IceCube Summer School 2025
Zoë Rechav

Event Selections

Event Selections

What are they?

General Techniques

Case Studies

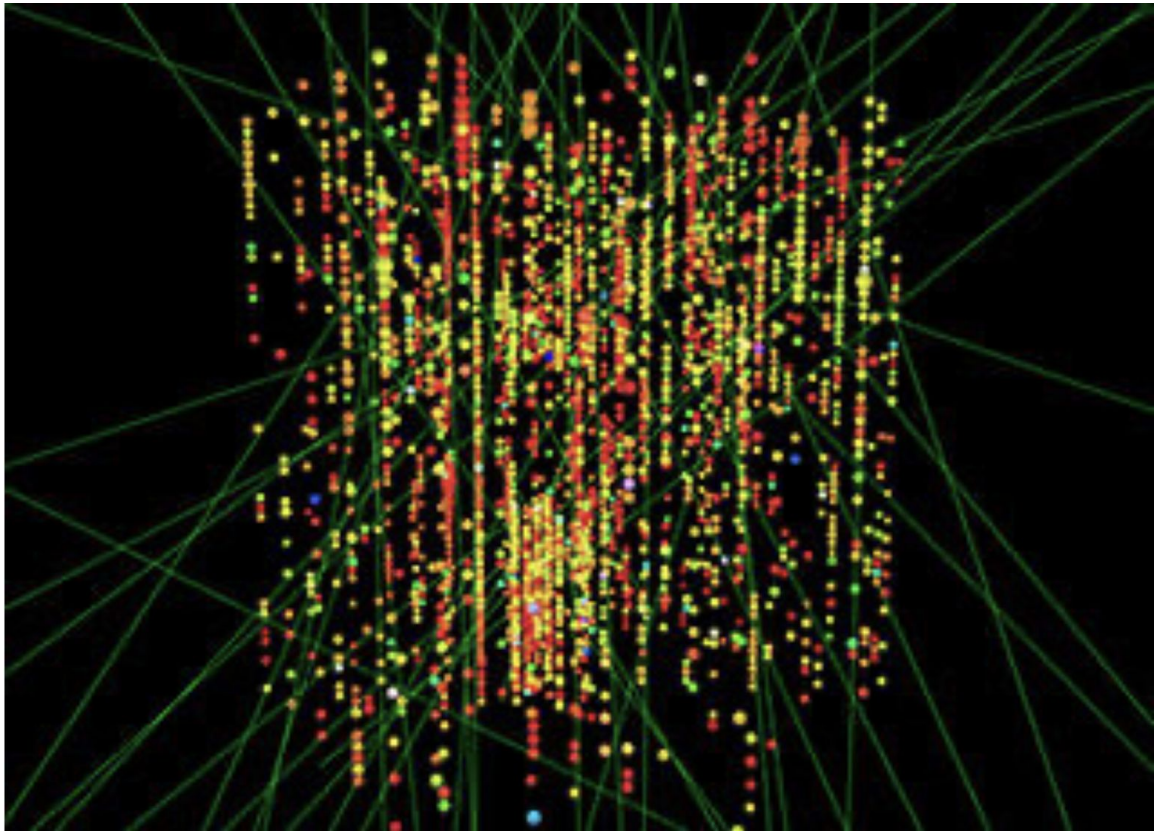
An Event Selection Is…

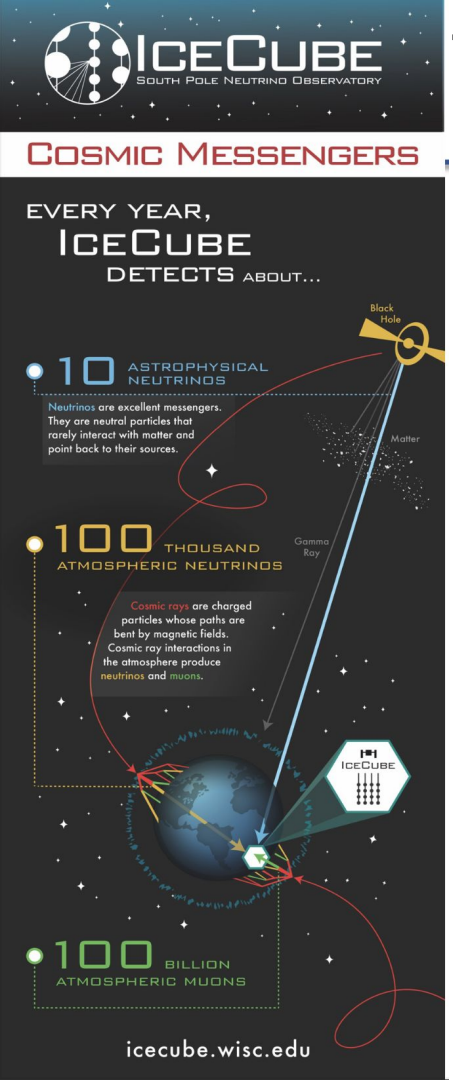
Data you have selected to
best answer a physics question

Data for Us → IceCube Events

- An event is just a series of **pulses**: charge and timing information from each DOM
- Detector is always taking data of events
- After cleaning and before ‘selecting’ events, roughly **4 million events** seen in the detector **per day**

a few microseconds in IceCube → looks like a mess

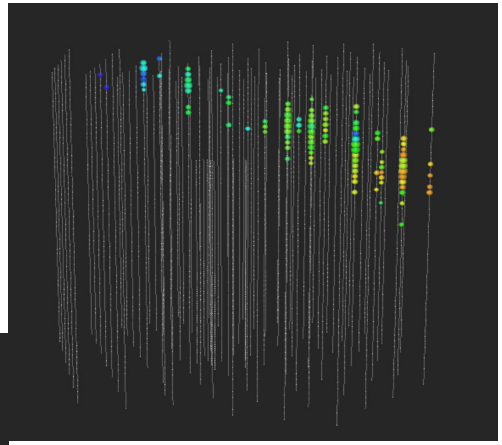




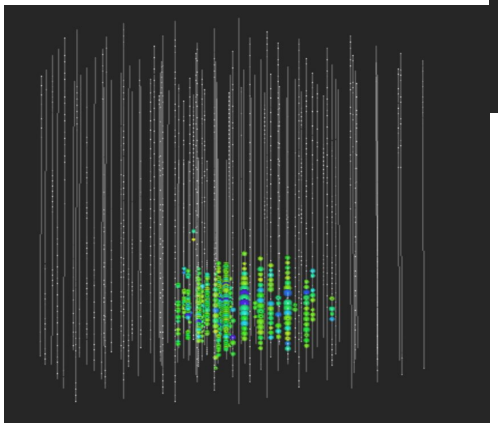
Types of Events

- Atmospheric Muons 100 Billion
- Atmospheric Neutrinos 100 Thousand
- Astrophysical Neutrinos 10

Track Event →
(angular resolution)



- Cascades
- Tracks



← Cascade Event
(energy resolution)

Mission of event selection → gather <u>your</u> events

Atmospheric Muons 100 Billion → Cosmic Ray
Atmospheric Neutrinos 100 Thousand → Oscillations, Diffuse
Astrophysical Neutrinos 10 → Diffuse, Point Source

Cascades
Tracks

Different analyses care about different types of events

Most of the job is →

- identifying events to answer your <u>physics question</u>
- keeping as many of your events as possible
- <u>developing/implementing techniques</u> to differentiate events
- a LOT <u>harder</u> than it sounds

Event Selections

What are they?

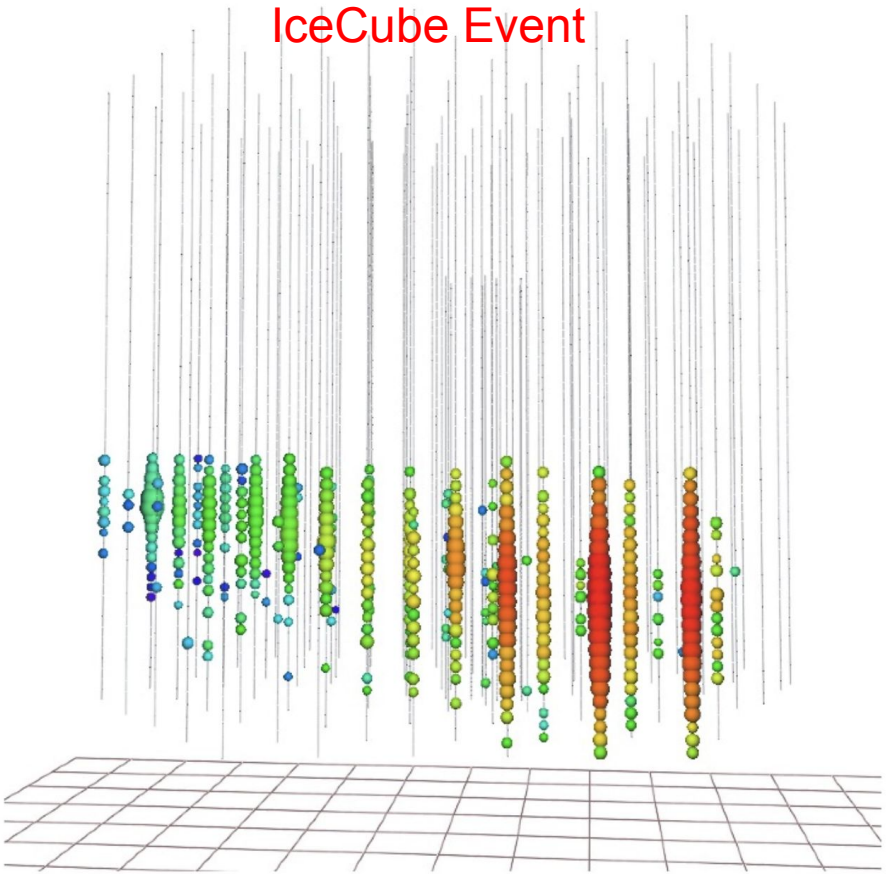
General Techniques

Case Studies

There are many techniques, I will only describe a few

The goal is design and implement new/updated techniques (that work)

Filtering – The First Step



For each event you have

- Charge
- Time

Information for each DOM in detector

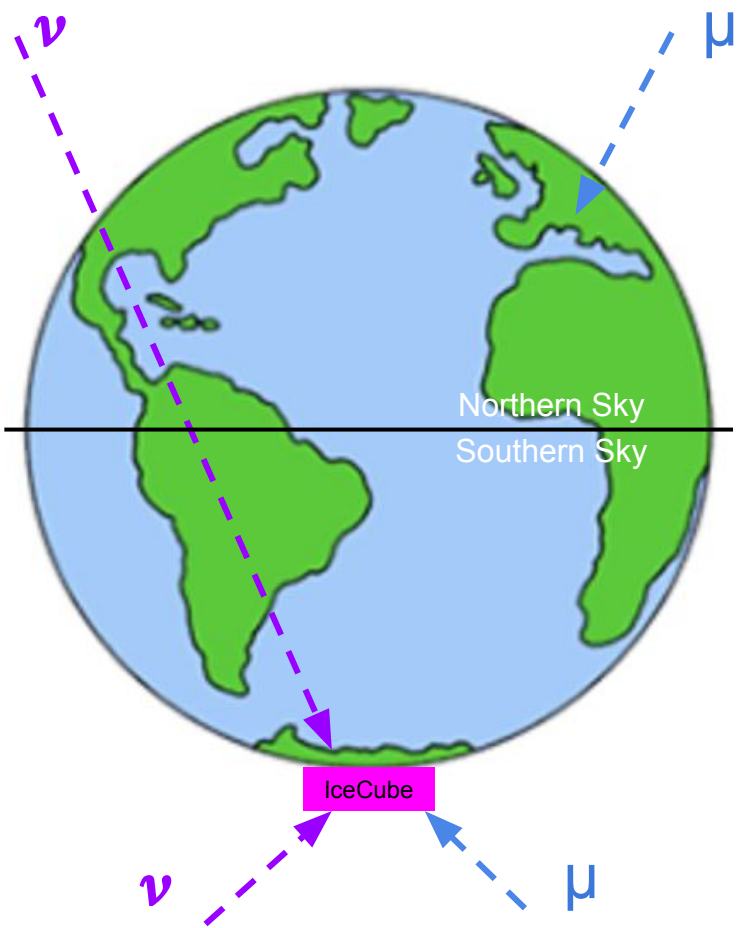
Can broadly identify event types

Some examples:

- Cascade Filter
- Muon Filter
- Deepcore Filter

from now on, assume my goal is an astrophysical neutrino selection

Post Filtering → **Find the Neutrinos**: Using Earth (event zenith)



Southern Sky:

- IceCube is on southern surface
- neutrinos **and** muons reach detector

Northern Sky:

- Earth is a muon shield
- Only neutrinos reach IceCube

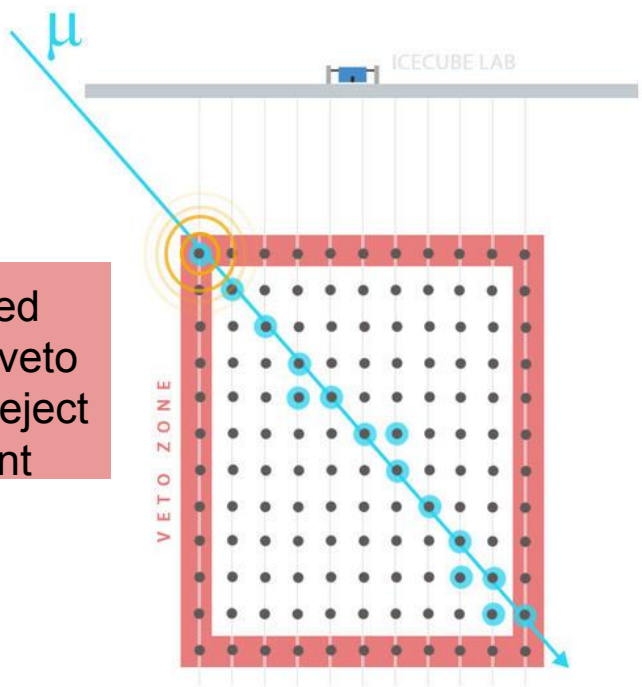
Looking at Northern sky only → eliminates most muons from your sample

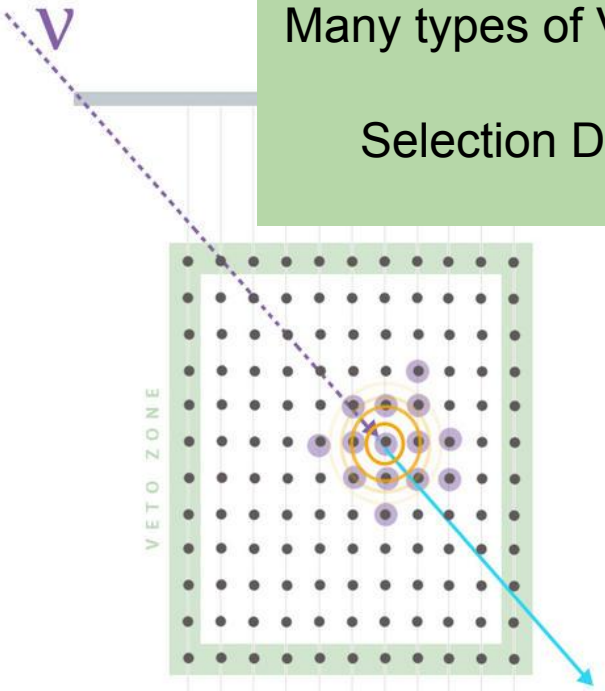
If you want to include Southern sky…

Find the Neutrinos: Active Veto Regions

- Muons leave light along entire path of travel (energy losses) → track-like
- Look for events that **don't do that** → more likely to be neutrinos

Deposited charge in veto region → reject the event



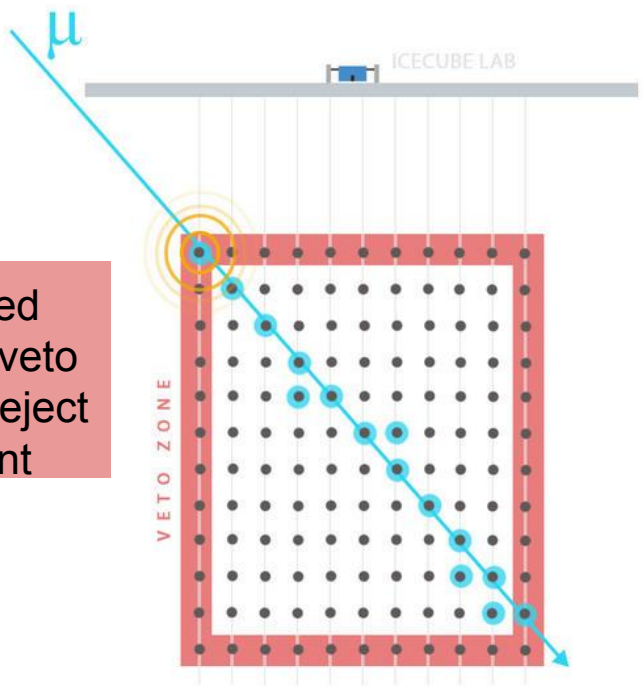


Many types of Veto Regions

Selection Dependent

Find the Neutrinos: Active Veto Regions

- Muons leave light along entire path of travel (energy losses) → track-like
- Look for events that **don't do that** → more likely to be neutrinos



Deposited charge in veto region → reject the event

Type 1 Veto Region:
- Layer of outer volume
- Good for HE Cascades

Find the Neutrinos: Active Veto Regions

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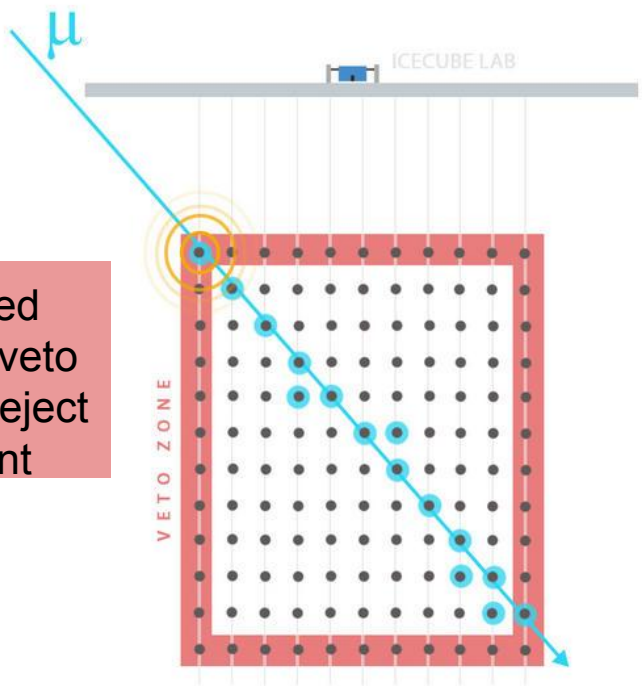
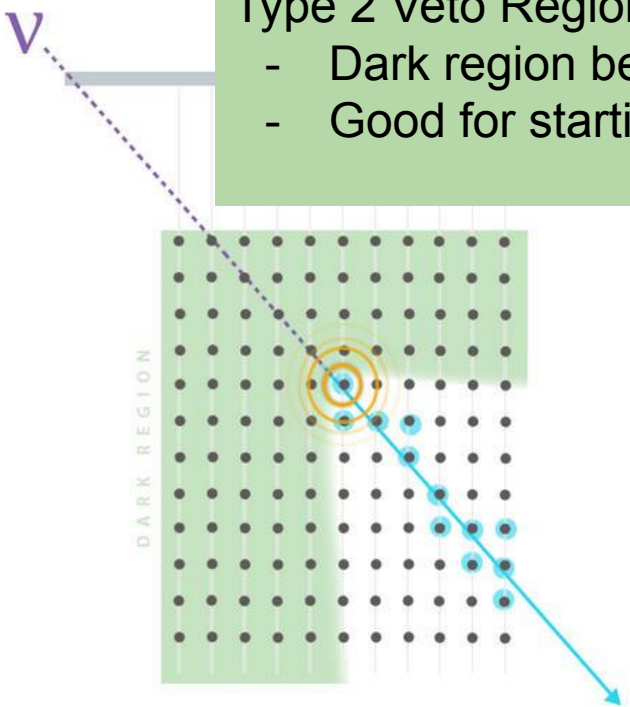


Deposited charge in veto region → reject the event

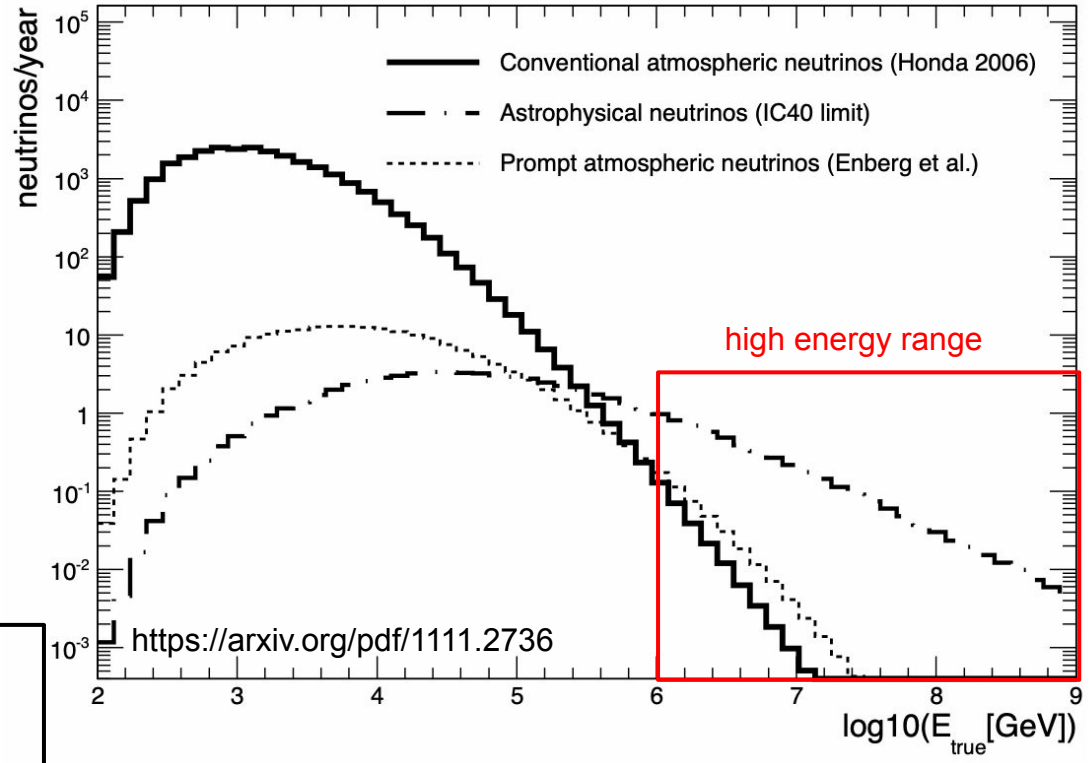


Type 2 Veto Region:
- Dark region behind vertex
- Good for starting tracks

Neutrinos: Atmospheric vs. Astrophysical (Energy)

- Looking only at neutrino events → cannot differentiate atmospheric vs. astrophysical

- Simplest case → Look at high energy range
  - Atmospheric neutrinos are lower in energy
  - high energy neutrinos are much more likely to be astrophysical



It starts to get difficult If you want to include lower energy range…

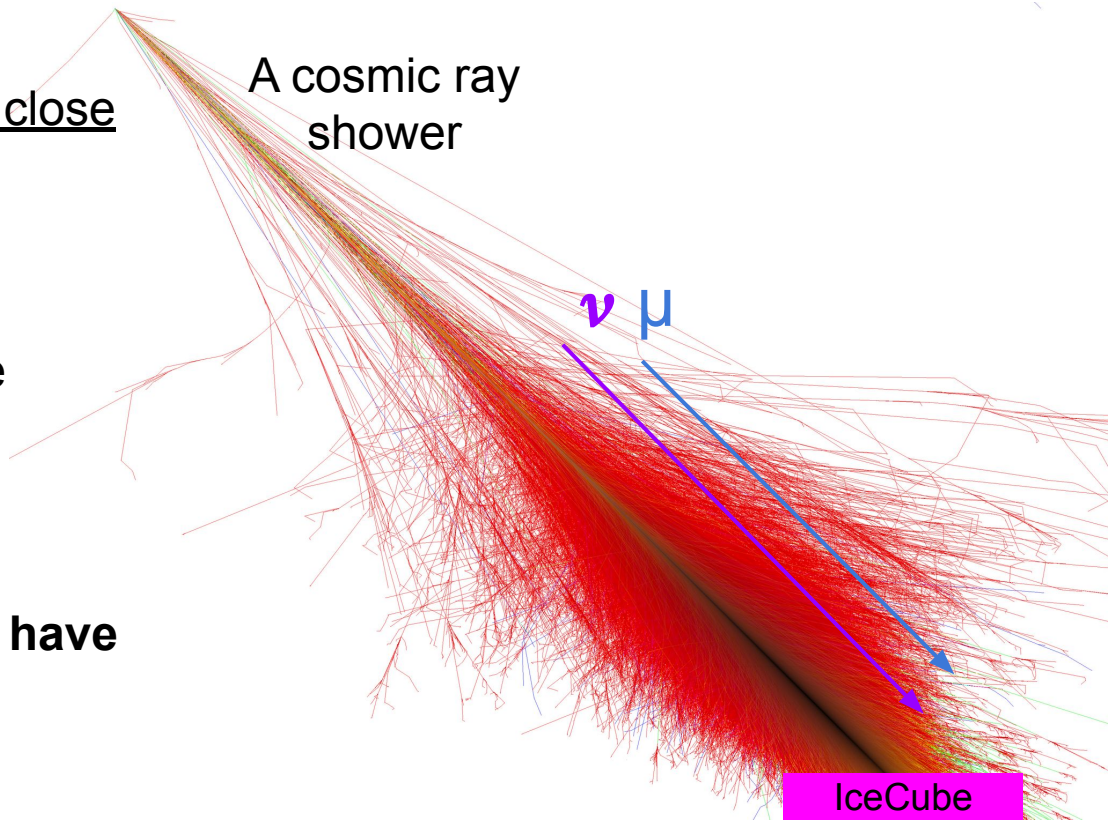
Neutrinos: Atmospheric vs. Astrophysical (Self Veto)

Cosmic Ray Showers produce atmospheric neutrinos with accompanying muons that reach IceCube

Neutrino and muons arrive very close together in time

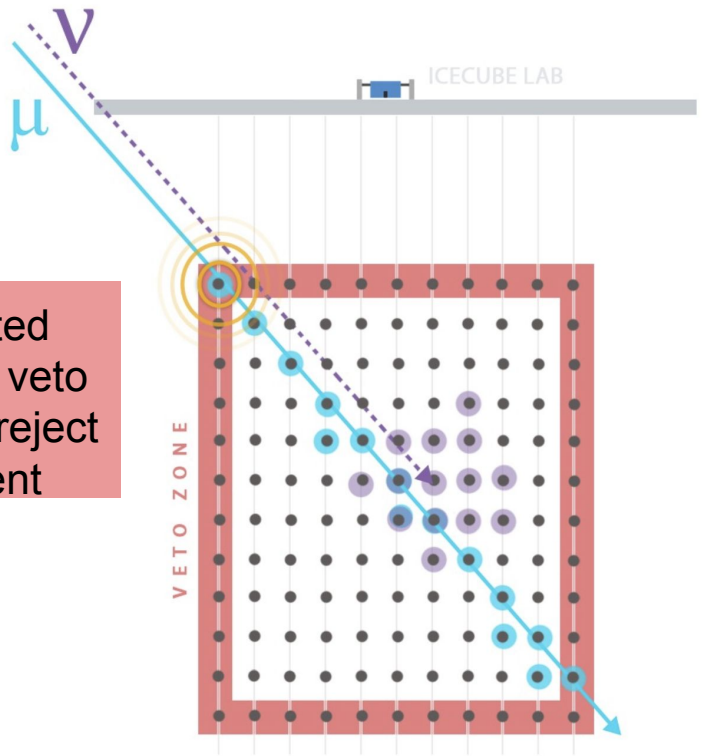
Atmospheric neutrinos can have accompanying muons

Astrophysical neutrinos **will not have** accompanying muons



Neutrinos: Atmospheric vs. Astrophysical (Self Veto)

When muon is rejected,
so is the atmospheric neutrino



Deposited charge in veto region → reject the event

This seems straightforward to account for, except for one problem

At IceCube we have neutrino only simulation (NuGen) and muon only simulation (Corsika, MuonGun)

We are not yet able to fully understand the relationship between same shower atmospheric neutrinos/muons

Cannot differentiate neutrinos if we don't also understand the atmospheric component

Neutrinos: Atmospheric vs. Astrophysical (Self Veto)

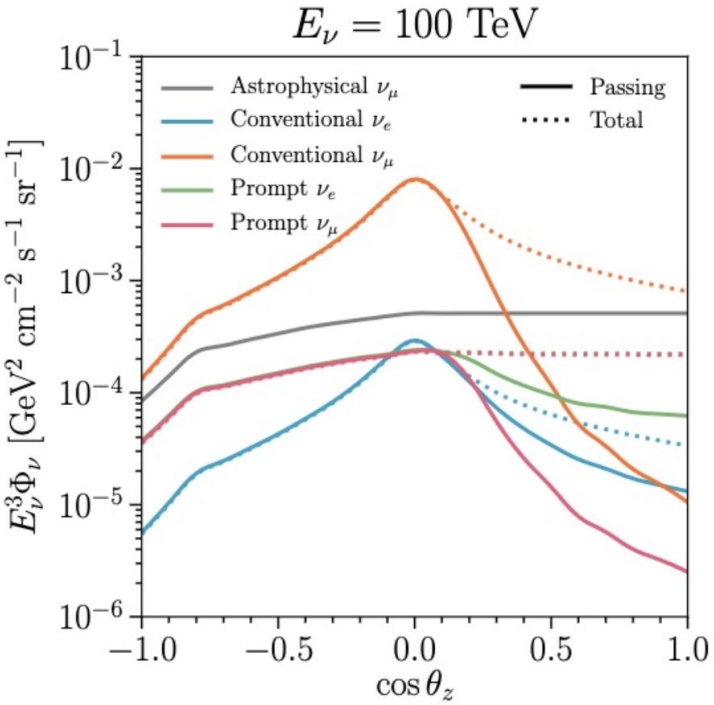
To understand the atmospheric neutrino flux, analyses must model the probability a neutrino will be rejected by its muons in a selection

Some methods:

- Assuming all events with an accompanying muon above a given energy threshold will be rejected (**Step Function**)
- **Injecting Muons** into your surviving neutrinos, and re-applying event selection to see how many events survive
  - Single muons using assumed spectrum
  - Muon Bundle injection using Corsika Simulation (me - my life's work)

RESULT

Higher proportion of astrophysical neutrinos in southern sky

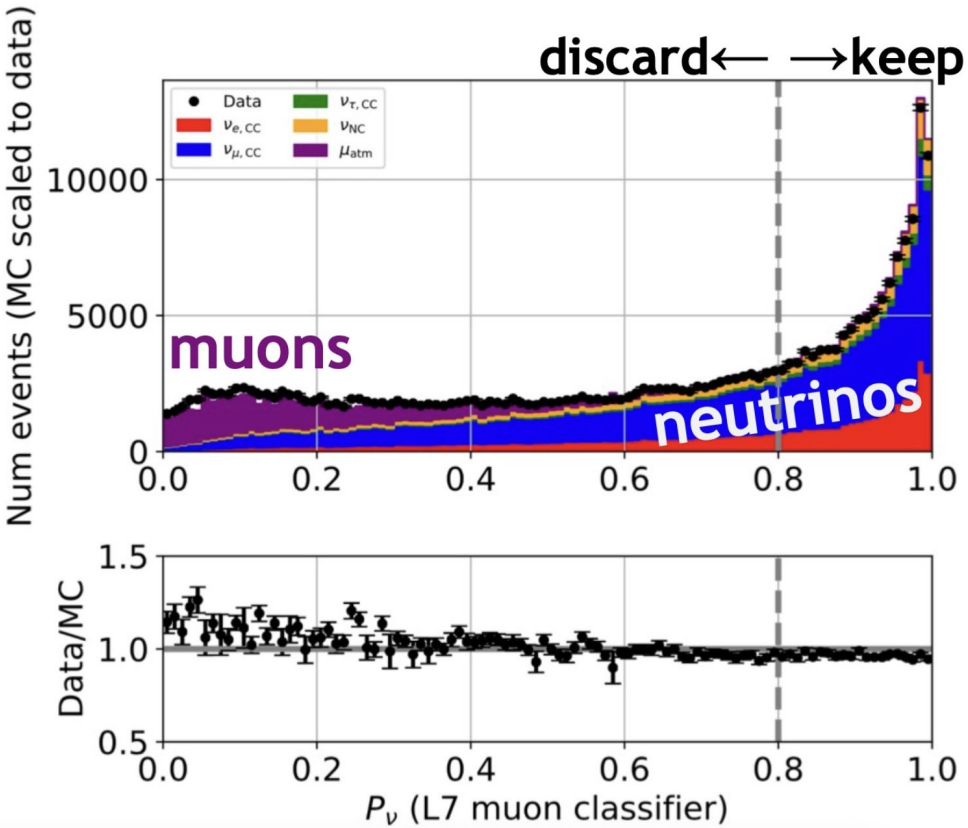


More Identification Methods: Neural Networks and BDTs

Can train neural networks and Boosted Decision Trees (BDTs) to differentiate between event types, <u>any event types</u>

Example BDT from OscNext (low energy deepcore events):

- Output 0 to 1
- More neutrino-y if ~1
- More muon-y if ~0
- Choose how strict you Want your classifier



LOTS of BDT classifiers in IceCube

They do all sorts of things

Event Selections

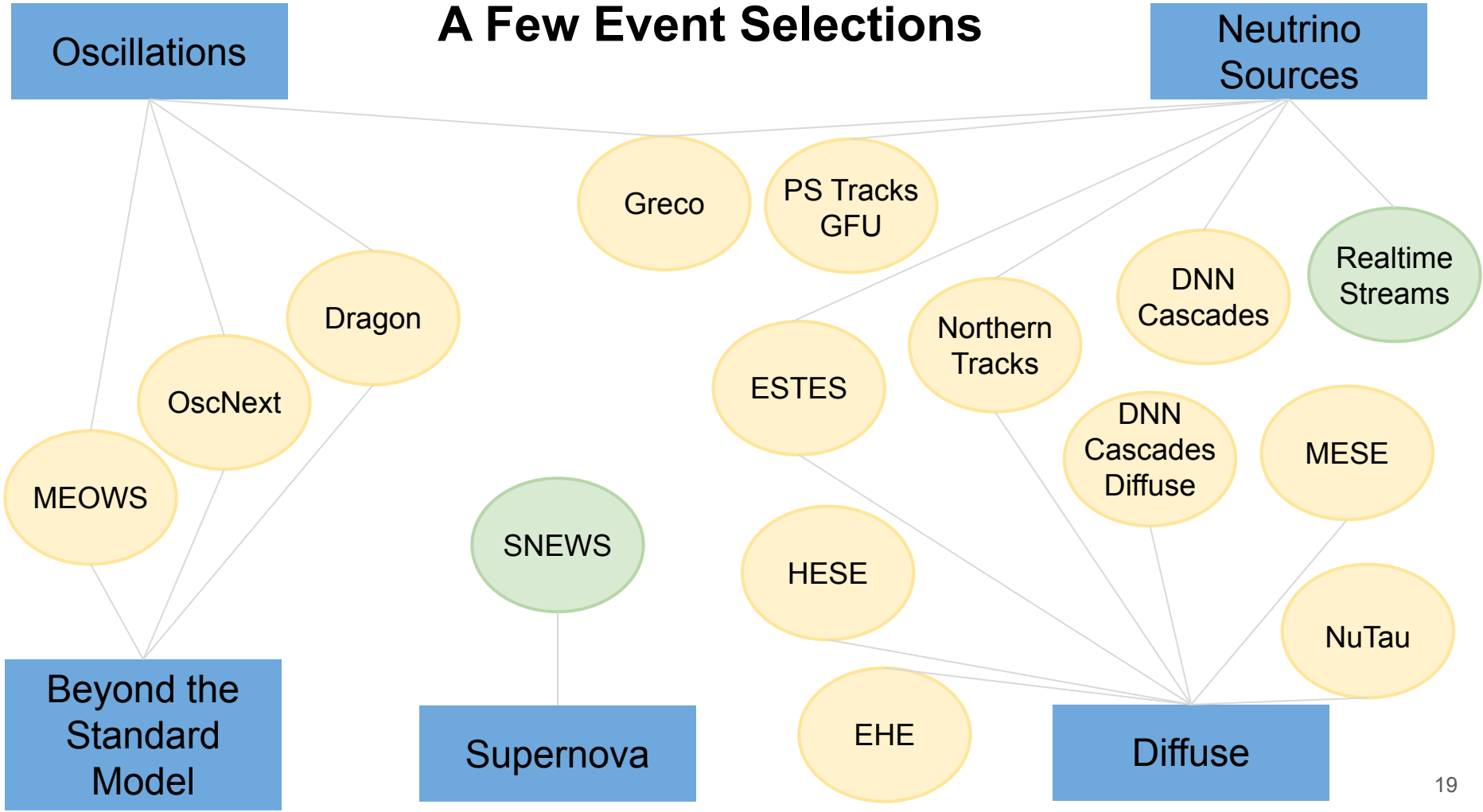
What are they?
General Techniques
Case Studies

There are many selections, I will only describe a few

The goal is design and implement new/updated selections!

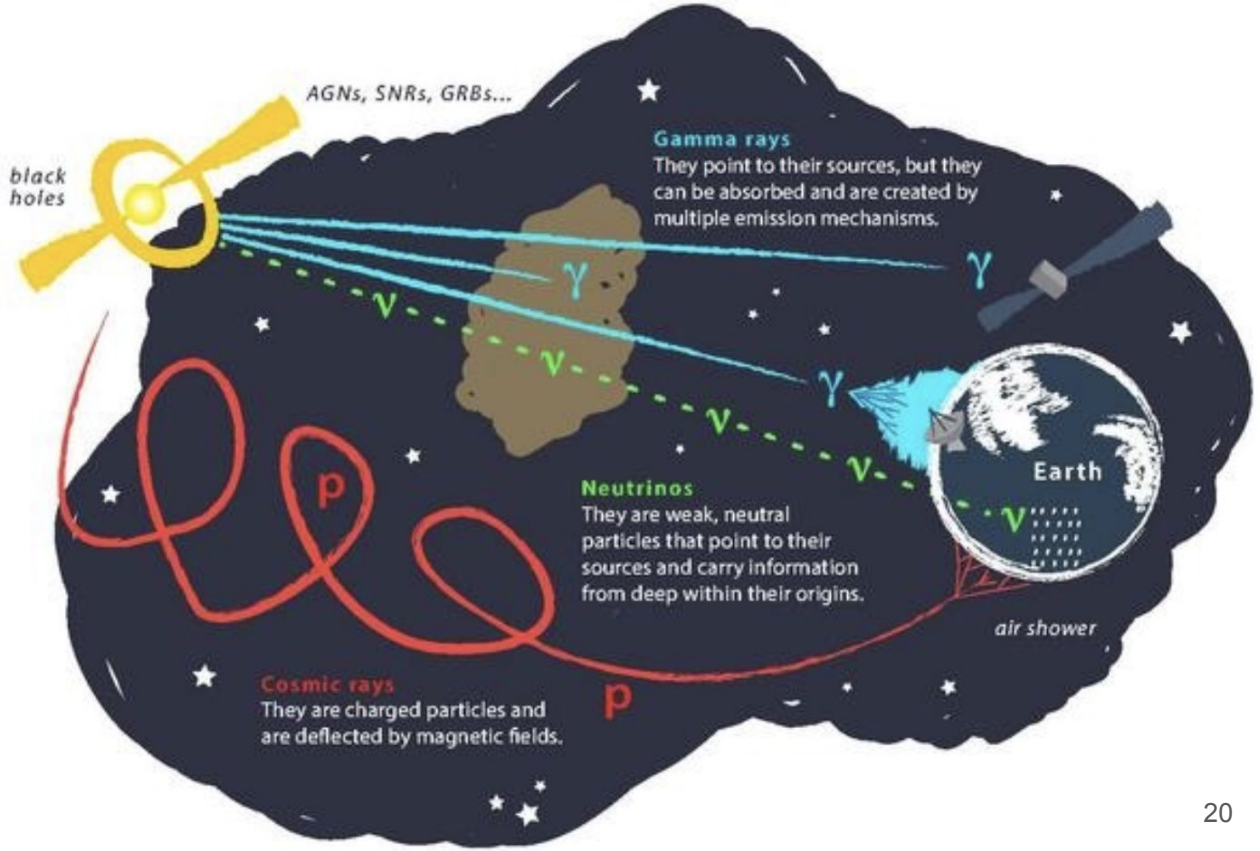
These selections were built to answer physics questions

A Few Event Selections



A Physics Question:
Where do Astrophysical Neutrinos Come From?

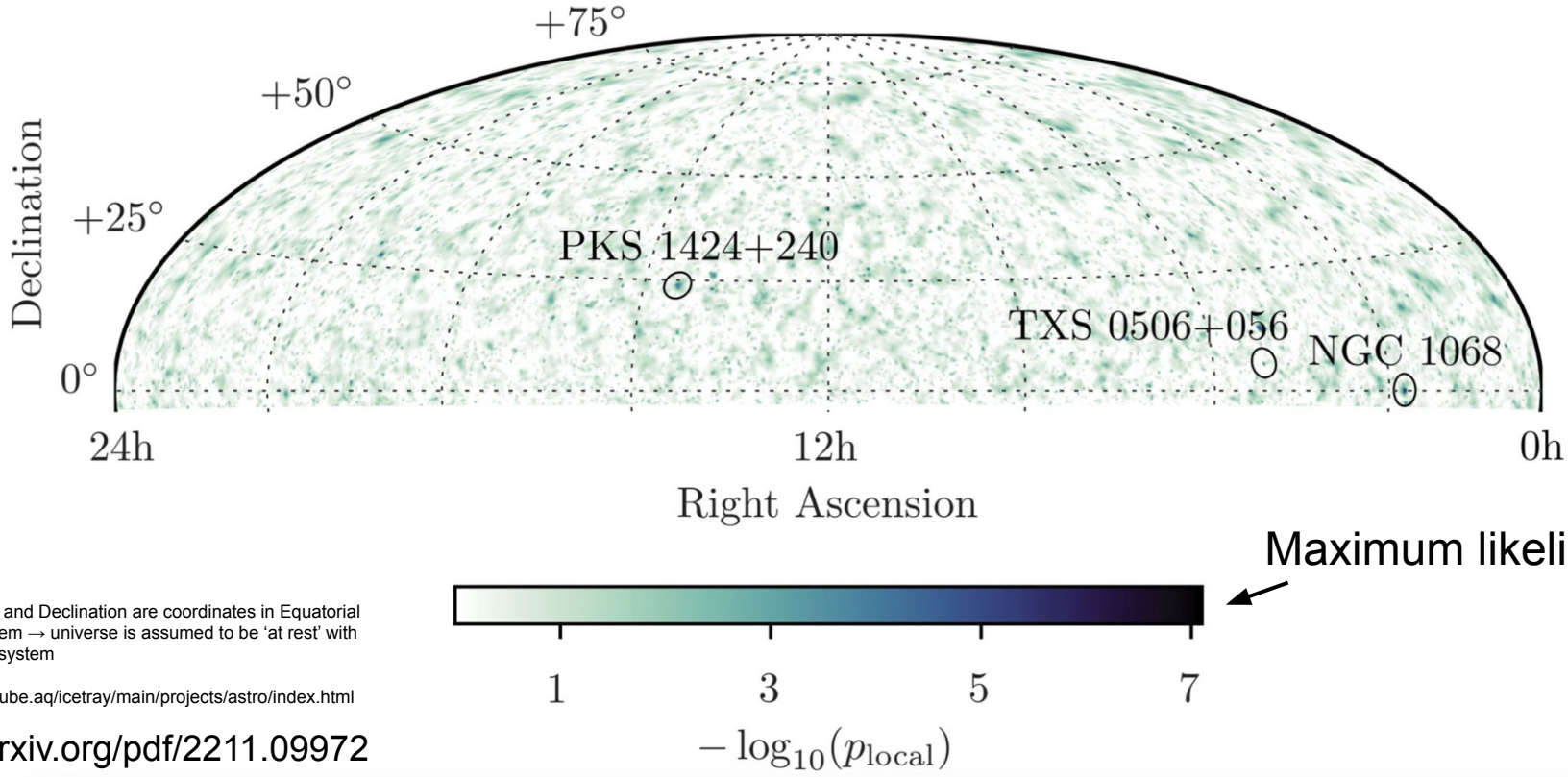
Potential Strategy → Use track events (good pointing/angular resolution)



Northern Tracks (Diffuse NuMu)

~76,000 events/yr

Goal: Identify neutrino emission from potential sources (galaxies, black holes, etc.)
Pinpointing likely sources by searching for <u>significant</u> neutrino excess



Right Ascension and Declination are coordinates in Equatorial Coordinate System → universe is assumed to be 'at rest' with respect to solar system

https://docs.icecube.aq/icetray/main/projects/astro/index.html

https://arxiv.org/pdf/2211.09972

Point Source (PS) Tracks

~120,000 events/yr

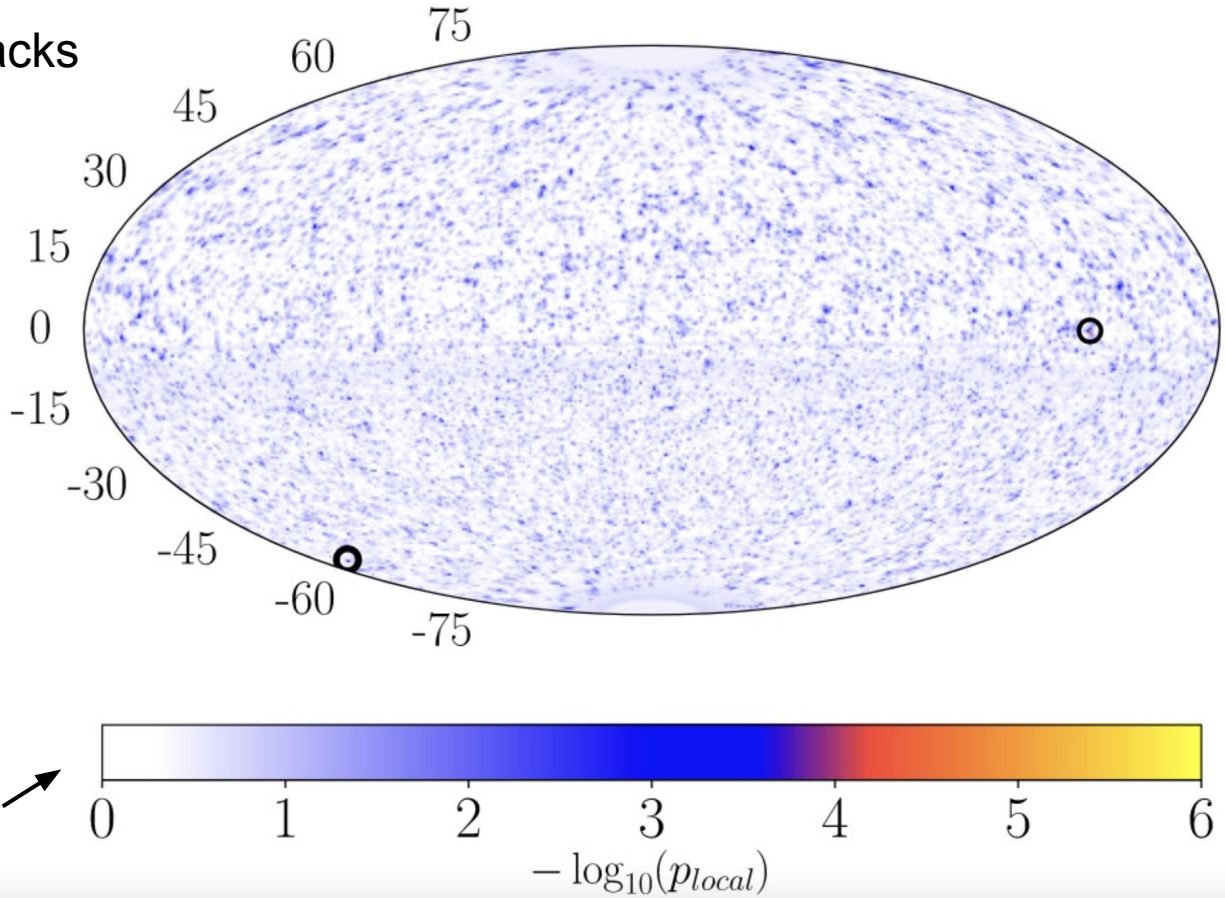
Goal: same as Northern Tracks

Includes:

- Southern Sky
- ‘All Sky’ sample
- More neutrino events per year

Harsh energy cut in southern sky to remove atmospheric muons

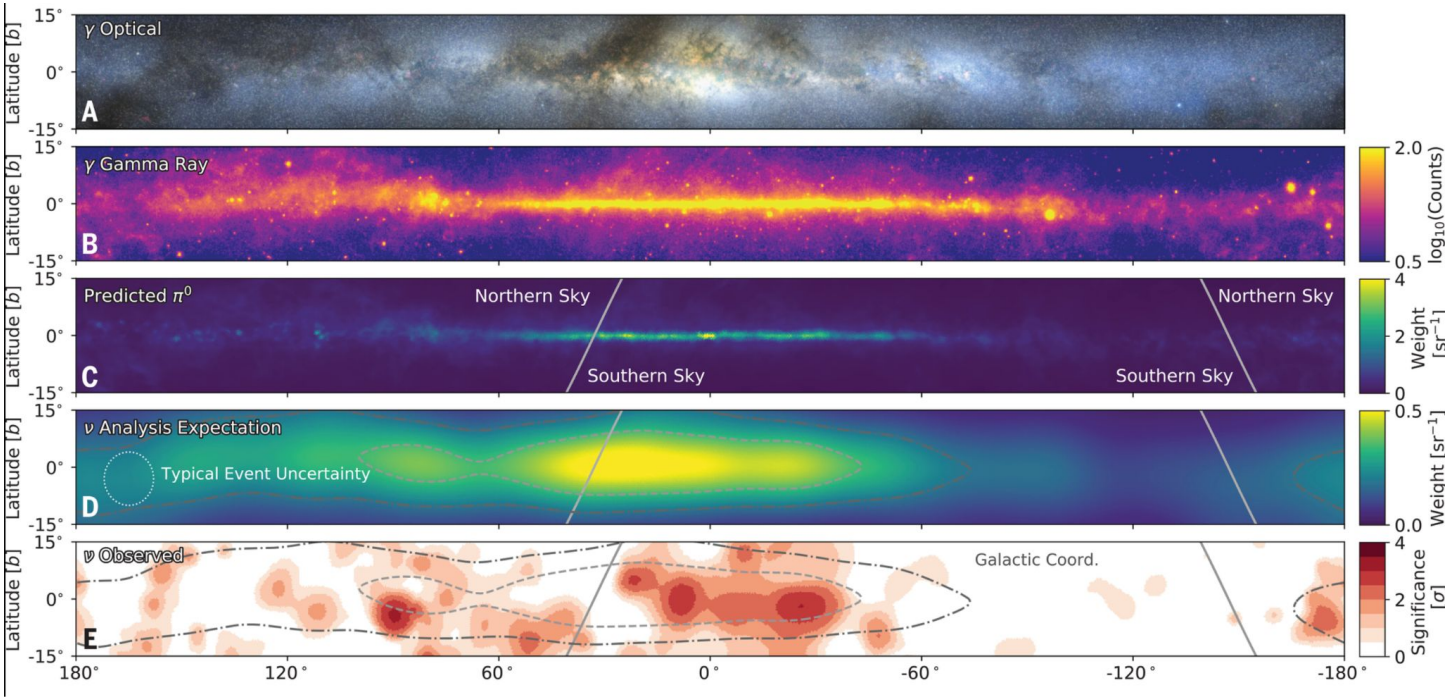
Maximum likelihood



https://arxiv.org/pdf/1910.08488

A Physics Question:
Are there high energy neutrinos in our galaxy? (yes!)

Potential Strategy → High statistics events, good angular and energy resolution)



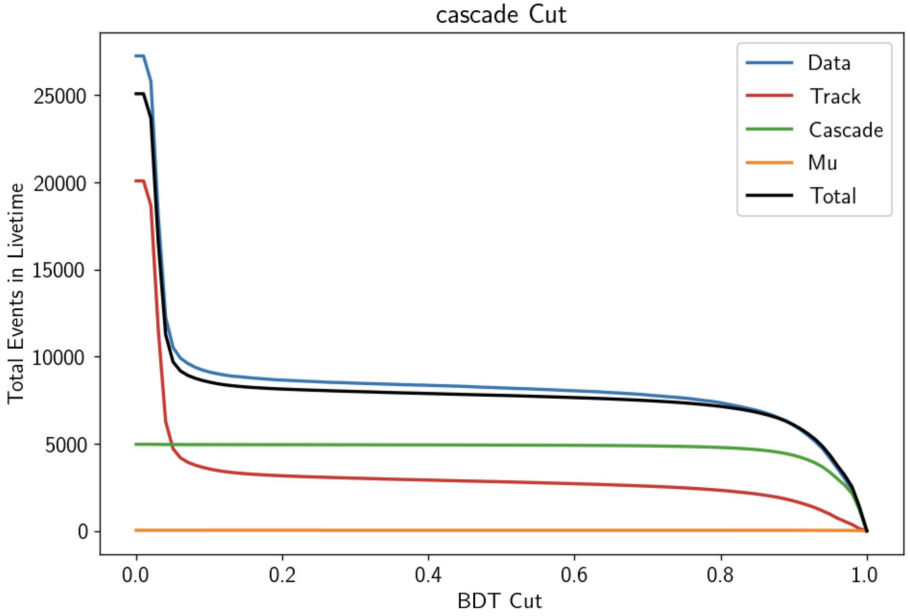
https://www.science.org/doi/10.1126/science.adc9818

DNNCascades and Machine Learning Techniques:

NO veto layers → only BDTs to eliminate muon background

High statistics/sensitivity Cascades selection, especially at lower energies

Used to **detect neutrino emission from Galactic Plane**



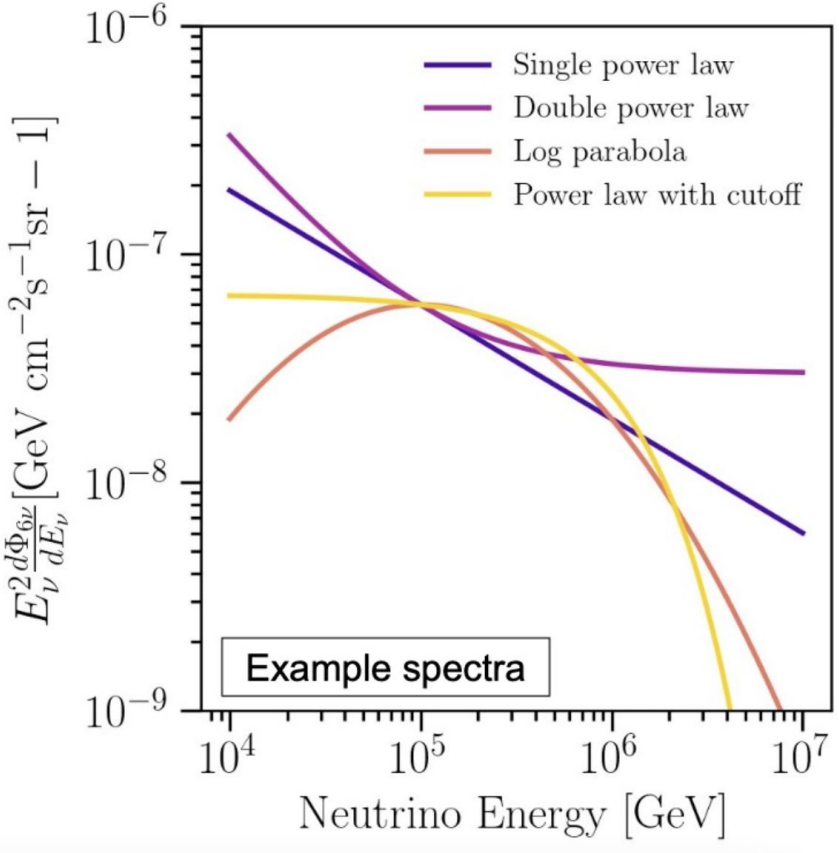
New discovery → lots of galactic plane analysis in IceCube right now
Lots of ways to approach this question

https://wiki.icecube.wisc.edu/index.php/File:Cascade_Neutrino_Source_Dataset_cascadeBDT_score.png

A Physics Question:
What does the Astrophysical Neutrino Flux Look Like?

Potential Strategy → Use events that start inside the detector

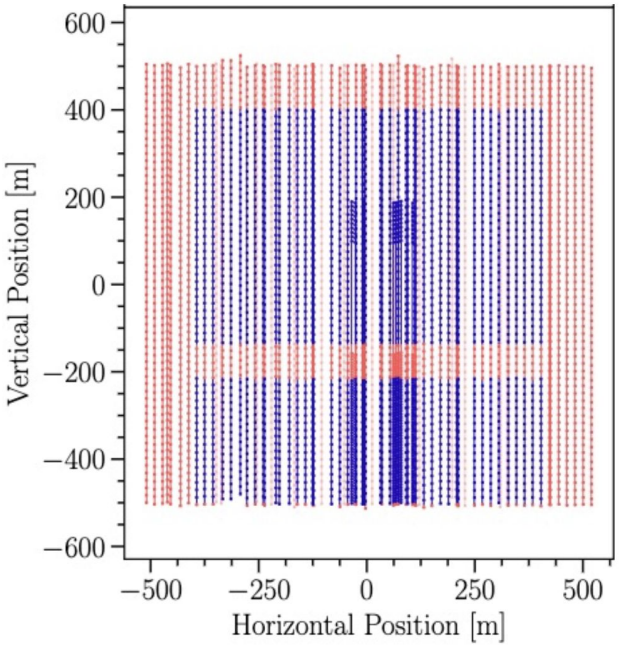
Starting Events have better energy resolution

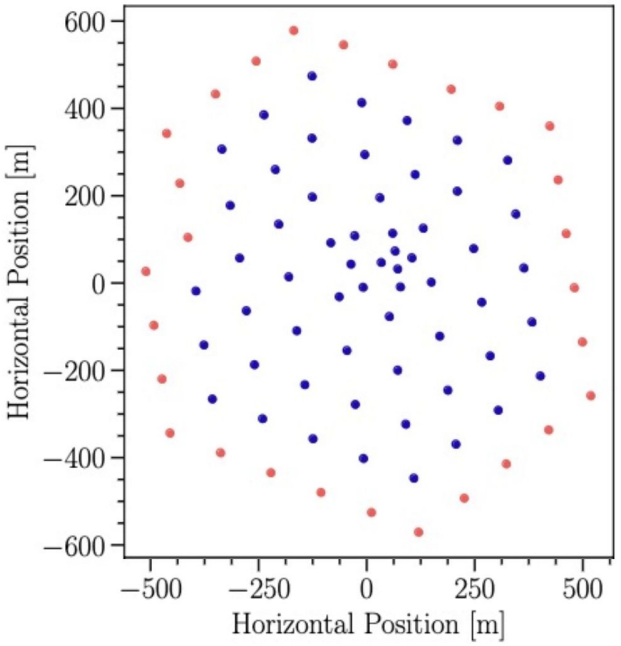


HESE: High Energy Starting Events

General Techniques Used:

- High energy only
- Outer layer veto (keep only events that start inside detector)
- Deposited charge > 6000 photoelectrons (help remove atmospheric background)

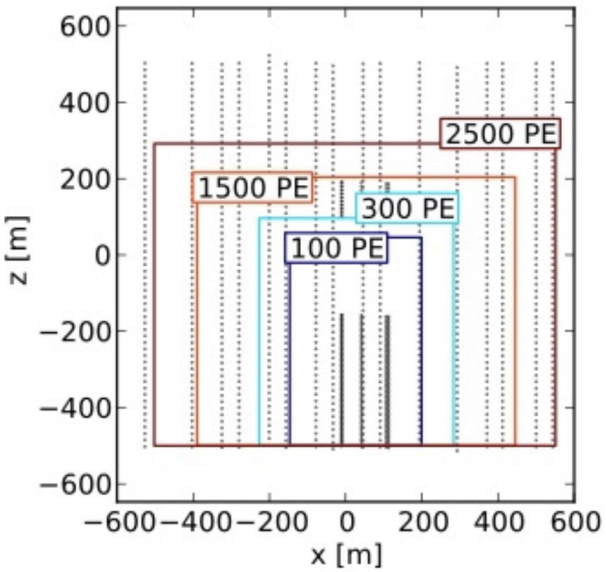


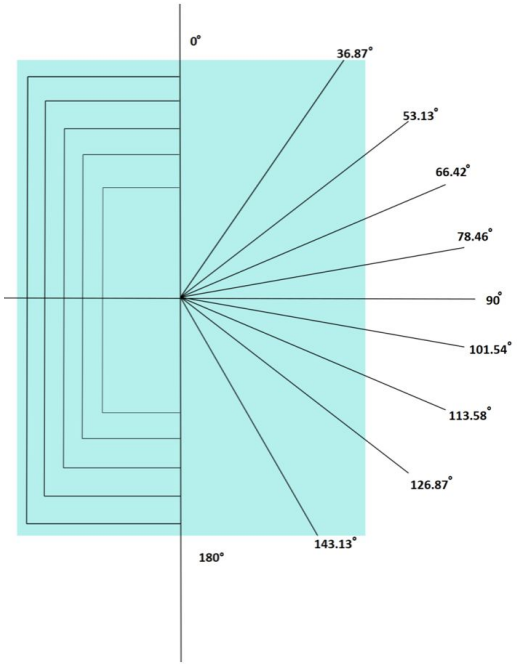


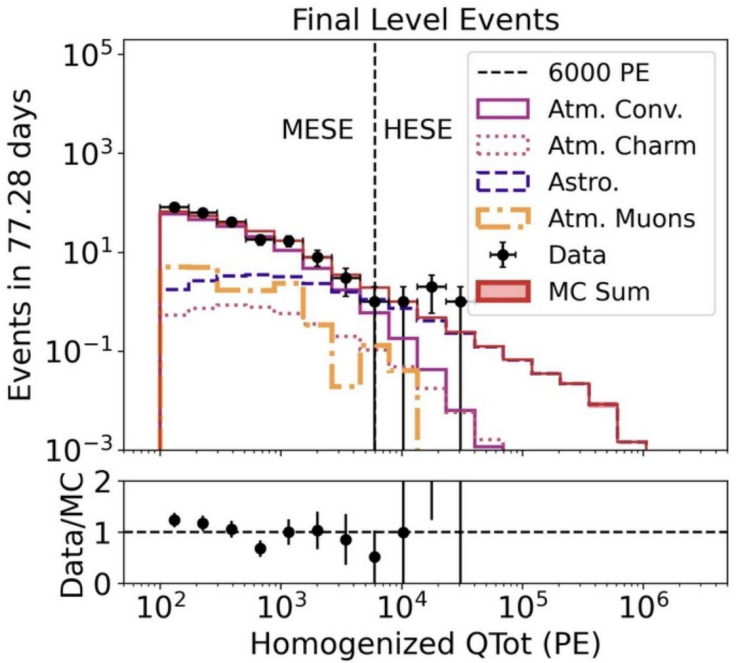
https://arxiv.org/pdf/2011.03545

MESE: Medium Energy Starting Events

- A sample with extended energy range compared to HESE
- Incorporates dynamic veto: energy and zenith dependent







https://wiki.icecube.wisc.edu/index.php/Medium_Energy_Starting_Events

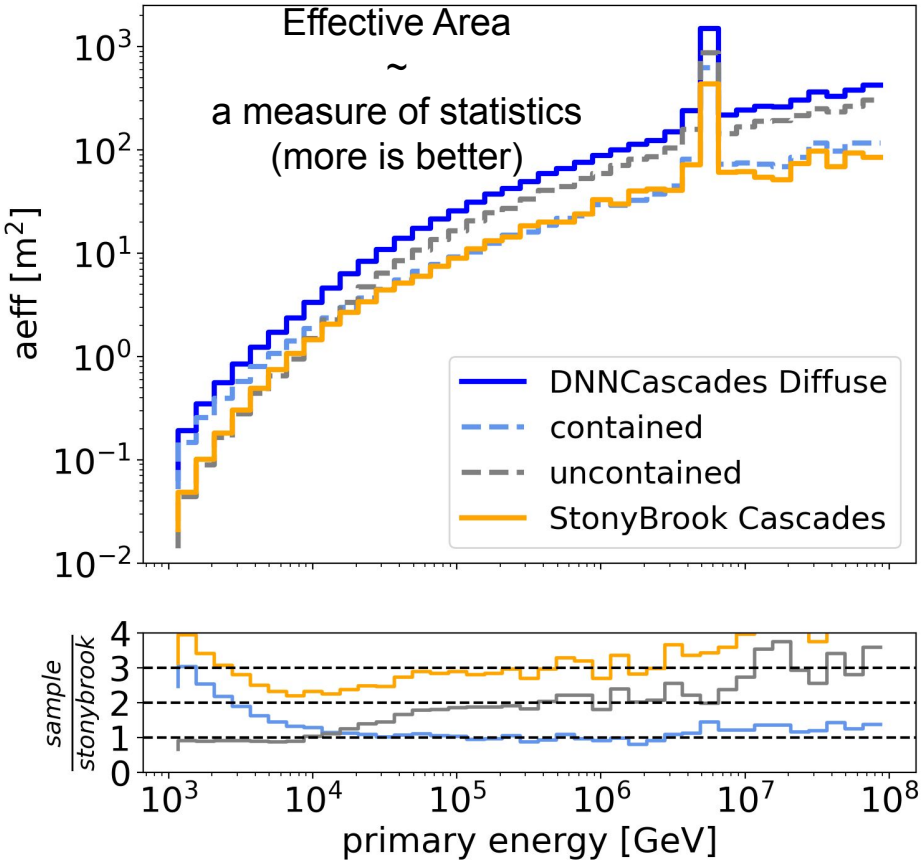
DNNCascades Diffuse

Extremely high statistics sample

Contained + uncontained cascades

Originally used to **detect neutrino emission from Galactic Plane**

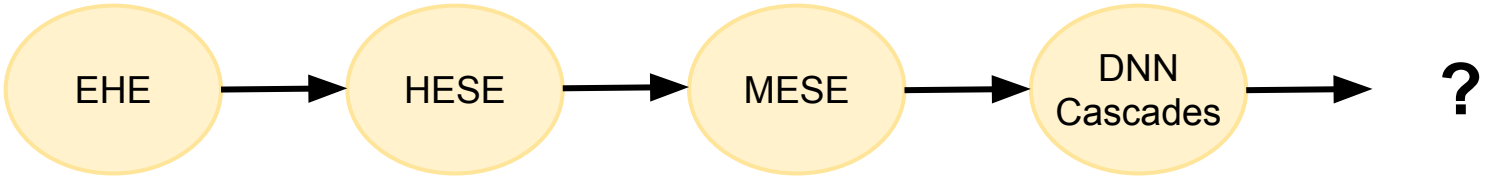
Zoë (me) Optimizing for Astrophysical Diffuse flux measurement



https://arxiv.org/pdf/2307.14842

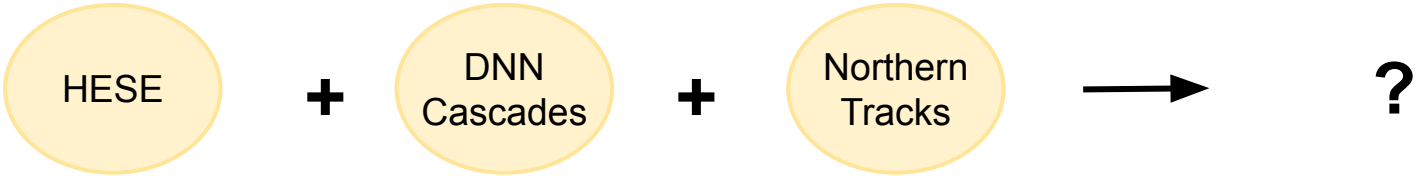
In General: Event Selections

Start with a physics goal → build with developing technologies/modeling methods



Future of Event Selections: Combined Selections

- moving into an era where combined event selections will reveal physics information to us → <u>increased sensitivity, statistics, etc</u>.
- Learning to account for overlapping events in selections (complicated process)



Summary

- Lots of event types, and lots of ways to select your events of interest
  - Event distribution
  - Morphology (zenith, energy, etc.)
  - Neural Networking and Machine Learning
- Many existing event selections today
  - Always update techniques when you use an existing for your analysis
  - Create your own techniques using physics principles!
  - Combining event selections → next era of IceCube Physics

Develop New Techniques, Develop New Selections!