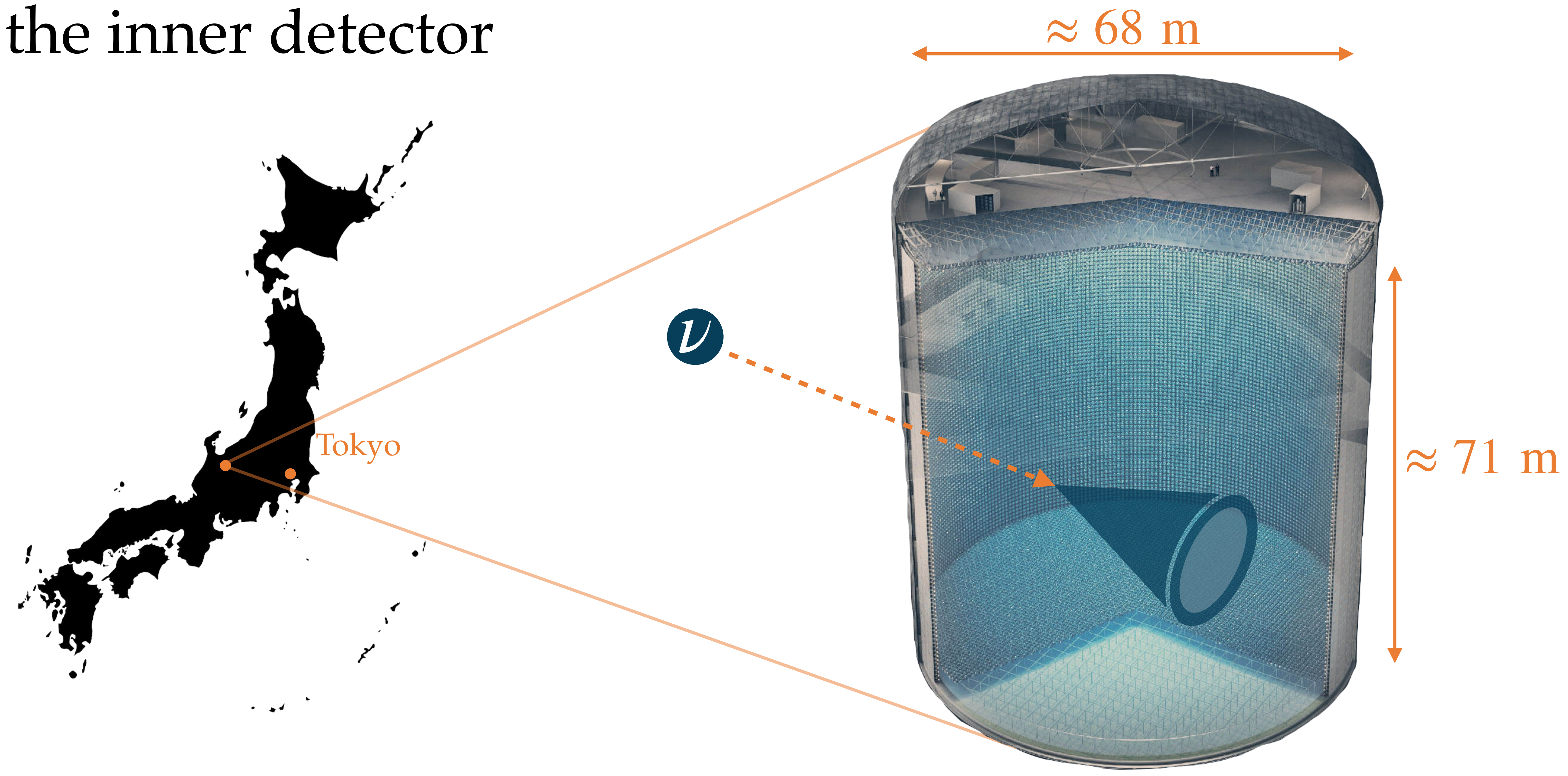
## Hyper-Kamiokande

- Construction: 2020 → 2027 (on-time)
- Water mass (**Fiducial mass**): 50 kton (22.5 kton)
- 20 000 **High Quantum Efficiency** PMTs in the inner detector
  - Diameter: 50 cm
  - Time resolution: $\sigma \approx 1.3$ ns
  - Photocathode coverage: 20%
- Located 650 m under Mt. Nijugoyama
  - **Shield from cosmic muons**

$\times \approx 8$

Hyper-Kamiokande: 258 kton (**186 kton**)

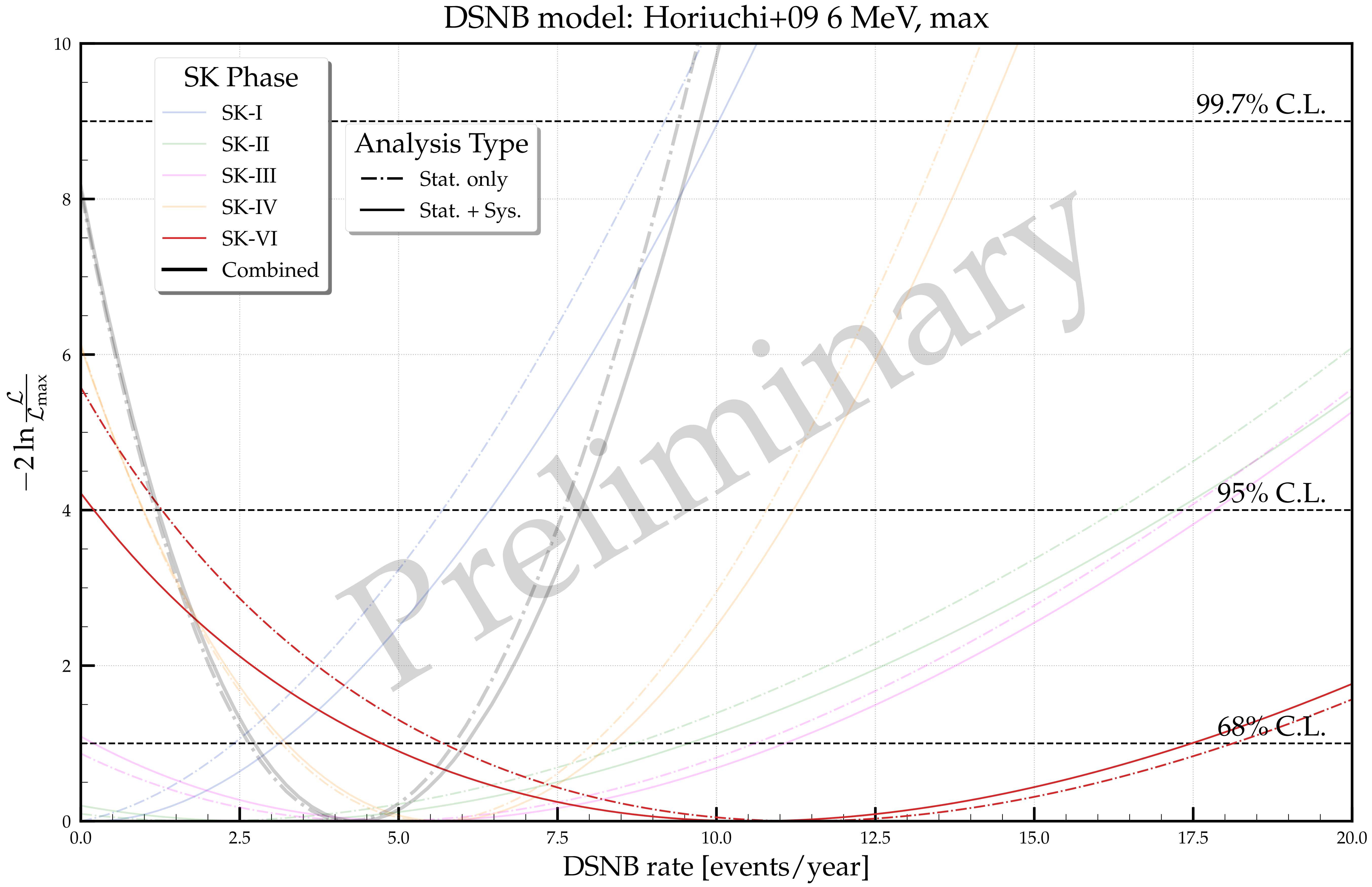
10 km from Super-K



## Likelihood for SK-VI

- Best-fit nuisance parameters for systematics contained in $\pm 1\,\sigma$
- Stat. dominated analysis
- SK-VI (stat. + sys.) $\approx 2\,\sigma$ excess
- Previous analysis:

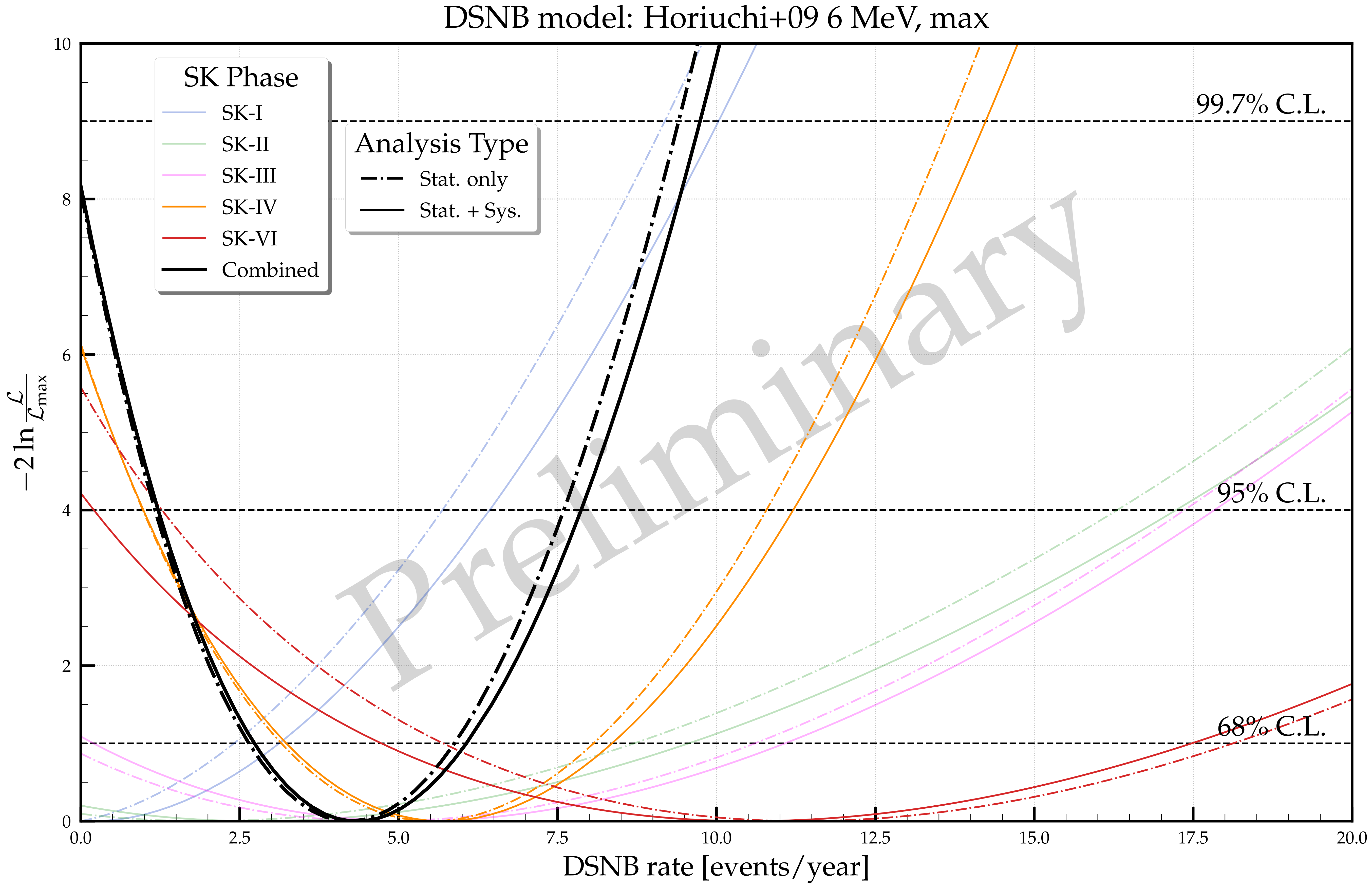
  SK-VI (stat. + sys.) $\approx 1.6\,\sigma$ excess



## Likelihood for SK-VI

- Best-fit nuisance parameters for systematics contained in $\pm 1\,\sigma$
- Stat. dominated analysis
- Combined (stat. + sys.) $\approx 2.8\,\sigma$ excess
- Previous analysis:

  Combined (stat. + sys.) $\approx 2.1\,\sigma$ excess

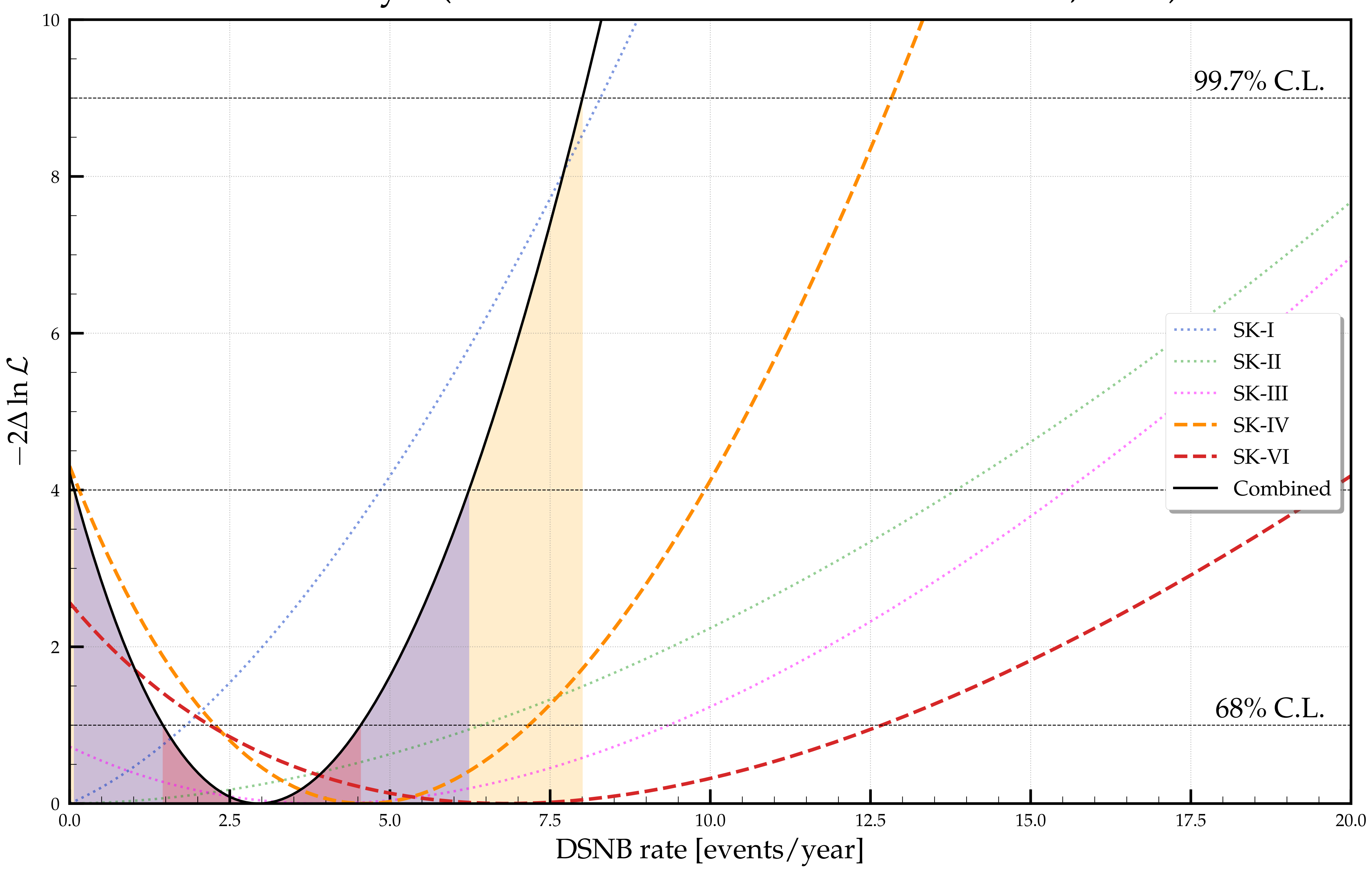


# Backup

## Likelihoods for SK-I → IV+VI

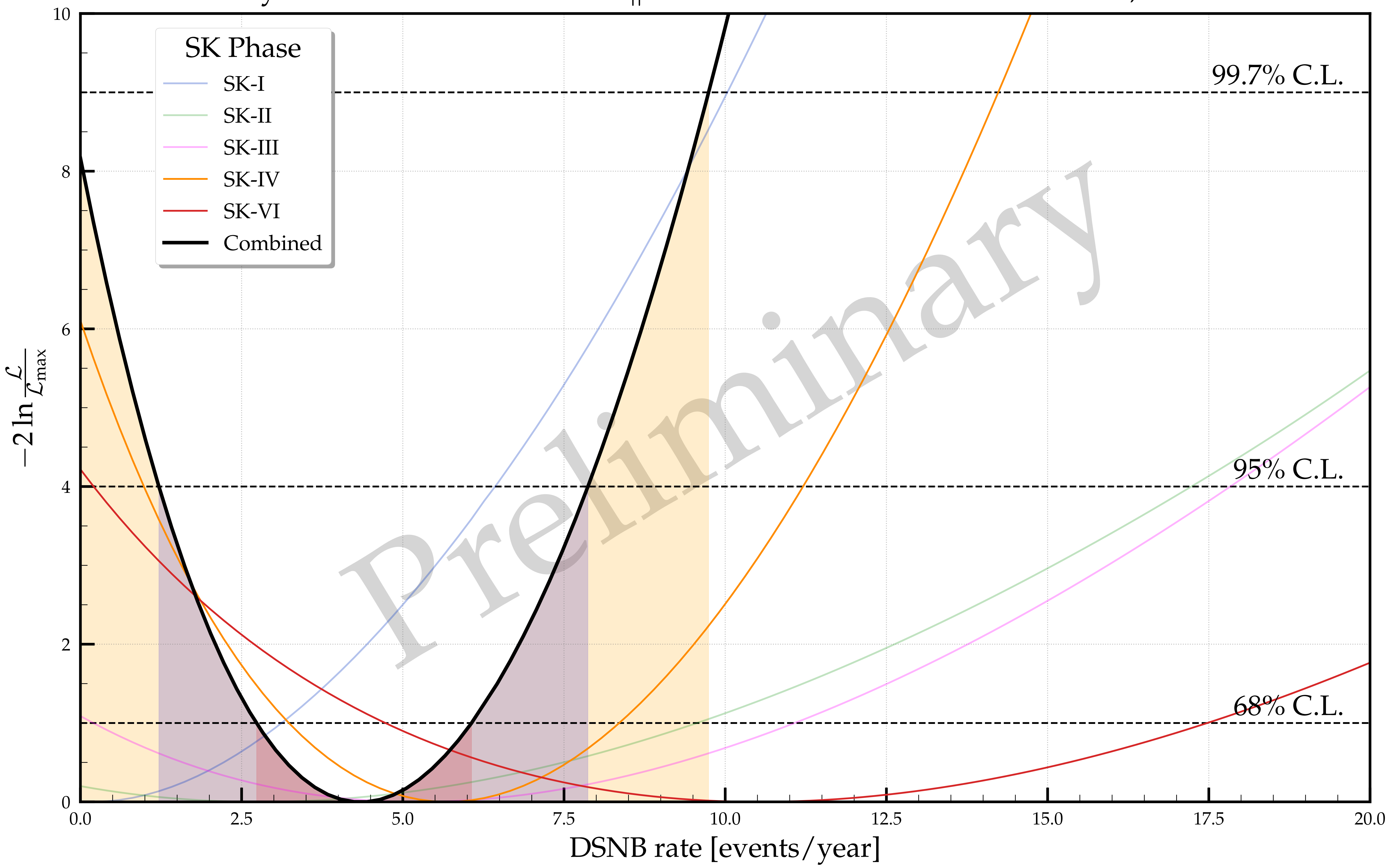
### Previous analysis

Stat. + sys. (DSNB model = Horiuchi+09 6 MeV, max)




### This work

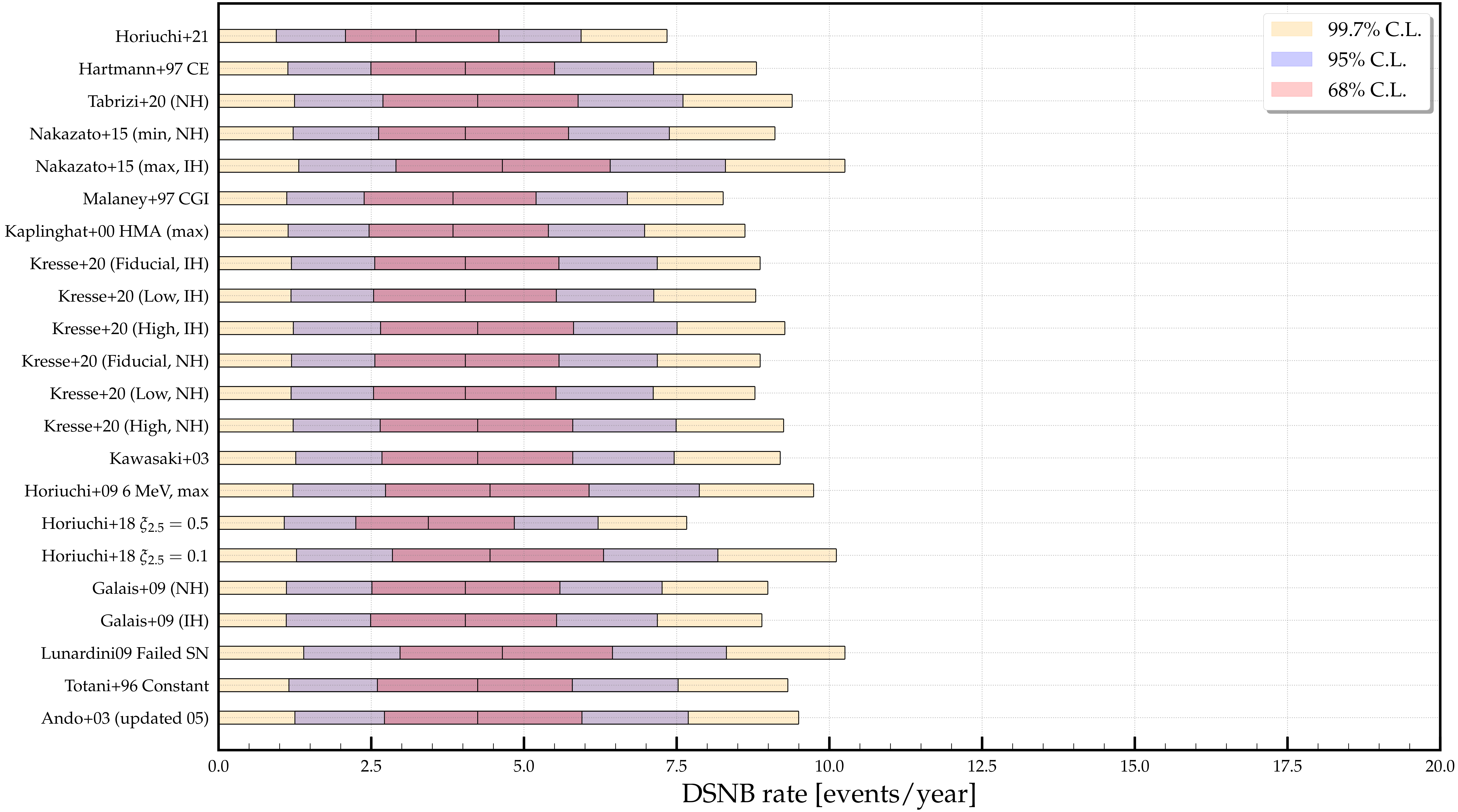
Systematic errors included || DSNB model: Horiuchi+09 6 MeV, max




We reconstruct more DSNB events than the previous analysis in each phase

# Backup

## Results for several models for SK-I → IV+VI



## Upper limits for several models for SK-I → IV+VI