Highlights from the IceCube Neutrino Observatory

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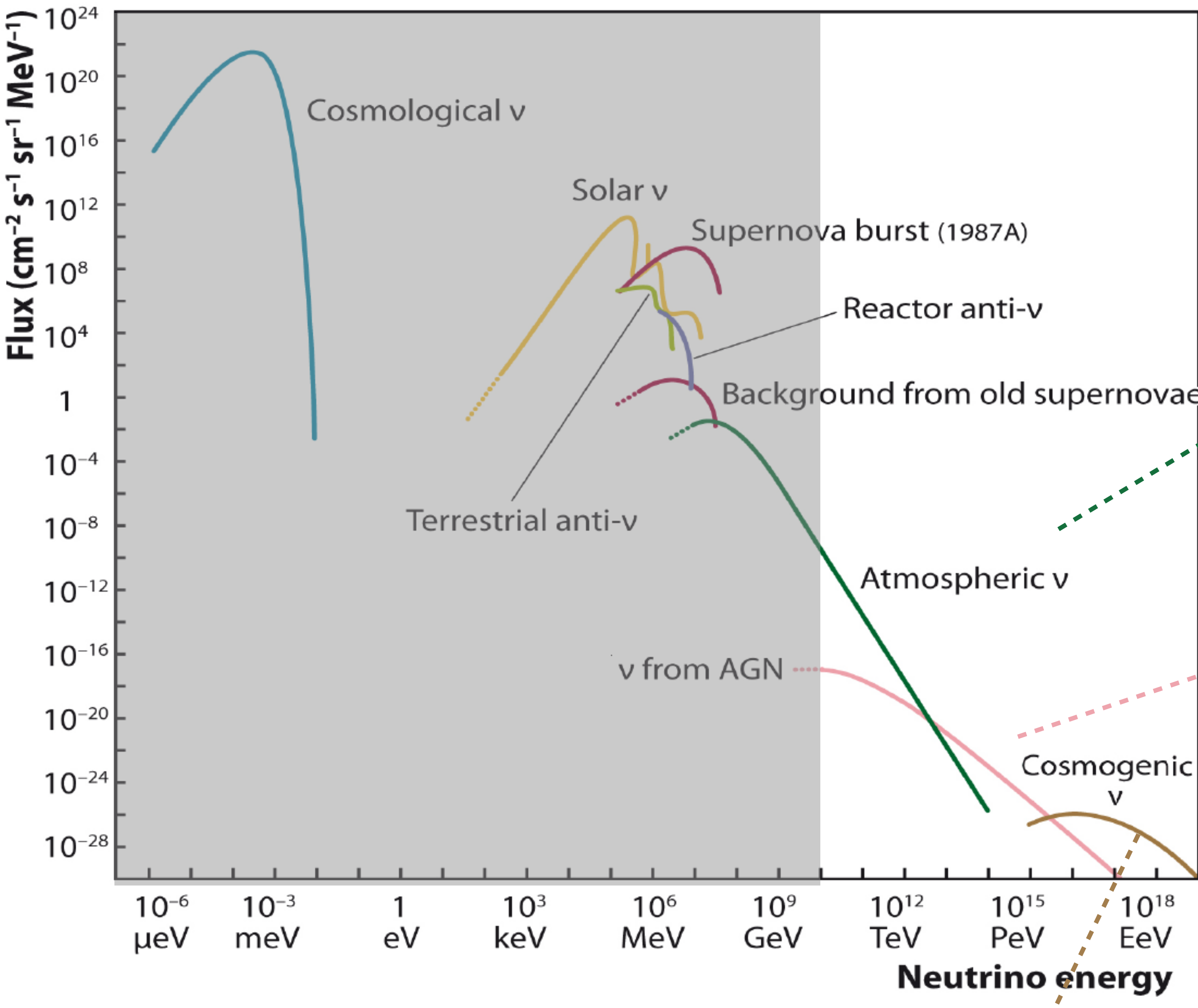
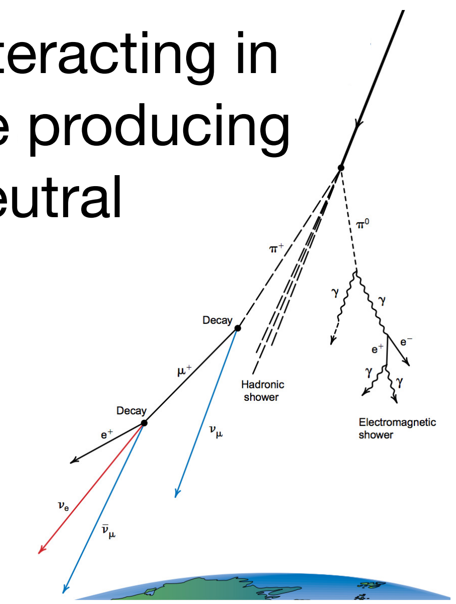
The Particle Frontier
Aspen Center for Physics
March 2018

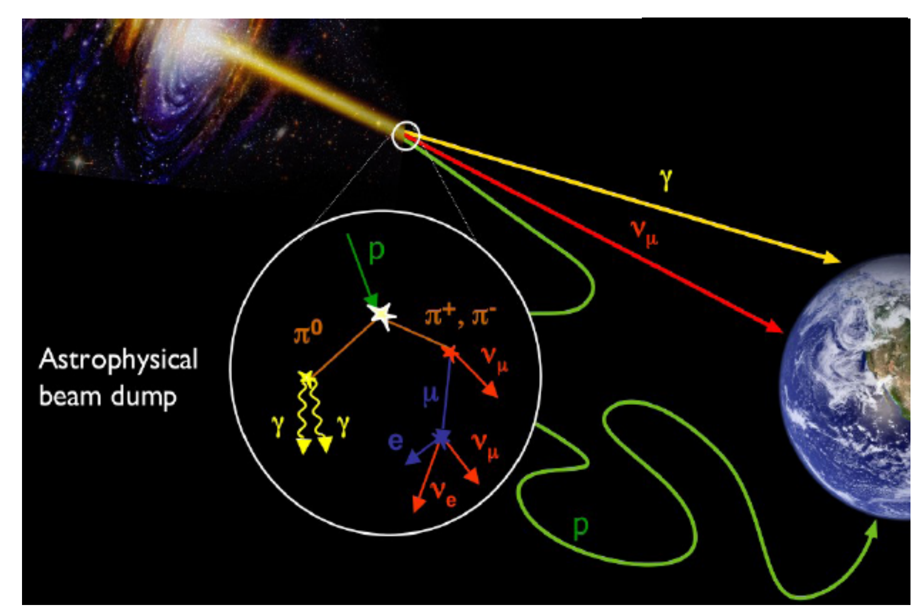
ICECUBE

Neutrino Spectrum



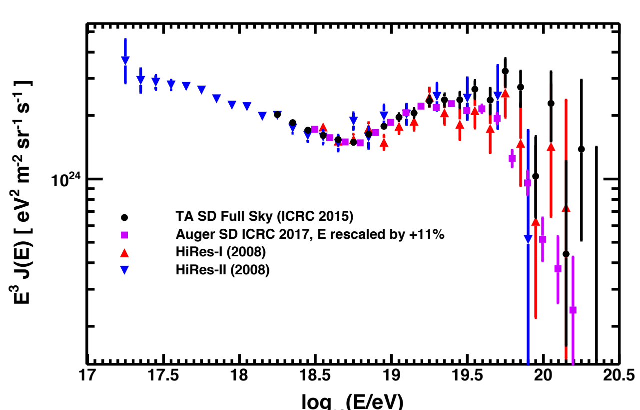
Cosmic rays interacting in the atmosphere producing charged and neutral mesons



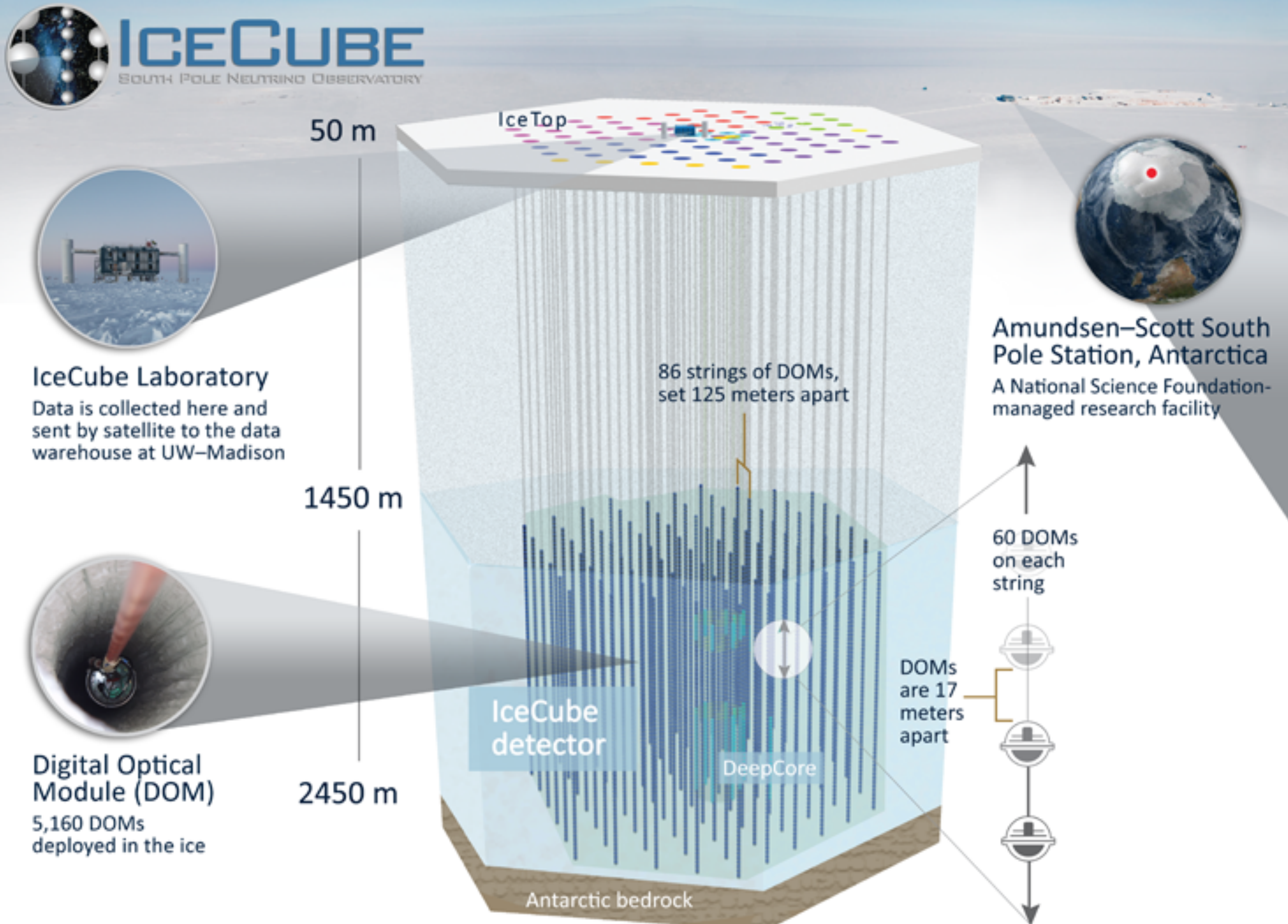


Astrophysical beam dumps

high-energy cosmic rays interacting with gas or radiation

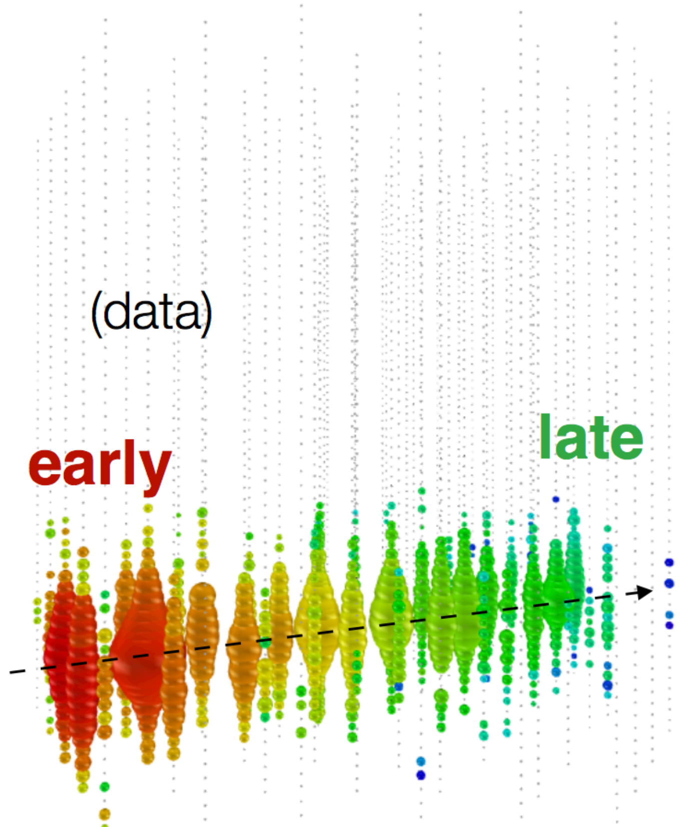


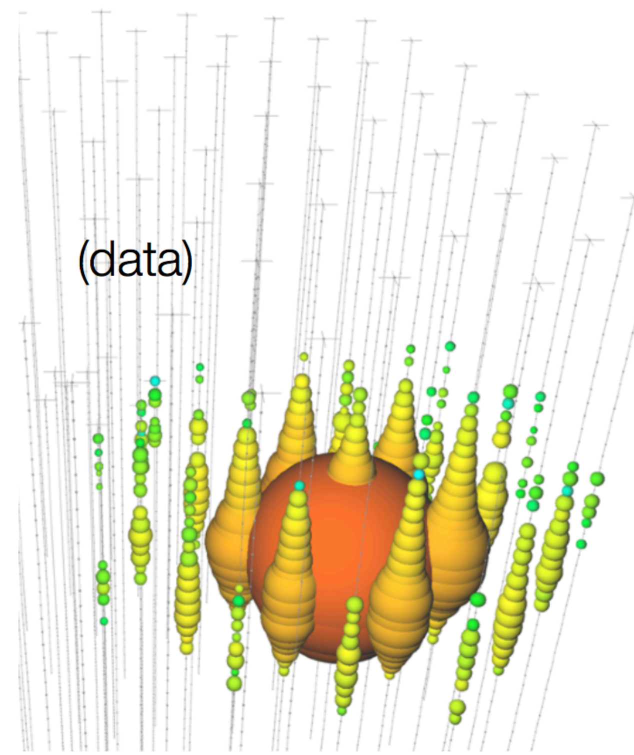
Ultra high-energy cosmic rays interacting with the Cosmic Microwave Background


IceCube
South Pole Neutrino Observatory
IceTop
50 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
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

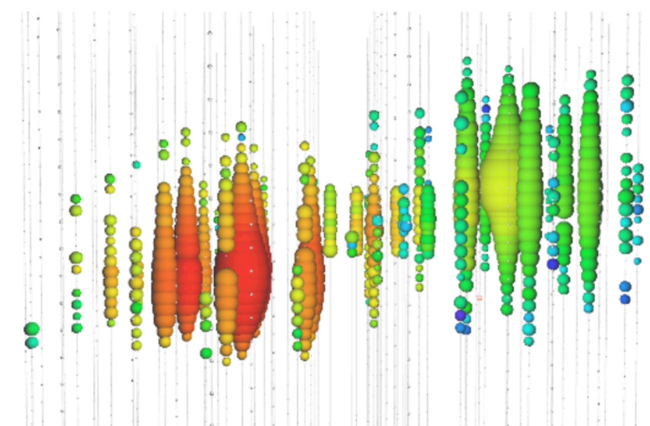
Event Signatures

Charged-current ν_μ	Neutral-current / ν_e	Charged-current ν_τ



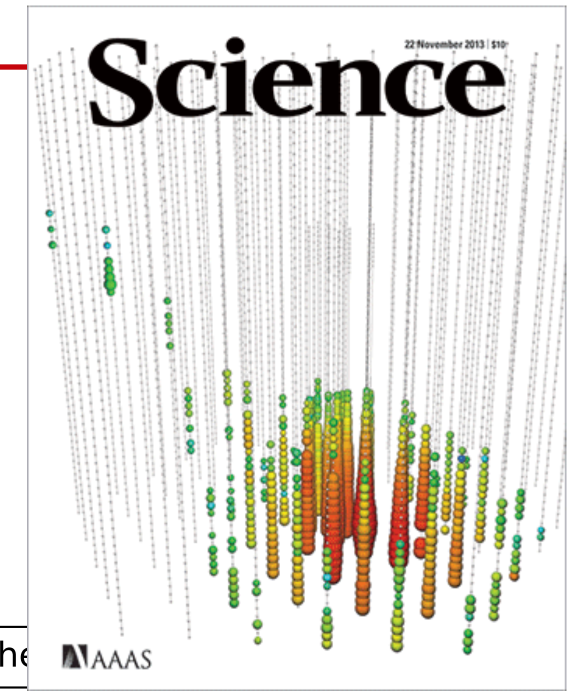


(simulation)

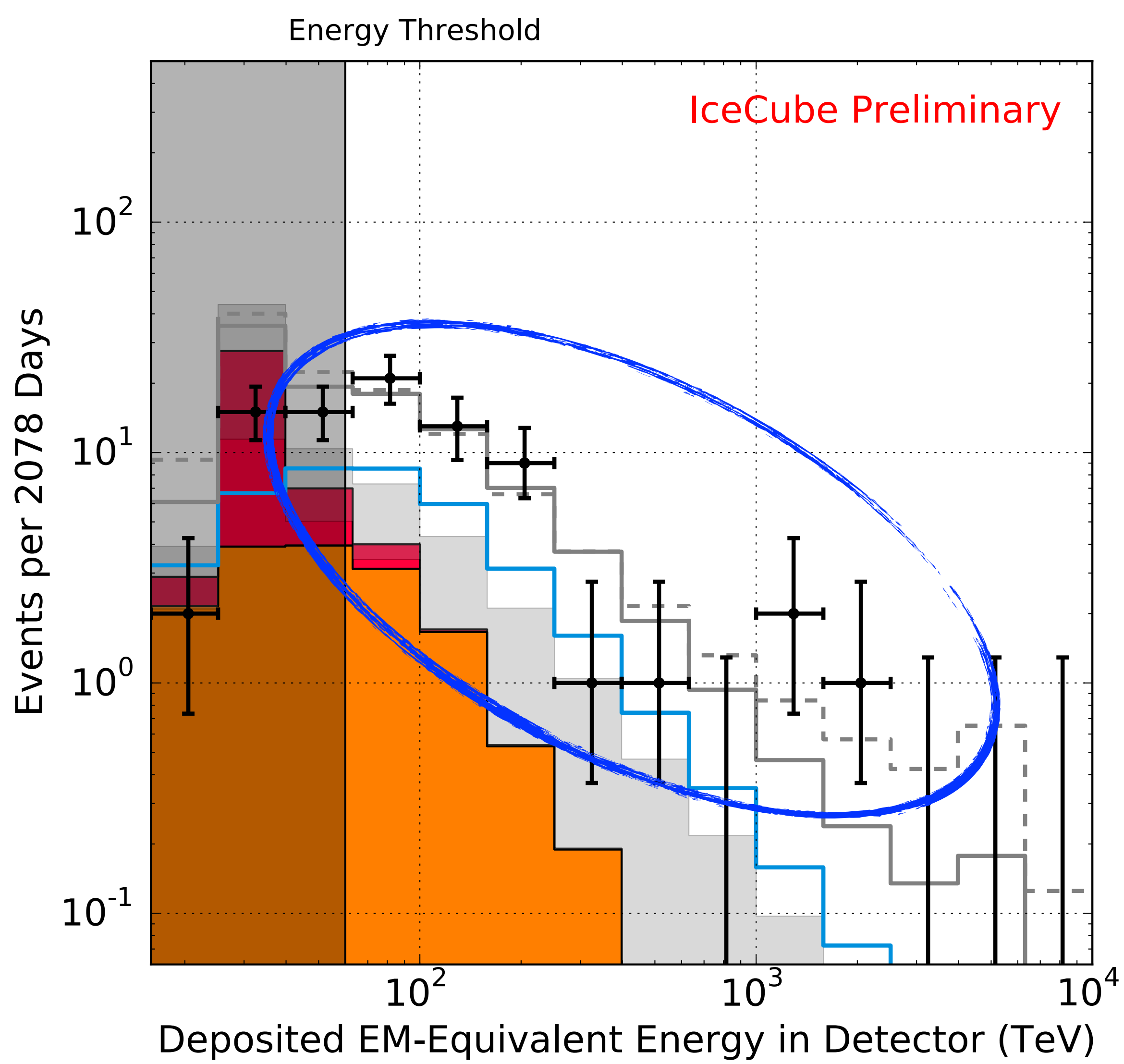


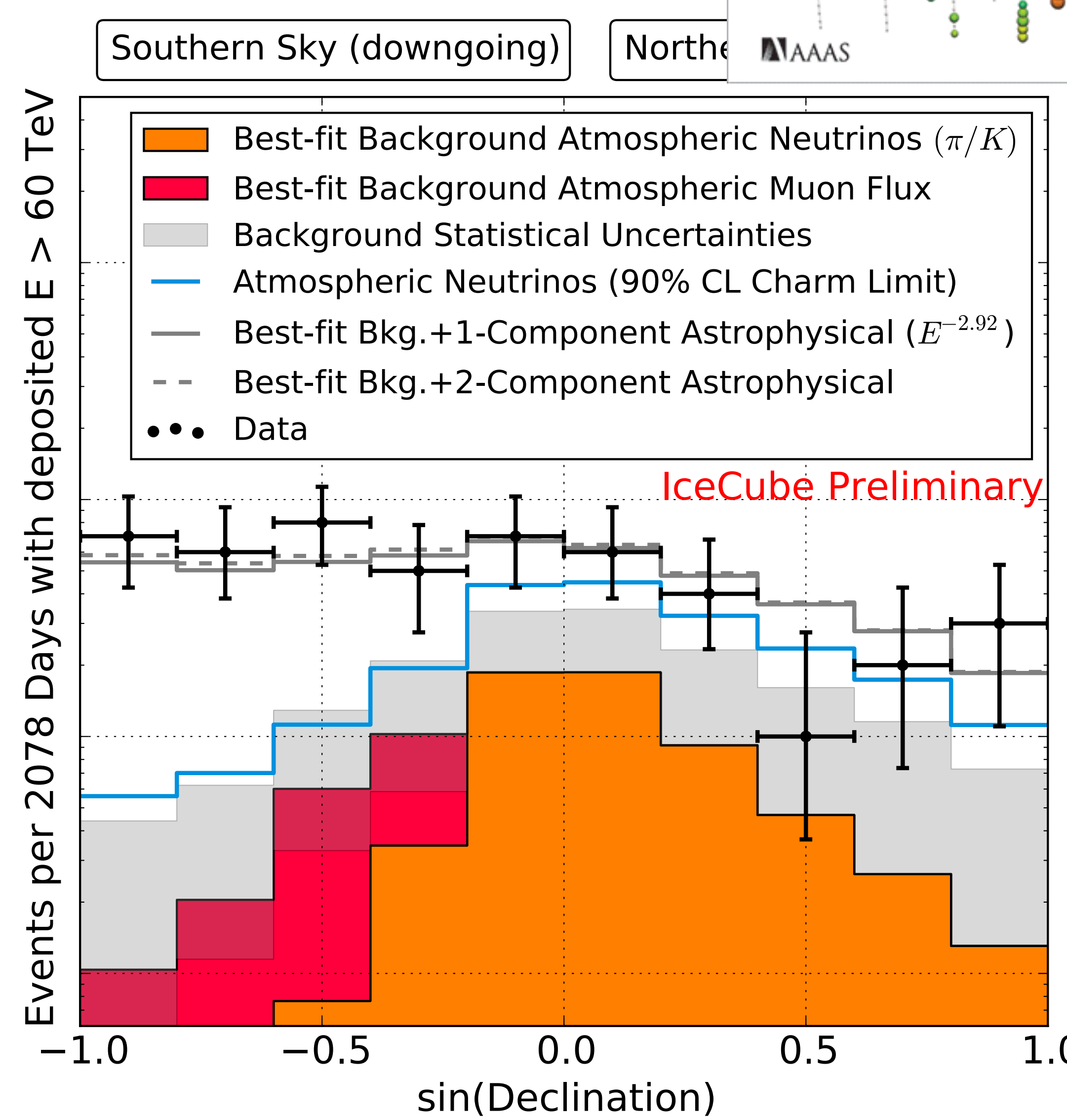
Up-going track	Isolated energy deposition (cascade) with no track	Double cascade
Factor of ~2 energy resolution ~0.5 degree angular resolution	15% deposited energy resolution 10 degree angular resolution (above 100 TeV)	(resolvable above ~100 TeV deposited energy)

Observation of High-Energy cosmic neutrinos



- **Discovery** of astrophysical neutrinos announced in 2013.
- Observation of **excess** over atmospheric background.
- 28 events with 2 PeV neutrinos in the first 2 years.
- **82** events in 6 years.



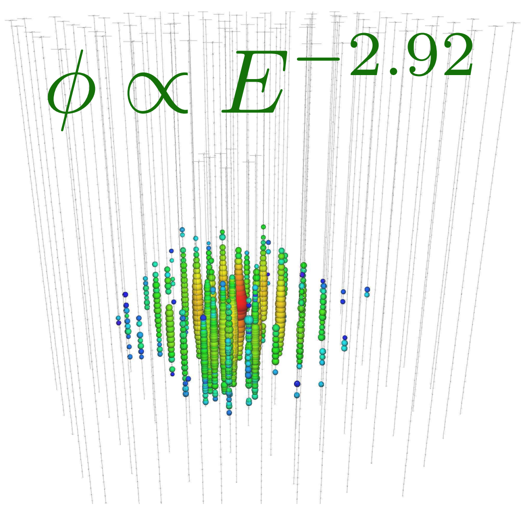


High-Energy Cosmic Neutrinos

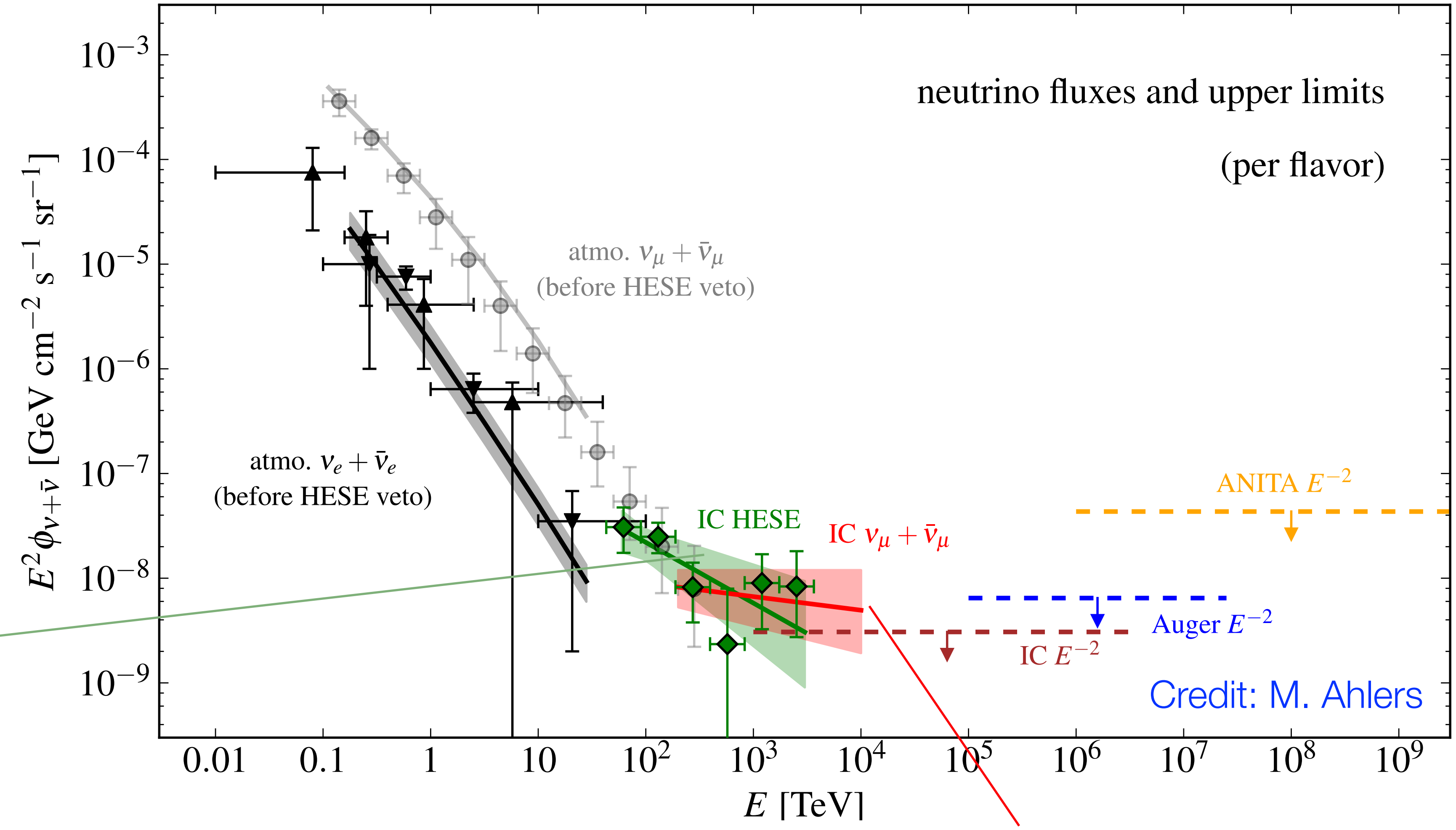
High-Energy Starting Events

6 years Observation ➛ 8σ

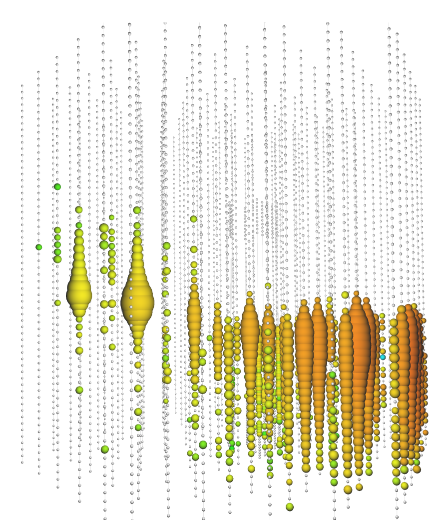
80 events (all flavor)



$\phi \propto E^{-2.92}$



- Observation confirmed in independent channels.
- Hardening of the spectrum at high energies.
- Low-energy excess hinting at spectral features.
- fluxes are compatible in the common energy range



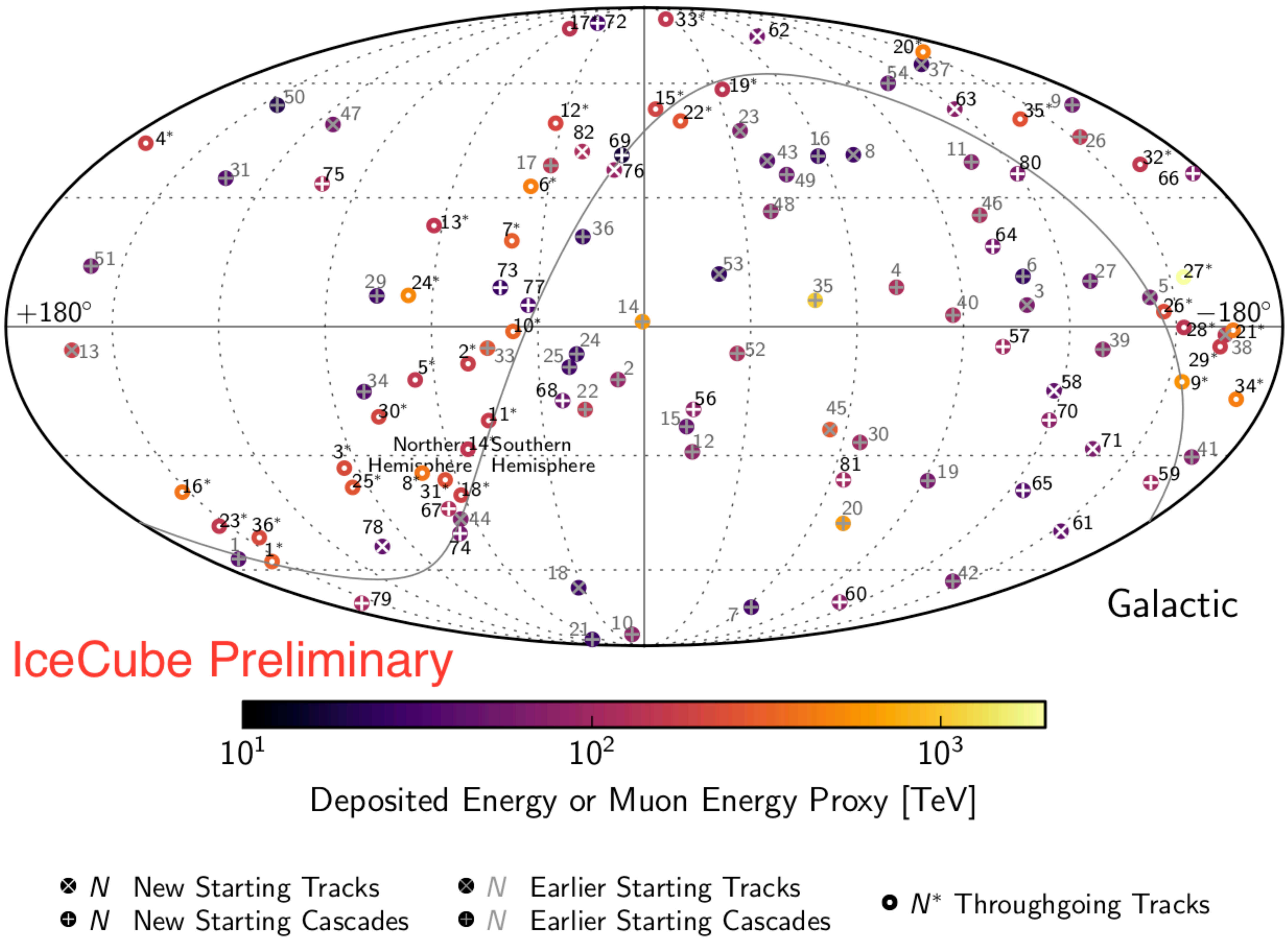
Up-going Muon Tracks

8 years Observation ➛ 6.7σ

~ 500 astrophysical neutrinos

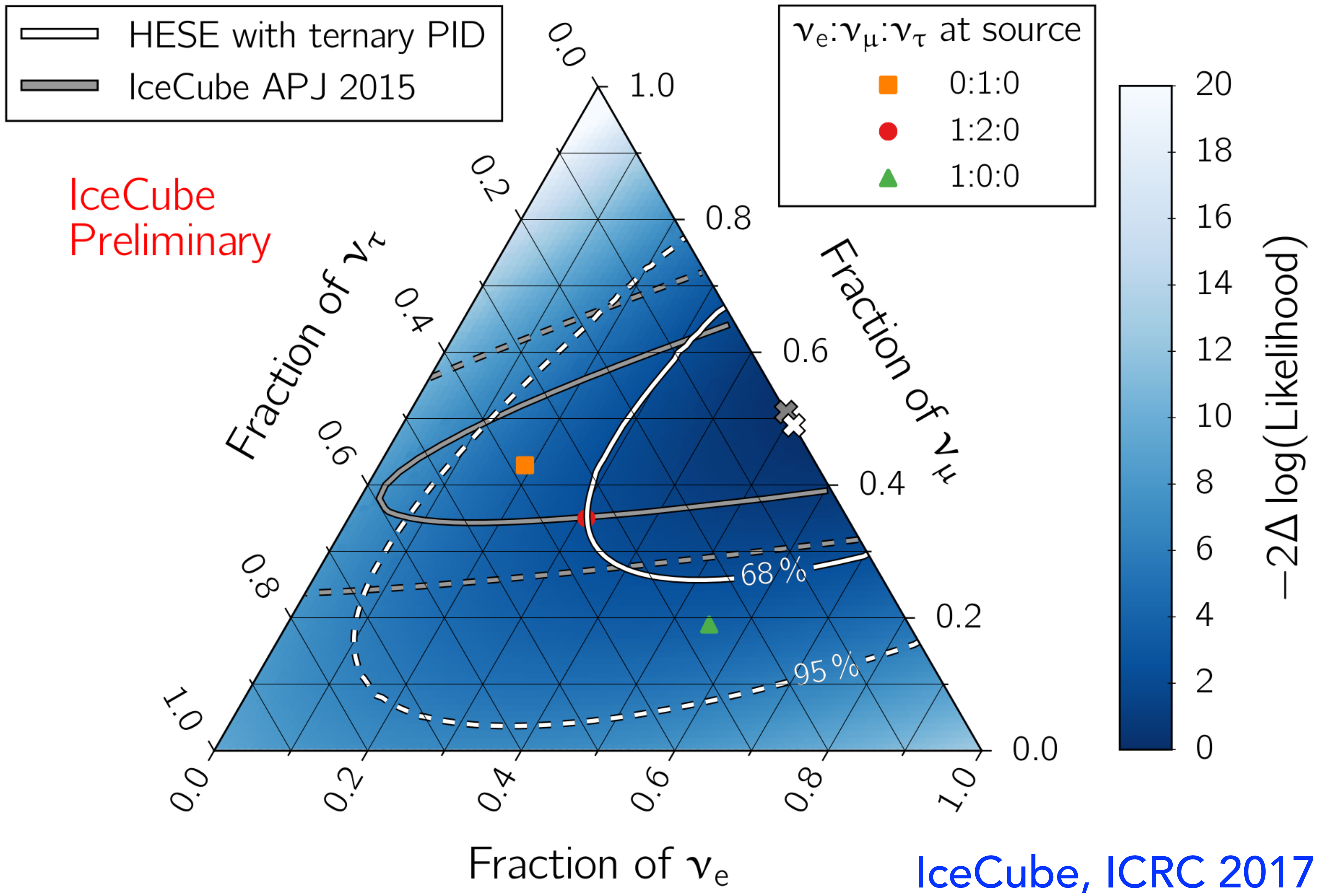
$\phi \propto E^{-2.19}$

Arrival Directions



Flavor Composition

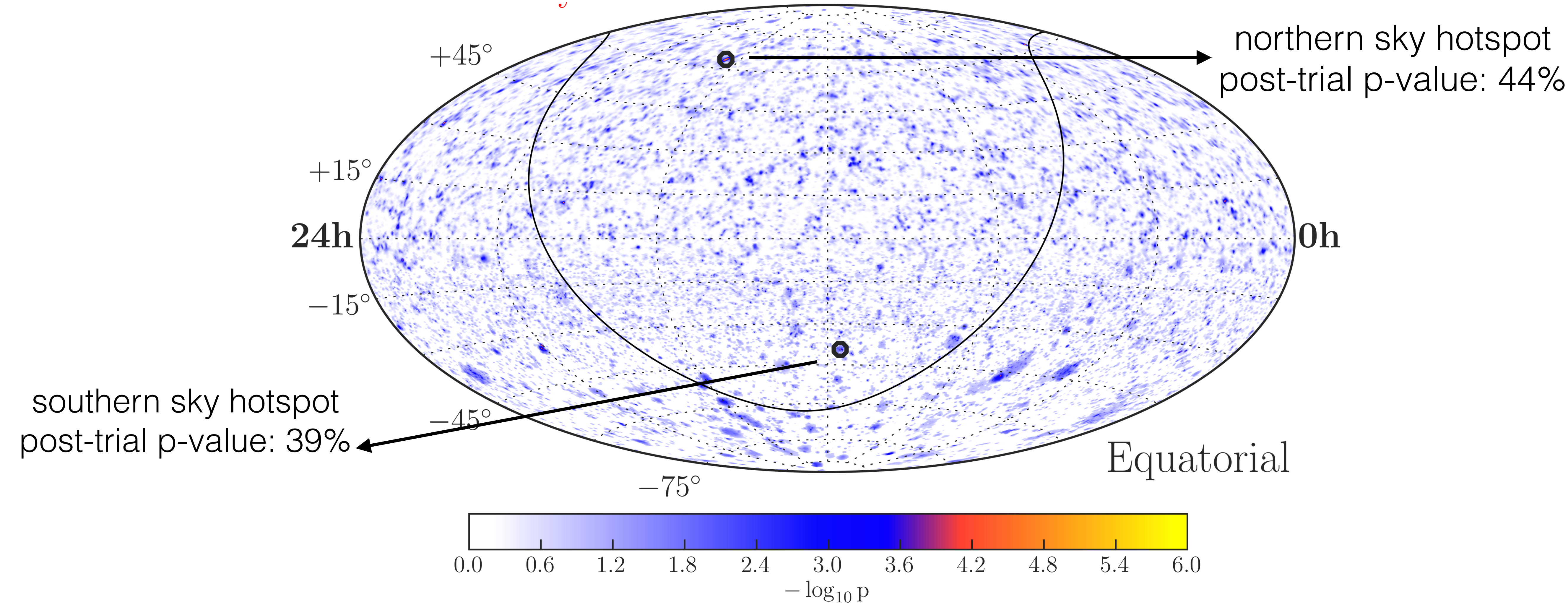
Flavor composition depends on the production scenario at the source.



IceCube, ICRC 2017

Flavor composition compatible with equal proportion of each flavor.

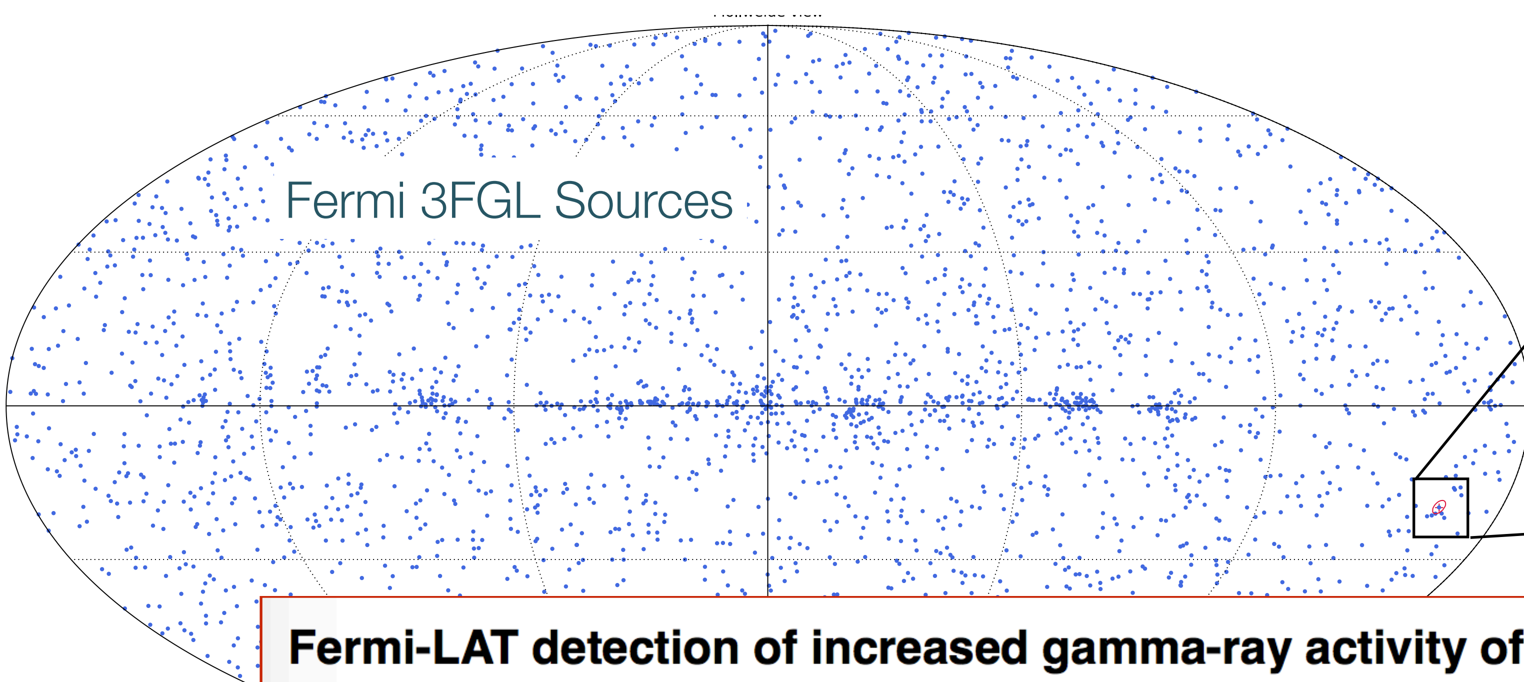
Origin of the cosmic neutrinos?

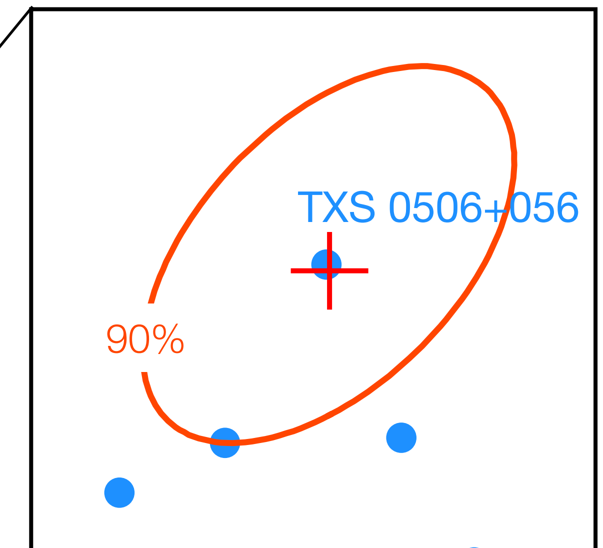


- IceCube searches for **steady** and **time dependent** neutrino emission point sources, extended sources, and catalog of sources.
- **No source class** confirmed as main origin of HE cosmic neutrinos.
- **Galactic** contribution is constrained to 15% of the total flux.
- Time dependent analyses benefit from lower backgrounds.
- **Realtime analysis** and follow-up studies offer unique opportunities to find sources.

IC 170922A

- IceCube issued an alert on September 22, 2017.
- Follow up observations by ANTARES, H.E.S.S. , **Fermi-LAT**, **Swift**, AGILE, **MAGIC**, HAWC, VERITAS and …



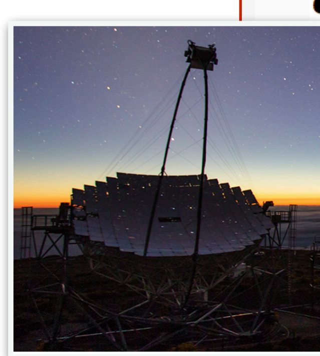


Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2
Credential Certification: David J. Th

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

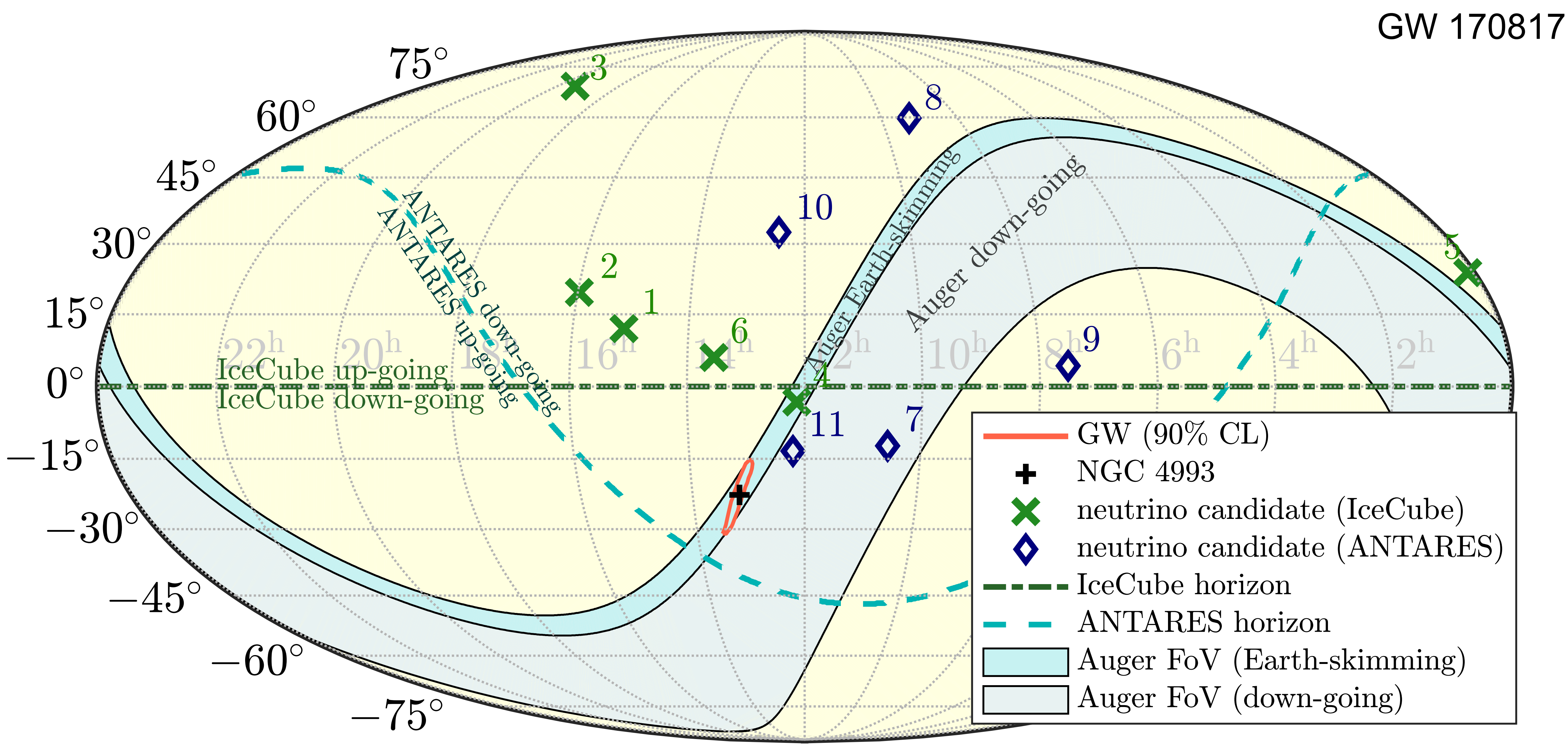
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)



- details coming soon!

Gravitational Waves follow-up

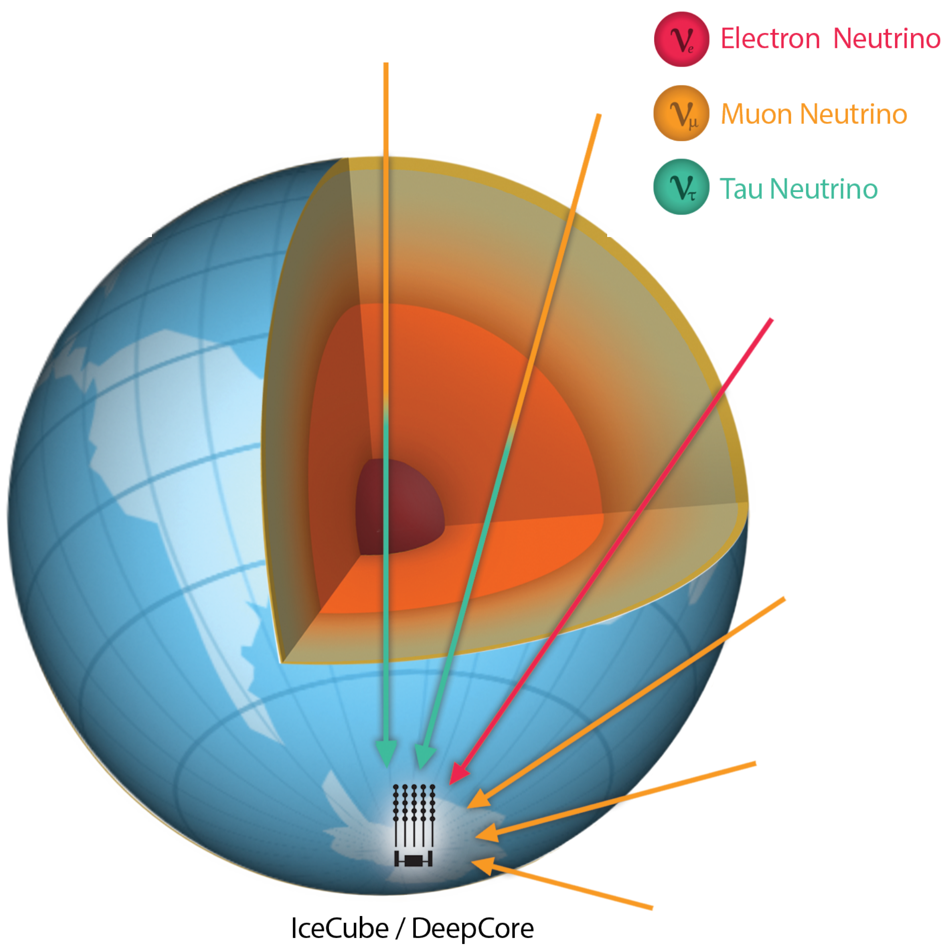
Binary Neutron Star Merger



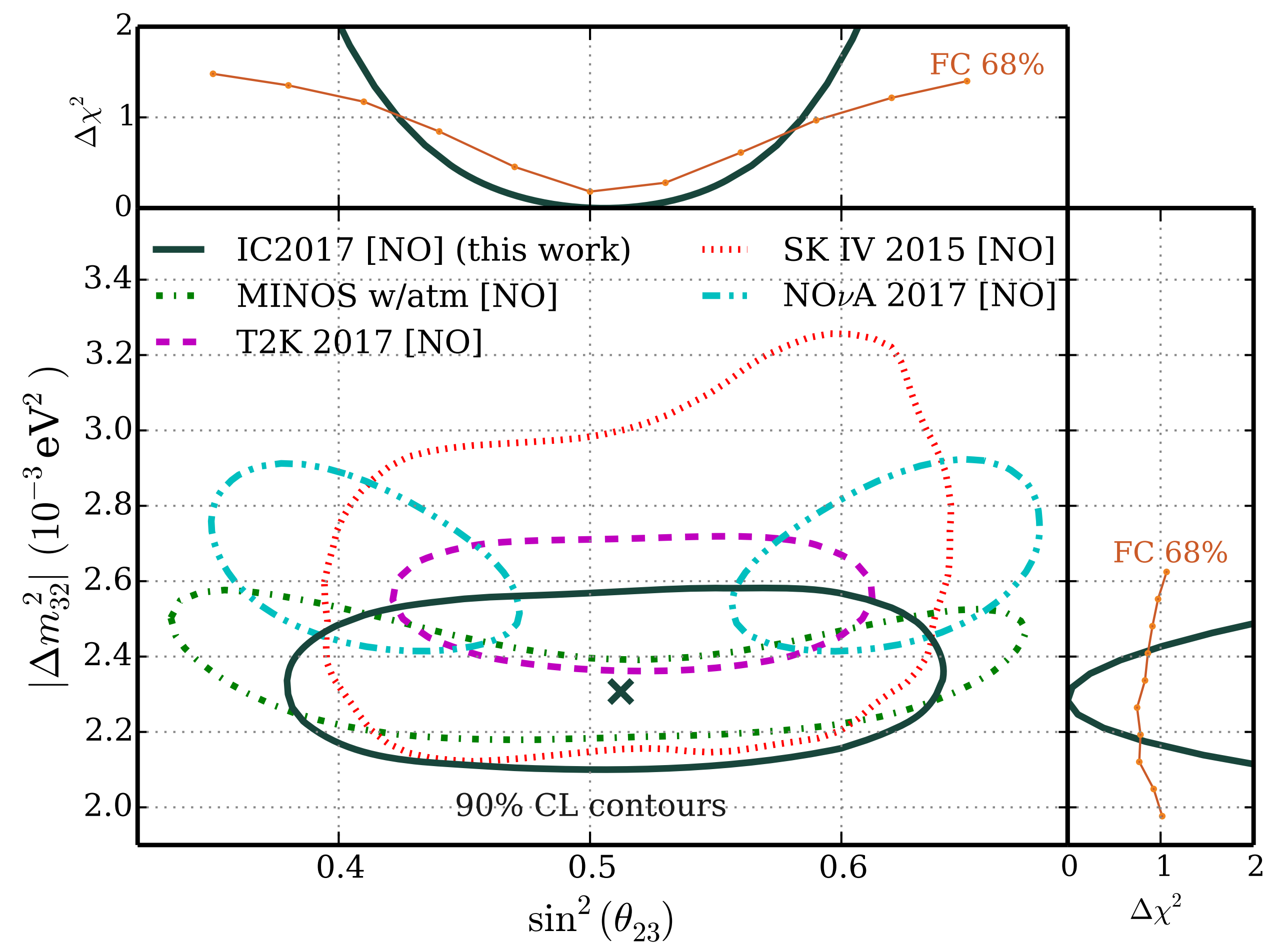
No coincident neutrino!

ANTARES, IceCube, Auger, LIGO/Virgo ApJL 850:L35 (2017)

Neutrino Oscillation



IceCube, PRL 2018



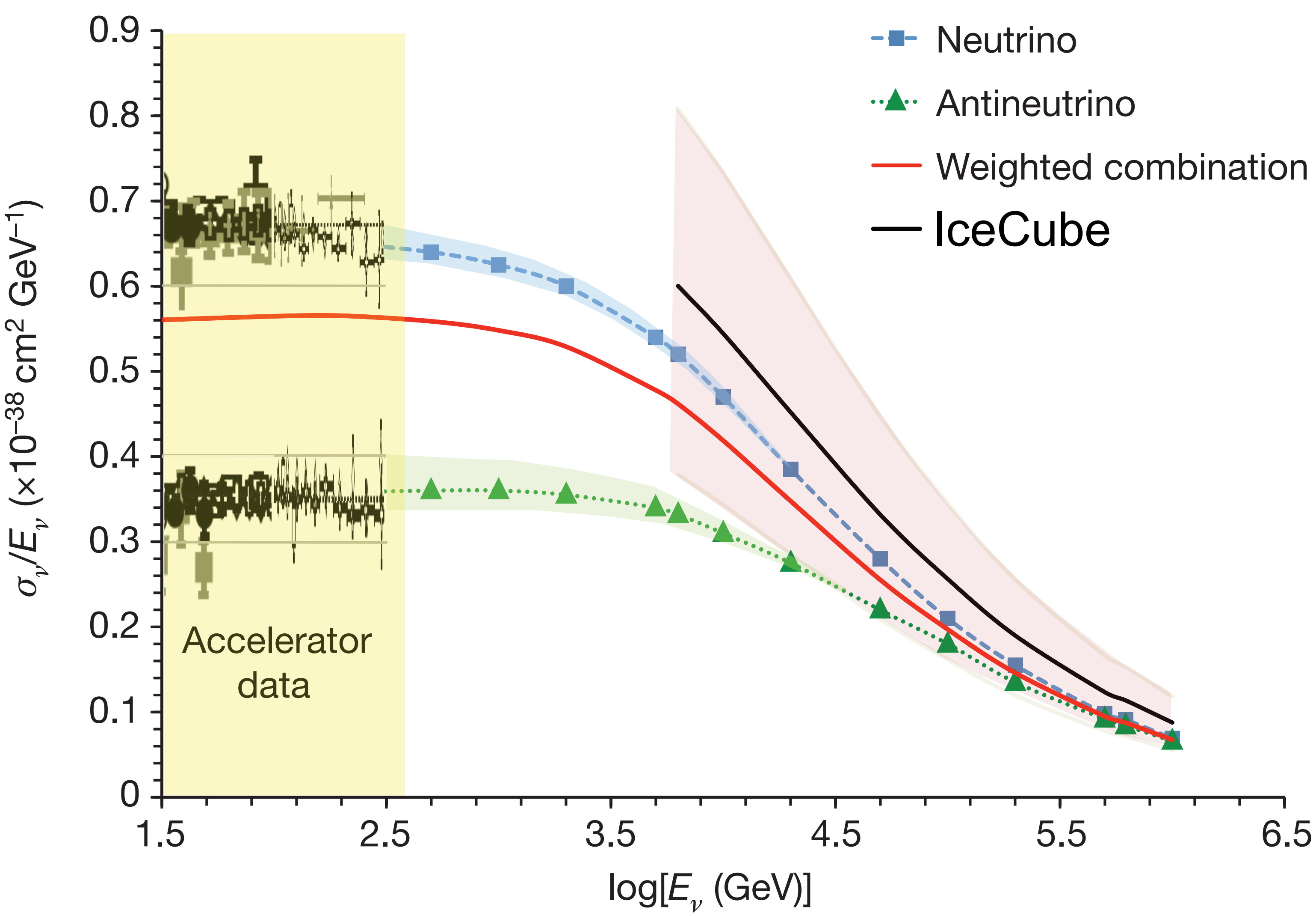
- 3 years of IceCube **Deep Core** data
- measurements of **muon neutrino disappearance**, over a range of baselines up to the diameter of the Earth
- Neutrinos from the full sky with reconstructed energies from 5.6 to 56 GeV

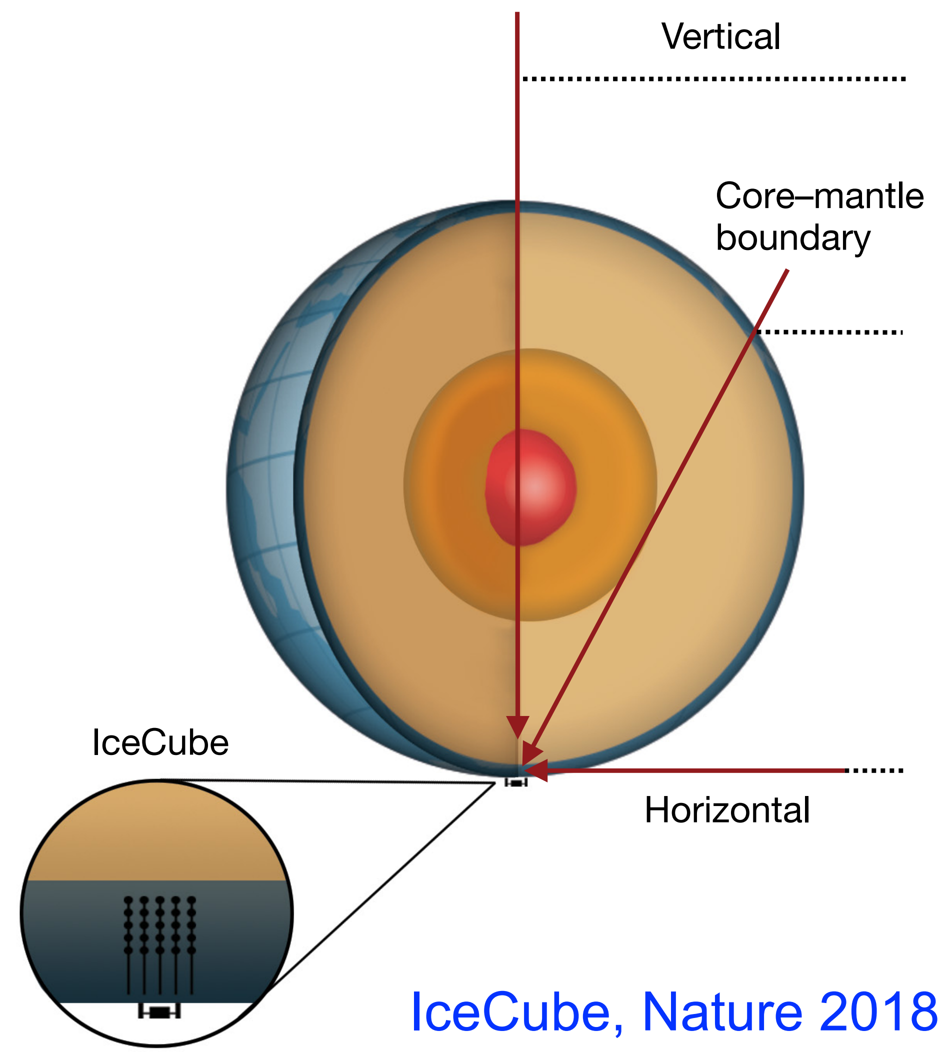
Normal Ordering best fits:

$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\text{eV}^2$$

$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$

Neutrino-Nucleus Cross Section





IceCube, Nature 2018

- **Absorption of neutrinos** in the earth a powerful tool to measure neutrino-nucleus cross section
- > 10000 high-energy muon neutrinos used in this analysis
- measuring the cross section between 6.3-980 TeV
- More than an order of magnitude higher than previous measurements

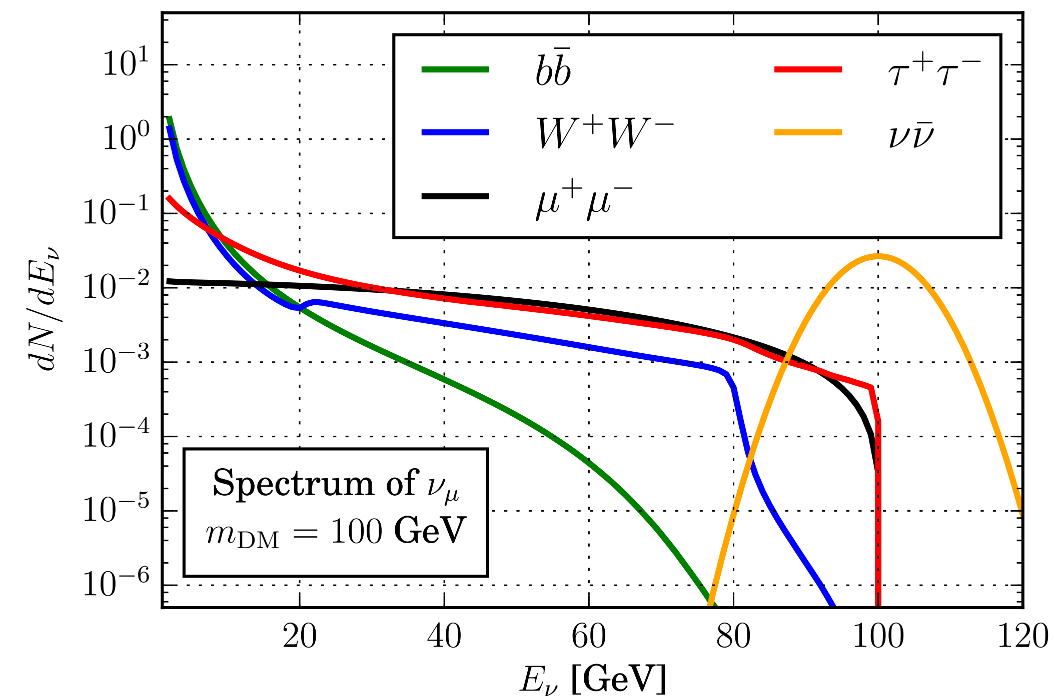
Indirect Dark Matter Search

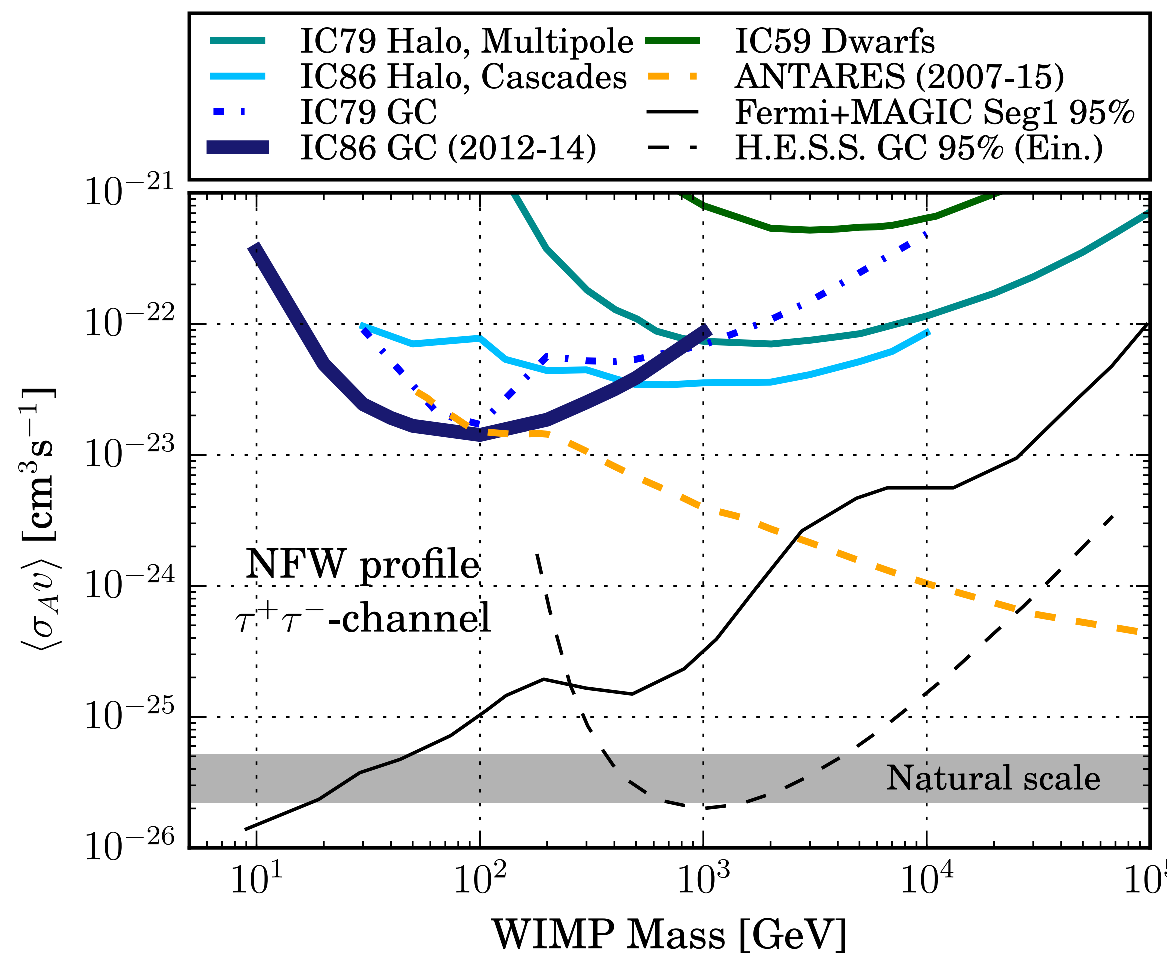
Annihilation in the Milky Way

$$\frac{d\Phi}{dE}(\Delta\Omega) = \frac{\langle\sigma_{\mathrm{A}} v\rangle}{4\pi \cdot 2m_{\mathrm{DM}}^2}\frac{dN}{dE}\int_{\mathrm{los}} \rho^2(r(l,\Delta\Omega))dl$$

- 3 years of data
- Galactic Center only accessible in down-going muons.
- Limiting dark matter mass between 10 GeV-1 TeV.
- No significant excess of neutrinos over the background of atmospheric neutrinos
- Strongest limit on the DM mass in self annihilation via tau (NSW profile)

IceCube, Eur.Phys.J. C 2017

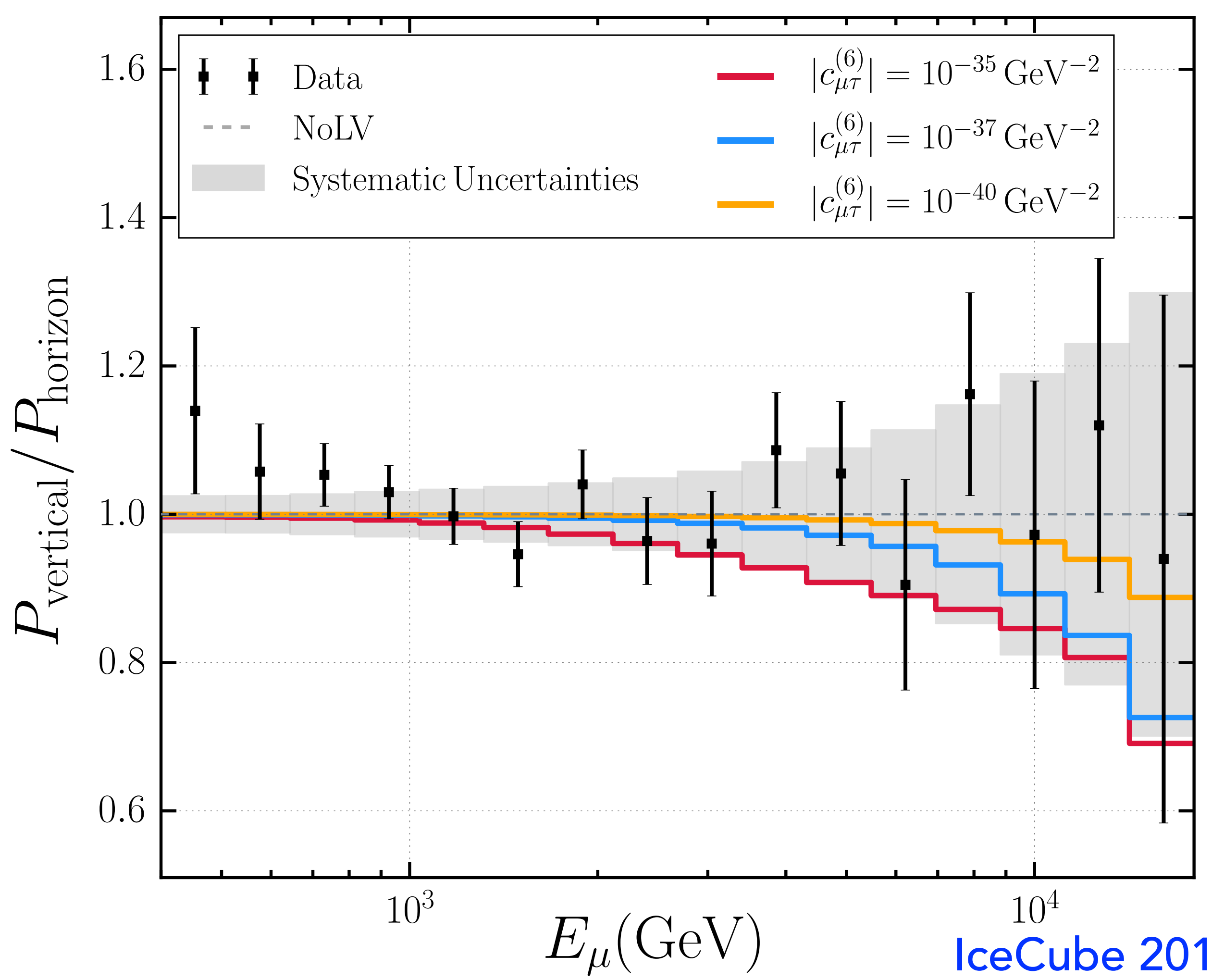


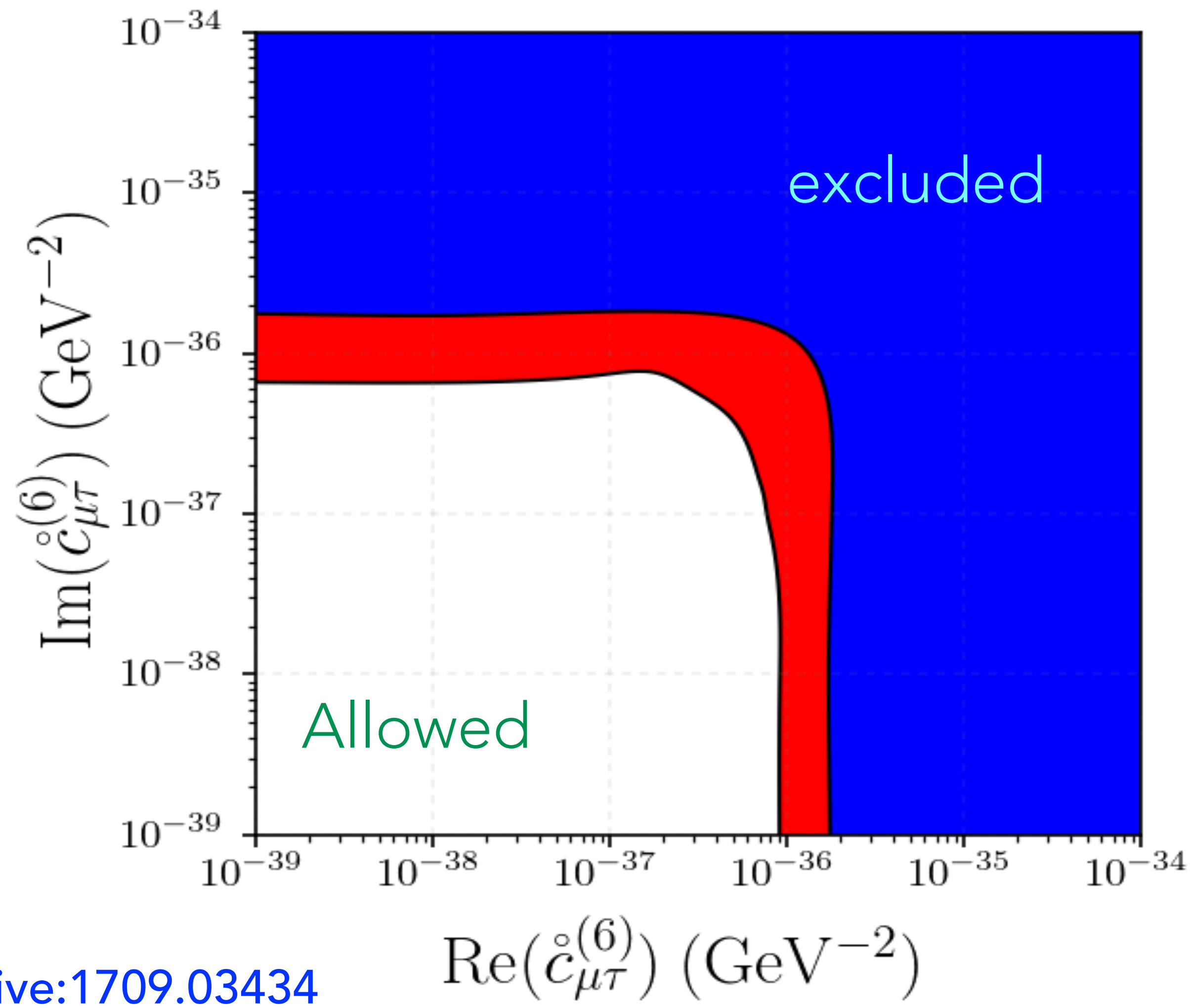


Lorentz Invariance Violation

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots \rightarrow \begin{pmatrix} \mathring{c}^{(6)}_{\mu\mu} & \mathring{c}^{(6)}_{\mu\tau} \\ \mathring{c}^{(6)*}_{\mu\tau} & -\mathring{c}^{(6)}_{\mu\mu} \end{pmatrix}$$

- **Atmospheric muon neutrinos** from northern hemisphere (400 GeV to 18 TeV)
- oscillation probability is different with **energy** and **baseline (direction)**
- Strongest bounds on SME Lorentz violating coefficients in neutrino sector

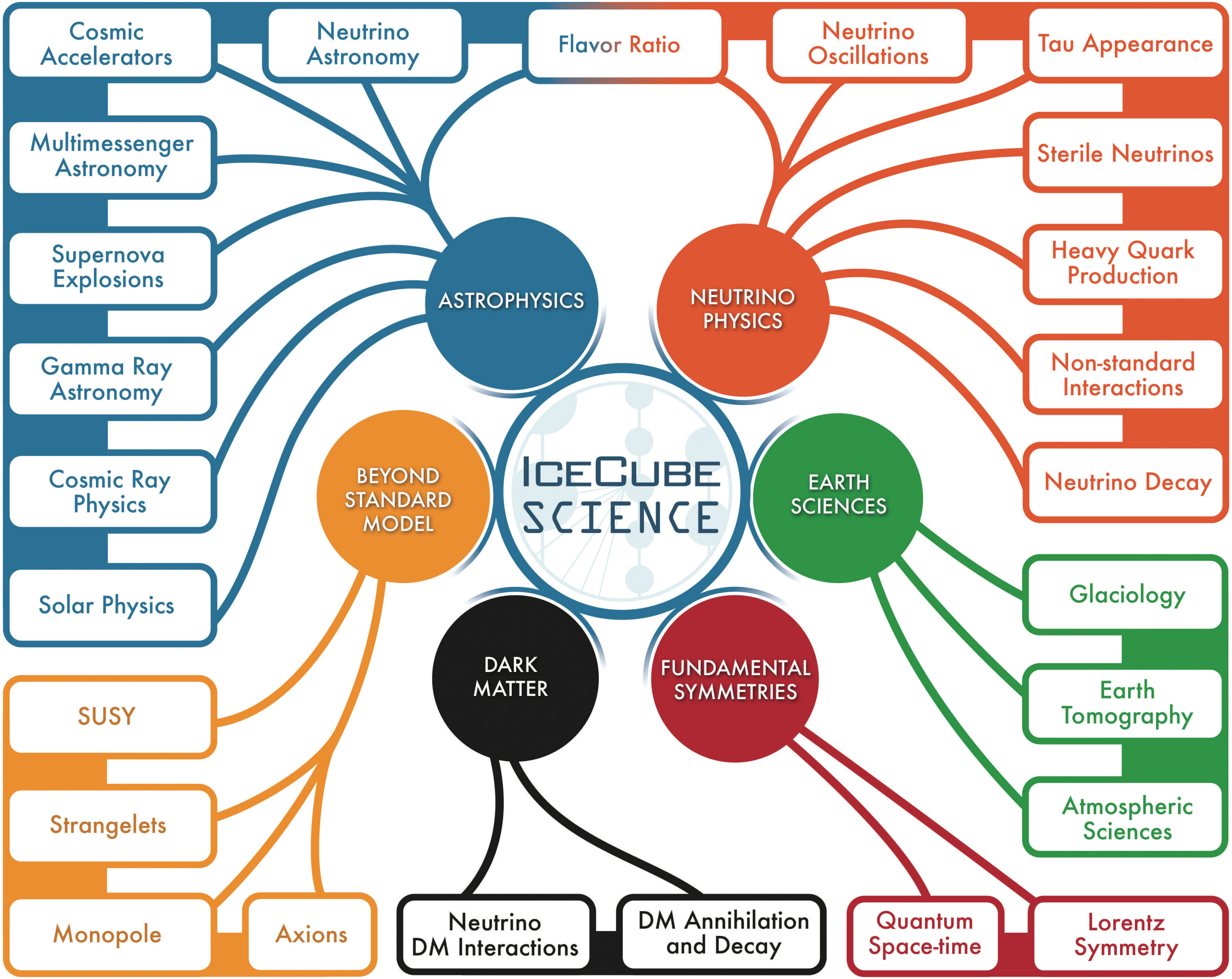




IceCube 2017, arXive:1709.03434

Summary

- IceCube has discovered and characterized a flux of high-energy astrophysical neutrinos between TeV and several PeV energies.
- The main sources of high-energy neutrinos are still unknown.
- The coincidence high-energy muon neutrino with a flaring gamma ray blazar may be the first identified high-energy neutrino source.
- Multi-messenger astrophysics with gamma rays, neutrinos, gravitational waves, and cosmic rays is now a reality and will help us to understand the high-energy Universe.
- IceCube access to high-energy regime serves as a powerful tool to study neutrino physics and physics beyond the standard model.


ICECUBE SCIENCE
ASTROPHYSICS
Cosmic Accelerators
Neutrino Astronomy
Multimessenger Astronomy
Supernova Explosions
Gamma Ray Astronomy
Cosmic Ray Physics
Solar Physics
Flavor Ratio
NEUTRINO PHYSICS
Neutrino Oscillations
Tau Appearance
Sterile Neutrinos
Heavy Quark Production
Non-standard Interactions
Neutrino Decay
EARTH SCIENCES
Glaciology
Earth Tomography
Atmospheric Sciences
FUNDAMENTAL SYMMETRIES
Quantum Space-time
Lorentz Symmetry
DARK MATTER
Neutrino DM Interactions
DM Annihilation and Decay
BEYOND STANDARD MODEL
SUSY
Strangelets
Monopole
Axions

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
Friedrich-Alexander-Universität Erlangen-Nürnberg
Humboldt–Universität zuBerlin
Ruhr-Universität Bochum
RWTH Aachen
Technische Universität Dortmund
Technische Universität München
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University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

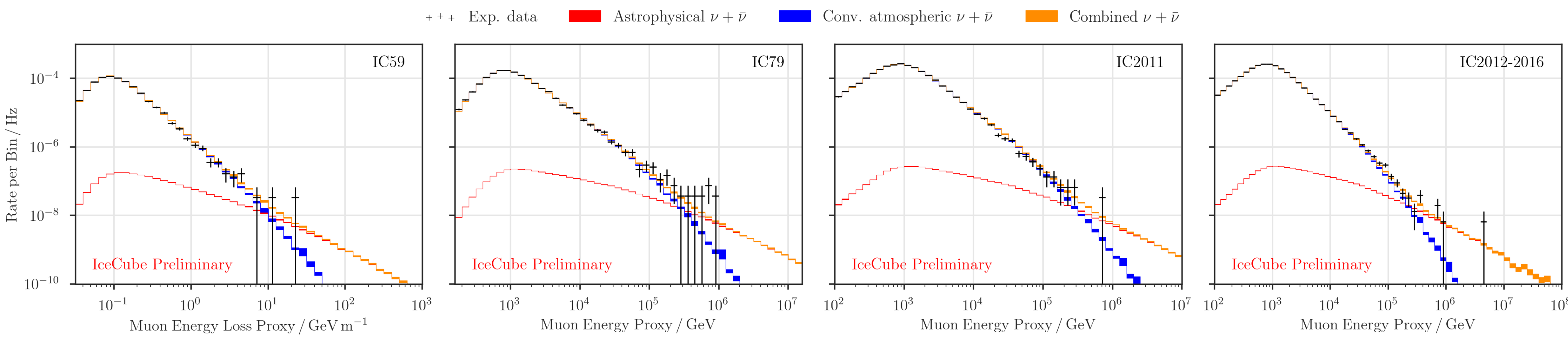
FUNDING AGENCIES

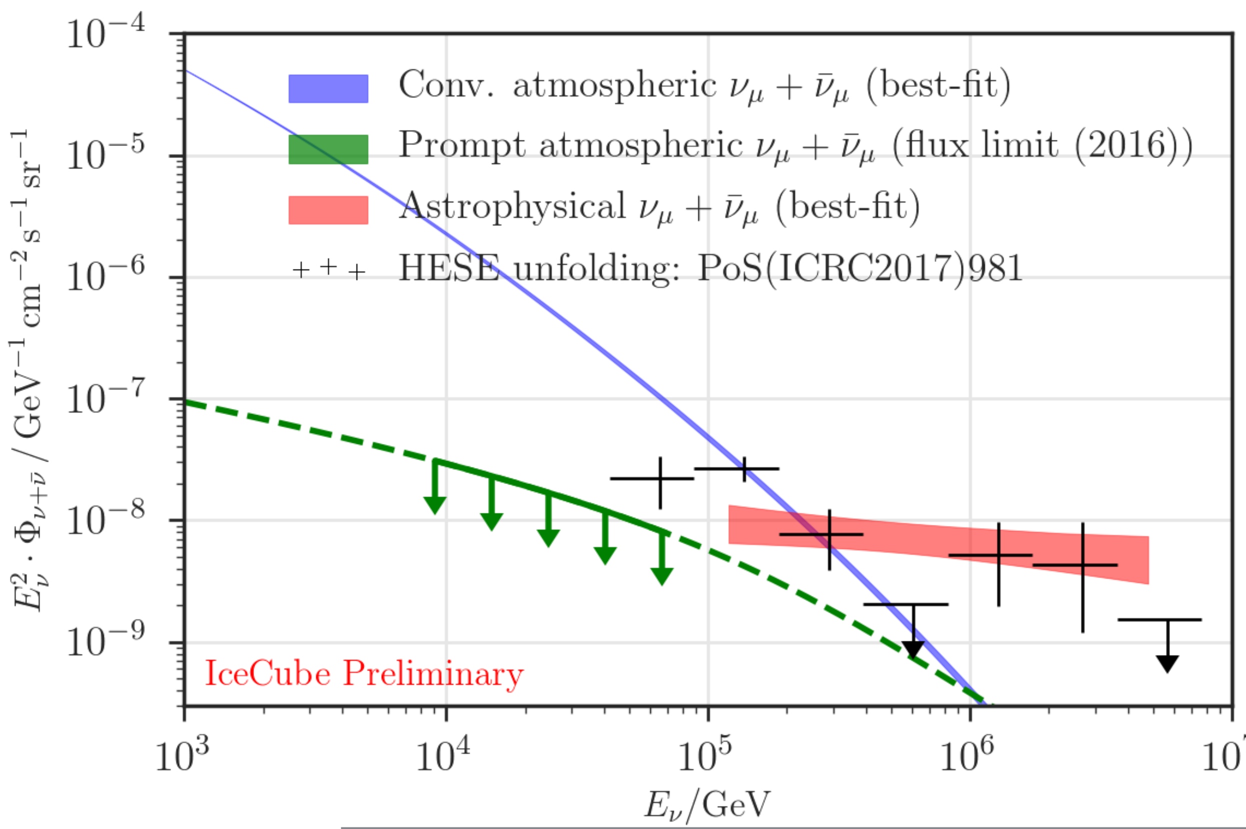
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg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

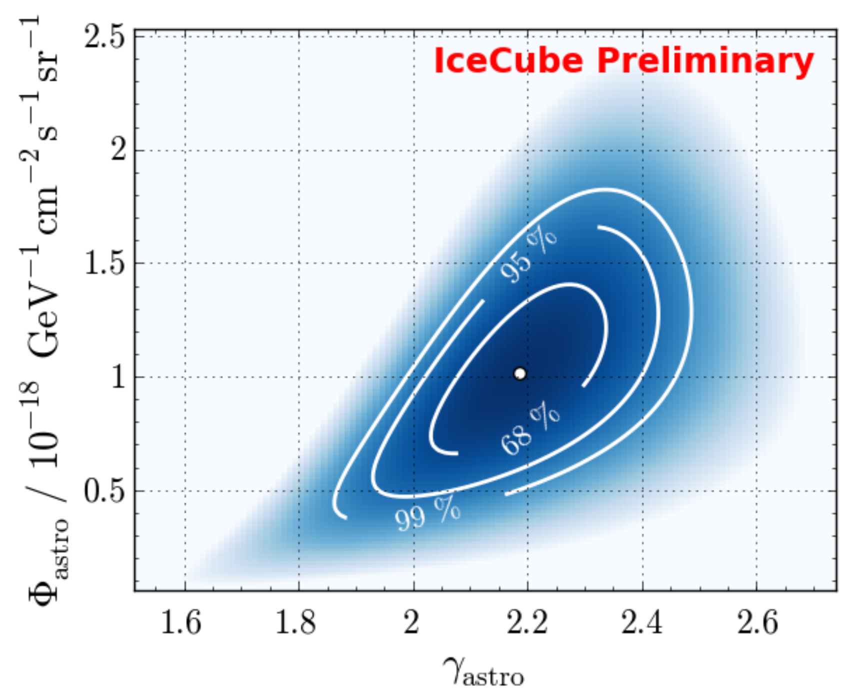
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Backup slides

Diffuse muon neutrino flux



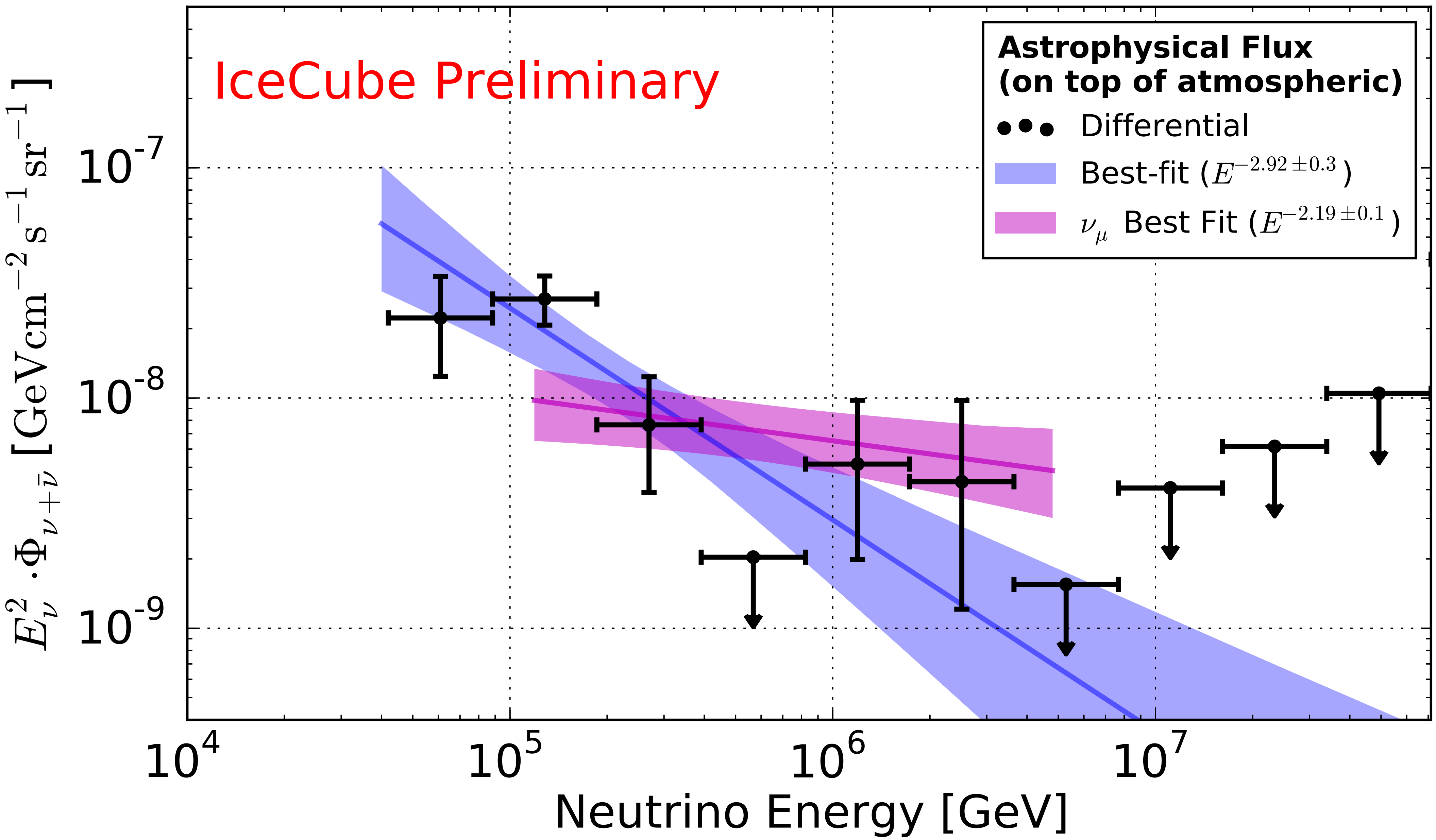




after 8 years → 6.7 sigma

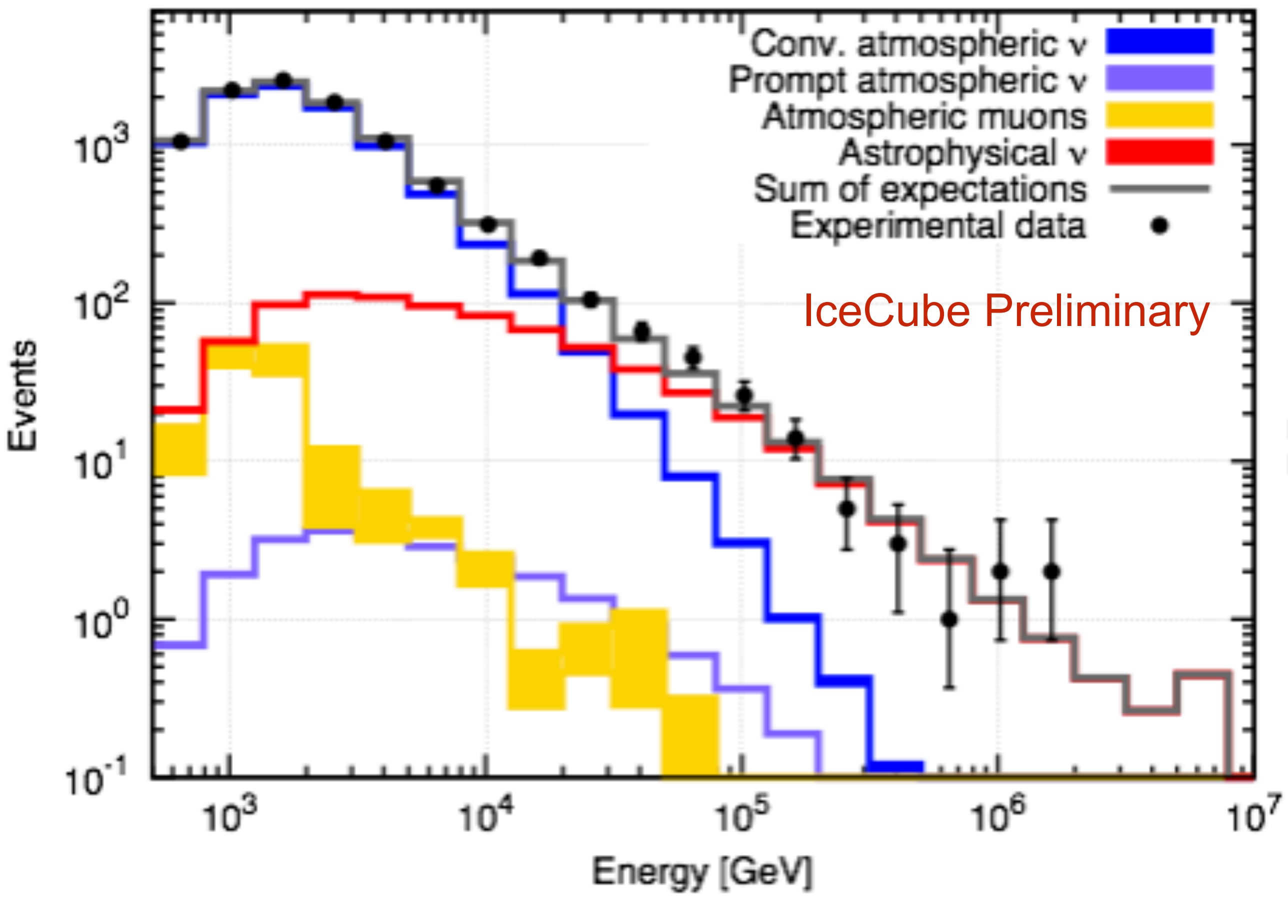
$$\frac{dN}{dE} = 1.01 \pm^{0.26}_{0.23} \times 10^{-18} \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-2.19\pm0.10} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

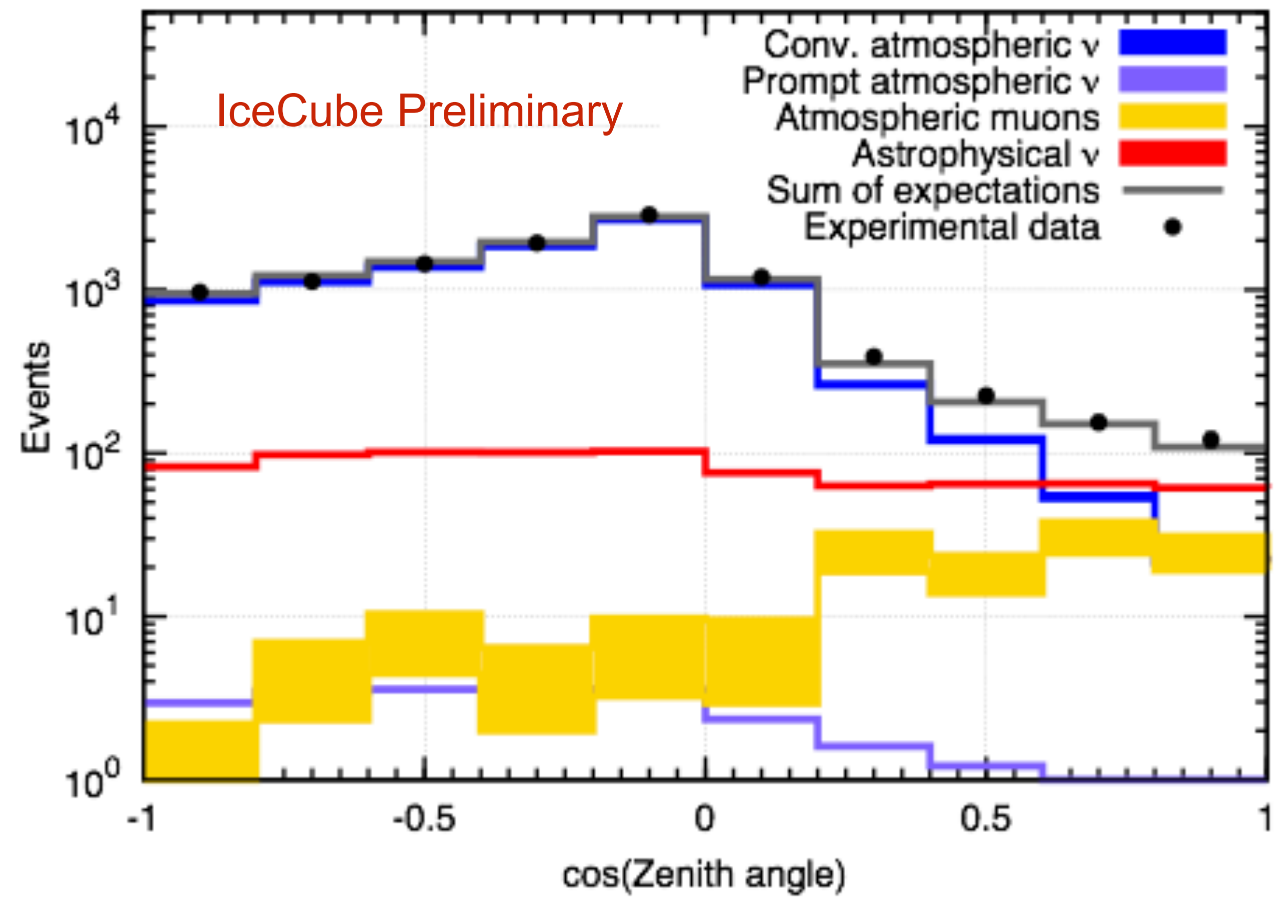
HESE 6 yr flux



Low-energy Starting Events

- Lowering the threshold in HESE selection to 1 TeV
- Better statistics and larger effective area

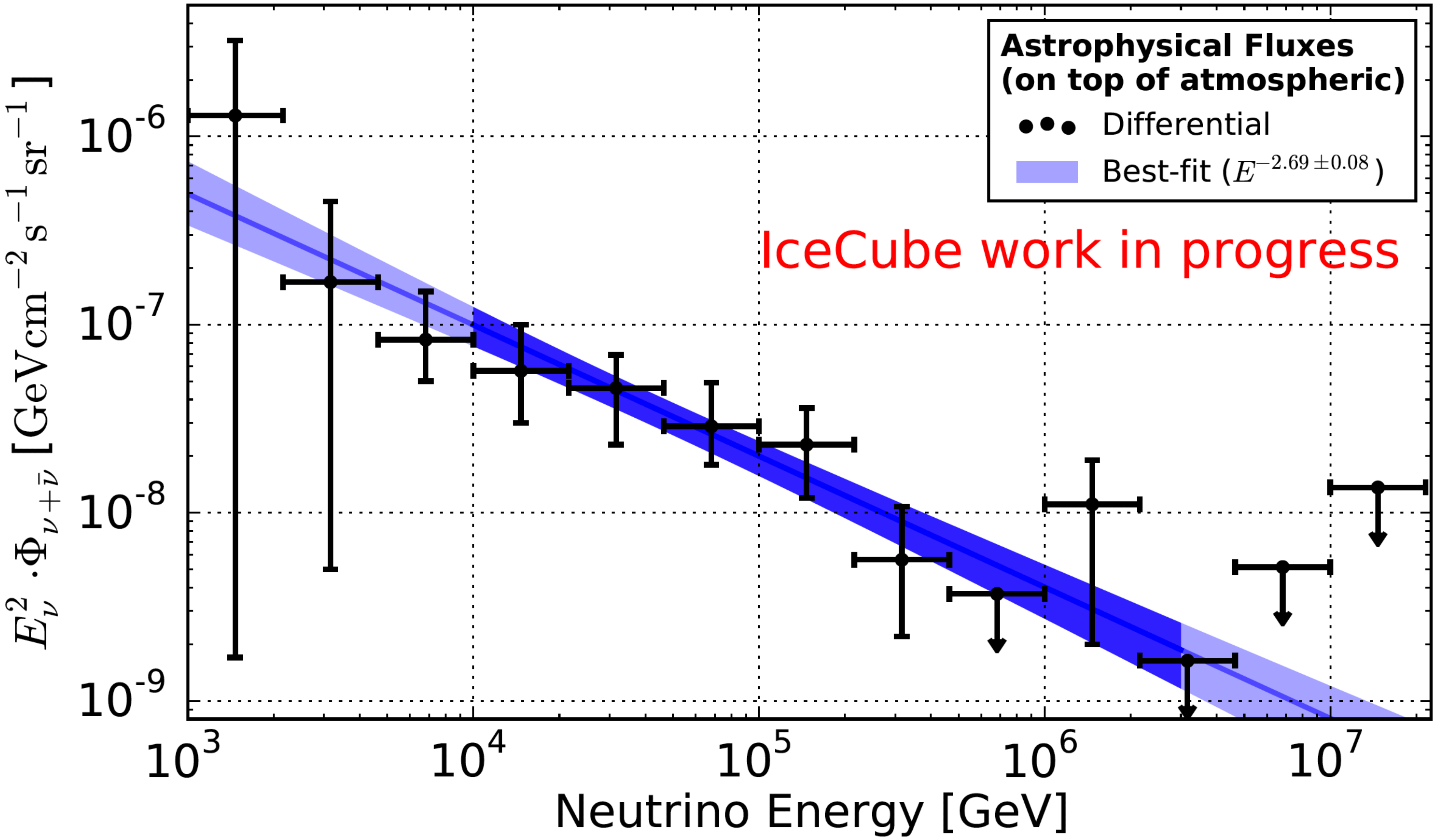




- a better understanding of the lower energy component

Low-energy Starting Events

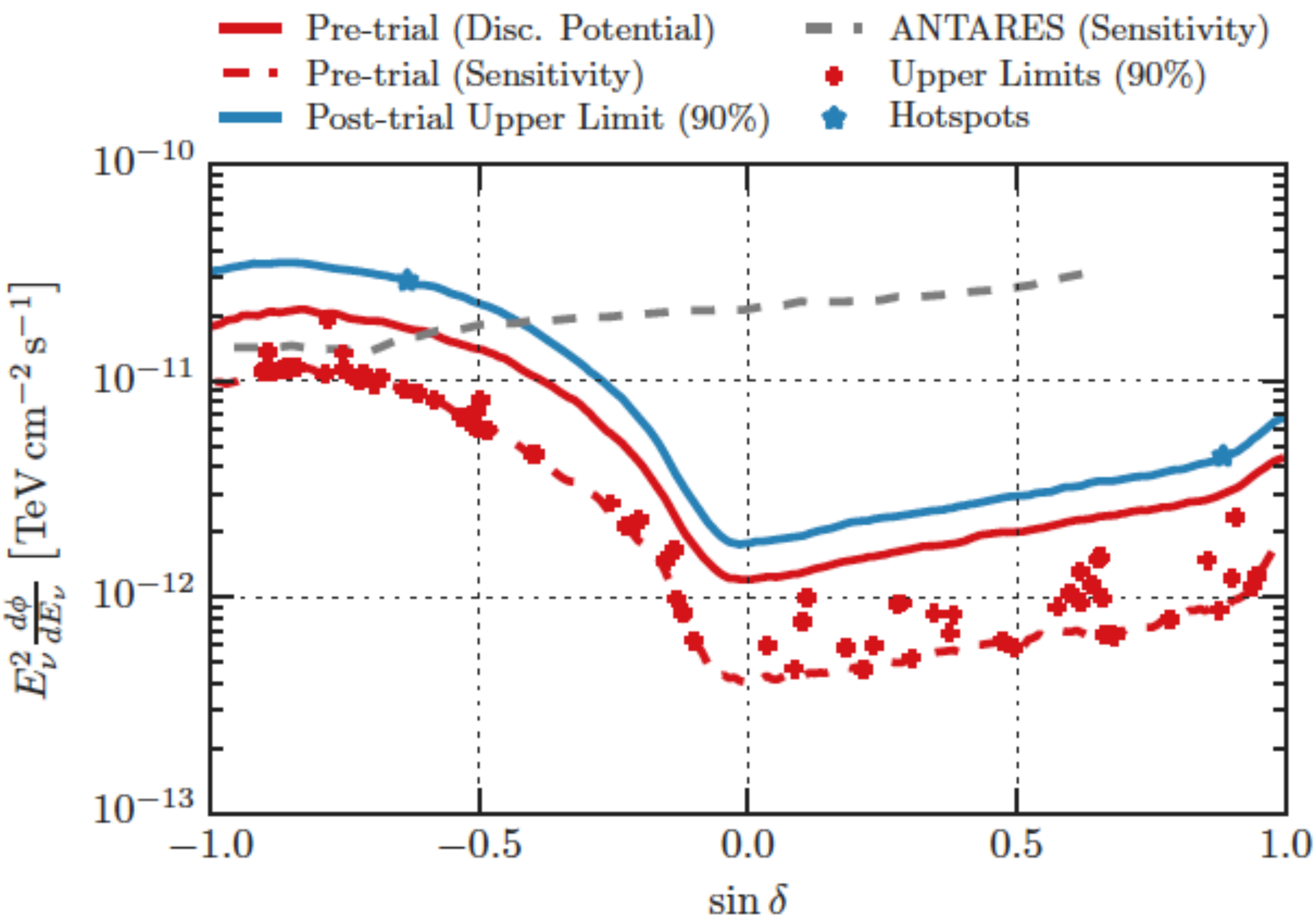
Lowering the threshold in HESE selection



best fit flux:

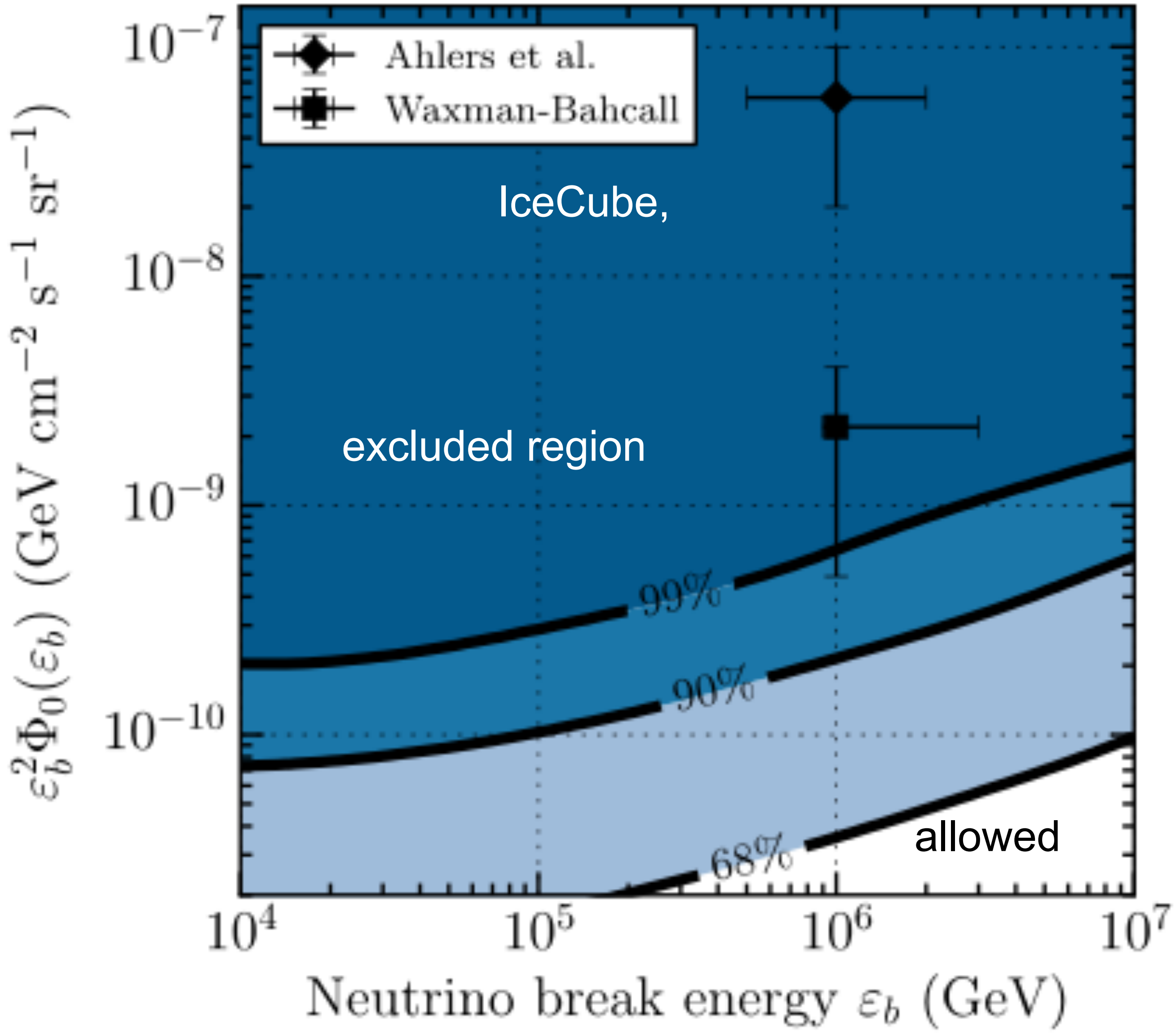
$$\frac{dN}{dE} = 2.1 \pm 0.3 \times 10^{-18} \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-2.69\pm0.08} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

IceCube point source sensitivity

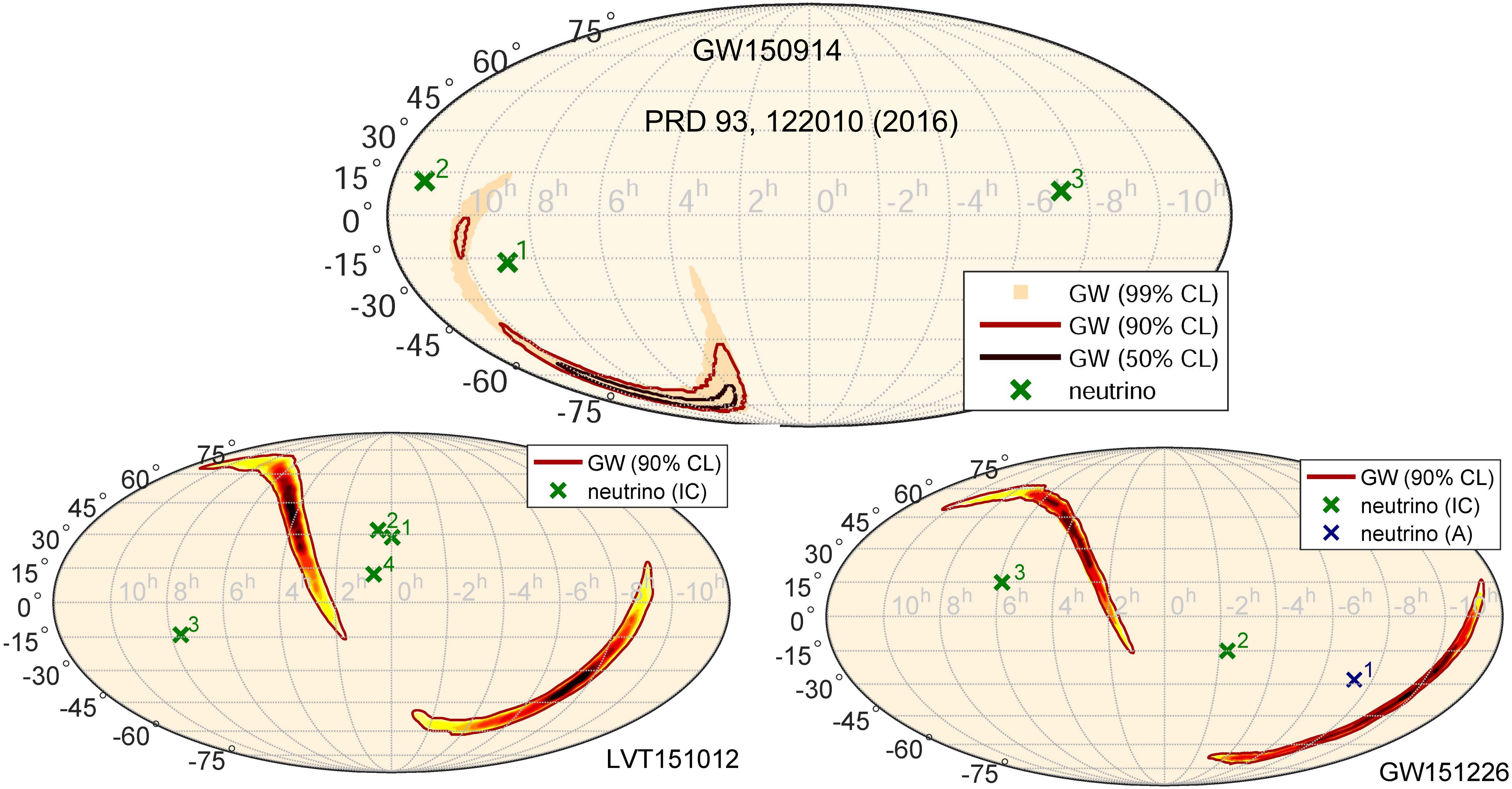


Limits on GRBs neutrino emission

- No association with five years of muon neutrino track events
- Conclusion: <1% of astrophysical neutrino flux is produced by GRBs
- Non-detection rules out GRBs as the source of UHE cosmic rays



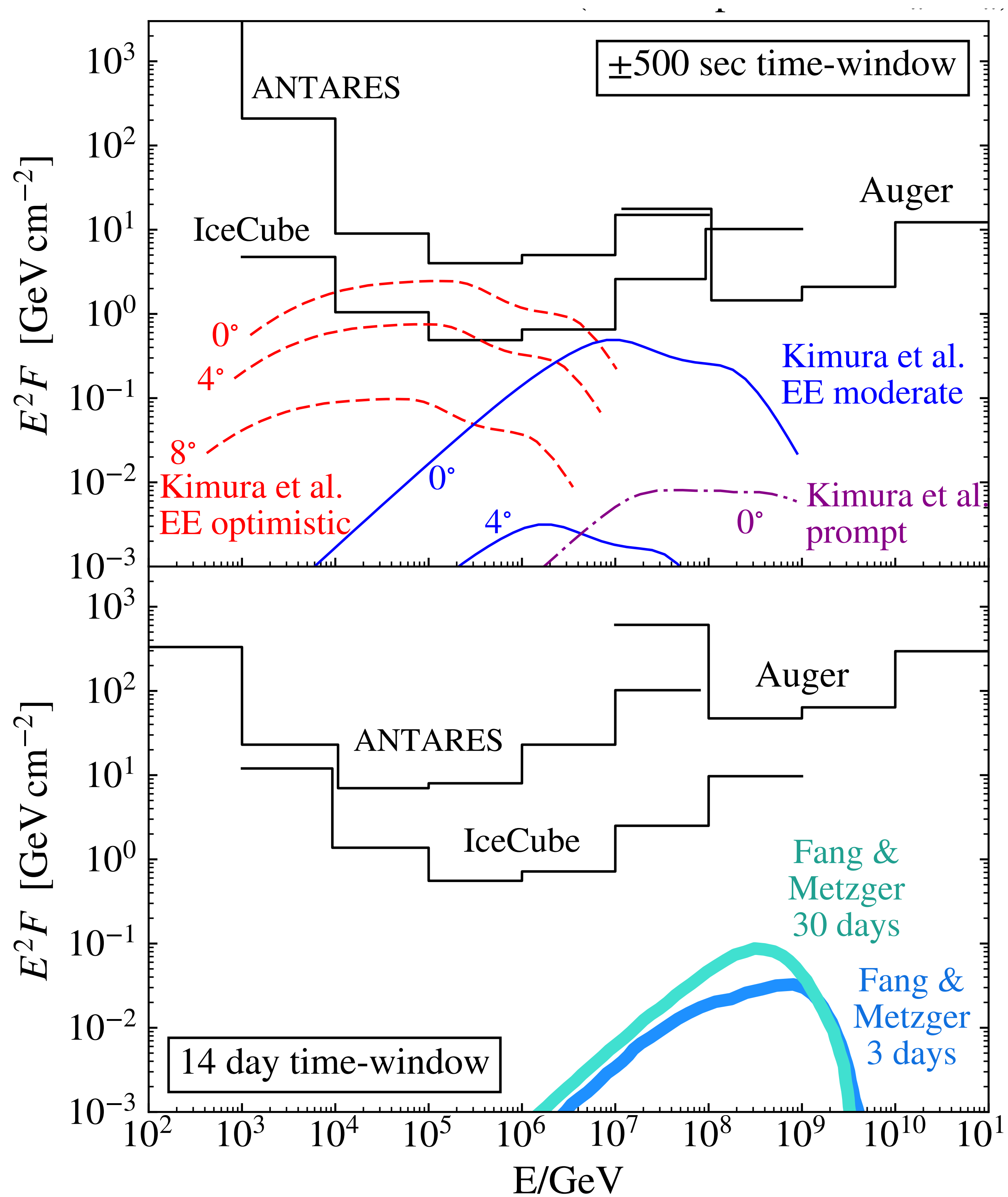
Black hole merger coincidence search



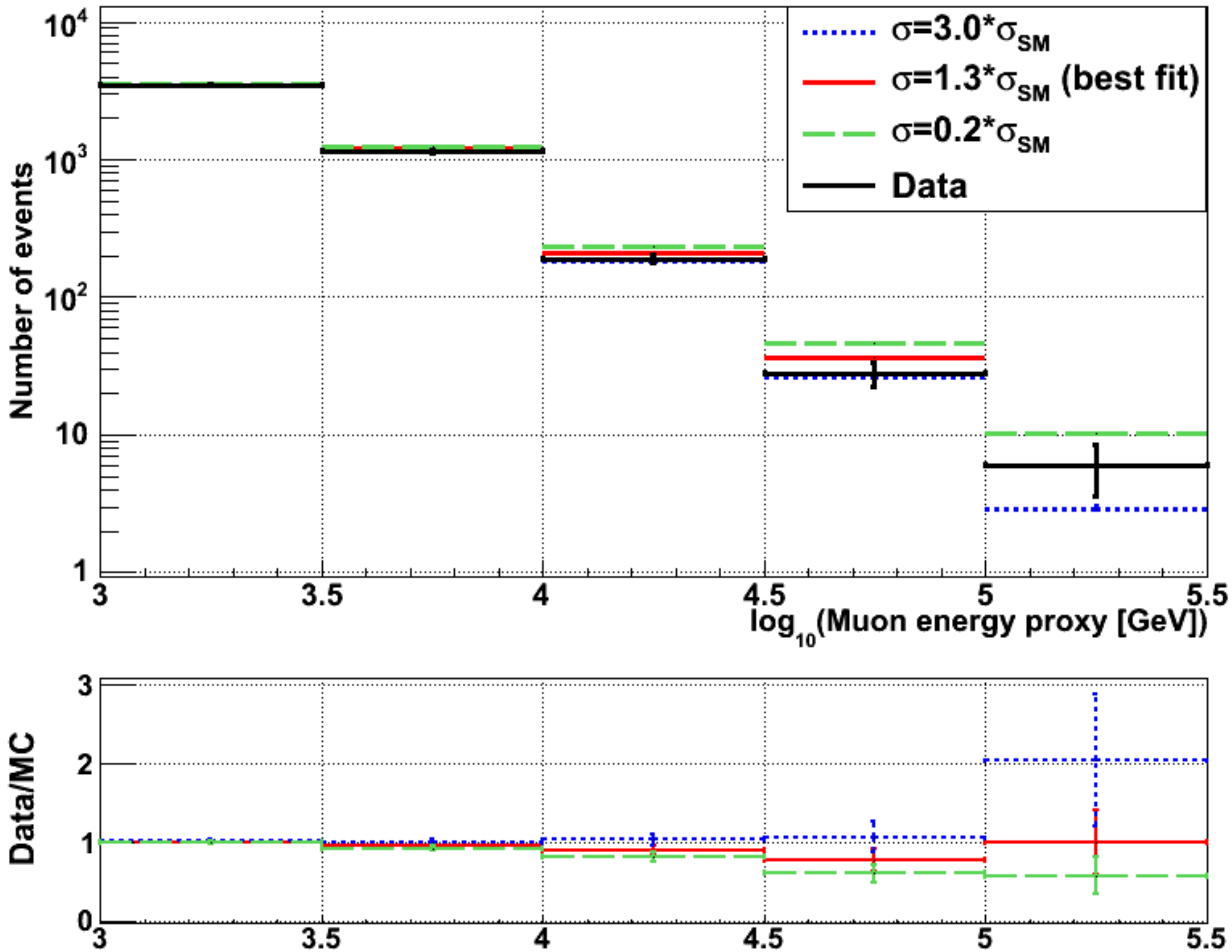
PRD 96, 022005 (2017)
ANTARES, IceCube, LIGO/VIRGO partnership

GW 170817 Neutrino limit

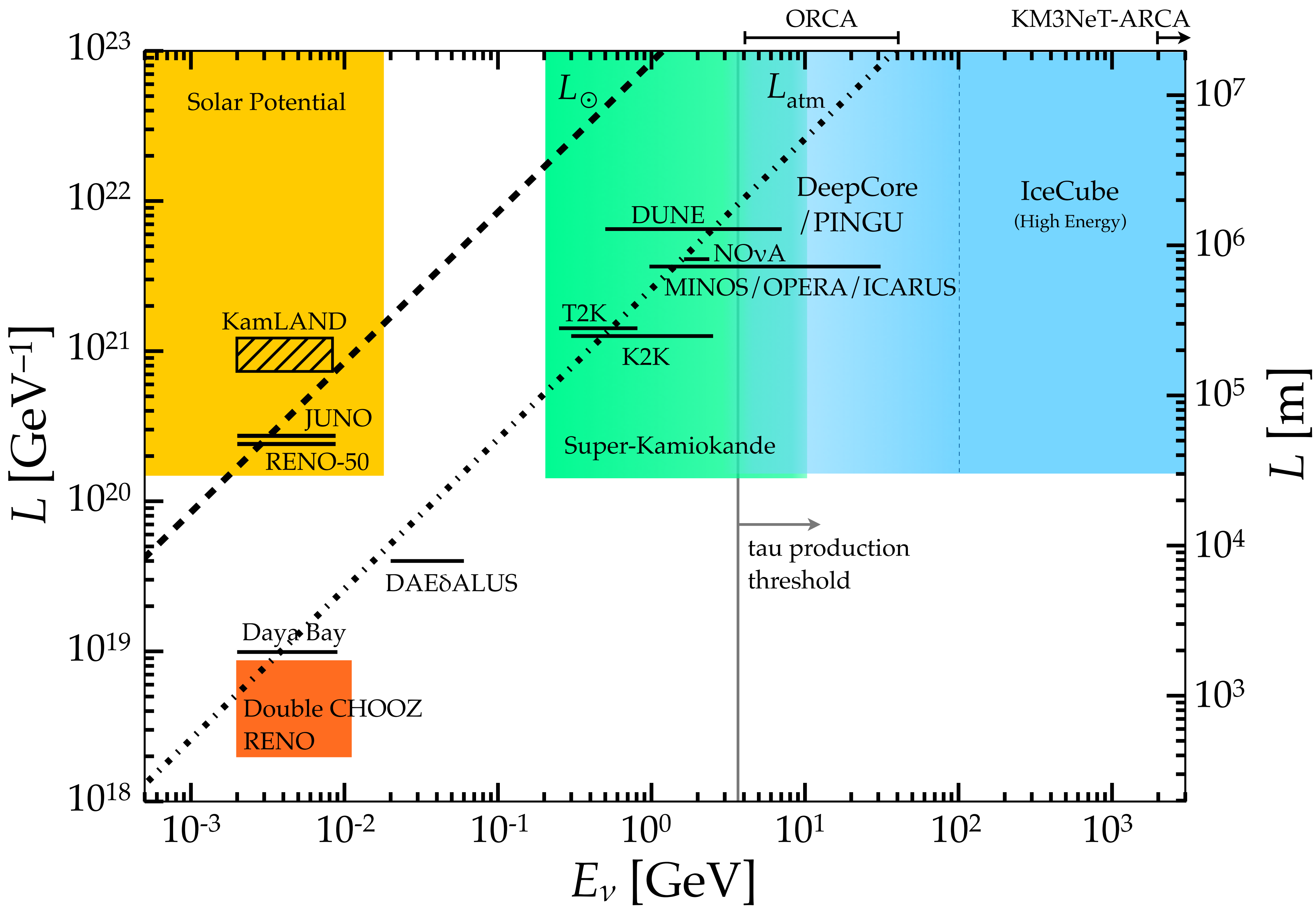
IceCube, ANTARES, and Auger 90% upper limit on the neutrino fluency (per flavor) for the binary neutron star merger.



Cross Section measurement

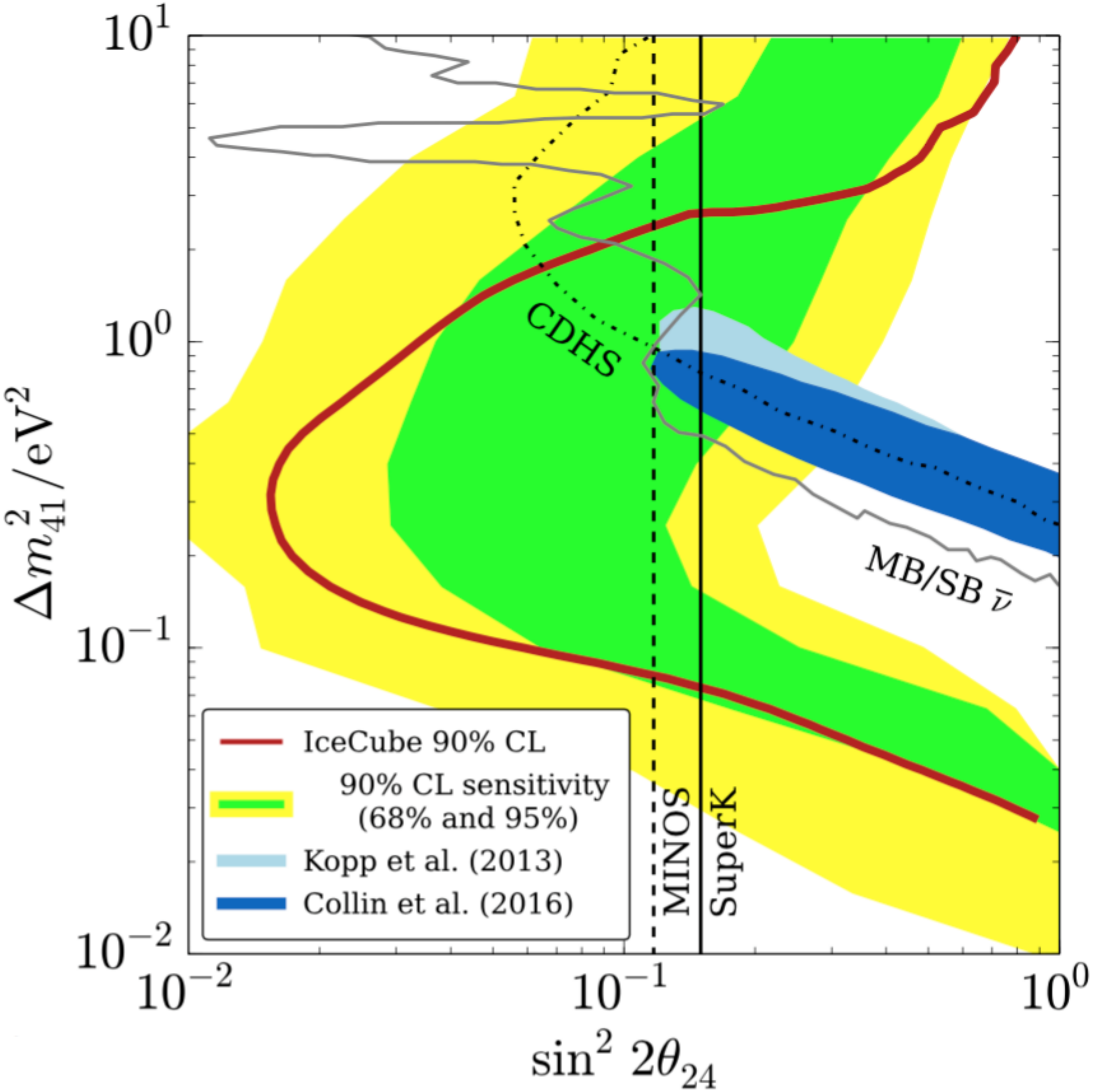


IceCube, Nature 551 (2017) 596



IceCube probes oscillation physics at baselines and energies inaccessible to LBL or reactor neutrino experiments – essential for constraining new physics

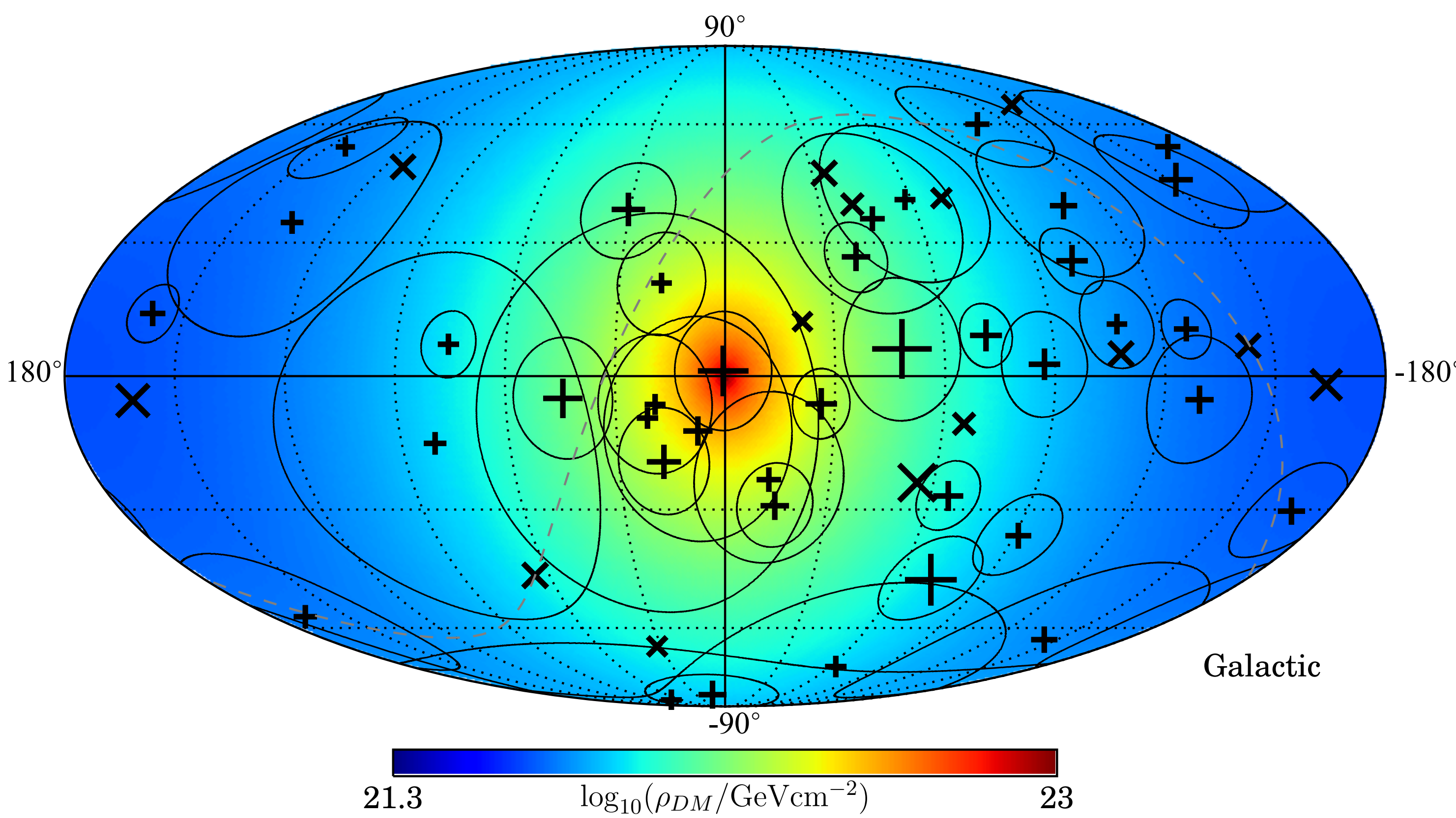
Sterile Neutrinos

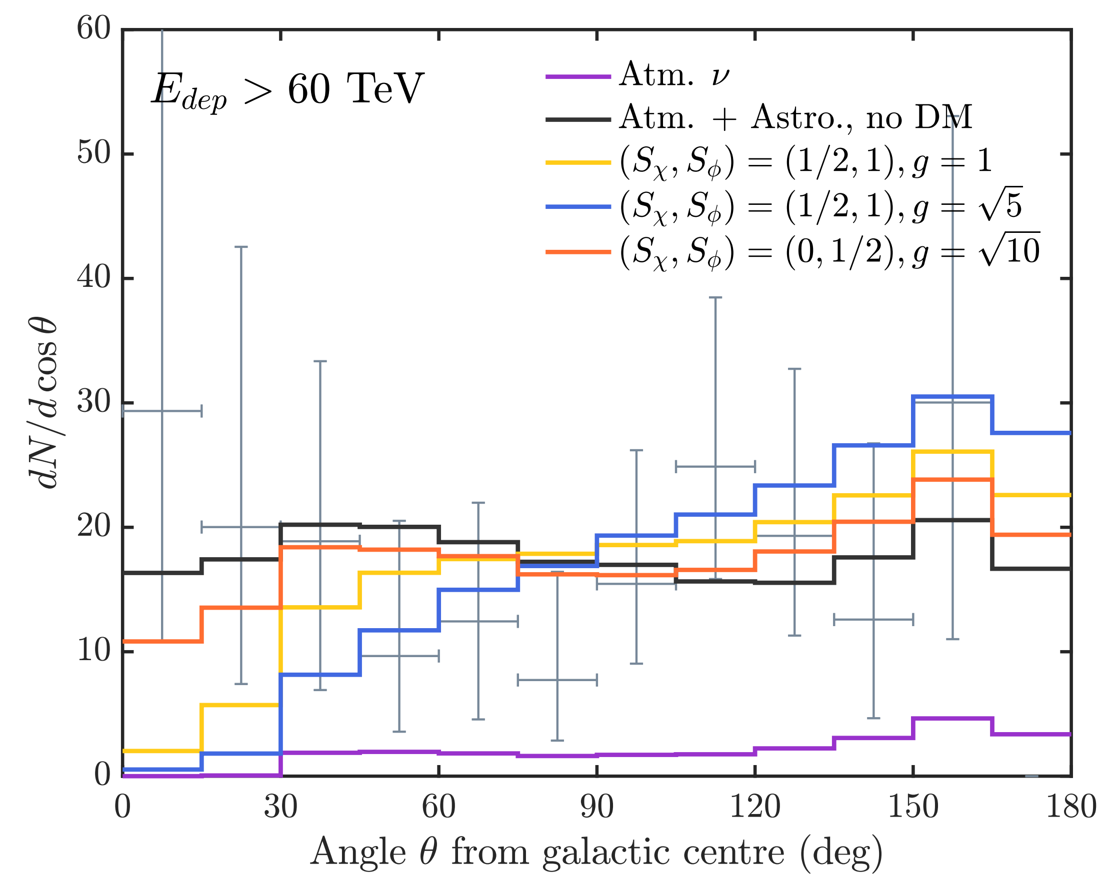


IceCube, PRL 2016

Dark Matter-Neutrino Interactions

Interaction of high-energy neutrinos with Galactic dark matter



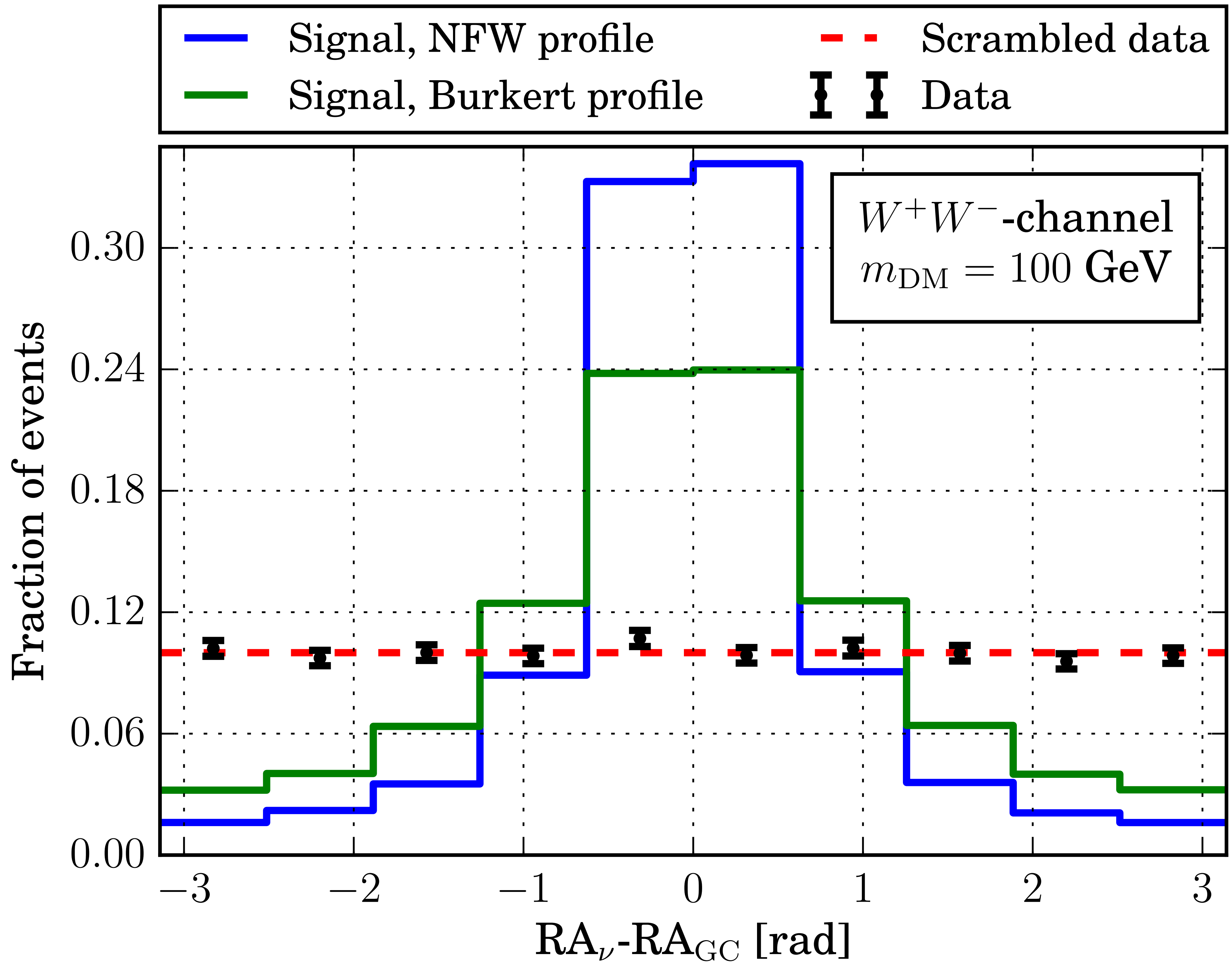


Expectation: fewer event from the Galactic Center

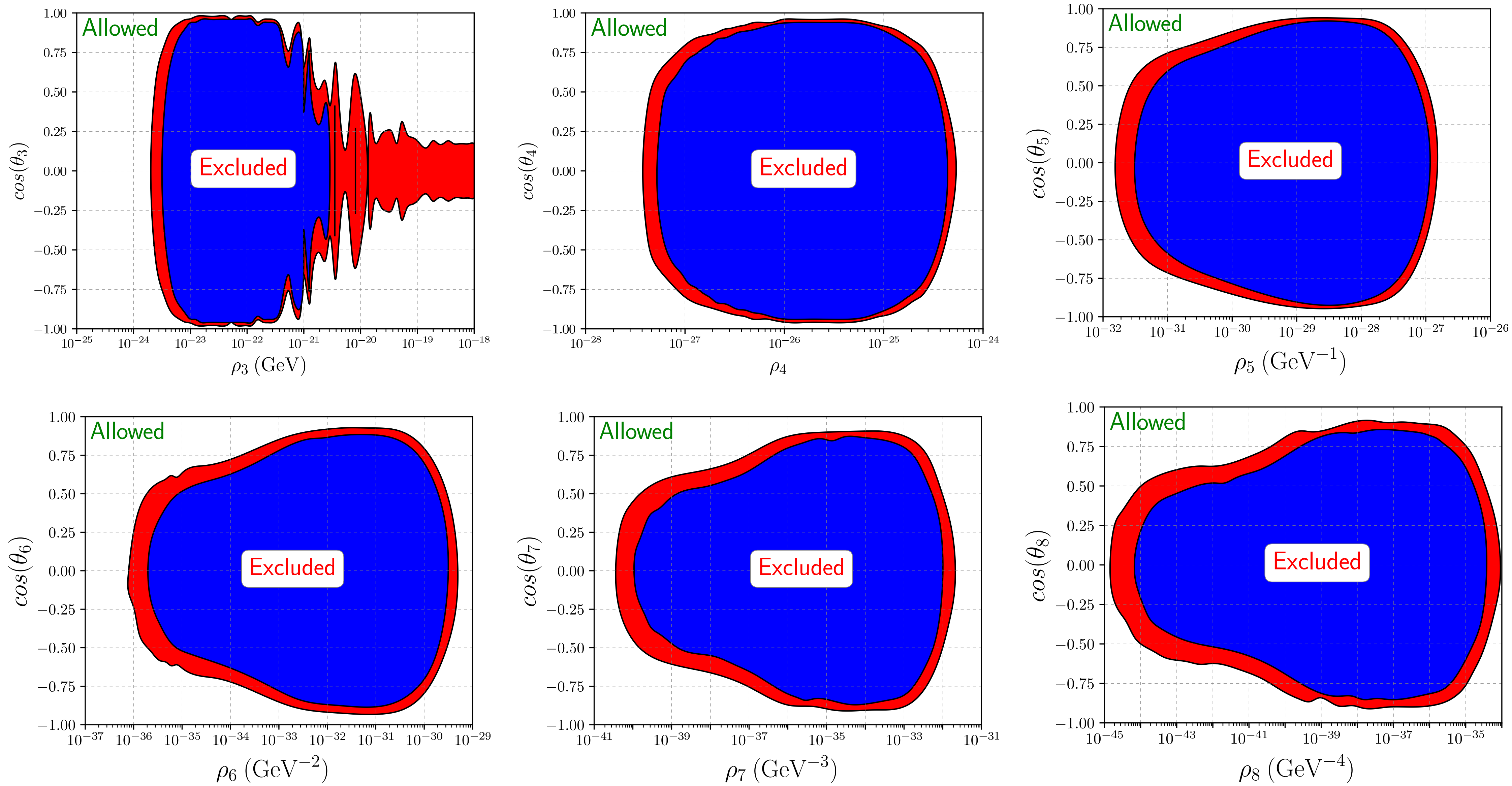
Observation: Anisotropy

Argüelles, AK, Vincent, PRL 2017

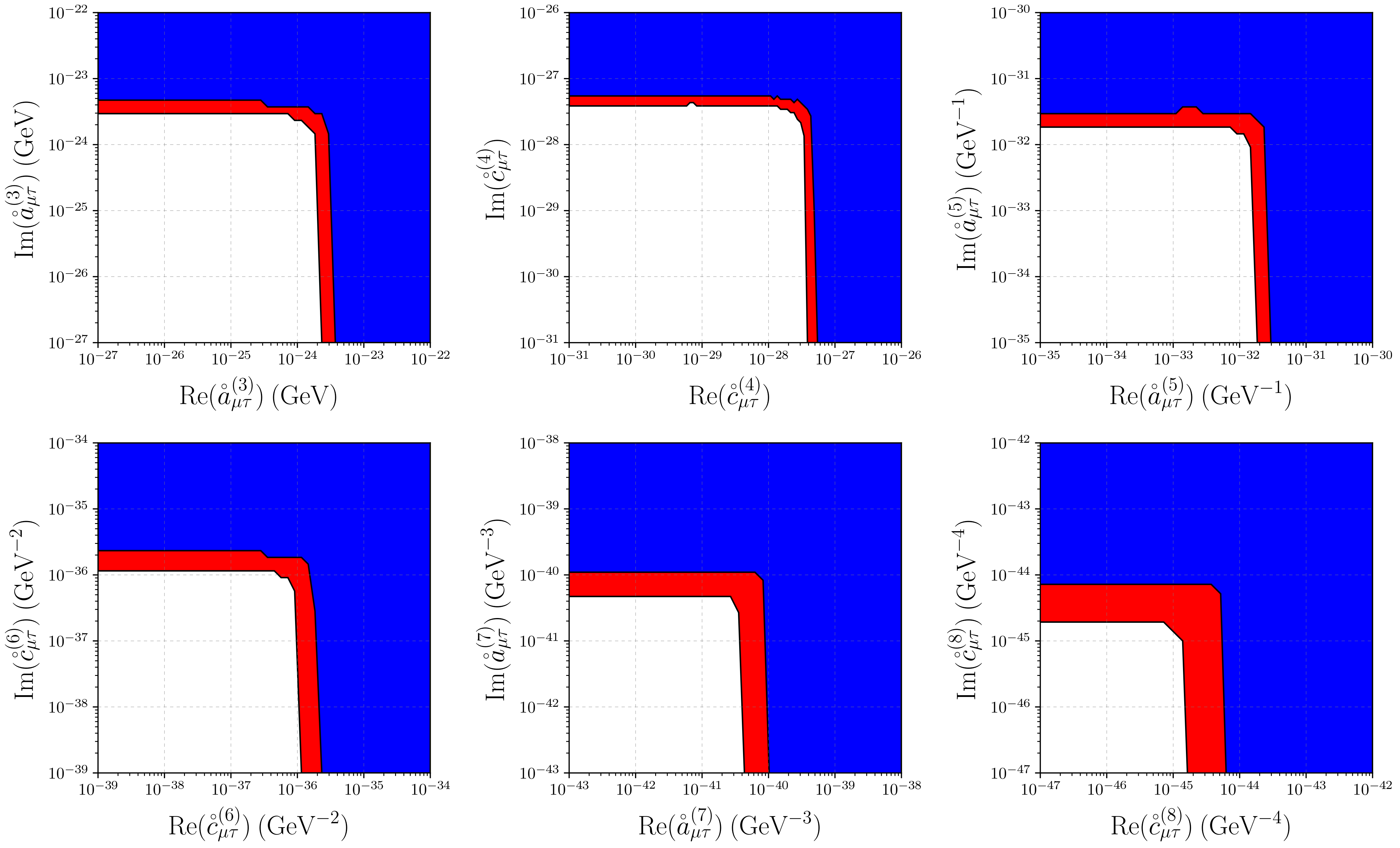
Dark Matter from GC



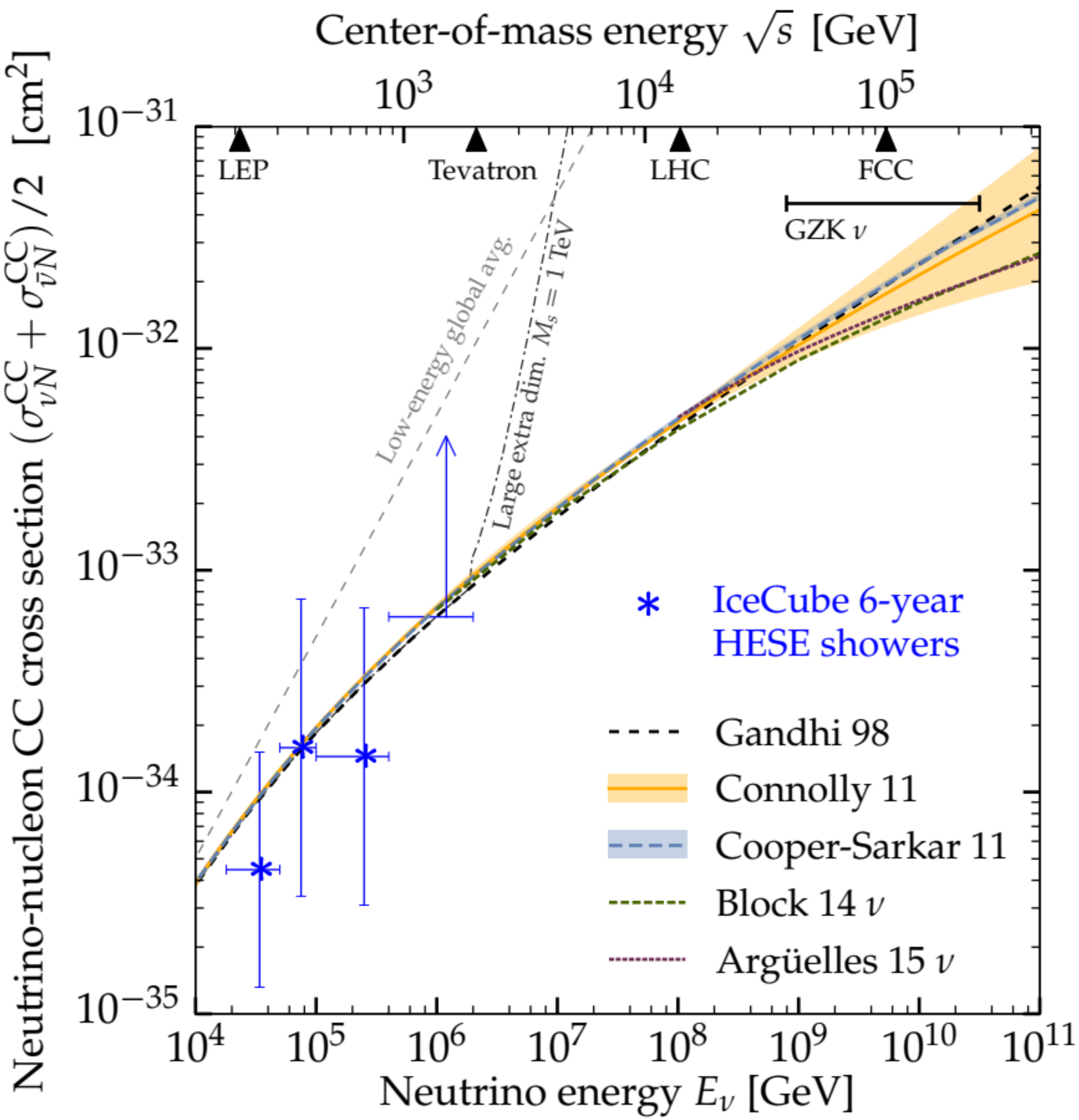
IceCube LV Search



IceCube LV Search



Cross section with HESE



Bustamante & Connolly, 2017