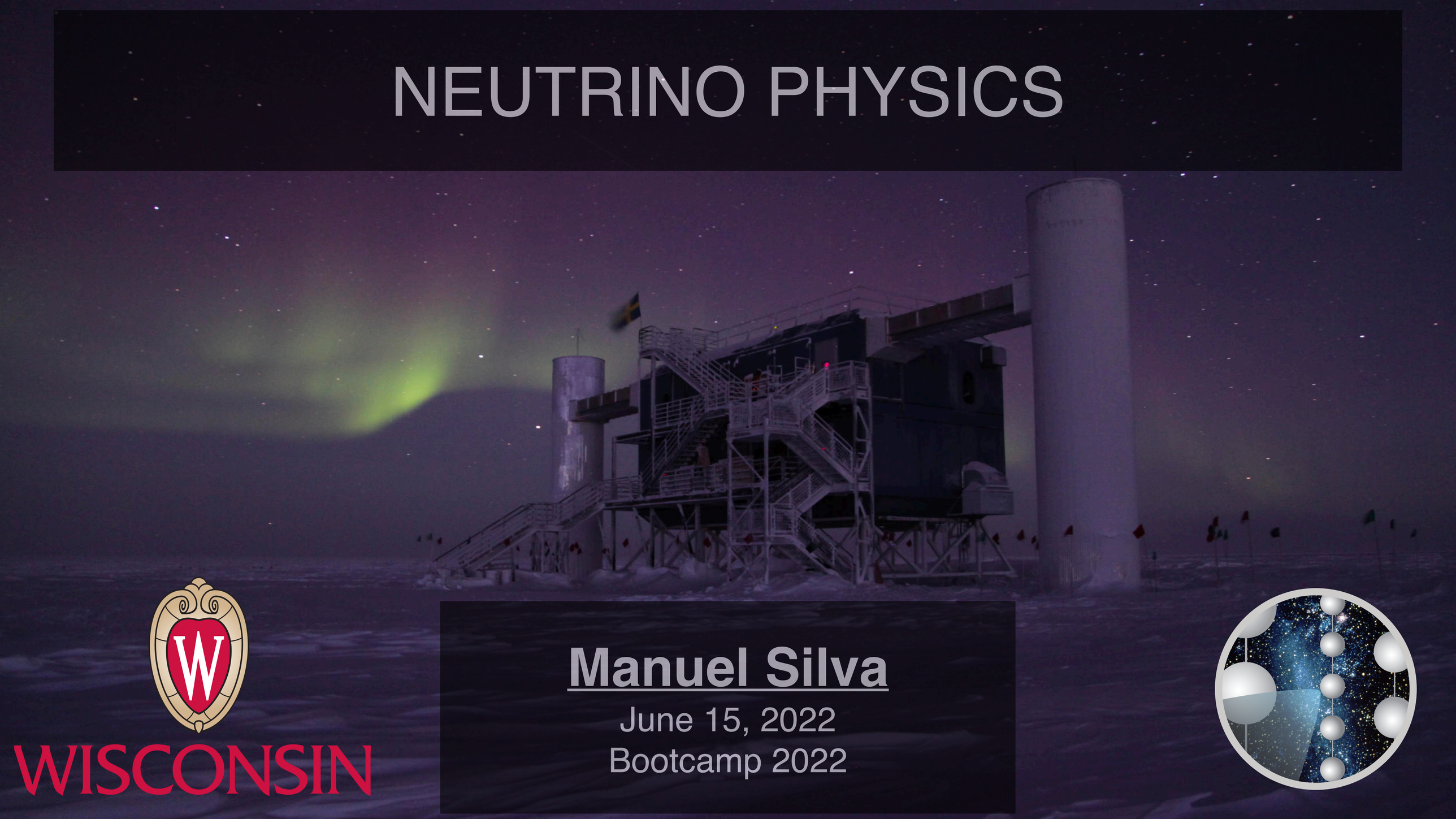
NEUTRINO PHYSICS



Manuel Silva

WISCONSIN

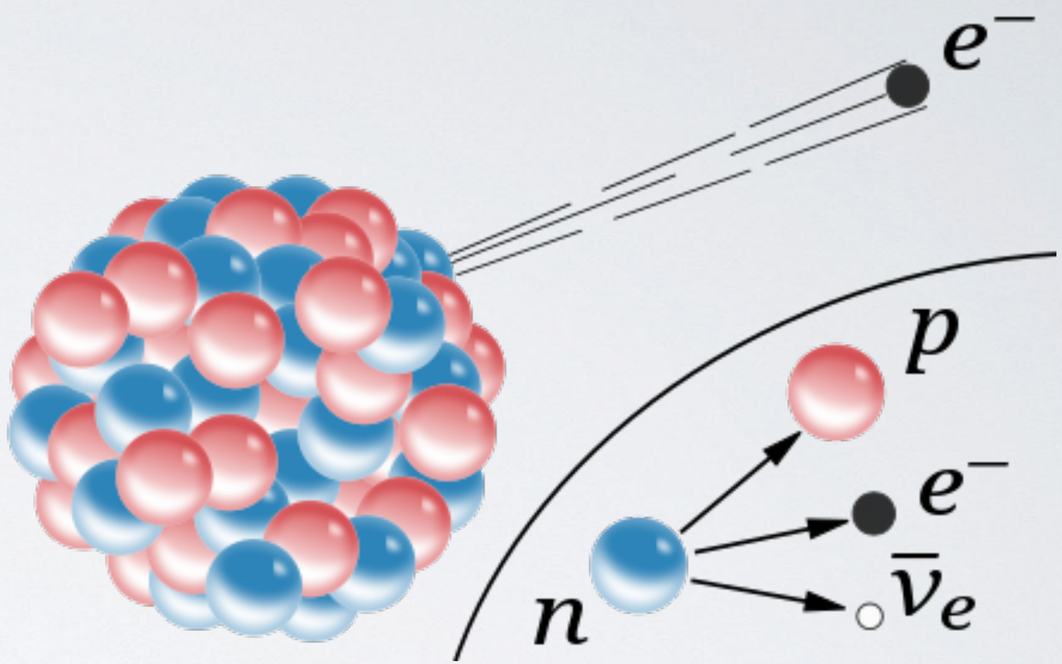
June 15, 2022

Bootcamp 2022

EARLY NEUTRINO THEORY

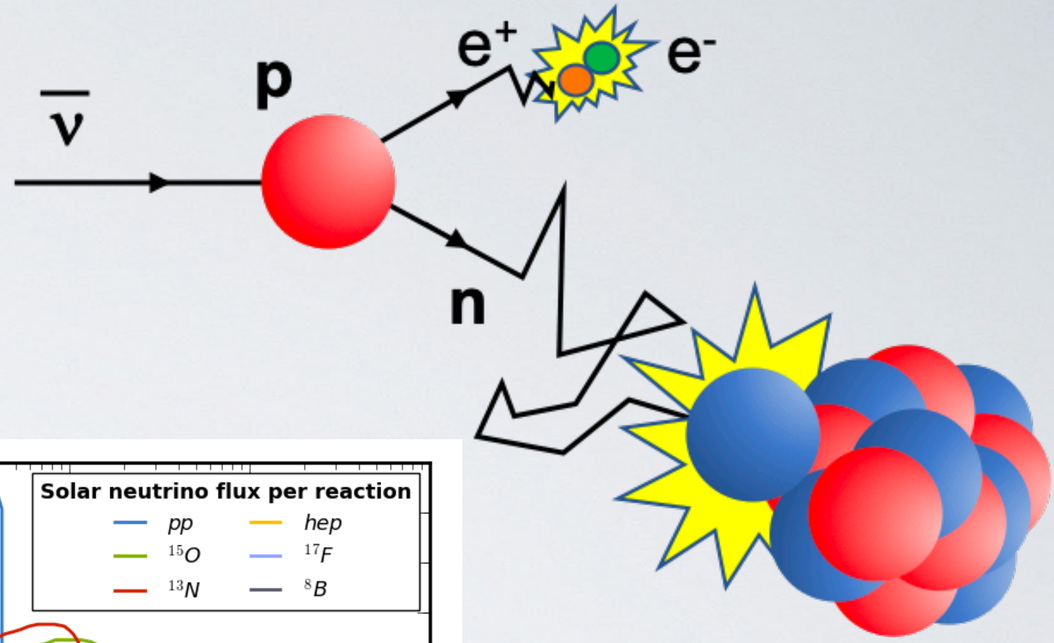
1930 - Pauli introduces concept of neutral particle that conserves energy and momentum in beta decay, names it neutron

1933 - Fermi develops theory of weak interactions, renames particle to little neutron or neutrino

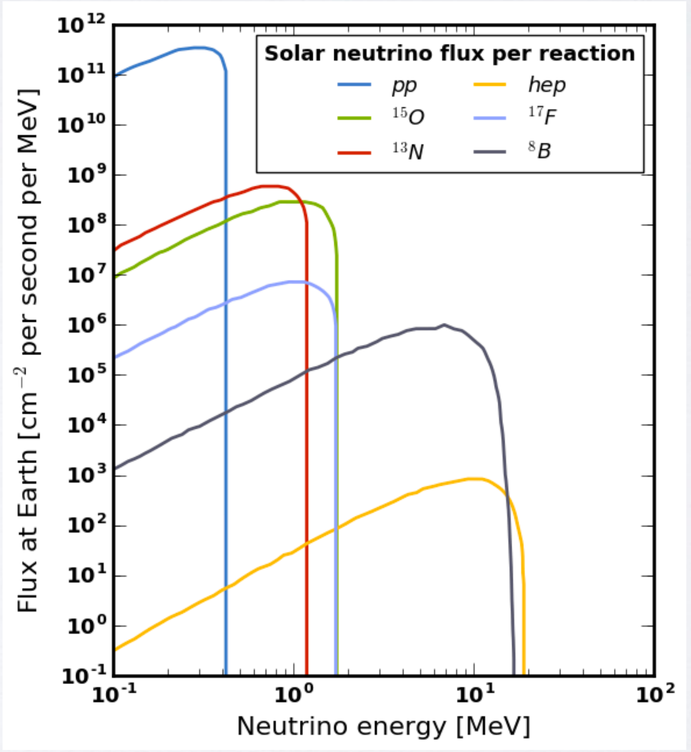


NEUTRINO DISCOVERED

1956 – Cowen and Reines discover the neutrino using inverse beta decay. Electron anti-neutrino produced by nearby nuclear reactor



1968 – Homestake experiment detects electron neutrinos from the sun, but the number observed is 1/3 what was expected.



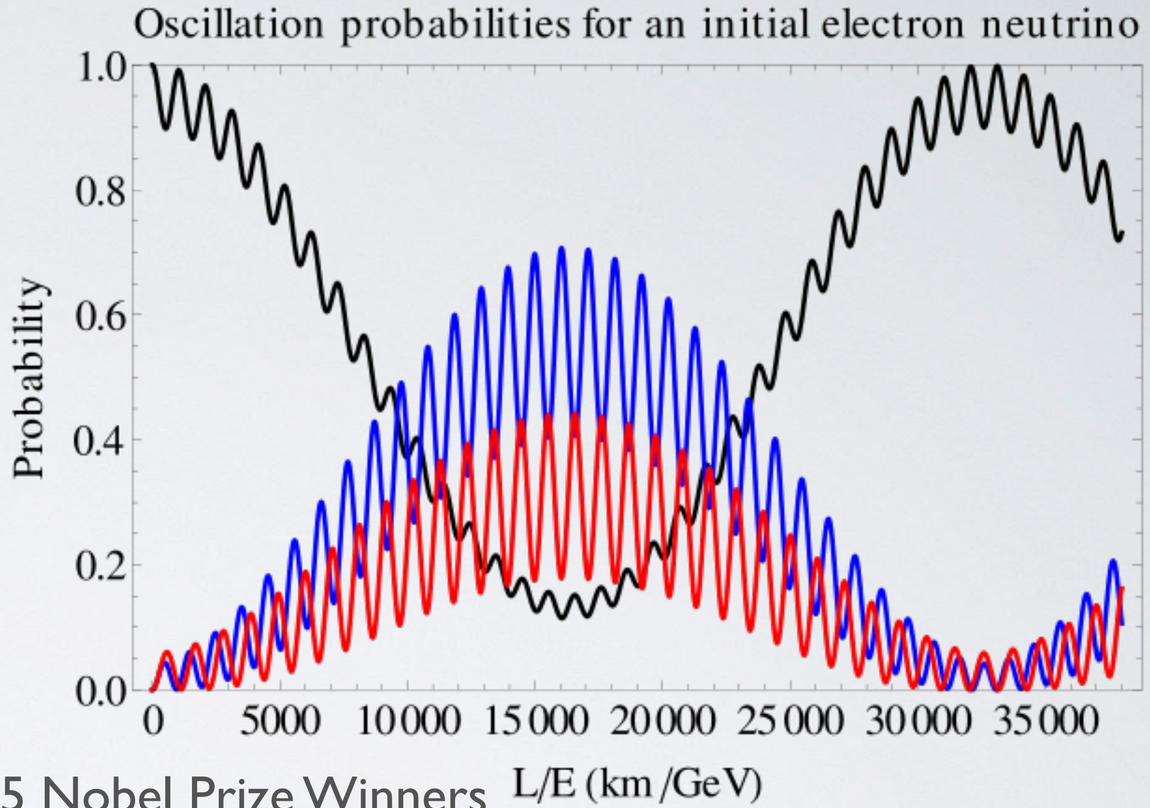
1968-2021 - All neutrino flavors seen, measure mass, measure charge, etc…

SOLAR NEUTRINO PROBLEM

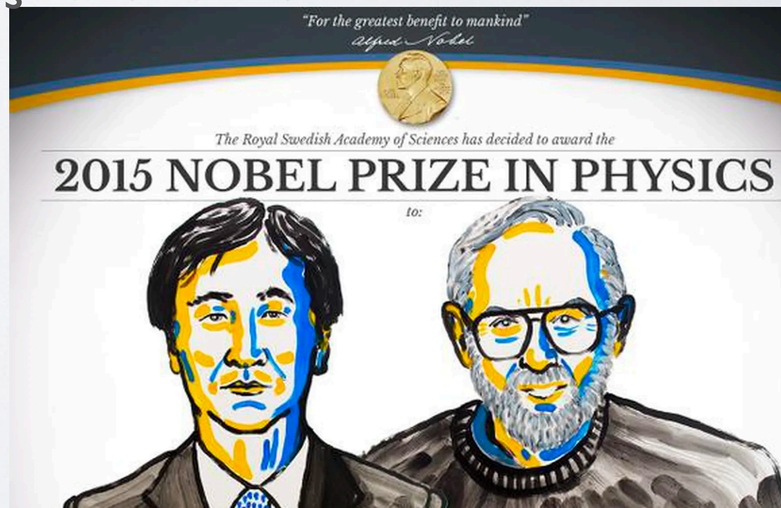
- Homestake only observed 1/3 of the predicted neutrinos, where did they all go?
  - Neutrino oscillations…

- They were only optimized to detect electron neutrinos, decades later confirmed solar neutrino problem and established neutrino oscillation

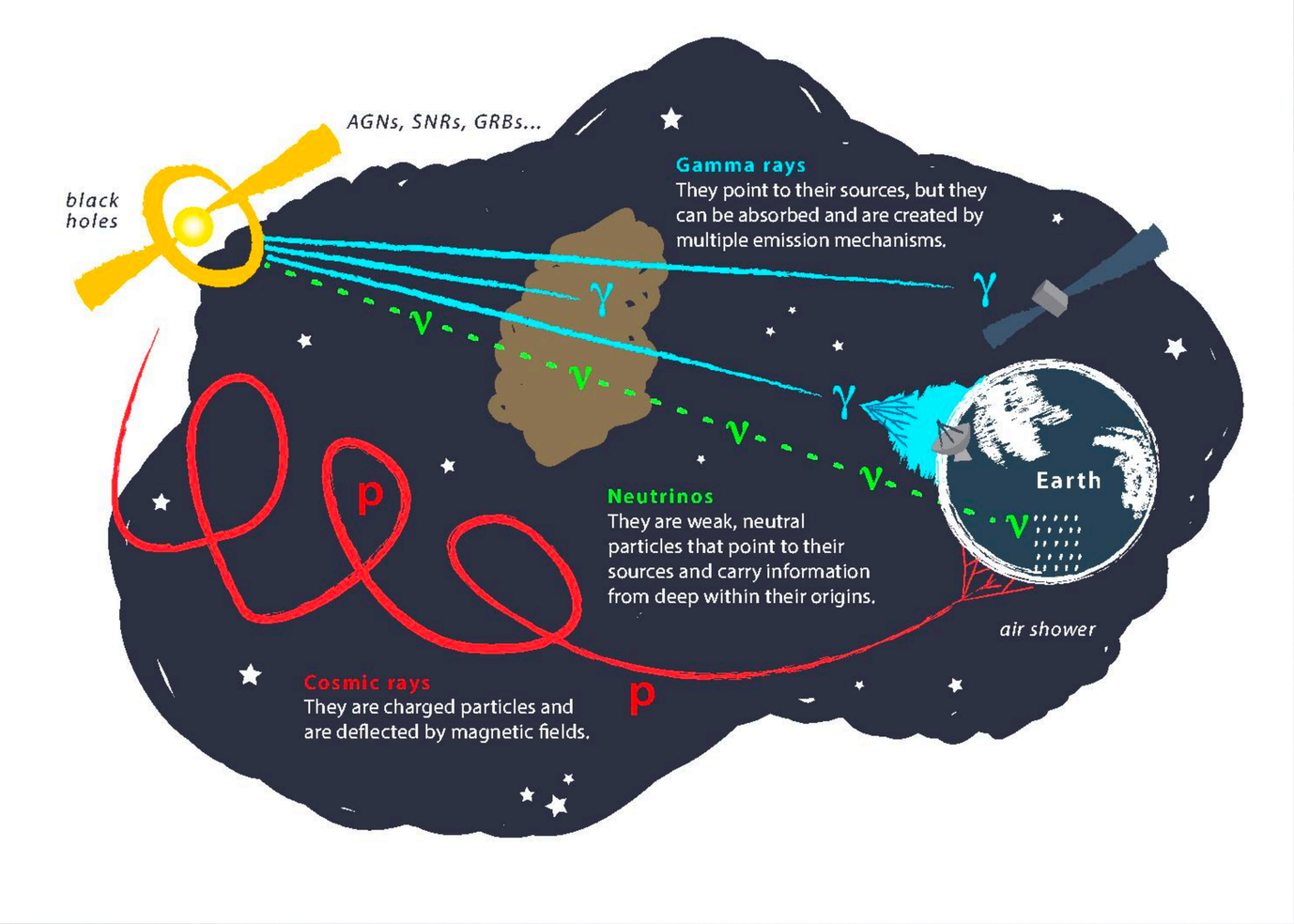
- Needed different detection techniques to detect all neutrino flavors



1995 Nobel Prize Winners
Cowen-Reines

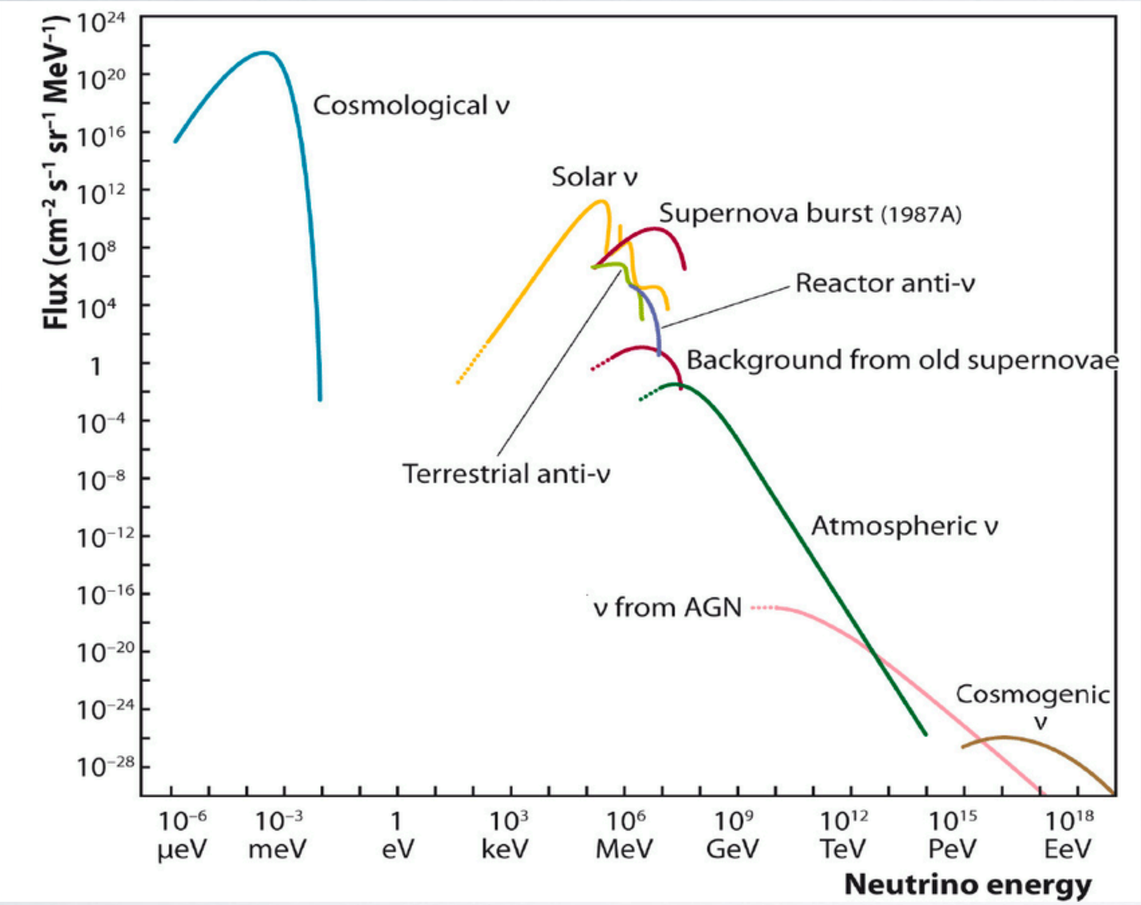


WHY ARE WE INTERESTED IN NEUTRINOS?



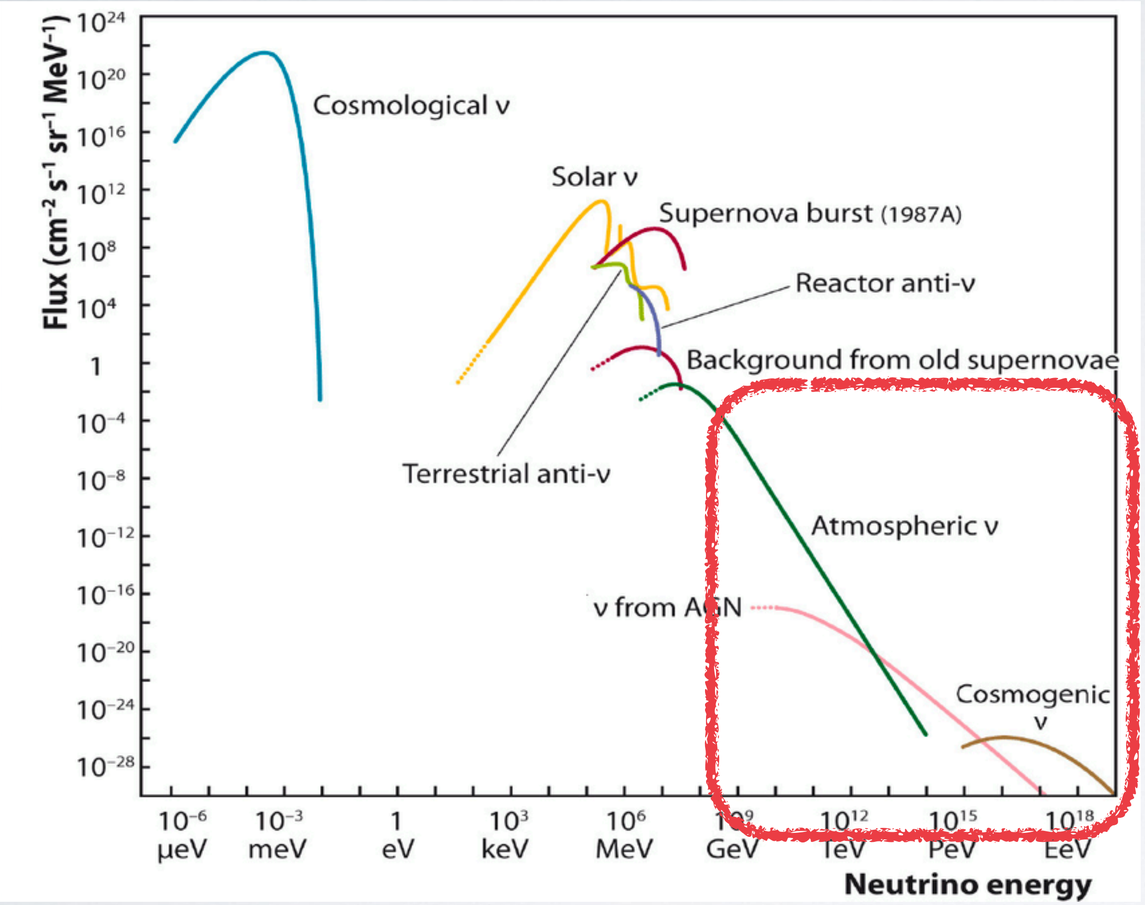
- Source of neutrinos also produces gamma rays and cosmic rays
- Neutrinos are neutral, aren't deflected by interstellar magnetic field
- Neutrinos are weakly interacting, can travel billions of light years without interacting

NEUTRINO SOURCES



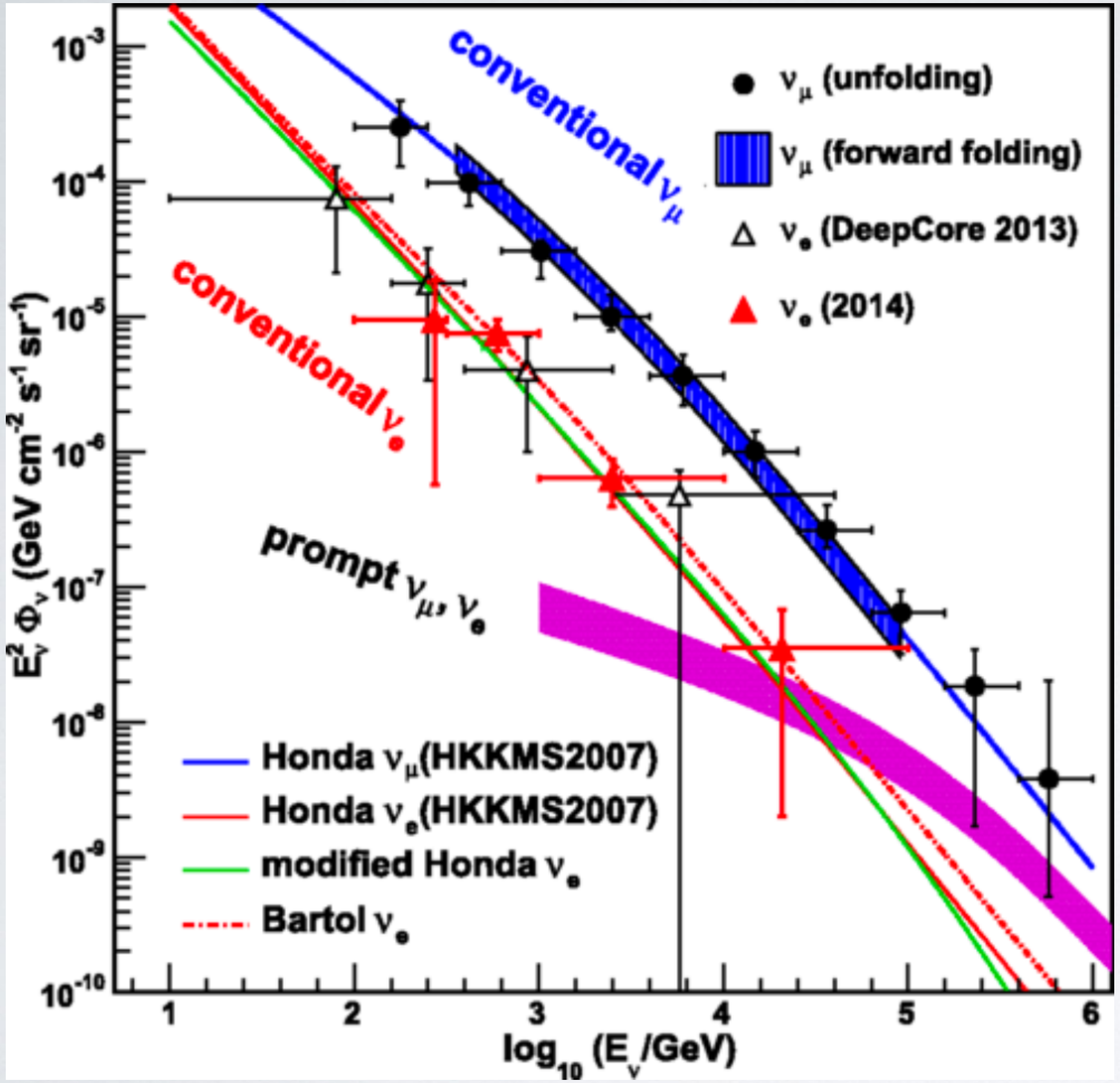
- Naturally produced neutrino from 1 μeV to 1 EeV in energy
- Flux scales rapidly with energy, the higher in energy the neutrino the lower the production rate

NEUTRINO SOURCES

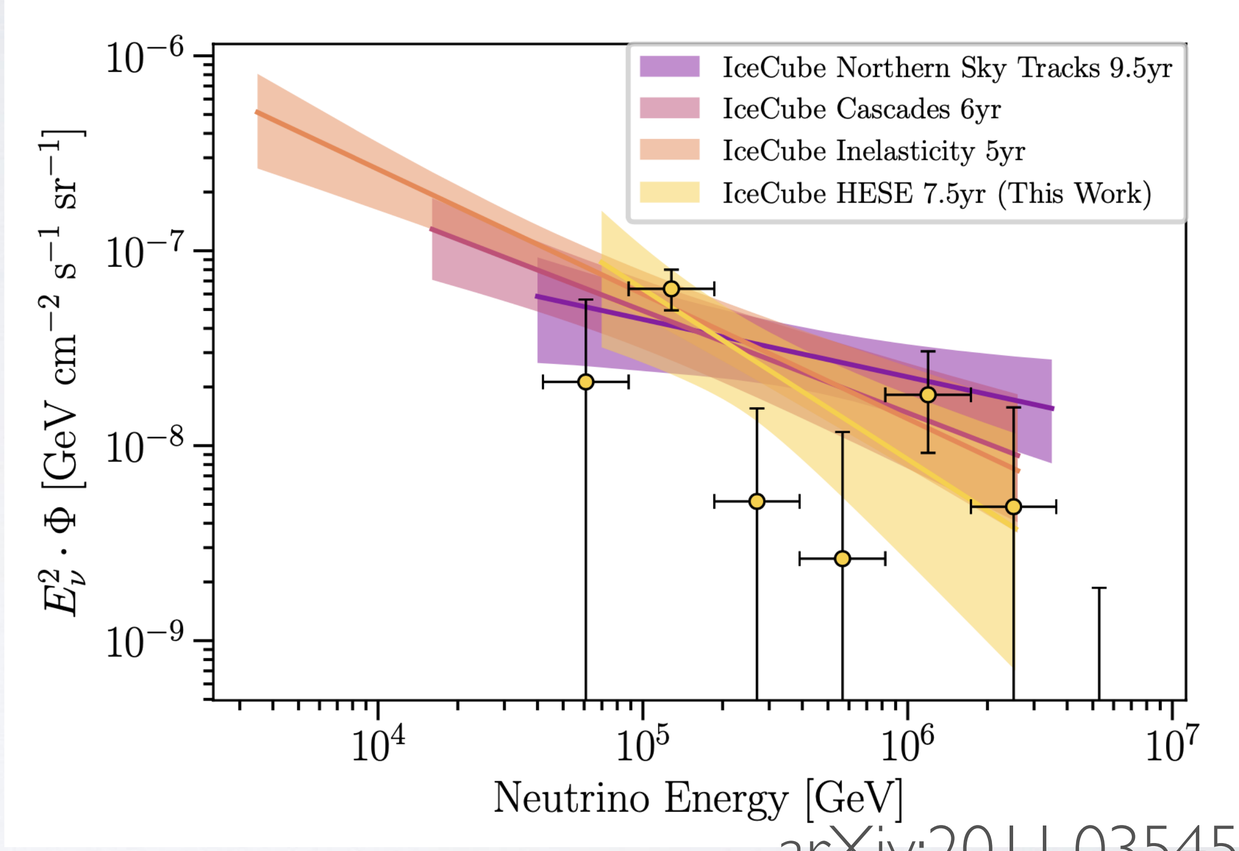


- Naturally produced neutrino from 1 μeV to 1 EeV in energy
- Flux scales rapidly with energy, the higher in energy the neutrino the lower the production rate
- IceCube optimized to observe neutrinos above 100 GeV (deepcore lowers this to 1 GeV)

RECENT FLUX MEASUREMENTS

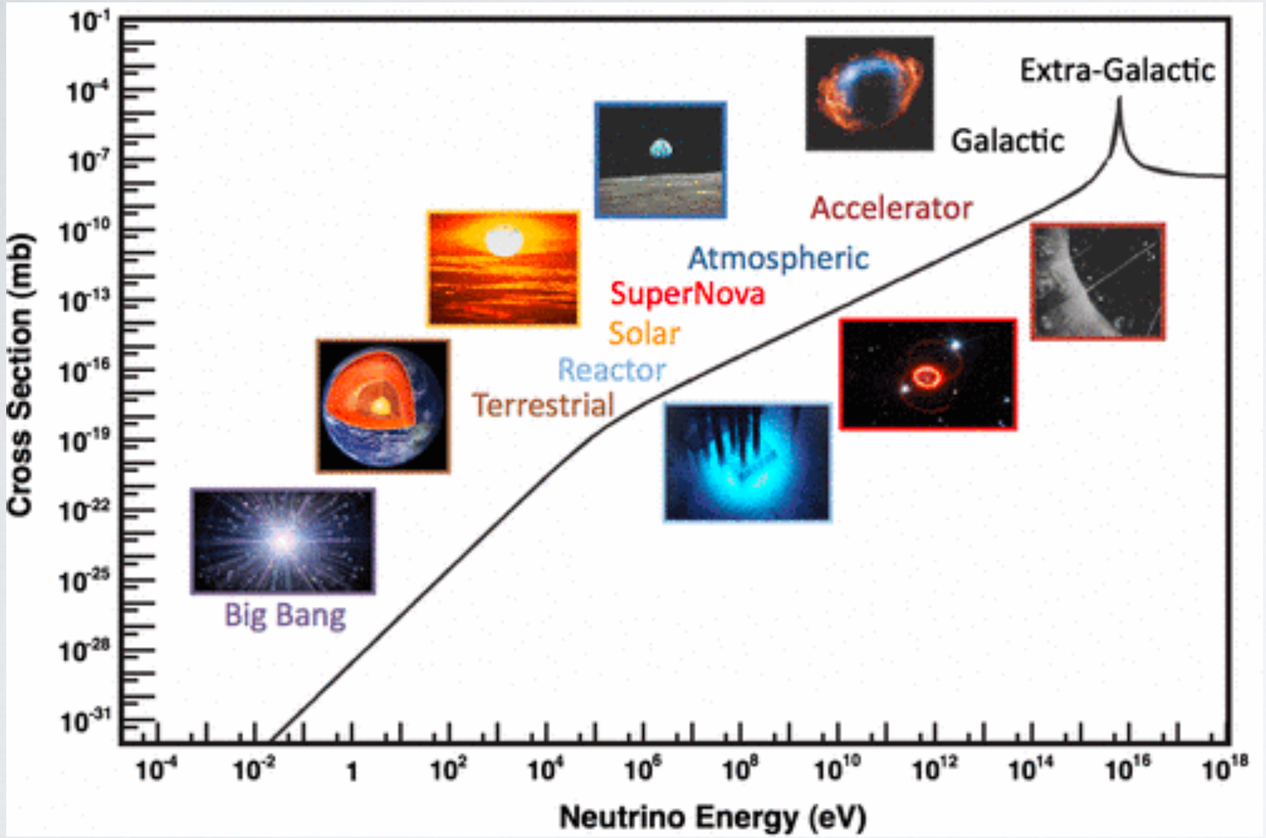


Phys. Rev. D 91, 122004



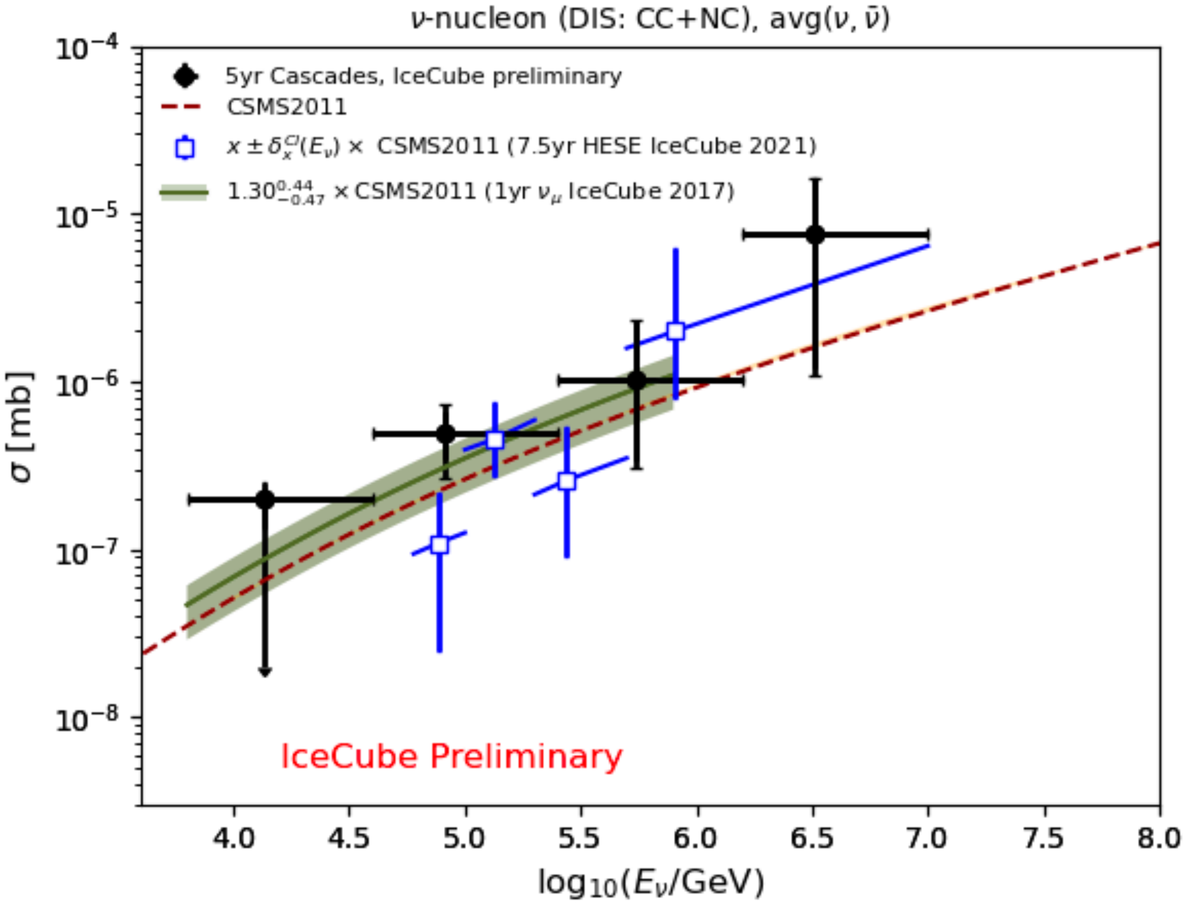
arXiv:2011.03545

NEUTRINO CROSS-SECTION



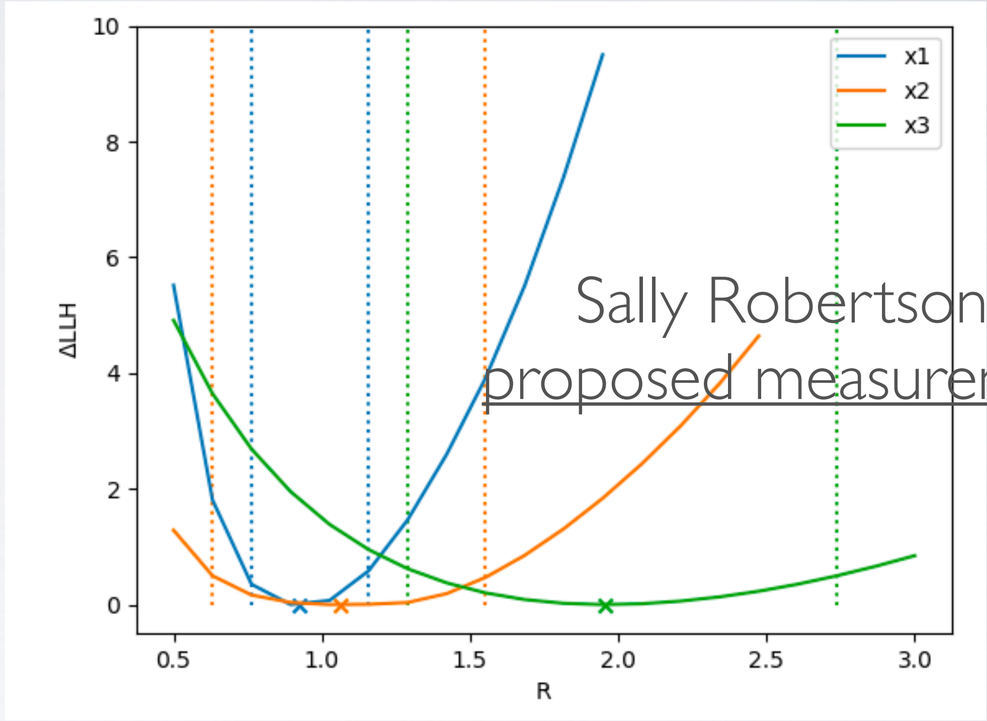
- Neutrino cross section is working in our favor, increases linearly with energy
- Above ~100GeV, deep inelastic scattering dominates
- The neutrino scatters off a nucleus in the ice and produces an electron, muon, tau and/or hadrons

CROSS-SECTION MEASUREMENT



Plot shown at Neutrino 2022 by Tom Stuttard.

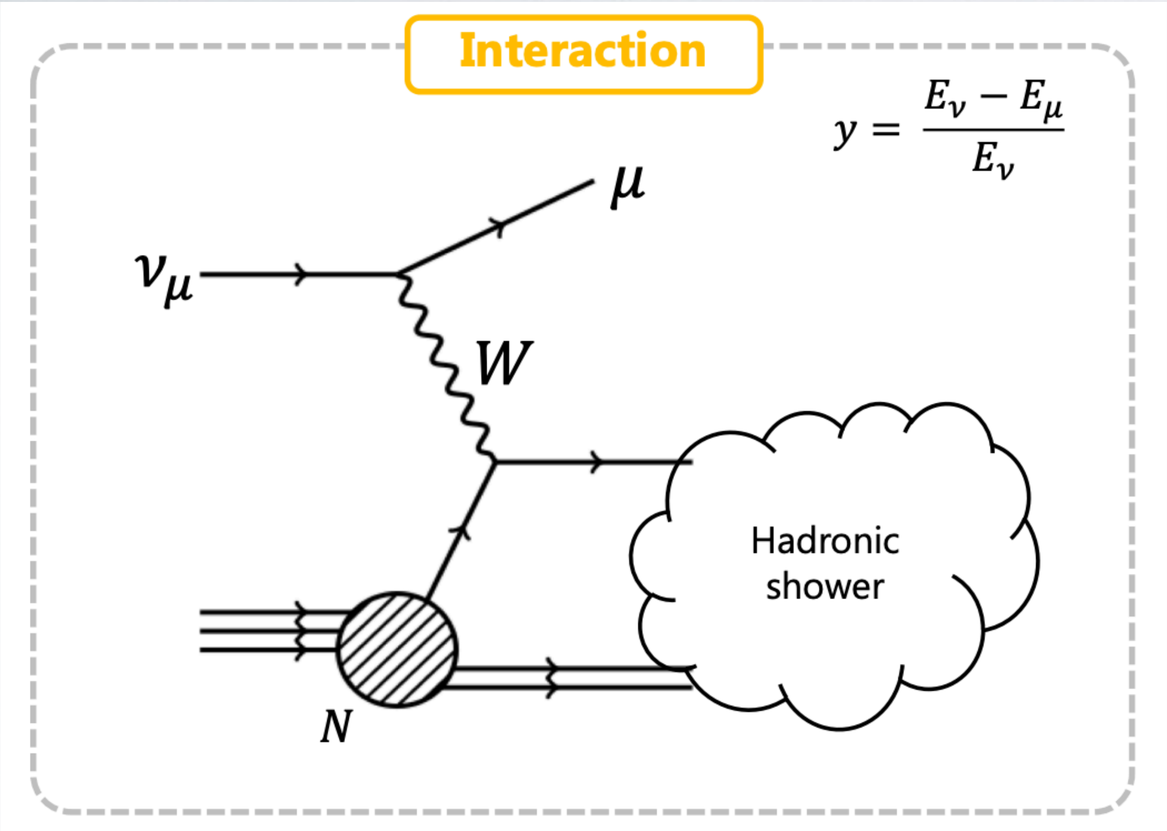
- Public results show good agreement with CSMS model

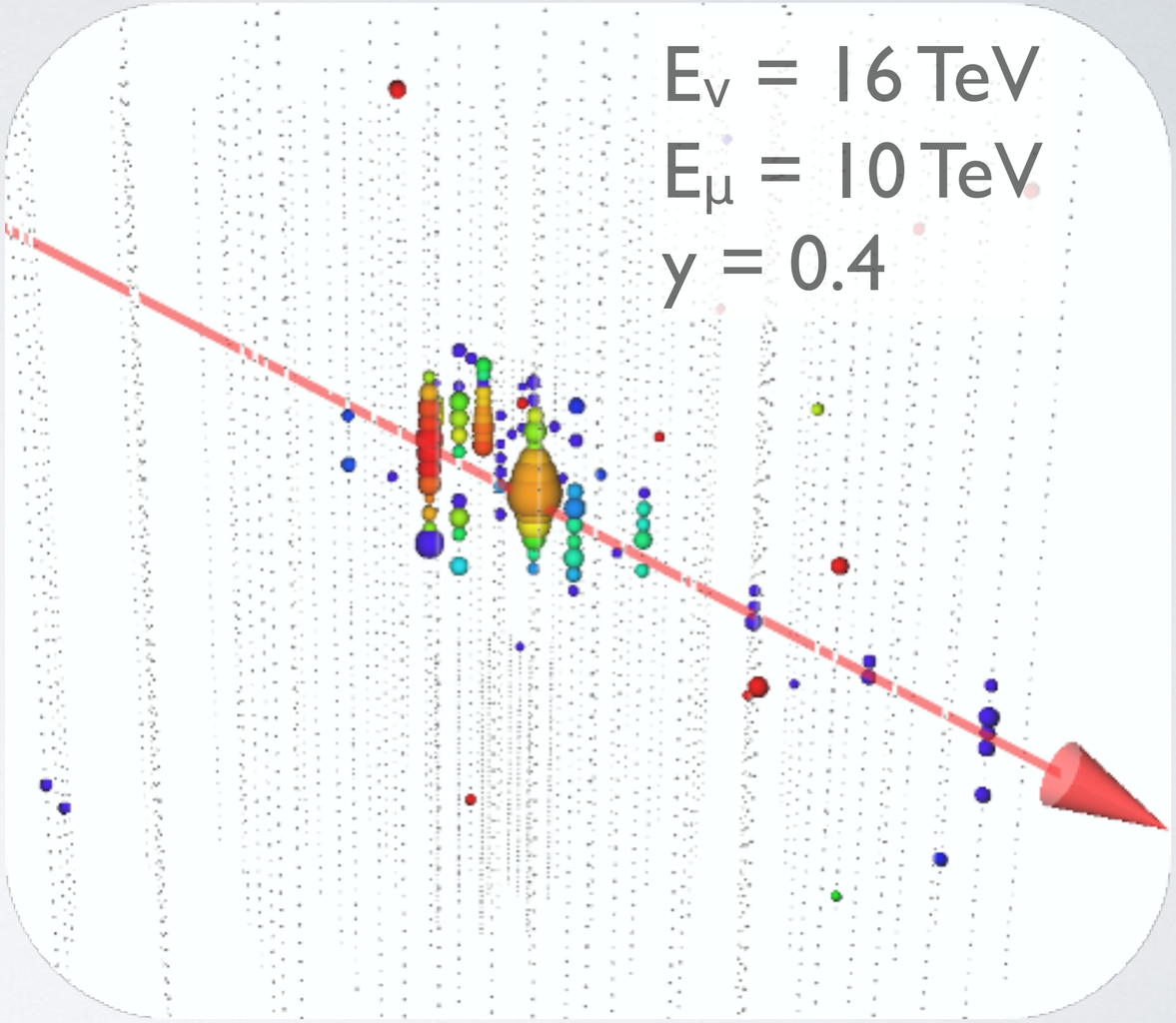


Sally Robertson's proposed measurement

Ongoing efforts to measure σ below 10 TeV (x1=1-10TeV, x2=10-100TeV, x2>100 TeV)

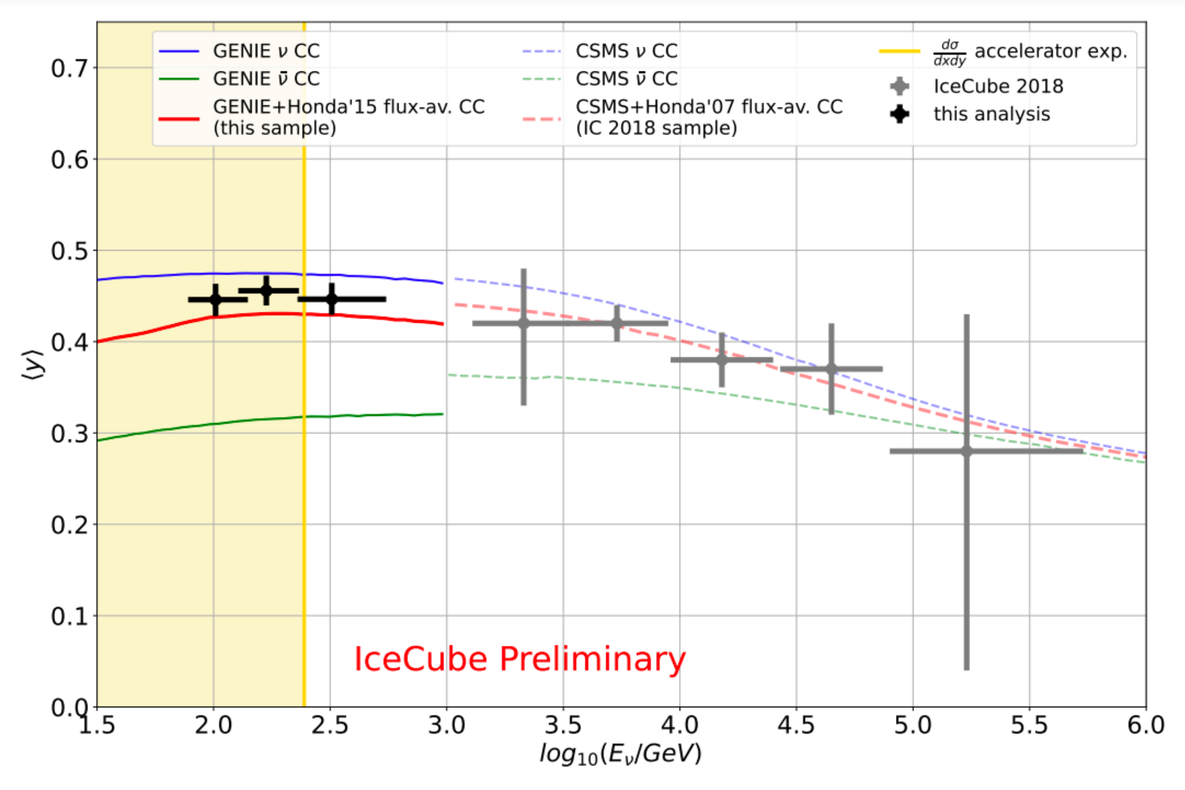
INELASTICITY (Y)





Plot shown at Neutrino 2022 by Tom Stuttard.

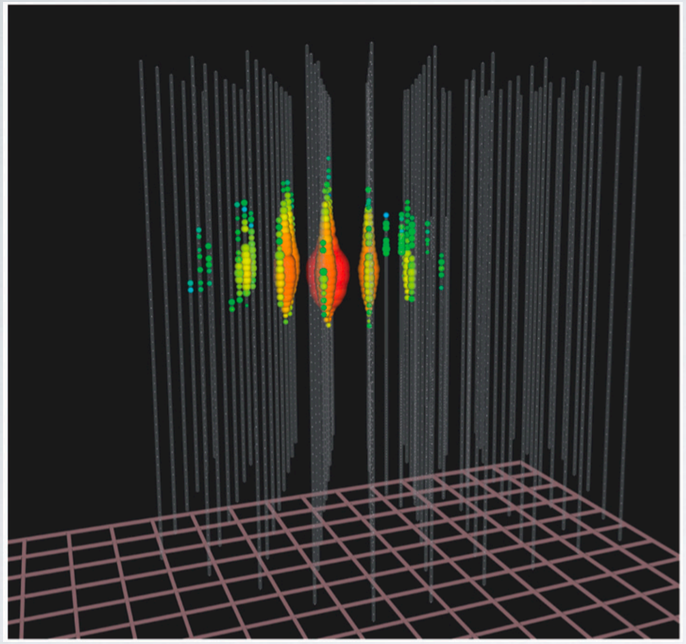
INELASTICITY MEASUREMENT



- Recent public result showed that below 1 TeV, the measured inelasticity prefers something that is more "CSMS"-like over something more "Genie"-like
- Are the theory models wrong? Is our measurement missing something? Stay tuned…

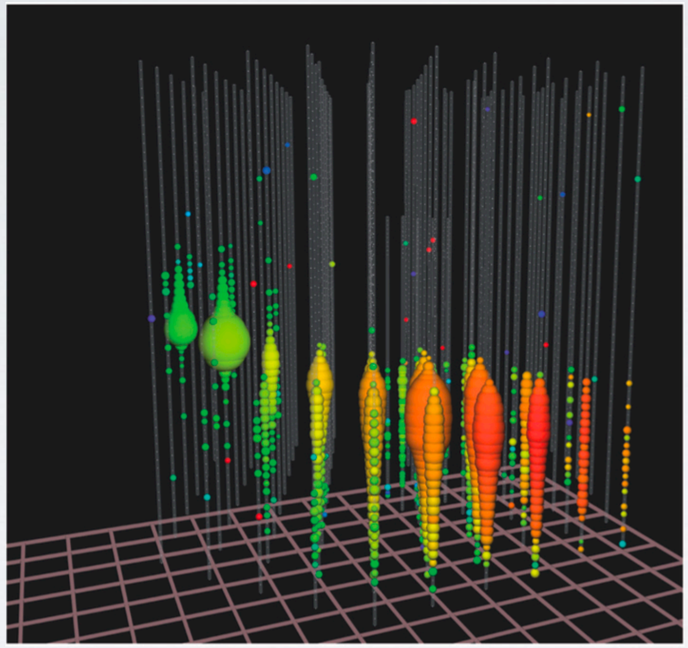
Plot shown at Neutrino 2022 by Tom Stuttard.

NEUTRINO FLAVOR IDENTIFICATION



<u>Cascades</u>

Mostly ν_e



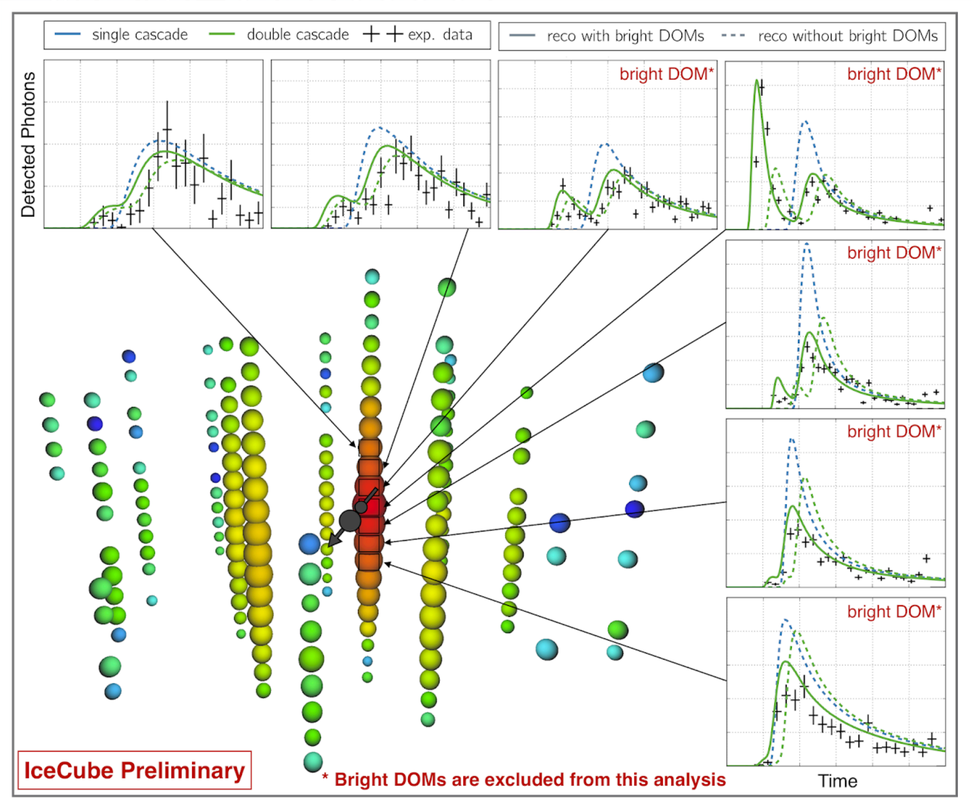
<u>Up-going Tracks</u>

Mostly ν_μ

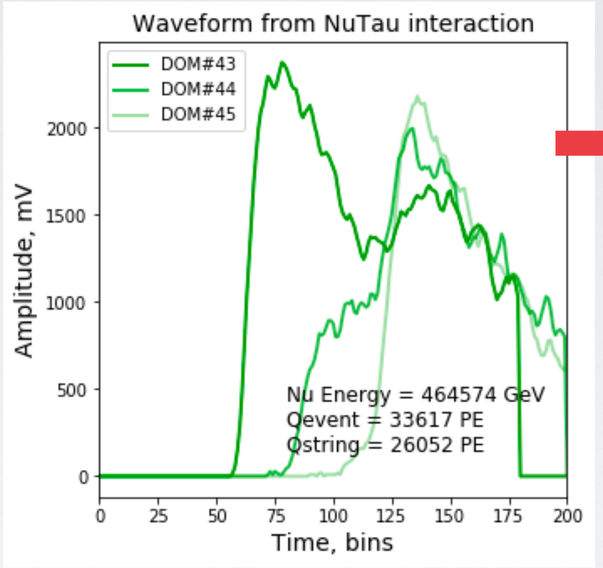
- Historically, IceCube has separated data into two categories
  - Cascades and upgoing tracks
- Cascades consist of all neutral current and electron/tau neutrino charged current interactions
- Upgoing tracks are charged current muon neutrino interactions only
  - Taus can technically decay and produce muons too! ~10-20% of the the total upgoing tracks

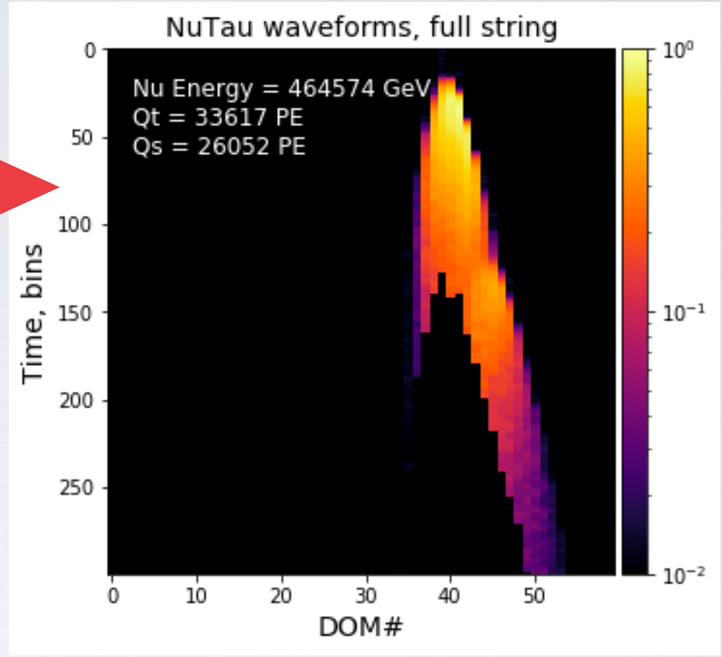
SEARCH FOR TAU NEUTRINOS

arXiv:2011.03561



- Tau neutrino classification using "double pulse" structure

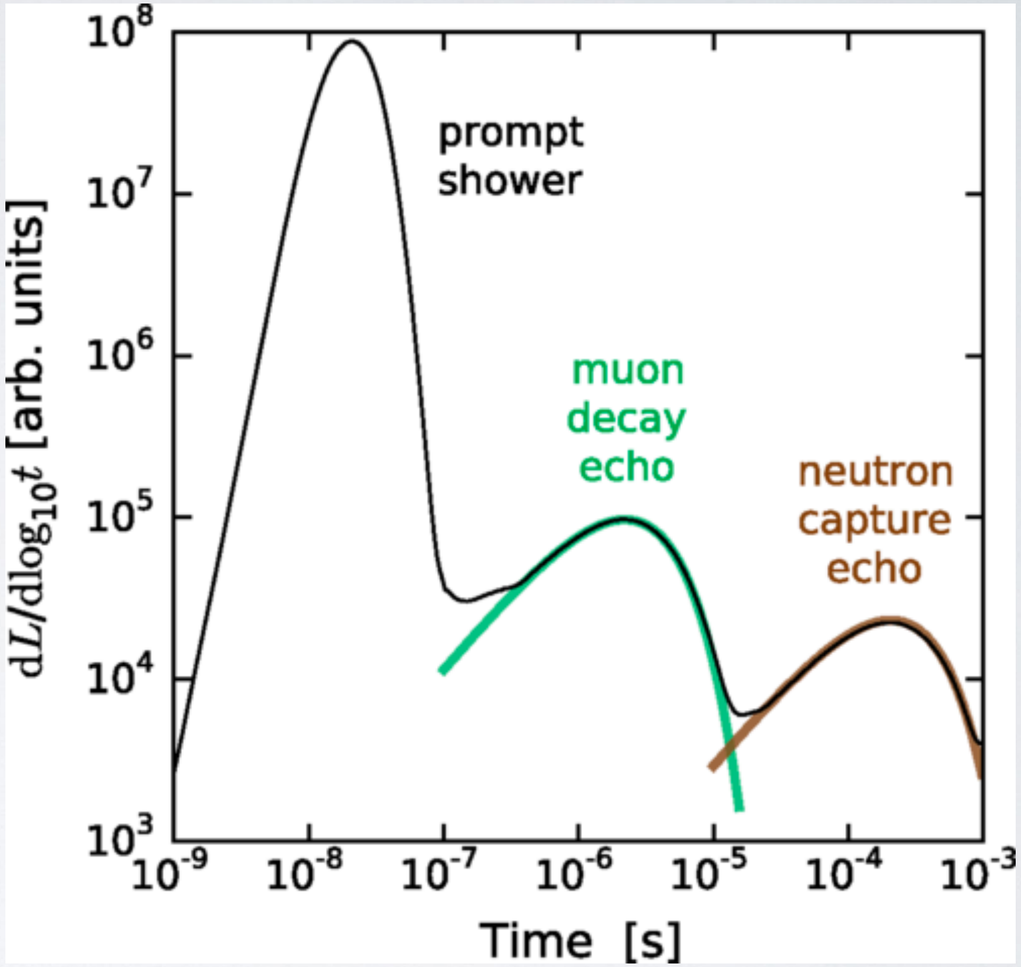




- Extension of "double pulse" with convolutional neural networks. Recent data shows significant presence of tau neutrinos in our data! Link

NEUTRON ECHO

- CC interactions all have a charged lepton emitted
- NC interaction hadron is the detectable signature
- Neutron scatters elastically in the ice until it is eventually captured by a nucleon
  - Gamma rays emitted ~1ms after the DIS



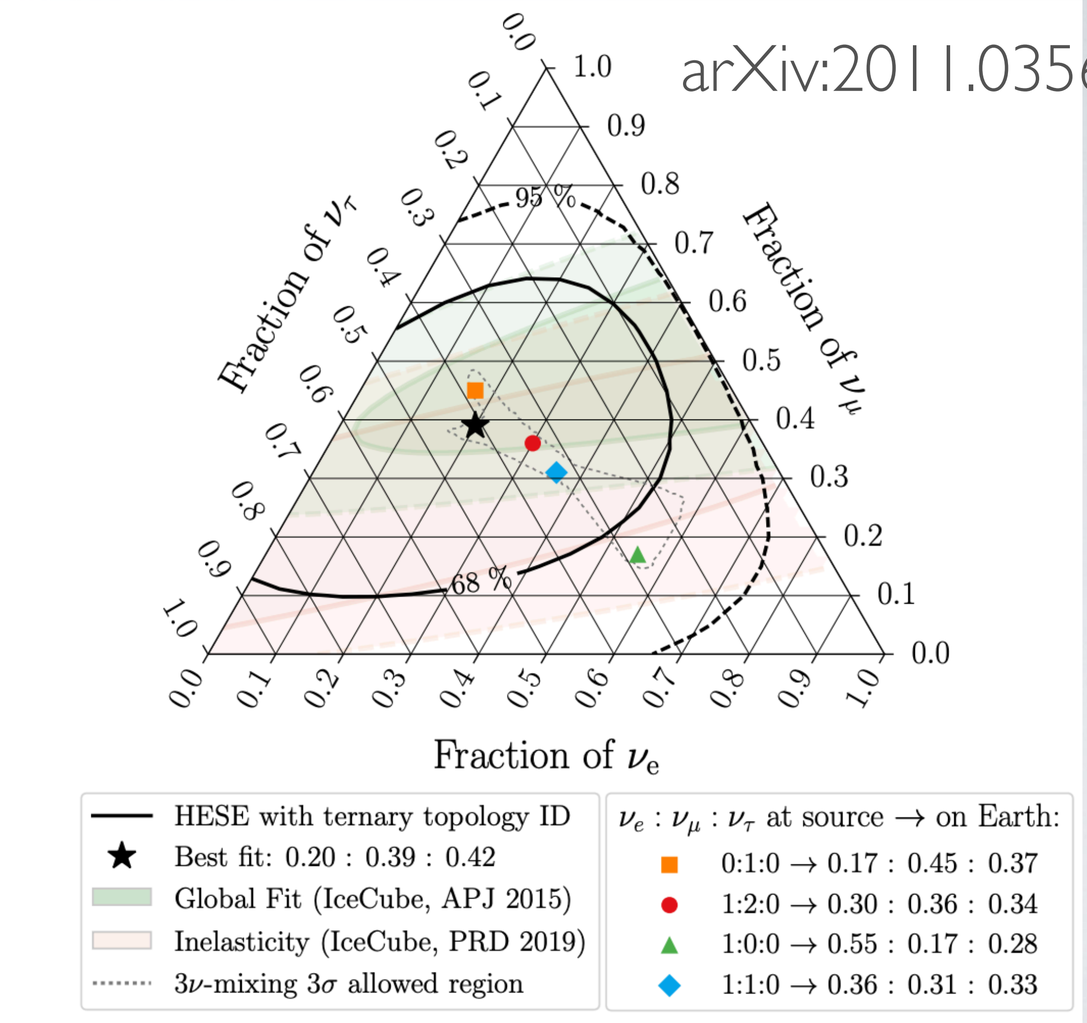
Phys. Rev. Lett. 122, 151101

NEUTRINO FLAVOR RATIO

- We can measure the total flux of astrophysical neutrinos per flavor
- Measurement shown as “flavor triangle”
- Most icecube measurements assume 1:1:1, this is because most theoretical neutrino emission models assume purely hadronic processes

$$p + p \rightarrow \pi^{\mp} \rightarrow \mu^{\mp} + \overset{(-)}{\nu}_{\mu} \rightarrow e^{\mp} + \overset{(-)}{\nu}_{e} + \nu_{\mu} + \overline{\nu}_{\mu}$$

- *Note: Quick flavor-ratio primer here*



GLASHOW RESONANCE

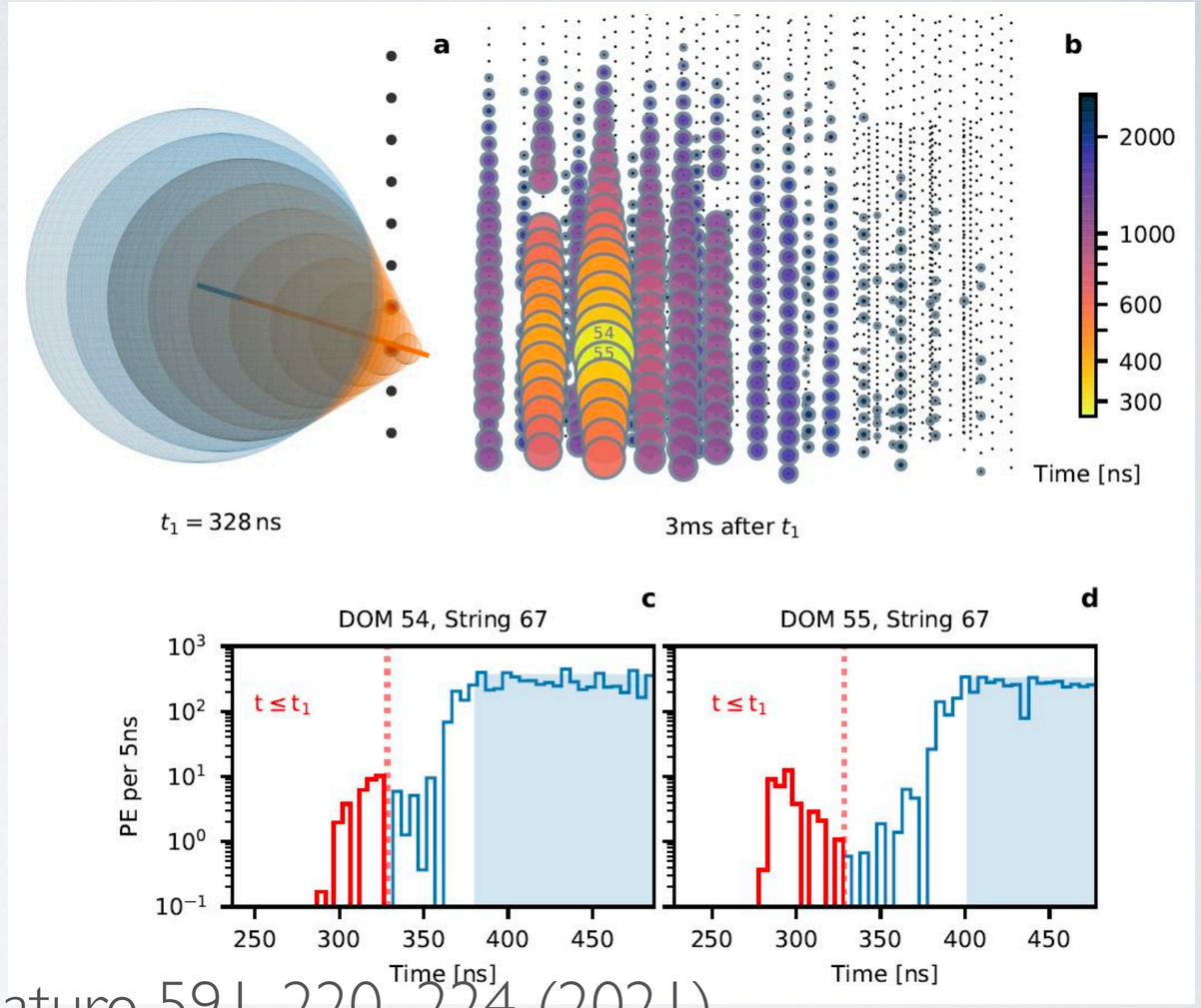
- Glashow resonance where electron antineutrino interacts with an electron

$$\bar{\nu}_e + e^- \rightarrow W^-$$

- Threshold anti-electron neutrino energy is ~6.3 PeV

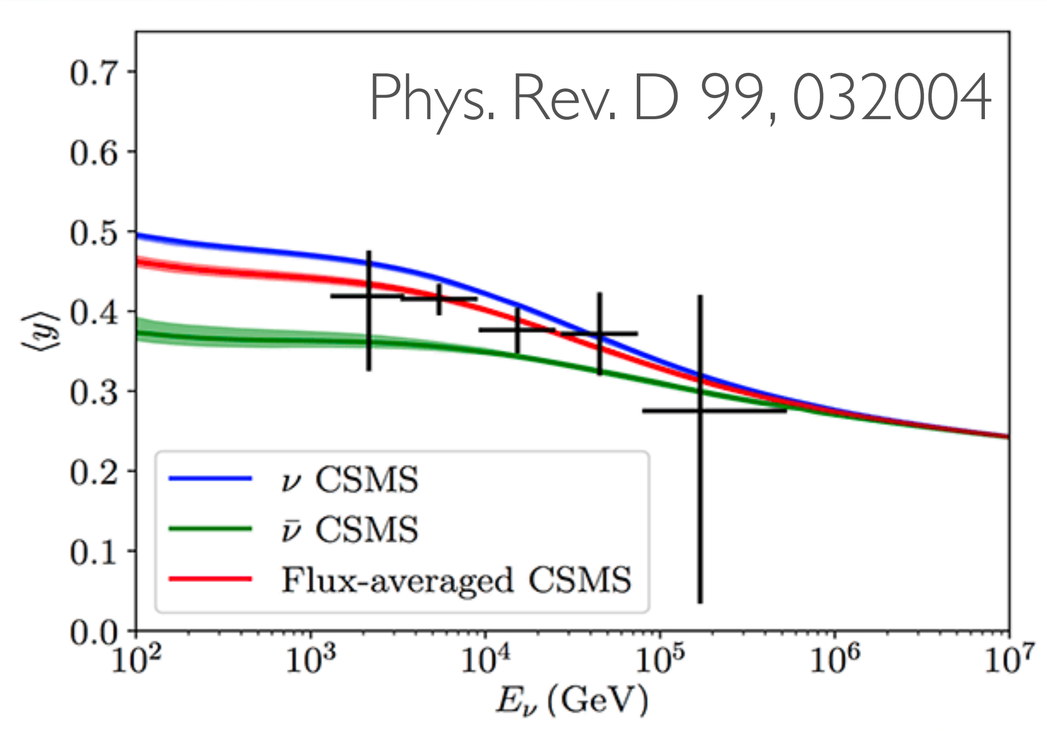
$$E_\nu = \frac{M_W^2 - (m_e^2 + m_\nu^2)}{2m_e} \approx \frac{M_W^2}{2m_e}$$

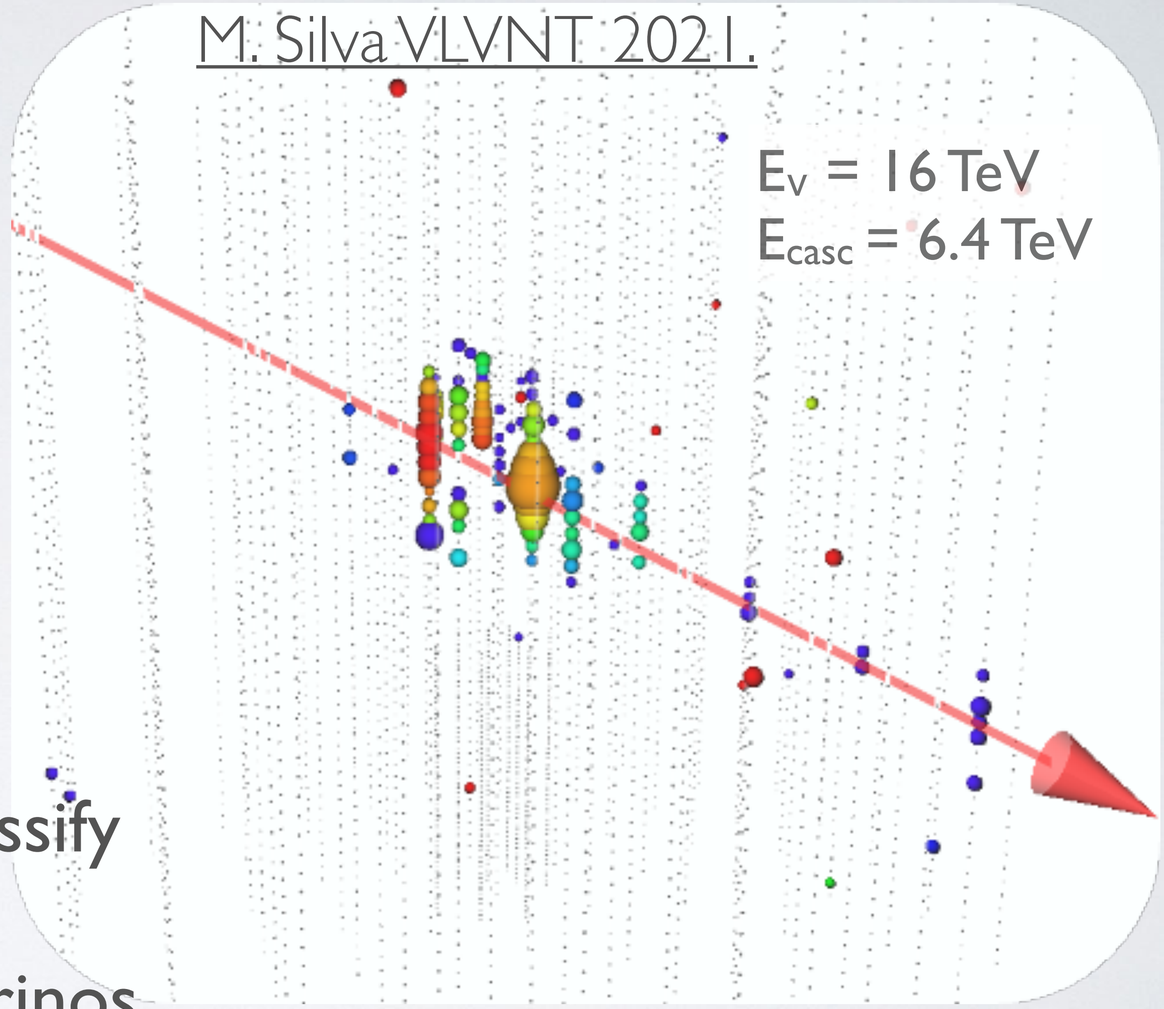
- Anti-electron neutrino to electron neutrino ratio is very important to understand how astrophysical neutrinos are produced



Nature 591, 220–224 (2021)

MUON NEUTRINO/ANTI-NEUTRINO CLASSIFICATION





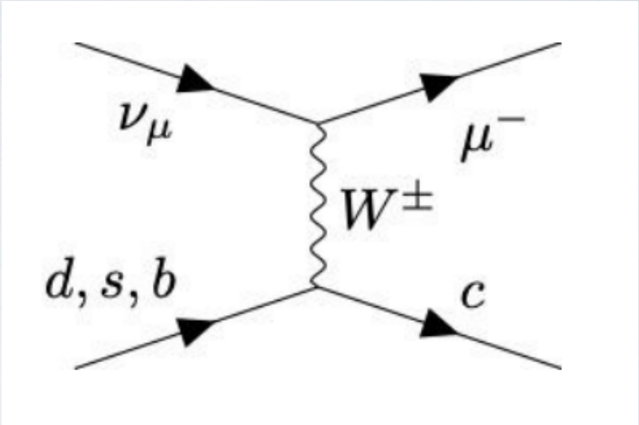
- Inelasticity of event could be used to classify events into neutrino/anti-neutrinos
- Can also be used to search for tau-neutrinos and particles from charmed interactions

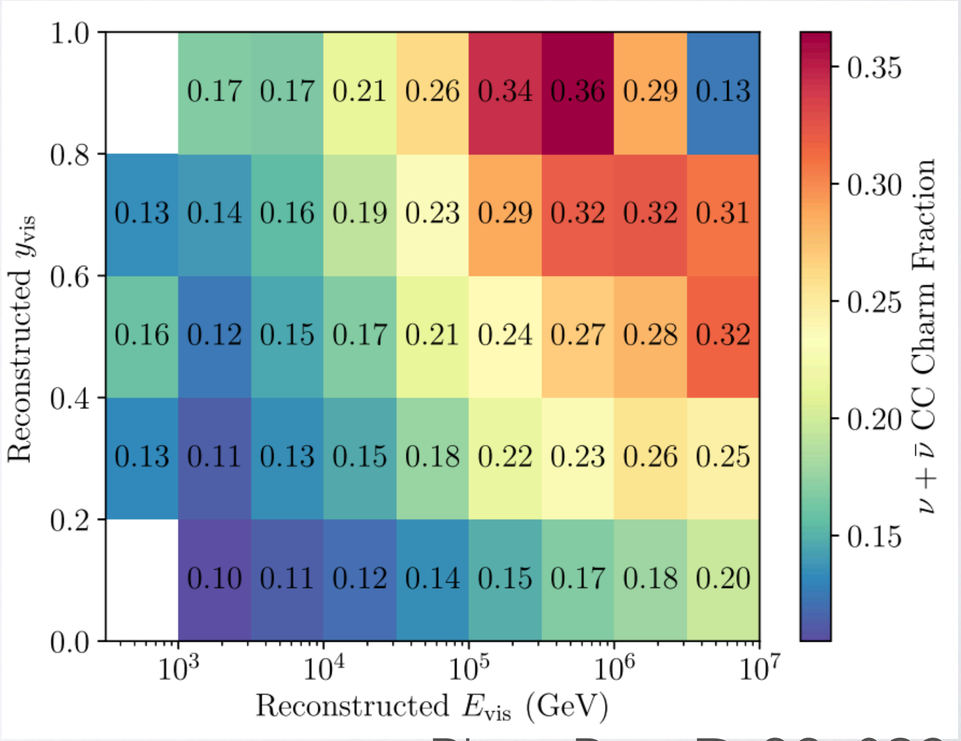
SEARCH FOR CHARM

- Recall that IceCube assumes CSMS cross-section for neutrino interactions above ~100 GeV
- However, CSMS omits interactions that could produce charmed particles (D-meson, λ-baryons)

- Recent publication states: "charm=0 excluded to 91% confidence"

- Ongoing efforts to increase dataset size and improve techniques. Link





Phys. Rev. D 99, 032004

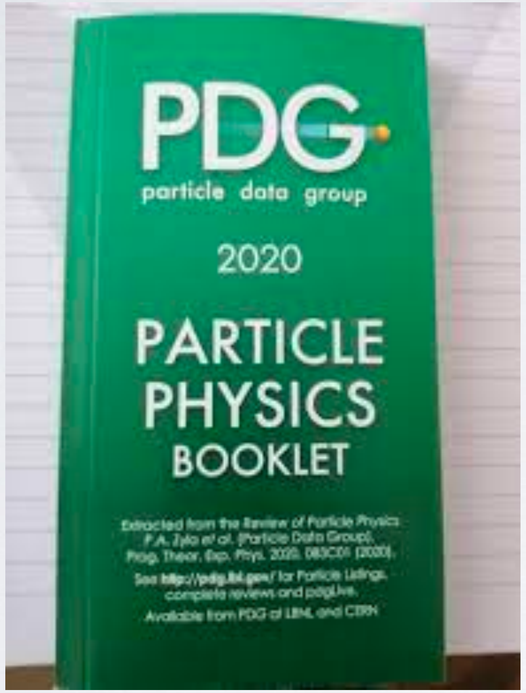
SUMMARY

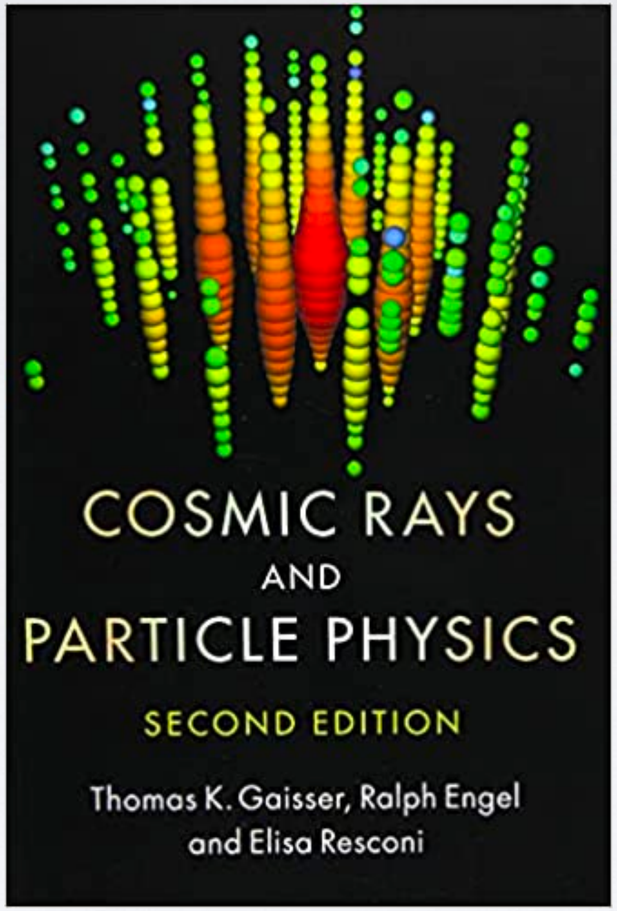
Neutrinos are one of the most interesting fundamental particles to study!
Several Nobel Prizes have already been won studying the neutrino

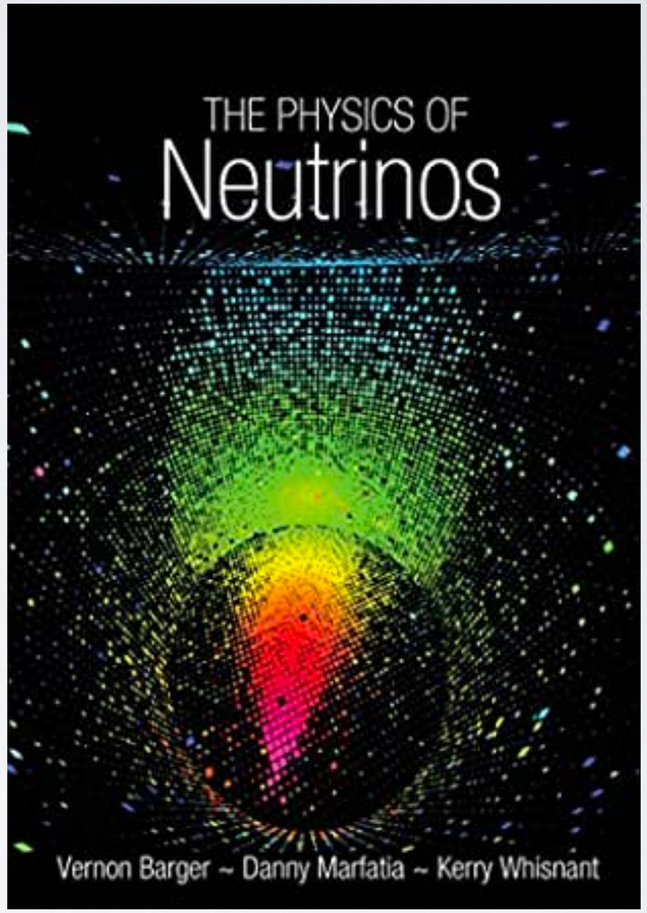
IceCube has access to a very large datasets. All flavor neutrinos. Wide energy ranges, etc…
So far we have measured the oscillation parameters of the neutrinos, the flux of atmospheric and astrophysical neutrinos, cross-section, etc…

Next phase of study include more precise measurements such as flavor identification, neutrino/anti-neutrino classification, etc….

NEUTRINO PHYSICS PRIMERS

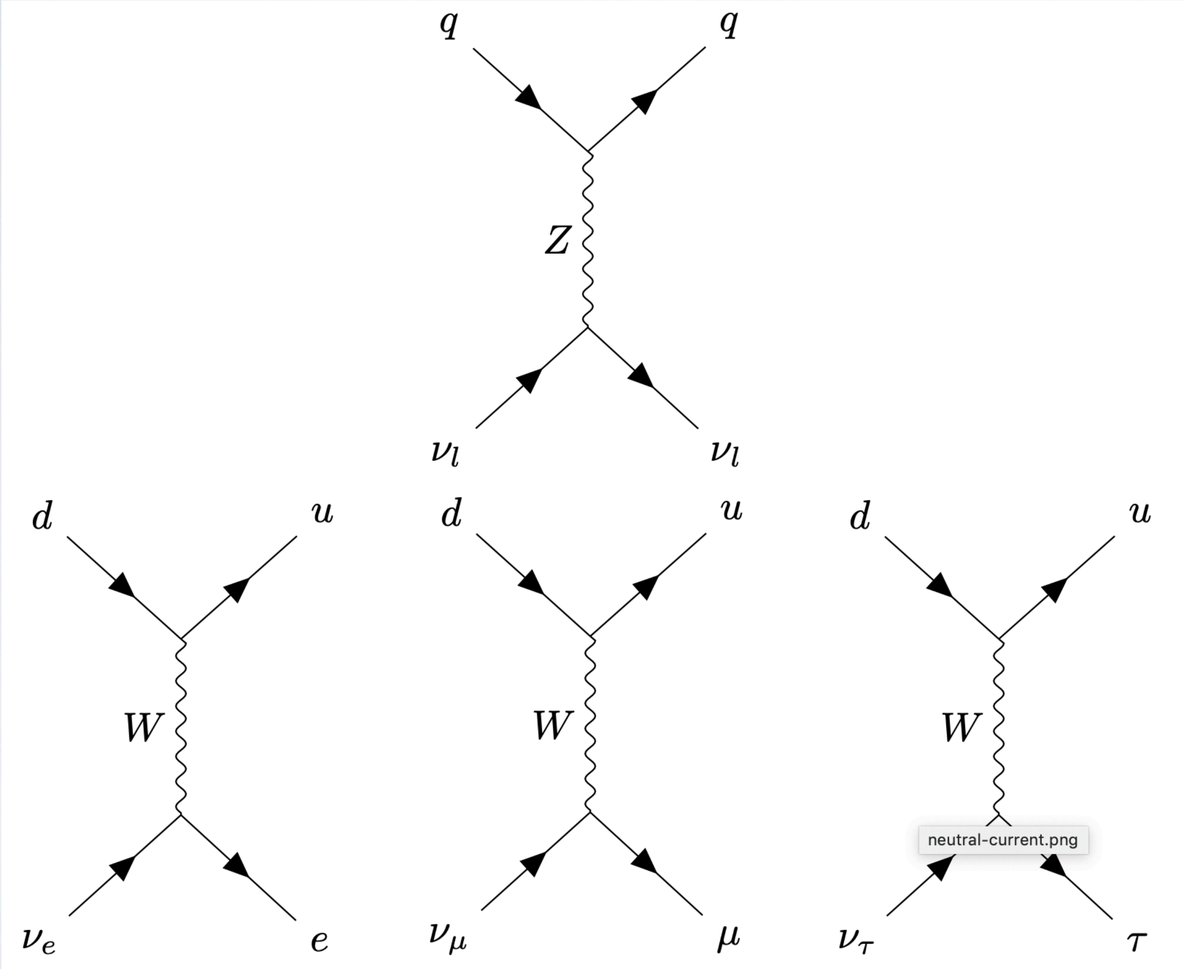






QUESTIONS??

DEEP INELASTIC SCATTERING



Neutral current

Charged current