Physics Analyses in IceCube

Kayla Leonard

Outline

1. Summary of Existing Analyses in IceCube
2. How To Create your own Analysis in IceCube

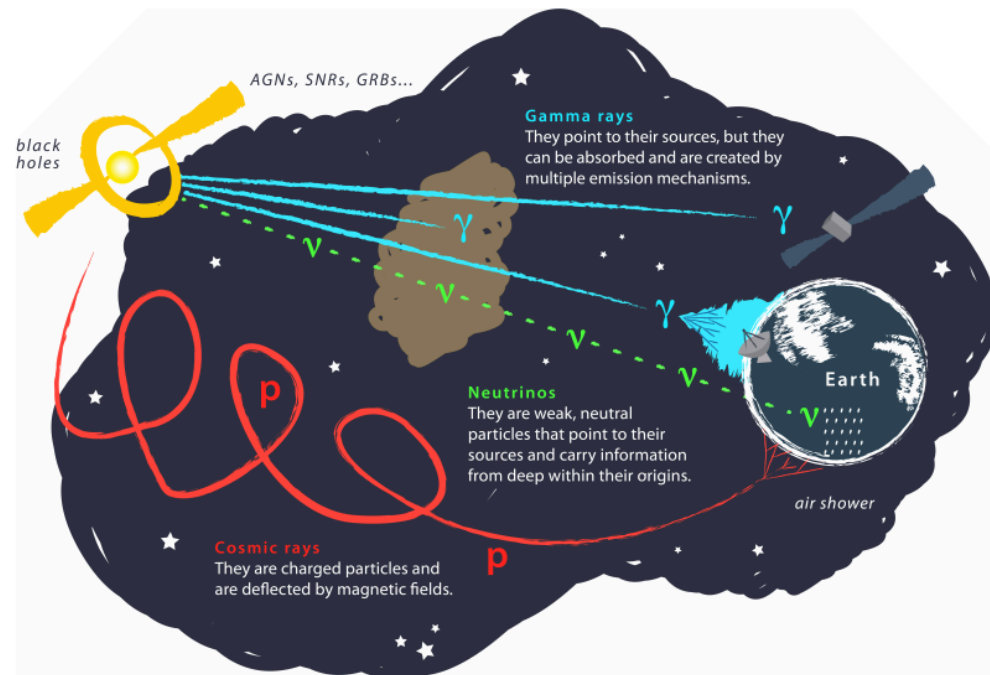# IceCube Working Groups

Analysis Working Groups:

- Neutrino Sources
- Diffuse
- Oscillations
- BSM
- Cosmic Rays
- Supernova

Technical Working Groups:

- Reconstruction & Systematics
- Calibration
- Simulation
- Software
- Realtime / ROC

Neutrino Sources Working Group

- High Energy Neutrinos are produced in intense comic accelerators in our Universe.

- The Neutrino Sources Working Group tests various theories to see if there are "hot spots" or clusters of neutrinos

- Clusters can be in both space and time
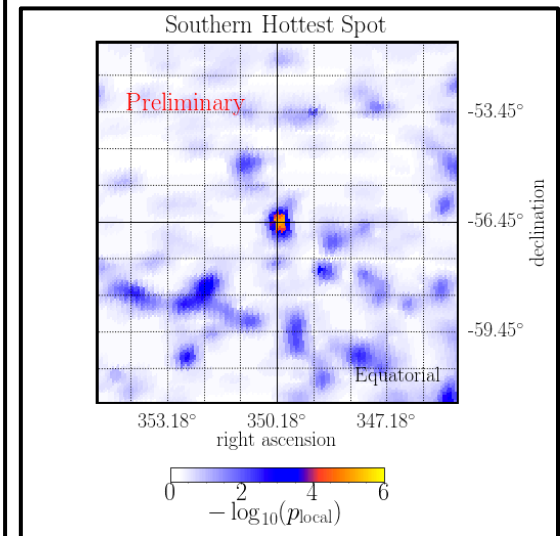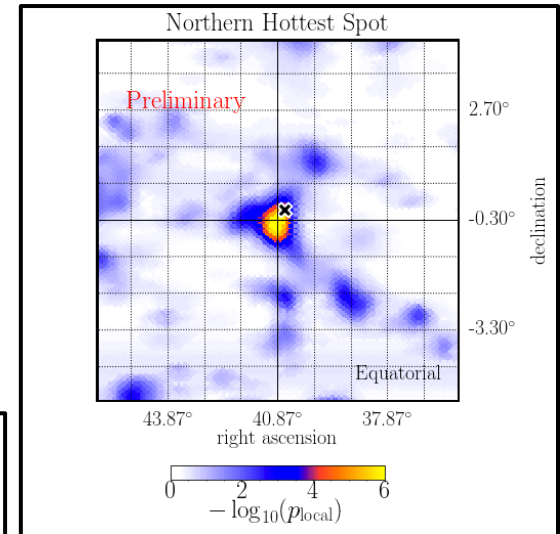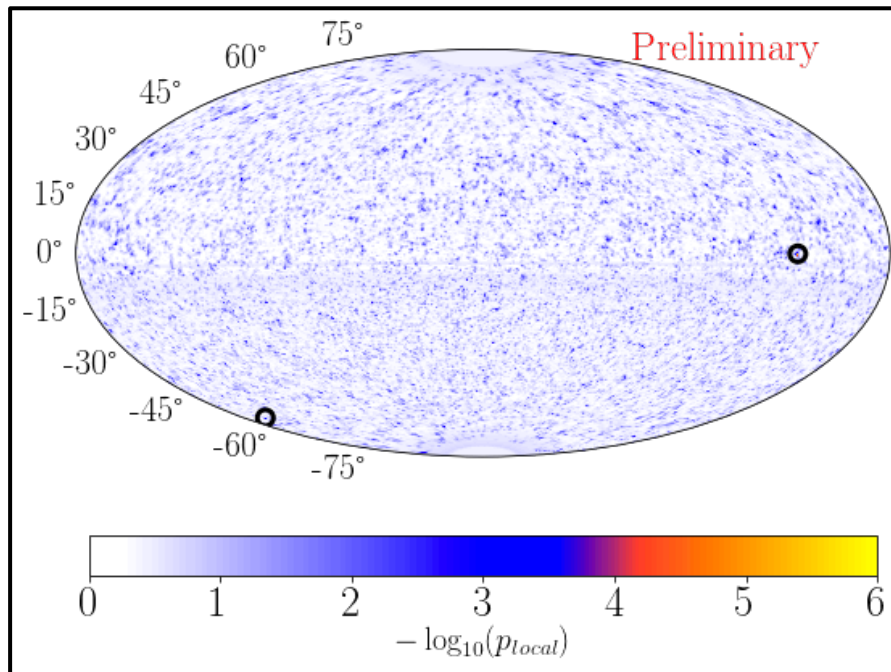
Neutrino Sources Analyses

	Spatial prior	Time integrated	Time dependent
Skymap	None	• 10 yr time integrated (all-sky scan)	• All-sky single flare fit
Singe source search	Single point	• TXS archival • Anita archival • Hydrangea archival	• TXS follow-up • Anita follow-up • Hydrangea follow-up
Catalog search	List of points	• 10 yr time integrated (catalog search)	• Blazar flare (one flare per source)
Stacking search	List of points	• Blazar stacking search • Pulsar wind nebulae	• Multi-flare blazar (multiple flares per source)
Template	Region of sky	• Galactic Plane	• Non-poissonian template fit • Gravitational Wave

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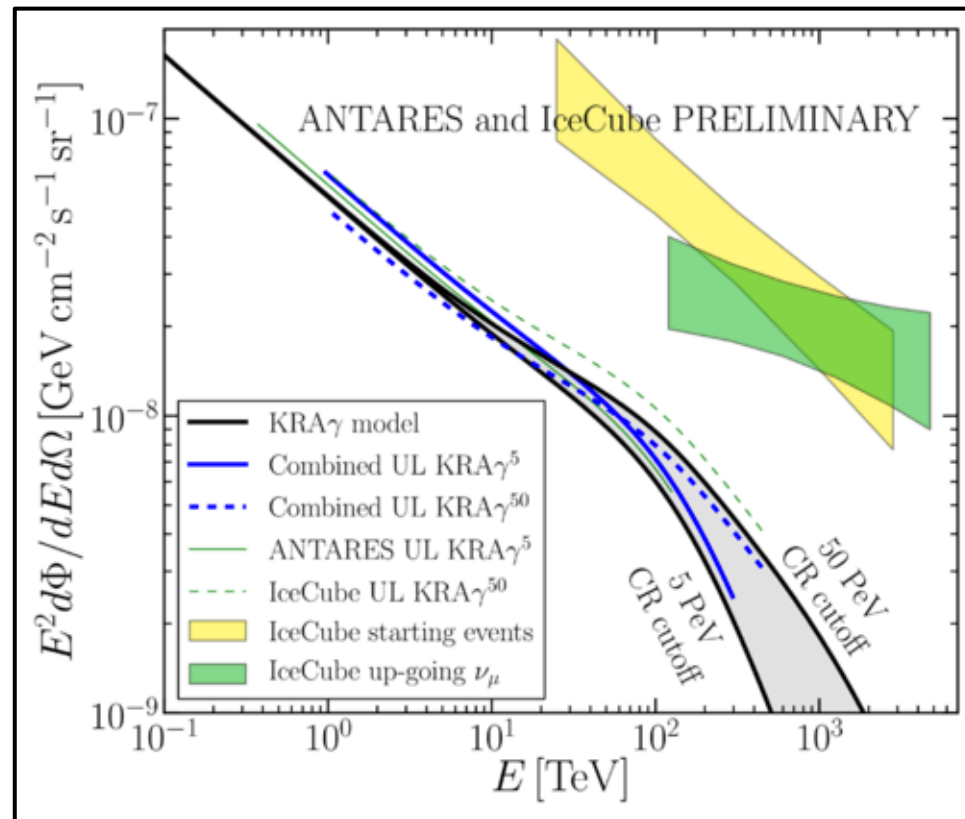## All-sky scan

- Look for any hotspot on sky

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Galactic Plane Template

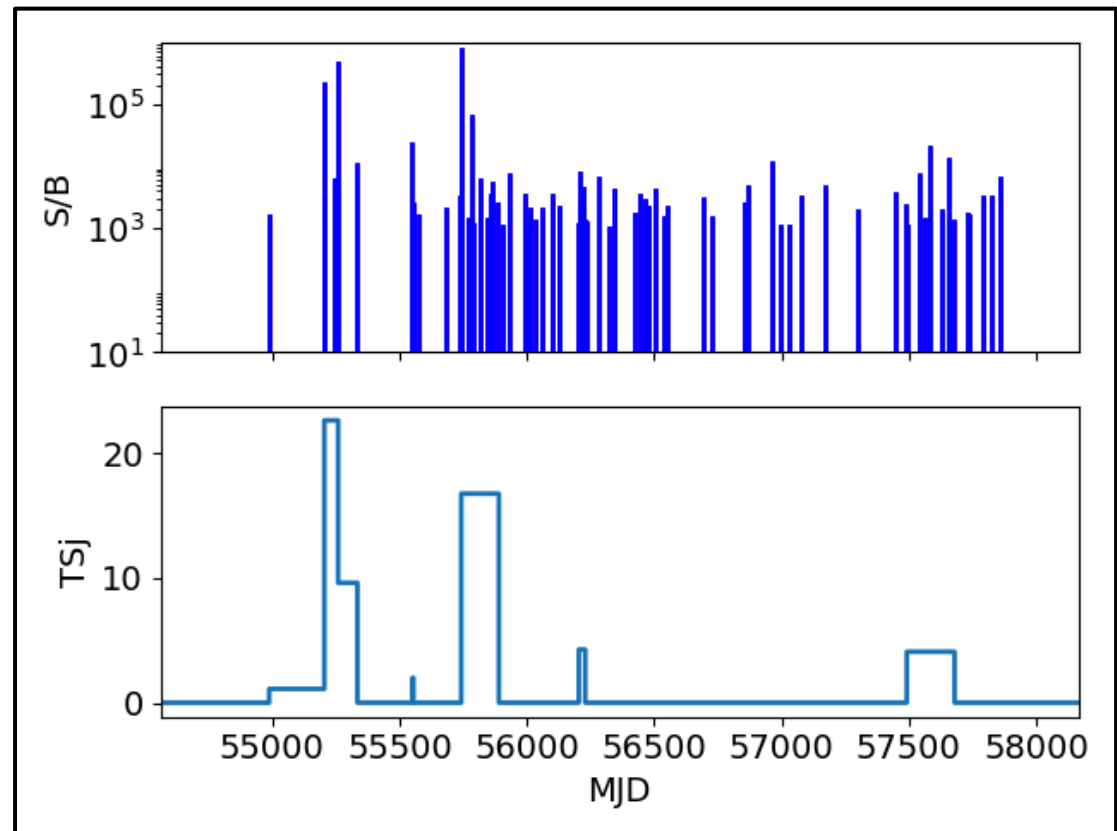- Use neutrinos in galactic plane region to test KRA-gamma model

ANTARES and IceCube PRELIMINARY

Legend:
— KRAγ model
— Combined UL KRAγ^5
- - - Combined UL KRAγ^{50}
— ANTARES UL KRAγ^5
- - - IceCube UL KRAγ^{50}
■ IceCube starting events
■ IceCube up-going ν_μ

5 PeV CR cutoff
50 PeV CR cutoff

y-axis: $E^2 d\Phi/dEd\Omega \,[\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}]$
x-axis: E [TeV]

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Multi-flare Blazar Stacking

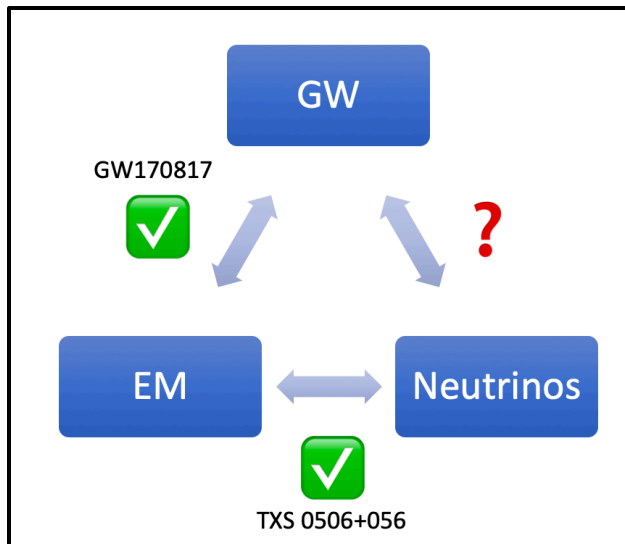• Look for clustering in *time* of events in a blazar catalog

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GW

GW170817 ✅ ❓

EM ↔ Neutrinos

✅
TXS 0506+056

Realtime

- Alert: We see a high energy neutrino that we want other telescopes to follow up

- Follow-up: Source is a single point that telescopes alerted us to

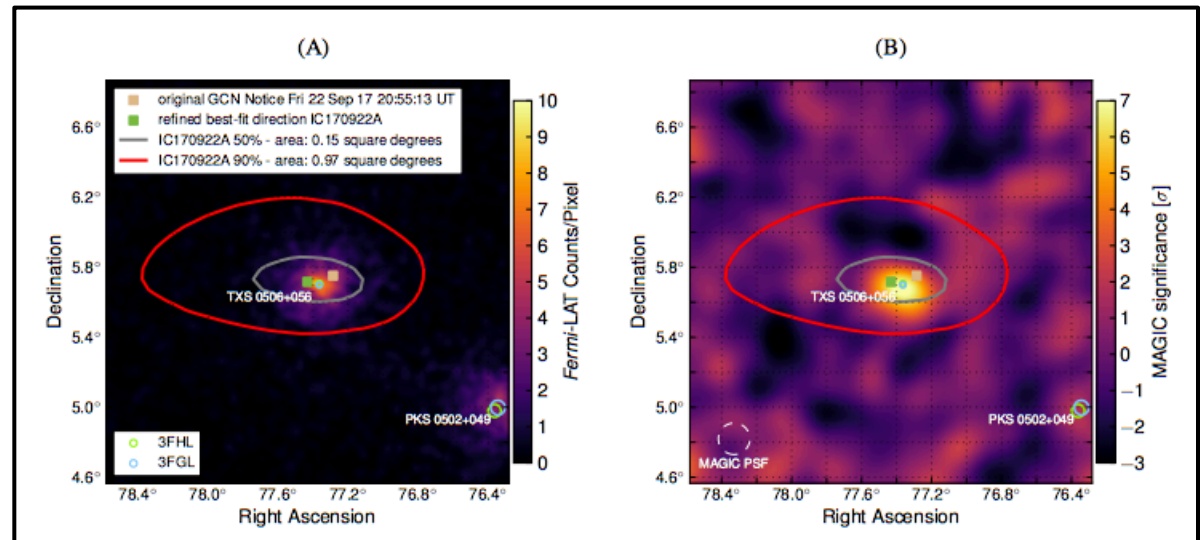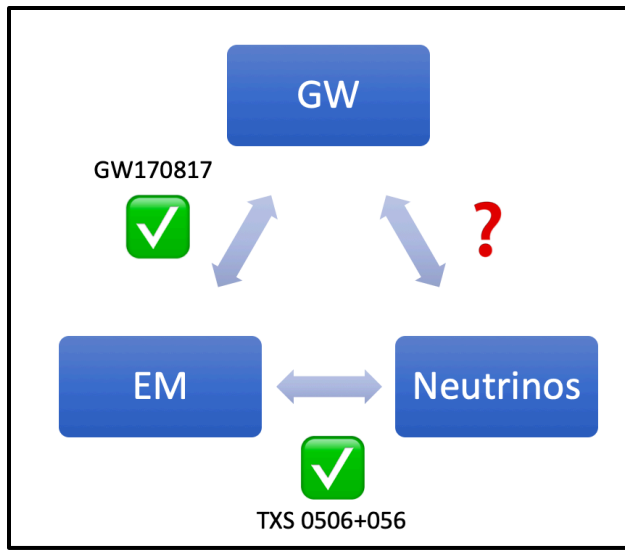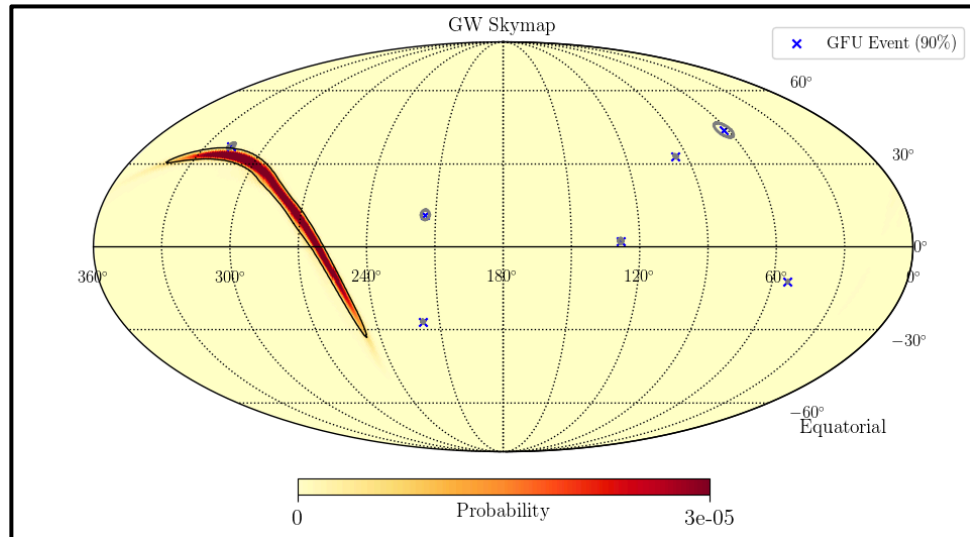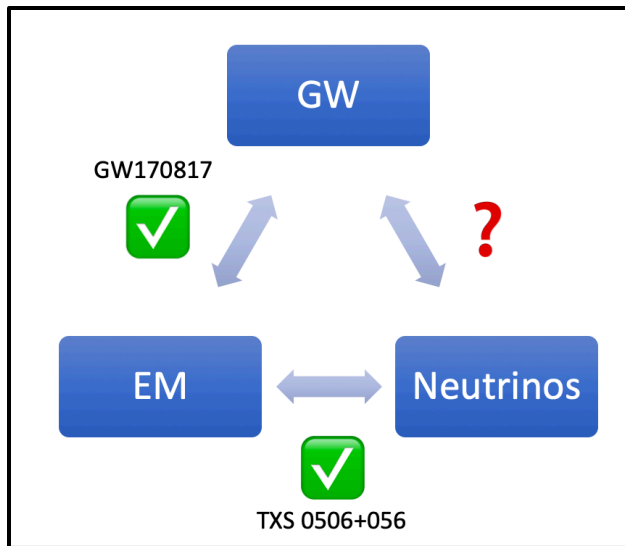- GW follow-up: Source is an extended contour from LIGO gravitational wave

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Diffuse Working Group

- Neutrinos are produced all around the Universe.

- It appears as an isotropic flux here at Earth.

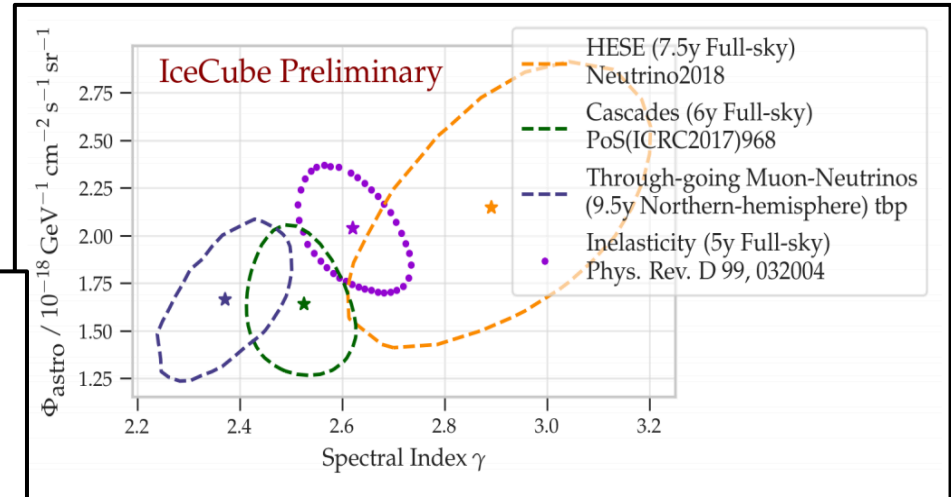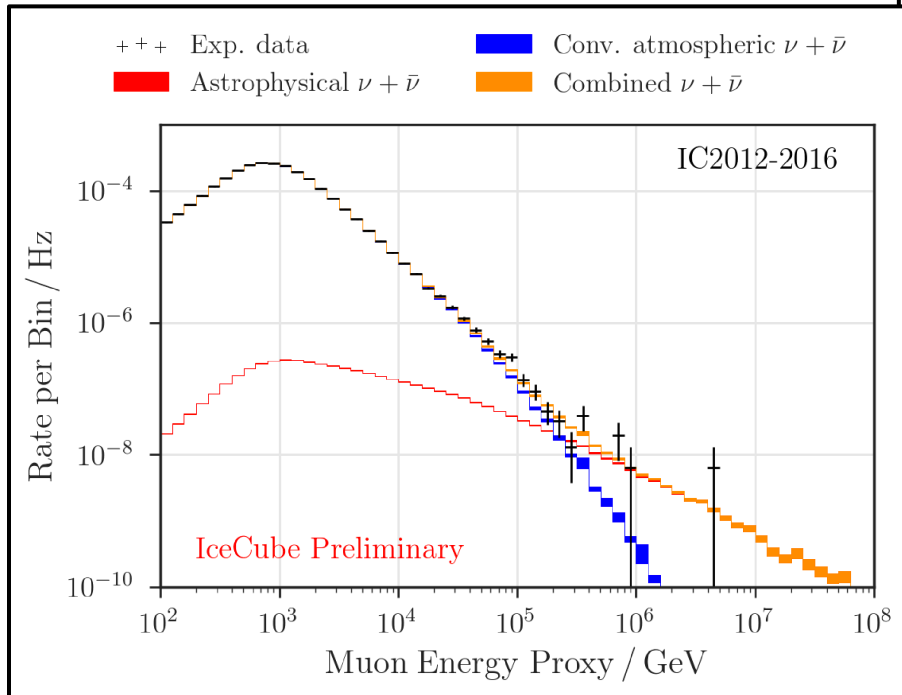- The Diffuse Working Group tries to measure the Diffuse Astrophysical Neutrino spectrum.
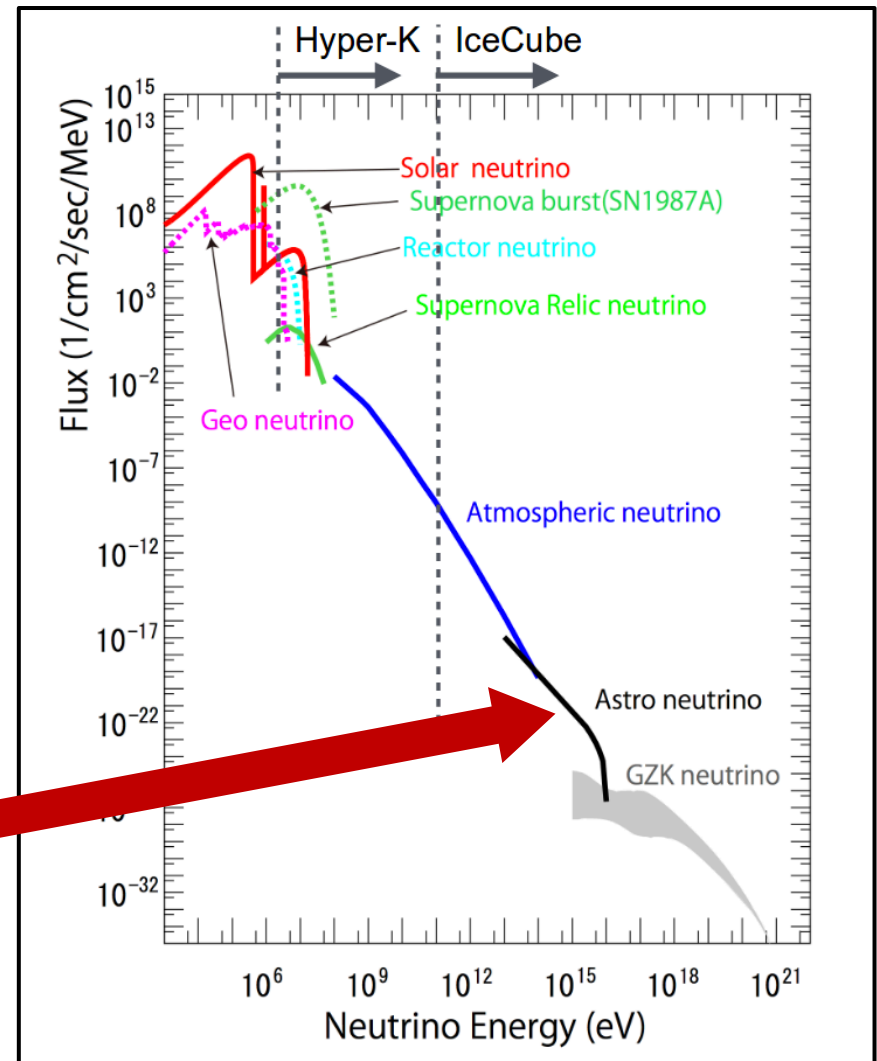
Diffuse Analyses

- Astrophysical Diffuse Spectrum
- Flavor ratio
- Tau neutrino identification

Diffuse Analyses

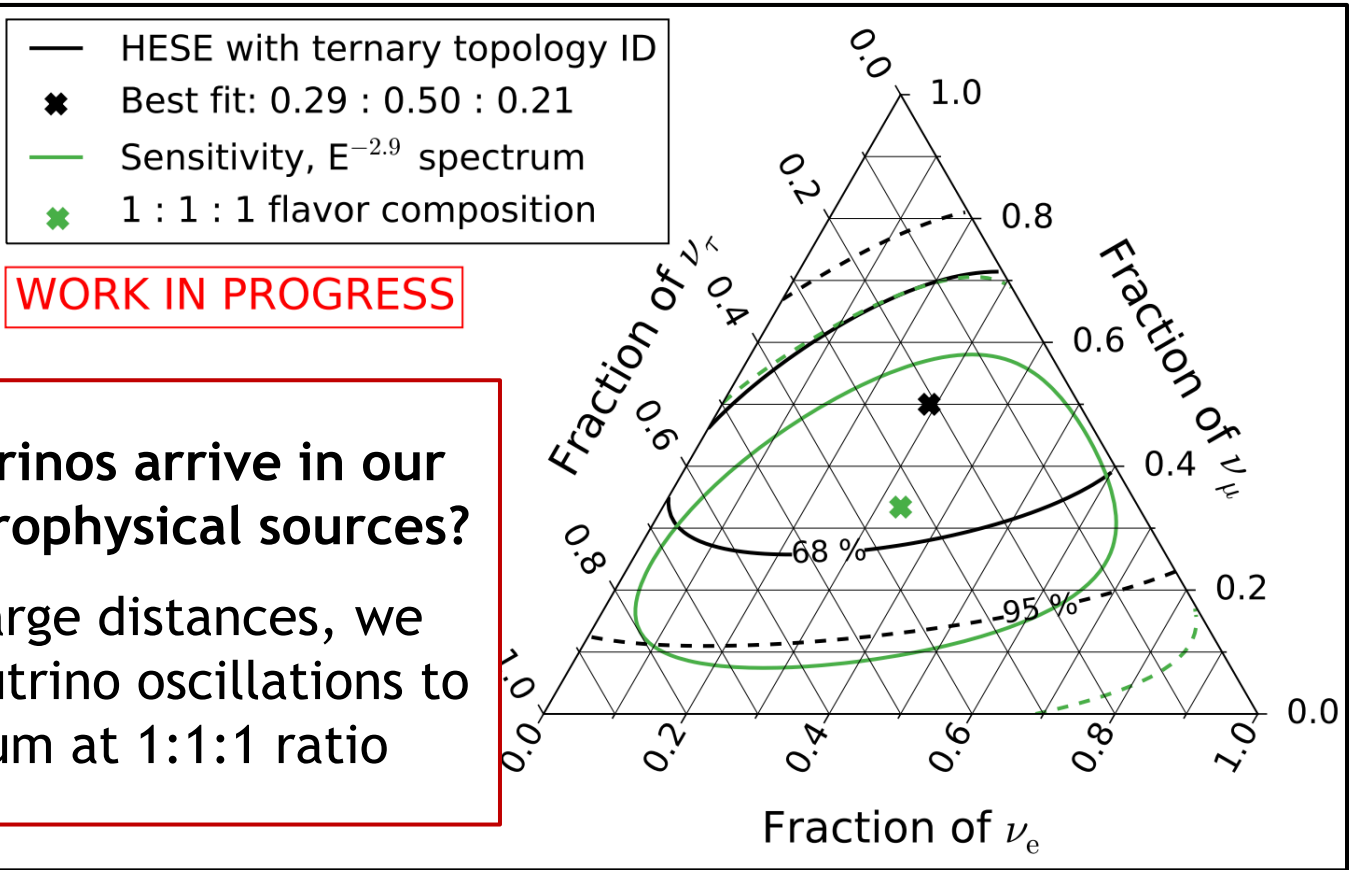- ## Astrophysical Diffuse Spectrum
- ## Flavor ratio
- ## Tau identification

What is the spectrum of diffuse astrophysical neutrinos?

$$N = \phi * (E/E_0)^{-\gamma}$$

Diffuse Analyses

- Astrophysical Diffuse Spectrum

- Flavor ratio

- Tau identific

What flavor neutrinos arrive in our detector from astrophysical sources?

Over very very large distances, we may expect all neutrino oscillations to reach equilibrium at 1:1:1 ratio

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— HESE with ternary topology ID

✖ Best fit: 0.29 : 0.50 : 0.21

— Sensitivity, $E^{-2.9}$ spectrum

✖ 1 : 1 : 1 flavor composition

WORK IN PROGRESS

Fraction of ν_τ

Fraction of ν_μ

Fraction of ν_e

68 %

95 %

Diffuse Analyses

- Astrophysical Diffuse Spec
- Flavor ratio
- Tau identification
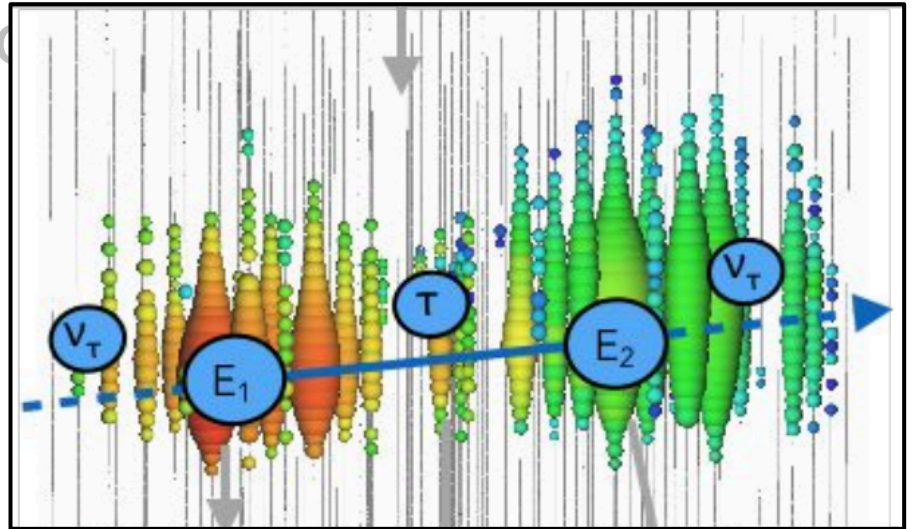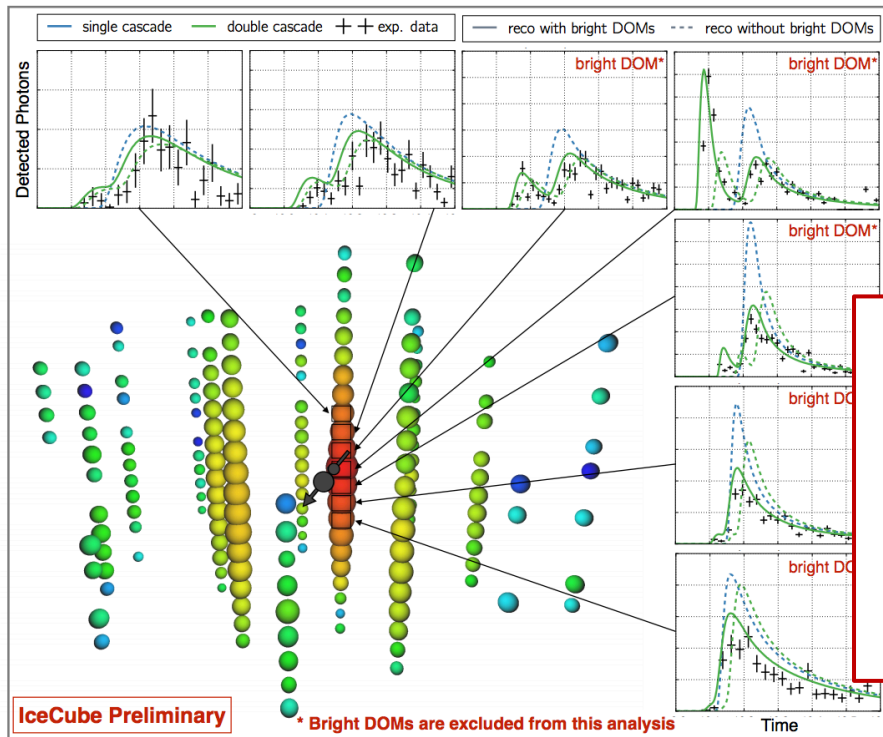
Tau particles decay quickly. If they are created and decay within the detector can we see both cascades?

Length of Track = 50 m per PeV * Energy
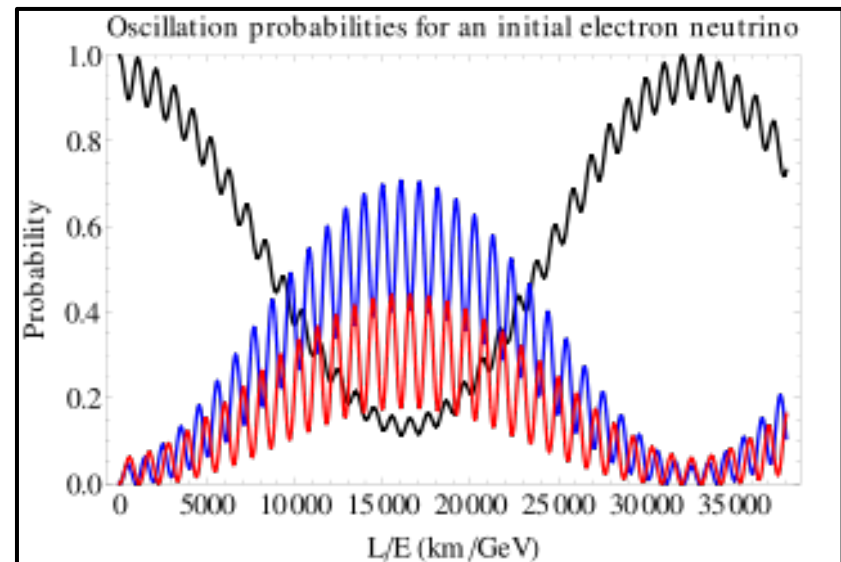
Oscillations Working Group

- The neutrino flavors (ν_e, ν_μ, ν_τ) are a linear combination of the neutrino mass states (ν_1, ν_2, ν_3).

- Neutrinos are created and measured in their flavor states. They propagate through space in their mass states.
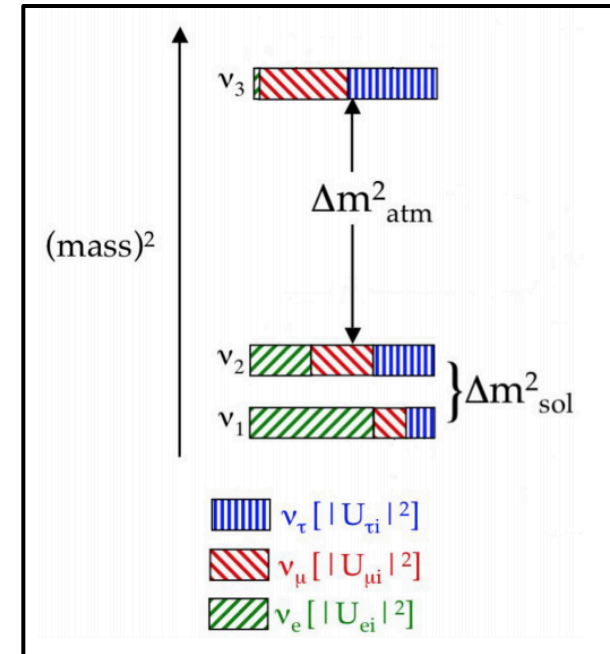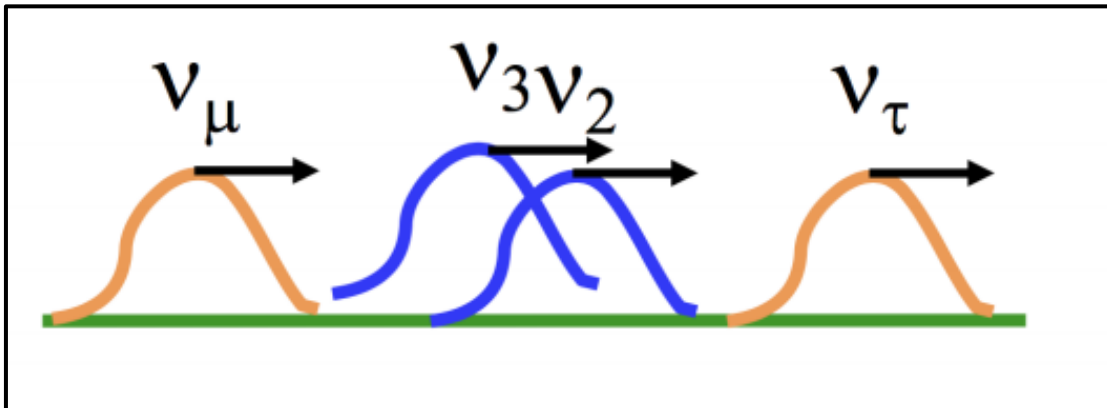
Oscillations Working Group

- If we know the what flavor a it was created as, we can calculate the probability of it being measured as a certain flavor at another point in time.

- Probability of starting as one flavor and measured as different flavor:

$$P_{\alpha \to \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

Oscillation probabilities for an initial electron neutrino

- N(ν_μ detected) = P($\nu_\tau \to \nu_\mu$) * N(ν_τ created)

Oscillation Analyses

- Atmospheric oscillation parameters
- Tau neutrino appearance
- Neutrino mass ordering
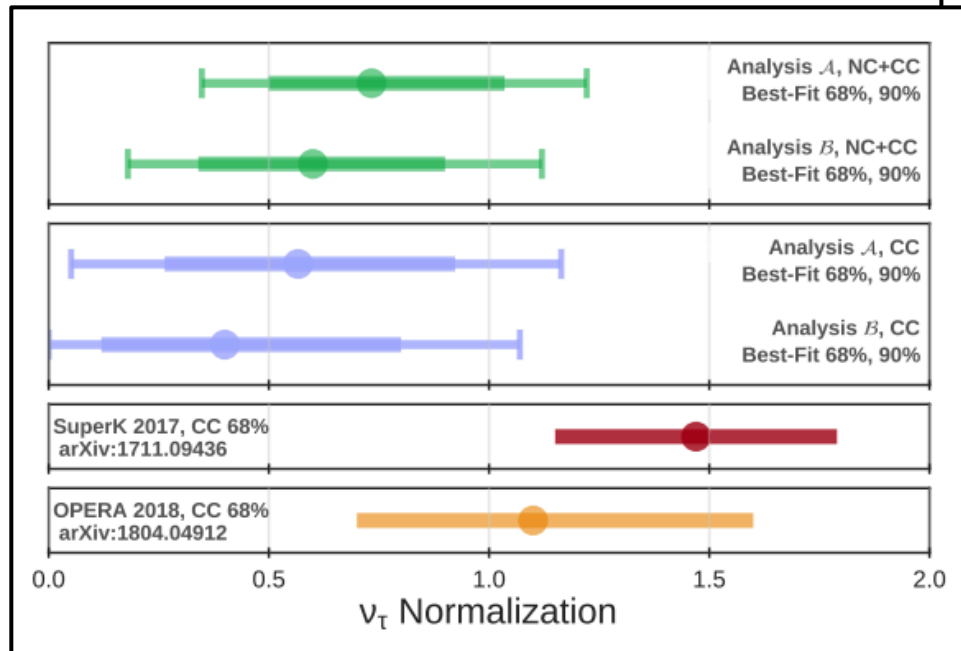- Non-standard interactions
- Sterile neutrinos

Oscillation Analyses

- Atmospheric oscillation parameters
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What are the parameters that describe neutrino oscillations?

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \left(\Delta m_{31}^2 \frac{L}{4E} \right)$$
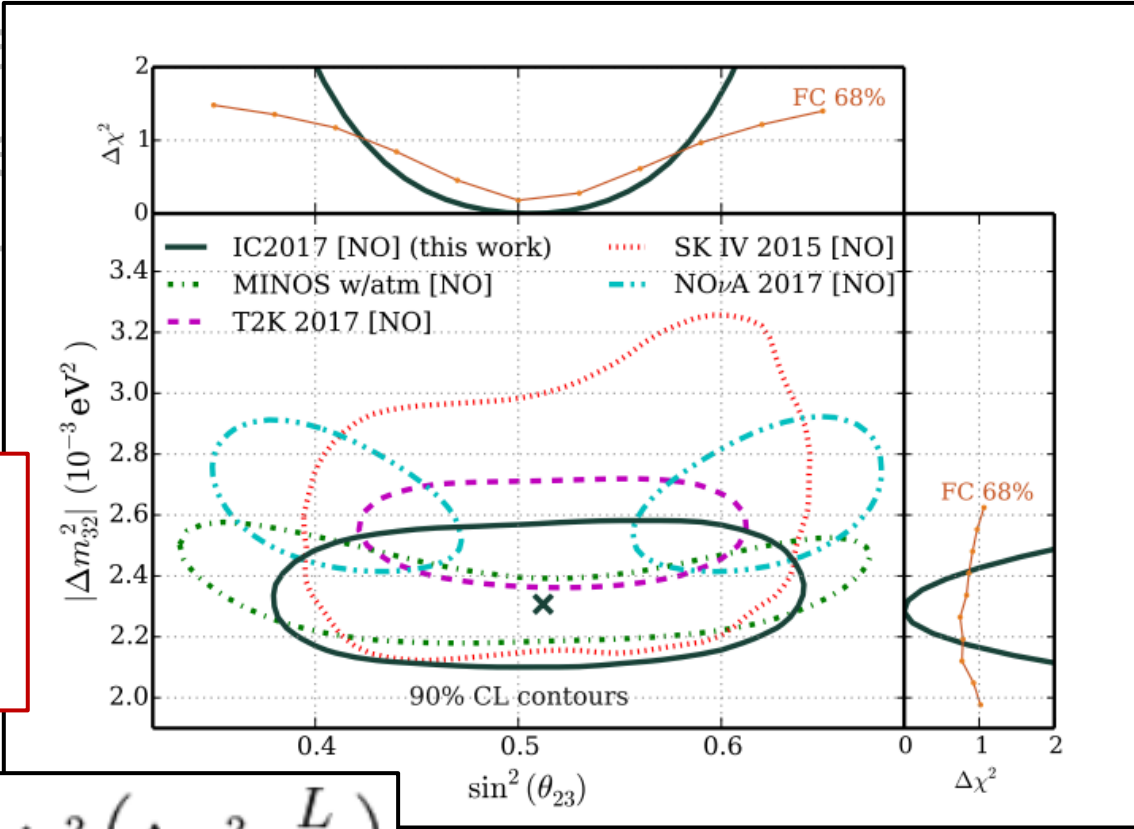
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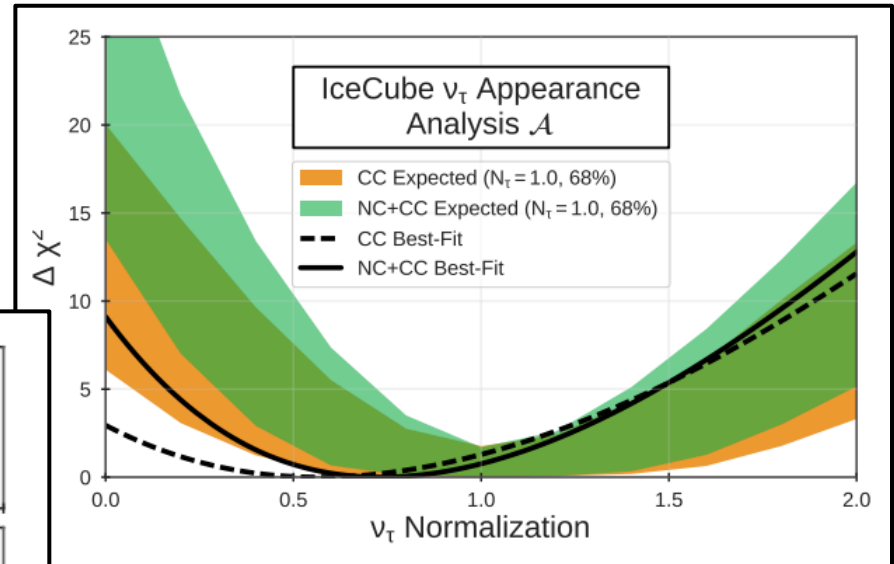
Do we see the number of tau neutrinos that we expect given the 3-flavor model?

Oscillation Analyses

- Atmospheric oscillation p
- Tau neutrino appearance
- **Neutrino mass ordering**
- Non-standard interaction
- Sterile neutrinos

normal hierarchy (NH)   inverted hierarchy (IH)
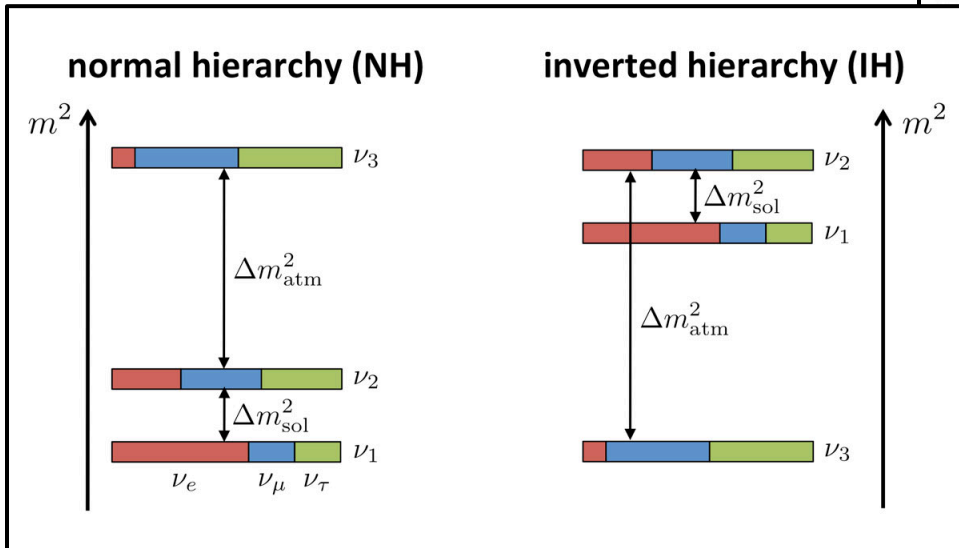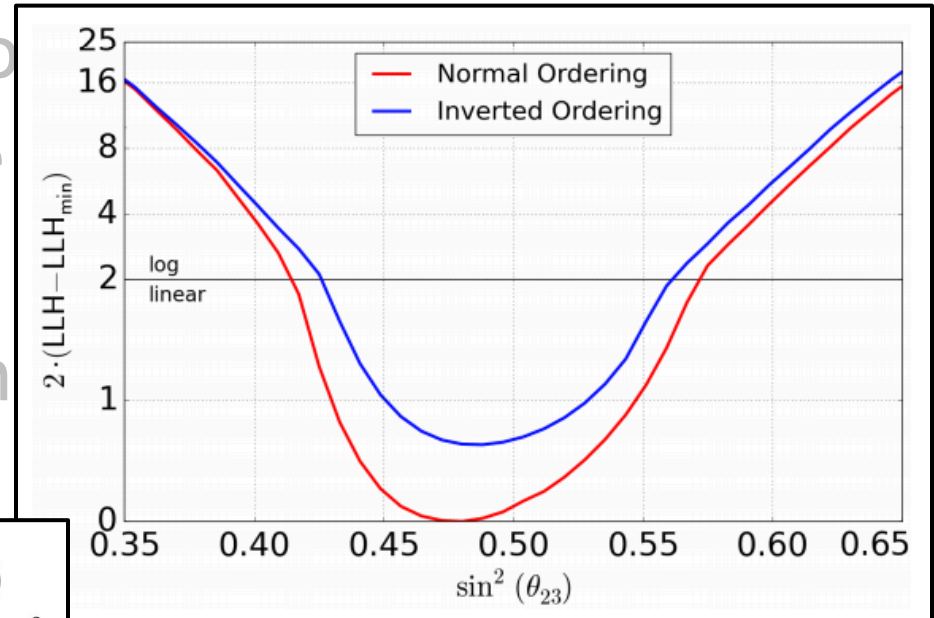
Which neutrino state is the heaviest?

Beyond the Standard Model (BSM)

- The Standard Model with the 3-Flavor Model of Neutrino Oscillations is widely accepted as correct.

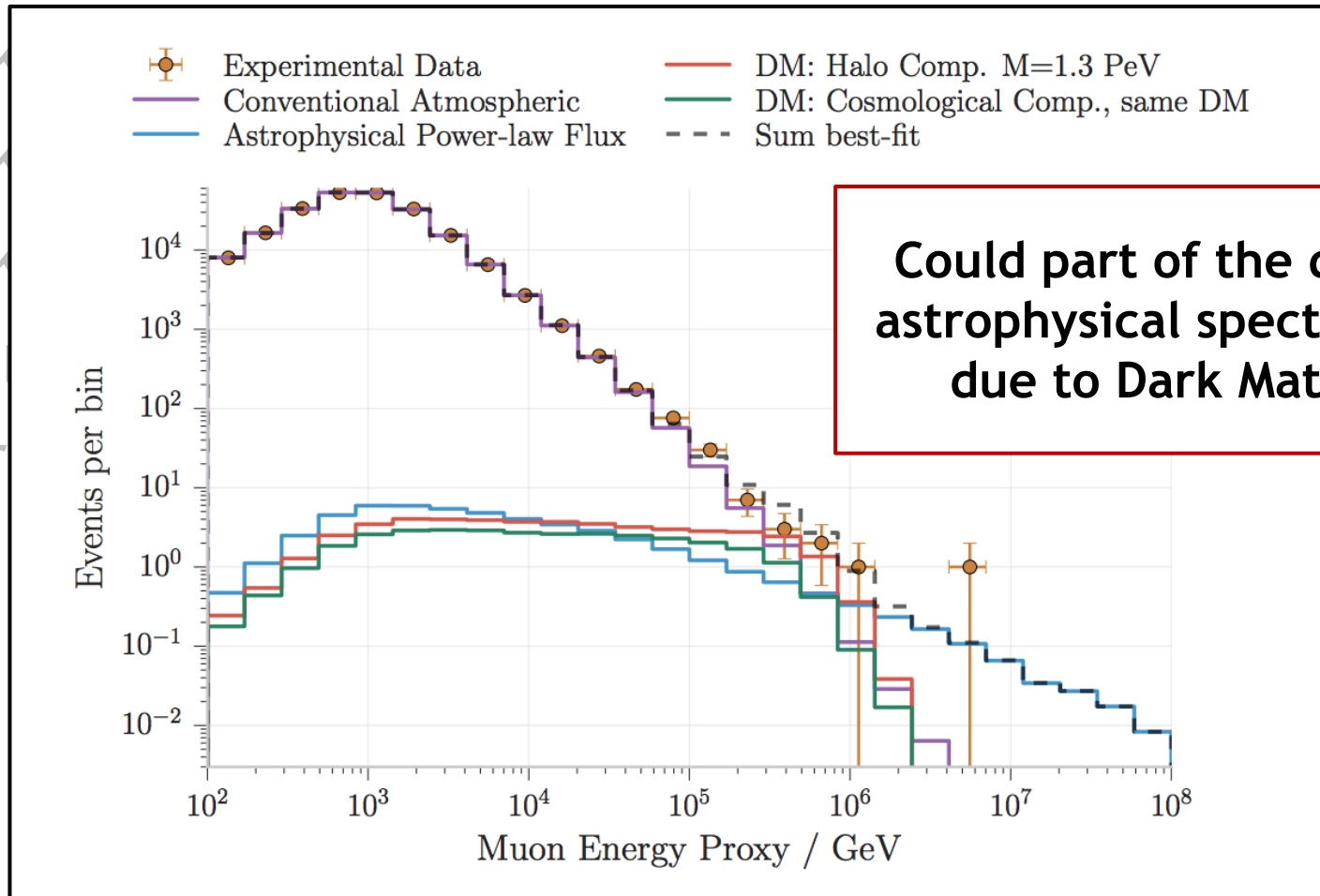- What if there's some other new physics out there?
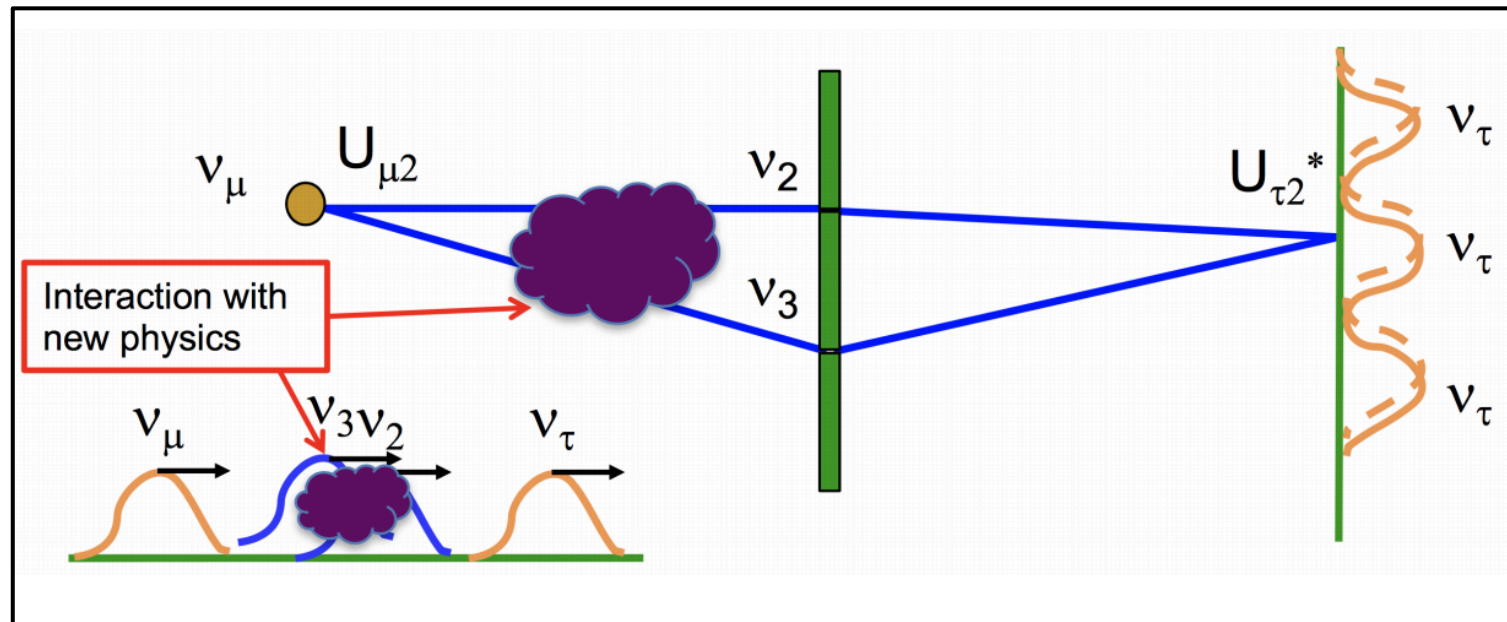
BSM Analyses

- Diffuse Dark Matter
- Dark Matter from the Galactic center
- Dark Matter from the Sun
- Dark Matter from the Earth
- Magnetic Monopoles
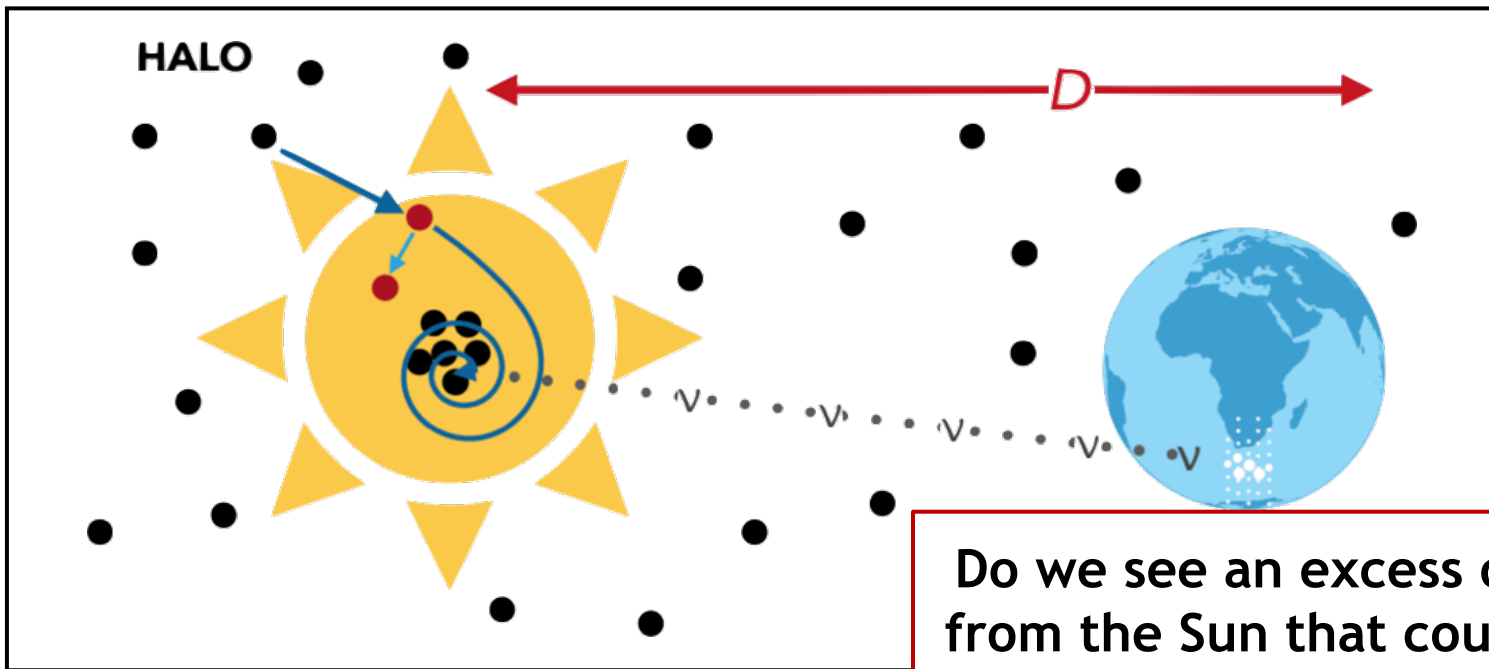- Sterile Neutrino Decay

BSM Analyses

- Diffuse Dark Matter

Could part of the diffuse astrophysical spectrum be due to Dark Matter?

BSM Analyses

- Diffuse Dark Matter
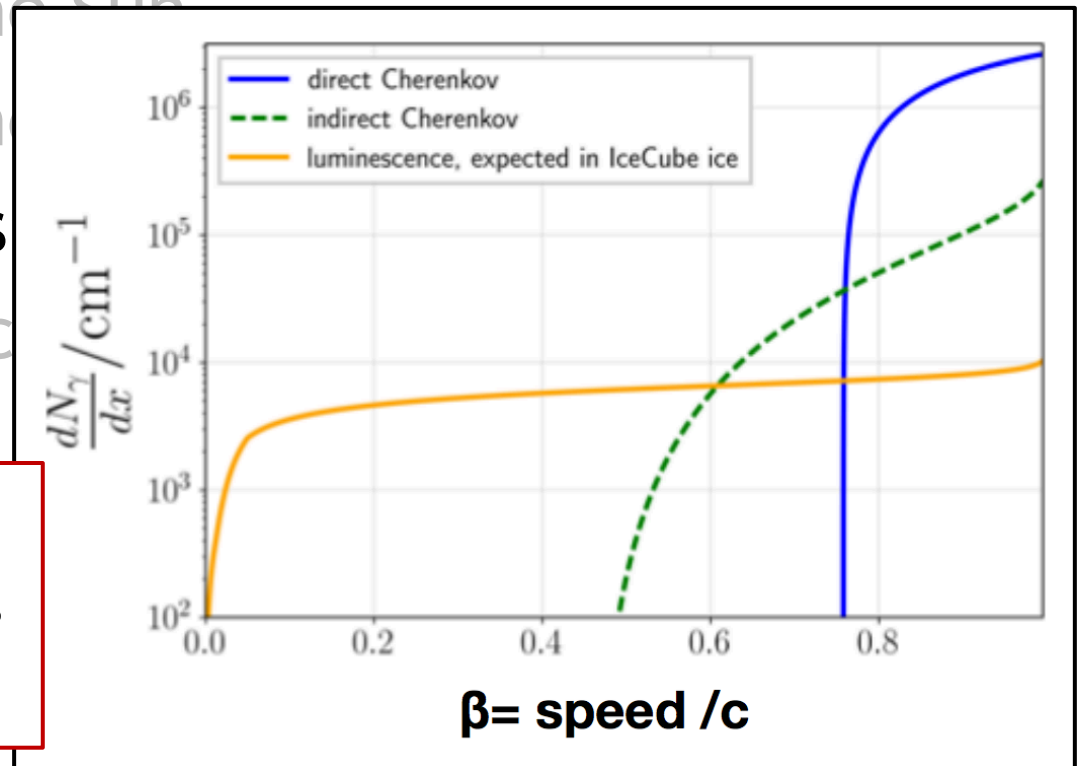- Dark Matter from the Galactic center
- Dark Matter from the Sun (Solar WIMP)

**Do we see an excess of neutrinos from the Sun that could be due to solar dark matter?**

BSM Analyses

- Diffuse Dark Matter
- Dark Matter from the Galactic center
- Dark Matter from the Sun
- Dark Matter from th
- **Magnetic Monopoles**
- Sterile Neutrino Dec

Is there evidence for slow non-relativistic monopoles in the detector?

Legend:
- direct Cherenkov
- indirect Cherenkov
- luminescence, expected in IceCube ice

Y-axis: $\frac{dN_\gamma}{dx} / \mathrm{cm}^{-1}$

X-axis: $\beta =$ **speed /c**

BSM Analyses

- Diffuse Dark Matter
- Dark Matter from the Galactic ce
- Dark Matter from the Sun
- Dark Matter from the Earth
- Magnetic Monopoles

- **Sterile Neutrino Decay**

(Assuming Normal Ordering)

$\Delta m_{41}^2 = 0.3/\text{eV}^2; \ \sin^2 2\theta_{24} = 0.1$
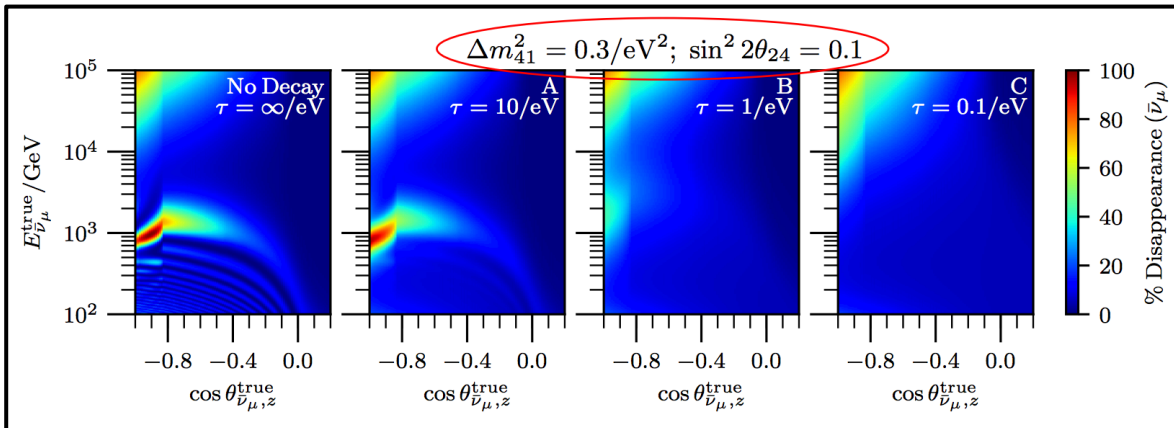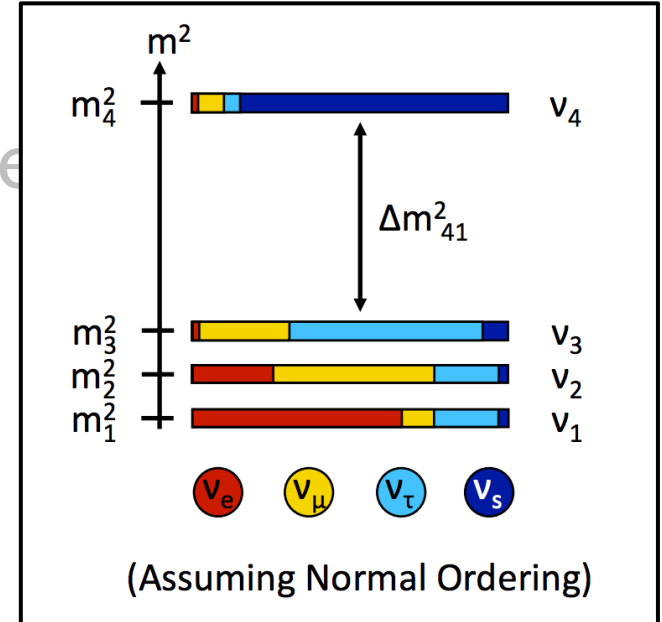
Do we see an excess or deficit of neutrinos that could be due to decaying sterile neutrinos?

Cosmic Ray Working Group

- When cosmic rays hit Earth's upper atmosphere, they produce showers of pions, kaons, muons, neutrinos, etc.

- There is a detector situated on top of IceCube called IceTop that is designed to look for these air showers.
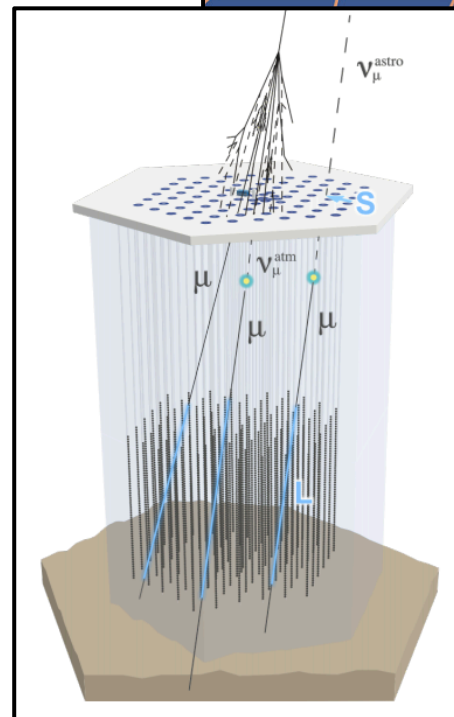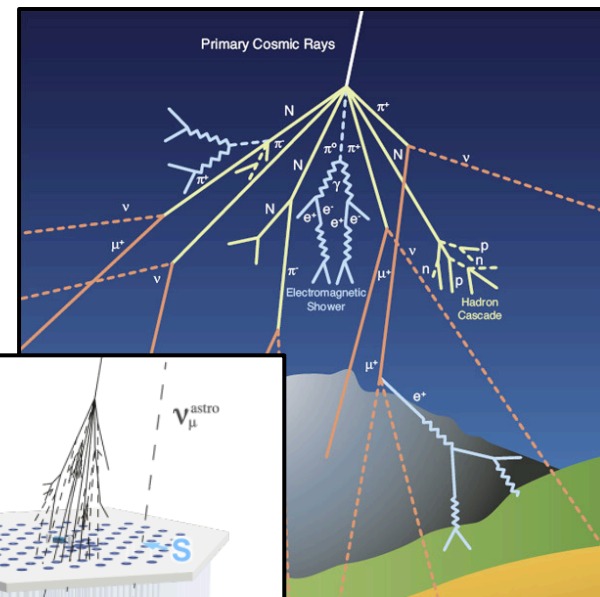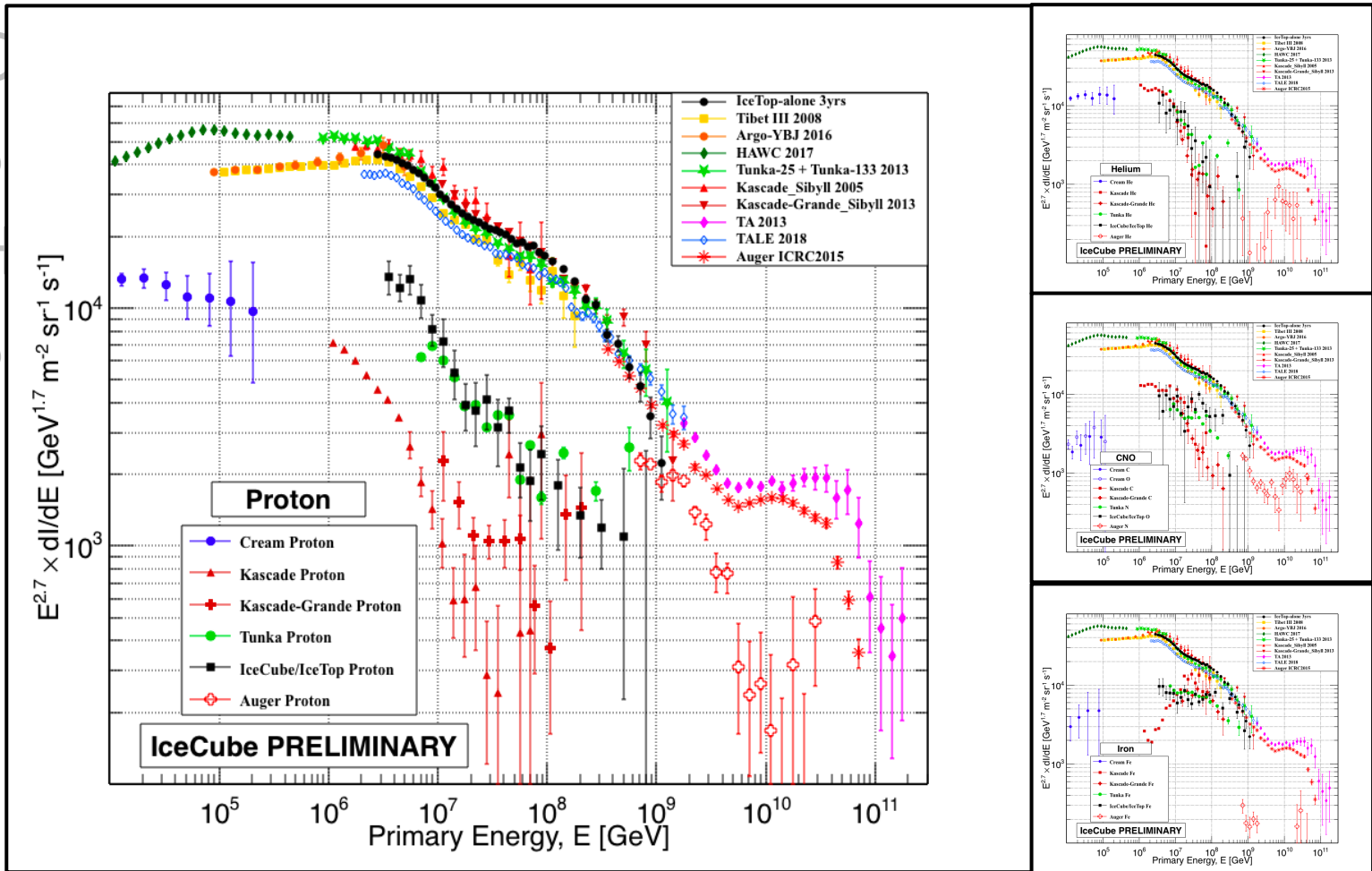
Cosmic Rays

- Cosmic ray spectrum & composition
- Cosmic ray anisotropy
- Sun/moon shadow
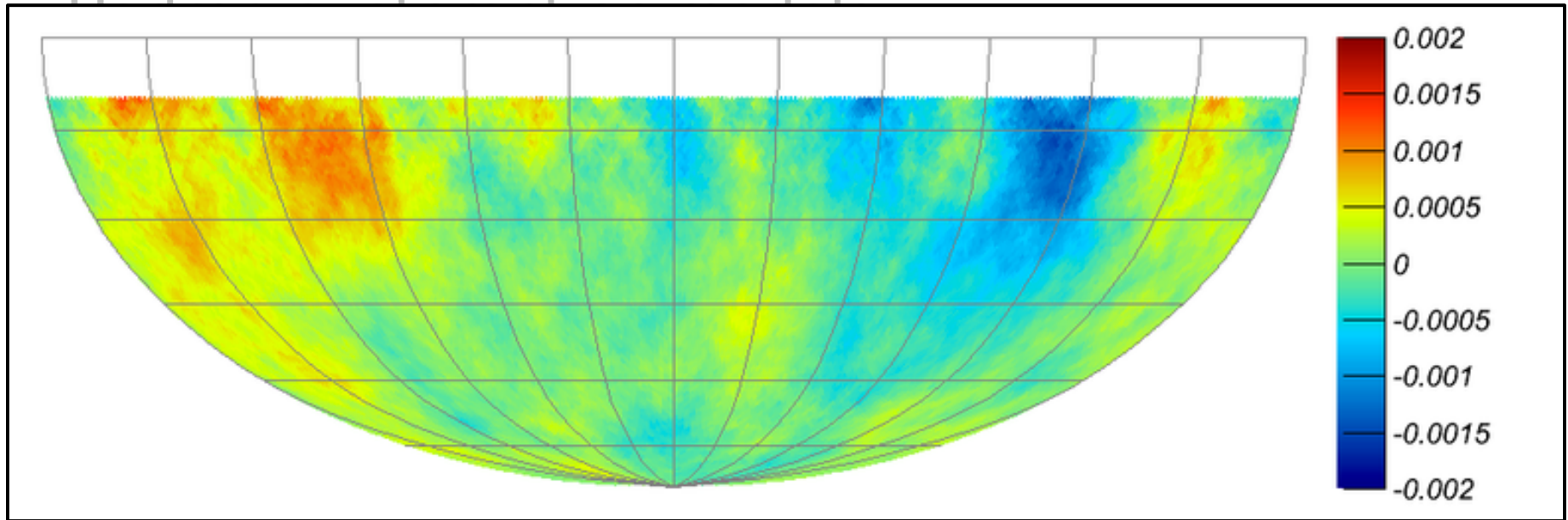- Hadronic interaction models
- Seasonal variations

Cosmic Rays
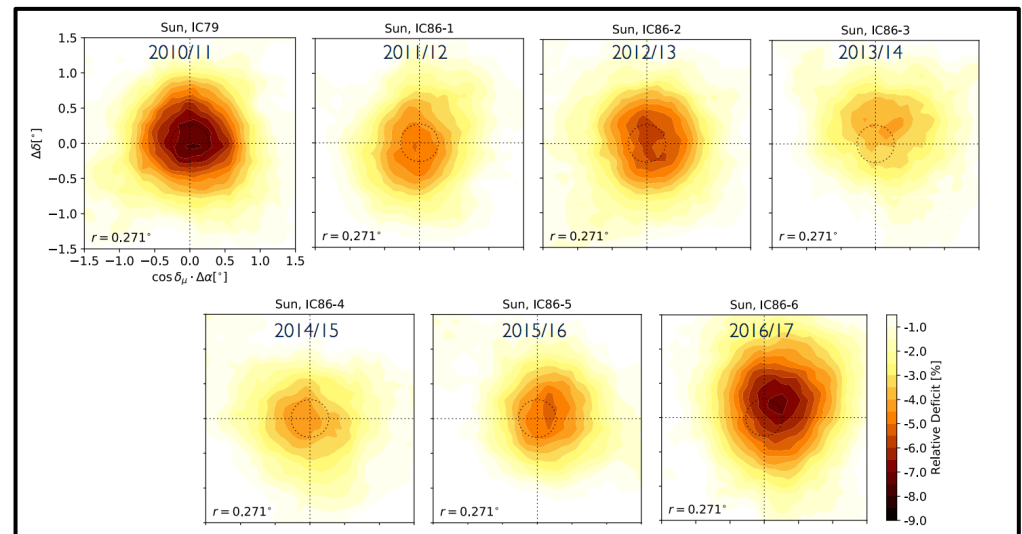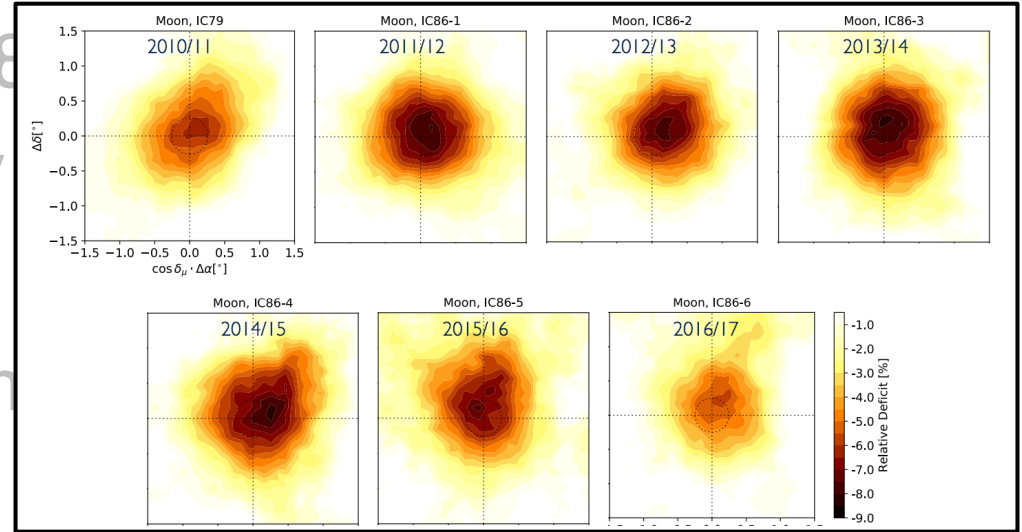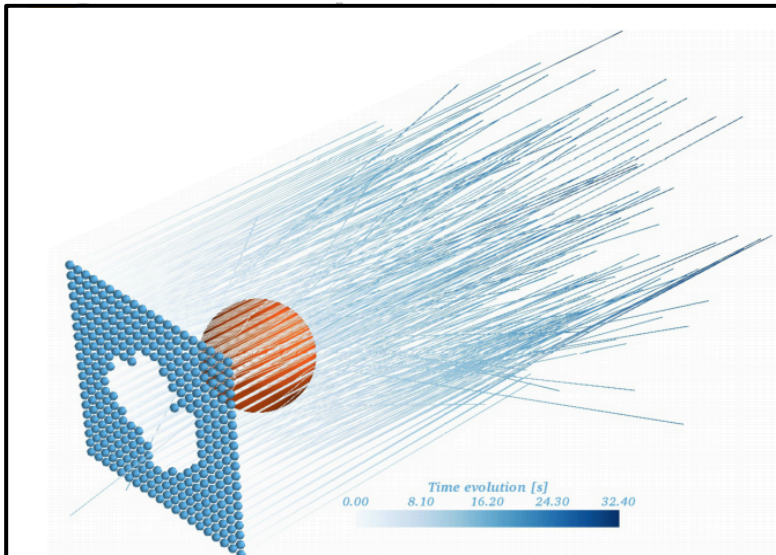
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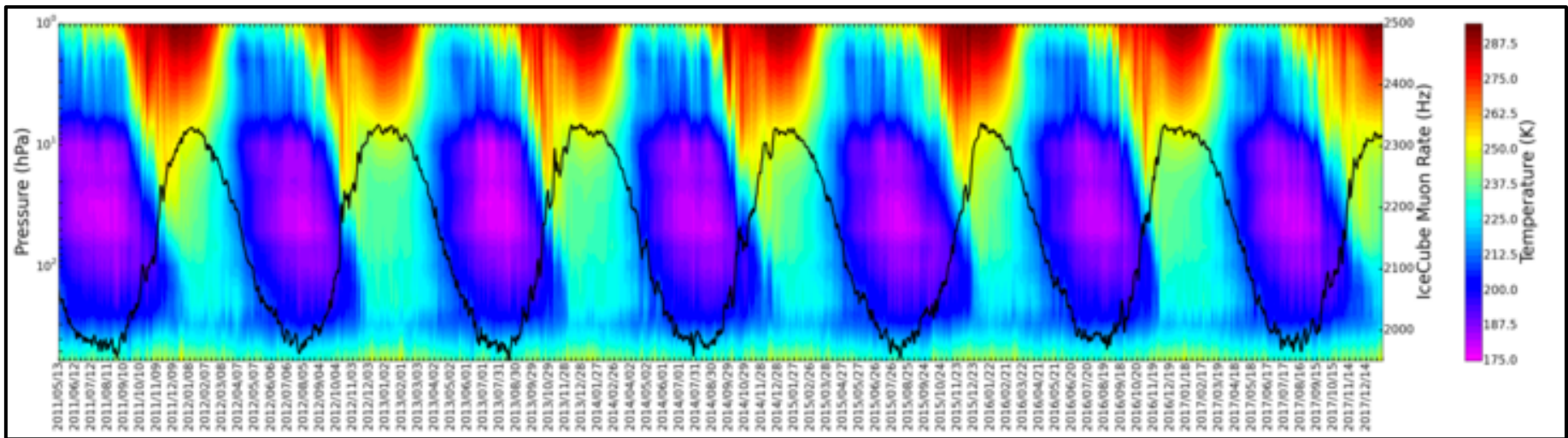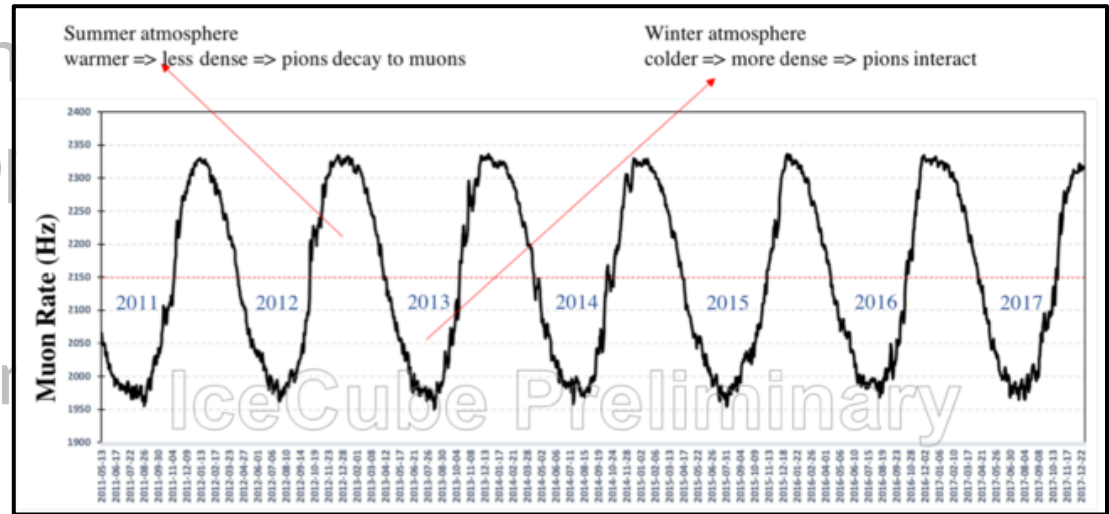- Cosmic ray anisotropy
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Cosmic Rays

- Cosmic ray spectrum &
- Cosmic ray anisotropy
- **Sun/moon shadow**
- Hadronic interaction m

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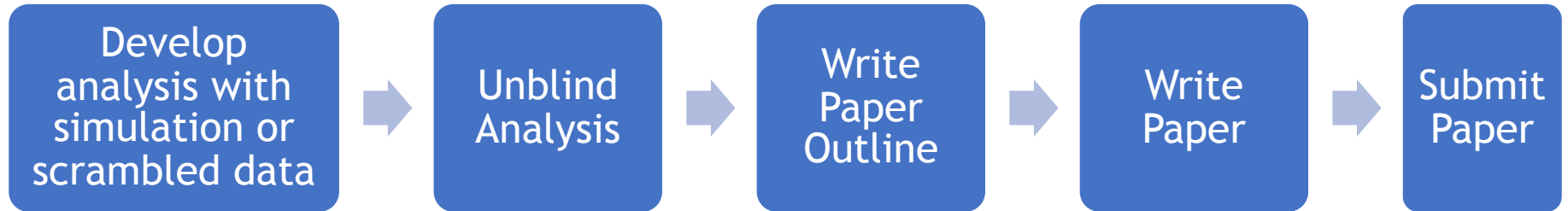- Sun/moon shadow
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2. How To Create your own Analysis in IceCube

Pipeline

Develop analysis with simulation or scrambled data → **Unblind Analysis** → **Write Paper Outline** → **Write Paper** → **Submit Paper**

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Unblinding approval from working group

Unblinding approval by analysis reviewers

Unblinding approval on analysis call

Present results on working group phone call

Outline approval from working group

Outline approval on analysis call

Paper draft approval from working group

Paper approved by review committee (3)
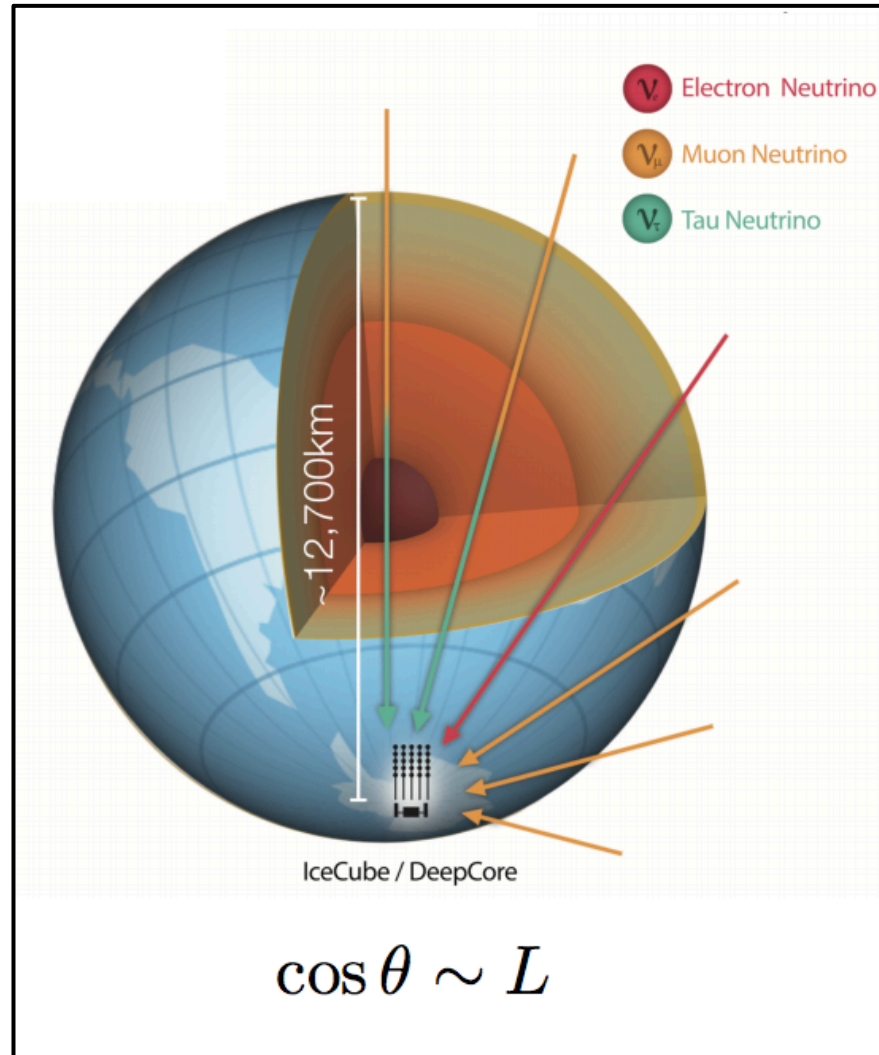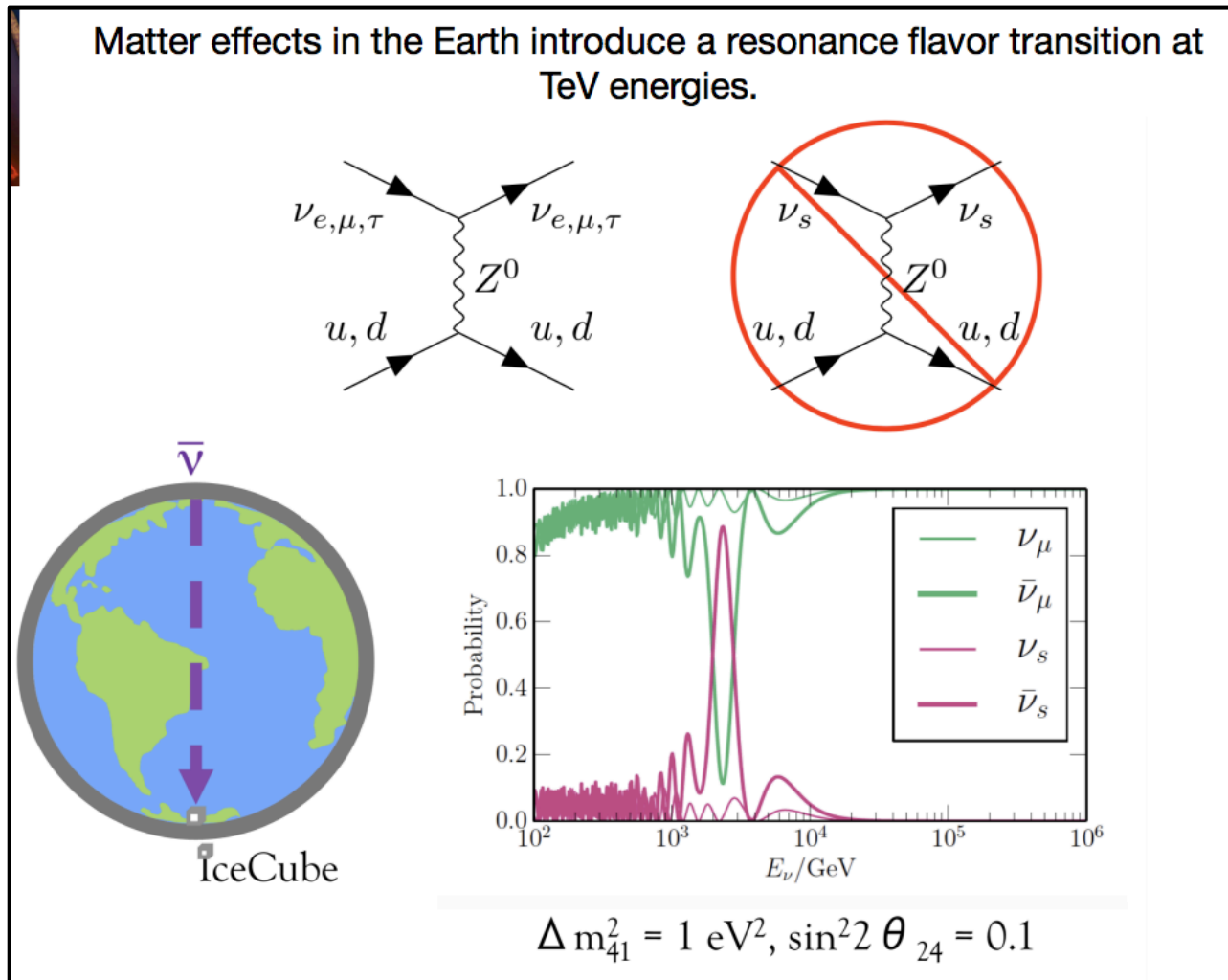
Paper circulated then approved by PubCom

Thanks! Questions?

Bonus Slides

Oscillation Baselines

Sterile Neutrinos

Matter effects in the Earth introduce a resonance flavor transition at TeV energies.

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Sterile Neutrinos