A calculation of the atmospheric neutrino flux at CJPL

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第三届“深地液氙暗物质、中微子研讨会”

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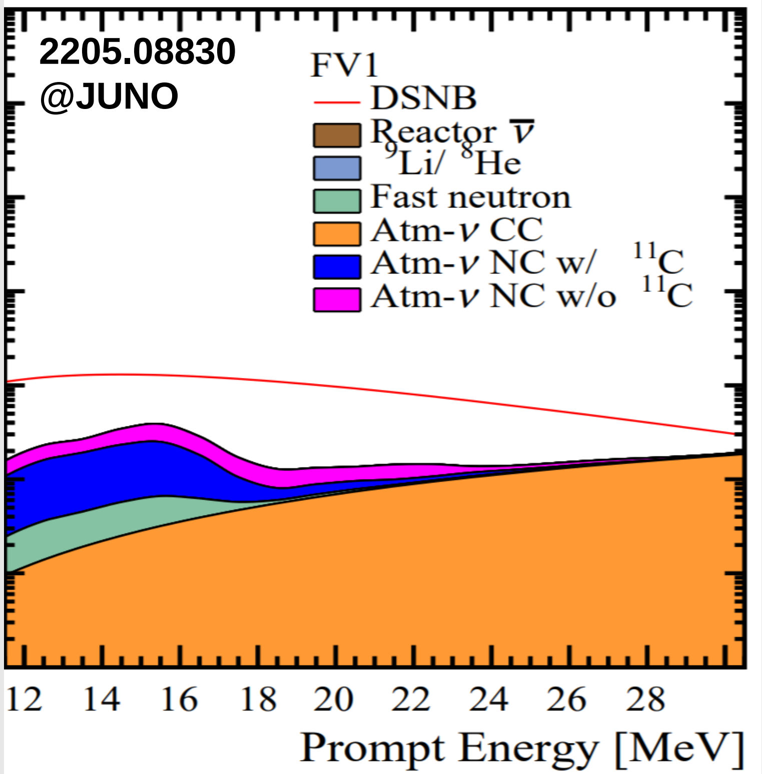
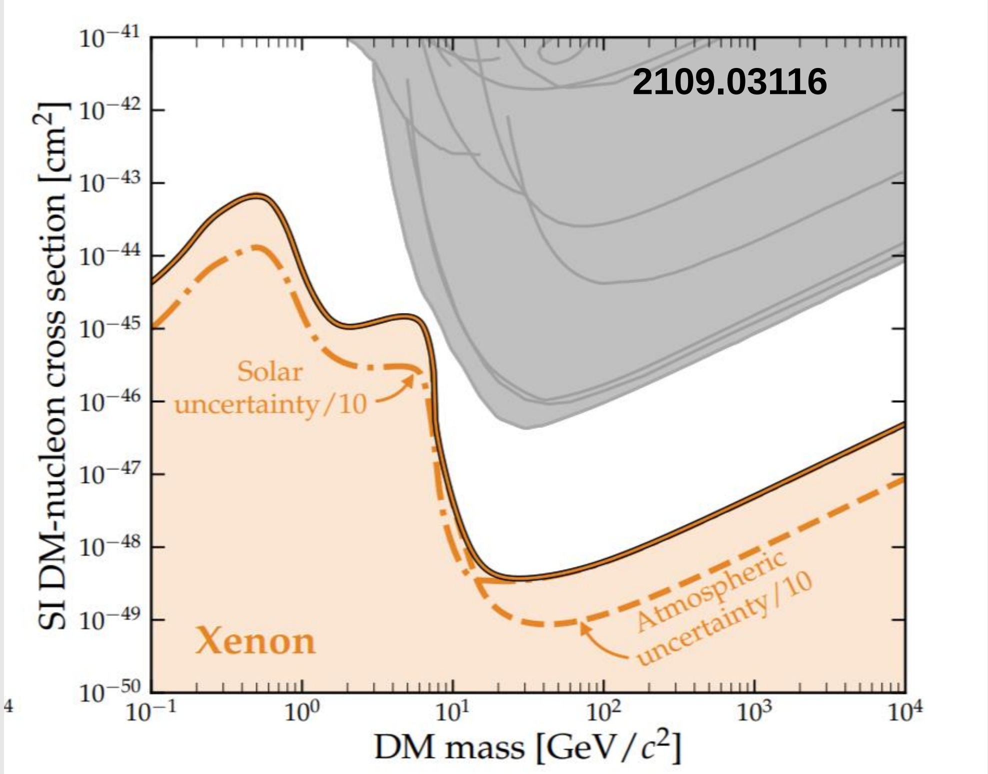
Motivation

Atmospheric neutrino flux:

- **Input of neutrino oscillations (discovery in 1998)**
- **Background of rare searches (DSNB & proton decay & dark matter)**





Atmospheric neutrinos

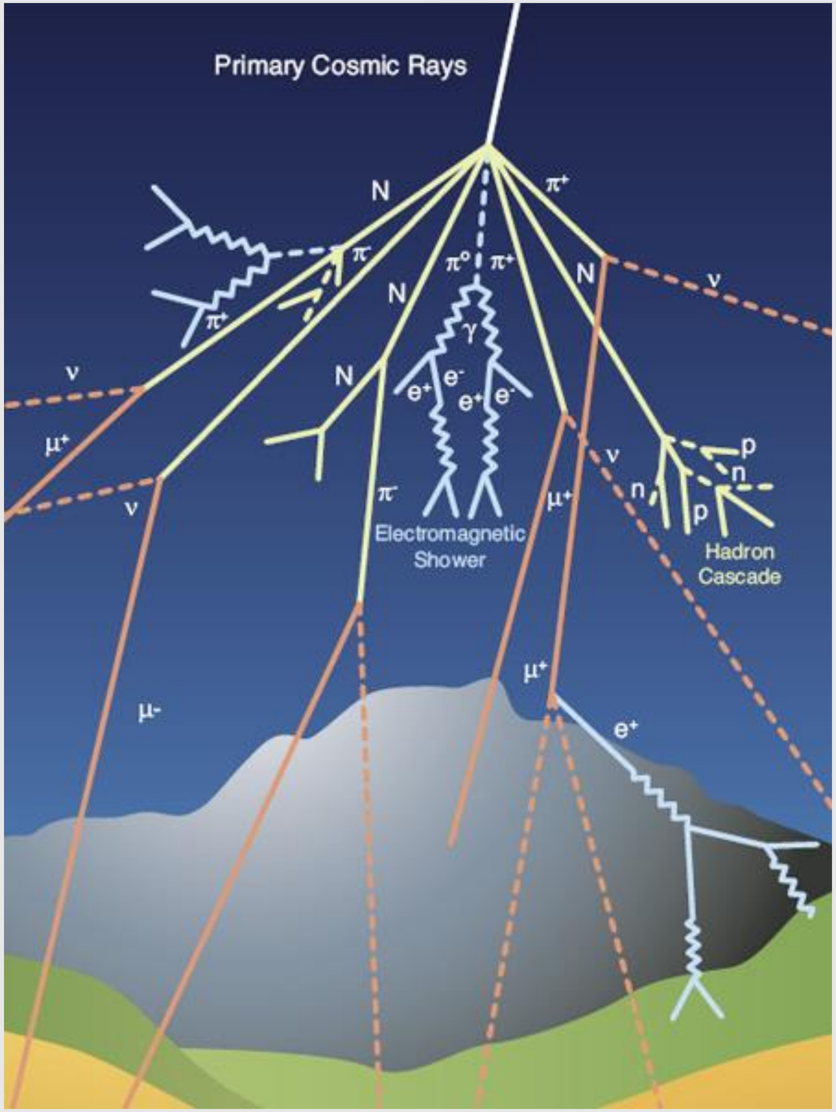
Atm-ν Sources:

Interactions of cosmic rays with nuclei in Earth's atmosphere, in the presence of geomagnetic field effect

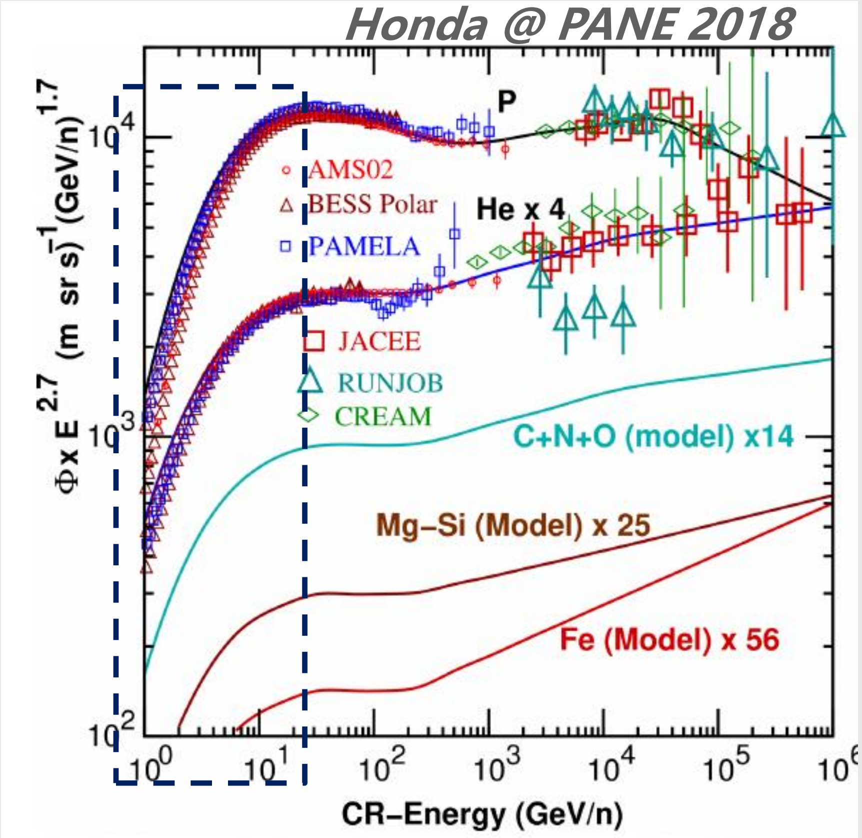
3D Atm-ν calculation:

$$\boldsymbol{\Phi_\nu} = \boldsymbol{\Phi_{primary}} \otimes \boldsymbol{R_{cut}} \otimes \boldsymbol{Y_\nu}$$ **(ν or μ)**

- ✓ $\boldsymbol{\Phi_{primary}}$: Primary cosmic ray flux
- ✓ $\boldsymbol{R_{cut}}(R_{cr}, latitude, longitude, \theta, \varphi)$: depend on geomagnetic field and rigidity of cosmic ray particle $R_{cr} \equiv \frac{P}{Ze}$
- ✓ $\boldsymbol{Y_\nu} = Yield_\nu(h, \theta)$: Hadronic Interaction Model, Air Profile, and meson-muon decays



Primary cosmic ray flux : $\Phi = \Phi_{primary} \otimes R_{cut} \otimes Y$



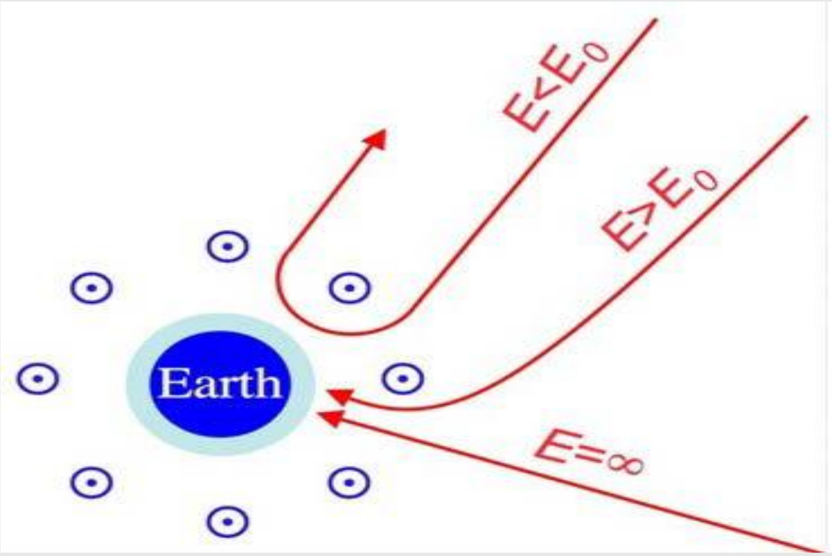
Latest cosmic ray model:

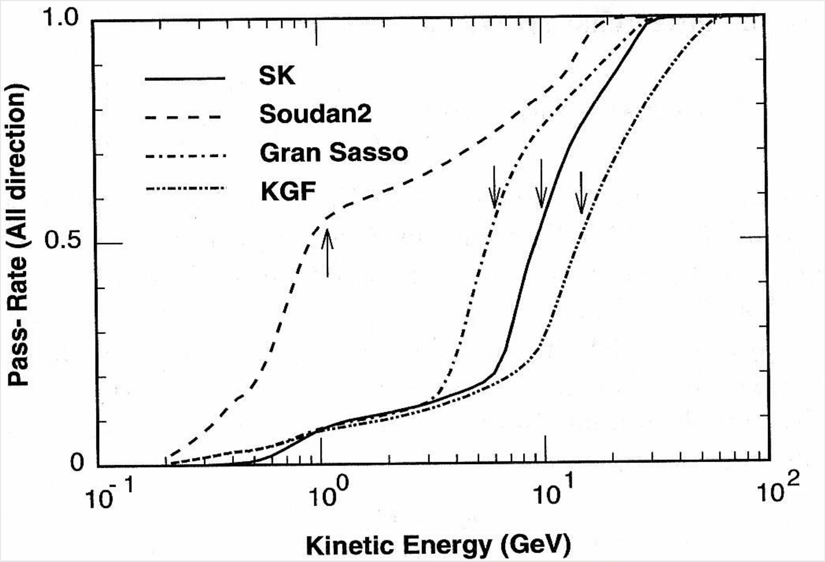
- Use B-spline function
- based on AMS02, BESS and so on
- Energy range upto 10^6 GeV

- **Large difference at low energies due to solar modulation**
- **Correct the effect by geomagnetic field in low energy range**
- **Use Liouville's theorem to ensure the conservation of particles in phase space**

Geomagnetic effects : $\Phi = \Phi_{primary} \otimes R_{cut} \otimes Y$

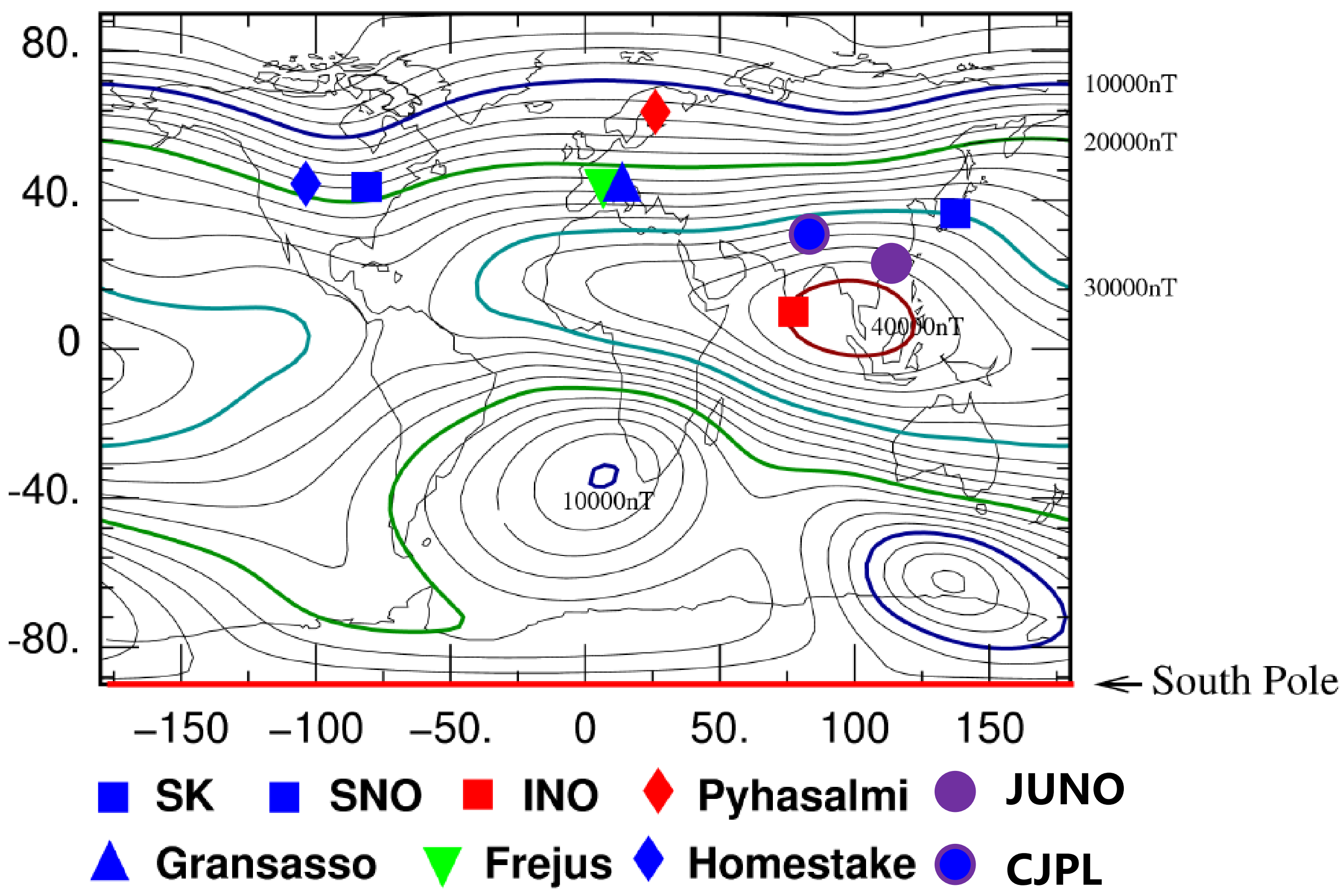
- **Geomagnetic field:**
  - Outside the atmosphere : as a filter ➔ allow higher energy and exclude lower energy (i.e., Rigidity cutoff)
  - Inside the atmosphere : bend charged secondaries
- **Depends on position, direction, and rigidity (radius of curvature)**
- **Back tracking technique : calculate cutoff rigidity**
  - Minimum momentum with which anti-particle escapes from the geomagnetic field





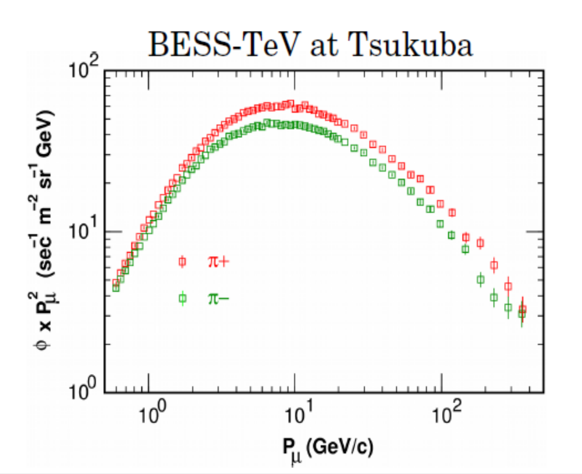
Geomagnetic effects

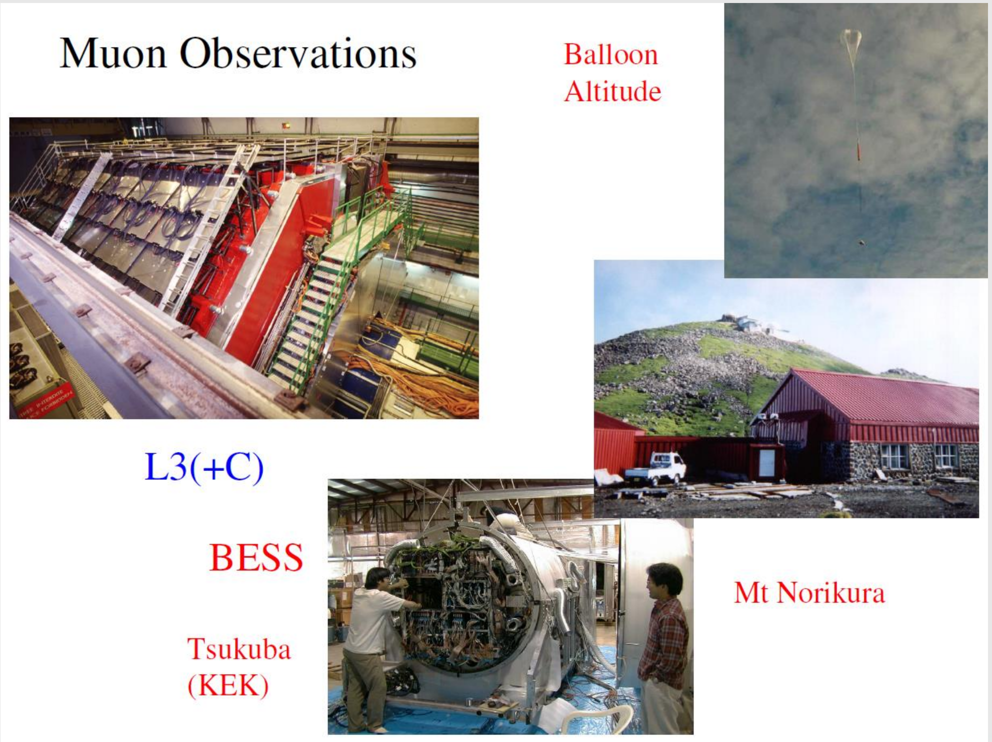
➢ **Geomagnetic field model : International Geomagnetic Reference Field (IGRF)**
IGRF10 Geomagnetic Horizontal Field Strength

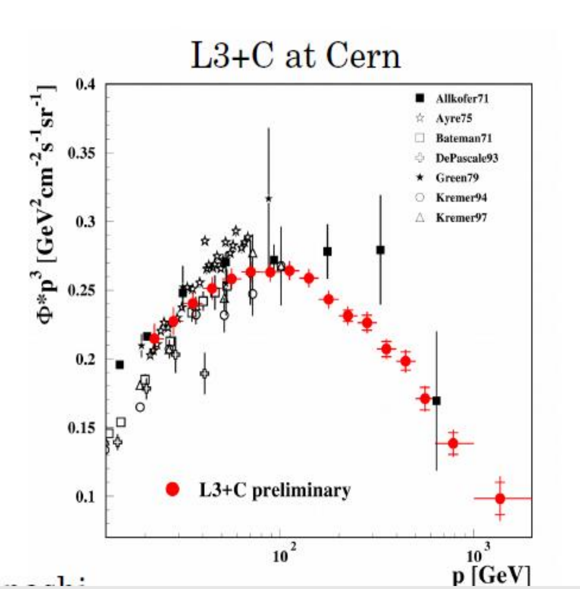


Hadronic interaction ： $\Phi = \Phi_{primary} \otimes R_{cut} \otimes Y$

- Models of hadron production : based on accelerator data
- For Honda 2017:
  - < 32GeV : JAM model
  - > 32GeV : modified DPMJET-III
- Muon observations to calibrate the hadronic models

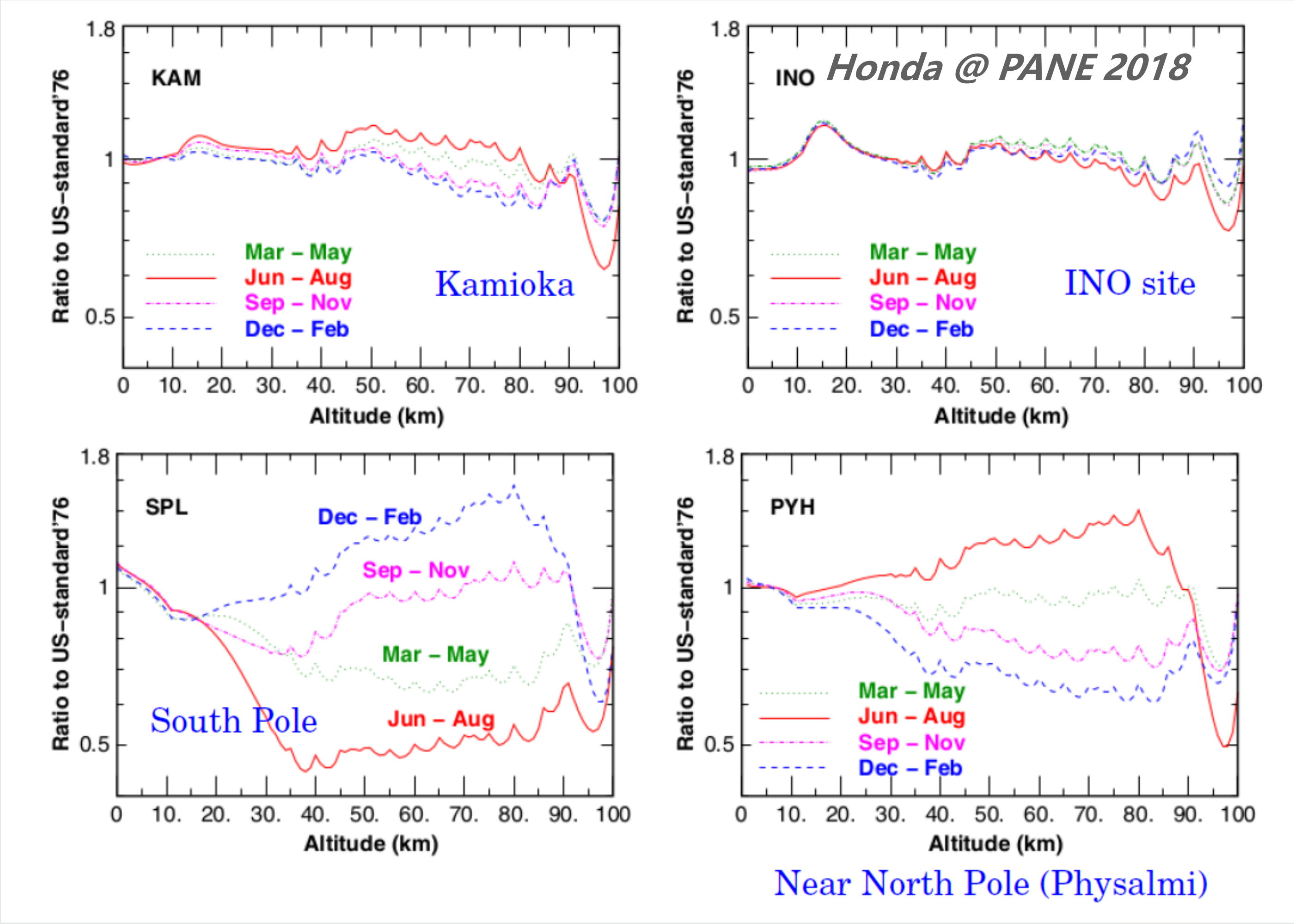






Air density： $\Phi = \Phi_{primary} \otimes R_{cut} \otimes Y$

- **NRLMSISE-00** instead of **US-standard 1976** to obtain position and seasonal variations

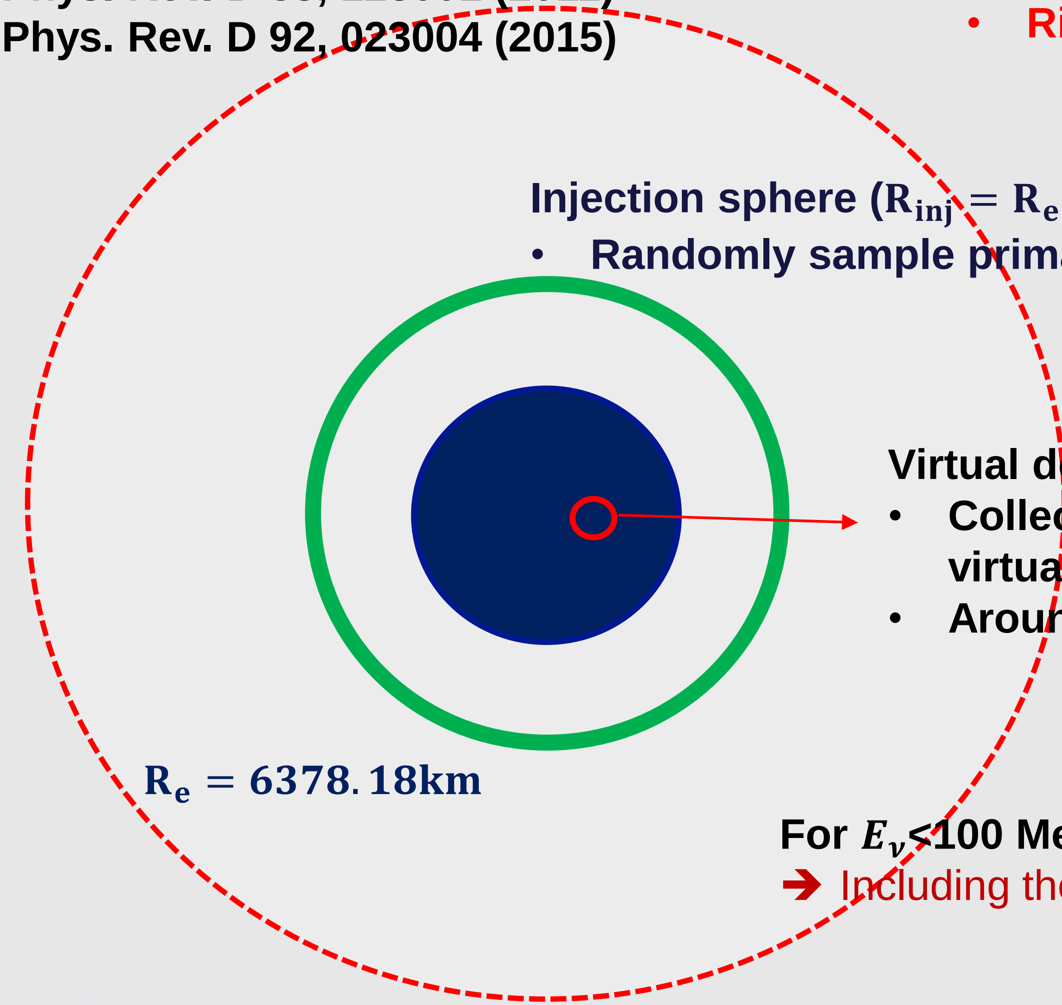


A full 3D calculation

Based on calculation scheme of Honda-flux model,
Phys. Rev. D 83, 123001 (2011)
Phys. Rev. D 92, 023004 (2015)

Simulation sphere ($R_e < R_{sim} \leq 10 \times R_e$)
- **Propagation of cosmic rays**
- **Rigidity cutoff test**

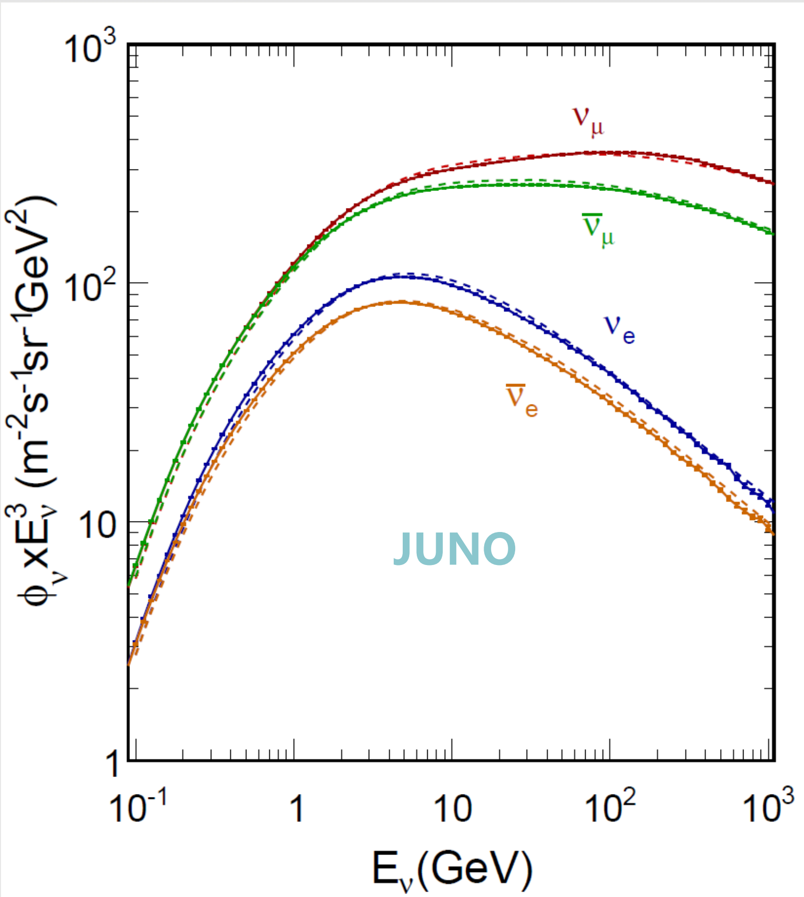
Injection sphere ($R_{inj} = R_e + 100$km)
- **Randomly sample primary cosmic ray**

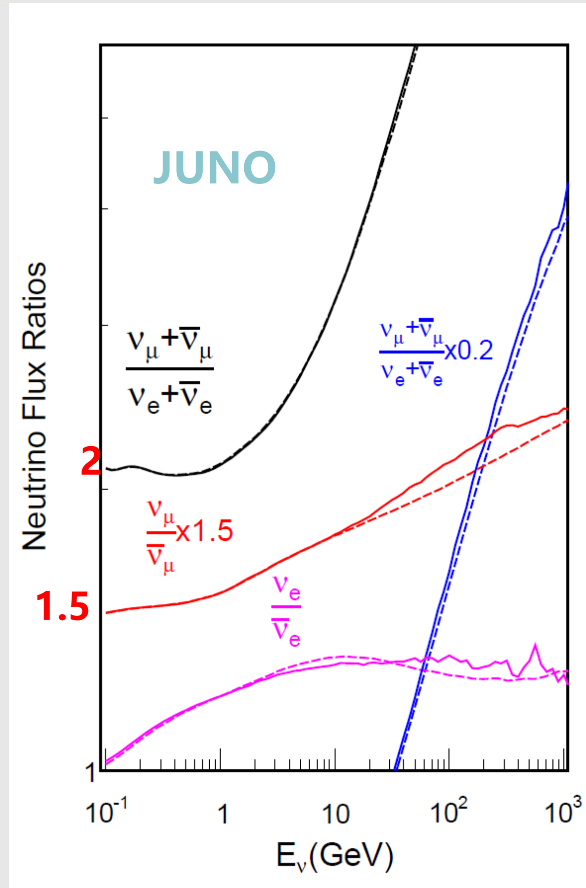


Virtual detector
- **Collect neutrinos passing through the virtual detector**
- **Around true detector**

For E_ν<100 MeV, there is an issue :
➔ Including the propagation of muons inside earth

Flux calculation: high energies





Assuming all mesons and muons decay :

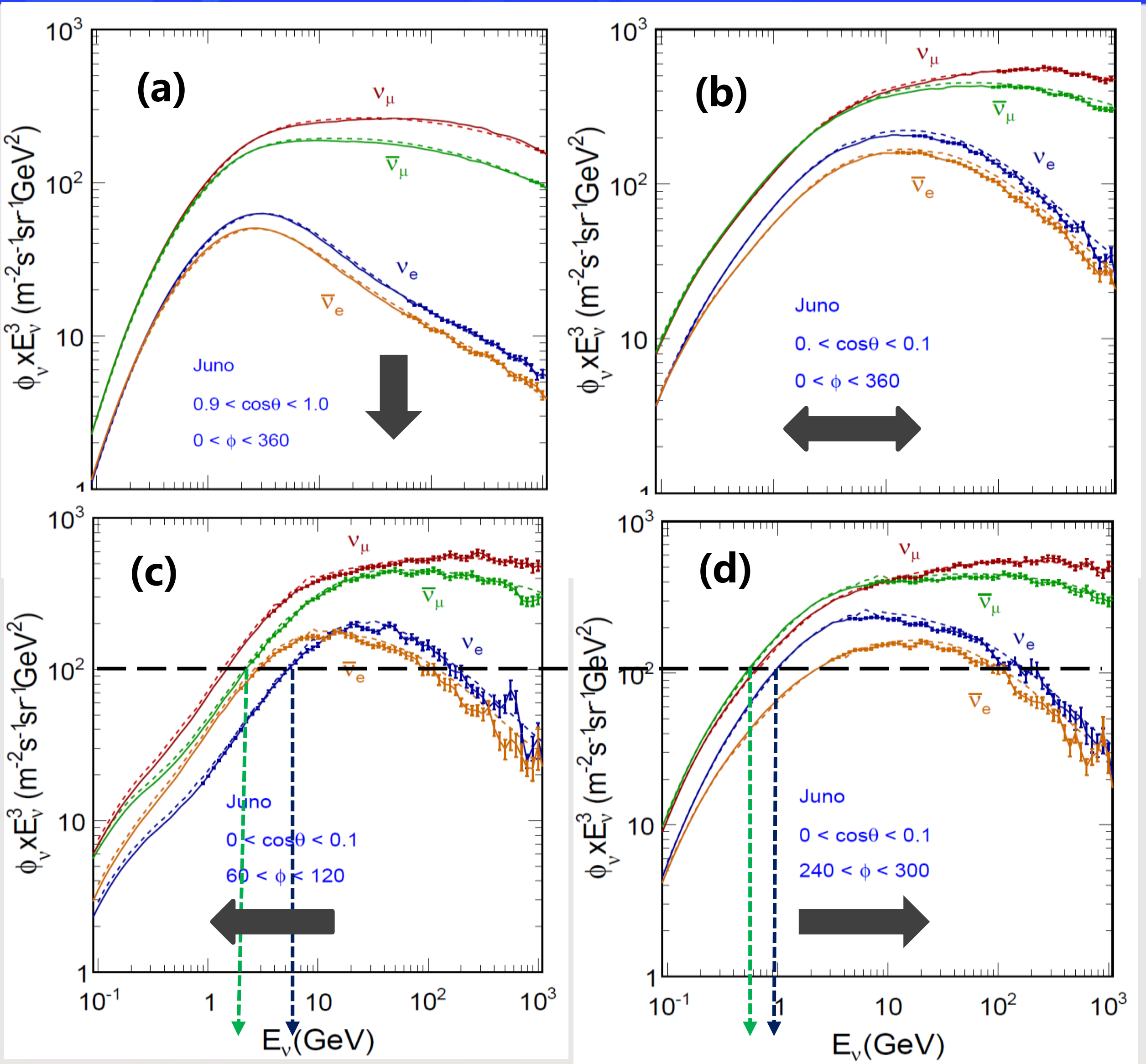
$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \sim 2$$

$$\frac{\nu_e}{\bar{\nu}_e} \sim 1$$

$$\frac{\nu_\mu}{\bar{\nu}_\mu} \sim 1$$

- **Dash line : fluxes with large-scale simulation**
- **Solid line : optimized calculation using re-weighting method**
- **The differences are due to less statistics for high energy range**

Flux calculation: high energies



(a): Vertical

(b): Horizontal

(a) compares (b) :

- **More flux in horizontal direction**

(c): Arriving from east (Horizontal)

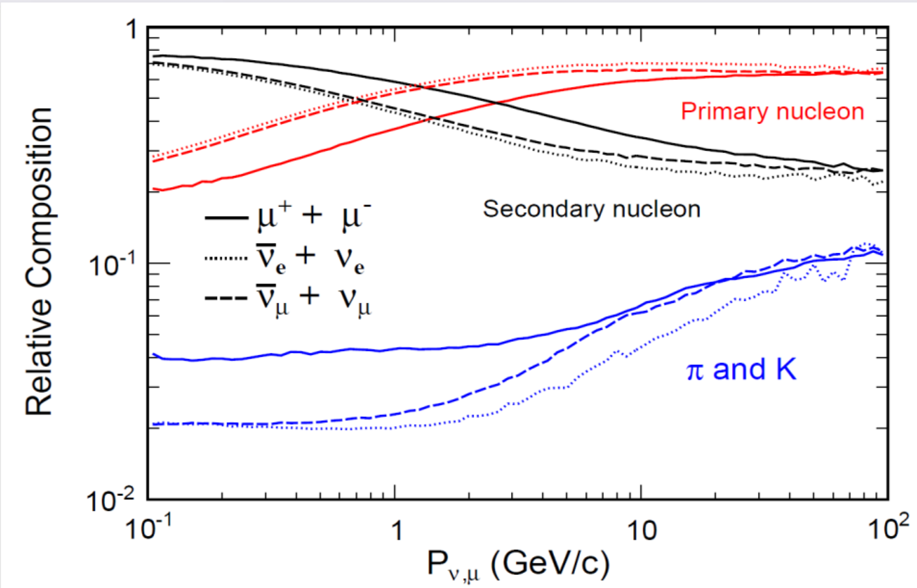
(d): Arriving from west (Horizontal)

(c) compares (d) :

- **Changes for $\bar{\nu}_\mu$ and ν_e are larger**
- **East-west differences due to geomagnetic field effect**

Error bar only include statistic uncertainty of simulation

Relative contributions of hadronic interaction



- The relative composition of the projectile of the last hadronic interaction
- The major projectile : nucleon (<100 GeV)
  - Secondary nucleon (< ~2 GeV)
  - Primary nucleon (> ~2 GeV)

Chain-1:

[Primary nucleon + Air] → π or K → **decay** → ν and μ

Chain-2:

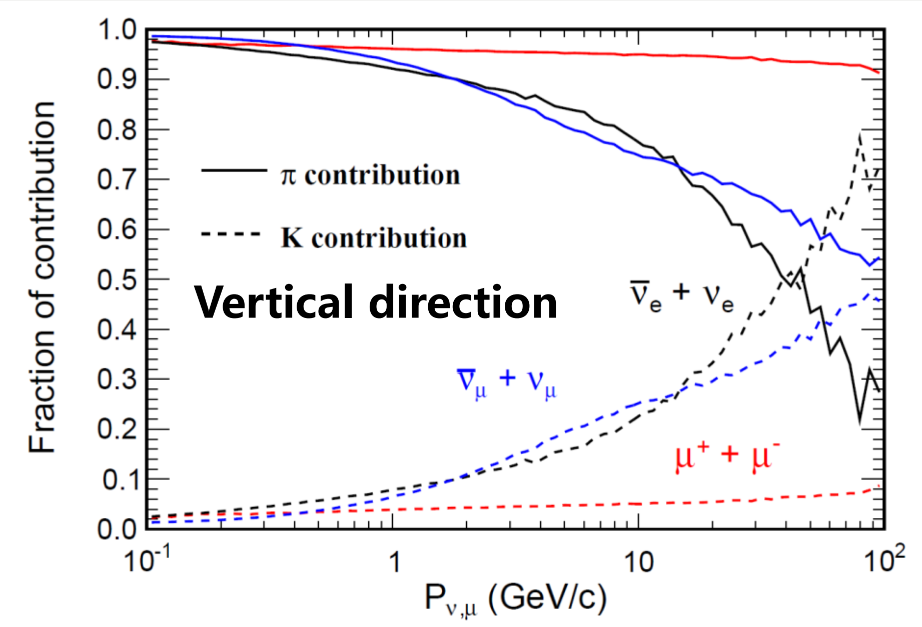
Primary nucleon + Air → [Secondary nucleon + Air] → π or K → **decay** → ν and μ

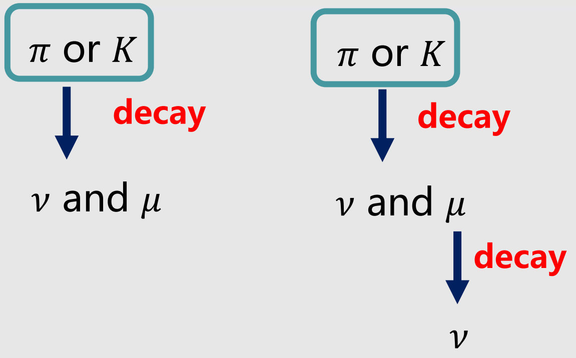
Chain-3:

[π or K + Air] → π or K → **decay** → ν and μ

[ ] The last hadronic interaction

Contributions to muon and neutrino

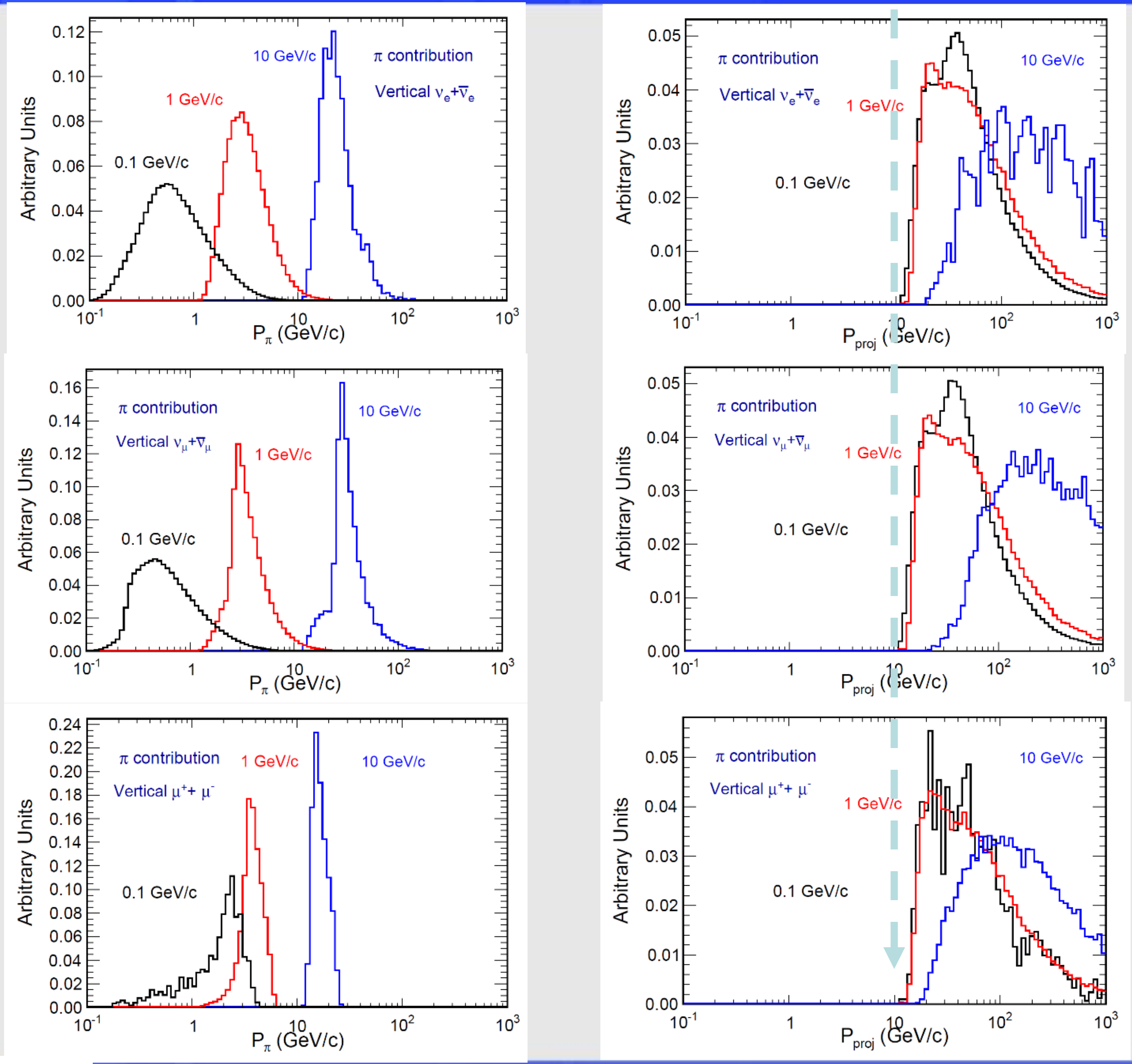




$K^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$	(63.5%)	$K_l^0 \rightarrow \pi^0 + \pi^+ + \pi^-$	(12.37%)
$\rightarrow \pi^\pm + \pi^0$	(21.2%)	$\rightarrow \pi^\pm + \mu^\mp + \nu_\mu(\bar{\nu}_\mu)$	(27.0%)
$\rightarrow \pi^\pm + \pi^+ + \pi^-$	(5.6%)	$\rightarrow \pi^\pm + e^\mp + \nu_e(\bar{\nu}_e)$	(38.6%)

- **The fractions of π-production and K-production contributions to atmospheric neutrinos and muon**
- Atmospheric muon:
  - π-production : dominant (< 100 GeV)
- Atmospheric neutrino:
  - π-production : dominant (< 10GeV)

Energy correlations of hadronic interactions



- $P_{\pi/K}$: momentum of meson, that produces observed muons or neutrinos
- P_{proj} : momentum of the primary nucleon
- There is a 10 GeV cutoff due to geomagnetic field effect

Strategies for precise flux at low energies

- Propagation of muon inside the earth
  - Should be included in the flux calculation
  - Contribute neutrinos (E_ν < 100 MeV)
  - Based on Physics Reports 354 (2001)
- Local considerations:
  - ✓ Local mountain profile
  - ✓ Local atmospheric density (measured)
  - ✓ Local geomagnetic field (measured)

◆ This presentation will focus on these

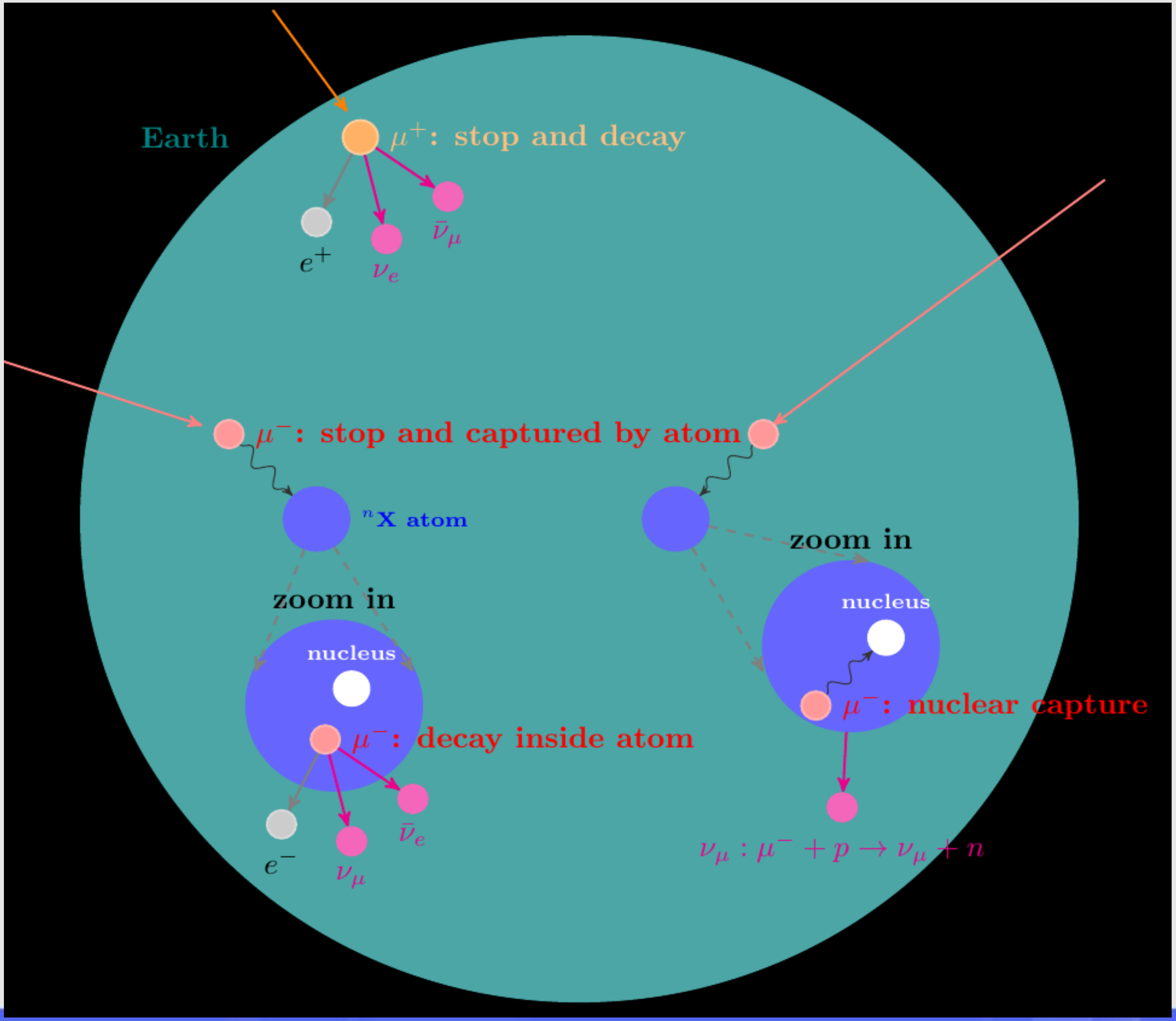
◆ Neutrino sources at low energies(<100 MeV): muon decay in the matter is the difficult and essential part

◆ Will add later

- Solar modulation effect for primary cosmic rays
- More muon flux measurements to calibrate the model (where are the data?)
- Accelerator data to constrain the hadronic model

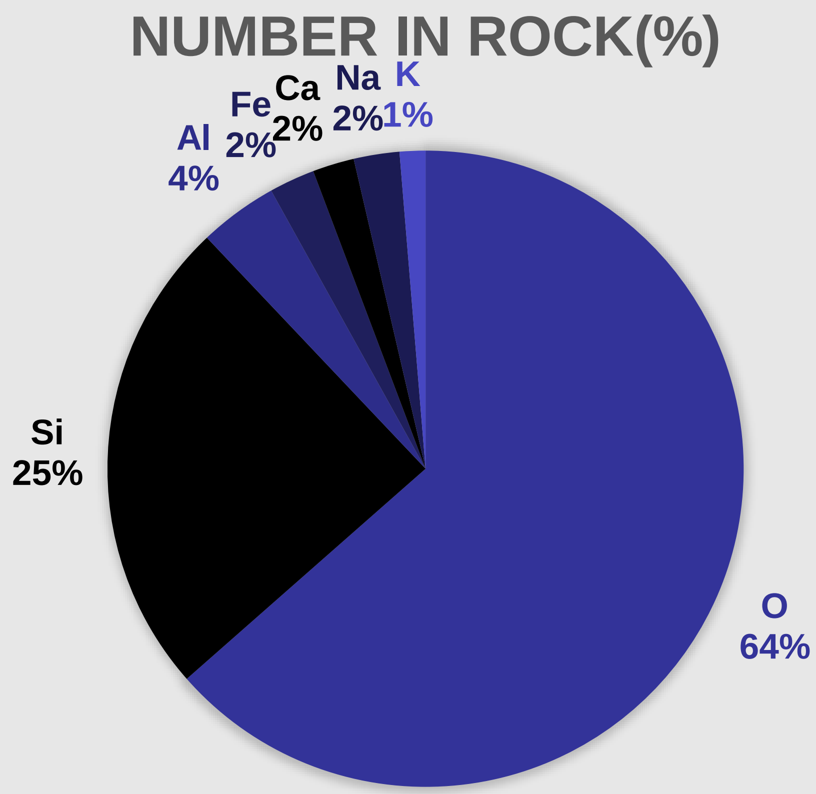
(see 2205.14766 and recent WANP2022 talks)

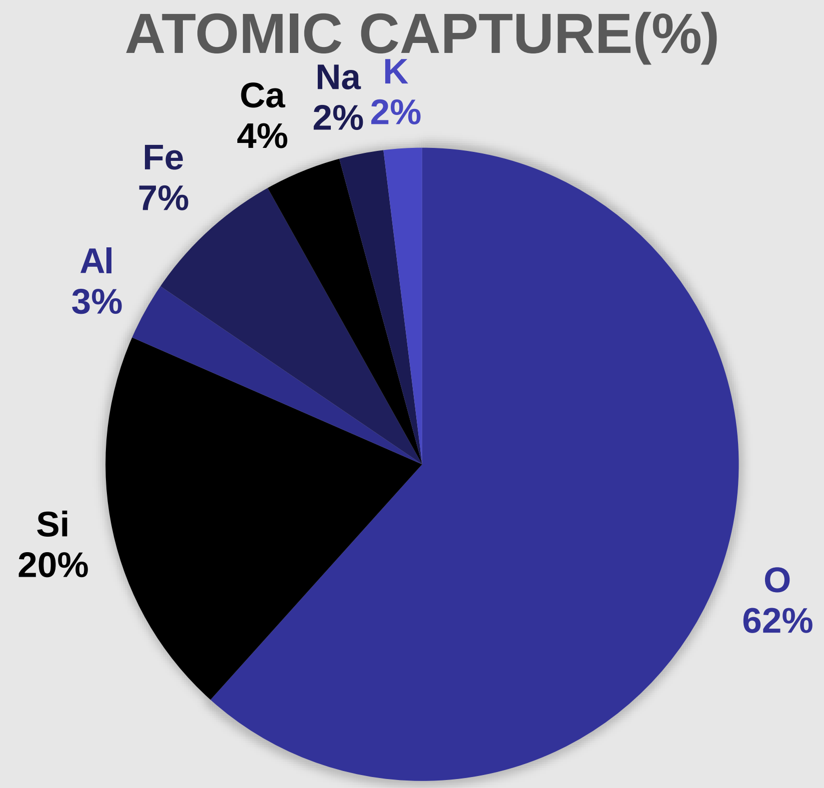
Physical processes of muons inside the Earth



Atomic absorption probability

- Consider most elements in the rock for μ^- capture





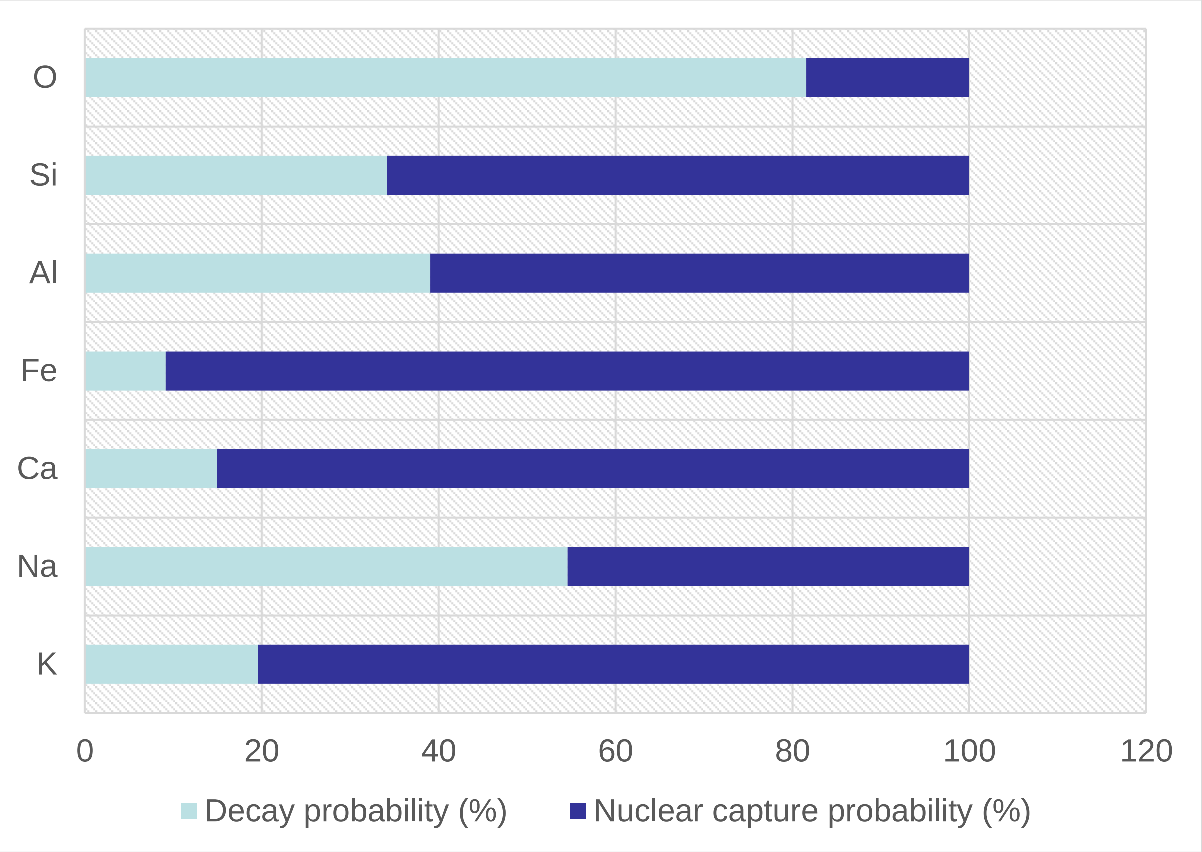
- In the sea, the atomic absorption probability by oxygen is 100%

PRD 99, 073007 (2019)

Nuclear capture probability

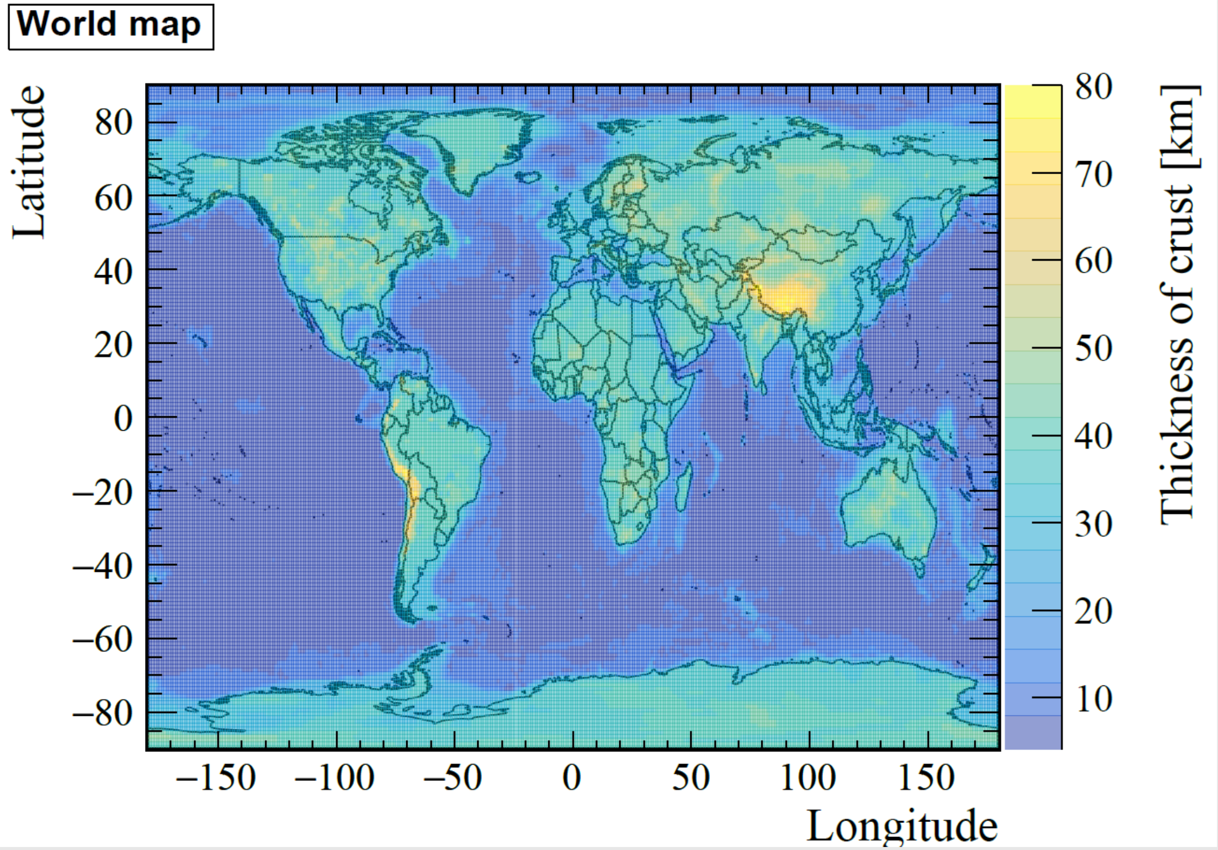
Mean lifetime

Elements	τ_{μ^-}(ns)
O	1795.4
Si	756
Al	864
Fe	206
Ca	332.7
Na	1204
K	435



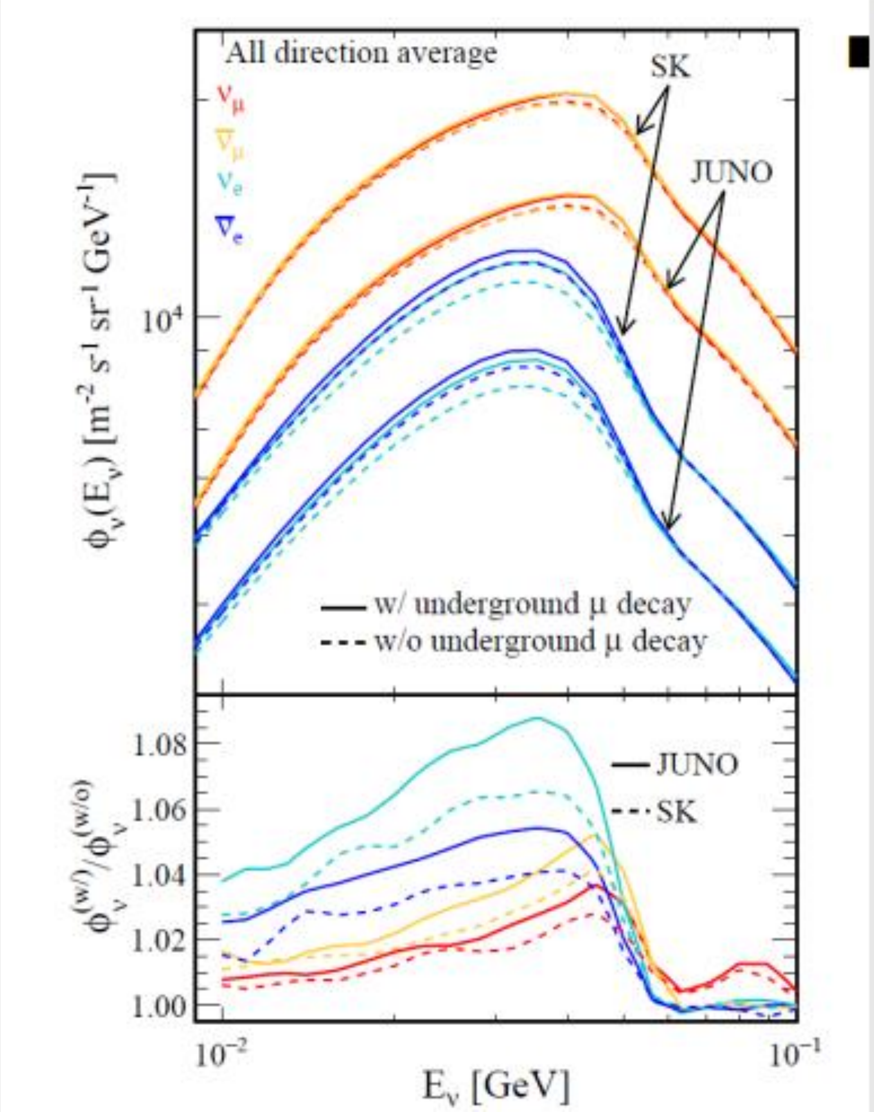
PRD 99, 073007 (2019)

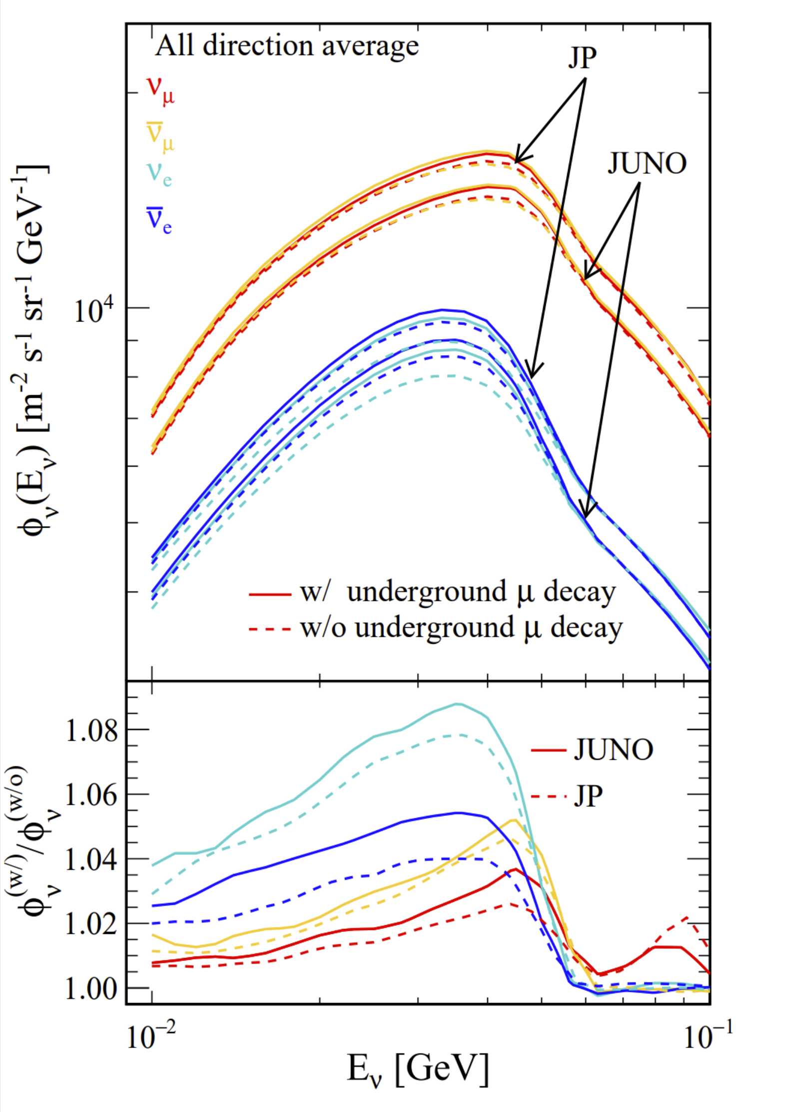
World map for muon hit point on the Earth



- For the global 3D simulation, according to the thickness of crust (data from CRUST1.0 model), determine the material (water or rock) of the position of muon inside the Earth
- For the Latitude > 70° and < 70°, we assumed the surface is covered by the ice.

Flux calculation: low energies





To-do list

- **Muon capture and decay inside earth (almost finished)**

- **Local information acquisition**

- **Time modulation effects:**

  a) solar modulation on primary cosmic flux and magnetic field

  b) seasonal (daily) modulation due to air density (temperature)

- **Uncertainty evaluation and improvement**

  a) Hadron interaction tunning using accelerator data

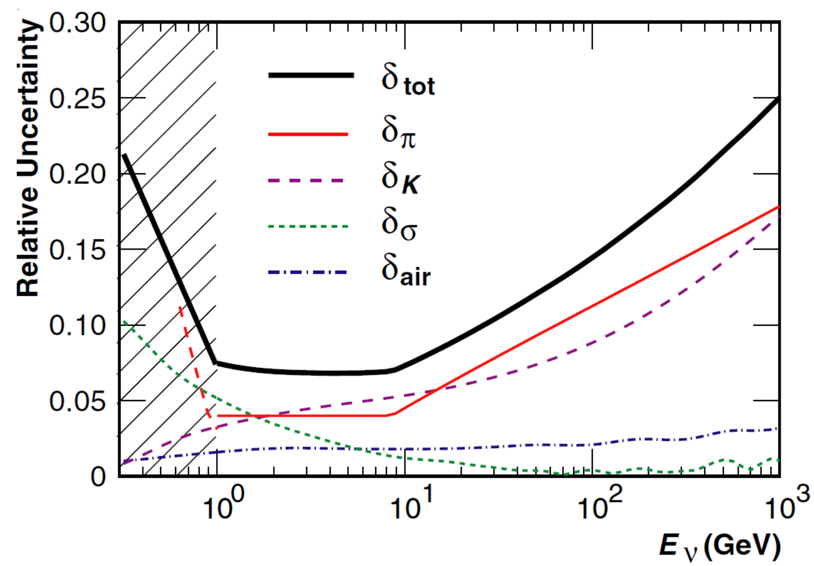
  b) muon flux energy spectrum measurement (lack of data)

Conclusion

- **A calculation of the atmospheric neutrino flux at CJPL is accomplished based on *Monte Carlo method***
- **Updates with muon capture & decay inside the Earth, local information, *hardon interaction (will do it later)***
- **CJPL (& Jiangmen) has smaller neutrino flux due to restrictive rigidity cut (larger magnetic field).**
- **Time modulation would be useful for the signal & background description**
- **Uncertainty study is on-going**

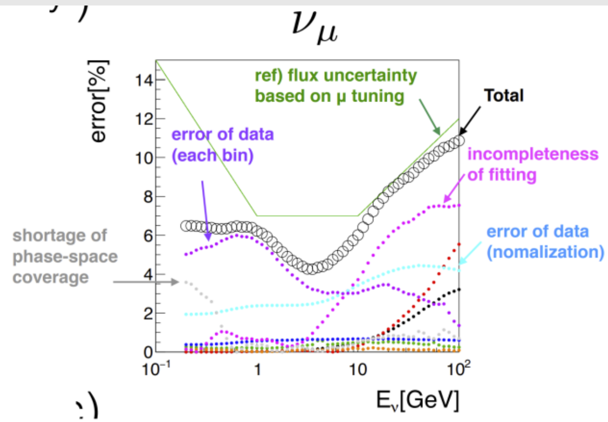
Thank you !

Uncertainty evaluation



PHYSICAL REVIEW D 75, 043006 (2007)

- δ_π μ -observation error + Residual of reconstruction
- δ_K Kaon production uncertainty
- δ_σ Mean free path (interaction crossection) uncertainty
- δ_{air} Atmosphere density profule uncertainty

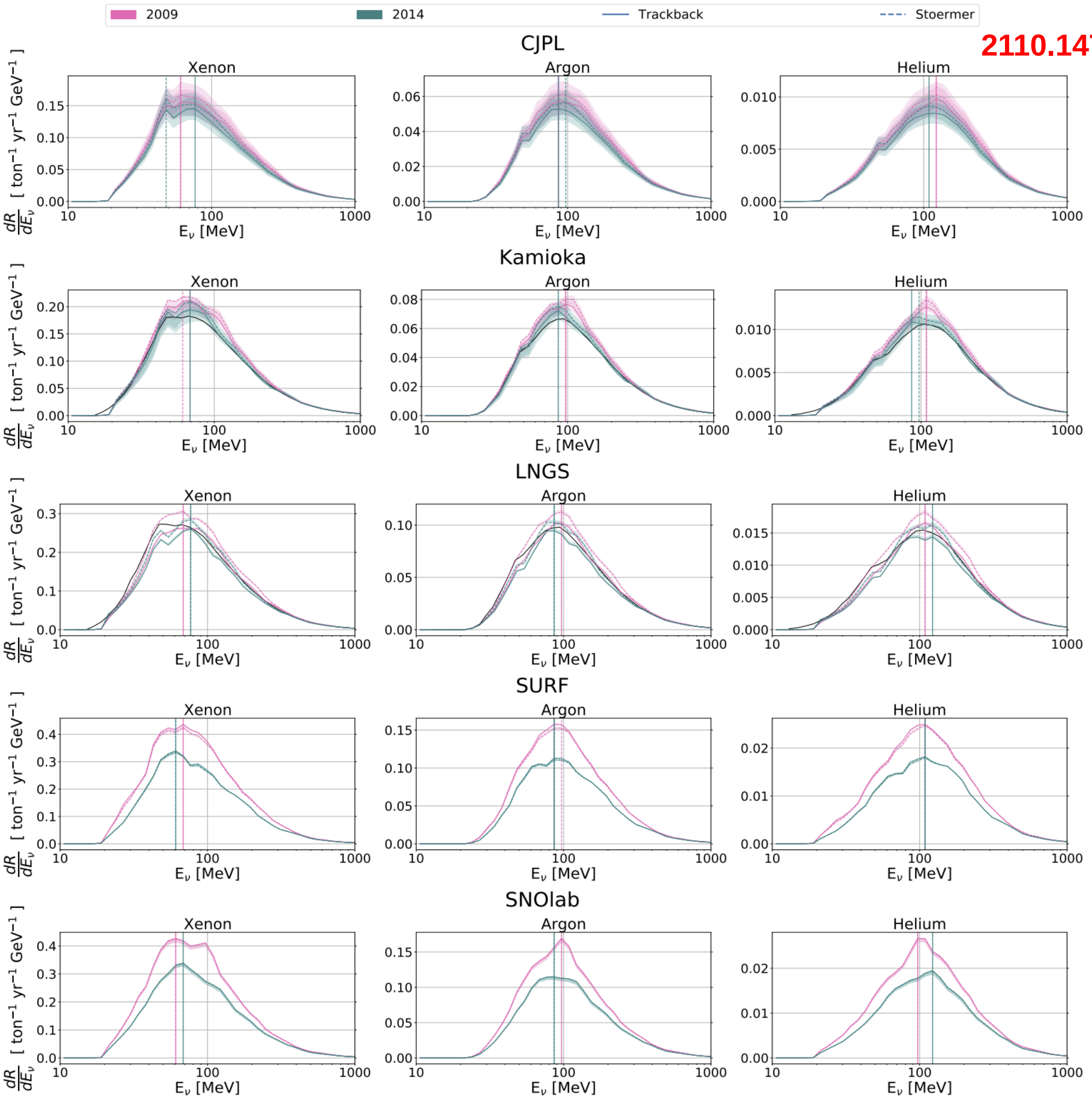


- lower E (<~5GeV): **error of measurement data**
  - HARP, E910 have larger error compared to NA61, NA49.
- higher E (>~5GeV) : **fitting incompleteness**
  - simultaneously fit NA61, NA49, and NA56 data (31~450 GeV)

* Uncertainty of total production cross-section is not included here. It should have relatively large uncertainty.

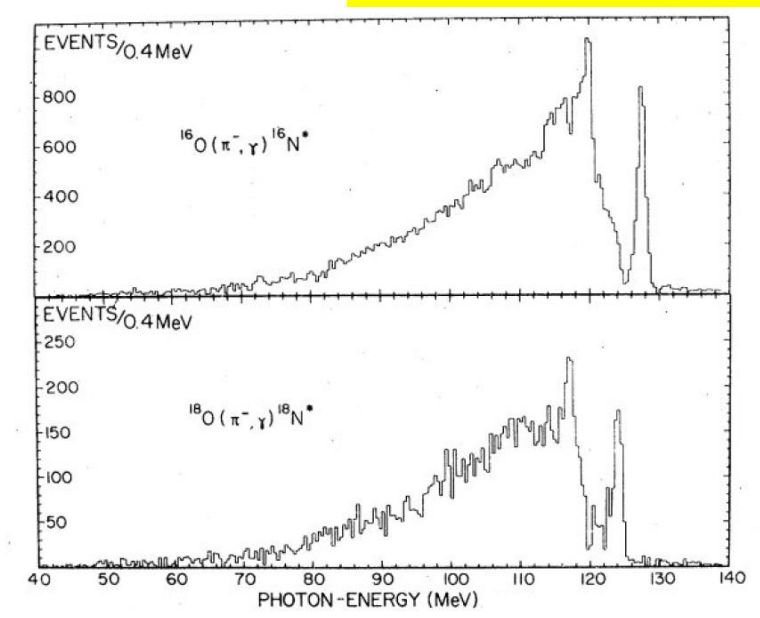
- Preliminary results re-tunned by Sato (WANP2022)
- Careful cross check is needed for a better understanding.

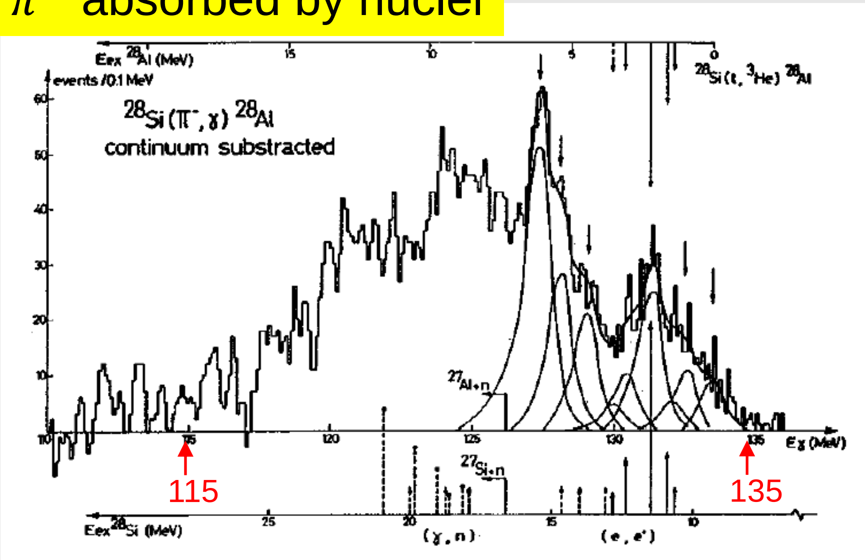
2110.14723


2009
2014
Trackback
Stoermer
CJPL
Kamioka
LNGS
SURF
SNOlab
Xenon
Argon
Helium
$\frac{dR}{dE_\nu}$ [ton^{-1} yr^{-1} GeV^{-1}]
E_ν [MeV]

ν_μ energy spectra from nuclear capture

γ spectrum data from π^- absorbed by nuclei

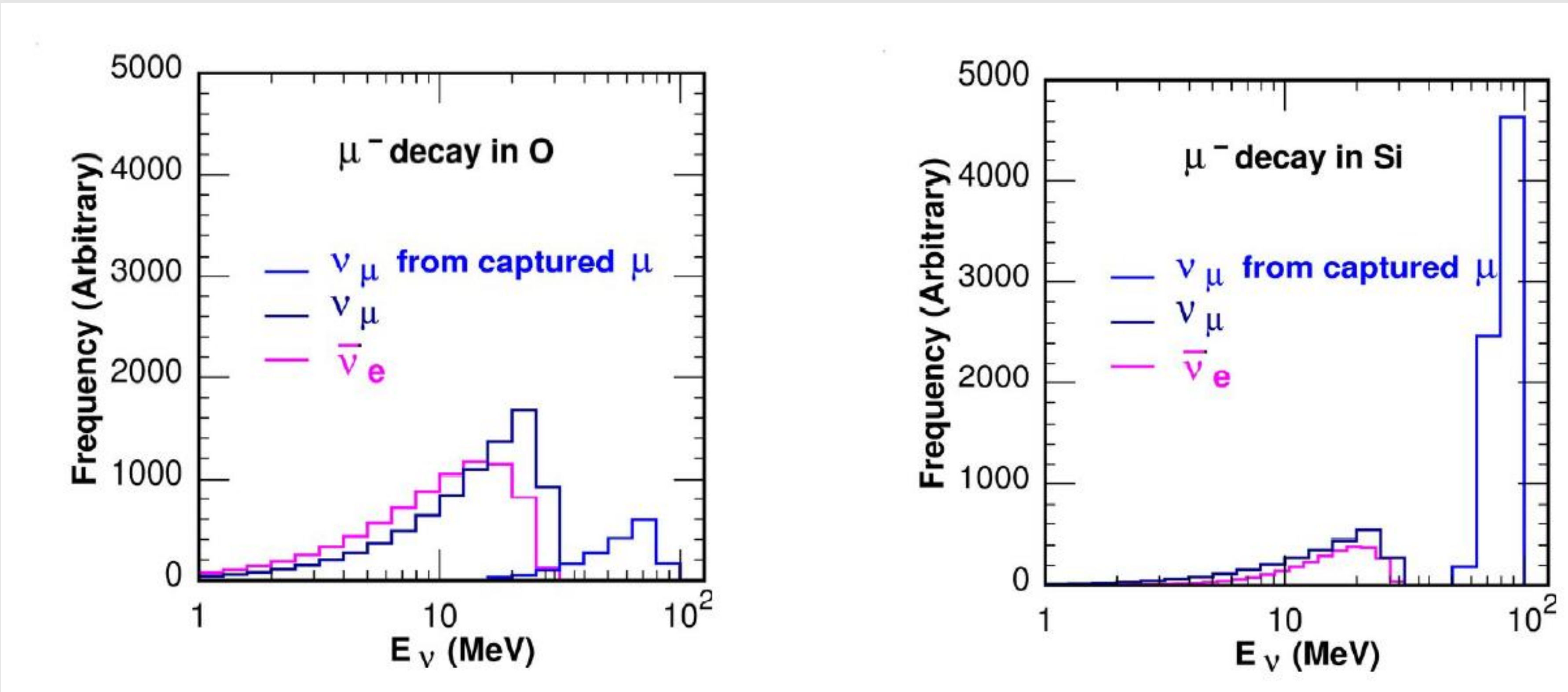




D. F. Measday, Phys. Rep. 354, 243 (2001).
G. Strassner et al., Phys. Rev. C 20, 248 (1979).

- The γ spectra from the reactions $^{16}\mathrm{O}(\pi^-,\gamma)^{16}\mathrm{N}^*$ and $^{28}\mathrm{Si}(\pi^-,\gamma)^{28}\mathrm{Al}^*$ assume to the ν_μ energy spectra from the nuclei capture
- No other experimental data for π^- captured on heavier nuclei above Si, use the results of Si for other heavier nuclei
- Will update the code if there are reasonable spectra from the π^- absorption in other nuclei.

Expected neutrino spectra



- When muon enters the rock or water, neutrino induced by the muon will follow the shapes shown in the above plots.