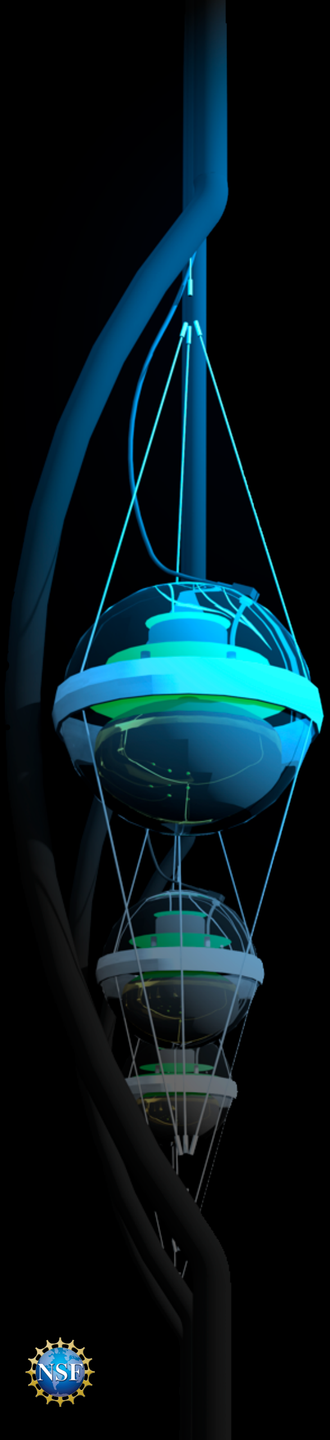
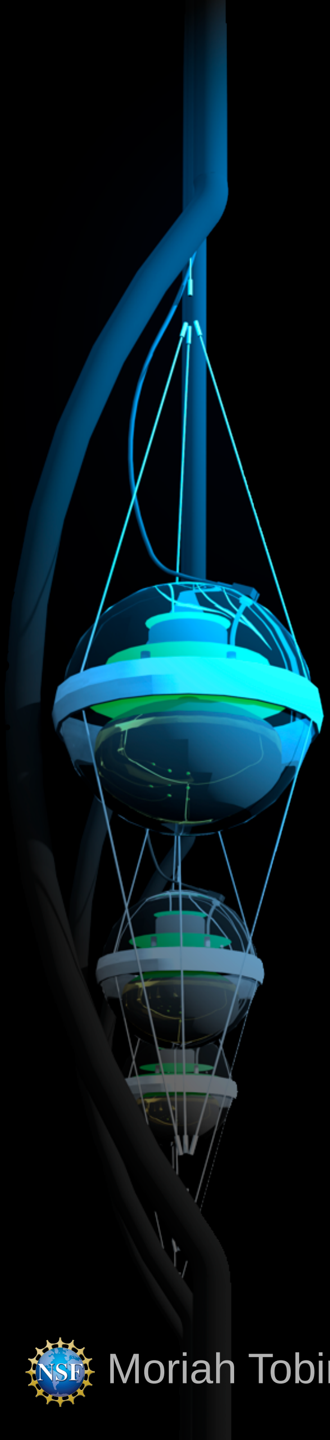


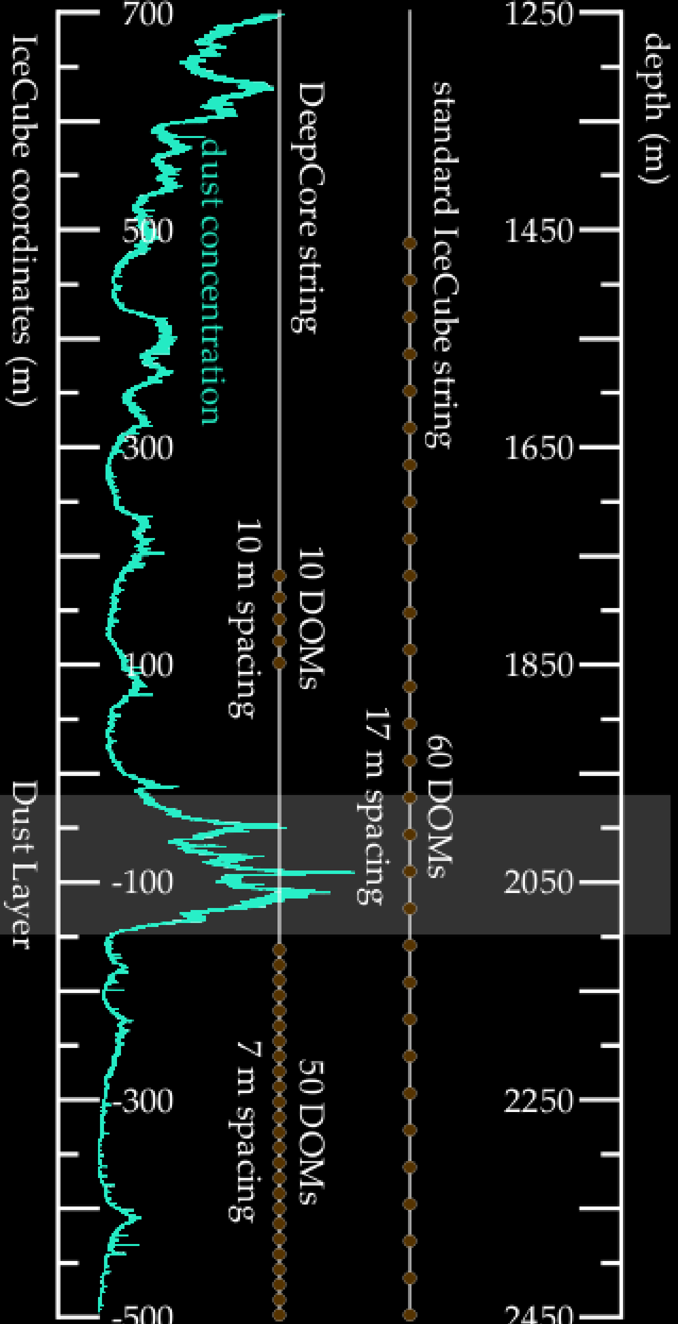
Low Energy Analyses: DeepCore

Madison IceCube Bootcamp 2016
Moriah Tobin
06.16.2016



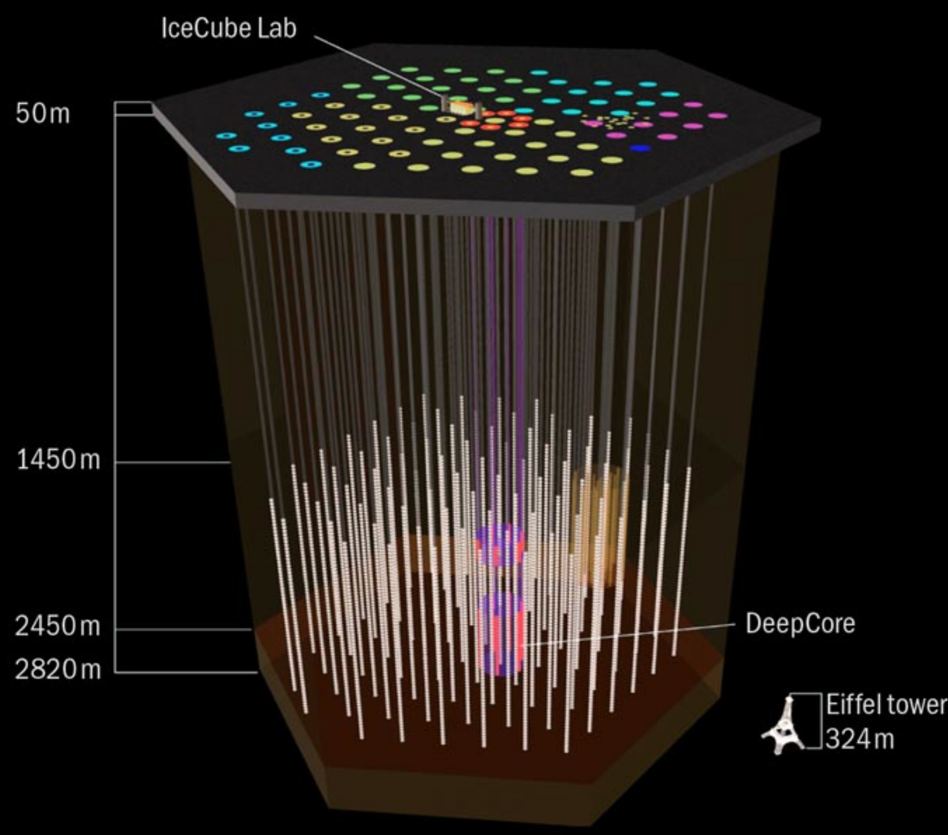
Outline

- Deep Core
- Example of Low Energy Analyses in Deep Core: Atmospheric Neutrino Oscillation
- Down the Rabbit Hole: Systematics in Deep Core



IceCube & DeepCore

- DeepCore optimized for lower energy events



Neutrino Oscillations

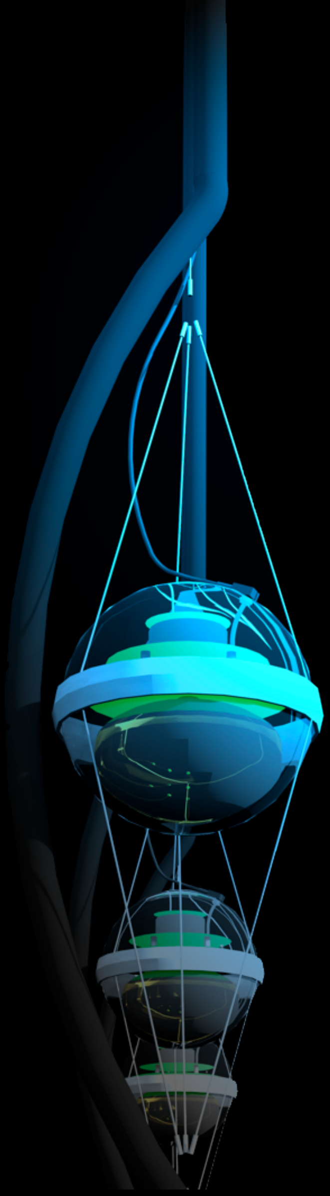
- Created in well-defined flavor states
- Propagate in well-defined mass states

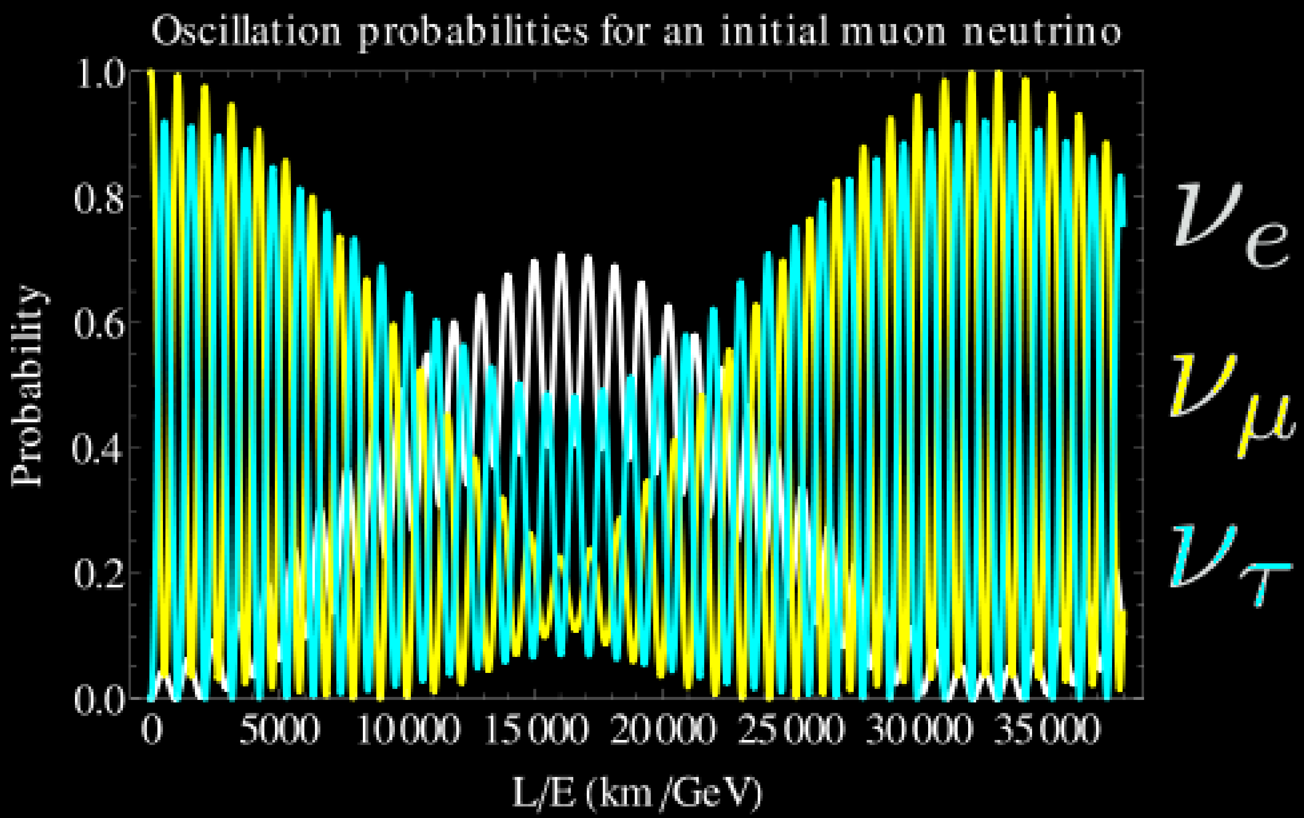
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij}$$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{atmospheric and} \\ \text{LBL accelerator}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{SBL reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{solar and} \\ \text{LBL reactor}}}$$

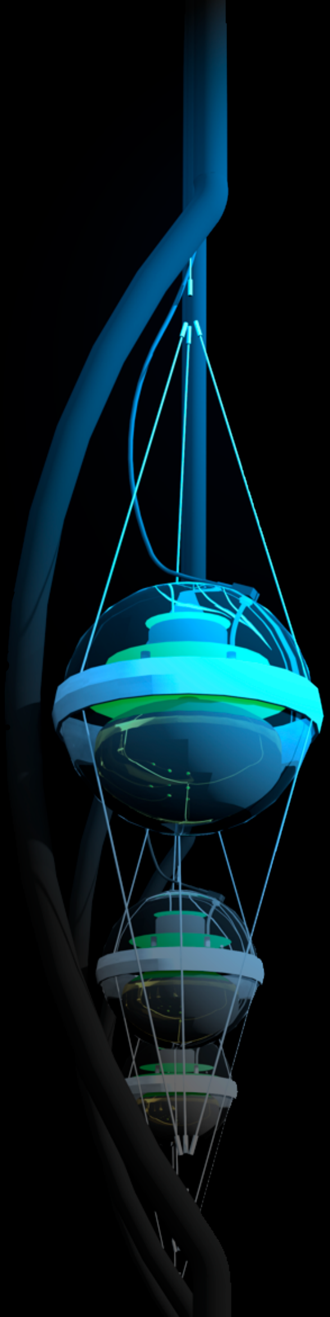
Neutrino Oscillations





* Image from: http://upload.wikimedia.org/wikipedia/en/1/12/Oscillations_muon_long.svg

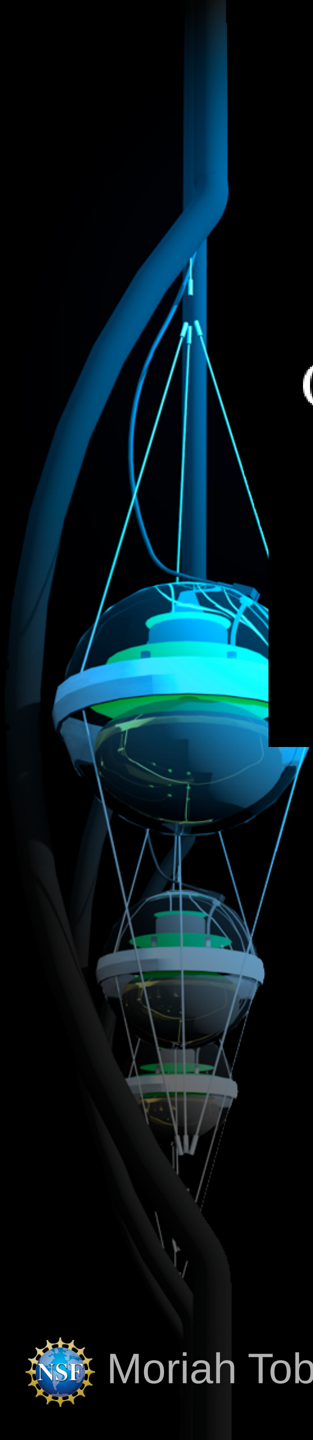
$$P(\nu_\mu \rightarrow \nu_\mu) \; = \; 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1 - \cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



Sterile Neutrinos

- Active (Standard) Neutrino
  - Yukawa coupling (mass)
  - Mixing
  - Lepton coupling (W±)
  - Weak scattering (Z)
- Sterile Neutrino
  - Yukawa coupling (mass)
  - Mixing

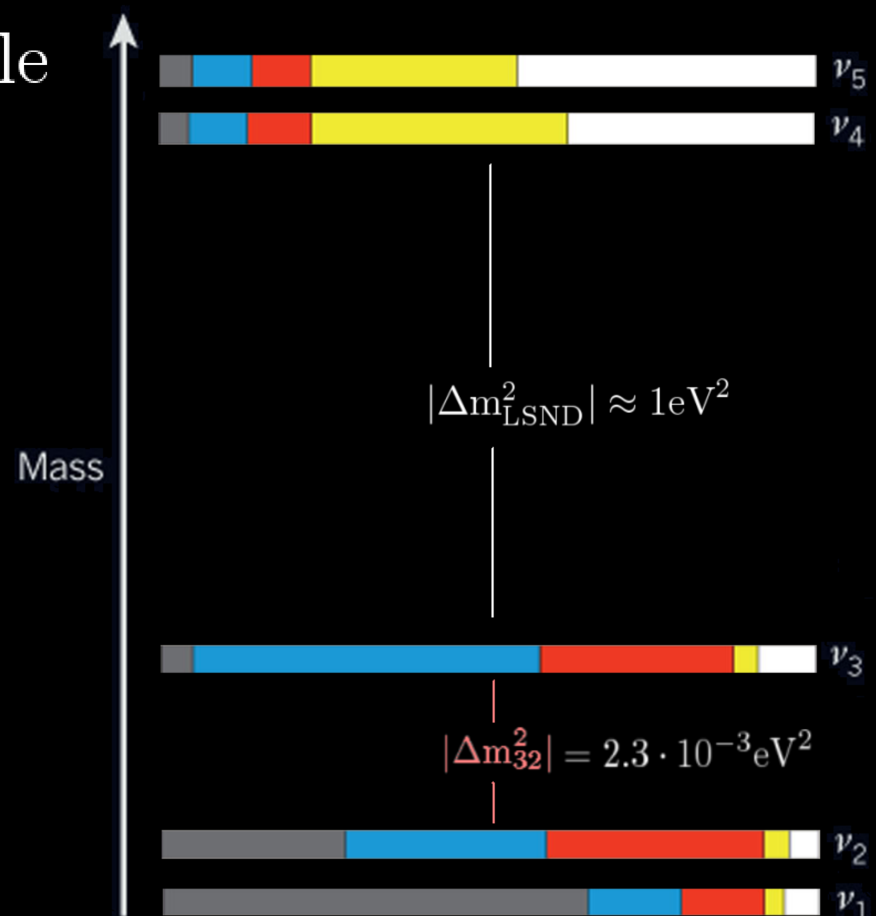
Sterile Neutrinos: Framework



Global Fit For Sterile Neutrinos 3 + 2

$$\Delta m^2_{41} = 1.10\,\mathrm{eV}^2$$

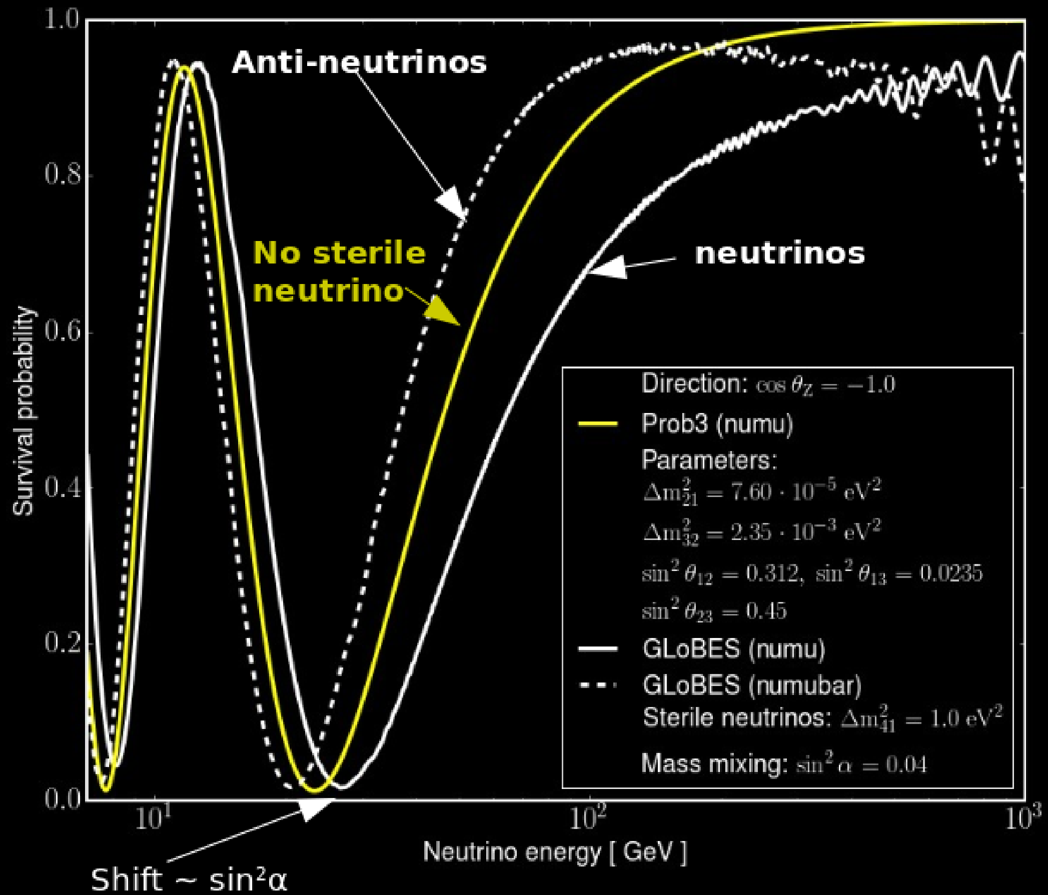
$$\Delta m^2_{51} = 0.82\,\mathrm{eV}^2$$



*Edited Image from: http://www.nature.com/nature/journal/v478/n7369/fig_tab/478328a_F1.html

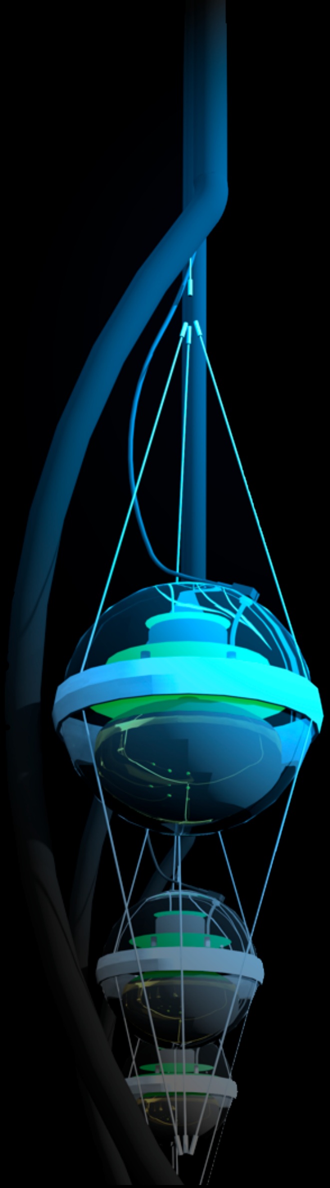
Low Energy Sterile Oscillations

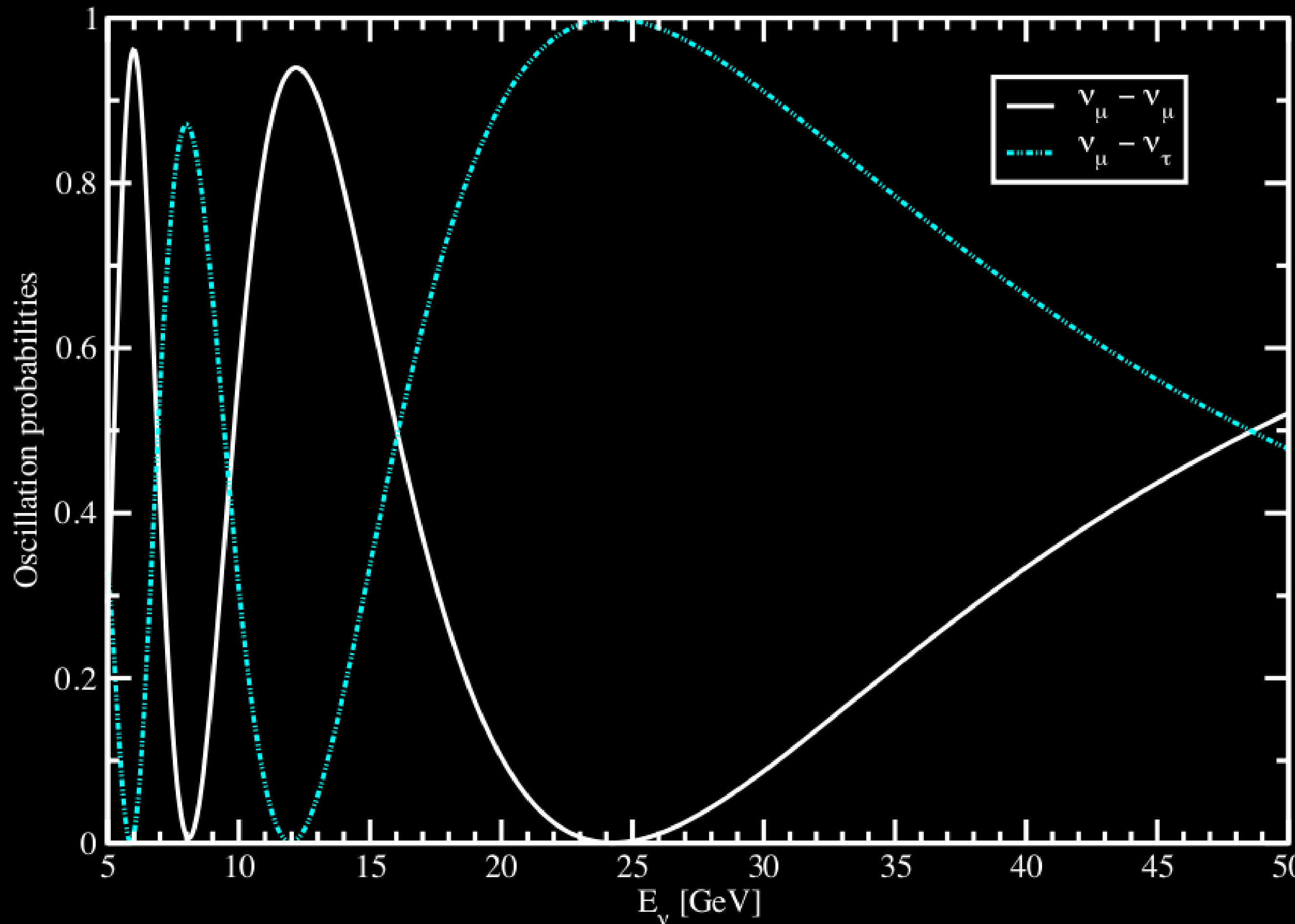
- Small Signal in Deep Core, Very Precise



Atmospheric Neutrino Oscillation

- Survival Probability Atmospheric $\nu_\mu \rightarrow \nu_\mu$

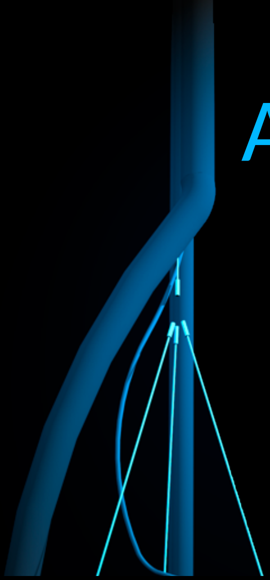


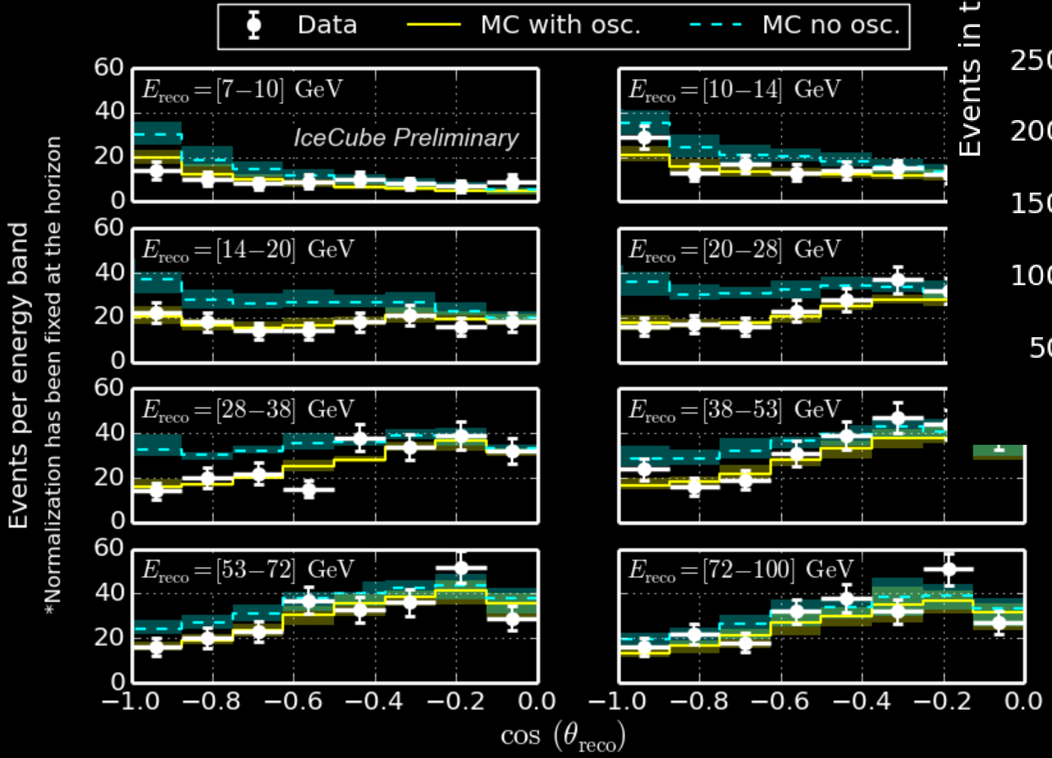


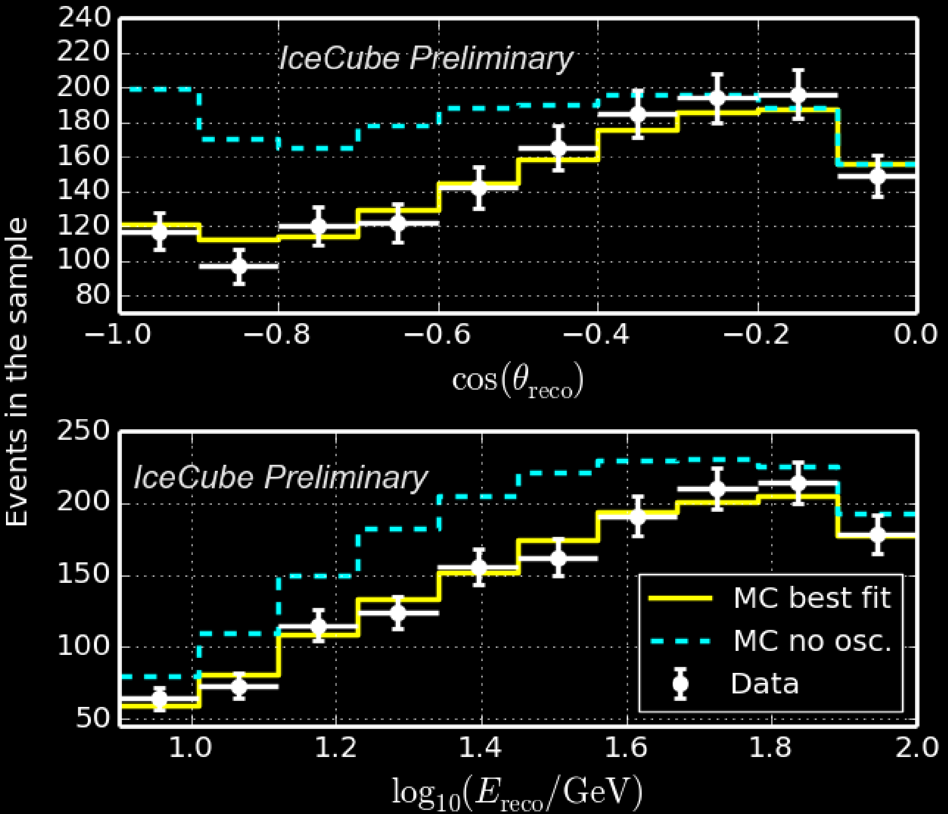
* Image from arXiv:1004.3519

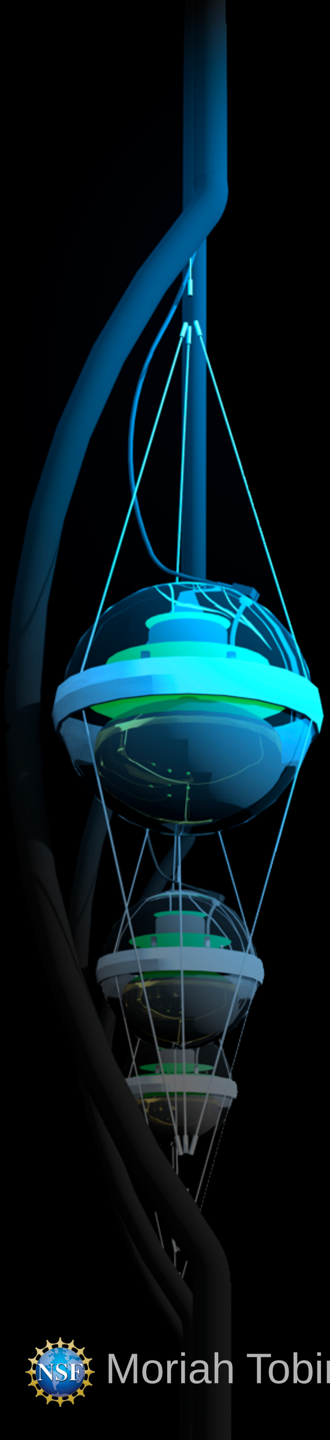
$$P(\nu_\mu \rightarrow \nu_\mu) \;=\; 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Atmospheric Oscillation Signal in Deep Core







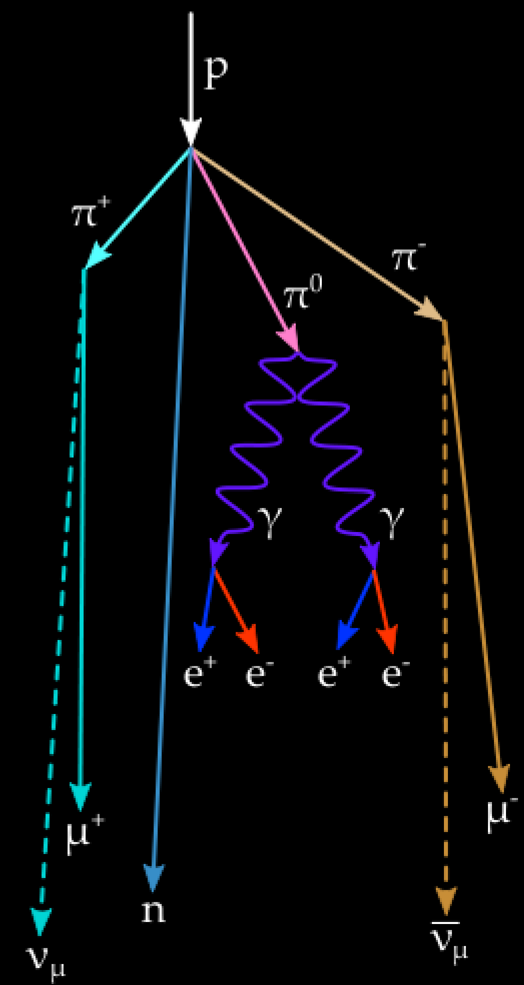


Atmospheric Neutrino Production

- Ratios, ν_e:ν_μ:ν_τ 1:2:0

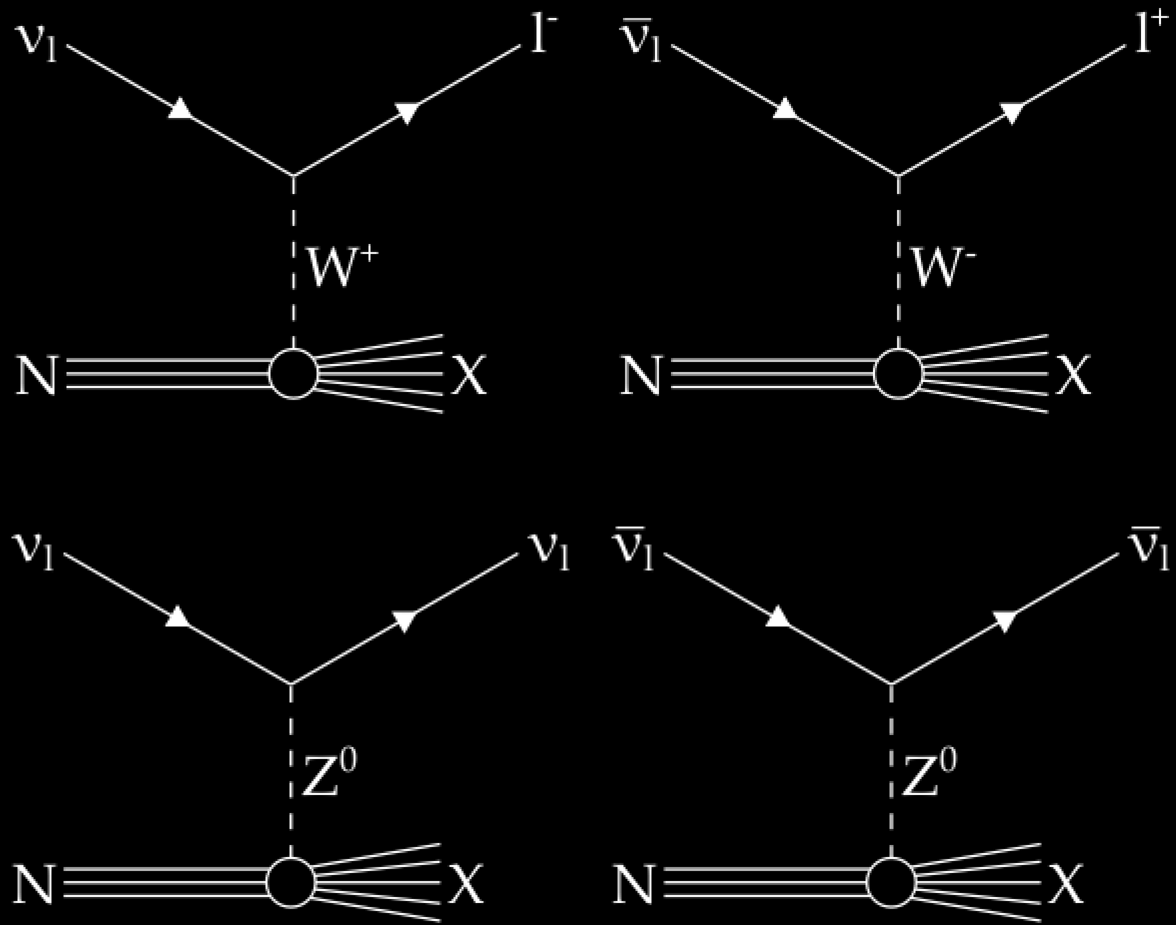
$$p \longrightarrow \pi^+(+K^+\ldots) \longrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$n \longrightarrow \pi^-(+K^-\ldots) \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \nu_\mu + \bar{\nu}_e$$



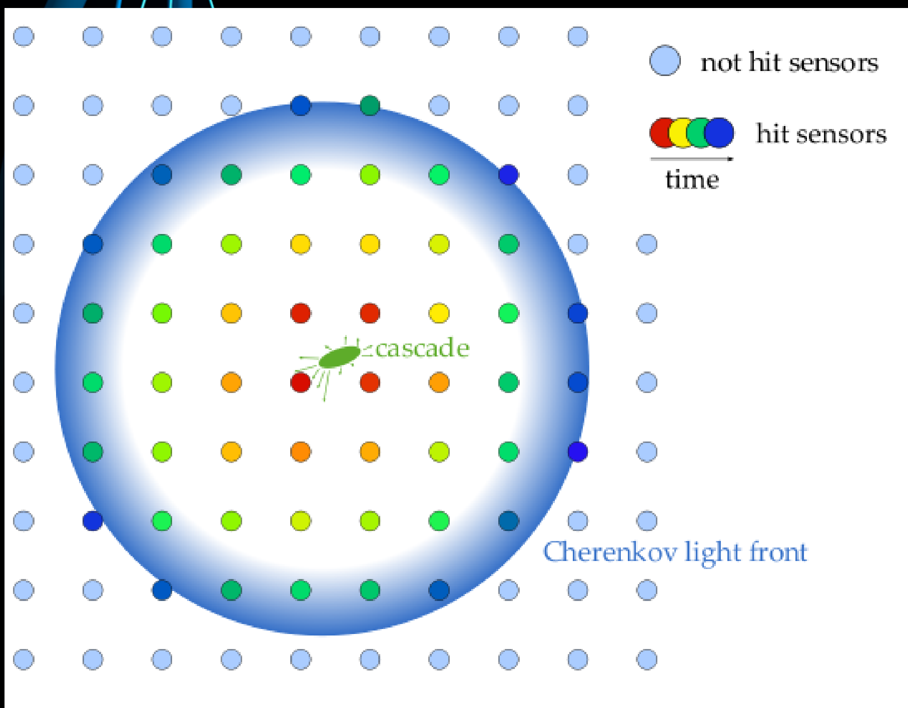
* Image from: T. K. Gaisser. Cosmic Rays and Particle Physics. Cambridge University Press, 1990

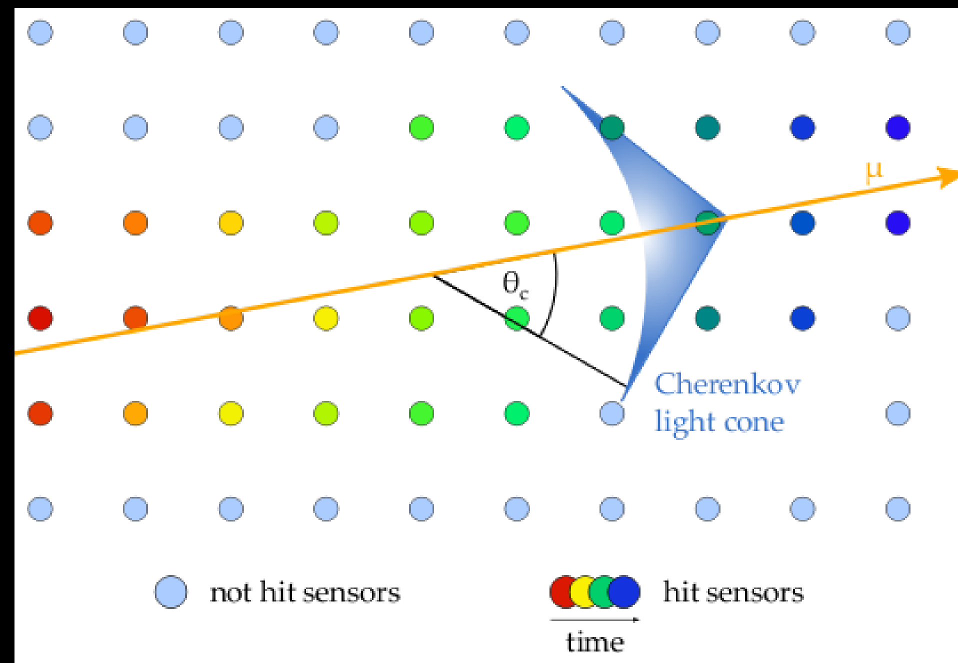
Low Energy Neutrino Events in the Detector



* Image from http://www.physik.rwth-aachen.de/fileadmin/user_upload/www_physik/Institute/Inst_3B/Forschung/IceCube/publications/diss_SE.pdf

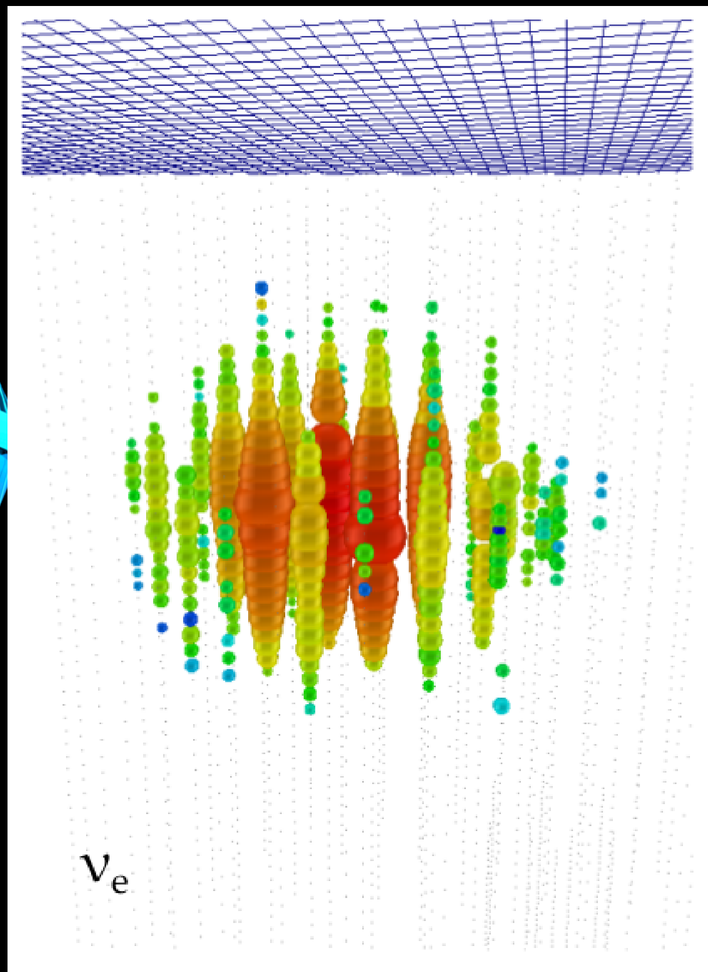
Reconstructing Events

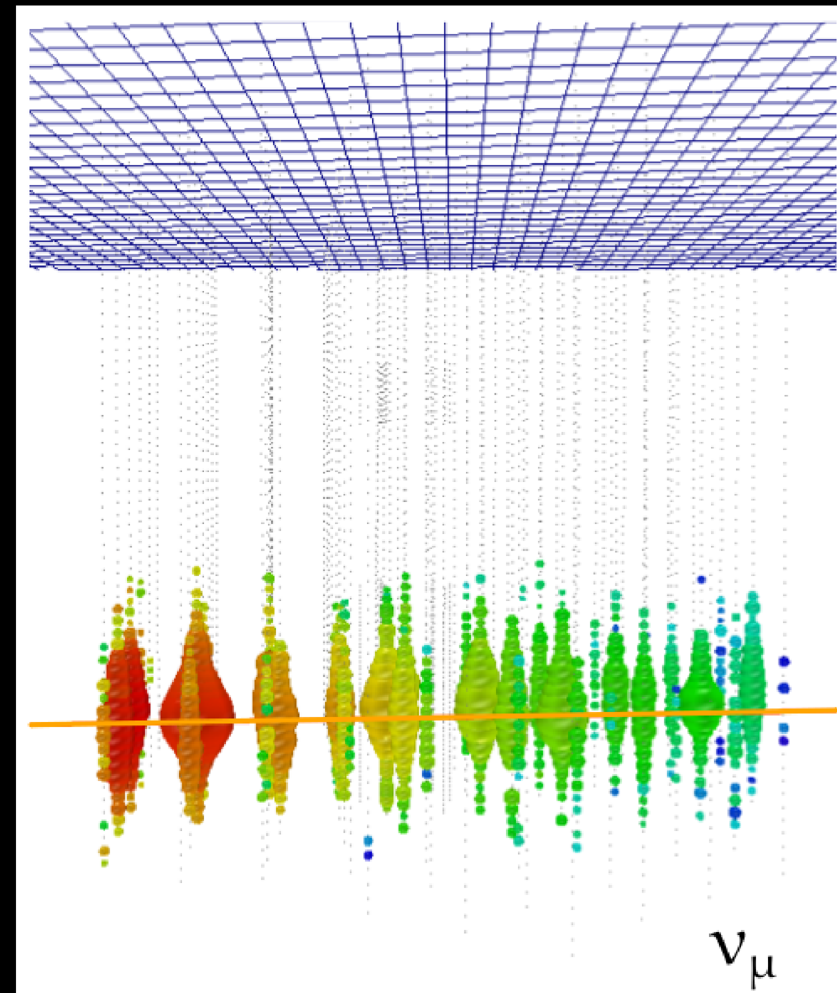




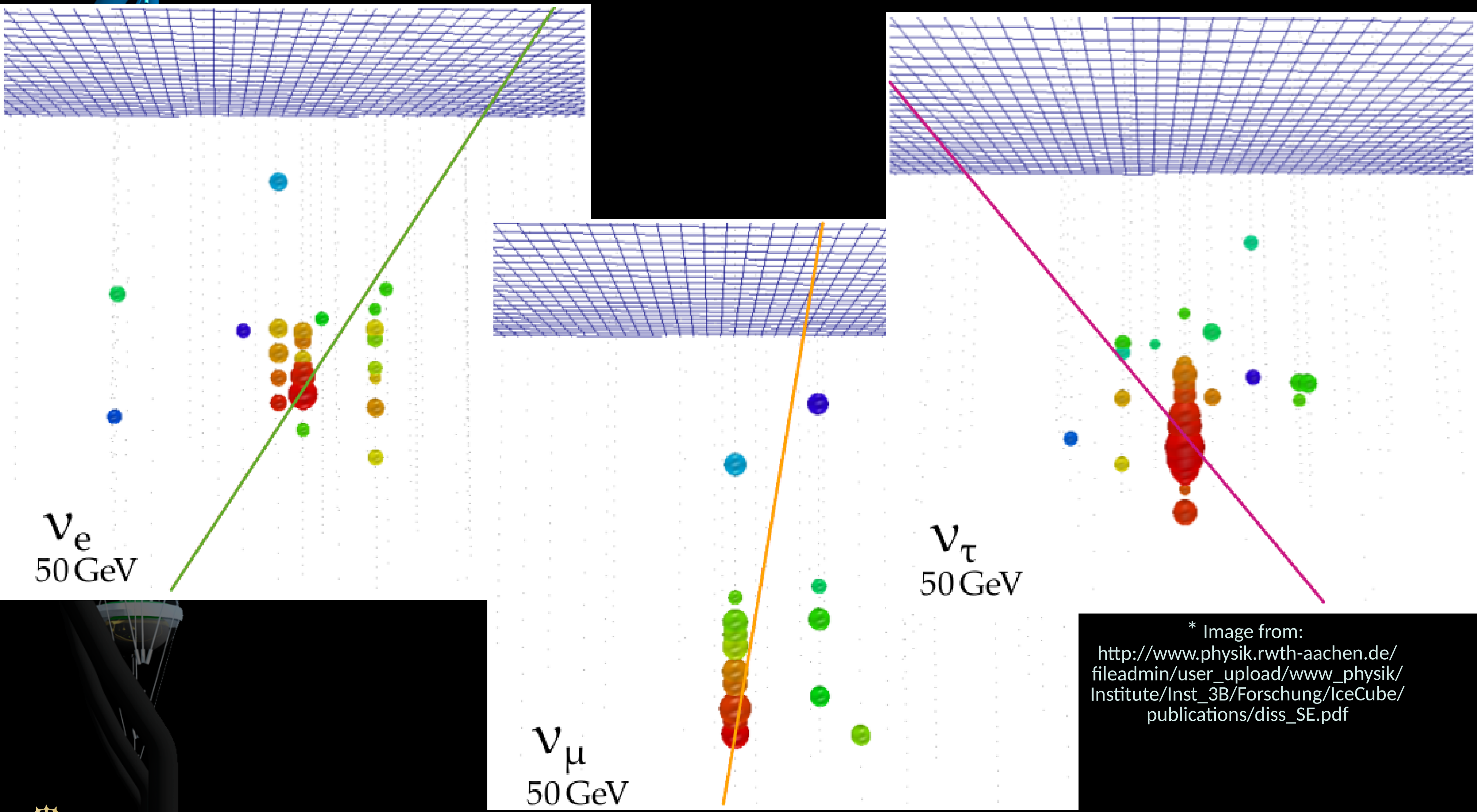
* Image from http://www.physik.rwth-aachen.de/fileadmin/user_upload/www_physik/Institute/Inst_3B/Forschung/IceCube/publications/diss_SE.pdf

Reconstructing Events

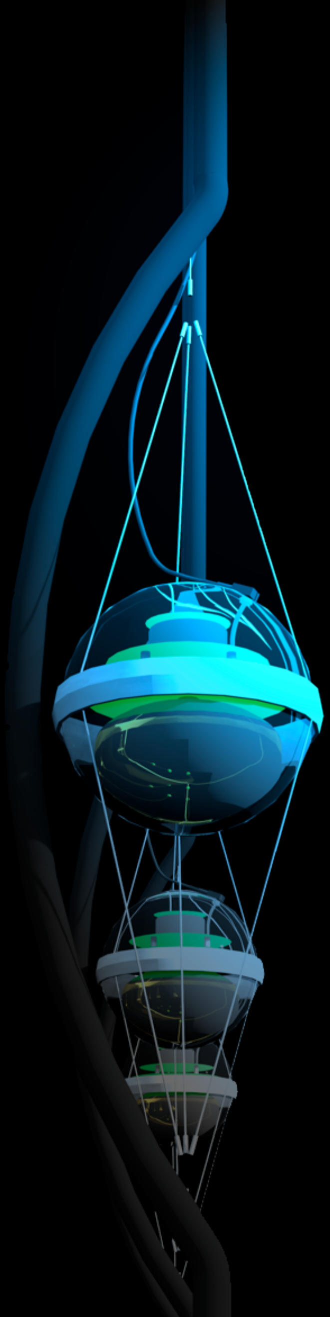




Reconstructing Low Energy Events



* Image from:
http://www.physik.rwth-aachen.de/fileadmin/user_upload/www_physik/Institute/Inst_3B/Forschung/IceCube/publications/diss_SE.pdf



Low Energy Events

- Very Large Effects from Noise
  - Noise Pulses can be a large fraction of the pulses in the event
- Low Number of Pulses/Event
  - Reconstruction becomes very difficult and tricky
- Dealing with Muon Contamination becomes significantly more difficult

Cosmic Ray Muons

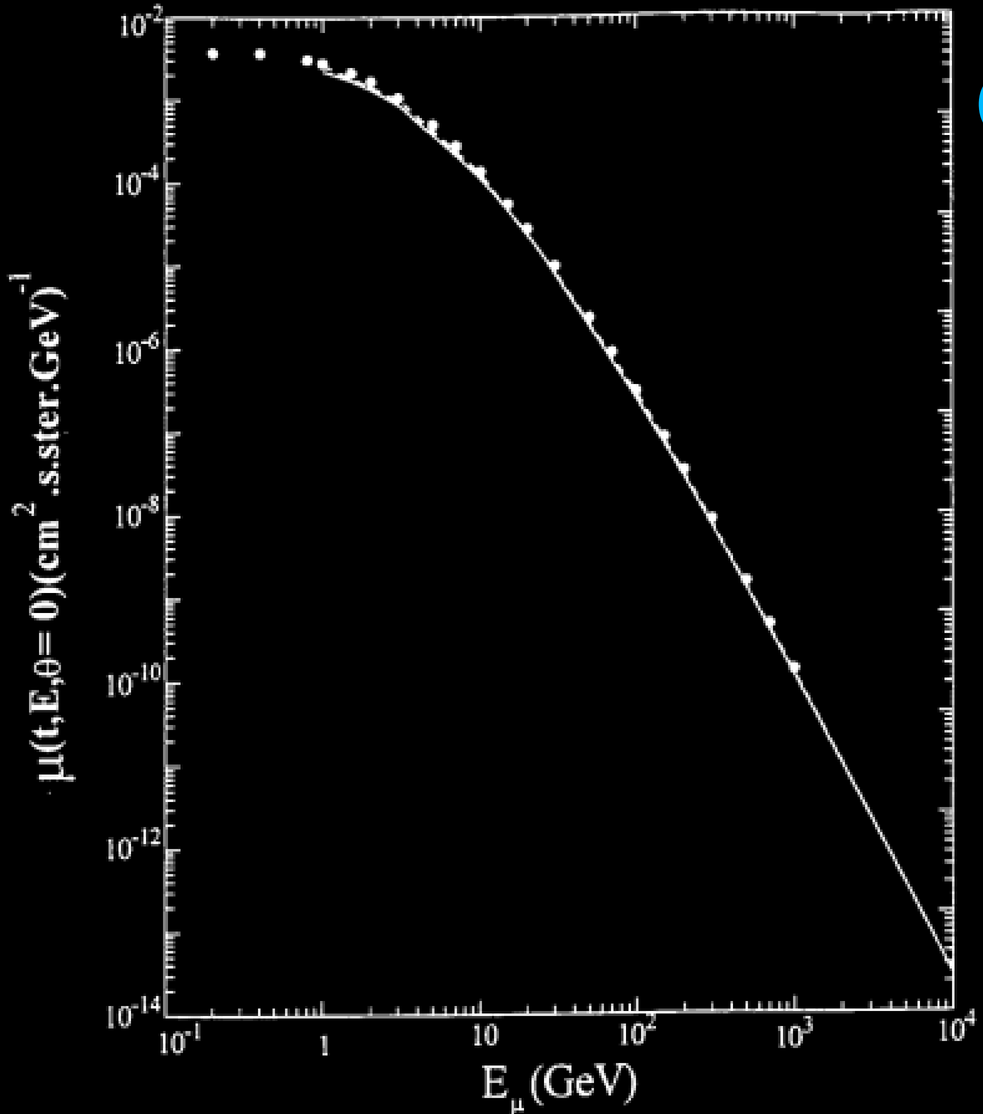
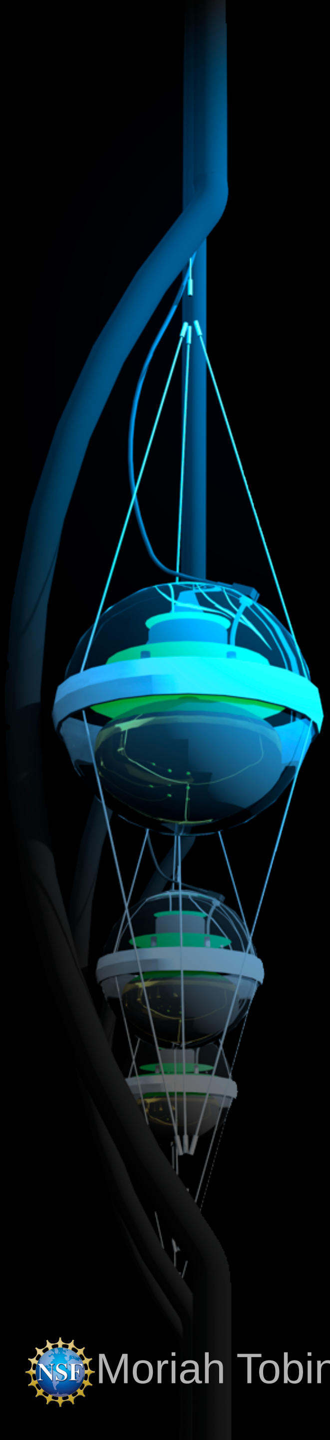
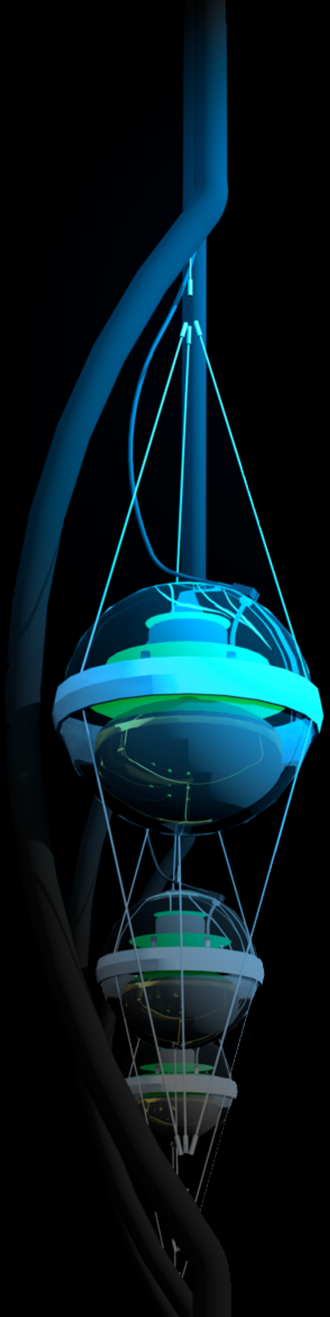


Figure 1. Vertical muon fluxes at sea level. The solid line is the flux calculated by Lipari (Lipari, 1993) and the dashed line is our calculated flux. Data are from (Allkofer, et al., 1971).





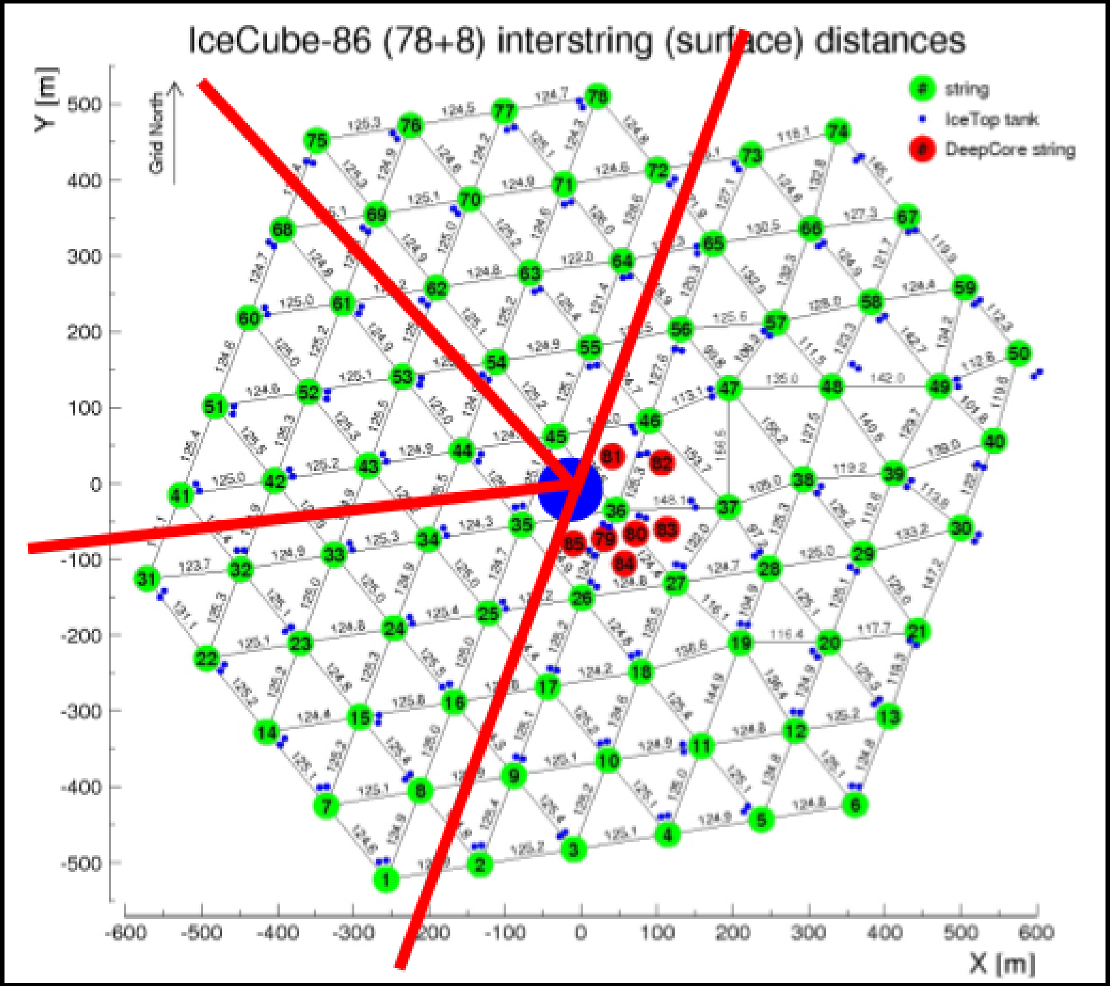
Muons: The Next Generation

	Juan Pablo	Matt Dunkman	Michael Larson
Events/Year	3,500	25,000	53,100
NuMu CC/Year	2,260	12,140	24,500
CR Muons/Year	40	5,910	12,200

- 1.25% Muons in Juan Pablo
- 24% Muons in Matt Dunkman
- 23% Muons in Michael Larson

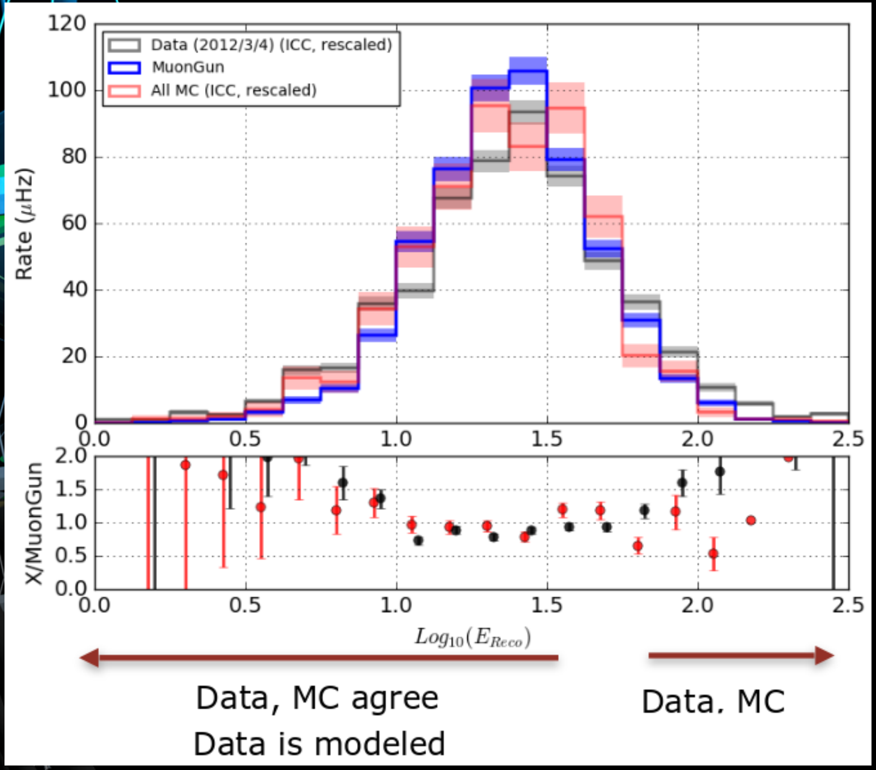
Current Status w/CR Muons

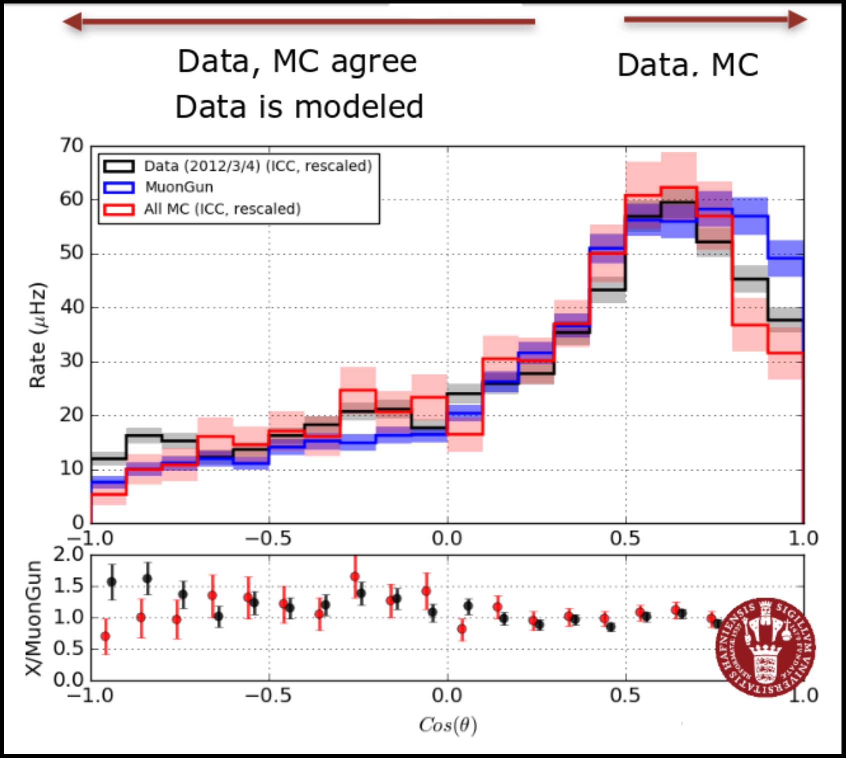
- Corridor Cut, and Inverted Corridor Cut

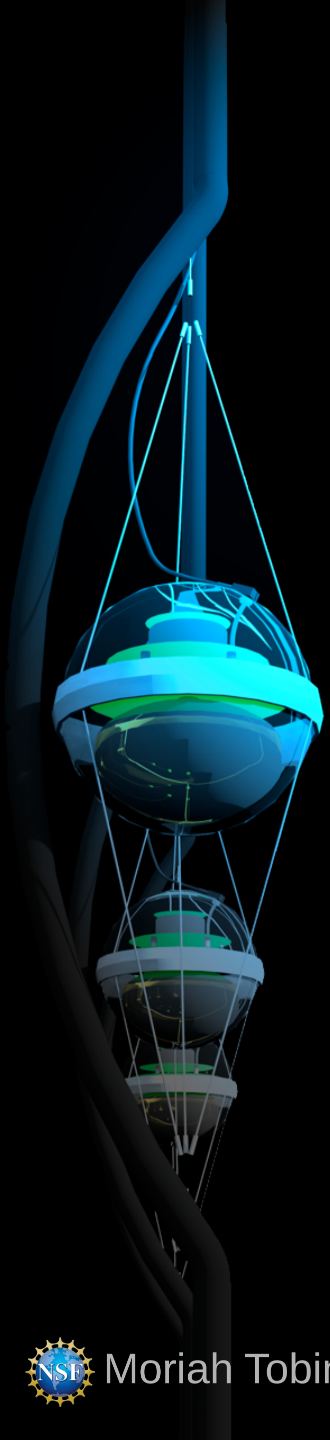


Current Status w/CR Muons

- Corridor Cut, and Inverted Corridor Cut

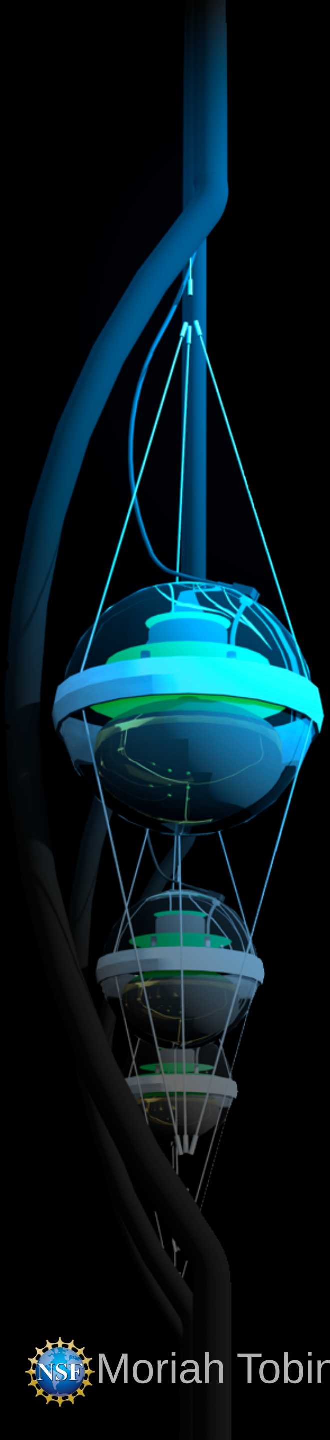




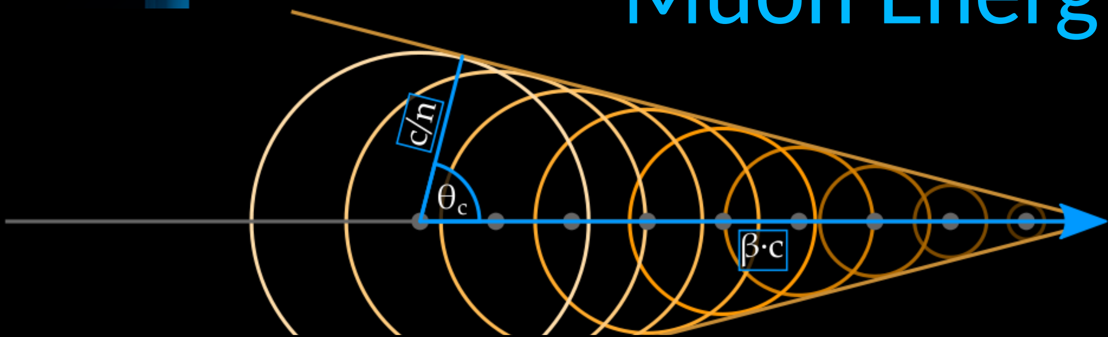


Deep Core Analyses

- Currently most high statistics analyses are suffering from Data/MC disagreement – this means there's lots to work on in this area!
- Low statistics analyses creating ultra high purity samples are doing interesting physics
- Lots of interesting background rejection and reconstruction algorithm problems to work on



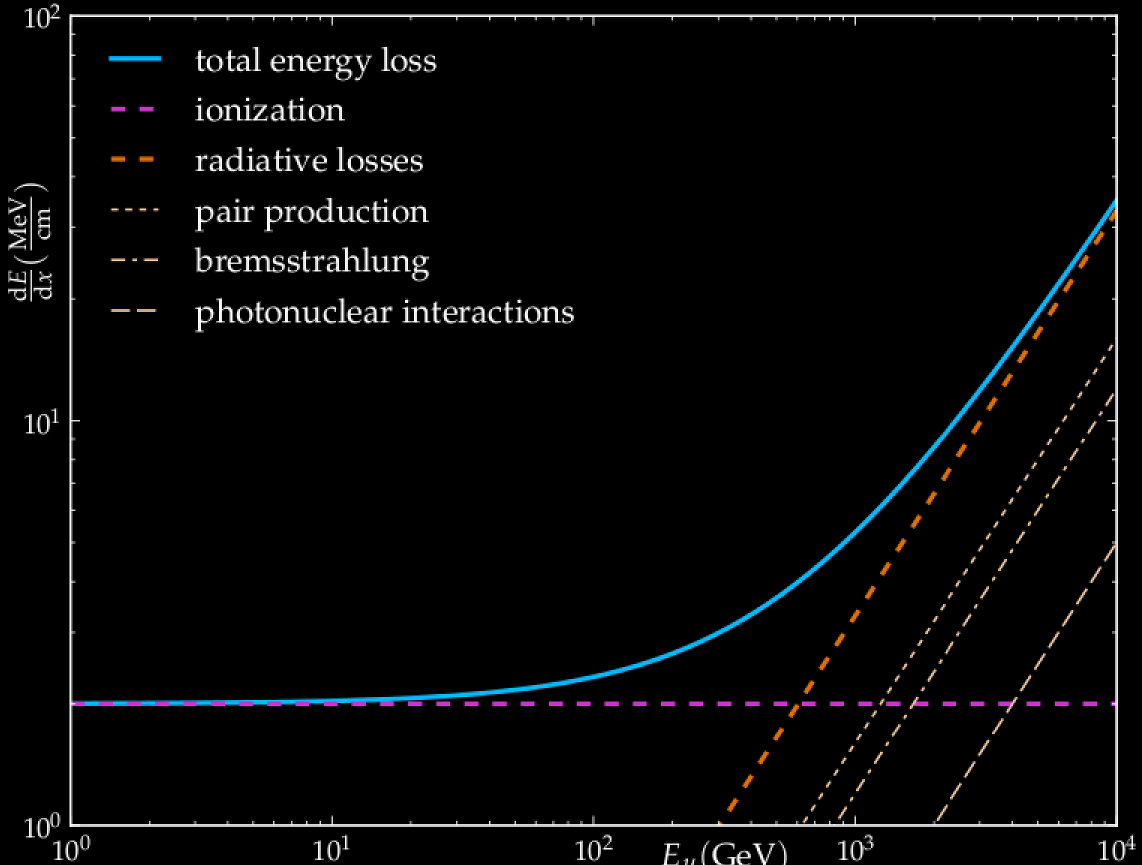
Muon Energy Loss

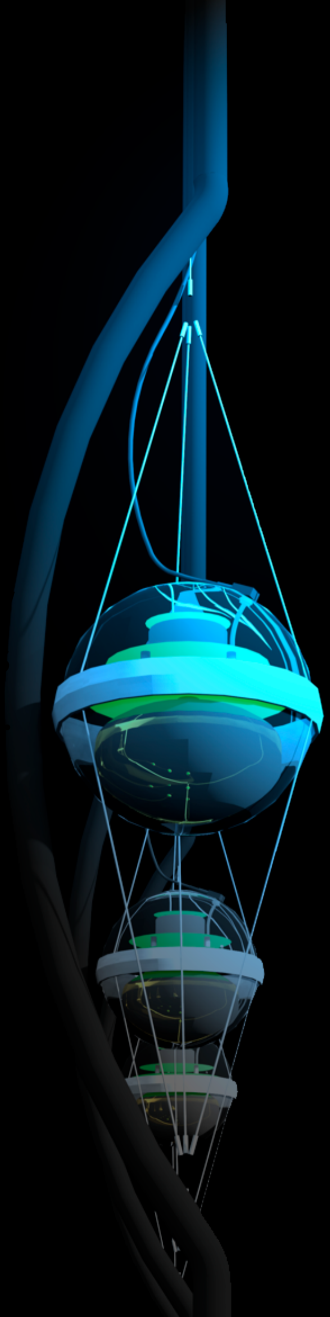


$$-\frac{1}{\rho}\frac{\mathrm{d}E}{\mathrm{d}x} = a(E) + b(E)\cdot E$$

$$a \approx 2.0\,\frac{\mathrm{MeV\,cm^2}}{\mathrm{g}}$$

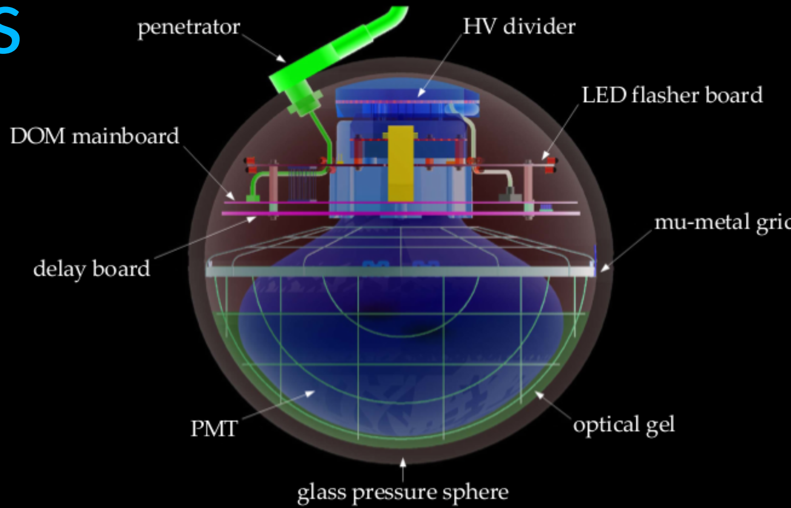
$$b \approx 3.3\cdot 10^{-6}\,\frac{\mathrm{cm^2}}{\mathrm{g}}$$

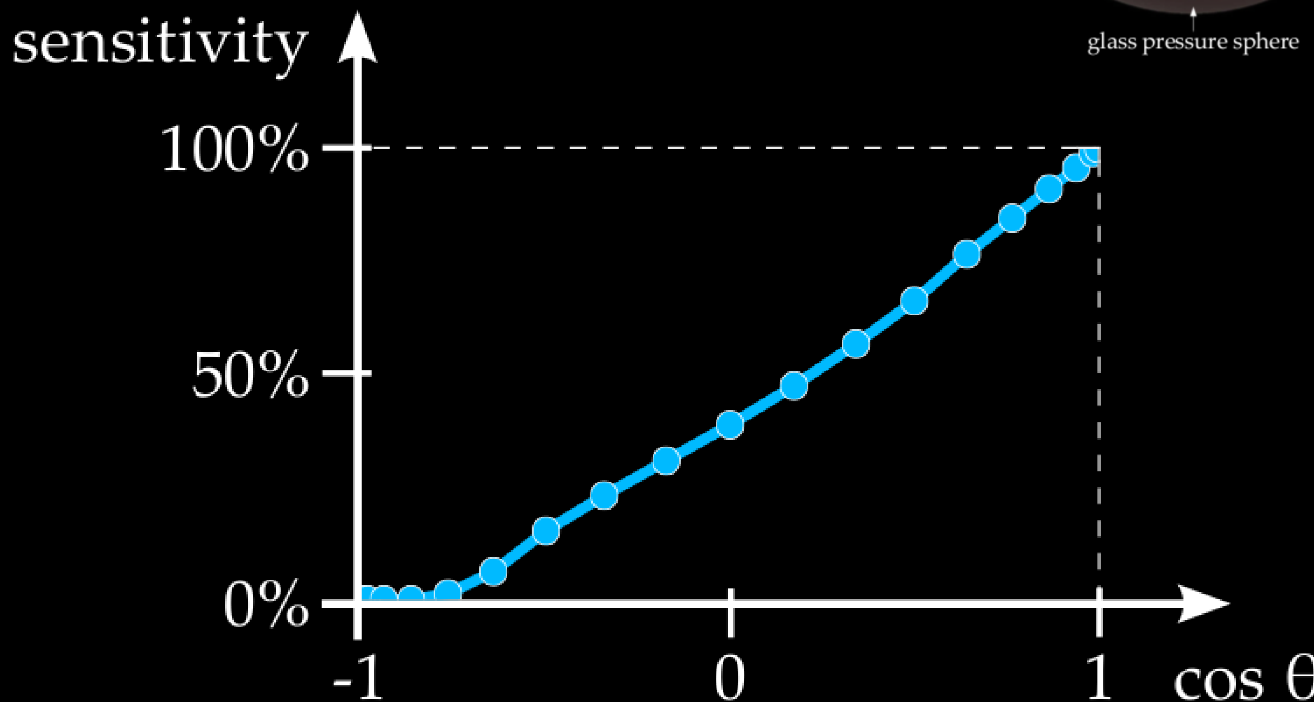




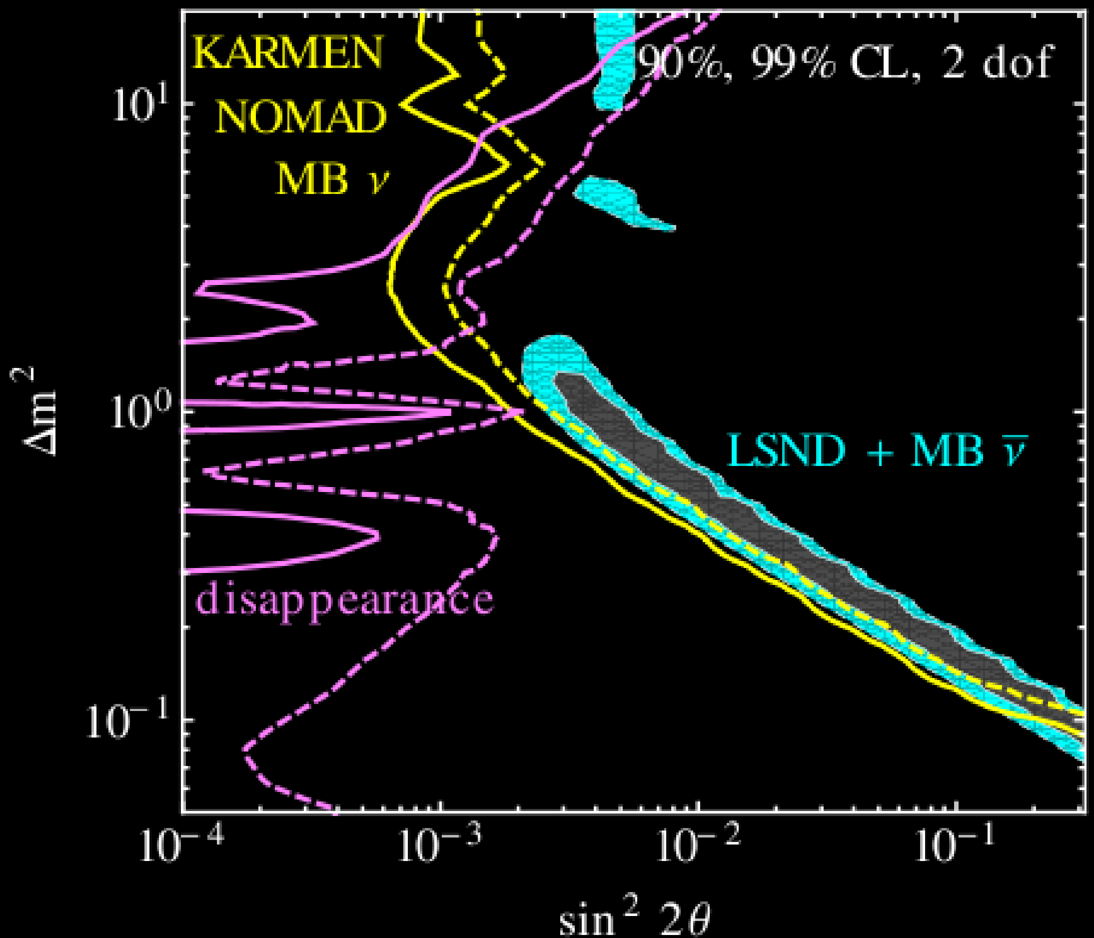
Down-Going Events

- Scattering



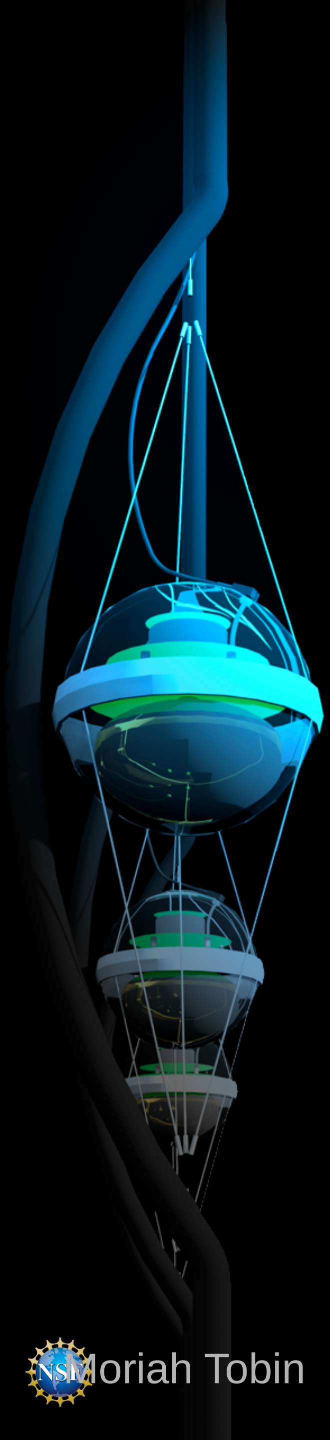


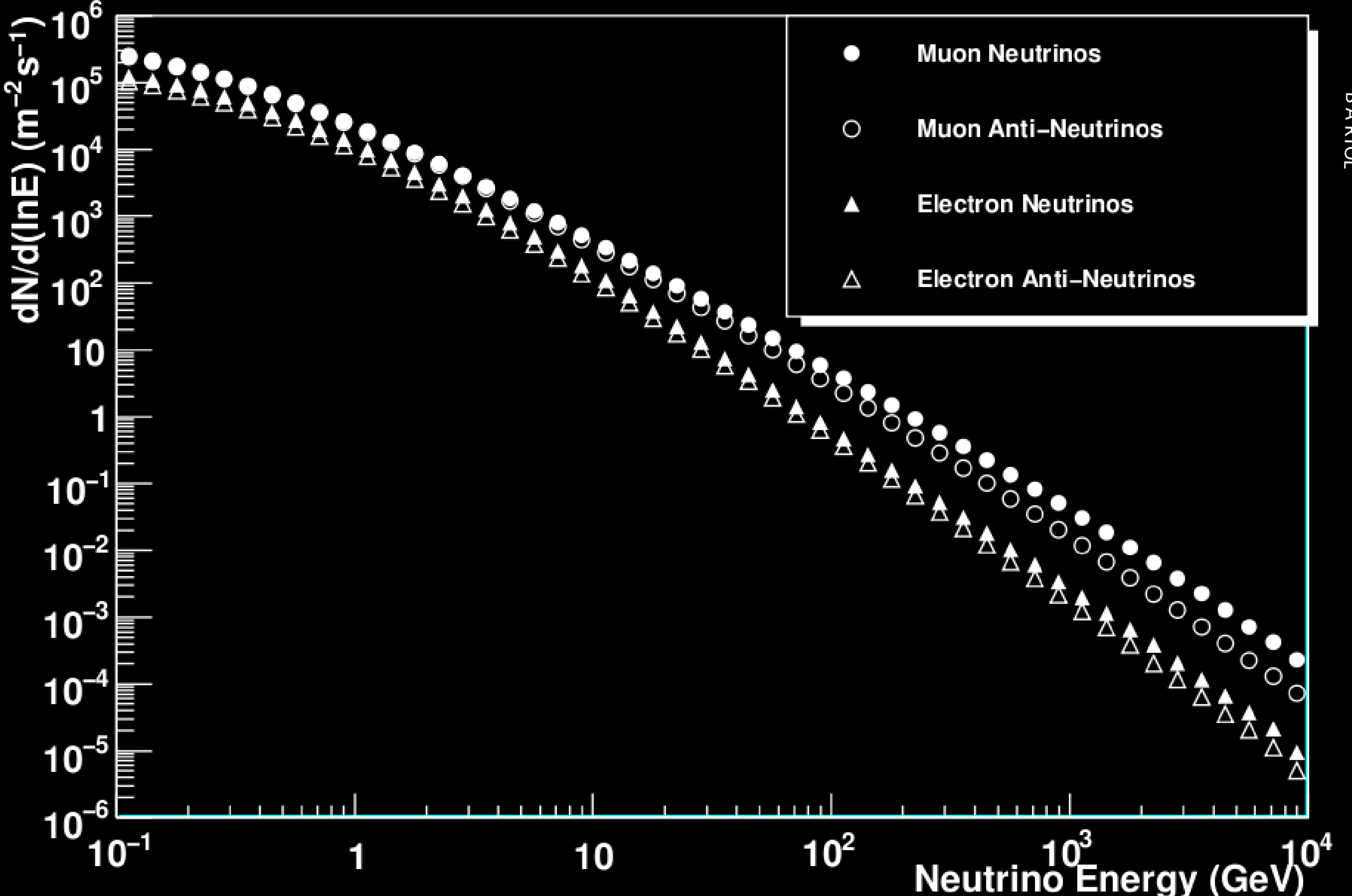
Sterile Neutrinos: A Tense Situation



* Image from arXiv:1204.5379v1

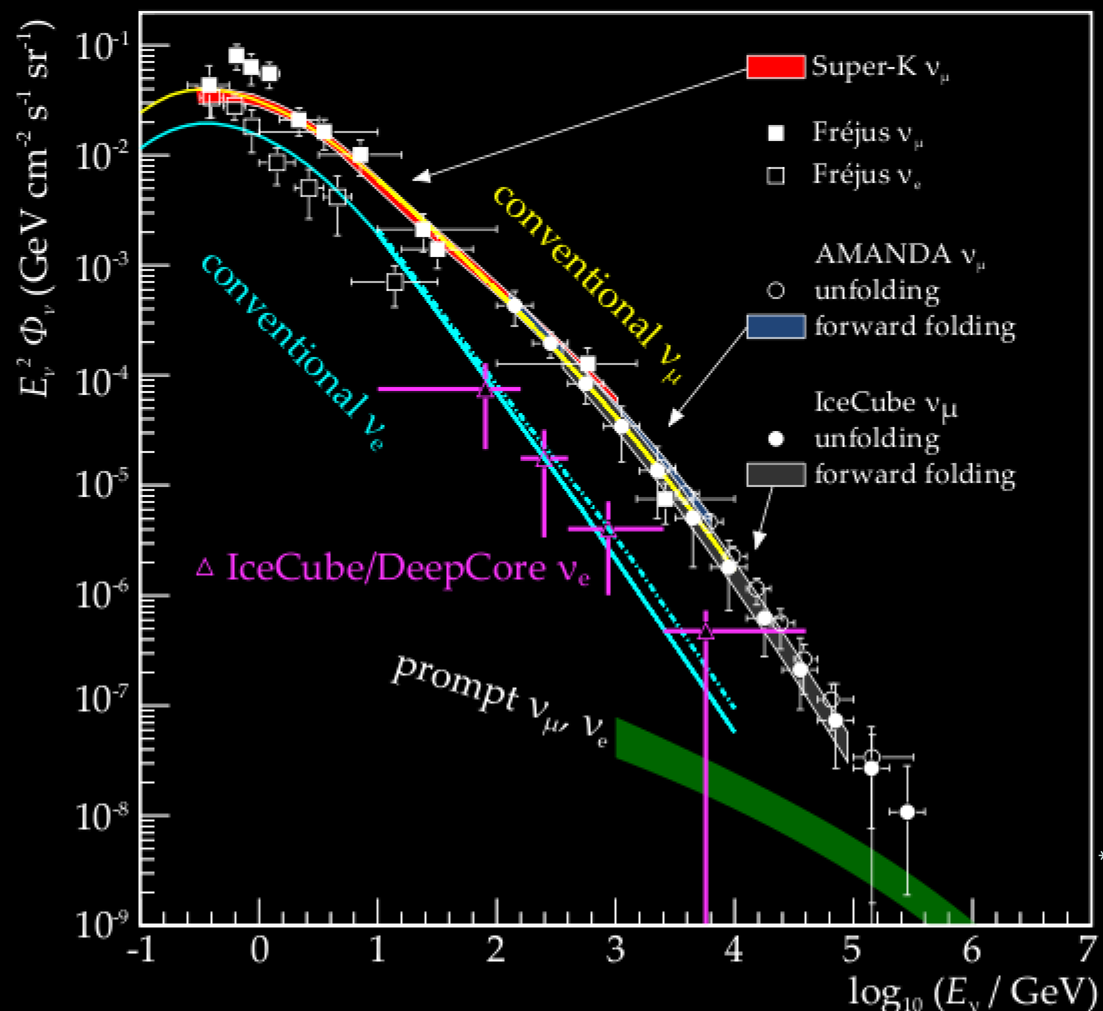
Atmospheric Neutrinos





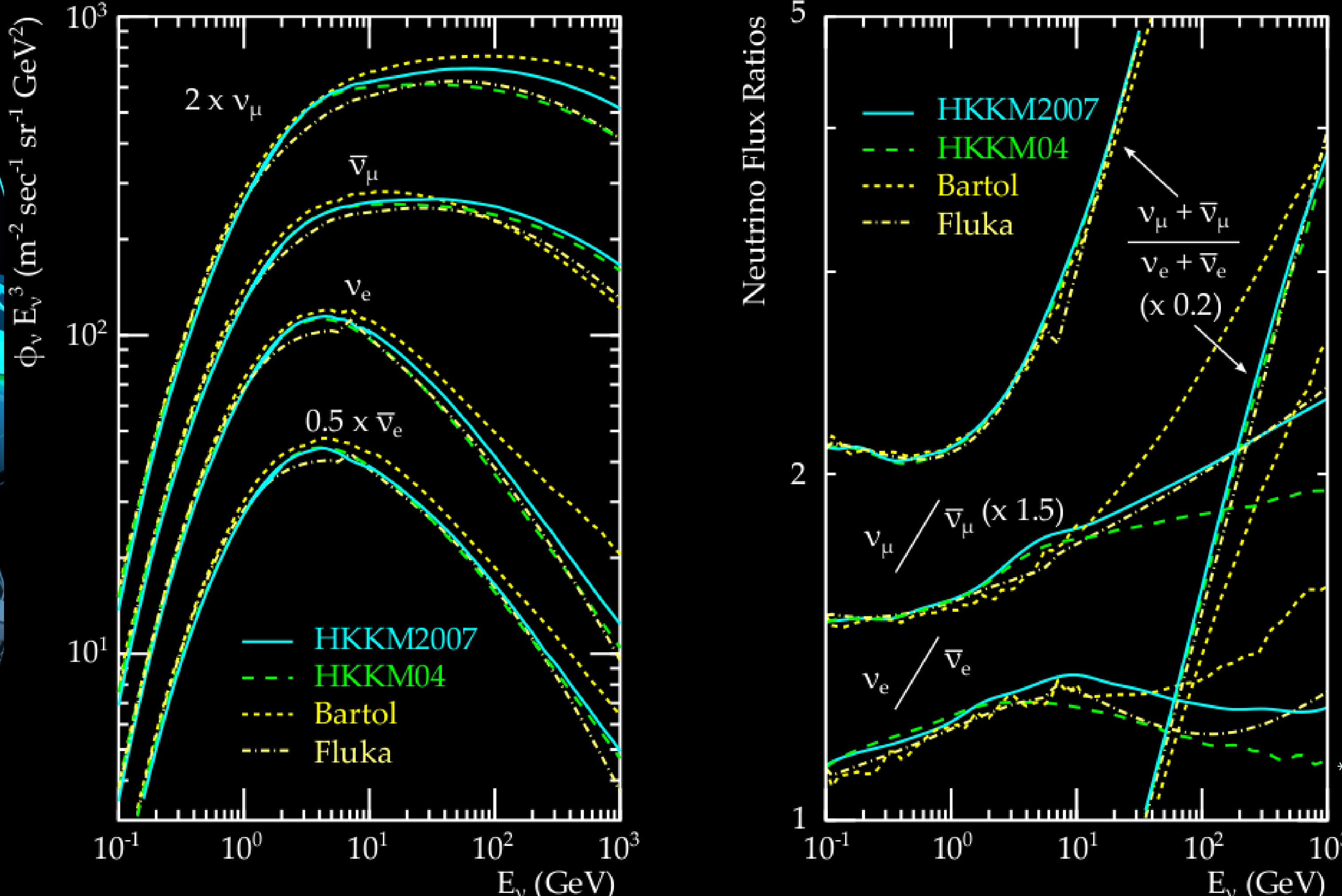
* Image from dspace.mit.edu/handle/1721.1/52783

Atmospheric Neutrino Spectrum - Backup



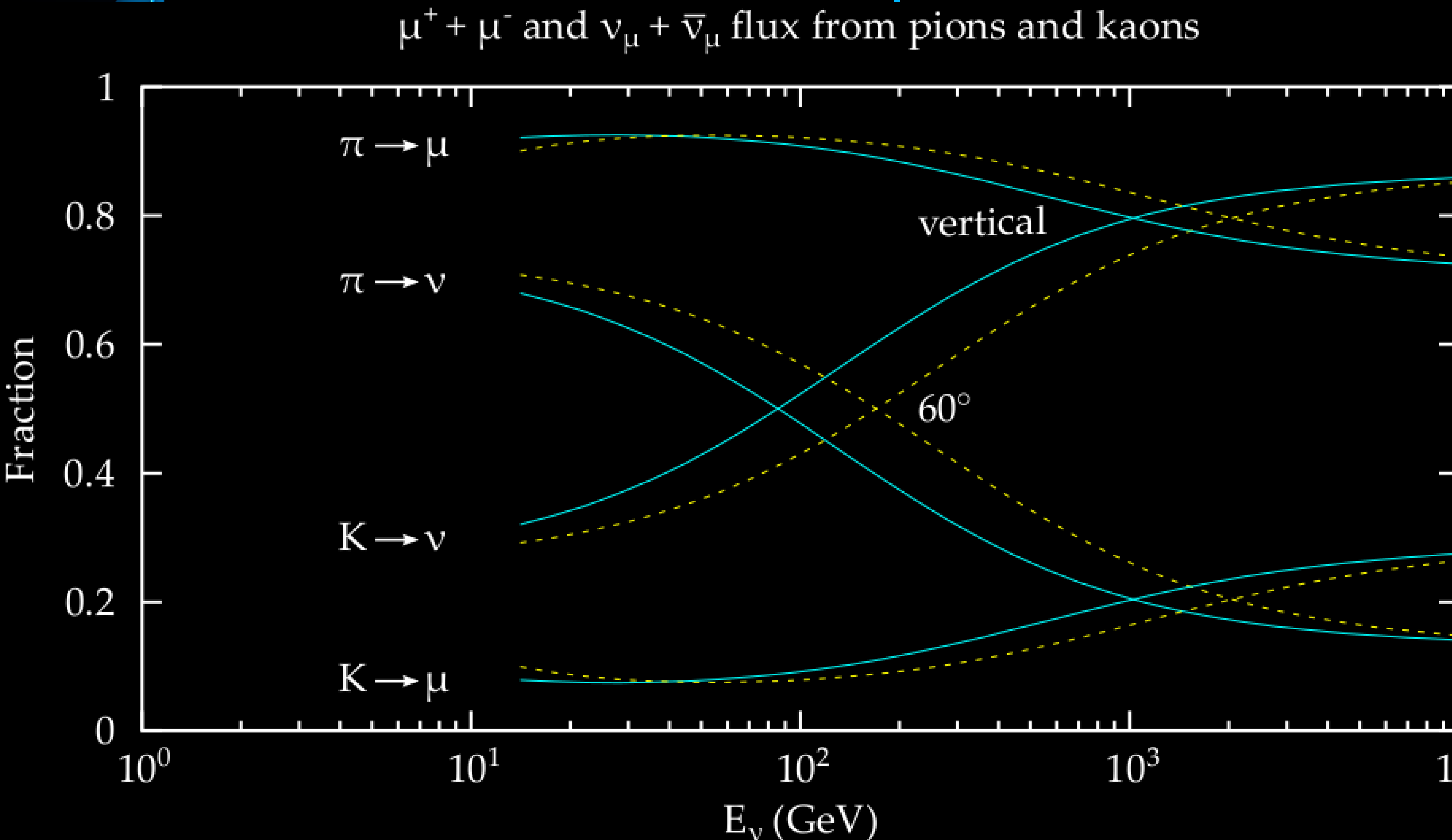
* Image from http://www.physik.rwth-aachen.de/fileadmin/user_upload/www_physik/Institute/Inst_3B/Forschung/IceCube/publications/diss_SE.pdf

Atmospheric Neutrino Models - Backup



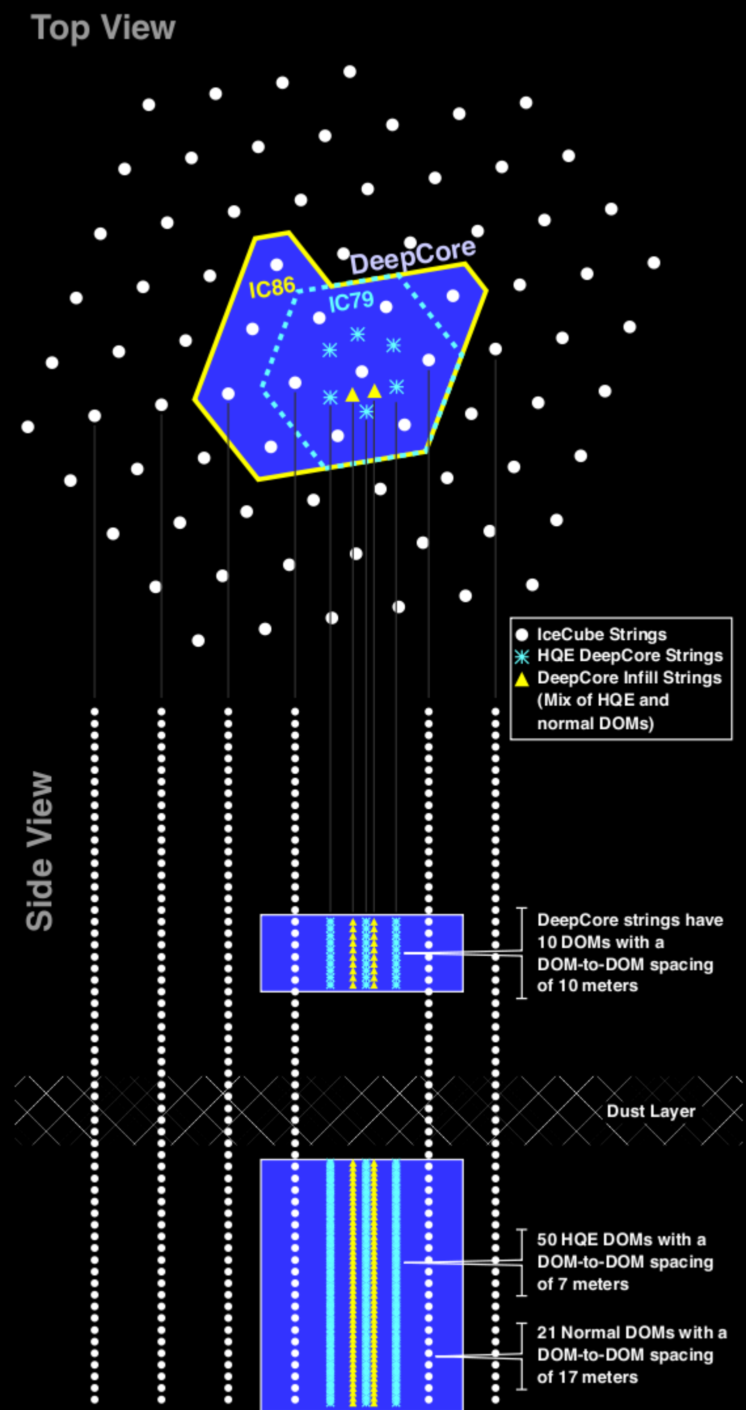
* Image from http://www.physik.rwth-aachen.de/fileadmin/user_upload/www_physik/Institute/Inst_3B/Forschung/IceCube/publications/diss_SE.pdf

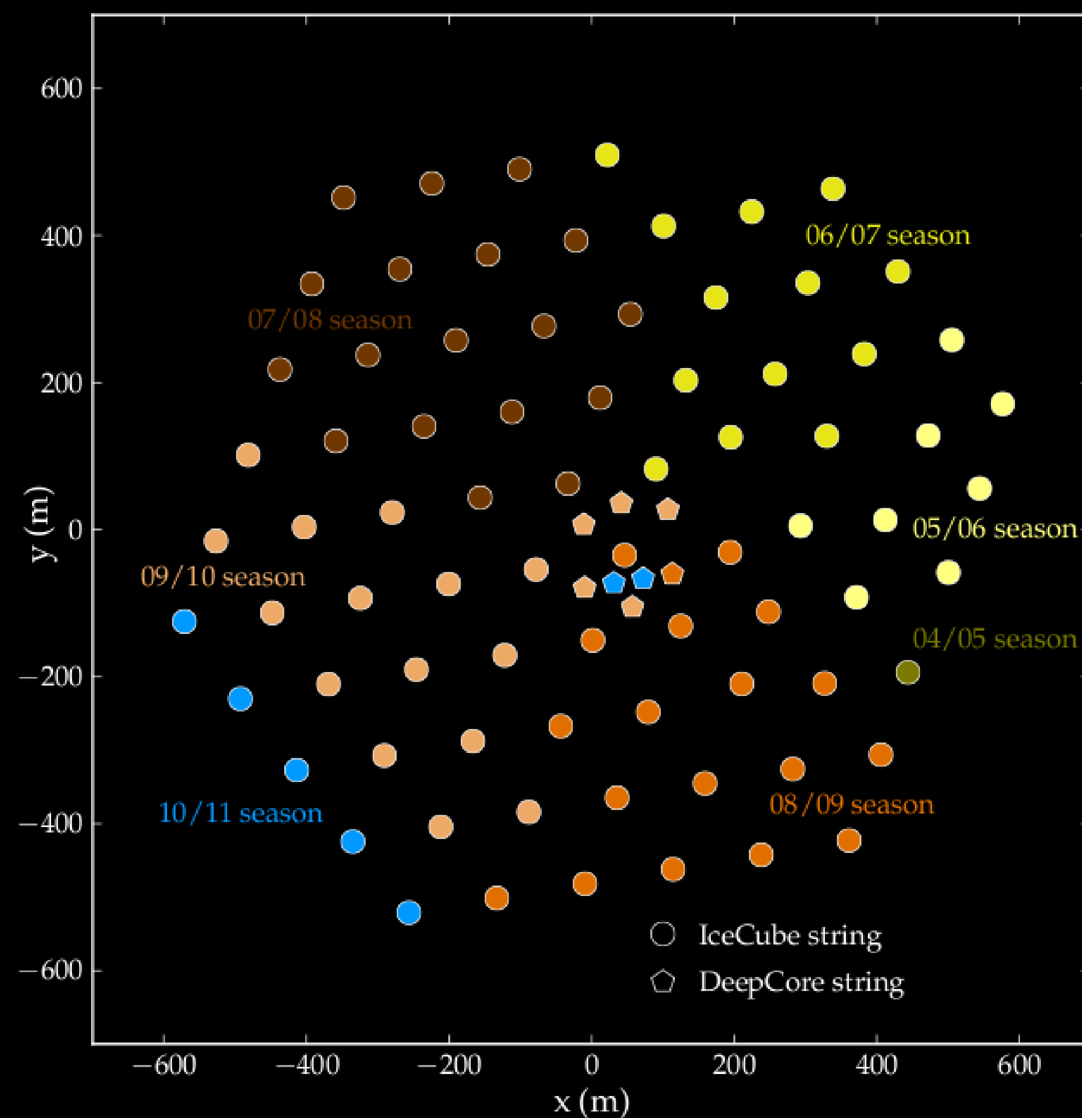
Atmospheric Neutrino Production - Backup

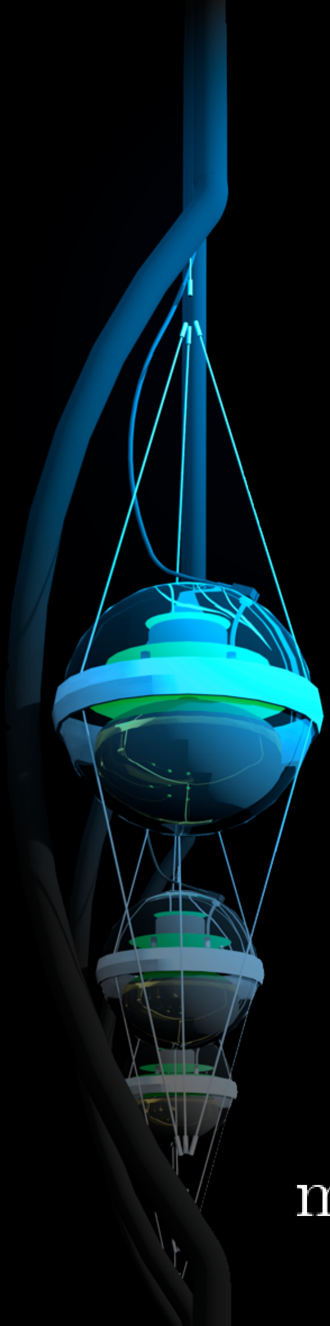


* Image from http://www.physik.rwth-aachen.de/fileadmin/user_upload/www_physik/Institute/Inst_3B/Forschung/IceCube/publications/diss_SE.pdf

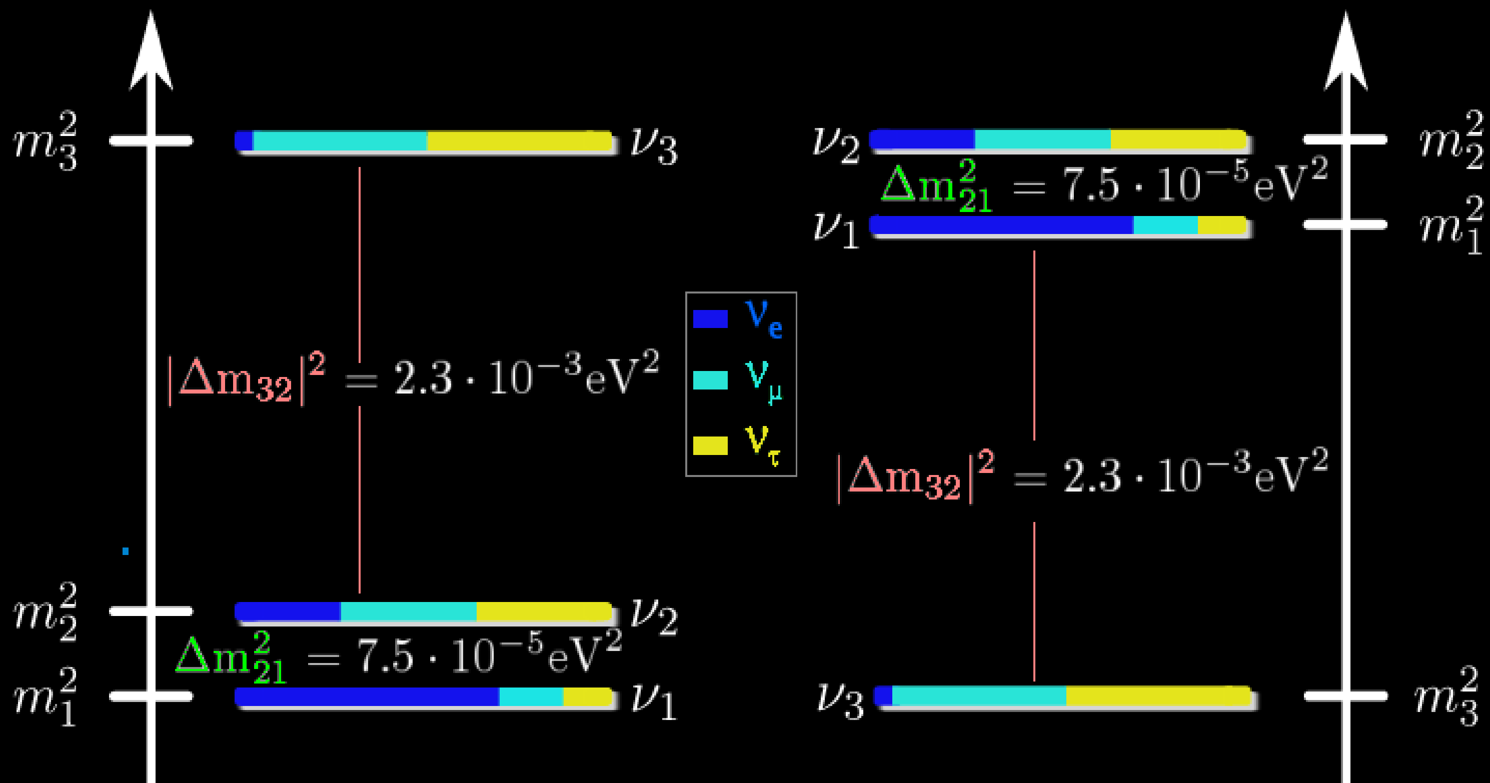
DeepCore 79 vs. 86





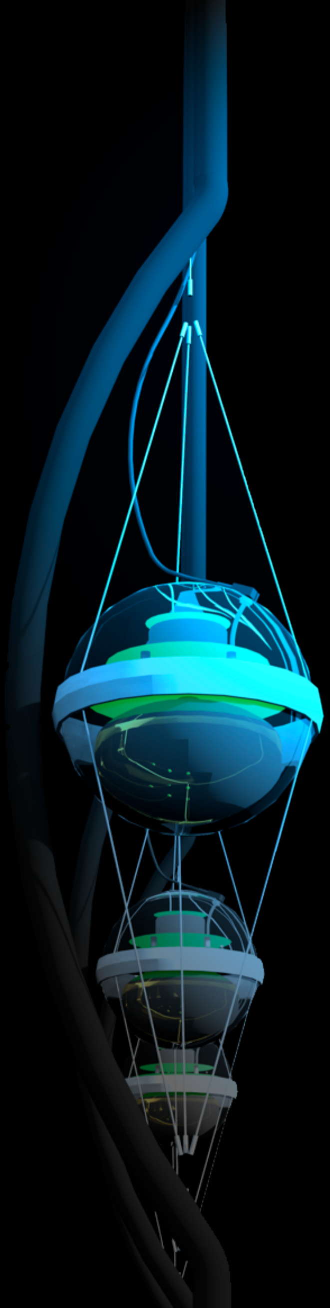


Neutrino Mass



*Edited Image from: http://inspirehep.net/record/1122848/files/figures_neutrino_hierarchy.png

$$\mathrm{m}_{\nu_e} < 0.2\,\mathrm{eV} \qquad \sum_{i=1}^{3} \mathrm{m}_i^2 < 0.24\,\mathrm{eV}^2 \quad (\mathrm{cosmic})$$

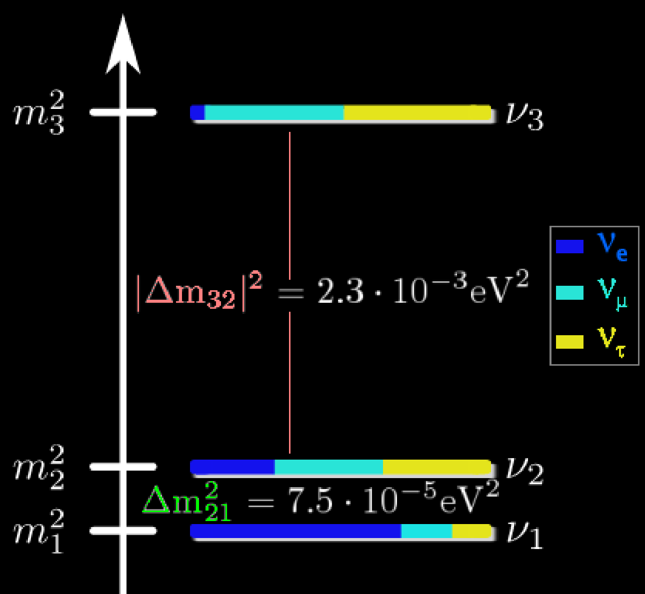


Neutrino Mass - Backup

$$\mathrm{m}_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \mathrm{m}_{\nu_i}^2} < 0.2\,\mathrm{eV}$$

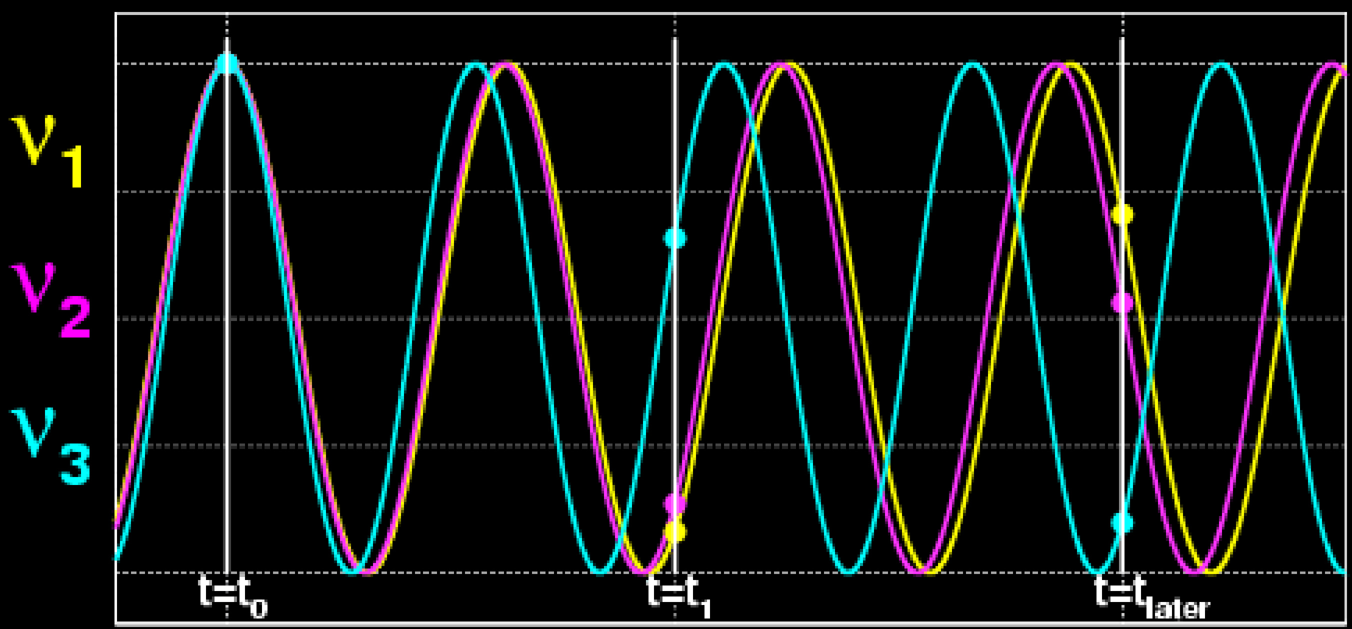
$$\mathrm{m}_{\nu_\mu} = \sqrt{\sum_{i=1}^{3} |U_{\mu i}|^2 \mathrm{m}_{\nu_i}^2} < 190\,\mathrm{keV}$$

$$\mathrm{m}_{\nu_\tau} = \sqrt{\sum_{i=1}^{3} |U_{\tau i}|^2 \mathrm{m}_{\nu_i}^2} < 18.2\,\mathrm{MeV}$$



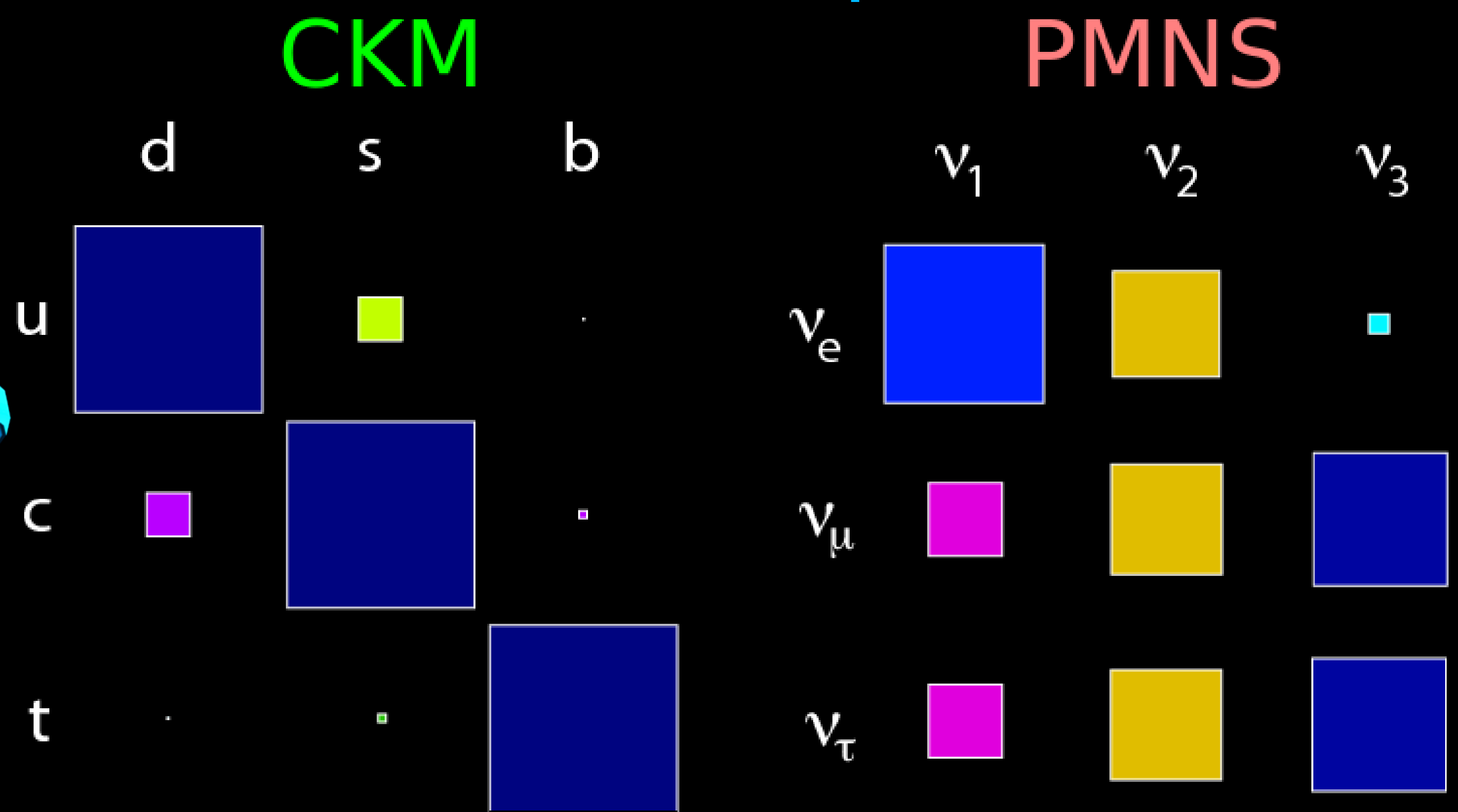
*Edited Image from: http://inspirehep.net/record/1122848/files/figures_neutrino_hierarchy.png

Neutrino Oscillations - Backup



* Image from: http://www-hep.physics.wm.edu/~vahle/homepage/nuwave.gif

Neutrino vs. Quark Flavor Mixing Backup



*Edited Image from: http://inspirehep.net/record/1209003/files/CKM-PMNS.png

Neutrino vs. Quark Flavor Mixing
Back-Up II

CKM

$$\begin{pmatrix} 0.97427 & 0.22534 & 0.00351 \\ 0.22520 & 0.97344 & 0.0412 \\ 0.00867 & 0.0404 & 0.999146 \end{pmatrix}$$

PMNS

$$\begin{pmatrix} 0.824 & 0.547 & 0.145 \\ -0.499 & 0.583 & 0.641 \\ 0.266 & -0.601 & 0.754 \end{pmatrix}$$