Determining Flavor Ratio of Diffuse Ultra-High Energy Cosmic Neutrinos by Event Direction Distribution of Askaryan Radio Array

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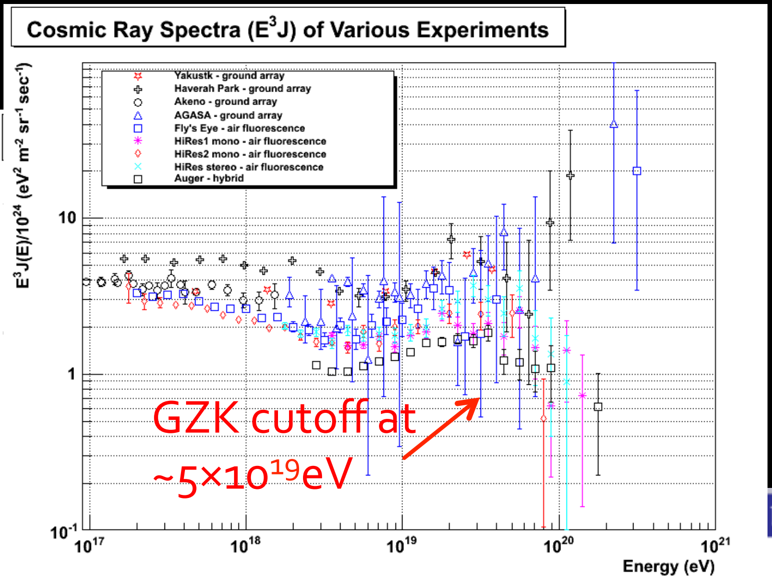
This talk is based on our published work:
S.H. Wang, P. Chen, J. Nam, and M. Huang,
JCAP 11 (2013) 062; arXiv:1302.1586

Outline

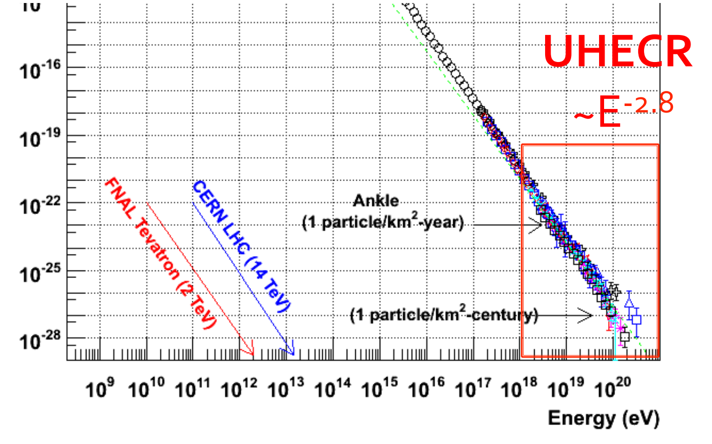
- What's Ultra-high energy cosmic neutrino (UHECN)?
- What's important about UHECN flavor composition?
- Detecting UHECN with ARA observatory at South Pole
- Constraining UHECN flavor ratio with event angular distribution
- Summery and future work

Ultra-High Energy Cosmic Rays & Neutrinos

- Cosmic rays with E > 10^{18} eV (UHECR) are observed.
  - Source (AGN, GRB)?
  - Acceleration mechanism?
- Neutrinos can be generated when UHECR interact with photon or matter
  - CMB photon → GZK cutoff in CR spectrum →**Cosmogenic neutrinos!**



GZK cutoff at ~5×10^{19}eV

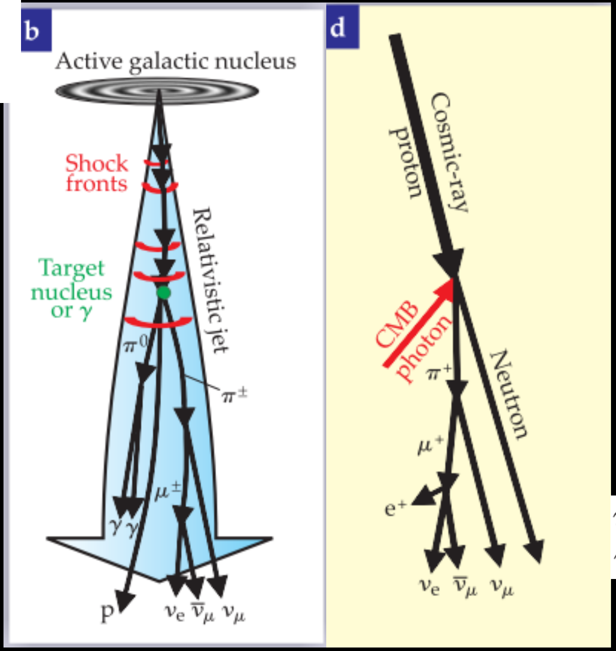


UHECR

~$E^{-2.8}$

from http://www.physics.utah.edu/~whanlon/spectrum.html

F. Halzen and S. Klein, Physics Today 2008



Astrophysical:

$$p + p \text{ or } p + \gamma \rightarrow \pi^{\pm} + \ldots$$

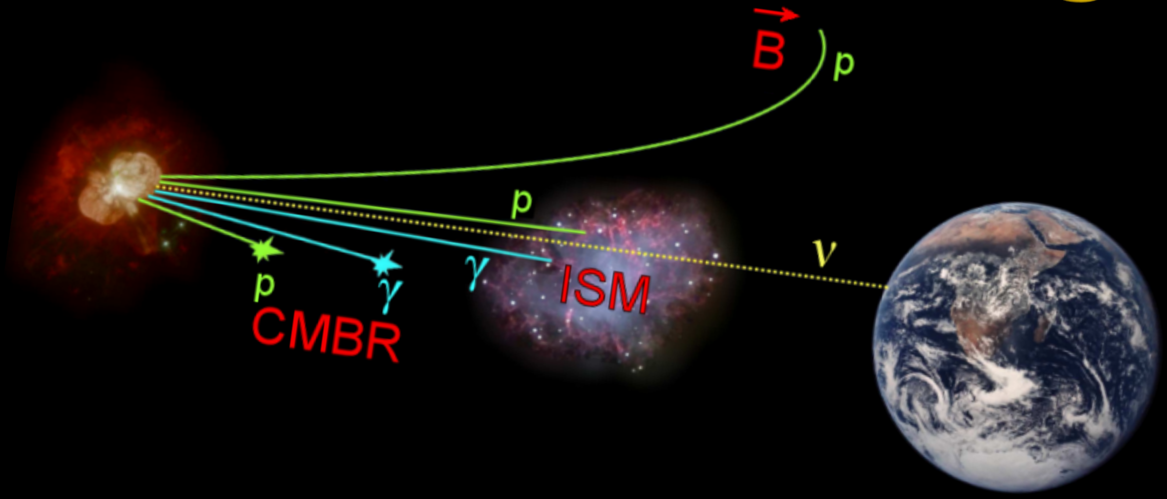
Cosmogenic:

$$p + \gamma_{CMB} \rightarrow \Delta^{+} \rightarrow \pi^{+} + n$$

Charged pion decay

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{\mu} + \nu_{e} + \bar{\nu}_{\mu}$$
$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \rightarrow e^{-} + \bar{\nu}_{\mu} + \bar{\nu}_{e} + \nu_{\mu}$$

UHECN as Cosmic Messenger



- Being electrically neutral and weakly interacting, UHECNs carry information from the sources
  - Energy spectrum
    - CR composition, source distribution, max acceleration energy
  - **Flavor ratio: relative flux between $\nu_e : \nu_\mu : \nu_\tau$**
    - Source size & B-field strength

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_\mu + \nu_e + \bar{\nu}_\mu$$

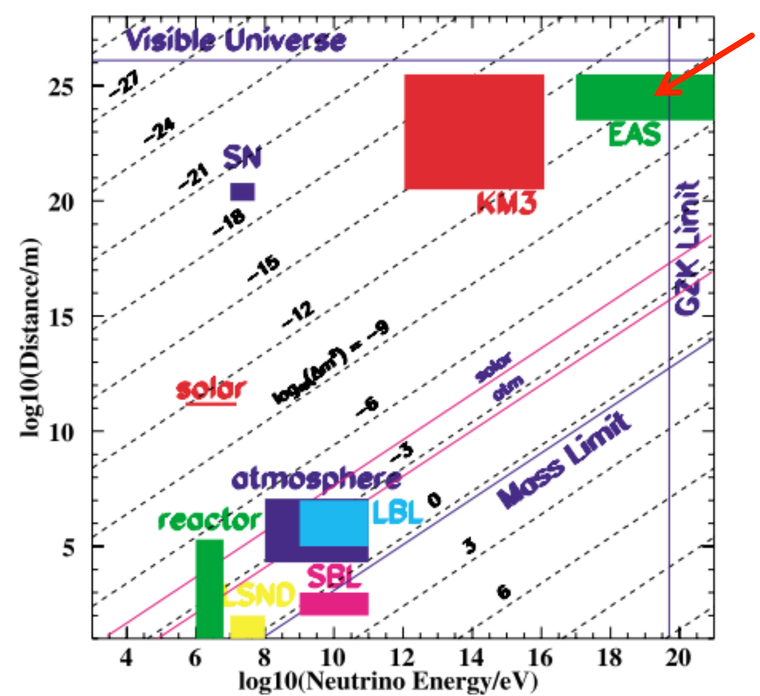
decay v.s. synchrotron cooling

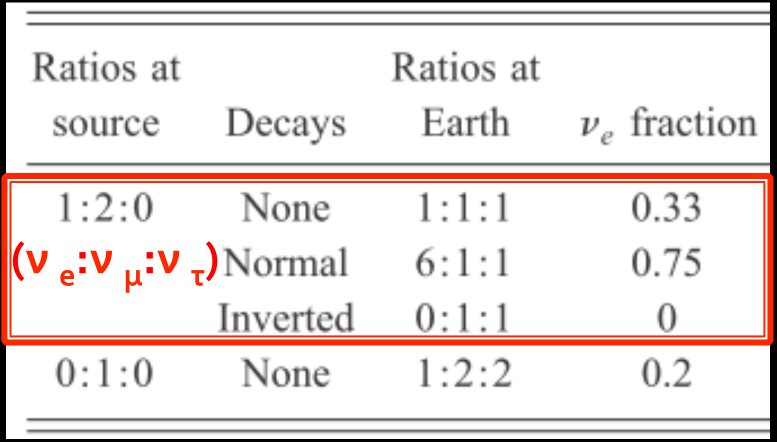
→ratio transition with E_ν (**1:2:0→0:1:0**)

Kotera et al., JCAP10 (2010); 013; S. Hümmer et al., Astropar. Phys. 34, 205 (2010).

UHECN as Beam Experiment

- UHECN is an unique probe with
  - Extremely high energy **(>10^{17} eV)**
  - Extremely traveling distance**(>Mpc)**
- Flavor ratio at Earth is determined by :
  - **Flavor ratio at source**
  - **Flavor transition in propagation**
    - Neutrino oscillation
    - Non-standard physics?
      - **Neutrino decay & mass hierarchy**
      - Sterile neutrinos with small Δm^2
      - CPT violation, Lorentz violation, etc.



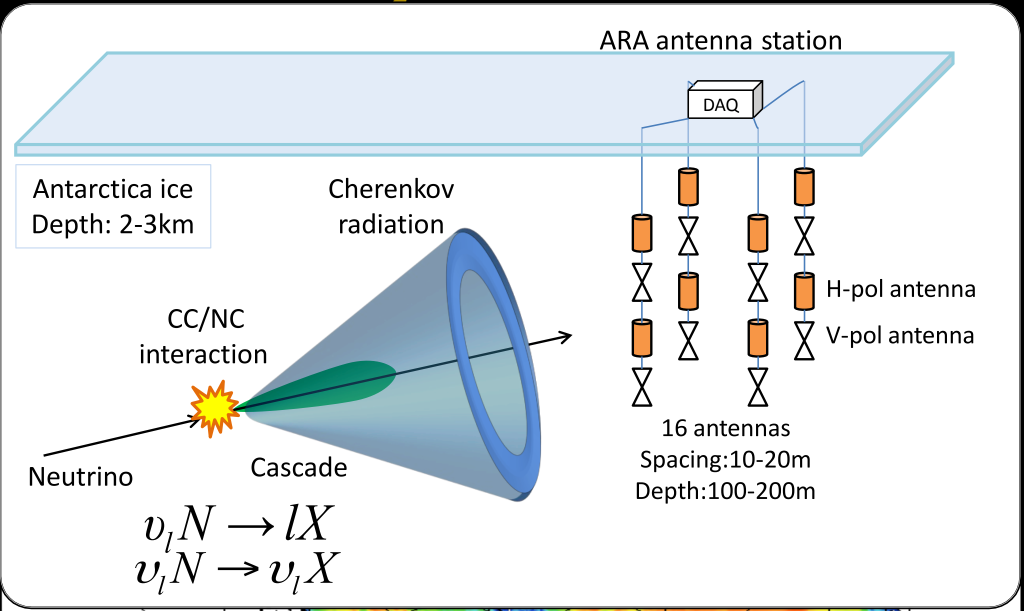


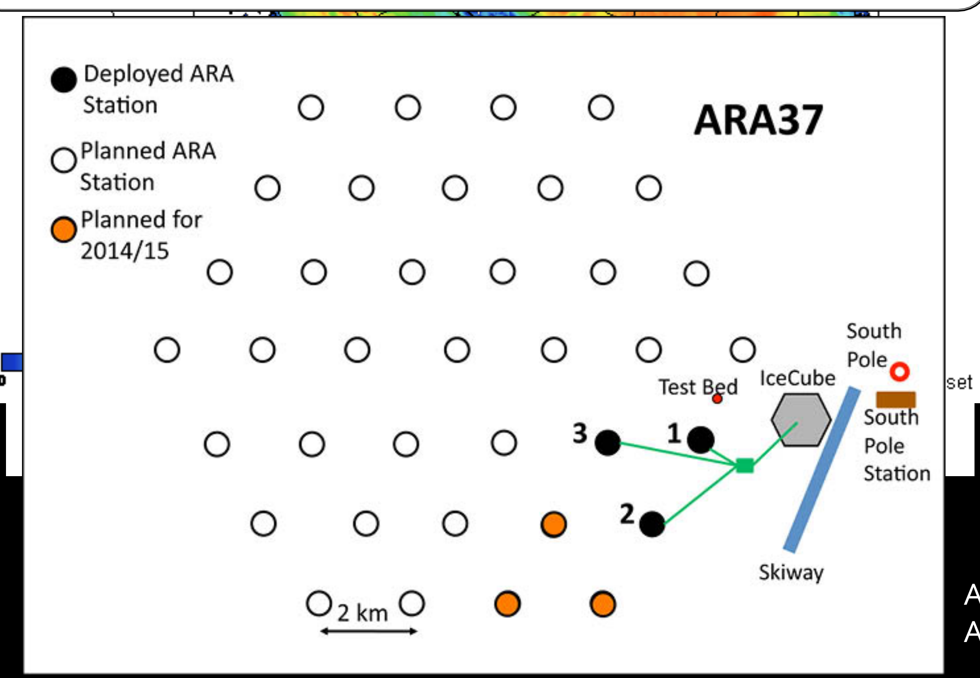
Ratios at source	Decays	Ratios at Earth	ν_e fraction
1:2:0	None	1:1:1	0.33
(ν_e:ν_μ:ν_τ)	Normal	6:1:1	0.75
	Inverted	0:1:1	0
0:1:0	None	1:2:2	0.2

J. Beacom et al. , Phys. Rev. Lett. 92, 011101 (2004);
G. Barenboim and C. Quigg, Phys. Rev. D 67, 073024 (2003);
D. Hooper et al., Phys. Rev. D 72, 065009 (2005).

J. Beacom et al. , Phys. Rev. Lett. 90, 181301 (2003).
J. Beacom et al., Phys. Rev. D 68, 093005 (2003)
P. Keraenen et al., Phys. Lett. B 574, 162 (2003)

Askaryan Radio Array at South Pole



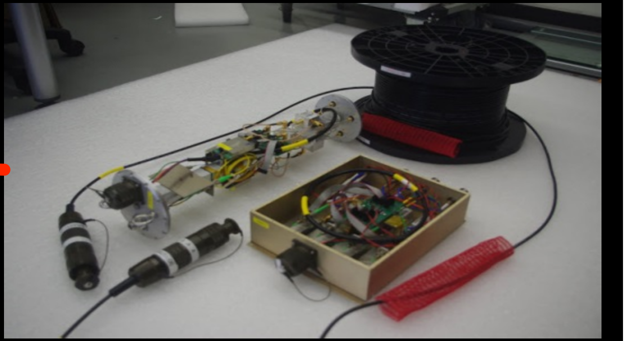


- Antarctic ice as target
  - vast, quiet, and clean
- Askaryan effect
  - radio Cherenkov pulse
- 37 stations, 3 deployed
  - ~200km² coverage
  - NTU participates
- ~50 UHECN events is expected in 3 year

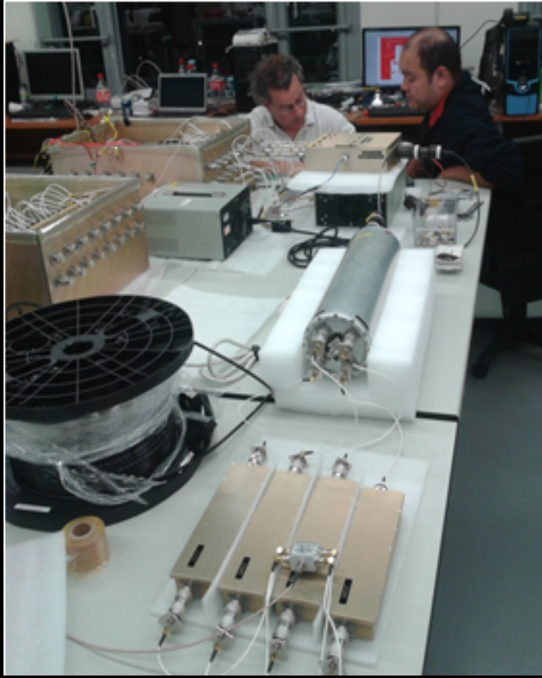
Allison et al. (ARA collaboration), Astropar. Phys. 35, 457 (2012),
Allison et al. , arXiv:1404.5285; http://ara.wipac.wisc.edu/home

NTU team successfully constructed ARA2 & ARA3 in 2012

DAQ



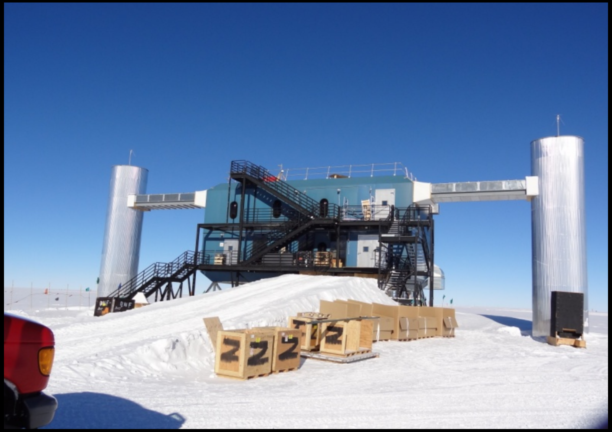
RF over Fiber

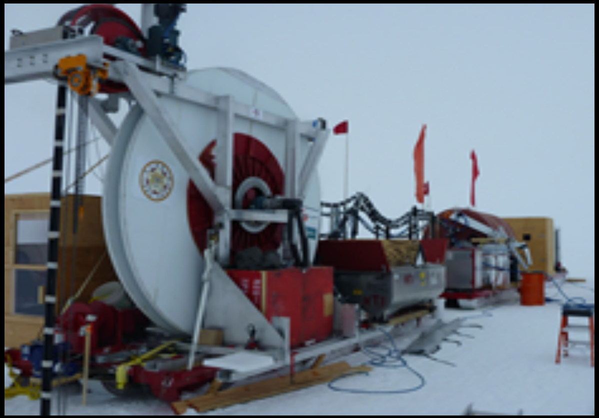


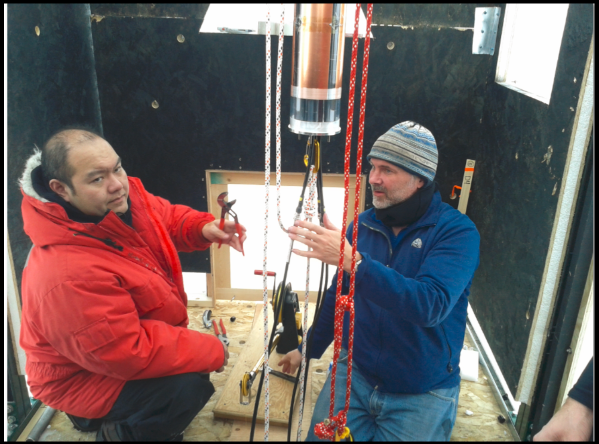
Low Noise Amplifier

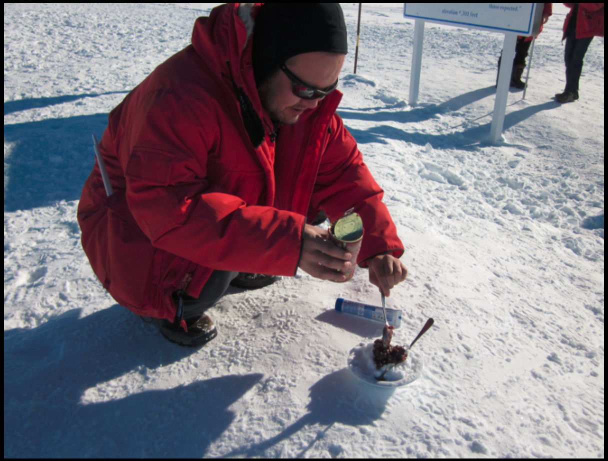
Antenna

South Pole Expedition for ARA 1 (2011-12), 2 &3 (2012-13) Deployment

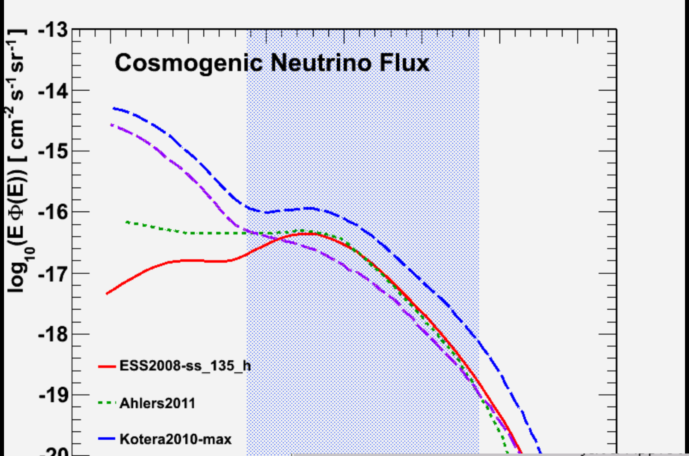




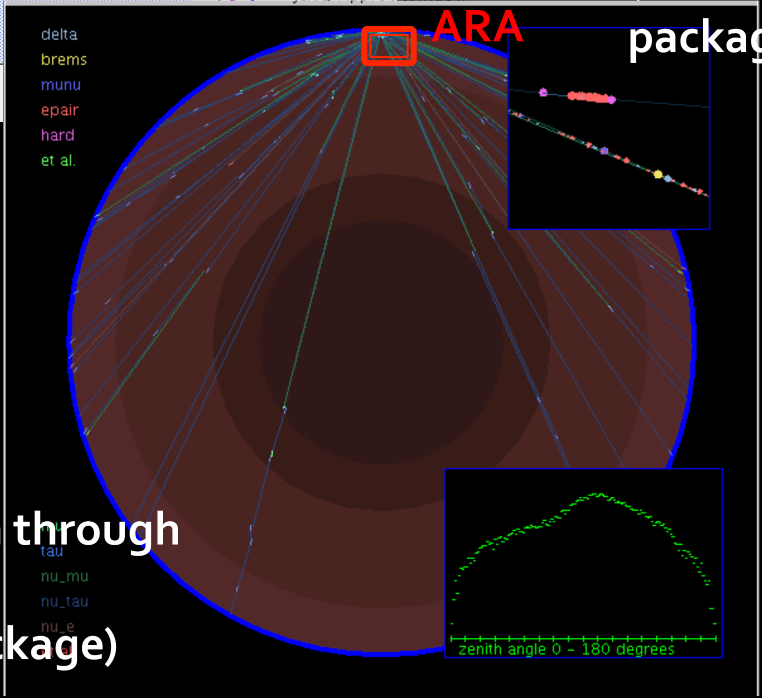




Simulation



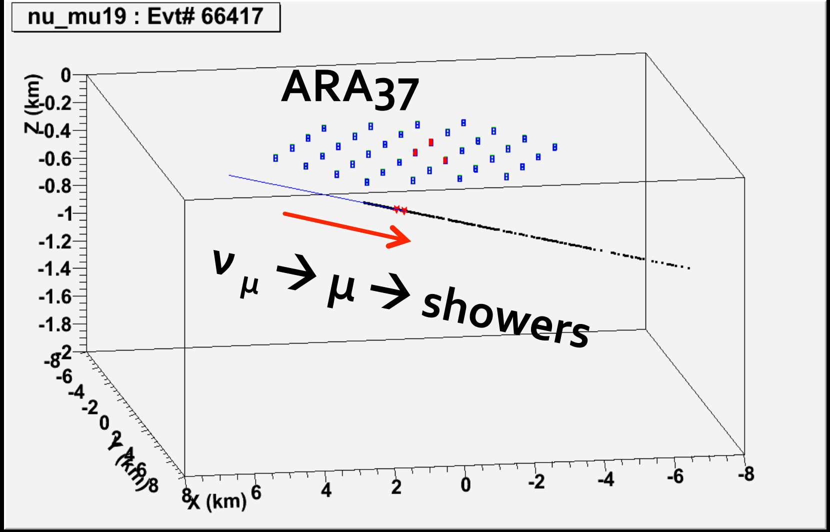
1. Event generation with given neutrino spectrum



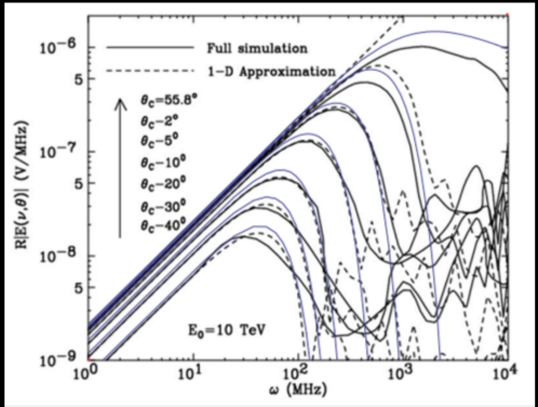
2. Propagation through the Earth (with MMC package)

3. Event detection (with SADE package)

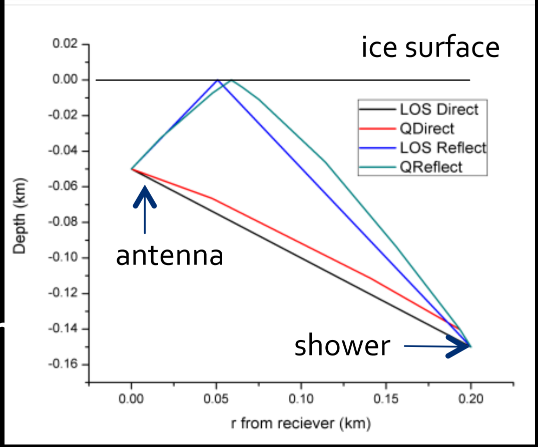
4. Neutrino events of all flavors



Radio Cherenkov emission

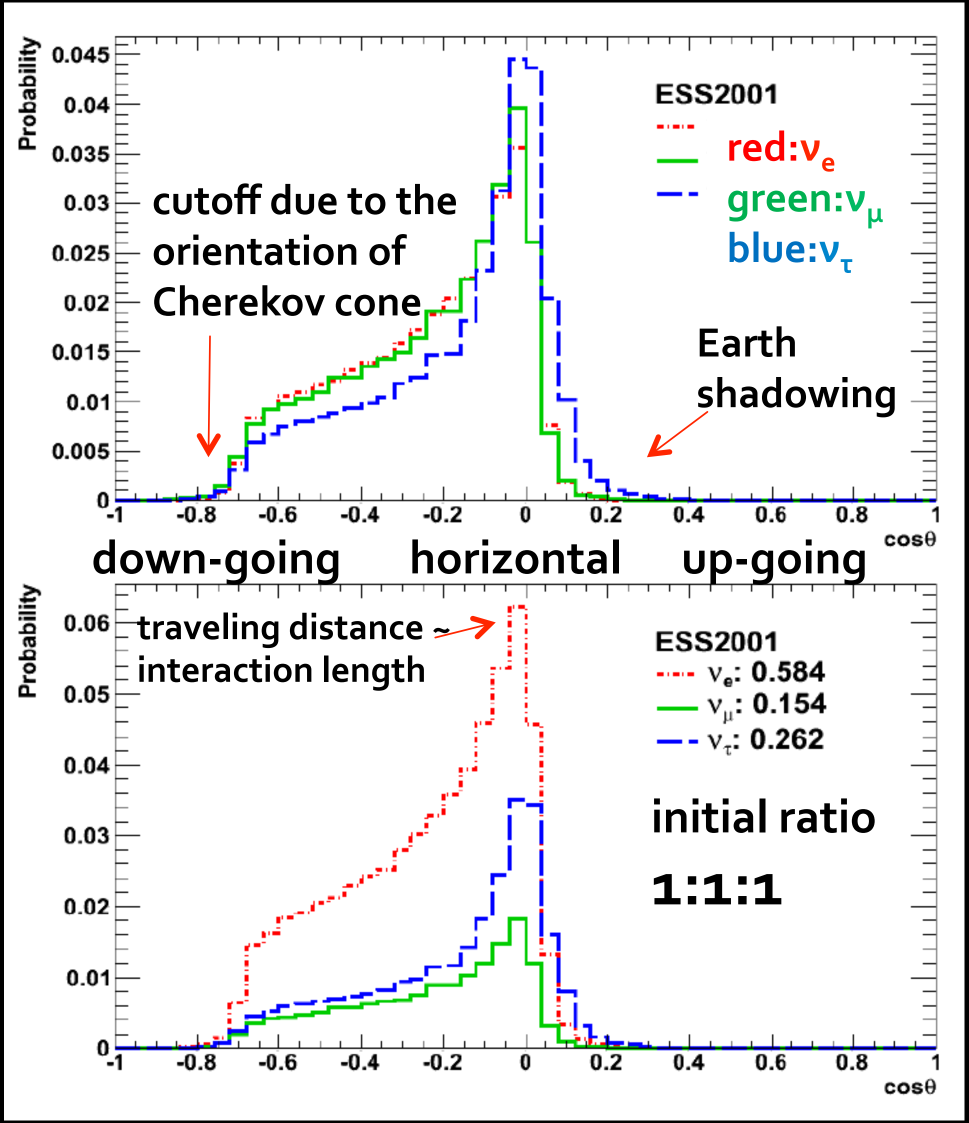


Ray propagation in ice



http://dima.lbl.gov/work/MUONPR/

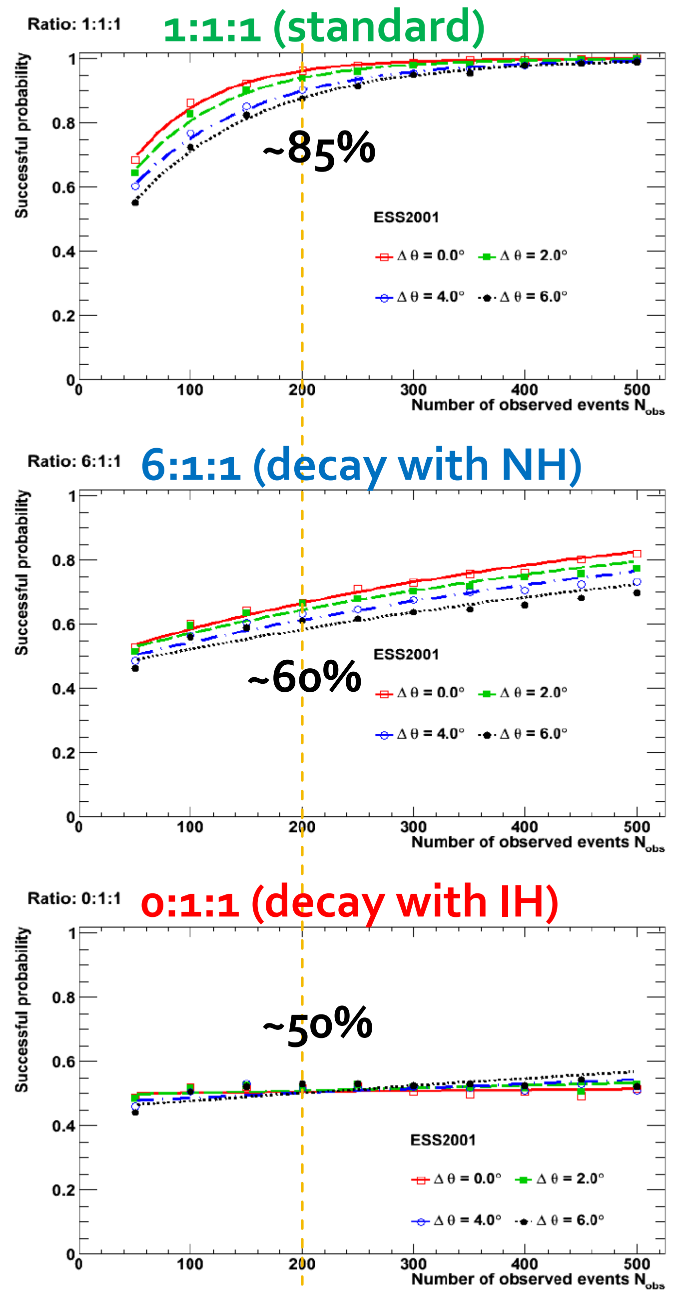
Expected Arrival Zenith Angular Distribution of Neutrino Events in ARA



- Neutrino CC interaction produces charged lepton $v_l N \rightarrow lX$
- Different energy-loss properties of charged leptons in matter lead to different event angular distribution
- ν_τ distribution is the most different
  - τ decay
  - ν_τ regeneration (ν_τ → τ →ν_τ).
- υ_e and υ_μ have similar shapes, extra constraint is required
  - υ_μ -ν_τ symmetry is assumed (i.e. the are of equal ratio).
- Initial ratio 1:1:1 → detected ratio 0.59:0.15:0.26

By fitting event angular distribution, UHECN flavor ratio can be extracted

Success Probability of Extracting ν_e Fraction

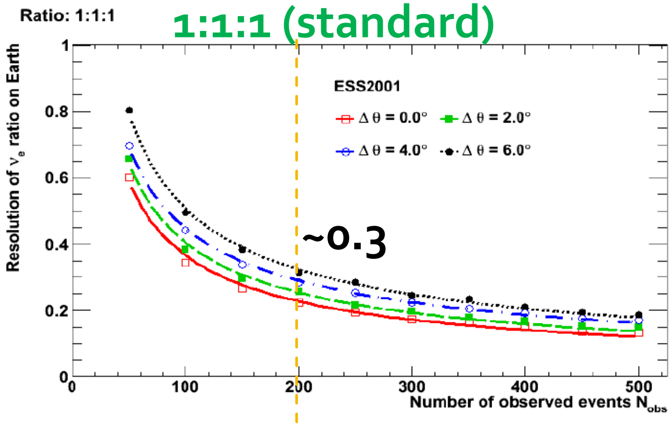


- ν_e Fraction f_e=[0,1]
  - expected f_e = 1/3 (standard), 0.75 (decay w/ NH), 0 (decay w/ IH)
- ∵random sampling, sometimes fitting gives unphysical f_e → fail
  - Generate ensemble of data sets to get the success probability
  - depend on number of events and angular resolution
- With angular resolution Δθ =6 ° and 200 events, the success probability is about 85%, 60%, and 50%, respectively

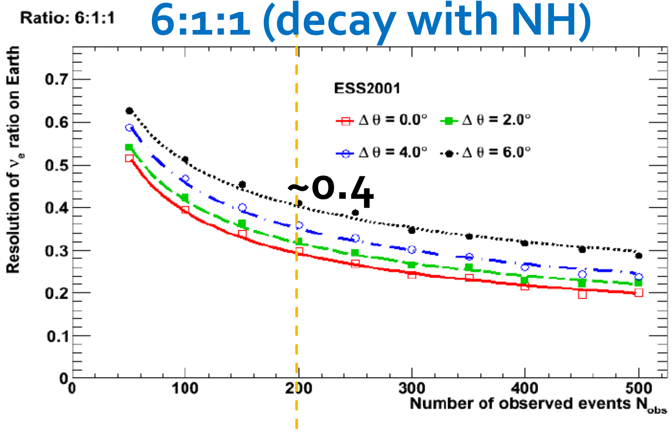
Δθ =0° (red), 2° (green) , 4° (blue), 6° (black)

Resolution of Extracted ν_e Fraction

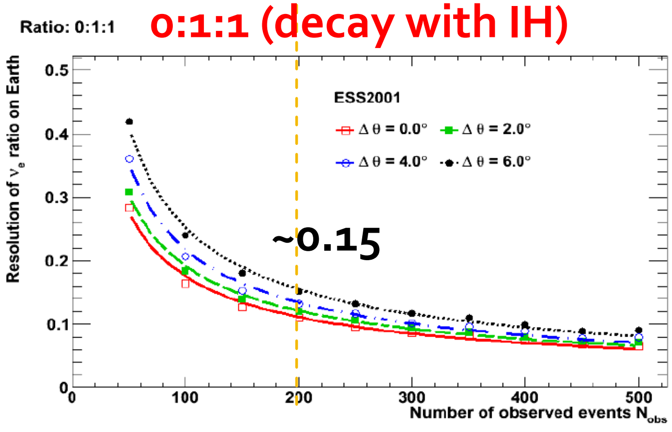
1:1:1 (standard)



6:1:1 (decay with NH)



0:1:1 (decay with IH)



- ν_e Fraction f_e=[0,1]
  - expected f_e = 1/3 (standard), 0.75 (decay w/ NH), 0 (decay w/ IH)
- ∵random sampling, extracted f_e may deviate from expected one
  - Generate ensemble of data sets to get the spread of extracted f_e
  - depend on number of events and angular resolution
- With angular resolution Δθ =6 ° and 200 events, the resolution (~68%CL) is about 0.3, 0.4, and 0.15, respectively
  - preliminary constraint on neutrino decay

Δθ =0° (red), 2° (green) , 4° (blue), 6° (black)

Summary and Future Work

- Measuring UHECN flavor ratio is important in both astrophysics and particle physics

- By fitting the direction distribution of neutrino events, a preliminary constraint on its flavor ratio can be set for the planned ARA37 configuration.

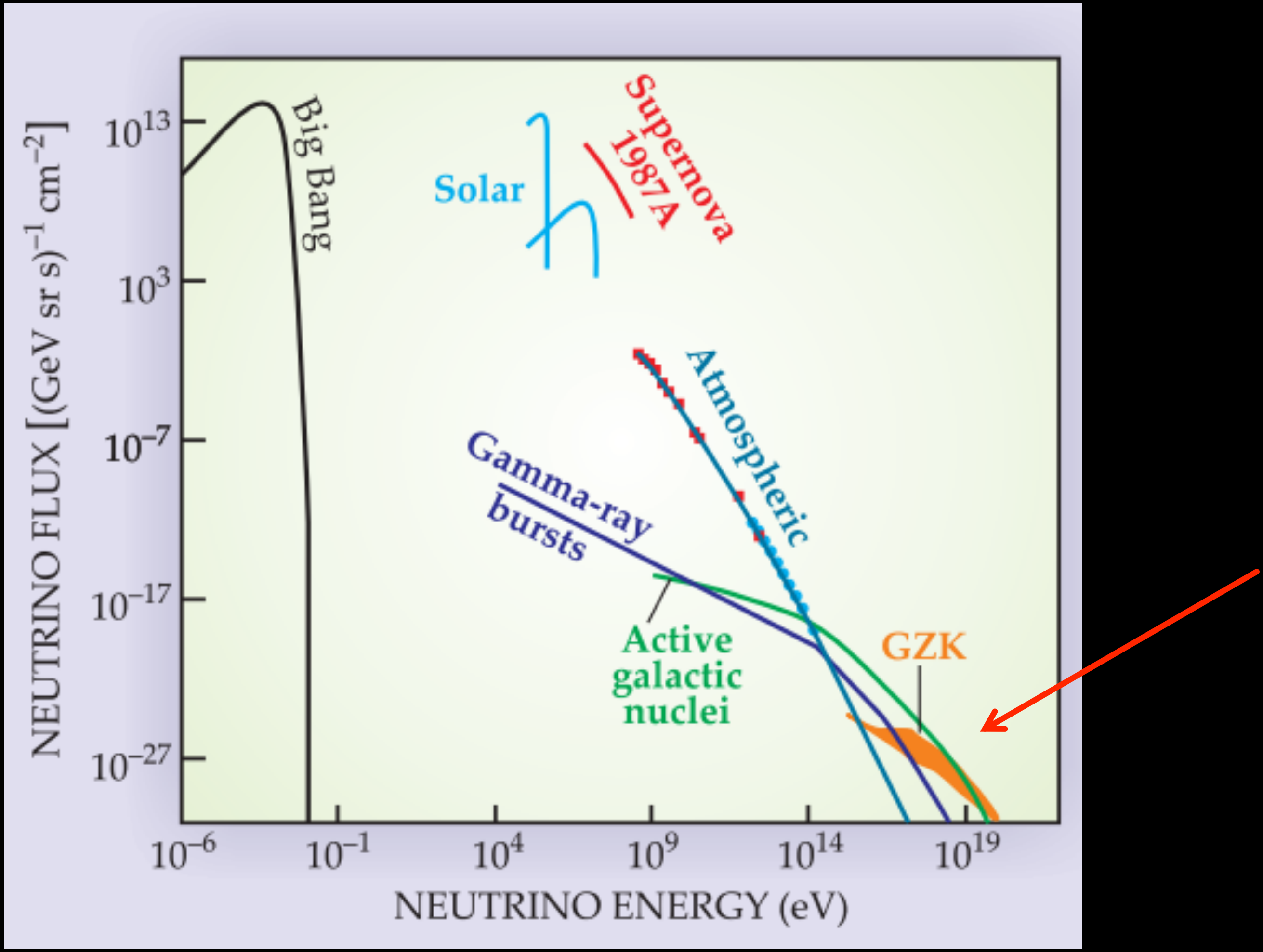
- Additional information (e.g. event topology, Cherenkov pulse characteristics) can be exploited to improve the resolution.
  - Identification of ν_e CC events.
  - Discrimination between electromagnetic and hadronic showers

Thanks for your attention!

http://www.southpolestation.com/

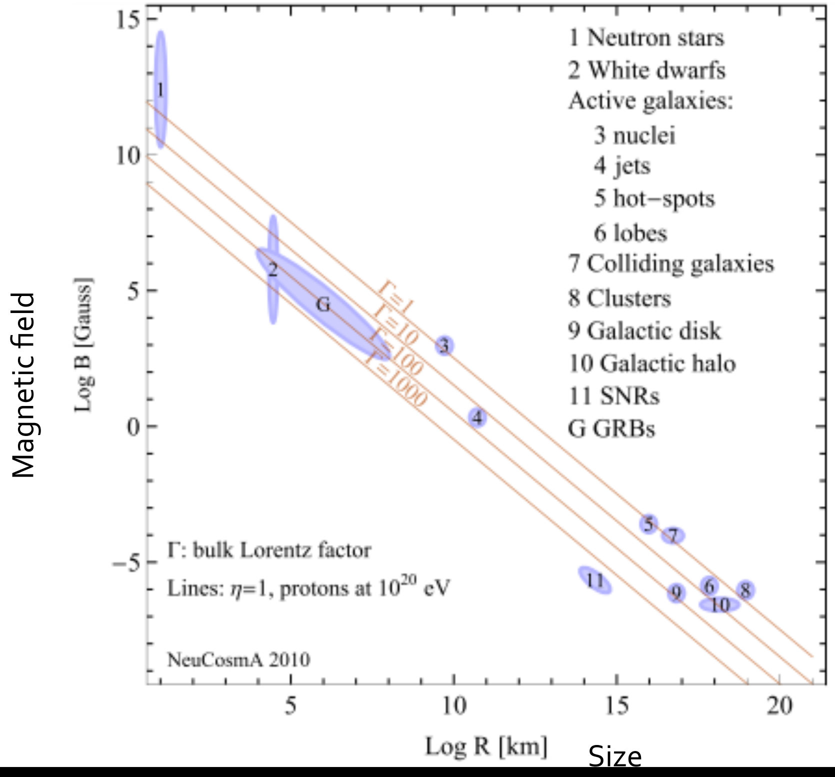
Backup

Cosmic Neutrino Spectrum

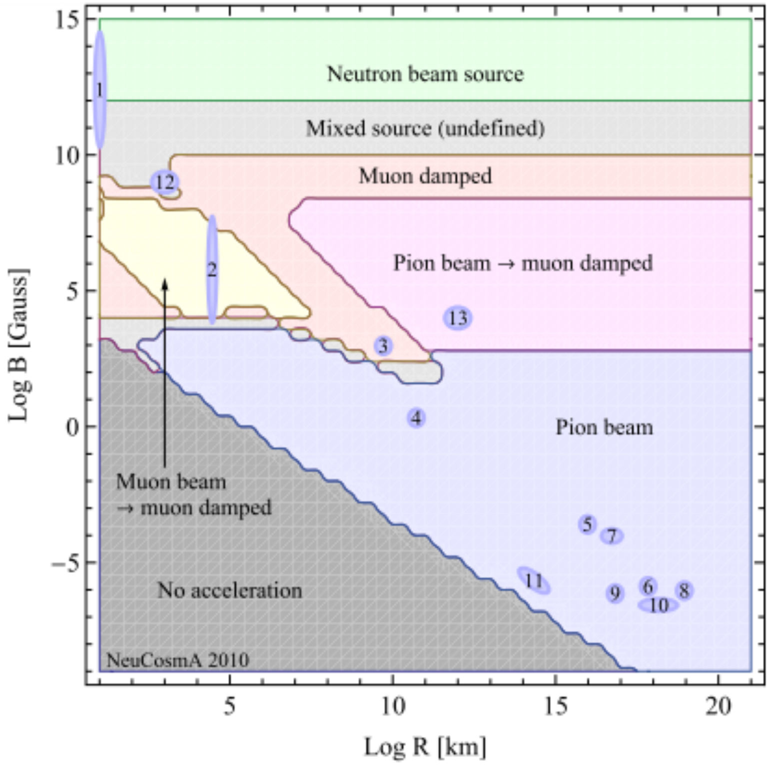


F. Halzen and S. Klein, Physics Today 2008

Neutrino Flavor Ratios Are Related to the Physical Properties of Neutrino Sources



Hillas plot



Neutrino source type

S. Hümmer et al., Astropar. Phys. 34, 205 (2010).

Neutrino Oscillation

- Neutrinos change flavor during propagation.
- The flavor eigenstate is not identical to the mass eigenstate:

flavor eigenstate α = e, μ,τ

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

mass eigenstate i = 1,2,3

where $U_{\alpha i}$'s are element of 3×3 mixing matrix.

- For cosmic neutrino, The neutrino flux at the source $\Phi_{\nu 0}$ and that arriving on Earth Φ_ν can be related by

$$\begin{pmatrix}\Phi_{\nu_e}\\ \Phi_{\nu_\mu}\\ \Phi_{\nu_\tau}\end{pmatrix} = \begin{pmatrix}P_{ee} & P_{e\mu} & P_{e\tau}\\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau}\\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau}\end{pmatrix}\begin{pmatrix}\Phi_{\nu_e0}\\ \Phi_{\nu_\mu0}\\ \Phi_{\nu_\tau0}\end{pmatrix} \simeq \begin{pmatrix}\frac{5}{9} & \frac{2}{9} & \frac{2}{9}\\ \frac{2}{9} & \frac{7}{18} & \frac{7}{18}\\ \frac{2}{9} & \frac{7}{18} & \frac{7}{18}\end{pmatrix}\begin{pmatrix}\Phi_{\nu_e0}\\ \Phi_{\nu_\mu0}\\ \Phi_{\nu_\tau0}\end{pmatrix}$$

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2|U_{\beta i}|^2$$

(tribimaximal mixing)

H. Athar, M. Jezabek, and O. Yosuda, Phys. Rev. D 62, 103007 (2000).
R.L. Awasthi and S. Choubey, Phys. Rev. D 76, 113002 (2007).

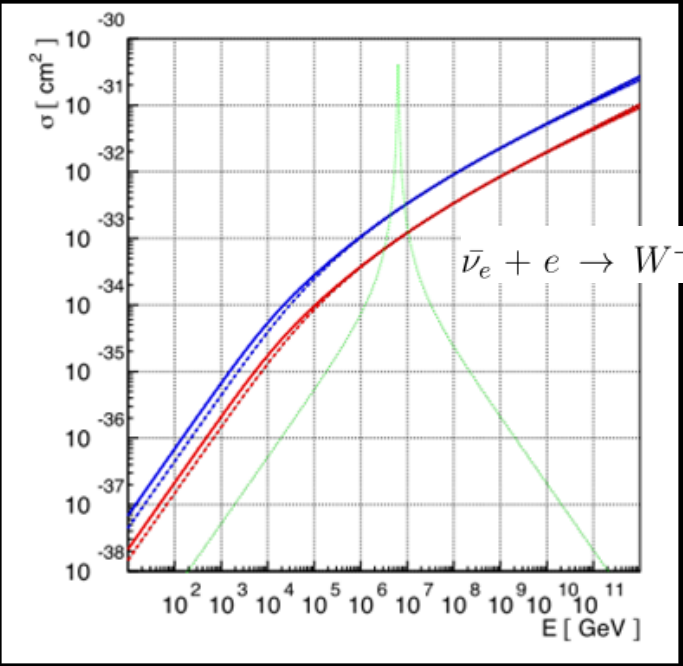
Neutrino Detection and Askaryan Effect

- Neutrinos interact with matter via CC or NC interactions and induce showers. $\upsilon_l N \rightarrow lX$ $\upsilon_l N \rightarrow \upsilon_l X$
- $$\begin{cases} \gamma + e^-_{atom} \rightarrow \gamma + e^- & \text{Compton scattering,} \\ e^+ + e^-_{atom} \rightarrow e^+ + e^- & \text{BhaBha scattering,} \\ e^- + e^-_{atom} \rightarrow e^- + e^- & \text{Møller scattering,} \\ e^+ + e^-_{atom} \rightarrow \gamma + \gamma & \text{electron-positron annihilation.} \end{cases}$$
- Increase in negative charges, and decrease in positive ones, developing into ~20% negative charge excess
- In dense medium, the shower size is compact, emitting coherent Cherenkov radiation at radio frequencies up to few GHz.

G.A. Askaryan, JETP Lett. 14, 441 (1962). D. Saltzberg et al., Phys. Rev. Lett. 86, 2802 (2001);
P.W. Gorham et al., Phys. Rev. D 72, 023002 (2005); P.W. Gorham et al., Phys. Rev. Lett. 99, 171101 (2007);

Interactions Included in MMC

Neutrinos

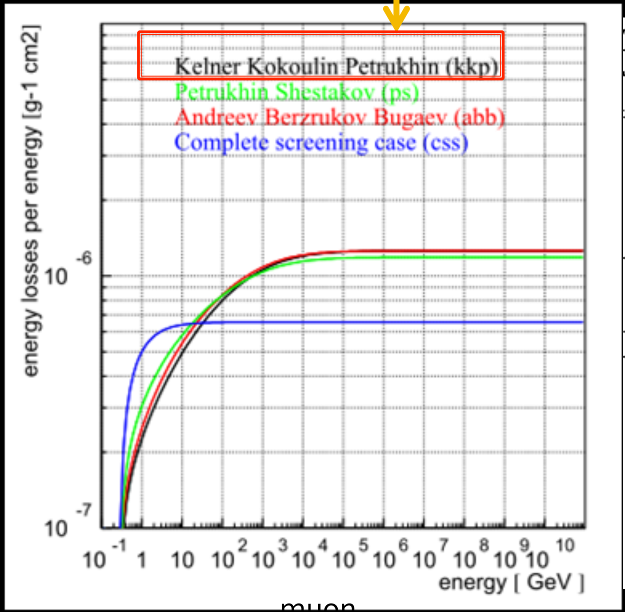


$\bar{\nu}_e + e \rightarrow W^- \rightarrow hadrons$

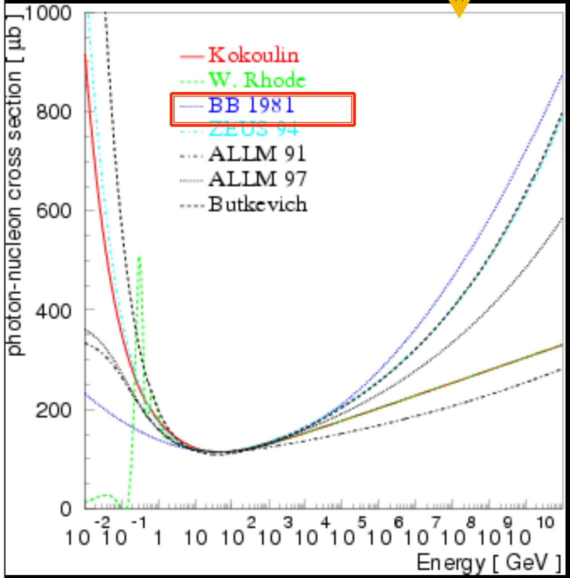
Cross sections from R. Gandhi et al., Phys. Rev. D (1998)

Charged leptons

- ionization loss
- Bremsstrahlung
- pair production
- photonuclear interaction
- μ, τ decay



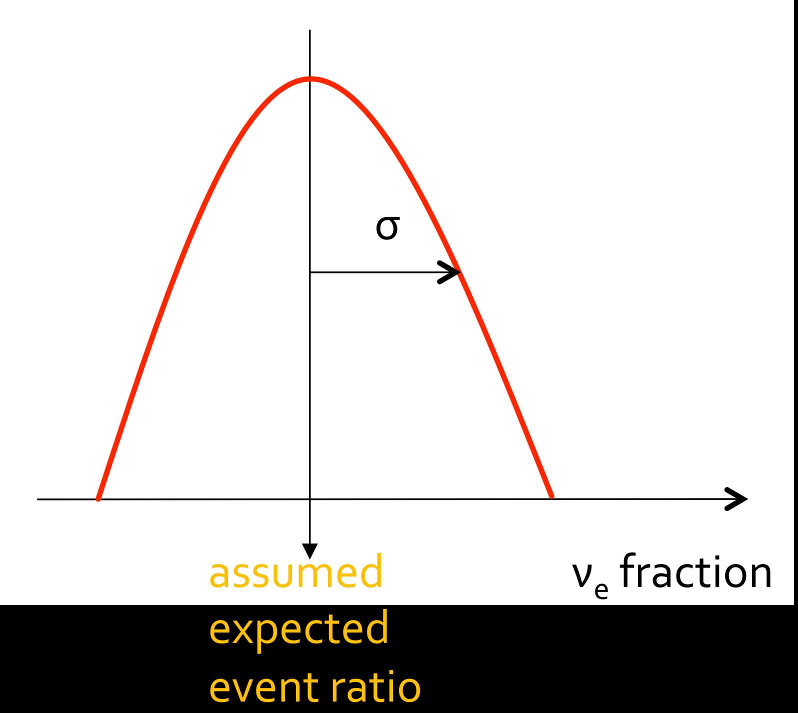
muon



The Resolution of ν_e Fraction

$$R_{\pm}(N_{\text{obs}}, \Delta\theta) = \sqrt{\frac{1}{N_s - 1}\sum_{i=1}^{N_s}(\hat{f}_{e,i} - f_{e,\text{exp}})^2}$$

Probability distribution of fitted ν_e fraction for given N_{obs} and Δθ



The reconstructed e event ratio is **a maximum likelihood estimator**, and it can be shown that it is asymptotic to a Gaussian distribution as N_{obs} increases. So the resolution R is an approximation to the standard deviation σ of the Gaussian.

the spread of its distribution result from finite number of events and imperfect angular resolution.