Neutrino Physics

IceCube Bootcamp - June 10th, 2019

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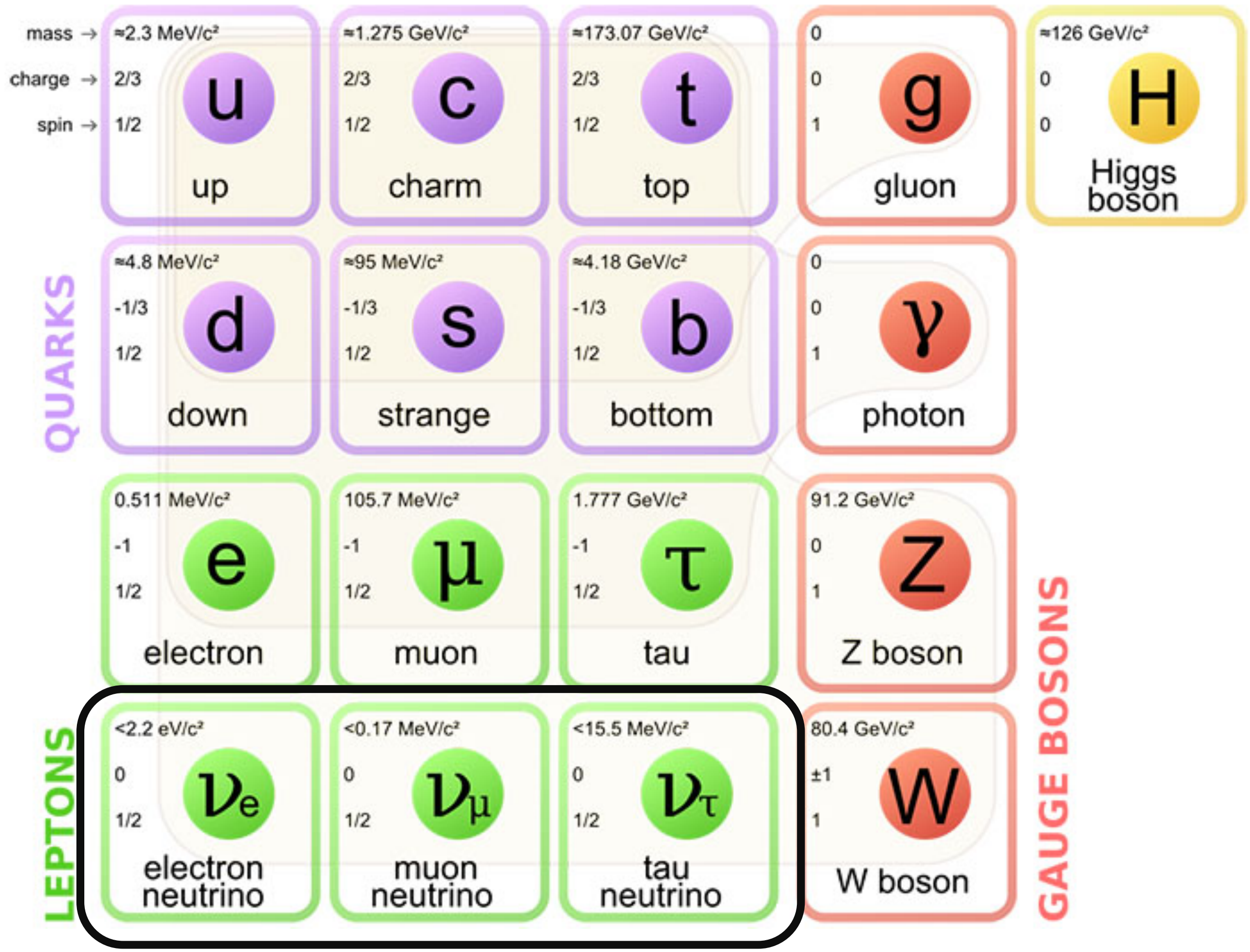
What Are Neutrinos?

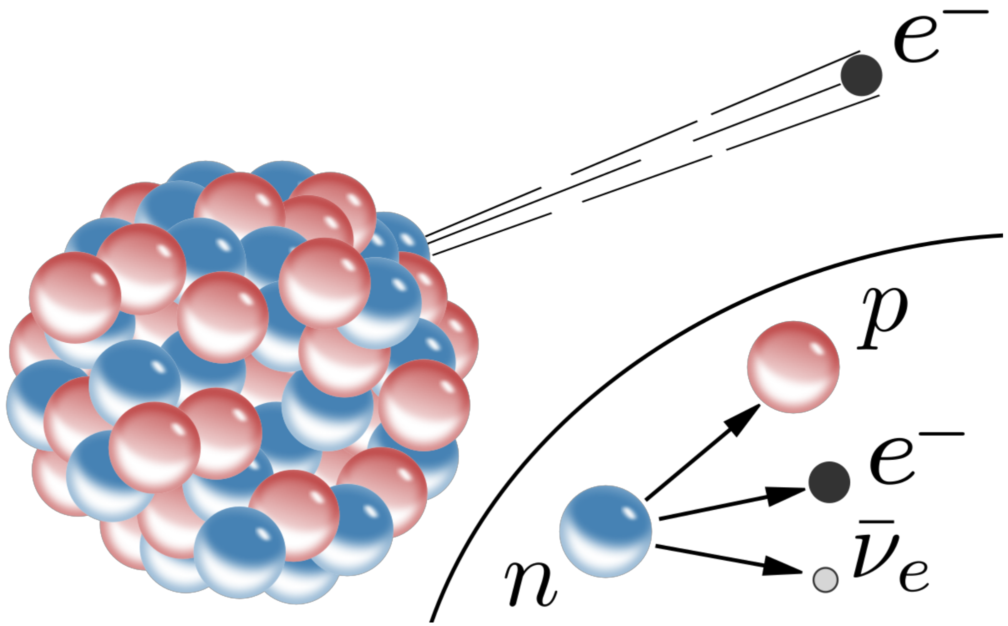
- Neutrinos are fundamental particles in the standard model
- They come in 3 flavors
  - Electron
  - Muon
  - Tau
- Neutral
- Only interact via weak interaction
- Very light (but still have mass)



https://www.abc.net.au/news/science/2017-07-15/the-standard-model-of-particle-physics-explained/7670338

What Are Neutrinos?

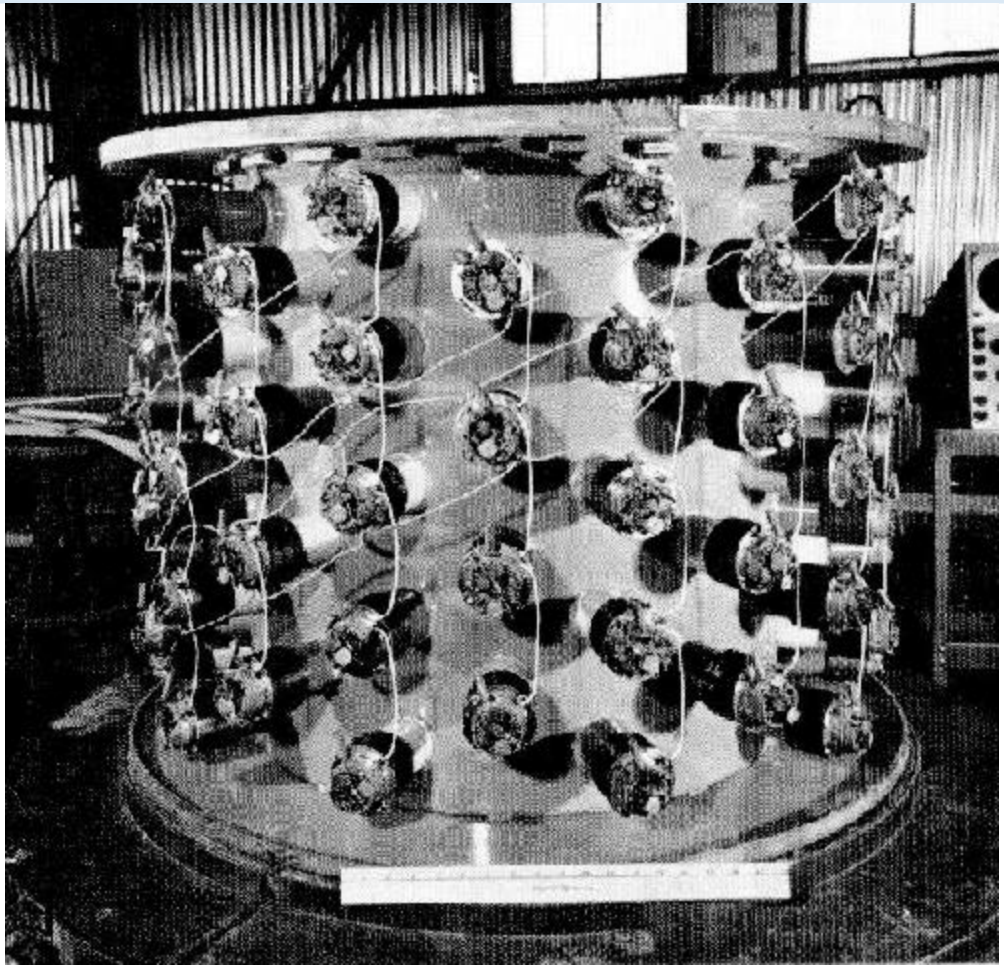
- They were first posited by Wolfgang Pauli in 1930 to solve the mystery of beta decay
- Spontaneous emission of an electron from a nucleus seemed to violate conservation of energy and momentum
- Pauli postulated the existence of an elusive particle that was also being emitted in the process



Beta Decay: $n \rightarrow p + e^- + \bar{\nu}_e$

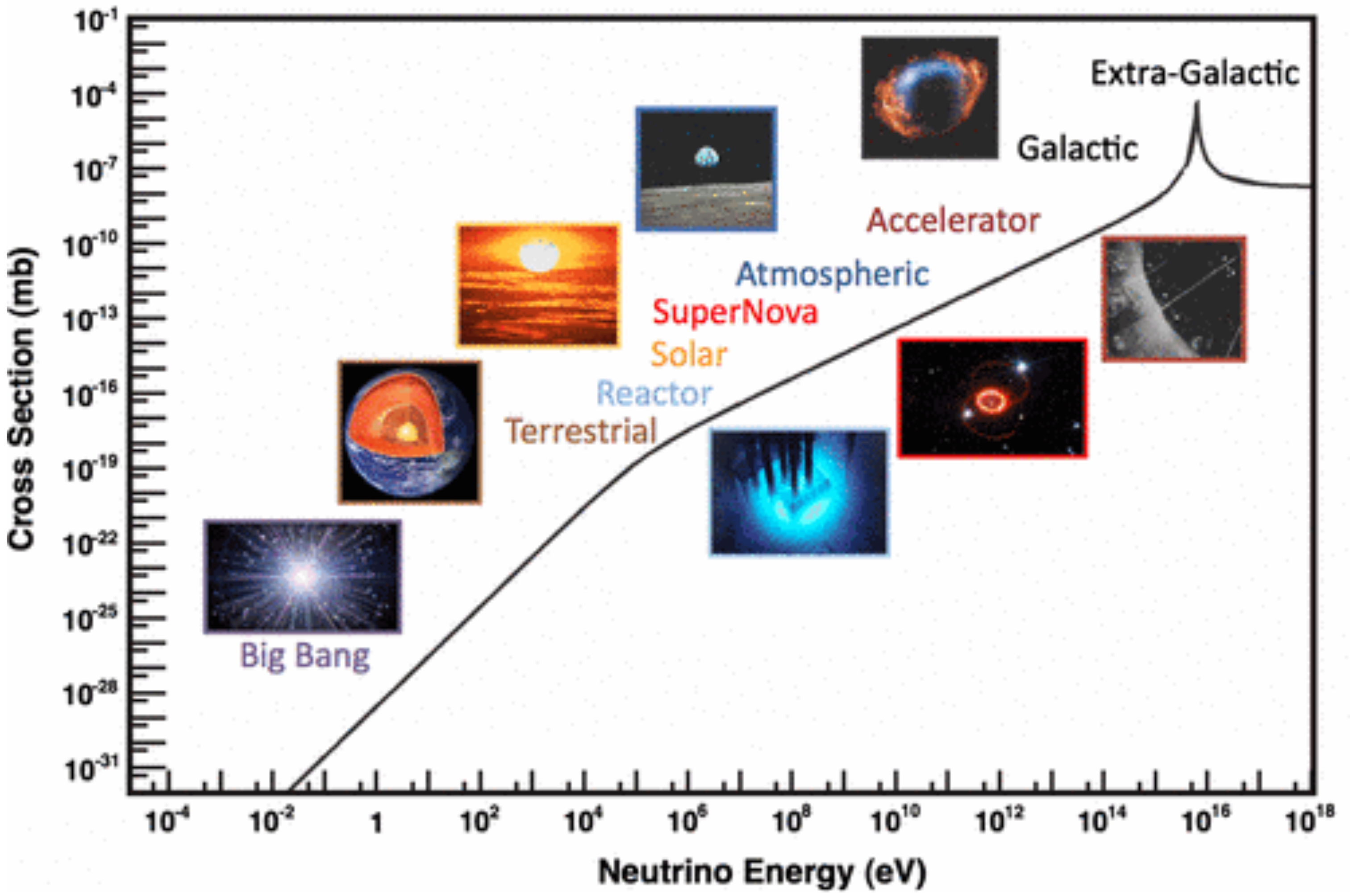
What Are Neutrinos?

- Neutrinos were first discovered in 1956 by Reines and Cowan
- Measured inverse beta decay caused by neutrinos from nuclear reactors
- Inverse Beta Decay: $p + \bar{\nu}_e \rightarrow n + e^{+}$
- Received Nobel Prize in 1995



Where Do They Come From?

- Astrophysical Sources:
  - Supernovae
  - AGN?
  - Neutron star mergers?
- Human Made:
  - Nuclear reactors
  - Particle accelerators
- Terrestrial:
  - Decay of radioactive material in earth
  - Cosmic rays in atmosphere



arXiv:1305.7513

Why Study Neutrinos?

- Neutrinos are one of the least understood particles in the standard model

- **Neutrinos have mass, but where does it come from?**
  - Exactly how much mass do neutrinos have?

- Neutrinos oscillate between the 3 flavors
  - What exactly are the properties of these oscillations?
  - Are there more than 3 flavors?

- Where are the most energetic neutrinos produced?

Why Study Neutrinos?

For Astrophysics: Neutrinos are great cosmic messengers!

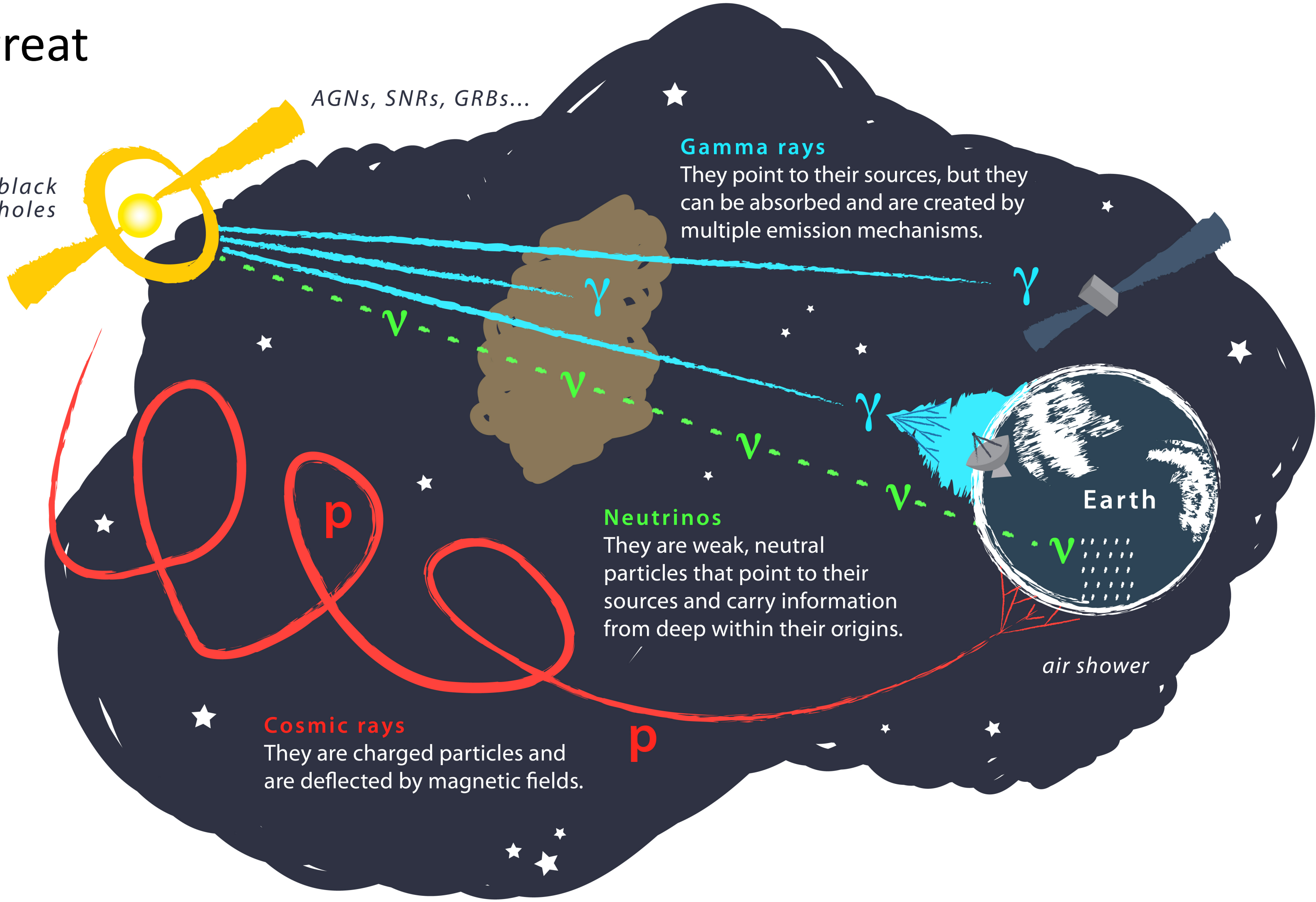
Weakly interacting

+

Neutral

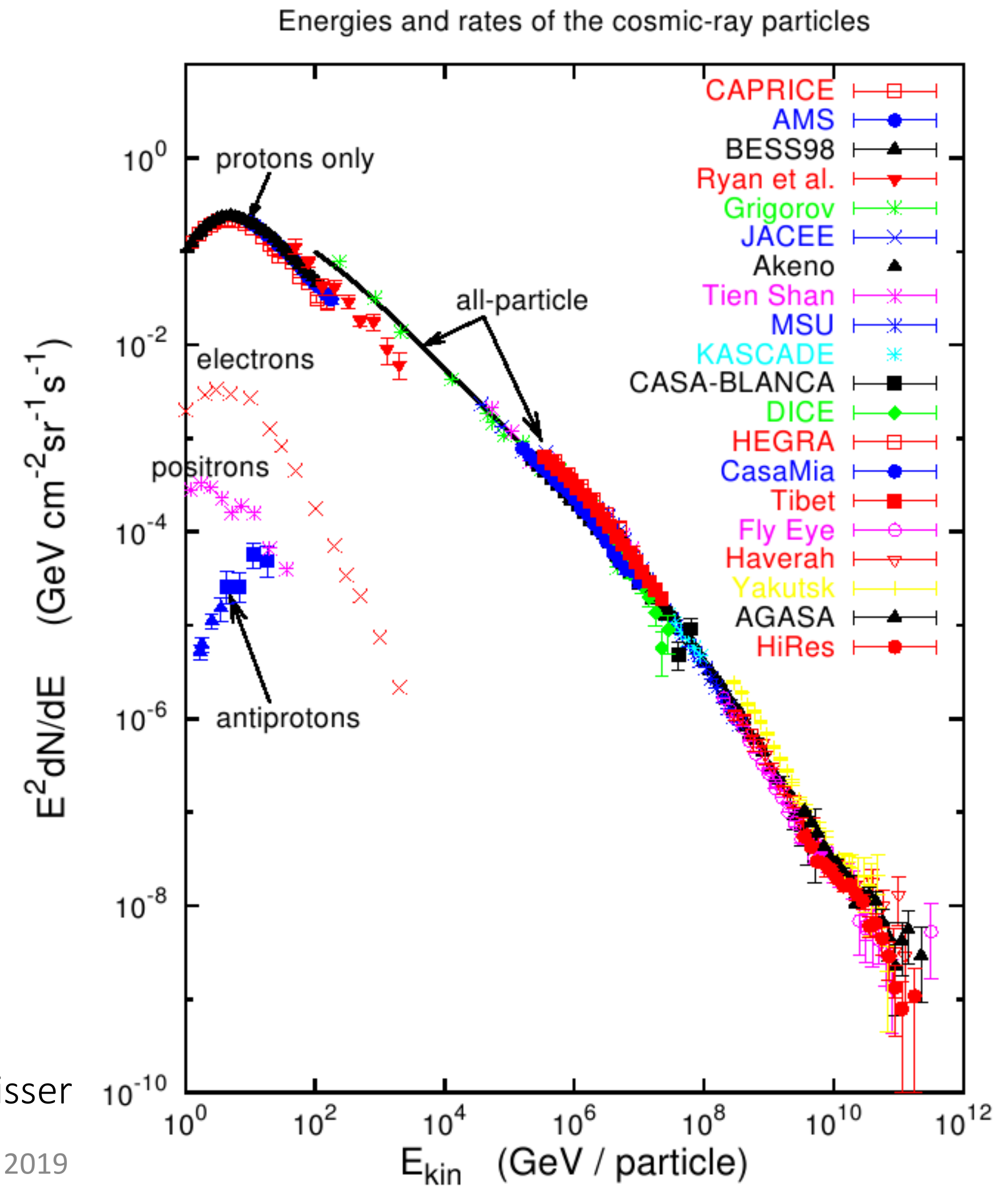
=

Direct probe to astrophysical source



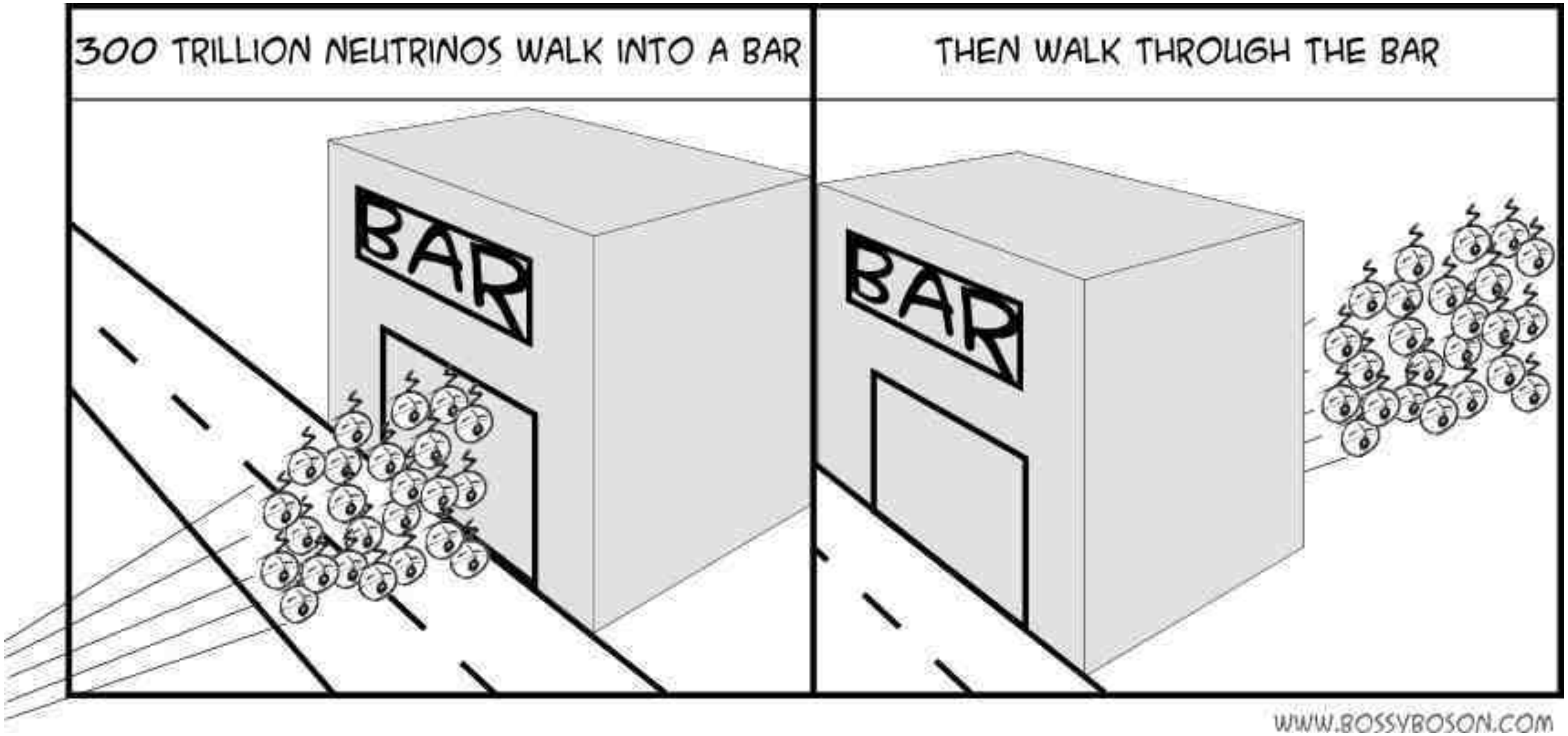
Why Study Neutrinos?

- Neutrinos can help us understand the origin of high energy cosmic rays
- Neutrinos are produced in hadronic interactions
  - $p + p \rightarrow p + p + \pi^{+}$
  - $\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$
- They should be produced at the same sources producing high-energy cosmic rays
- Studying neutrinos can help us identify cosmic accelerators and the physics that drives them



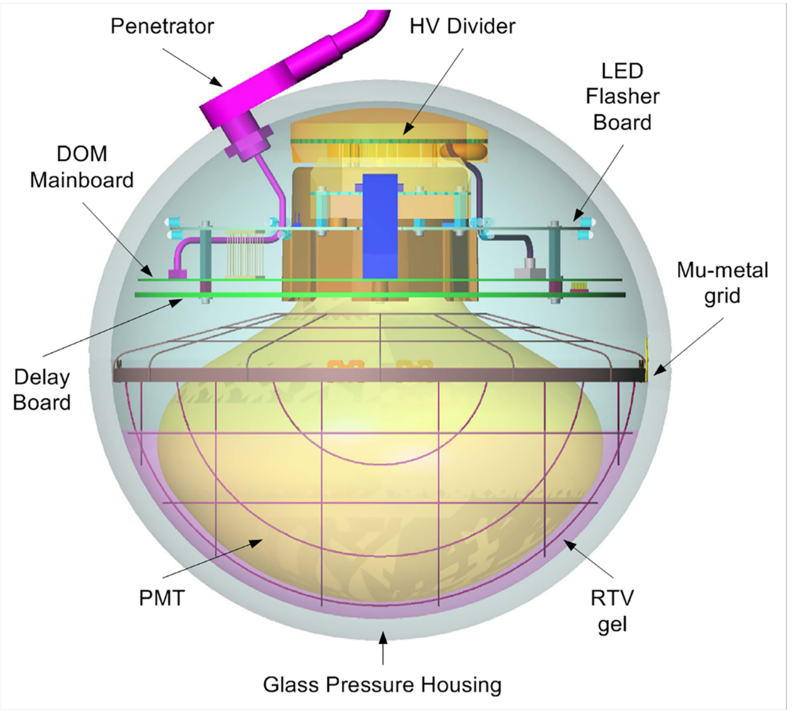
Credit: T. Gaisser

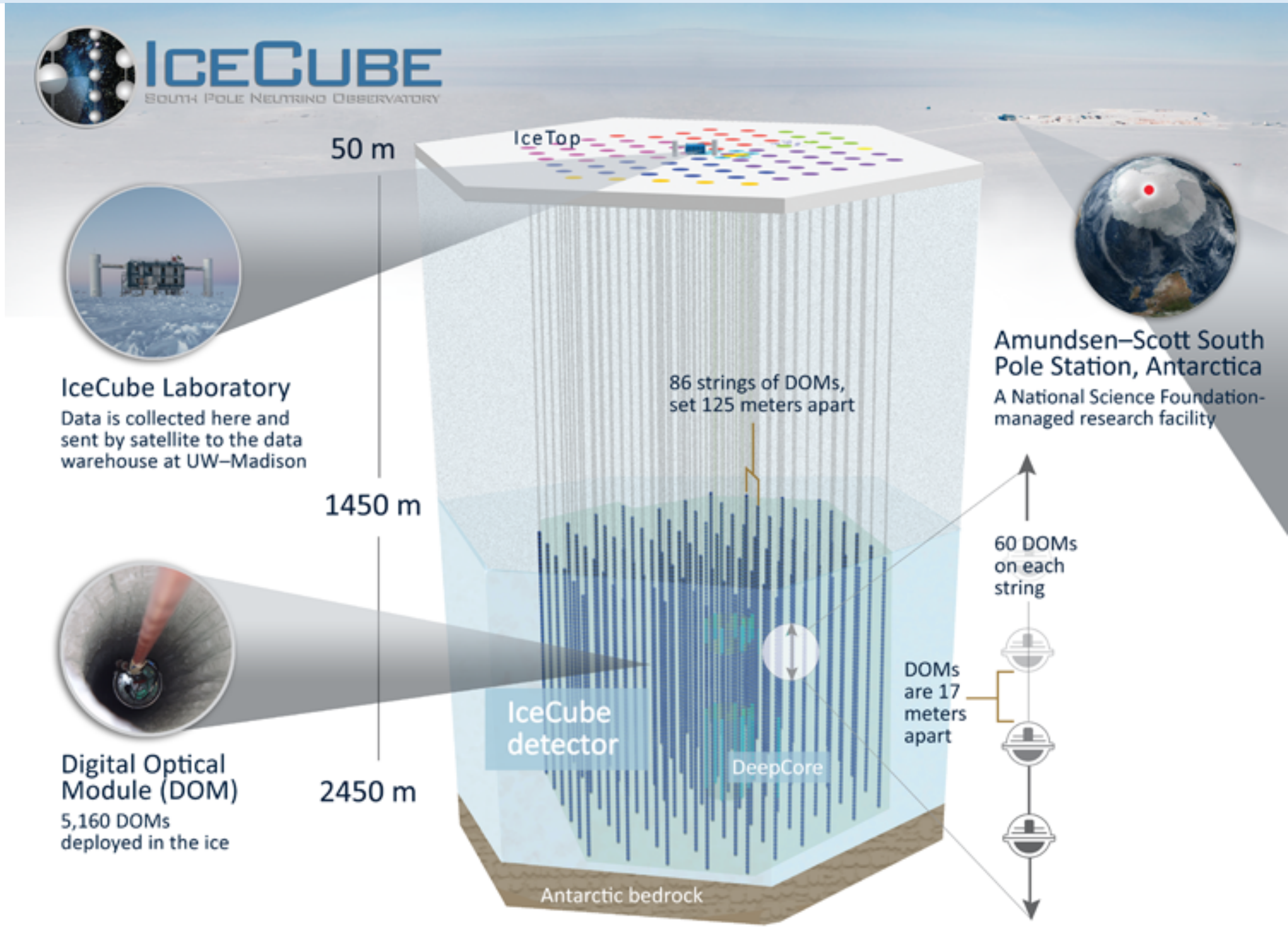
Ok so neutrinos are cool and worth studying but how do we go about detecting them?



Detecting Neutrinos

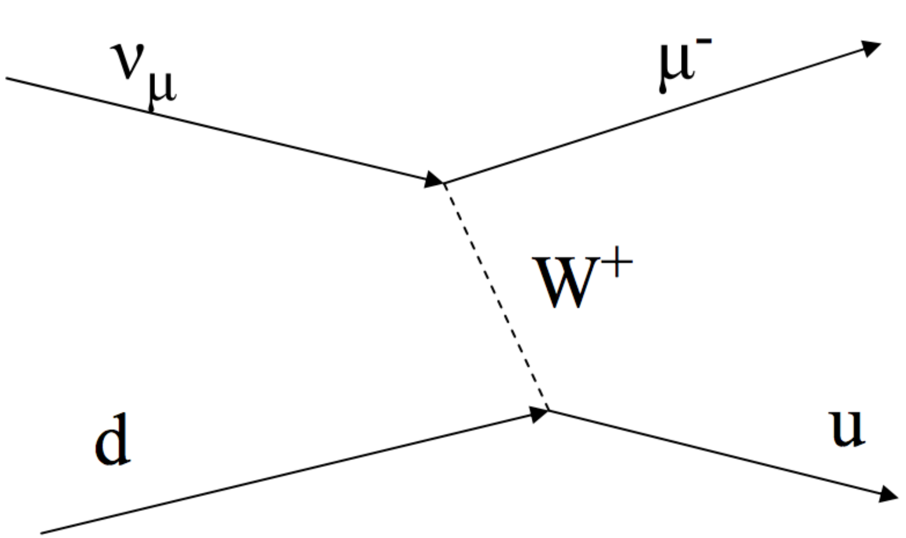
- Neutrinos are very hard to detect
- Require a very large volume to get enough interactions



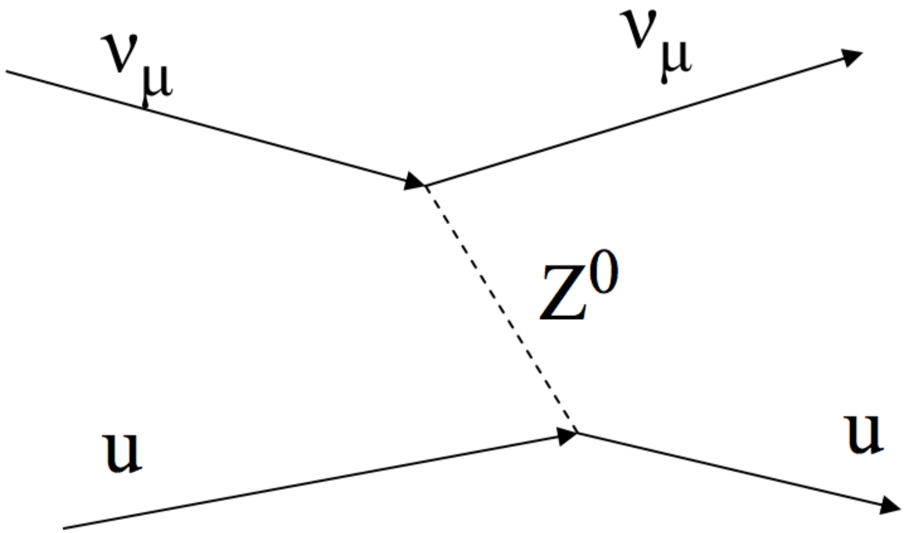


Detecting Neutrinos

Charged Current



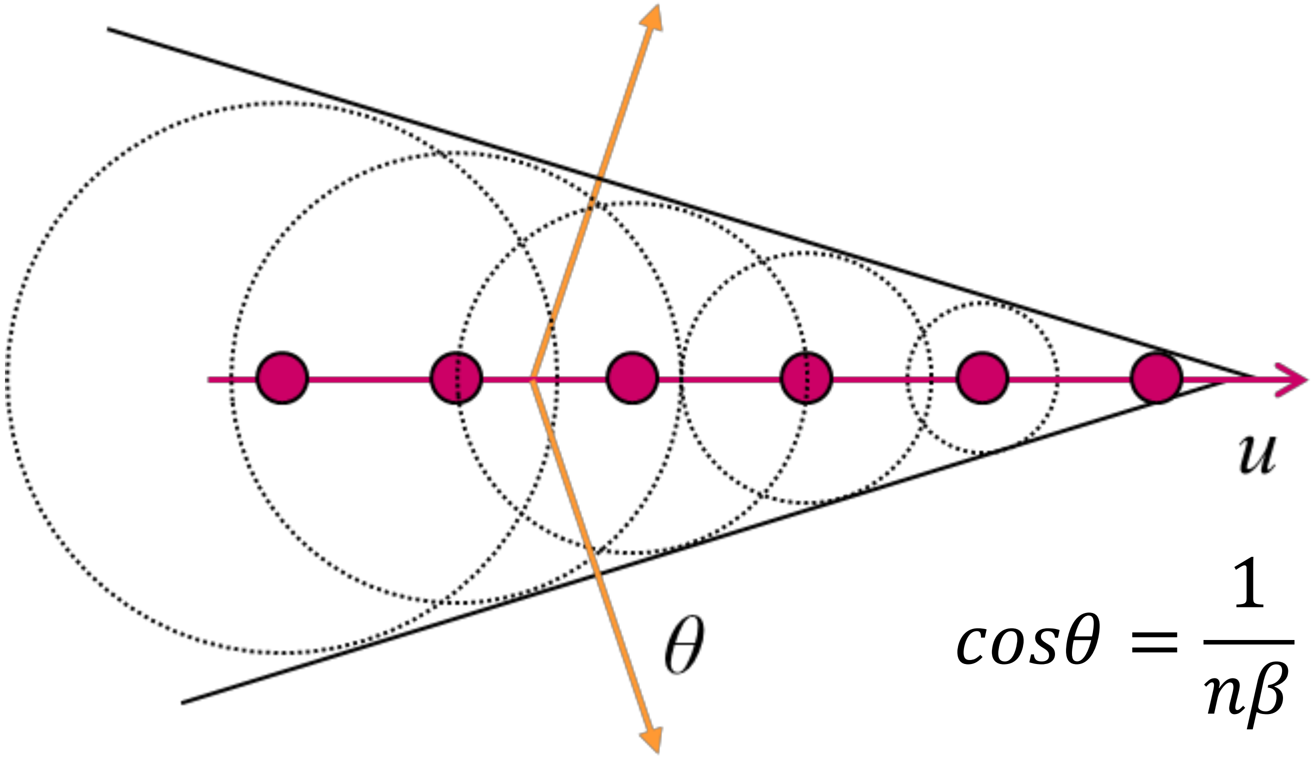
Neutral Current



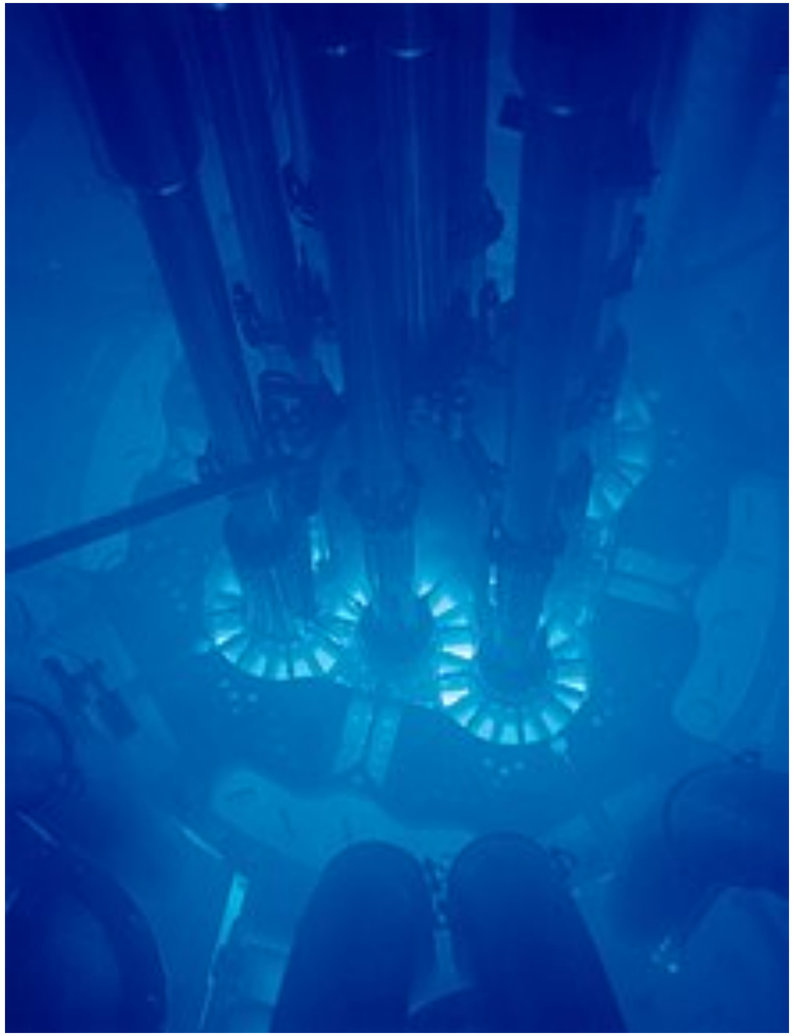
Cherenkov Radiation

We can detect neutrino via Cherenkov radiation emitted by the charged particles which are created in neutrino interactions

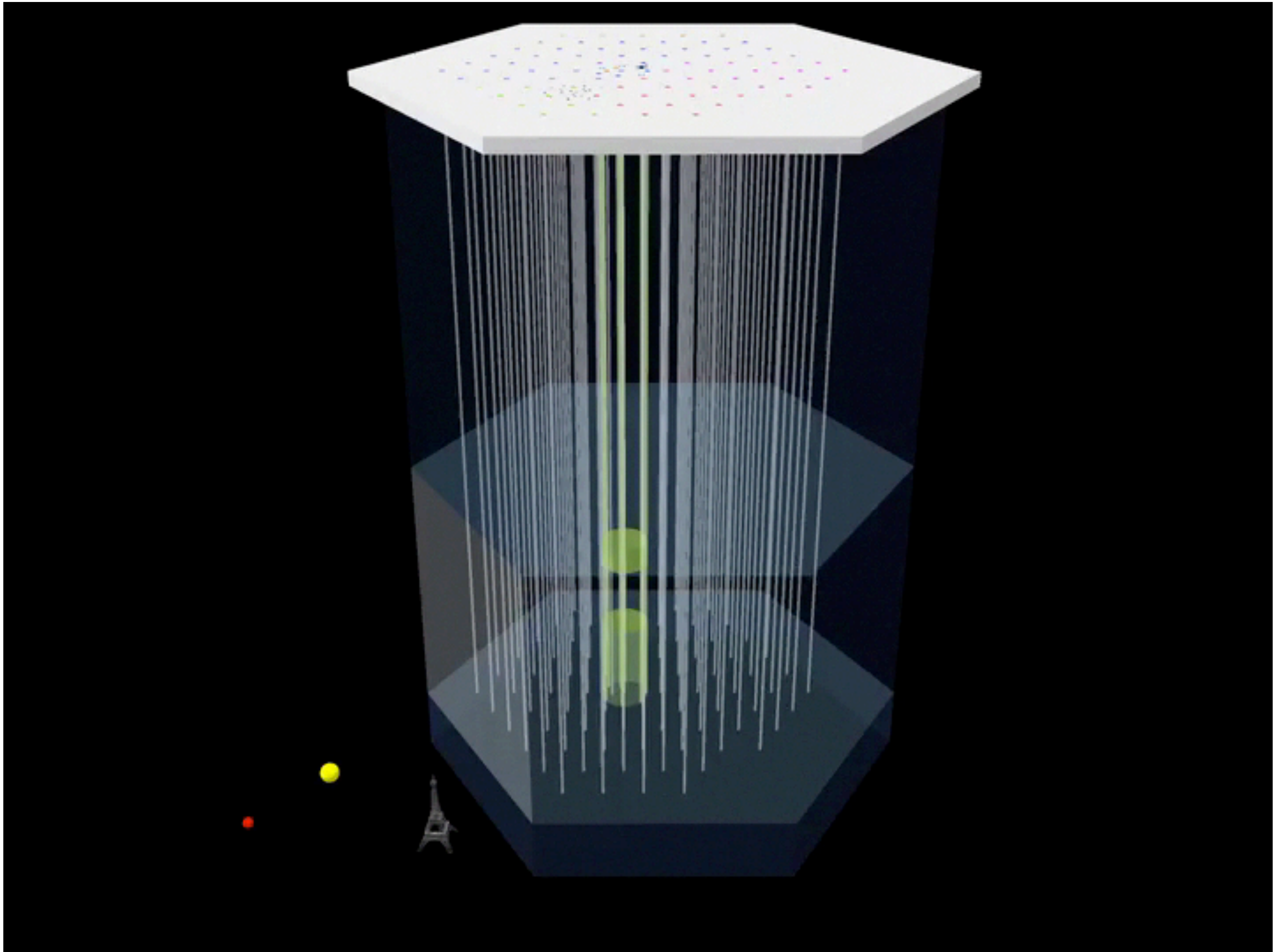
Cherenkov radiation is produced when a charged particle travels through a medium faster than light travels through that medium



$$cos\theta = \frac{1}{n\beta}$$

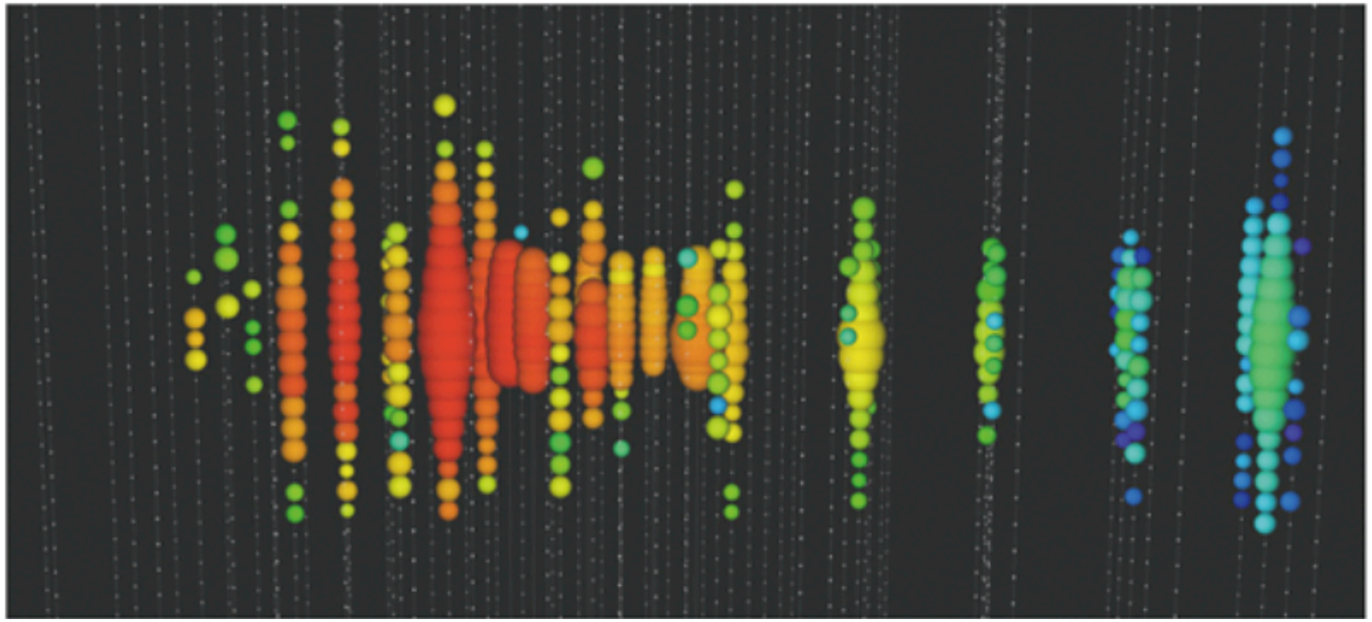


https://en.wikipedia.org/wiki/Cherenkov_radiation and http://large.stanford.edu/courses/2014/ph241/alaeian2/



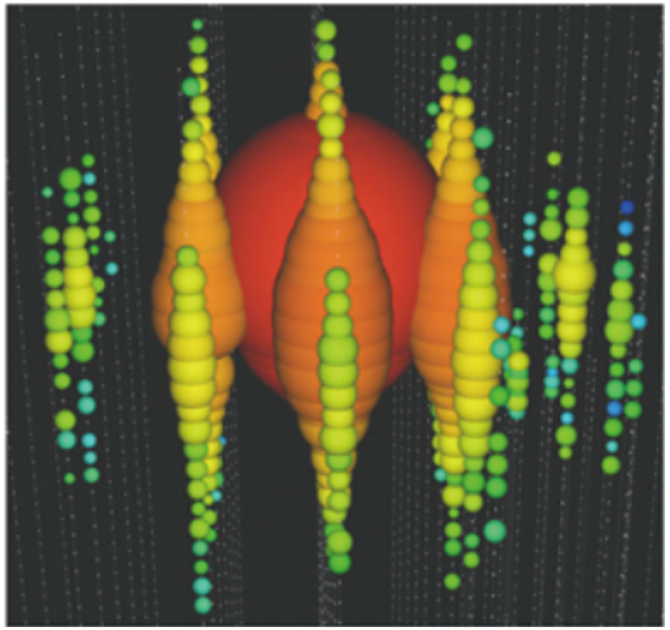
Events in IceCube

Tracks



Angular Resolution $\lesssim 1°$

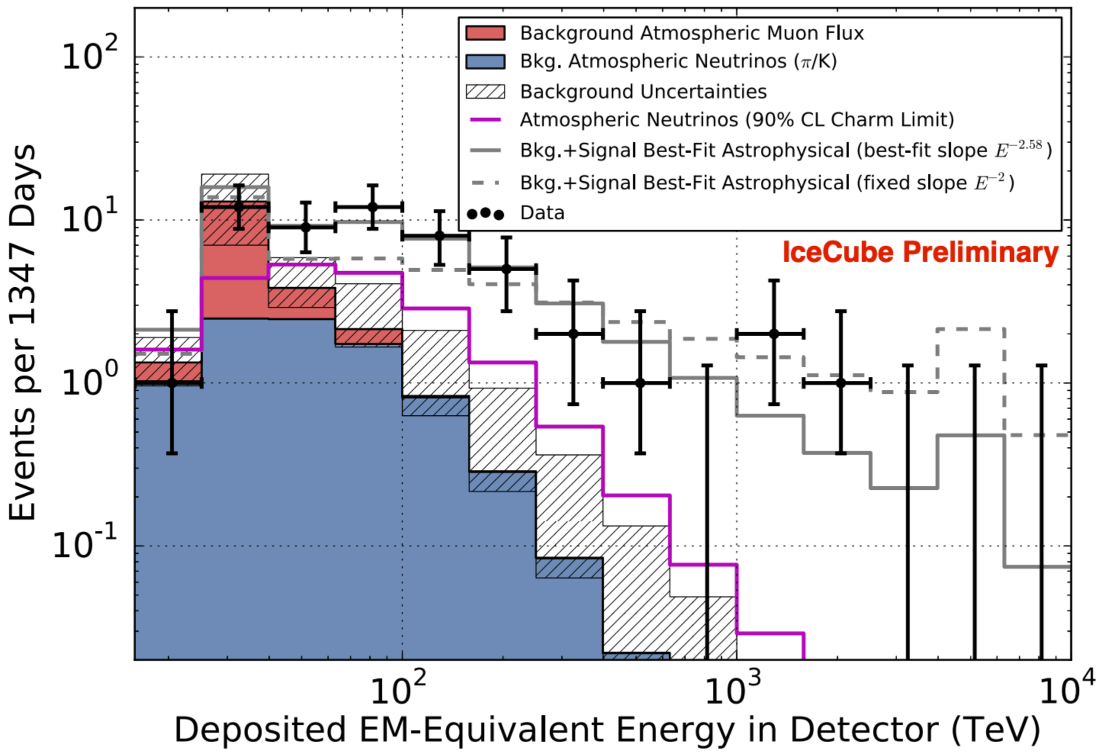
Cascades



Angular resolution $\gtrsim 10°$

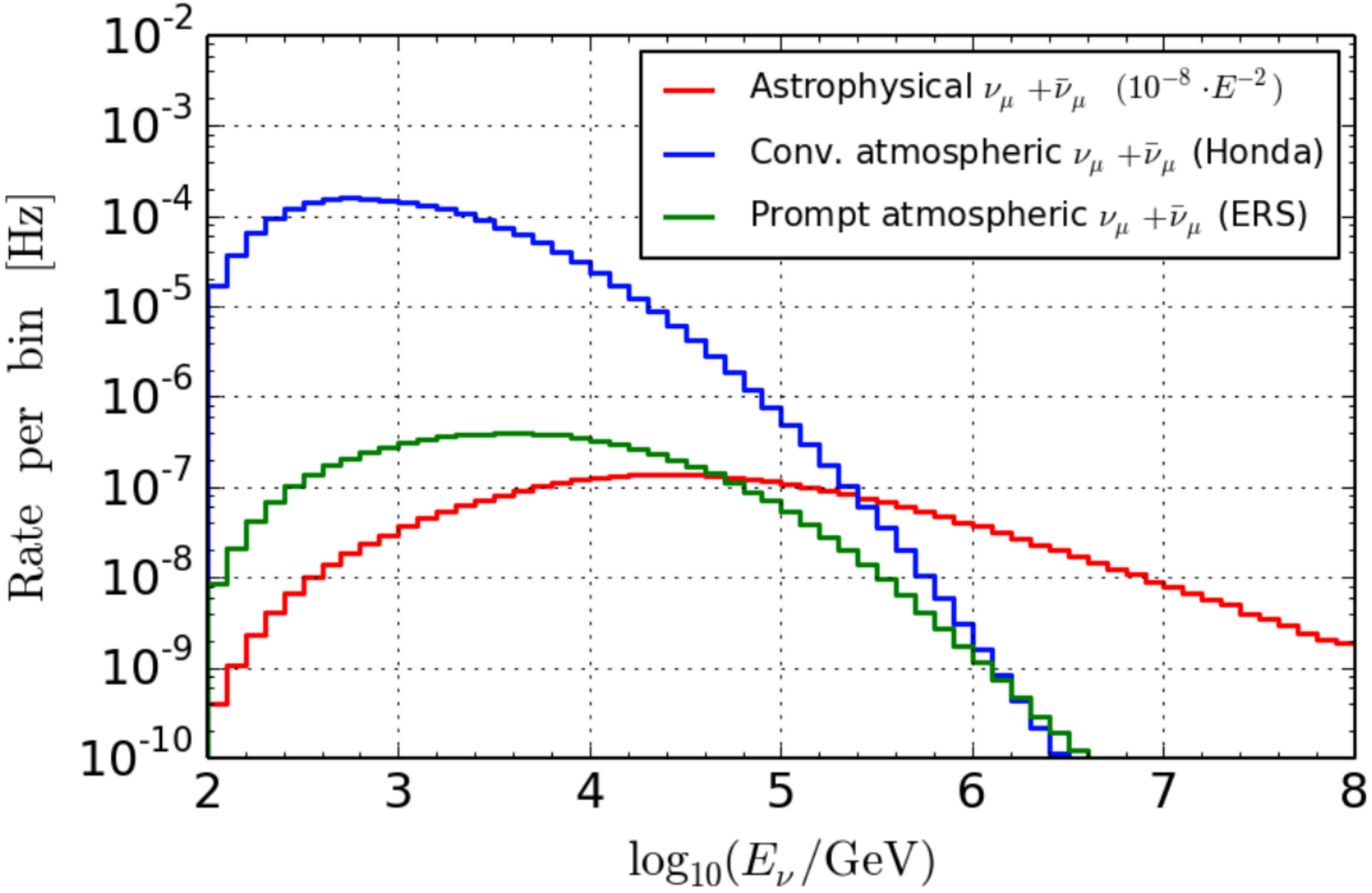
Discovery of Cosmic Neutrinos

- First discovered in 2013 and has since been confirmed in multiple analyses
- A clear excess of astrophysical neutrinos is observed over the atmospheric backgrounds
- Excess is more significant at higher energies since atmospheric neutrinos have a softer spectrum than astrophysical neutrinos



arXiv:1510.05223

Backgrounds in IceCube



Looking for astrophysical neutrinos is very hard because the background are huge!

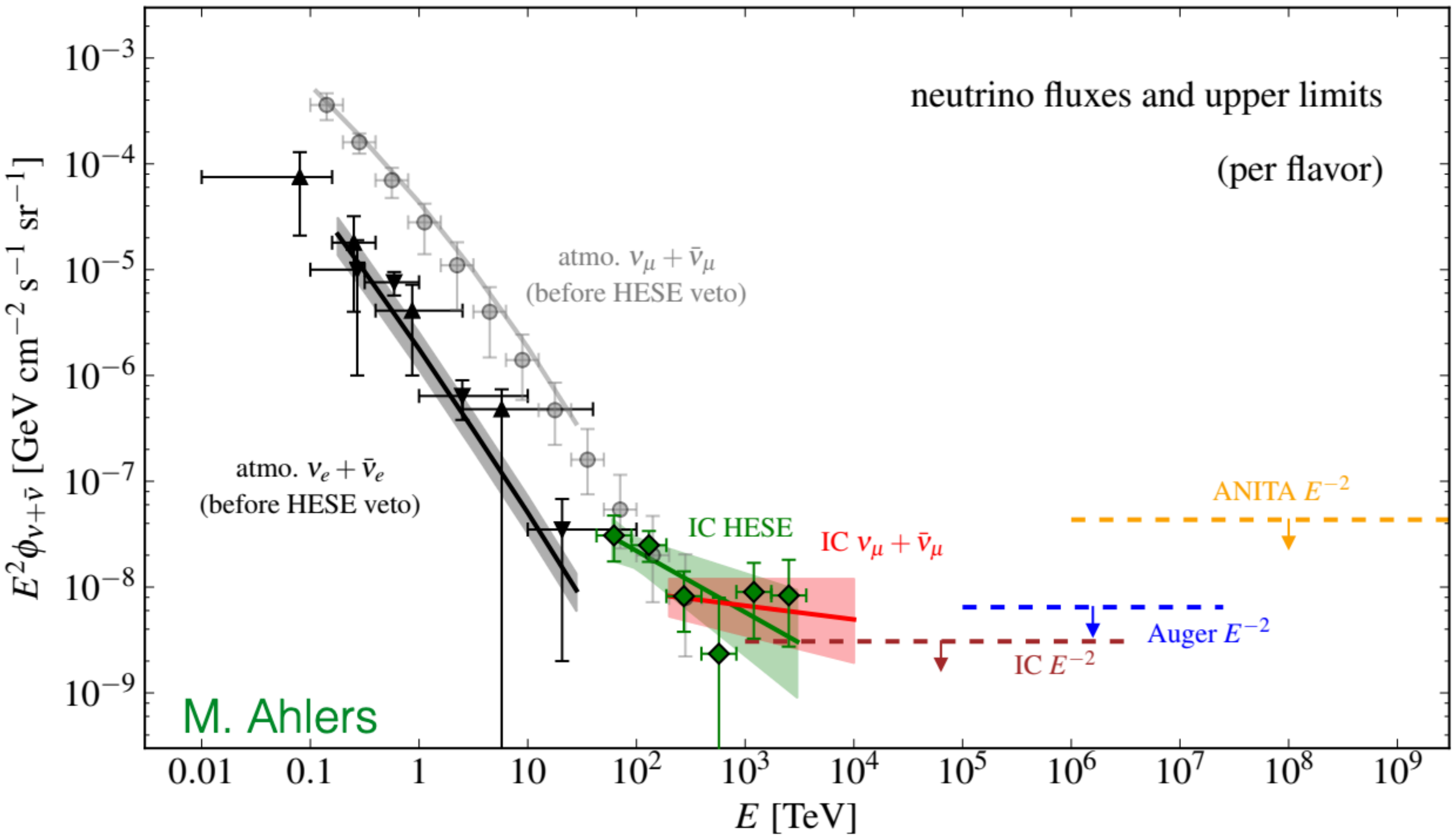
Main backgrounds:

- Atmospheric muons (south)
- Atmospheric neutrinos (north+south)

- "**Conventional**" = Neutrinos from pion, kaon, muon decays

- "**Prompt**" = Neutrinos from Charm decays

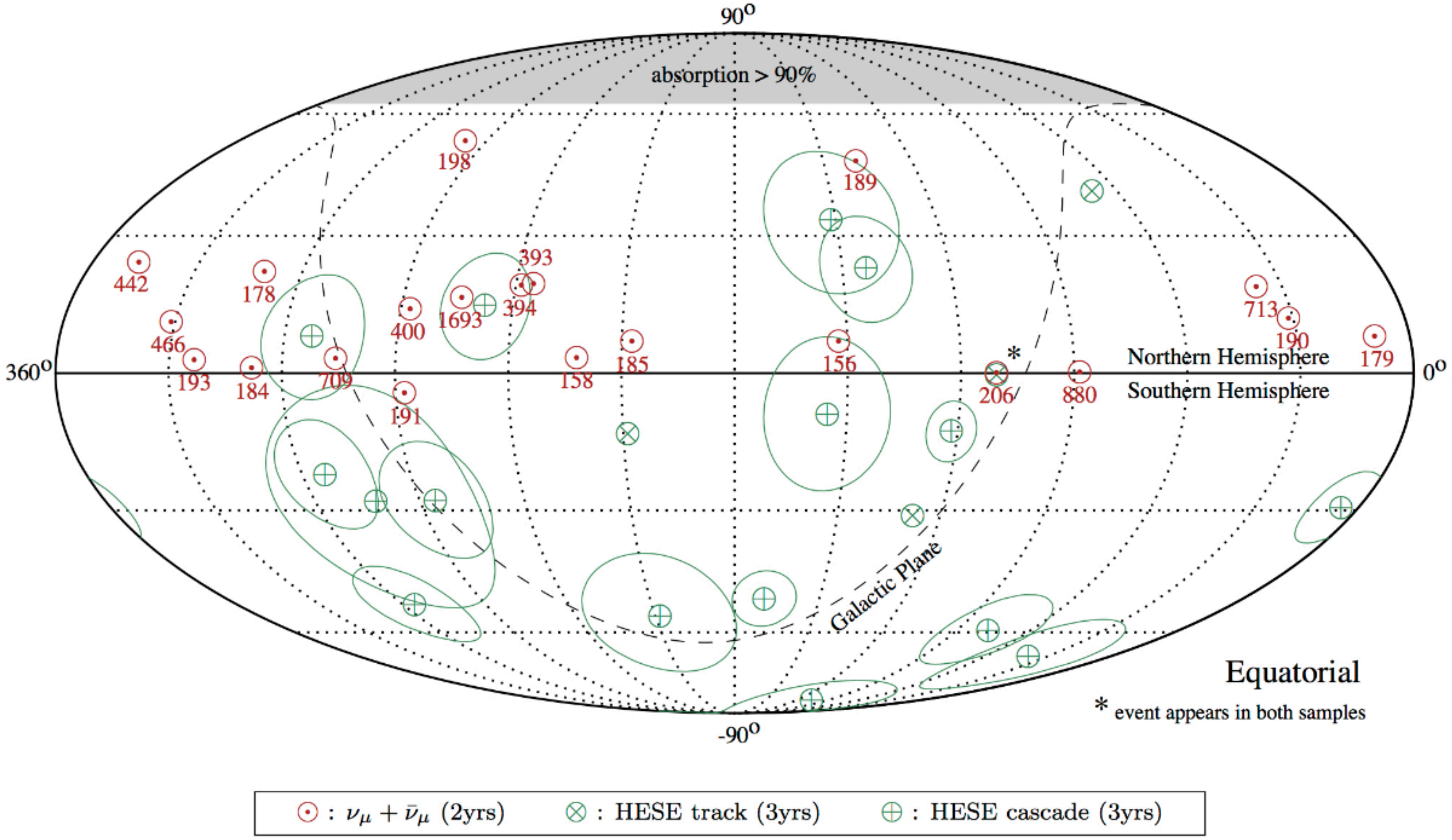
Diffuse Neutrino Flux



Diffuse flux has been measured yet the source of this flux remains largely unknown

TXS 0506+056 was a flaring blazar that was identified as a cosmic neutrino source

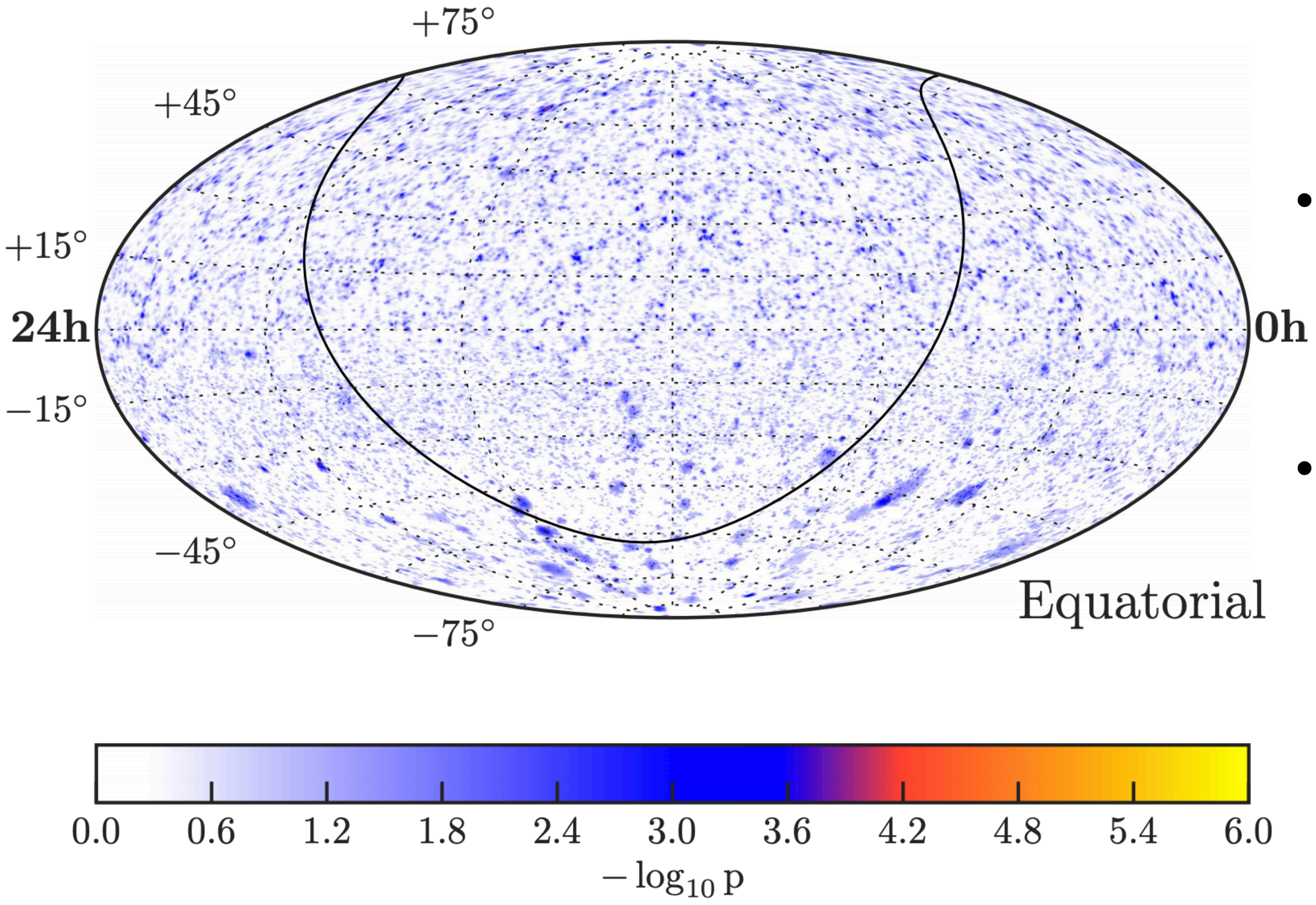
The Neutrino Sky



Highest energy events from the HESE sample

Event arrival directions are consistent with an isotropic background

The Neutrino Sky

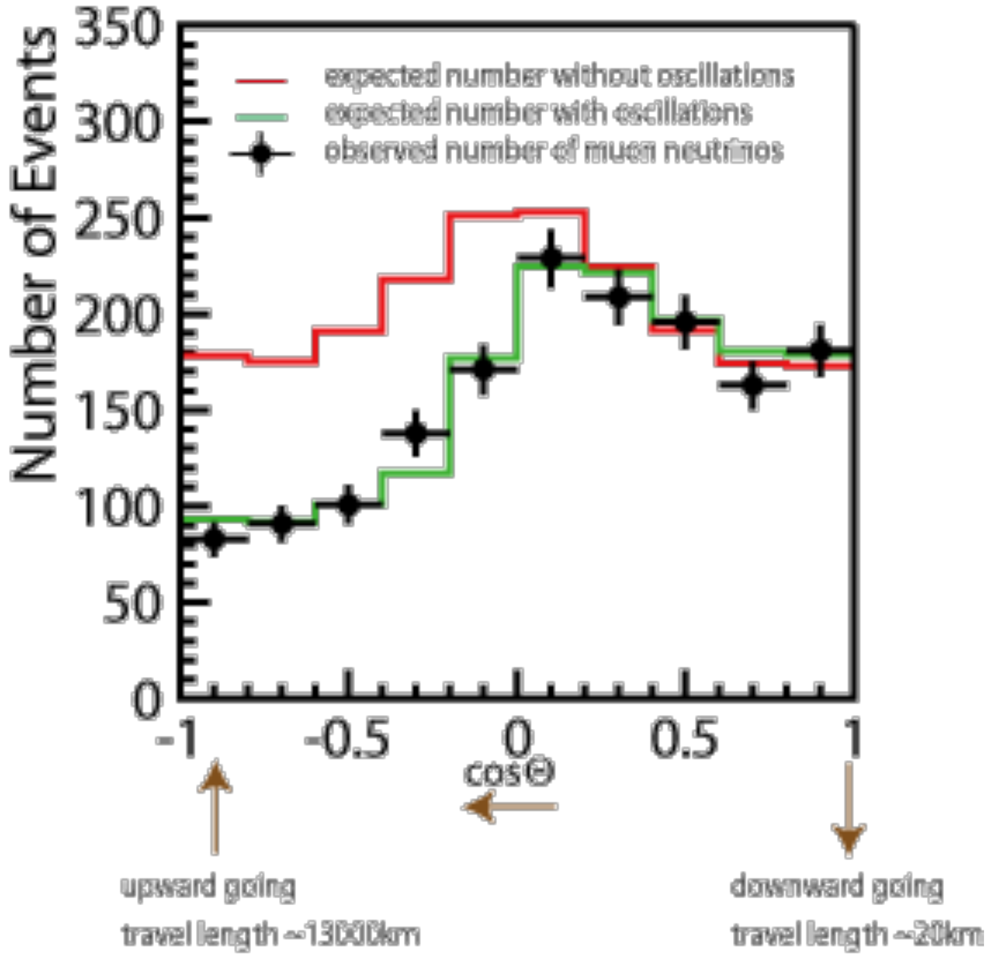


arxiv: 1609.04981

- Time integrates searches for sources have not yielded an significant results
- Does the majority of the diffuse flux come from transient sources?

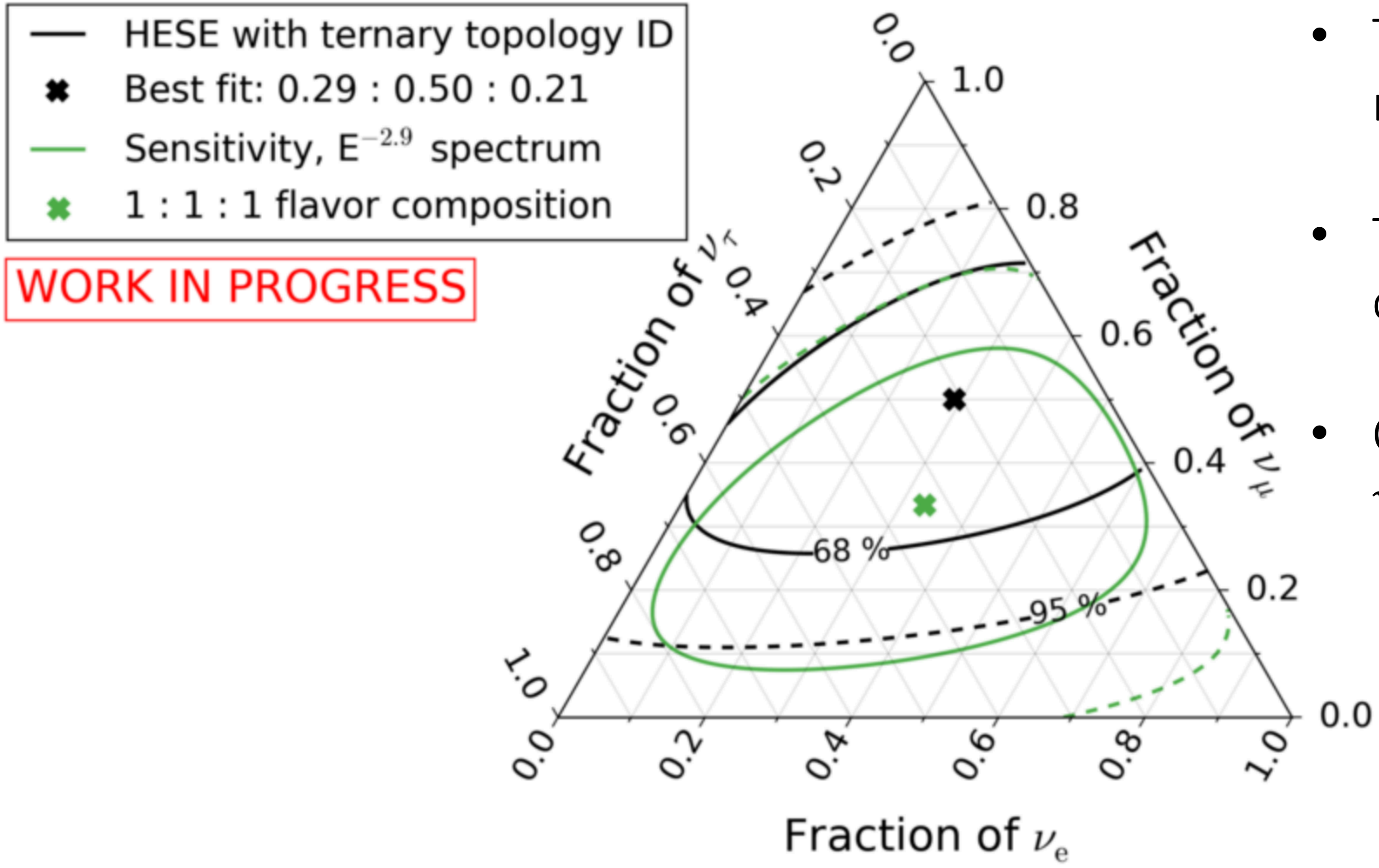
Neutrino Flavors and Oscillations

- The effects of neutrino oscillations were first seen in the Homestake Experiment in the late 1960s
- A deficit in the expected ν_e flux led to the solar neutrino problem
- In 1998 Super-Kamiokande made precise measurements of atmospheric neutrino flux and confirmed neutrino oscillations and thus the existence of neutrino mass



http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/atmnu-e.html

Neutrino Flavors and Oscillations



- There are analyses in IceCube that measure the flavor of neutrinos
- The best fit flavor composition is consistent with 1:1:1
- Cannot distinguish between ν_e and ν_τ cascades

Summary

- Neutrinos are weird (but awesome!)

- There is a lot we don’t understand
  - Where are they produced?
  - Where does their mass come from?
  - Are there more flavors?

- They are great cosmic messengers
  - Weakly interacting + neutral

- Sources of neutrinos remain largely unknown despite many ongoing searches