CascadeS

A Sterile Neutrino Search in IceCube

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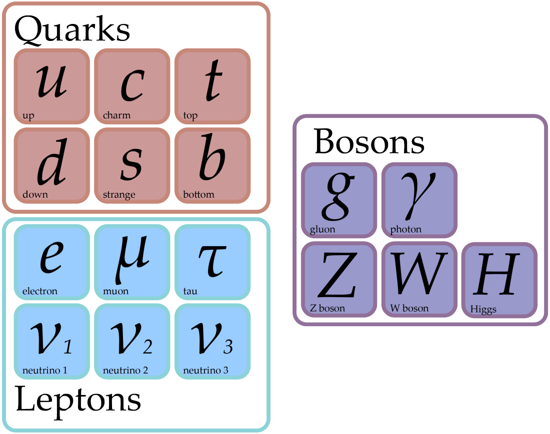
Neutrinos

Neutrino Fast Facts

- Have mass, don't know why
- At least three
- Probably Dirac?
- Are only left-handed??



Answers may lead to new, exciting, physics

Neutrino Oscillations

Neutrinos' flavor eigenstates are not mass eigenstates!

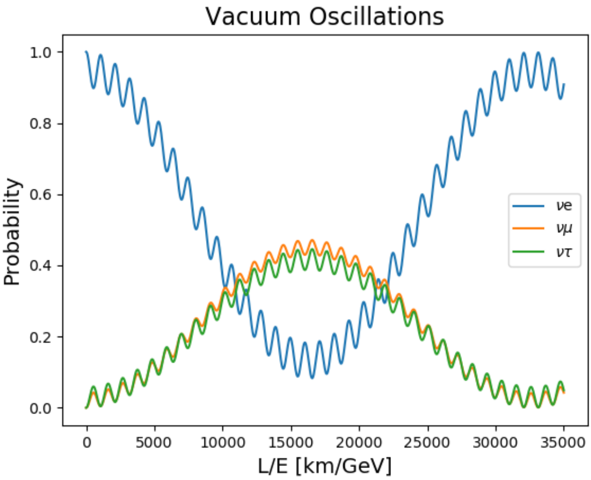
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

- Complex Unitary "PMNS" Mixing matrix U
- Expressed as three mixing angles θ_{ij}, phase angle δ
- Δm^2_{ij} - mass squared splittings

$$P \propto \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu} \tag{2}$$

Three-Neutrino Oscillations

$$P(\nu_e \rightarrow \nu_i) \tag{3}$$

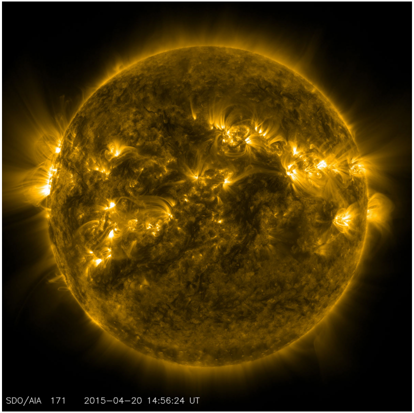


The Matter Effect (MSW)

- ν_e forward scattering with $W^{\pm}$
- $\bar{\nu}_e$ back-scattering

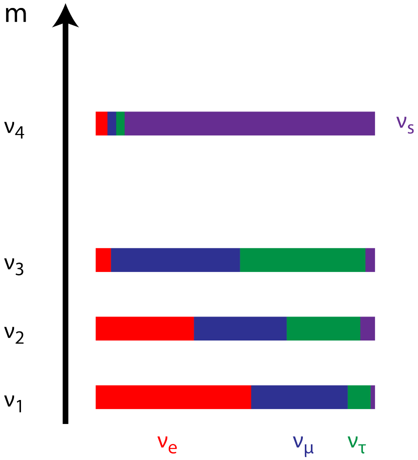
- Neutrino matter-potential
- Matter effects neutrino oscillation

- $\rightarrow$ SNO



Source: NASA/SDO

Free Parameters



Normal Neutrino Mass Ordering, with bonus sterile neutrino

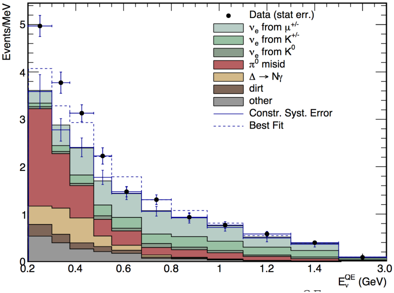
- Masses too small to probe*

- θ_{12}, Δm^2_{12} - solar neutrinos
- θ_{13} - reactor neutrinos
- θ_{23} - atmospheric neutrinos
- $\left|\Delta m^2_{31}\right|$
- δ_{CP} - T2K, NOνA

Steriles!

- LSND, MiniBooNE oscillation anomaly
- A combined 6σ excess

- Issues with 3 neutrino model
- 3+1 Sterile neutrino? (bounds to be discussed later)

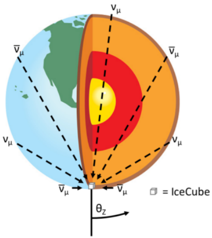


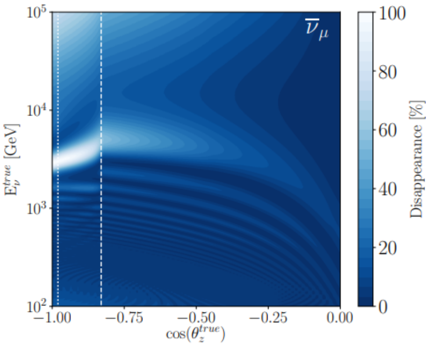
Source: MiniBooNE Collaboration

Matter Enhanced Oscillations With Steriles (MEOWS)

Peculiar Resonance!

- eV^2-scale mass-squared splitting
- TeV-scale energies
- Earth-crossing neutrinos
- Anti-muon neutrinos

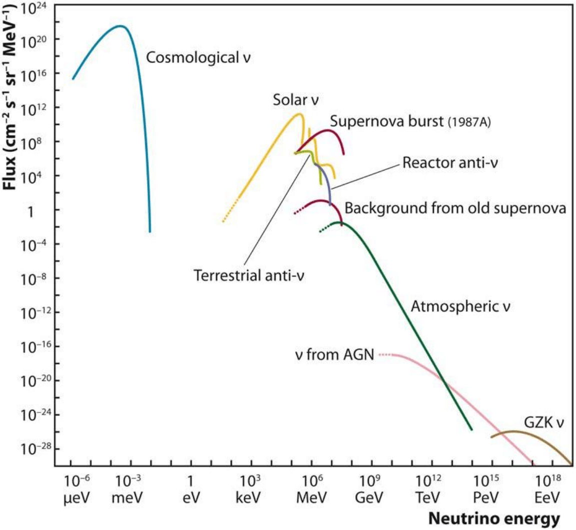


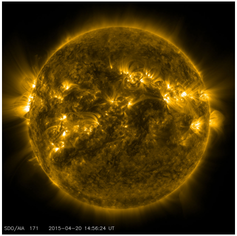


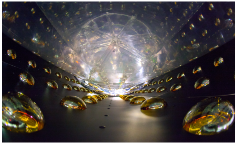
MEOWS Paper

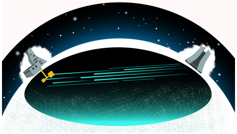
$\Delta m^2_{41} = 1.3\text{eV}^2$ and $\sin^2(2\theta_{24}) = 0.07$

Where do they come from?

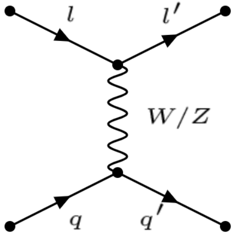


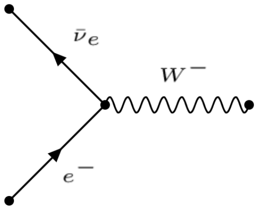






Dominant Atmospheric Neutrino Interactions



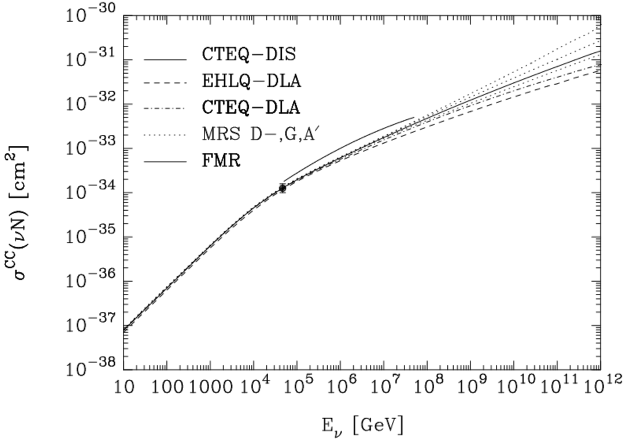


Detection Channels for highest-energy neutrinos (atmo / astro)

- Deep Inelastic Scattering
- Resonant W-boson production (Glashow - 6.3 PeV)

Neutrino Cross Section

Cross section $\sim$ interaction probability



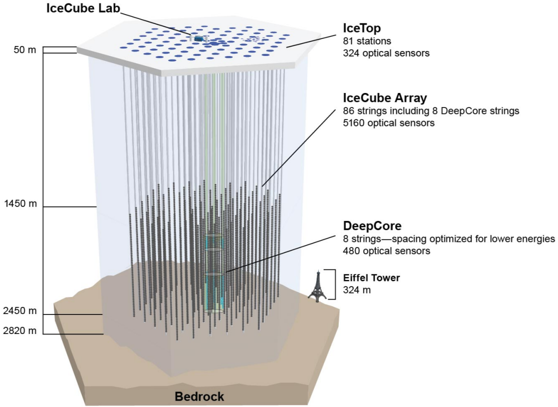
Charge-current ν_μ-nucleon cross sections

Source: Gandhi et al.

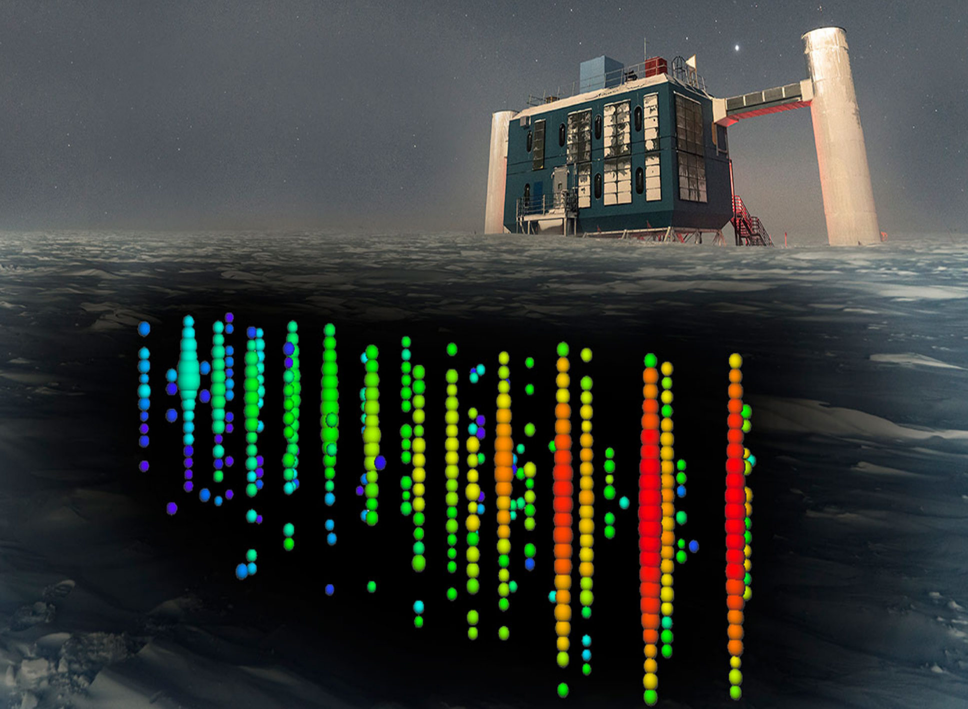
Large-Volume Cherenkov Detectors

- Tiny Cross Section
- *Rapidly* falling flux

- Need **big** detector

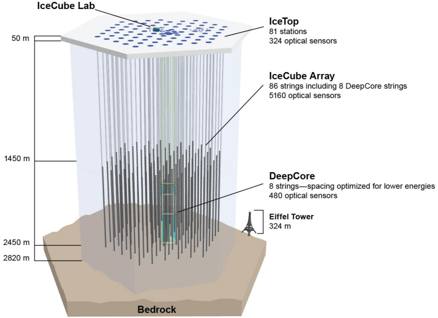


$$\text{Rate} = \overbrace{\sum_{\alpha}}^{\nu\text{ types}} \int d\Omega \int dE_\nu \underbrace{V^{\text{eff}}_{\nu_\alpha}(E_\nu, \Omega)}_{\text{volume}} \overbrace{T_n}^{\text{targets}} \underbrace{\sigma(E_\nu)}_{\text{cross section}} \underbrace{\phi_{\nu_\alpha}(E_\nu, \Omega)}_{\text{flux}} \quad (4)$$



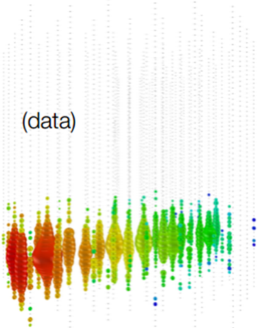
IceCube Neutrino Observatory

- $\sim$1km^3 of Antarctic ice
- $\sim$40 ATLAS' tall
- Neutrino interactions create charged particles
- Cherenkov Light
- 5,160 DOMs: PMTs encased in ice

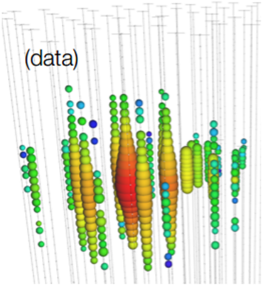


IceCube Event Topologies

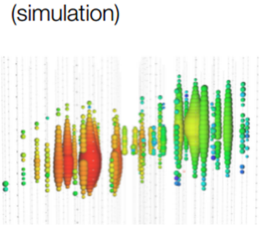
Charged-current ν_μ	Neutral-current / ν_e	Charged-current ν_τ



Up-going track



Isolated energy deposition (cascade) with no track

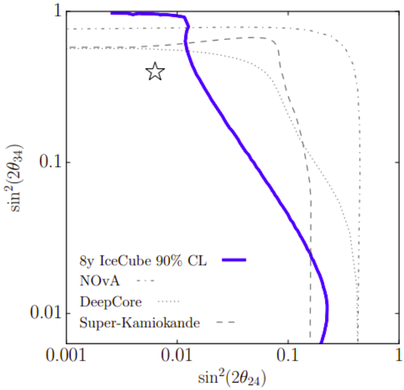


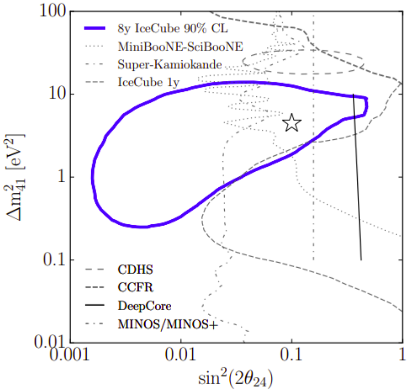
"Double-bang"

*Note! "Bang" separation in Tau events only ~5cm/TeV

MEOWS

- *Matter Enhanced Oscillations With Steriles* (MEOWS) analysis
- MSW Resonance
- IceCube's up-going muon tracks

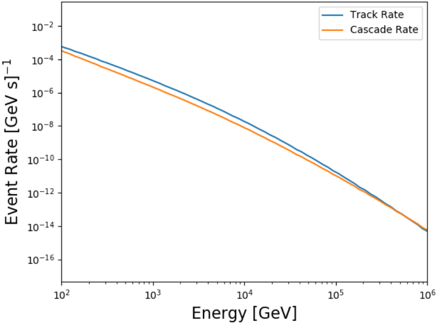




What about cascades?

- Cascades are a significant proportion of flux
- Question: Could cascades be used to improve existing bounds?

- Look for possible cascade appearance, various parameters
- Stay within existing bounds

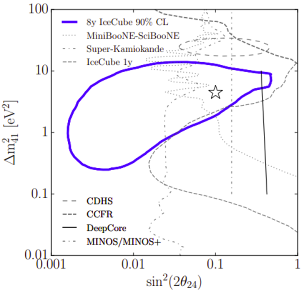


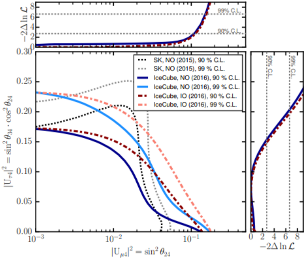
Starting event rates for track-like and cascade-like events. Made using HillasGaisser2012, SIBYLL23C, and 3 neutrino model.

Existing Bounds

- θ_{i4}, Δm^2_{14}, δ_{cp}
- Existing aggressive bounds (90% CL)
  - MINOS $\theta_{24} < 7°$, $\theta_{34} < 26°$
  - DeepCore $\theta_{24} < 19°$, $\theta_{34} < 24°$
- θ_{14} poorly constrained, usually assumed zero

Links: Minos, Deepcore, MEOWS



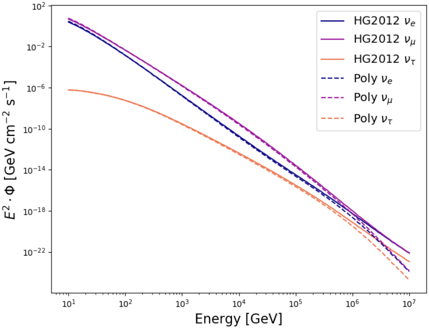


Generating Fluxes

1. Generate Atmospheric Neutrinos
2. Propagate Flux
3. Energy Deposition
4. Emulate Reconstruct
5. Compare to null

1. Generate Neutrino Flux

- Matrix Cascade Equations (MCEq) generates atmospheric ν flux
  - CR Flux (HG2012, Polygonato, etc)
  - Interaction Model (SIBYLL23c, QGSJet-II)
- Sterile doesn't affect this

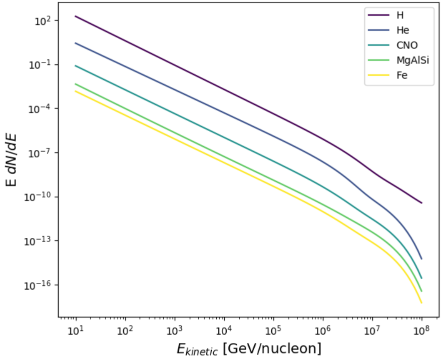


Comparing HillasGaisser2012 with Polygonato,

Nominalized over zeniths

- Defines flux of progenitor nuclei
- Knee/Ankle - different sources

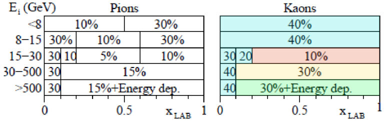
- GZK cutoff $\sim 10^{10}$ GeV
- Measurements from CR air showers

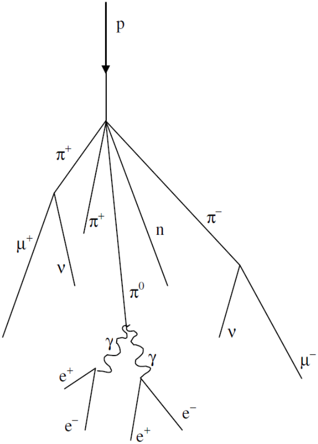


HillasGaisser-2012 H4a CR Model

1b. Interaction Models

- ν production rates from accelerator experiments
- Projections for high energies
- Different models for different projections

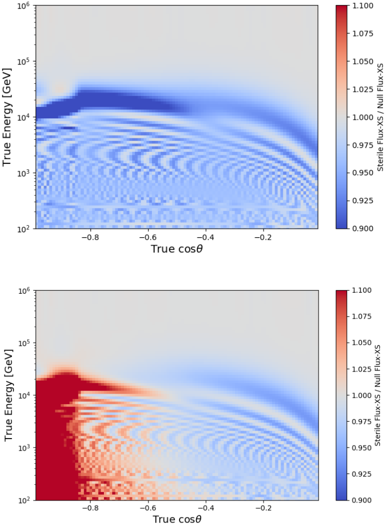




Example air shower

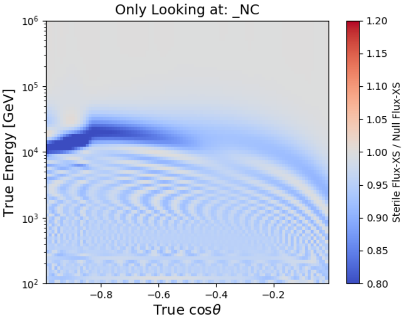
2. Propagate Neutrino Flux

- Propagate flux through Earth with nuSQuIDS
  - Oscillations, Earth interactions
  - Tau Regeneration
- On Right, neutrino fluxes
  - $\times(\sigma_{NC} + \sigma_{CC}^{e,\tau})$
  - (top) MEOWS Best Fit, $\theta_{14} = \theta_{34} = 0$, $\theta_{24} = 9^\circ$
  - (bottom) And with $\theta_{34} = 13^\circ$
  - Both $\Delta m^2_{41} = 4.47\text{eV}^2$

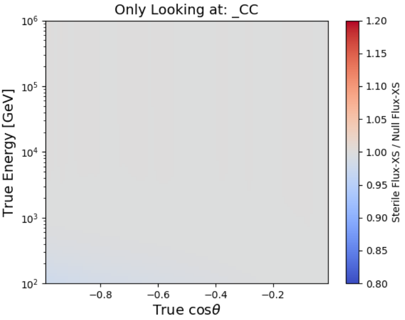


Neutral vs Charged Current

NC Flux Ratio



CC Flux Ratio

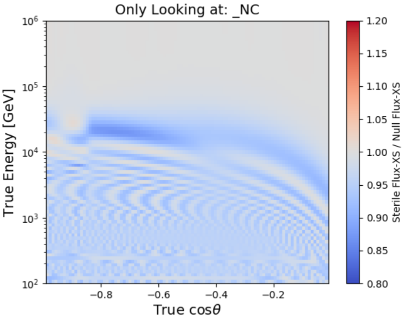


Looking at MEOWS best fit with $\theta_{34} = 0$.

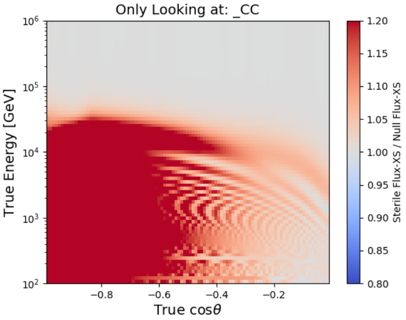
HillasGaisser2012, SIBYLL 2.3c

Neutral vs Charged Current

NC Flux Ratio



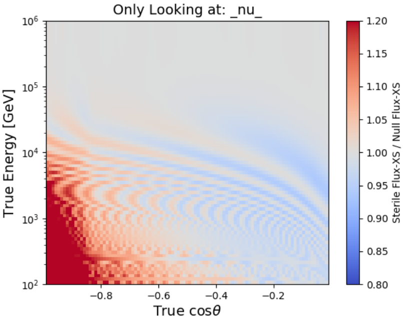
CC Flux Ratio



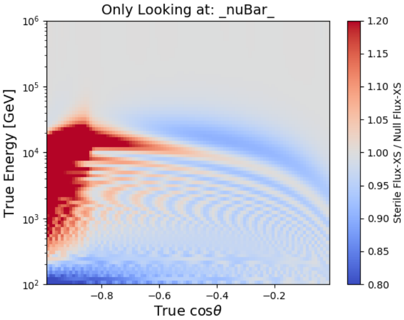
Looking at MEOWS best fit with $\theta_{34} = 13$.

HillasGaisser2012, SIBYLL 2.3c

Neutrino



Anti-Neutrino



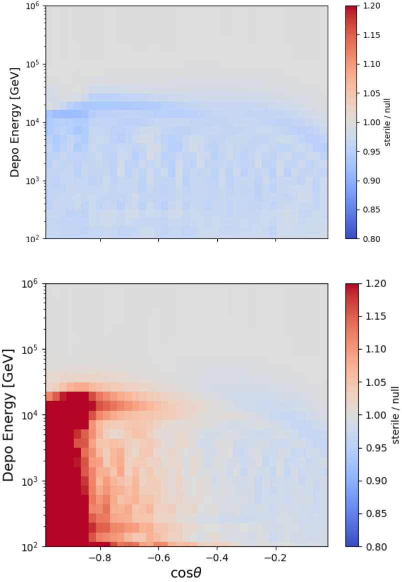
Looking at MEOWS best fit with $\theta_{34} = 13^\circ$.

HillasGaisser2012, SIBYLL 2.3c

3. Make Neutrinos Interact

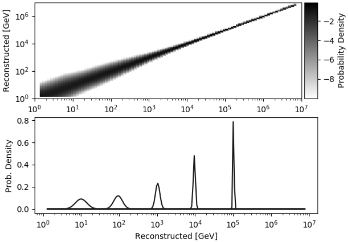
- CSMS differential cross sections
- Integrate over event, lepton energy
- NC Interaction
  - Only hadronic energy deposited
- CC Interaction
  - electron - All
  - Muon - **track**
  - Tau - Weird

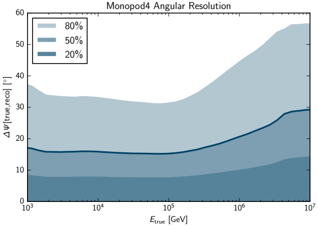
$$\tau^{\pm} \rightarrow \nu_\tau + \text{stuff}^{\pm}$$



4. Reconstruction

- Energy Reco Paper reconstruction (link)
  - Energy deposited to reconstructed
- Monopod is True to Reconstructed
  - angular error; Kent distribution to get zenith

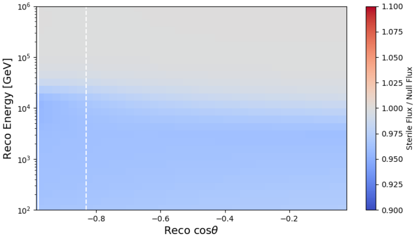


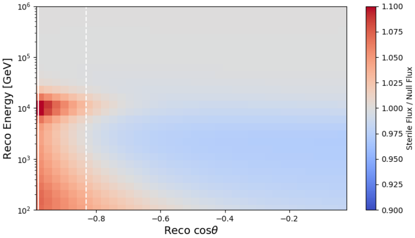


https://arxiv.org/abs/1705.02383

Reconstruction Incorporated

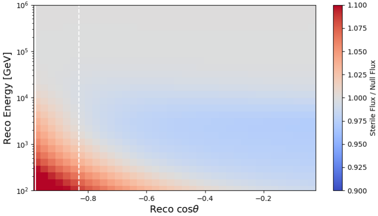
- Probability-based reconstruction, binning-considerate
  - Integrate over true/reco angles, true/depo/reco energy
- Appearance signal is still maintained
  - (top) MEOWS best-fit,
  - (bottom) with $\theta_{34} = 13°$



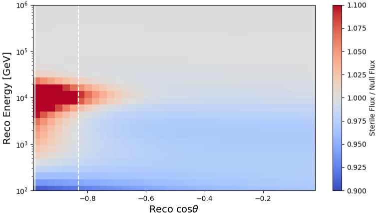


Nu and Nubar

Neutrino



Anti-Neutrino



Looking at MEOWS best fit with $\theta_{34} = 13^\circ$.

HillasGaisser2012, SIBYLL 2.3c

Generation!

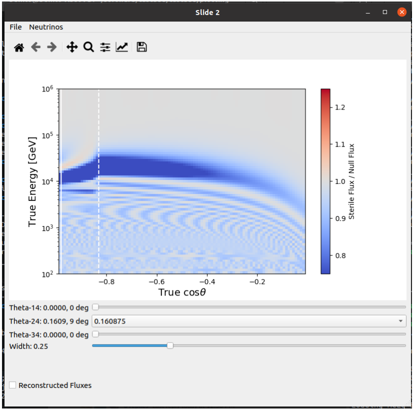
Generating Fluxes and Cascade MC

- 2000 Fluxes generated
  - Various CR flux, interaction models
  - $\theta_{14} \in [0, 180]$
  - $\theta_{24} \in [0, 12]$
  - $\theta_{34} \in [0, 40]$
  - $\Delta m^2_{14} = 4.47\text{eV}^2$

Phase Space Exploration App

- Allows exploring sterile neutrino parameter space
- Toggle neutrino fluxes
- Raw Flux, Reconstructed flux

- Let's see if the video works



GitHub Link

Okay, so what was that?

Mid-Point Emphasis

- Non-zero θ_{34} could give rise to cascade appearance
- IceCube may be sensitive to this appearance

- IceCube may be poised to make an unprecedented direct measurement of θ_{34}

We Need MC

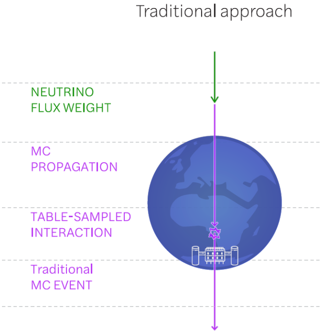
GitHub Link

MC Generation Schema

Traditional Generation

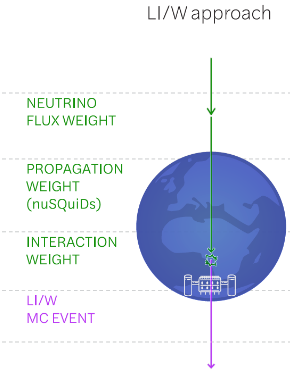
1. Make neutrino
2. Force interaction near detector
3. Calculate 'weight' of event

- All steps are closely linked
- Can't change fluxes or physics post-sim



Developments

- Efficient algorithms solving neutrino transport now available
- Separate, discrete problems
  - Flux Calculation
  - **Event Generation near detector**
  - **Event Weighting**
- Events can be simulated. Reweighted later on

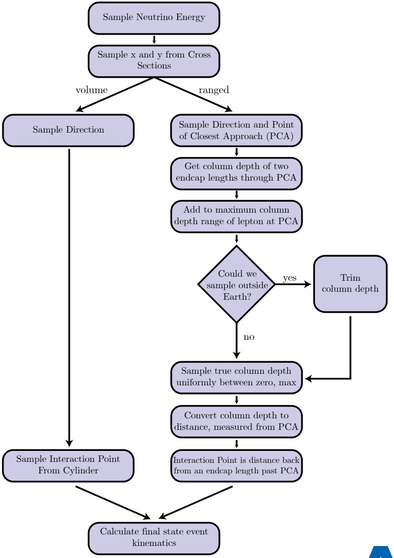


Lepton Injector and Lepton Weighter

Event Generation

Tracks? Hard. Cascades? Easy

- Sample Direction
- Power-law energy
- Kinematics?
  Metropolis-Hastings, σ_{Exy}
- Sample location in cylinder



Event Re-weighting

For weighting, calculate the total generation probability per sub-sample

$$p_{\mathrm{MC}} \equiv \overbrace{N_{MC}}^{\text{generated}} \frac{1}{\underbrace{\Omega_{\mathrm{gen}}}_{\text{solid angle}} \underbrace{A_{\mathrm{tot}}}_{\text{area}}} \overbrace{\frac{1}{\sigma_{\mathrm{tot}}}}^{\text{total xs}} \underbrace{\frac{\partial^2 \sigma}{\partial x \partial y}}_{\text{diff. xs}} \cdot \overbrace{\frac{\Phi(E)}{\int_{E_{min}}^{E_{max}} \Phi(E) dE}}^{\text{normalized event flux}} \tag{5}$$

Then calculate the weight

$$w_{\mathrm{gen}} \equiv \left[\sum p_{\mathrm{MC}} \right]^{-1} \tag{6}$$

Event Re-weighting

New event weight

$$w_{\text{event}} = \underbrace{X_{\text{col}} \times N_A}_{\text{interaction sites}} \times \overbrace{\partial_{xy}\sigma}^{\text{target xs}} \times \underbrace{\Phi_{\text{target}}}_{\text{target flux}} \times w_{\text{gen}} \tag{7}$$

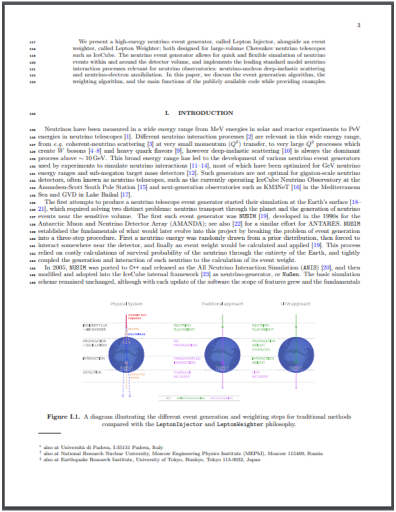
For one set of simulated events

- Any desired cross-section
- Any desired neutrino flux

Big for testing new physics hypotheses!

LI/W Accolades

- Paper accepted for publication in CPC
- LI/W Talk given "2020 Outstanding Graduate Student Presentation Award" by APS



3

We present a high-energy neutrino event generator, called Lepton Injector, alongside an event weighter, called Lepton Weighter; both designed for large-volume Cherenkov neutrino telescopes such as IceCube. The neutrino event generator allows for quick and flexible simulation of neutrino events within and around the detector volume, and implements the leading standard model neutrino interaction processes relevant for neutrino observatories: neutrino-nucleon deep-inelastic scattering and neutrino-electron annihilation. In this paper, we discuss the event generation algorithm, the weighting algorithm, and the main functions of the publicly available code while providing examples.

I. INTRODUCTION

Neutrinos have been measured in a wide energy range from MeV energies in solar and reactor experiments to PeV energies in neutrino telescopes [1]. Different neutrino interaction processes [2] are relevant in this wide energy range, from *e.g.* coherent-neutrino scattering [3] at very small momentum (Q^2) transfer, to very large Q^2 processes which create W bosons [4–8] and heavy quark flavors [9], however deep-inelastic scattering [10] is always the dominant process above $\sim 10\,\mathrm{GeV}$. This broad energy range has led to the development of various neutrino event generators used by experiments to simulate neutrino interactions [11–14], most of which have been optimized for GeV neutrino energy ranges and sub-megaton target mass detectors [12]. Such generators are not optimal for gigaton-scale neutrino detectors, often known as neutrino telescopes, such as the currently operating IceCube Neutrino Observatory at the Amundsen-Scott South Pole Station [15] and next-generation observatories such as KM3NeT [16] in the Mediterranean Sea and GVD in Lake Baikal [17].

The first attempts to produce a neutrino telescope event generator started their simulation at the Earth's surface [18–21], which required solving two distinct problems: neutrino transport through the planet and the generation of neutrino events near the sensitive volume. The first such event generator was `NUSIM` [19], developed in the 1990s for the Antarctic Muon and Neutrino Detector Array (AMANDA); see also [22] for a similar effort for ANTARES. `NUSIM` established the fundamentals of what would later evolve into this project by breaking the problem of event generation into a three-step procedure. First a neutrino energy was randomly drawn from a prior distribution, then forced to interact somewhere near the detector, and finally an event weight would be calculated and applied [19]. This process relied on costly calculations of survival probability of the neutrino through the entirety of the Earth, and tightly coupled the generation and interaction of each neutrino to the calculation of its event weight.

In 2005, `NUSIM` was ported to `C++` and released as the All Neutrino Interaction Simulation (`ANIS`) [20], and then modified and adopted into the IceCube internal framework [23] as neutrino-generator, or `NuGen`. The basic simulation scheme remained unchanged, although with each update of the software the scope of features grew and the fundamentals

Figure I.1. A diagram illustrating the different event generation and weighting steps for traditional methods compared with the `LeptonInjector` and `LeptonWeighter` philosophy.

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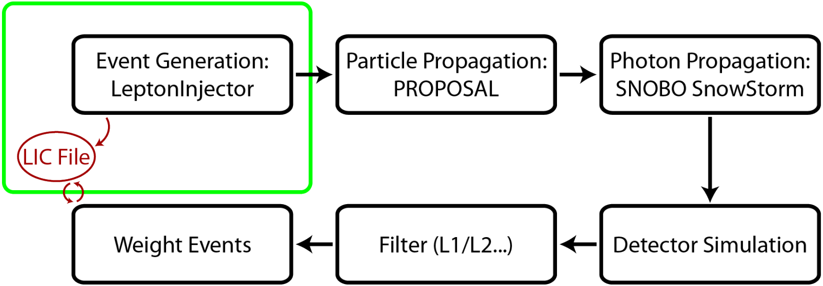
From Here...

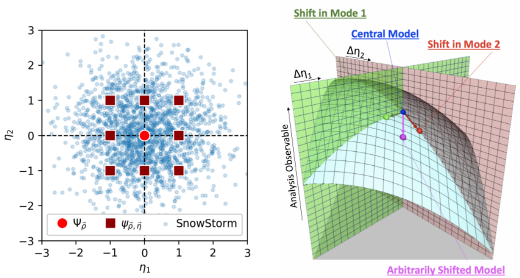
The Rest of the Generation



SnowStorm

- Developed by UTA's own Ben Jones
- Novel treatment of ice systematic uncertainties

- 'Nuisance parameters' describe systematic uncertainties
- Shuffle ice model for each event
- Incorporates systematic uncertainties on reconstruction uncertainty



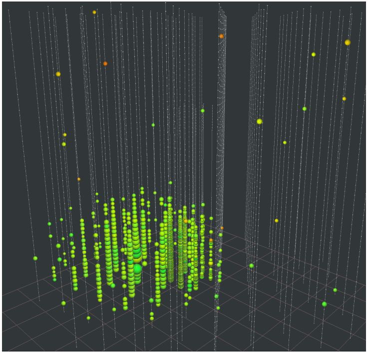
SnowStorm, SnowSuite

- Brought SnowStorm into MC Generation Schema
- SnowSuite: python scripts to generate MC
- Co-recipient of 2020 IceCube Impact Award

MC

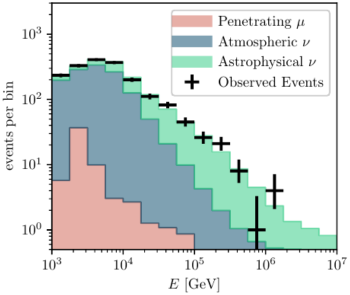
- Adapted MEOWS MC Generation processors
- 2 Million NC cascades generated up to first filtering level

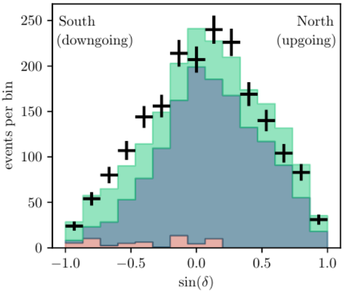
- LI/W Pipeline - events can be reweighted to any flux!



Going Forwards

- **M**edium **E**nergy **S**tarting **E**vents Data sample
  - 95% pure sample $E_\nu > 1$ TeV
  - Established reconstruction & veto techniques
  - See if these can be improved
  - MESE Paper





Calculate Sensitivities

- Simulate measurements with no signal, only background
- Look at average upper-limit of true values

- CL's below that limit not very exciting

Analysis Tools

GolemFit, MEOWS Analysis tools

- Fitter for θ_{24}, Δm^2_{41}
- Elegantly handles systematic uncertainties
  - Prior/Posterior for *all* nuisance params
- Optimized for tracks

- Modify for cascade analysis
- Investigate scope of this

Summary and Outlook

- Showed non-zero θ_{34} could give rise to cascade appearance
- Helped develop new MC tools for this analysis
- IceCube's MESE data sample ideal for this energy/topology

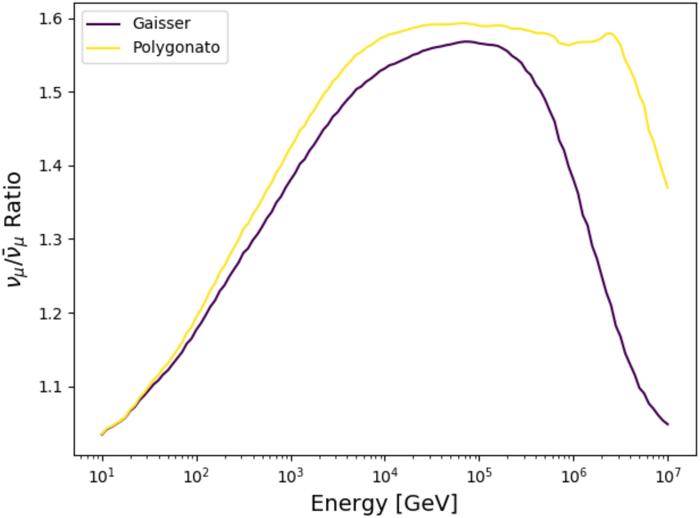
- To do:
  - Data sample, reconstruction
  - Calculate Sensitivities
  - Adapt MEOWS analysis tools for a cascade analysis

Unprecedented constraint on Sterile Neutrinos

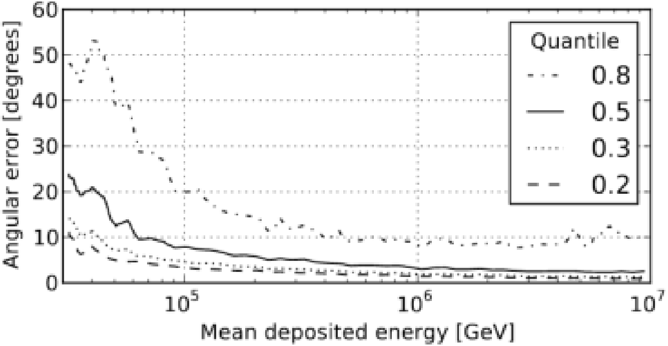
Thank you!
Questions?

Backup

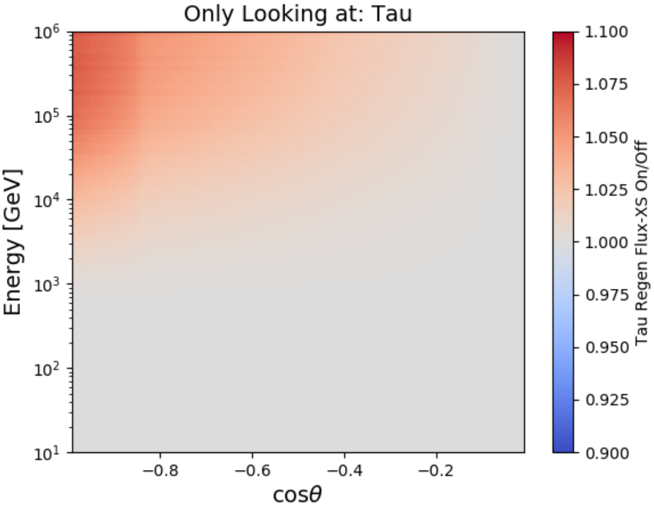
Nu/Nubar Ratios



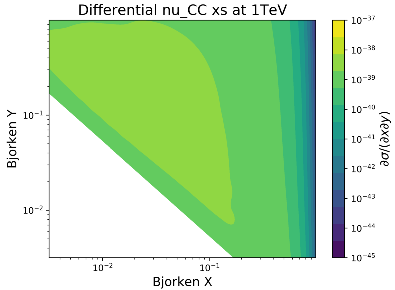
E Reco Paper Angular Error



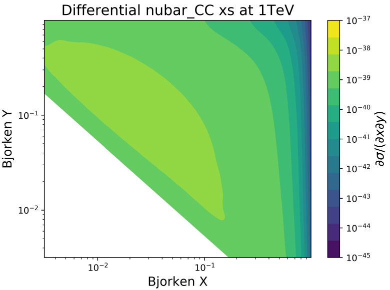
Tau Regeneration



Neutrino

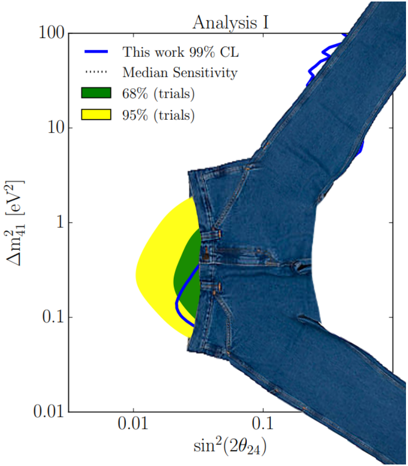


Anti-Neutrino



If Brazil Bands Wore Pants

Would they wear them like this?



Or like this?