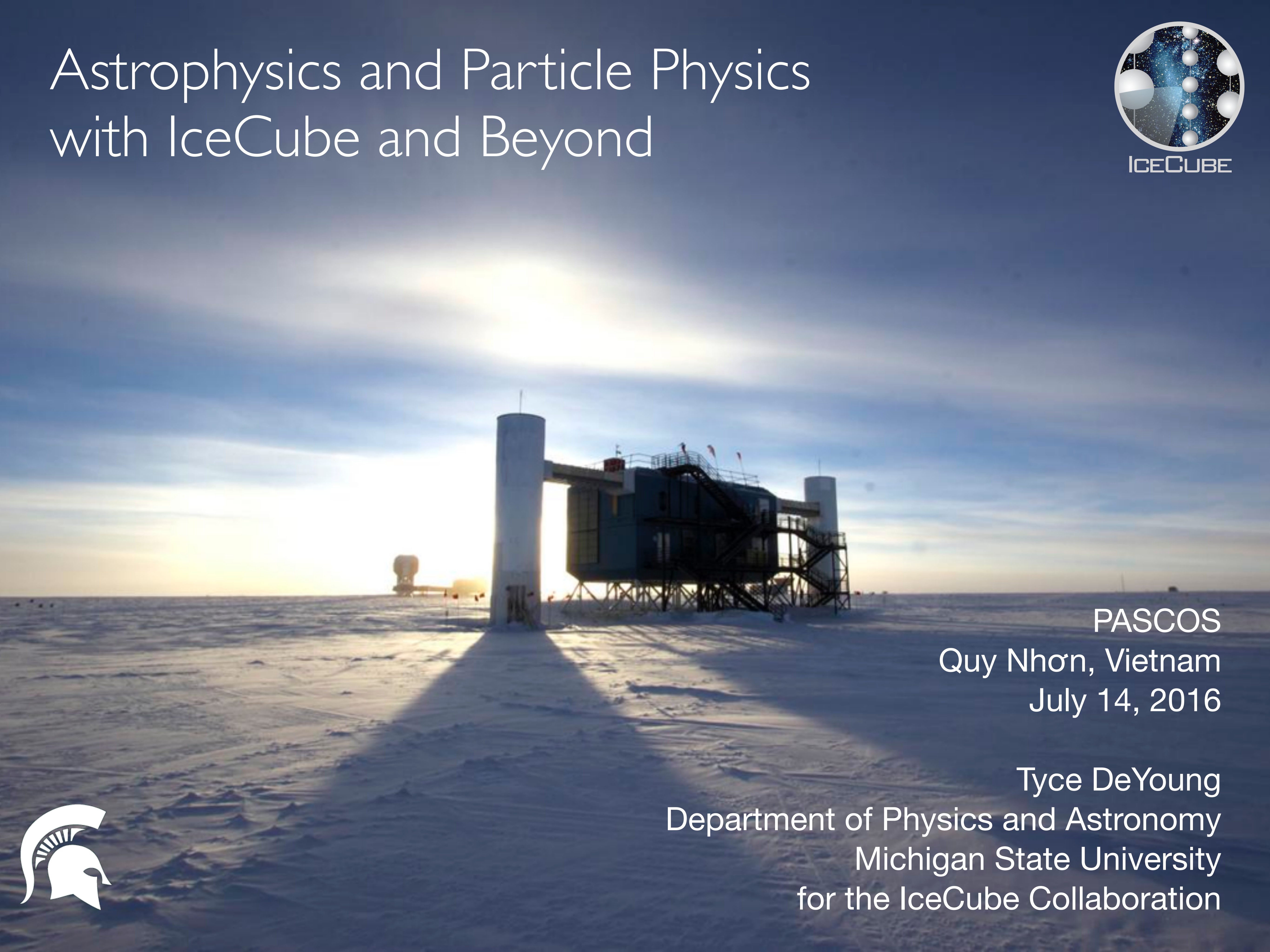


Astrophysics and Particle Physics with IceCube and Beyond

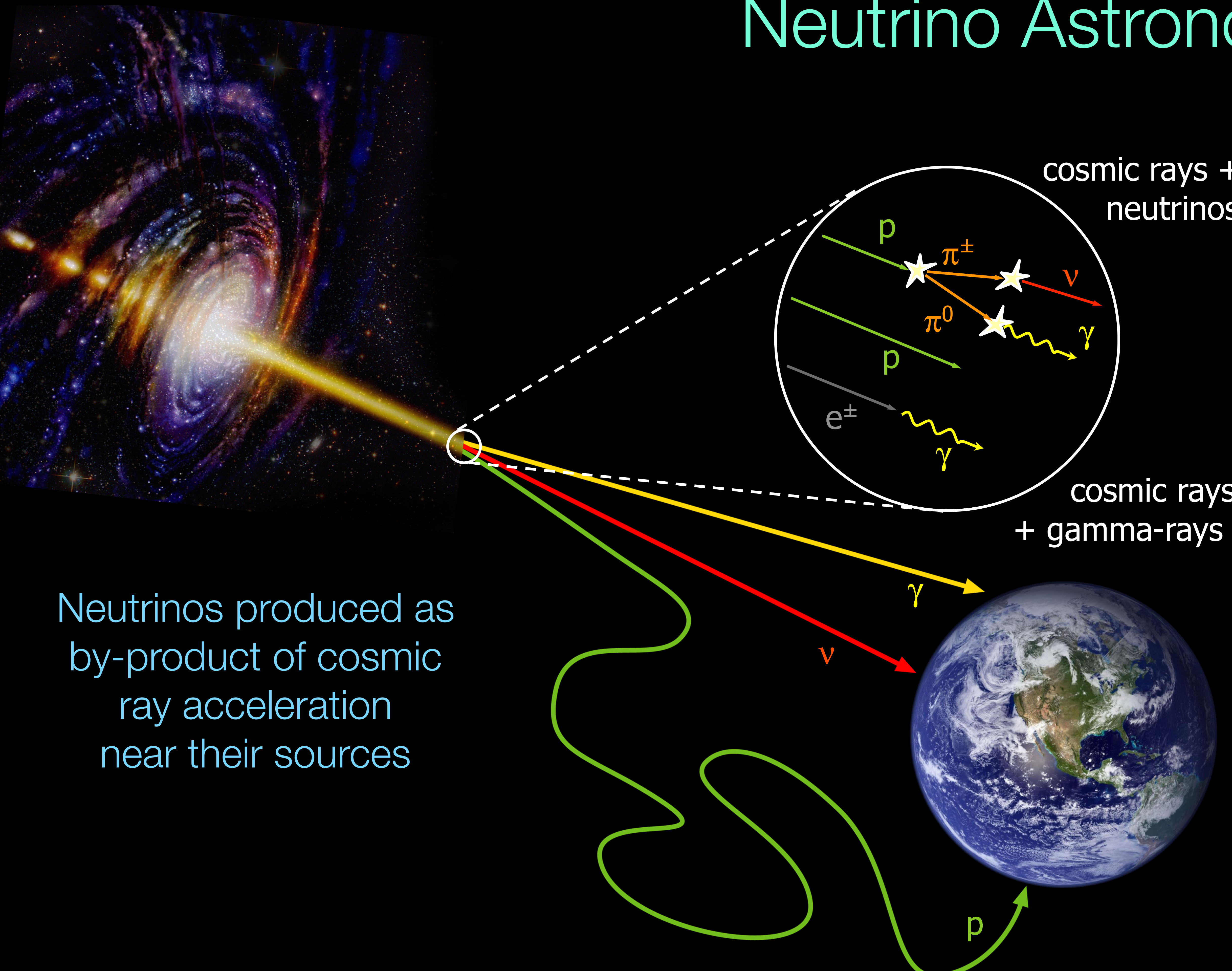
PASCOS
Quy Nhơn, Vietnam
July 14, 2016

Tyce DeYoung
Department of Physics and Astronomy
Michigan State University
for the IceCube Collaboration

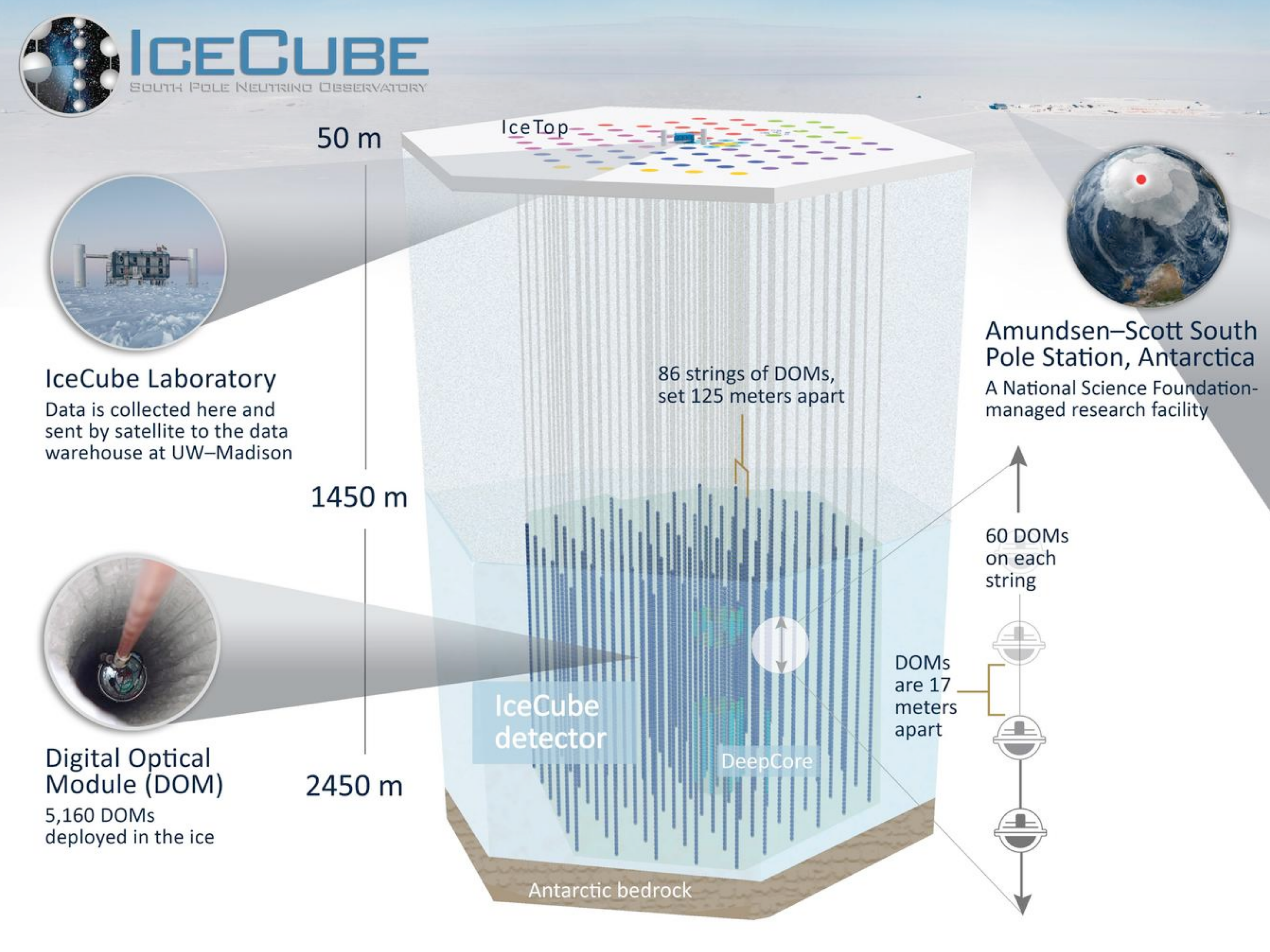
Outline

- The IceCube Neutrino Observatory
- Observations of very high energy neutrinos
- Particle physics with IceCube
- Future Plans: IceCube Gen2

Neutrino Astronomy



Neutrinos produced as
by-product of cosmic
ray acceleration
near their sources

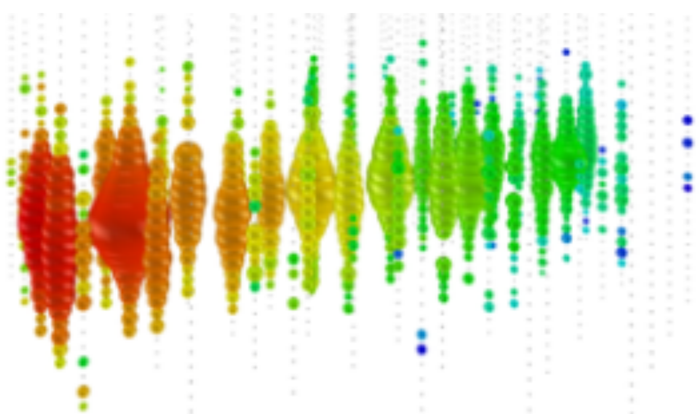

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
50 m
IceTop
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock


IceCube L
Data is colle
sent by sate
warehouse
Digital Optical
Module (DOM)
5,160 DOMs
deployed in the ice
South
rctica
ndation-
ility
Antarctic bedrock
TOS1RK
IceCube
Detector Completion
5years
IceCube Detector Completion

Neutrino Signatures

Track

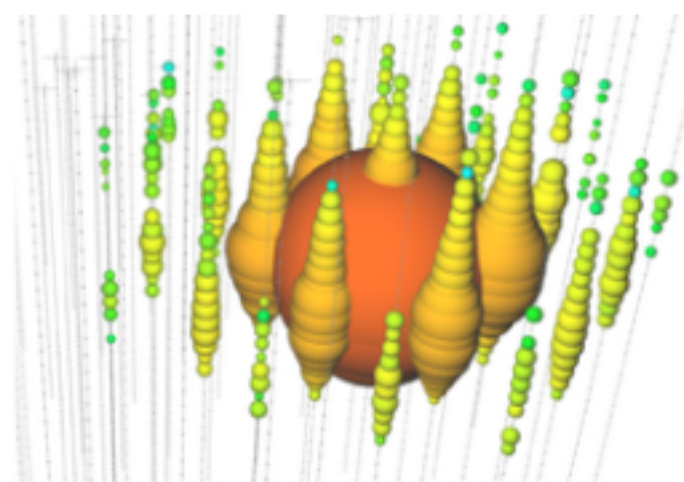
ν_μ CC



- angular resolution <1°
- usually enter IceCube from outside
- factor of 2 resolution on E_μ (not E_ν)

Cascade

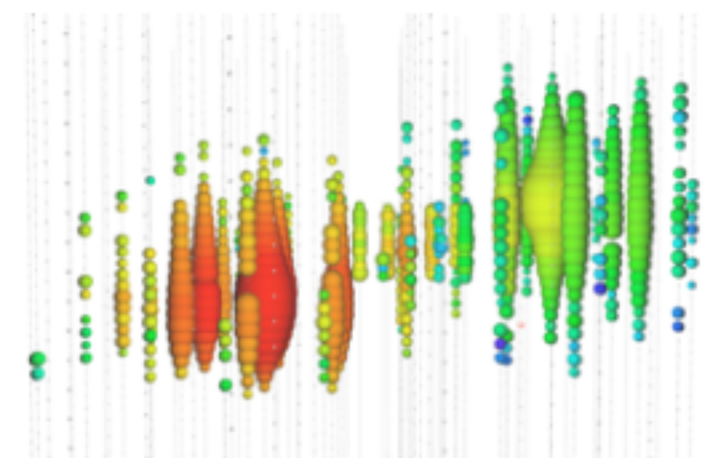
ν_e CC, ν_x NC, low-E ν_τ



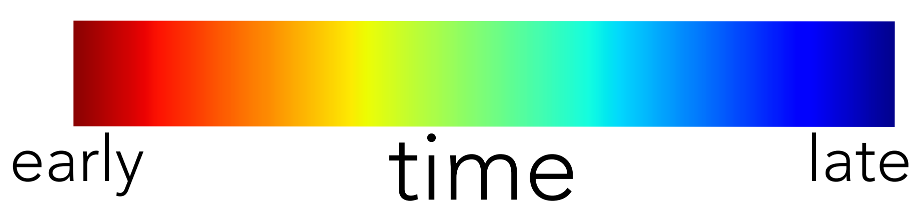
- angular resolution approximately 10°-15°
- 15% resolution on deposited energy

Double Bang (MC)

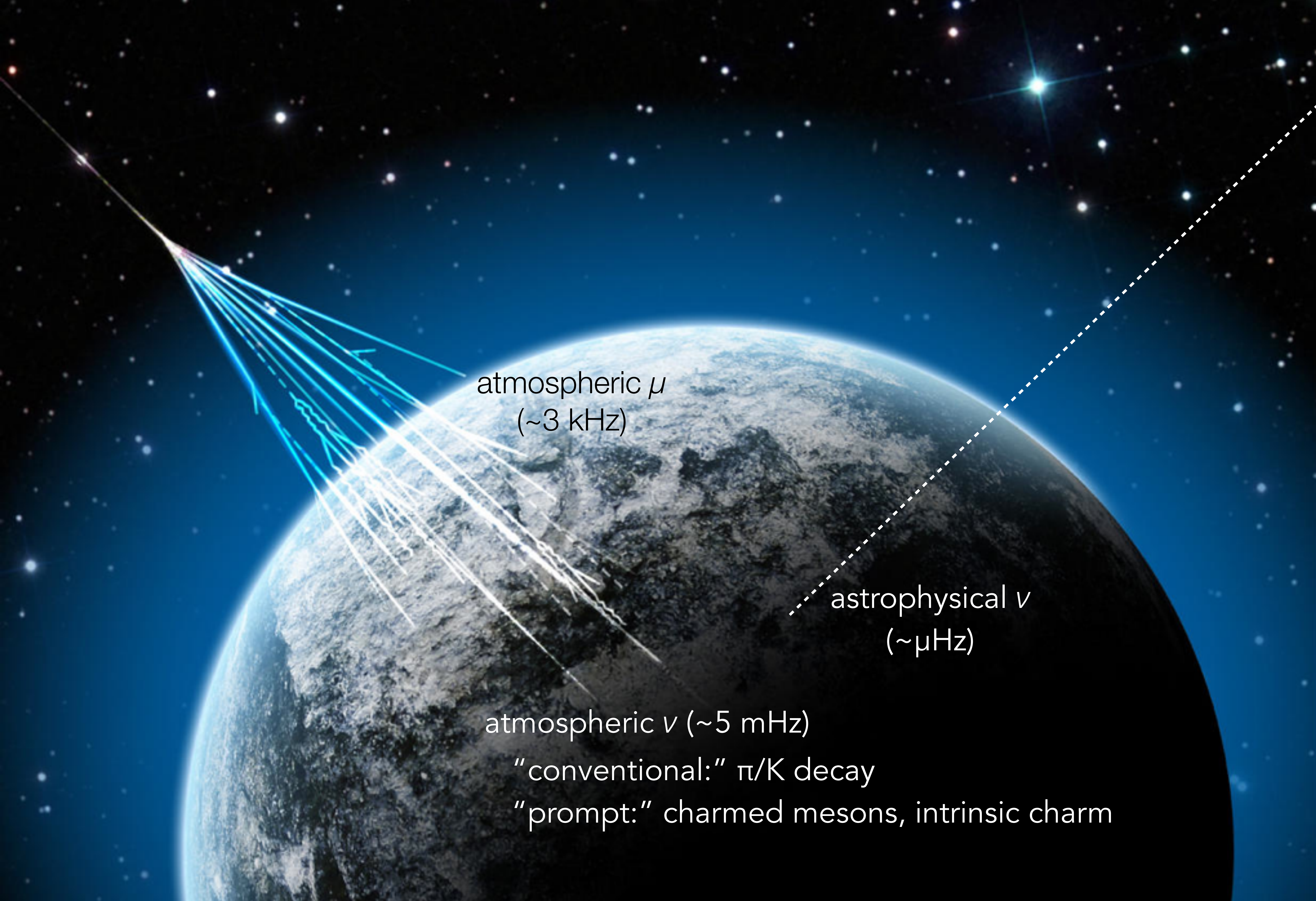
one high-E ν_τ topology



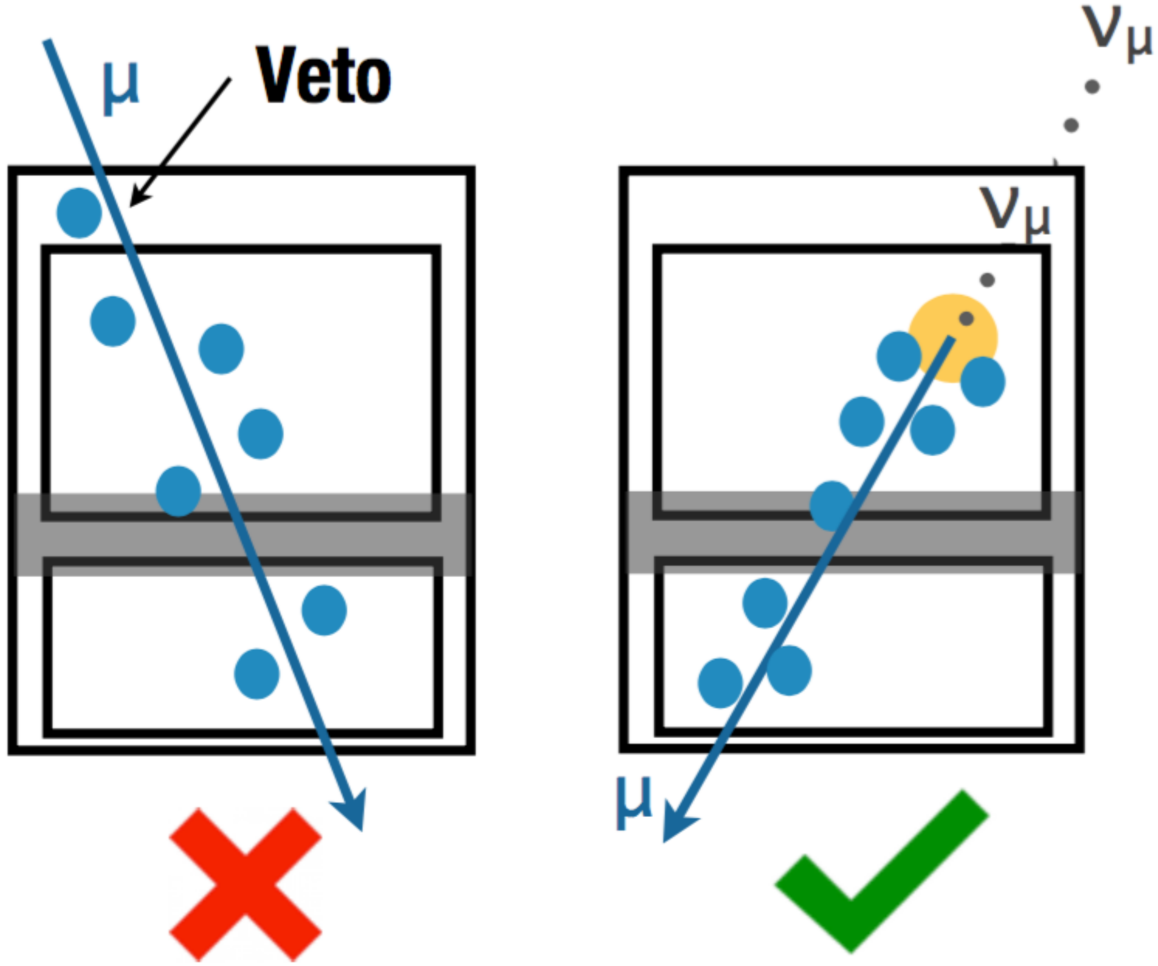
- τ lepton decay length $c\tau_\tau \approx$ 50 m/PeV
- second cascade at decay vertex (except $\tau \rightarrow \mu\nu_\mu$, 17% BR)
- not yet observed

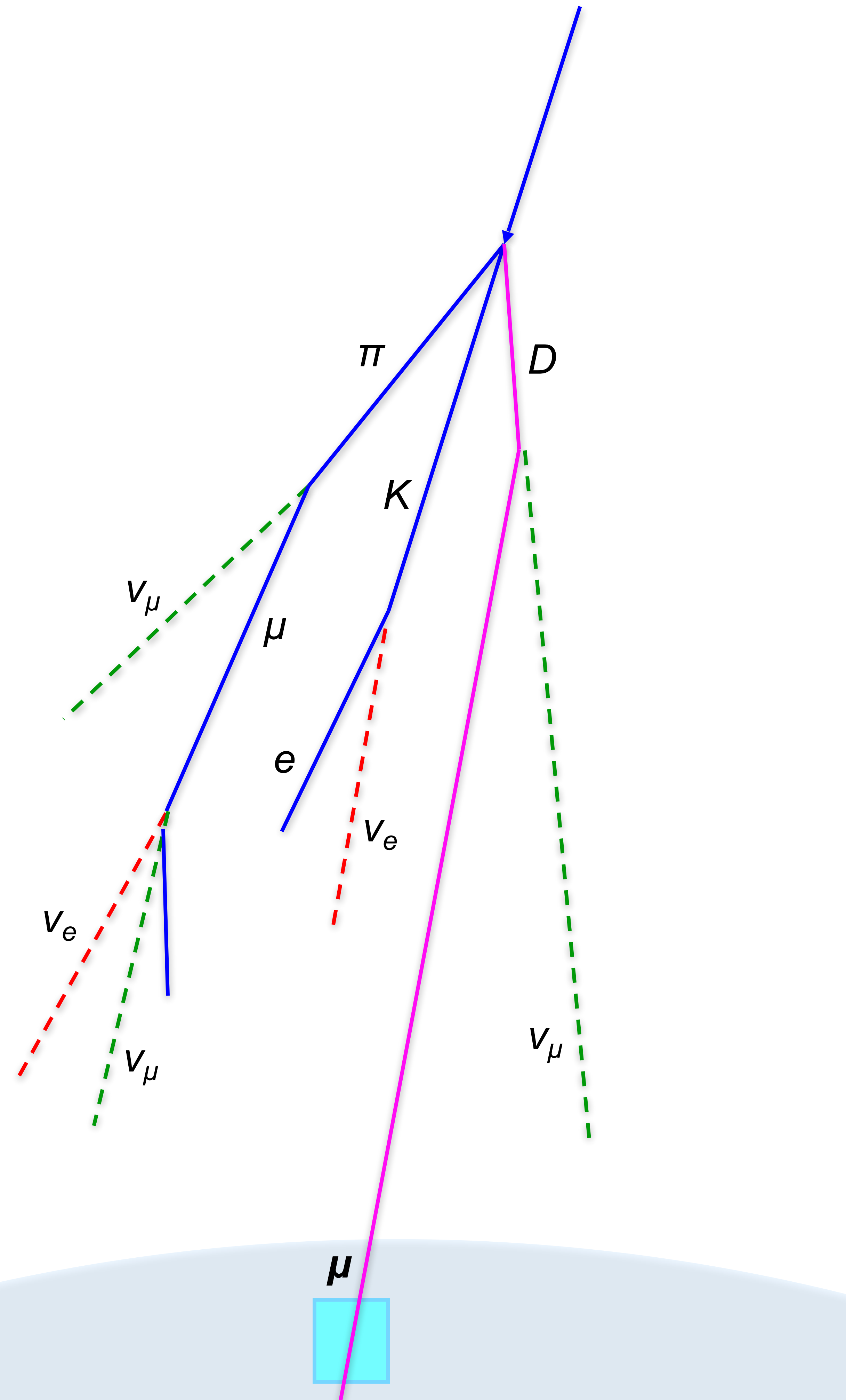


Signals and Backgrounds

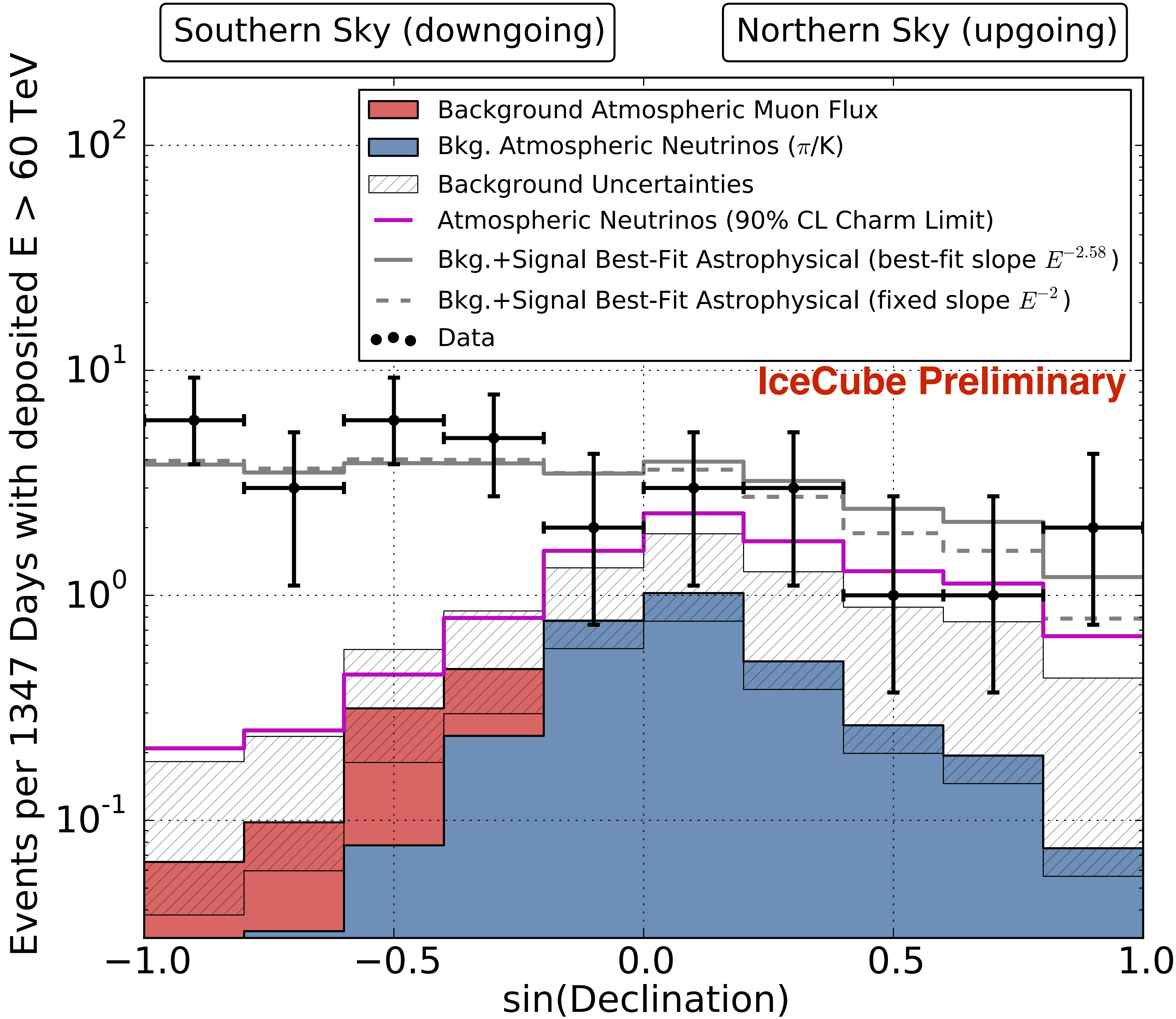


Atmospheric Muon and Neutrino Veto

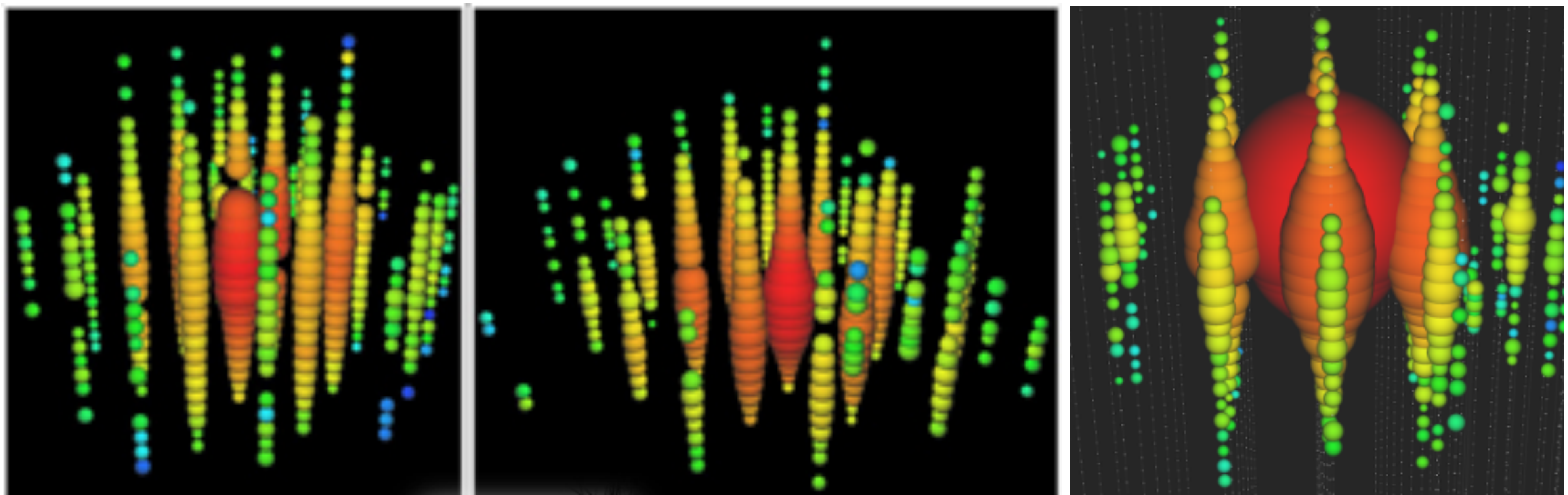




- Schönert et al. 2009, Gaisser et al. 2014


Southern Sky (downgoing)
Northern Sky (upgoing)
Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Bkg.+Signal Best-Fit Astrophysical (best-fit slope $E^{-2.58}$)
Bkg.+Signal Best-Fit Astrophysical (fixed slope E^{-2})
Data
IceCube Preliminary
Events per 1347 Days with deposited E > 60 TeV
sin(Declination)
10^{2}
10^{1}
10^{0}
10^{-1}
−1.0
−0.5
0.0
0.5
1.0

Astrophysical Neutrinos



"Bert"
1.04 PeV
Aug. 2011

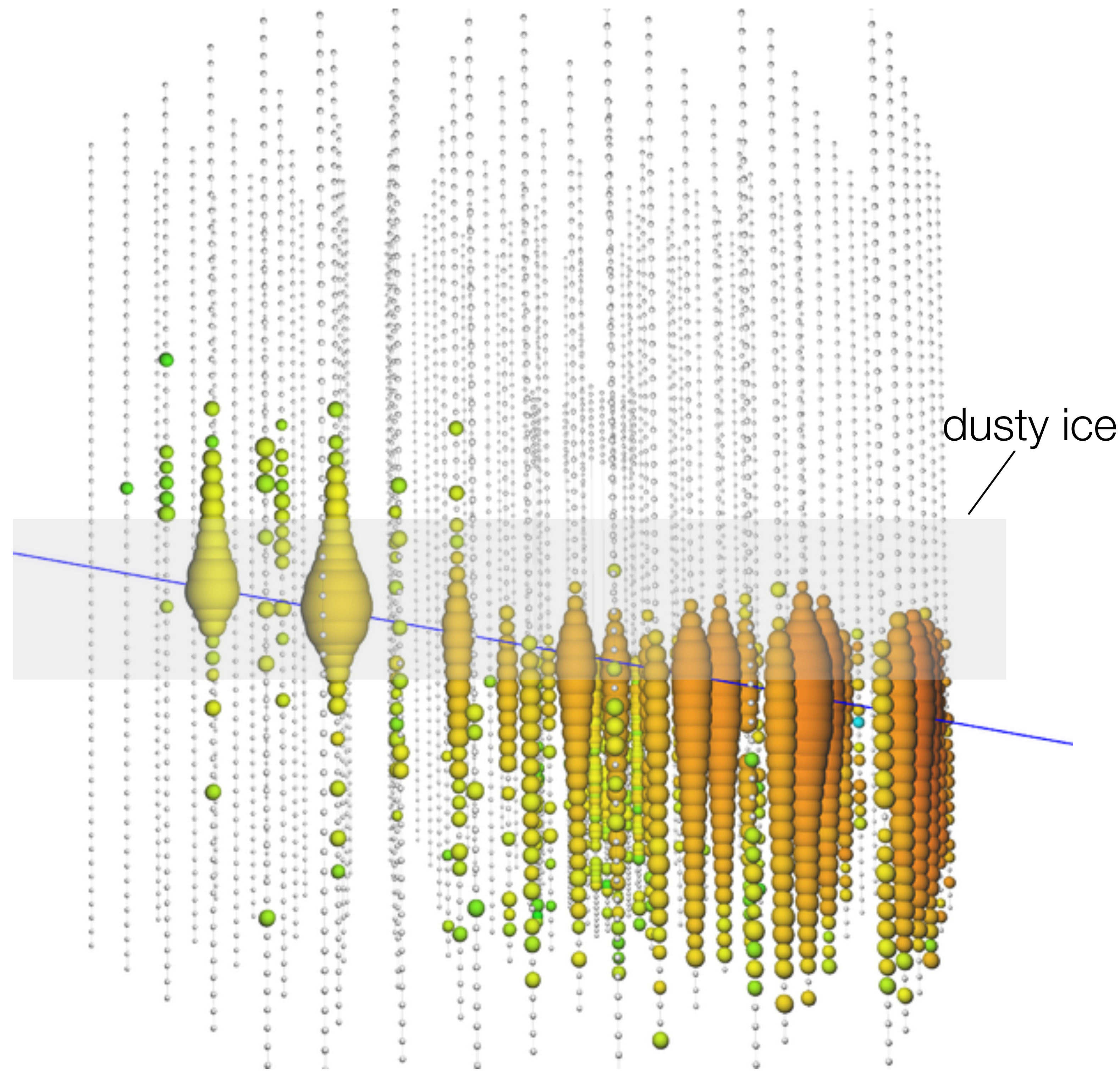
"Ernie"
1.14 PeV
Jan. 2012

"Big Bird"
2 PeV
Dec. 2012

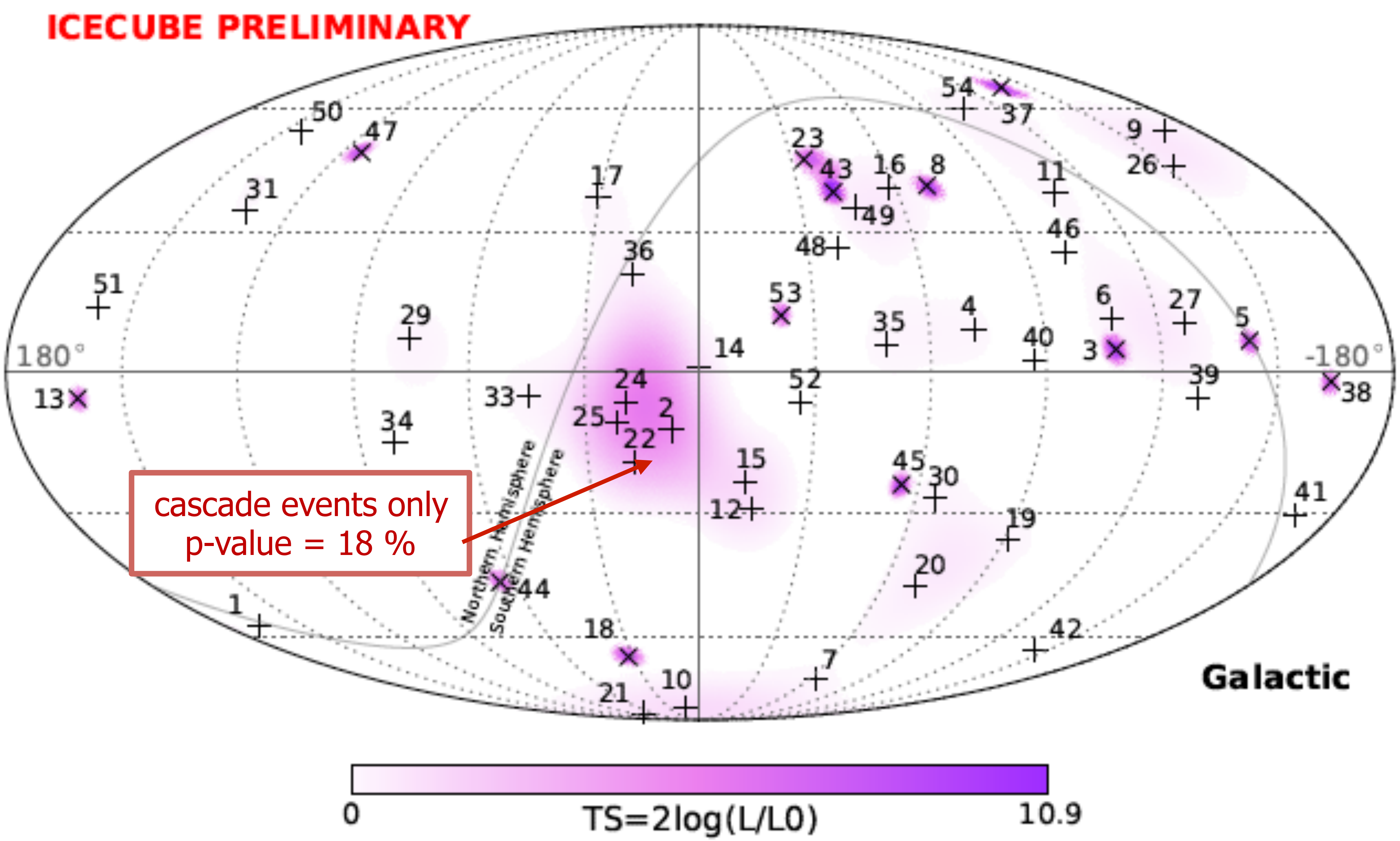
- Equal-flavor flux (oscillations) will produce mostly ν_e/ν_τ/NC cascades
  - Easiest to identify as astrophysical since most energy deposited in detector

Upward-Going Muon Neutrinos

- Also observe 5.6σ excess in high-energy ν_μ passing through the Earth – completely independent observation channel
- Highest energy neutrino yet: 2.6 ± 0.3 PeV deposited in detector
  - *Lower limit on E_ν*
- Up-going track (ν_μ)
  - Declination 11.5°, 11/6/14



Where Do They Come From?

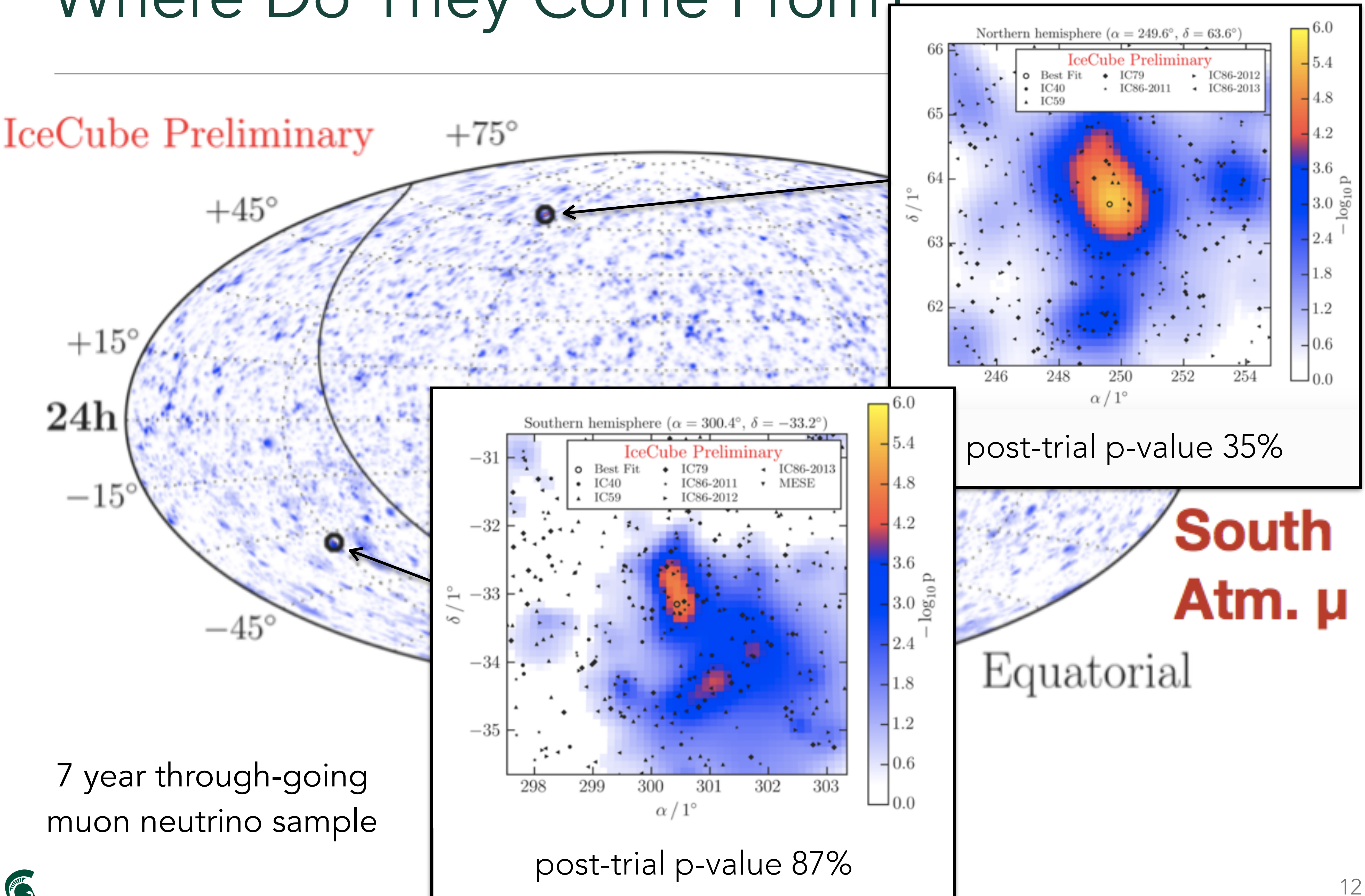


4 year high energy starting event sample

Largely isotropic – extragalactic origin

Sub-dominant galactic component cannot be ruled out

Where Do They Come From?



7 year through-going muon neutrino sample

Possible Source Classes

✗ Gamma Ray Bursts

- No more than 1% of the observed HE neutrino flux is associated with GRBs
- However, limits on UHECR-GRB models are constraining but not definitive

? Active Galactic Nuclei

- No correlation found: < 30% of astrophysical neutrino flux is correlated with 2LAC blazar catalog (even less if weighted by gamma ray emission)
- Possible to evade limits if production is from special sub-populations

? Starburst Galaxies and other transparent Cosmic Ray Reservoirs

- Gamma rays co-produced along with neutrinos would exceed residual Fermi-LAT diffuse gamma ray flux not attributable to blazars *(Murase et al. 2013, Bechtol et al. 2015)*

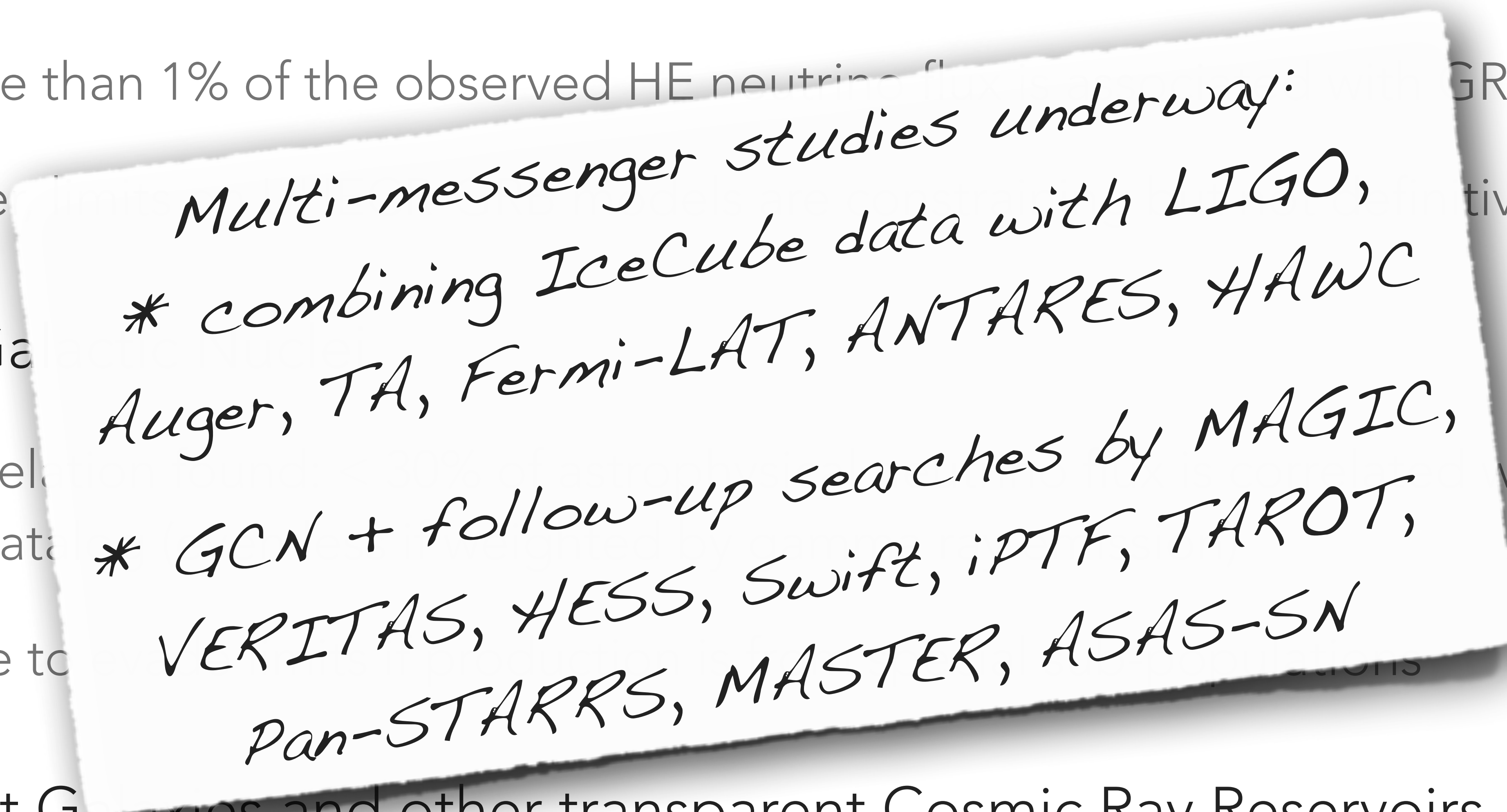
Possible Source Classes

✗ Gamma Ray Bursts

- No more than 1% of the observed HE neutri... GRBs
- Howeve... tive

? Active Ga...

- No correl... with 2LAC blazar cat...
- Possible to... ...ations



? Starburst Ga... and other transparent Cosmic Ray Reservoirs

- Gamma rays co-produced along with neutrinos would exceed residual Fermi-LAT diffuse gamma ray flux not attributable to blazars *(Murase et al. 2013, Bechtol et al. 2015)*

The High Energy Universe

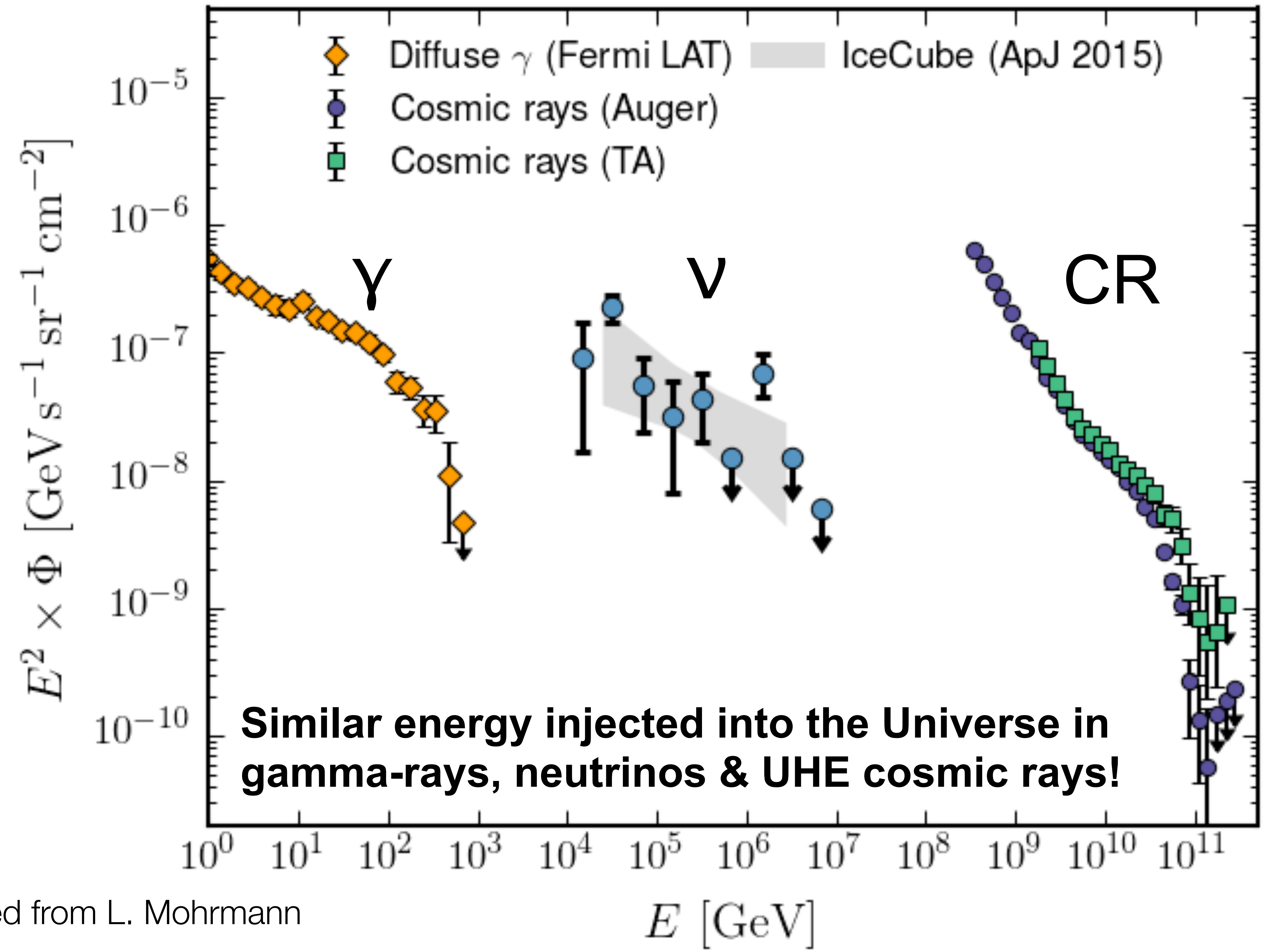
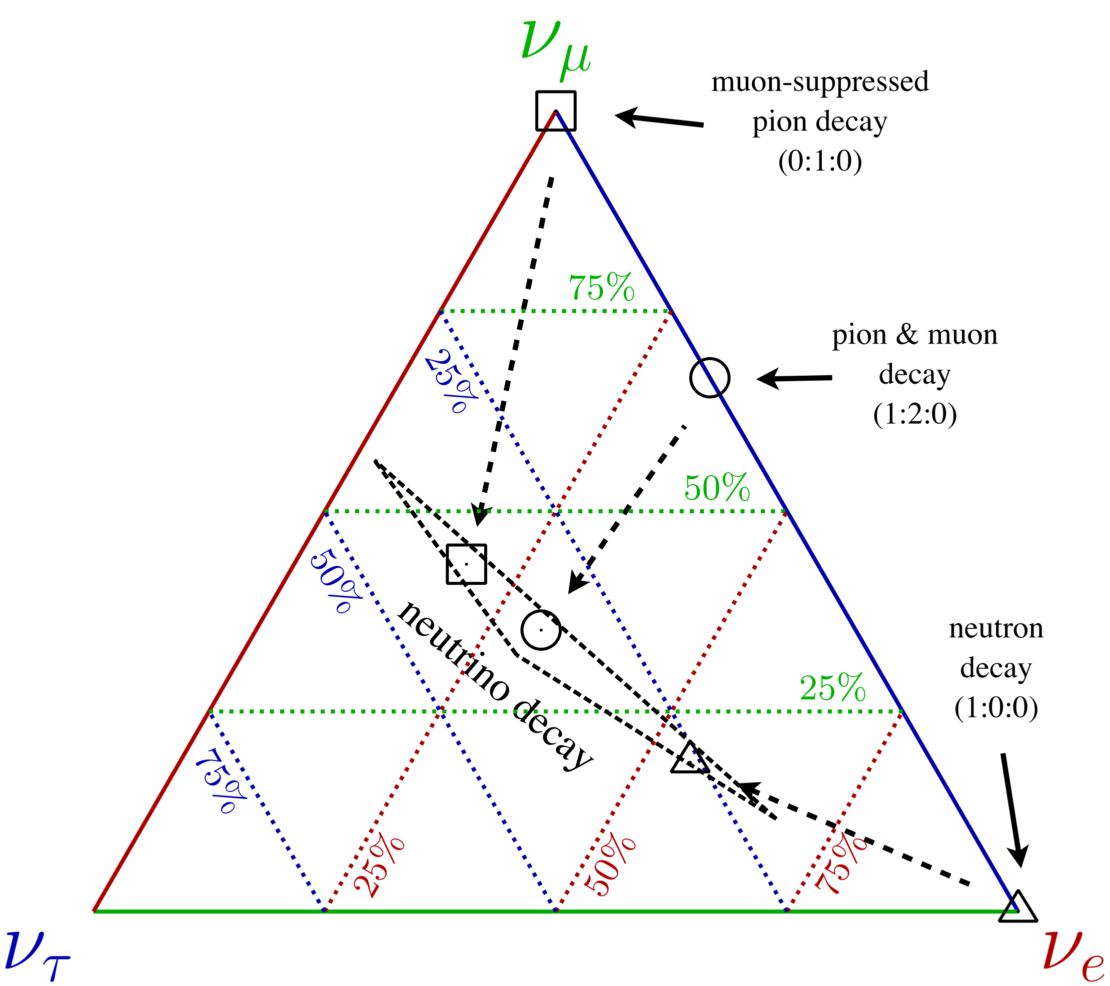
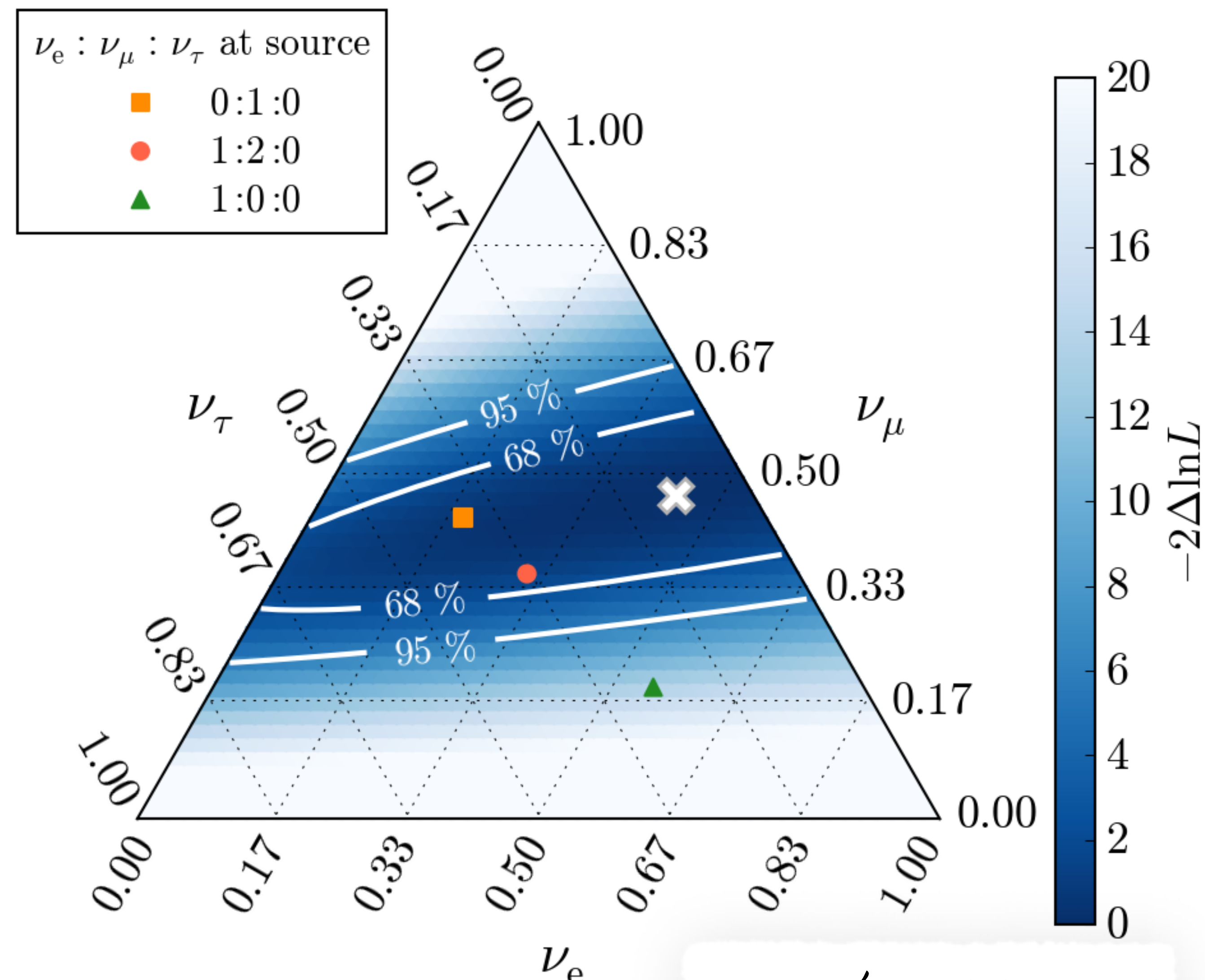


Fig. adapted from L. Mohrmann

Flavor Ratios

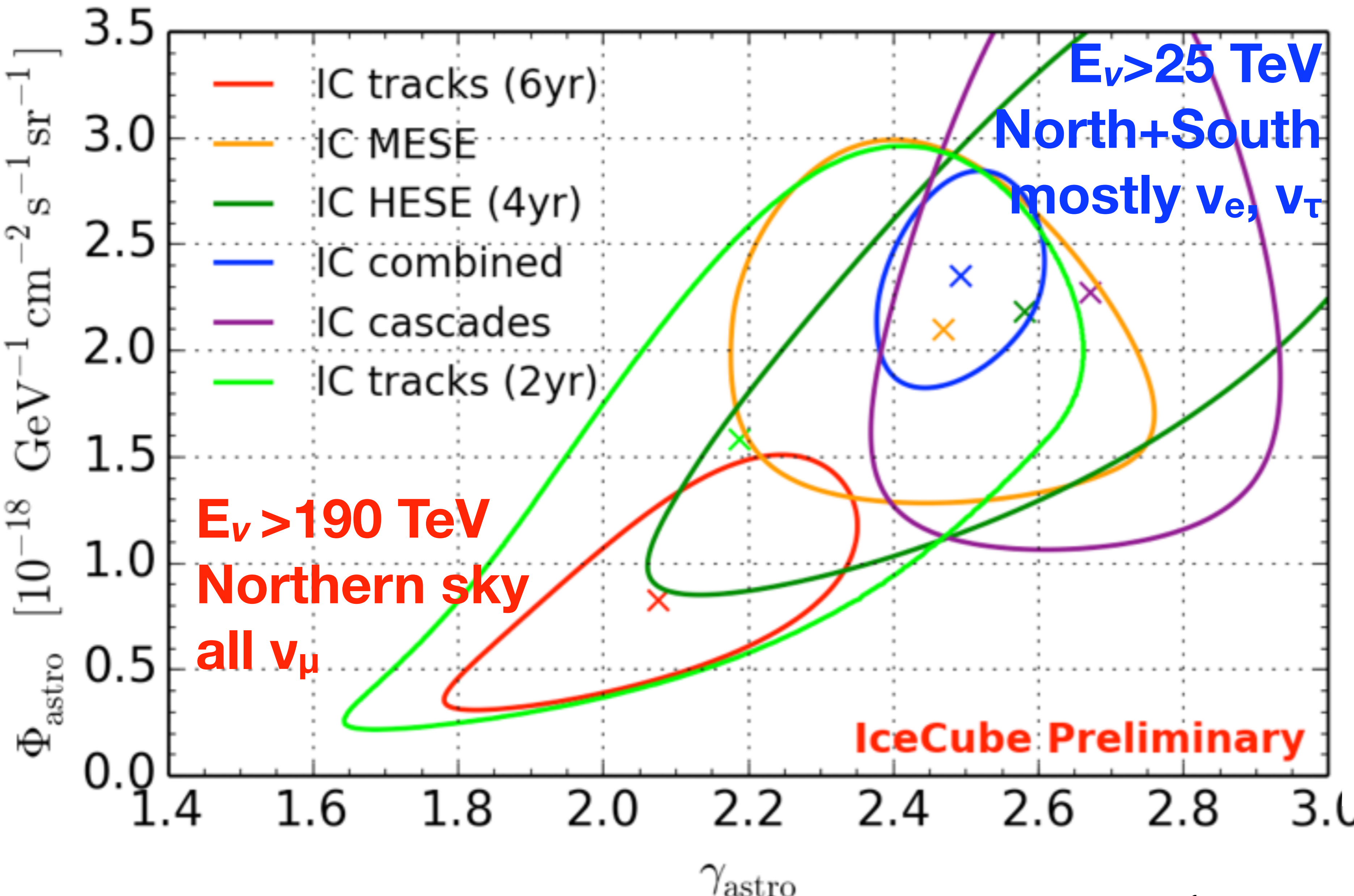


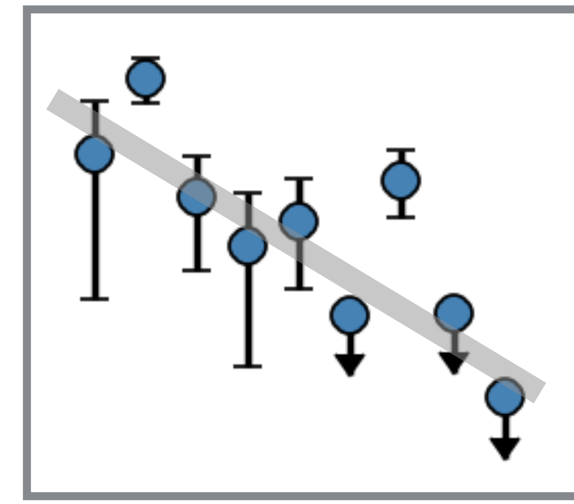


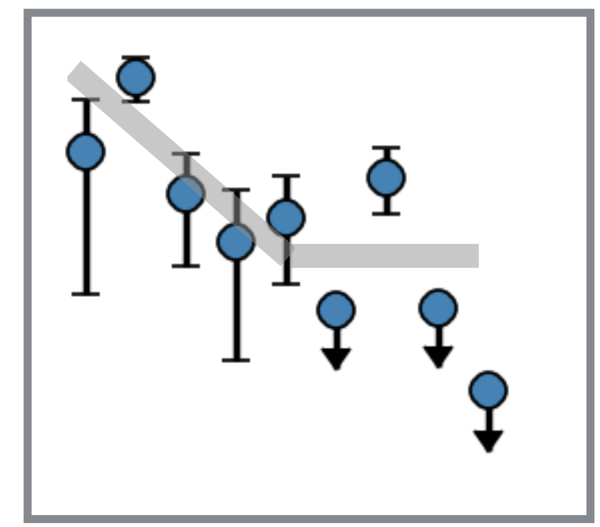
caveat: assumes a unified flux!

- Astrophysical effects can alter flavor ratio at source
  - After oscillations, all sources should wind up inside the triangle – otherwise, new physics required!

The Plot Thickens





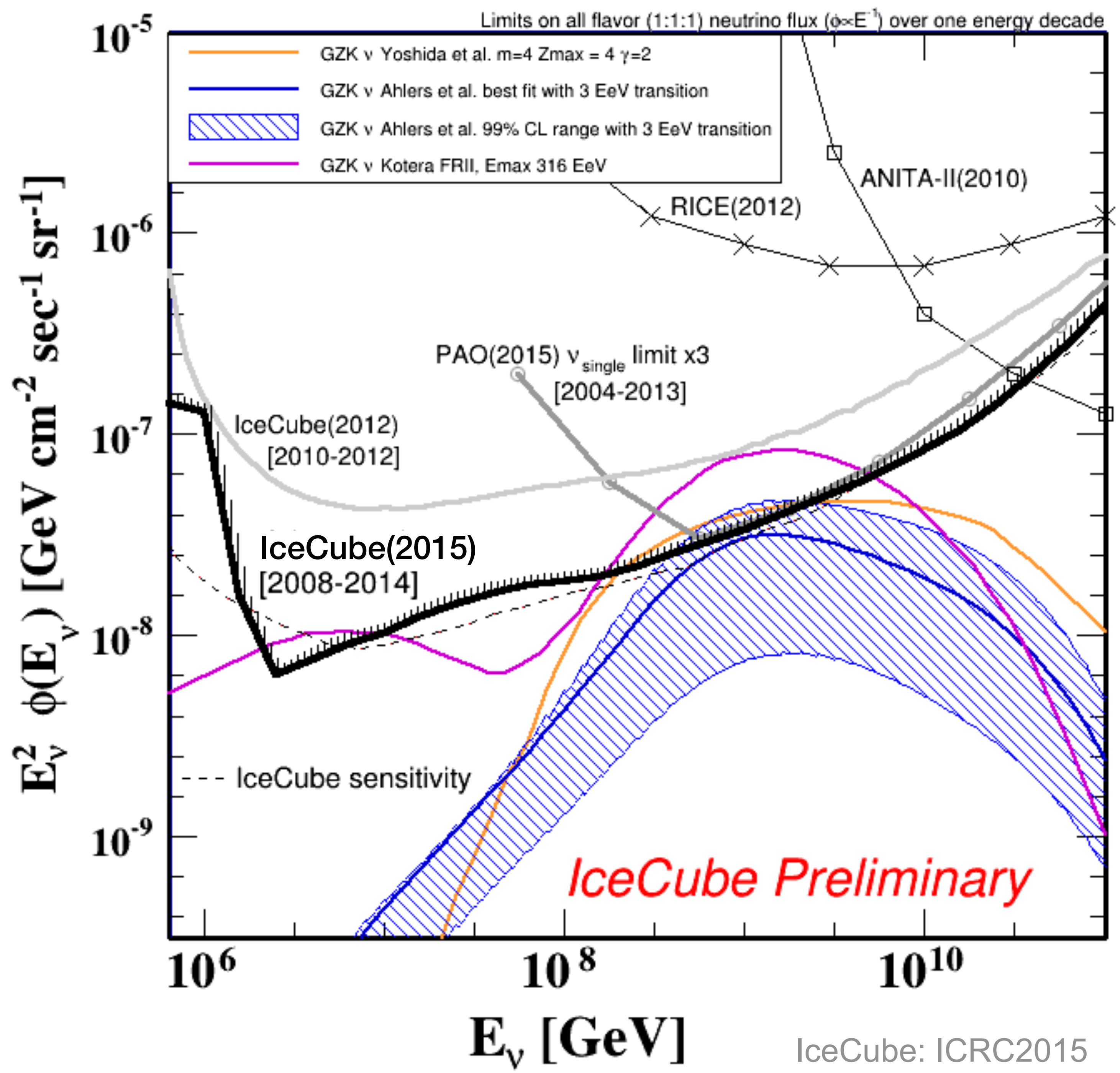


Combined spectral index: γ = –2.5 ± 0.1
High energy tracks: γ = –2.1 ± 0.1

Are we seeing a break in the spectrum, anisotropy, multiple components,...?

Cosmogenic (BZ) Neutrinos

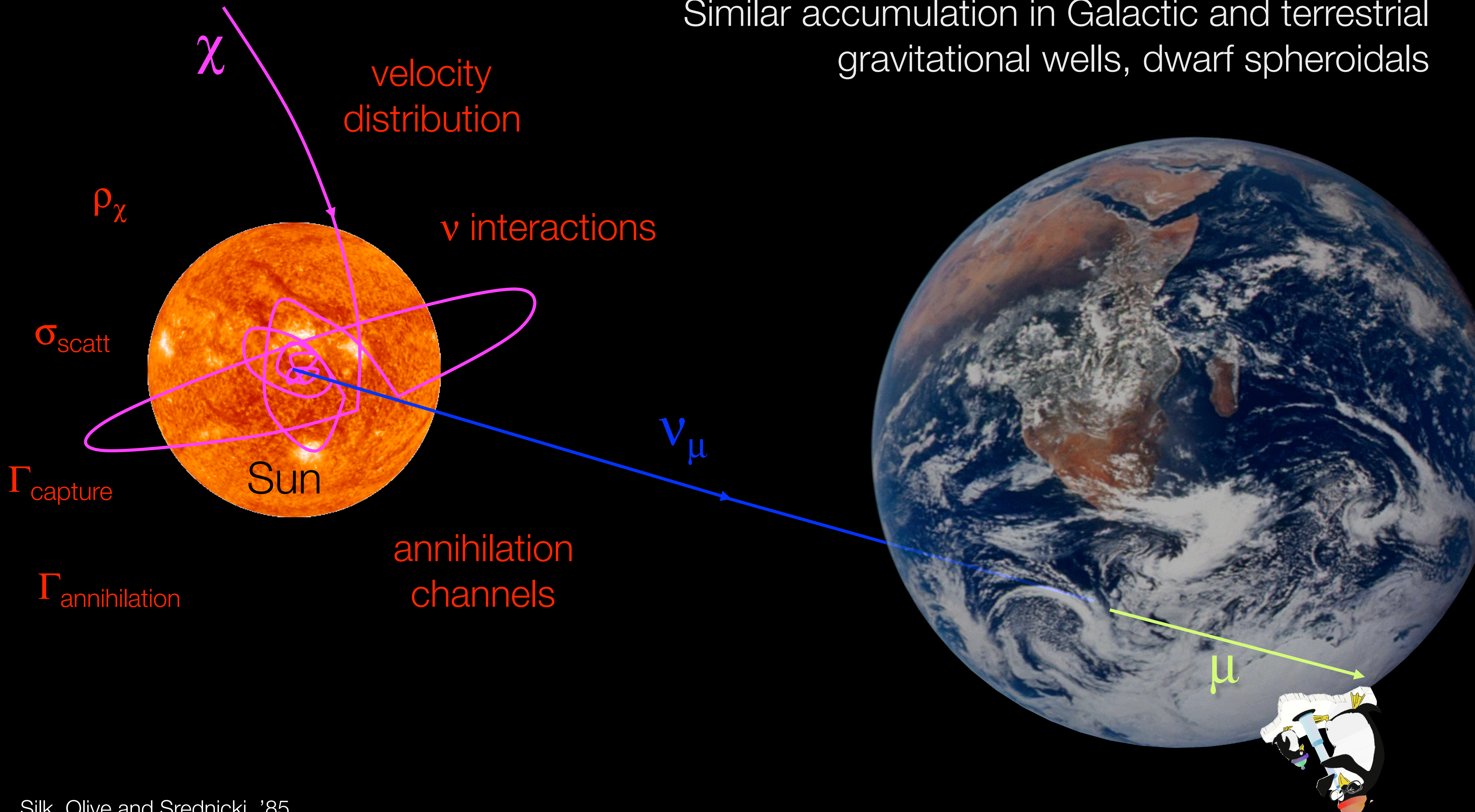
- Produced when UHECR interact with CMB – primary uncertainty is CR composition
- EHE analysis sensitive to 1 PeV – 2 EeV range
- Non-detection with 6 yr of data becoming a serious constraint on proton fraction of UHE cosmic ray flux
  - Limits on mixed or heavy composition more model-dependent



IceCube: ICRC2015

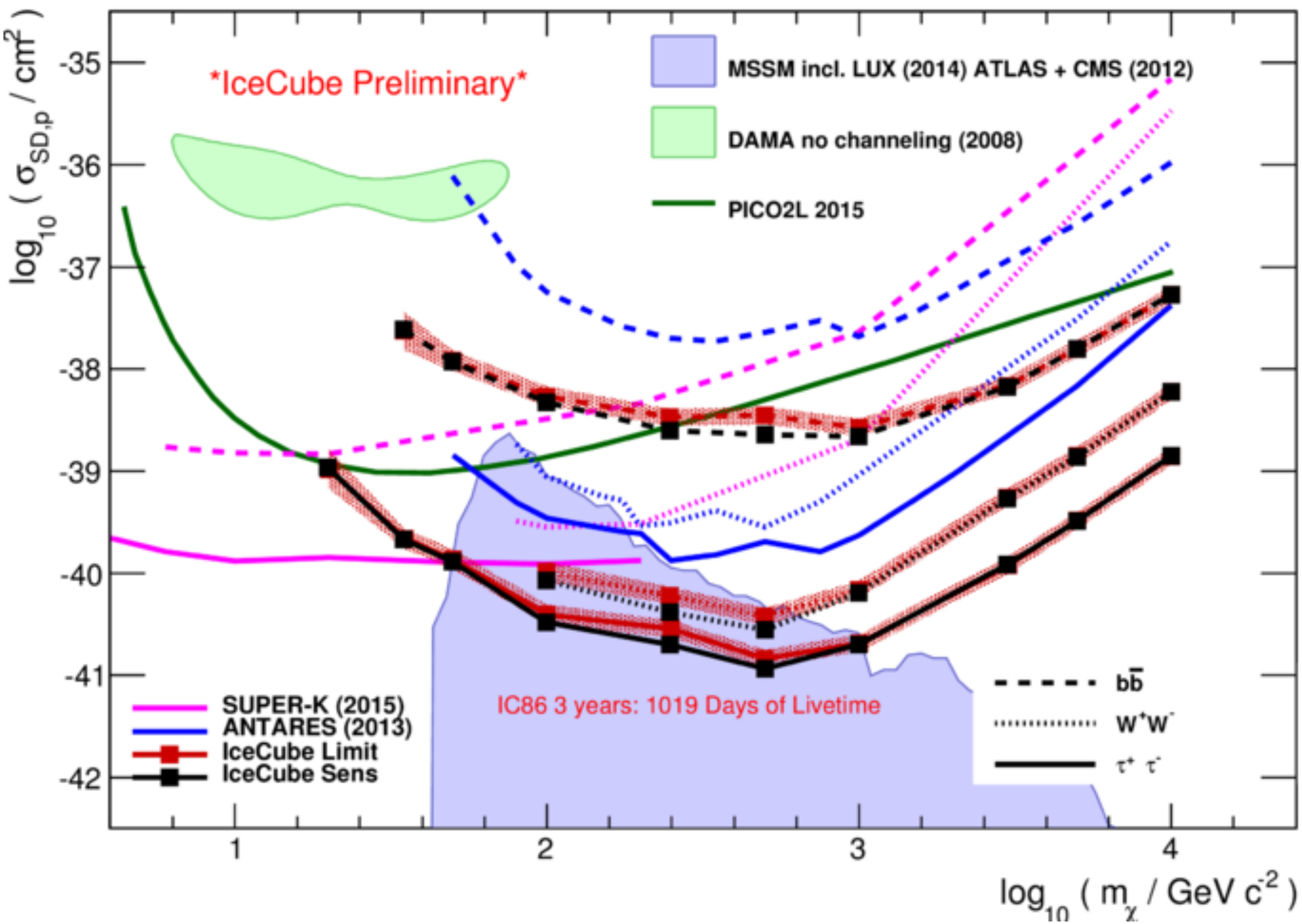
Indirect Searches for Dark Matter

Similar accumulation in Galactic and terrestrial gravitational wells, dwarf spheroidals



Silk, Olive and Srednicki, ’85
Gaisser, Steigman & Tilav, ’86
Freese, ’86
Krauss, Srednicki & Wilczek, ’86
Gaisser, Steigman & Tilav, ’86
et alia

Can also probe dark matter decay models, other types of dark matter

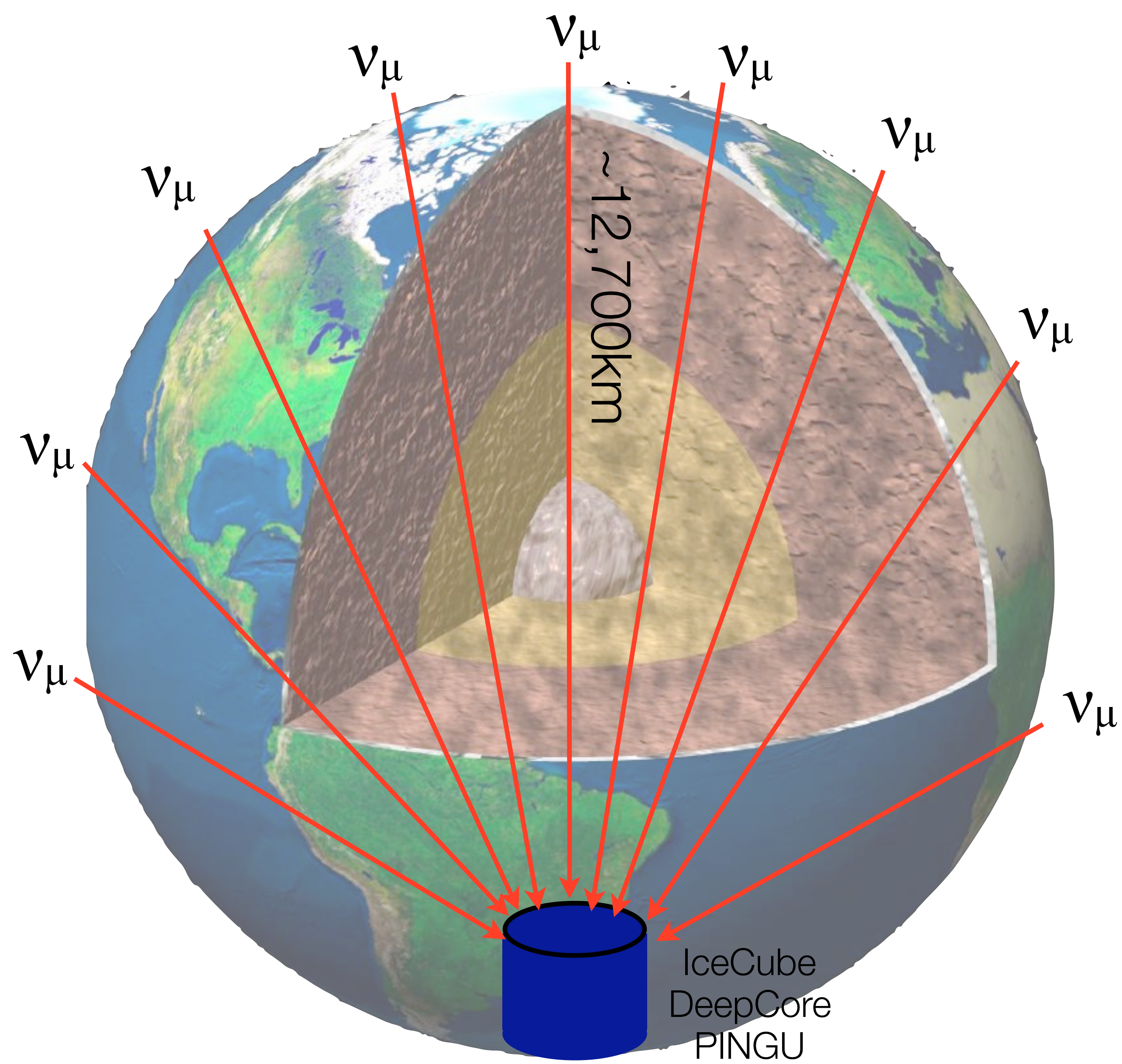


Solar WIMP Annihilation

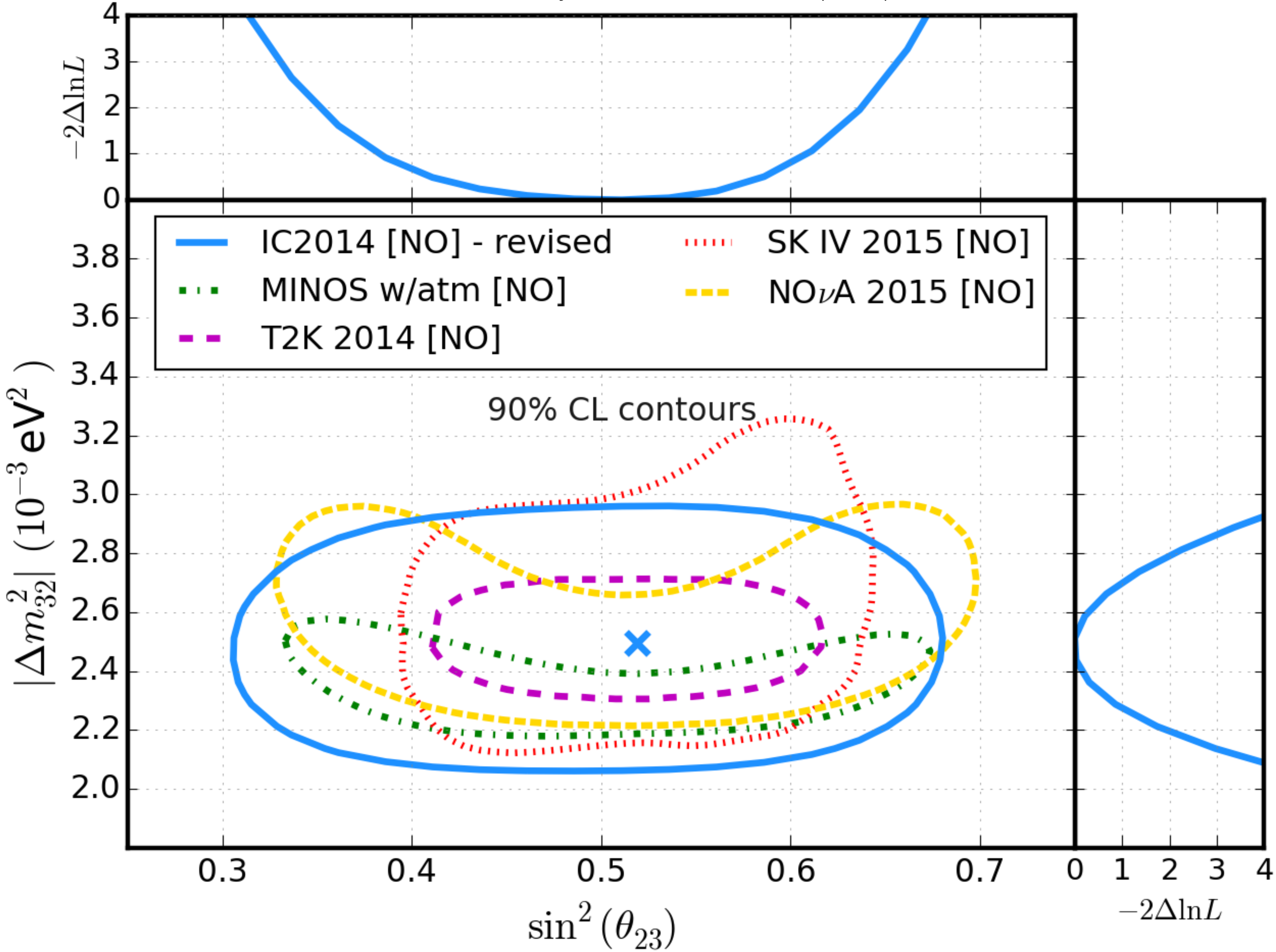
Leading limits for SD nuclear scattering with massive WIMPs, for most assumed annihilation products

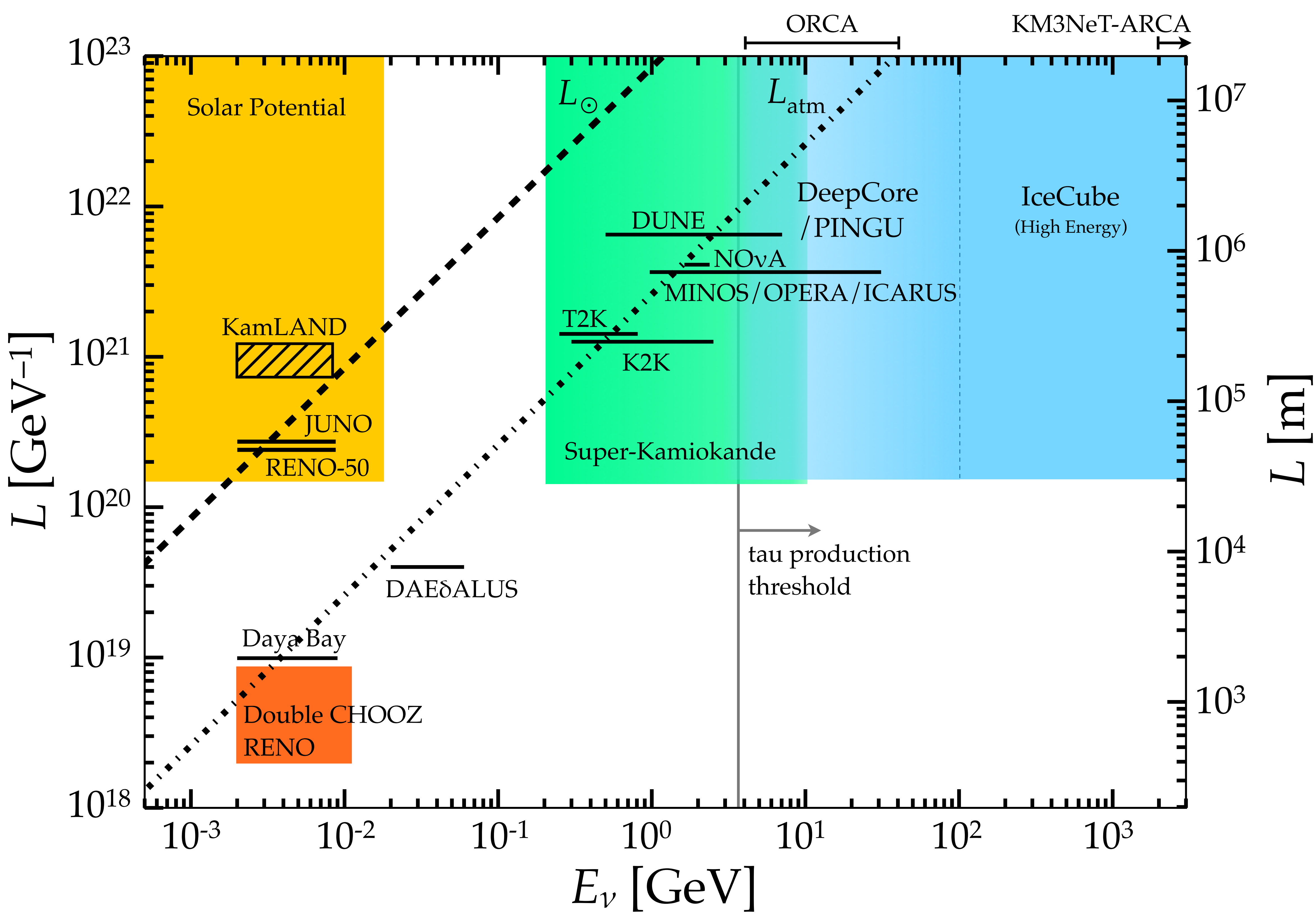
Oscillations with Atmospheric Neutrinos

- Neutrinos available over a wide range of baselines, few GeV to 10's of TeV
- Oscillations produce distinctive pattern in energy-angle space
  - Effectively, a range of near to far beams rather than near and far detectors
- Significant matter effects for neutrinos traversing Earth's core



Phys. Rev D91, 072004 (2015), Neutrino 2016

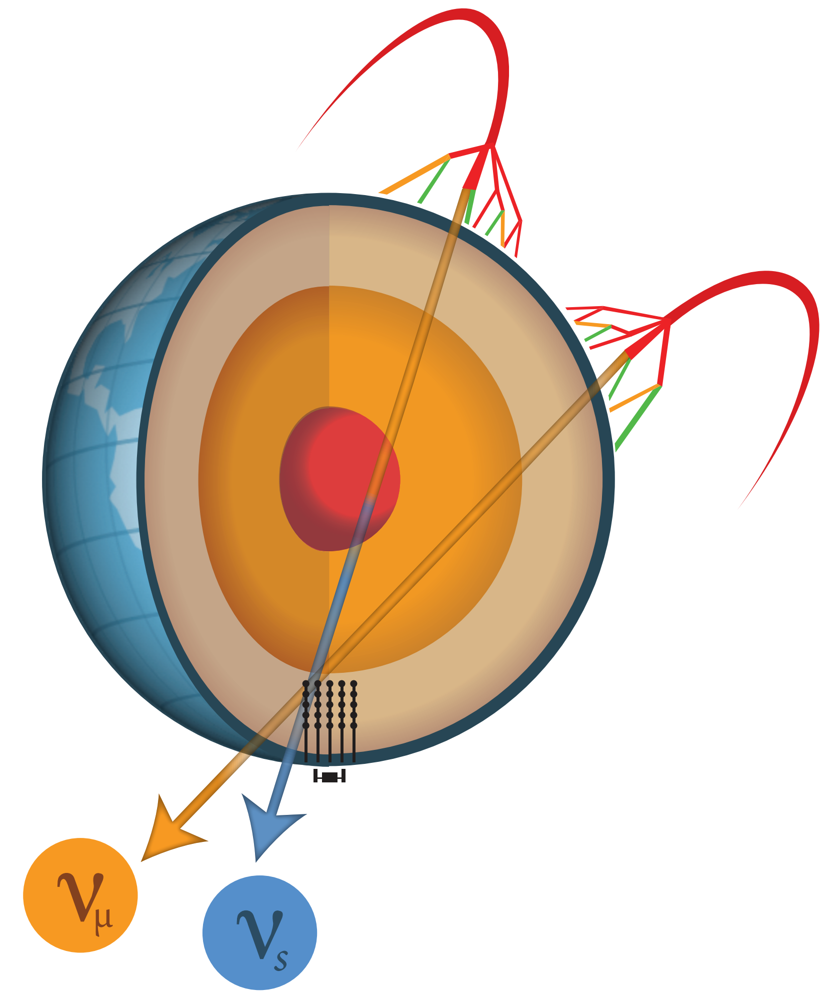


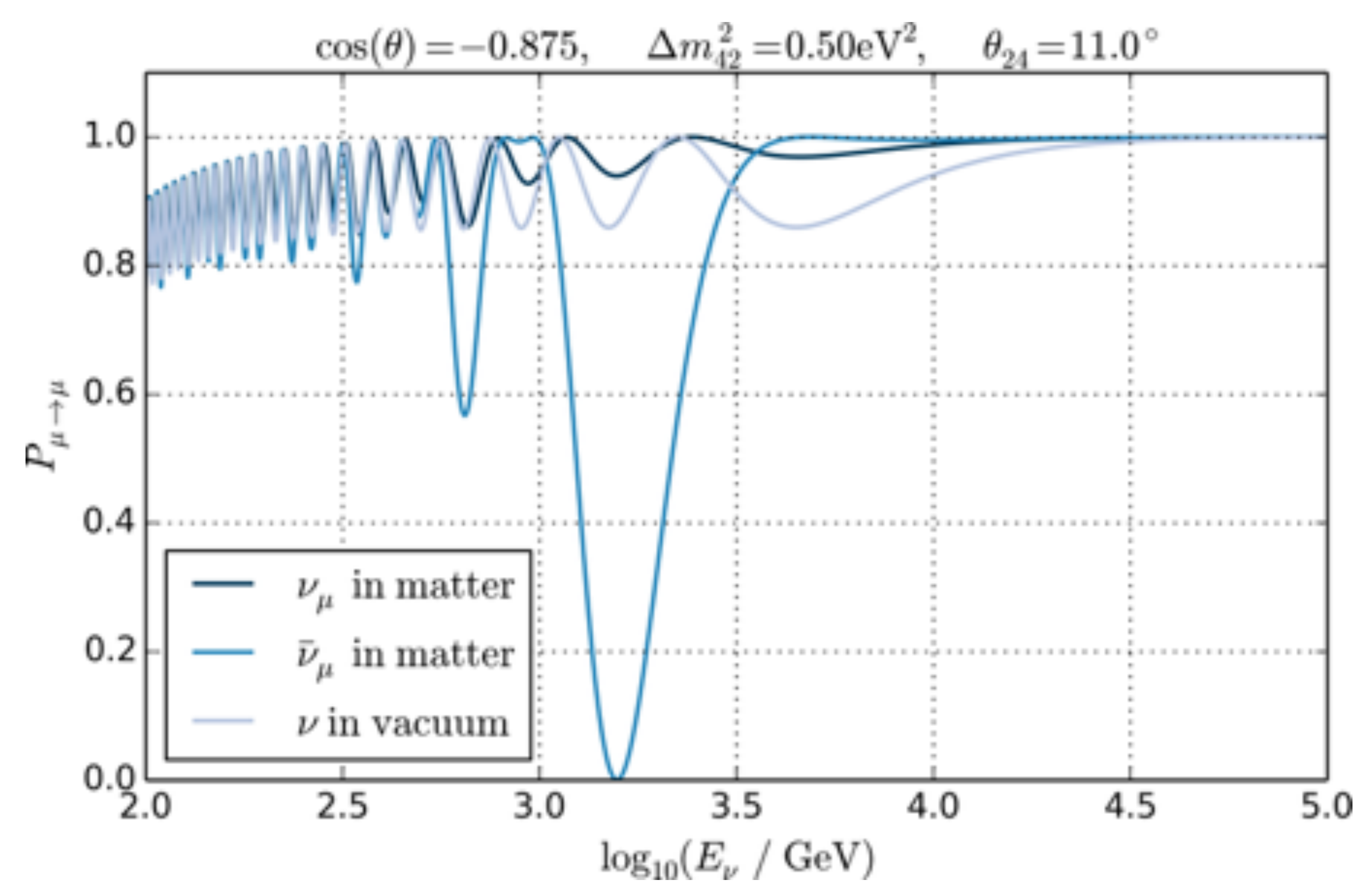


Probing oscillation physics at a range of baselines and energies not accessible to long-baseline or reactor neutrino experiments

Sterile Neutrinos

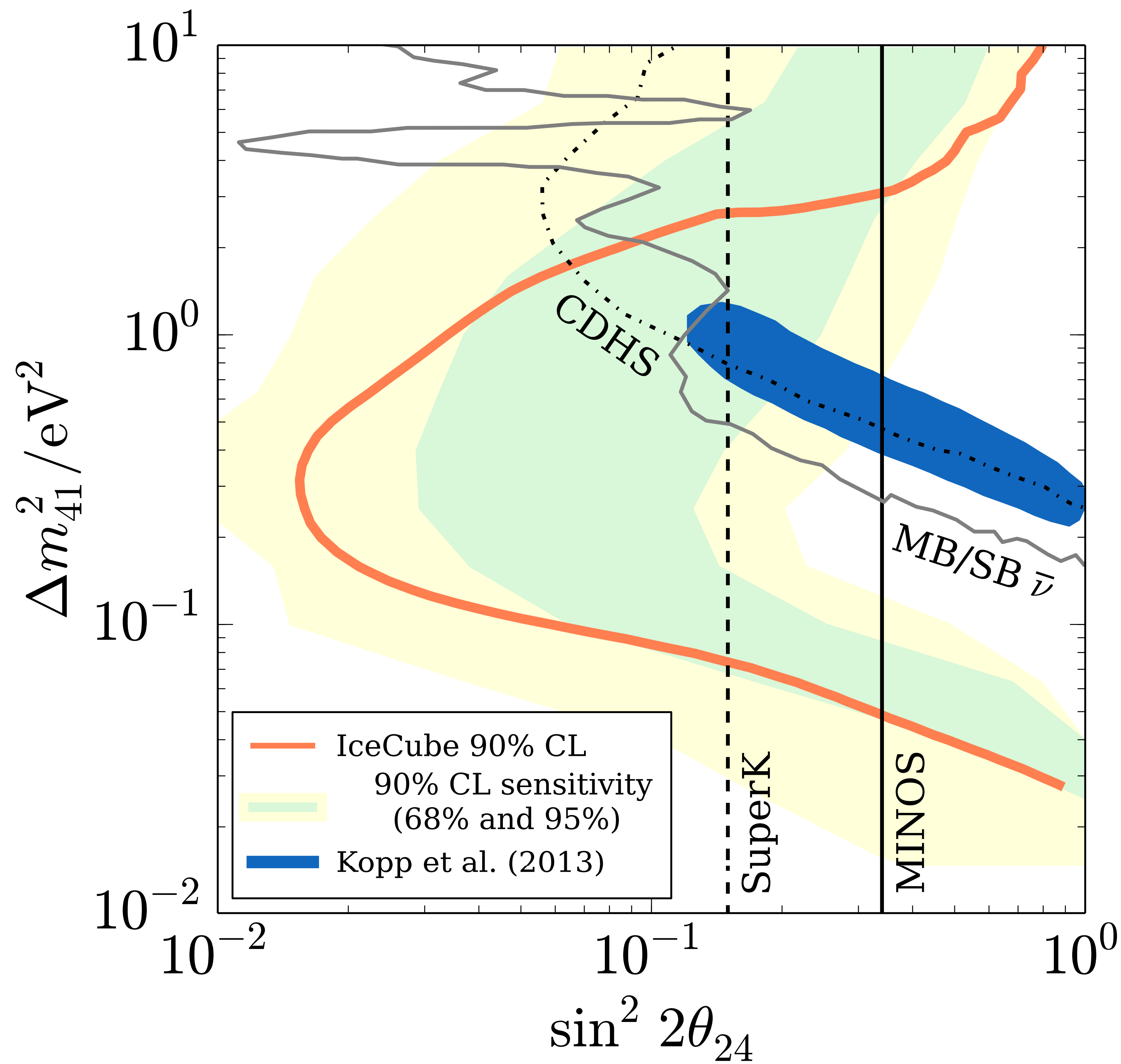
- Existence of sterile neutrino state produces MSW resonant $\bar{\nu}_\mu$ disappearance for particular neutrino energy, angle (=matter profile)
  - Location of resonance depends on sterile neutrino mixing parameters
- Fortuitously, preferred range around 1 eV^2 leads to resonance at TeV scale – core IceCube energy range





Sterile Neutrino Limits

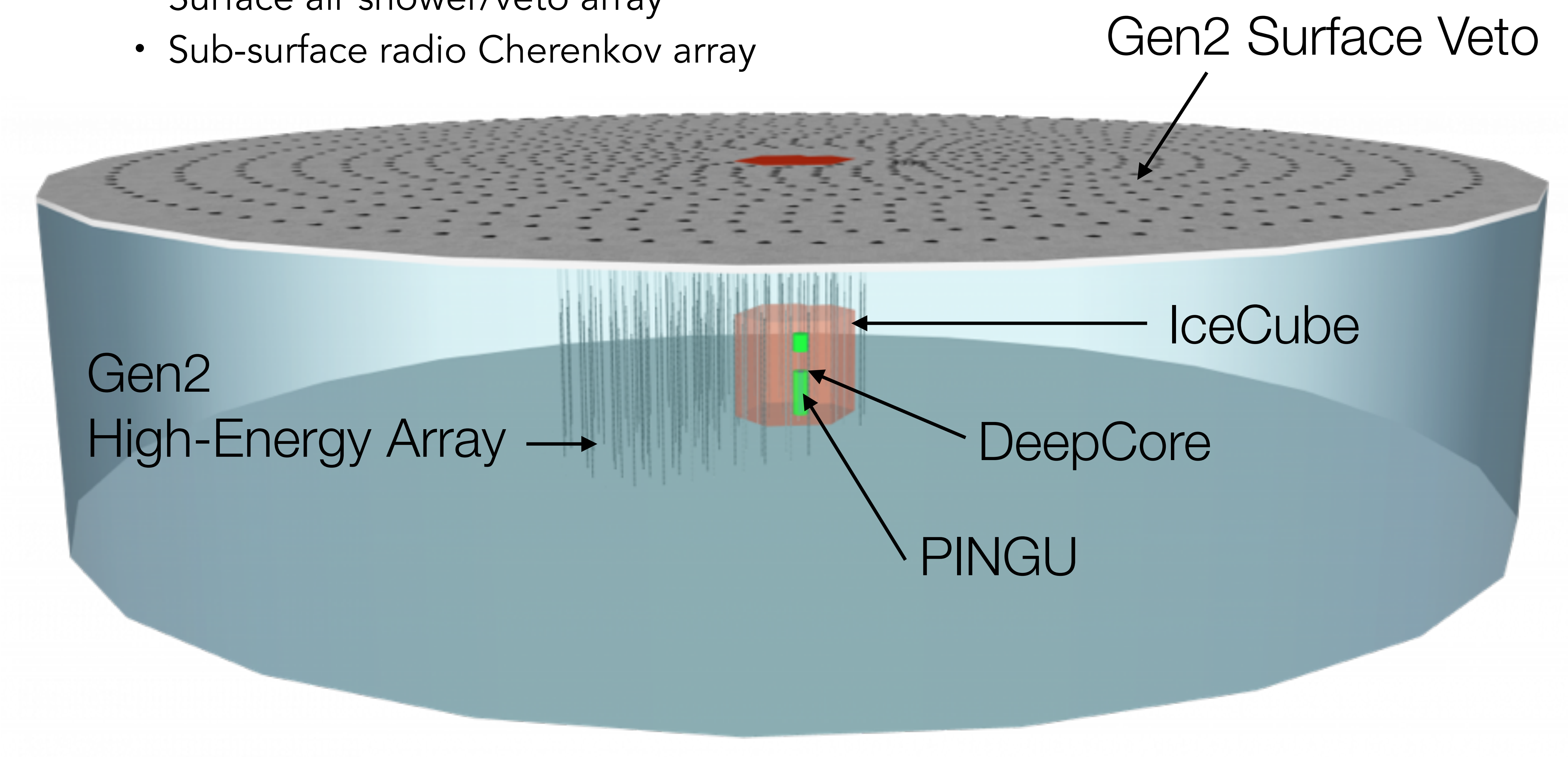
- Strong constraints on θ_{24} for Δm^2 around 0.1–2 eV^2
  - θ_{14} and θ_{34} assumed to be zero
  - Exclude parameter space favored by appearance experiments



ICECUBE GEN2

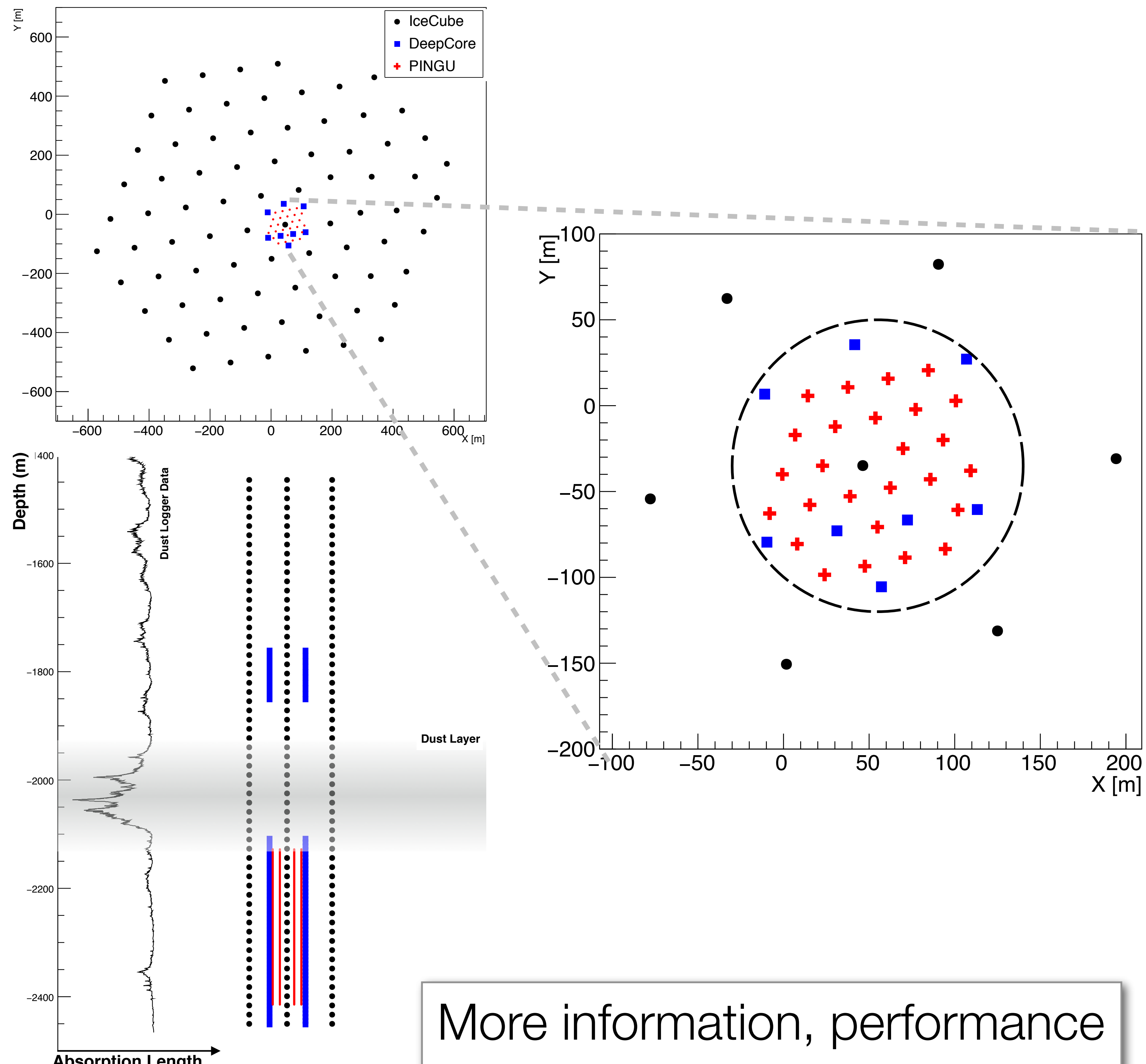
A neutrino facility addressing a wide range of scientific topics spanning GeV-EeV energies

- Gen2 high energy array
- PINGU low energy extension
- Surface air shower/veto array
- Sub-surface radio Cherenkov array



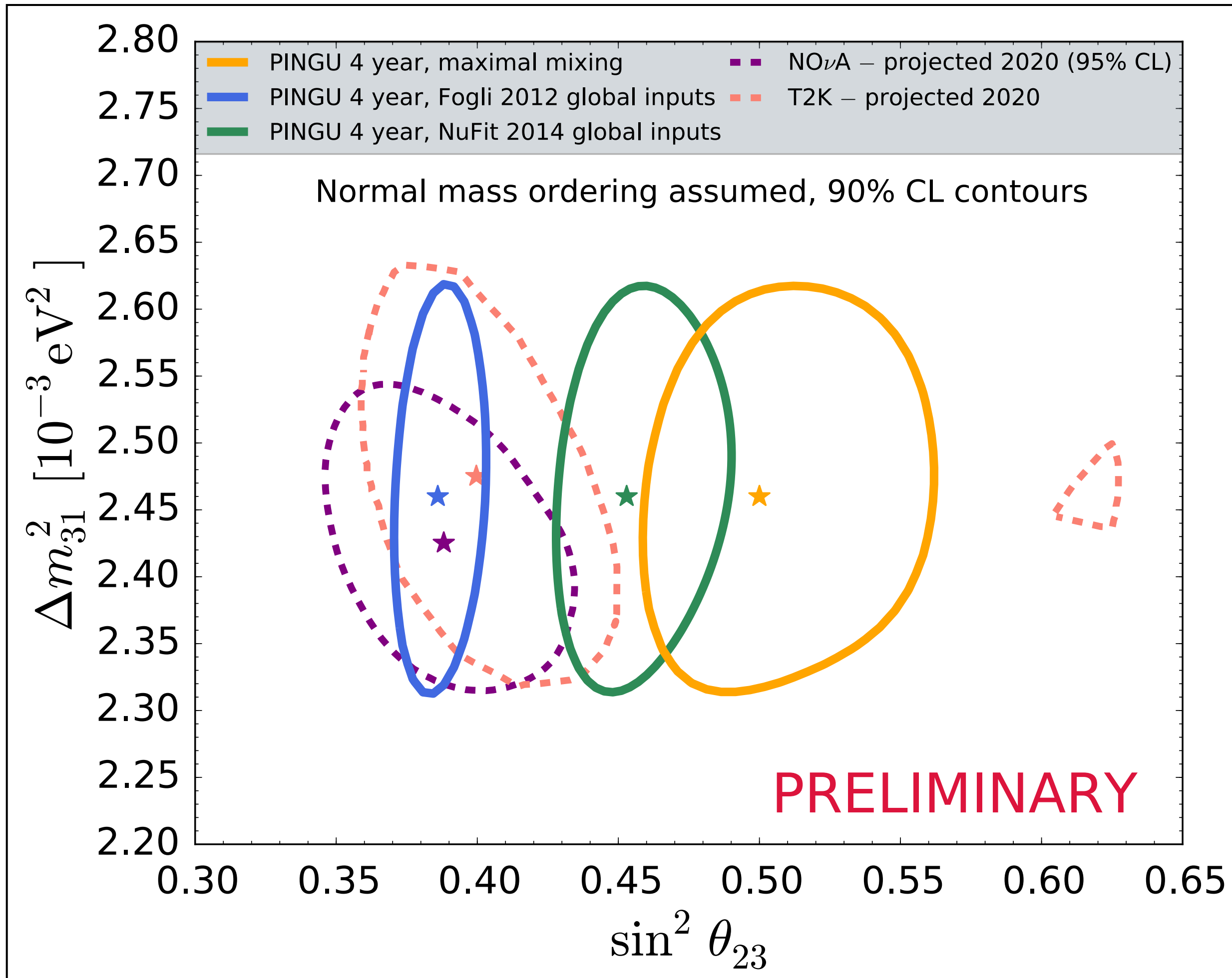
PINGU

- 26 additional, very densely instrumented strings embedded in DeepCore
  - Additional calibration devices to better control detector systematics
- 6 MTon fiducial volume with few GeV energy threshold



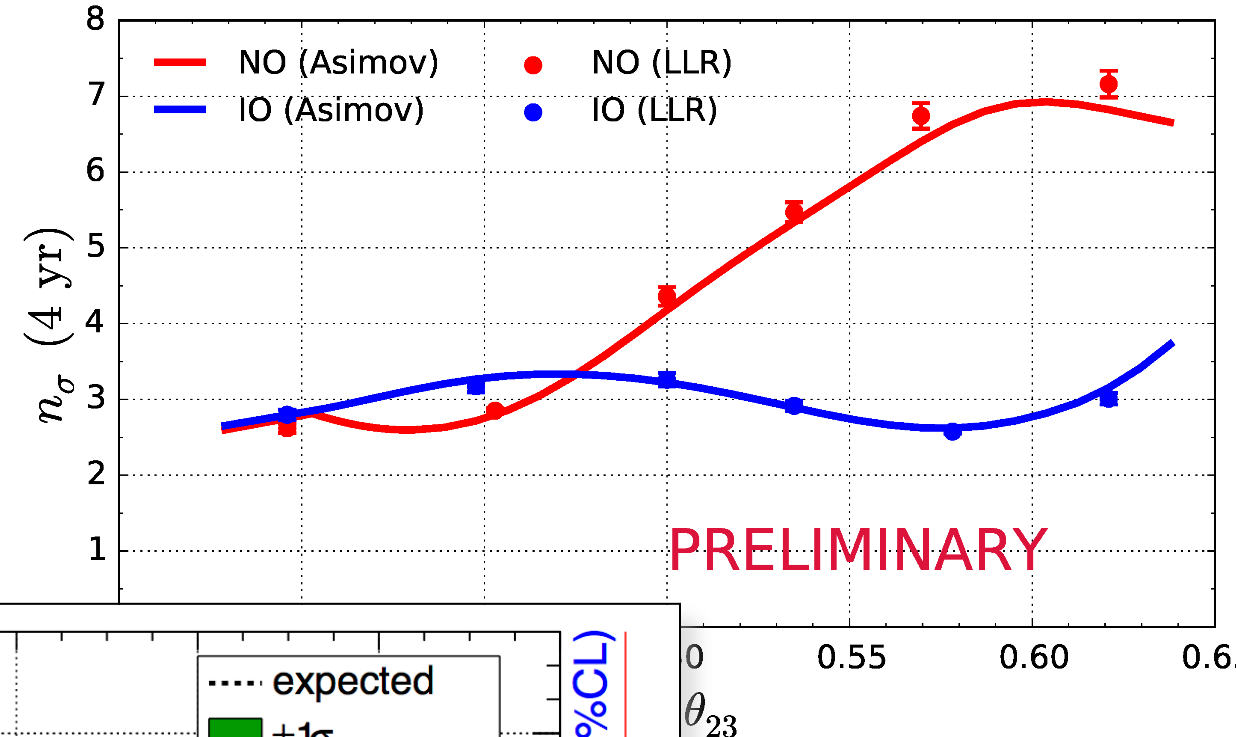
More information, performance estimates in updated Letter of Intent, arXiv:1607.02671

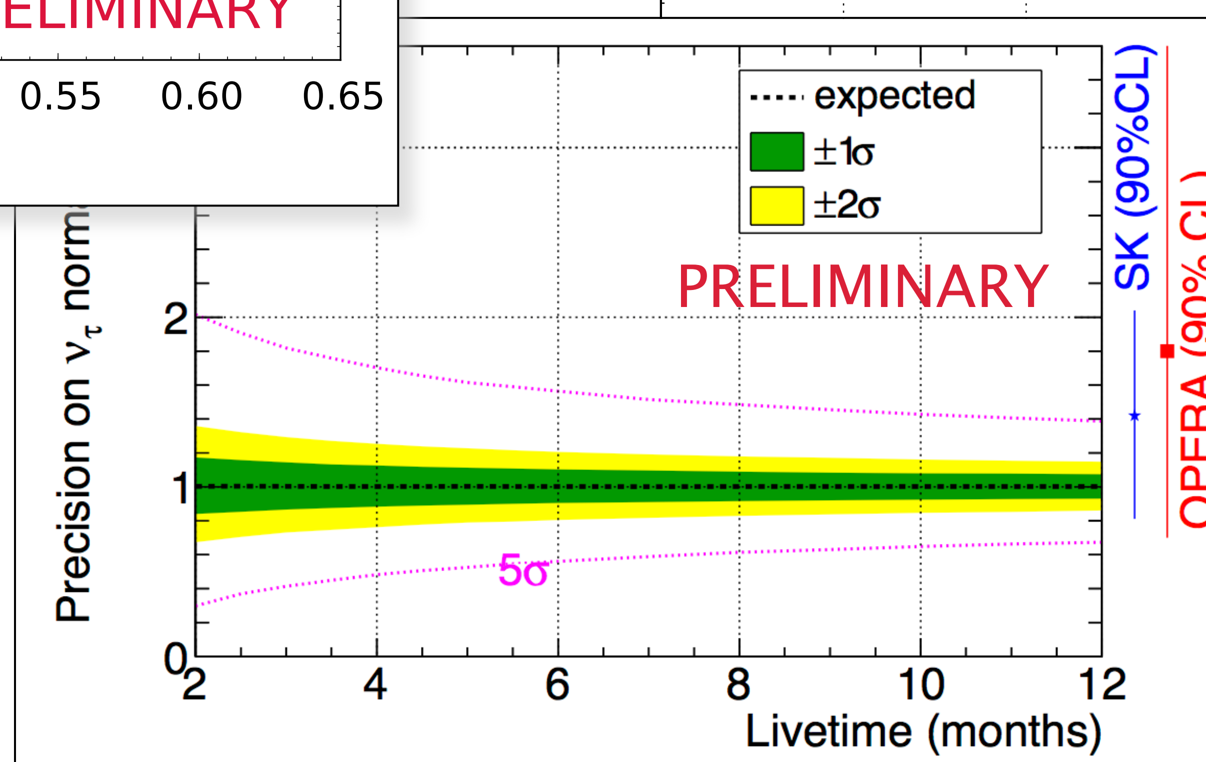
Neutrino Physics with PINGU



Measurement of mixing parameters with different method/energy range – Excellent sensitivity to octant of θ_{23}

Determination of the neutrino mass ordering





Precision measurement of ν_τ appearance – probe unitarity of PMNS matrix

Summary and Outlook

- IceCube has established the existence of a flux of high energy astrophysical neutrinos with observations in multiple channels
  - Some evidence that the flux may be more complex than an isotropic, equal-flavor power law spectrum
  - Identity of the sources elusive, some candidates ruled out, multi-messenger observations
  - Similar energies in ν, γ, extragalactic CR fluxes – gives important constraints on origins
  - No observation of cosmogenic (BZ) neutrinos yet
- IceCube is also sensitive to a range of neutrino and BSM physics
  - Neutrino oscillations, sterile neutrinos, dark matter, Lorentz violation, monopoles, etc.
- Planning underway for IceCube-Gen2: accelerate progress toward understanding astrophysical neutrinos, rich neutrino physics and dark matter program with PINGU

The IceCube-Gen2 Collaboration

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)