NEUTRINO PHYSICS

WISCONSIN

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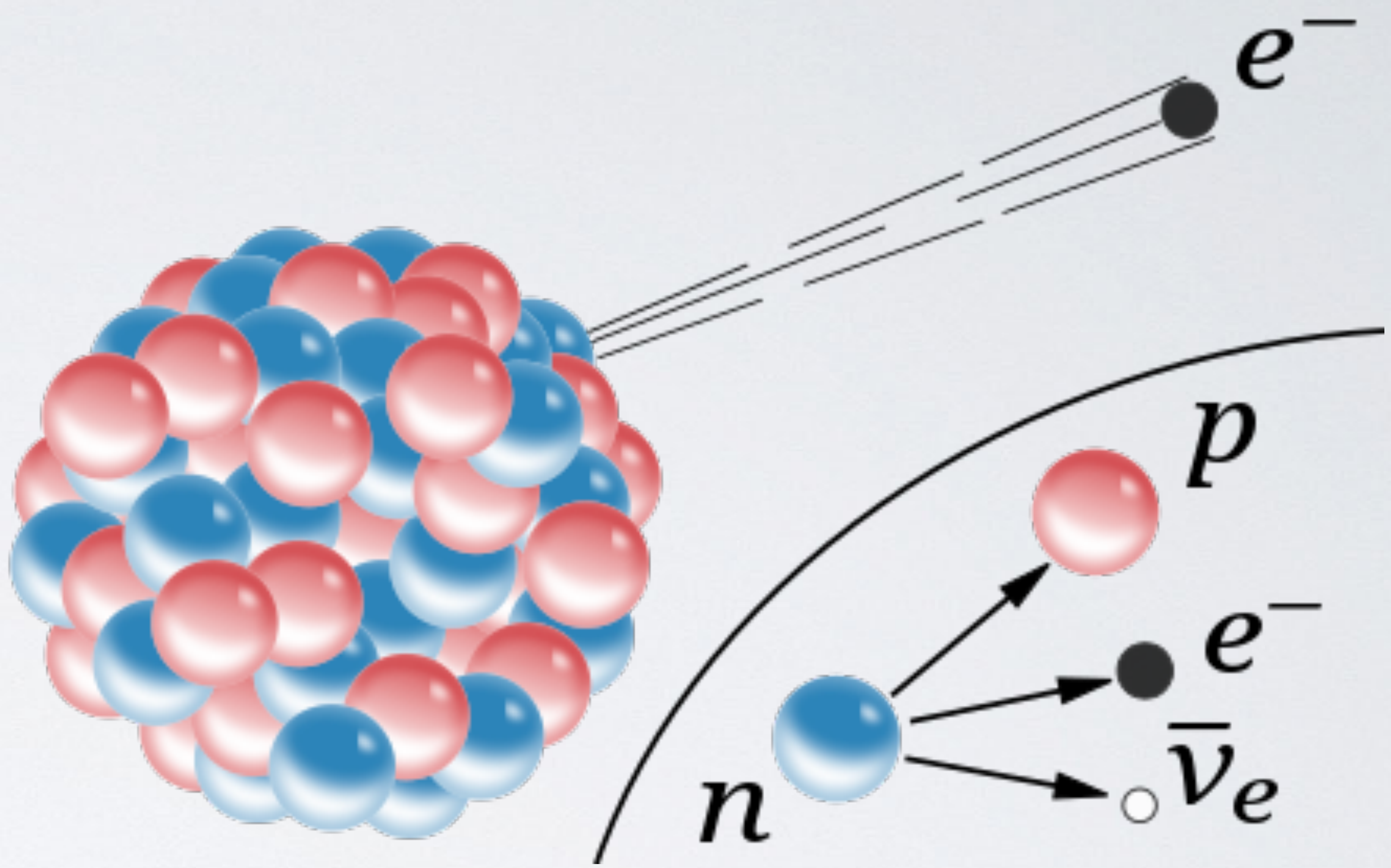
Bootcamp 2021

EARLY NEUTRINO THEORY

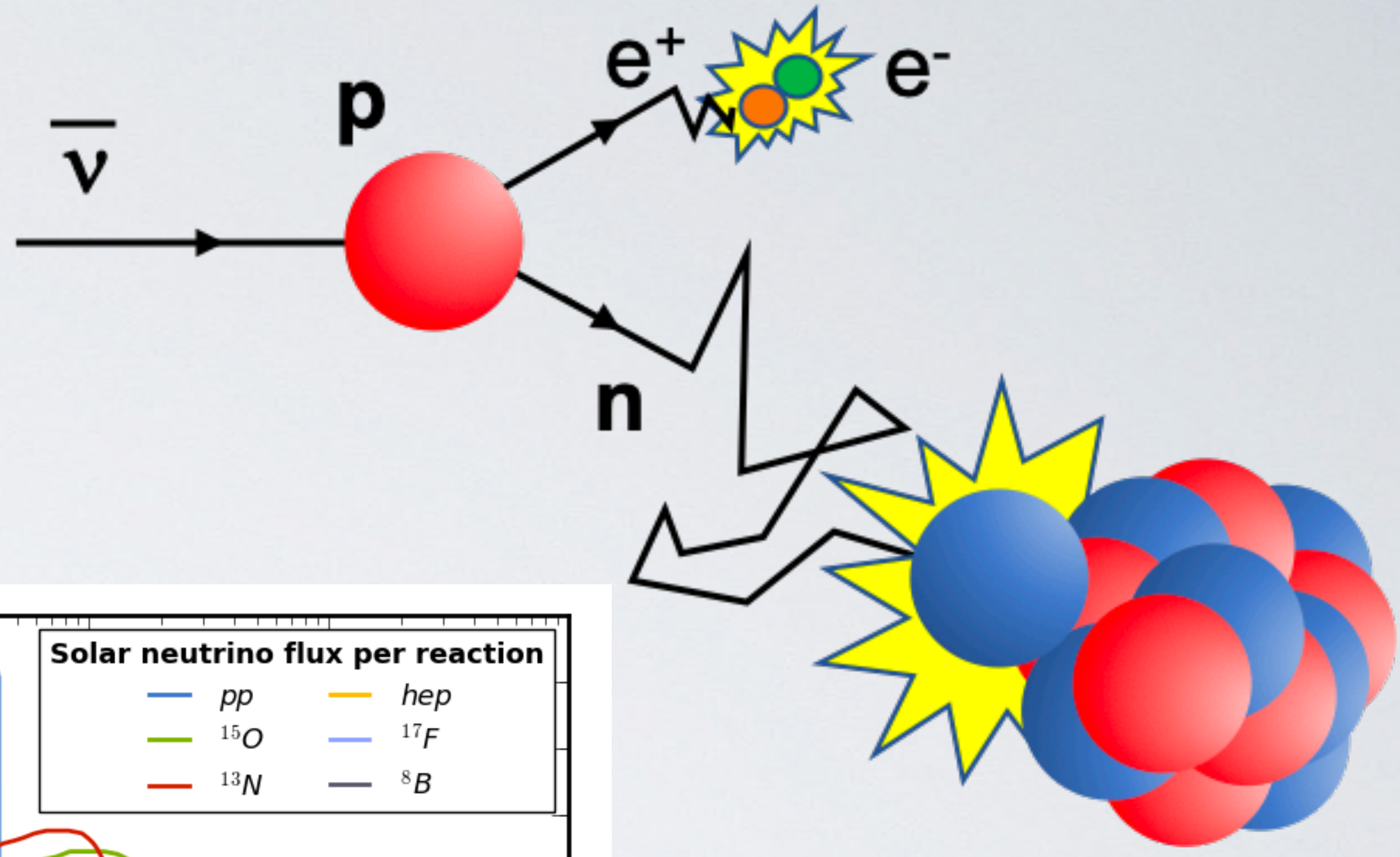
1930 - Pauli introduces concept of neutral particle that conserves energy and momentum in beta decay, names it neutron

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

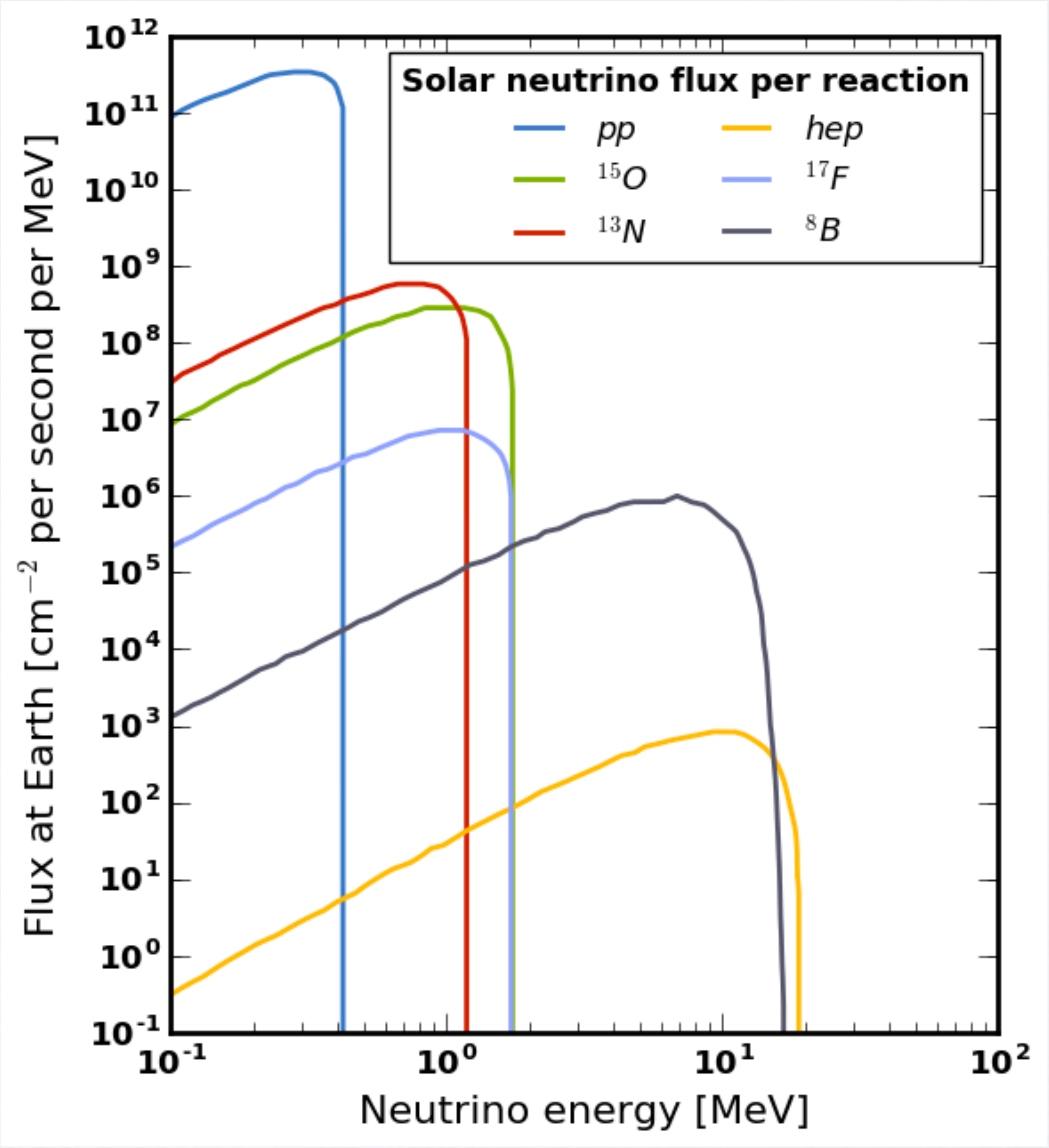


NEUTRINO DISCOVERED

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.



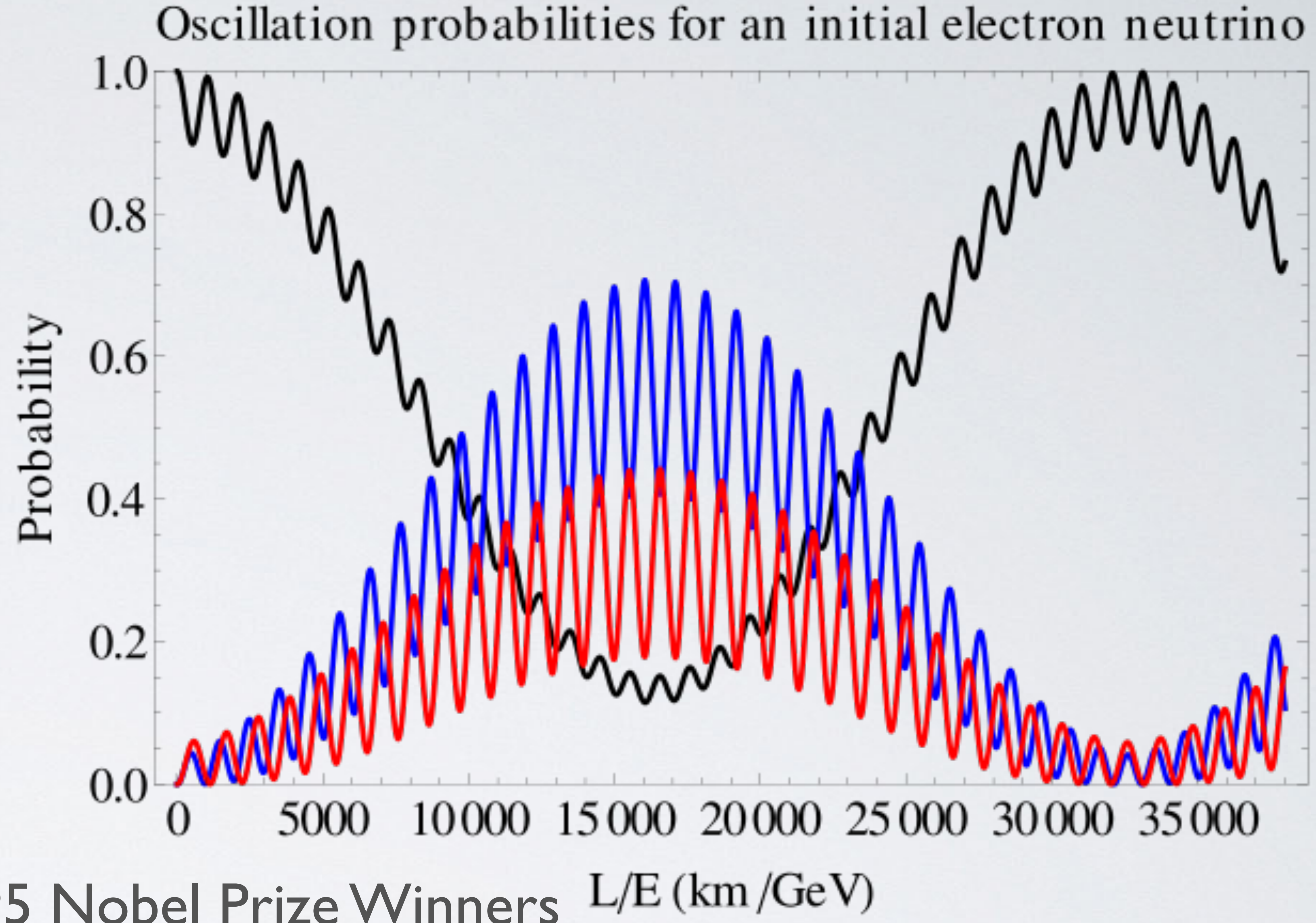
1968-2021 - All neutrino flavors seen, measure mass, measure charge, etc…

SOLAR NEUTRINO PROBLEM

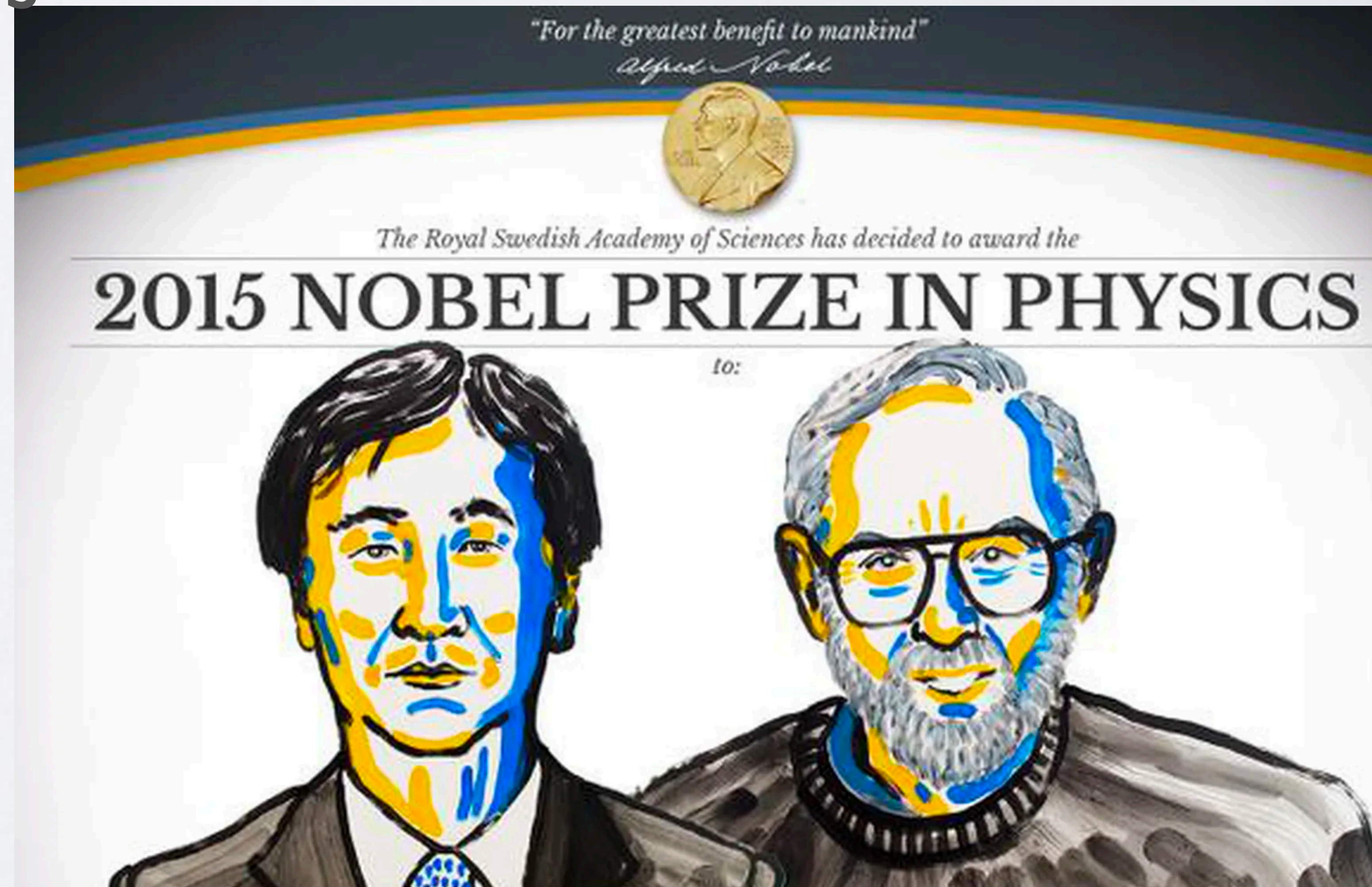
- Homestake only observed 1/3 of the predicted neutrinos, where did they all go?
  - Neutrino oscillations…

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

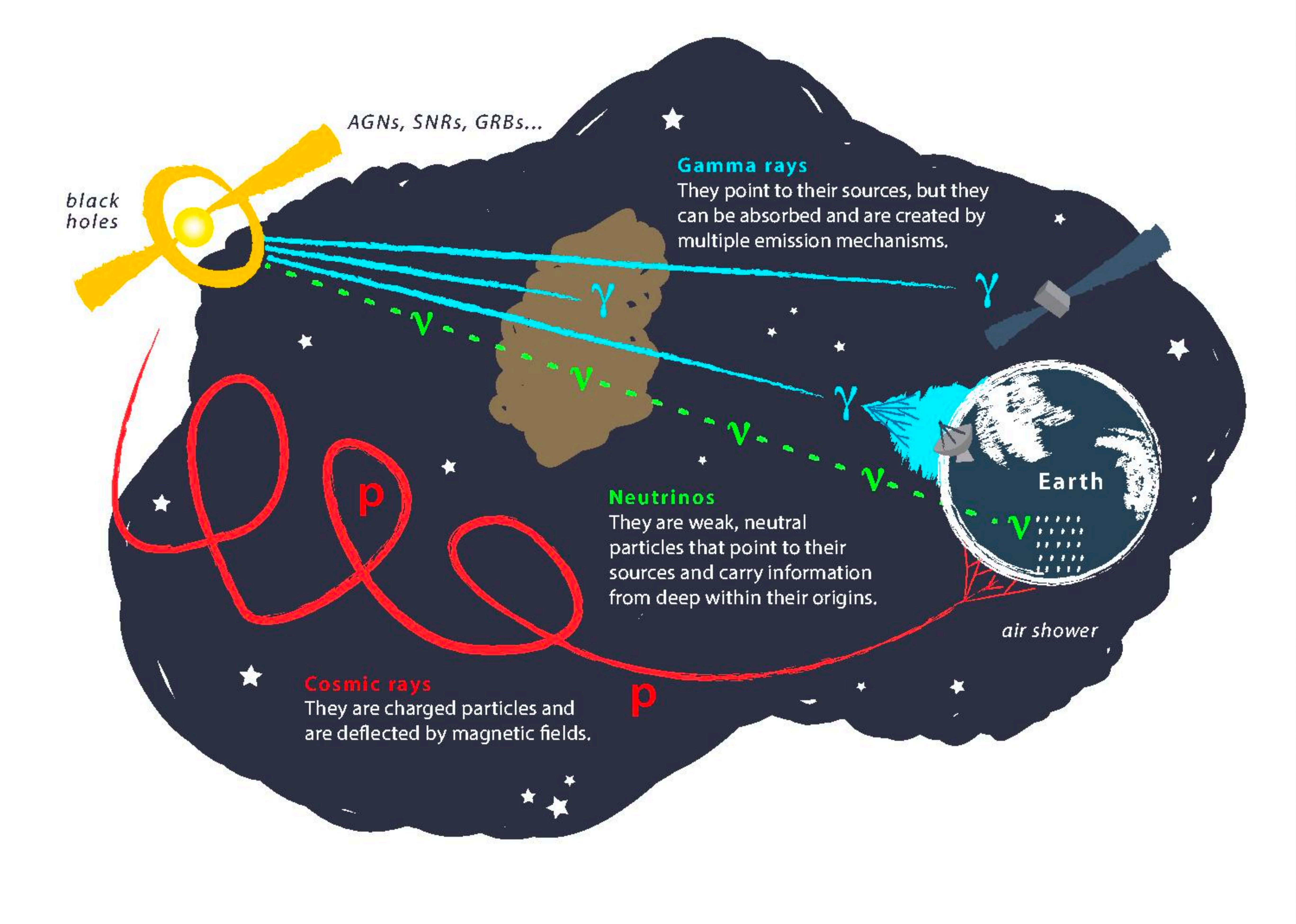
- Needed different detection techniques to detect all neutrino flavors



1995 Nobel Prize Winners
Cowen-Reines

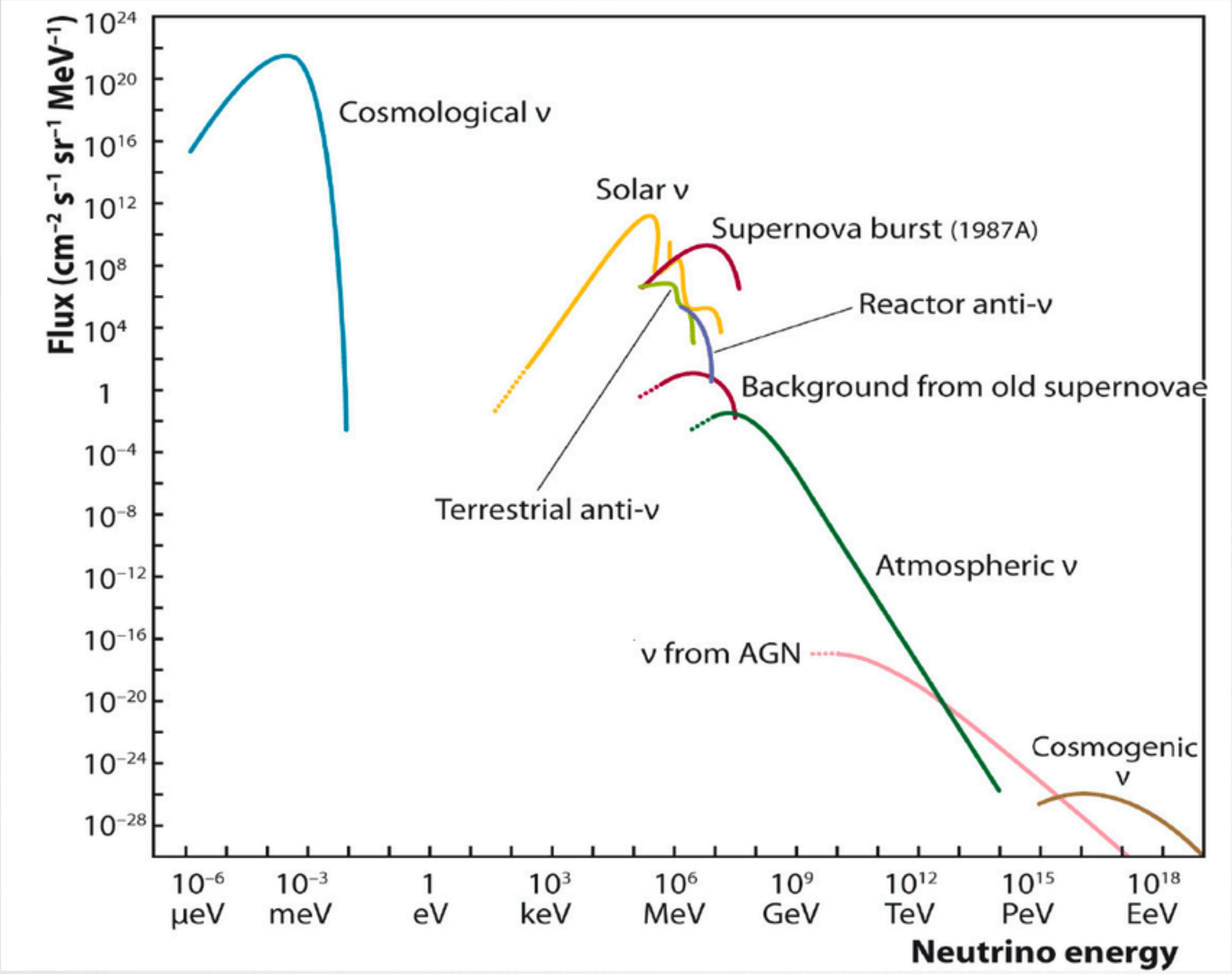


WHY ARE WE INTERESTED IN NEUTRINOS?



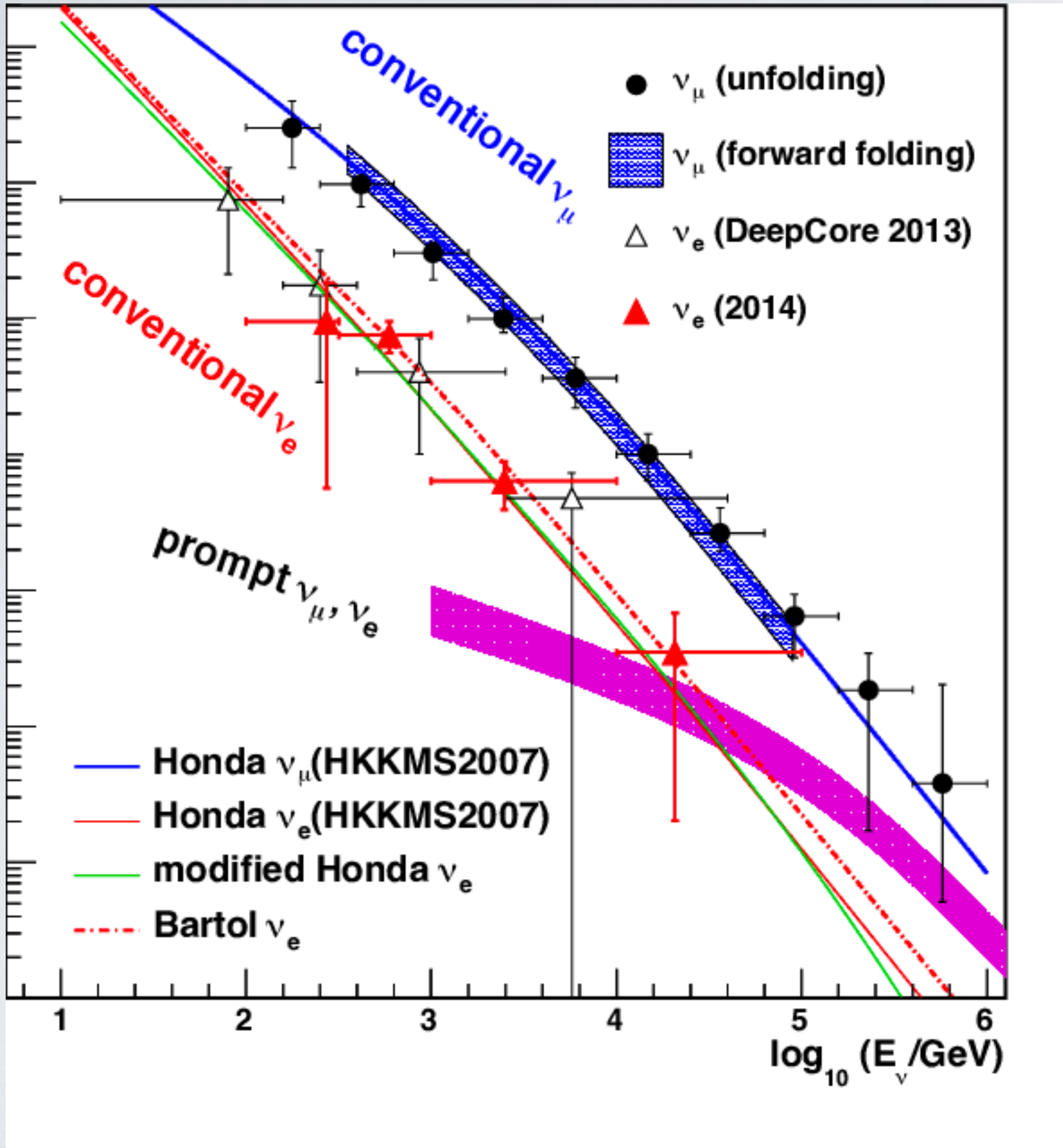
- Source of neutrinos also produces gamma rays and cosmic rays
- Neutrinos are neutral, aren't deflected by interstellar magnetic field
- Neutrinos are weakly interacting, can travel billions of light years without interacting

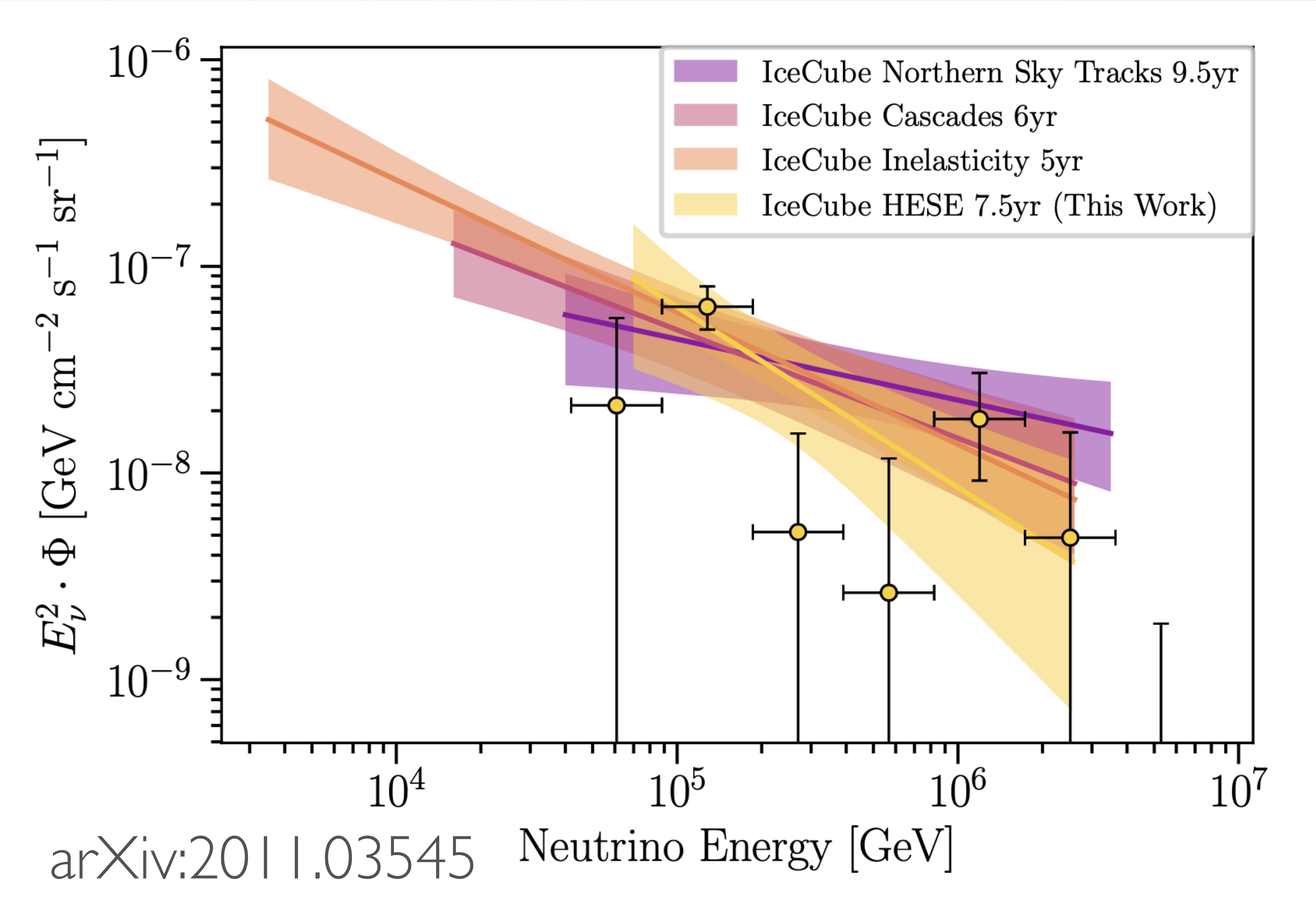
NEUTRINO SOURCES



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

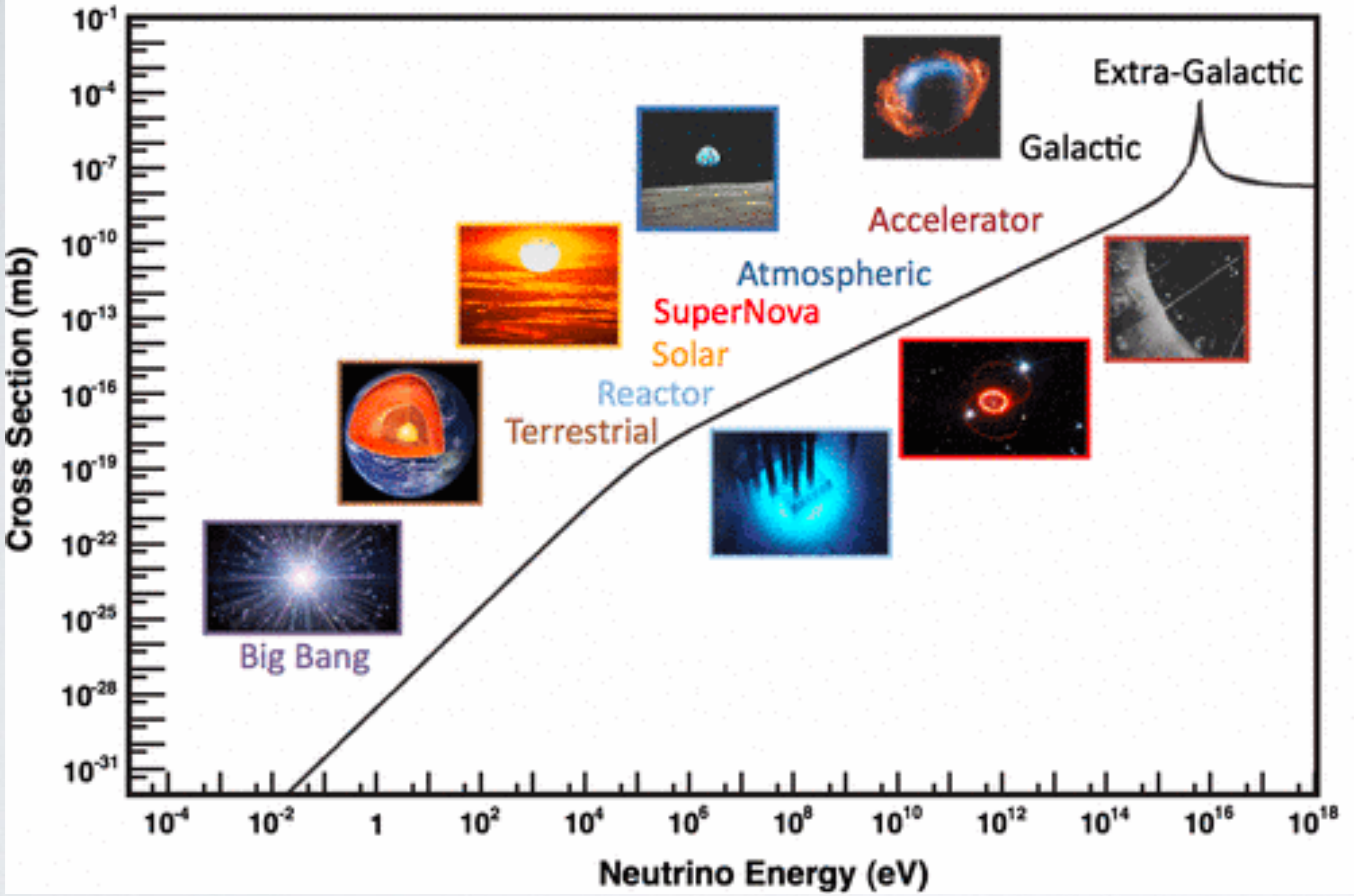
ICECUBE FLUX MEASUREMENTS





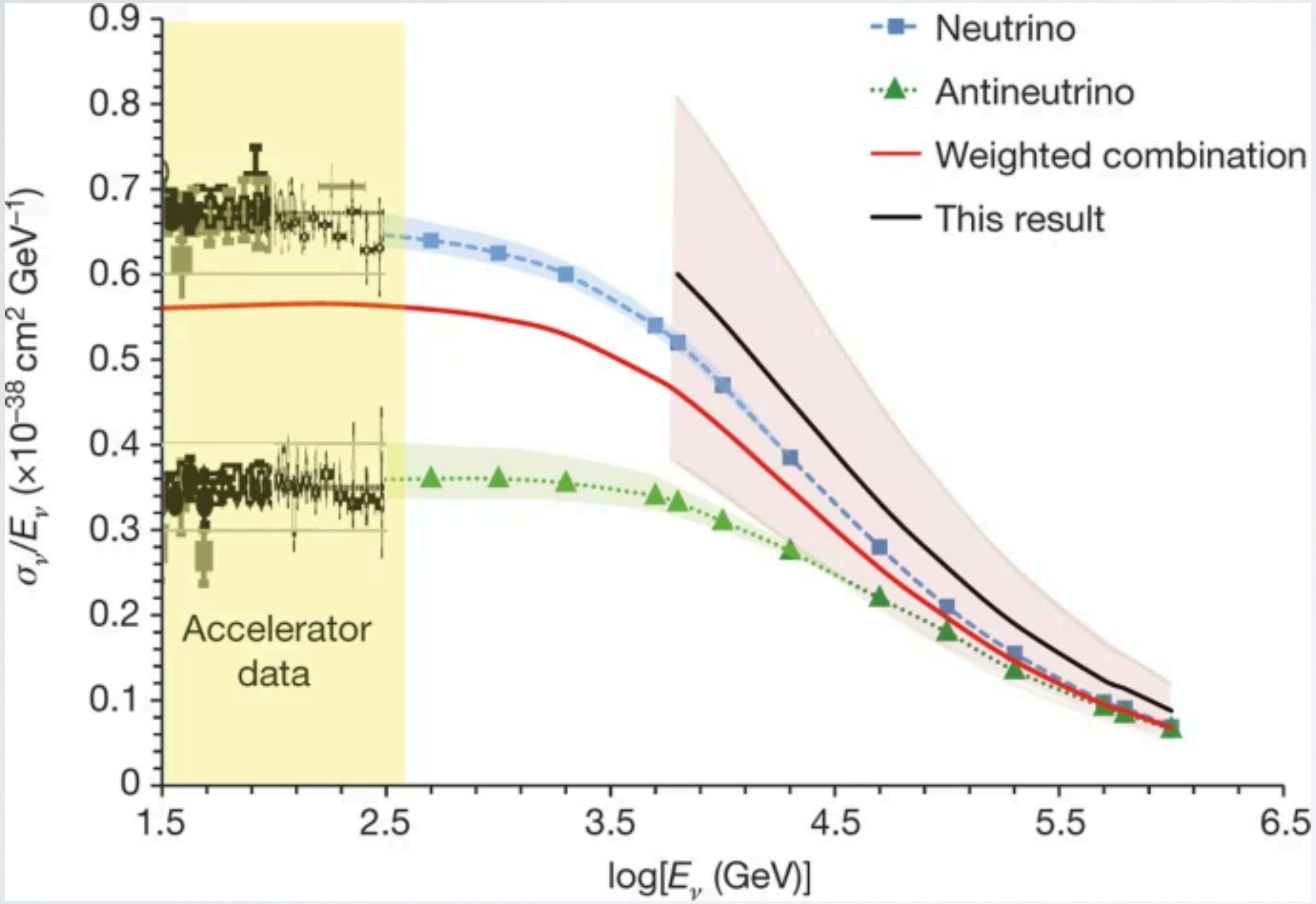
arXiv:2011.03545

NEUTRINO INTERACTION PROBABILITY

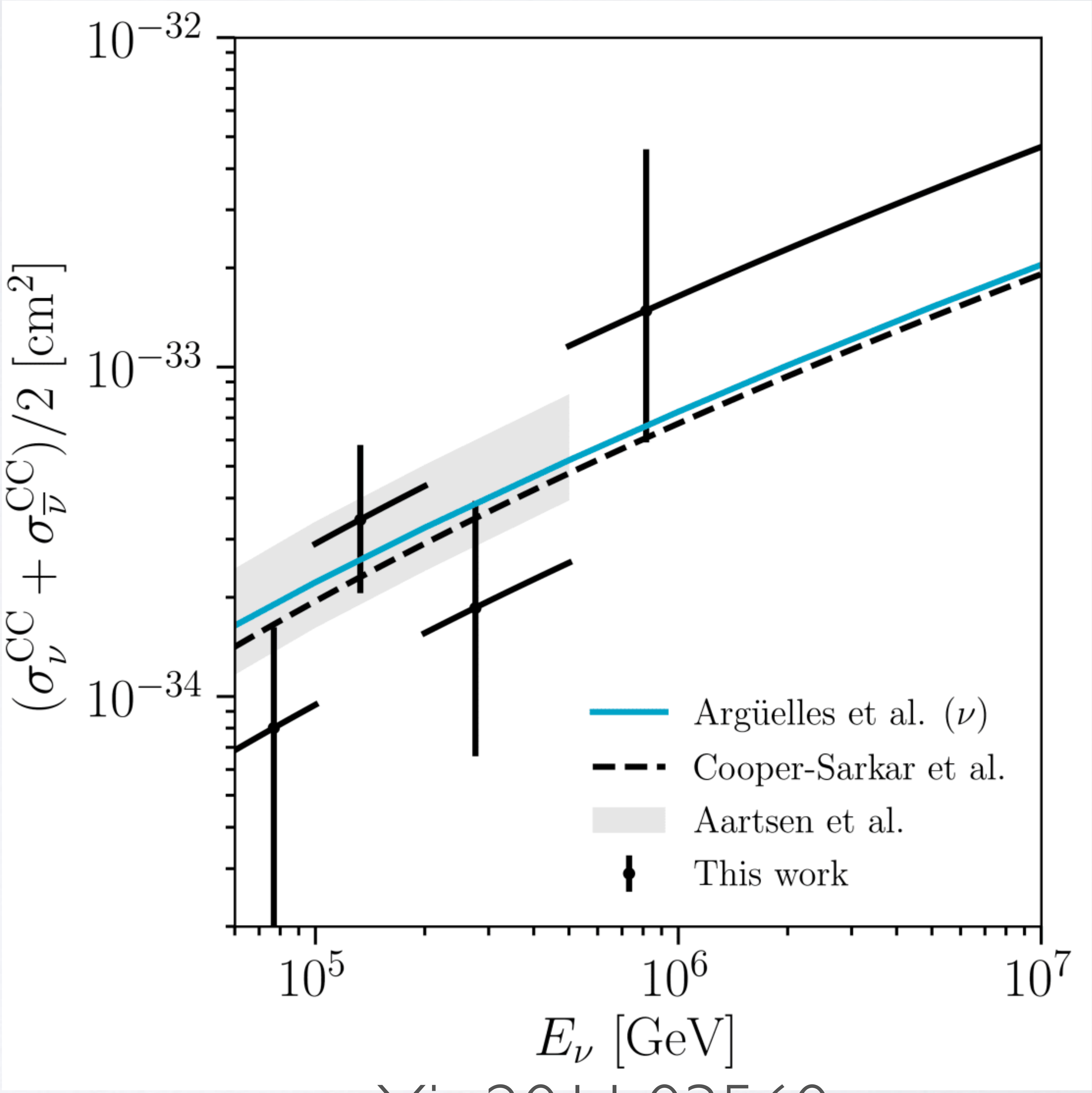


- Neutrino cross section is working in our favor, increases linearly with energy
- At IceCube energies, deep inelastic scattering dominates
- The neutrino scatters off a nucleus in the ice and produces an electron, muon, tau and/or hadrons

ICECUBE CROSS-SECTION MEASUREMENTS



Nature 551, 596–600 (2017)



arXiv:2011.03560

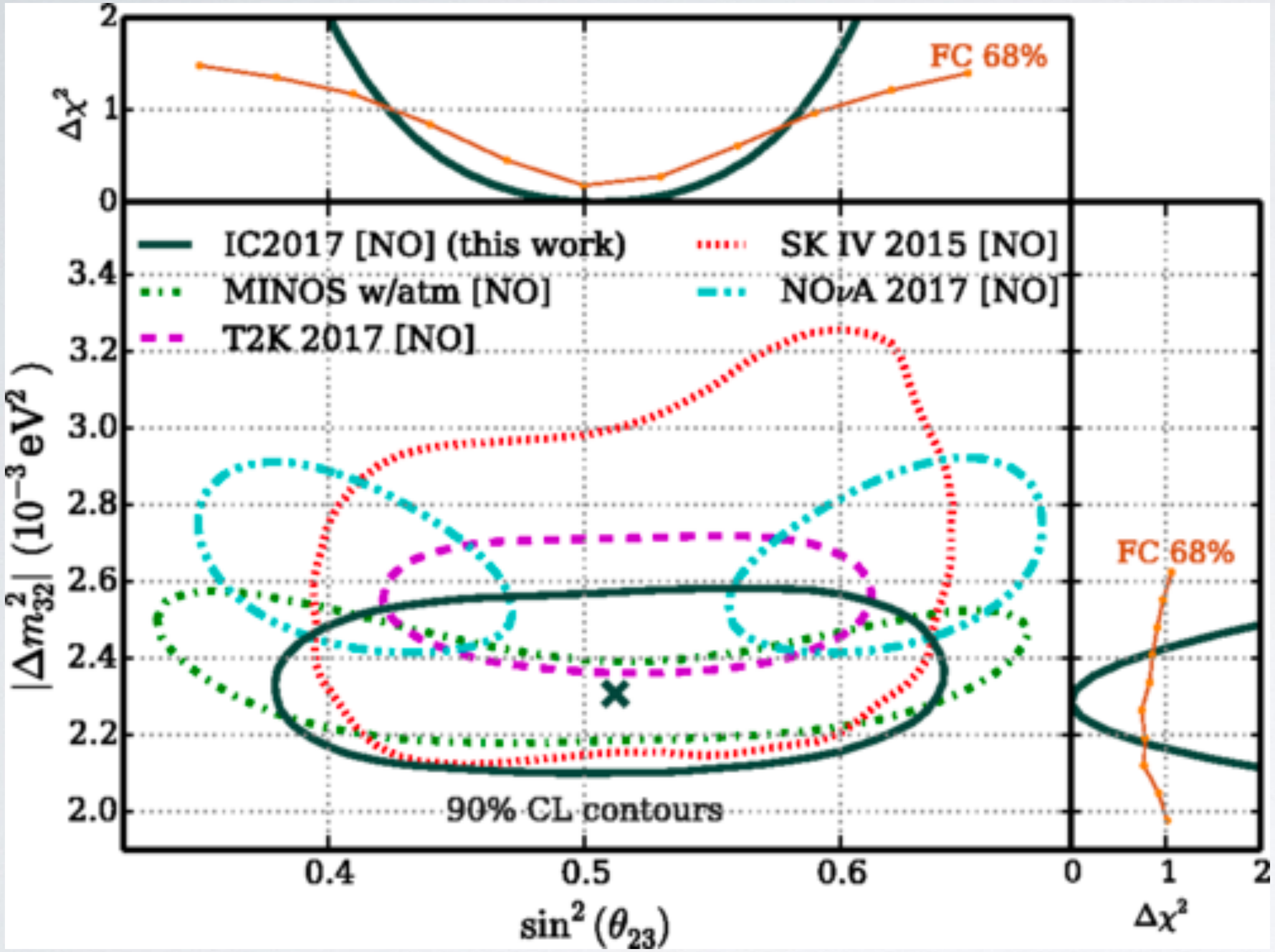
NEUTRINO OSCILLATIONS

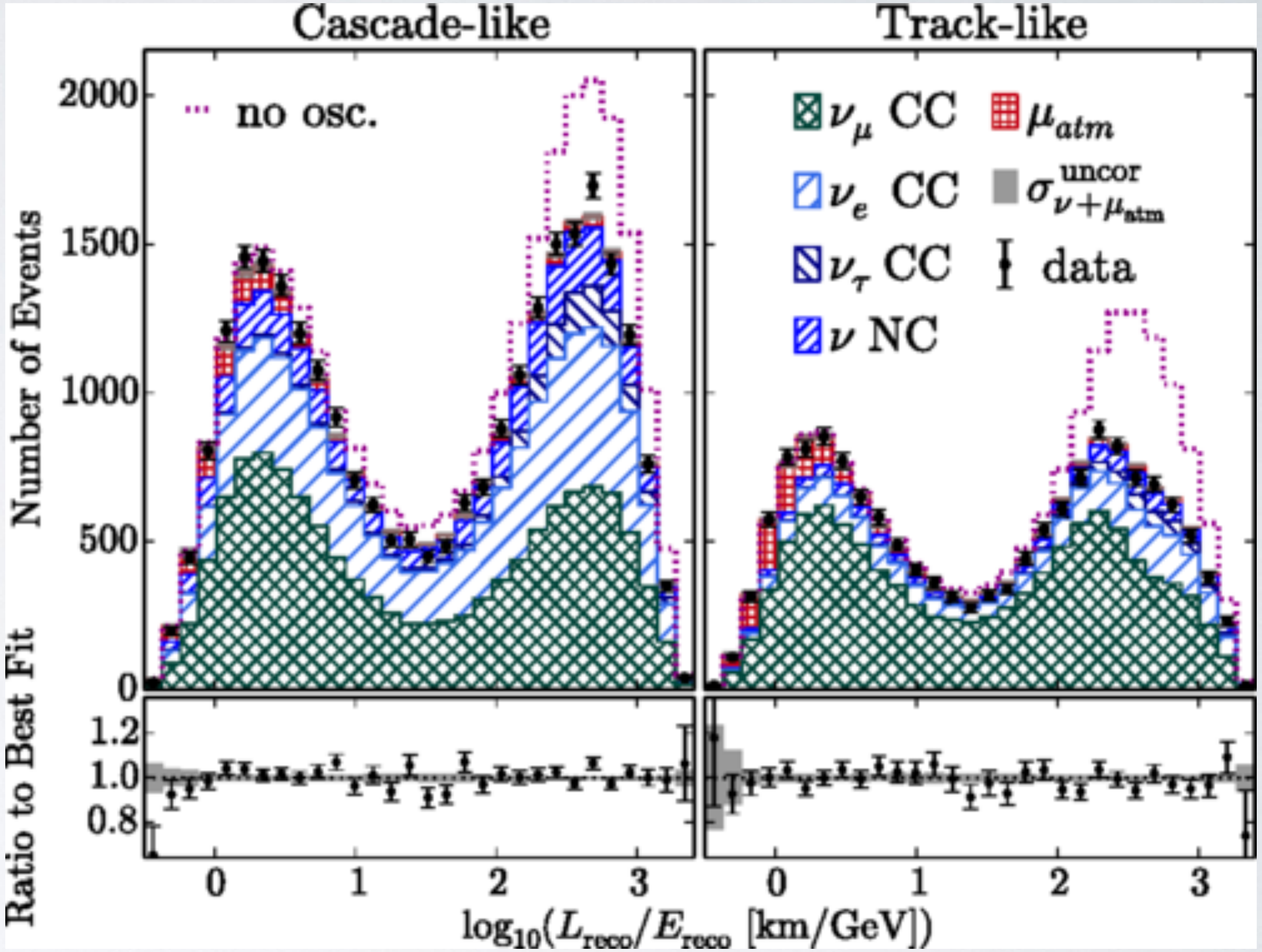
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$
$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+ 2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right),$$

- PMNS matrix defines three neutrino mass and three neutrino flavors eigenstates
- θ_{12} θ_{13} θ_{23}… are referred to as the mixing angles
- The angles and Δm2 are related and measured simultaneously

ICECUBE OSCILLATION MEASUREMENT

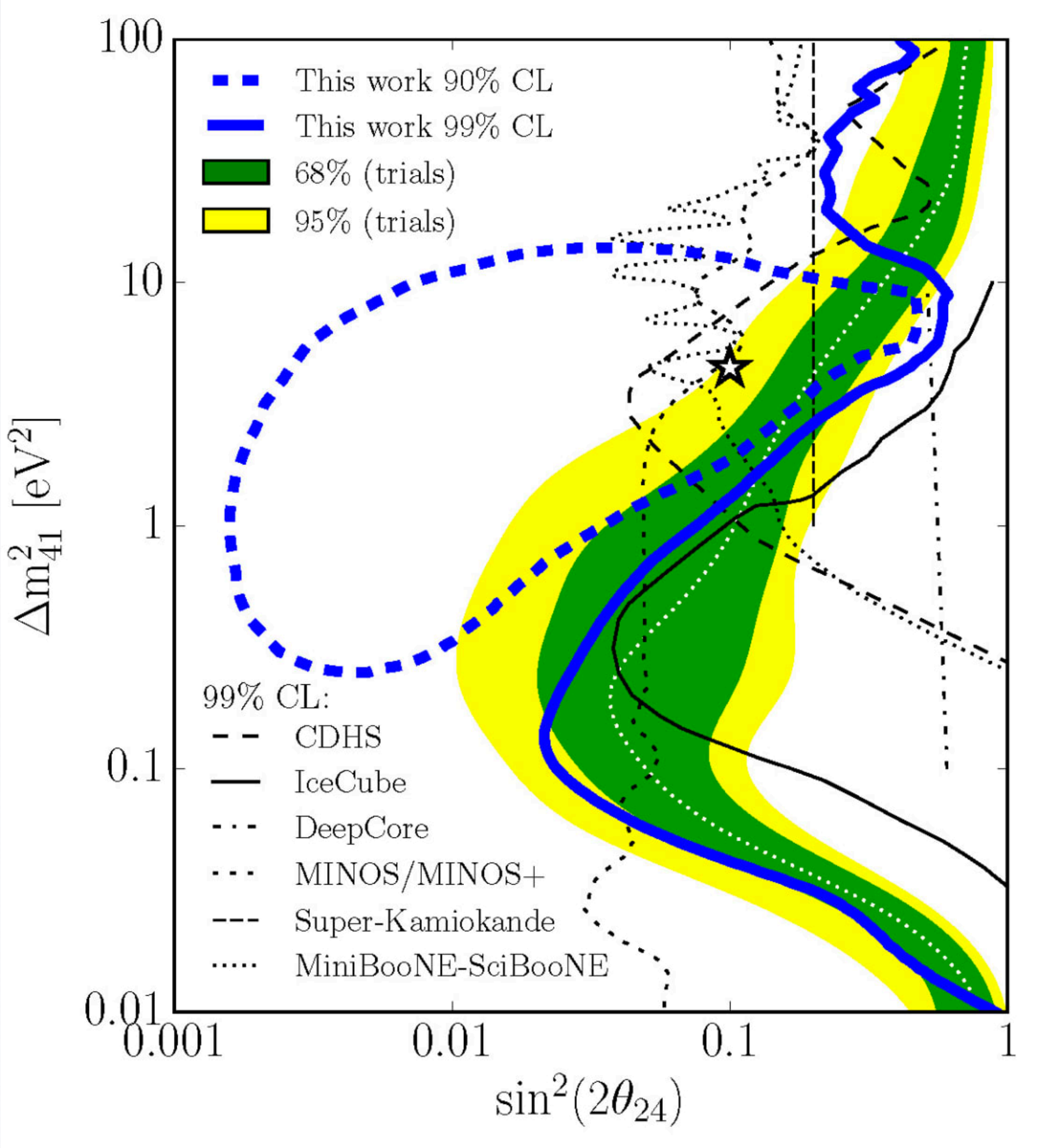




Phys. Rev. Lett. 120, 071801

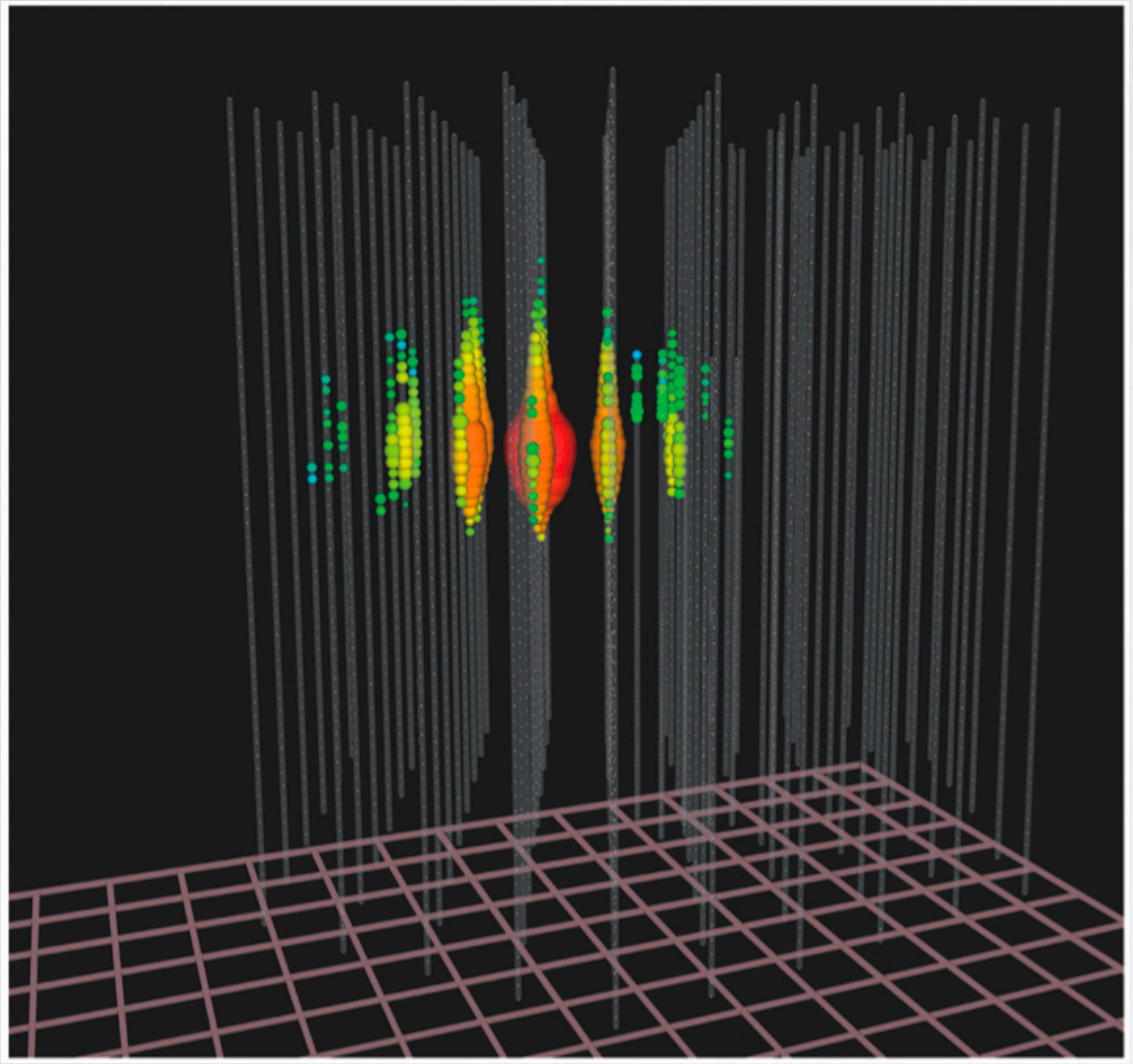
BEYOND THE STANDARD MODEL

- We assume there are 3 neutrino flavors, but what is there is a 4th neutrino? A sterile neutrino?
- Sterile because it only interacts with gravity
- IceCube "detects" sterile ν via oscillation effects from incoming atmospheric neutrinos

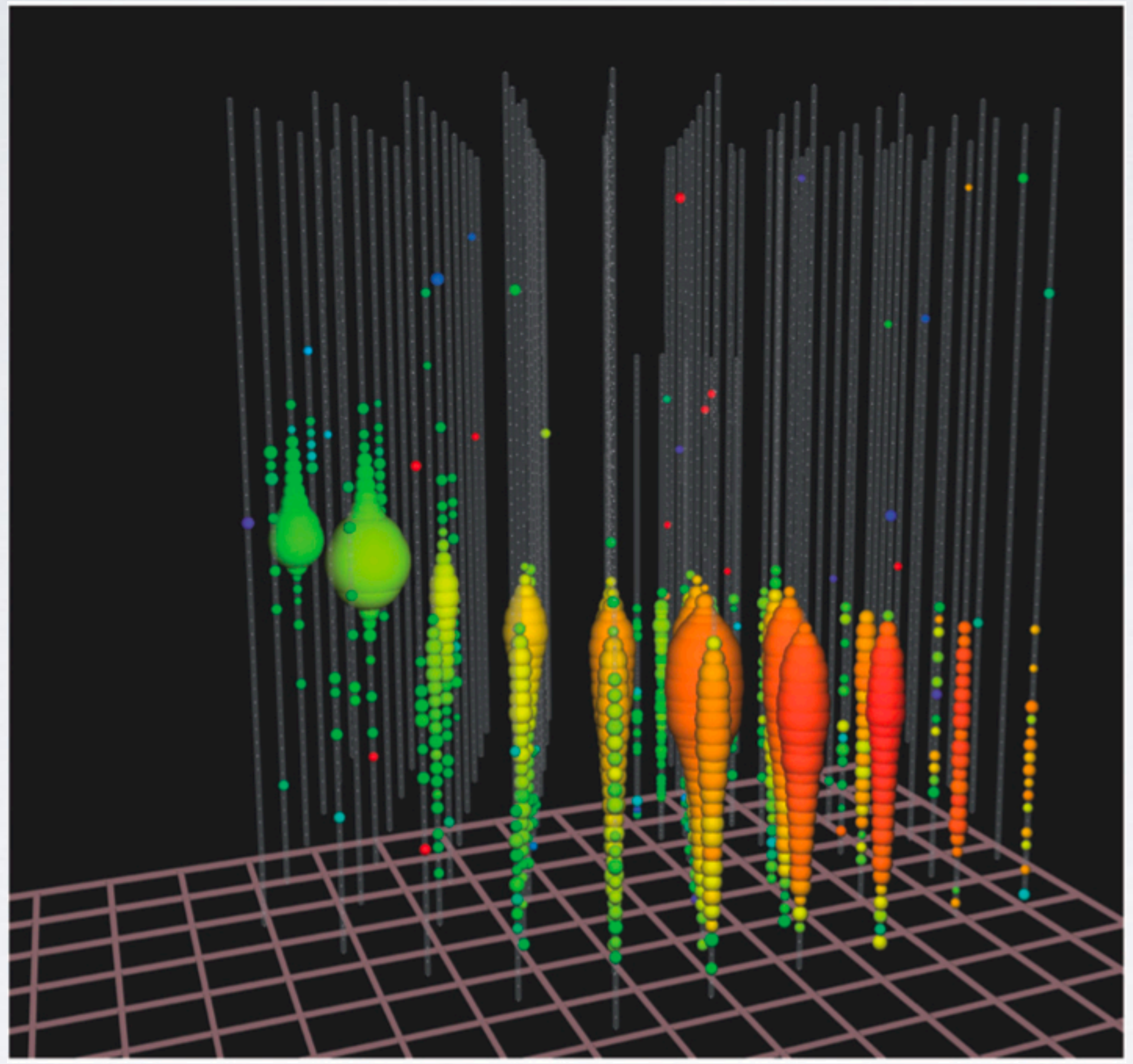


Phys. Rev. Lett. 125, 141801

NEUTRINO FLAVOR IDENTIFICATION



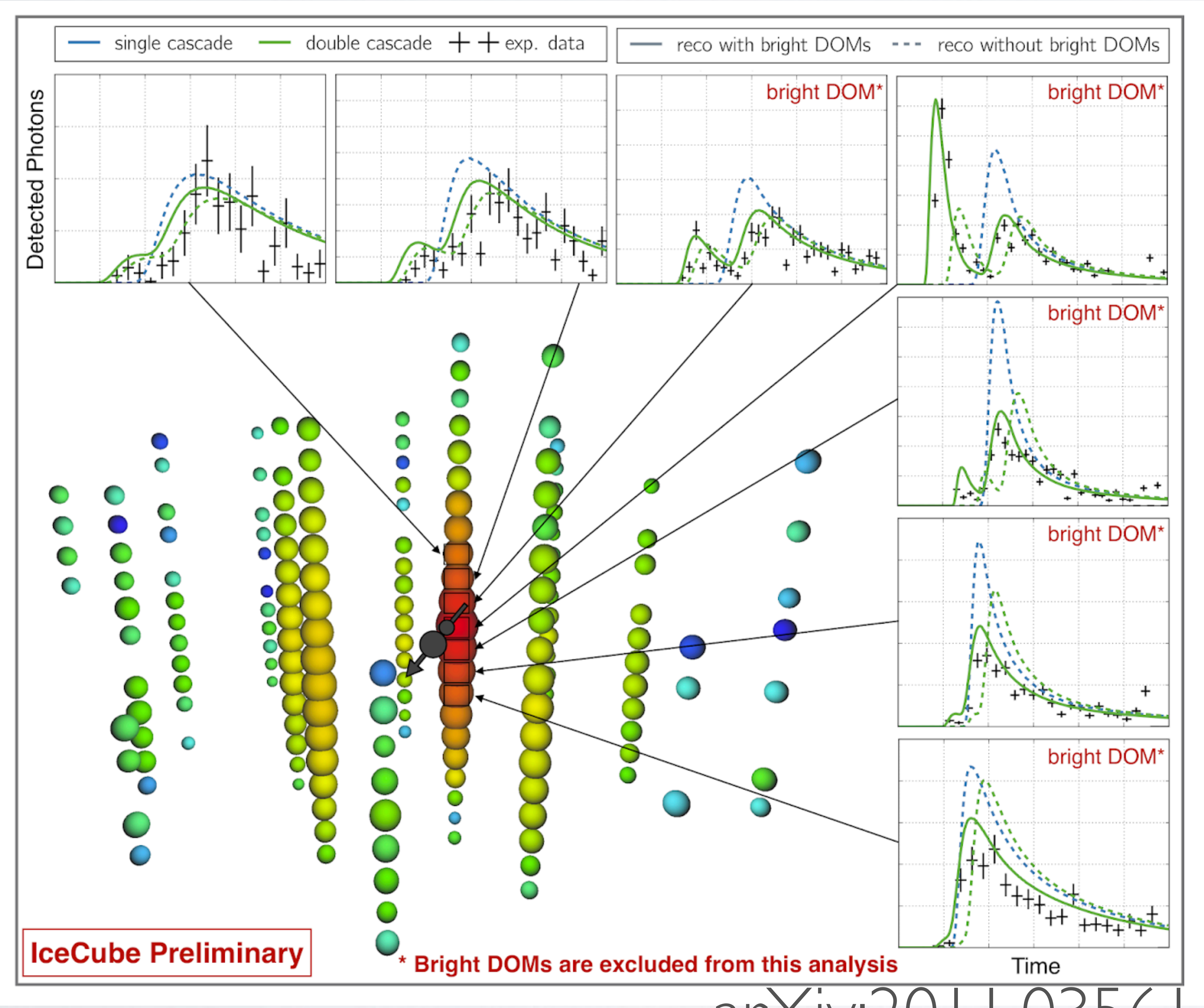
Cascades



Up-going Tracks

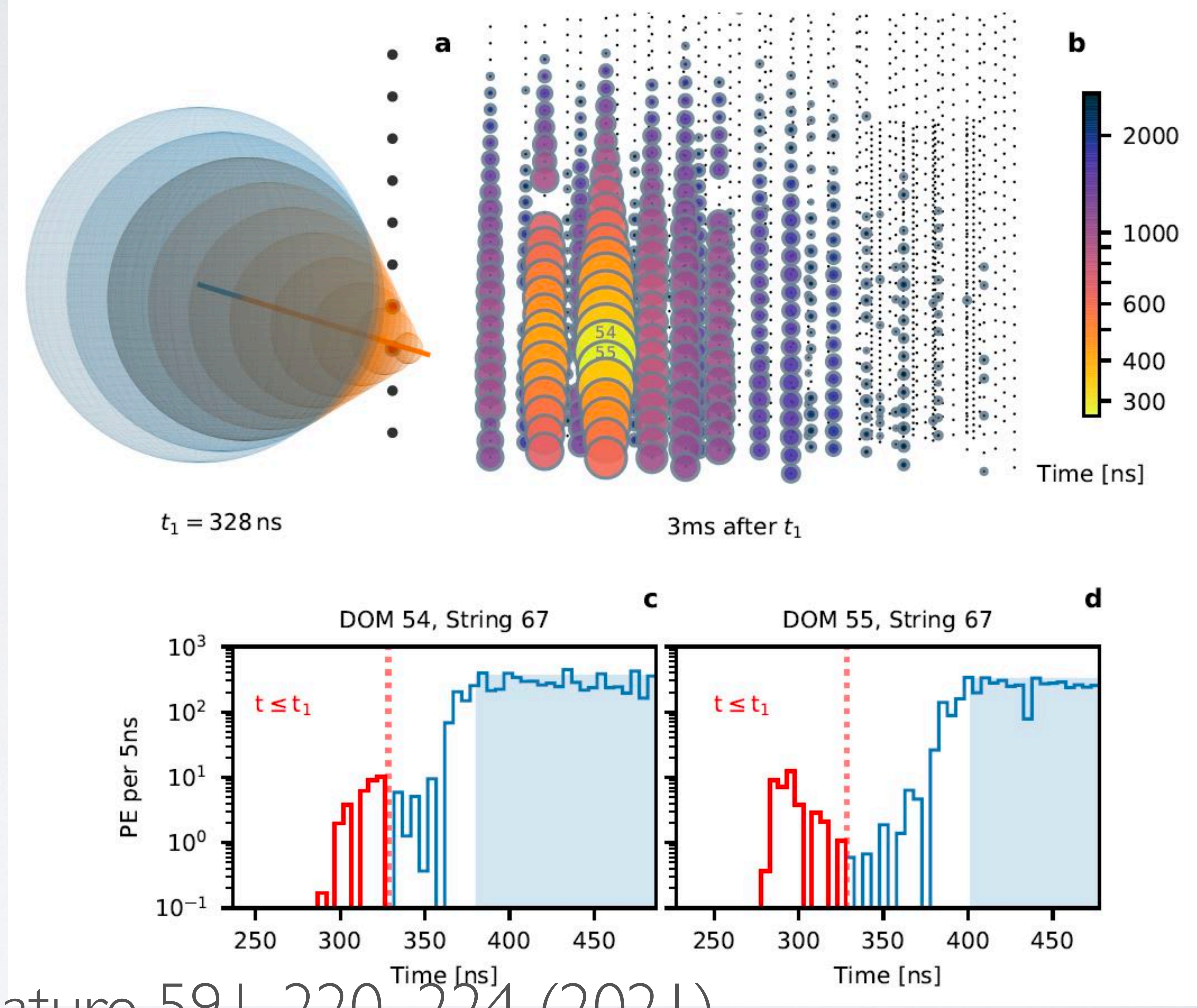
- Historically, IceCube has separated data into two categories
  - Cascades and upgoing tracks
- Cascades consist of all neutral current and electron/tau neutrino charged current interactions
- Upgoing tracks are charged current muon neutrino interactions only
  - Recent developments show that tau decay inside the Earth contributes to tracks!

FLAVOR IDENTIFICATION



arXiv:2011.03561

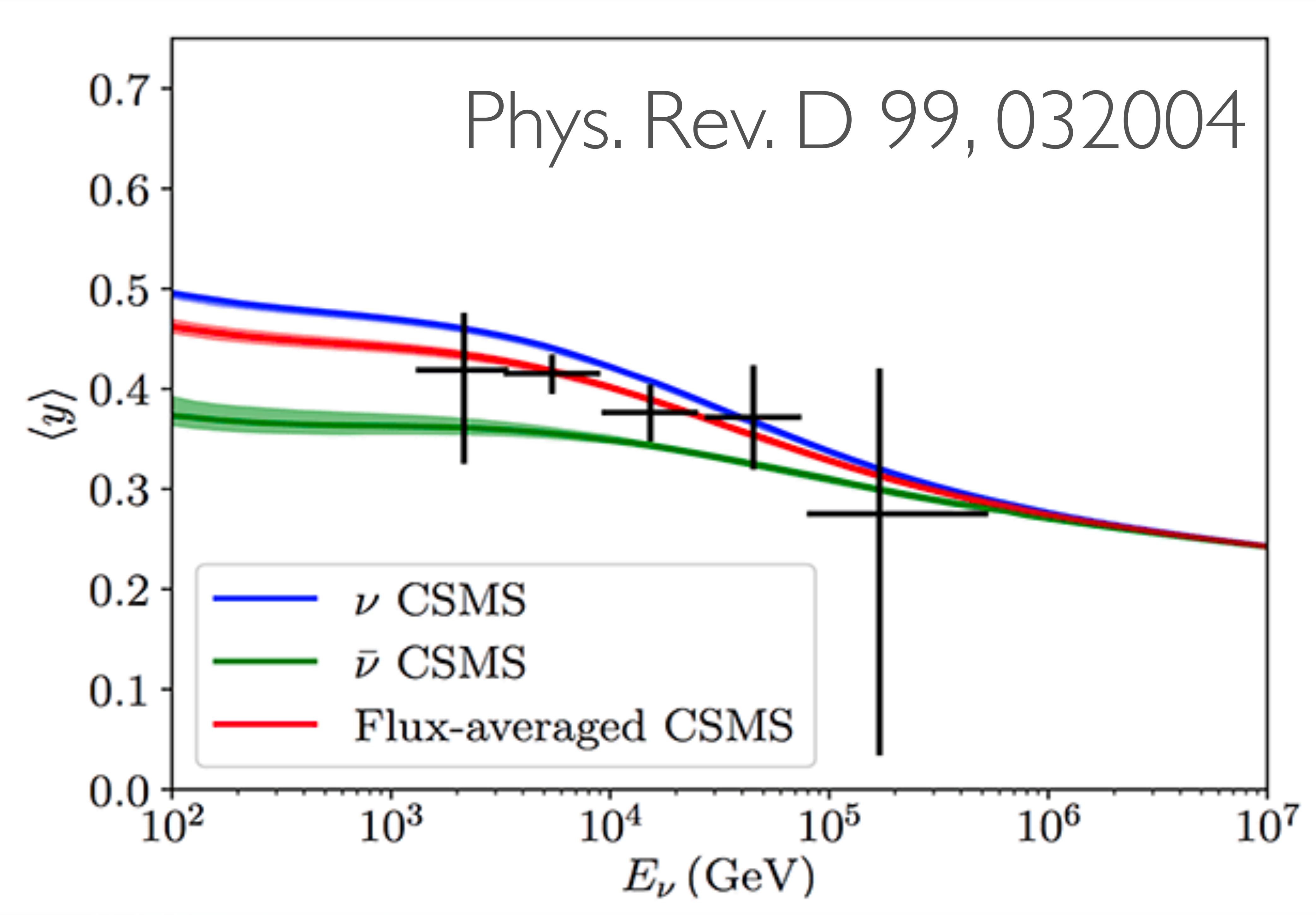
- Tau neutrino classification using "double pulse" structure

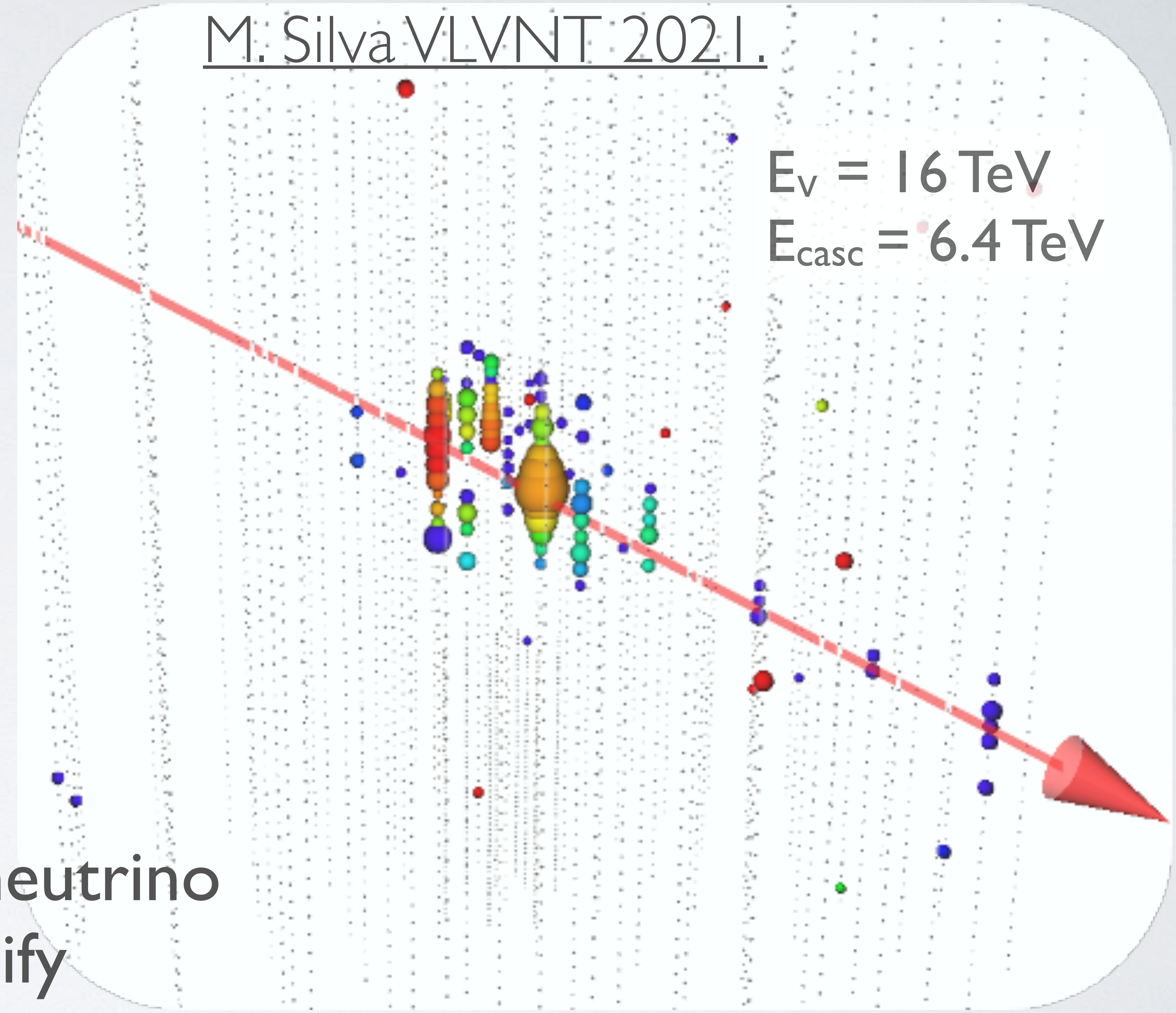


Nature 591, 220–224 (2021)

- Glashow resonance where electron antineutrino at 6 PeV interacts with an election

MUON NEUTRINO/ANTI-NEUTRINO CLASSIFICATION

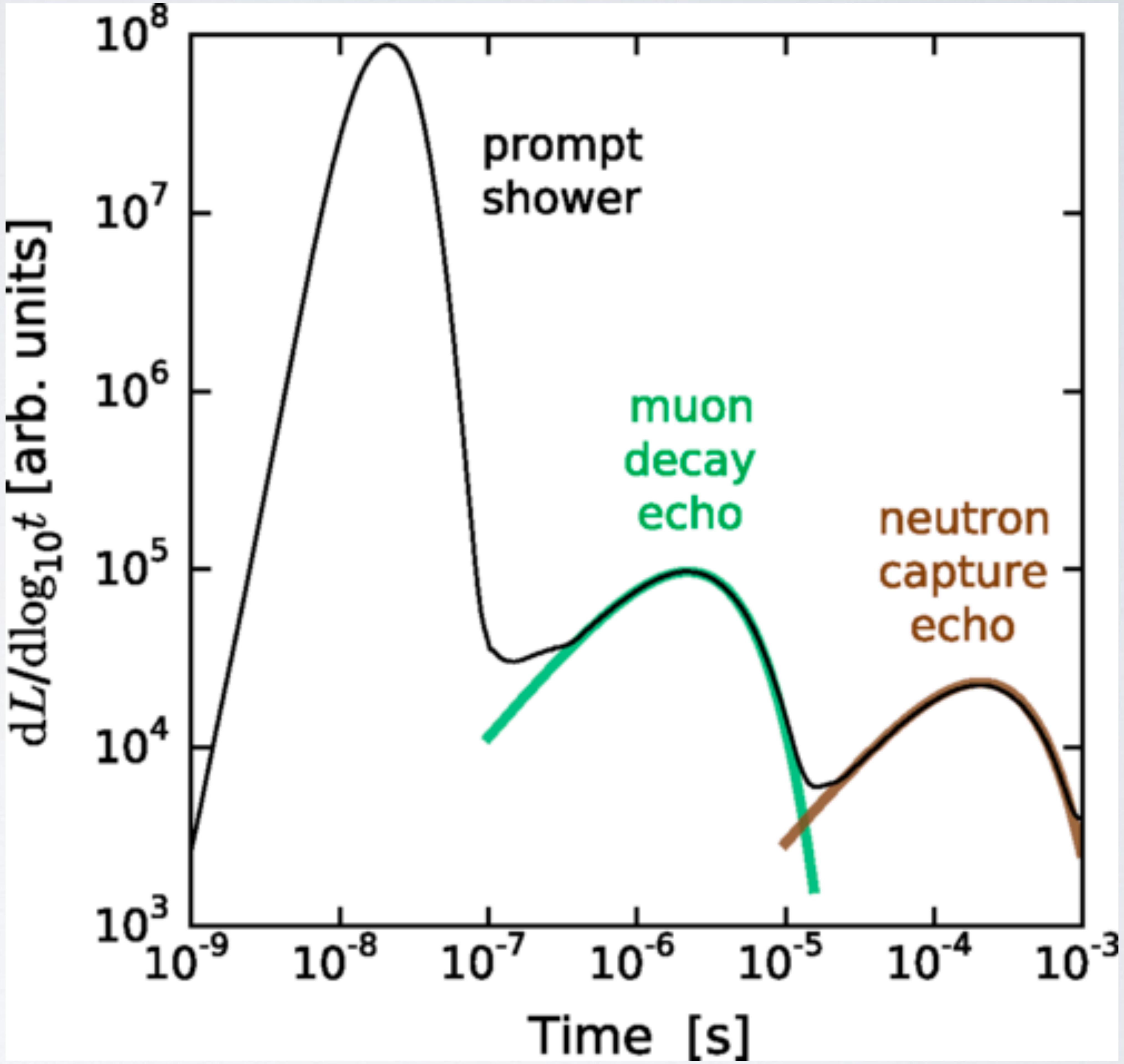




- <y> = Energy in cascade/Total Energy of neutrino
- Inelasticity of event could be used to classify events into neutrino/anti-neutrinos

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

SUMMARY

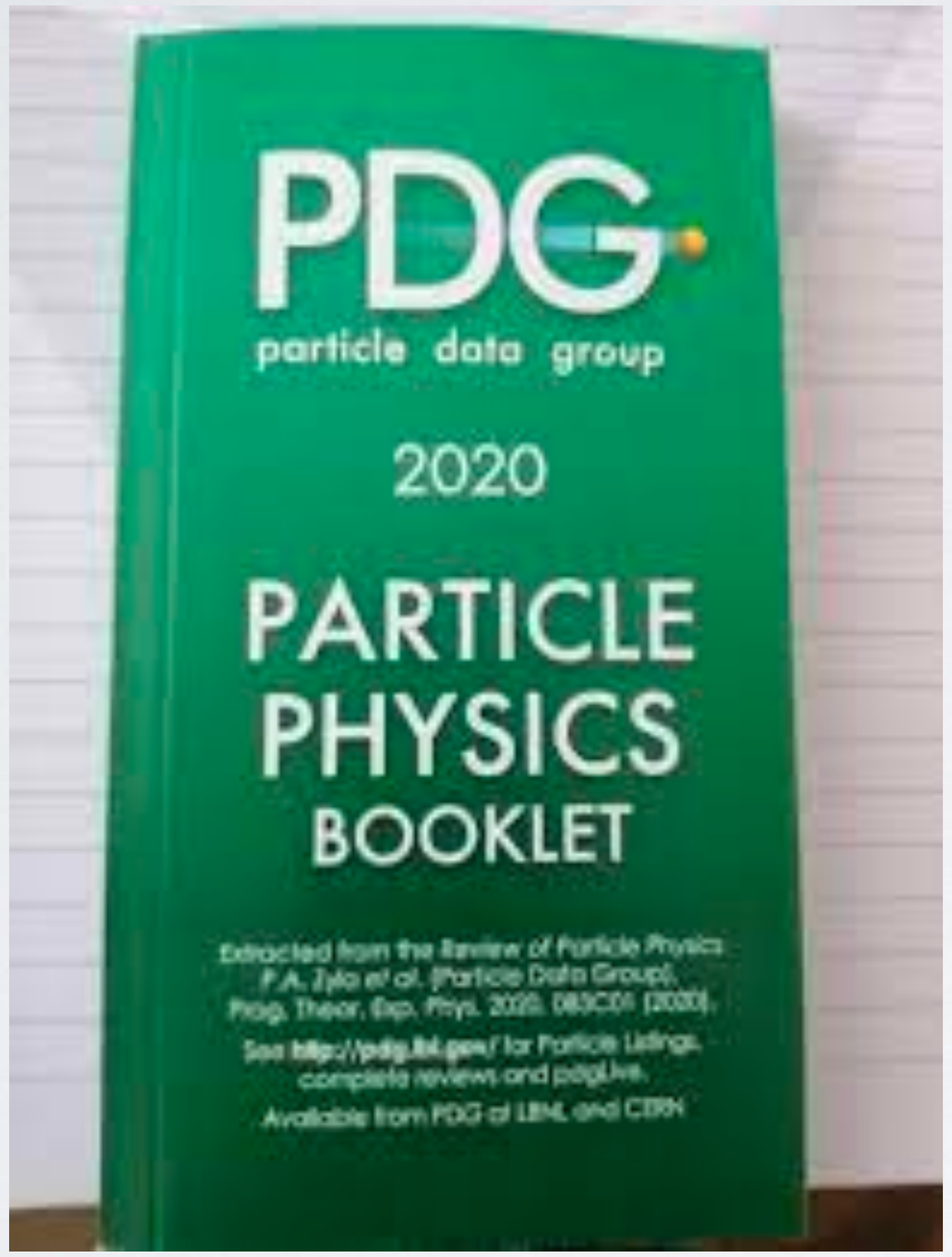
Neutrinos are one of the most interesting fundamental particles to study!

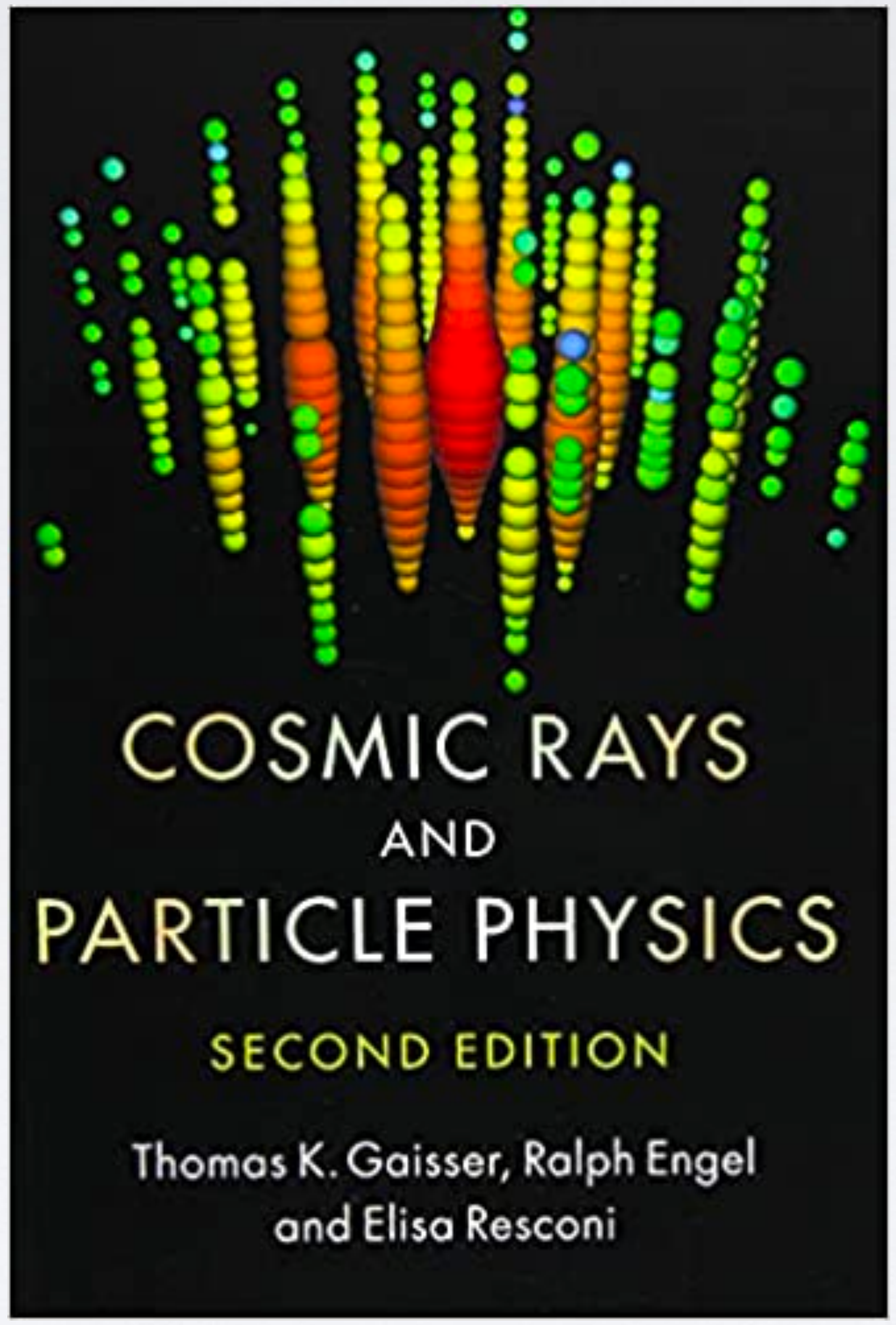
Several Nobel Prizes have already been won studying the neutrino

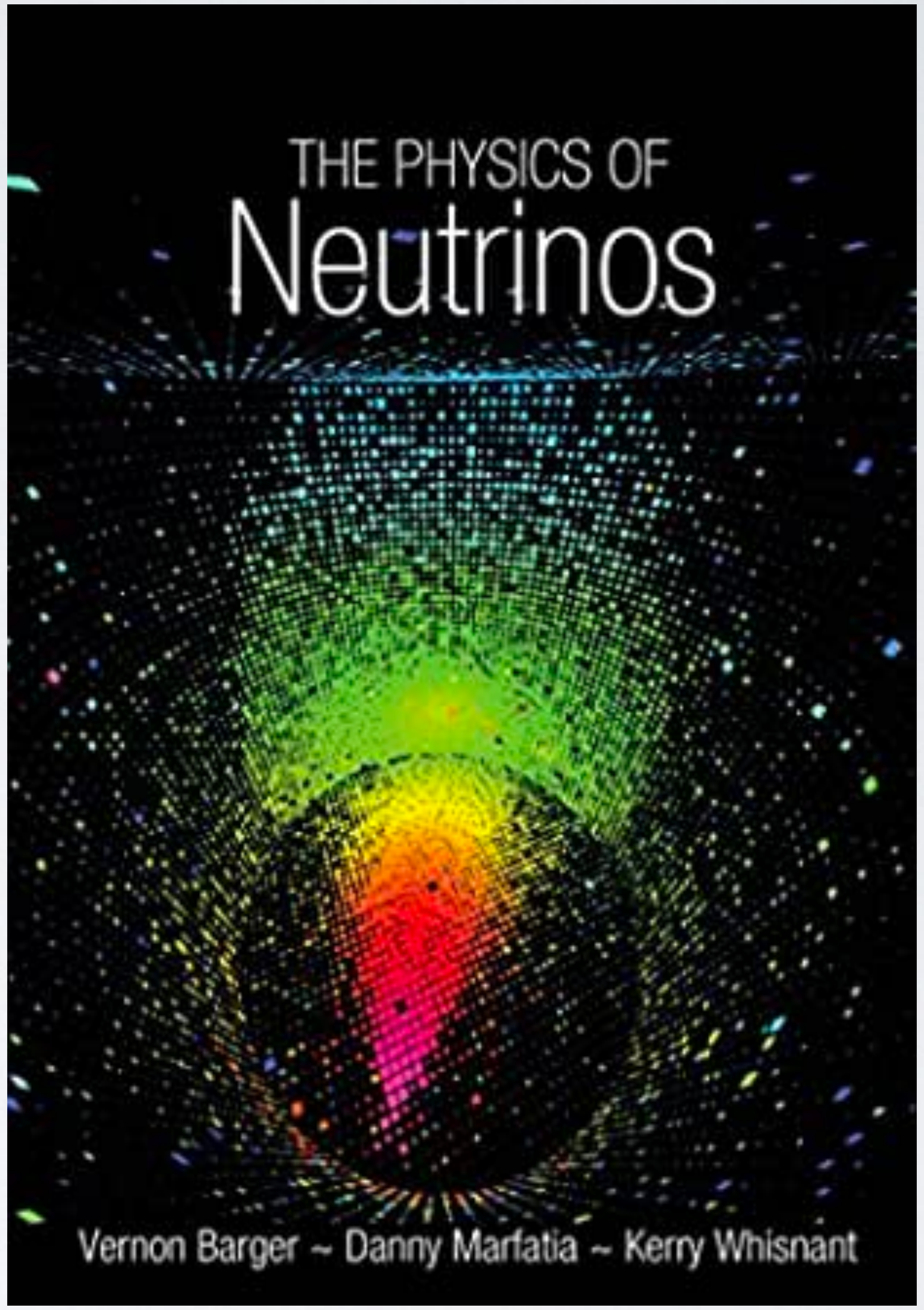
IceCube has measured the oscillation parameters of the neutrinos, the flux of atmospheric and astrophysical neutrinos, cross-section, etc…

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

NEUTRINO PHYSICS PRIMERS

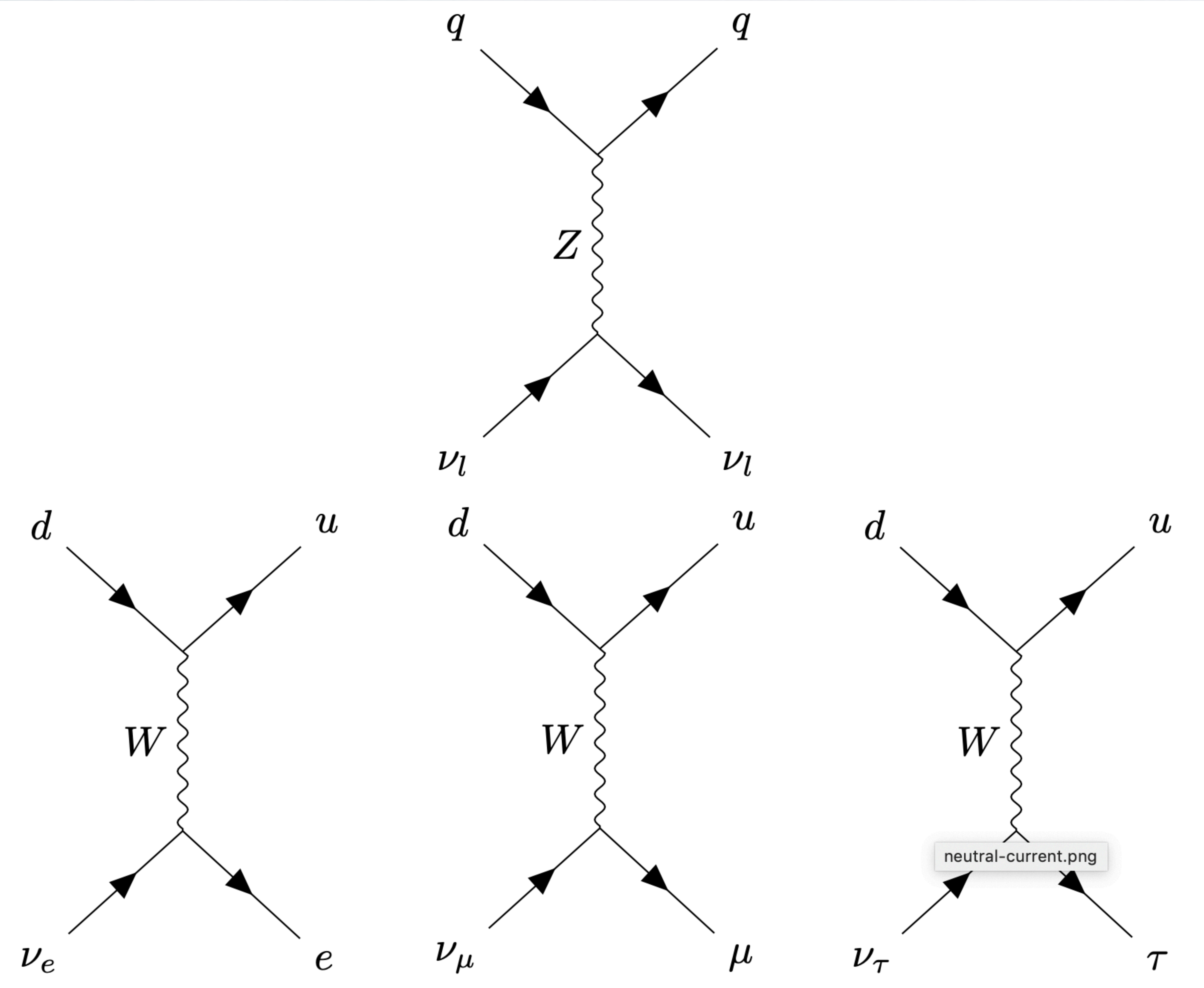






QUESTIONS??

DEEP INELASTIC SCATTERING



Neutral current

Charged current