Measuring the Neutrino Flavor Ratio from the Galactic Plane with IceCube

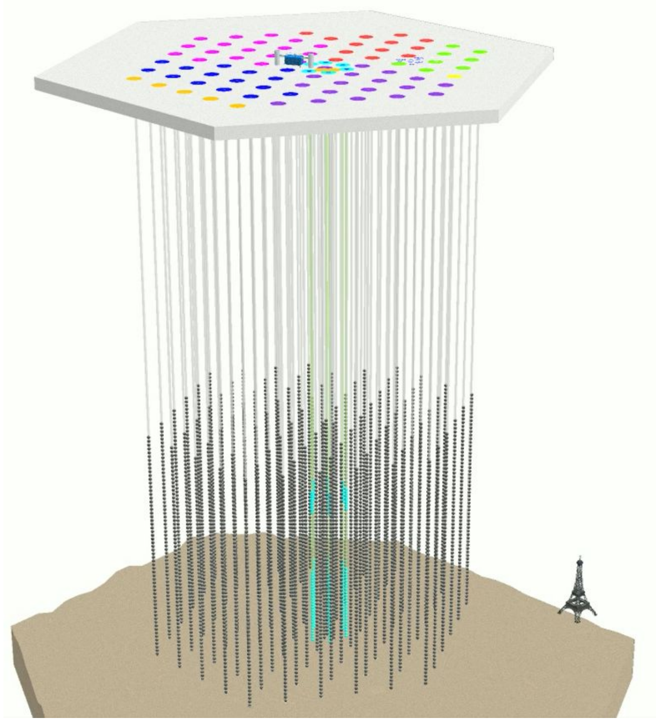
John Hardin, MIT 6/10/25
On behalf of the IceCube Collaboration

Outline

- What is IceCube
- Neutrinos in IceCube
- IceCube and the Milky Way
- Neutrino Flavor and the Milky Way
- Breaking down Galactic Emissions

What is IceCube

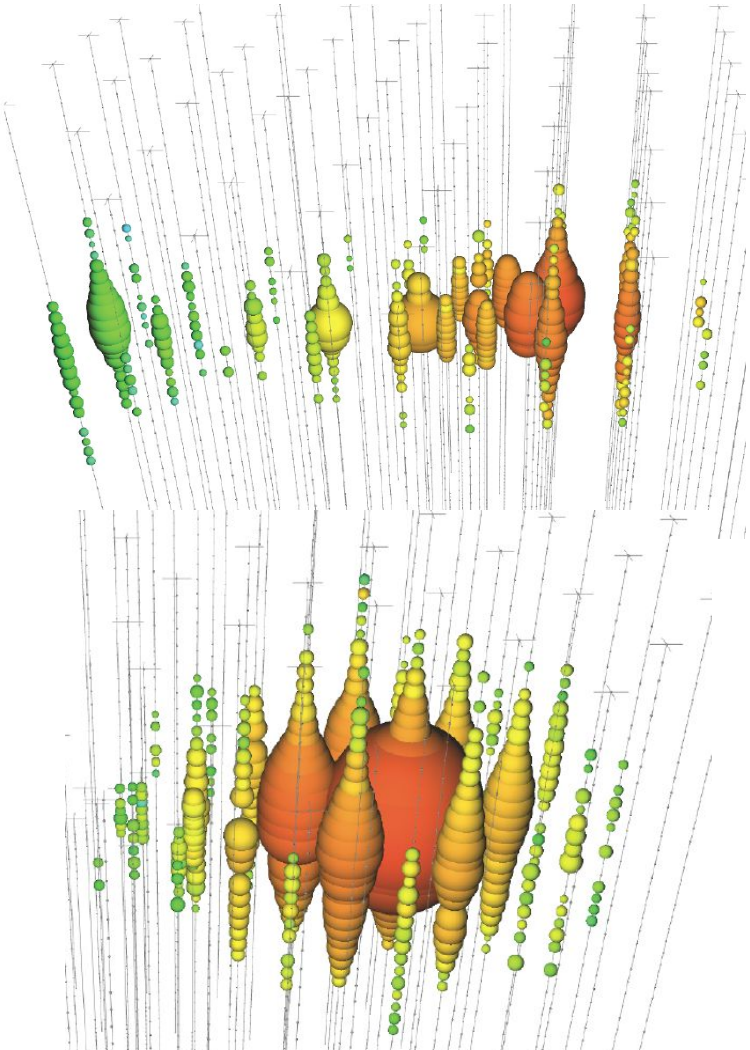
- Array of strings at the South Pole
- More than 5000 PMTs in a cubic kilometer of ice
- Sees neutrinos > ~100 GeV
  - Though this is being upgraded

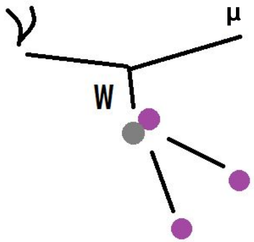


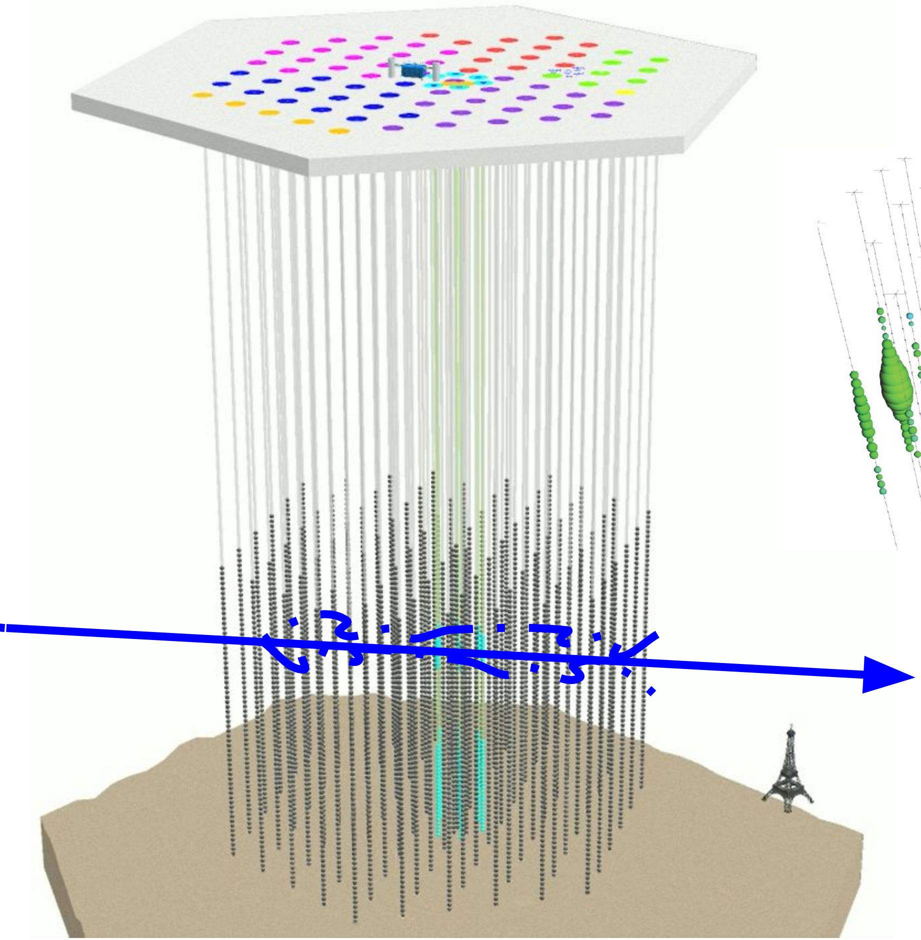
Neutrinos in IceCube

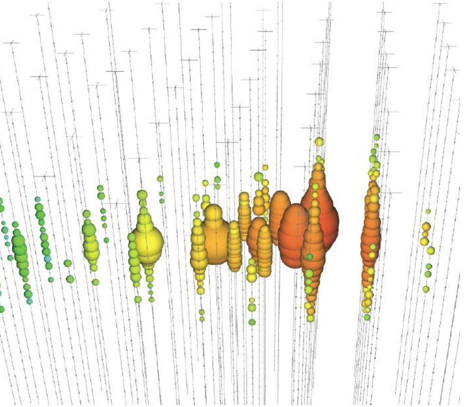
Events in IceCube

- We have 2 types of events
- Long, cylindrical “Tracks”
- Short, spherical, “Cascades”
- These trade off in precision between energy and angle
- They come from different interactions



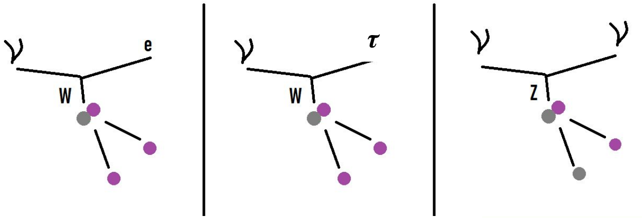


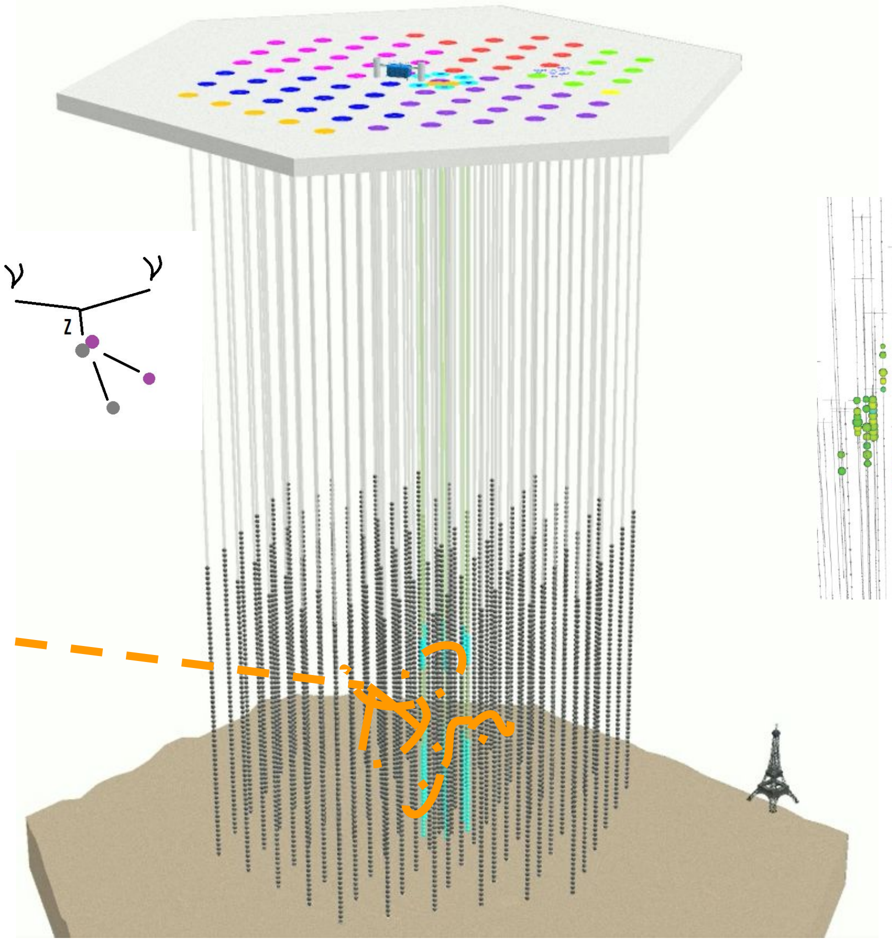


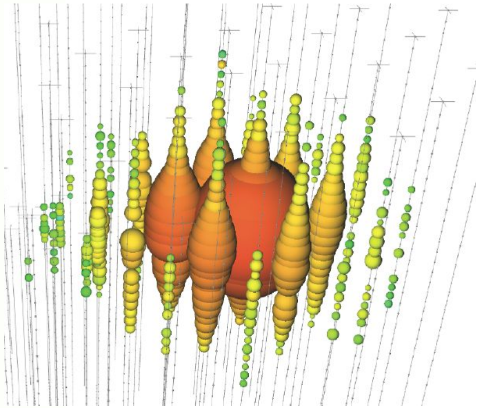


IceCube

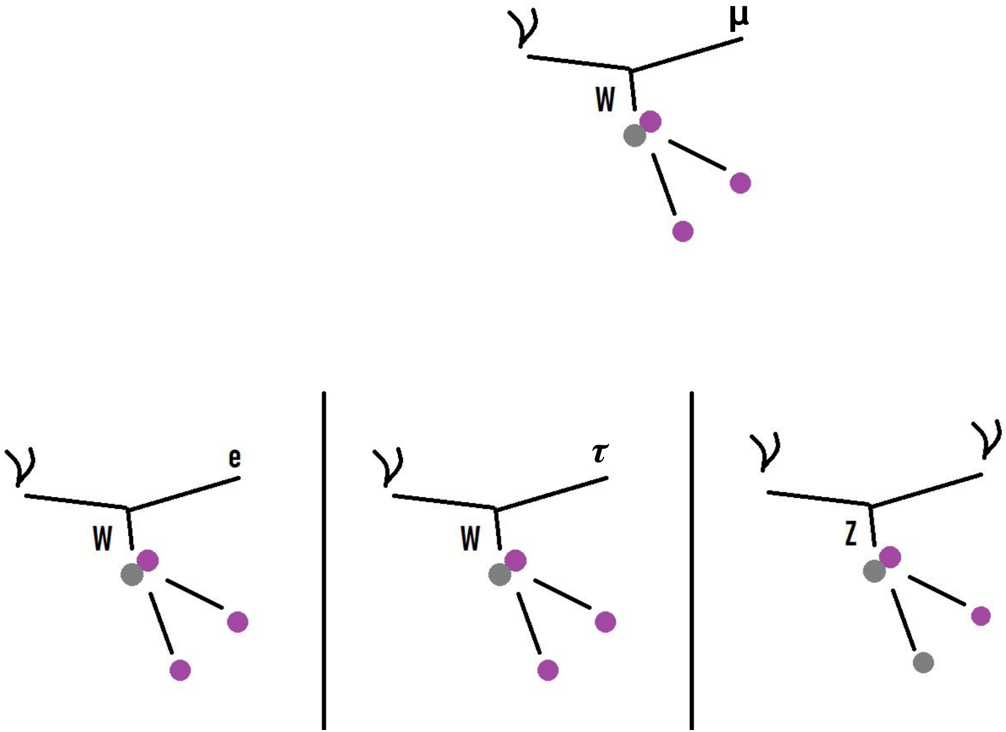

Credit: Spencer Axani
Time
https://fwlibraryfoundation.org/kuan-wei/







IceCube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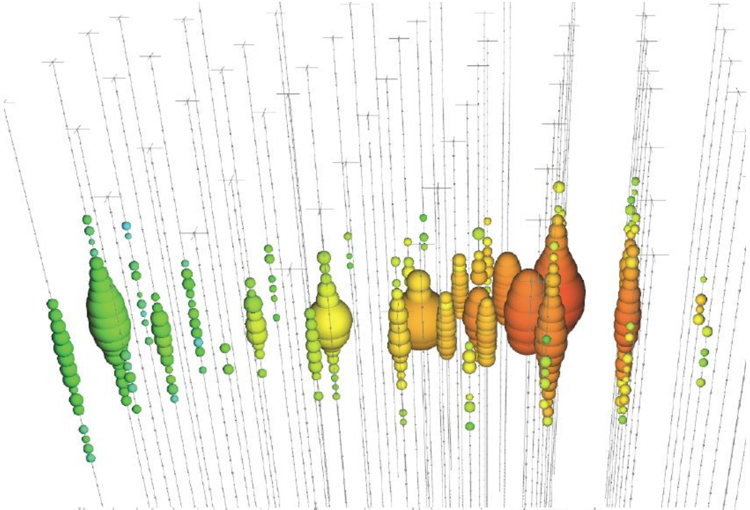
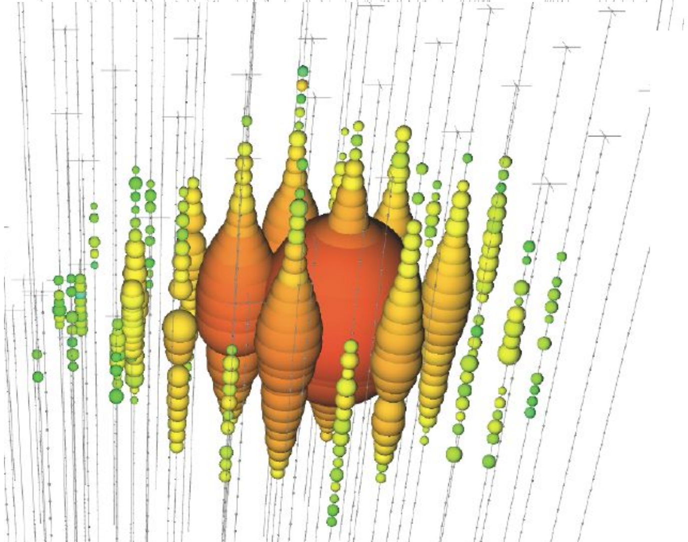
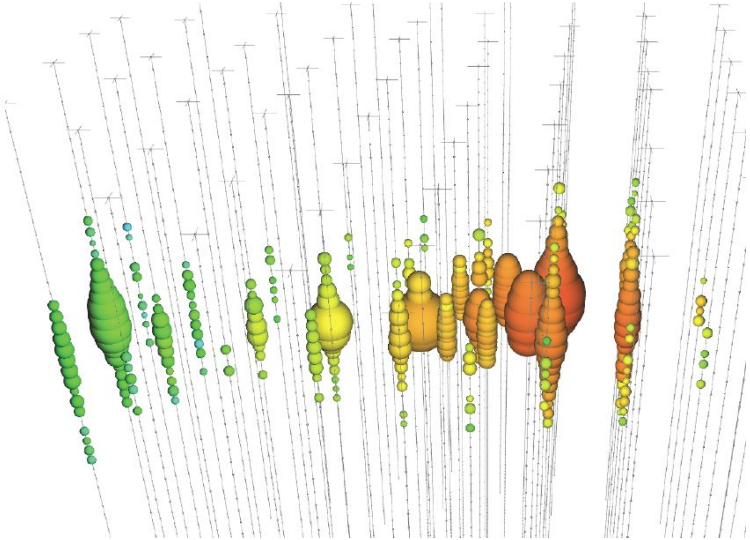




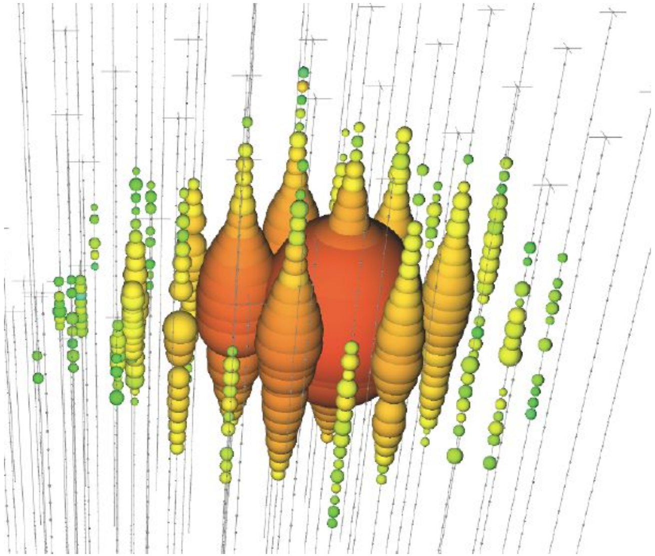
Event Types

Track



Good at direction
“Bad” at energy

Cascade

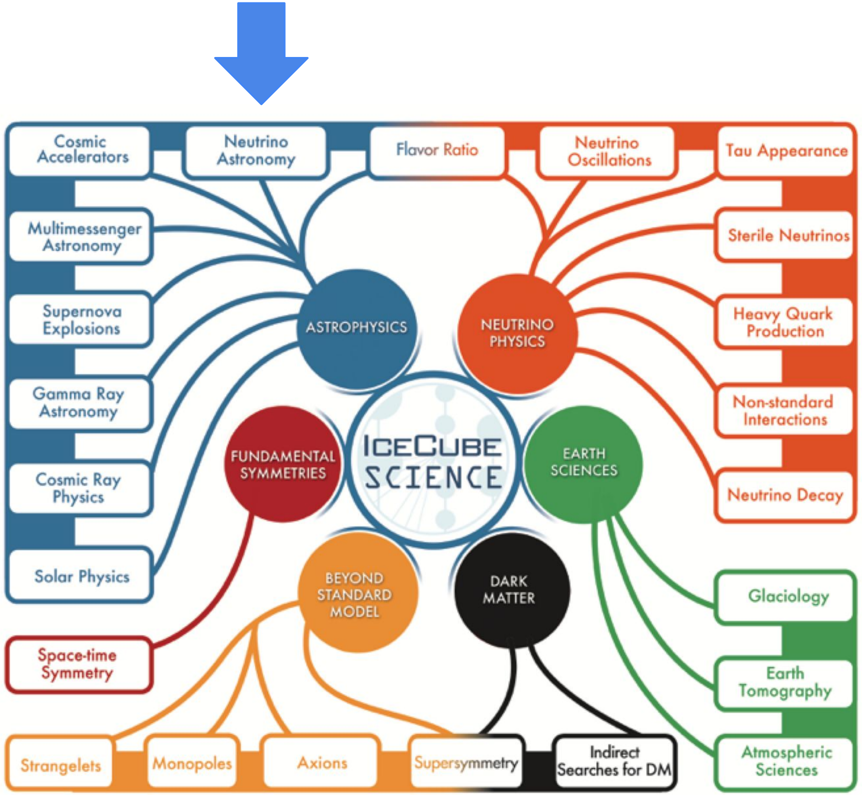


“Bad” at direction
Good at energy

https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

IceCube Physics

- IceCube also does Astronomy
- You may have heard it mentioned



The Galactic Plane with IceCube

The New York Times

Neutrinos Build a Ghostly Map of the Milky Way

Astronomers for the first time detected neutrinos that originated within our local galaxy using a new technique.

Share full article

The IceCube Neutrino Observatory at the Amundsen-Scott South Pole Station in Antarctica. Yuya Makino, IceCube/NSF

By Kenneth Chang

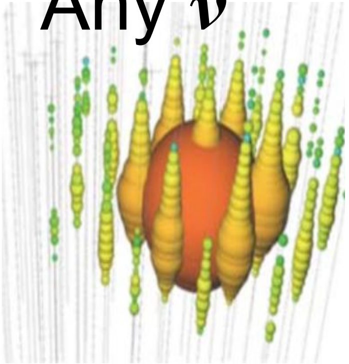
June 29, 2023

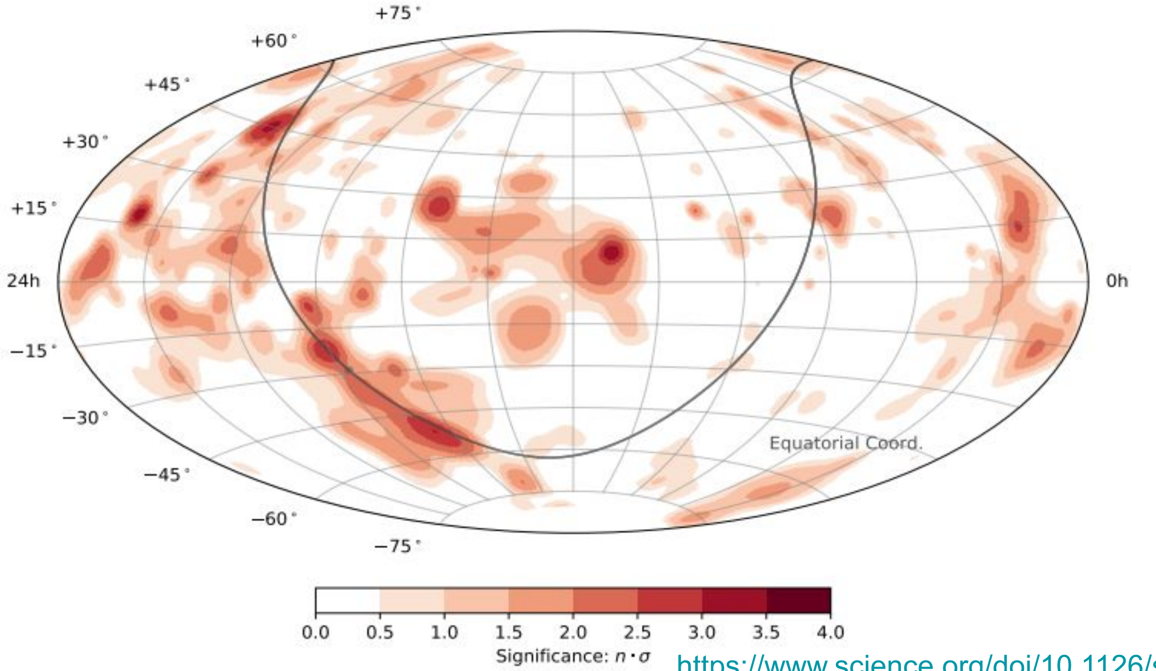
https://www.nytimes.com/2023/06/29/science/neutrinos-milky-way-map.html

This IceCube can see the Galactic Plane

- This result is only in cascades - therefore there is little to no flavor sensitivity

Any ν



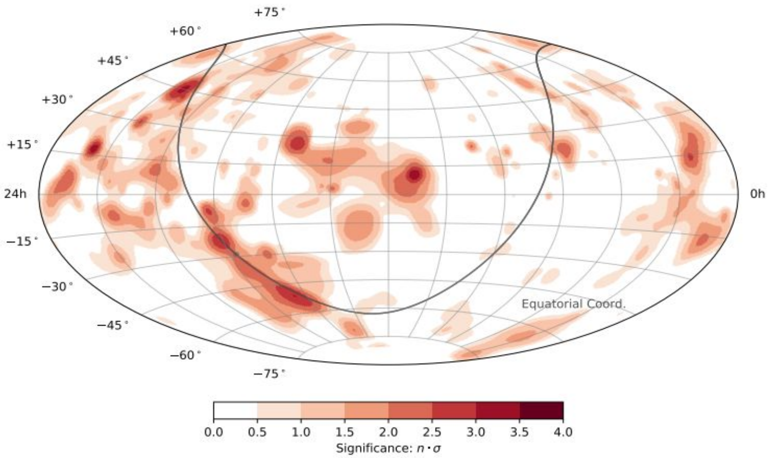


https://www.science.org/doi/10.1126/science.adc9818


The Milky Way

Made possible by recent reconstruction improvements

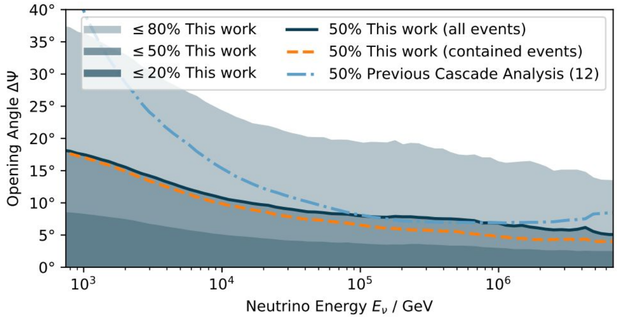
- Recent major upgrades in IceCube reconstruction made this possible
- Leads to better pointing
  - Smaller measurement error makes bumps more visible
- AND admits more events
- Used a Machine Learning technique to quickly produce likelihoods

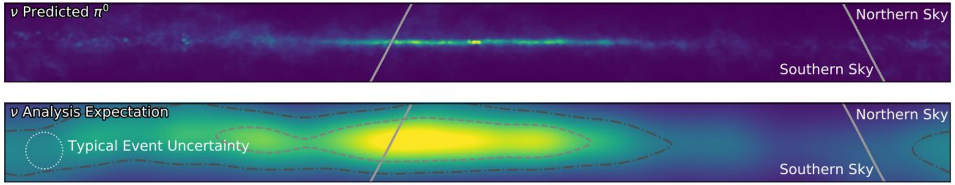


Observation of high-energy neutrinos from the Galactic Plane
https://www.science.org/doi/10.1126/science.adc9818

Template Fitting

- The improved sample needs to be analyzed to detect the galactic plane
- We want to fit the amplitude of a template against data driven background
- How do we do that?

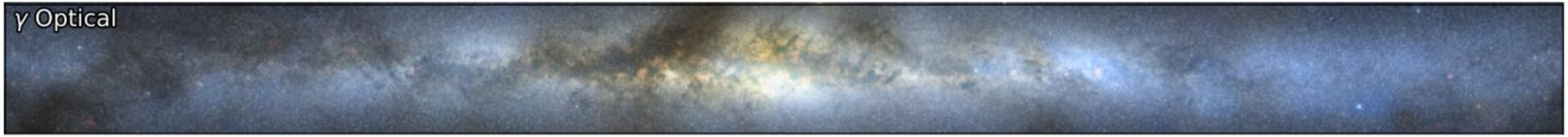


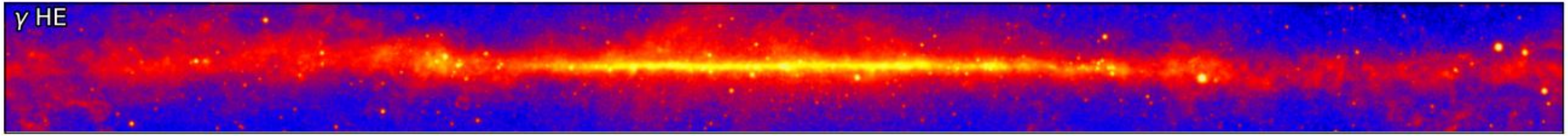


4.5σ

The picture in photons

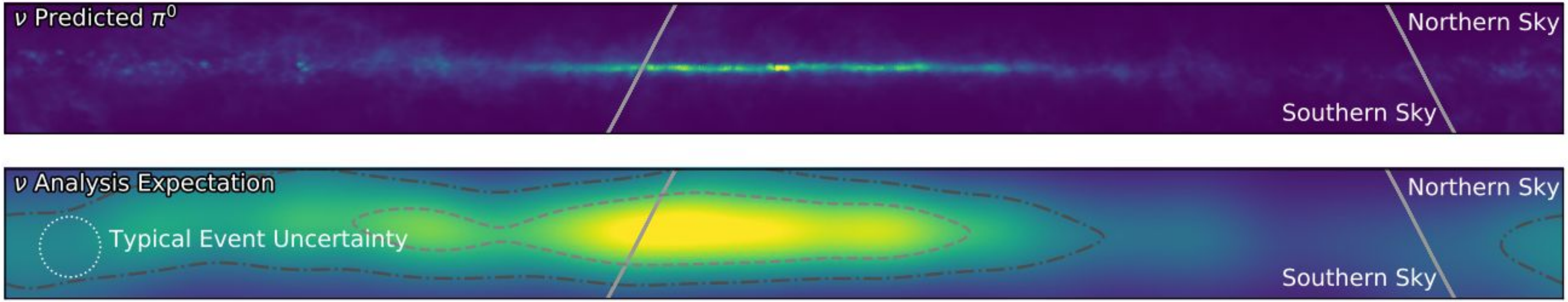
- We sit in the plane of the Milky Way, so our galaxy appears as a great circle in the sky
- The optical view of this band (top)
- The gamma ray view of the same band (bottom)

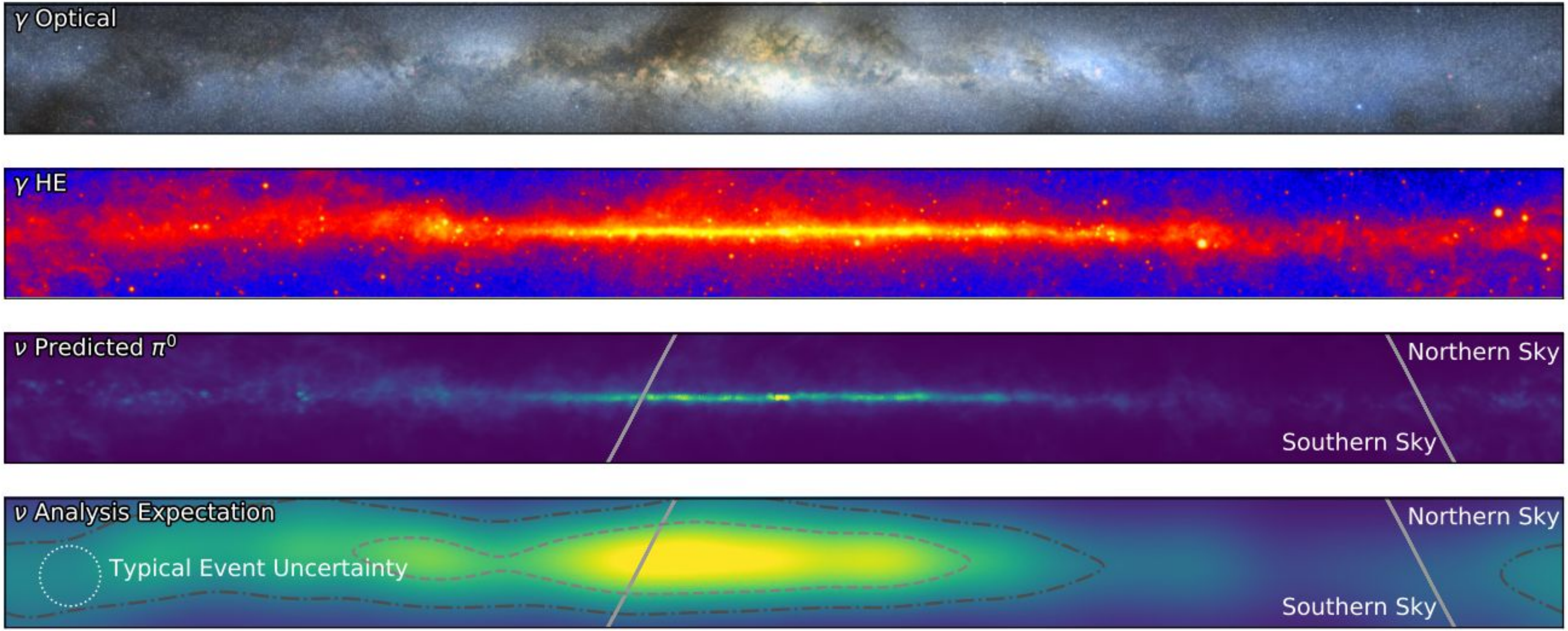


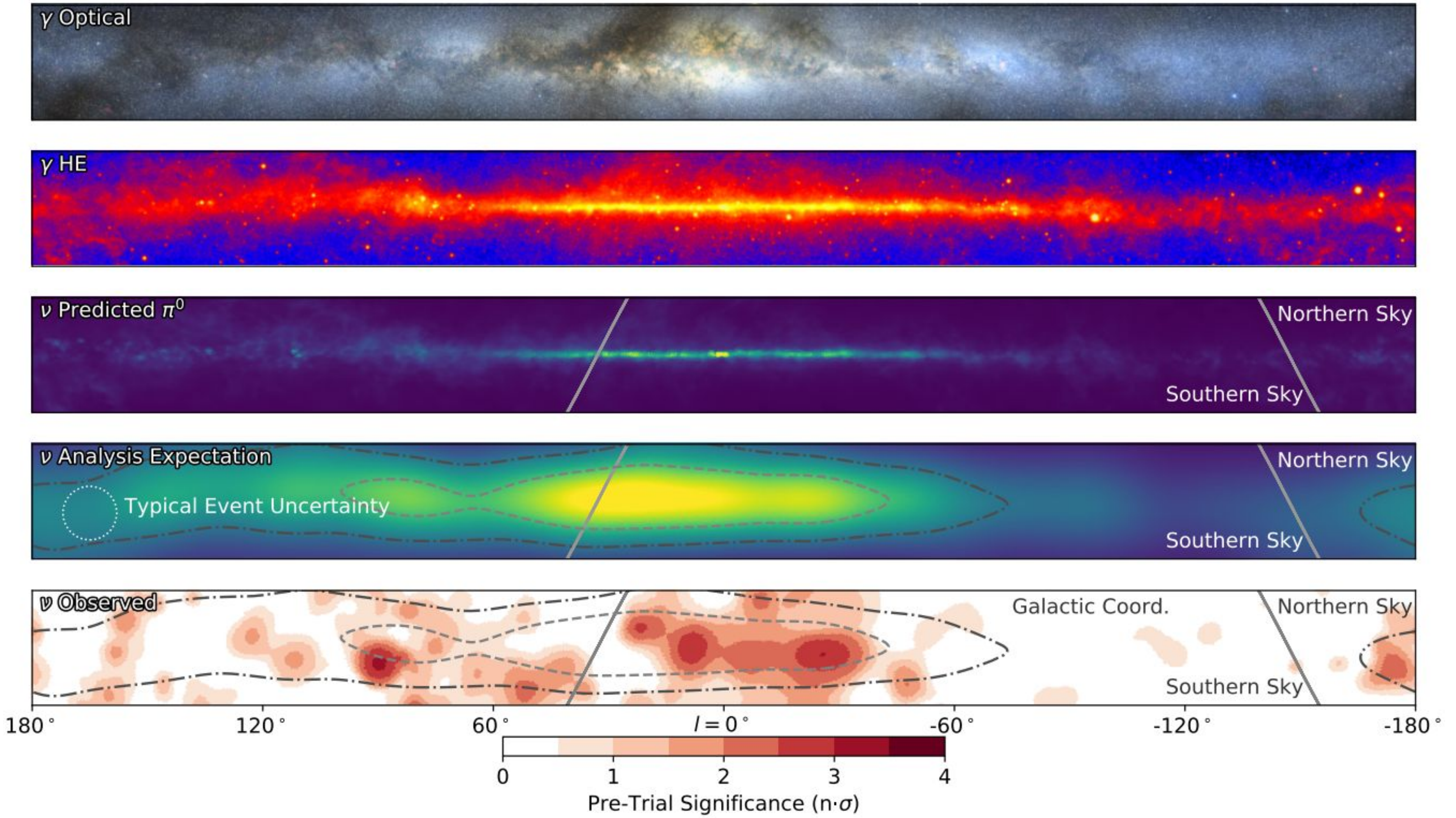


Converting to neutrinos

- The High Energy neutrinos seen by IceCube are expected to be produced by high energy charged particles scattering off interstellar gas
- Models of this behavior are used to predict the incident neutrino spectrum, and then spread by IceCube resolution



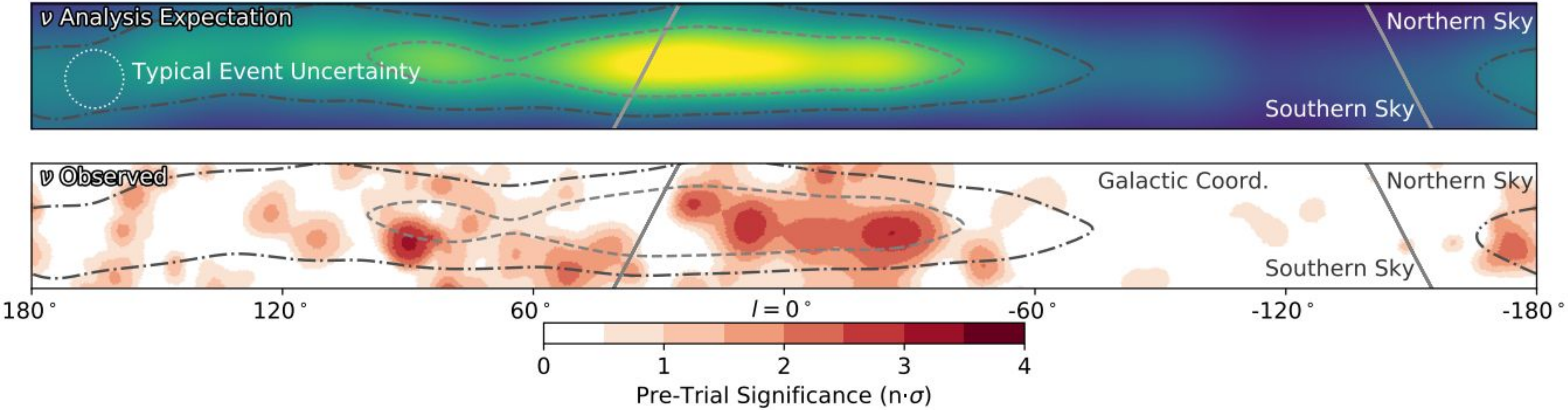

γ Optical
γ HE
ν Predicted π0
Northern Sky
Southern Sky
ν Analysis Expectation
Typical Event Uncertainty
Northern Sky
Southern Sky



γ Optical
γ HE
ν Predicted π⁰
Northern Sky
Southern Sky
ν Analysis Expectation
Typical Event Uncertainty
ν Observed
Galactic Coord.
180°
120°
60°
l = 0°
-60°
-120°
-180°
0
1
2
3
4
Pre-Trial Significance (n·σ)

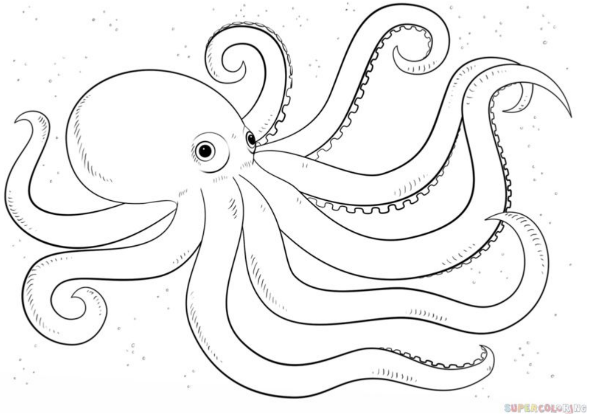
Significant excess

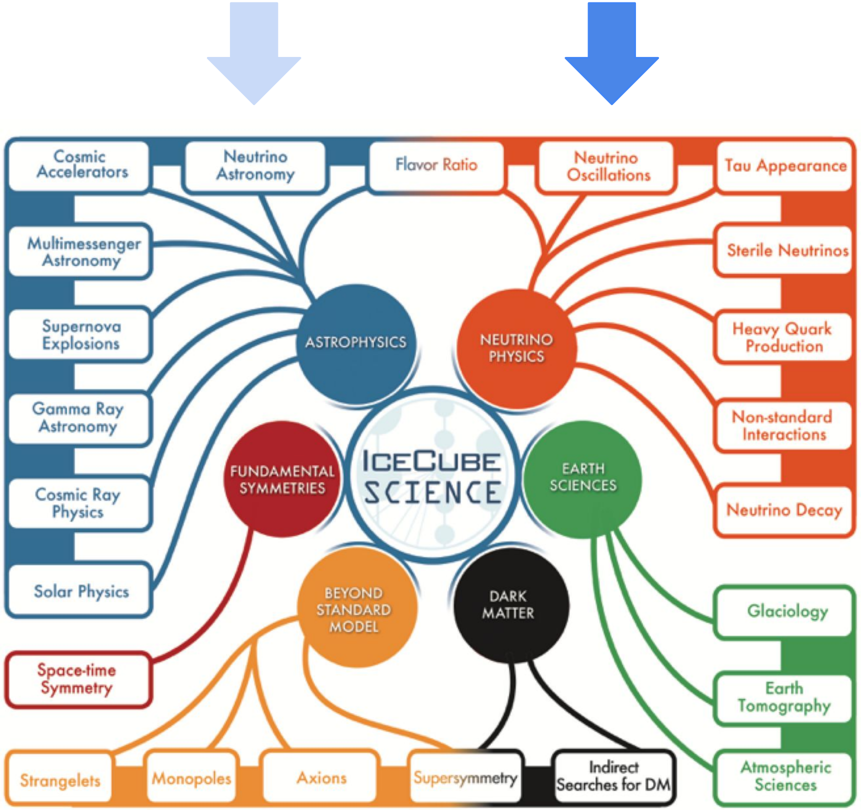
- The galactic plane excess is significant at the 4.5σ level
- The excesses are over a background produced in a data driven fashion
    - Regions outside of the plane are used for background estimation



Non-astronomy with IceCube

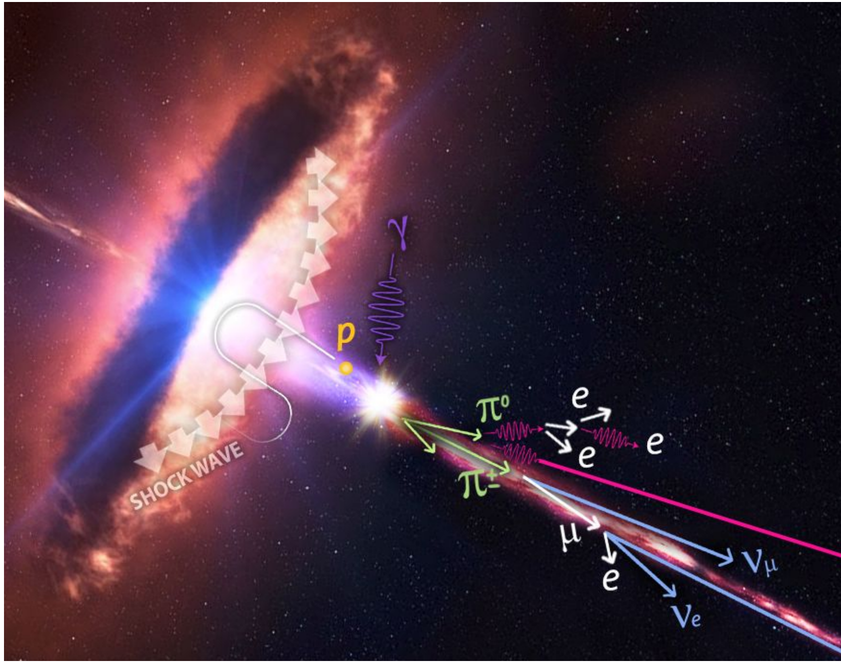
What else can IceCube do?





The mixing matrix Set the Mixture at Earth

- Neutrinos are emitted over distances much larger than their oscillation length
- The oscillations average out
- The properties of the neutrino mixing matrix mean that the observed ratio is very close to 1:1:1



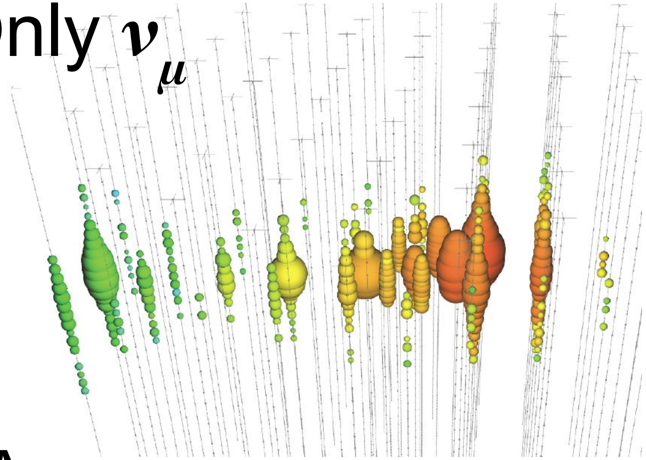
Unless…

- All of this works only based on what we currently know about neutrinos
- But new physics could distort the flavor ratio
- IceCube is sensitive to flavor

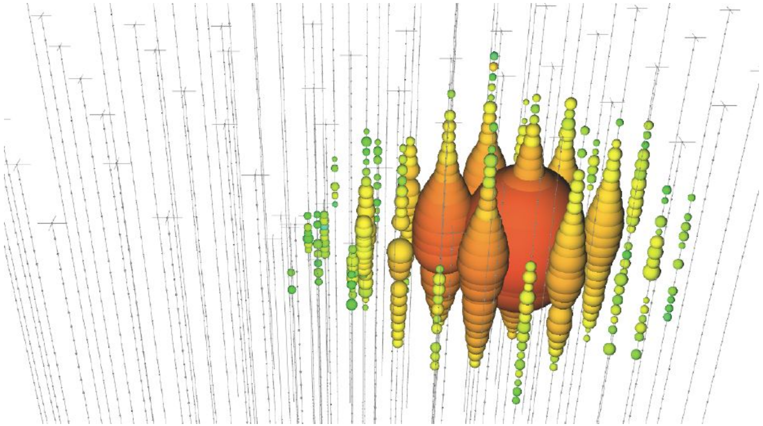
Reminder: 2 Types of Events

- Our tracks can only be produced by muon neutrinos
- The cascades can be produced by any type of neutrino
- The relative cross sections can tell us something about the incoming flavor

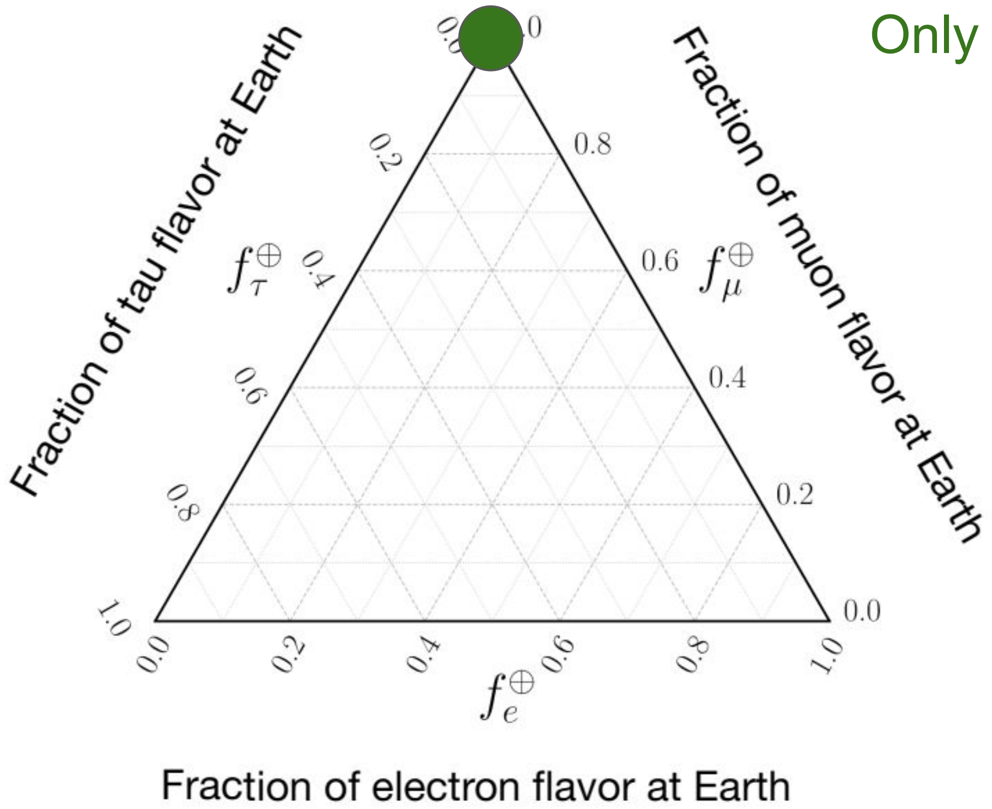
Only ν_μ



Any ν

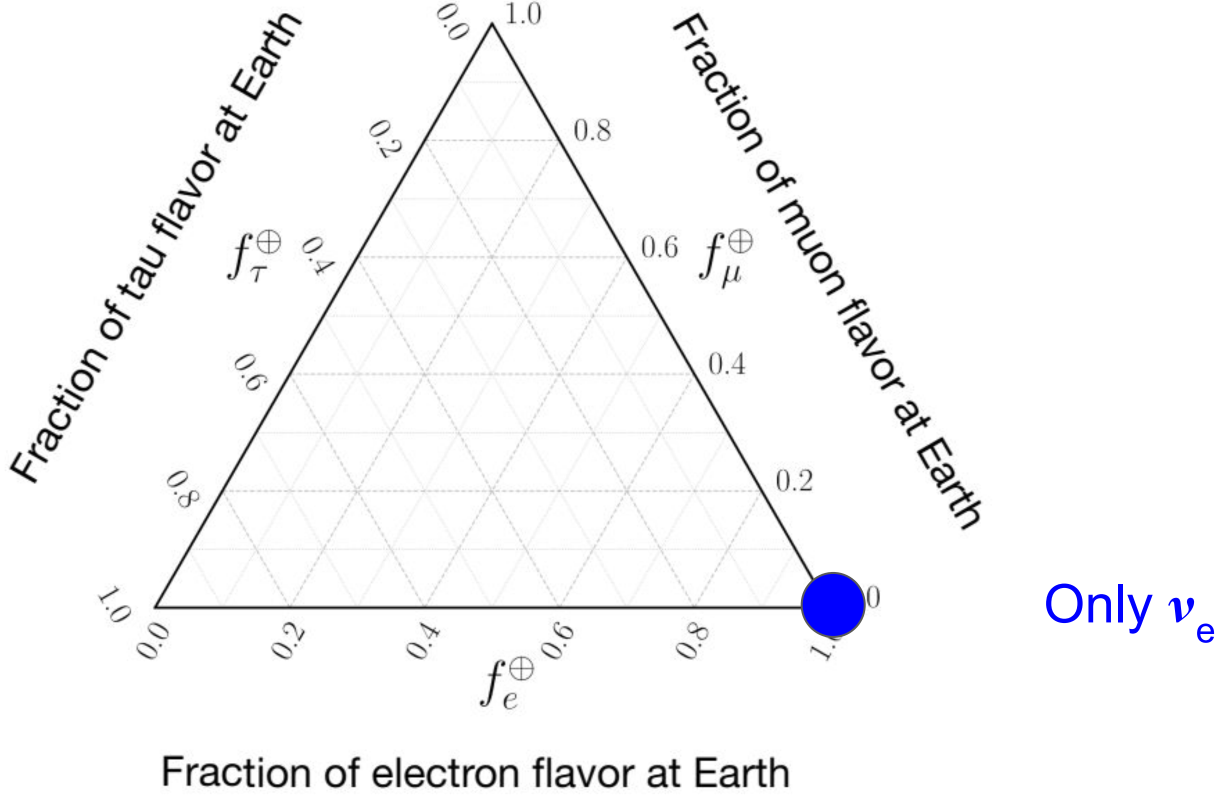


Describing Flavors: The Flavor Triangle

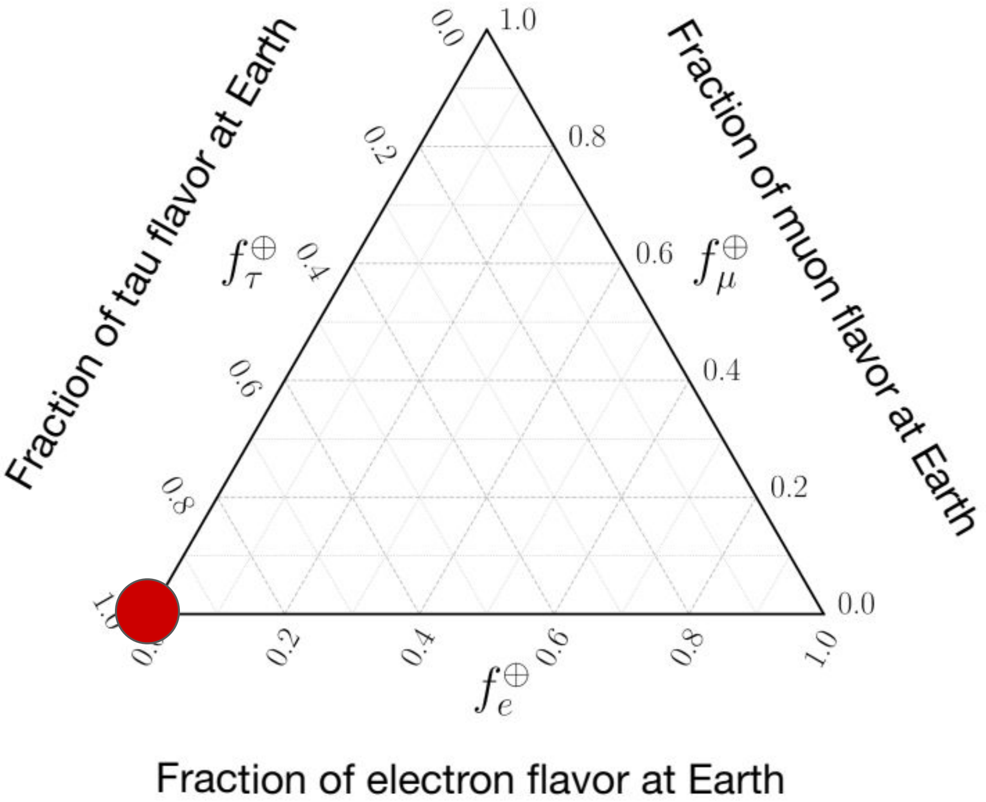


Only ν_μ

Describing Flavors: The Flavor Triangle



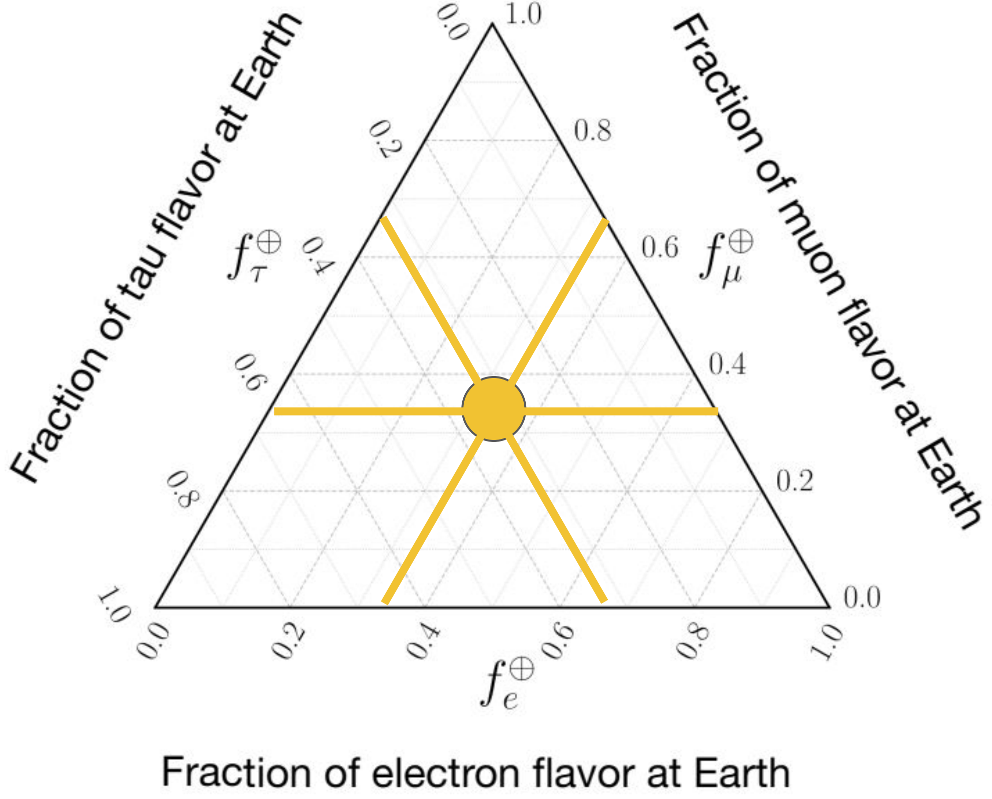
Describing Flavors: The Flavor Triangle



Only ν_τ

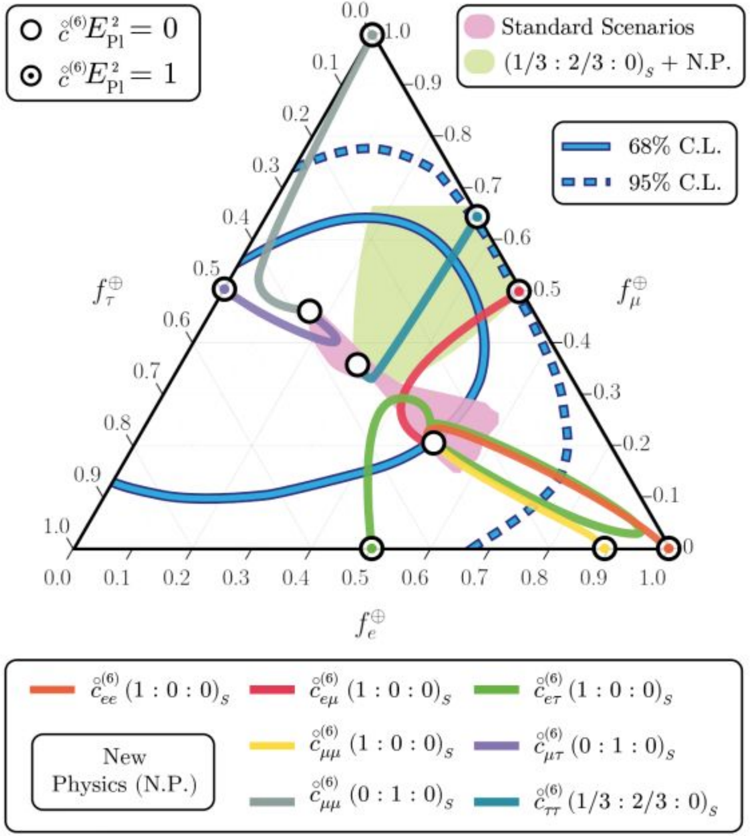
Describing Flavors: The Flavor Triangle

Equally Mixed



IceCube flavors before the Galactic Plane

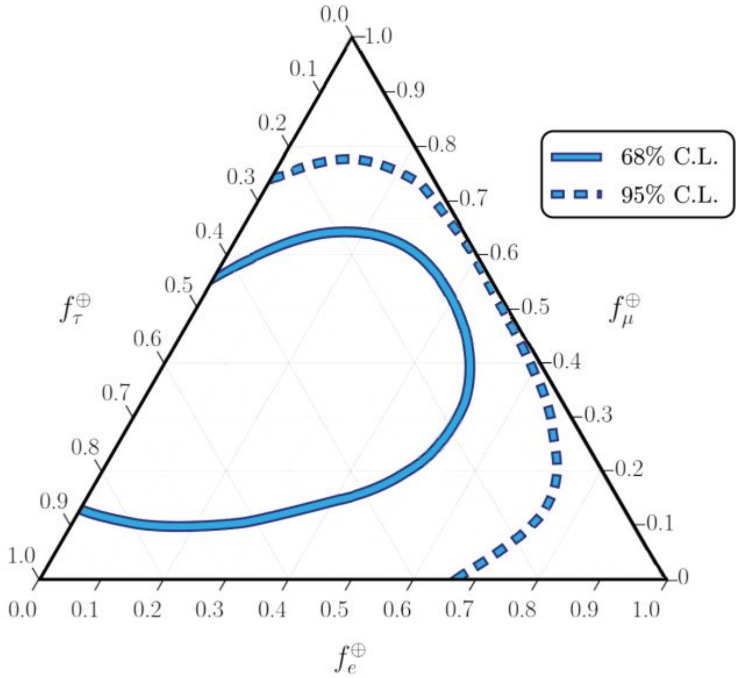
- You have to be sure the neutrinos are astrophysical
- This is done by only looking at the very highest energies



https://arxiv.org/abs/2111.04654, **Search for Quantum Gravity Using Astrophysical Neutrino Flavour with IceCube**

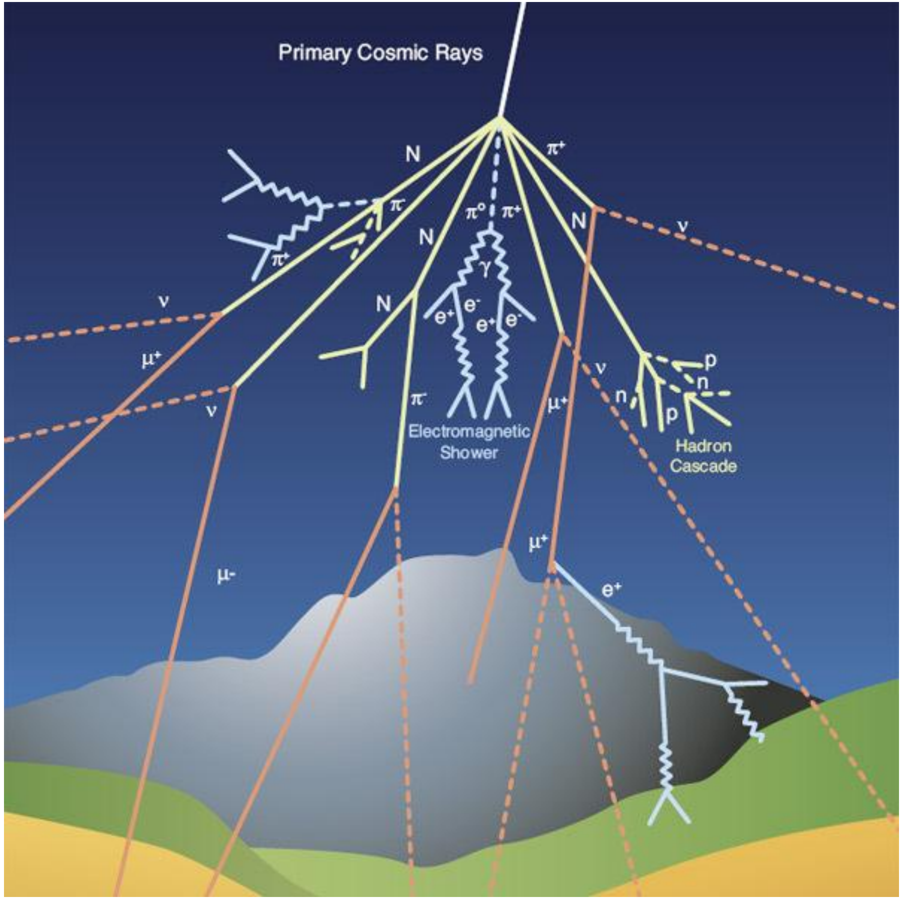
IceCube flavors before the Galactic Plane

- Other regions are possible Beyond the Standard Model
- These are the actual exclusion bands from the 2021 analysis

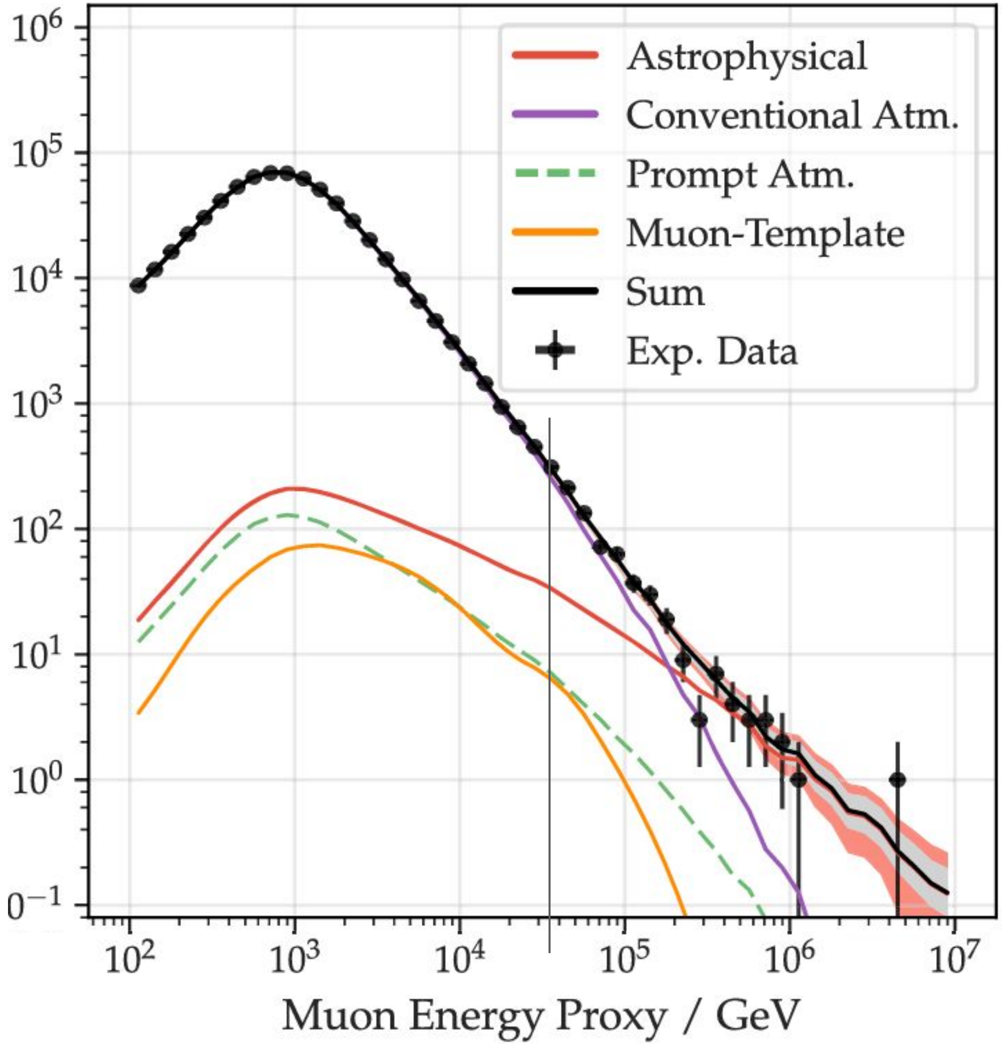


Background: Atmospherics

- We have to restrict to extremely high energies because atmospheric neutrinos are at lower energies
- Atmospheric neutrinos haven't travelled far enough to have the extremely long baseline effects



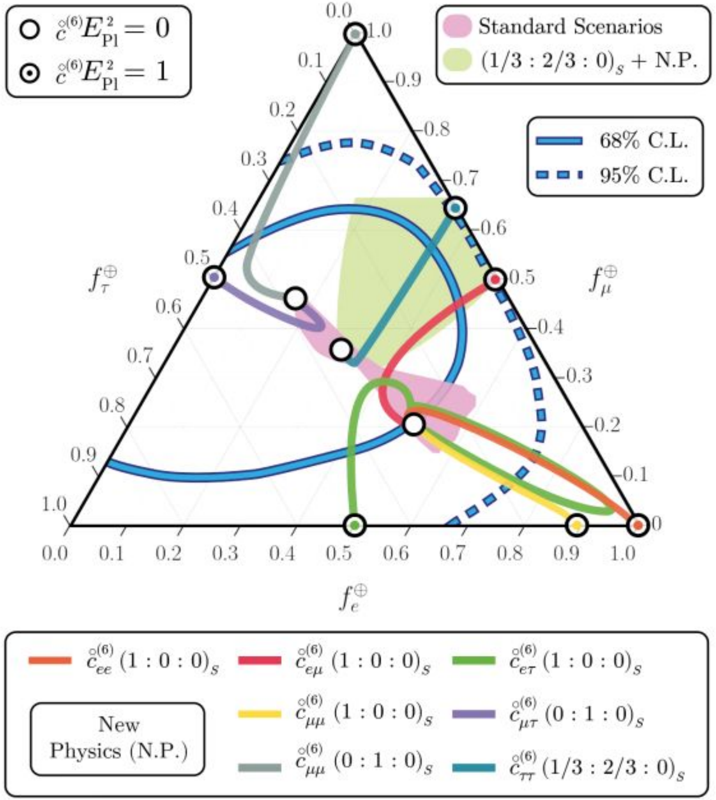
Atmospheric Background



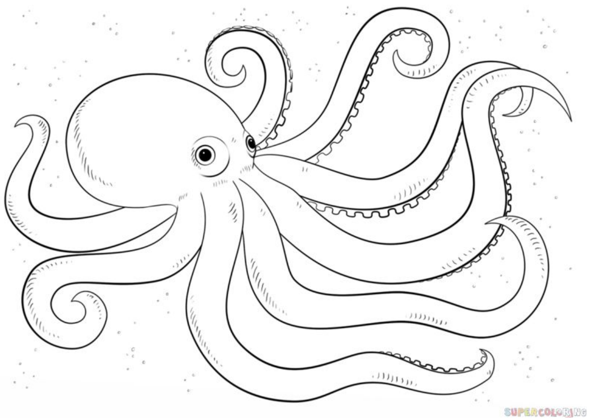
[Improved Characterization of the Astrophysical Muon–neutrino Flux with 9.5 Years of IceCube Data - IOPscience]

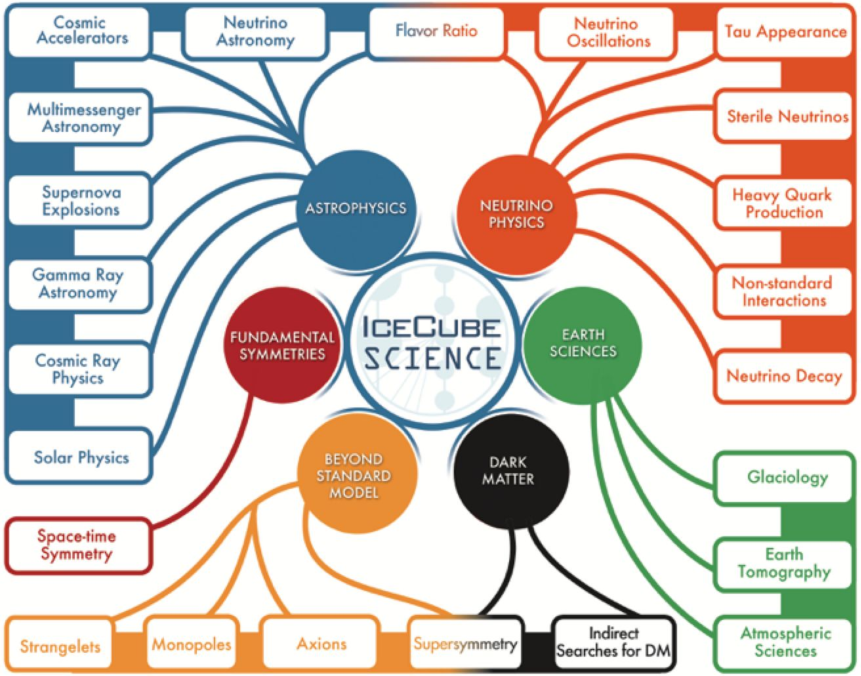
The All Sky Analysis

- This was an important measurement that excluded some possibilities
- It looked at the whole sky equally
- But, we might be able to do better
- Because:



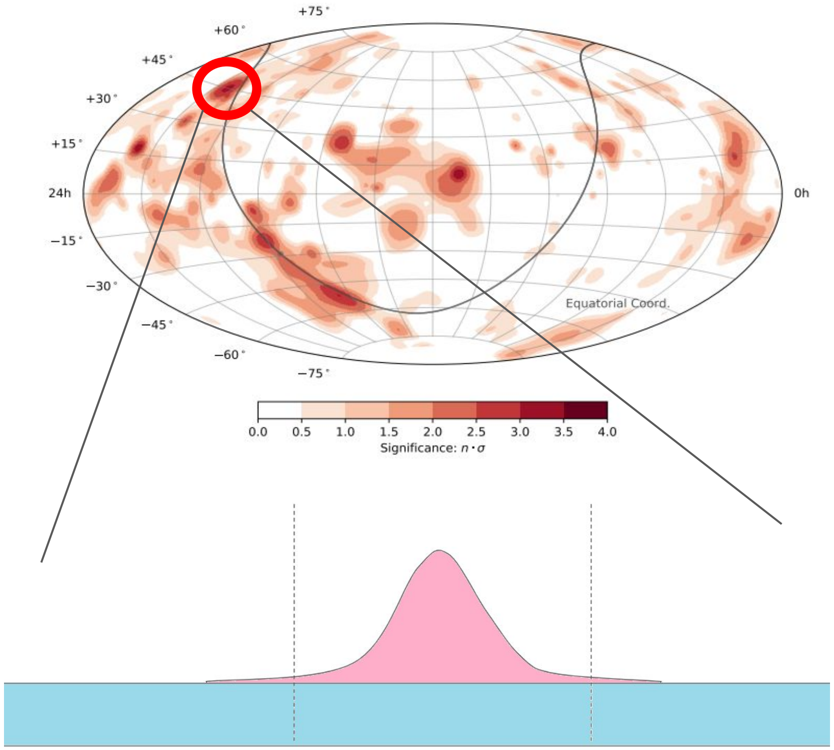
Bringing it all Together





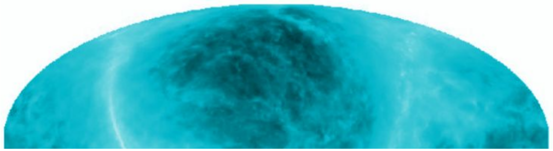
The Galactic Plane Localizes Neutrinos

- Instead of scanning the entire sky, we now just need to look at a small part of it
- We can identify extremely long baseline neutrinos with energy AND direction, where previously, we just had energy
- In tracks, this is restricting to ~4% of the sky



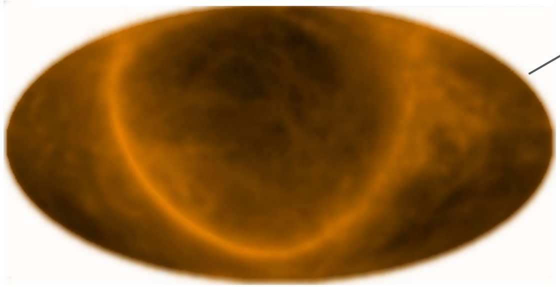
Track Sample
- High Purity
- Northern Sky
- Starting Separation
- DNN based reconstruction

Sensitivity to:
- Muon Neutrinos
- Some Tau Neutrinos

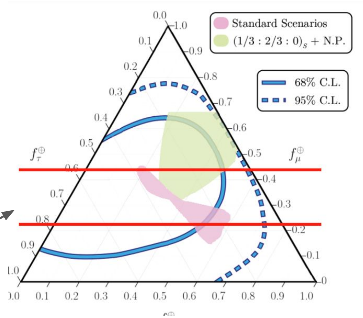


Cascade Sample
- High Energy resolution
- All Sky
- Hybrid-DNN based reconstruction

Sensitivity to:
- All Flavors



Look at both samples with the same galactic plane model

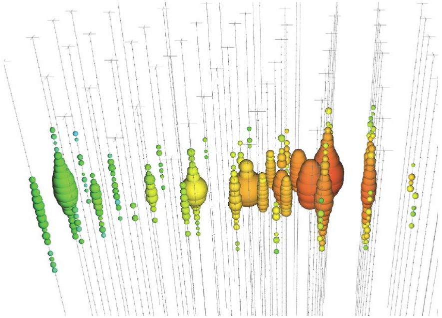


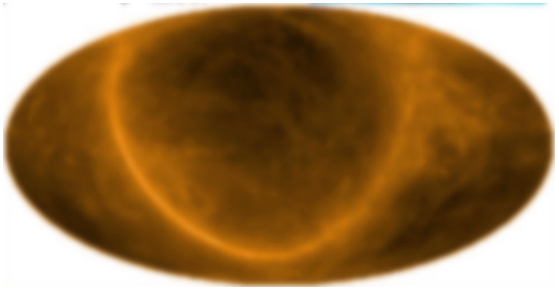
Extract Flavor Ratios

We can extract both Tracks and Cascades

- Our different event topologies give us access to different neutrino flavors
- If we do this in both tracks and cascades, we can measure the flux and flavor ratio in 3 dimensions

in





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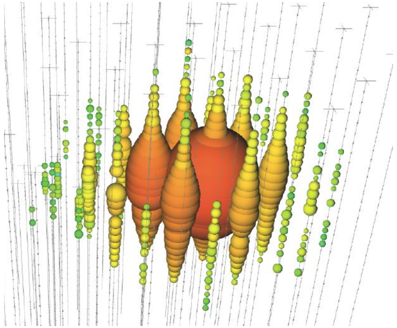
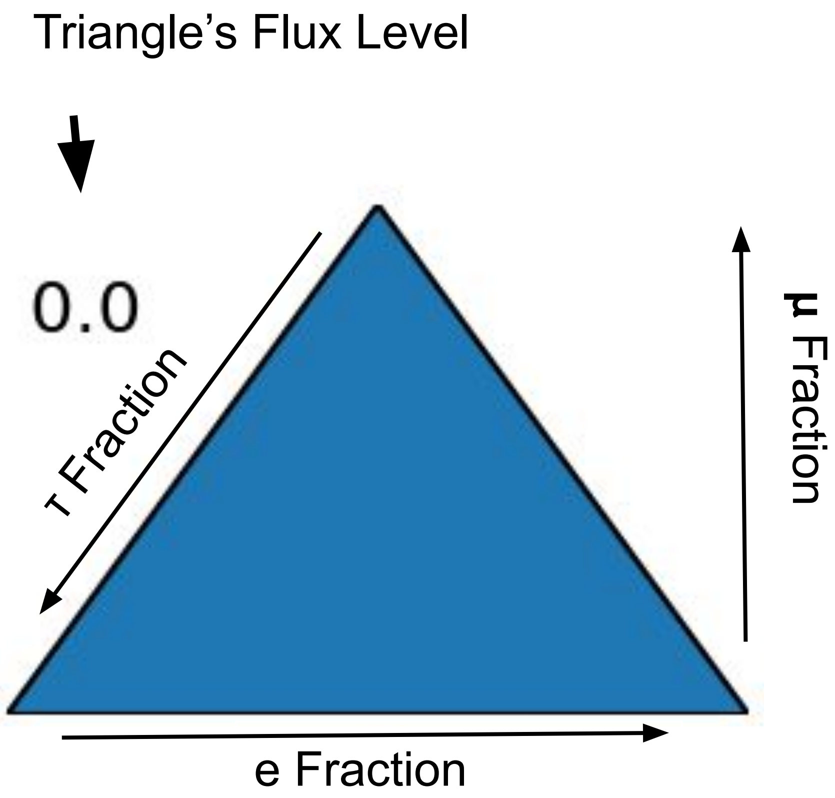


The Three Dimensions

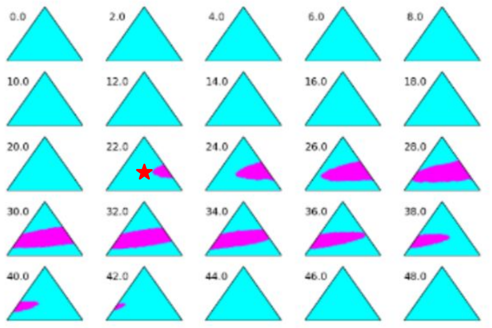
- We have 1 dimension of total flux (in units of 1/TeV cm^2s @100 TeV)
  - This is for the Pi0 galactic map
- And 2 dimensions of flavor ratio (constrained)
- We represent this in a grid of triangles at different flux levels
- The best fit point of the original galactic plane study was at a flux of 22.0
- First, let’s look at some realizations of 1σ regions:



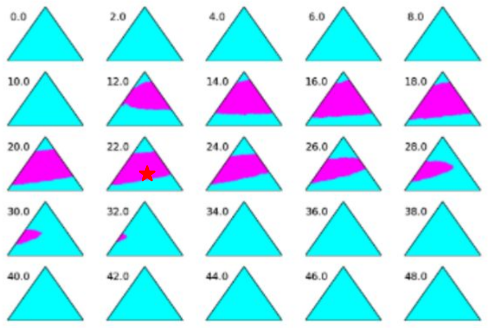
5 Typical realizations, 68% C.L.

IceCube Simulation

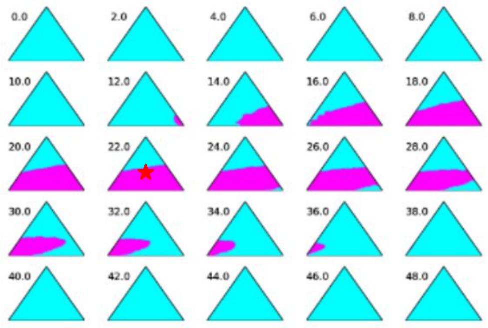
Random realization 1



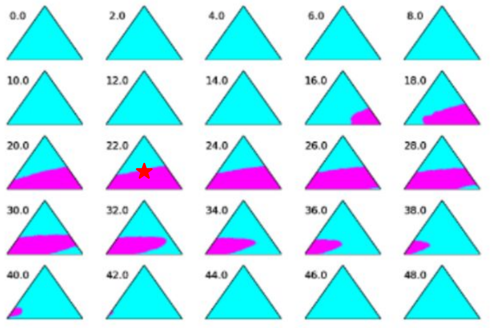
Random realization 2



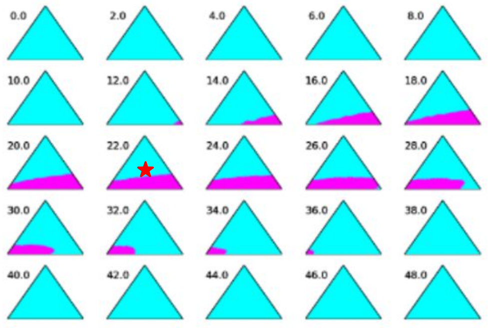
Random realization 3



Random realization 4



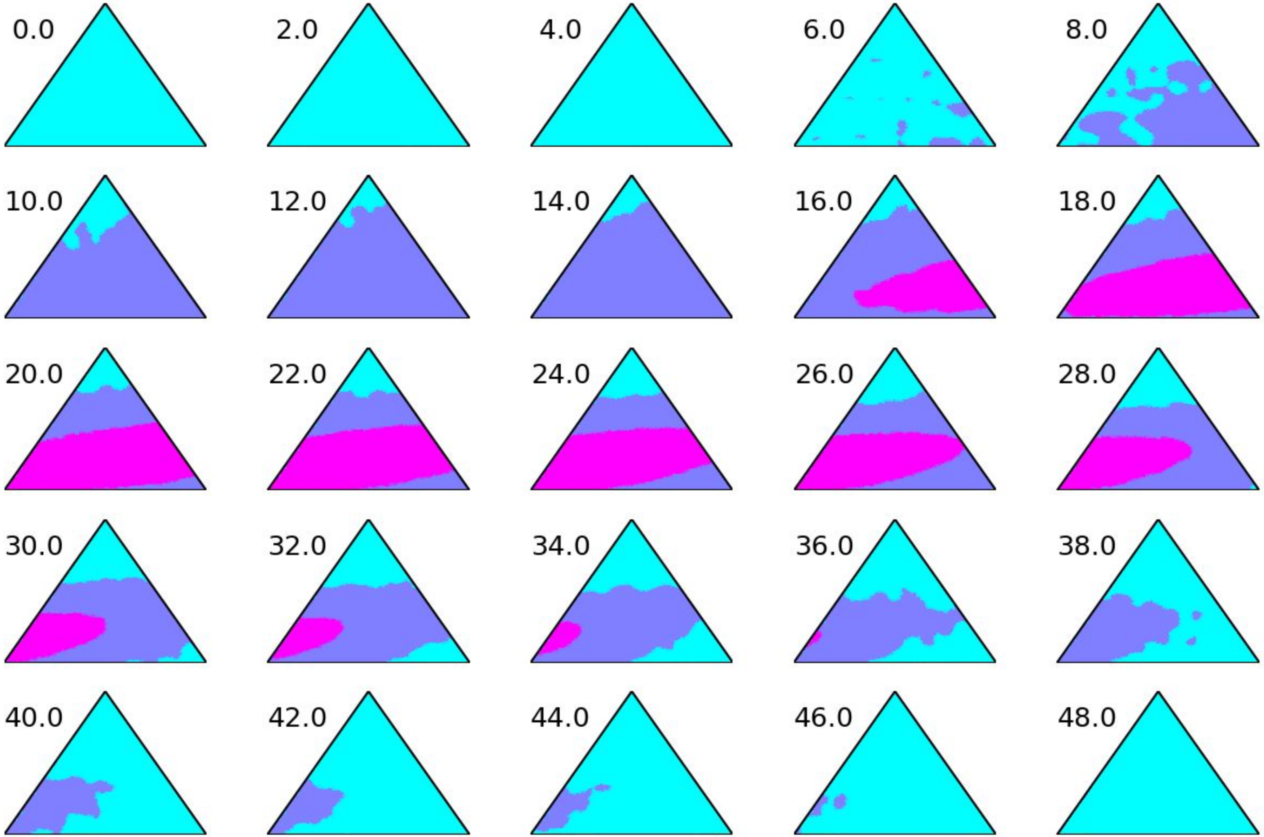
Random realization 5



Note the characteristic slant - this is due to the fact that we have minimal ability to discriminate between e and tau flavors

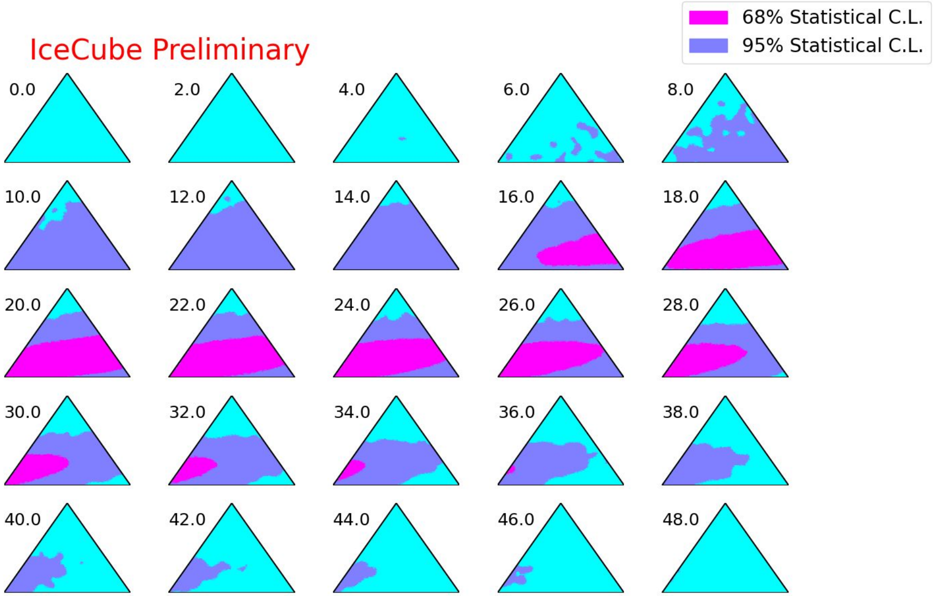
And, for our Pi0 template Regions:

1σ and 2σ Regions



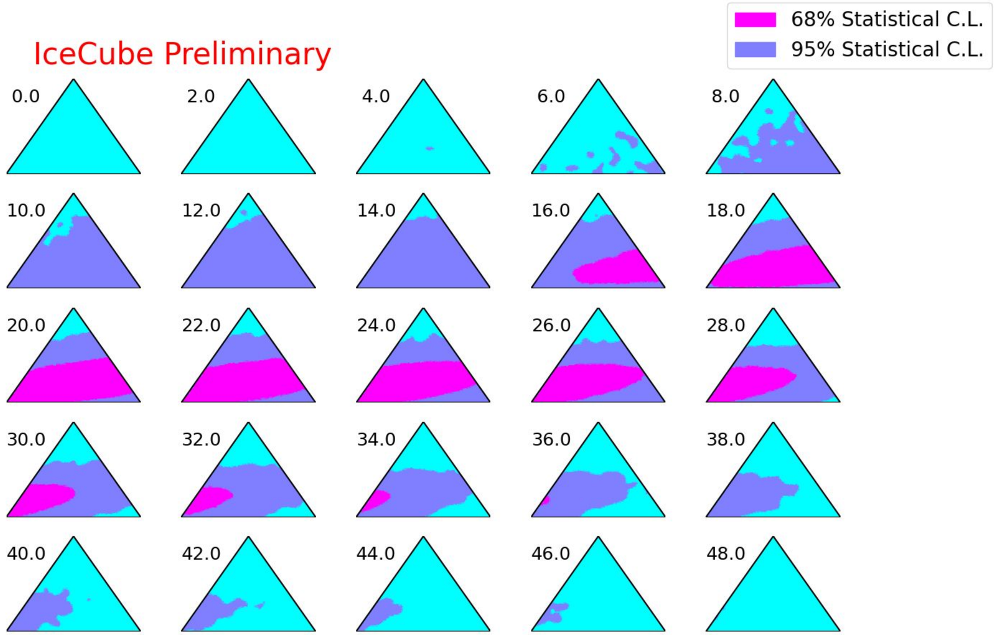
Results

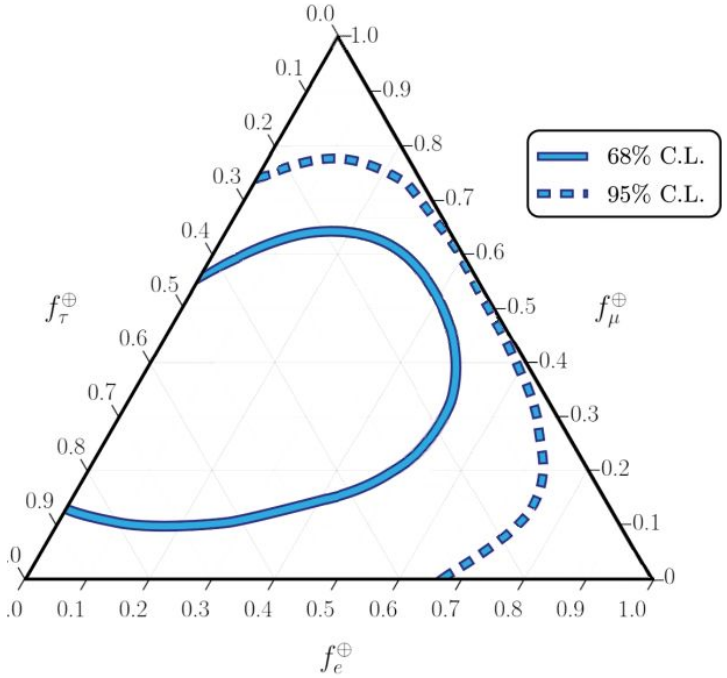
- This region looks very much like we expected
- Approximately the right size, and covers the correct region
- Constrains BSM theories predicting a non-uniform ratio
- First measurement of the neutrino flavor ratio from outside the solar system



Comparing a slice to 2021

Note that this is all sky vs Milky-way only. We are competitive in terms of size on the triangle.

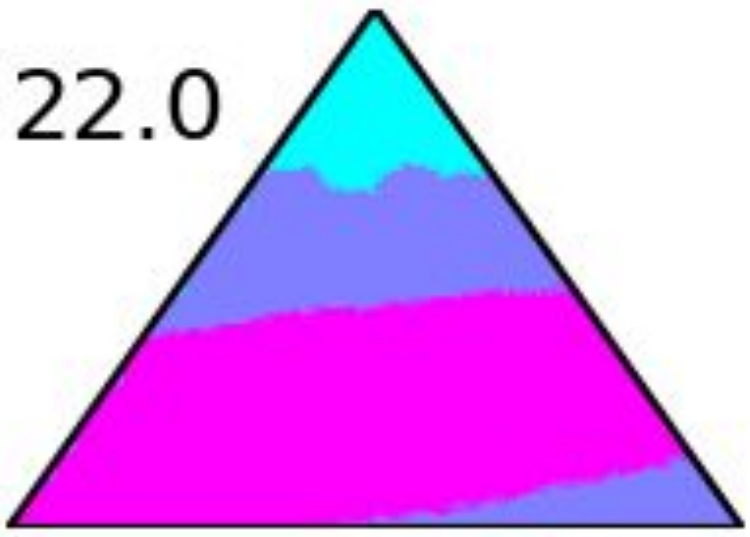


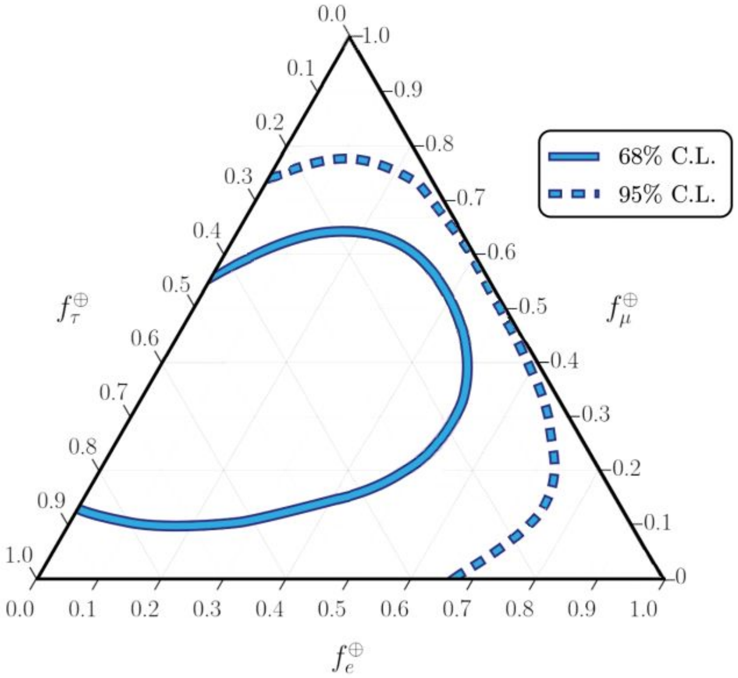


Comparing a slice to 2021

Compare to a slice (not profiled!), and you can see the relative size. Note that these are mostly statistically independent samples.

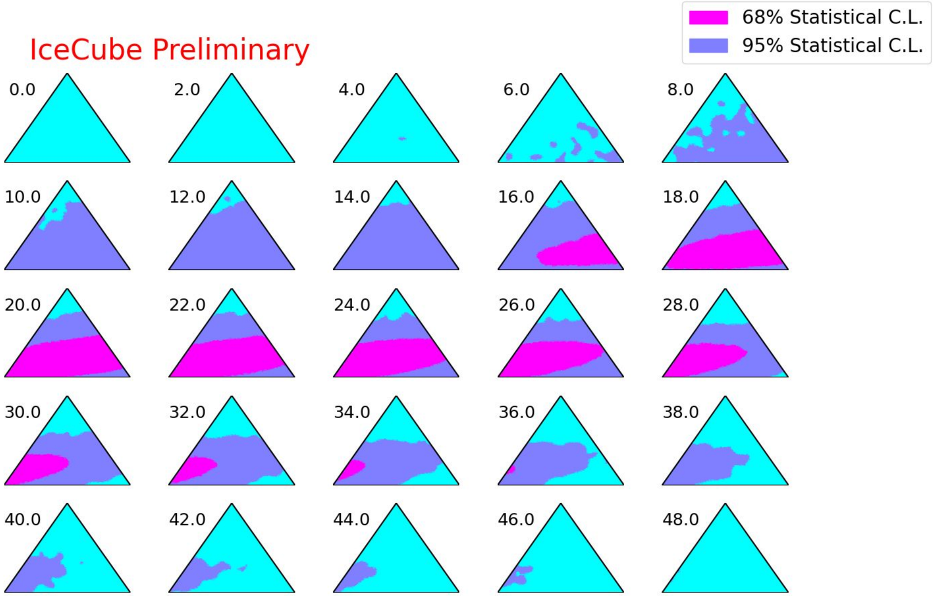
IceCube Preliminary





Up Next

- Now that we have this machinery, we can branch out
- Primarily, we are aiming to look at event by event information with modern ML techniques
    - Inelasticity
    - PID



Flavored Neutrinos Contain Tons of Physics

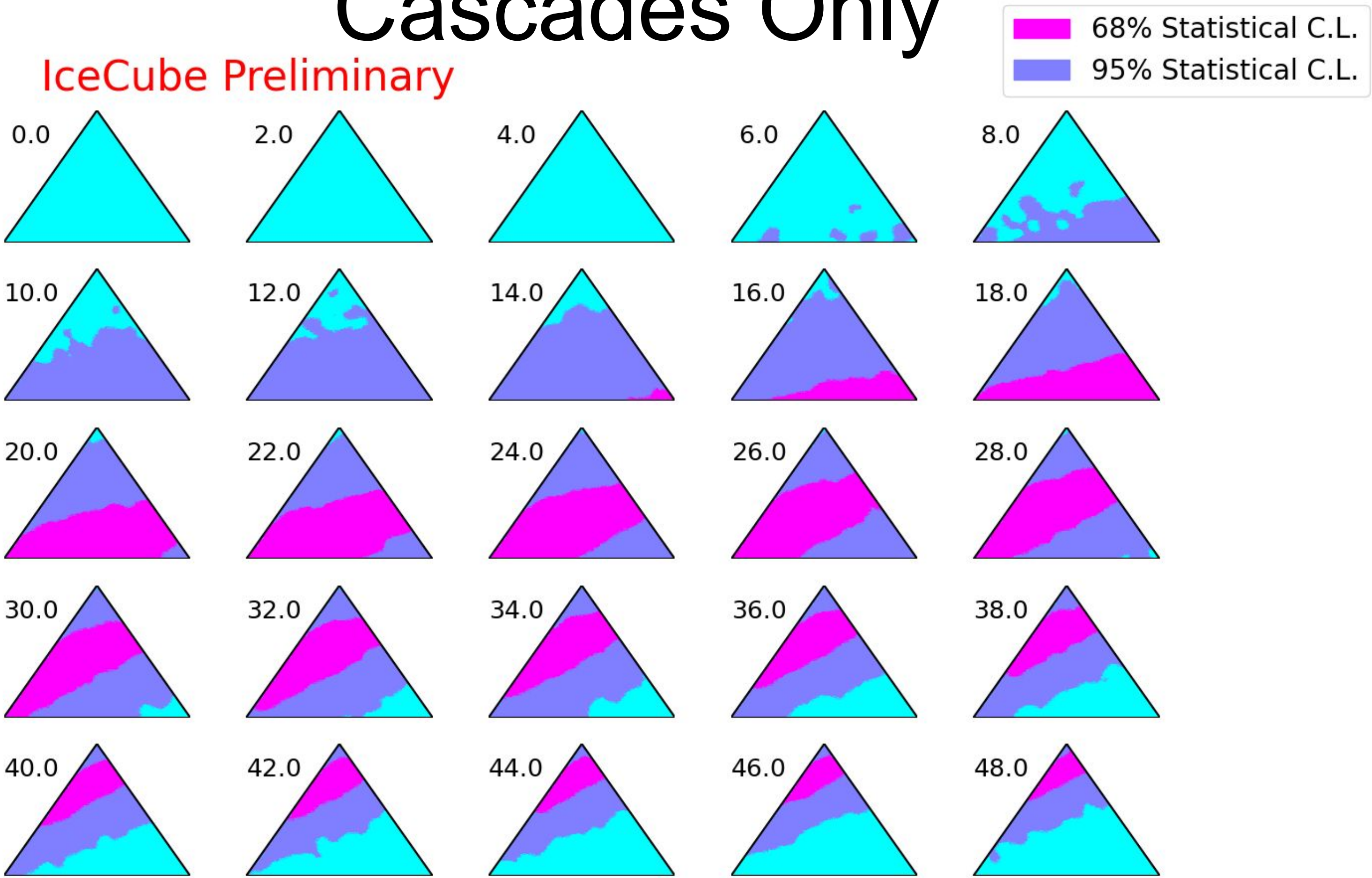
- We have measured the flavor composition of neutrinos coming from the Milky Way for the first time
- This is just the beginning of what we can do with this data
- Stay tuned - more analyses and an upgraded detector will let us do even better soon

Thank You

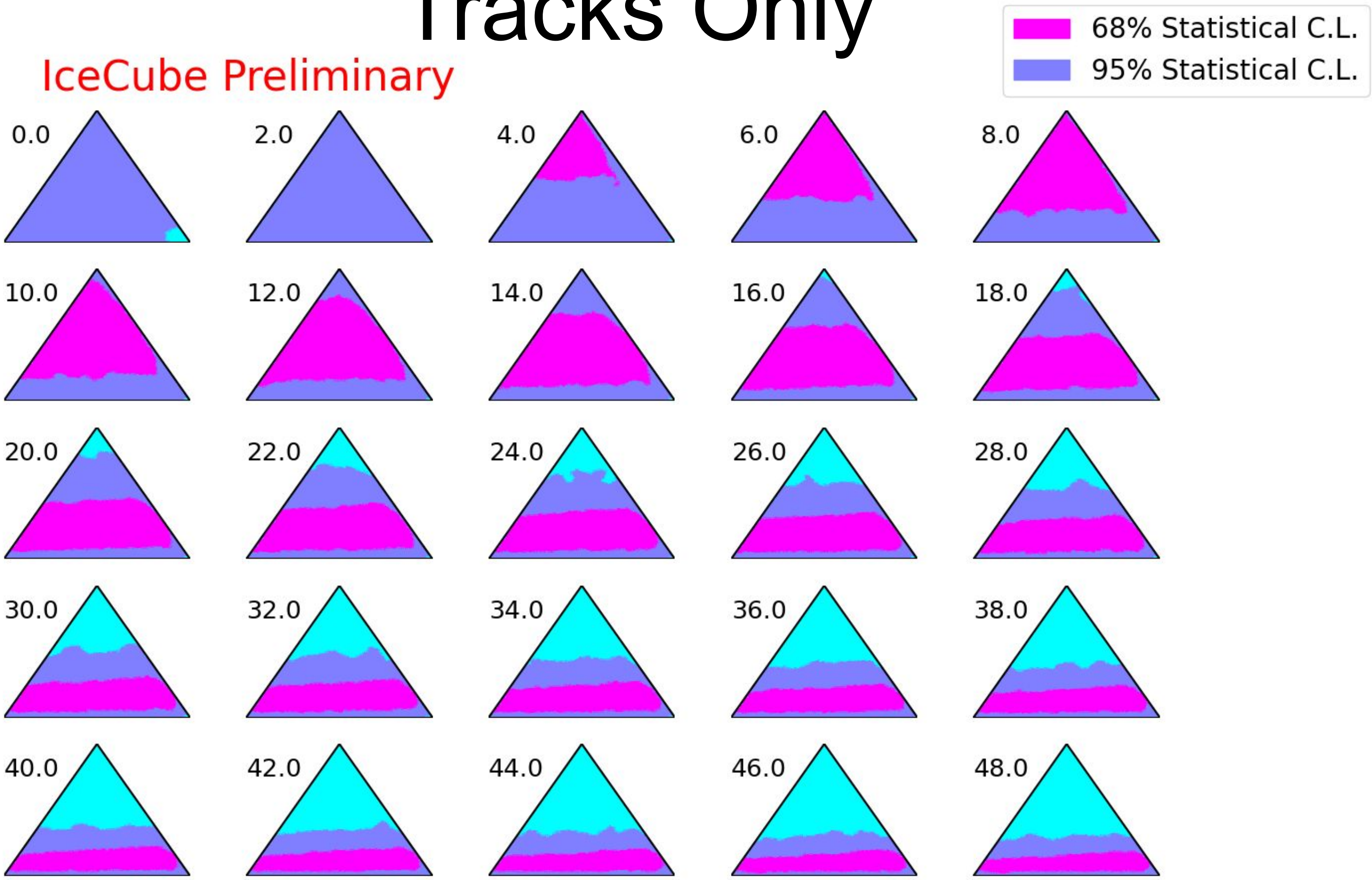
Backup

Splits

Cascades Only



Tracks Only

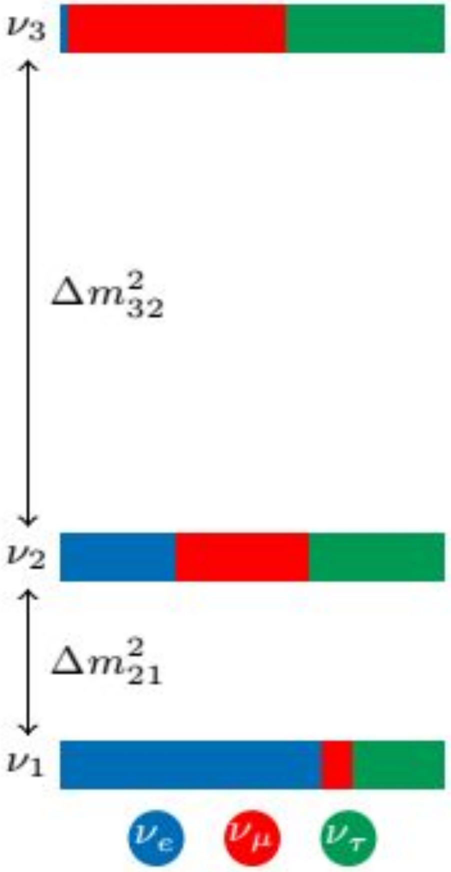


IceCube Preliminary
68% Statistical C.L.
95% Statistical C.L.
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
24.0
26.0
28.0
30.0
32.0
34.0
36.0
38.0
40.0
42.0
44.0
46.0
48.0

How do they oscillate?

- Mass and flavor states are not the same
- Similar to quark sector
- Is NOT diagonal
- Mass states are still a rotation of the flavor states
- Oscillation:

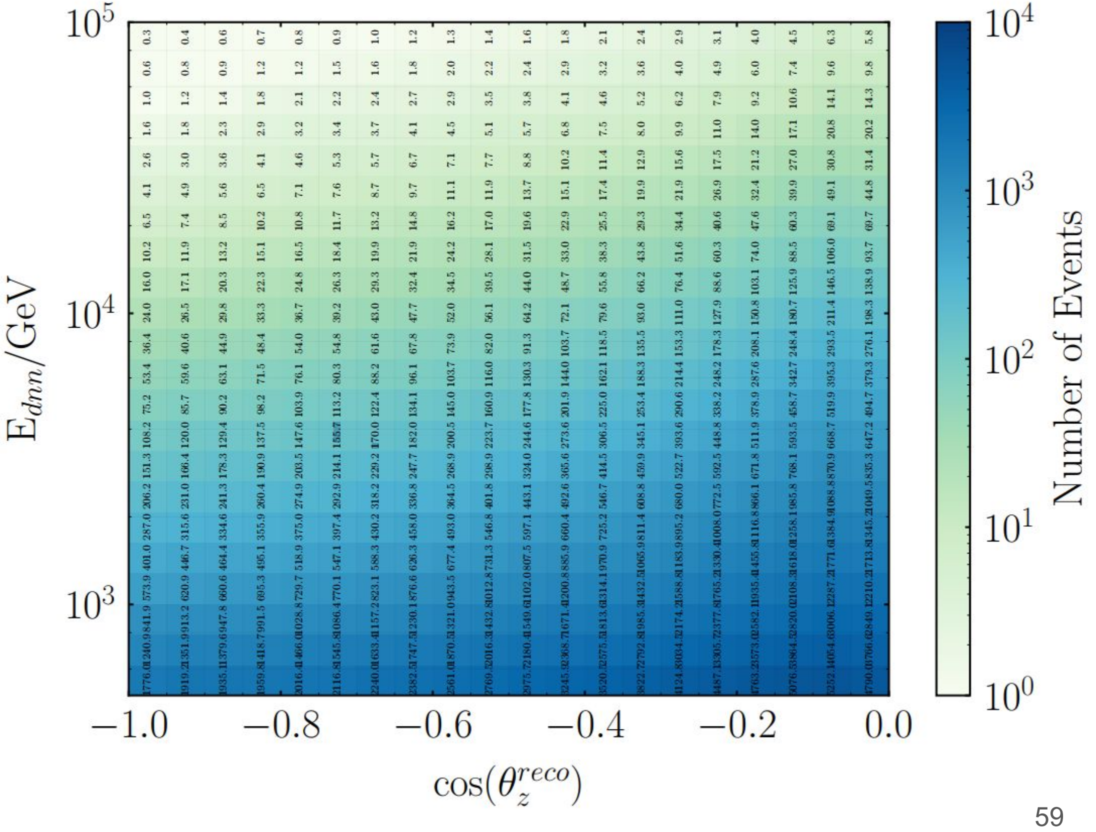
$$sin^2(1.27\frac{\Delta m^2 L[eV^2 km]}{E[GeV]})$$



Phys. Rep. 884, arxiv:1906.00045

What Track sample do we use?

- Extremely pure (>99.9%) sample of upgoing (Northern) tracks (Muon Charged Current)
- Primarily looking at atmospheric neutrinos
- ~360k events
- This gives you an idea of the distribution on the sky



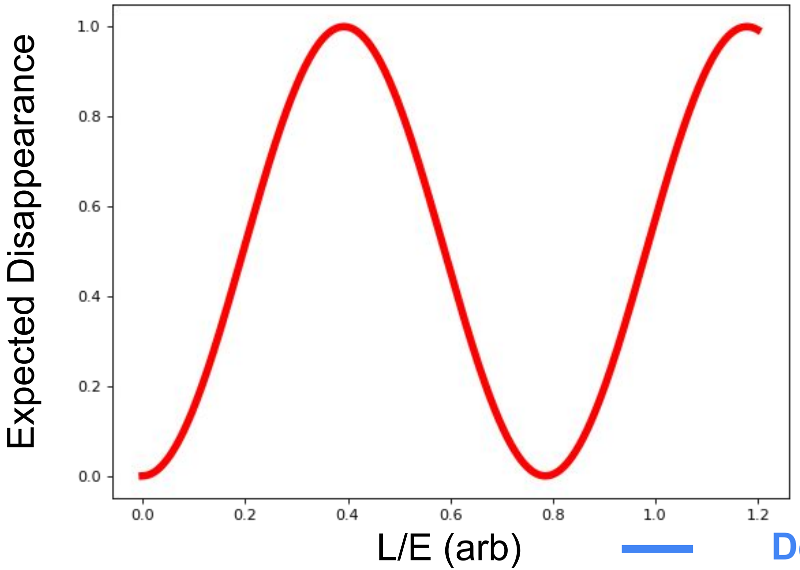
Neutrino Oscillation from Extremely Long Baselines

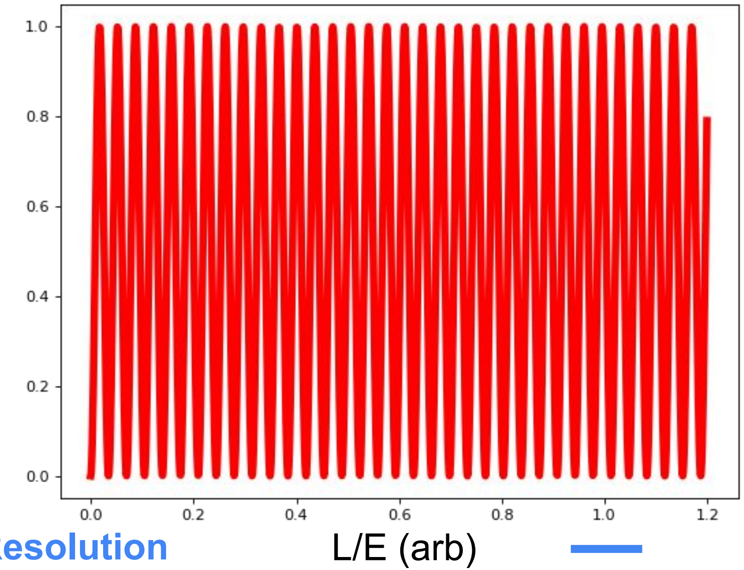
- Terrestrial experiments are short baselines
- But IceCube is looking for astrophysical neutrinos, which are emitted over very large distances at many energies
- IceCube can also look at earth-scale baselines, but that is another talk

Neutrino Oscillations over Extremely Long Baselines

- Over extremely long baselines, very small changes in energy can cover many oscillation lengths
- This leads to an expected flattening of the flavor ratio

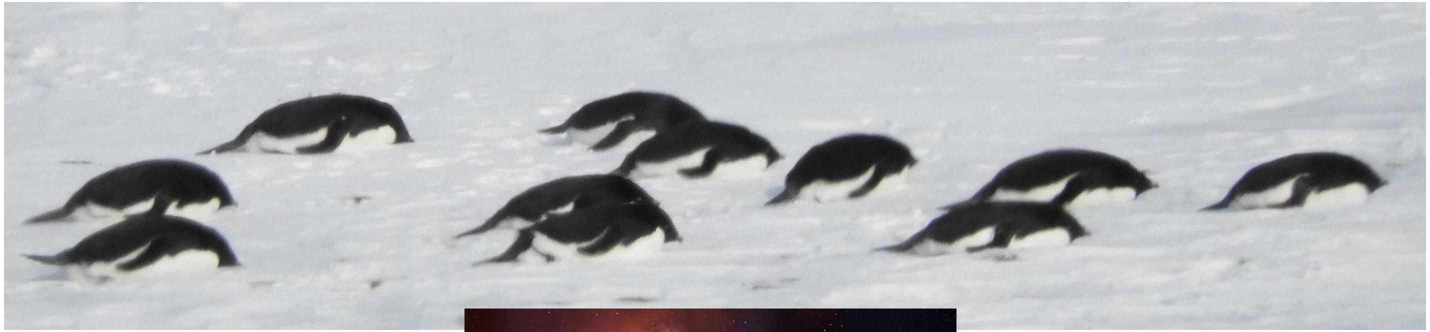
$$sin^2(1.27\frac{\Delta m^2 L[eV^2 km]}{E[GeV]})$$

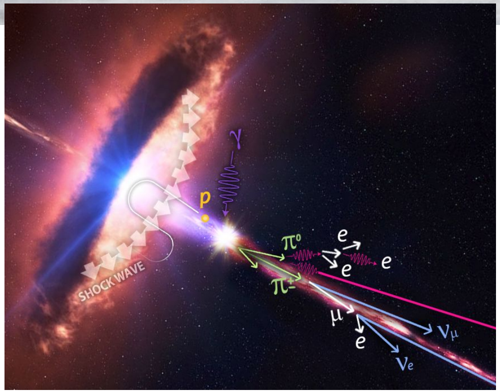




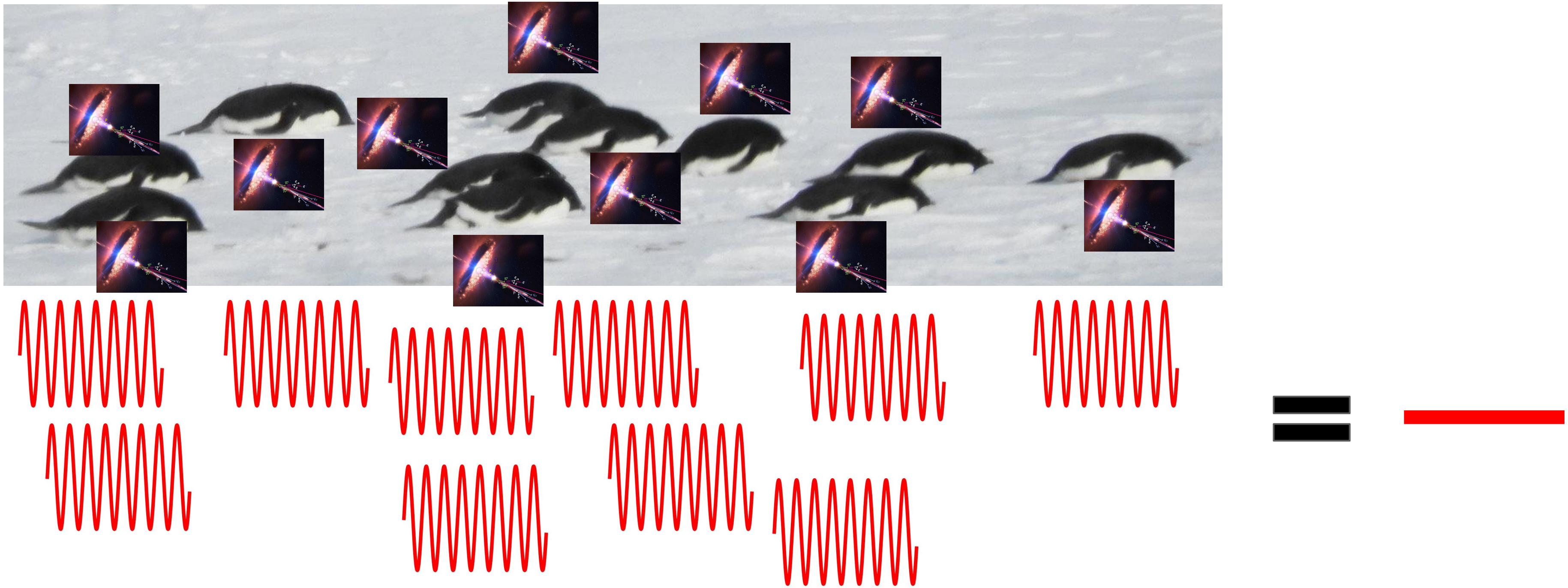
— Detector Resolution

But this isn’t the only effect flattening the oscillations





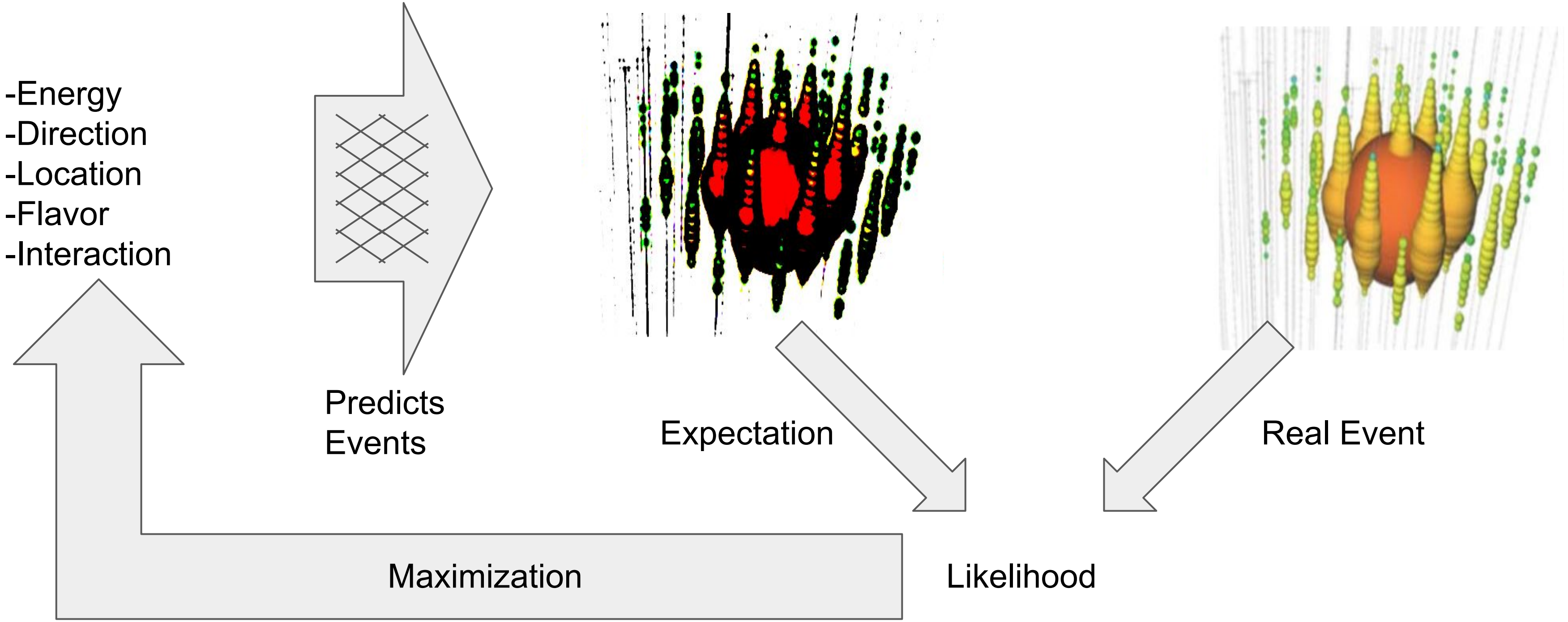
Neutrino emission over astronomical distances

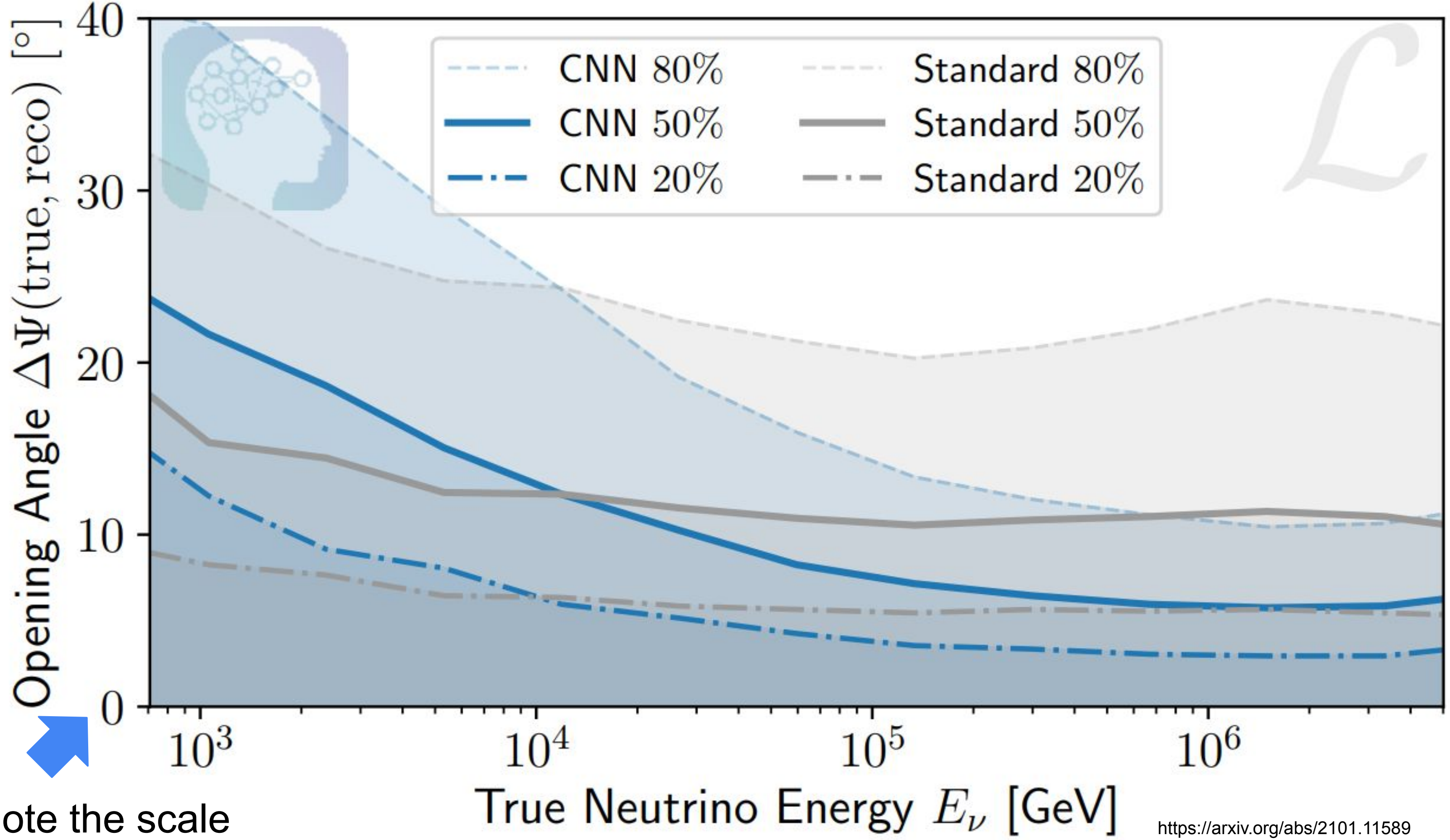


The new machine learning technique

- Works as a fast Monte Carlo
- Quickly convert hypothetical particle kinematics to a likelihood for optimization
- Optimizing based on this model produced a much better angular resolution and allowed for a larger acceptance
- Ultimately, resulted in ~60k cascades to analyze for excess in the galactic plane

Using Generative Machine Learning for Reconstruction





Note the scale

https://arxiv.org/abs/2101.11589