Unveiling the DSNB with high energy neutrinos

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IFT – Madrid 12/03/2025

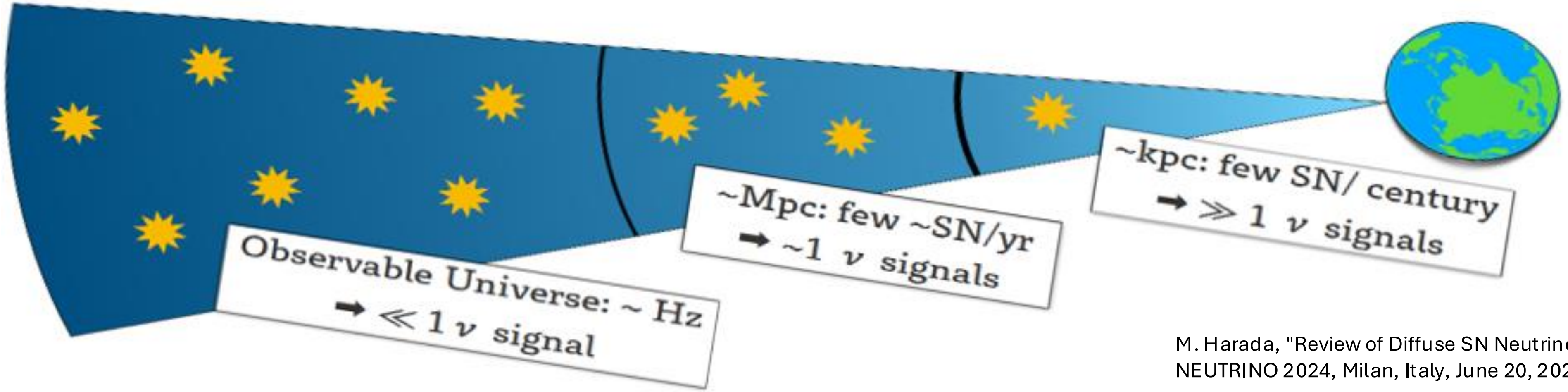
Outline of the talk

- The Diffuse Supernova Neutrino Background
- The SuperKamiokande neutrino detector
- Atmospheric neutrinos in SK
- Event rate of foregrounds in SK
  - Computation of the atmospheric neutrino flux
  - Cross-sections

The Diffuse Supernova Neutrino Background

- Core-collapse supernovae are huge emitters of neutrinos: ~ 99% of energy emission via ν's:
  - Neutrino physics
  - Supernovae physics (although DSNB is thermalized…)
  - New physics? (see this workshop!)

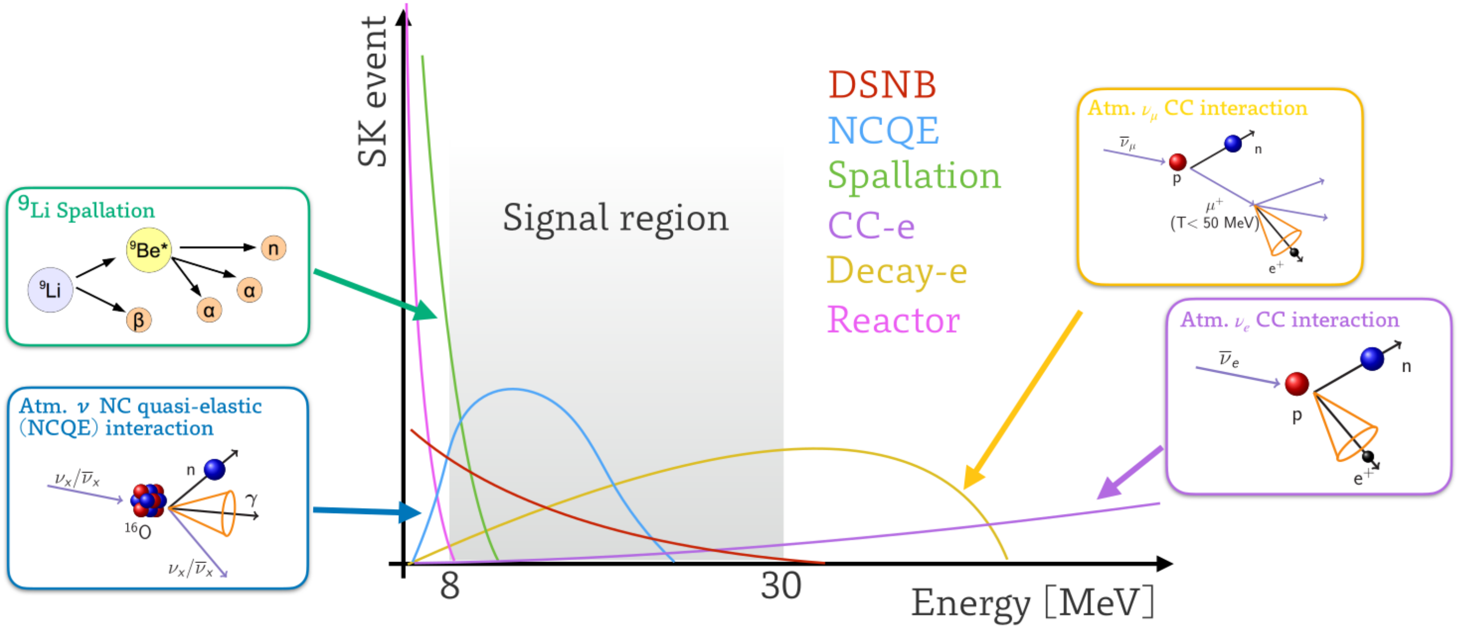
- In the Milky Way: not enough SNs. Outside MW: more SNs, but very small flux!



M. Harada, "Review of Diffuse SN Neutrino Background," NEUTRINO 2024, Milan, Italy, June 20, 2024.

The Diffuse Supernova Neutrino Background

- *"The weak glow of (...) neutrinos (...) from distant core-collapse supernovae."* [1]
- Particle and cosmological SM prediction: **no DSNB implies new physics**!
- Problem: small flux, lots of foregrounds[2]



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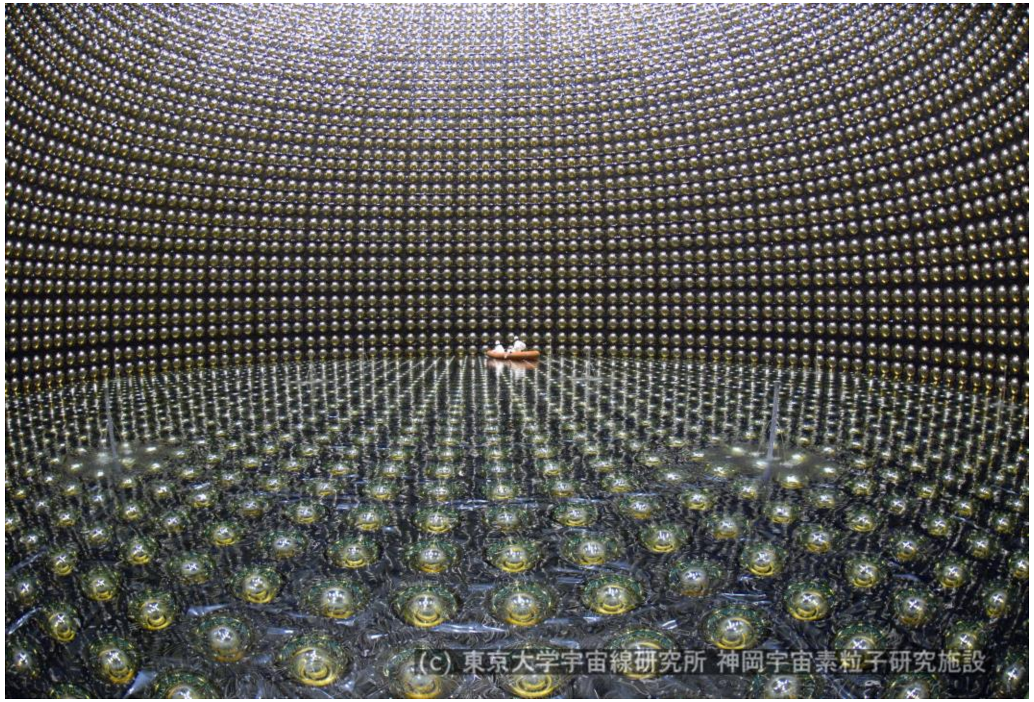
1. J. F. Beacom, "The Diffuse Supernova Neutrino Background," *Annu. Rev. Nucl. Part. Sci., arXiv: 1004.3311*

2. M. Harada, "Review of Diffuse SN Neutrino Background," NEUTRINO 2024, Milan, Italy, June 20, 2024.

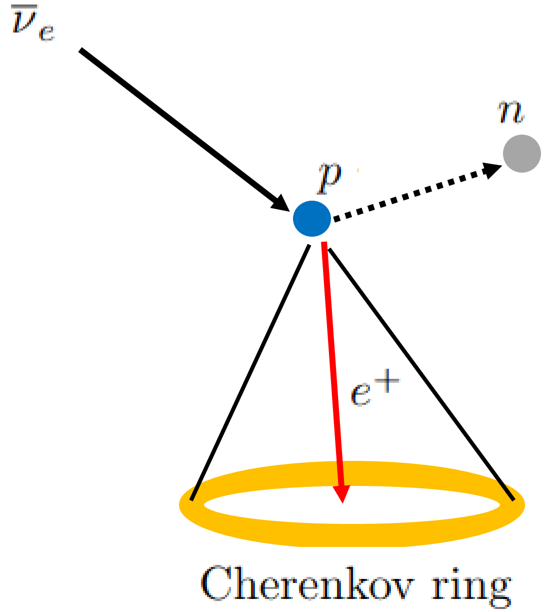
The SuperKamiokande neutrino detector

- Cherenkov water detector located in Kamioka, Japan



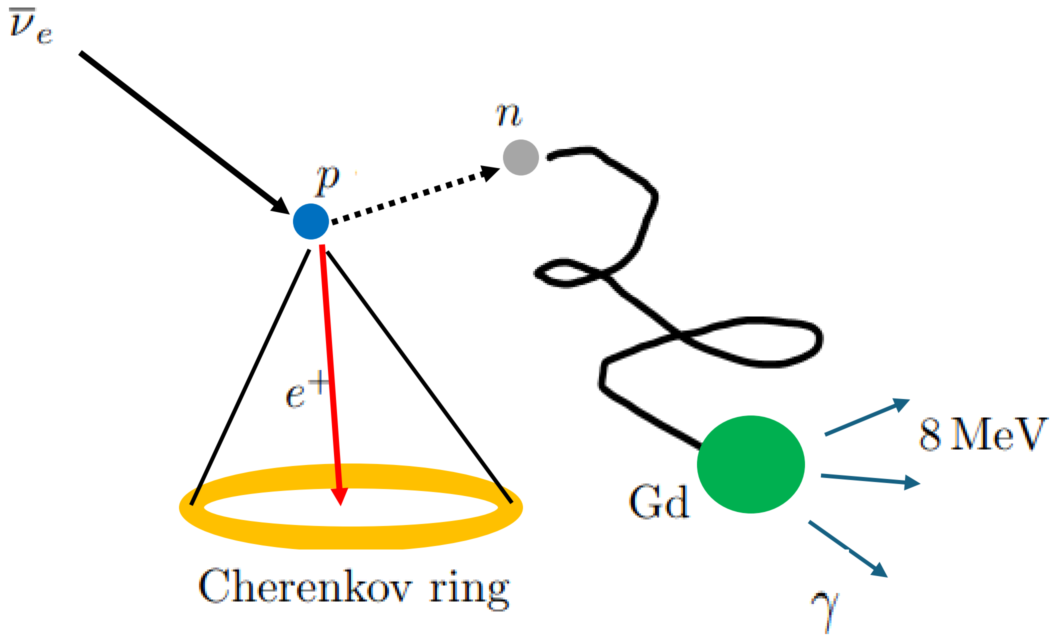
Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

- PMTs for neutrino detector via IBD



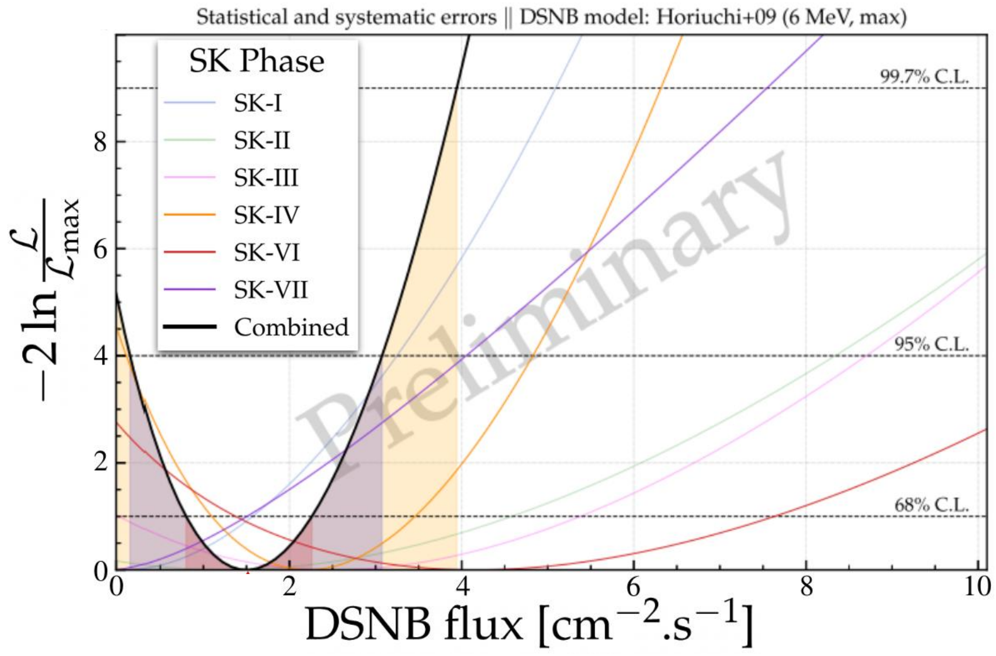
The SuperKamiokande neutrino detector

- SK – VI onwards: Gd doping



(neutron tagging also possible with H, but smaller signal)

- Recently, hint of DSNB in SK!

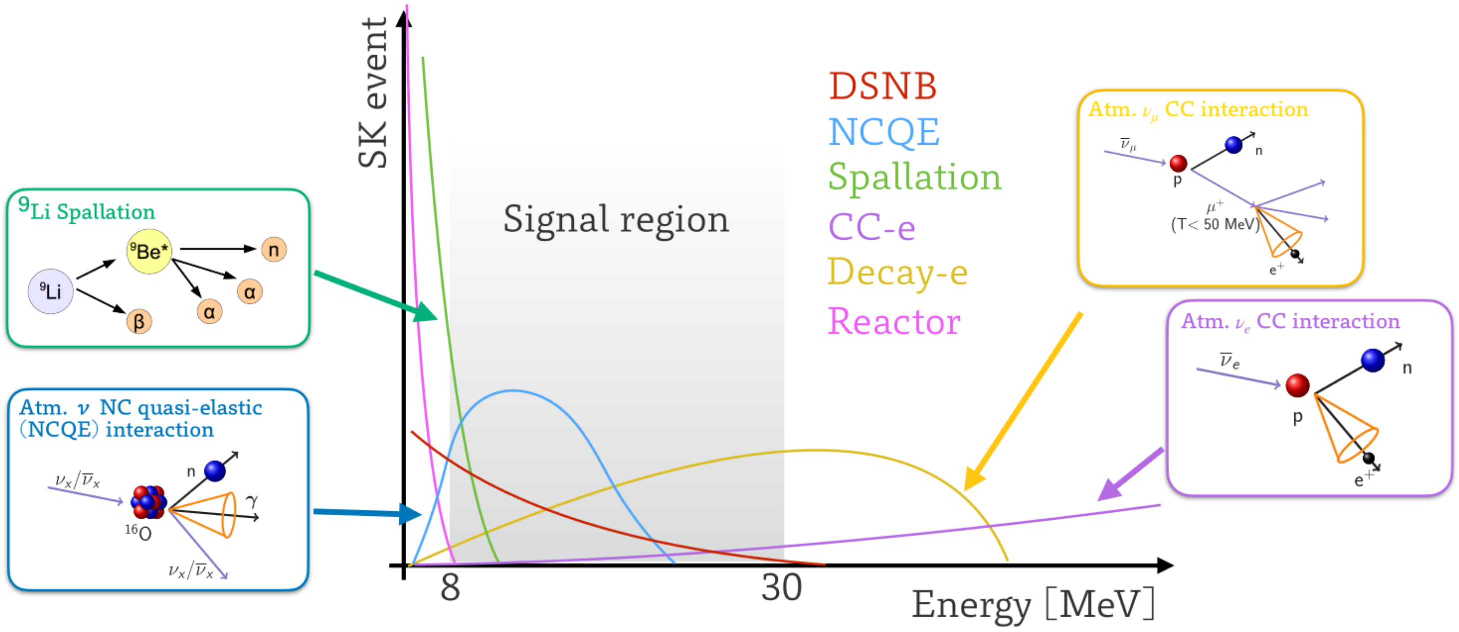


Best fit: $1.4^{+0.8}_{-0.6}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

M. Harada, "Review of Diffuse SN Neutrino Background," NEUTRINO 2024, Milan, Italy, June 20, 2024.

DSNB backgrounds in SK

- Main backgrounds (foregrounds) come from atmospheric neutrinos
- IBD – like signals will be registered as events
- Neutron tagging helps!



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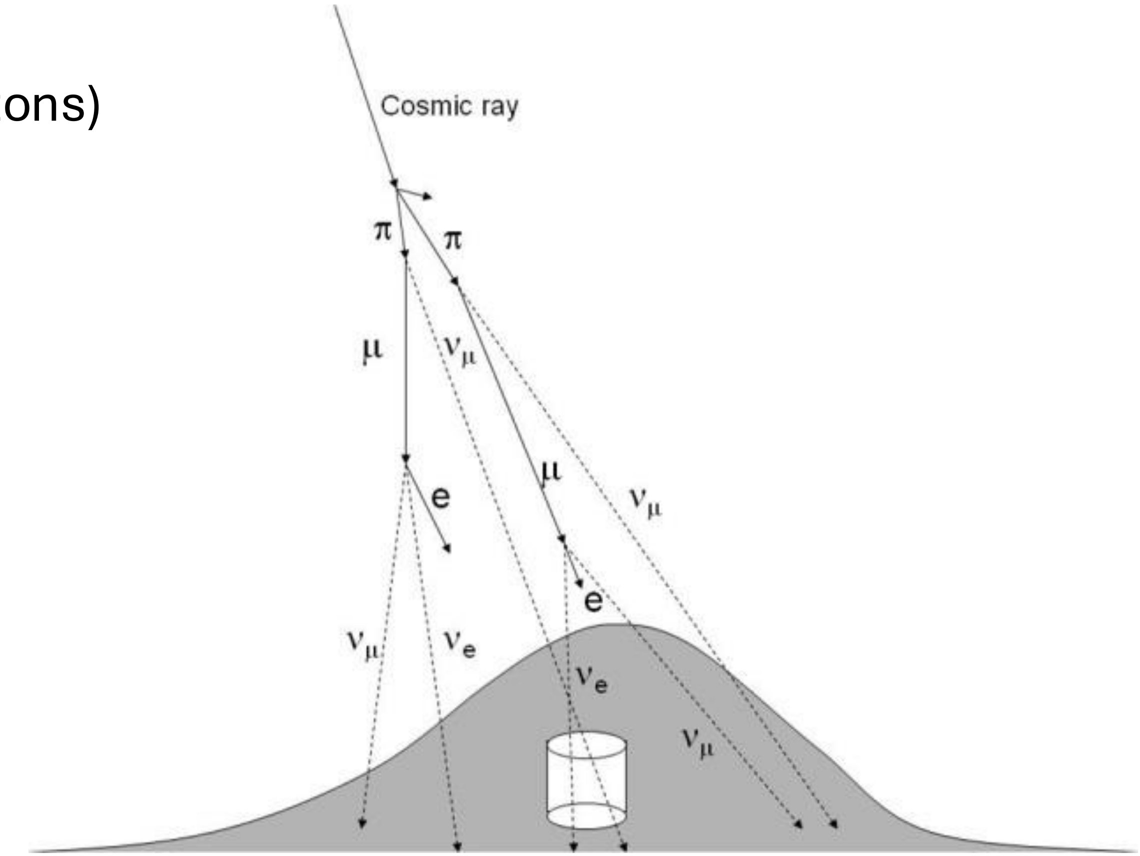
Atmospheric neutrinos in SK

- Neutrinos coming from cosmic rays (mainly protons) via decays (e.g. muon decay, pion decay)

- Typically produced at 15 km

- Energy range: ~ 10's MeV - 100's TeV

- Irreducible background for DSNB searches



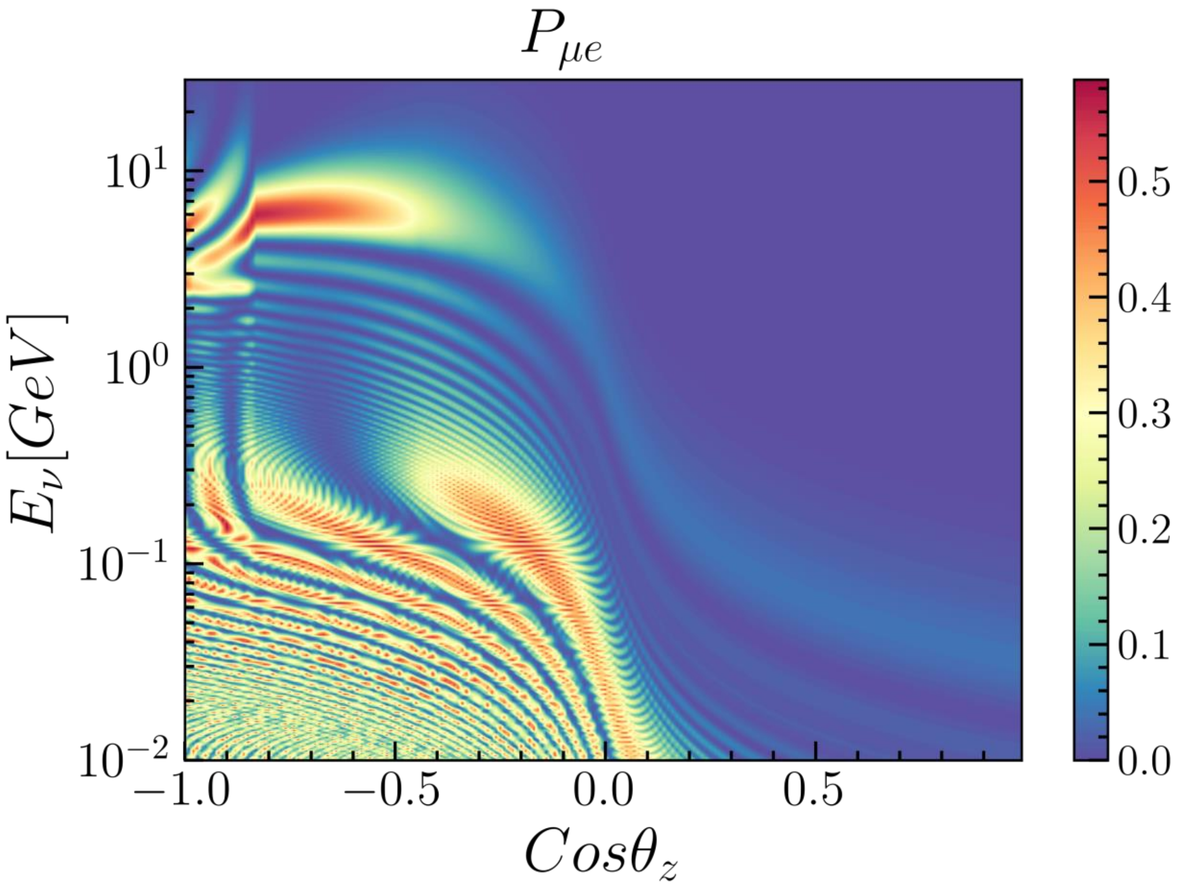
Takaaki Kajita in the Proceedings of the Japan Academy, Series B, Physical and Biological Sciences (10.2183/pjab.86.303)

Atmospheric neutrinos in SK

- Atmospheric neutrinos present flavor conversion via **neutrino oscillations**

- At the energies and baseline considered, they can alter our fluxes by a factor ~2

$$\Phi_\alpha(E_\nu) = \sum_\beta P_{\beta\alpha}(E_\nu, \theta_Z)\Phi_\beta(E_\nu)$$



Event rates in SK

- We will compute the expected number of event in SK for DSNB and main backgrounds

$$N = N_{targ} \int dT_{rec} dT_e dE_\nu \frac{d\sigma}{dT_e} \frac{d\Phi}{dE_\nu} f(T_{rec}, T_e)$$

f: Gaussian smearing function

- Additionally, we must take atmospheric neutrino oscillation into account

$$N_{atm} \propto \int dE_\nu \int d\Omega \frac{d\Phi}{dE_\nu}(E_\nu, \theta) P_{osc}(E_\nu, \theta)$$

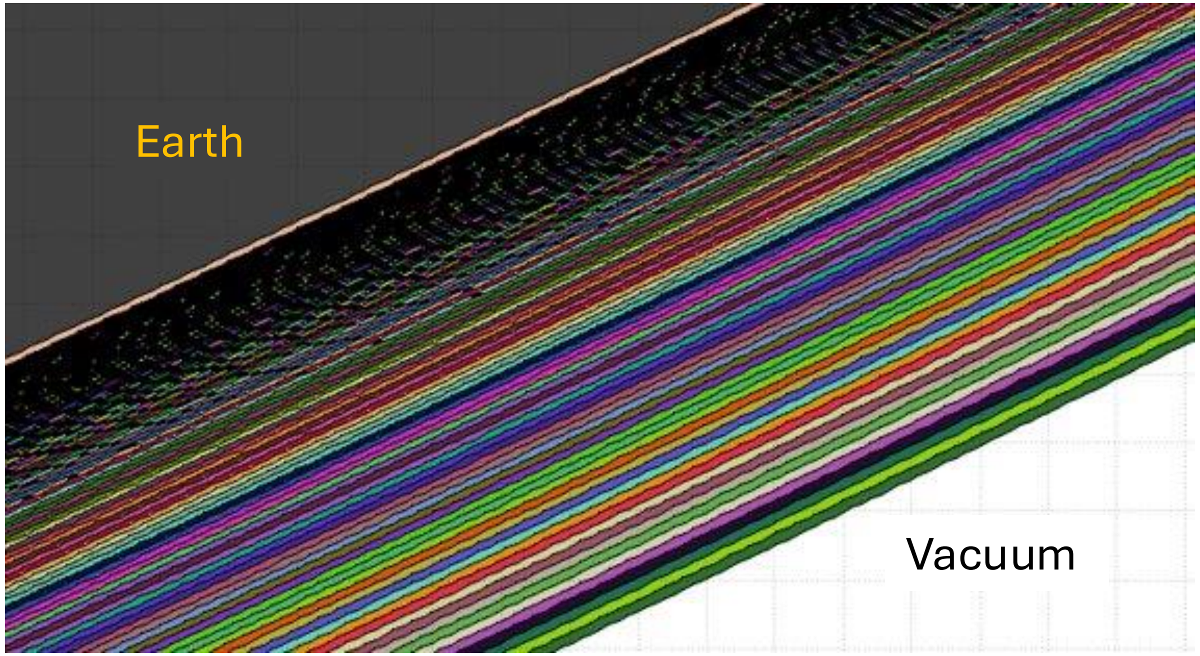
"Oscillated flux"

Computation of atmospheric neutrino flux

- FLUKA: MonteCarlo simulation package. Manages production and transport of particles through various media

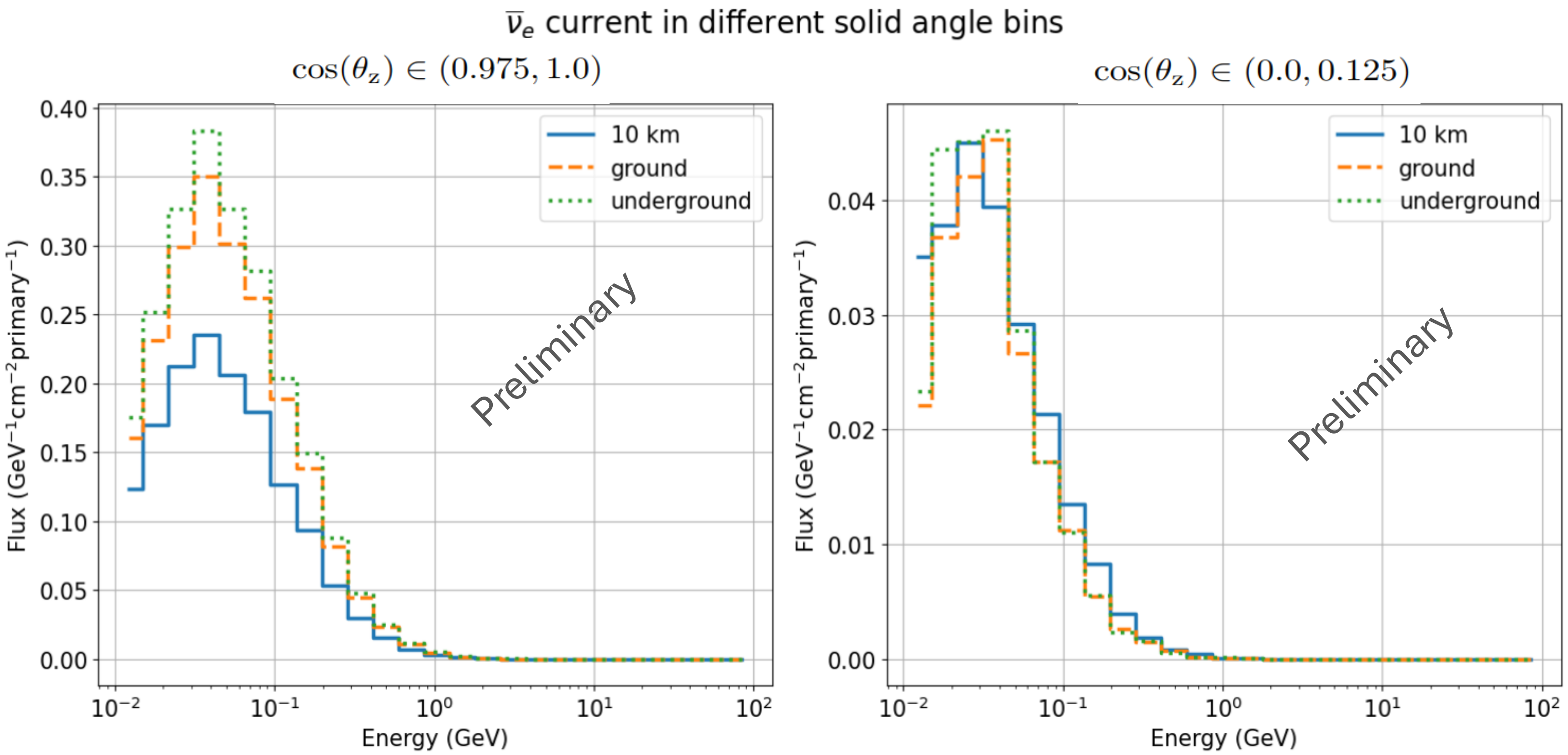
- Use cosmic rays as source, with detailed atmospheric model + geomagnetic field

- Simulate Earth with 1km Si layer



Computation of atmospheric neutrino flux

- Solid angle distribution of flux. Comparison



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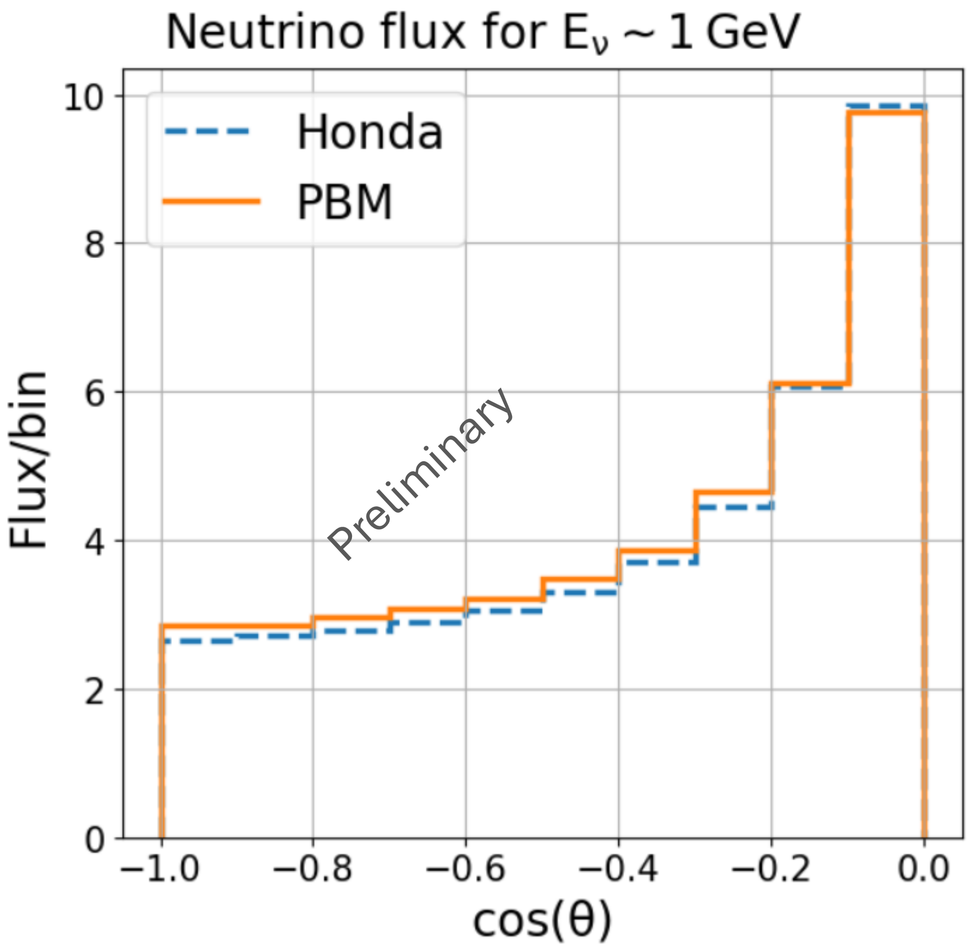
Honda: http://www-rccn.icrr.u-tokyo.ac.jp/mhonda/public/nflx2014/index.ht

Computation of atmospheric neutrino flux

- Solid angle distribution of flux. Comparison

- Fluka allows for solid angle binning

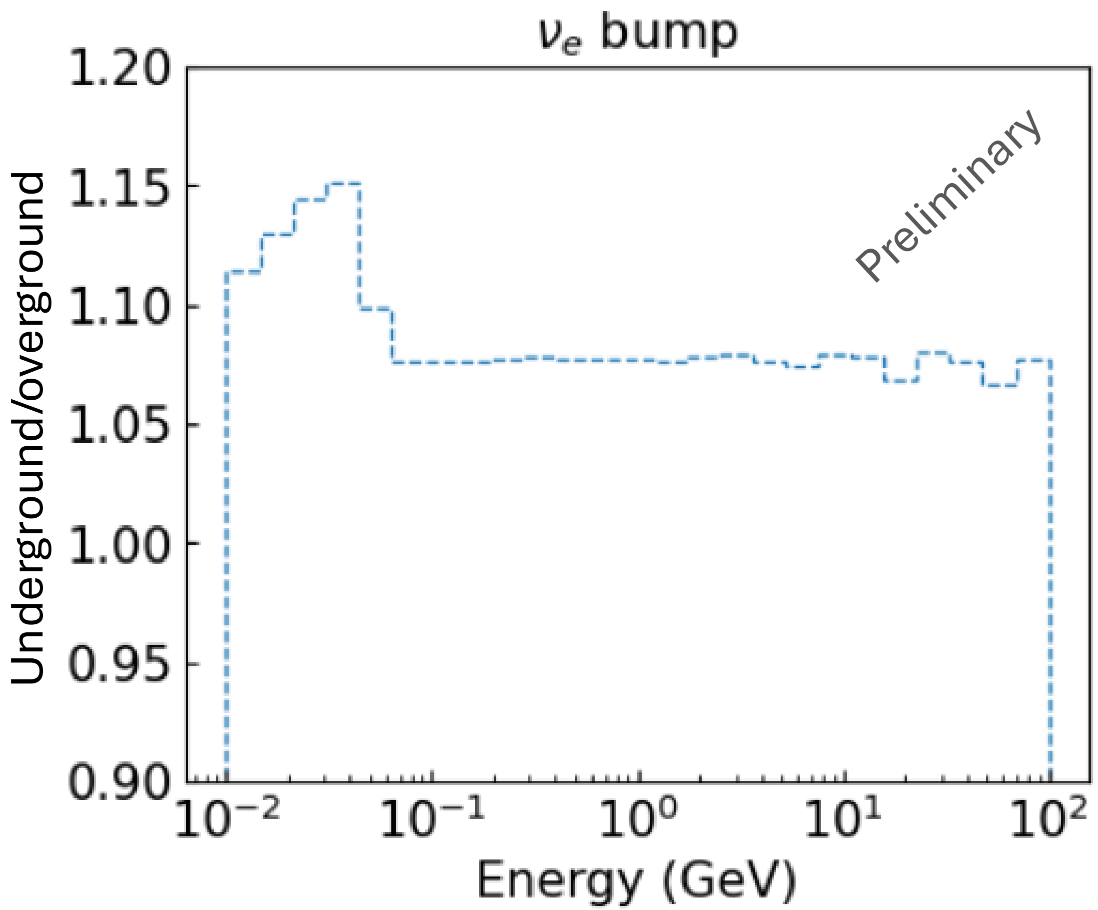
(we obtain zenithal distribution)



Computation of atmospheric neutrino flux

- Integrated fluxes **reproduce features** and fit well other computations

- "The bump": highly energetic muons arrive to Earth and decay at rest



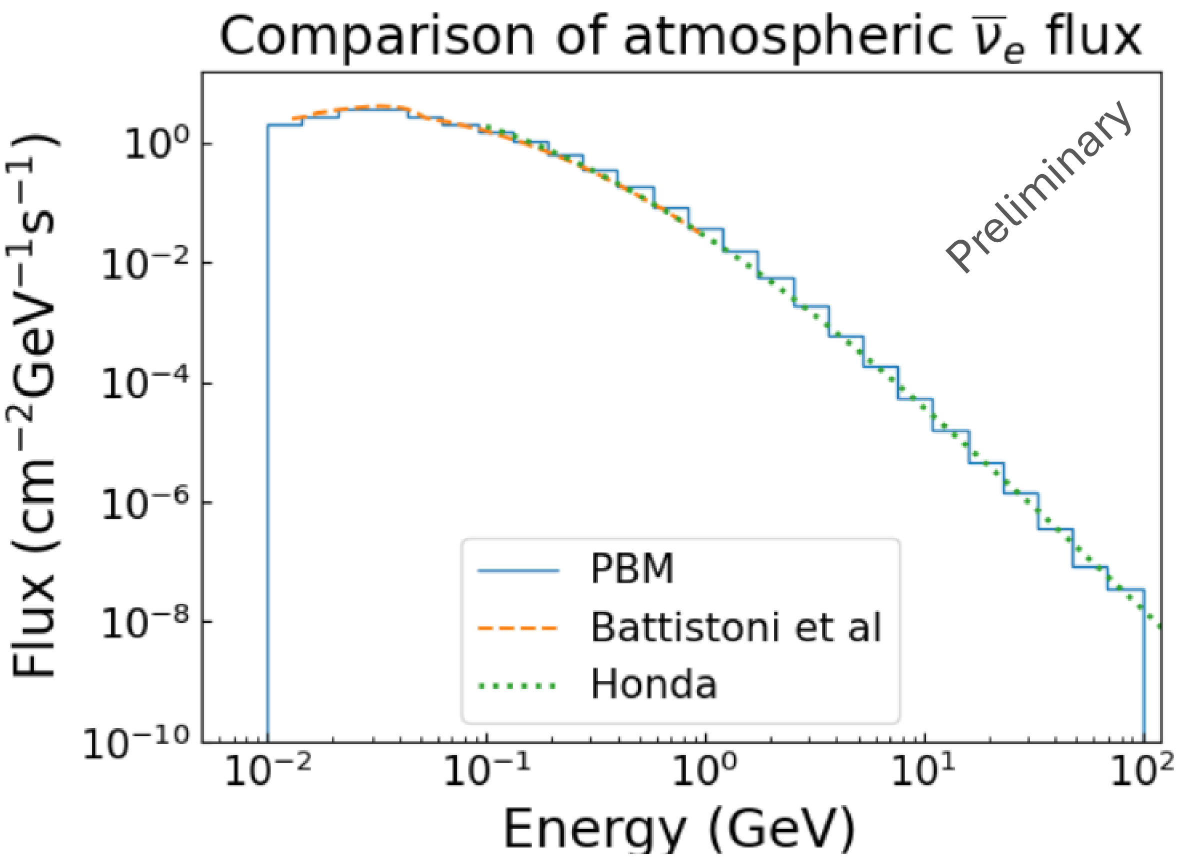
Honda: http://www-rccn.icrr.u-tokyo.ac.jp/mhonda/public/nflx2014/index.ht

Fluka: G. Battistoni, A. Ferrari, T. Montaruli, and P.R. Sala, “The atmospheric neutrino flux below 100mev: The fluka results” Astroparticle Physics

Computation of atmospheric neutrino flux

- Integrated fluxes reproduce features and **fit well other computations**

- Good agreement with literature (after some normalization)



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Computation of cross-sections

- Background event topologies: $\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu$ Charged Current

- We will not consider Neutral Current (90% cuts)

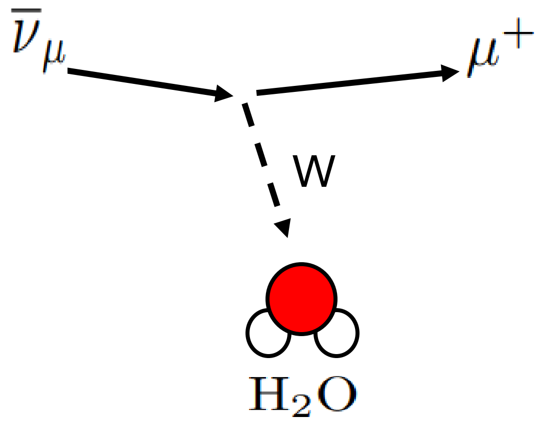
- Electron (anti)neutrinos: well-known Inverse Beta Decay

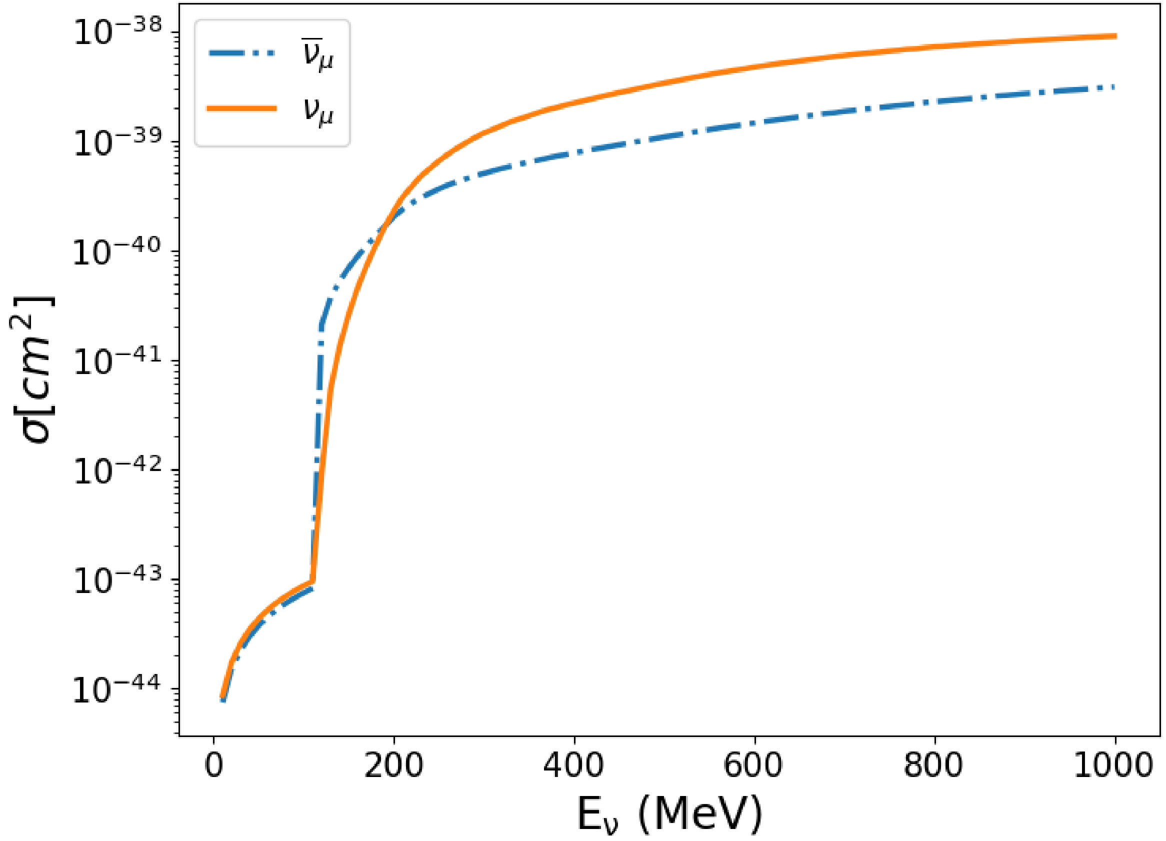
- Muon (anti)neutrino cross-section: convolution of cross-sections

$$\frac{\mathrm{d}\sigma_{\mathrm{inv}}}{\mathrm{dT_e}} \simeq \sigma_{\mathrm{tot}} \frac{\mathrm{N_{inv}}}{\mathrm{N_{tot}}} \frac{\mathrm{dN_e}}{\mathrm{dT_e}}$$

Computation of cross-sections

- We compute $\nu_\mu, \overline{\nu}_\mu$ CC cross-section in water using NuwRo (MC neutrino event generator)





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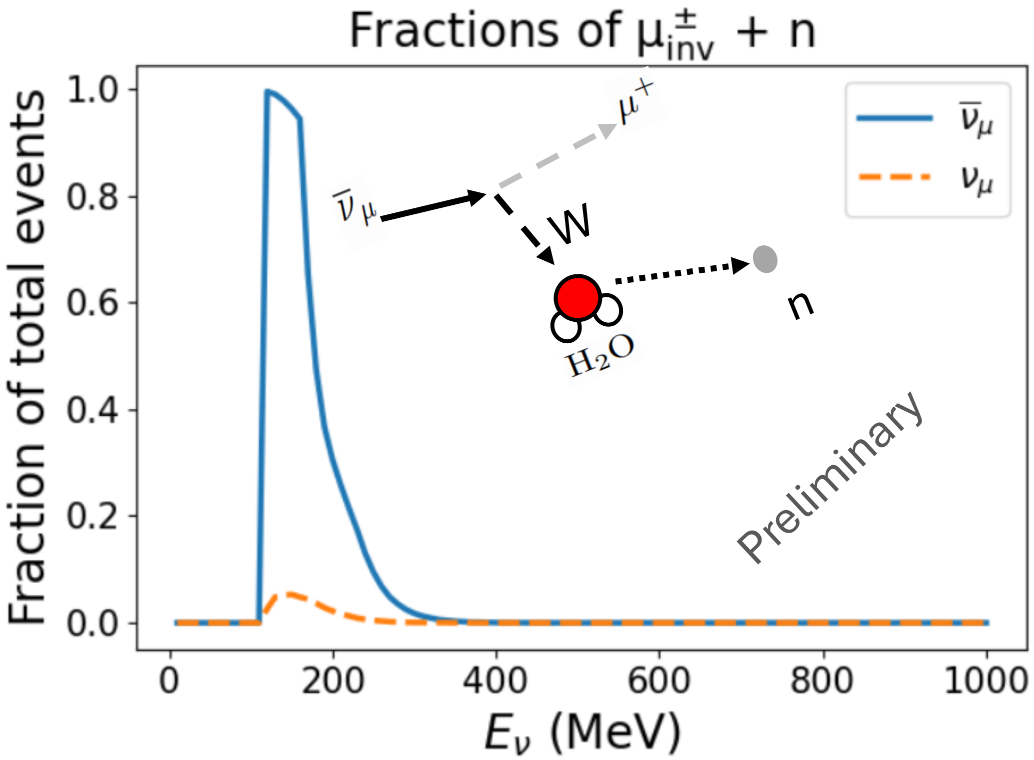
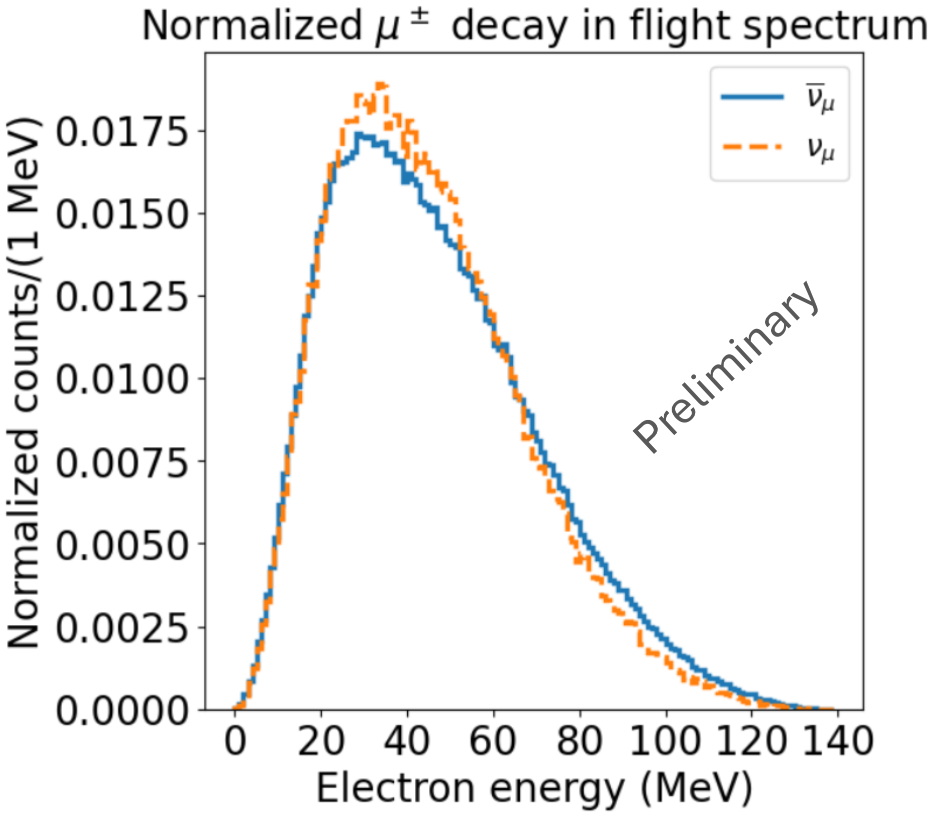
Computation of cross-sections

- Invisible muon only: $E_{\mu}^{\text{th}} = \dfrac{m_{\mu}c^2}{\sqrt{1-\frac{1}{n^2}}}$



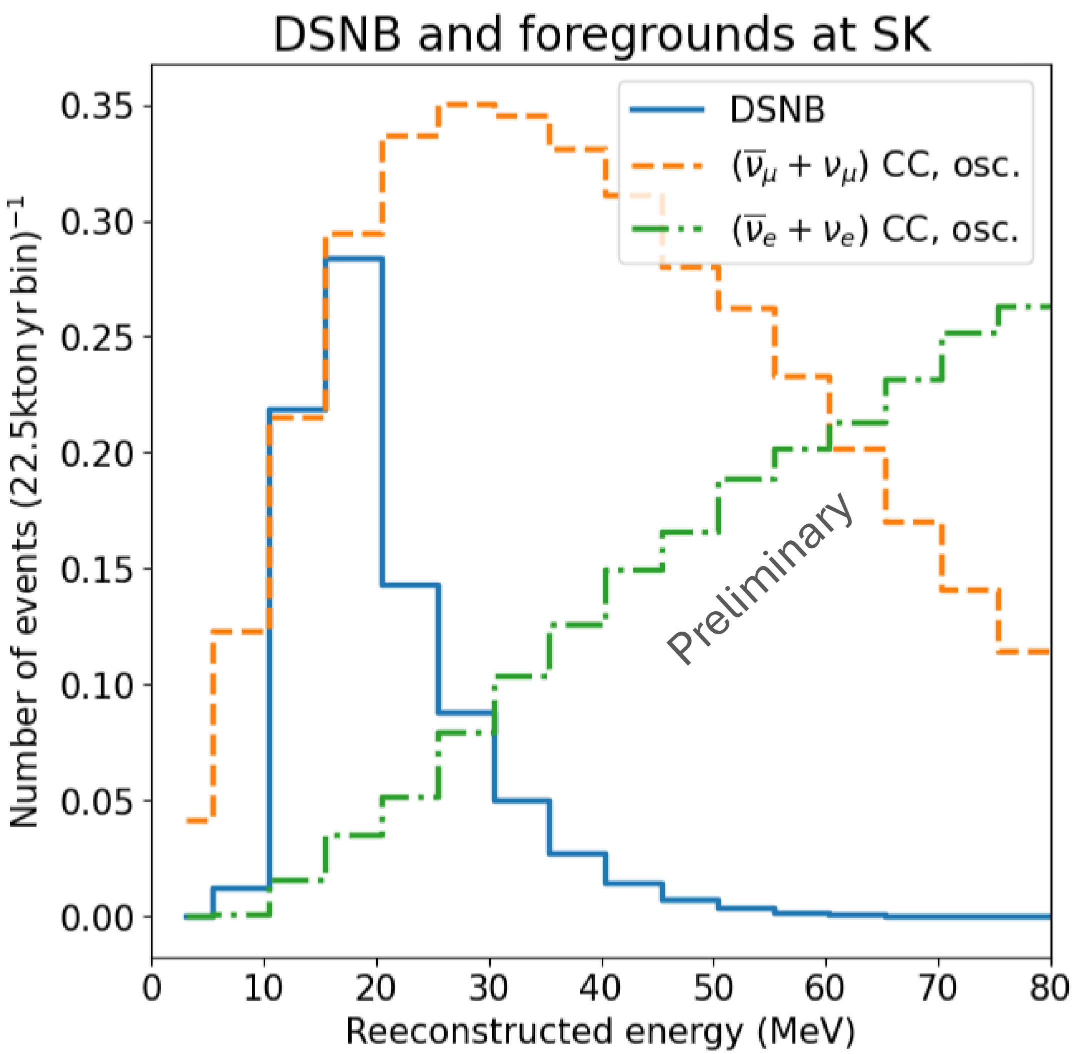
- Invisible muon decay in flight:



The DSNB window

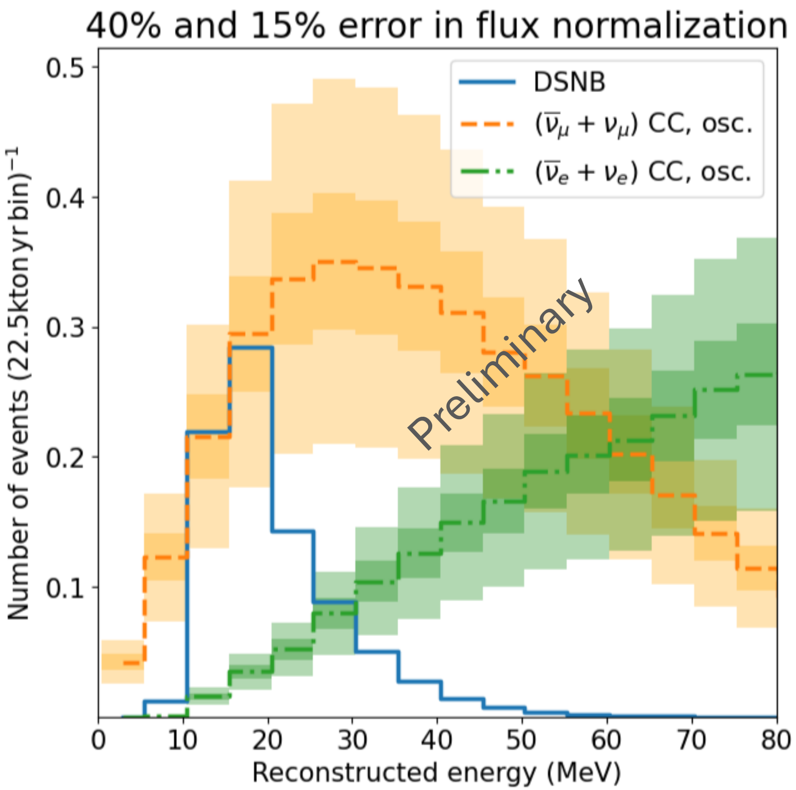
- DSNB is shadowed by atmospheric Neutrinos, but contributions are of the same order

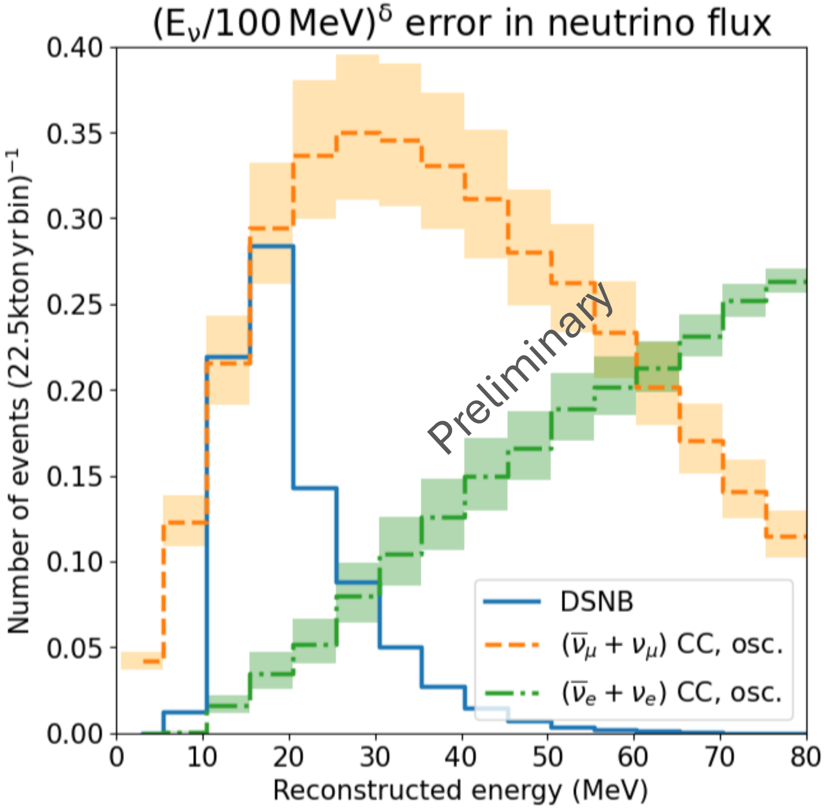
- Characterization of atmospheric Neutrino fluxes is fundamental



Uncertainties in neutrino fluxes

$$\Phi_\alpha(E, \cos\zeta) = f_\alpha(E, \cos\zeta)\Phi_0 \left(\frac{E}{E_0}\right)^\delta \eta(\cos\zeta)$$ [1]





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1. C. A. Argüelles, P. Fernández, I. Martínez-Soler, and M. Jin, "Measuring Oscillations with a Million Atmospheric Neutrinos," *Phys. Rev. X*, arXiv 2211.02666

Conclusions

- The DSNB is at the edge of sensitivity of current experiments
- Characterization of neutrino fluxes at low energies is fundamental to clear foregrounds of the DSNB
- Uncertainties affecting neutrino fluxes have to be correctly assessed
- Knowledge of high energy neutrino fluxes must be used in order to improve our description at ~ MeV

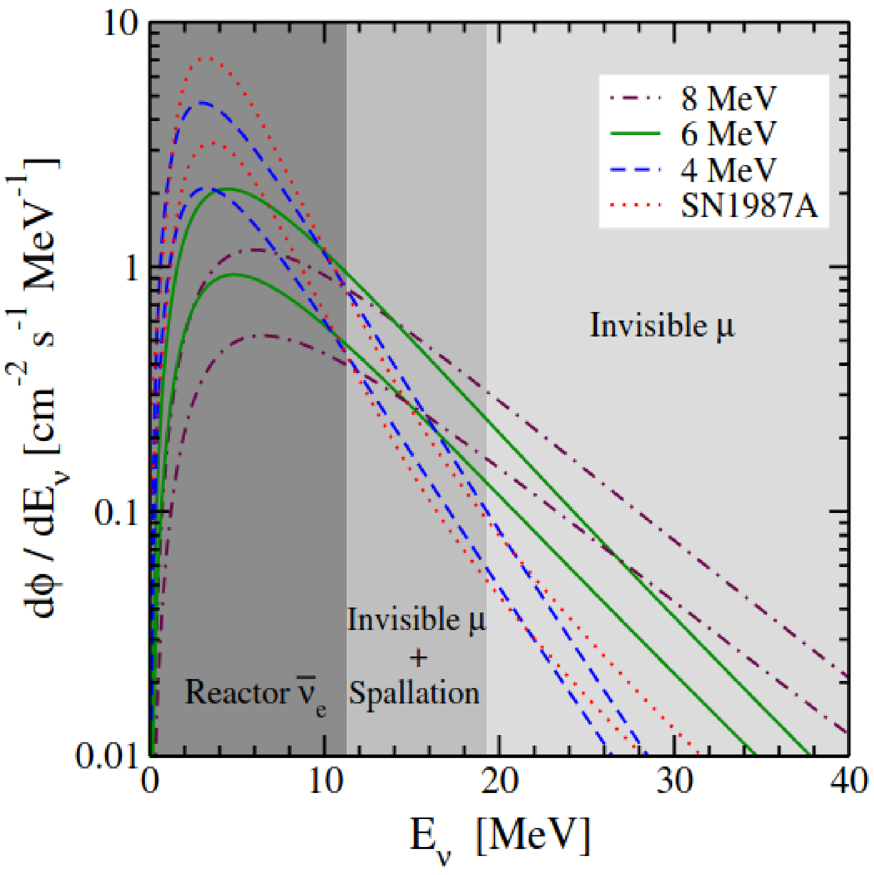
Backup slides

DSNB flux computation

- Horuichi 09 flux

- Convolution of rate of CCSN and emission rate of neutrinos, redshifted

$$\frac{d\phi(E)}{dE} = c \int R_{\rm CCSN}(z) \frac{dN(E')}{dE'} (1+z) \left| \frac{dt}{dz} \right| dz$$



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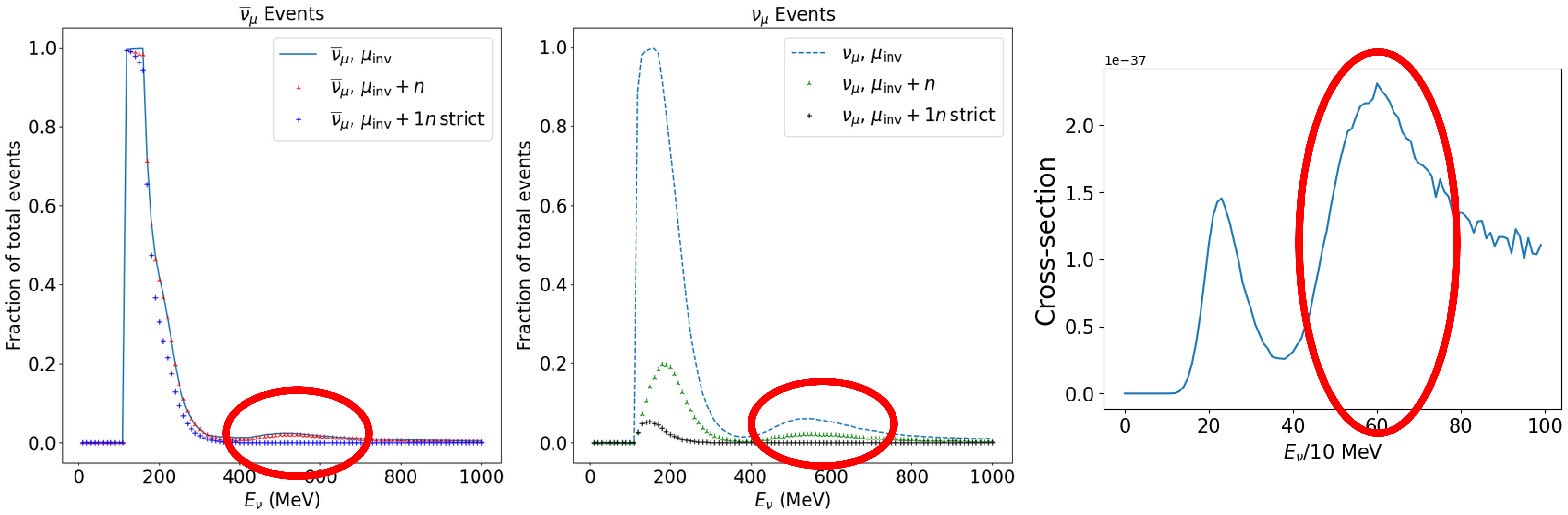
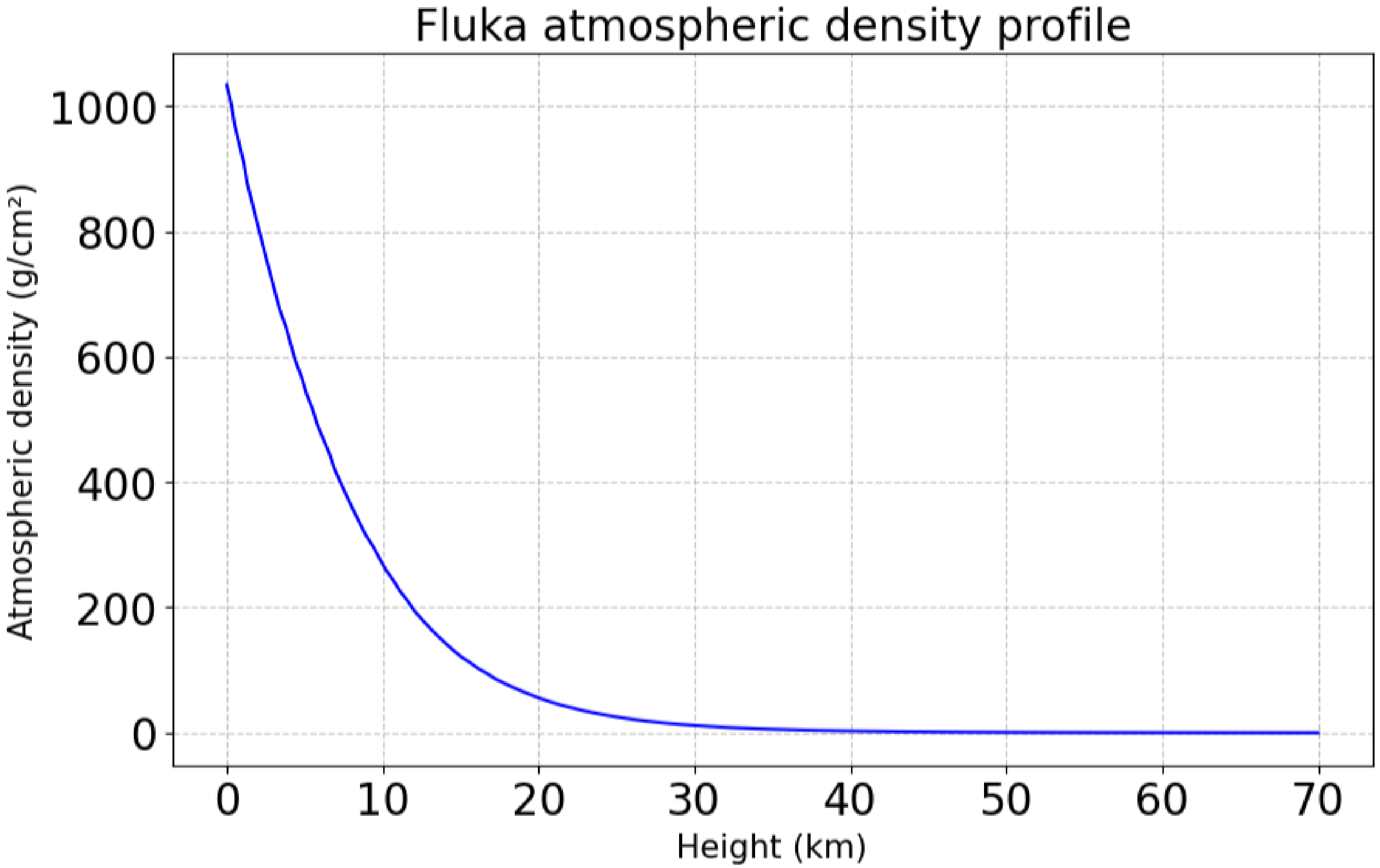
Horiuchi, S., Beacom, J. F., and Dwek, E., "Diffuse supernova neutrino background is detectable in Super-Kamiokande," *Phys. Rev. D*, arXiv: 0812.3157.

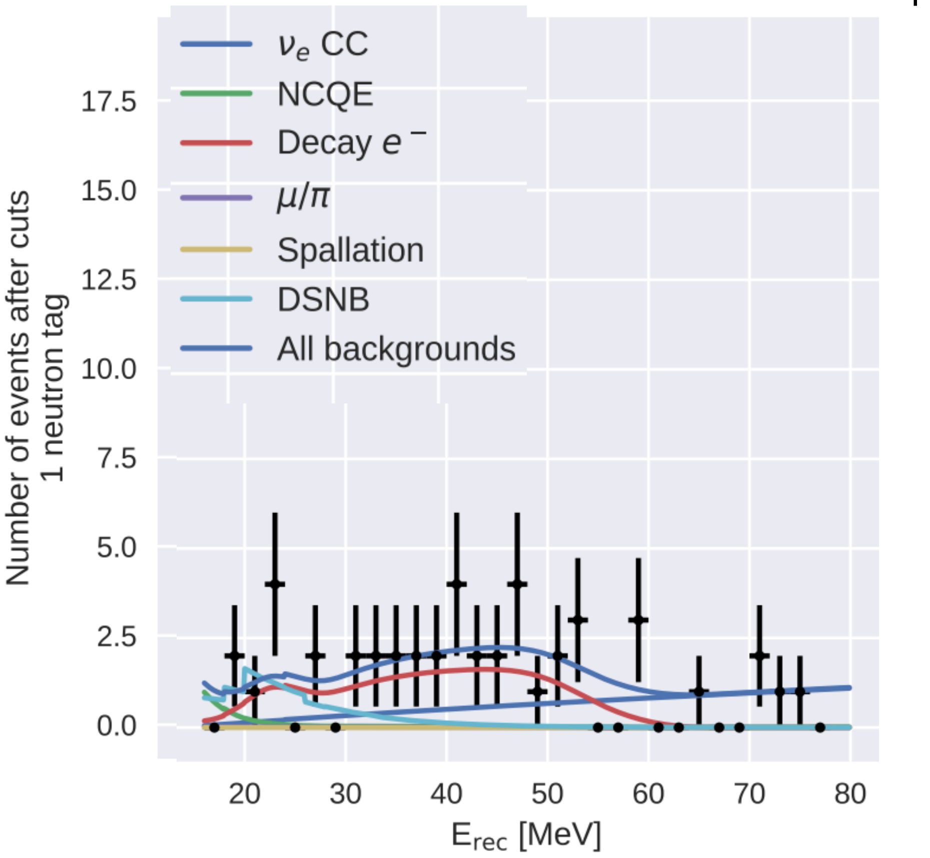
Non-strict cuts in event topology

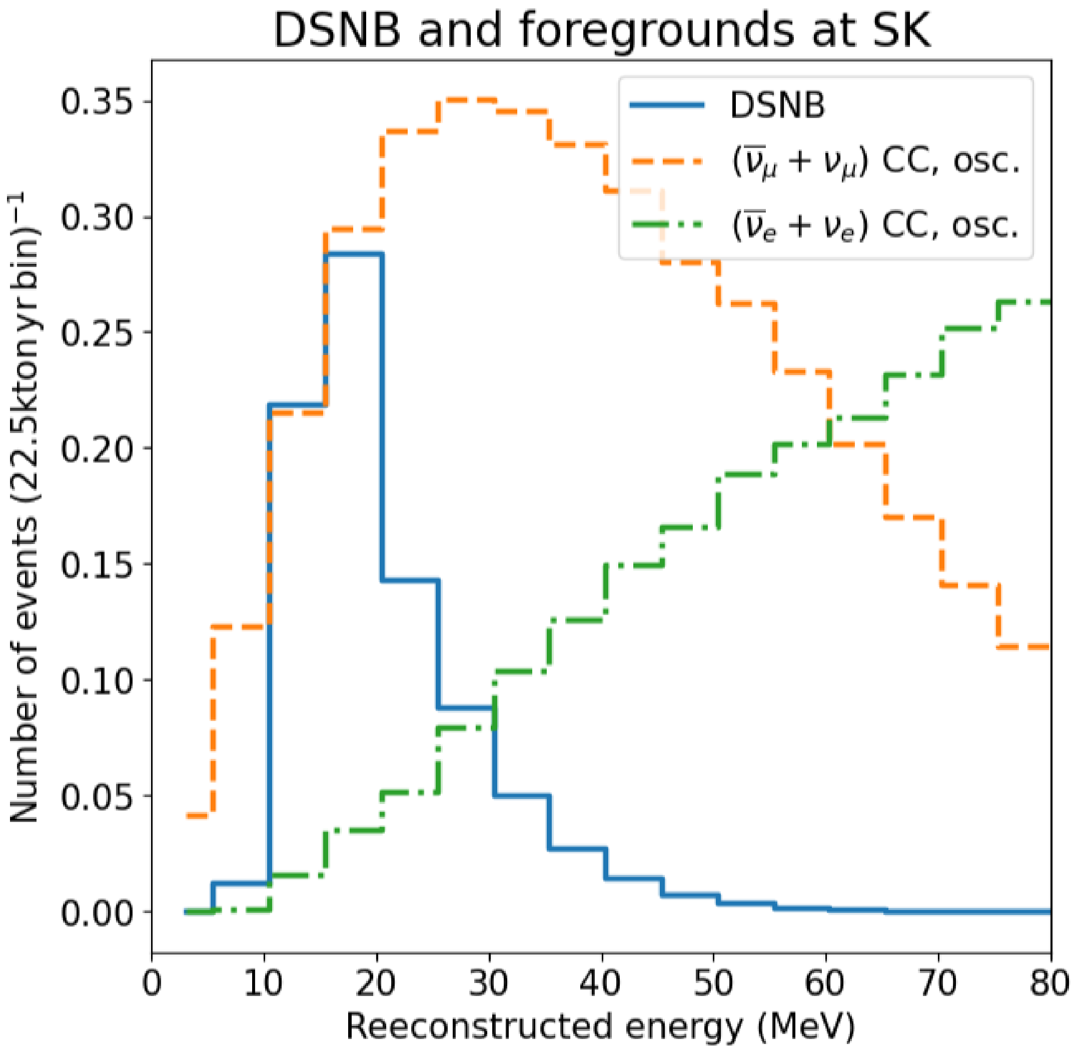


Fluka atmospheric density profile



Comparison with SK





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1. Super-Kamiokande Collaboration, "Diffuse supernova neutrino background search at Super-Kamiokande," *Physical Review D*, arXiv: 2109.11174