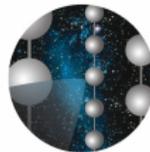


Sterile Neutrino Search in IceCube Neutrino Observatory

Jordi Salvadó

Carlos Argüelles, Ben Jones



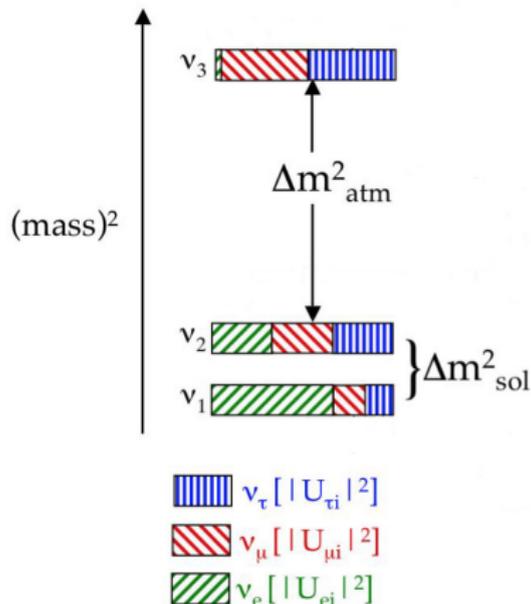
IceCube



TAUP 2015

Neutrino oscillations

Neutrino oscillations : mass eigenstates (ν_i ; $i = 1, 2, 3$) and flavor eigenstates (ν_α ; $\alpha = e, \mu, \tau$) are not the same.



$$\Delta m_{\text{sol}}^2 = 7.5 \times 10^{-5} \text{eV}^2$$

$$|\Delta m_{\text{atm}}^2| = 2.4 \times 10^{-3} \text{eV}^2$$

$$\nu_i = \sum_{\beta} U_{\beta i} \nu_{\beta}$$

$$U = U(\theta_{12}, \theta_{23}, \theta_{13}, \delta^{CP})$$

$$|U| \simeq \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.3 & 0.7 & 0.6 \\ 0.4 & 0.5 & 0.8 \end{pmatrix}$$

[B. Kayser, hep-ph/0506165 (2004)]

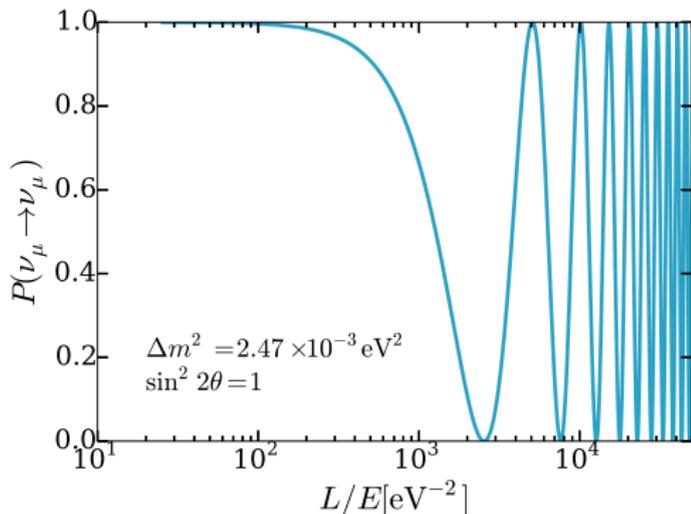
[C. Gonzalez-Garcia et al., JHEP 12 (2012)]

Neutrino oscillations

In two generations the oscillation probability at a given distance L and energy E in vacuum

$$P_{\nu_\alpha \rightarrow \nu_\alpha} \left(\frac{L}{E} \right) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

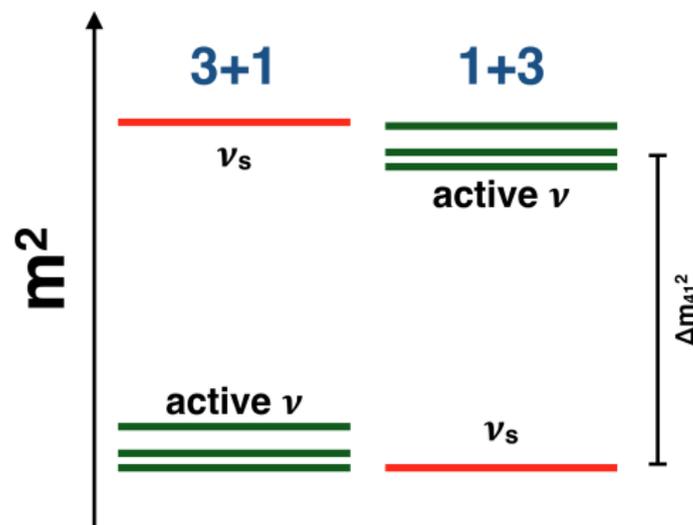
- ▶ $\sin^2 2\theta$: oscillation amplitude
- ▶ Δm^2 : oscillation frequency
 - ▶ $L/E \ll 1/\Delta m^2 \rightarrow$ no oscillations
 - ▶ $L/E \sim 1/\Delta m^2 \rightarrow$ oscillations
 - ▶ $L/E \gg 1/\Delta m^2 \rightarrow$ fast oscillations ("averaged")



Motivation : short baseline anomalies

- ▶ **LSND** found $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation with $\Delta m^2 \sim 1 \text{eV}^2$ and $\sin^2 2\theta \sim 0.003$
- ▶ MiniBoone $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
 - ▶ No significant excess at high energies ($E > 475 \text{ MeV}$)
 - ▶ Unexplained events at low energies, interpretation as oscillations similar to LSND: $\Delta m^2 \sim 1 \text{eV}^2$
- ▶ Gallium Anomaly, SAGE and GALLEX event rates lower than expected, can be explained by ν_e disappearance with $\Delta m^2 \geq 1 \text{eV}^2$
- ▶ New reactor flux calculation (Mueller et al., 1101.2663, P. Huber, 1106.0687) 3% higher, tension in short-baseline ($L \leq 100 \text{m}$) experiments, can be explained by ν_e disappearance with oscillation with $\Delta m^2 \sim 1 \text{eV}^2$.

Simplified sterile neutrino model

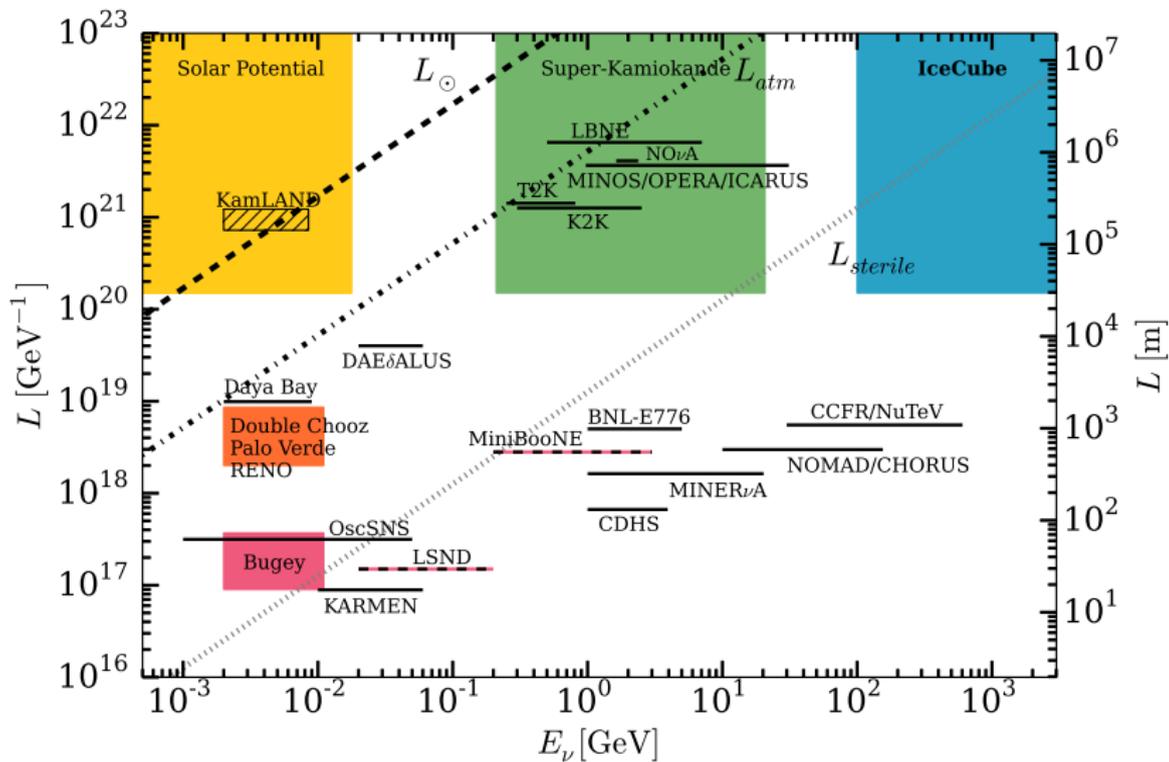


Only parameters : θ_{24} and Δm_{41}^2

Assumptions

- ▶ We only **one** sterile neutrino $\rightarrow (3 + 1)$ or $(1 + 3)$ models.
- ▶ $\theta_{14} = 0$ and $\theta_{34} = 0$
 \rightarrow only θ_{24} .

Experiments : $L_{\text{osc}} = 2\pi \frac{E}{\Delta m^2} \mid \Delta m_{\text{LSND}}^2 = 1\text{eV}^2$



[modified from J.S. Diaz and V.A. Kostelecky, Phys.Lett. B700, 25 (2011)]

Matter effects: Mikheyev-Smirnov-Wolfenstein

The ν oscillation probability in two generations in matter is

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\theta_M \sin^2 \left(\frac{\Delta m_M^2 L}{4E_\nu} \right)$$

where θ_M and Δm_M^2 satisfy

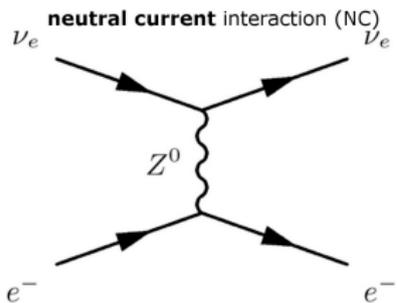
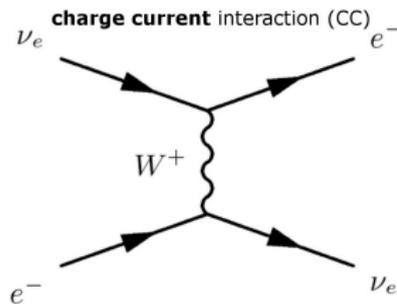
$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{A}{\Delta m^2 \cos 2\theta}}$$

and $A = \pm 2\sqrt{2}EG_F N$, N number density. Resonant flavor transition can happen if

$$E_\nu^{\text{res}} = \mp \cos 2\theta \frac{\Delta m^2}{2N} \frac{1}{\sqrt{2}G_F}$$

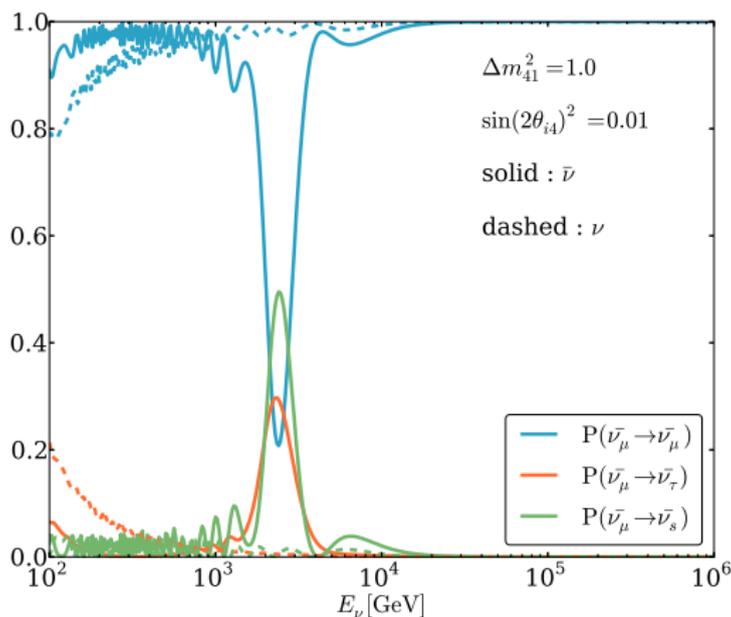
this resonance (MSW) can **enhance the transition between active and sterile neutrinos.**



MSW with the Sterile Neutrino at Earth

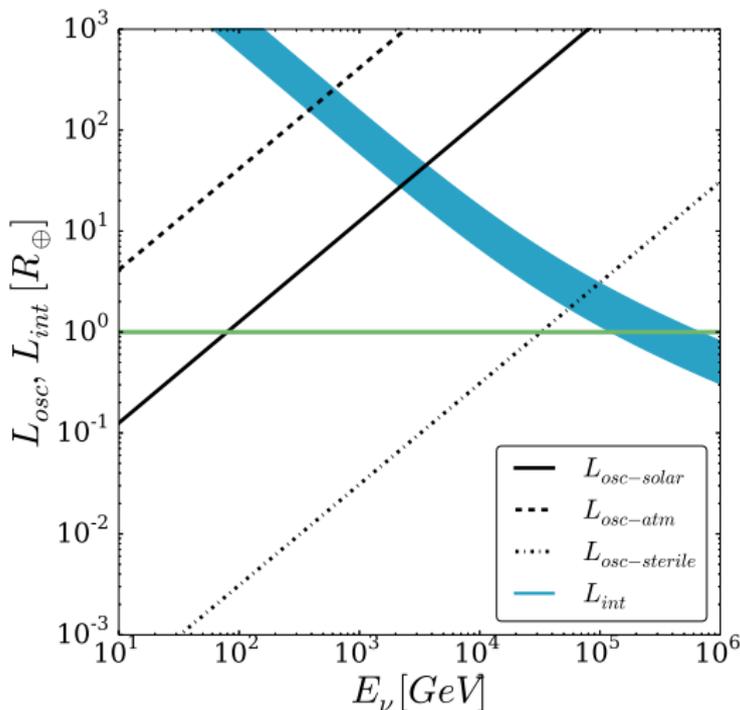
In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N} \sim O(\text{TeV})$$



MSW with the Sterile Neutrino at Earth

- ▶ IceCube measures atmospheric neutrinos at these energies
- ▶ But scattering processes (NC & CC) should be included in the propagation at these energies



SQuIDS/nu-SQuIDS

C.A. et al. [arXiv:1412.3832, CPC 2015.06.022.]

C.A. et al. [In preparation]

What is it?

Is a software framework written in C++ that **evolves quantum mechanical ensembles**.
nu-SQuIDS **calculates neutrino propagation** (oscillation+interactions).

What can it do?

- Calculate neutrino oscillation probabilities in 3 generations (can configure mixing angles, CP phases, and mass splittings).
- Ready to use in: short baseline, long baseline, atmospheric, and solar neutrino oscillation experiments.
- Incorporates neutrinos' non-coherent interactions (includes tau regeneration).
- Can handle collective neutrino interactions (e.g. super nova), as well neutrino-antineutrino interactions.
- Easily extendable to BSM physics scenarios. **Sterile neutrinos, NSI, and LV already implemented!**

Get it here:

<https://github.com/jsalvado/SQuIDS>

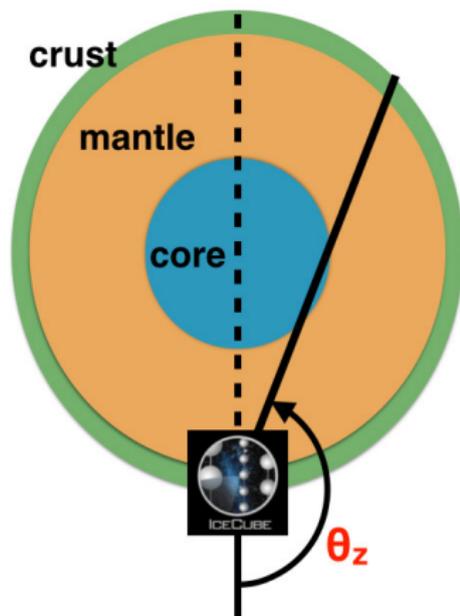
<https://github.com/arguelles/nuSQuIDS>



SQuIDS
Simple Quantum Integro Differential Solver

The Earth and the geometry

We have to solve the differential equations for each zenith angle considering the appropriate Earth density in the path.



core :

$$\cos \theta_z \sim [-1, -0.8]$$

mantle :

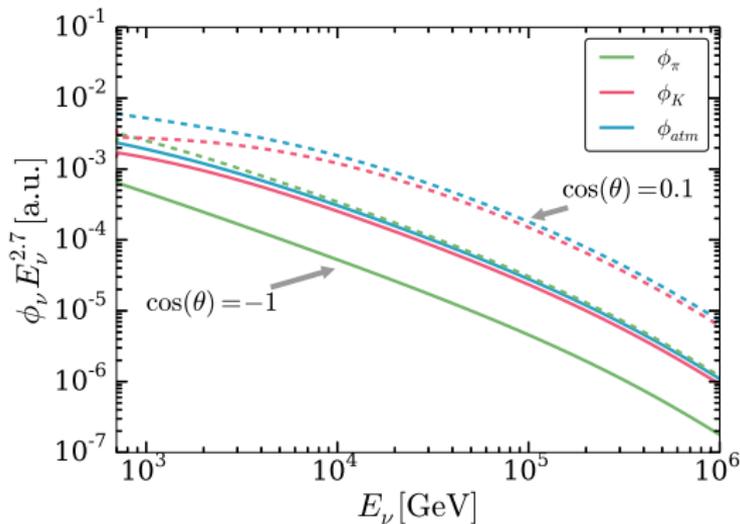
$$\cos \theta_z \sim [-0.8, -0.1]$$

crust :

$$\cos \theta_z > -0.1$$

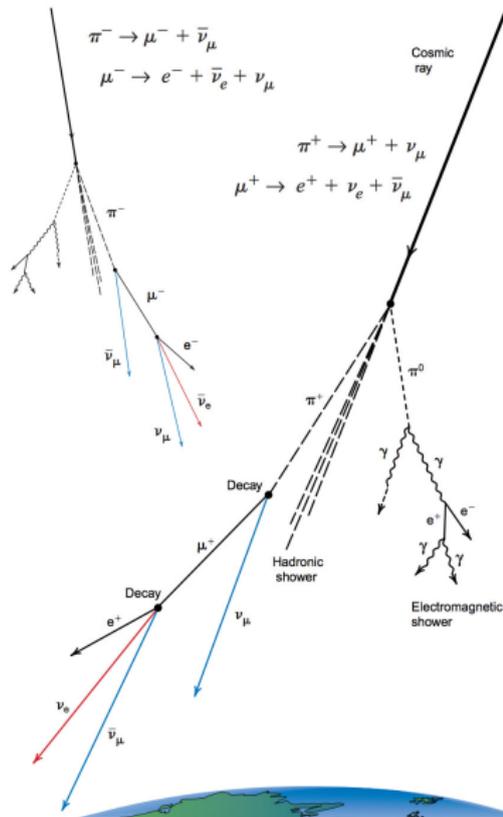
The **initial** atmospheric neutrino flux

The **conventional atmospheric neutrino (muon) flux** originates from the decay of π^\pm and K^\pm in the atmosphere.

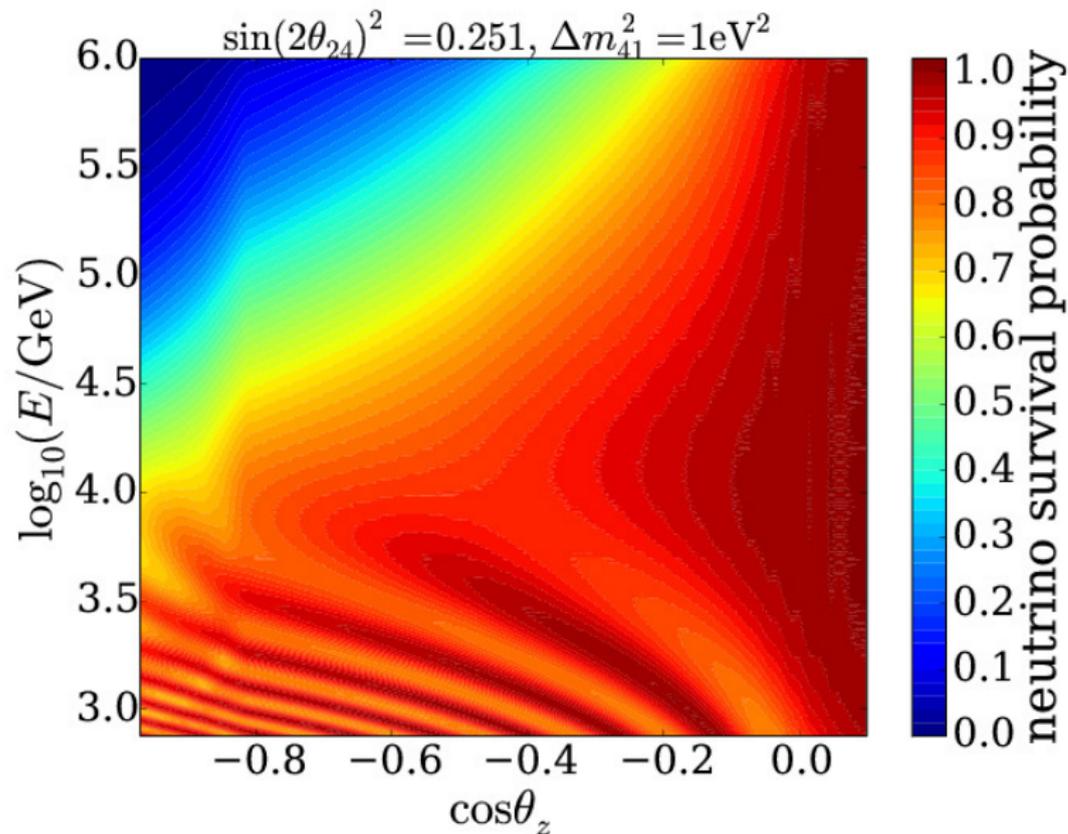


[Honda et al., Phys.Rev.D75:043006 (2007)]

[Louis et al., Los Alamos Science Number 25 (1997)]

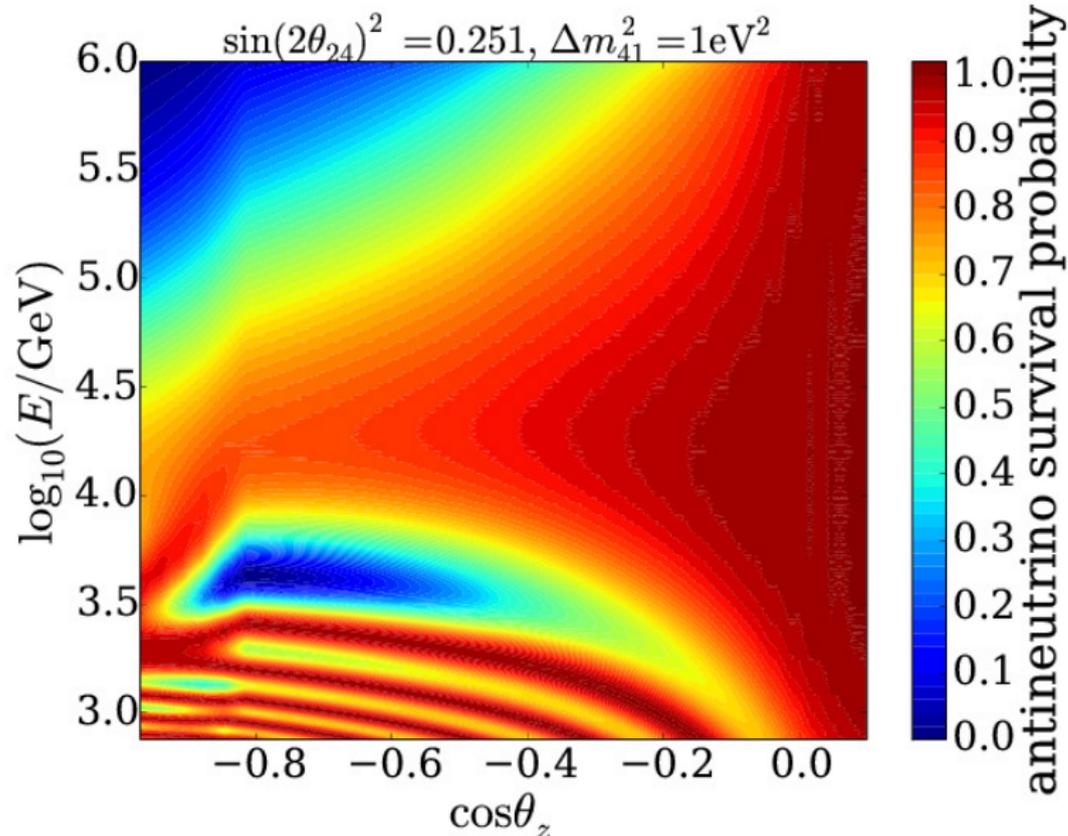


Oscillogram $\phi_\mu^{3+1}/\phi_\mu^{ini}$ for $\Delta m_{41}^2 = 1\text{eV}^2$, $\sin(2\theta_{24})^2 = 0.251$



[Carlos Argüelles, J.S., C. Weaver. *SQuIDS*, CPC 2015.06.022.]

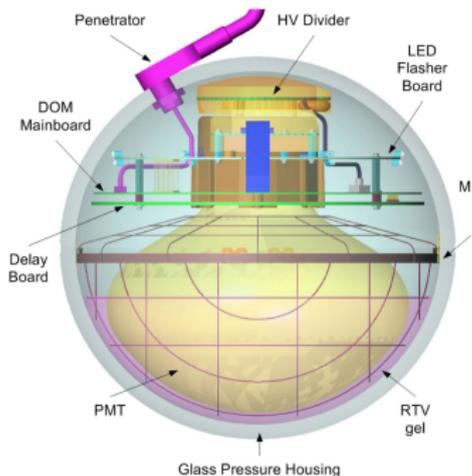
Oscillogram $\phi_\mu^{3+1} / \phi_\mu^{ini}$ for $\Delta m_{41}^2 = 1\text{eV}^2$, $\sin(2\theta_{24})^2 = 0.251$



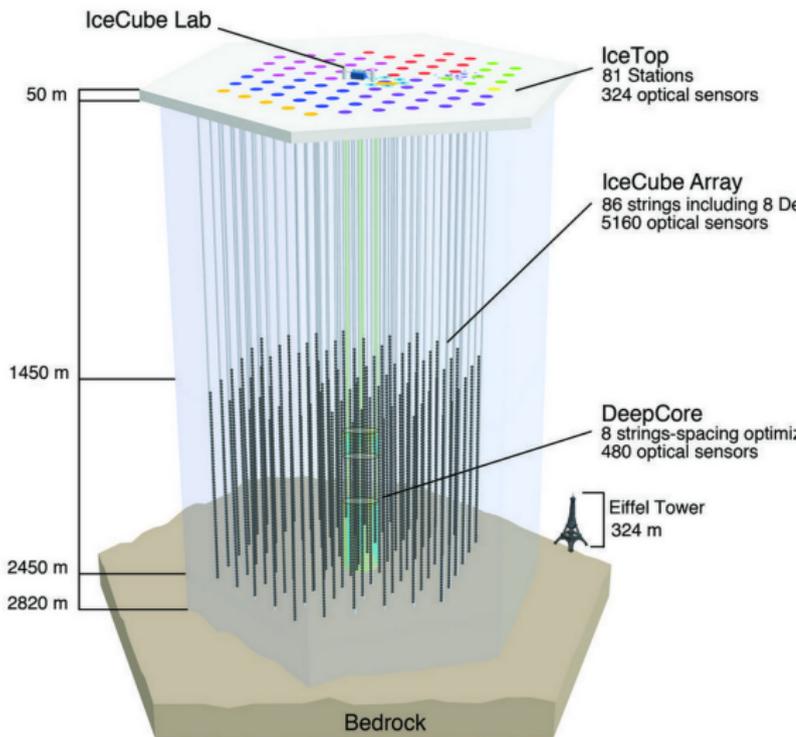
[Carlos Argüelles, J.S., C. Weaver. *SQuIDS*, CPC 2015.06.022.]

The IceCube experiment

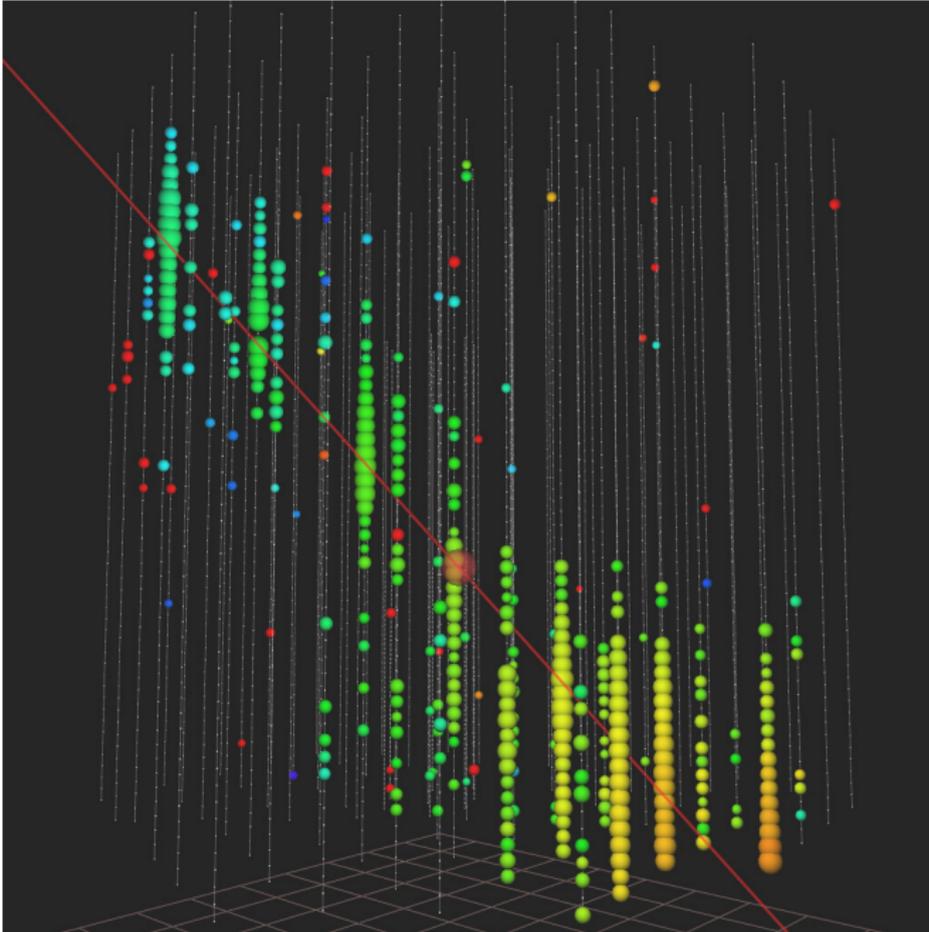
- ▶ 100 GeV to ∞
- ▶ $< 0.5^\circ$ μ angular resolution
- ▶ $< 15\%$ energy resolution



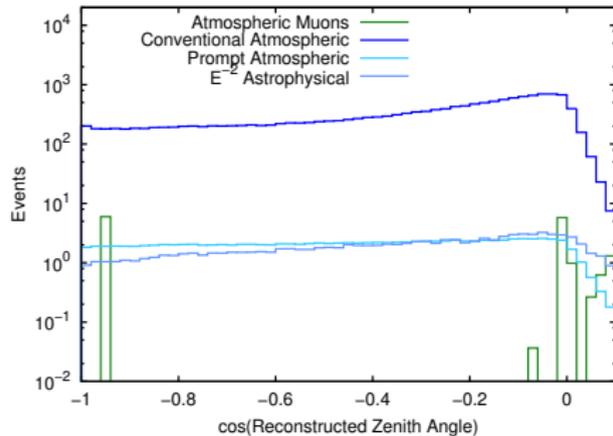
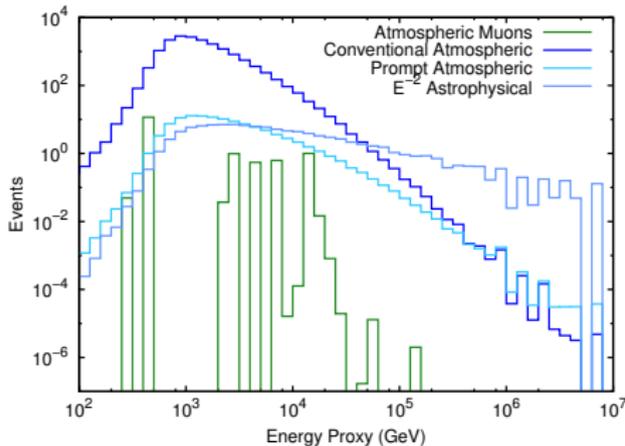
D.O.M.



Muon event in IceCube



Backgrounds!

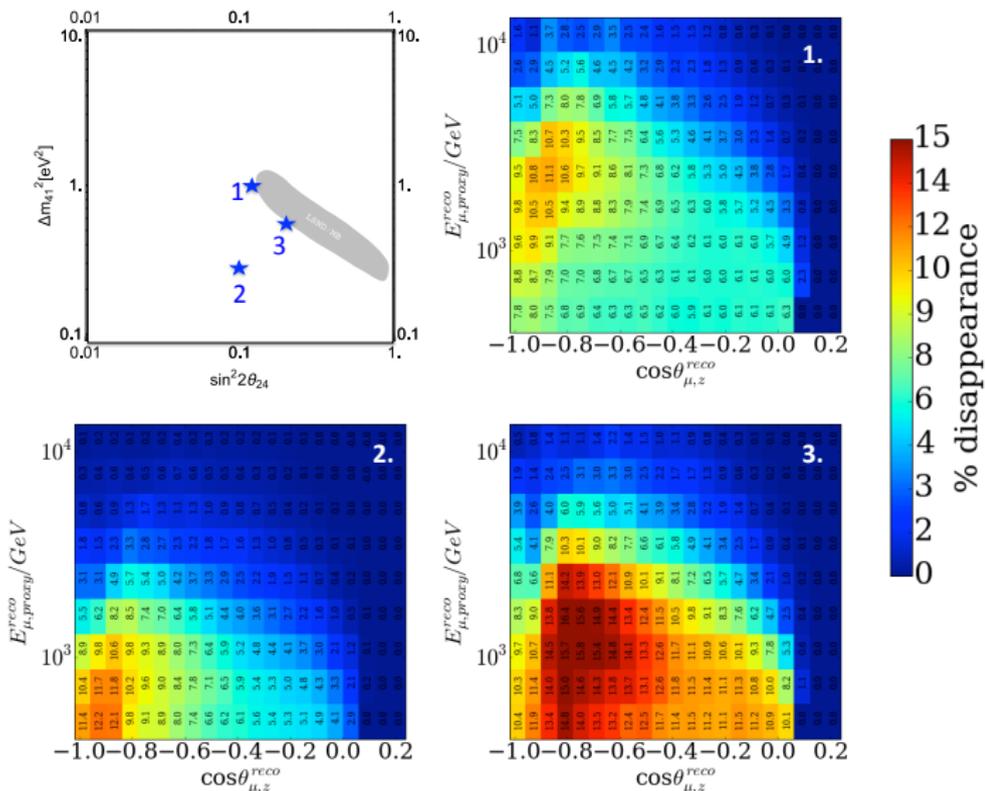


After cuts, in the region of interest $E \sim O(\text{TeV})$ **very small background** remains!

[Plots courtesy of [Christopher Weaver](#) - IC79+86 Diffuse Analysis]

The Signal!

Signal in reconstructed quantities for three points in the parameter space.



Systematics!

Systematics are **super** important; *some more than others*. This are the systematics we considered:

- ▶ DOM efficiency
- ▶ Flux continuous parameters
 - ▶ spectral index
 - ▶ π/K ratio
 - ▶ $\nu/\bar{\nu}$ ratio
- ▶ Air shower hadronic models
- ▶ Primary cosmic ray fluxes
- ▶ Hole Ice
- ▶ Neutrino cross sections
- ▶ Bulk ice scattering/absorption
- ▶ Earth model

continuous systematics
discrete systematic

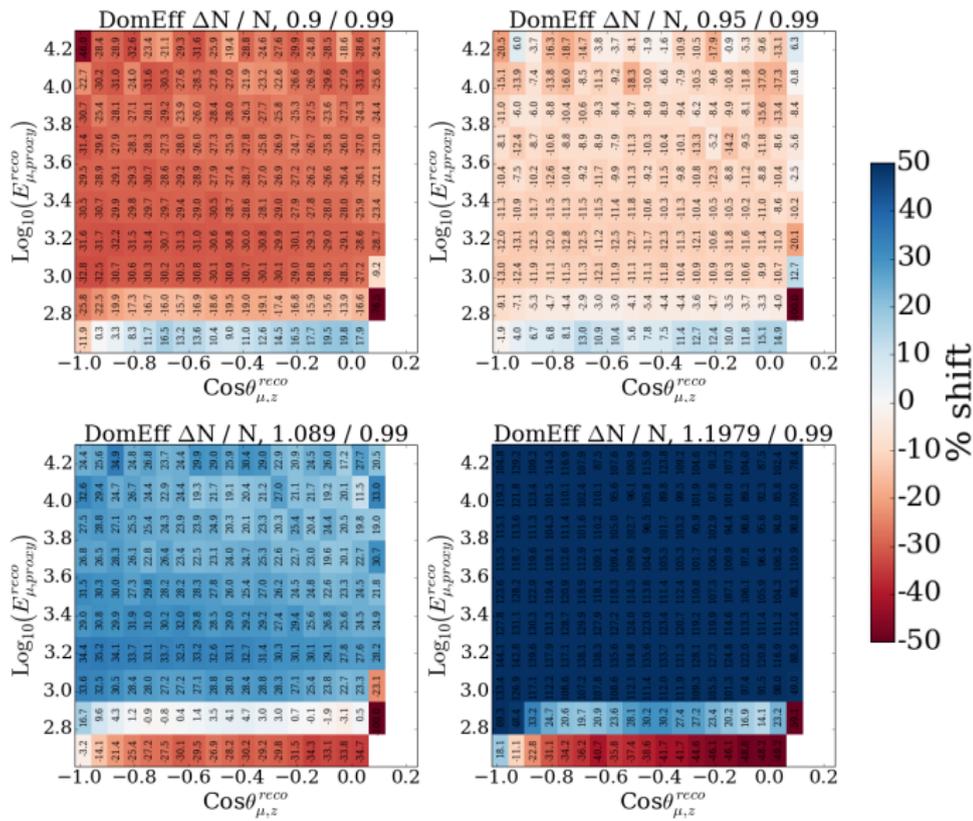


Important

Not important

Detector Systematics: DOM efficiency!

We use a photospline parametrization build on $(E_{rec}, \cos \theta_{rec}, \text{DOM}_{eff})$ space.



Flux Systematics

We parametrize the atmospheric flux with the following systematics parameters

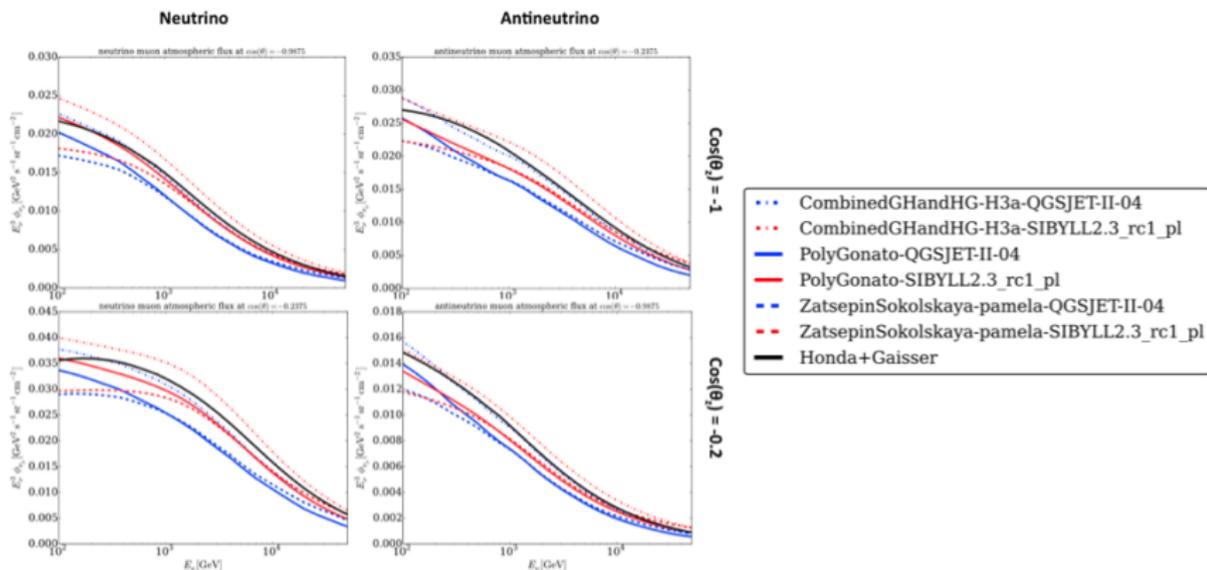
$$\phi_{atm}(\cos \theta, E_\nu) = N_0 \mathcal{F}(\delta) \left(\phi_K(\cos \theta, E_\nu) + R_{\pi/K} \phi_\pi(\cos \theta, E_\nu) \right) \times E_\nu^{-\Delta\gamma}$$

- ▶ Flux normalization (N_0): no prior.
- ▶ Atmospheric flux slope ($\Delta\gamma$): gaussian prior (0.,0.05).
- ▶ Pion/Kaon ratio ($R_{\pi/K}$): gaussian prior (1.0,0.1).
- ▶ atmospheric density uncertainty (δ): gaussian prior (0,0.05).
- ▶ $\nu/\bar{\nu}$ ratio: gaussian prior (1.,0.05).

More on Flux Systematics!

Main uncertainties in the neutrino flux are capture by the *continuous* parameters.

Subleading effects we will treat using *discrete* flux variants.



[Fedynitch et al. arXiv:1504.06639]

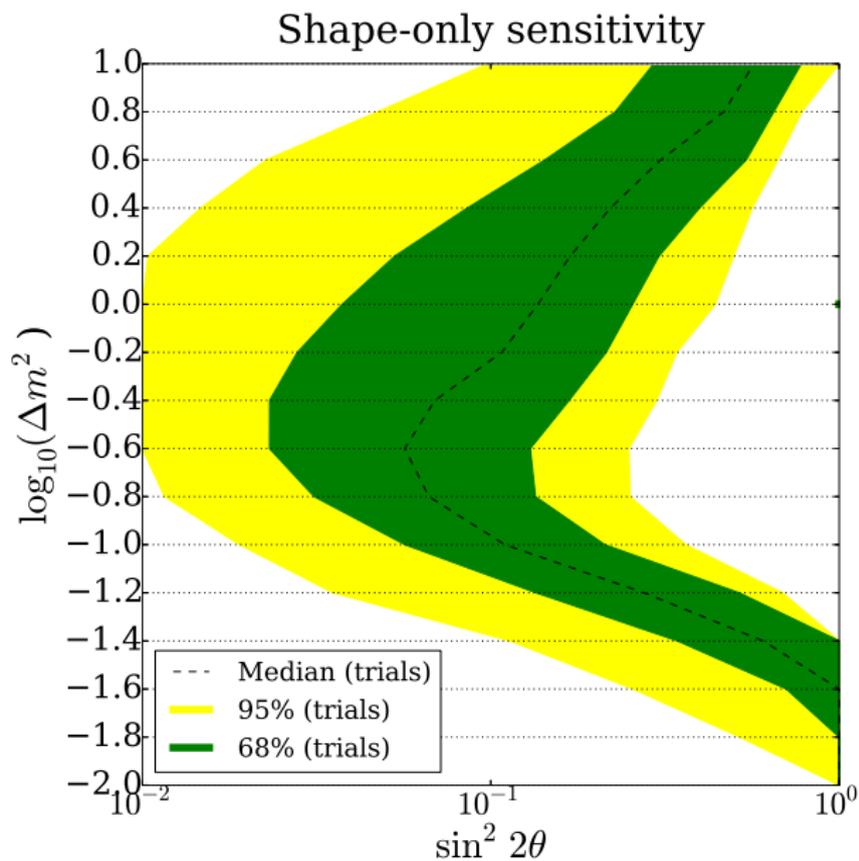
[Collins et al. URL: <http://dspace.mit.edu/handle/1721.1/98078>]

Statistics!

We did a standard binned maximum likelihood fit.

$$\log \mathcal{L}(\sin^2 2\theta_{24}, \Delta m_{41}^2) = \min_{\vec{\theta}, \{d\}} \left(\sum_{i=1}^{N_{bins}} \left[x_i \log \lambda_i(\vec{\theta}, d) - \lambda_i(\vec{\theta}, d) \right] + \sum_{\eta} \frac{(\theta_{\eta} - \Theta_{\eta})^2}{\sigma_{\eta}^2} \right),$$

Sensitivity!

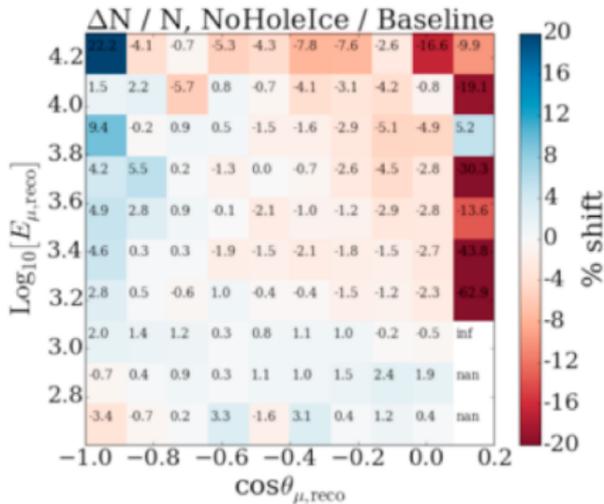
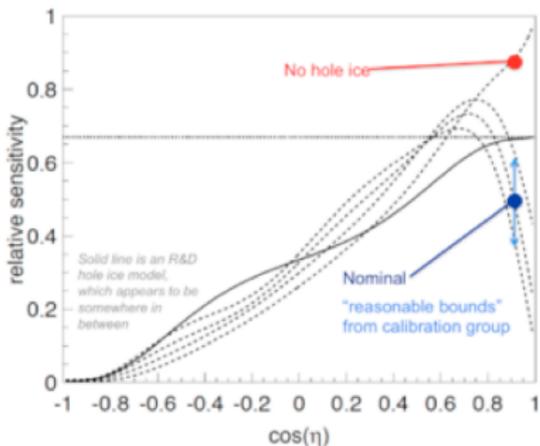


¡Thanks!

iBKP Slides

Detector Systematics: Hole Ice!

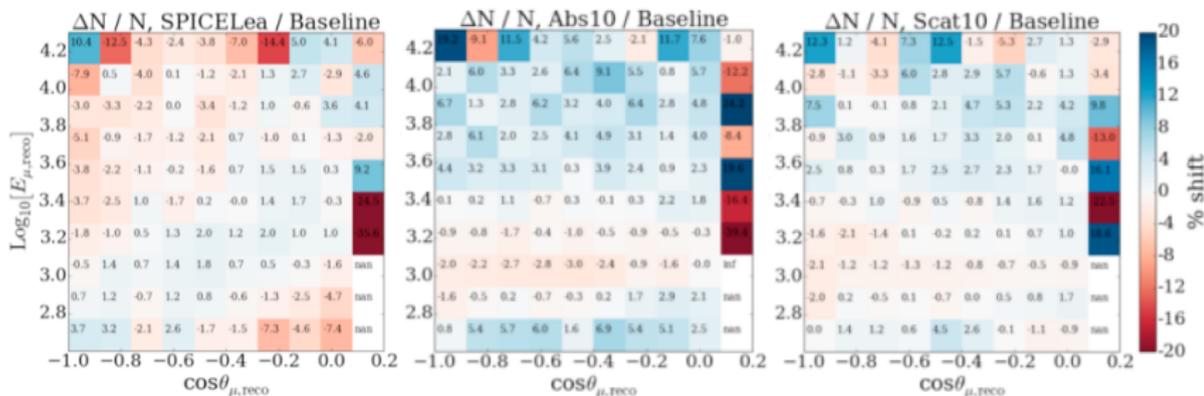
We use an extreme variant to see the scale of the effect. Found it very small compared to statistical errors.



Discrete no hole ice variant will be used.

Detector Systematics: Ice variants!

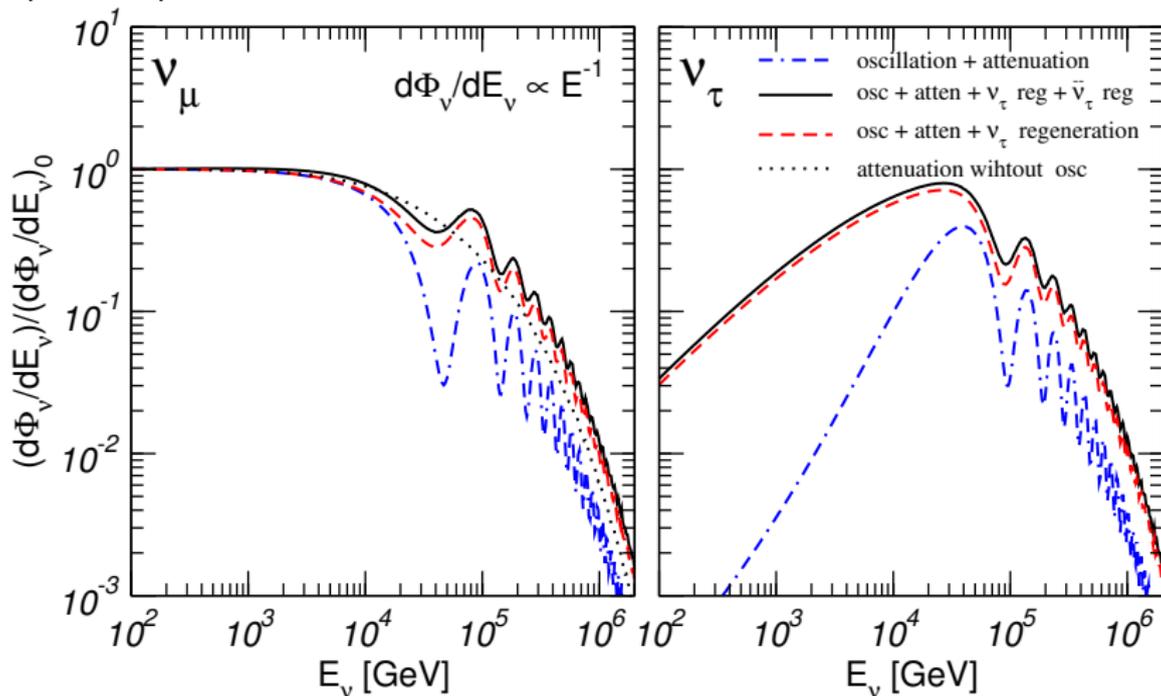
We use SpiceMie ice model is used. We compare with SpiceLea and change the model parameters by 10%. The effect is small.



Discrete ice variants will be used.

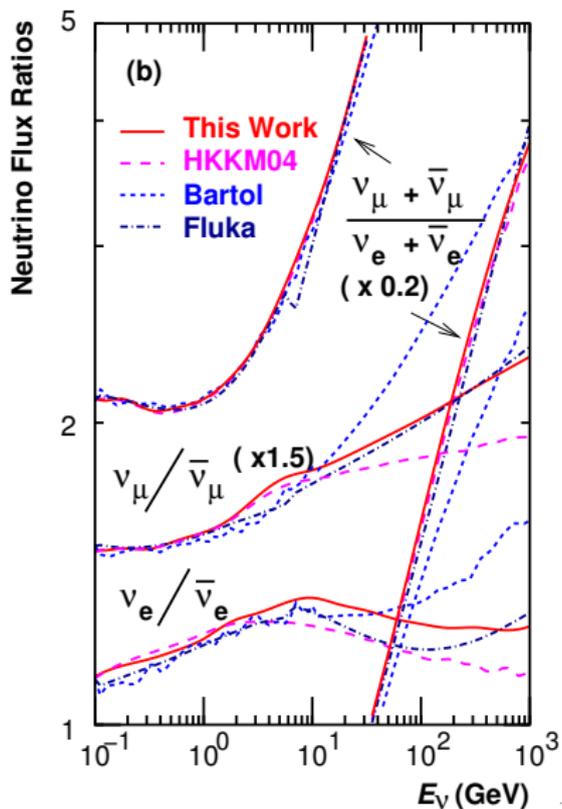
The effect of tau-regeneration

The importance of regeneration effects greatly depend on the spectral power. Here shown for LV-induced oscillations.



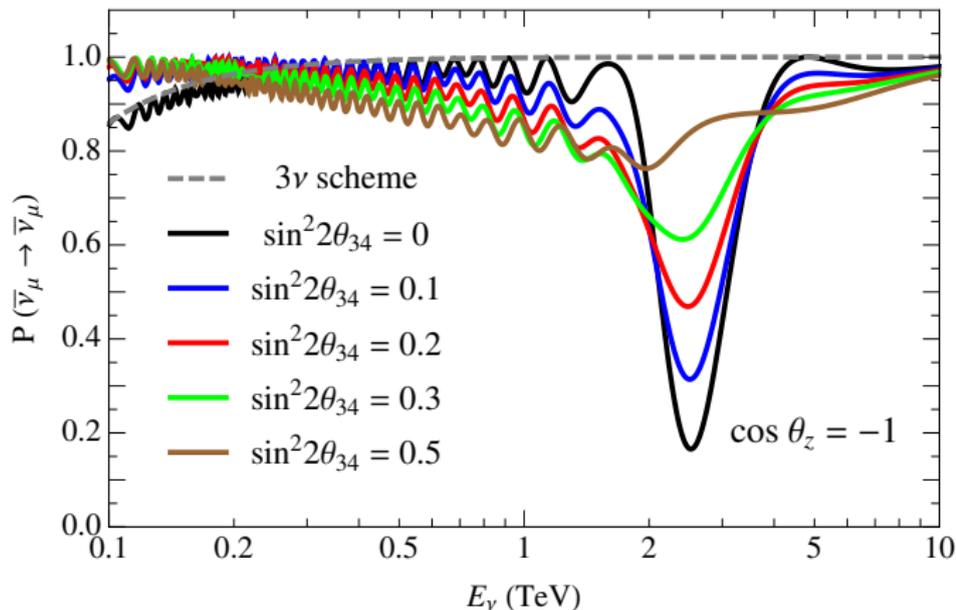
[Gonzales-Garcia et al., Phys.Rev. D71 (2005) 093010]

Initial neutrino to antineutrino ratio



[Honda et al., Phys. Rev. D4 (2007) 043006]

Effect of other mixing angles



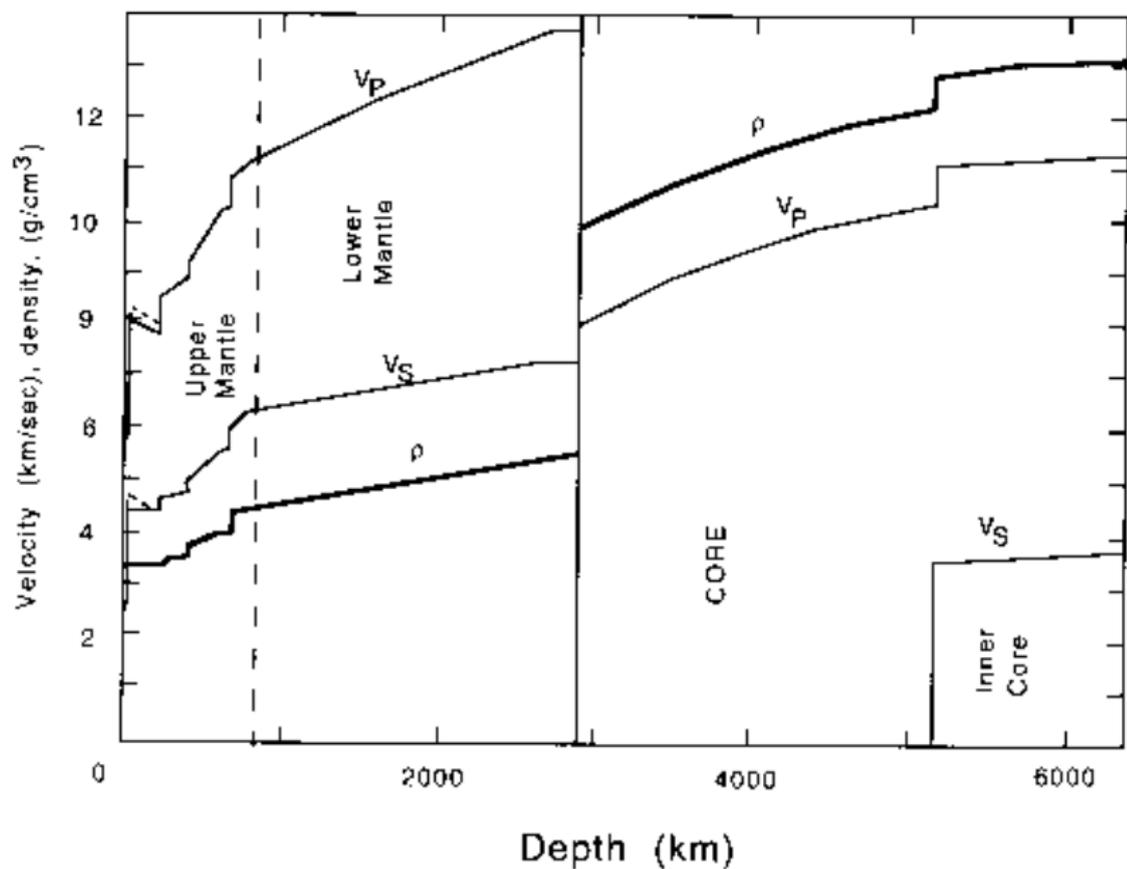
[Esmaili et al., JHEP12 (2013) 014]

More Motivation? ... cosmology ...

- ▶ Λ CDM + N_{eff} with WMAP9 + spt + act
 $N_{\text{eff}} = 3.89 \pm 0.67$ (68%CL)
- ▶ Λ CDM + m_ν with WMAP9 + spt + act + SN1a
 $\sum m_\nu < 0.56 \text{eV}$ (95%CL)
- ▶ $w\Lambda$ CDM + m_ν with WMAP9 + spt + act + SN1a
 $\sum m_\nu < 1.2 \text{eV}$ (95%CL)
- ▶ Λ CDM + m_ν + N_{eff} with Planck + WP + spt + act
 $\sum m_\nu < 0.6 \text{eV}$ $N_{\text{eff}} = 3.29^{+0.67}_{-0.64}$ (95%CL)
- ▶ Λ CDM + m_ν + N_{eff} with Planck + WP + spt + act + BAO
 $\sum m_\nu < 0.28 \text{eV}$ $N_{\text{eff}} = 3.32^{+0.54}_{-0.52}$ (95%CL)

[Planck Collaboration, arXiv:1303.5076]

Earth model



nu/nubar errors

