Diffuse Supernova Neutrino Background

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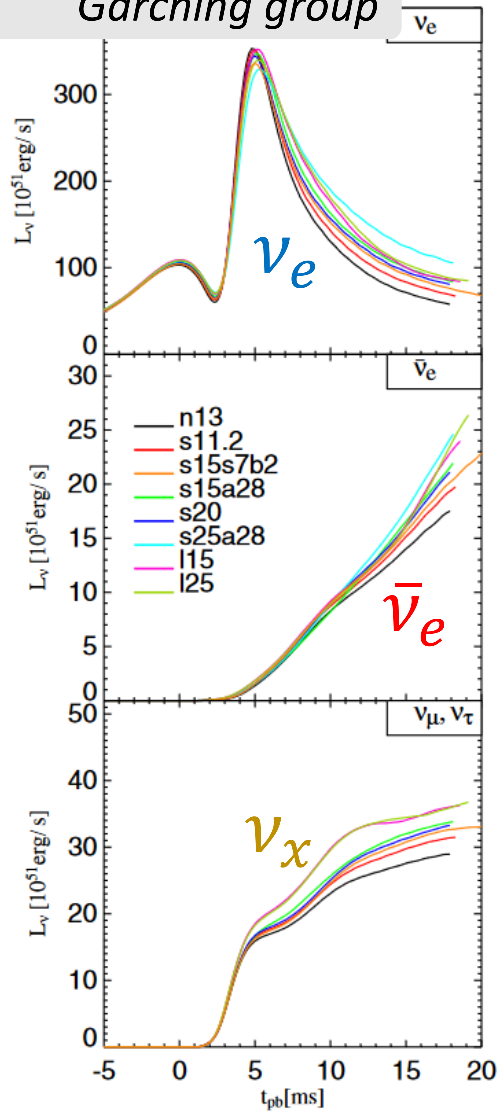
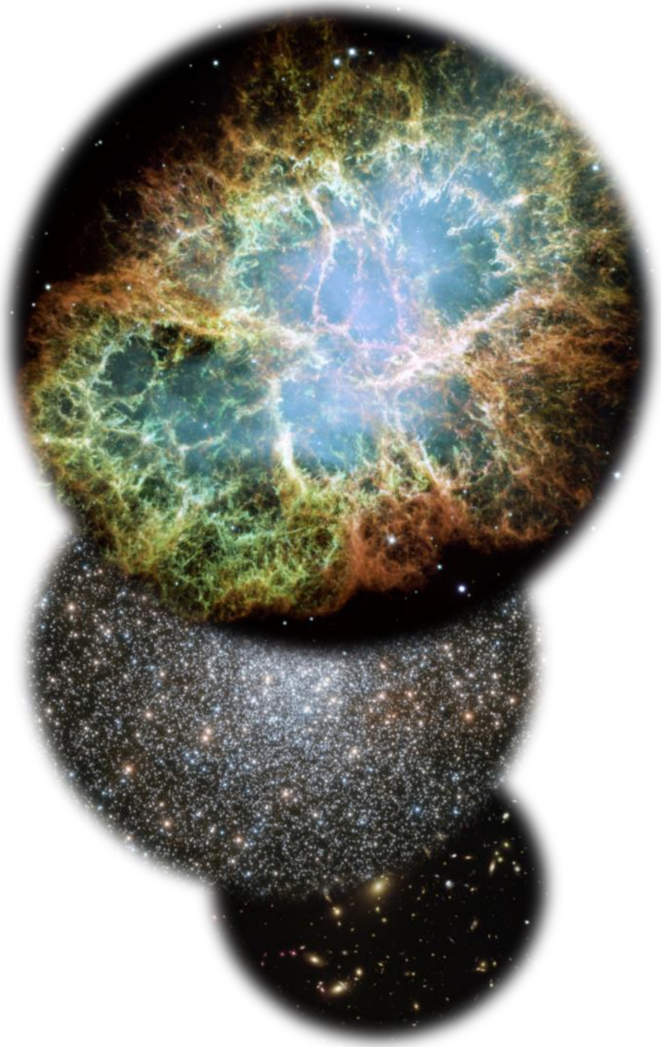
35th Rencontres de Blois

Core-collapse supernovae and neutrino emission

Garching group



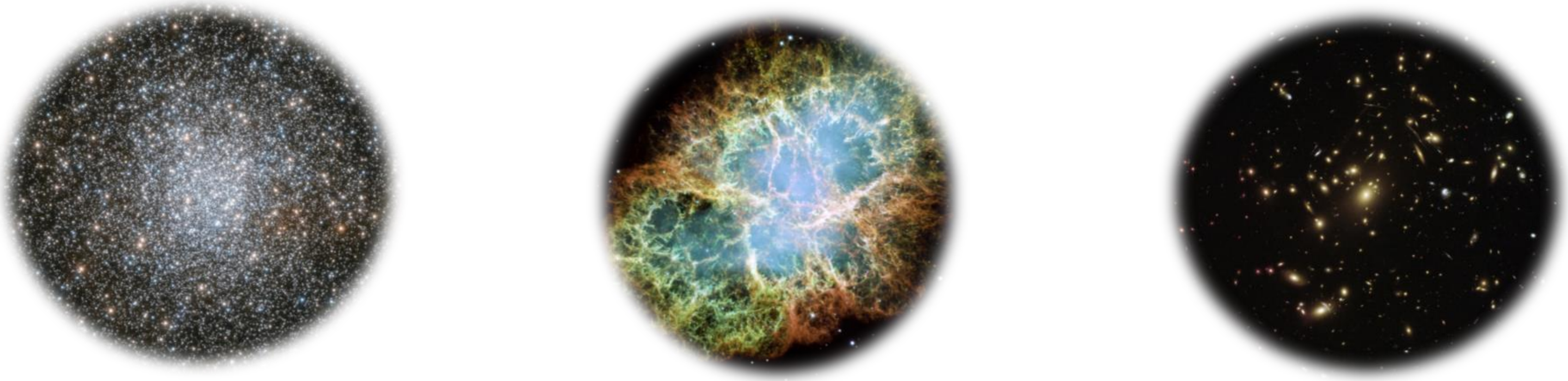
- Massive stars ($> 8\mathrm{M}_\odot$) result in **core-collapse supernovae** (CCSNe) at the end of their lives.
- CCSNe leave behind either a **neutron star** or a **black hole** depending on the ability of the outgoing shockwave not to fall back inward.
- Local CCSNe are rare, but one CCSN happens somewhere in the observable universe $\sim$**1/sec**.
- Details of CCSN mechanism are **not fully understood** and **3D simulations are challenging**.
- About **99% of all energy** released is in the form of **10^{58} neutrinos**.
- Neutrinos from all such CCSNe should form an ambient sea of particles, the **Diffuse Supernova Neutrino Background** (DSNB).



What is the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{dt}}{dz}\right| dz dM$$

DSNB = **Supernova** rate × **Neutrinos** emitted per supernova × Universe **expansion**



- In a **general modeling approach** for the DSNB, we need the **CCSN rate**, the **ν emission flux**, and **expansion**.

What is the Diffuse Supernova Neutrino Background?

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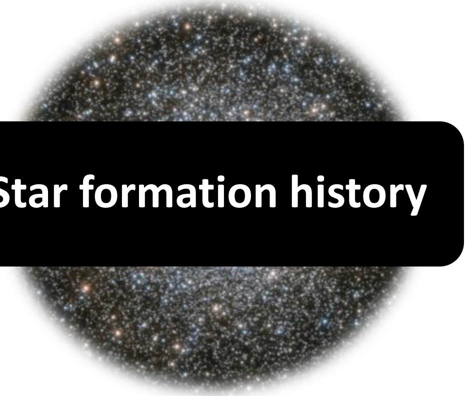
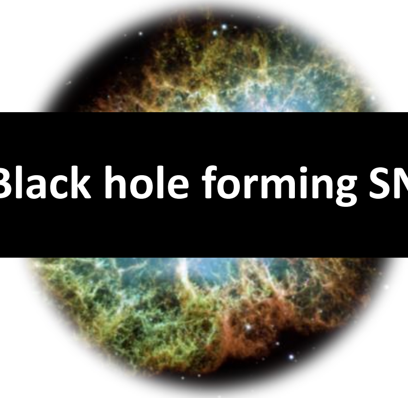
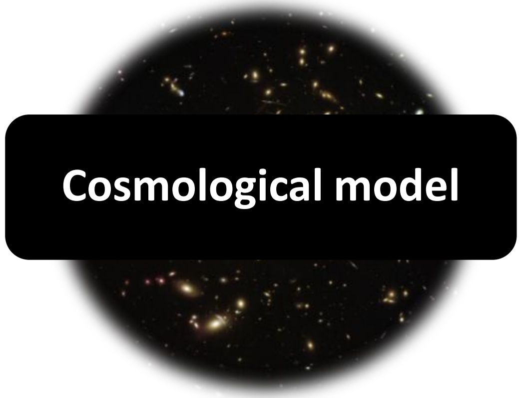
Probe these!



Star formation history



Black hole forming SN

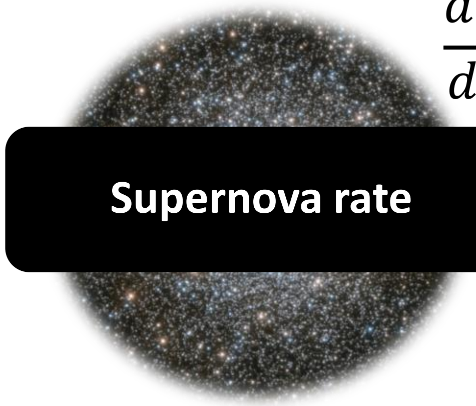


Cosmological model

- In a **general modeling approach** for the DSNB, we need the **CCSN rate**, the **ν emission flux**, and **expansion**.
- DSNB predictions are dependent on a variety of **parameters** (e.g., the **star formation rate** in the universe or the fraction of supernovae that form **black holes**).
- We are then capable of probing aspects across **astrophysics**, **particle physics**, and **cosmology**.

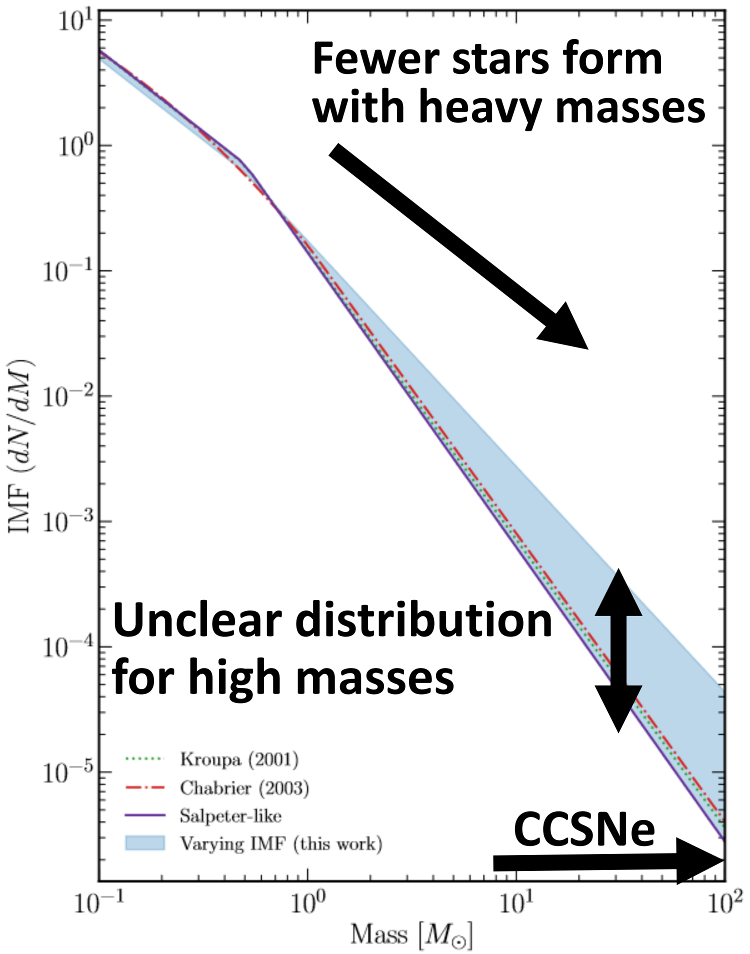
Ingredients of the Diffuse Supernova Neutrino Background

$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{dt}}{dz}\right| dzdM$$



Supernova rate

J.J. Ziegler et al., MNRAS ***517*** *(2022) 2471*



Fewer stars form with heavy masses

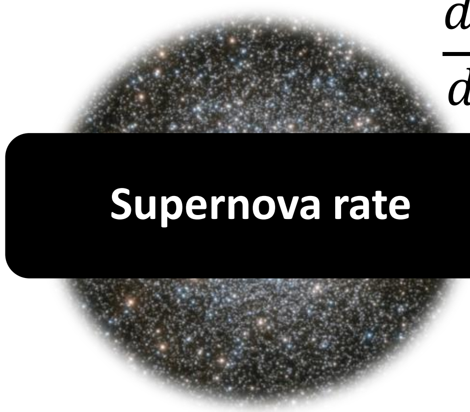
Unclear distribution for high masses

CCSNe

- On cosmic timescales, we can **directly relate** the **CCSN rate to the star formation rate**.
- **Traditional methods** to measure star formation rates based on **assumptions about** their relationship to **luminosity in a given star-forming region** of a galaxy.
- Star formation rates can then **heavily depend on assumptions of mass distributions of stars formed** (initial mass function or “**IMF**”).

Ingredients of the Diffuse Supernova Neutrino Background

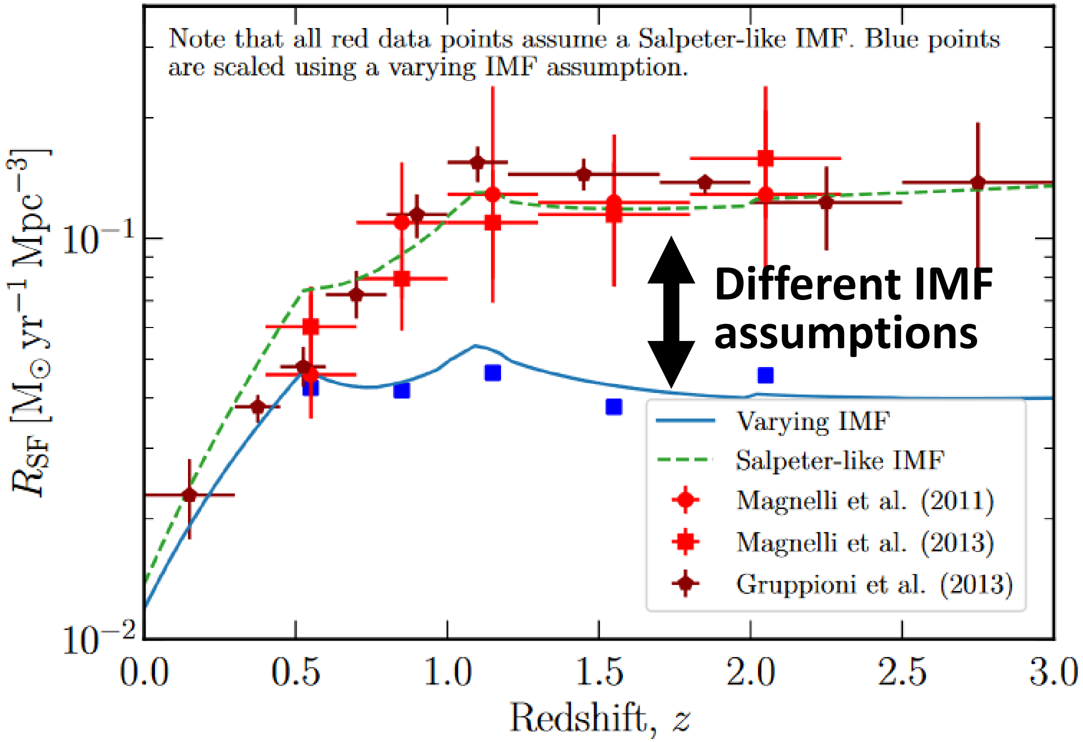
$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{d}t}{dz}\right| dz\,dM$$



Supernova rate

- On cosmic timescales, we can **directly relate** the **CCSN rate to the star formation rate**.
- **Traditional methods** to measure star formation rates based on **assumptions about** their relationship to **luminosity in a given star-forming region** of a galaxy.
- Star formation rates can then **heavily depend on assumptions of mass distributions of stars formed** (initial mass function or "**IMF**").
- In addition, the **absolute normalization of star formation is uncertain**, which is directly proportional to DSNB flux.

*J.J. Ziegler et al., MNRAS **517** (2022) 2471*


Note that all red data points assume a Salpeter-like IMF. Blue points are scaled using a varying IMF assumption.

Different IMF assumptions

Ingredients of the Diffuse Supernova Neutrino Background

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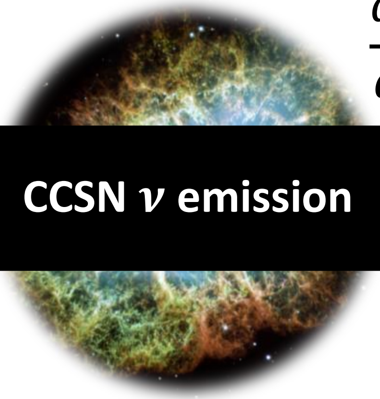
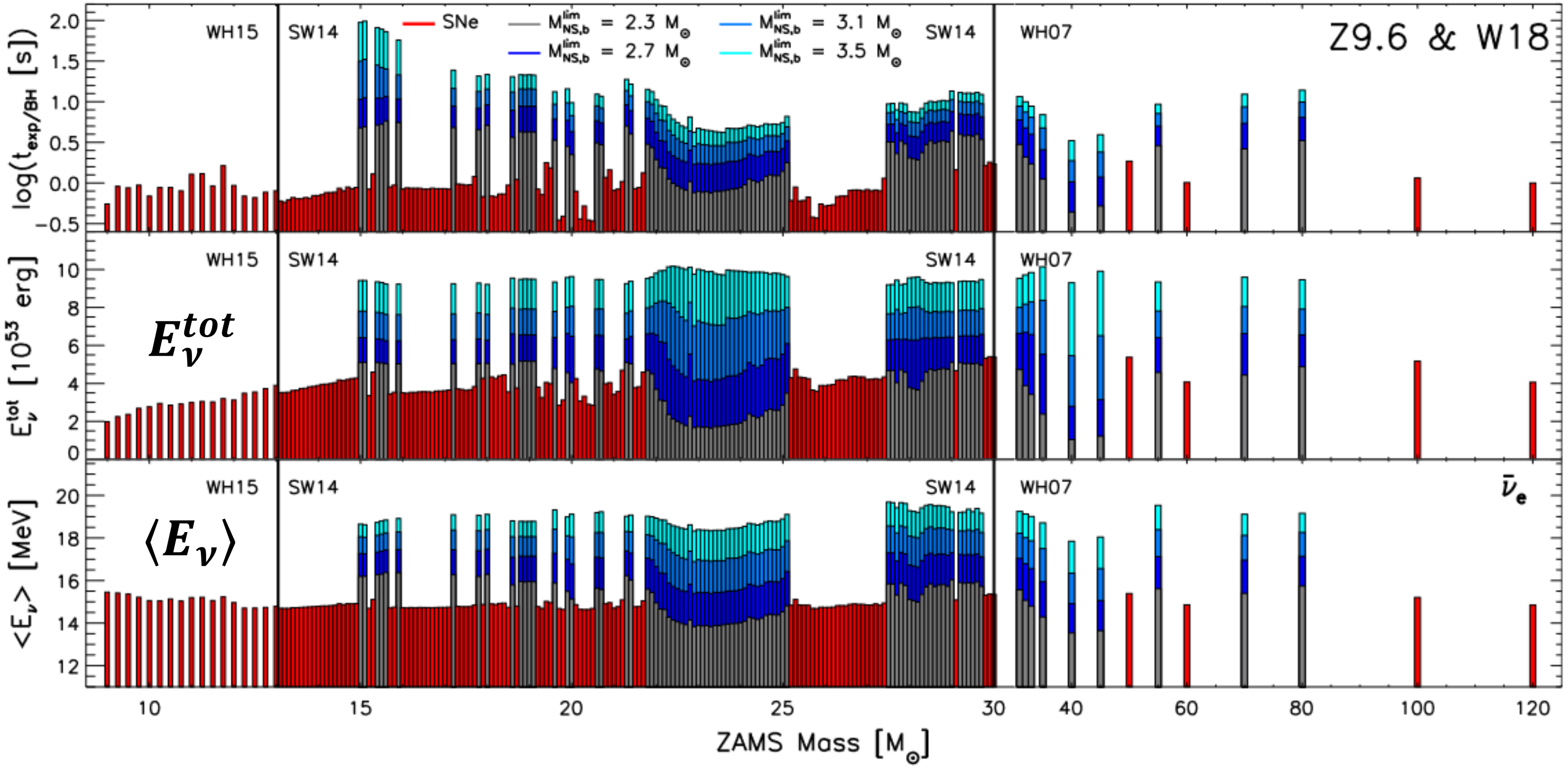


CCSN ν emission

Heavier stars

D. Kresse et al., ApJ ***909*** *(2021) 169*



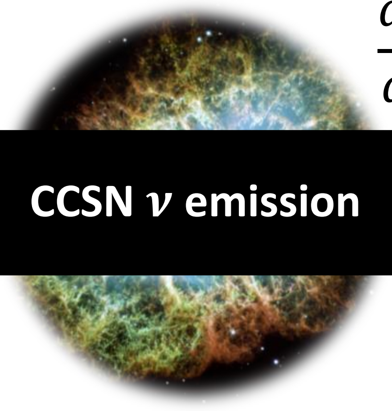
- The **landscape of CCSNe** is **difficult to simulate** and can significantly vary the emitted neutrino spectra.

Neutron star formed

Black hole formed

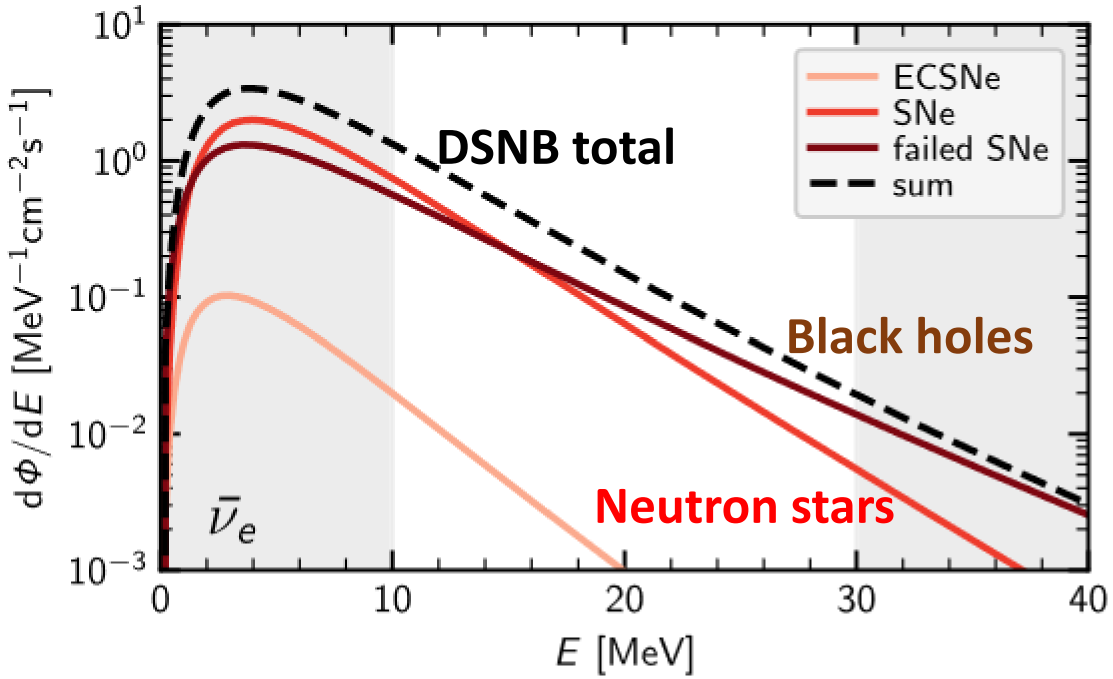
Ingredients of the Diffuse Supernova Neutrino Background

$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{dt}}{dz}\right| dz\,dM$$



CCSN ν emission

D. Kresse et al., ApJ ***909*** *(2021) 169*



- The **landscape of CCSNe** is **difficult to simulate** and can significantly vary the emitted neutrino spectra.
- **Differences** between **neutron star-forming CCSNe** and **black hole-forming CCSNe** alter the DSNB.

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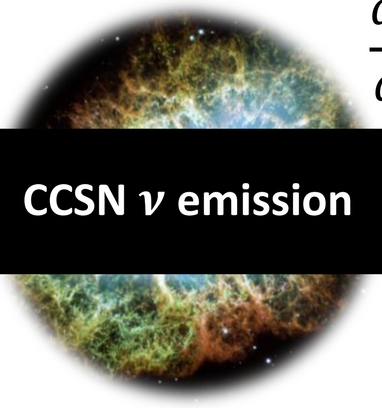
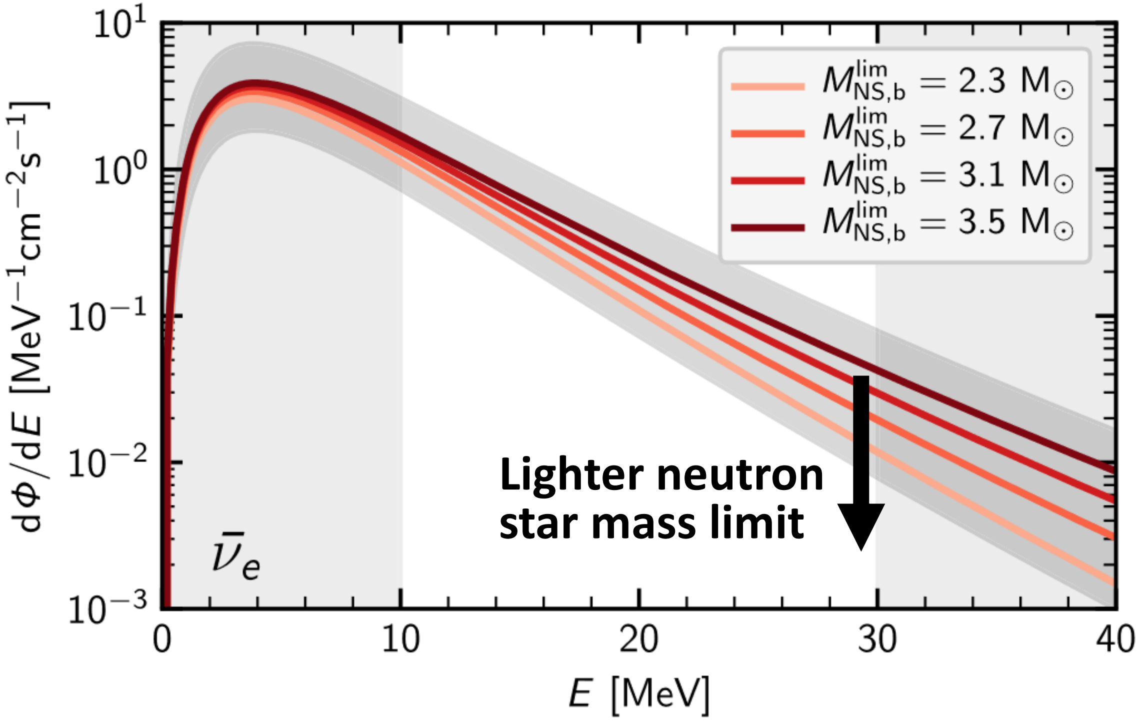
$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{dt}}{dz}\right| dz\,dM$$



CCSN ν emission

D. Kresse et al., ApJ ***909*** *(2021) 169*

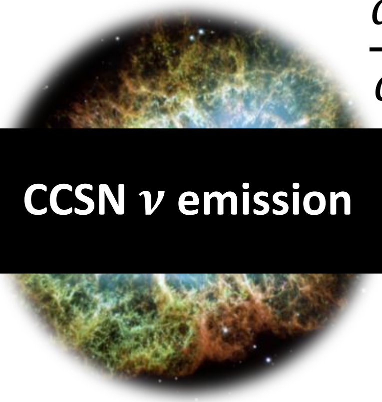


Lighter neutron star mass limit

- The **landscape of CCSNe** is **difficult to simulate** and can significantly vary the emitted neutrino spectra.
- **Differences** between **neutron star-forming CCSNe** and **black hole-forming CCSNe** alter the DSNB.
- **Astrophysical uncertainties** such as the **neutron star mass limit** influence the CCSN collapse and emission.

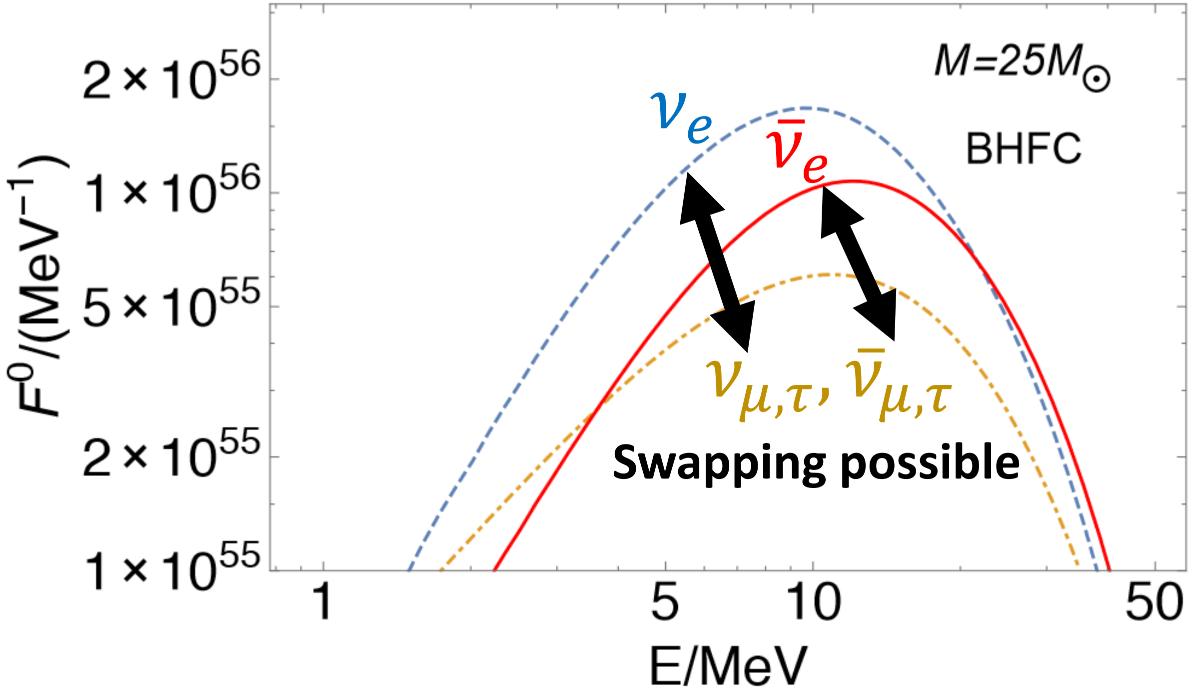
Ingredients of the Diffuse Supernova Neutrino Background

$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{dt}}{dz}\right| dzdM$$



CCSN ν emission

A. Priya and C. Lunardini, JCAP 11 (2017) 031

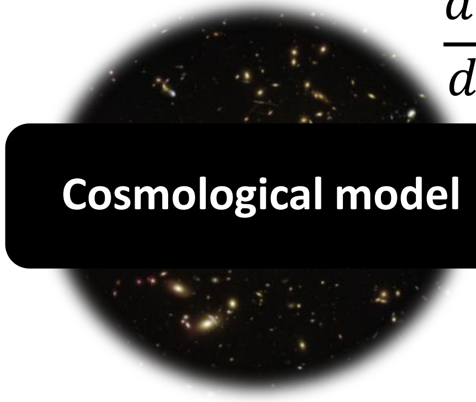


Swapping possible

- The **landscape of CCSNe** is **difficult to simulate** and can significantly vary the emitted neutrino spectra.
- **Differences** between **neutron star-forming CCSNe** and **black hole-forming CCSNe** alter the DSNB.
- **Astrophysical uncertainties** such as the **neutron star mass limit** influence the CCSN collapse and emission.
- **Neutron propagation** through the dense explosion can **swap flavors in non-trivial ways** [talk MC Volpe].

Ingredients of the Diffuse Supernova Neutrino Background

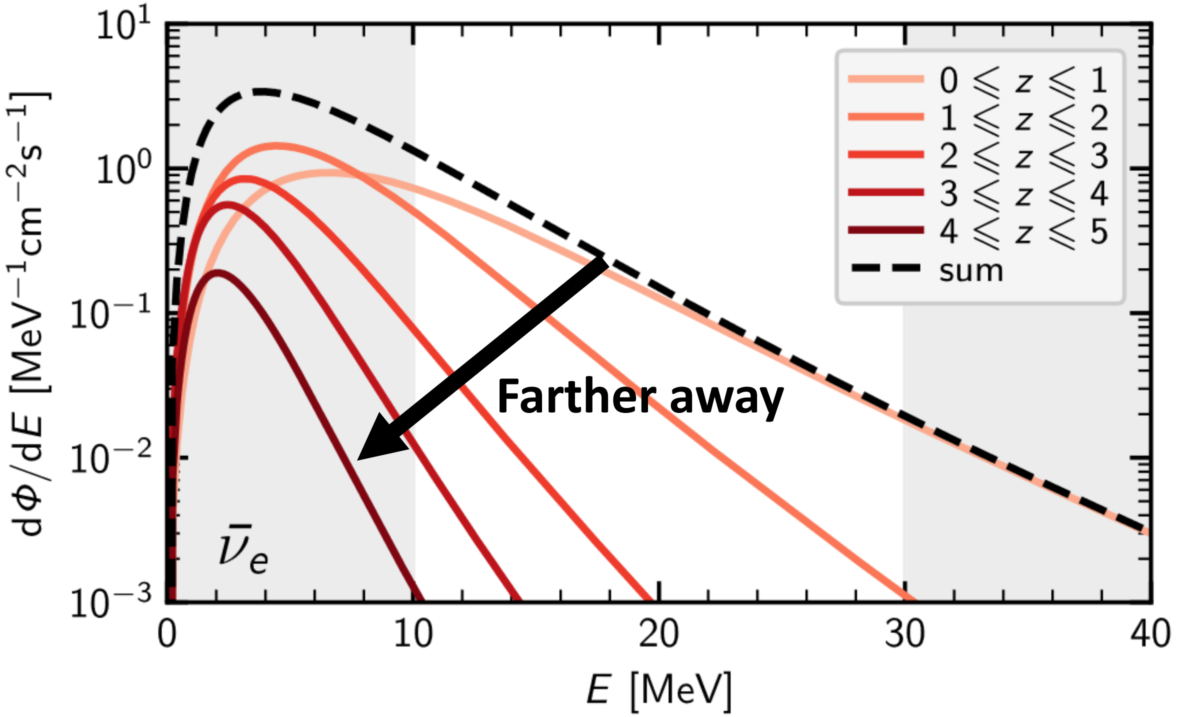
$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{dt}}{dz}\right| dz\,dM$$



Cosmological model

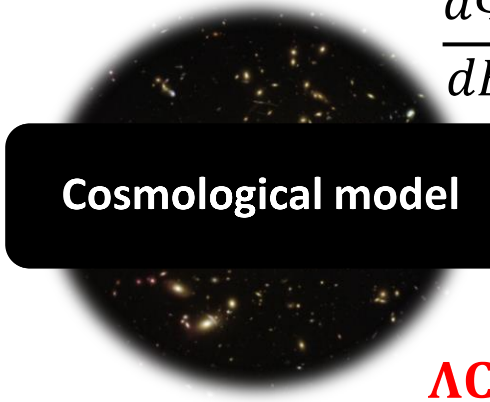
D. Kresse et al., ApJ **909** (2021) 169

- Since CCSNe at **non-zero redshift contribute** to the DSNB, we are **sensitive to cosmological expansion**.
- Can consider redshifts up to $z = 5$, but usual searches are limited to above around 10 MeV ($z \leq 2$ then).



Ingredients of the Diffuse Supernova Neutrino Background

$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{dt}}{dz}\right| dzdM$$

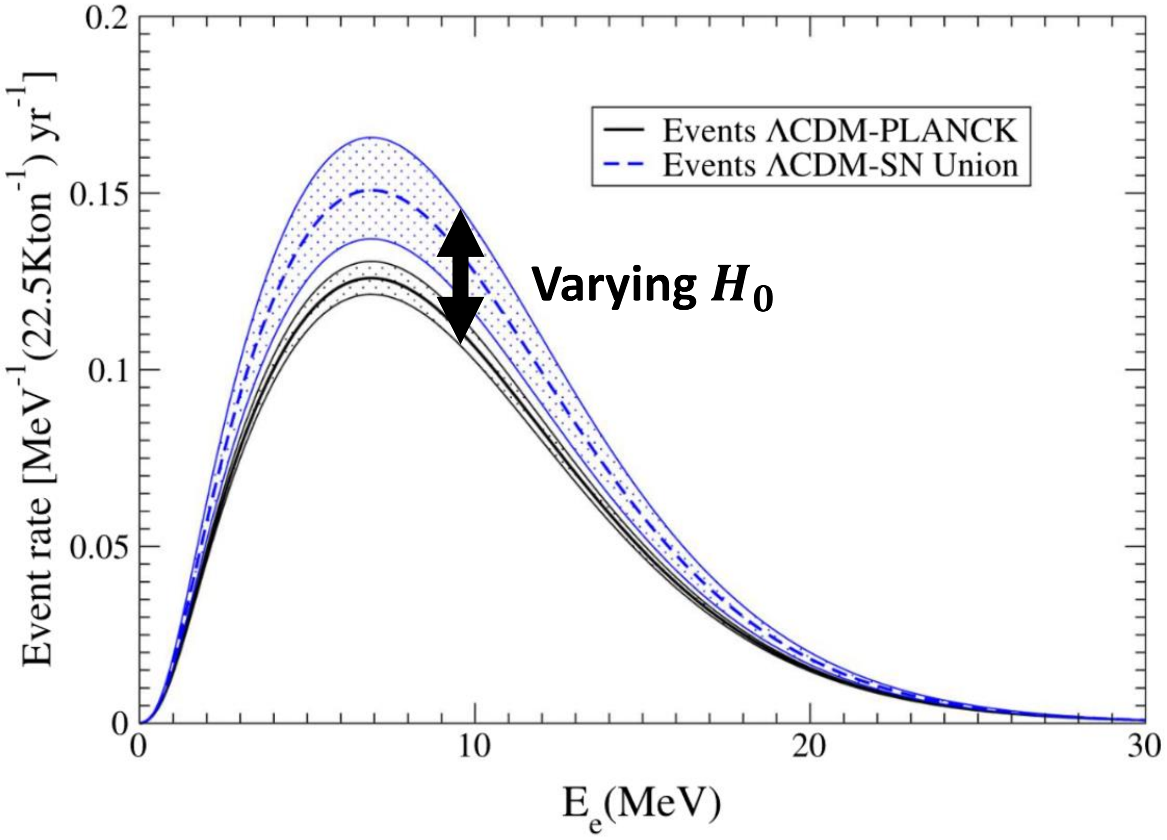


Cosmological model

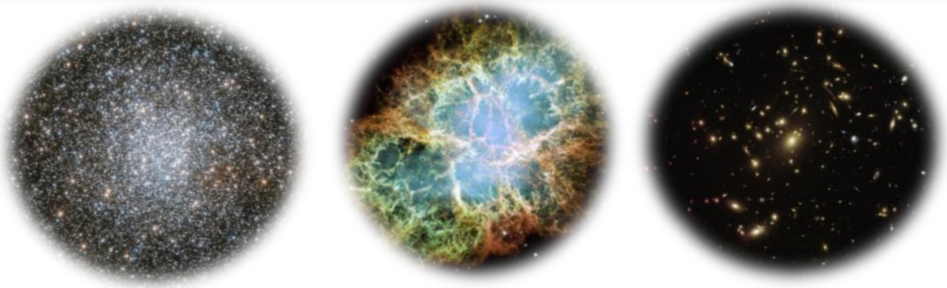
$\mathbf{\Lambda CDM}$: $H(z) = \boldsymbol{H_0}\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}$

- Since CCSNe at **non-zero redshift contribute** to the DSNB, we are **sensitive to cosmological expansion**.
- Can consider redshifts up to $z = 5$, but usual searches are limited to above around 10 MeV ($z \lesssim 2$ then).
- Values for the **Hubble constant H_0** can be obtained separately with tension in the PLANCK/Sne results.
- Differences in DSNB flux, especially above 10 MeV are **sub-leading to other uncertainties and physics**.

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

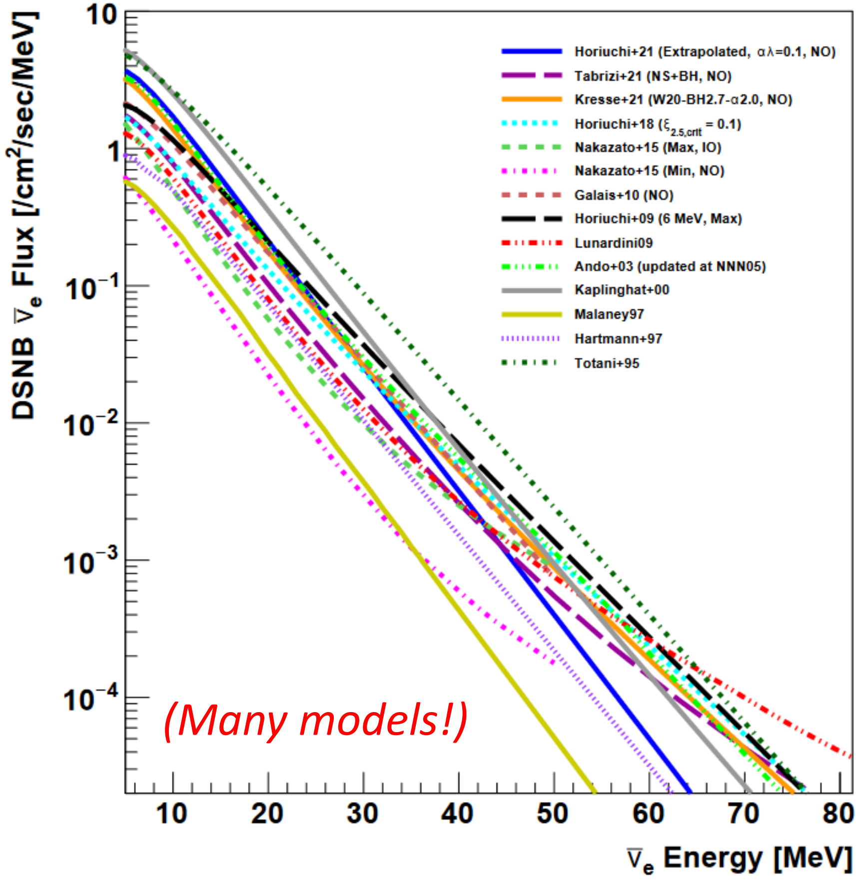


Many possibilities for modeling the DSNB



$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M)\left[\frac{dF(E(1+z),M)}{dM}\right]\left|c\,\frac{\mathrm{dt}}{dz}\right| dz dM$$

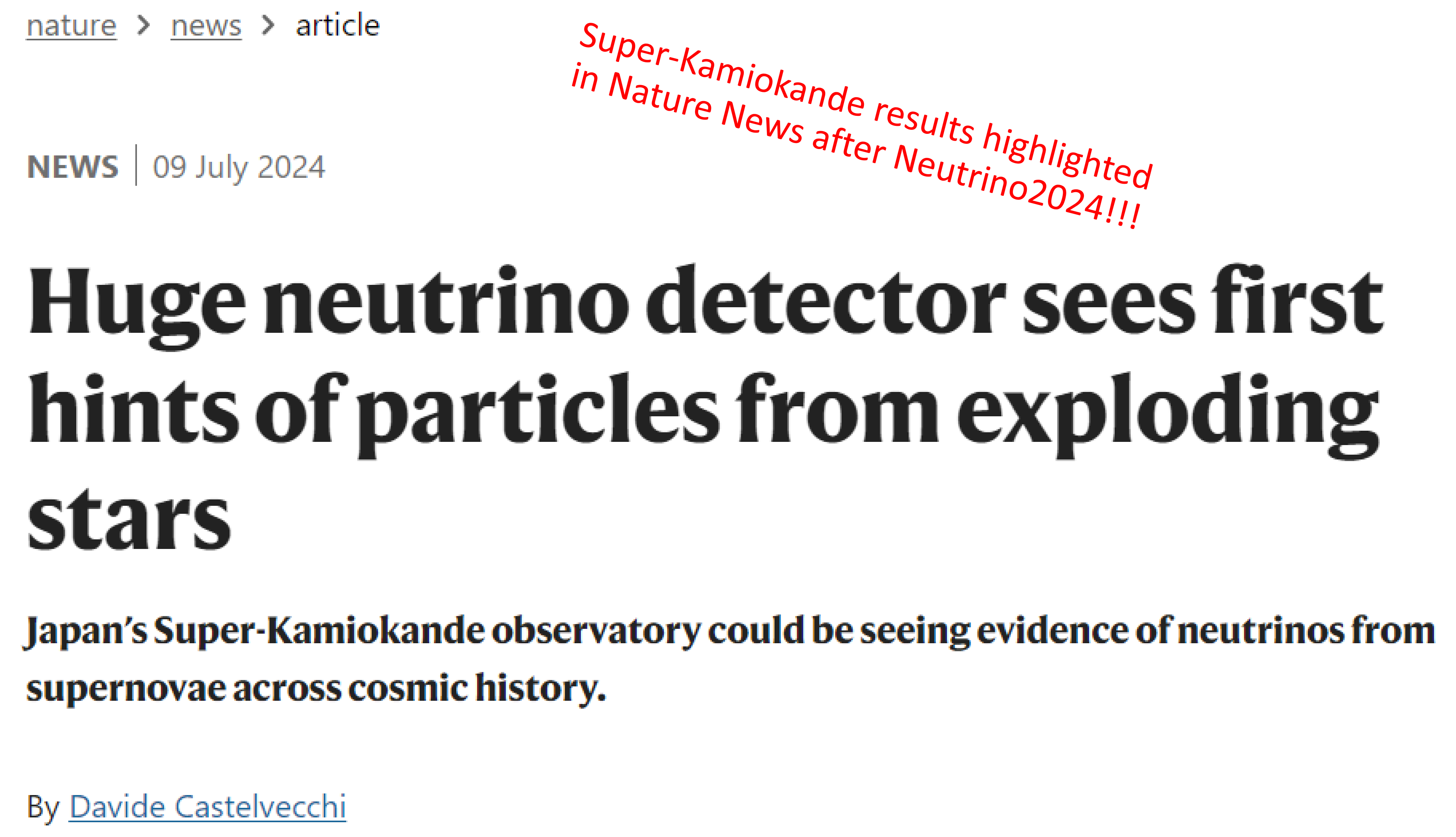
- This parameterization is one of many, and others can include more nuanced or different contributions.
- Globally, **uncertainties on star formation rates** lead to an **uncertain normalization** on the DSNB flux.
- The **mixture** of neutron star-forming and black hole-forming CCSNe alters the **DSNB spectral shape**.
- A first detection of the DSNB will be focused on the normalization with sensitivity to spectral shape later.
- Where do we stand now in experimental searches…?



(Many models!)

*Abe et al., Phys. Rev. D **104** (2021) 122002*

Current status of experimental searches for DSNB



nature > news > article

NEWS | 09 July 2024

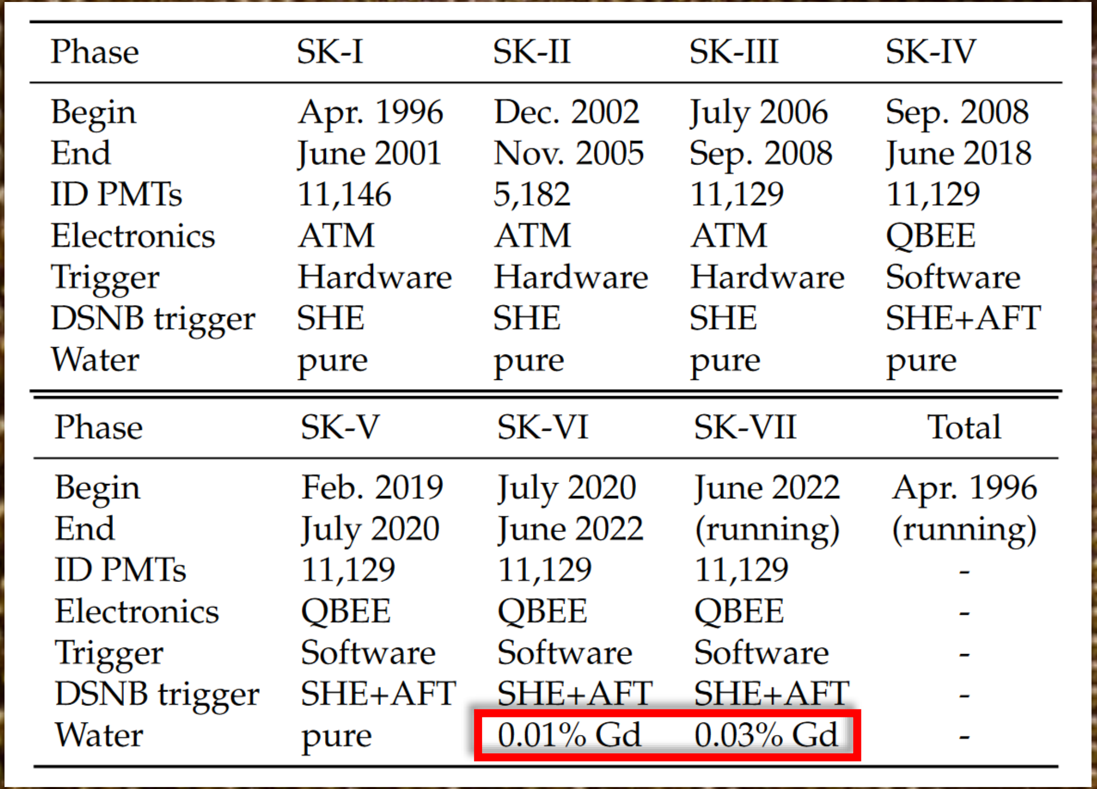
Huge neutrino detector sees first hints of particles from exploding stars

Japan's Super-Kamiokande observatory could be seeing evidence of neutrinos from supernovae across cosmic history.

By Davide Castelvecchi

Super-Kamiokande results highlighted in Nature News after Neutrino2024!!!

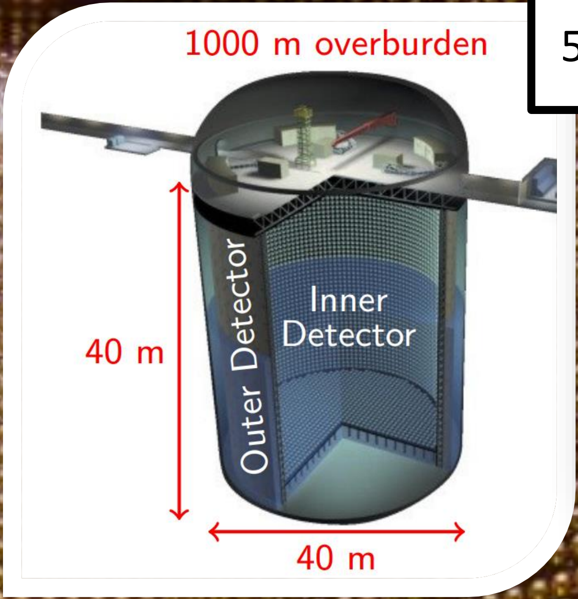
Super-Kamiokande: World-leading water Cherenkov experiment



Phase	SK-I	SK-II	SK-III	SK-IV
Begin	Apr. 1996	Dec. 2002	July 2006	Sep. 2008
End	June 2001	Nov. 2005	Sep. 2008	June 2018
ID PMTs	11,146	5,182	11,129	11,129
Electronics	ATM	ATM	ATM	QBEE
Trigger	Hardware	Hardware	Hardware	Software
DSNB trigger	SHE	SHE	SHE	SHE+AFT
Water	pure	pure	pure	pure

Phase	SK-V	SK-VI	SK-VII	Total
Begin	Feb. 2019	July 2020	June 2022	Apr. 1996
End	July 2020	June 2022	(running)	(running)
ID PMTs	11,129	11,129	11,129	-
Electronics	QBEE	QBEE	QBEE	-
Trigger	Software	Software	Software	-
DSNB trigger	SHE+AFT	SHE+AFT	SHE+AFT	-
Water	pure	0.01% Gd	0.03% Gd	-

- Pure water phases I-IV: *PRD* **104** (2021) 122002
- First Gd results phase VI: *ApJL* **951** (2023) 2, L27



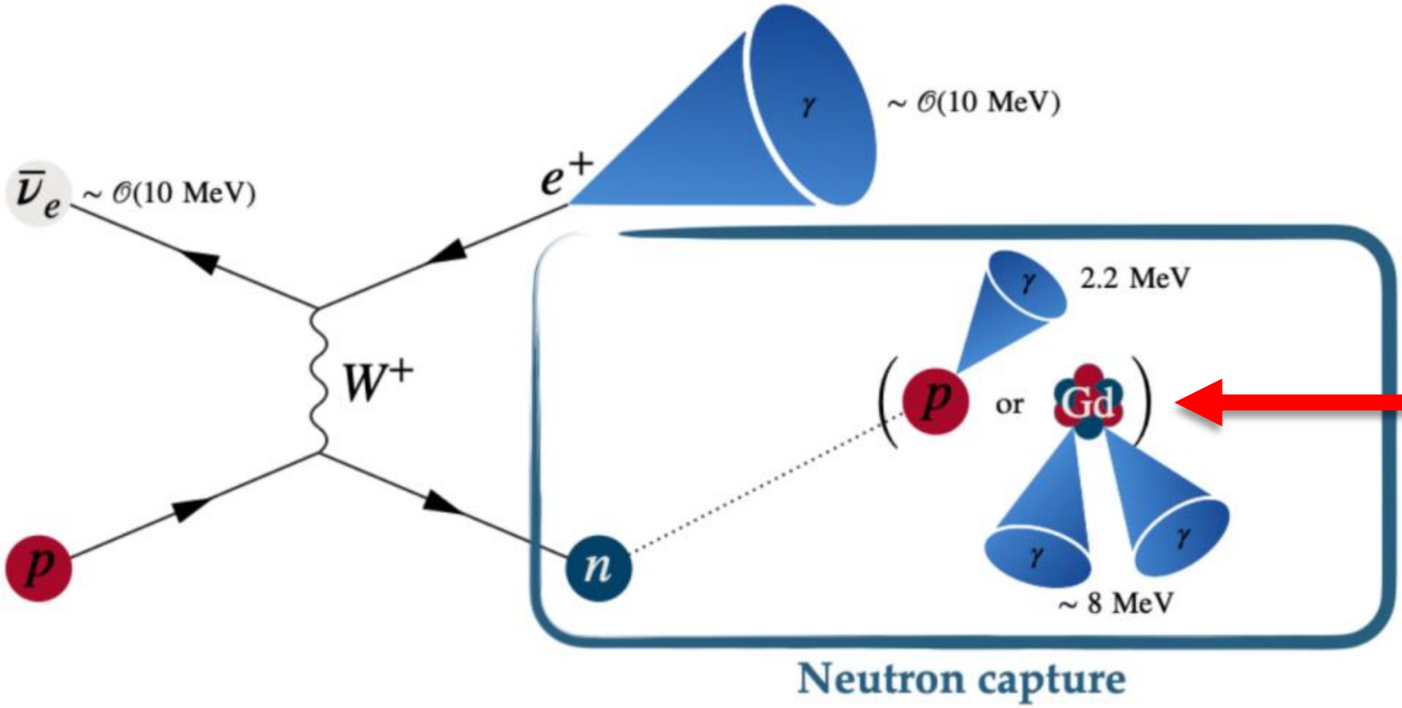
50kton = how many Château de Blois?

- Running **since 1996** (denoted by phases I-VII).
- Around **11 000 PMTs in inner detector** with an outer detector muon veto.
- **Gadolinium-doped** water since 2020 for easier neutron capture identification (SK-VI/VII)!

Super-K DSNB target interaction channel: Inverse beta decay

A two-flash signal!

IBD Signal $\bar{\nu}_e + p \rightarrow \boxed{e^+ + n}$



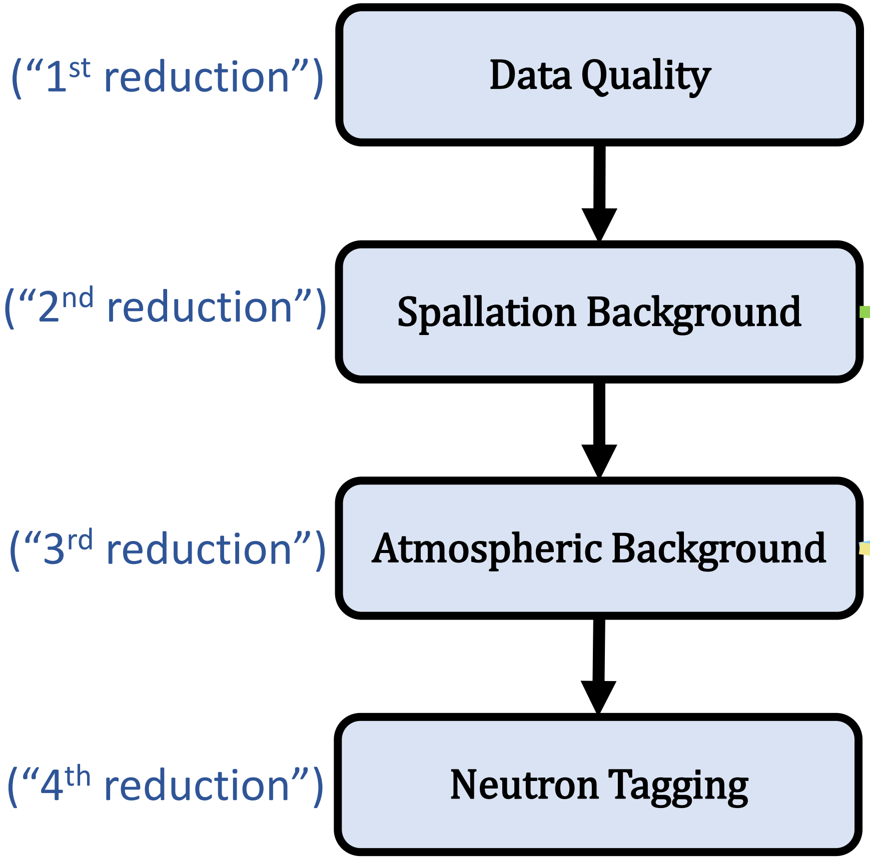
Gadolinium loading 2020s!

Super-K DSNB analysis: Reduction steps

(Two-part inverse beta decay signal!)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

(positron) + (delayed neutron capture)

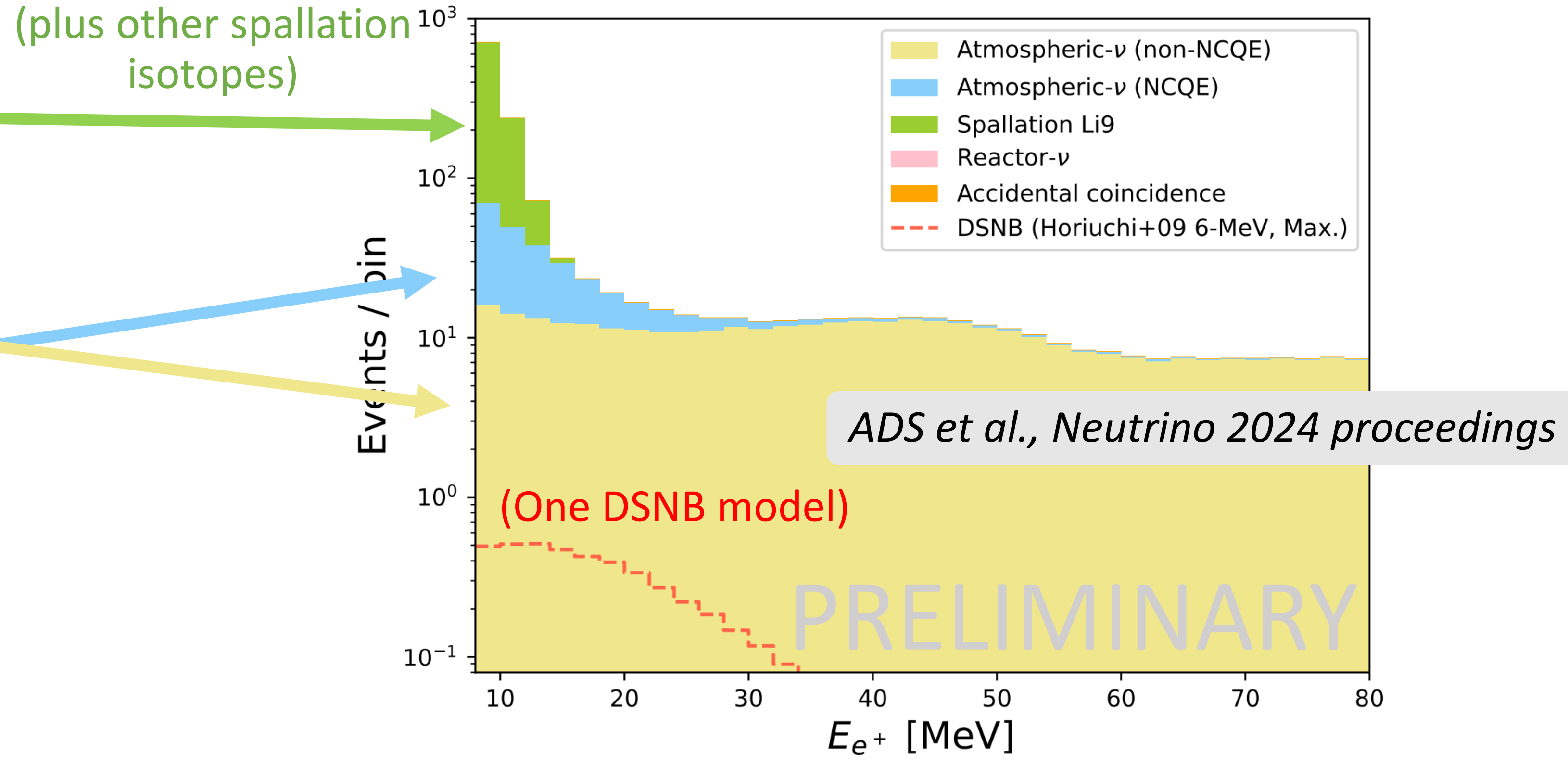


(“1st reduction”) **Data Quality**

(“2nd reduction”) **Spallation Background**

(“3rd reduction”) **Atmospheric Background**

(“4th reduction”) **Neutron Tagging**



(plus other spallation isotopes)

(One DSNB model)

ADS et al., Neutrino 2024 proceedings

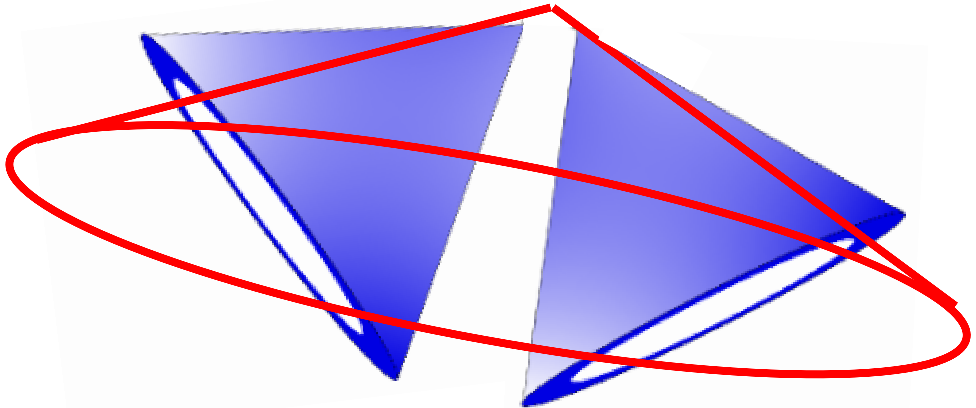
Super-K DSNB analysis: Reduction steps

("1st reduction") **Data Quality**

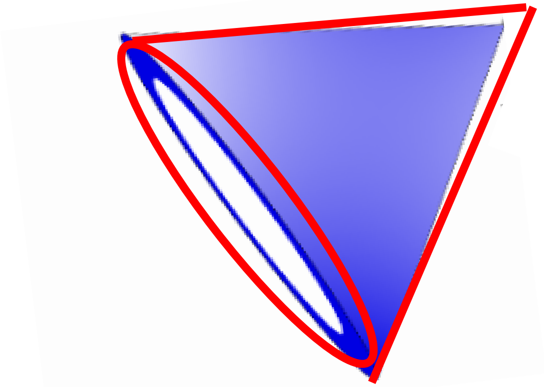
("2nd reduction") **Spallation Background**

("3rd reduction") **Atmospheric Background**

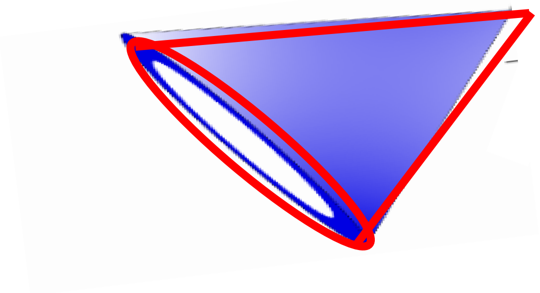
- Atmospheric neutrino interactions can produce **multi-cone prompt events**.
- Heavy charged leptons near the Cherenkov threshold have **small opening angles**.
- θ_c: Opening angle assuming one cone.



(multi-cone reconstructed as single-cone)

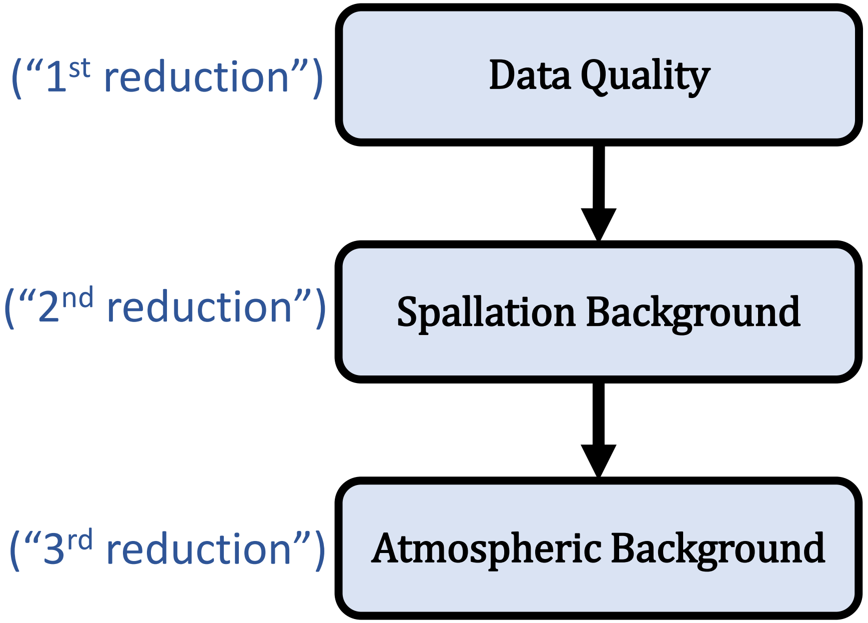


(IBD-like single-cone $\theta_c \approx 42°$)



(μ/π-like single cone near threshold)

Super-K DSNB analysis: Reduction steps

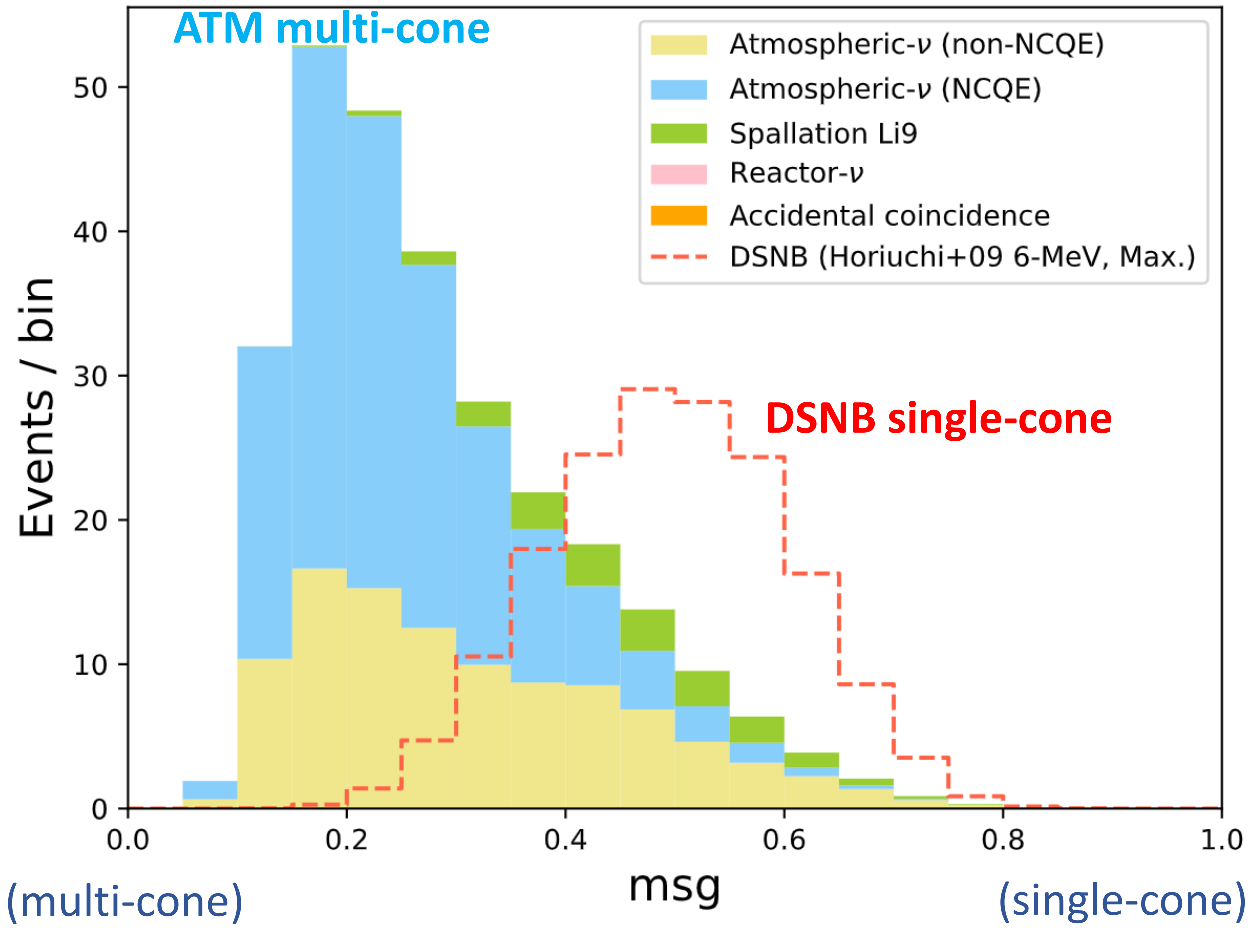


("1st reduction") **Data Quality**

("2nd reduction") **Spallation Background**

("3rd reduction") **Atmospheric Background**

- Atmospheric neutrino interactions can produce **multi-cone prompt events**.
- Multiple scattering goodness (MSG): a repurposed variable capable of **distinguishing between likely single- and multi-cone events**.



ADS et al., Neutrino 2024 proceedings

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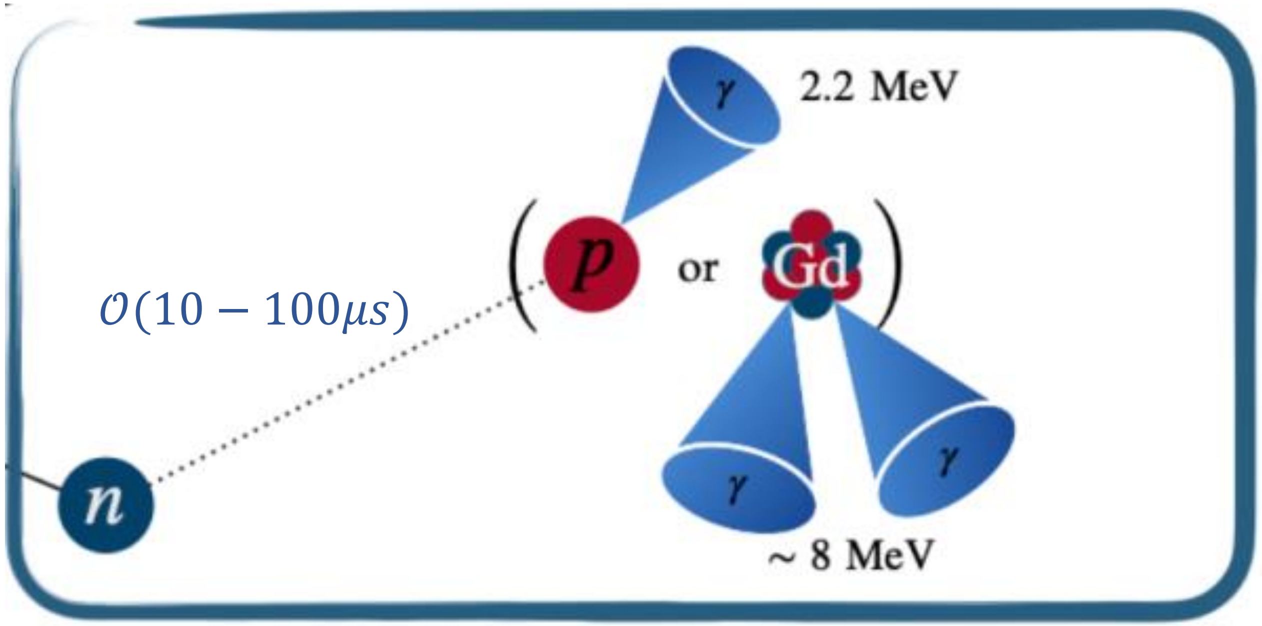
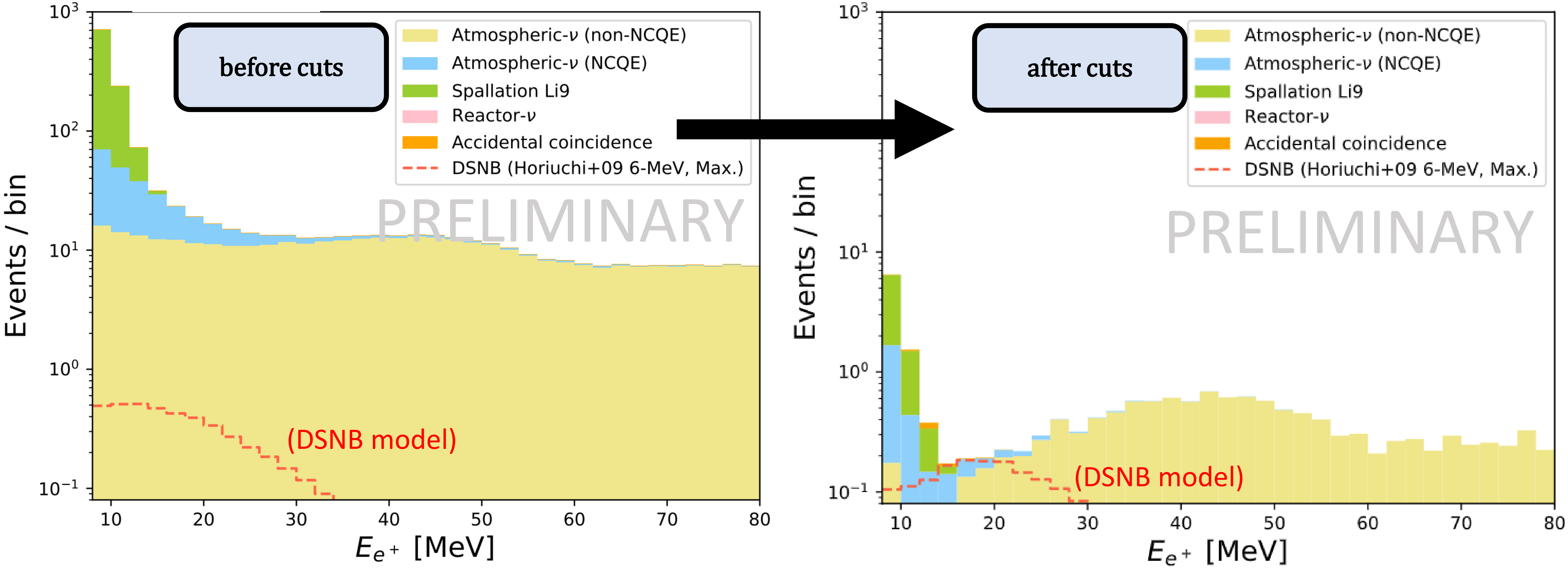


- The **Boosted Decision Tree (BDT)** neutron tagging tool was used in the 2021 DSNB paper and was updated for SK-Gd.
- The **Neural Network (NN)** tool has been introduced as a new technique in SK-Gd for the DSNB analysis.
- **Both** the BDT and the NN **achieve less than 0.1% mistag rates** for neutron tagging **efficiencies above 60%** in SK7.

Super-K DSNB analysis: Before and after cuts



ADS et al., Neutrino 2024 proceedings

Super-K DSNB analysis: Final samples (spectral fit)

Data Quality

Spallation Background

Atmospheric Background

Neutron Tagging

Cut Optimization and Systematics Evaluation

DSNB model-independent (binned analysis)

DSNB model-dependent (spectral analysis)

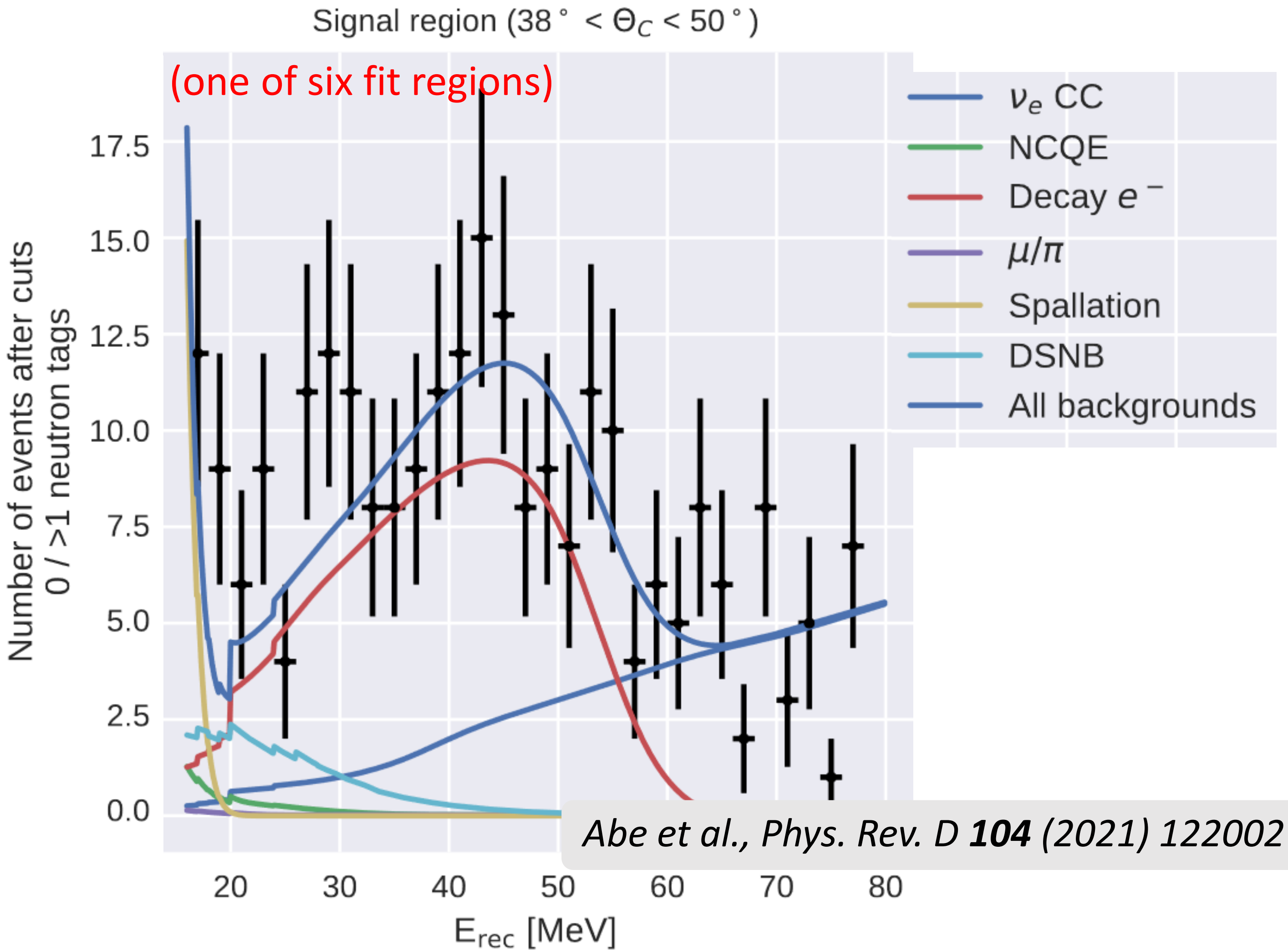
(spectral fit regions w/16 MeV threshold)

θ_c (across) ntag (below)	$20^\circ - 38^\circ$	$38^\circ - 50^\circ$	$78^\circ - 90^\circ$
ntag≠1	μ/π BG	mis-ID DSNB	multi-cone atm. ν
ntag=1	μ/π BG	tagged DSNB	multi-cone atm. ν

Super-K DSNB analysis: Spectral fit approach

$$\mathcal{L}(\{N_j\}) = e^{-\sum_{j=1}^{N_{type}} N_j} \prod_{i=1}^{N_{obs}} \sum_{j=1}^{N_{type}} N_j \mathrm{PDF}_j^{(r)}(\mathrm{E_i})$$

- Perform **unbinned extended maximum likelihood fit** on six categories of events ($N_{type} = 6$) (not same as 6 fit regions).
- **Without systematic uncertainties** on the PDFs, the fit would **only vary the six N_j**.



Abe et al., Phys. Rev. D ***104*** *(2021) 122002*

Super-K DSNB analysis: Spectral fit approach

$$\mathcal{L}(\{\ldots\}) = e^{-\sum_{j=1}^{N_{type}} N_j} \prod_{i=1}^{N_{obs}} \sum_{j=1}^{N_{type}} N_j \mathrm{PDF}_j^{(r)}(\mathrm{E_i})$$

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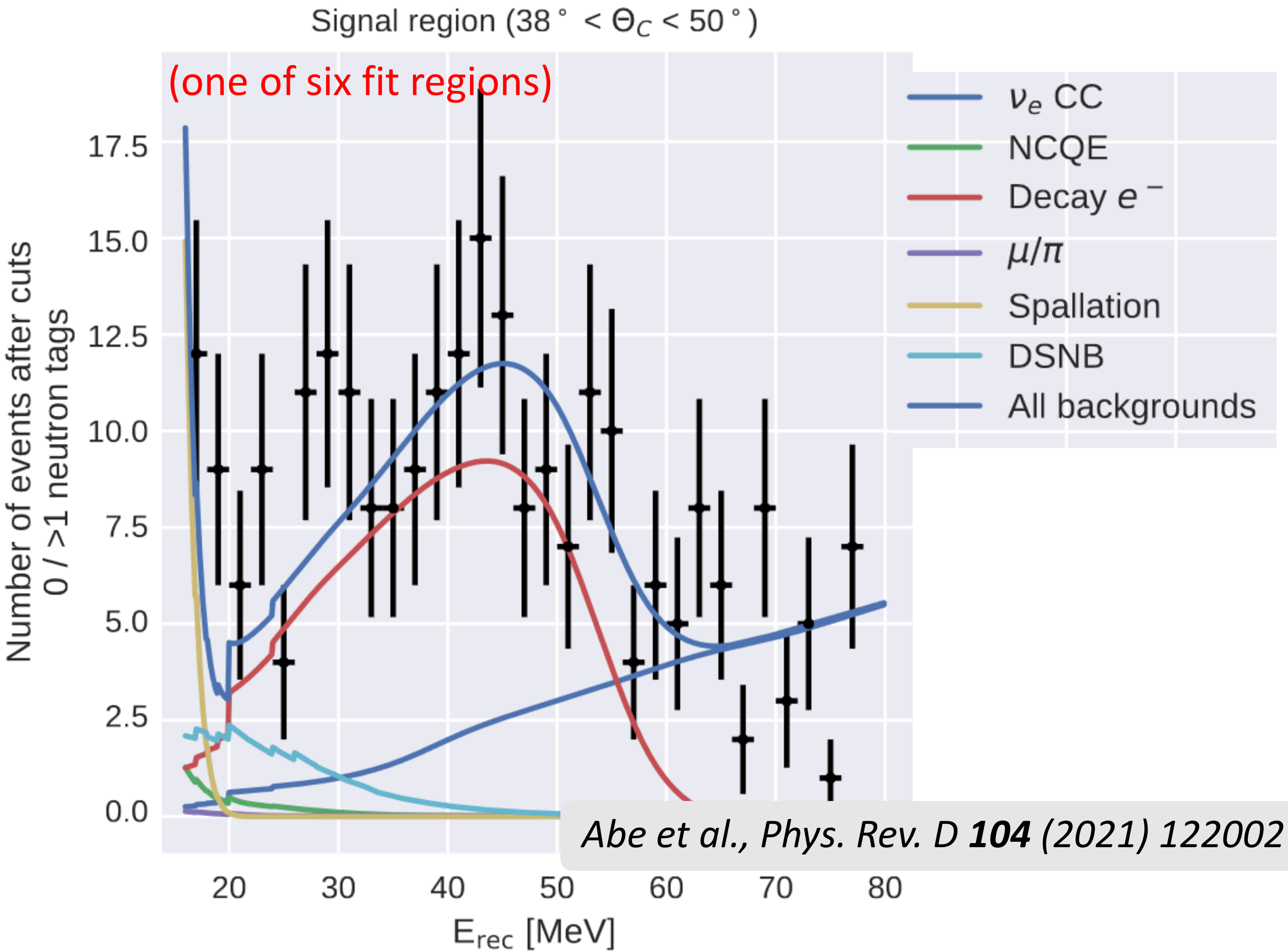
- **Without systematic uncertainties** on the PDFs, the fit would **only vary the six N_j**.
- **With systematic uncertainties**, the **PDF shapes can vary** with free parameters.



(one of six fit regions)

Abe et al., Phys. Rev. D ***104*** *(2021) 122002*

Super-K DSNB analysis: Spectral fit approach

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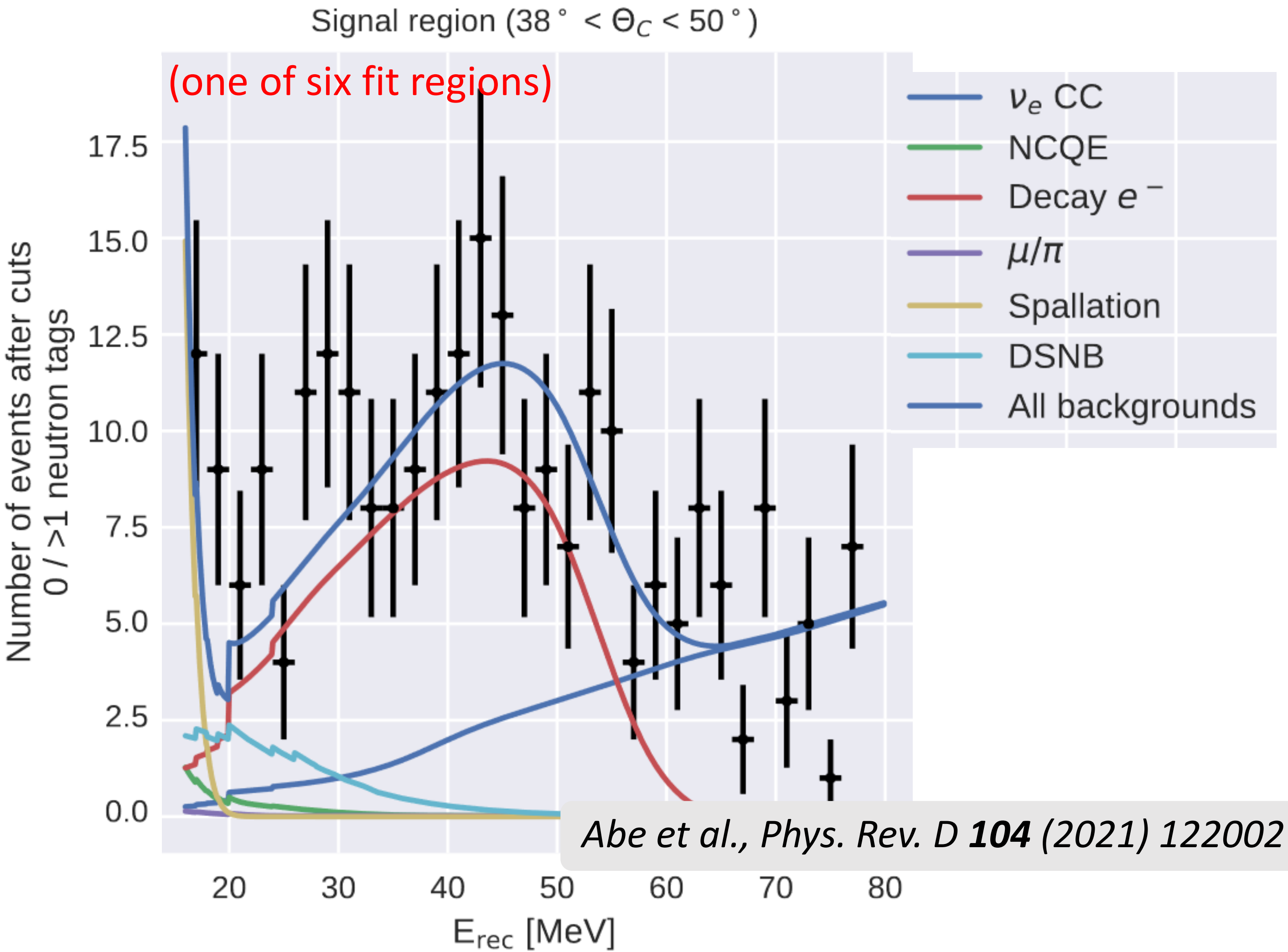

Abe et al., Phys. Rev. D ***104*** *(2021) 122002*

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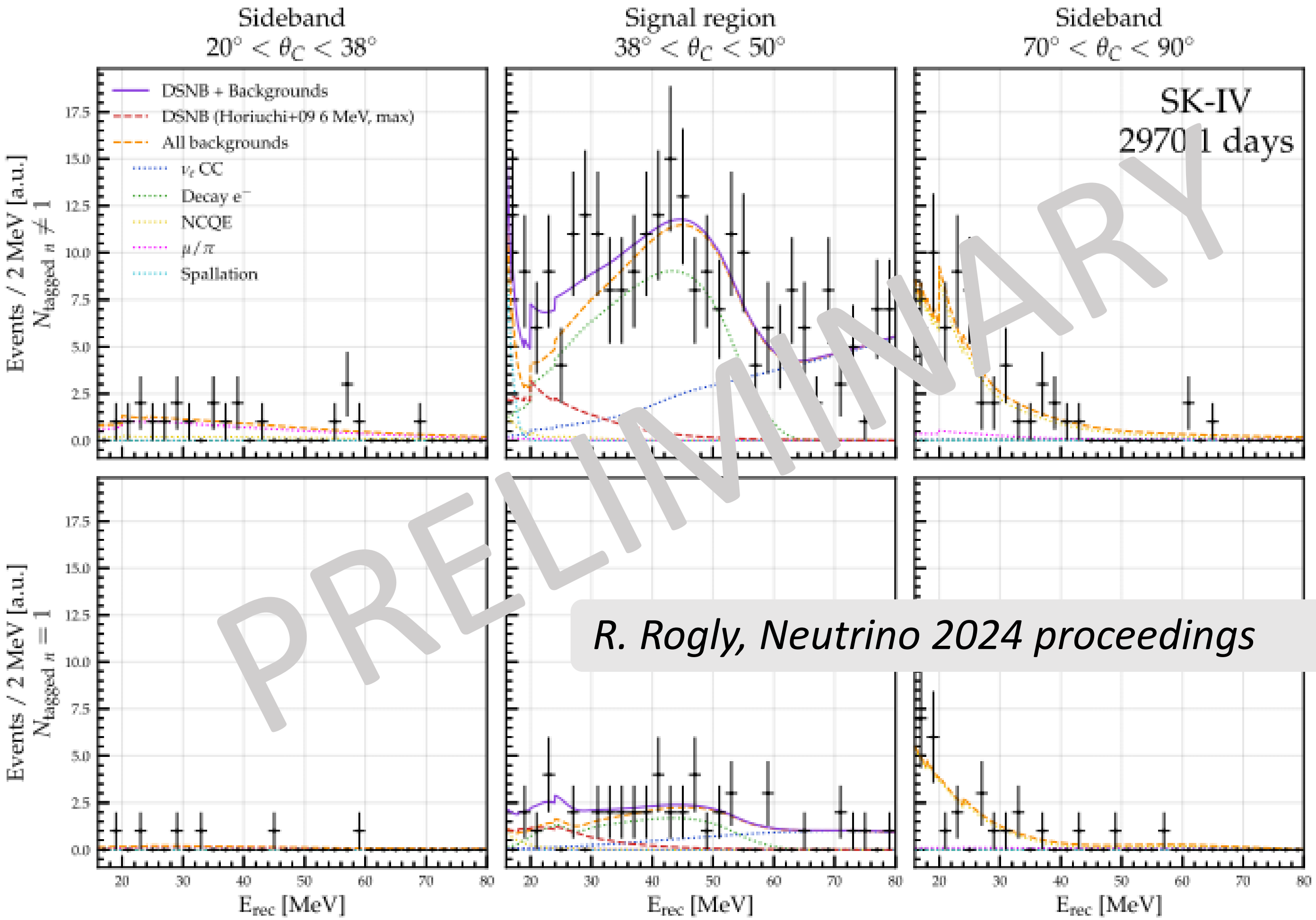
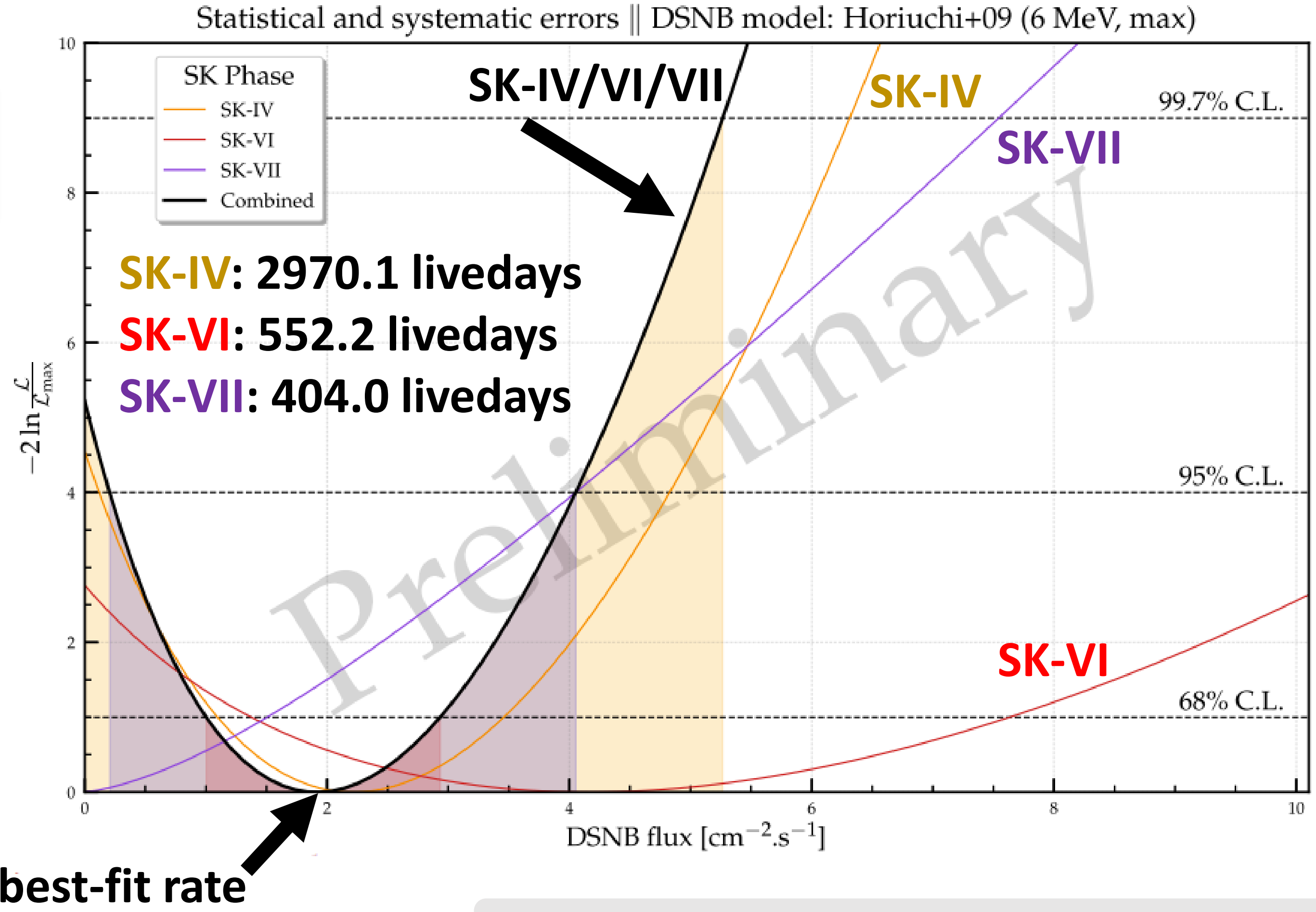
- The fit has **no explicit constraint on the individual N_j** (i.e., a shape-only analysis).
- Here is an example of one post-fit (SK-IV) with all 6 fit regions.



R. Rogly, Neutrino 2024 proceedings

Super-K DSNB analysis: Spectral analysis results

- SK-IV/VI/VII combined spectral analysis results in **2.3σ rejection of BG-only** hypothesis.
- This is **model-dependent**, but all DSNB models tested show very similar results.



SK-IV: 2970.1 livedays

SK-VI: 552.2 livedays

SK-VII: 404.0 livedays

A. Beauchêne, Neutrino 2024 proceedings

R. Rogly, Neutrino 2024 proceedings

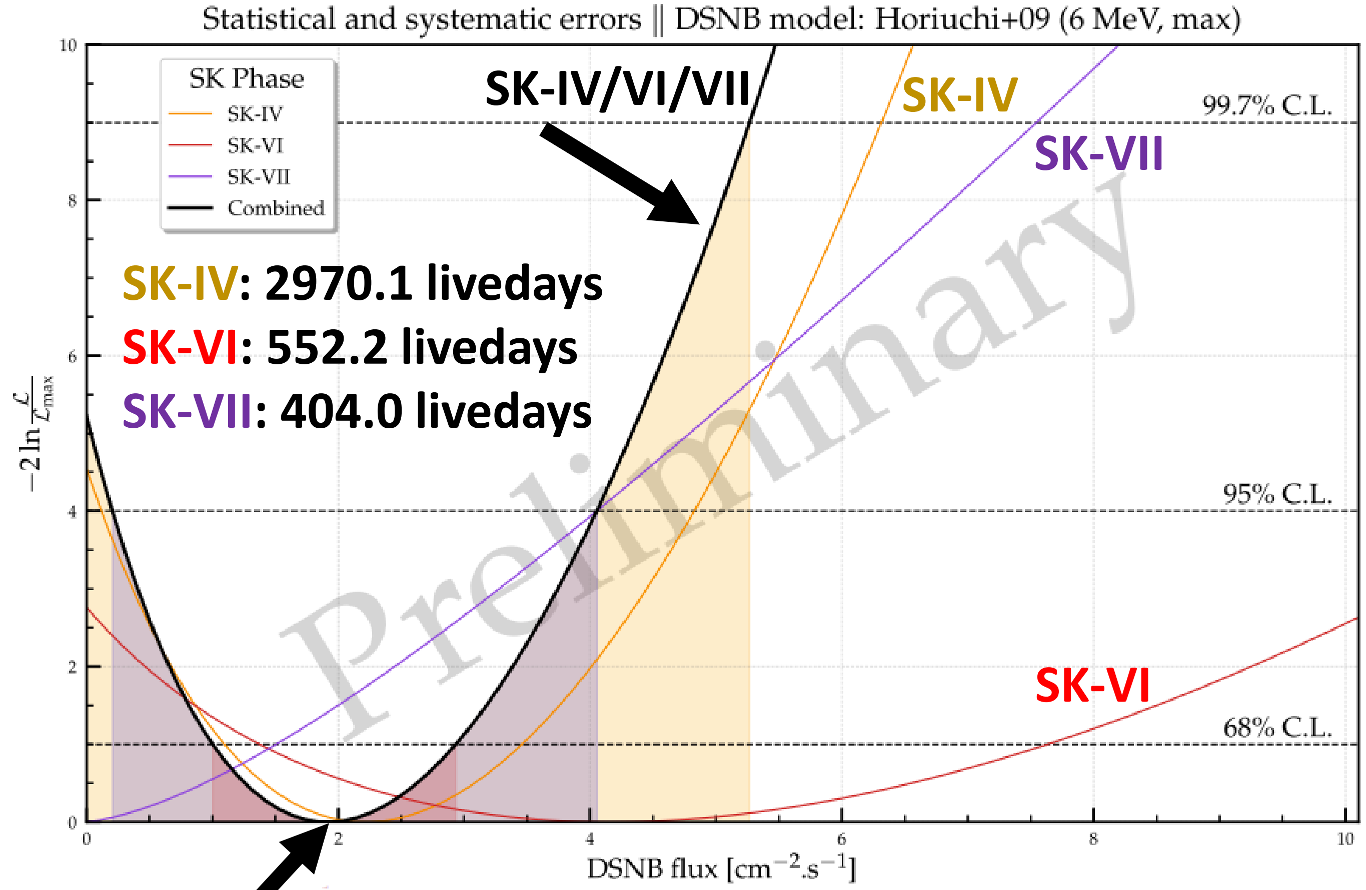
M. Harada, Neutrino 2024 proceedings

Super-K DSNB analysis: Spectral analysis results

- SK-IV/VI/VII combined spectral analysis results in **2.3σ rejection of BG-only** hypothesis.
- This is **model-dependent**, but all DSNB models tested show very similar results.
- A **large part of the best-fit strength comes from the pure-water SK-IV** phase.
- In parallel, can **perform a binned analysis with background-only hypothesis test** (DSNB model-independent).

A. Beauchêne, Neutrino 2024 proceedings

R. Rogly, Neutrino 2024 proceedings



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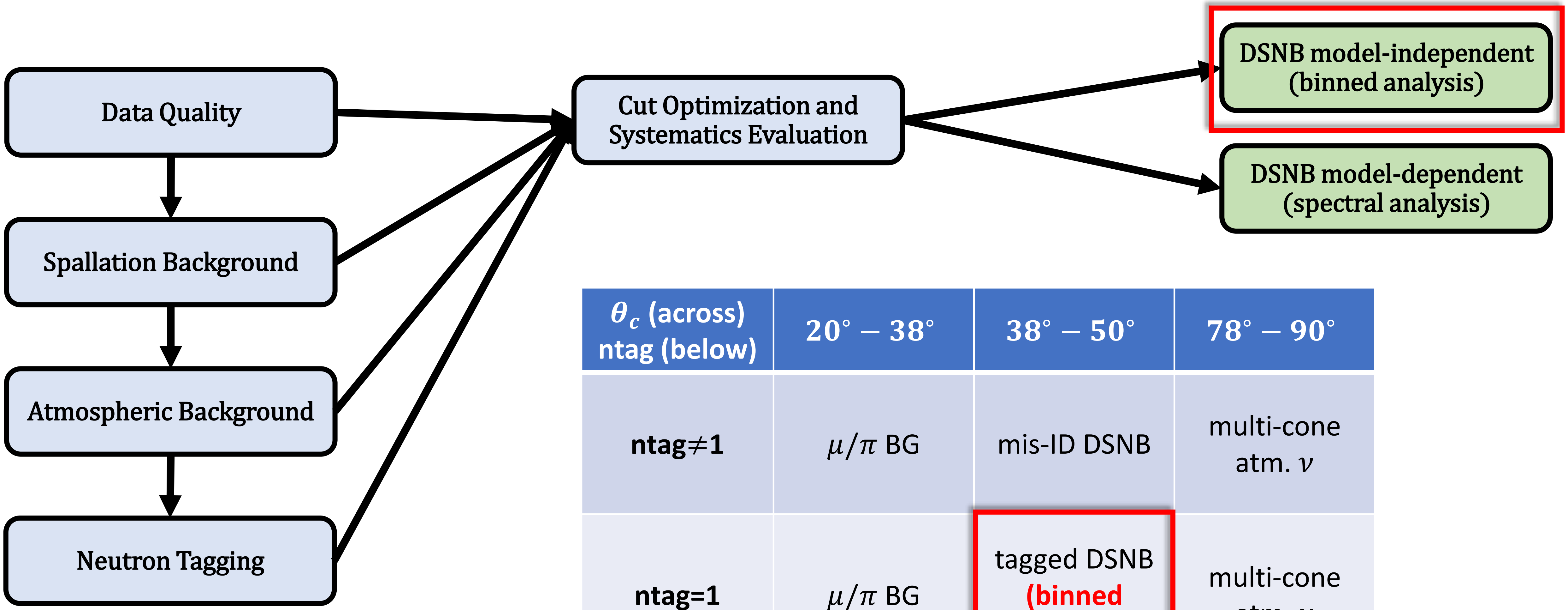
best-fit rate

M. Harada, Neutrino 2024 proceedings

Super-K DSNB analysis: Final sample (binned analysis)


Data Quality

Spallation Background

Atmospheric Background

Neutron Tagging

Cut Optimization and Systematics Evaluation

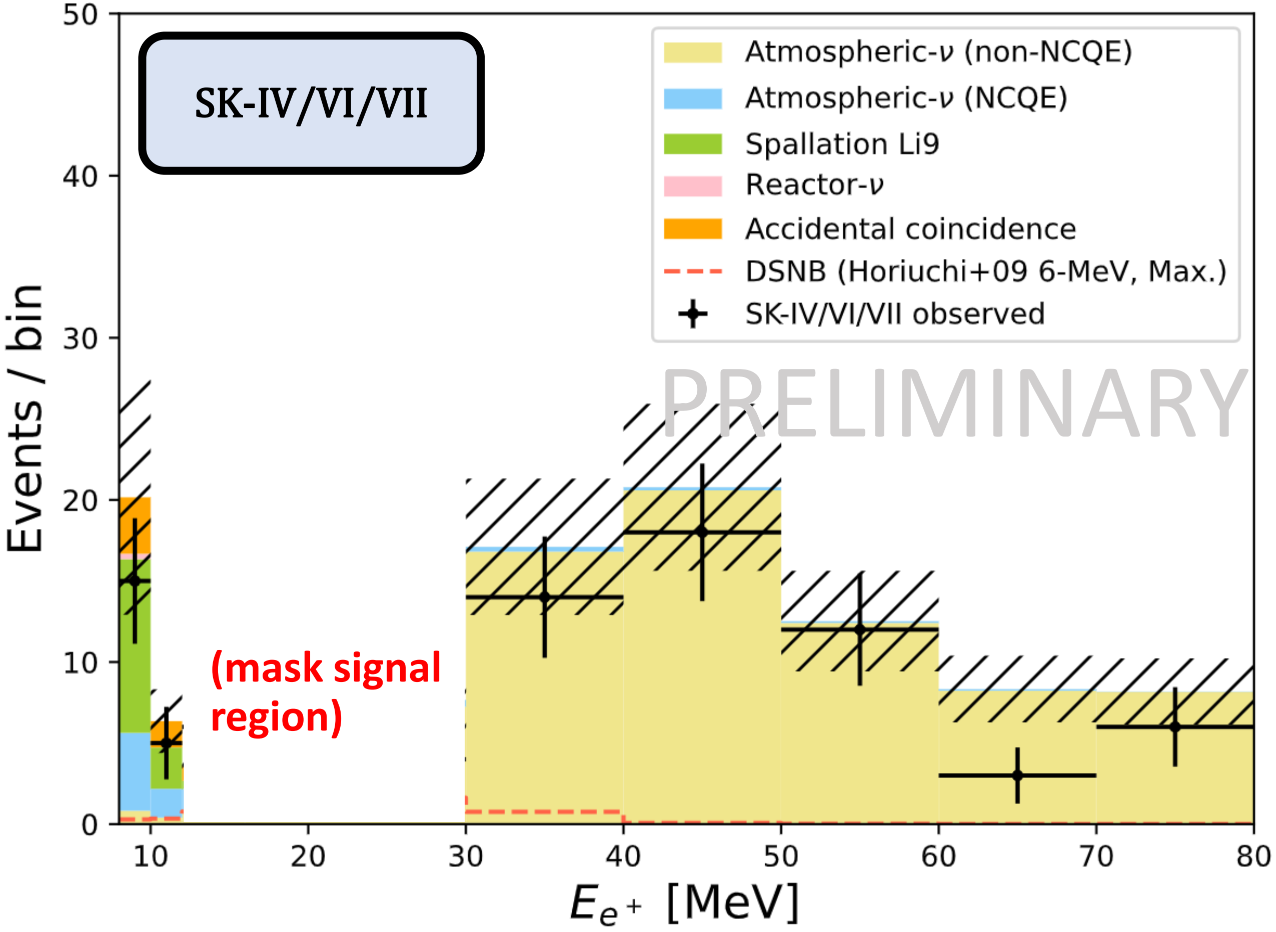
DSNB model-independent (binned analysis)

DSNB model-dependent (spectral analysis)

θ_c (across) ntag (below)	$20^\circ - 38^\circ$	$38^\circ - 50^\circ$	$78^\circ - 90^\circ$
ntag≠1	μ/π BG	mis-ID DSNB	multi-cone atm. ν
ntag=1	μ/π BG	tagged DSNB **(binned analysis)**	multi-cone atm. ν

Super-K DSNB analysis: Binned analysis results for SK-IV/VI/VII

- Data and Monte Carlo simulation predictions are **simply stacked** for all three periods for visualization.



ADS et al., Neutrino 2024 proceedings

Super-K DSNB analysis: Binned analysis results for SK-IV/VI/VII

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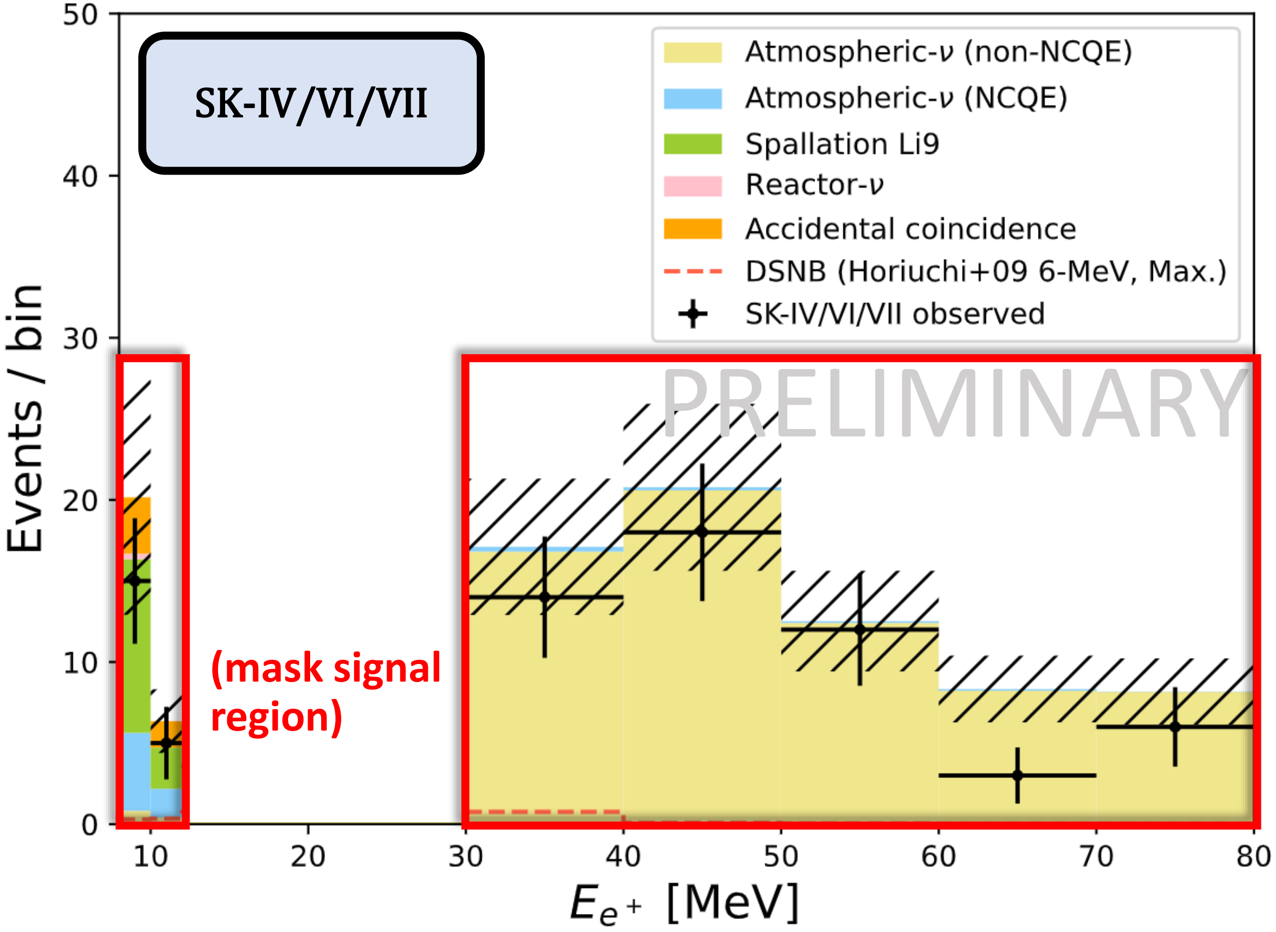
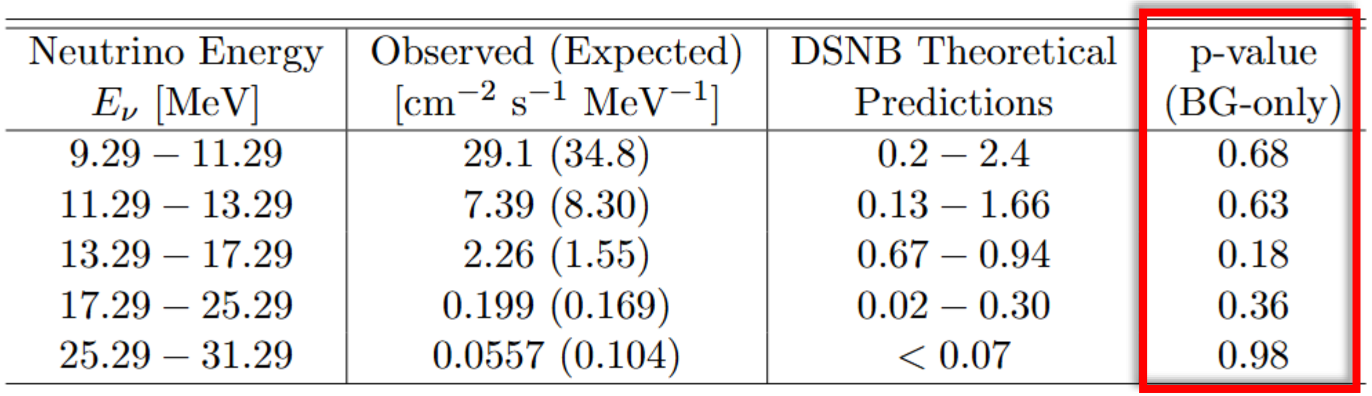


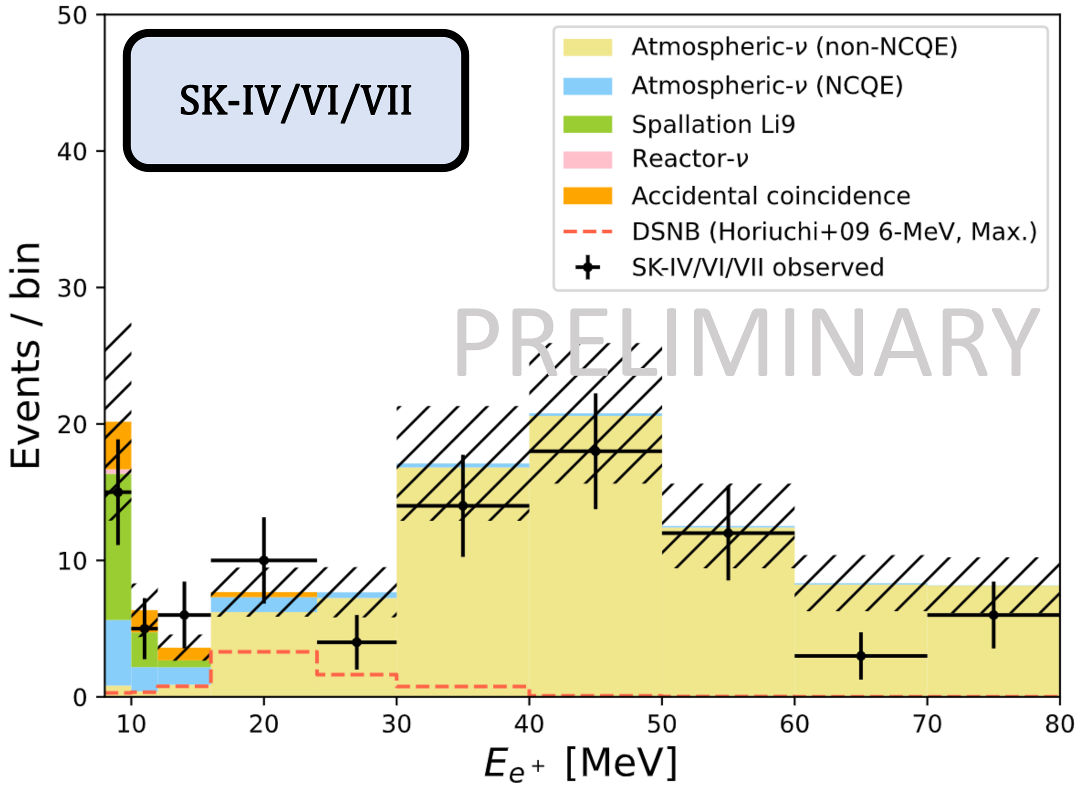
ADS et al., Neutrino 2024 proceedings

Super-K DSNB analysis: Binned analysis results for SK-IV/VI/VII



Neutrino Energy E_ν [MeV]	Observed (Expected) [$\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{MeV}^{-1}$]	DSNB Theoretical Predictions	p-value (BG-only)
9.29 – 11.29	29.1 (34.8)	0.2 – 2.4	0.68
11.29 – 13.29	7.39 (8.30)	0.13 – 1.66	0.63
13.29 – 17.29	2.26 (1.55)	0.67 – 0.94	0.18
17.29 – 25.29	0.199 (0.169)	0.02 – 0.30	0.36
25.29 – 31.29	0.0557 (0.104)	< 0.07	0.98

- Data and Monte Carlo simulation predictions are **simply stacked** for all three periods for visualization.
- **Sideband regions** (below 12 MeV and above 30 MeV) show good data/MC agreement.
- **No significant excess** observed in any energy bin with smallest p-value $p = 0.18$.



ADS et al., Neutrino 2024 proceedings

Super-K DSNB analysis: Binned analysis results for SK-IV/VI/VII

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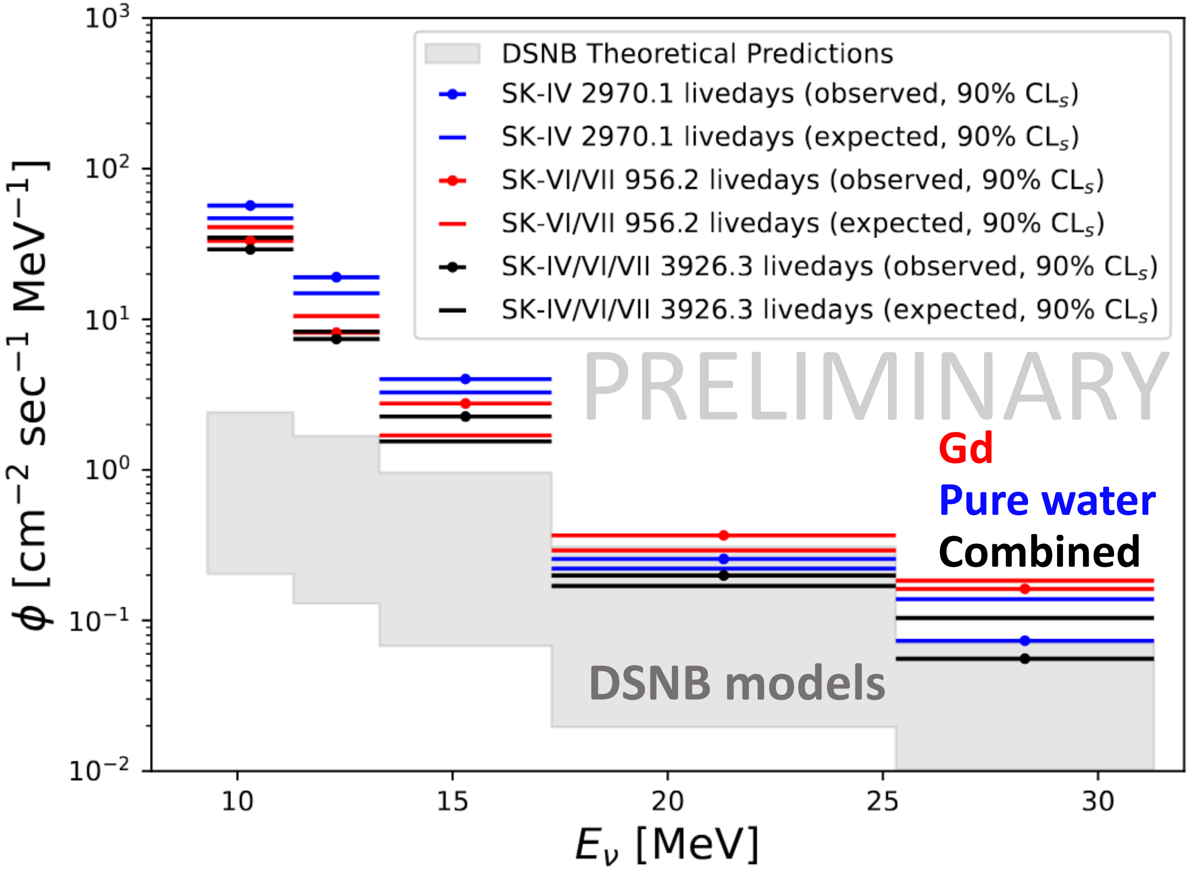
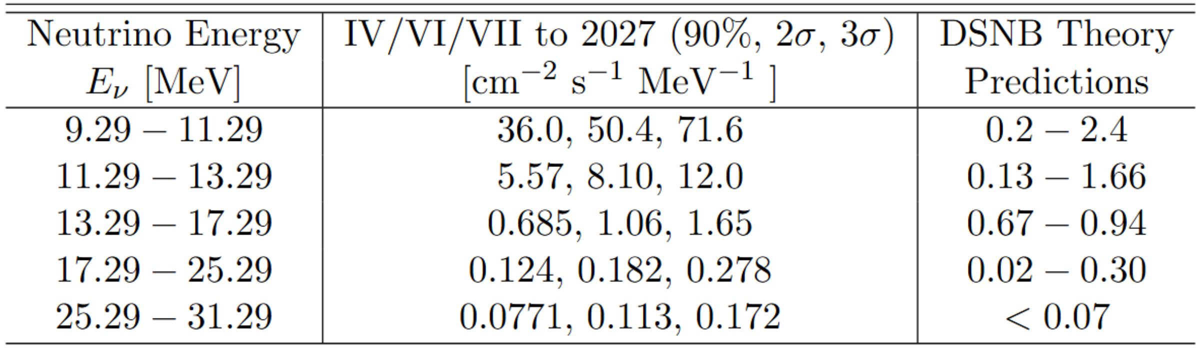
- **Sideband regions** (below 12 MeV and above 30 MeV) show good data/MC agreement.
- **No significant excess** observed in any energy bin with smallest p-value $p = 0.18$.
- The **tightest observed limits** on the DSNB were set.



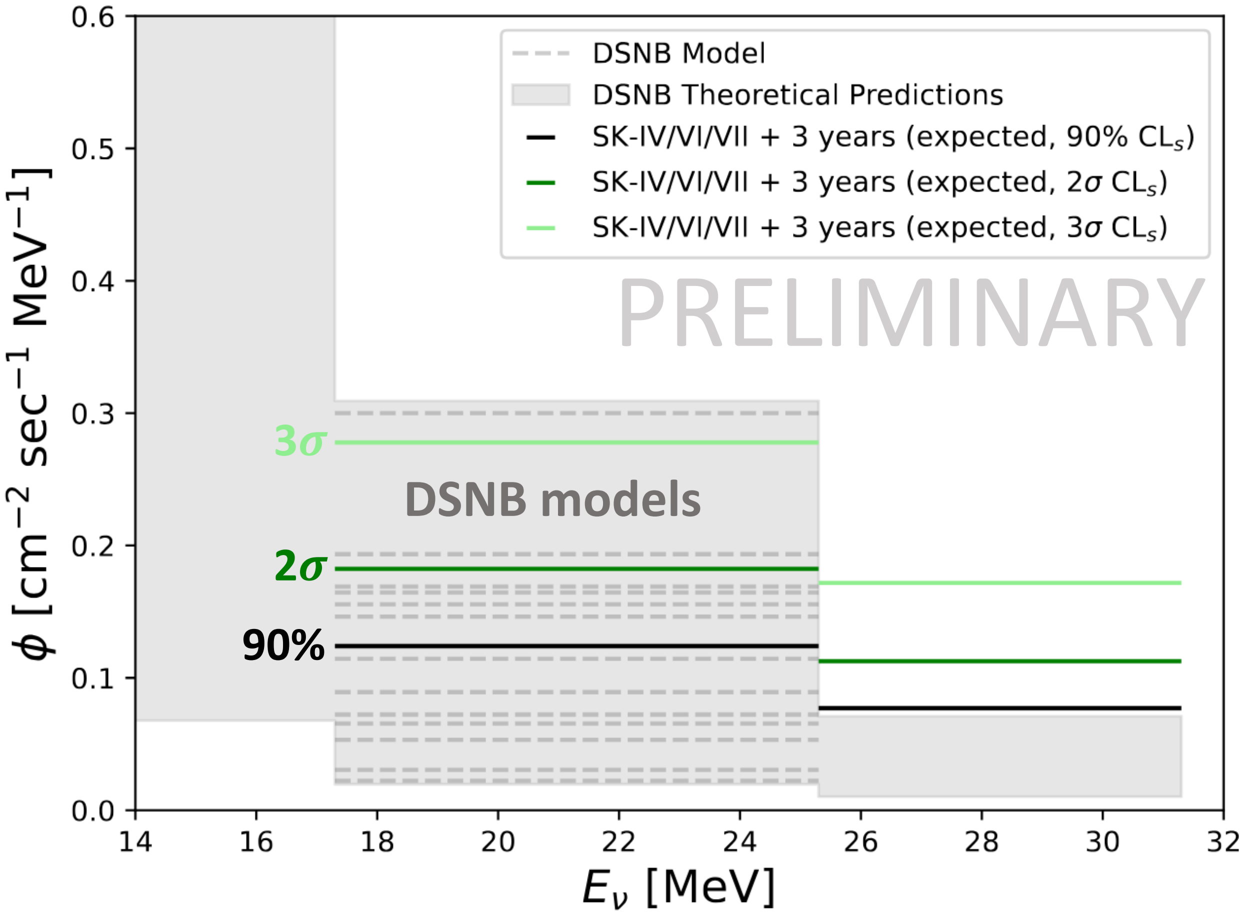
ADS et al., Neutrino 2024 proceedings

Super-K DSNB analysis: Binned analysis projections



Neutrino Energy E_ν [MeV]	IV/VI/VII to 2027 (90%, 2σ, 3σ) [$\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{MeV}^{-1}$]	DSNB Theory Predictions
9.29 – 11.29	36.0, 50.4, 71.6	0.2 – 2.4
11.29 – 13.29	5.57, 8.10, 12.0	0.13 – 1.66
13.29 – 17.29	0.685, 1.06, 1.65	0.67 – 0.94
17.29 – 25.29	0.124, 0.182, 0.278	0.02 – 0.30
25.29 – 31.29	0.0771, 0.113, 0.172	< 0.07

- Data and Monte Carlo simulation predictions are **simply stacked** for all three periods for visualization
- **Sideband regions** (below 12 MeV and above 30 MeV) show good data/MC agreement.
- **No significant excess** observed in any energy bin with smallest p-value $p = 0.18$.
- The **tightest observed limits** on the DSNB were set.
- We are in the **most sensitive Super-K phase** to date with more data and other experiments to come…



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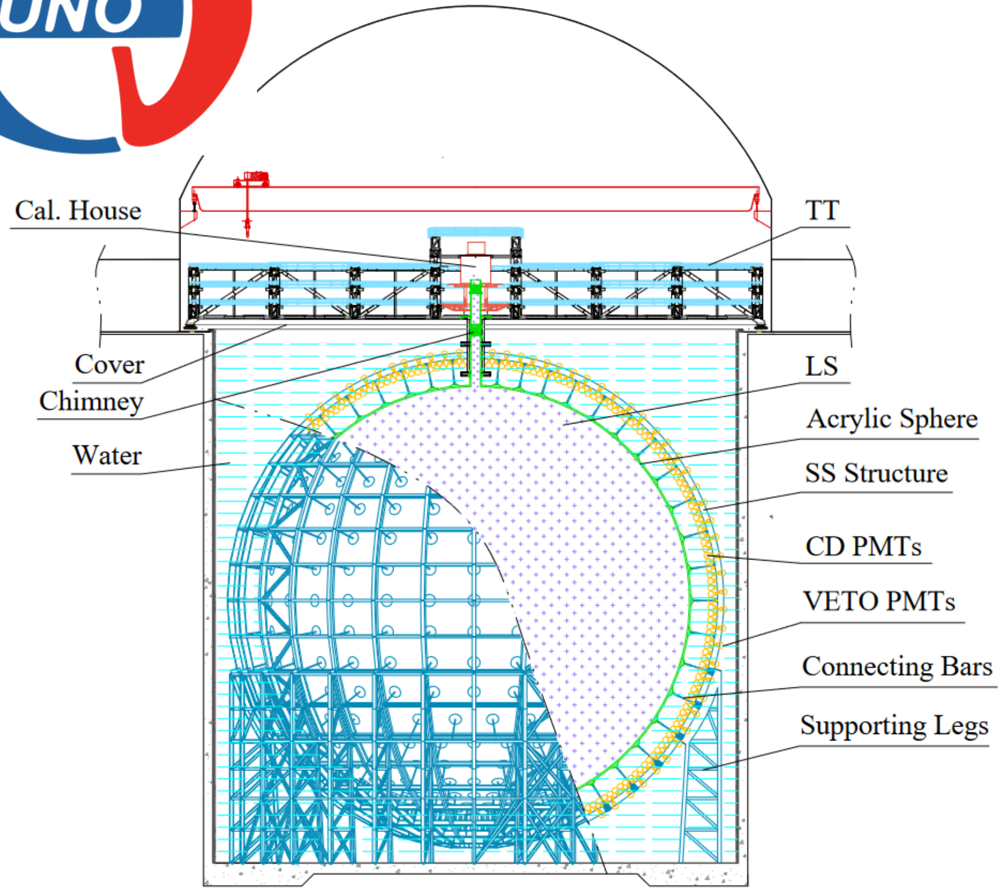
The experimental searches for DSNB are multiplying

- There are a **variety of experiments** between now and the beginning of the 2030s that will be sensitive to the DSNB.
- **Super-Kamiokande** will continue through this decade.
- **Hyper-Kamiokande** is under construction for start in 2027.
- **JUNO** (Jiangmen Underground Neutrino Observatory) is set to start data-taking next year [talk M. Lecocq].
- **DUNE** (Deep Underground Neutrino Experiment) will come online in phases with the first happening at the end of this decade.
- **LZ** is even in the game [talk Q. Xia]!

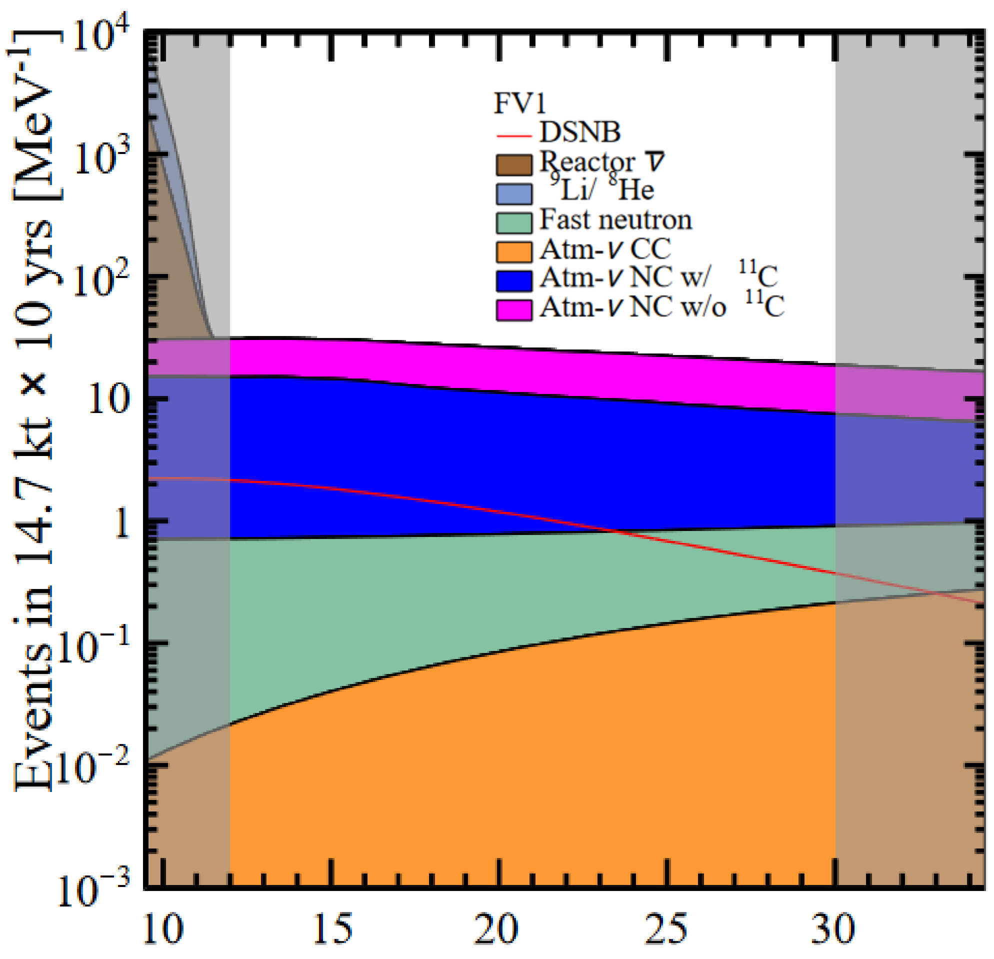
JUNO: Jiangmen Underground Neutrino Observatory



- The **Jiangmen Underground Neutrino Observatory** (JUNO) is in its final stages of construction in Guangdong province, China.
- It will be a **20 kton liquid scintillator** detector under 700 meters of rock (1800 meters w.e.).
- The **inner diameter** of the liquid scintillator region will measure **35.4 meters**.
- Highly effective energy reconstruction will be targeted with **almost 18,000 20-in. PMTs** and **another 25,600 3-in. PMTs** filling the gaps between.
- The **outer cylinder** serves as a water Cherenkov **veto** with 2,400 20-in. PMTs.

*A. Abusleme, JCAP **10** (2022) 033*

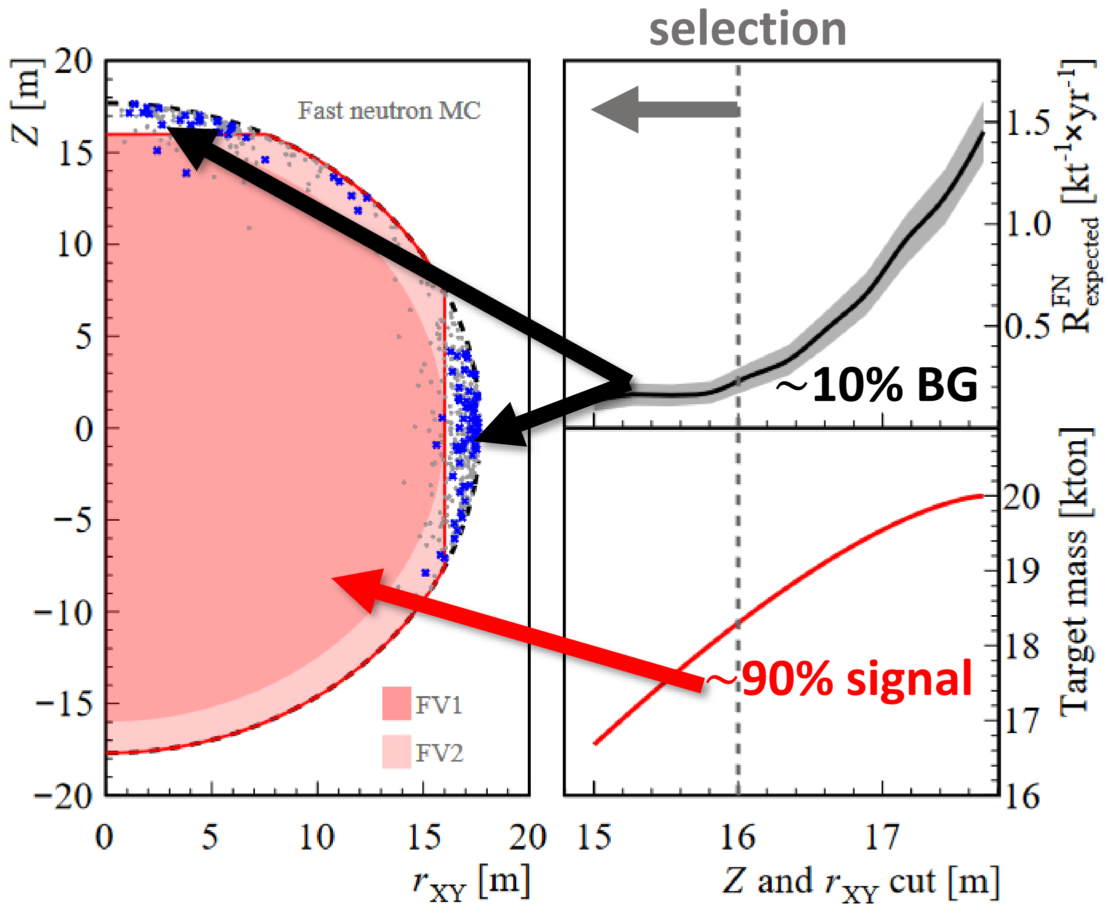
JUNO: First backgrounds to consider



*A. Abusleme, JCAP **10** (2022) 033*

- For its DSNB analysis, JUNO will have a few categories of backgrounds.
  - **Reactor $\overline{\nu}_e$**: The IBD interactions of reactor neutrinos **exactly mimics the DSNB signal** and **sets the energy threshold at 12 MeV**.
  - **Atmospheric $\overline{\nu}_e$**: These undergo IBD interactions to **exactly mimic the DSNB also**, and they **limit the search from above**.
  - **Spallation**: Production of Li-9 and He-8 by cosmic ray muons above 12 MeV can be **largely removed by muon ID** in the veto.

JUNO: Fast neutron background removal from spallation



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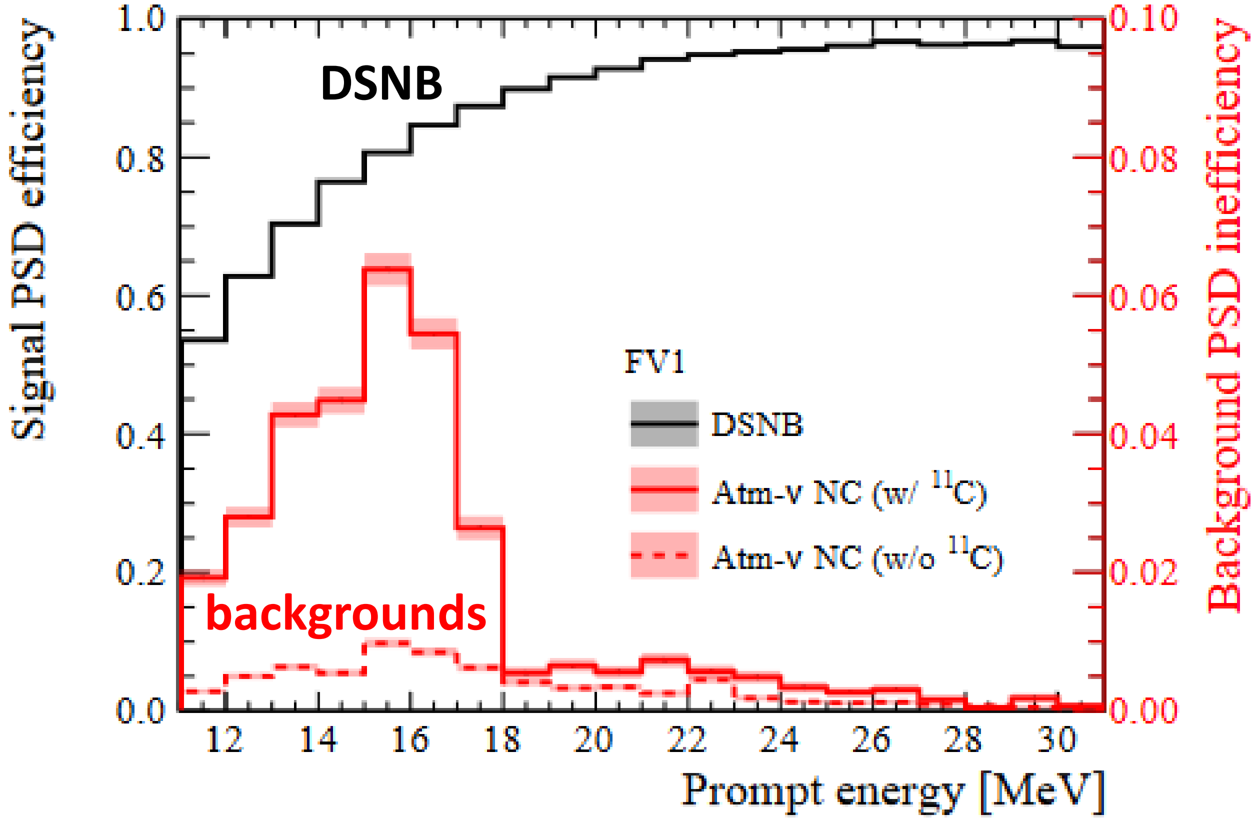
  - **Fast neutrons**: **Untagged cosmic ray muons** can generate a prompt signal with a delayed neutron capture – **remove with volume cuts**.

A. Abusleme, JCAP ***10*** *(2022) 033*

Atmospheric neutrino neutral-current interaction removal



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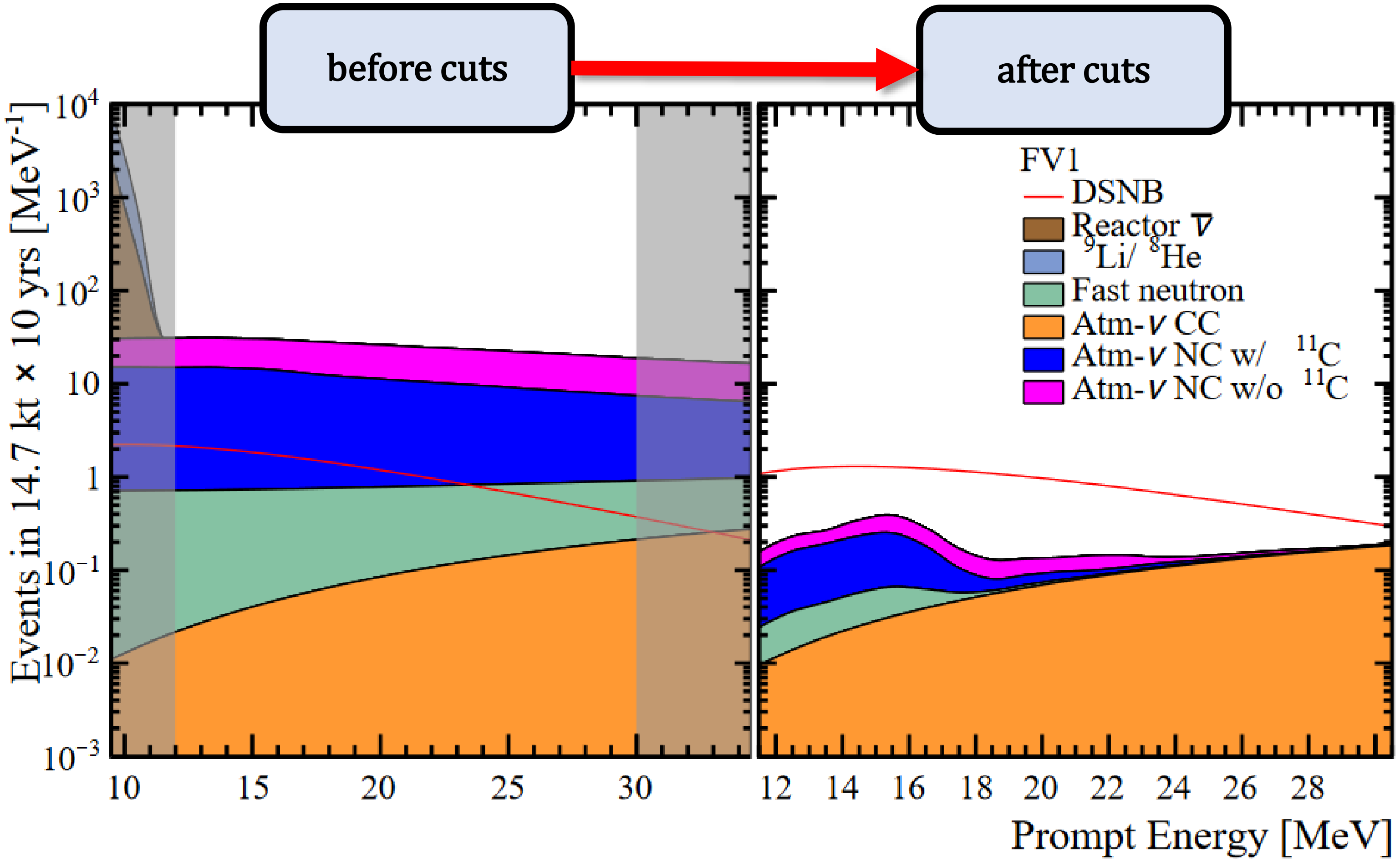
  - **Fast neutrons**: **Untagged cosmic ray muons** can generate a prompt signal with a delayed neutron capture – **remove with volume cuts**.
  - **Atmospheric ν neutral-current**: **Interactions on C-12** can lead to beta decays with a three-part signal – **use pulse shape discrimination**.

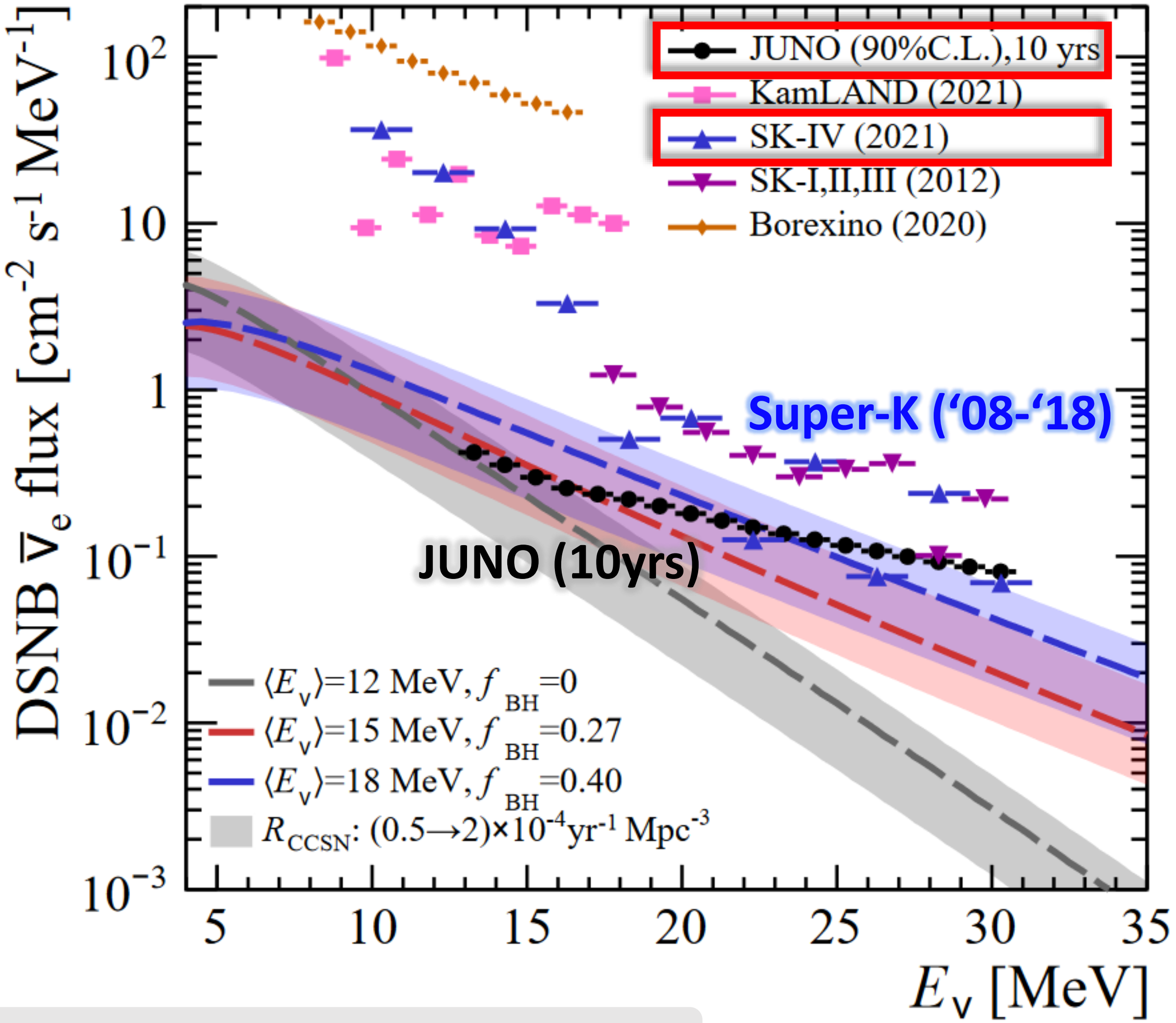
JUNO DSNB after reduction steps



- Again, the search window is limited to [12, 30] MeV.
- Final energy spectra after all reduction steps demonstrate **orders of magnitude reduction of total backgrounds**.
- Reference model has **about 1 DSNB event-per-MeV** (15 MeV blackbody with $f_{BH} = 0.27$) in final sample.
- How does this compare to Super-K?

*A. Abusleme, JCAP **10** (2022) 033*

Comparison of Super-K and JUNO sensitivity to DSNB



*A. Abusleme, JCAP **10** (2022) 033*

- We can try to **compare** the projected **JUNO** sensitivity for DSNB to that of **Super-K**.
- After **10 years of JUNO data-taking**, we can expect **comparable sensitivity to SK-IV** limits from 2021 when **looking above 20 MeV**.

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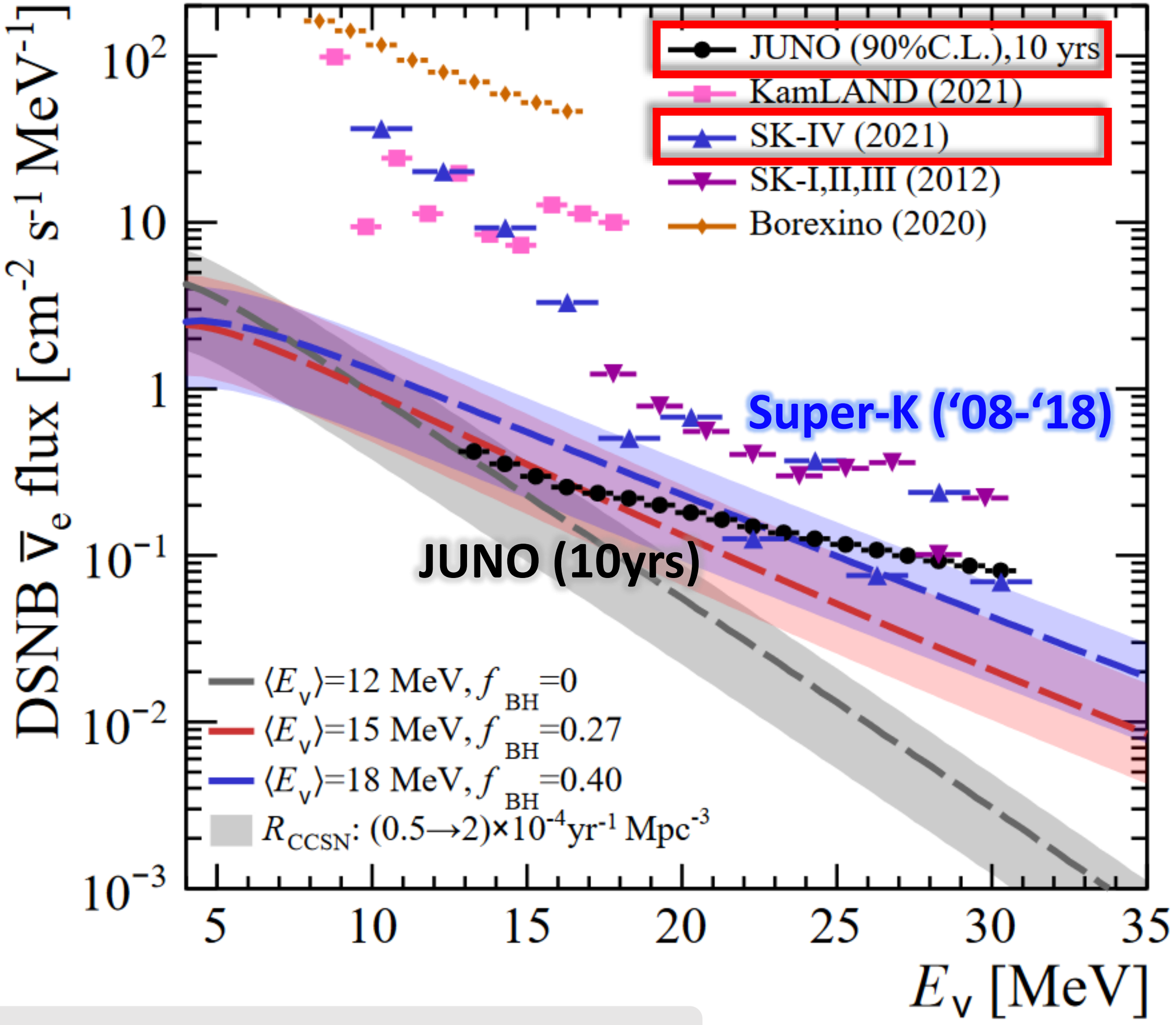

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- Above 16 MeV, **1yr Hyper-K ≈ 8yr Super-K**.

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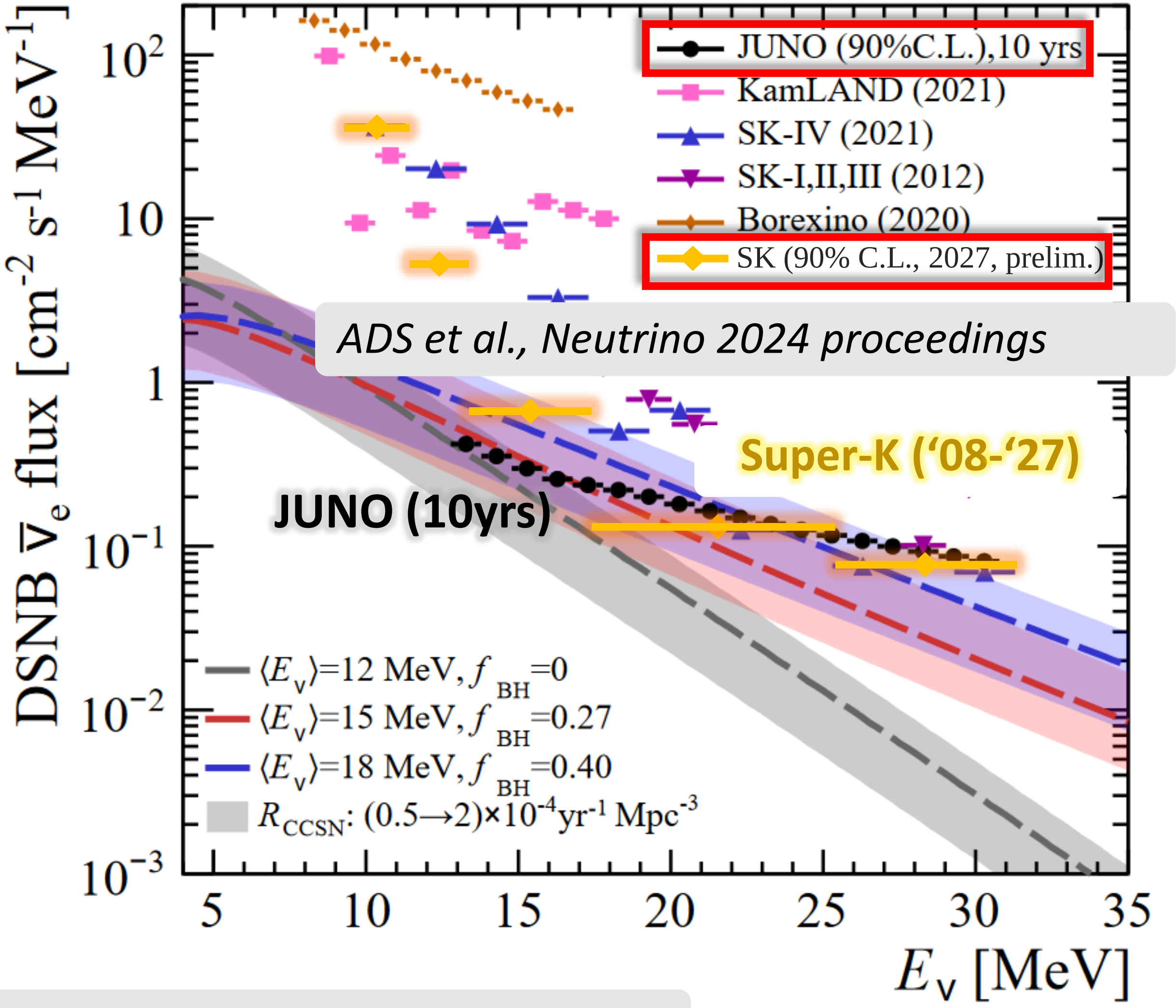

ADS et al., Neutrino 2024 proceedings

A. Abusleme, JCAP ***10*** *(2022) 033*

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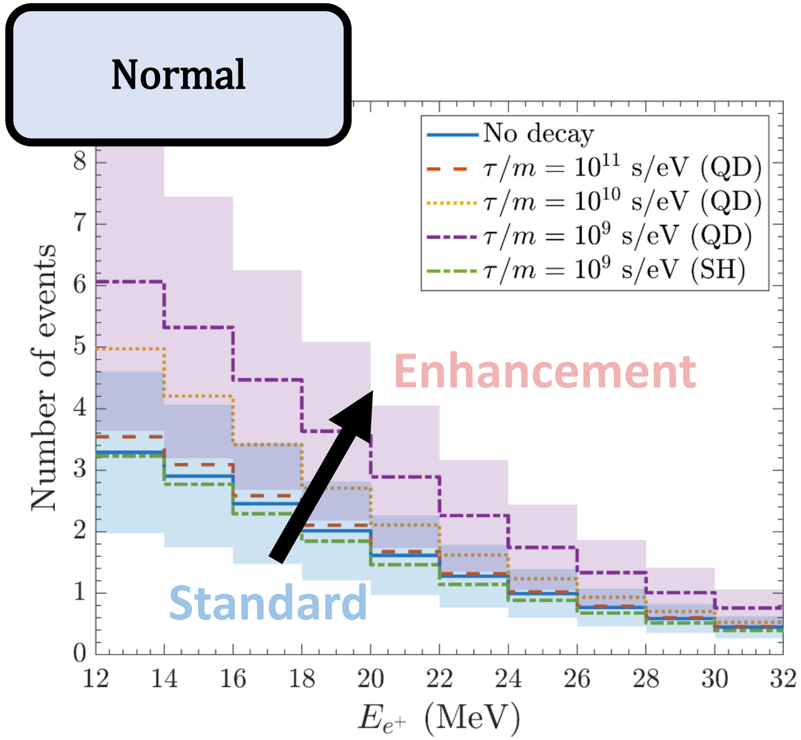
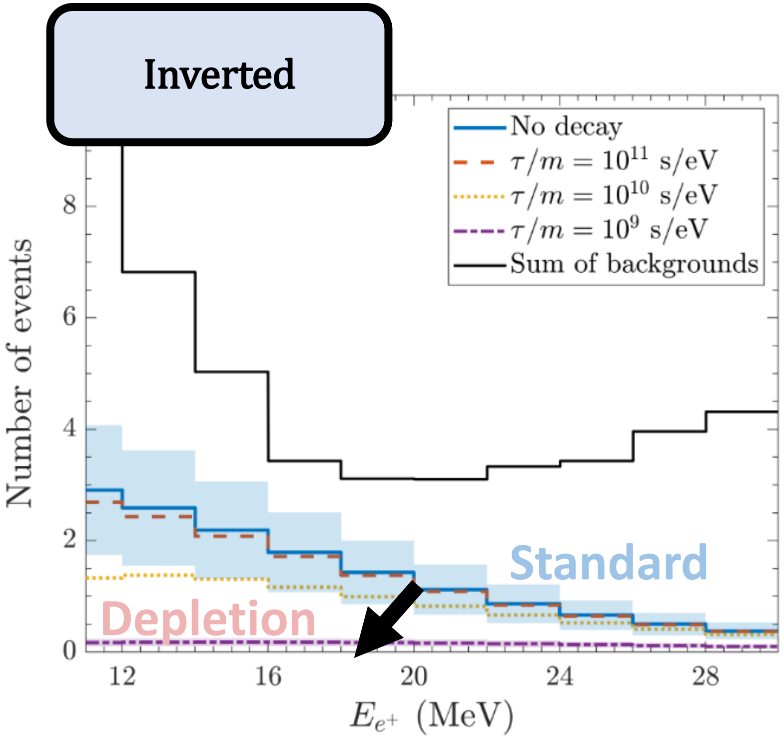
- After **10 years of JUNO data-taking**, we can expect **comparable sensitivity to SK-IV** limits from 2021 when **looking above 20 MeV**.
- Above 16 MeV, **1yr Hyper-K ≈ 8yr Super-K**.
- We can plot the **projected sensitivity of Super-K** for **all neutron-tagging periods until 2027**.
- Once more, the **high-energy limits** remain highly **comparable**.
- **JUNO is expected to better** than Super-K (and then Hyper-K) **at lower energies** from its background reduction.
- **JUNO** and **Super-K/Hyper-K** searches are expected to be **complementary** in this way.

Non-standard and “exotic” physics with the DSNB

- Once we have a DSNB detection, what **other new, exciting physics** is possible?

DSNB with neutrino non-radiative decay





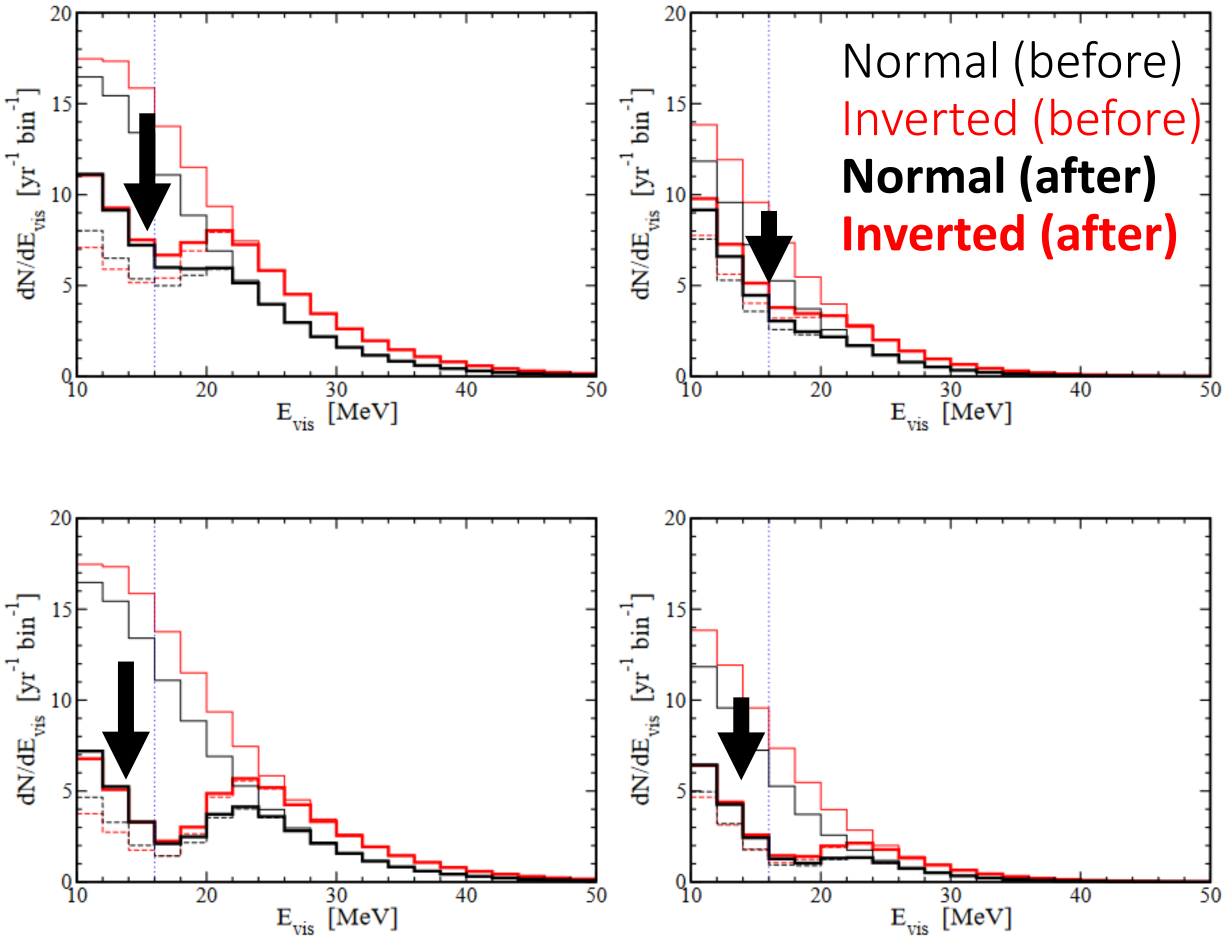
P. Ivañez-Ballesteros and M.C. Volpe,
*PRD **107** (2023) 023017*

$$\nu_i \rightarrow \nu_j + \phi, \qquad \nu_i \rightarrow \bar{\nu}_j + \phi$$

$$\Gamma_{\nu_i} = \frac{m_i}{E_\nu} \sum_{m_j < m_i} \left(\tilde{\Gamma}(\nu_i \rightarrow \nu_j) + \tilde{\Gamma}(\nu_i \rightarrow \bar{\nu}_j) \right)$$

- Imagine a scenario of **neutrino non-radiative decay** for which heavier states can decay into lighter states along with a (nearly) massless scalar.
- **Three limiting scenarios can be identified** as quasi-degenerate (QD), strongly hierarchy (SH) in normal ordering and then inverted ordering.
- In **normal ordering**, the QD case for short enough lifetimes causes an **increase in DSNB flux at Super-K** from “heavy” flavor states decaying into the “lighter” $\bar{\nu}_e/\nu_e$.
- In **inverted ordering**, short enough lifetimes lead to **high suppression of DSNB flux at Super-K** from “heavy” $\bar{\nu}_e$ decaying into “lighter” $\nu_\tau/\bar{\nu}_\tau$.

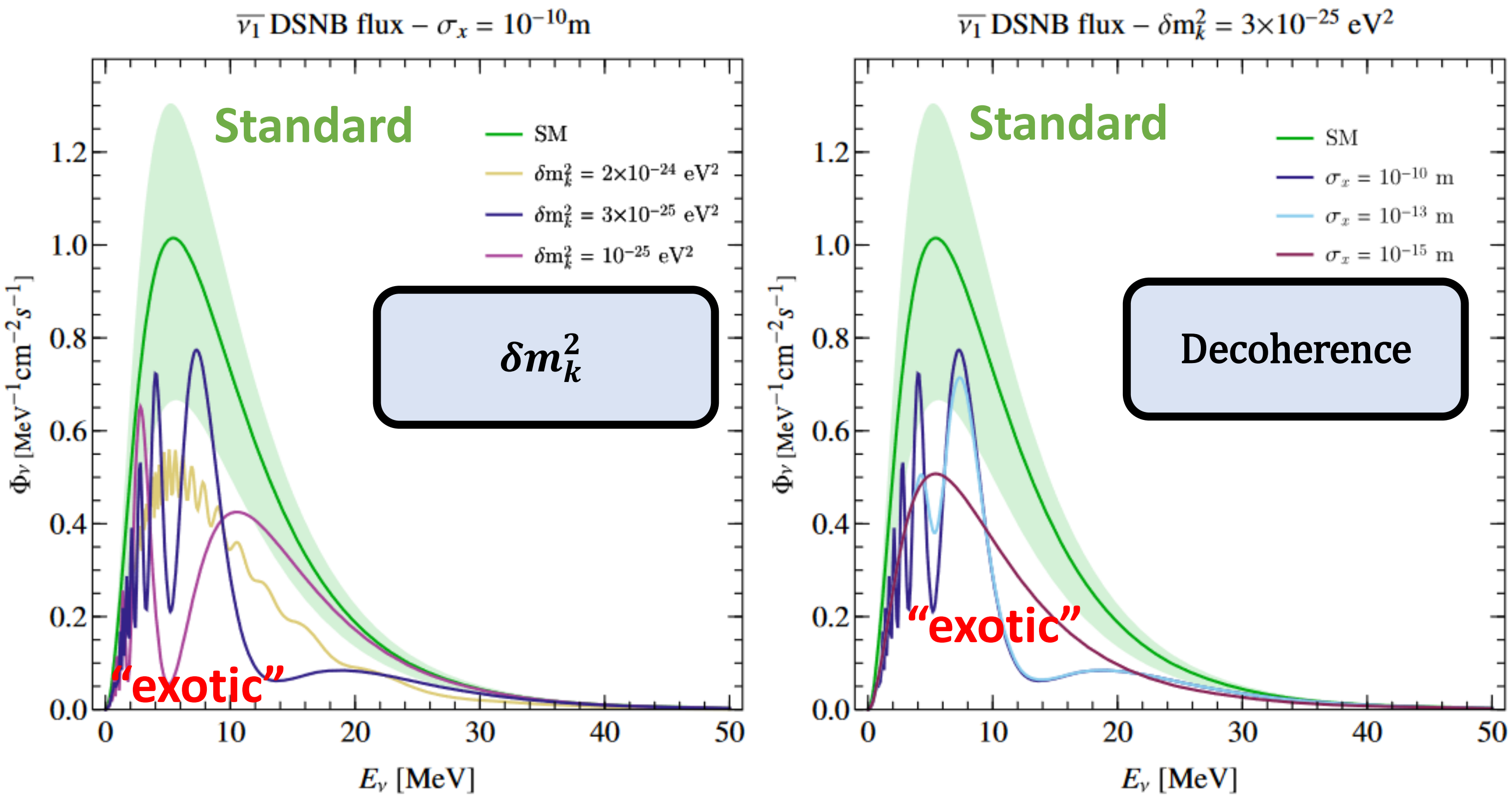
DSNB with resonant interactions with dark matter



- Consider a **general coupling of neutrinos to dark matter** through $g_i \nu_i^\dagger \phi N$ for ν masses i.
- For significant effects to be possible on the DSNB, the requirement of ϕ and N to be of the order of 10 MeV **makes only the ν_τ coupling significant** for which $g_i \propto U_{\tau i}$.
- **N_e and N_μ couplings can be ignored** due to strict constraints of meson decay experiments.
- We can consider a situation in which a resonant energy of $\sim$20 MeV exists through which DSNB neutrinos can be absorbed.
- Depending on the exact model, a **depletion in DSNB flux occurs in Hyper-K** at and below the resonant energy of 20 MeV.

Y. Farzan and S. Palomares-Ruiz,
*JCAP **06** (2014) 014*

DSNB with sterile oscillation, wave-packet considerations

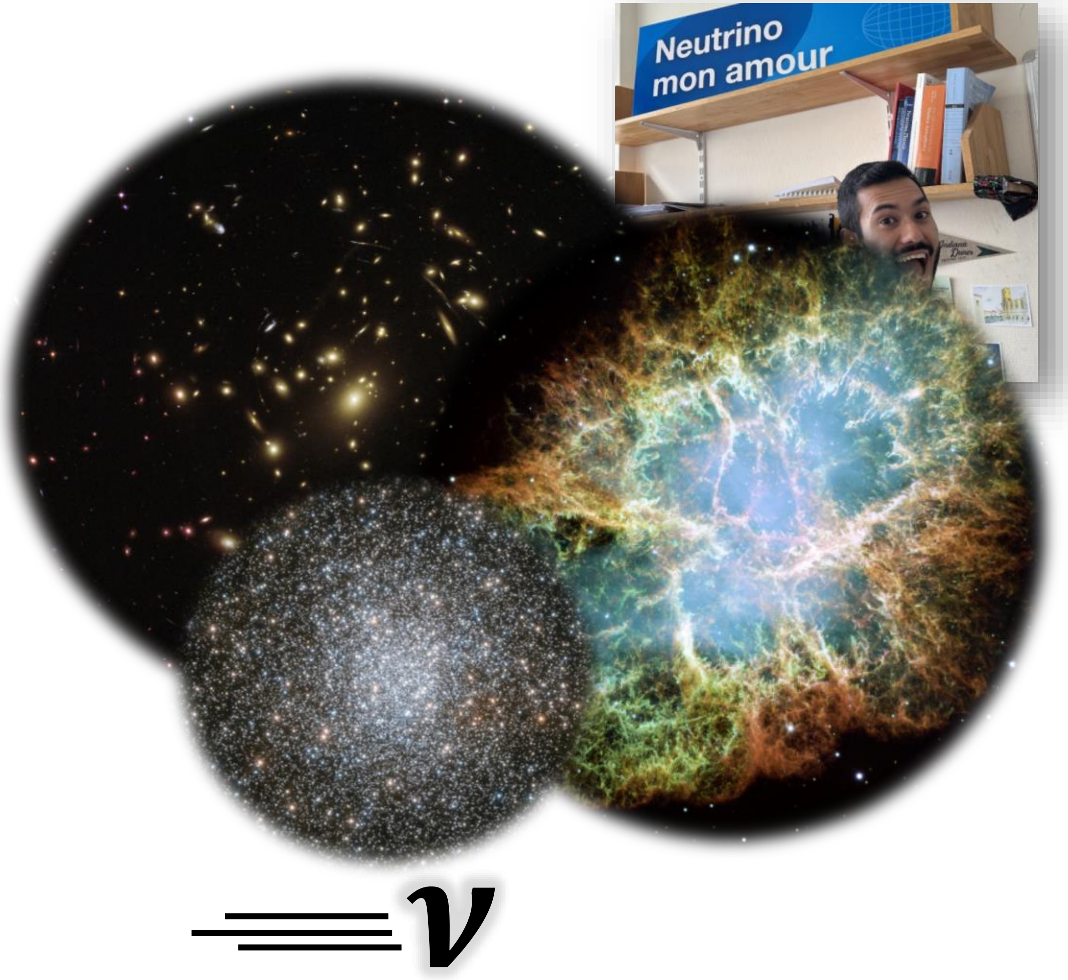


A. de Gouvêa et al., PRD ***102*** *(2020) 123012*

- Another "exotic" scenario is possible when probing the DSNB for new physics.
- In a situation where neutrinos are pseudo-Dirac (i.e., actually Majorana but largely preserve Dirac behavior), there can be **non-trivial active-sterile neutrino oscillations** with extremely small mass-squared differences.
- Additionally, wave packet sizes σ_x can play a crucial role in the mixture of states arriving at Earth from the DSNB.
- In this picture, the **spectral shape can be quite different** from a DSNB predicted by the Standard Model.

DSNB summary and outlook

- The **Diffuse Supernova Neutrino Background** (DSNB) is a never-before-seen source of astrophysical neutrinos.
- To date, the most **sensitive experiment is Super-Kamiokande** with its most recent results presented at the Neutrino 2024 conference in Milan, Italy.
- **Next-generation experiments** like Hyper-Kamiokande, the Jiangmen Underground Neutrino Observatory (JUNO), and the Deep Underground Neutrino Experiment (DUNE) show **promising sensitivity** to the DSNB as well.
- **Several uncertainties** dominate theoretical calculations for DSNB flux, such as the **star formation history** and the **average neutrino emission spectra** for supernovae.
- A DSNB signal could **probe new physics** such as **neutrino non-radiative decay**, interactions with **dark matter**, and presence of **sterile neutrinos**.



Selected DSNB references (1/2)

- Super-K DSNB searches
  - **Review of diffuse supernova neutrino background**
    M. Harada, Neutrino 2024 proceedings (**2024**)
  - **New limits on the low-energy astrophysical electron antineutrinos at SK-Gd experiment**
    ADS et al., Neutrino 2024 proceedings (**2024**)
  - **Diffuse Supernova Neutrino Background Search at Super-Kamiokande**
    K. Abe et al., PRD 104 (2021) 122002
  - **Search for Astrophysical Electron Antineutrinos in Super-Kamiokande with 0.01% Gadolinium-loaded Water**
    M. Harada et al., ApJL 951 (**2023**) 2, L27
  - **Diffuse Supernova Neutrino Background Search at Super-Kamiokande**
    K. Abe et al., PRD 104 (2021) 122002
- Other experimental searches for DSNB
  - **Hyper-Kamiokande Design Report**
    K. Abe et al., arXiv:1805.04163 (2018)
  - **Prospects for detecting the diffuse supernova neutrino background with JUNO**
    A. Abusleme et al., JCAP 10 (2022) 033
  - **Measuring the supernova unknowns at the next-generation neutrino telescopes through the diffuse neutrino background**
    K. Møller et al., JCAP 05 (2018) 066
  - **Prospects for Detection of the Diffuse Supernova Neutrino Background with the Experiments SK-Gd and JUNO**
    Y.F. Li et al., Universe 8 (2022) 181

Selected DSNB references (2/2)

- DSNB as a probe (continued)
  - **Fundamental physics with the diffuse supernova background neutrinos**
    A. de Gouvêa et al., PRD 102 (2020) 123012
  - **Neutrino non-radiative decay and the diffuse supernova neutrino background**
    P. Ivañez-Ballesteros and M.C. Volpe, PRD 107 (**2023**) 023017
  - **Dips in the diffuse supernova neutrino background**
    Y. Farzan and S. Palomares-Ruiz JCAP 06 (2014) 014
  - **Diffuse neutrino supernova background as a cosmological test**
    J. Barranco et al., J. Phys. G 45 (2018) 055201
- DSNB ingredients
  - **Non-Universal Stellar Initial Mass Functions: Large Uncertainties in Star Formation Rates at $z \approx 2 - 4$ and Other Astrophysical Probes**
    J.J. Ziegler et al., MNRAS 517 (2022) 2471-2484
  - **Stellar Collapse Diversity and the Diffuse Supernova Neutrino Background**
    D. Kresse et al., ApJ 909 (2021) 169
  - **Diffuse neutrinos from luminous and dark supernovae: prospects for upcoming detectors at the O(10) kt scale**
    A. Priya and C. Lunardini, JCAP 11 (2017) 031
- Gd-loading
  - **First gadolinium loading to Super-Kamiokande**
    K. Abe et al., J. NIMA 1027 (2022) 166248
  - **Second gadolinium loading to Super-Kamiokande**
    K. Abe et al., J. NIMA 1065 (**2024**) 169480

Backup

Super-K DSNB analysis details

More JUNO/SK sensitivity studies

DUNE DSNB external study

Neutrino propagation in CCSNe

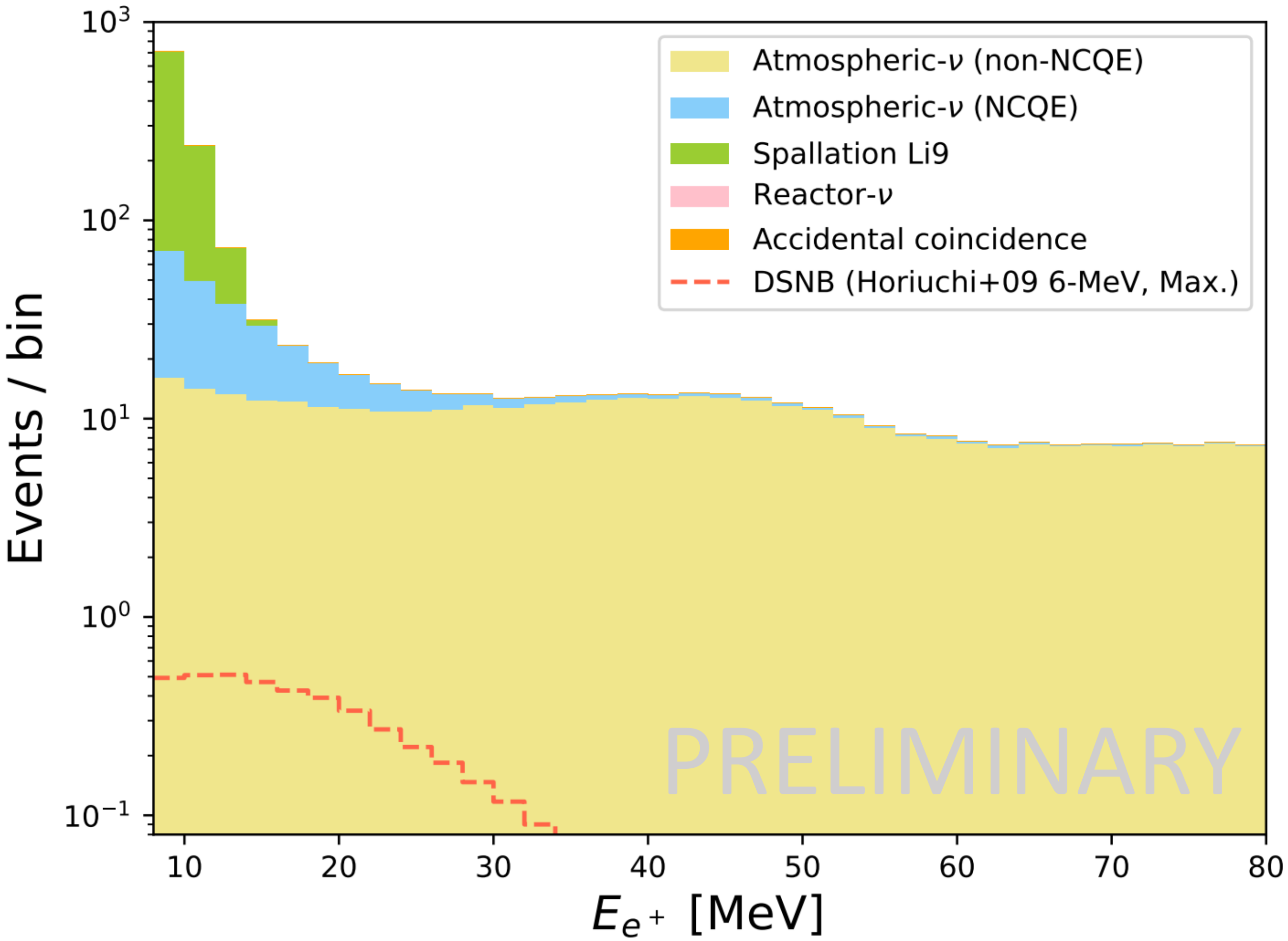
Super-K DSNB analysis details

(backup page)

Super-K DSNB analysis: Reduction steps

("1st reduction") **Data Quality**

- Only keep events that are **well reconstructed** by BONSAI (bsgood>0.5).
- Event **reconstruction becomes difficult near the walls** he detector (dwall>200cm).
- **Radon contamination** is concentrated near the detector walls (dwall+effwall).
- Focus on **events without OD activity** that would be associated with cosmic ray muons (trigger requirements).

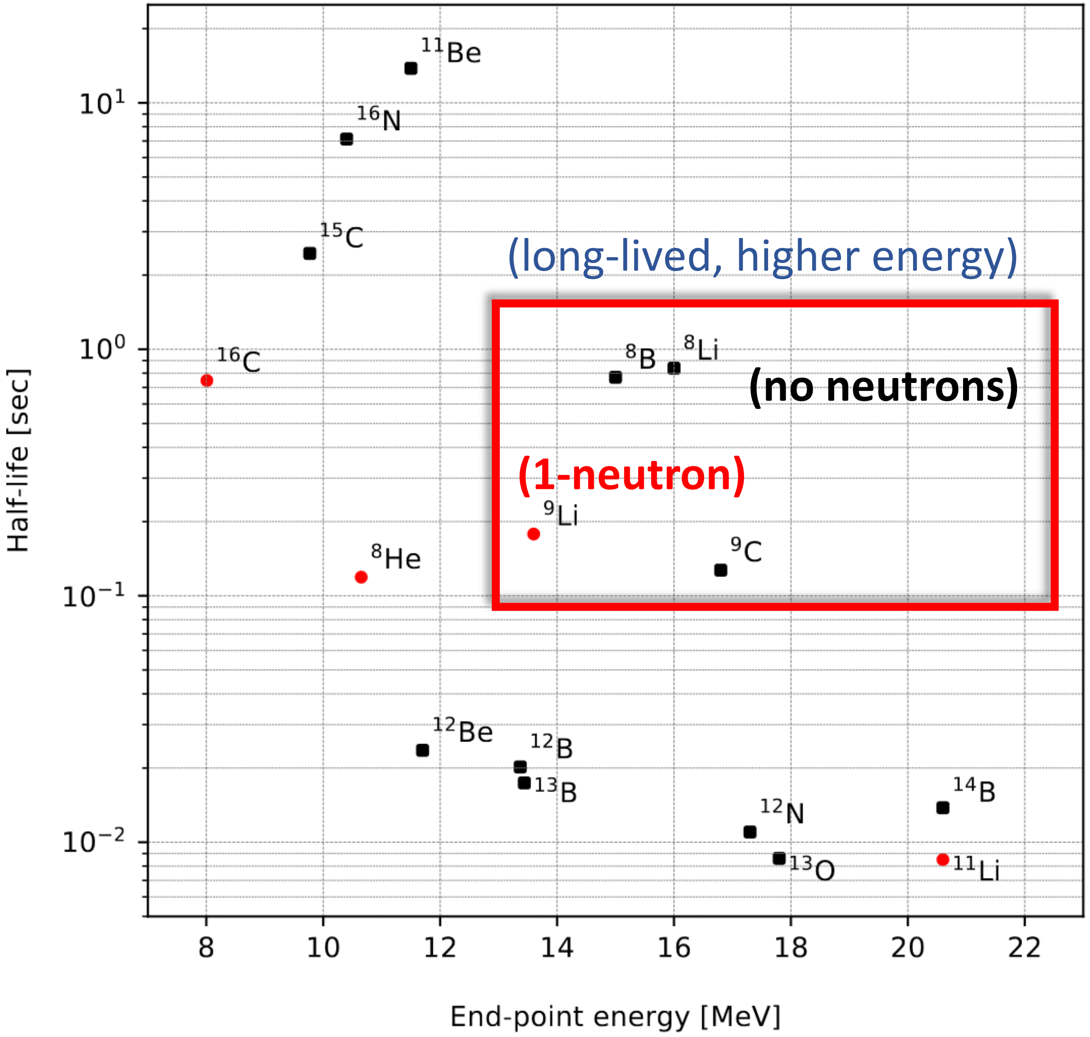


Super-K DSNB analysis: Reduction steps

("1st reduction") **Data Quality**

("2nd reduction") **Spallation Background**

- Spallation **isotopes with longer half-lives are more difficult to reject** since it is harder to associate them to a parent muon.
- Isotopes without neutrons can be **largely rejected when tagging neutron** captures.
- **Li-9** produces a neutron in an IBD-like signal.



(long-lived, higher energy)

(no neutrons)

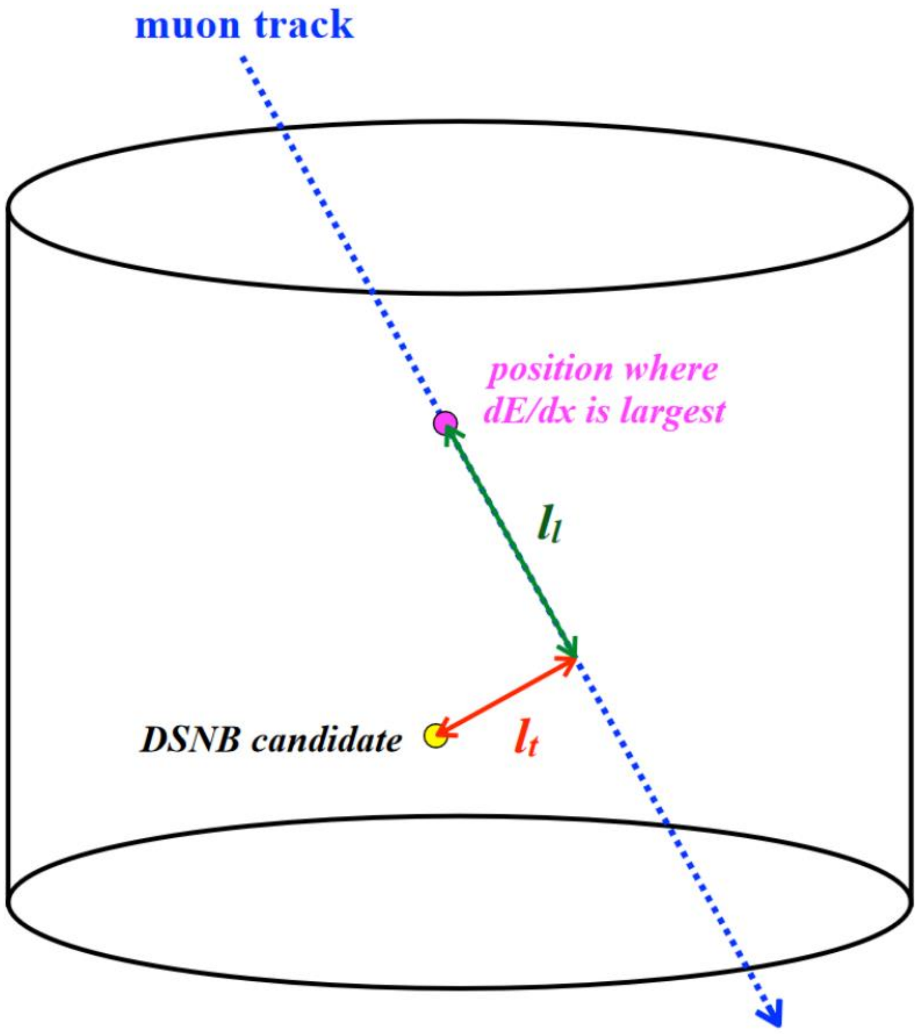
(1-neutron)

Super-K DSNB analysis: Reduction steps

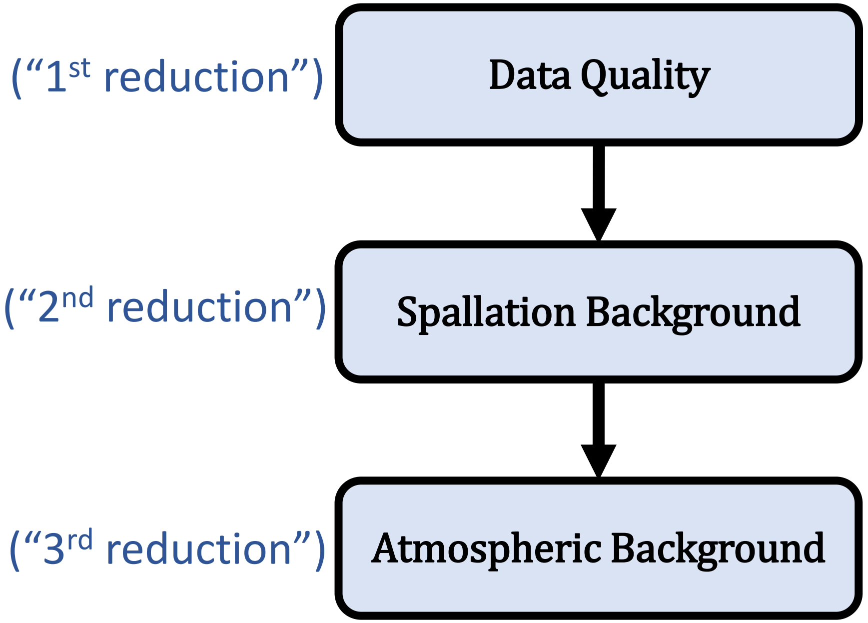
("1st reduction") **Data Quality**

("2nd reduction") **Spallation Background**

- Remove **events within 1 ms** a muon passing through the tank (time cut).
- Remove **events within 4 m** to a low-energy event (multiple-spallation).
- Remove events identified within/close to a "**neutron cloud**" created by passing muons.
- Apply a set of energy-dependent **box cuts** and **spallation likelihood cuts**.



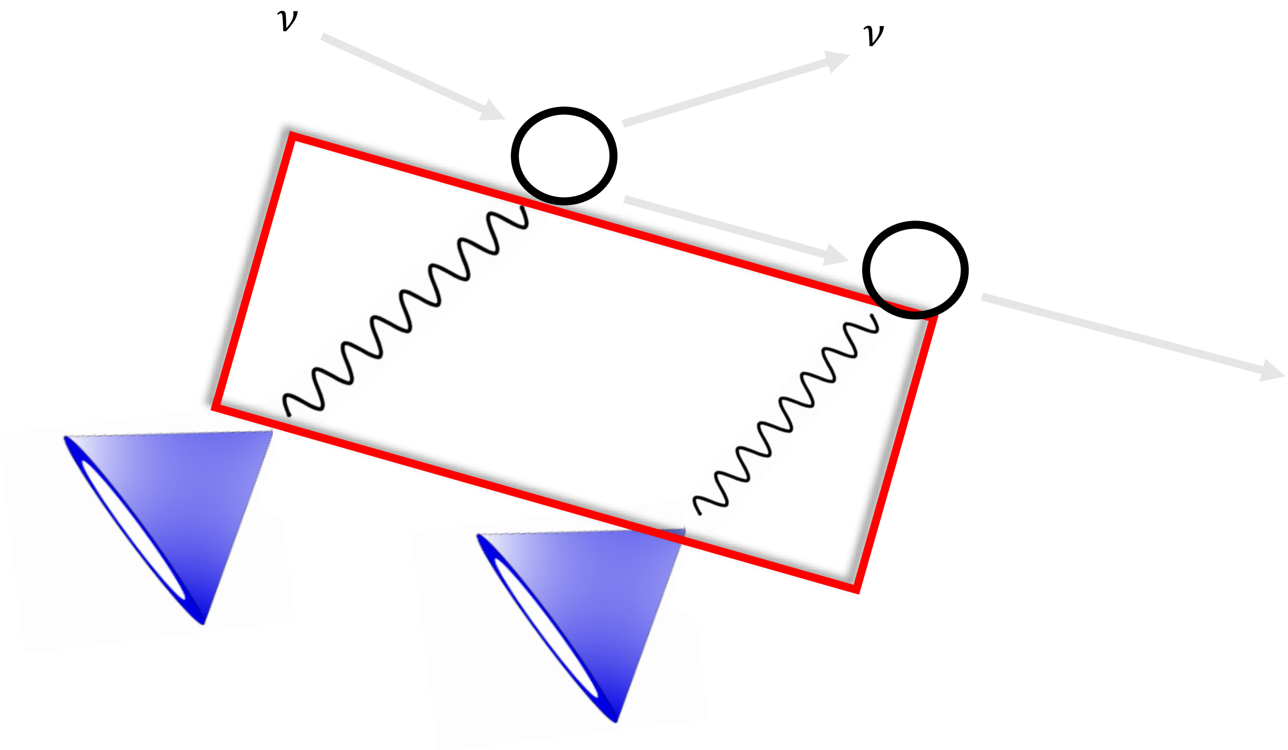
Super-K DSNB analysis: Reduction steps


(“1st reduction”) **Data Quality**

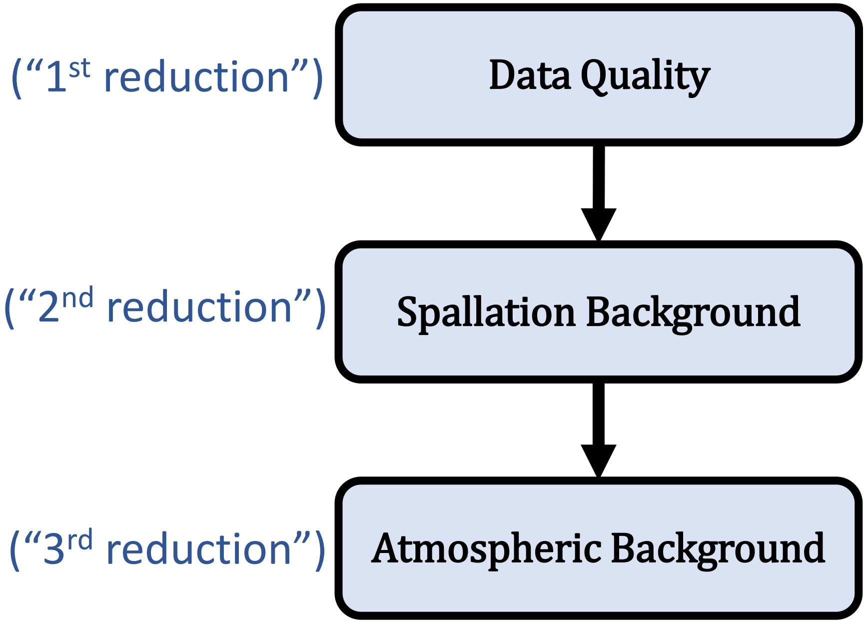
(“2nd reduction”) **Spallation Background**

(“3rd reduction”) **Atmospheric Background**

- Atmospheric neutrino interactions can produce **multi-cone prompt events**.



Super-K DSNB analysis: Reduction steps

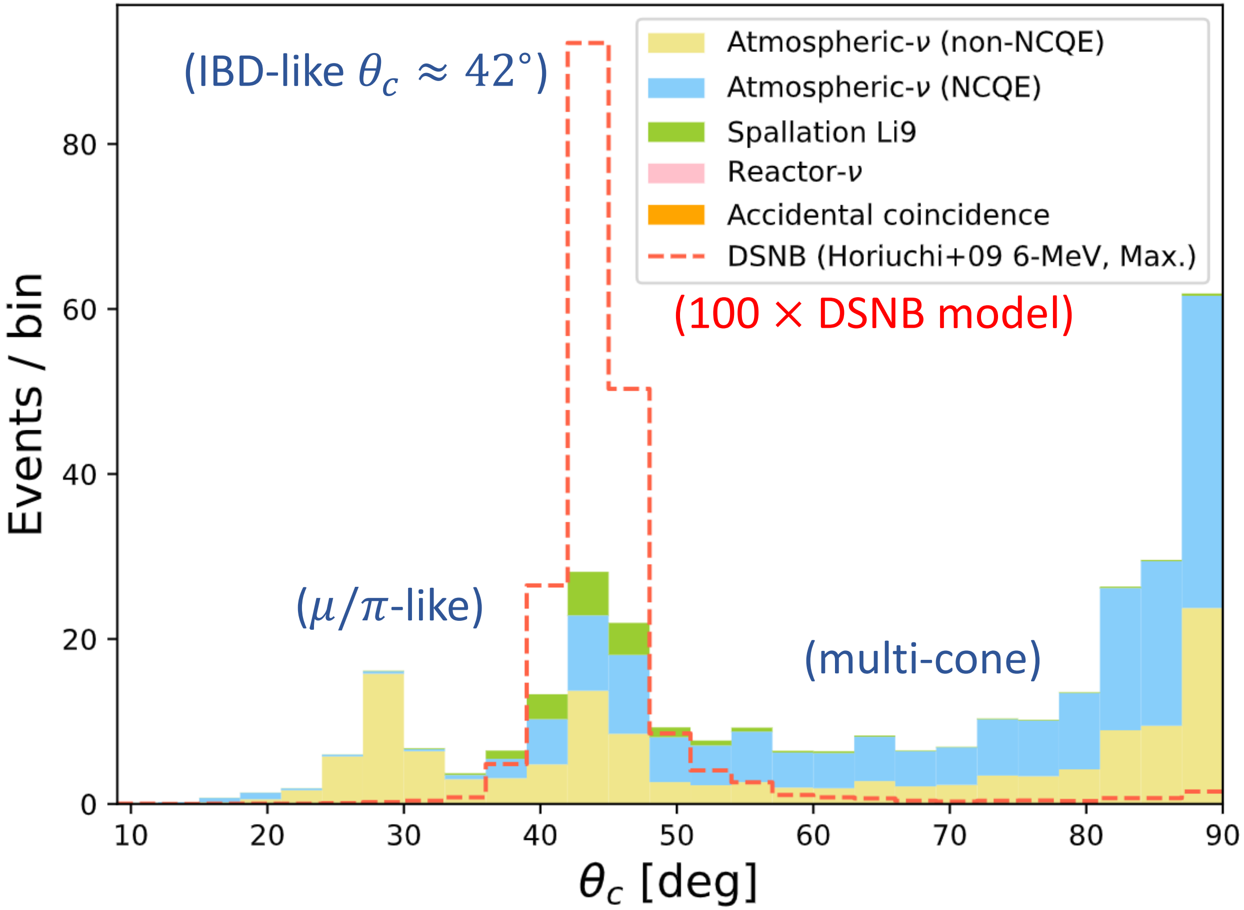


(“1st reduction”) **Data Quality**

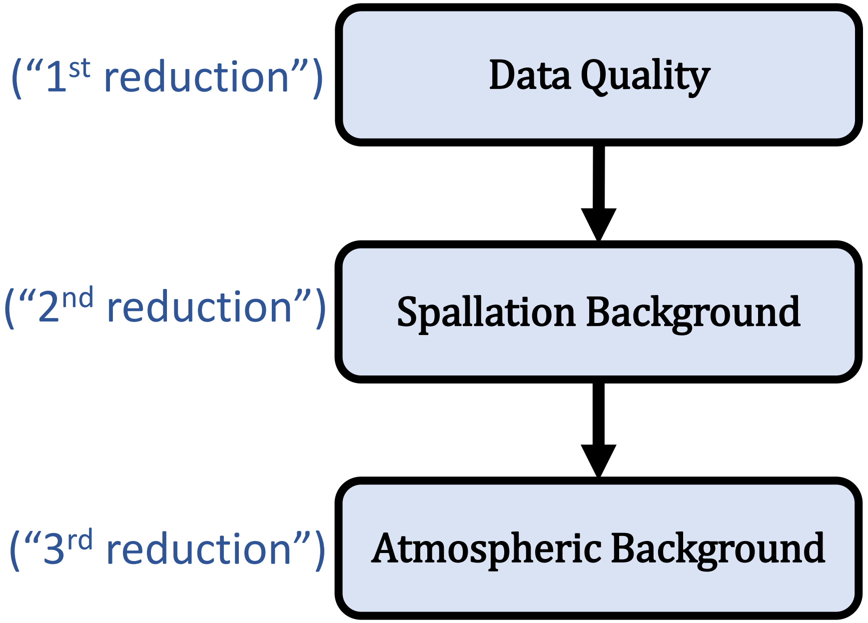
(“2nd reduction”) **Spallation Background**

(“3rd reduction”) **Atmospheric Background**

- Atmospheric neutrino interactions can produce **multi-cone prompt events**.
- Heavy charged leptons near the Cherenkov threshold have **small opening angles**.
- θ_c: Opening angle assuming one cone.



Super-K DSNB analysis: Reduction steps



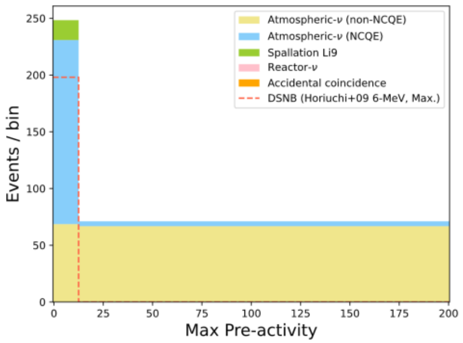
(“1st reduction”) **Data Quality**

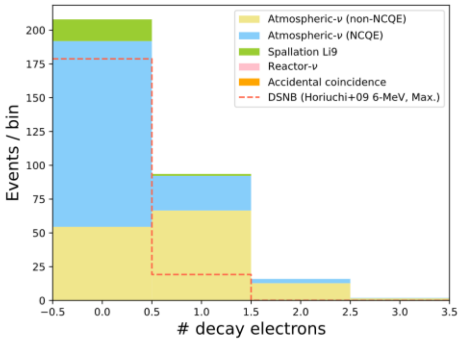
(“2nd reduction”) **Spallation Background**

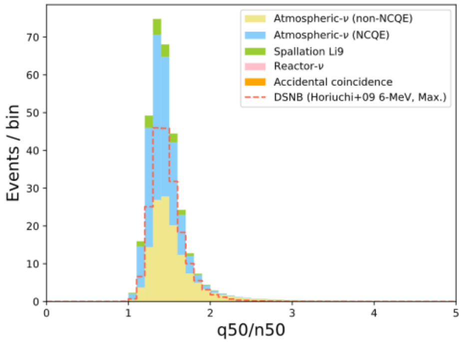
(“3rd reduction”) **Atmospheric Background**

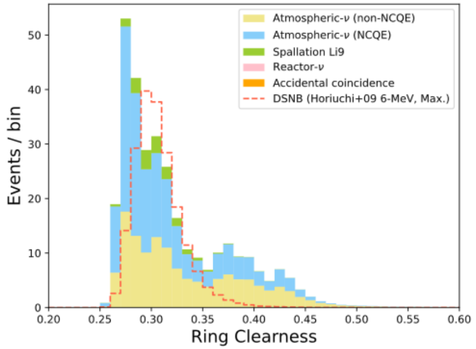
- IBD events will have **low PMT activity before the main prompt peak**, unlike some double-peak atmospheric neutrino backgrounds (maxpre).
- **μ/π decays** can be tagged as “**decay electrons**” (nmue).
- Heavy charged leptons will deposit **more charge-per-PMT** than IBD at higher energies (q50/n50).
- These particles will also create **clearer Cherenkov rings** than lighter $e^{\pm}$ (L_{clear}).

(see backup)

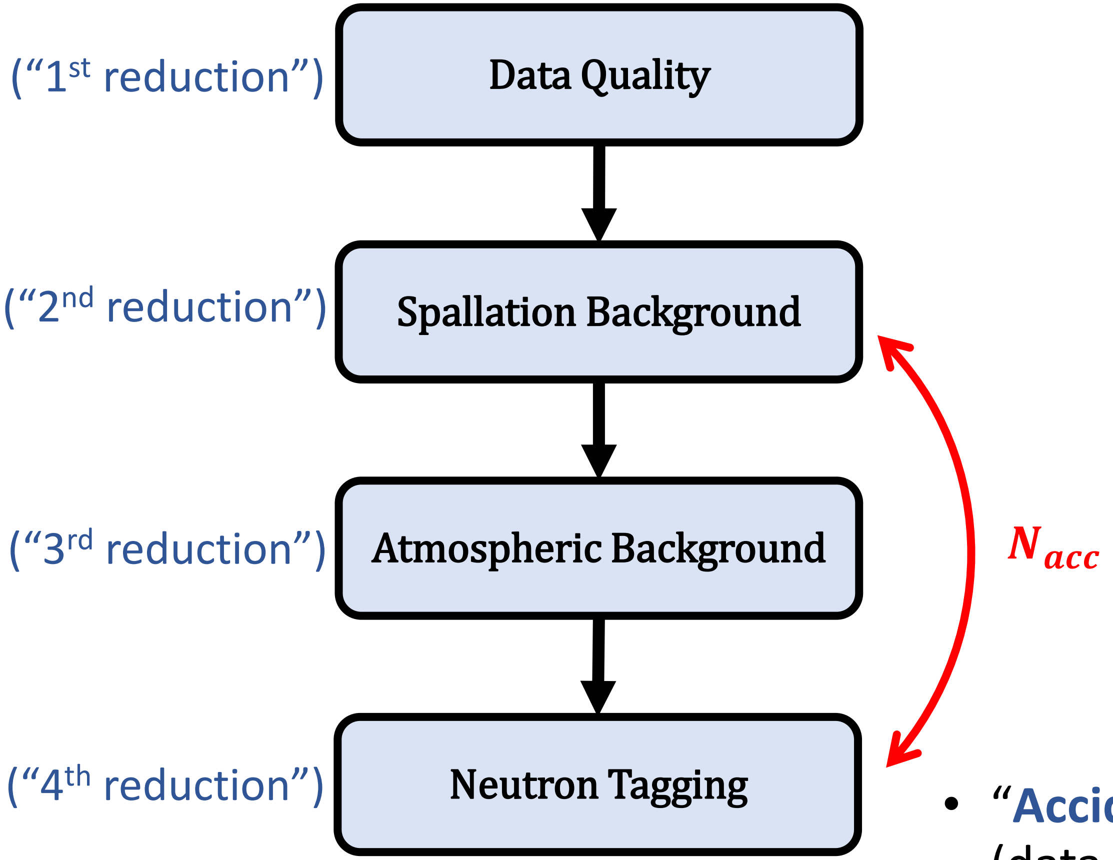








Super-K DSNB analysis: Reduction steps



("1st reduction") Data Quality

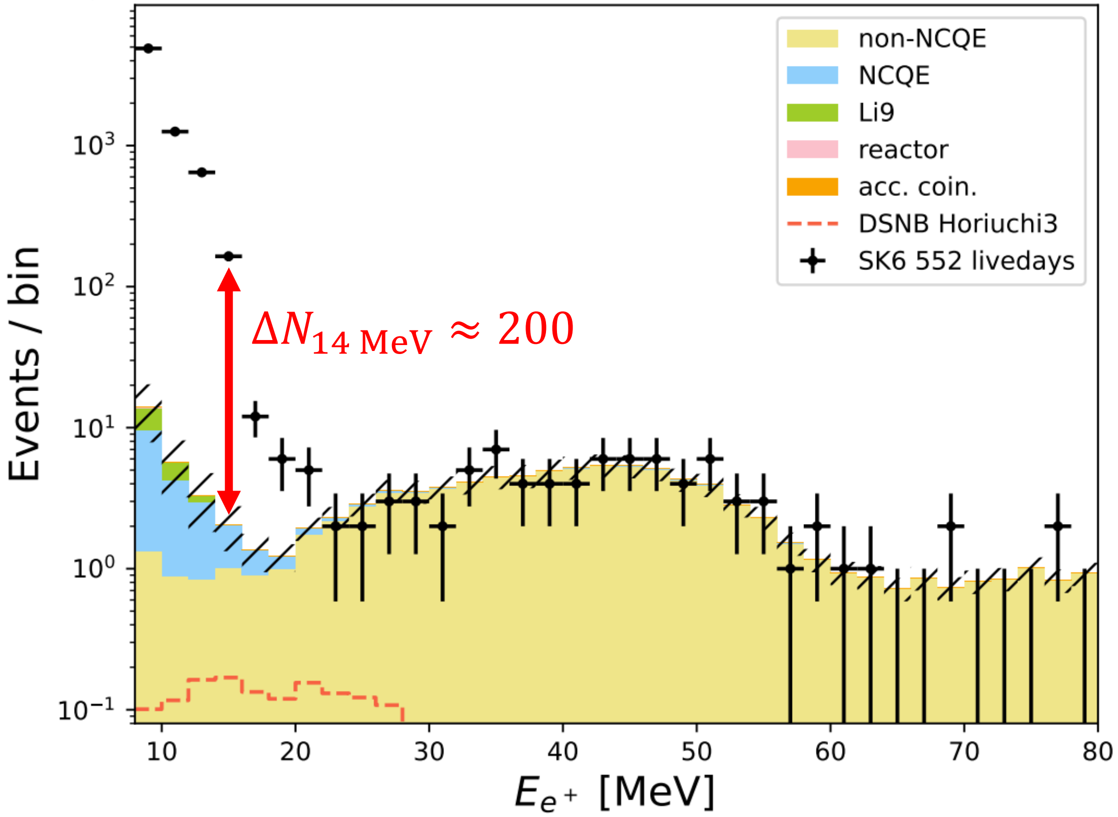
("2nd reduction") Spallation Background

("3rd reduction") Atmospheric Background

("4th reduction") Neutron Tagging

N_{acc}

e.g., 200 (pre-ntag) × (0.1% misID) = 0.2 misID (post-ntag)

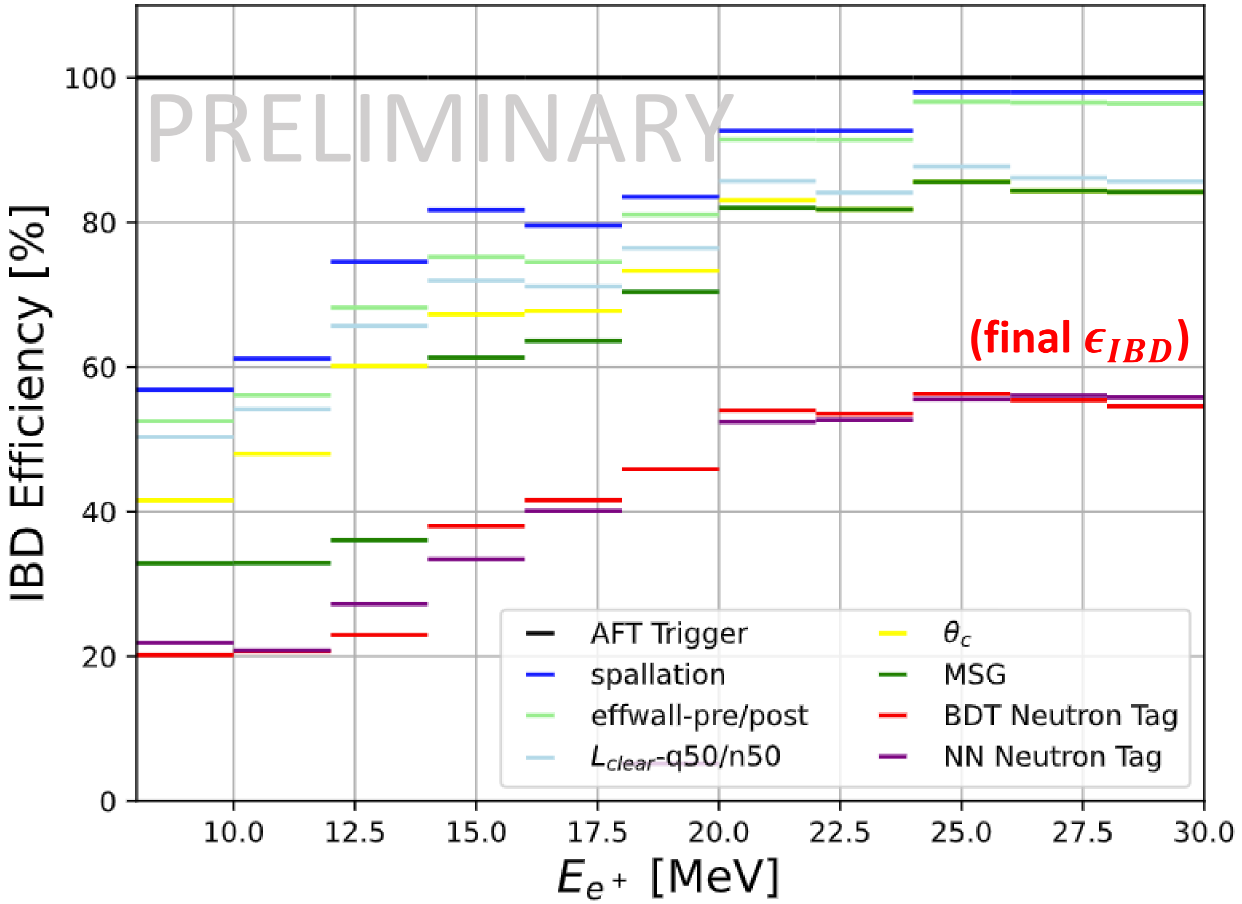


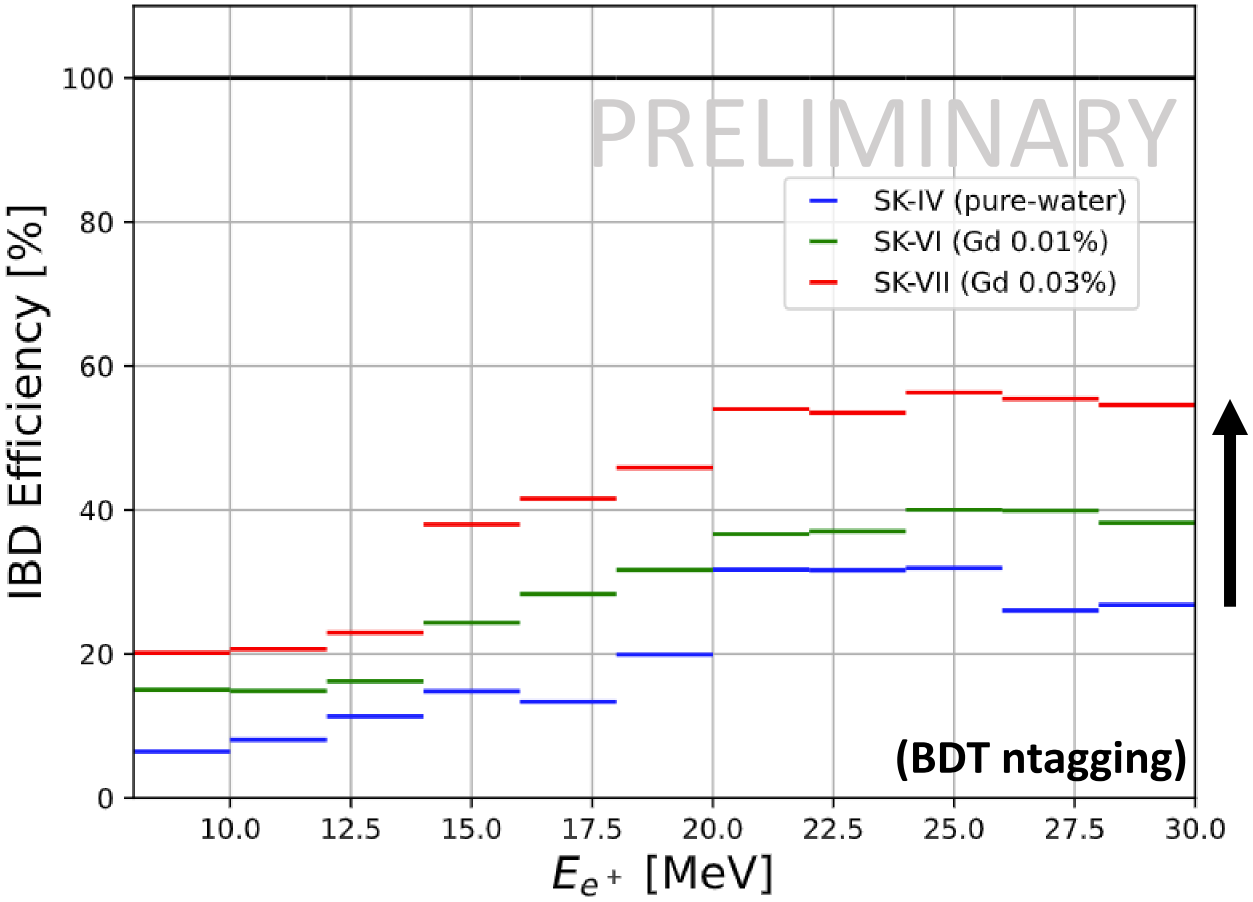
- "**Accidental coincidences**" are calculated with the ΔN_i per bin in (data-MC) before neutron tagging and the mis-tag rate $f_{misID,i}$.

$N_{acc,i} = f_{\mathrm{misID},i}\Delta N_i$ *(prediction for after neutron tagging)*

SK-VII IBD signal efficiency after successive reduction steps

- The addition of Gd in each **SK-Gd phase significantly improves** the final IBD signal efficiency.

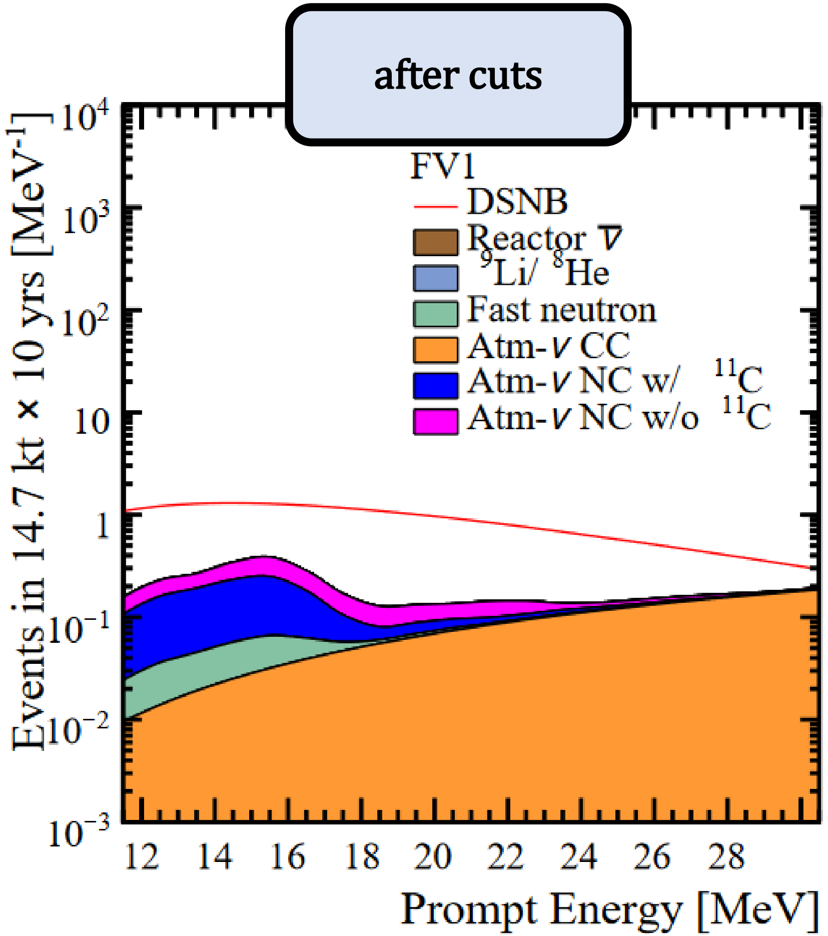


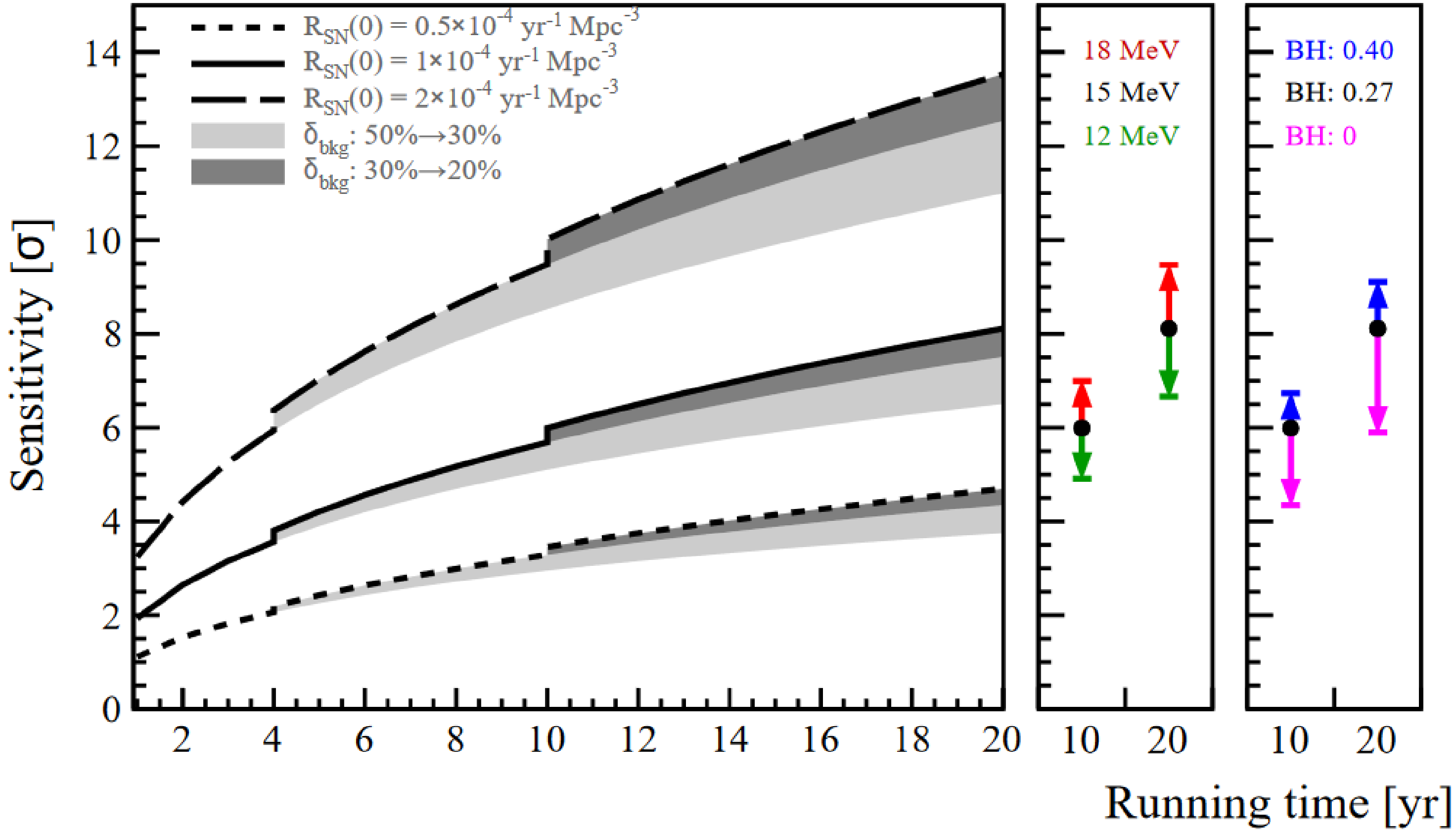


More JUNO/SK sensitivity studies

(backup page)

JUNO DSNB sensitivity

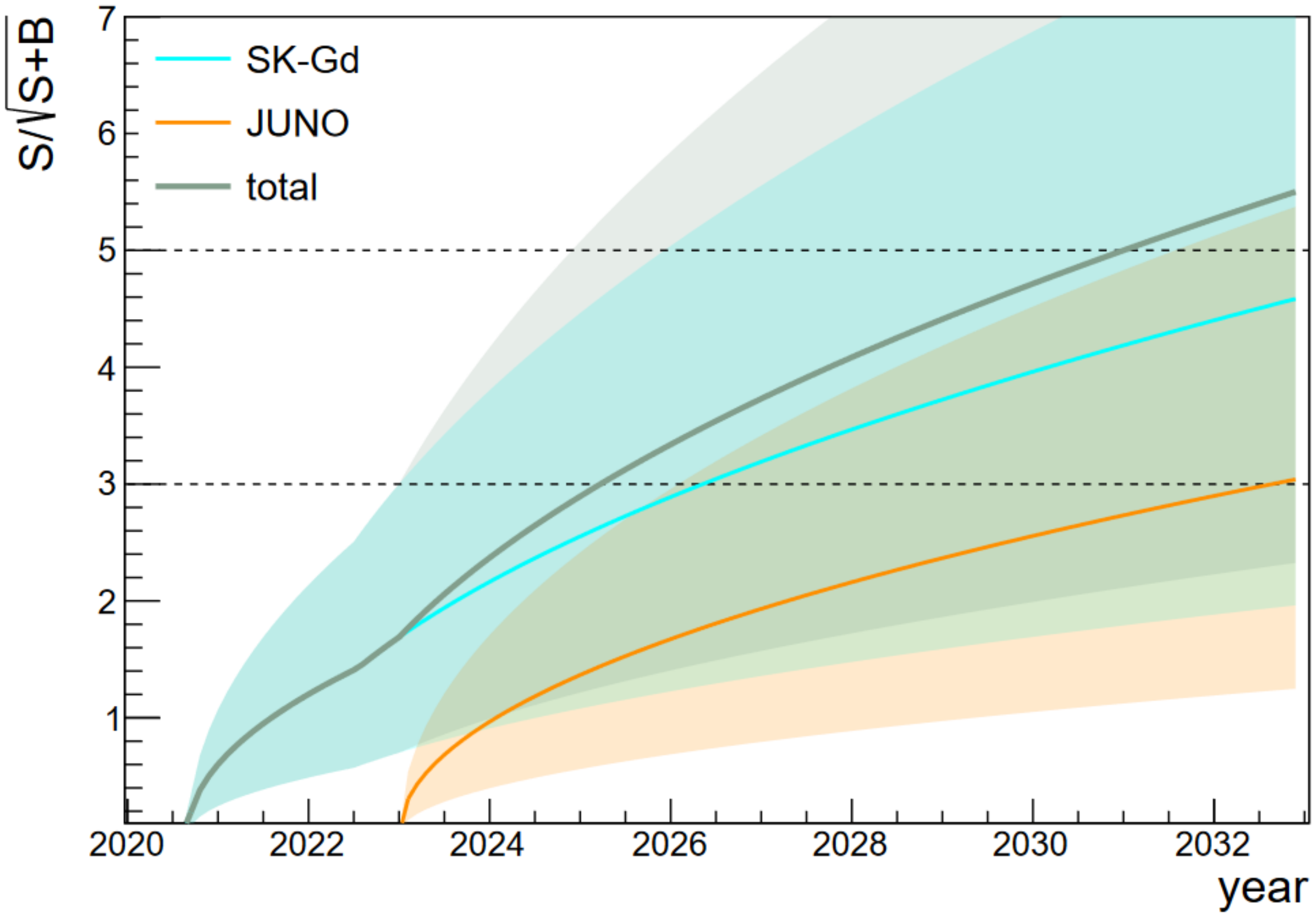

after cuts



- Reference model demonstrates **3σ sensitivity after about 4 years** of data-taking.

A. Abusleme, JCAP ***10*** *(2022) 033*

Comparison of SK-Gd and JUNO DSNB sensitivity



- Text

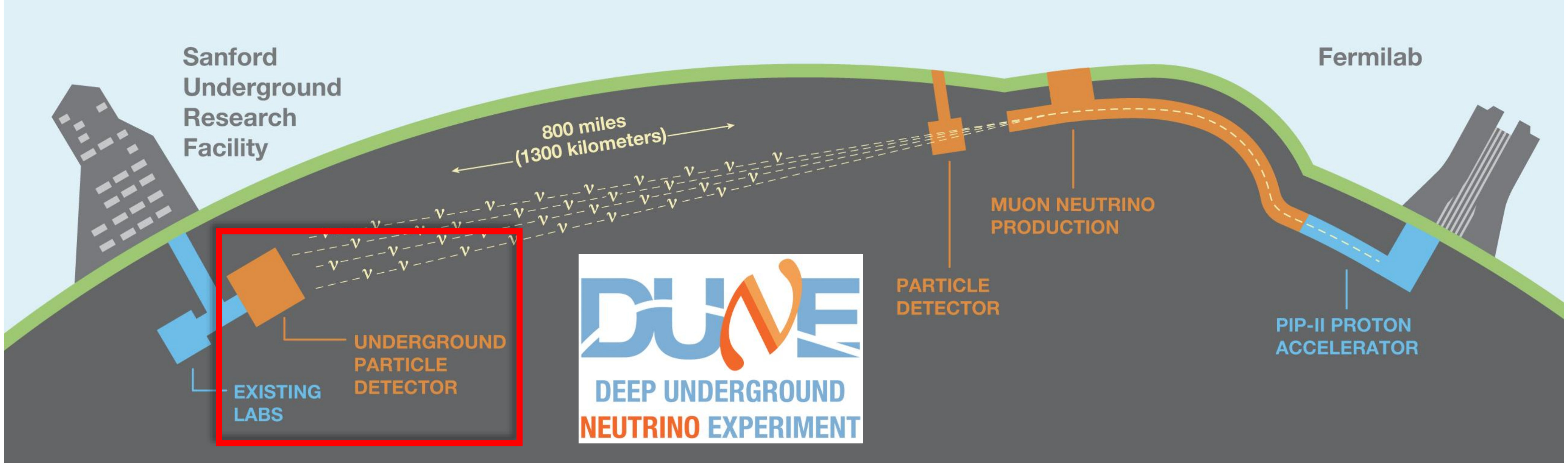
Y.F. Li et al., Universe 8 (2022) 181

DUNE DSNB external study

(backup page)

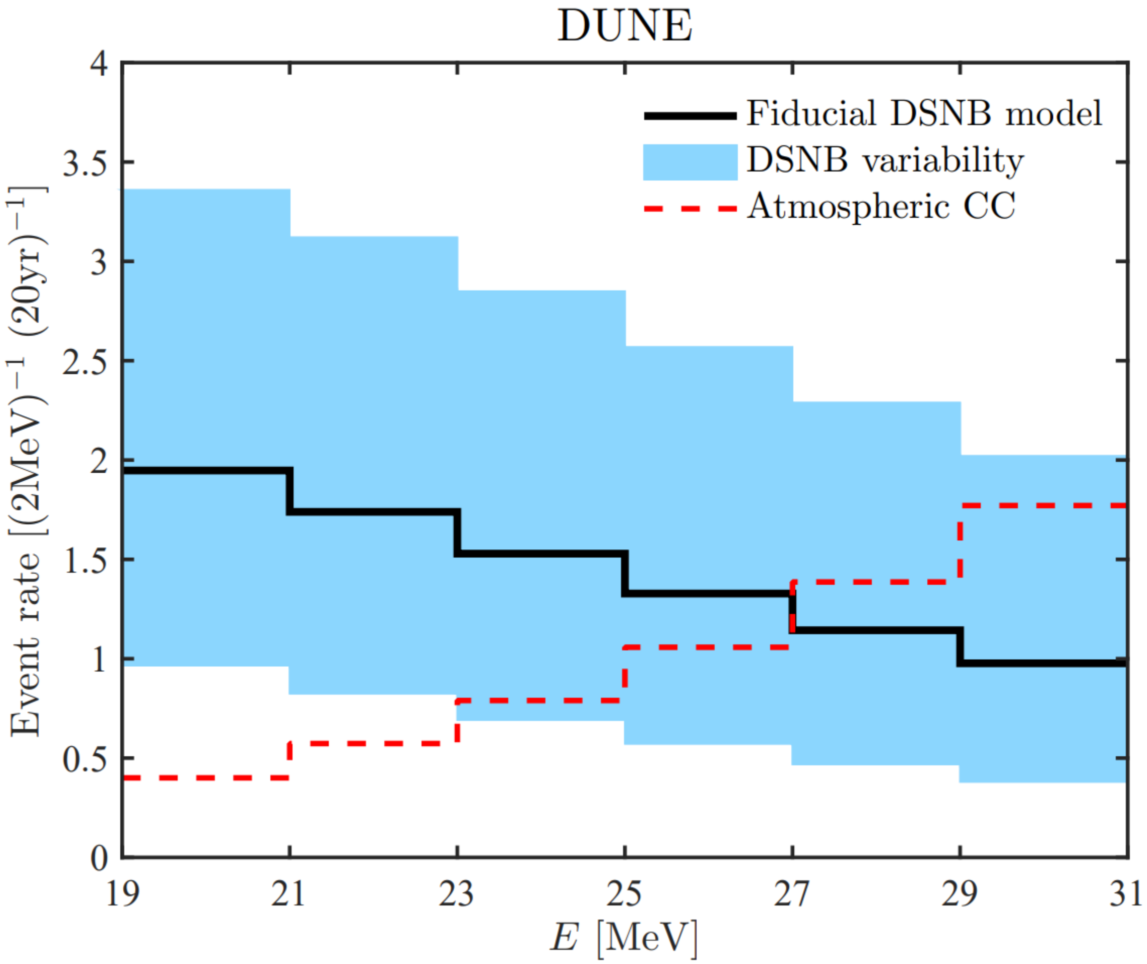
DUNE: Deep Underground Neutrino Experiment

- The **Deep Underground Neutrino Experiment** (DUNE) is a next-generation experiment between Fermilab and Sanford in the United States.
- A **40-kton liquid argon detector** is anticipated in South Dakota to receive neutrinos from Fermilab near Chicago.
- Beyond accelerator neutrino studies, DUNE will have sensitivity to plenty of other sources, including the DSNB.



Source: Fermilab National Laboratory

DUNE sensitivity to DSNB



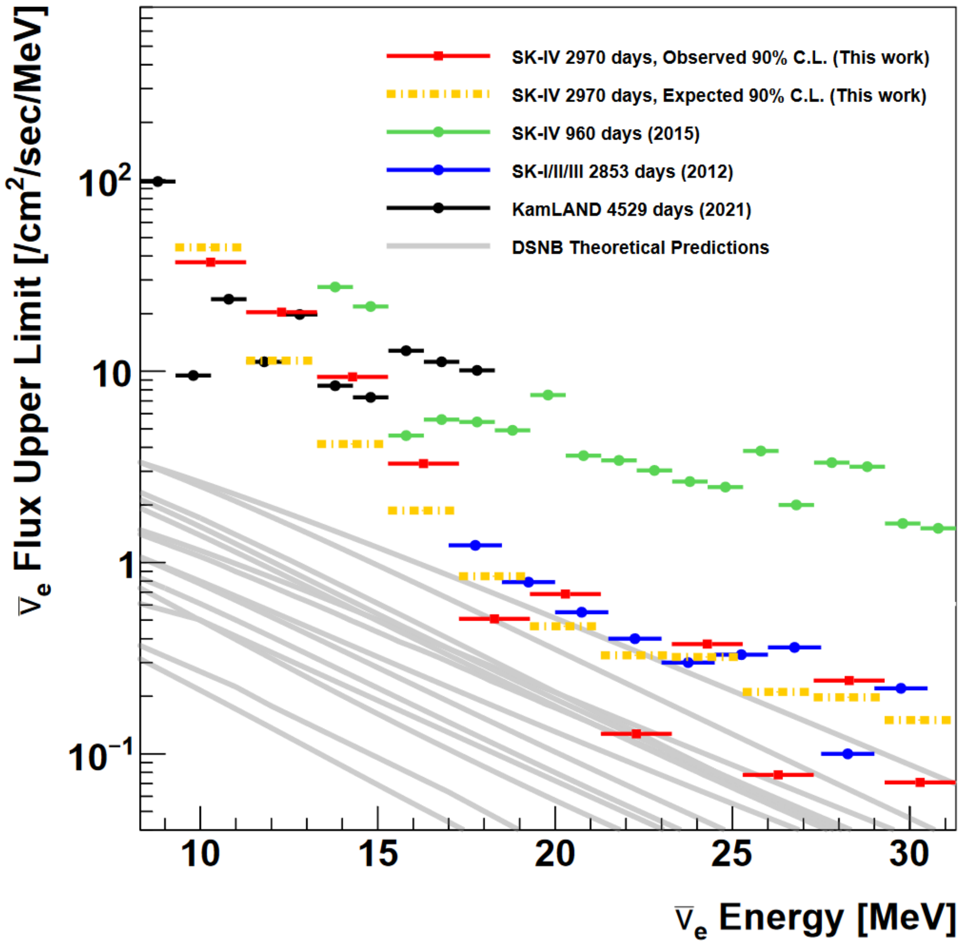
*K. Møller et al., JCAP **05** (2018) 066*

- DUNE will be **sensitive to the ν_e flux** from the DSNB (unlike that of $\bar{\nu}_e$ for experiments like Super-K/Hyper-K/JUNO through IBD).
- Target channel is **ν_e scattering off argon** to give an electron and potassium.
- Studies are underway by the collaboration, and an **external sensitivity analysis** considered **backgrounds similar to the ICARUS** detector (also liquid argon).
- The search is **limited below by solar neutrinos** (B-8 and *hep* fluxes).
- From above, **atmospheric ν_e** cover the DSNB.
- While few events are anticipated, this is a **complementary search to $\bar{\nu}_e$** searches.
- What else can we learn from a DSNB detection?

Neutrino propagation in supernovae

(backup page)

Estimating DSNB sensitivity using upper limits (throw toys)



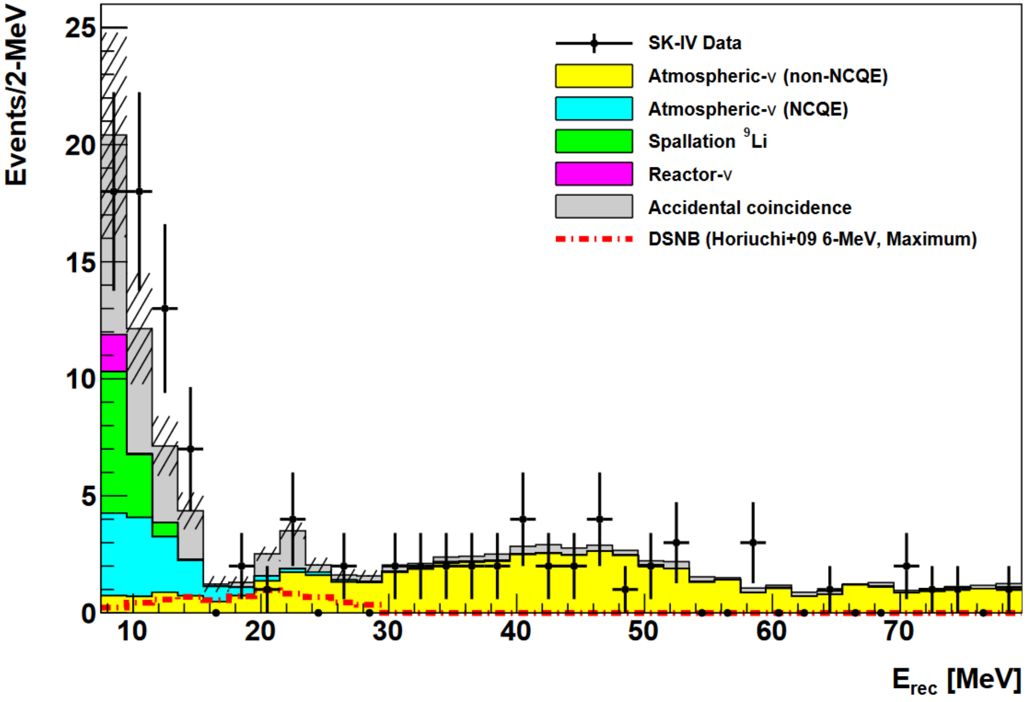
Phys. Rev. D ***104***, *122002 (2021)*

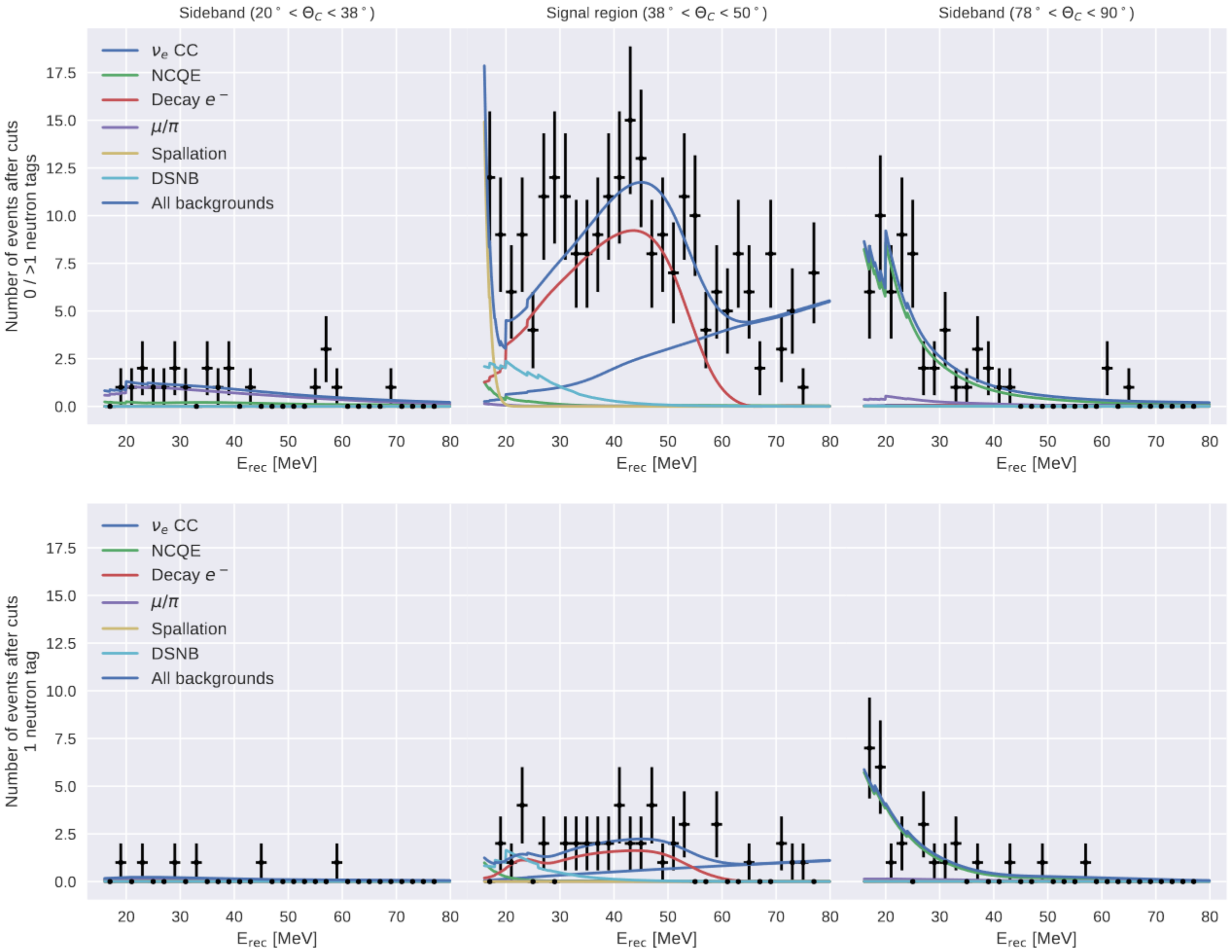
Upper limit steps

1. Sample $N_{obs}(E_{rec})$ from $\mathbf{P}\left(\boldsymbol{N}\left(\boldsymbol{\mu} = \boldsymbol{N_{pred}}, \boldsymbol{\sigma} = \boldsymbol{\delta N_{sys}}\right)\right)$
2. Sample $N_{pred}(E_{rec})$ from $\mathbf{P}\left(\boldsymbol{N_{pred}}\right)$
3. Perform $\boldsymbol{N_{obs}(E_{rec}) - N_{pred}(E_{rec})}$ to generate PDF of excess BG events after **many toys thrown**
4. **Integrate excess BG PDF** until reach 90% of curve to define number of events N_{90}^{limit} for 90% CL
5. Convert N_{90}^{limit} into **flux limit** $\boldsymbol{\phi_{90}^{\text{limit}}}$

$$\phi_{90}^{\text{limit}} = \frac{N_{90}^{\text{limit}}}{t \cdot N_p \cdot \bar{\sigma}_{\text{IBD}} \cdot \epsilon_{\text{sig}}}$$

SK-IV DSNB analysis results in more detail



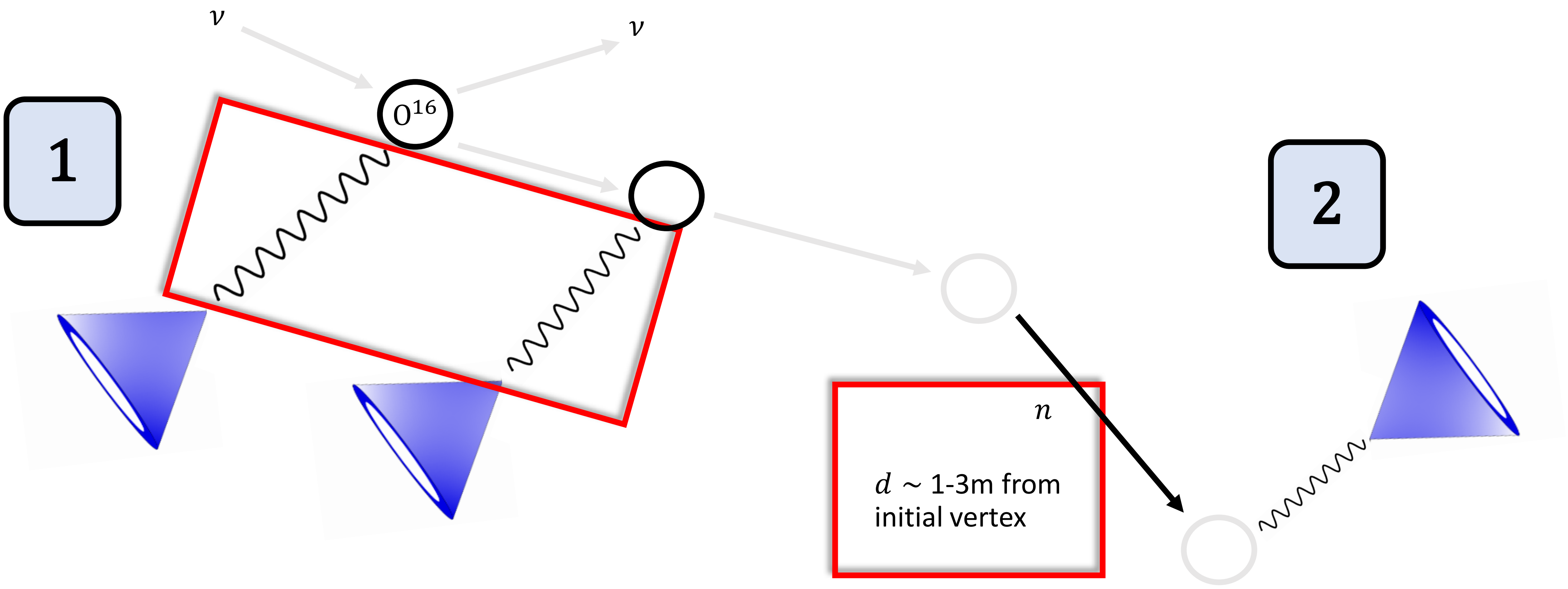


Phys. Rev. D ***104****, 122002 (2021)*

“Multiple Scattering Goodness” cut in Super-K DSNB analysis

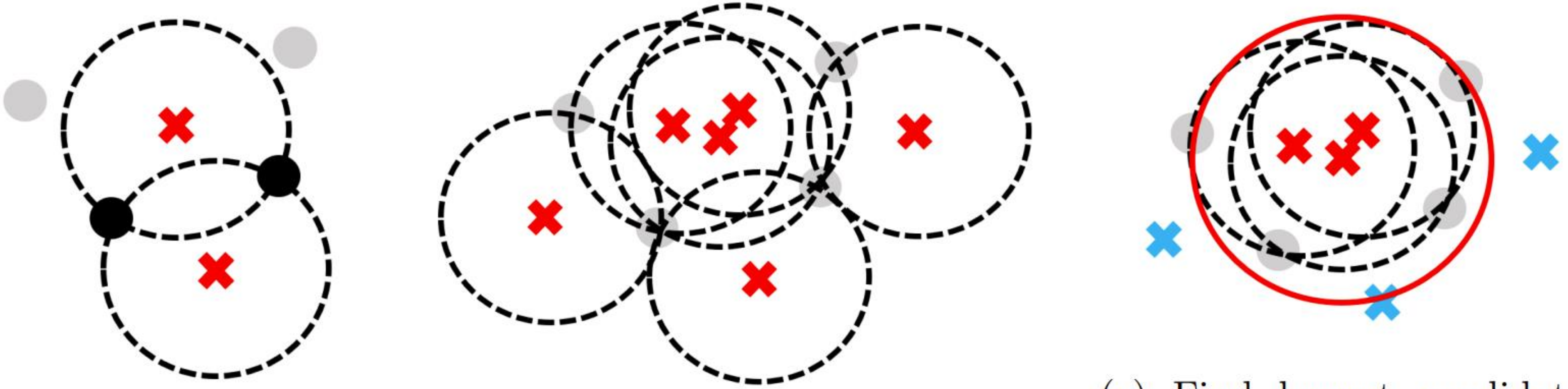
(backup page)

Differences of overall NCQE from DSNB IBD signal



d ~ 1-3m from initial vertex

MSG definition



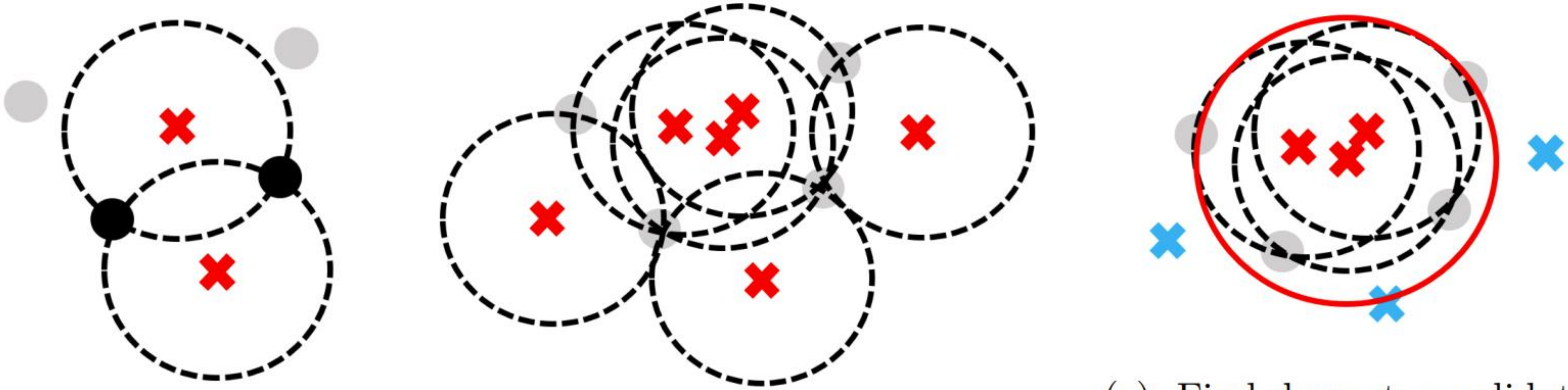
(a) Identify candidate cones per pair (here, black) of PMTs hit.

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

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

Figure 63: Steps for defining MSG variable. The hit PMTs are in gray, the candidate directions are crosses, and those found in the largest cluster are kept a red color.

Comparison of $\boldsymbol{\theta}_c$ and MSG variables



(a) Identify candidate cones per pair (here, black) of PMTs hit.

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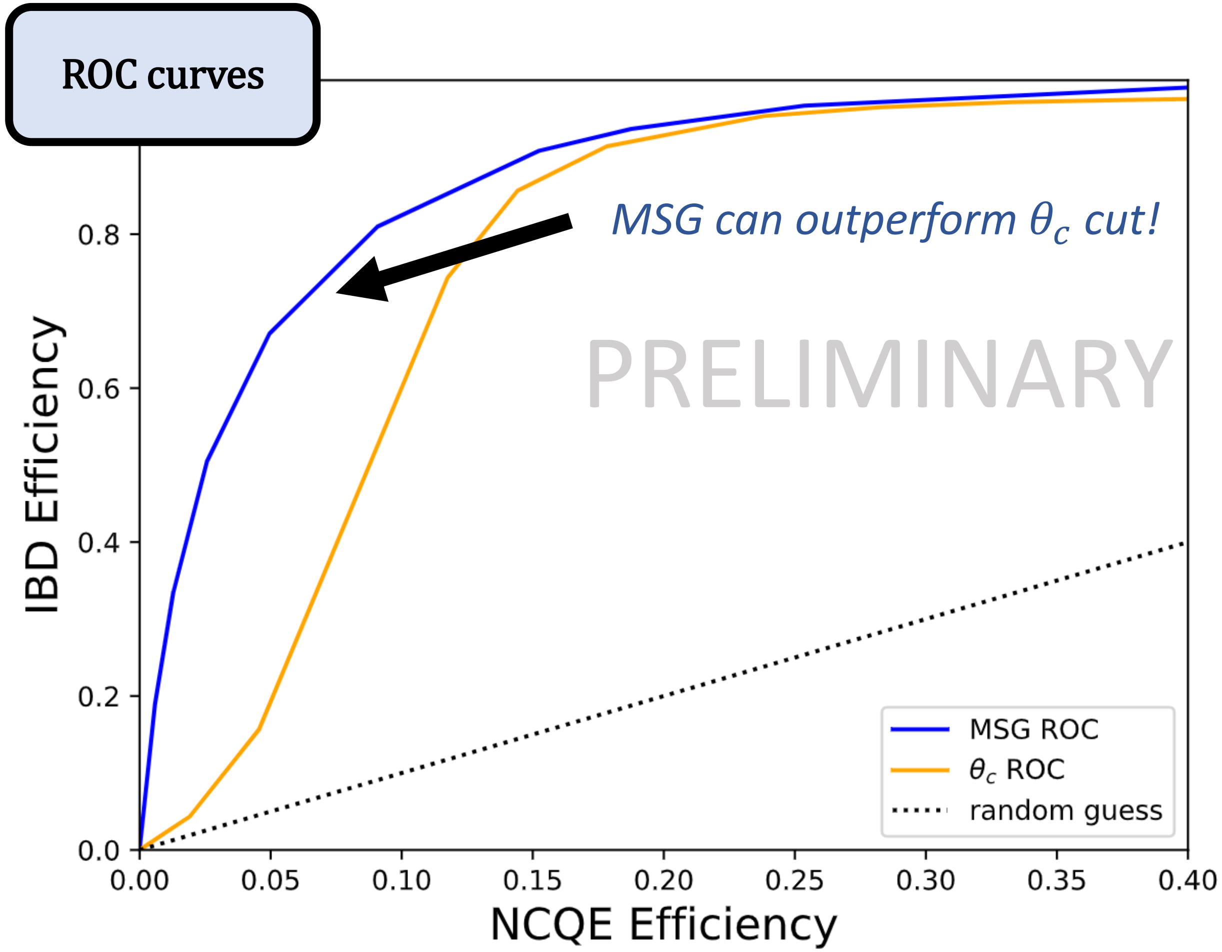
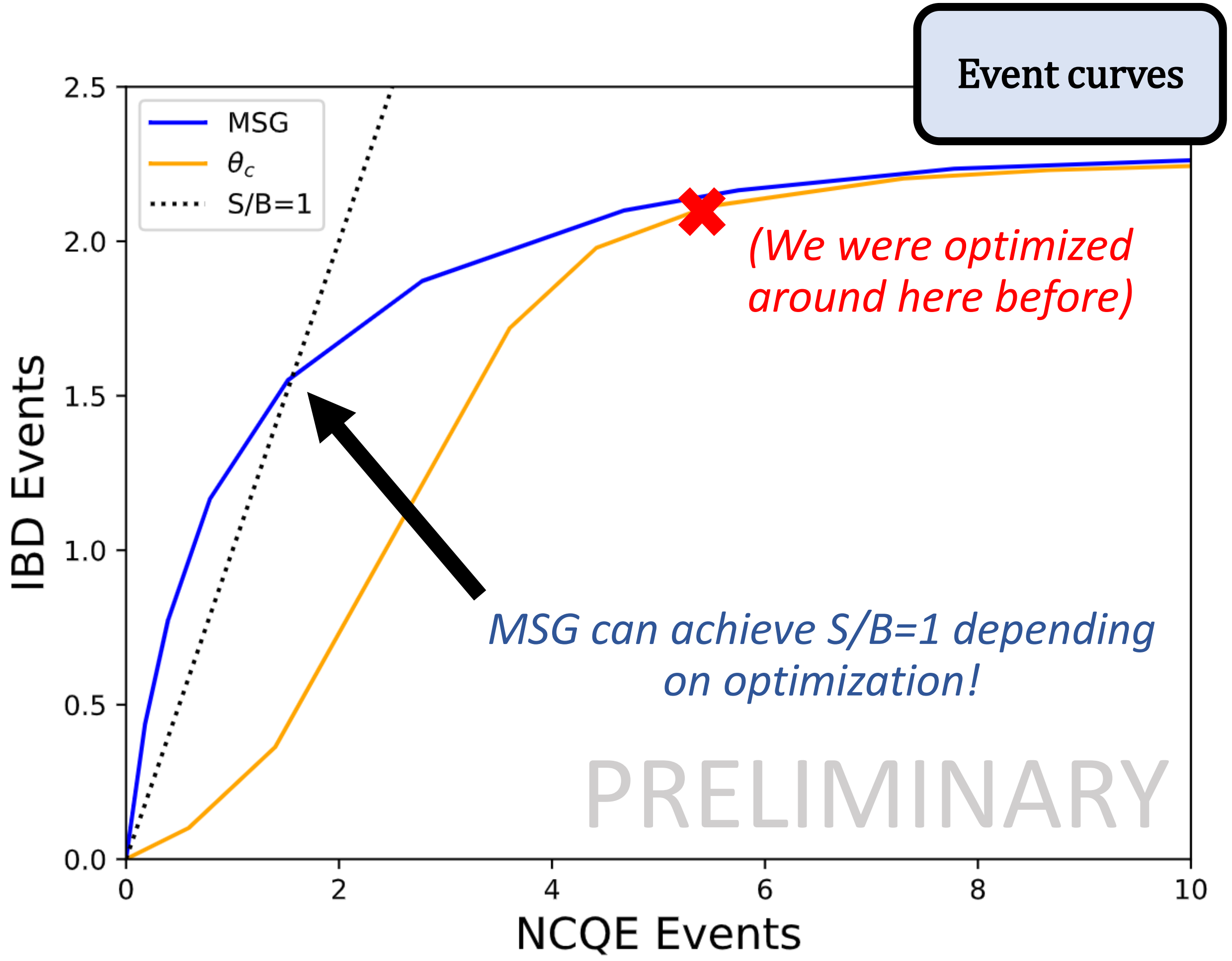
Figure 63: Steps for defining MSG variable. The hit PMTs are in gray, the candidate directions are crosses, and those found in the largest cluster are kept a red color.

SK6 MSG and θ_c cut comparisons ($E_{e^+} \in [8, 24]$ MeV)



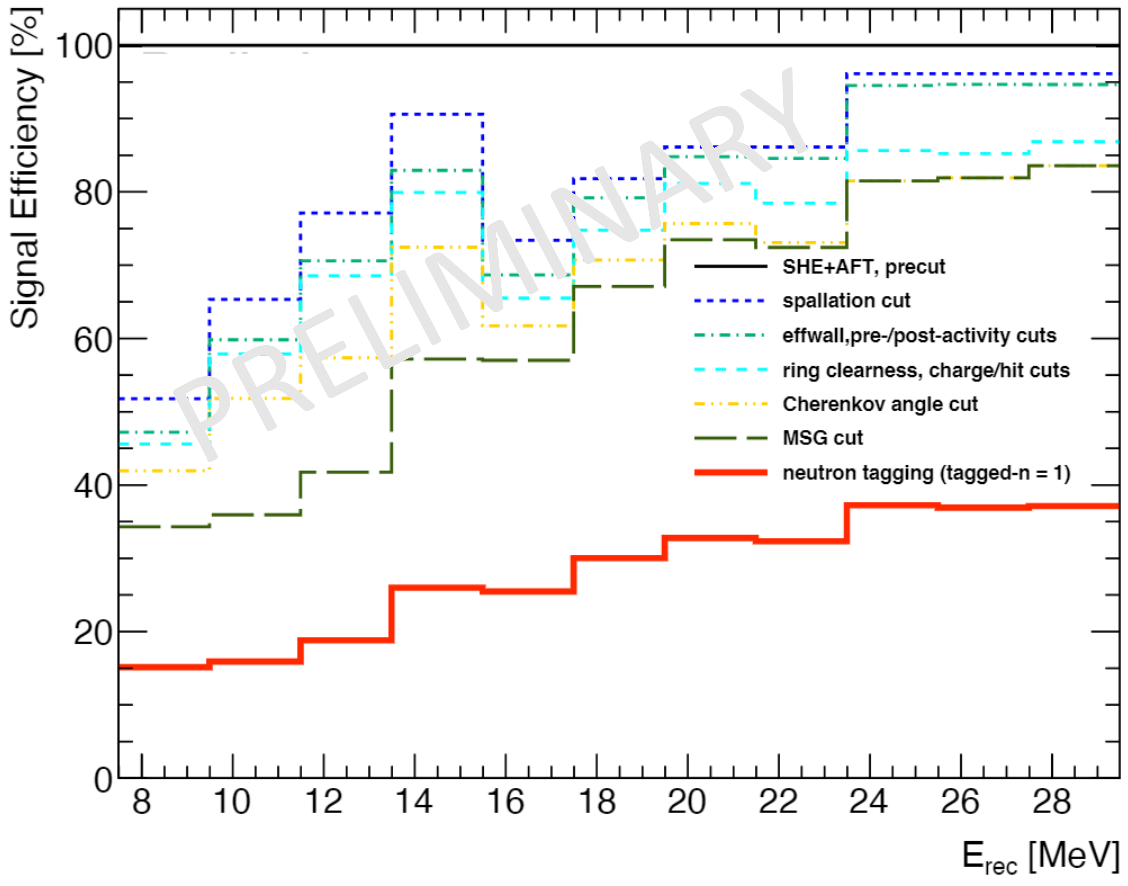
MSG can outperform θ_c cut!

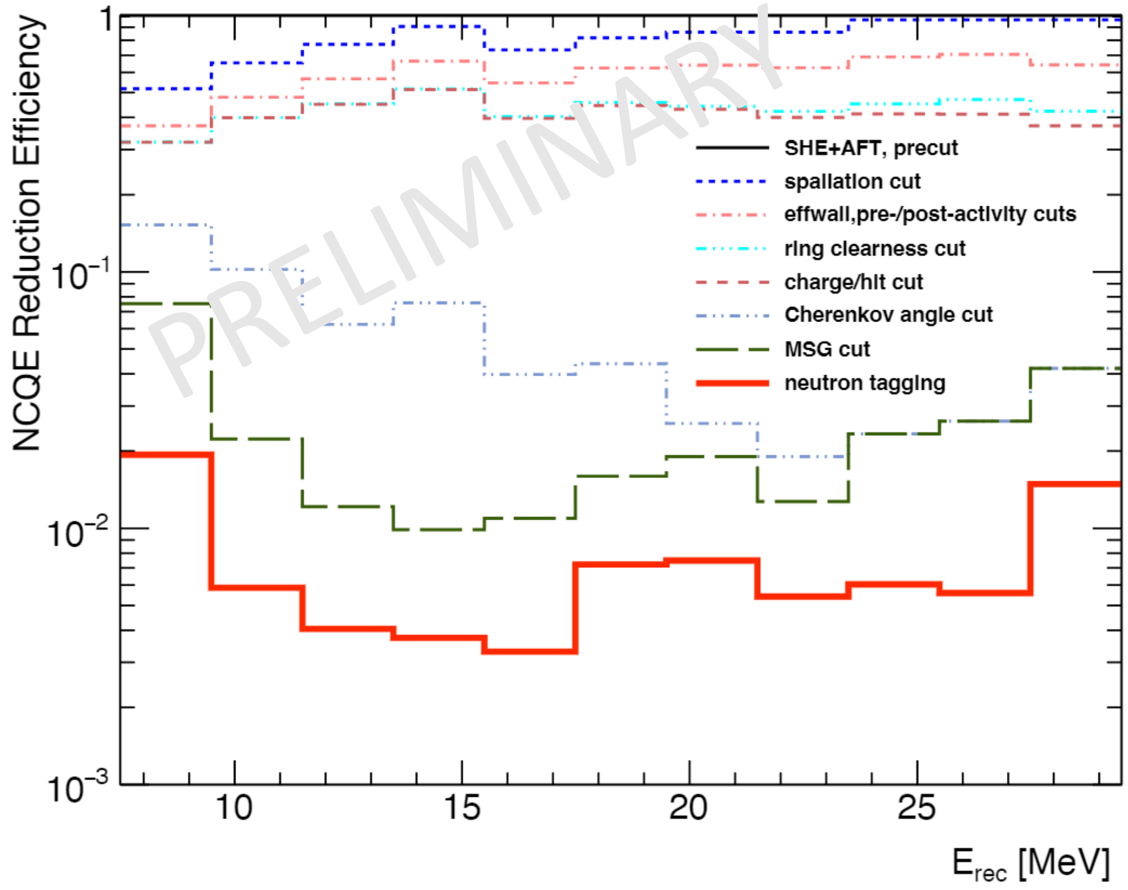


(We were optimized around here before)

MSG can achieve S/B=1 depending on optimization!

Signal and NCQE background efficiencies after cuts





ADS, Moriond proceedings (2024)

Neutrino propagation in CCSNe

(backup page)

Neutrino oscillations from mismatched mass, flavor states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

(flavor basis)

(mass basis)

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_x\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

(2-flavor framework)

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

(approximations)

$$|\nu_e(L)\rangle = \boldsymbol{e}^{-\frac{\boldsymbol{i m_1^2 L}}{\boldsymbol{2E}}} \cos\theta\,|\nu_1\rangle + \boldsymbol{e}^{-\frac{\boldsymbol{i m_2^2 L}}{\boldsymbol{2E}}} \sin\theta\,|\nu_2\rangle$$

(different phases in t-evolution)

$(\Delta m^2_{ij} \equiv m^2_i - m^2_j)$

(frequency of oscillation)

$$\boxed{P_{ee} = |\langle\nu_e(L)|\nu_e\rangle|^2 = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$$

(amplitude of oscillation)

Parameterizing full mixing matrix between mass, flavor bases

(flavor basis) *CP-violating Dirac phase* *Majorana phases* *(mass basis)*

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$s_{ij} \equiv \sin\theta_{ij}\,,\, c_{ij} \equiv \cos\theta_{ij}$$

$\theta_{12} = 33.41^{\circ}{}^{+0.75^{\circ}}_{-0.72^{\circ}}$, $\theta_{23} = 49.1^{\circ}{}^{+1.0^{\circ}}_{-1.3^{\circ}}$, $\theta_{13} = 8.54^{\circ}{}^{+0.11^{\circ}}_{-0.12^{\circ}}$, $\delta_{CP} = 196^{\circ}{}^{+42^{\circ}}_{-25^{\circ}}$ *Source: NuFIT 2022*

(maximal mixing?) *(hints of CP-violation)*

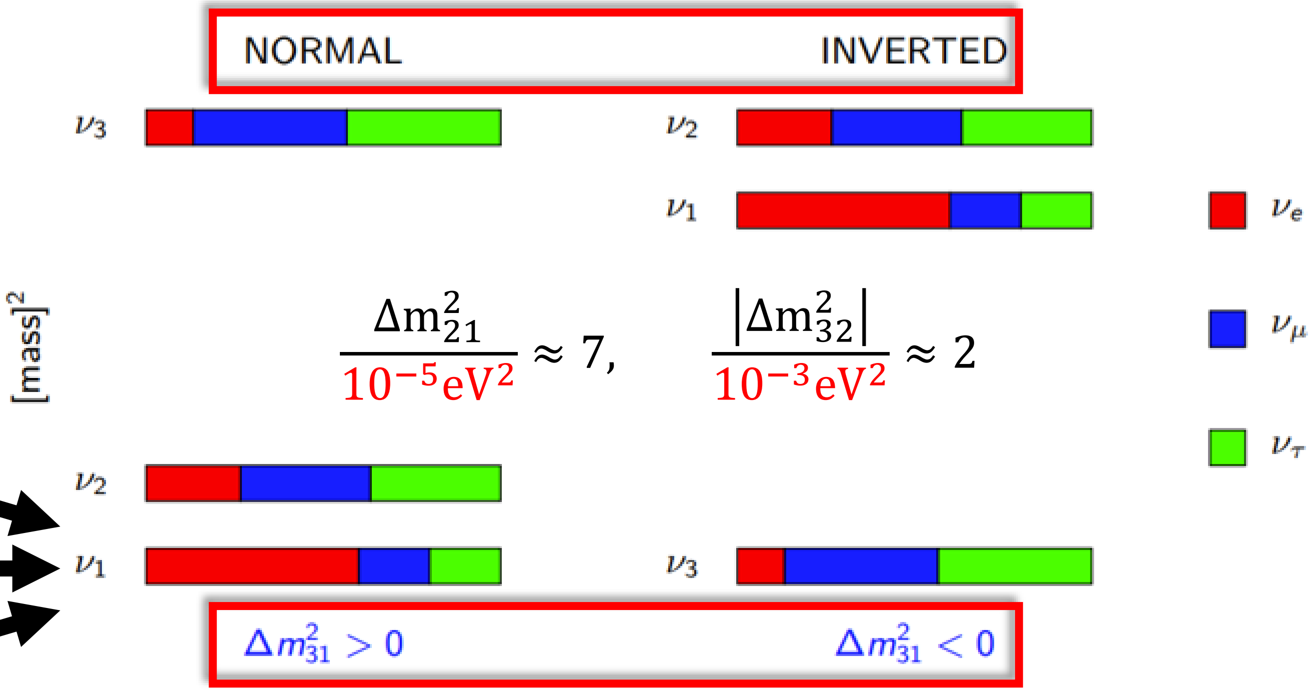
The mass hierarchy problem (normal vs inverted)

$$|U_{PMNS}| \approx \begin{pmatrix} 0.8 & 0.5-0.6 & 0.1-0.2 \\ 0.2-0.5 & 0.5-0.7 & 0.6-0.8 \\ 0.3-0.5 & 0.5-0.7 & 0.6-0.8 \end{pmatrix}$$

$$|\langle\nu_e|\nu_1\rangle|^2 = |U_{e1}|^2 \approx 0.8^2 = 0.64$$

$$|\langle\nu_\mu|\nu_1\rangle|^2 = |U_{\mu1}|^2 \approx 0.4^2 = 0.16$$

$$|\langle\nu_\tau|\nu_1\rangle|^2 = |U_{\tau1}|^2 \approx 0.4^2 = 0.16$$



$$\frac{\Delta m^2_{21}}{10^{-5}\text{eV}^2} \approx 7, \quad \frac{|\Delta m^2_{32}|}{10^{-3}\text{eV}^2} \approx 2$$

Punchline for the effect of matter on neutrino propagation

The Sun

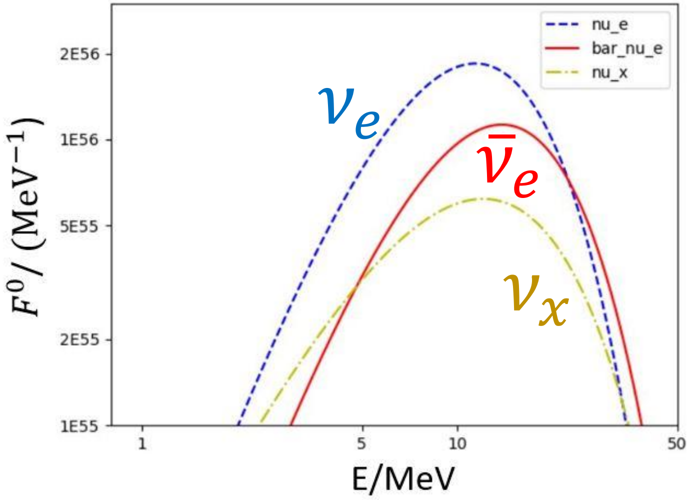
$$\boxed{F_{\nu_e}^{2>1} = |\langle \nu_e|\nu_2\rangle|^2 F_{\nu_e}^0 \approx 0.3 F_{\nu_e}^0 \qquad m_2 > m_1!}$$

$$F_{\nu_e}^{1>2} = |\langle \nu_e|\nu_1\rangle|^2 F_{\nu_e}^0 \approx 0.7 F_{\nu_e}^0$$

Different mass orderings give different final spectra!

Supernovae

(time-integrated SN neutrino spectra)



$$m_3 > m_2 > m_1 \; ? \quad F_{\nu_e}^{3>2} = \left(0 \times F_{\nu_e}^0\right) + \left(1 \times F_{\nu_x}^0\right)$$

$$m_2 > m_1 > m_3 \; ? \quad F_{\nu_e}^{2>3} = \left(0.3 \times F_{\nu_e}^0\right) + \left(0.7 \times F_{\nu_x}^0\right)$$

Modified flavor oscillations in the presence of matter (2 flavors)

(usual Hamiltonian) *(additional CC potential for ν_e)*

$$H = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \sqrt{2}G_F n_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

$$\boxed{\tan 2\theta_M} = \frac{\left(\frac{\Delta m^2}{2E}\right)\sin 2\theta}{\left(\frac{\Delta m^2}{2E}\right)\cos 2\theta - \sqrt{2}G_F n_e}$$

(new effective mixing angle)

Mikheyev-Smirnov-Wolfenstein (MSW) effect

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos\theta_M \end{pmatrix} \boxed{\begin{pmatrix} |\nu_{1M}\rangle \\ |\nu_{2M}\rangle \end{pmatrix}}$$

(new propagation basis)

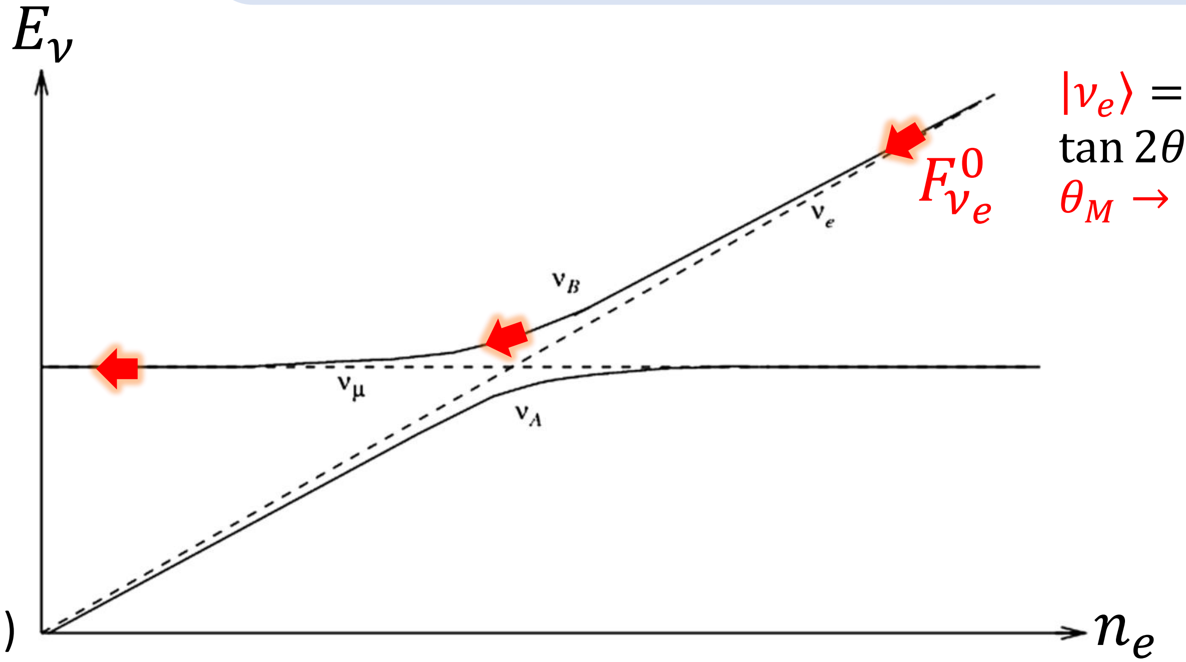
Two flavors!

Modified flavor oscillations in the presence of matter (2 flavors)

Mikheyev-Smirnov-Wolfenstein (MSW) effect

$$\tan 2\theta_M = \frac{\left(\frac{\Delta m^2}{2E}\right)\sin 2\theta}{\left(\frac{\Delta m^2}{2E}\right)\cos 2\theta - \sqrt{2}G_F n_e}$$

$$\begin{pmatrix}|\nu_e\rangle \\ |\nu_\mu\rangle\end{pmatrix} = \begin{pmatrix}\cos\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos\theta_M\end{pmatrix}\begin{pmatrix}|\nu_{1M}\rangle \\ |\nu_{2M}\rangle\end{pmatrix}$$



$|\nu_e\rangle = \cos\theta_M|\nu_{1M}\rangle + \sin\theta_M|\nu_{2M}\rangle \sim |\nu_{2M}\rangle$
$\tan 2\theta_M \to 0^-$
$\theta_M \to 90°$

$|\nu_{2M}(n_e = 0)\rangle = |\nu_2\rangle$
$\tan 2\theta_M \to \tan 2\theta$
$\theta_M \to \theta$

Vacuum ($n_e = 0$)

MSW resonance
$\tan 2\theta_M \to \infty$
$\theta_M \to 45°$

Observed from Sun ($\Rightarrow \Delta \mathrm{m}^2_{21} > 0$)!

$$\boxed{F^{2>1}_{\nu_e} = |\langle\nu_e|\nu_2\rangle|^2 F^0_{\nu_e} \approx 0.3 F^0_{\nu_e}}$$

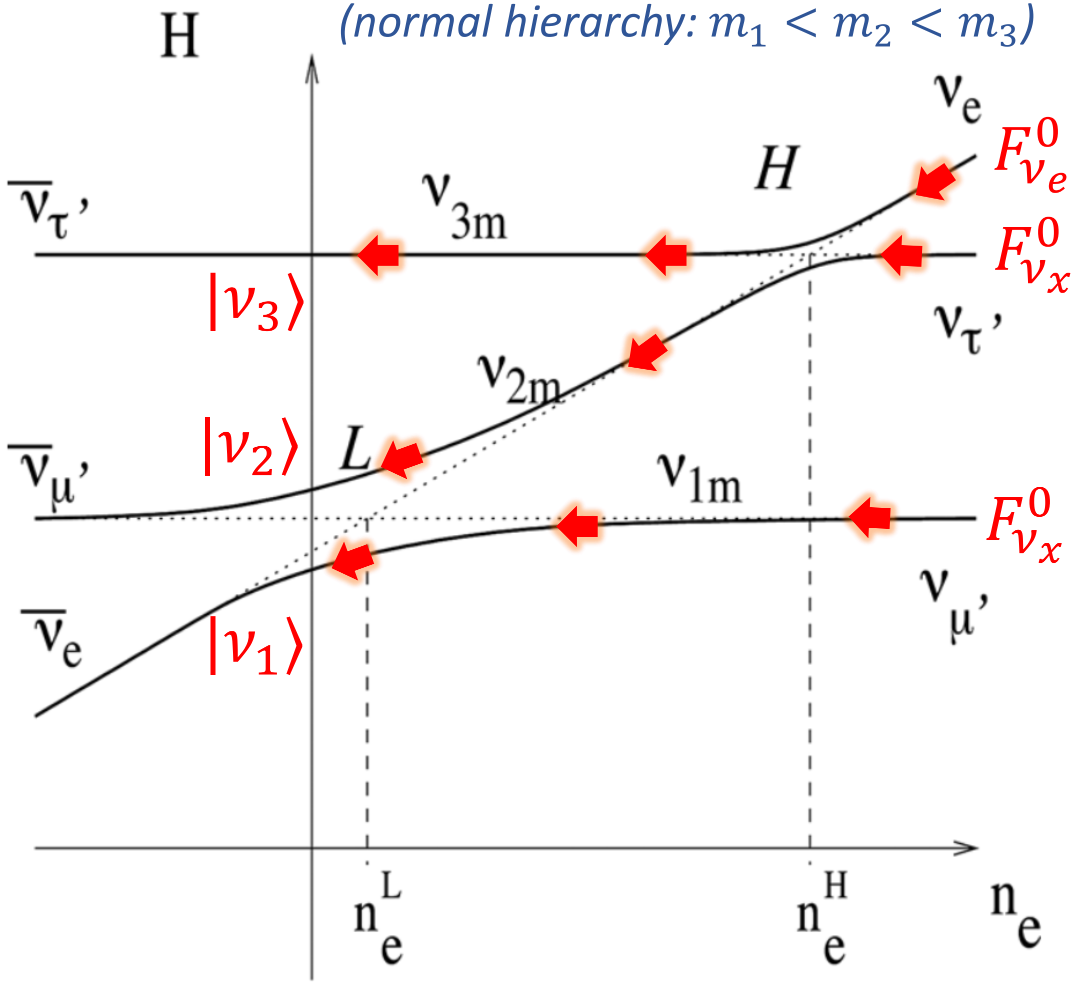
$$F^{1>2}_{\nu_e} = |\langle\nu_e|\nu_1\rangle|^2 F^0_{\nu_e} \approx 0.7 F^0_{\nu_e}$$

Two flavors!

Example calculation of flavor oscillations in supernovae

$$
\begin{aligned}
F_{\nu_e}^{NH} &= |U_{e3}|^2 F_{\nu_e}^0 + \cdots , \qquad |U_{e3}|^2 = |\langle \nu_e | \nu_3 \rangle|^2 \\
&= \left| s_{13} e^{-i\delta_{CP}} \right|^2 F_{\nu_e}^0 + \cdots , \\
&= s_{13}^2 \, F_{\nu_e}^0 + |U_{e2}|^2 F_{\nu_x}^0 + \cdots , F_{\nu_x}{}^0 \equiv F_{\nu_\mu}^0 = F_{\nu_\tau}^0 \\
&= s_{13}^2 \, F_{\nu_e}^0 + s_{12}^2 c_{13}^2 F_{\nu_x}^0 + |U_{e1}|^2 F_{\nu_x}^0 \\
&= s_{13}^2 \, F_{\nu_e}^0 + s_{12}^2 c_{13}^2 F_{\nu_x}^0 + c_{12}^2 c_{13}^2 F_{\nu_x}^0
\end{aligned}
$$

(normal hierarchy: $m_1 < m_2 < m_3$)



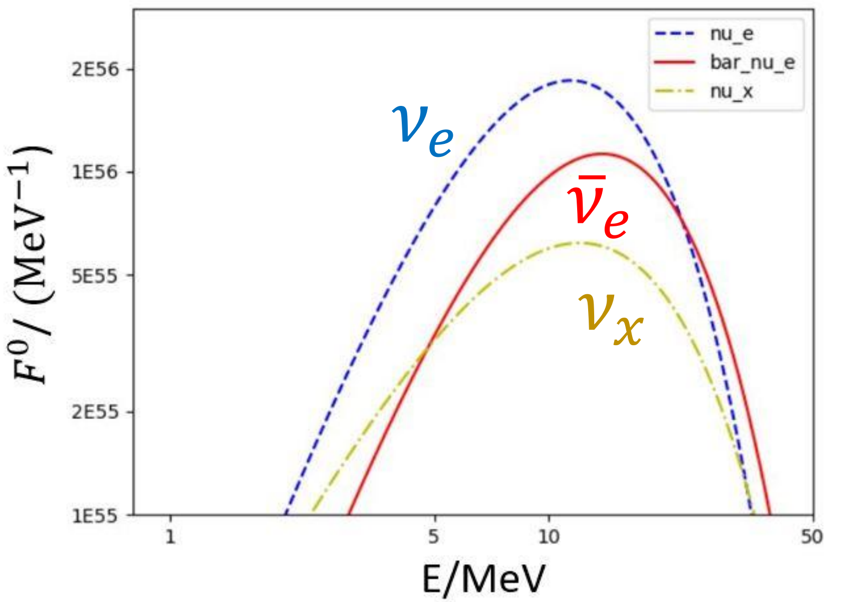
Three flavors!

Example calculation of flavor oscillations in supernovae

$$F_{\nu_e}^{NH} = |U_{e3}|^2 F_{\nu_e}^0 + \cdots\,, \qquad |U_{e3}|^2 = |\langle \nu_e | \nu_3 \rangle|^2$$
$$= \left| s_{13} e^{-i\delta_{CP}} \right|^2 F_{\nu_e}^0 + \cdots\,,$$
$$= s_{13}^2\, F_{\nu_e}^0 + |U_{e2}|^2 F_{\nu_x}^0 + \cdots, F_{\nu_x}{}^0 \equiv F_{\nu_\mu}^0 = F_{\nu_\tau}^0$$
$$= s_{13}^2\, F_{\nu_e}^0 + s_{12}^2 c_{13}^2 F_{\nu_x}^0 + |U_{e1}|^2 F_{\nu_x}^0$$
$$= s_{13}^2\, F_{\nu_e}^0 + s_{12}^2 c_{13}^2 F_{\nu_x}^0 + c_{12}^2 c_{13}^2 F_{\nu_x}^0$$

$$\boxed{\begin{aligned} F_{\nu_e}^{NH} &= \left(0 \times F_{\nu_e}^0\right) + \left(1 \times F_{\nu_x}^0\right) \\ F_{\nu_e}^{IH} &= \left(0.3 \times F_{\nu_e}^0\right) + \left(0.7 \times F_{\nu_x}^0\right) \end{aligned}}$$

(time-integrated SN neutrino spectra)



MSW: Different mass hierarchies
give different final spectra!

Three flavors!