Recent Results from the IceCube Neutrino Observatory

Jim Madsen

UWRF, WIPAC

KAVLI IMPU

Tokyo, Japan November 19, 2019

Photo: Benjamin Eberhardt, IceCube/NSF

Outline

- Introduction
- IceCube Neutrino Observatory
- Astrophysical Neutrinos
- Atmospheric Neutrinos
- IceCube Upgrade and IceCube-Gen2
- Summary

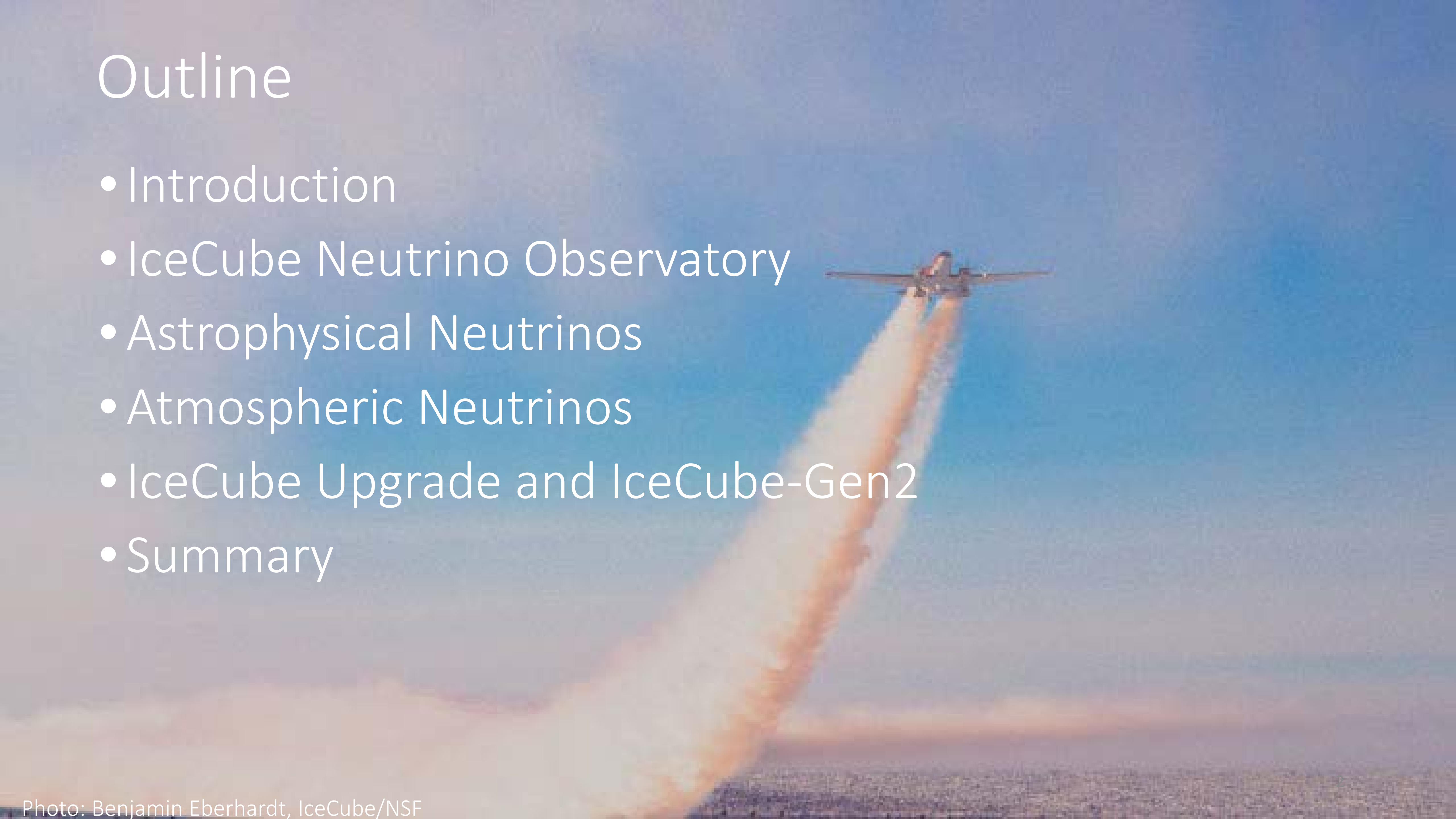
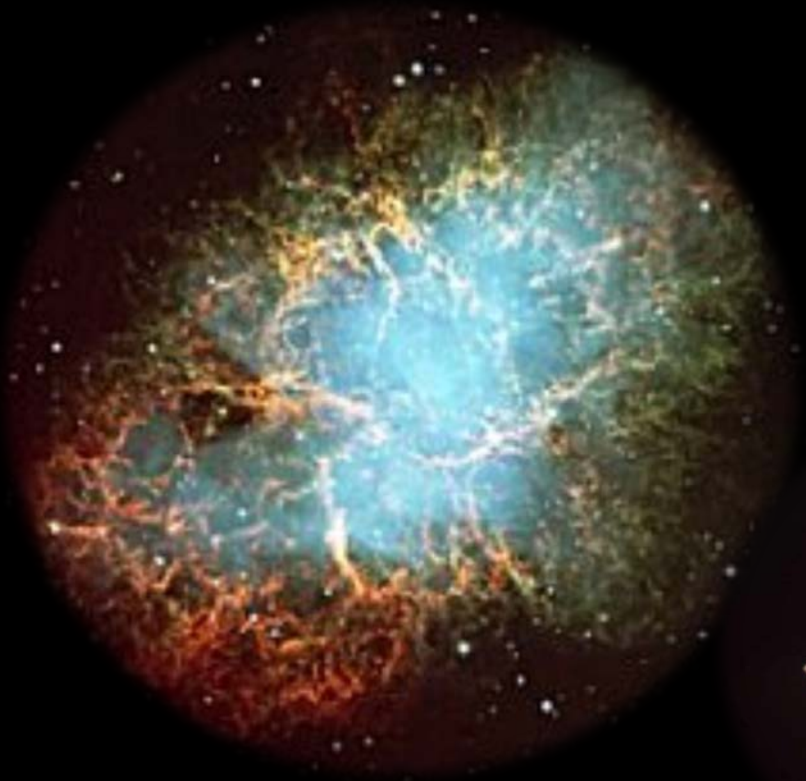
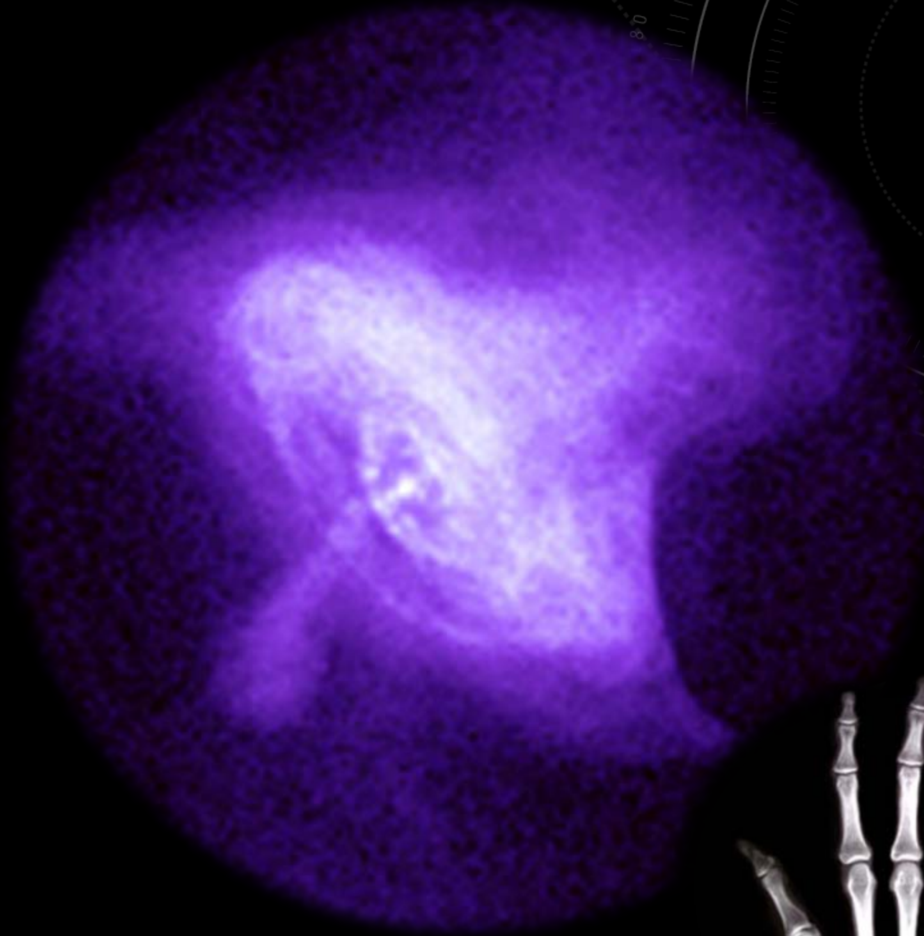
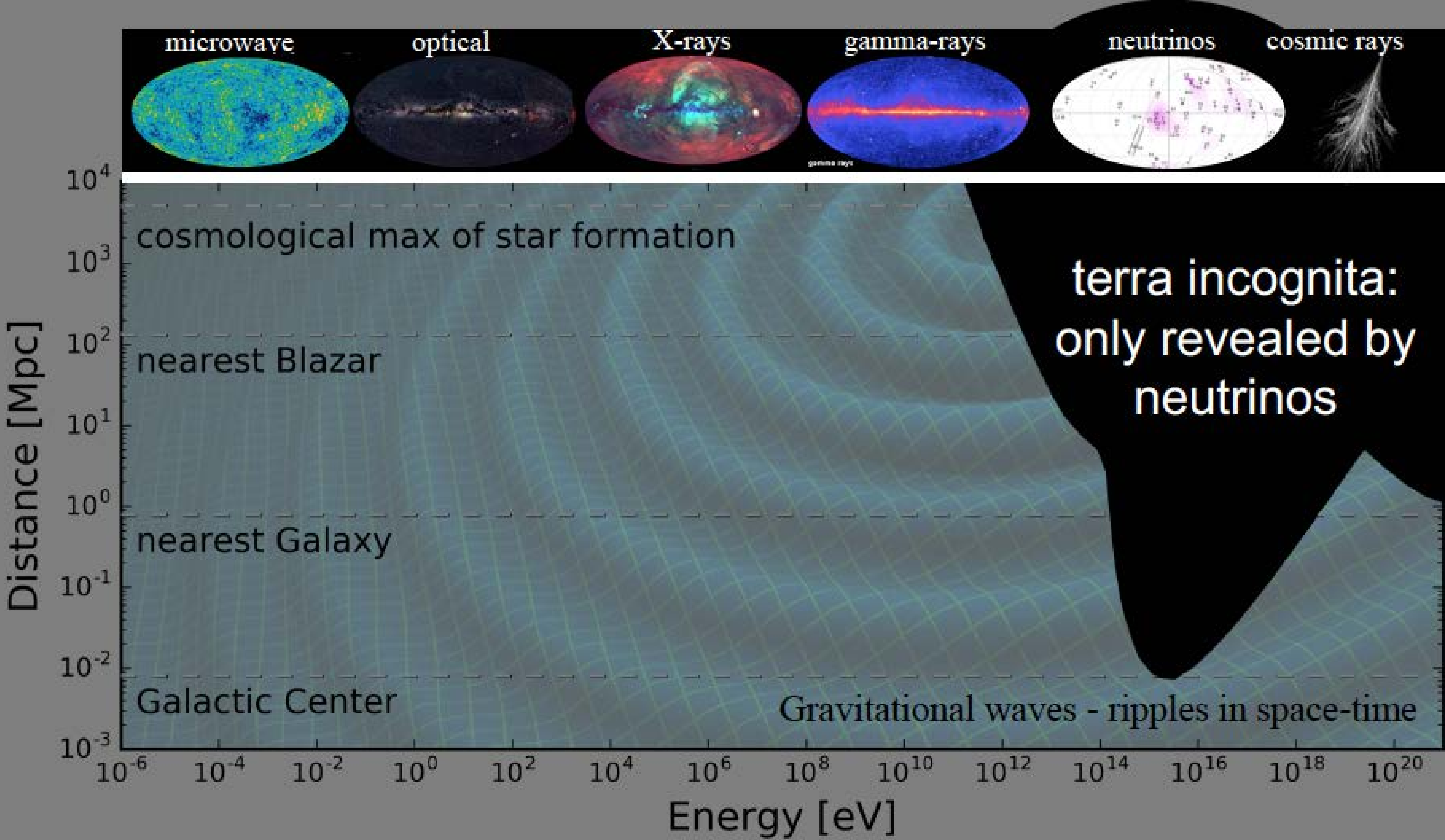


Photo: Benjamin Eberhardt, IceCube/NSF

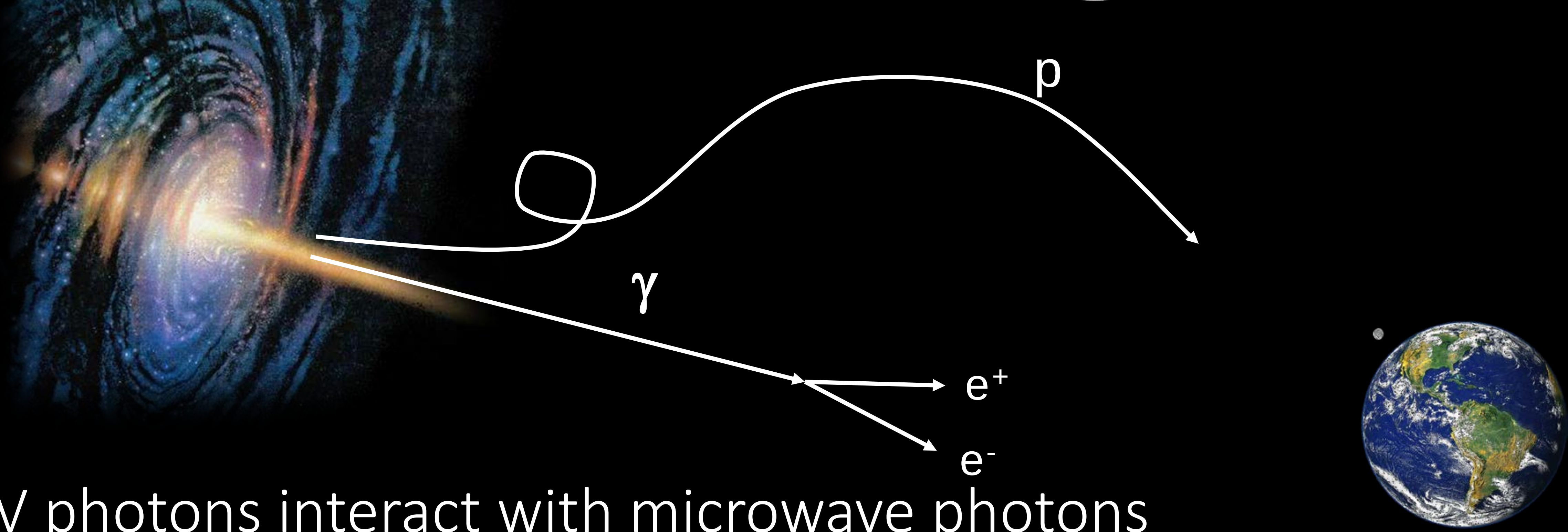
Multimessenger Astronomy





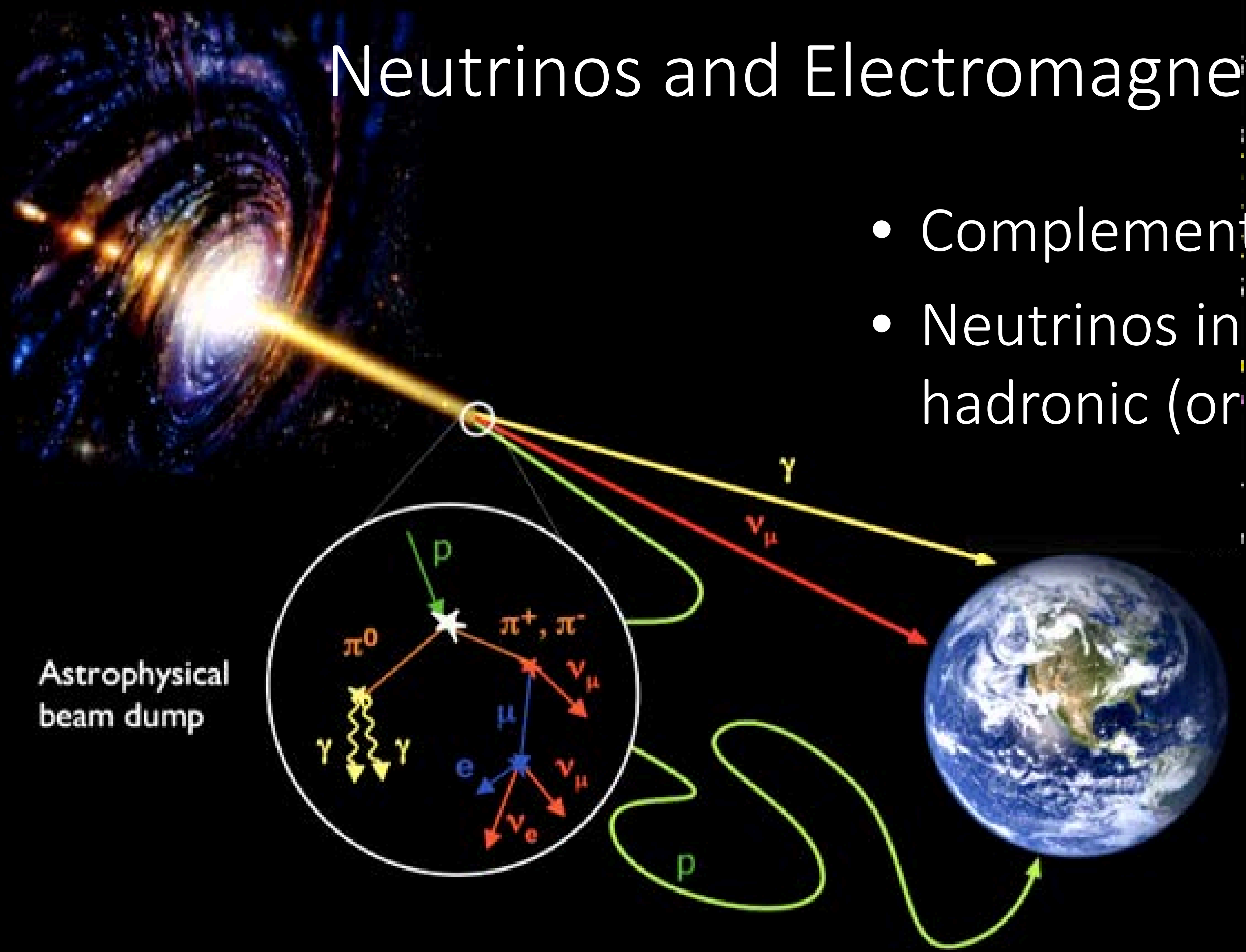

microwave
optical
X-rays
gamma-rays
neutrinos
cosmic rays
cosmological max of star formation
nearest Blazar
nearest Galaxy
Galactic Center
terra incognita:
only revealed by
neutrinos
Gravitational waves - ripples in space-time
Distance [Mpc]
Energy [eV]
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20}

The Opaque Universe



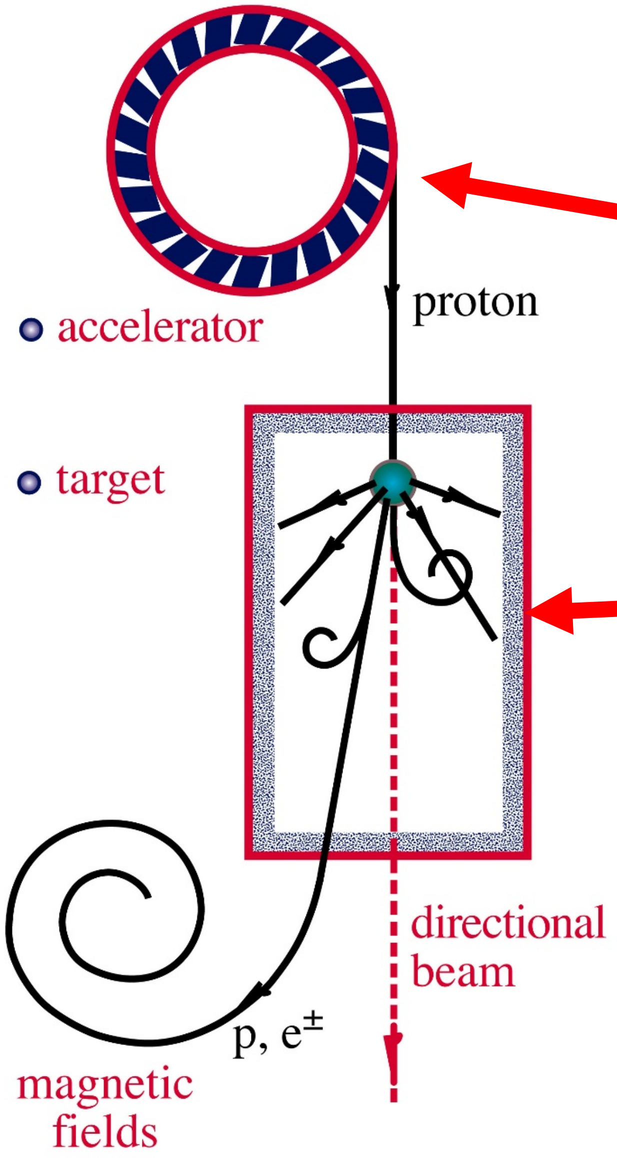
- PeV photons interact with microwave photons ($411/cm^3$) before reaching telescopes
- Need new cosmic messenger: neutrinos

Neutrinos and Electromagnetic Signals



- Complementary
- Neutrinos indicate a hadronic (or exotic) source

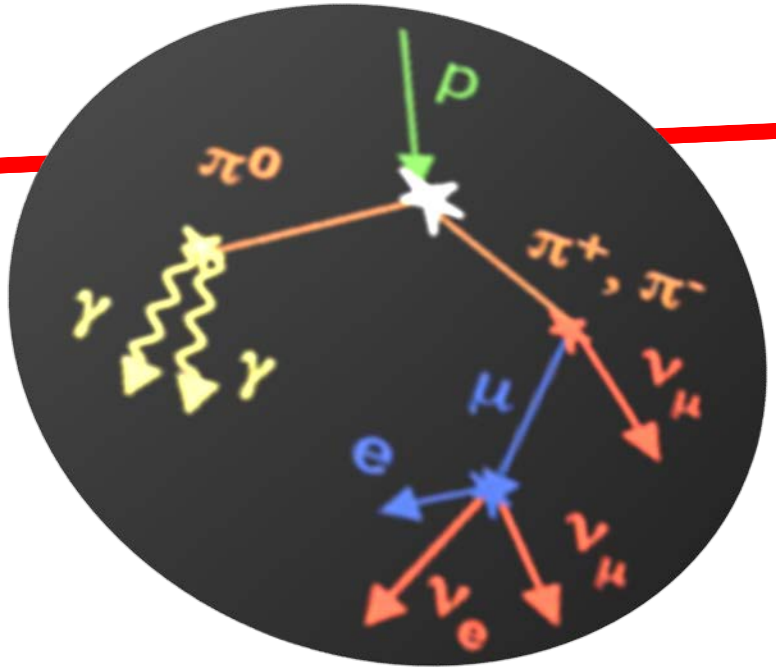
Neutrino (γ-ray) Production



Cosmic accelerator powered by gravitational energy

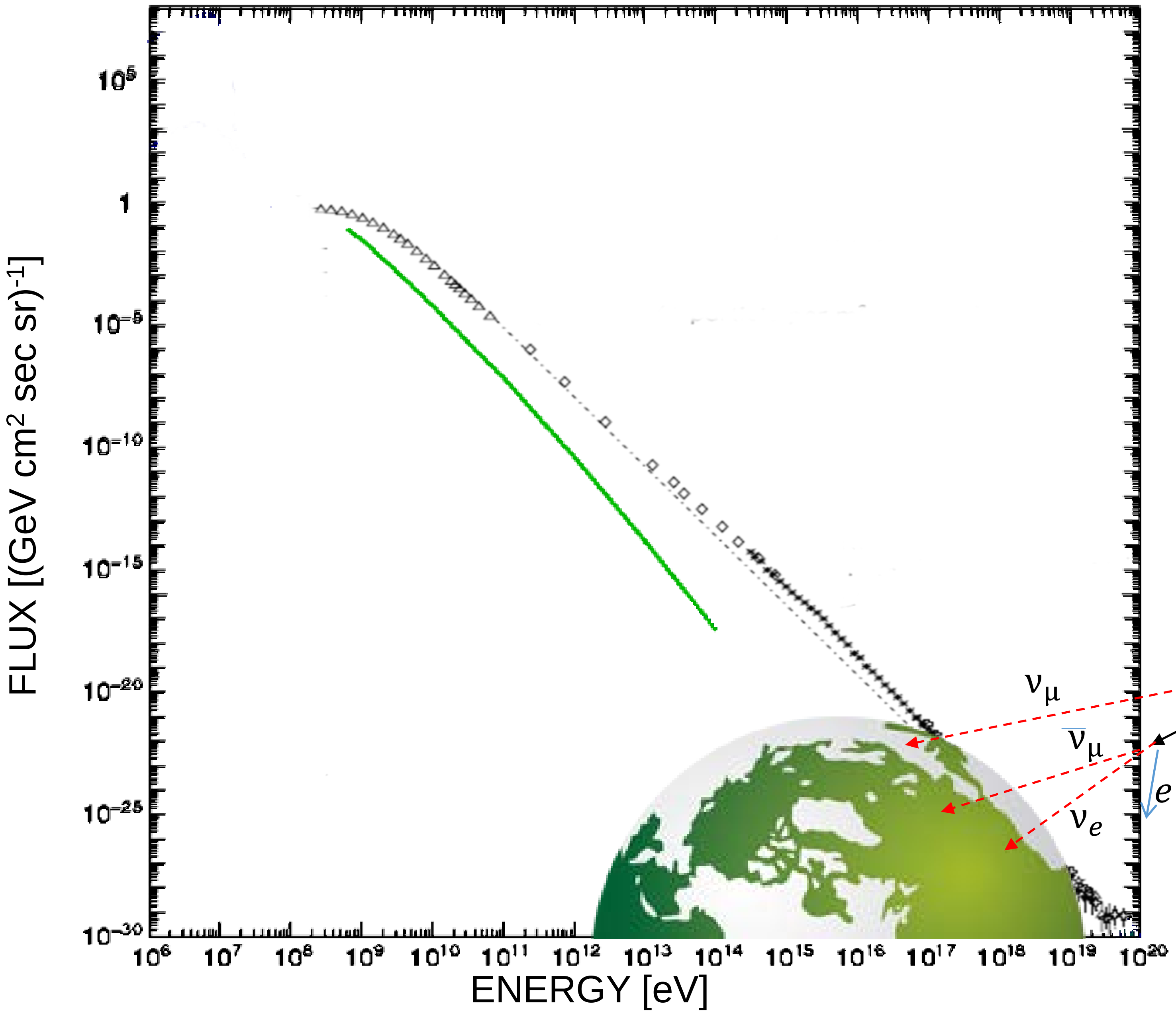
Black hole or neutron star

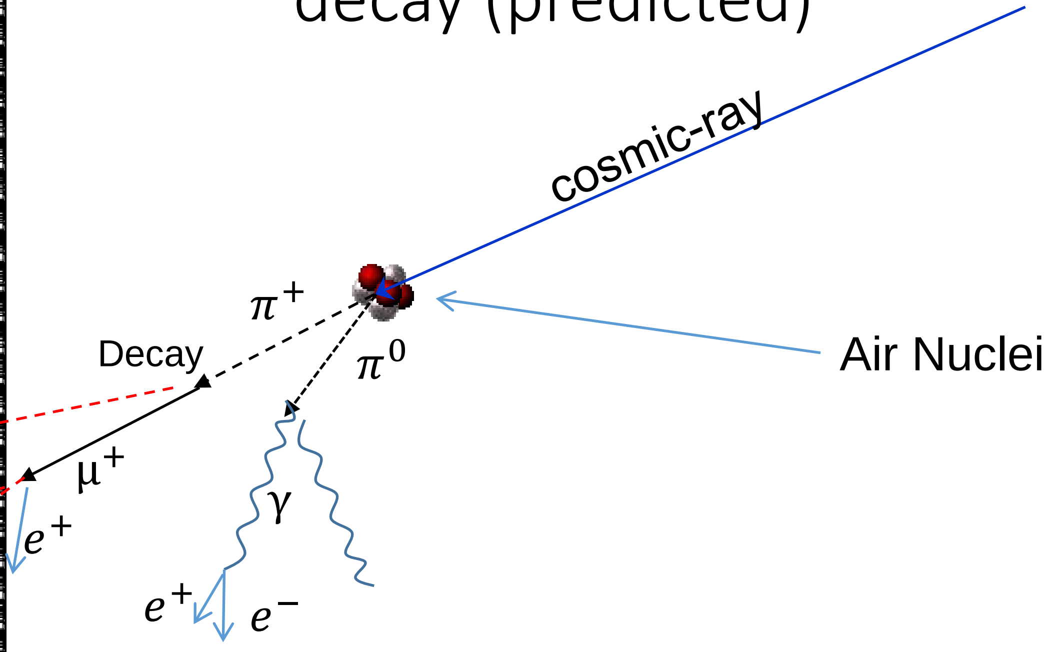
Radiation and dust



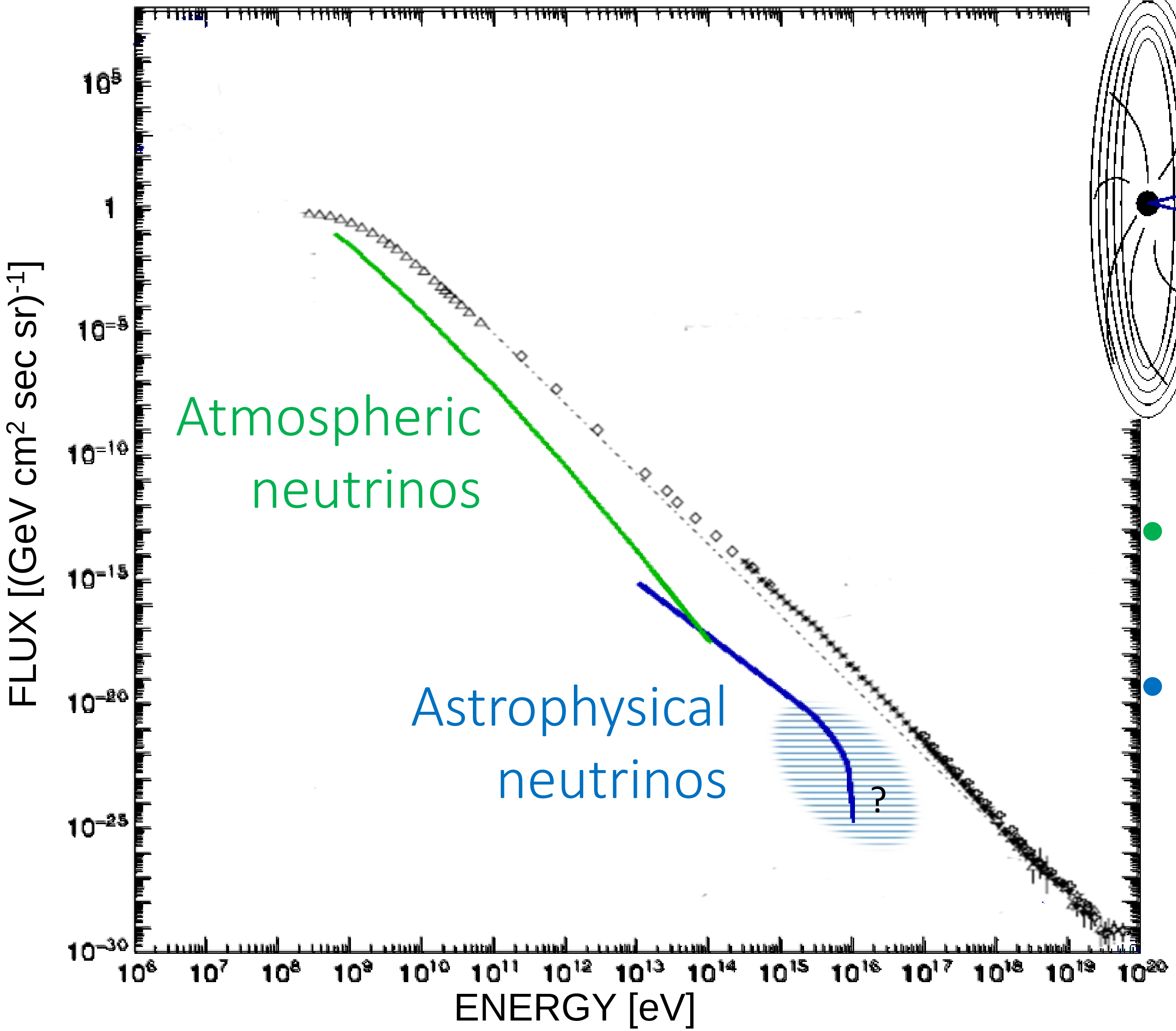
Atmospheric Neutrinos

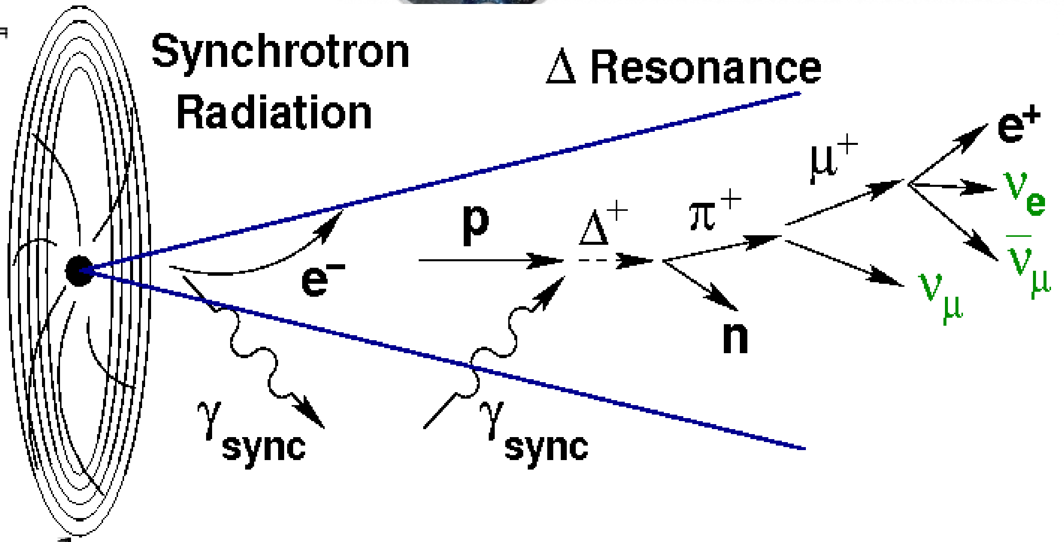
- Cosmic rays up to knee
  - ν from π and K decay
- Around and above knee
  - ν from charmed meson decay (predicted)





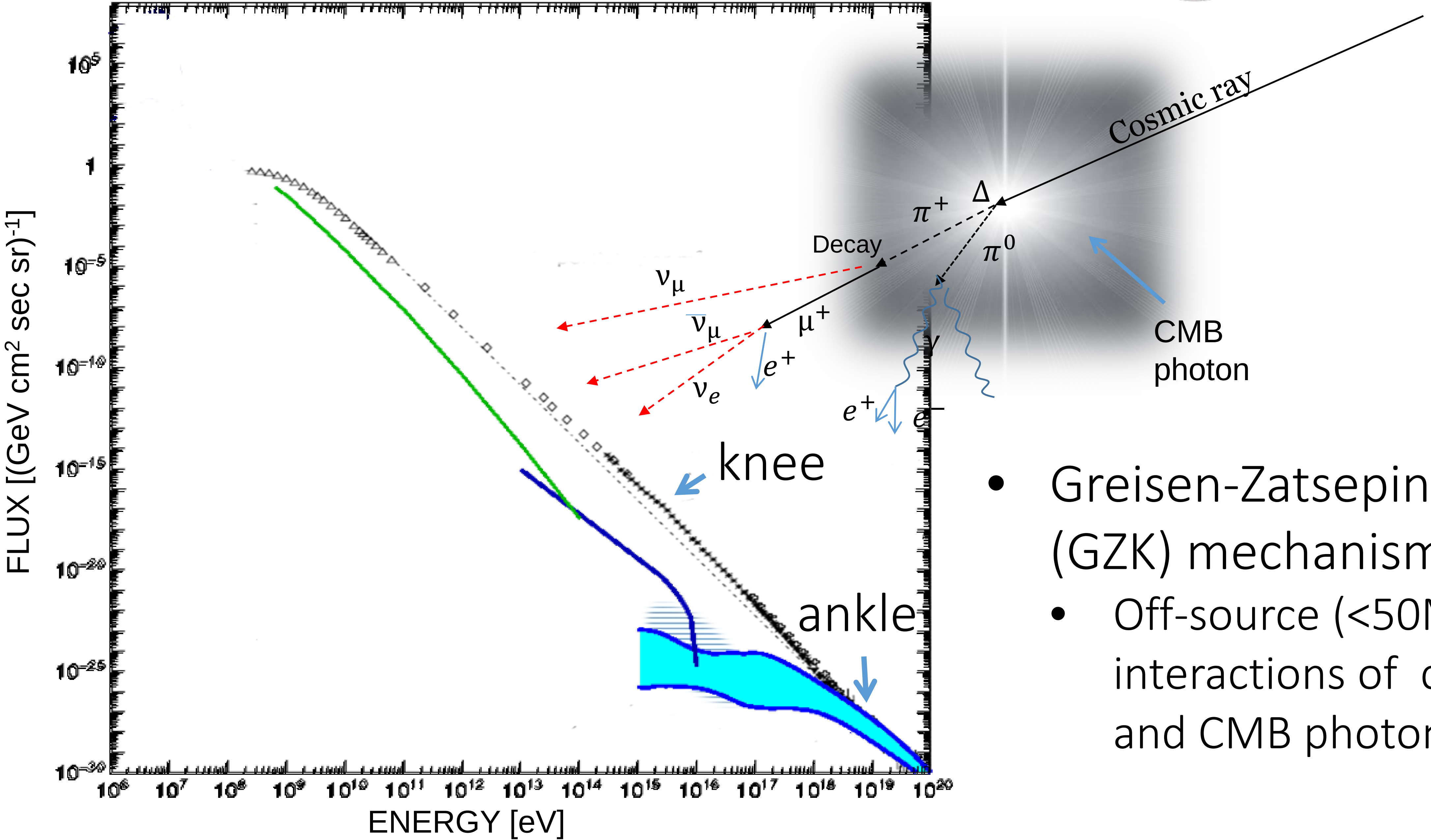
Astrophysical Neutrinos





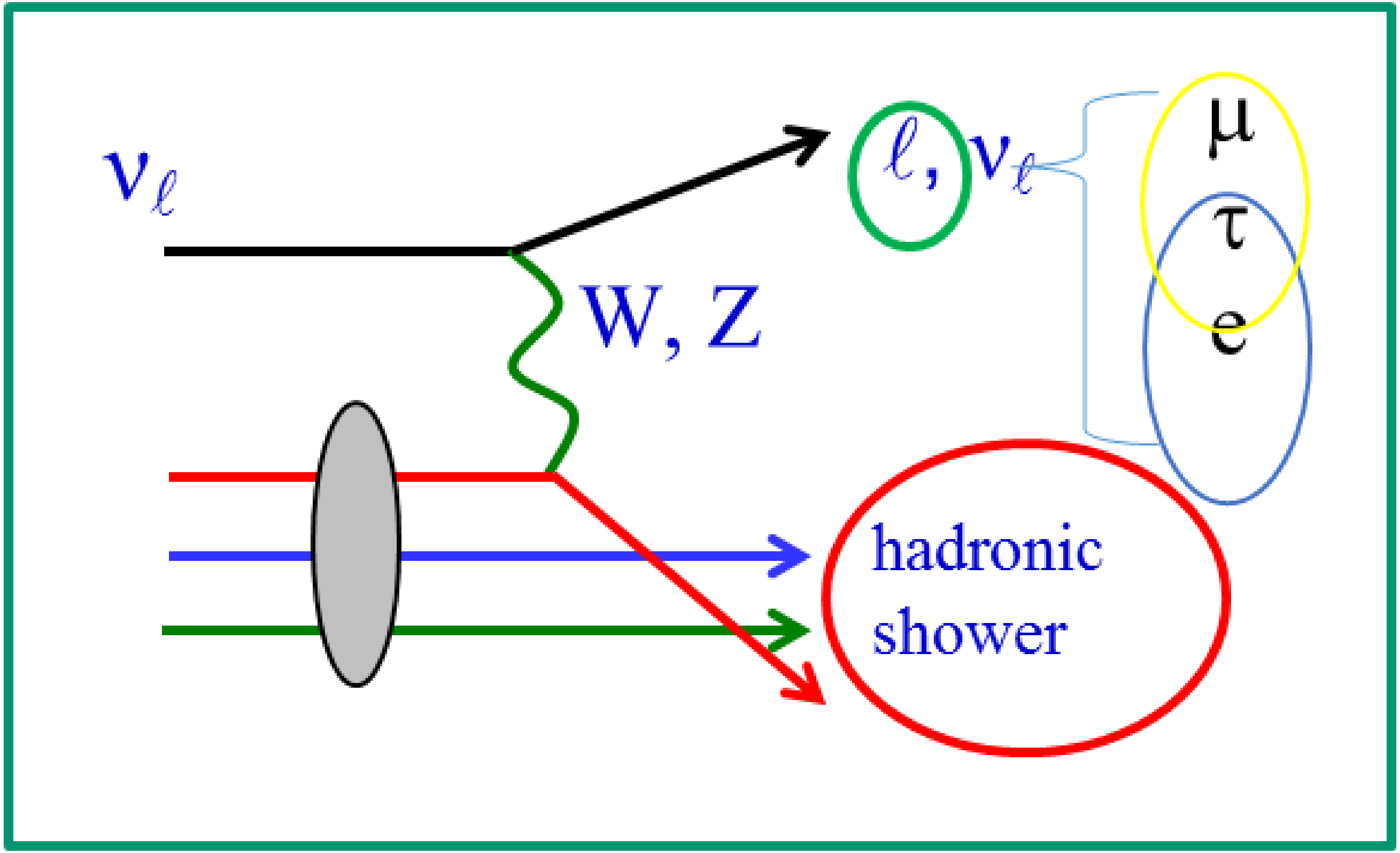
- Atmospheric to astrophysical
  - ~10TeV-100TeV
- Astrophysical neutrinos
  - p+γ interactions or
  - p+p interaction with matter

Cosmogenic (GZK) neutrinos



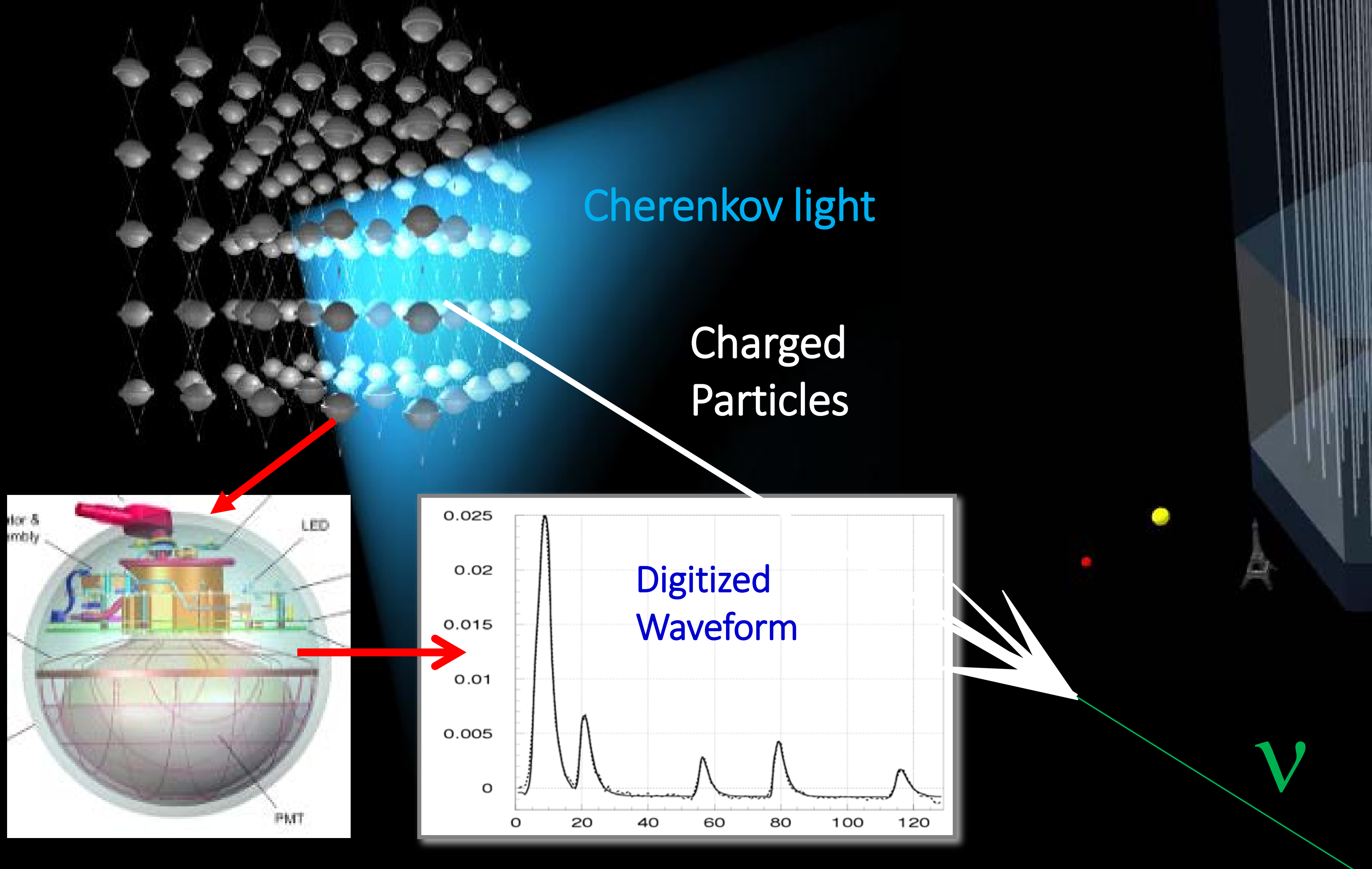
- Greisen-Zatsepin-Kuzmin (GZK) mechanism
  - Off-source (<50Mpc) interactions of cosmic ray and CMB photons

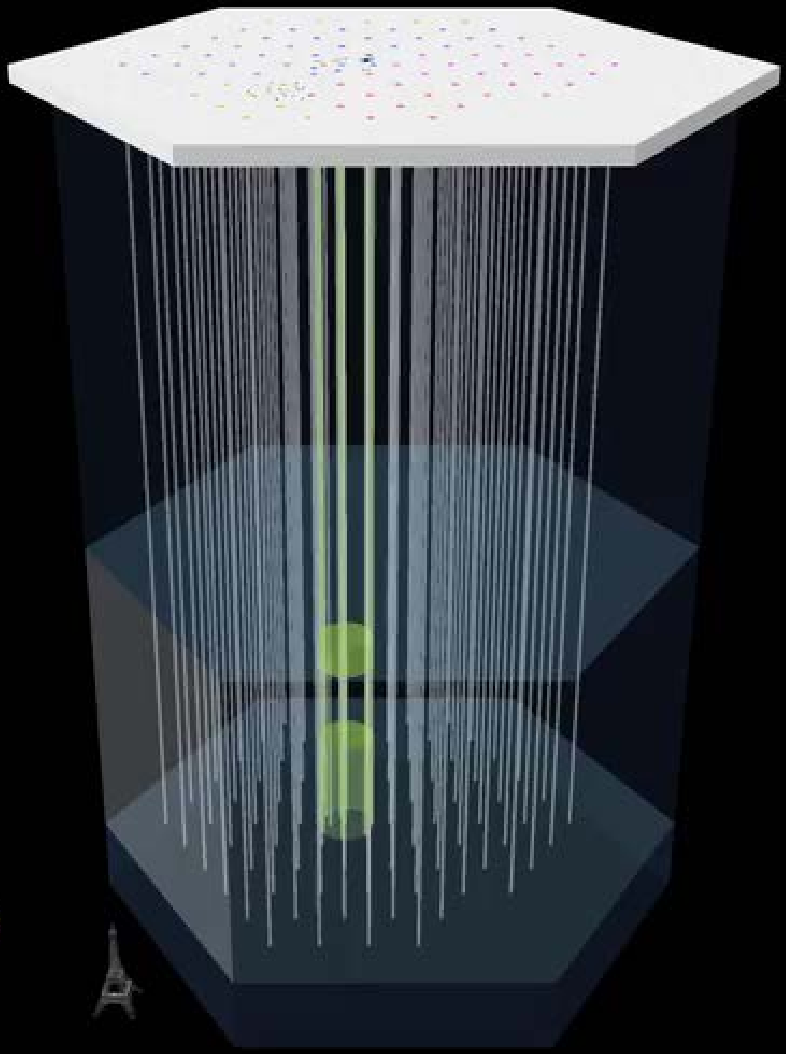
Detecting Neutrinos

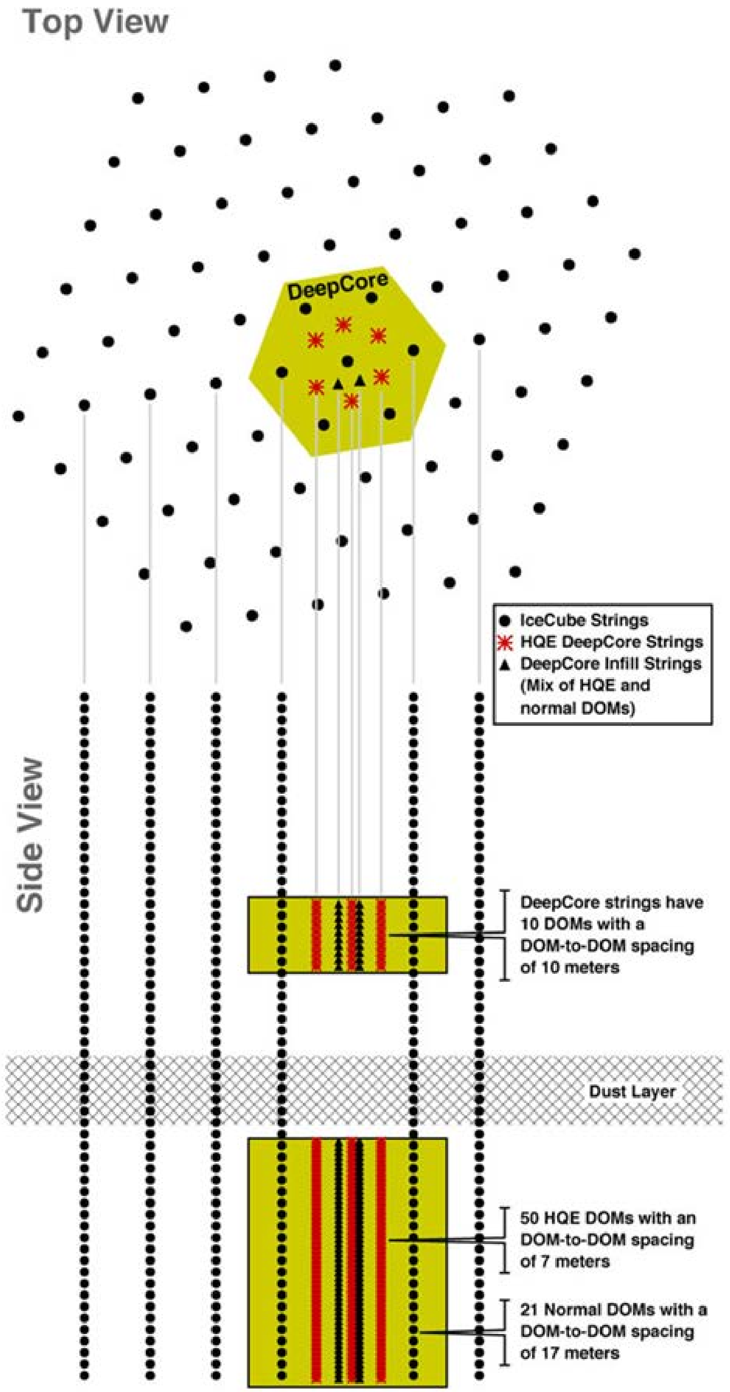


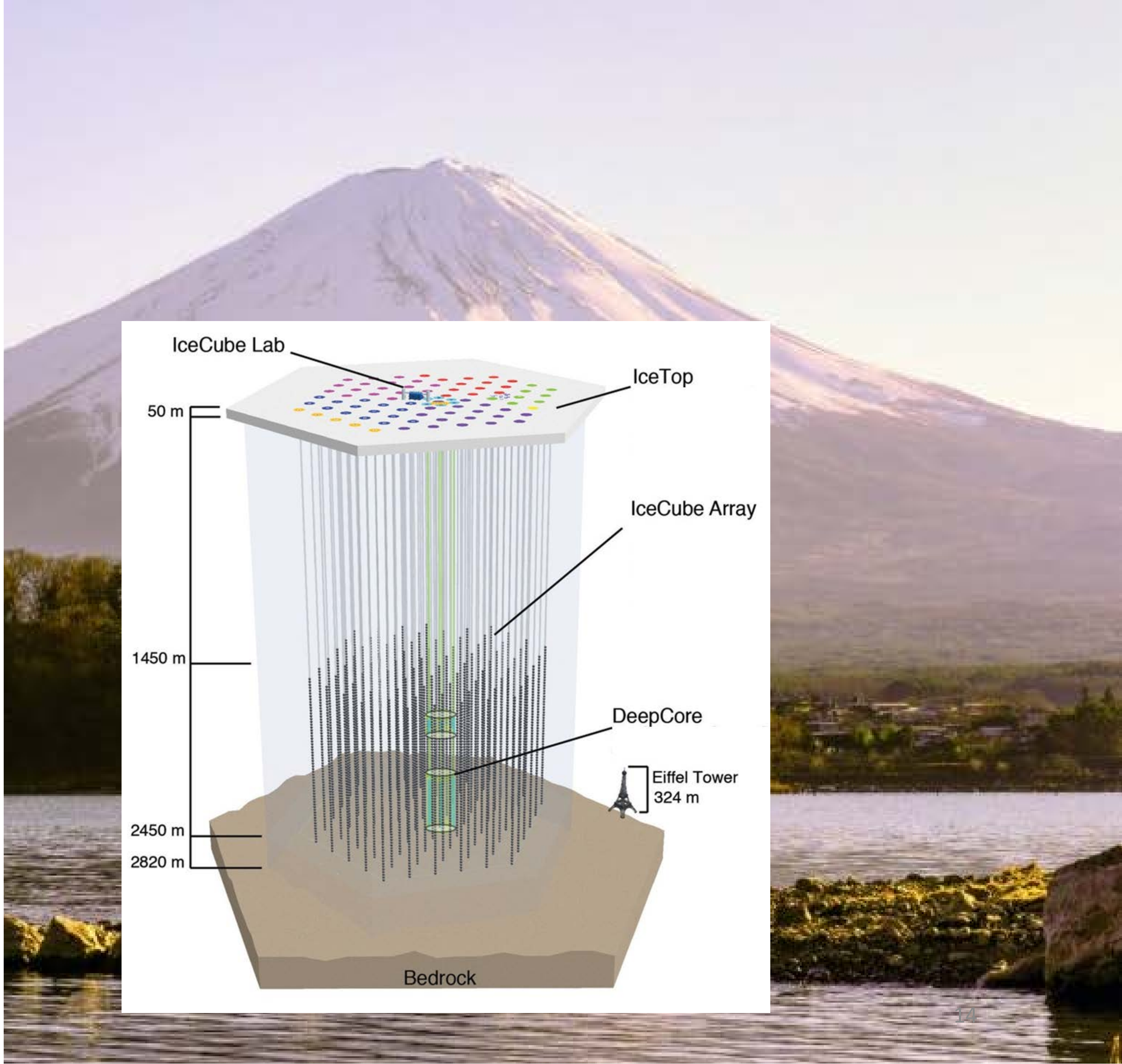
Optical Detection

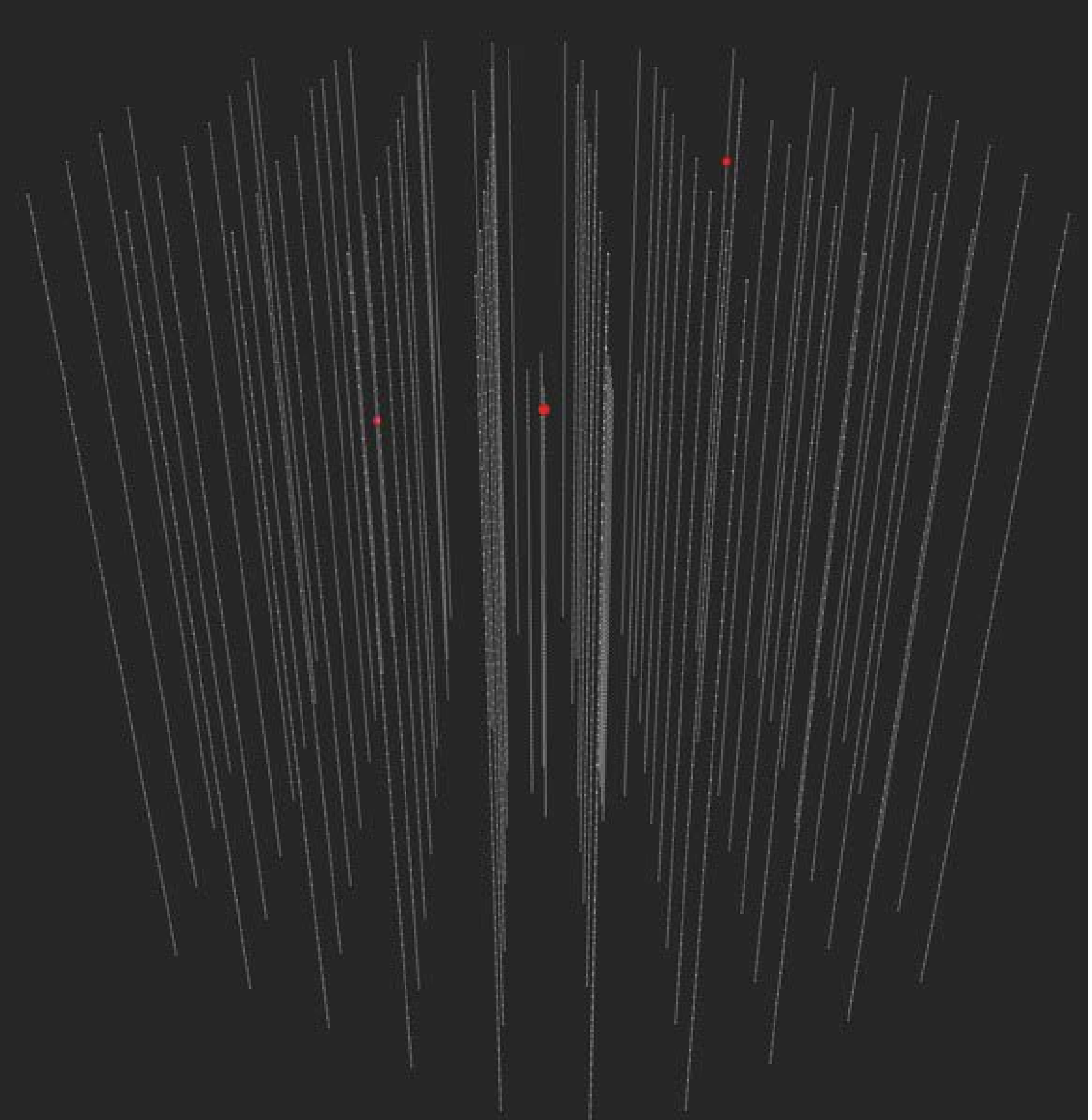
Array of photomultiplier tubes in a dark transparent material

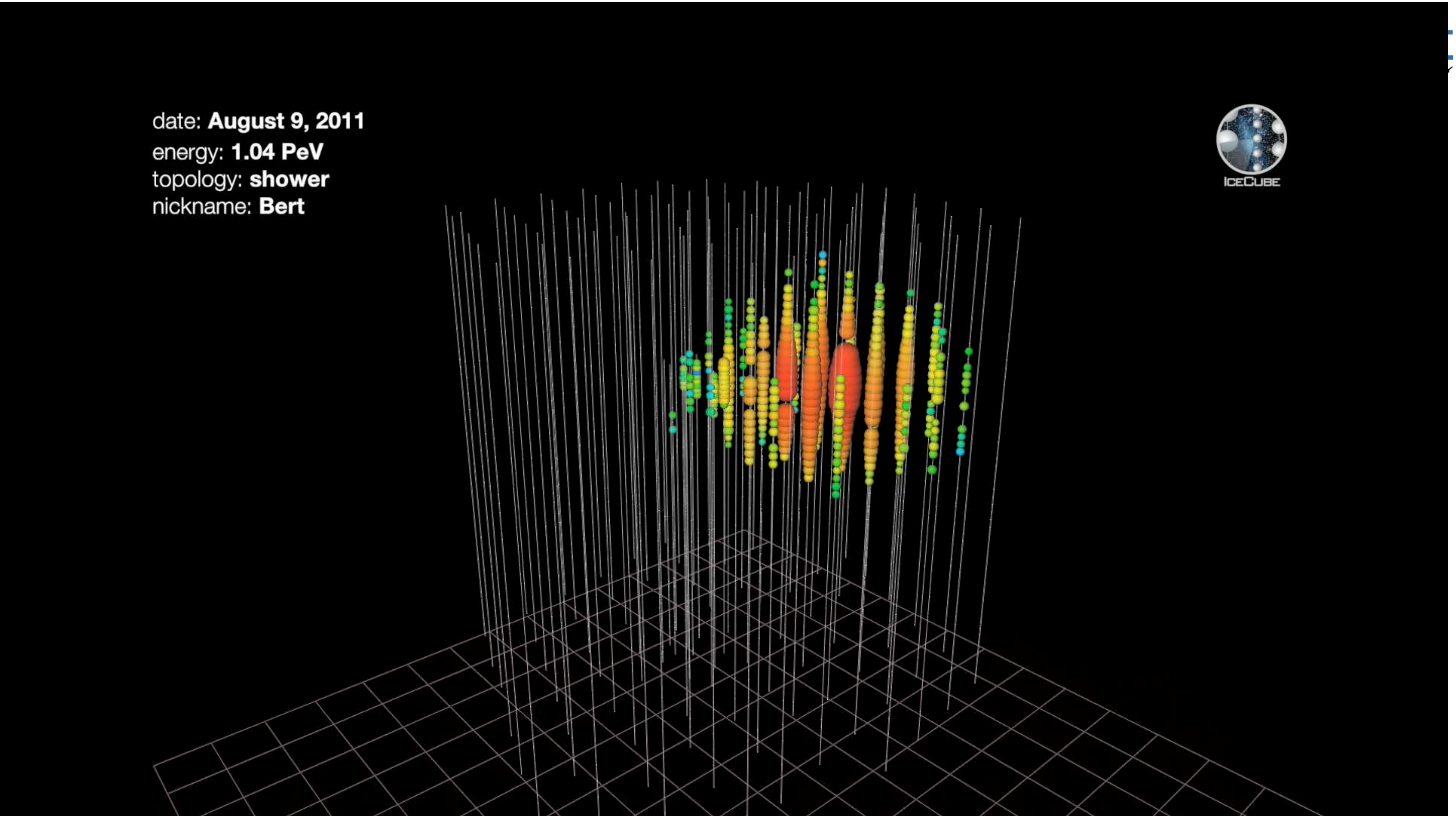




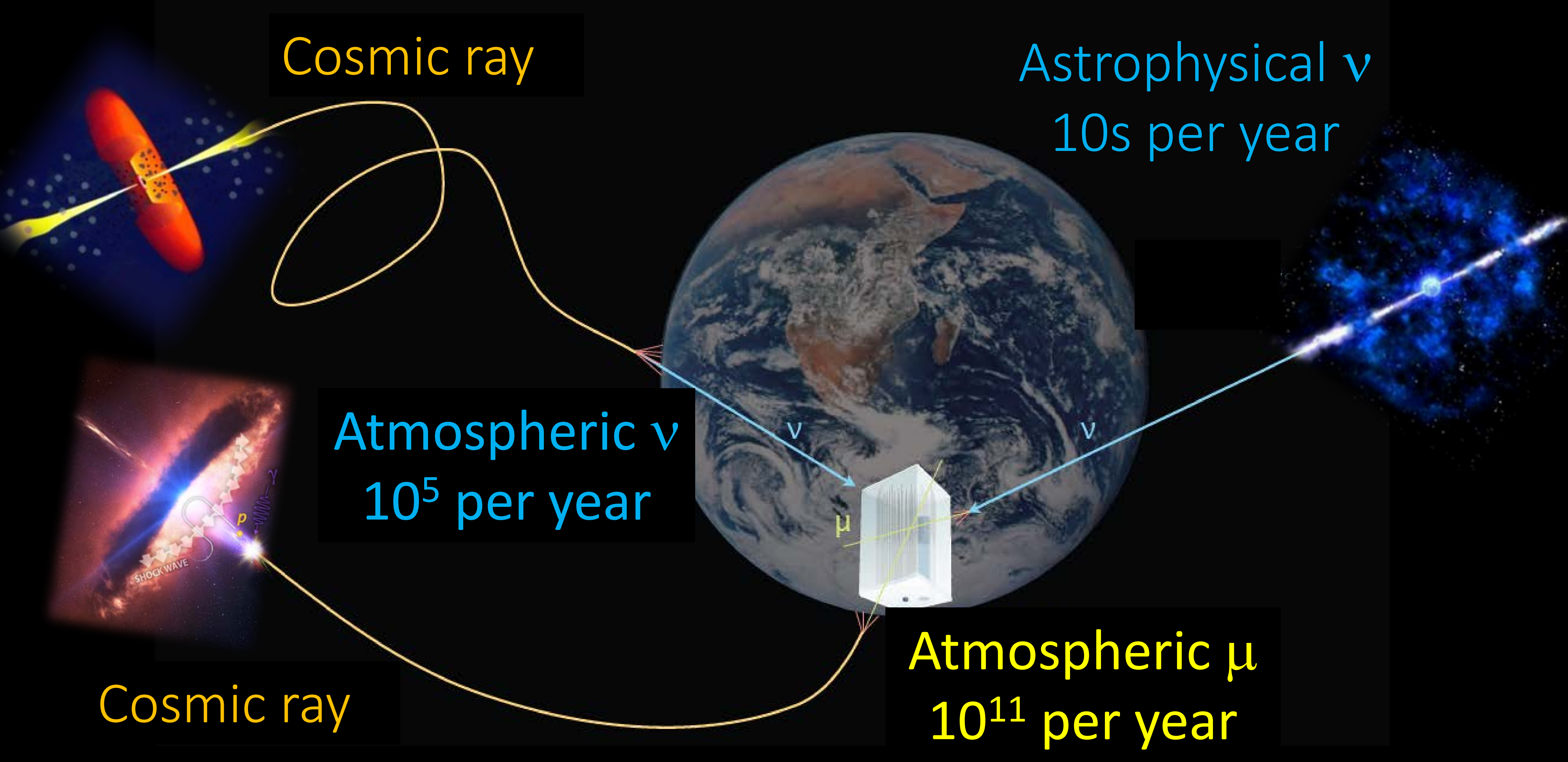

Top View
DeepCore
IceCube Strings
HQE DeepCore Strings
DeepCore Infill Strings (Mix of HQE and normal DOMs)
Side View
DeepCore strings have 10 DOMs with a DOM-to-DOM spacing of 10 meters
Dust Layer
50 HQE DOMs with an DOM-to-DOM spacing of 7 meters
21 Normal DOMs with a DOM-to-DOM spacing of 17 meters


IceCube Lab
IceTop
50 m
IceCube Array
1450 m
DeepCore
Eiffel Tower
324 m
2450 m
2820 m
Bedrock




date: **August 9, 2011**
energy: **1.04 PeV**
topology: **shower**
nickname: **Bert**
ICECUBE

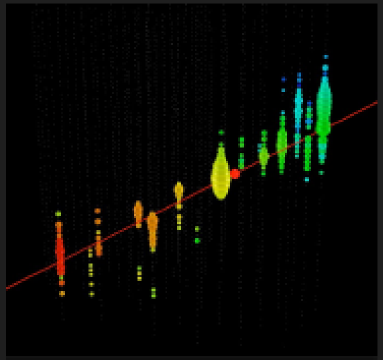
Signals and Backgrounds



IceCube Signals

time

CC Muon Neutrino

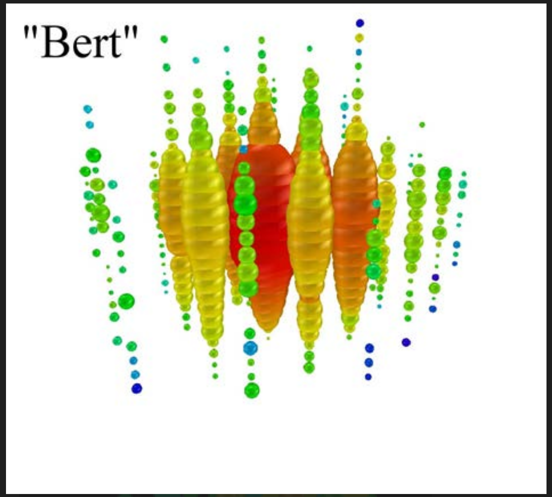


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino



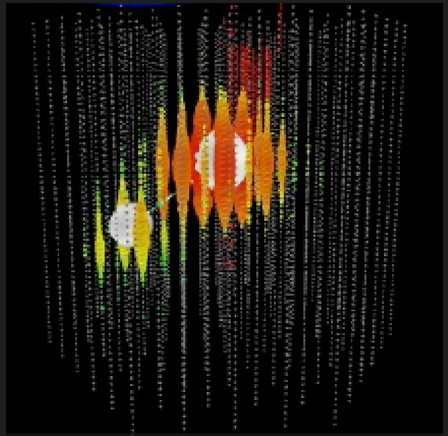
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

CC Tau Neutrino



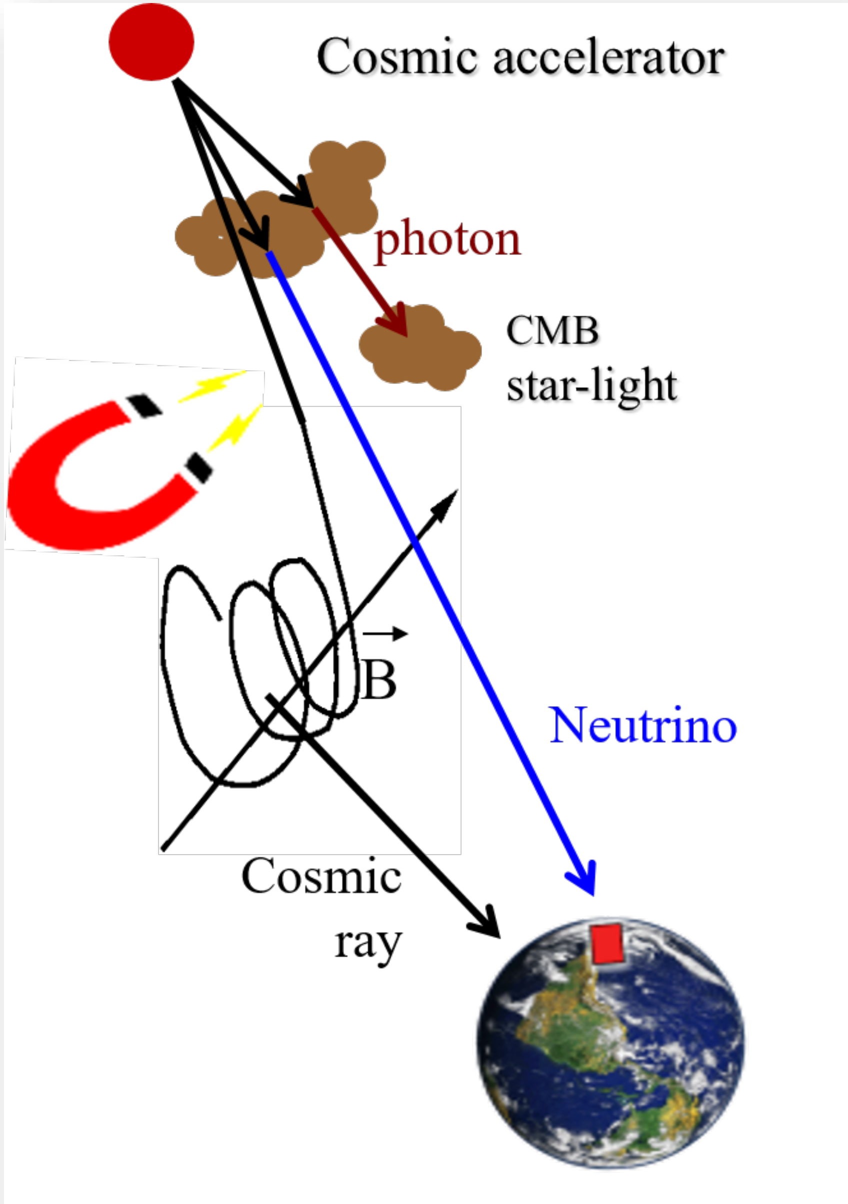
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" (≳10PeV) and other signatures (simulation)

published

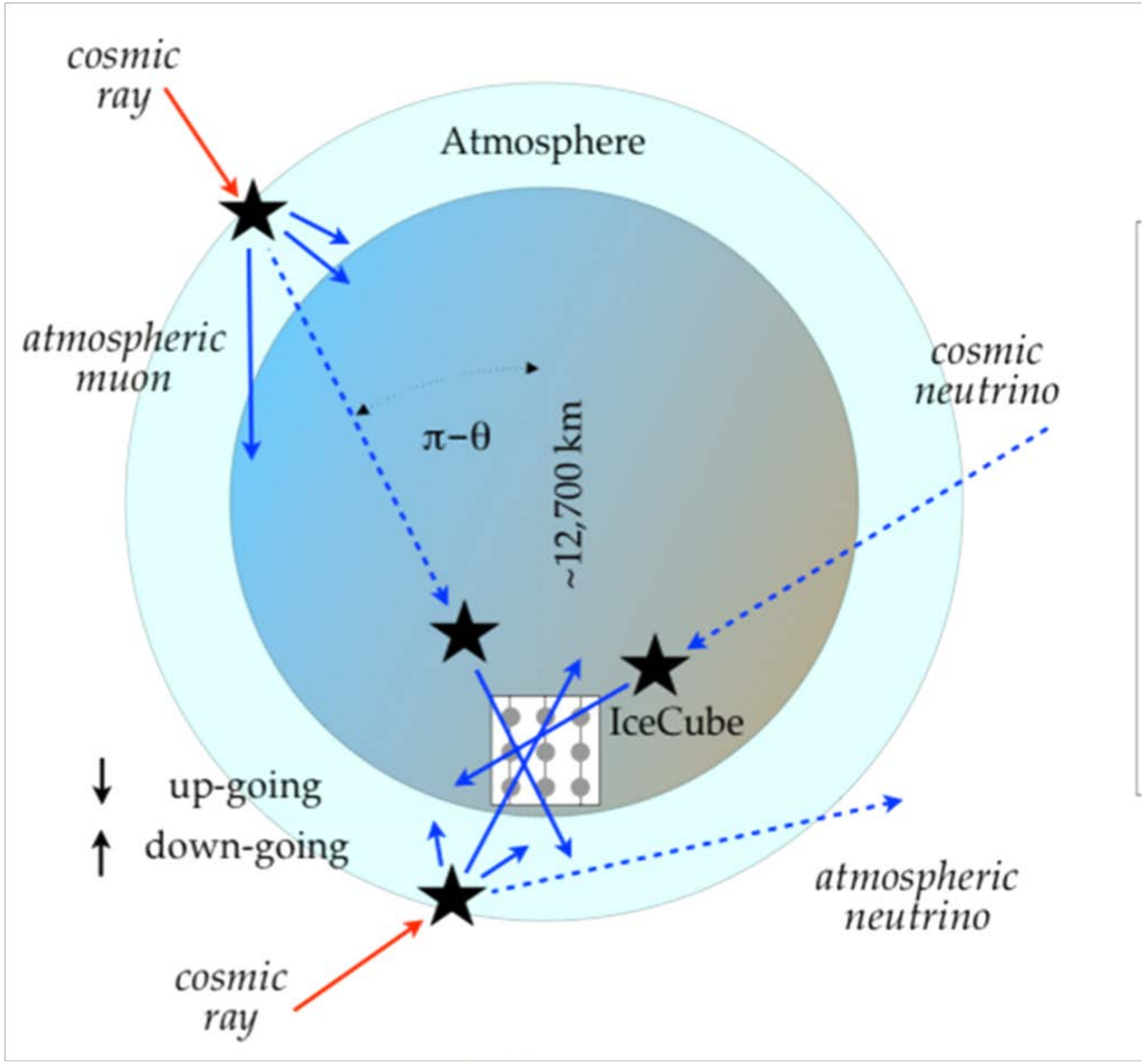
(not observed yet: τ decay length is 50 m/PeV)

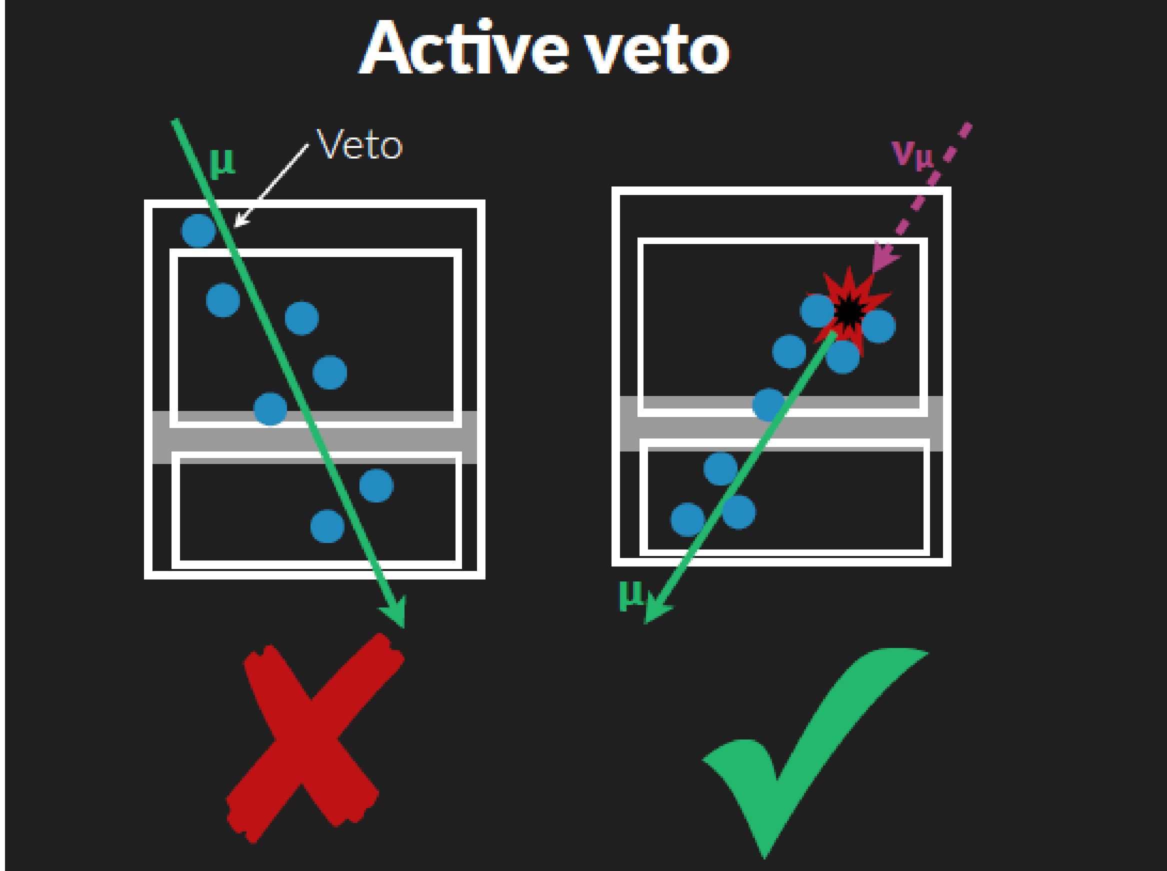
Neutrinos as Cosmic Messengers



- Challenge: Identify astrophysical ν's
  - IceCube yearly events
    - ~10^{11} cosmic ray muons
    - ~10^{5} atmospheric ν's
    - ~10's astrophysical ν's
- Discriminators
  - Energy — Yes
  - Multimessenger — Yes
  - Flavor (tau) — Yes
  - Hotspots — Maybe

Isolating Neutrino Events

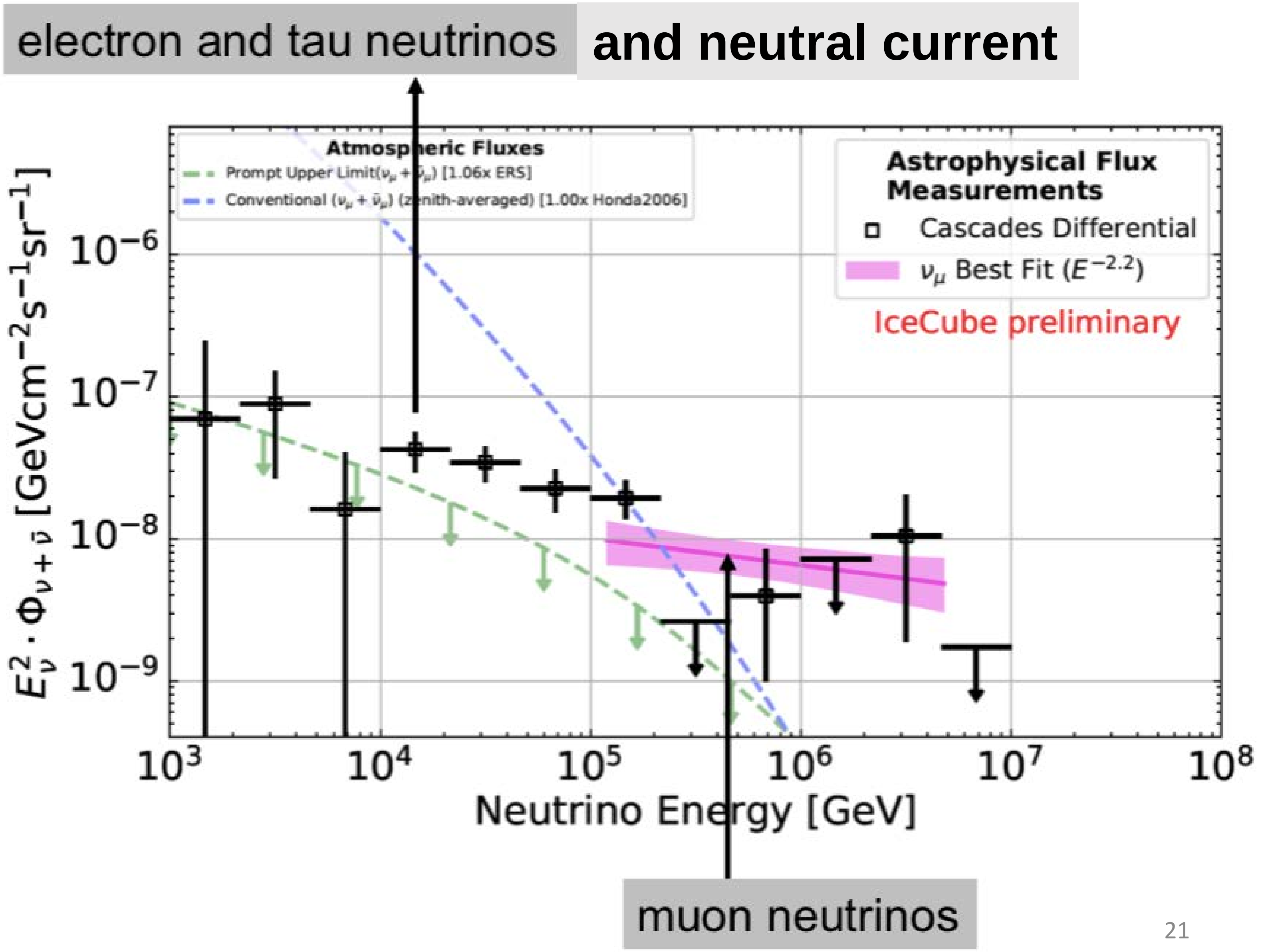




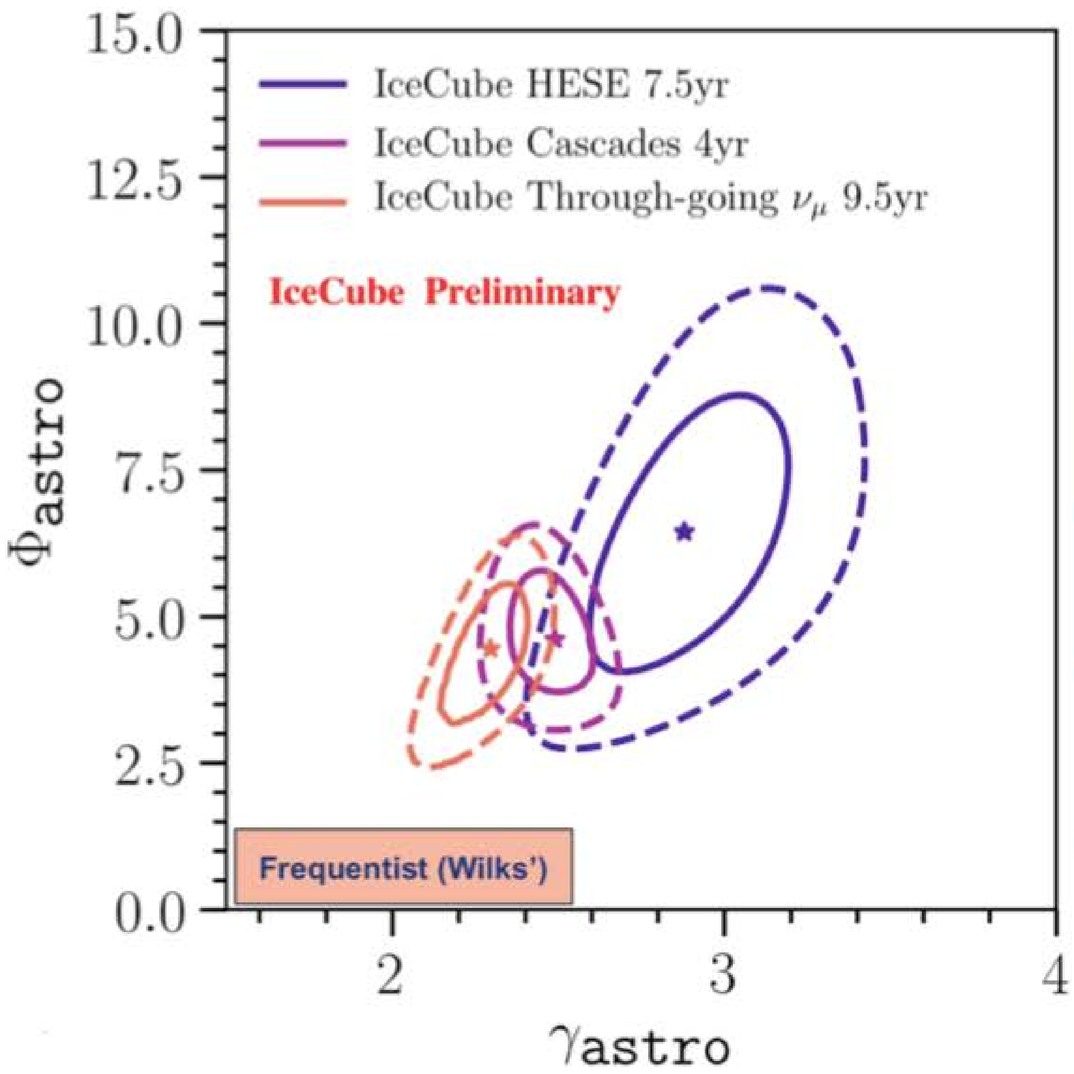
Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky

IceCube Diffuse ν Flux

- A.Schneider PoS(ICRC2019) 1004
- H. Niederhausen PoS(ICRC2017) 968
- J. Stettner PoS(ICRC2019) 1017
- Fig. From F. Halzen (ICRC2019)



IceCube Diffuse ν Flux



$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\mathrm{astro}} \left(\frac{E_\nu}{100\mathrm{TeV}} \right)^{-\gamma_{\mathrm{astro}}} \cdot 10^{-18}\ [\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$$

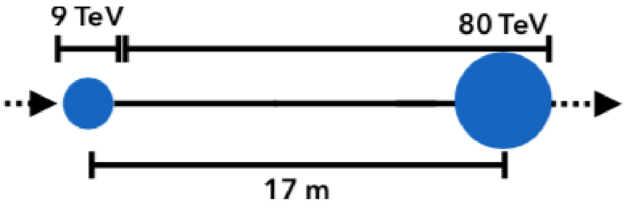
Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ, τ	2.89
Cascades	5 TeV - 5 Pev	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

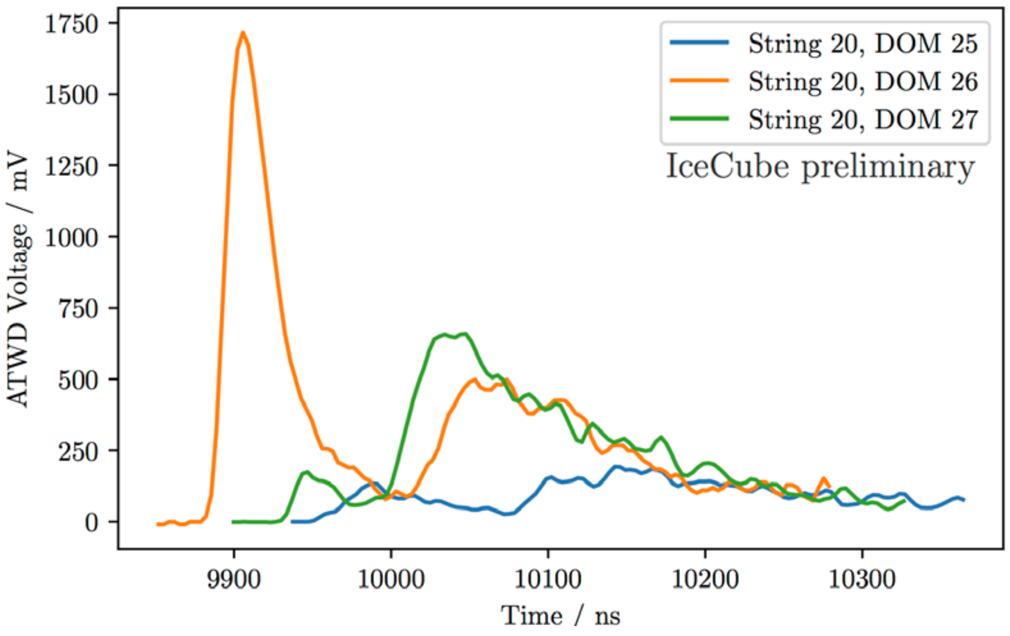
Differences in single power-law parameters not in tension with each other but may hint at an additional spectral structure

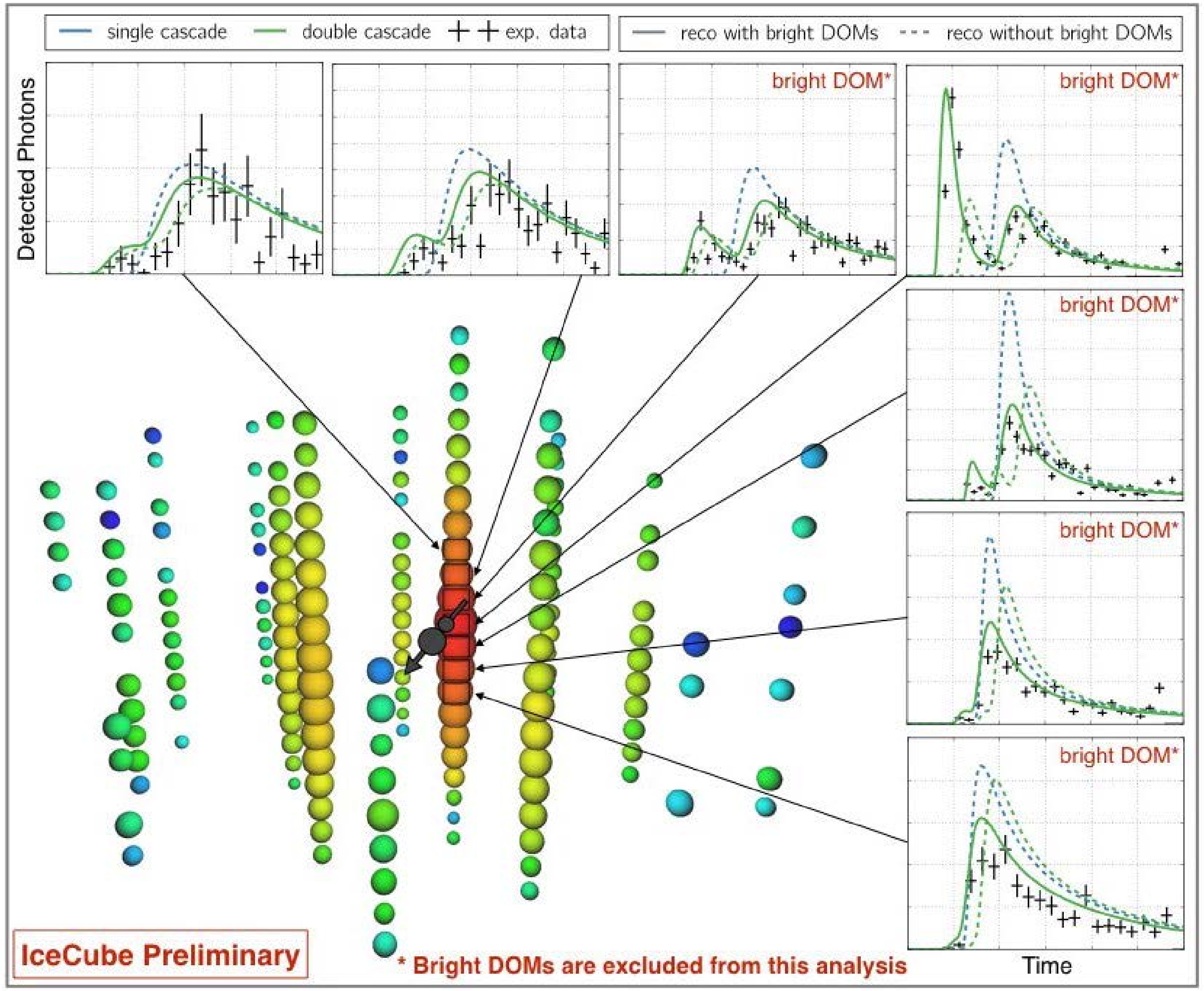
A. Kappes, D. Williams (ICRC2019)

IceCube Diffuse ν Flux: Flavor

- 7.5 year HESE all-flavor ν sample
  - Double cascades, double pulse searches
  - First identification of ν_τ

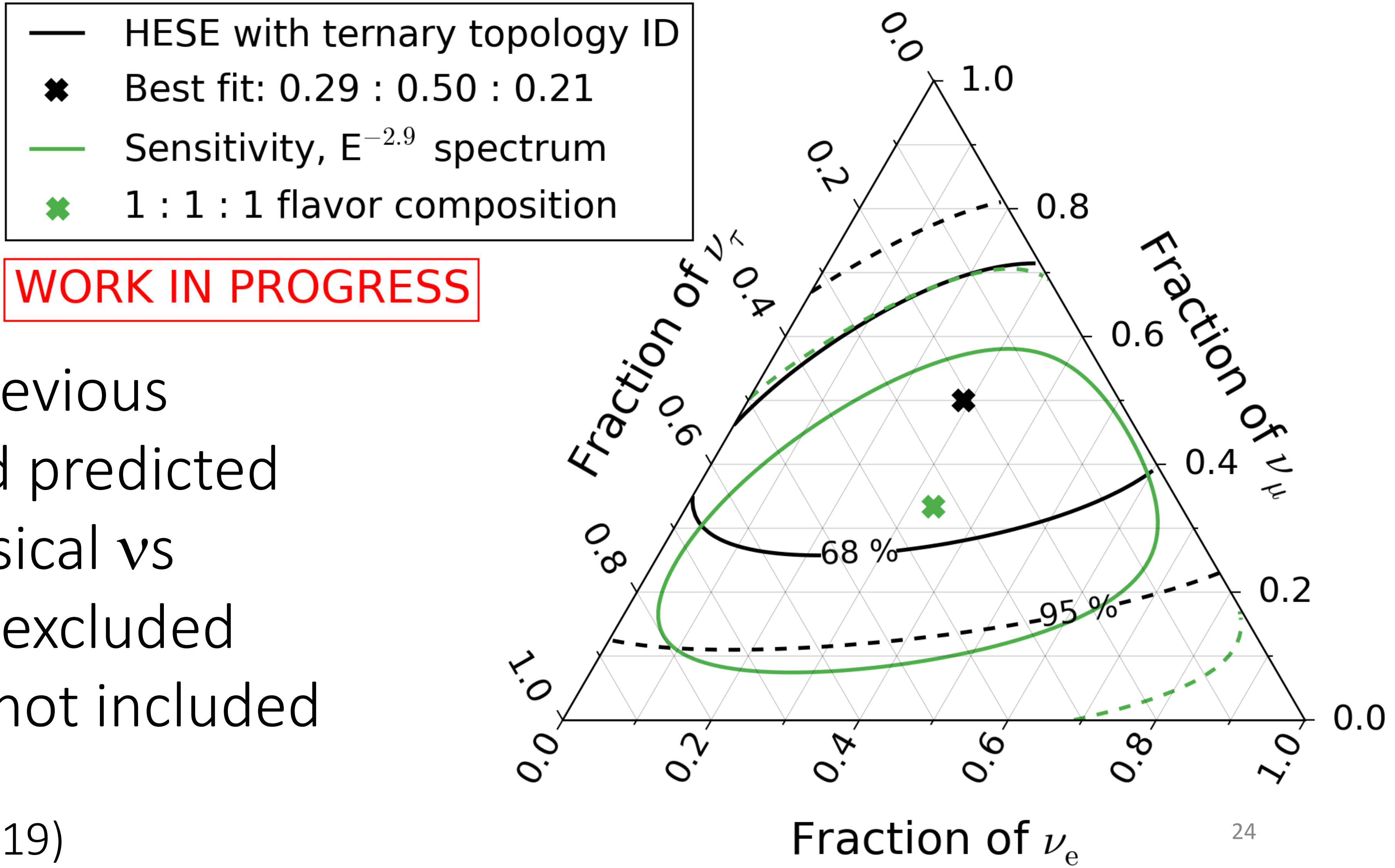






J. Soedingrekso, L. Wille (ICRC2019)

IceCube Diffuse ν Flux: Flavor

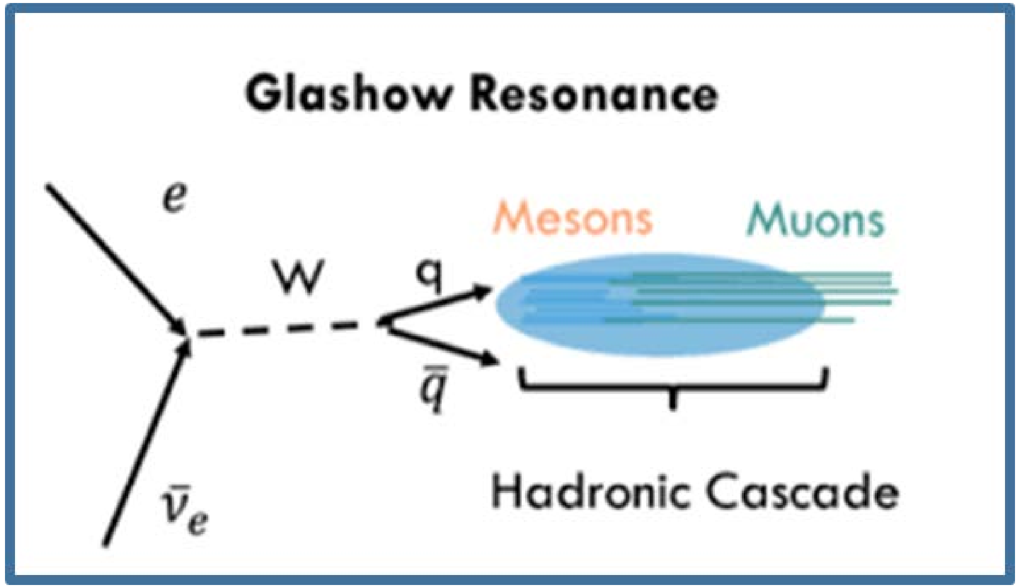


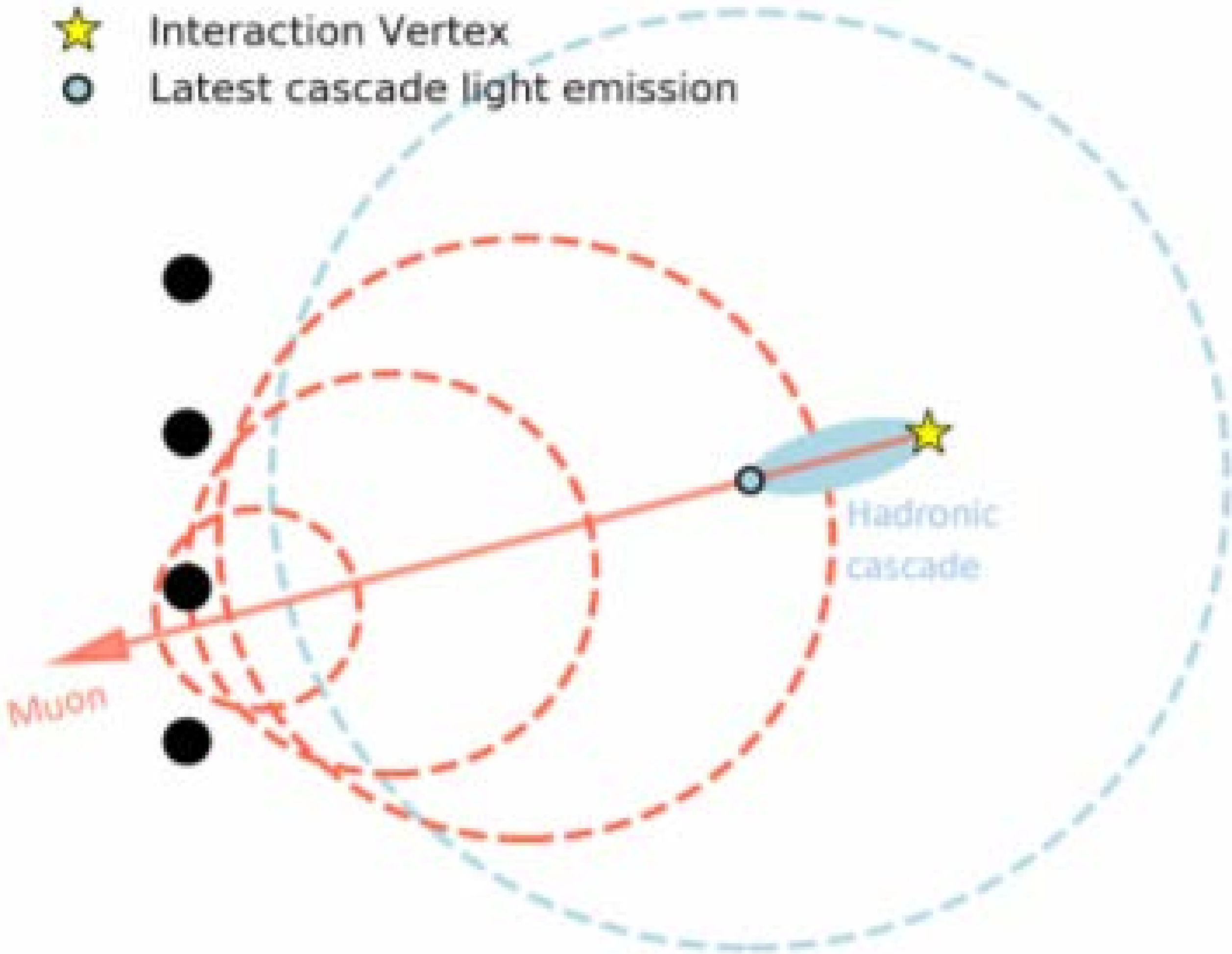
- Consistent with previous IceCube result and predicted 1:1:1 for astrophysical νs
- Zero ν_τ cannot be excluded
- Systematic errors not included

J. Stachurska (ICRC2019)

Glashow Resonance

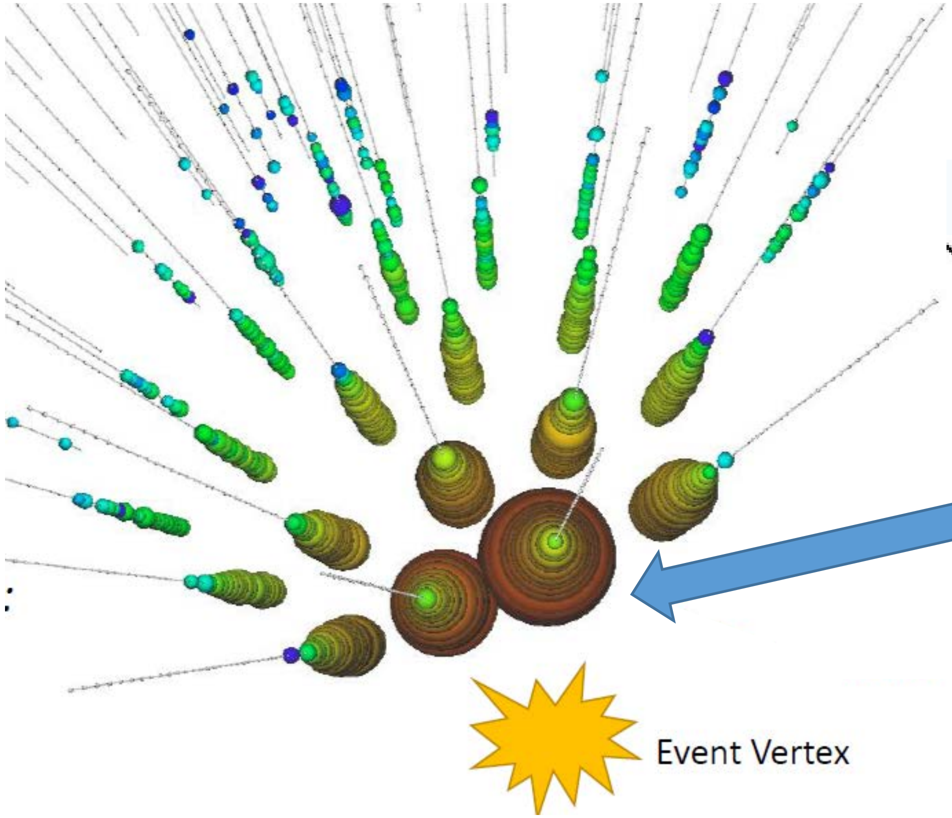
- Creates real W-boson
- W decays hadronically producing muons
- Muons travel ahead of Cherenkov light
- Early light signature

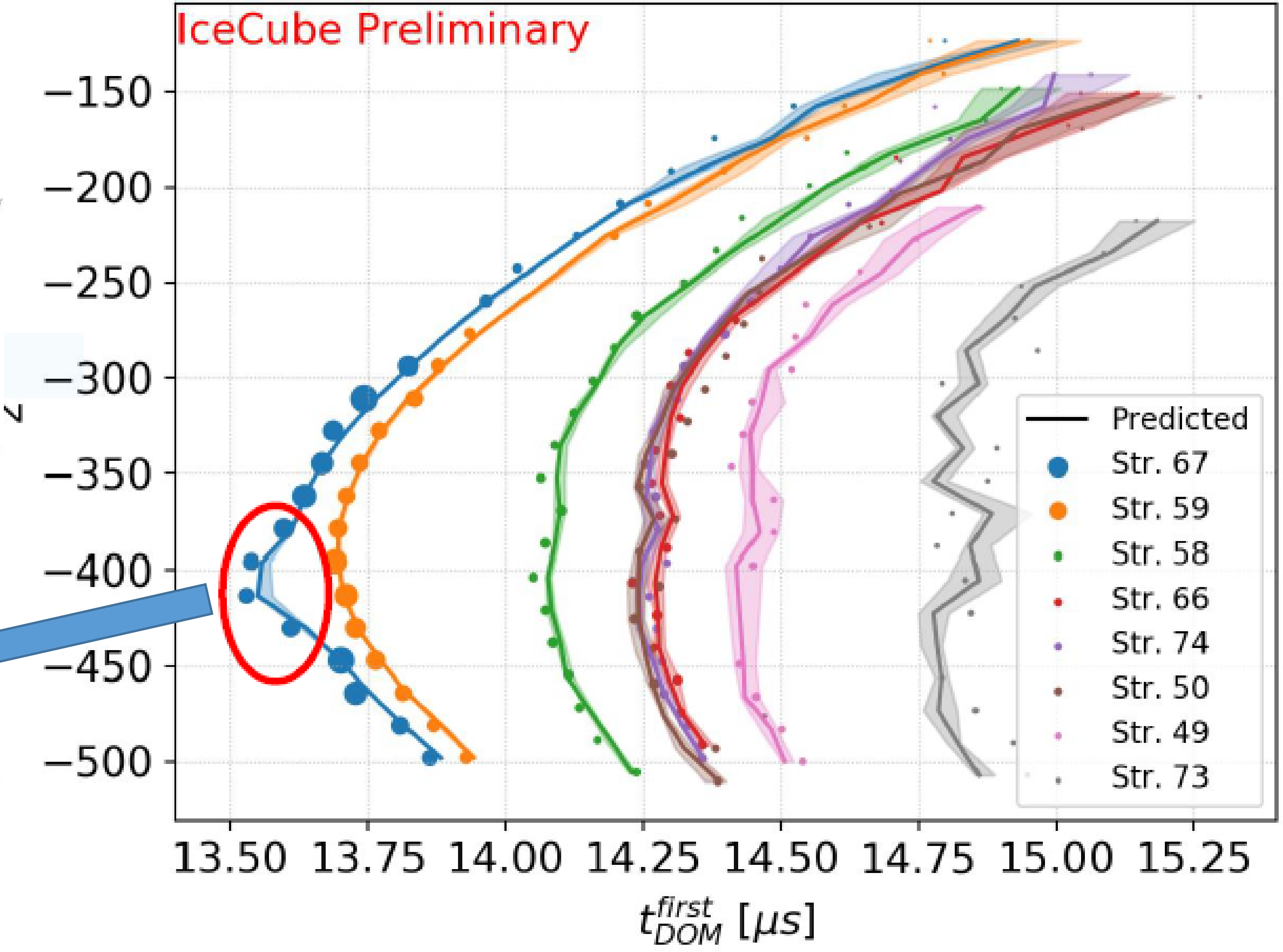




Glashow Resonance Candidate

- 6.3 PeV neutrino energy

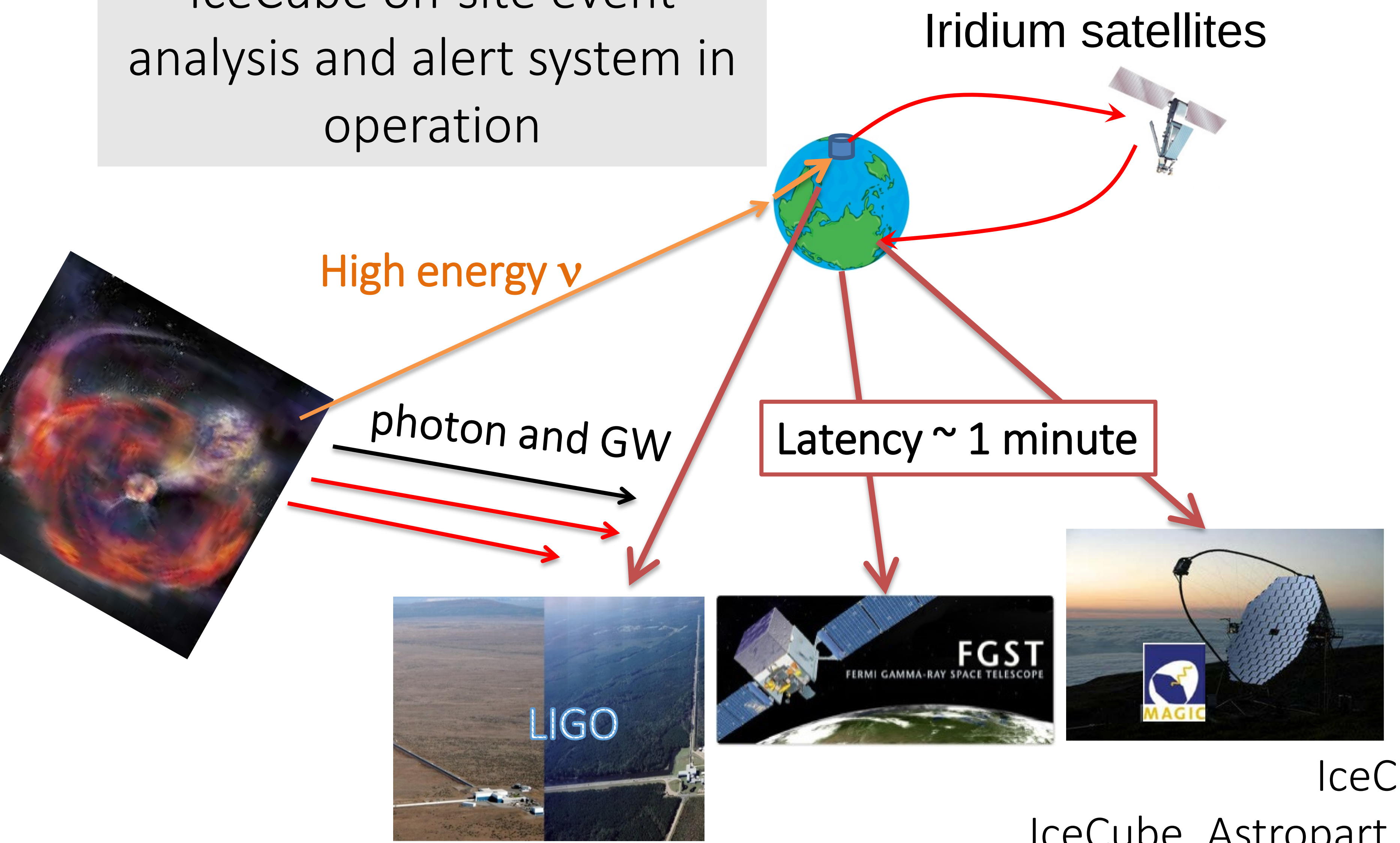




L. Lu (ICRC2019)

Neutrino Online Alert System

IceCube on-site event analysis and alert system in operation

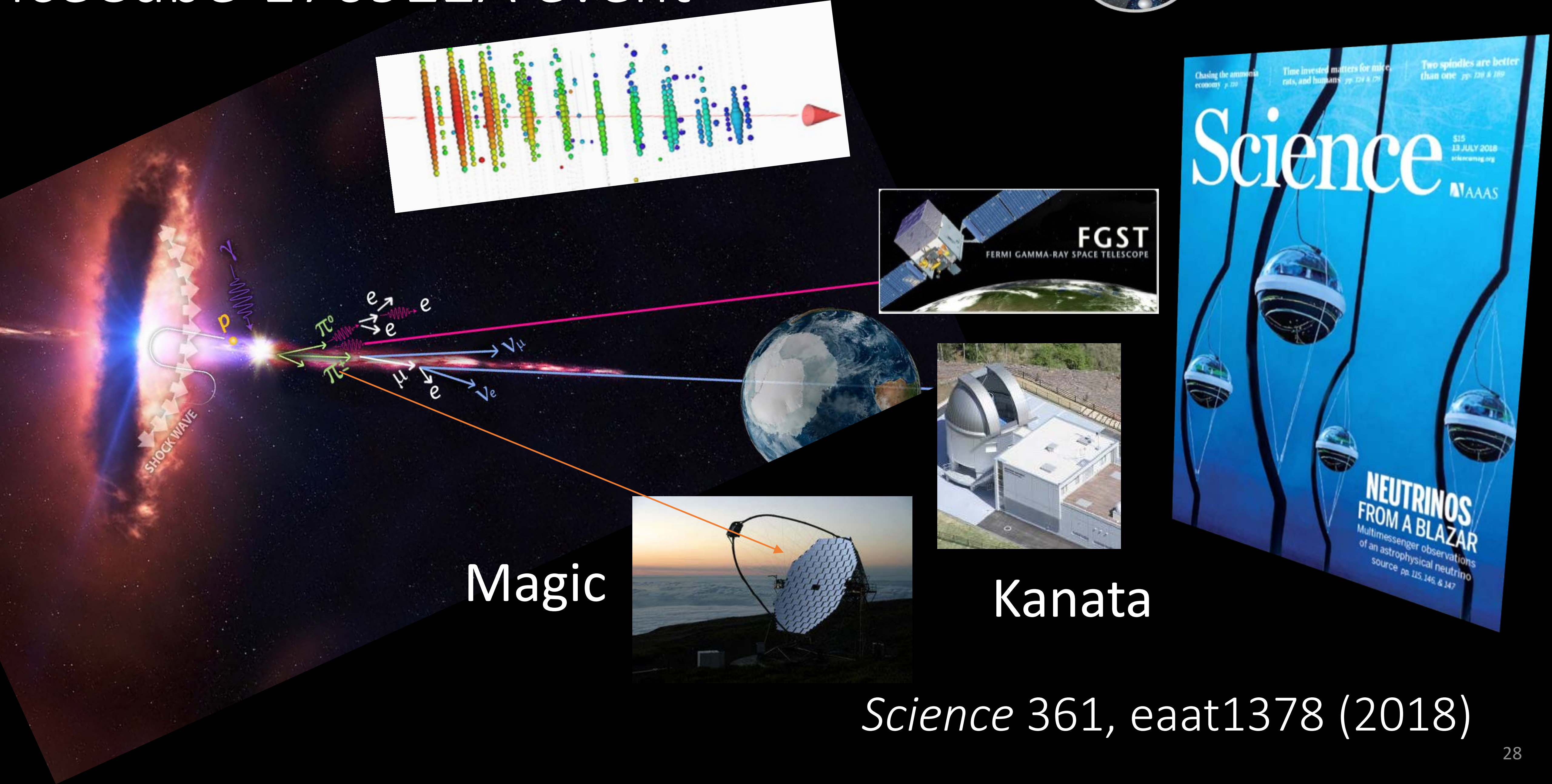


Before 2016 April, private alert system existed. BUT background dominant

April 2016: Activated public online channel with signal efficiency of >30-50% (EHE and HESE channels)

IceCube, 1309.6979 (ICRC)
IceCube, Astropart. Phys. 92 (2017) 30-41

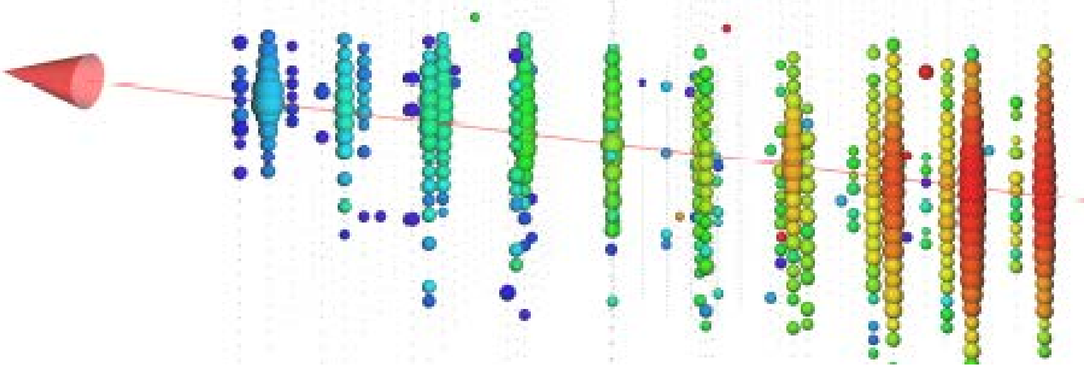
IceCube-170922A event



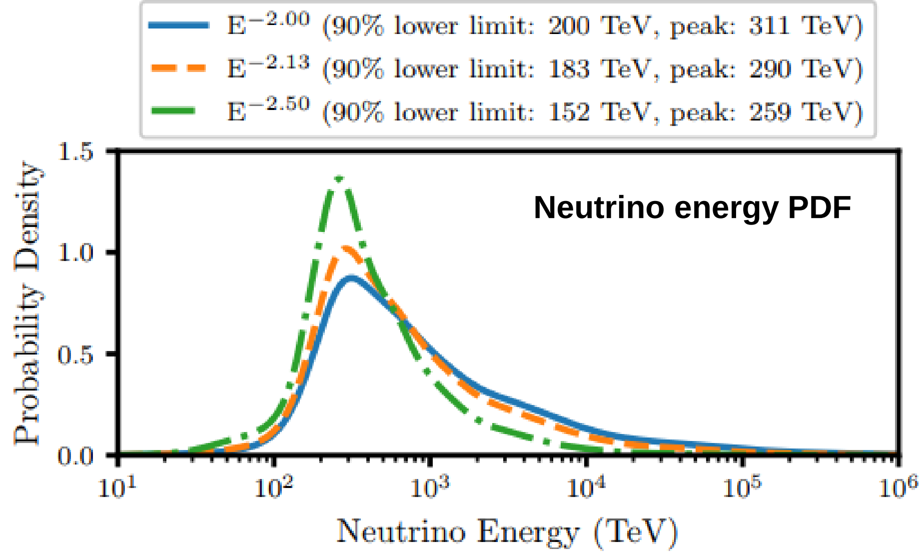
Science 361, eaat1378 (2018)

IceCube-170922A Follow up

23.7 ± 2.8 TeV muon energy loss in the detector

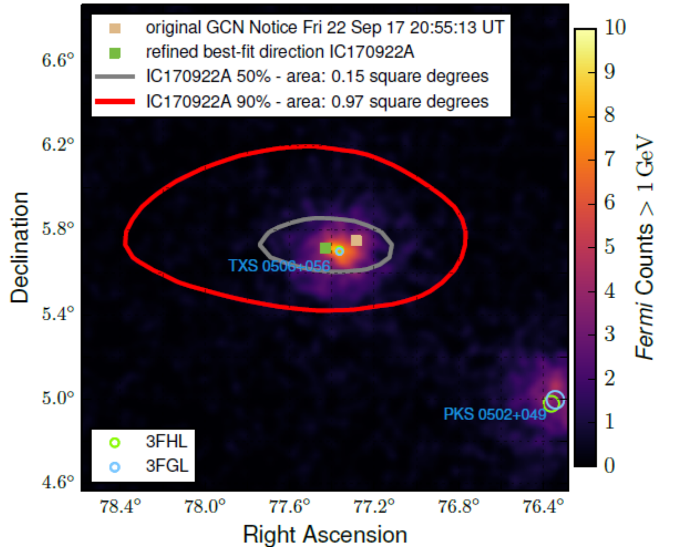


a most probable neutrino energy of 290 TeV



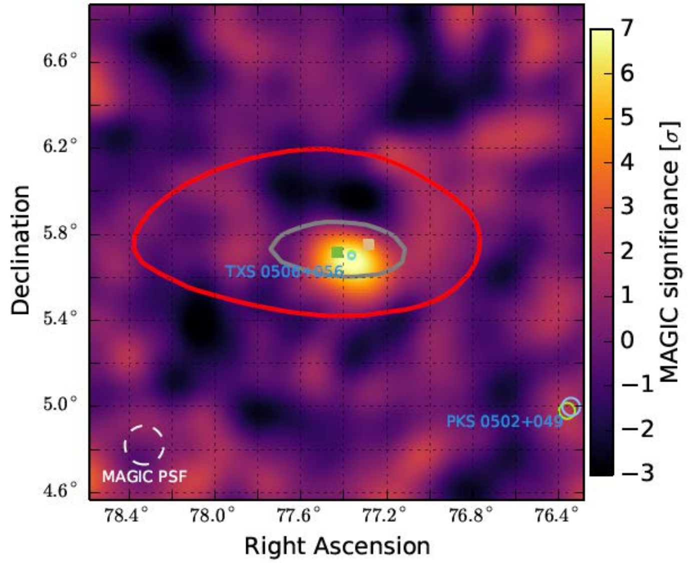
HE γ observations

- Fermi-LAT(20MeV - 300 GeV) reported gamma-ray flaring blazer TXS 0506+056 (ATel#10791)

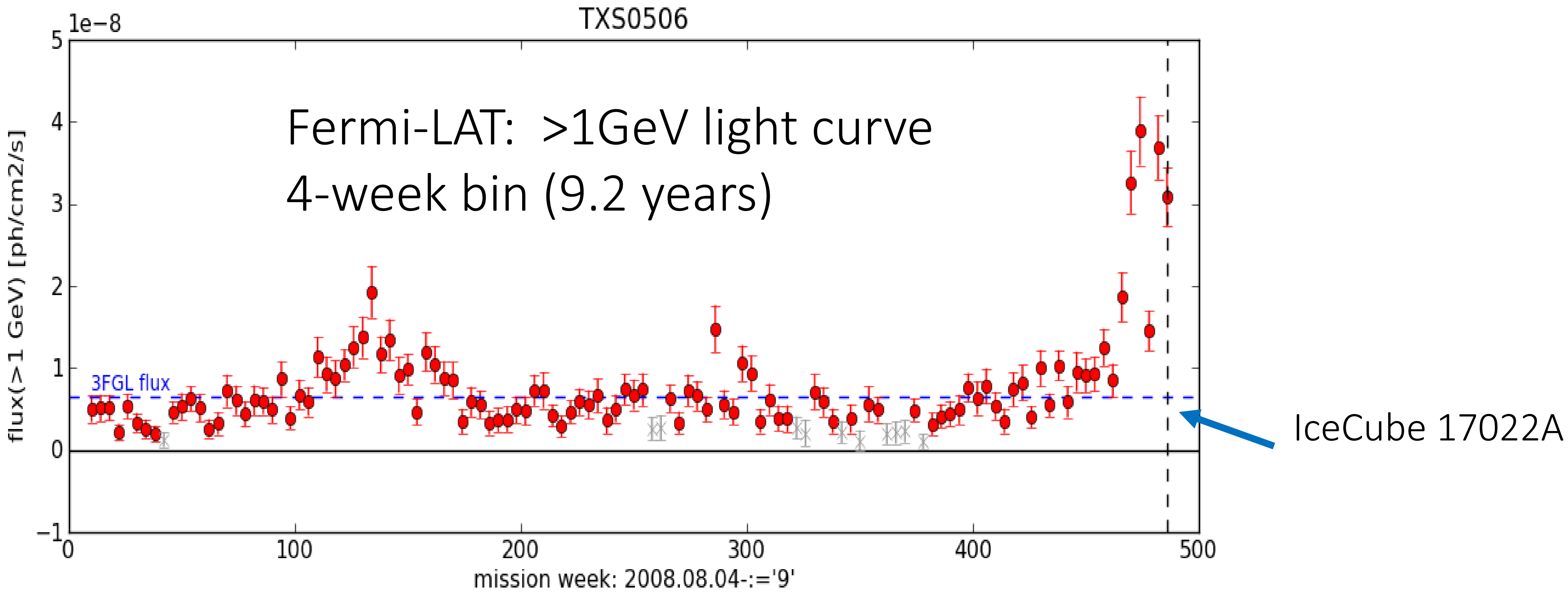


VHE γ observations

- Magic telescope (E > 100GeV) saw TXS 0506+056 at >6.2σ (ATel#10817)



ν–γ Correlation Analysis



no correlation vs correlation → 4.1σ → Corrections 10 previous alerts and 41 archival events → ≈3σ

Independent Point Source Analysis

IceCube Collaboration
Science 361, 147-151 (2018)

- $L = \prod_i^N (\frac{n_s}{N} P_S + \frac{n_b}{N} P_B)$

- $P_S = P_{spatial}(\vec{x}) \cdot \mathrm{W}_{\mathrm{energy}}(\mathrm{E}_{\mathrm{reco}}, \sin\theta) \cdot W_{temporal}(t)$

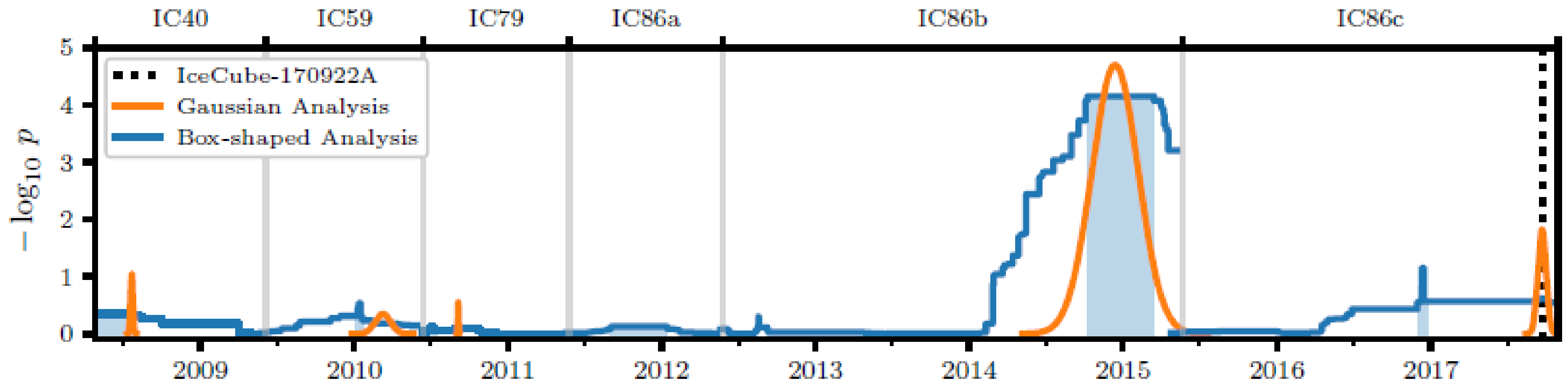
2D Gaussian

θ-dependent acceptance x power-law signal flux
parameters: spectral index and normalization

square and Gaussian
parameters: center time and time window

- Signal+BG hypothesis vs BG only
- Best fit ($n_s = 13.3, \gamma = 2.1, T_0, =$ 2014 Dec 13, $T_W = 110 days$)
- $p = 2.0 \times 10^{-4}$, corresponds to 3.5σ

- p-values from scrambled data
- Corrected look-elsewhere effect



Walter Winter's ICRC 2019 Talk

Summary (long)

Interpretation in terms of one-zone models

😀 Simplest possible geometry, few parameters

😀 Describe SED and time response reasonably well (modulo some discussion of UV data)

🧐 Have to accept that <u>either</u> L_{edd} is significantly exceeded <u>or</u> that neutrino energies does not match

🧐 2014-15 neutrino flare: more than two neurino events difficult to accommodate

Interpretation in terms of multi-zone models:

😀 External radiation fields (e.g. disk, sheath) or compact core models promising

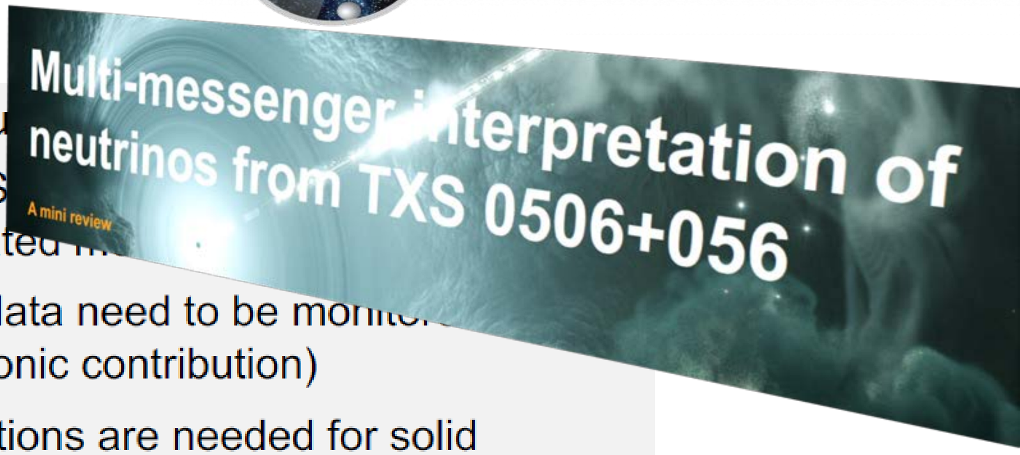
😀 Can produce substantially larger neutrino event numbers with reasonable energetics

😀 Some models (compact core, jet-cloud) can produce a spectral hardening in gamma-rays (2014-15 flare)

🧐 Too early for solid conclusions, mostly because of sparseness of data

What did we learn qu

- Time-response of S leptonically dominated
- X-ray/gamma-ray data need to be monito (indicative for hadronic contribution)
- More such associations are needed for solid conclusions on predicted neutrino event rates

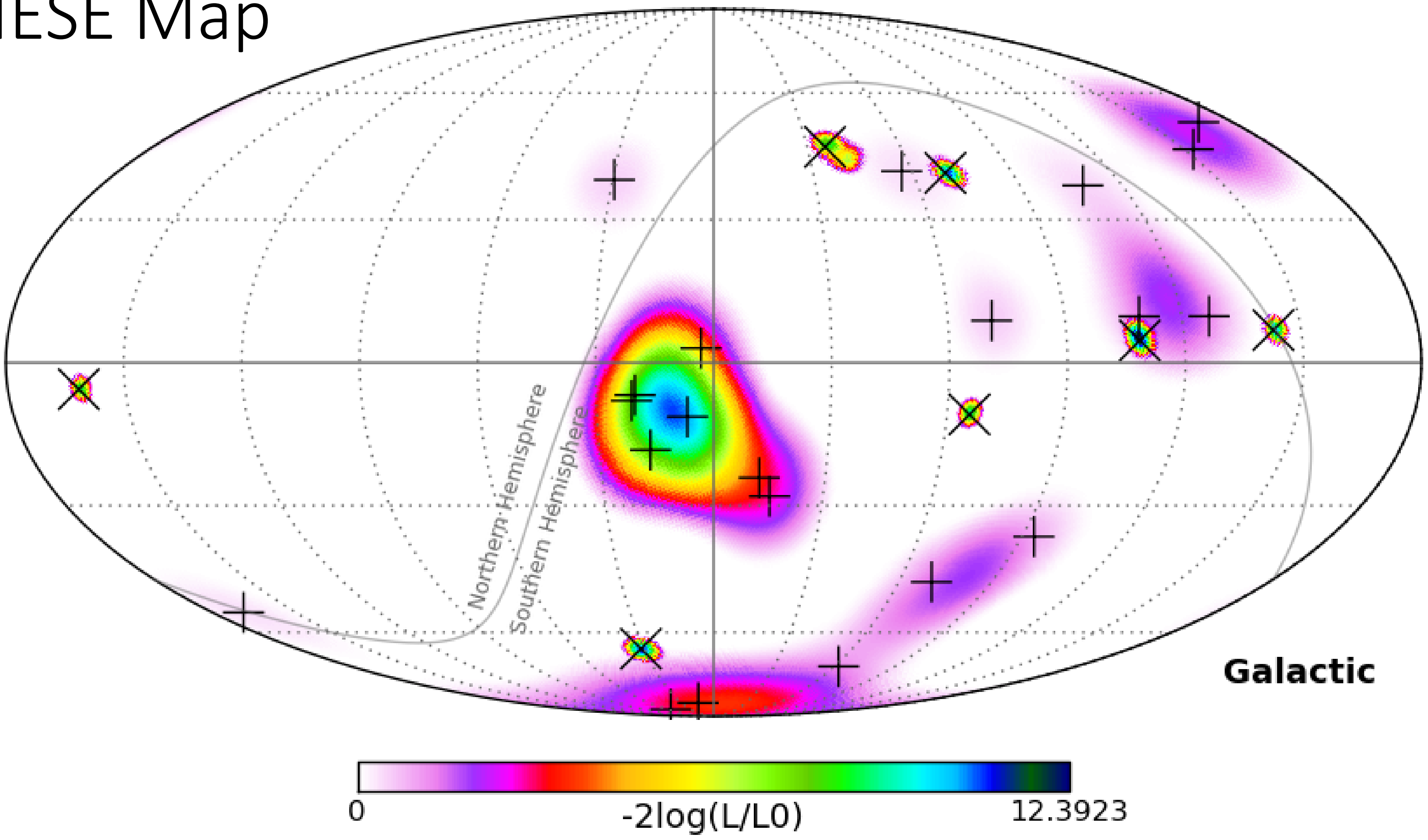


What did we learn qualitatively from 2014-15 flare?

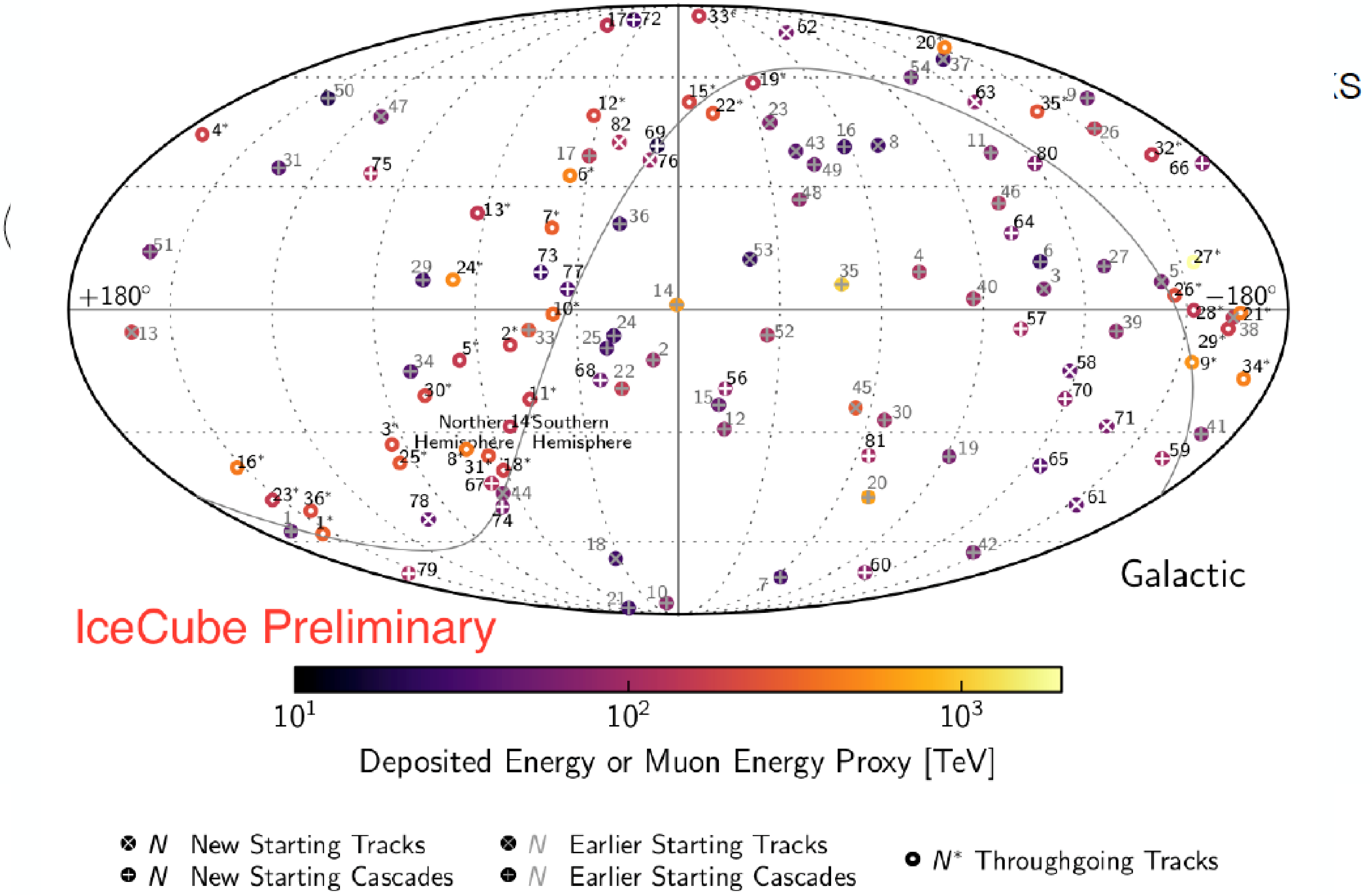
- Description of 13 events requires high radiation density with imprints in the SED which seem to be *in contradiction to observations*
- Up to five events plausible in external radiation field model
- Expected (neutrino) spectral shape very different from IceCube analysis (power law). Consequences?
- Need multi-wavelength monitoring to exclude that signal shows up elsewhere

Evolution of Point Source Search

2 year HESE Map

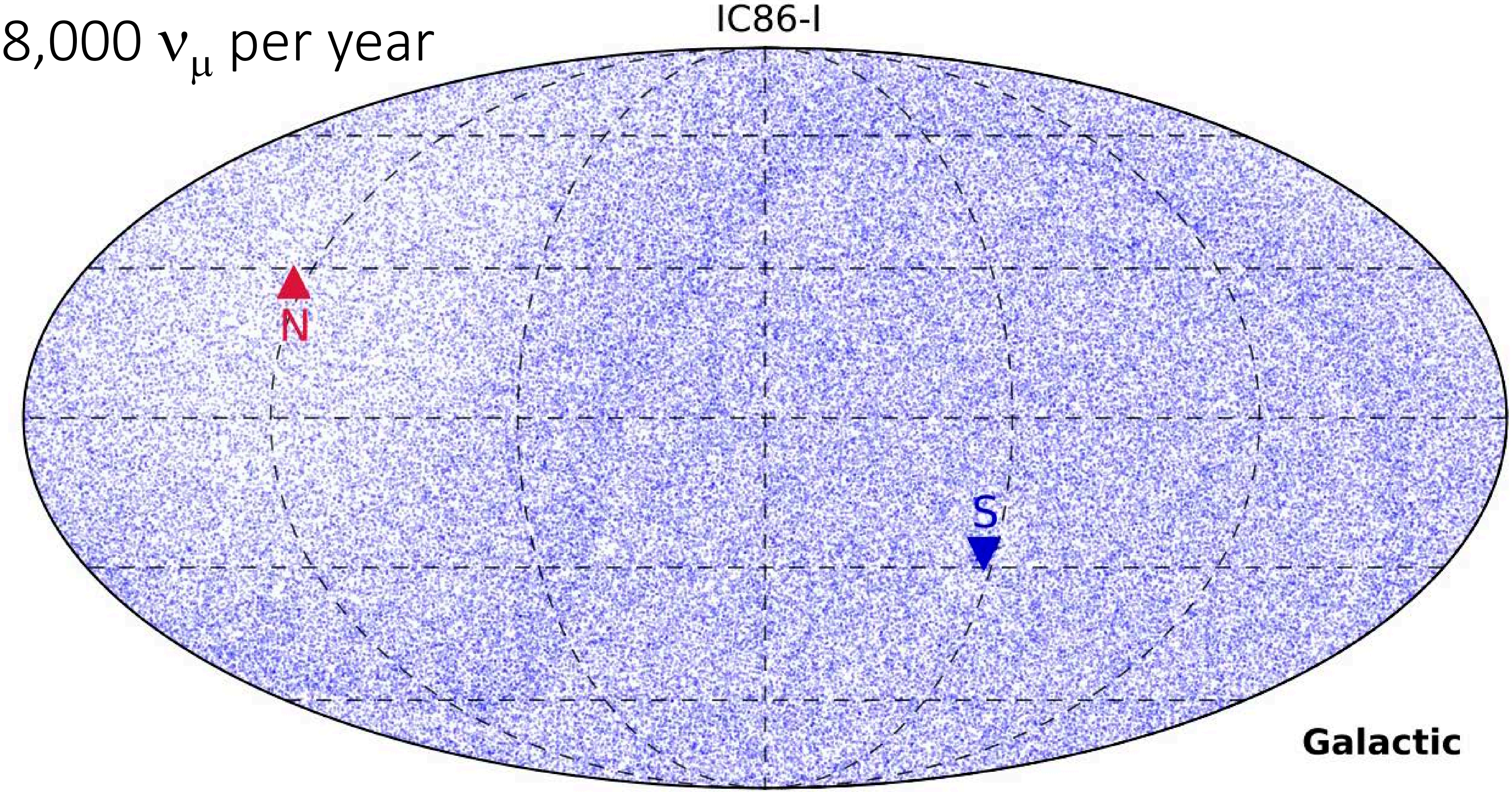


Current Astrophysical Neutrinos



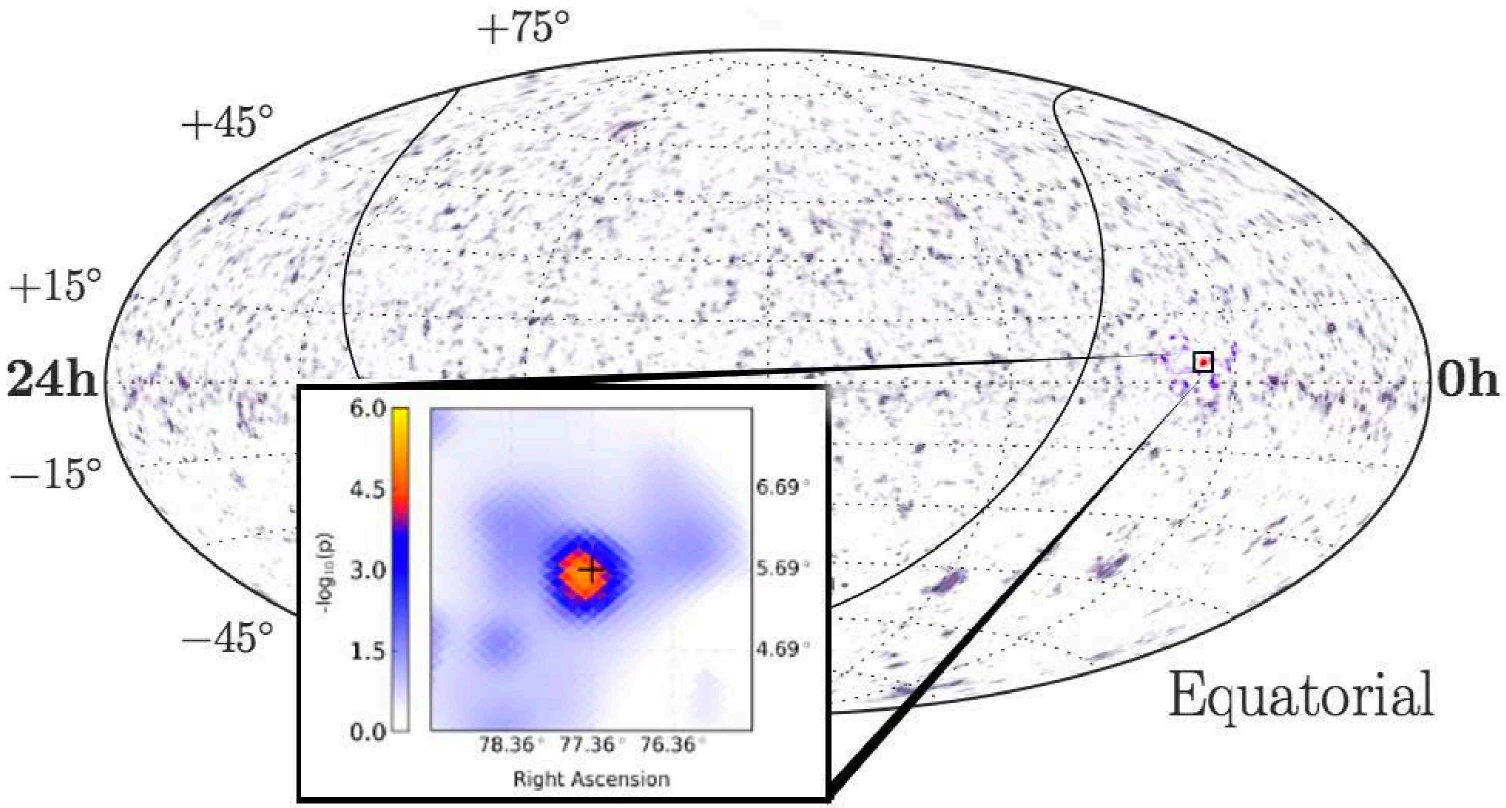
Muon Neutrino Sky Map

~138,000 ν_μ per year

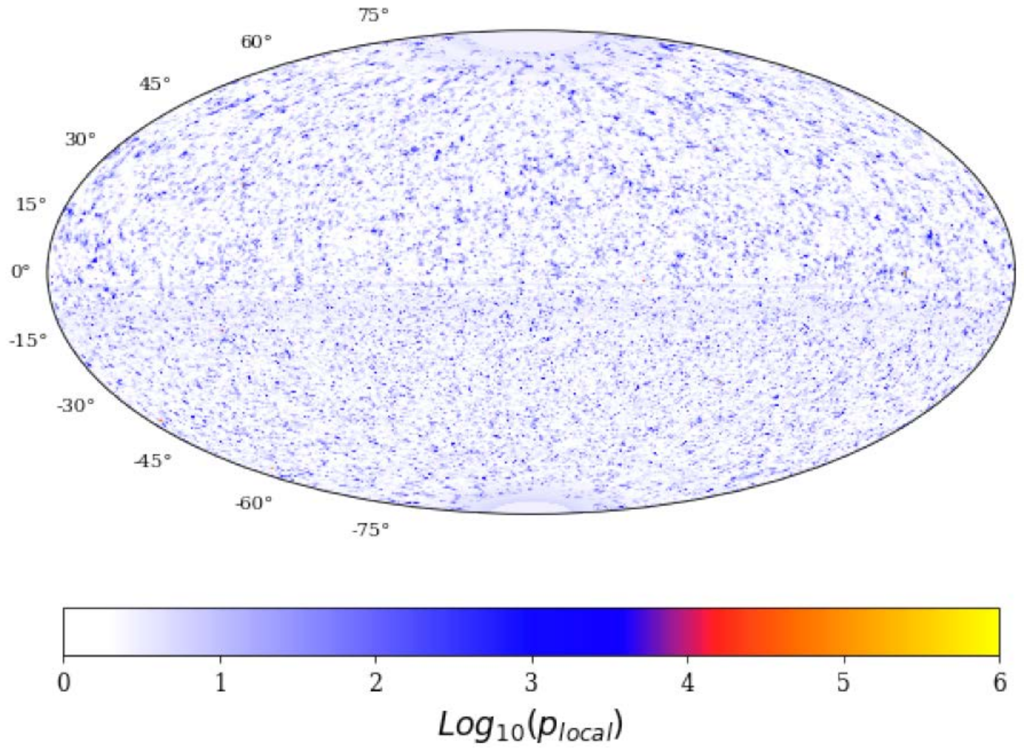


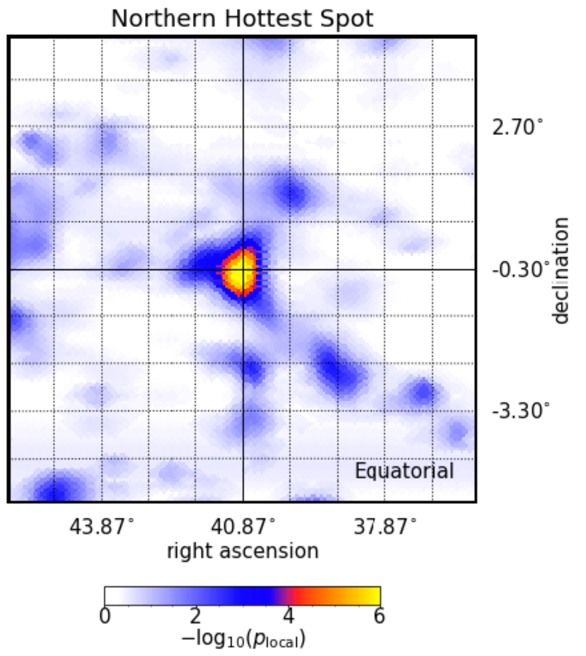
10 year IceCube Sky map

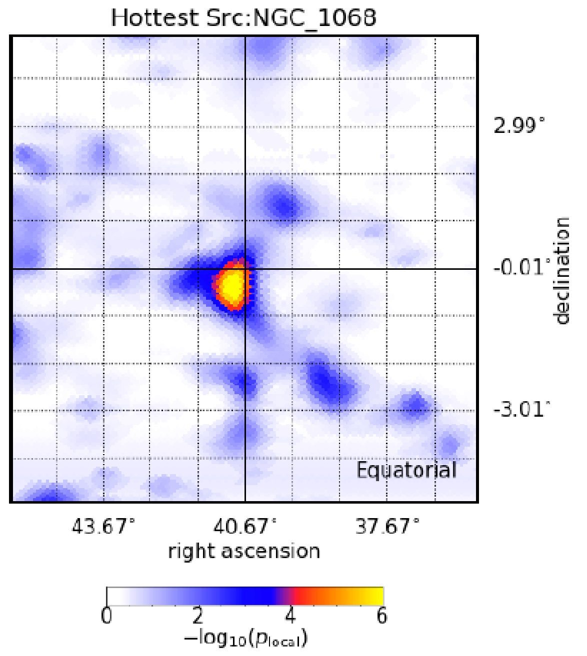
- Evidence for nonuniform distribution in Northern Sky ~ 3σ
- 4 main contributors in directions of
  - Seyfert II galaxy
    - NGC 1068,
  - Blazars
    - TXS 0506+056,
    - PKS 1424+240
    - GB6 J1542+6129



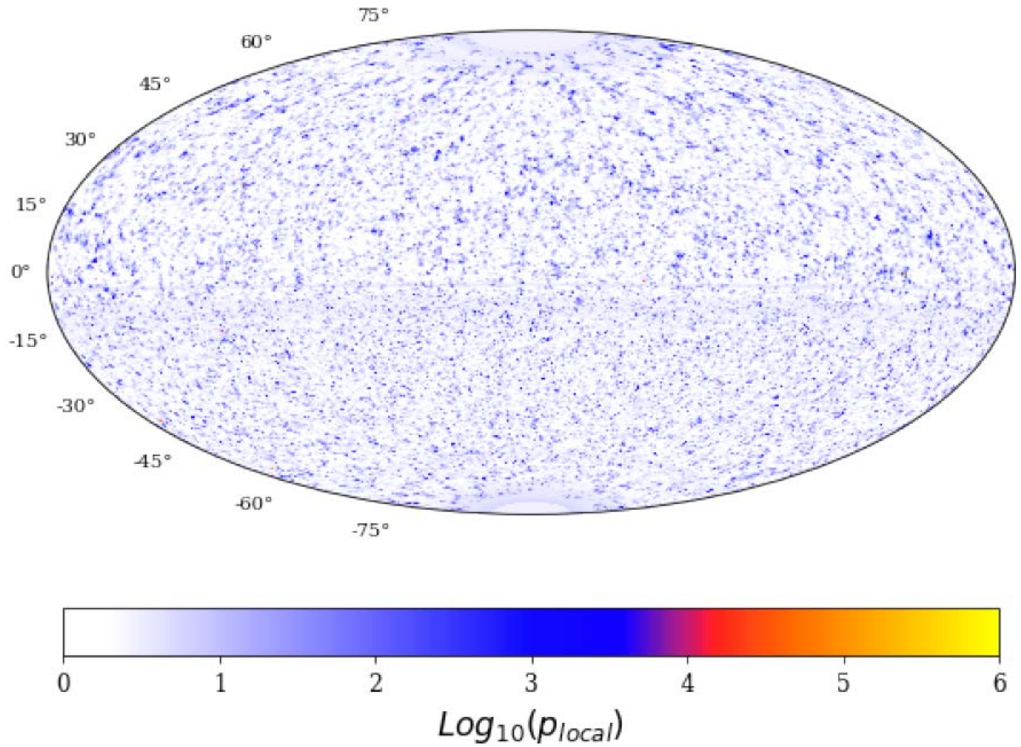
10 years of muon neutrinos

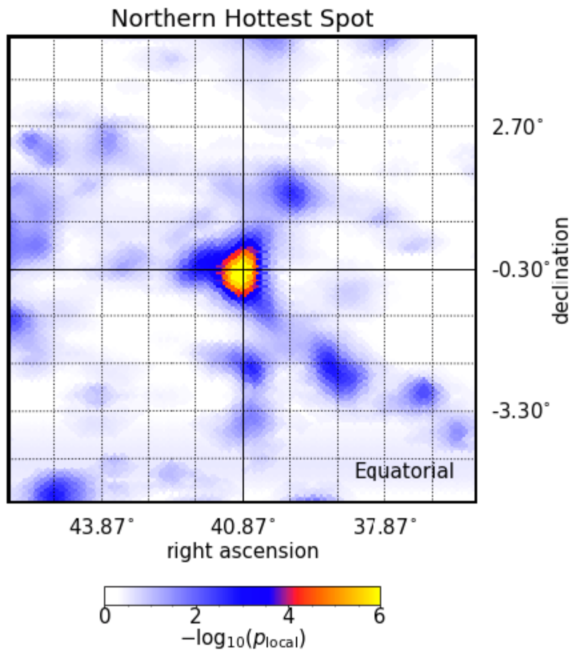


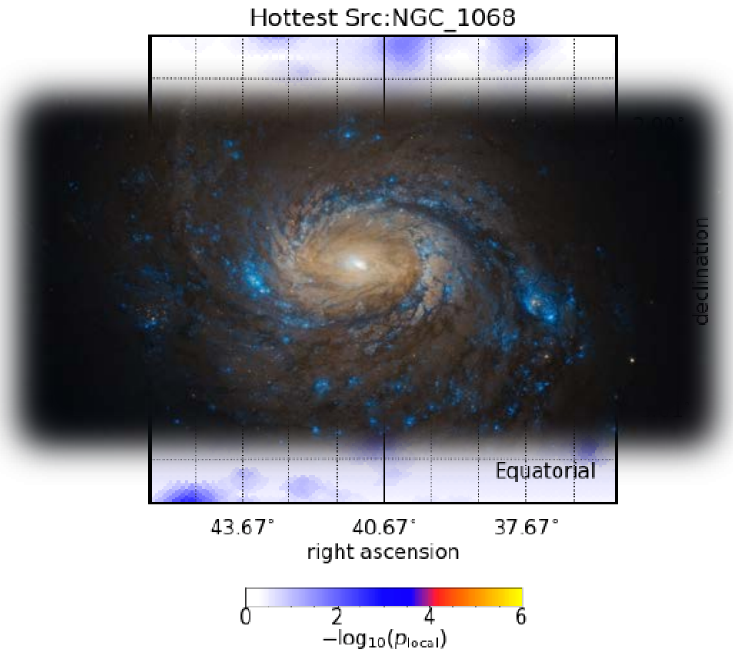




10 years of muon neutrinos



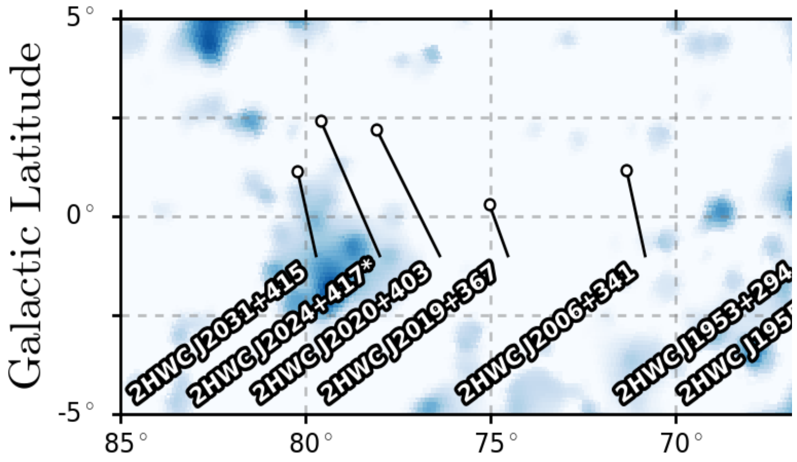


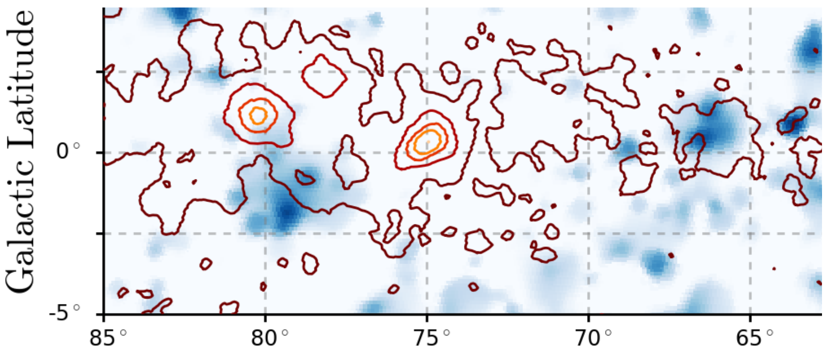


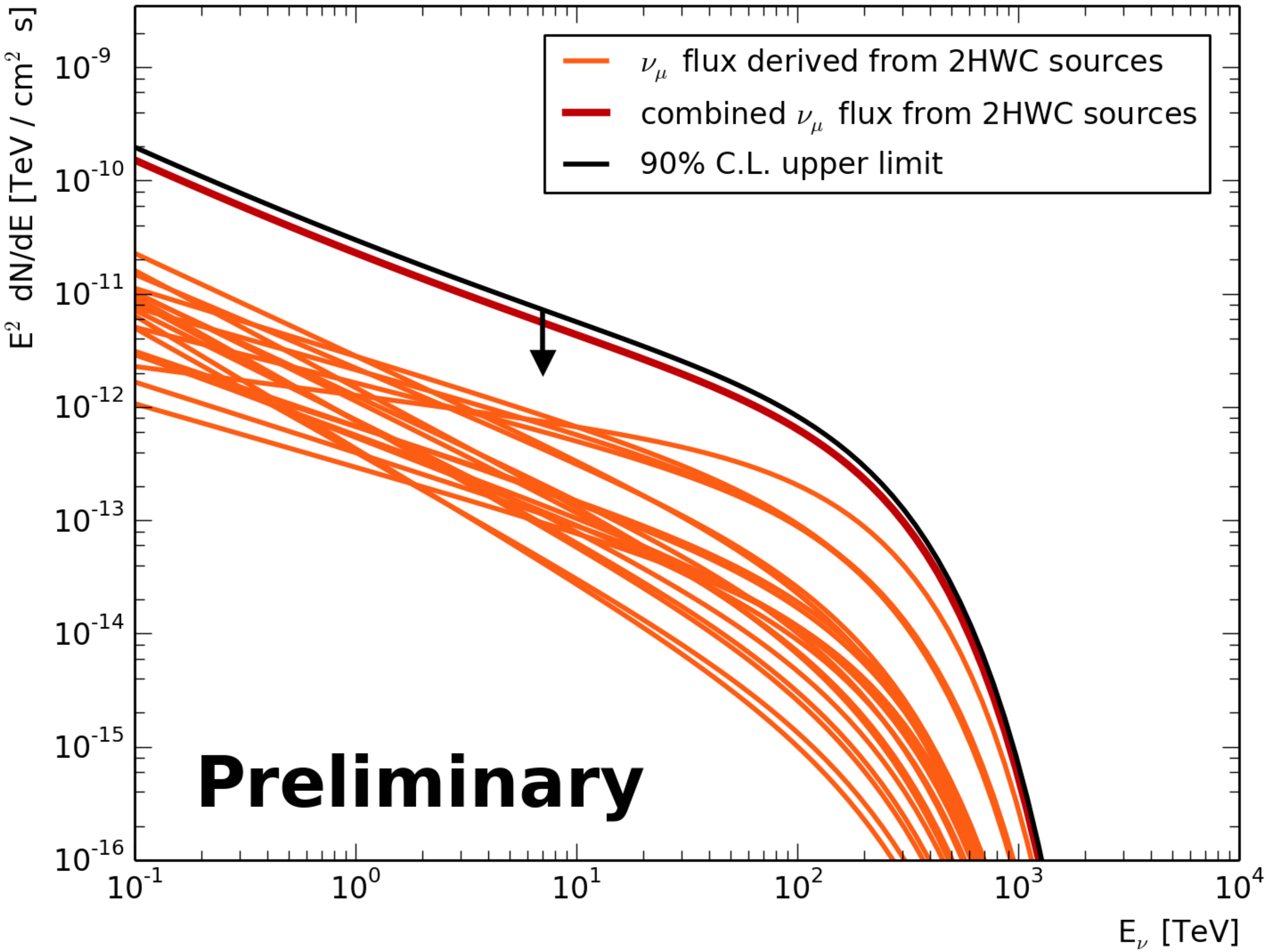
Tessa Carver

HAWC Photons/IceCube Neutrinos

- Look for galactic ν v
- As predicted but no





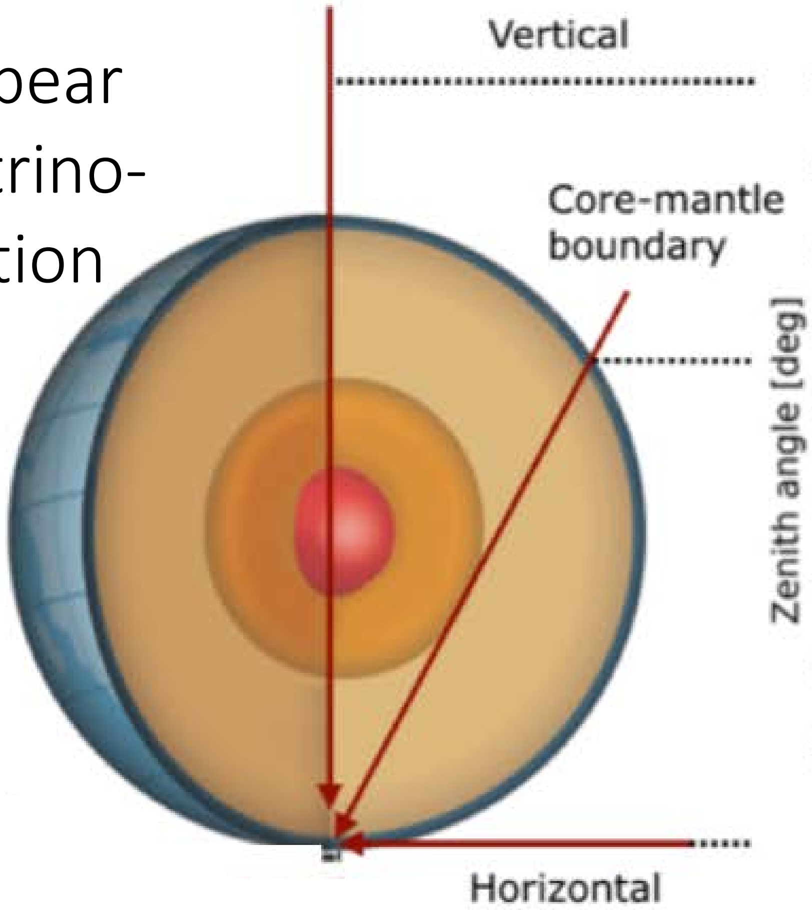


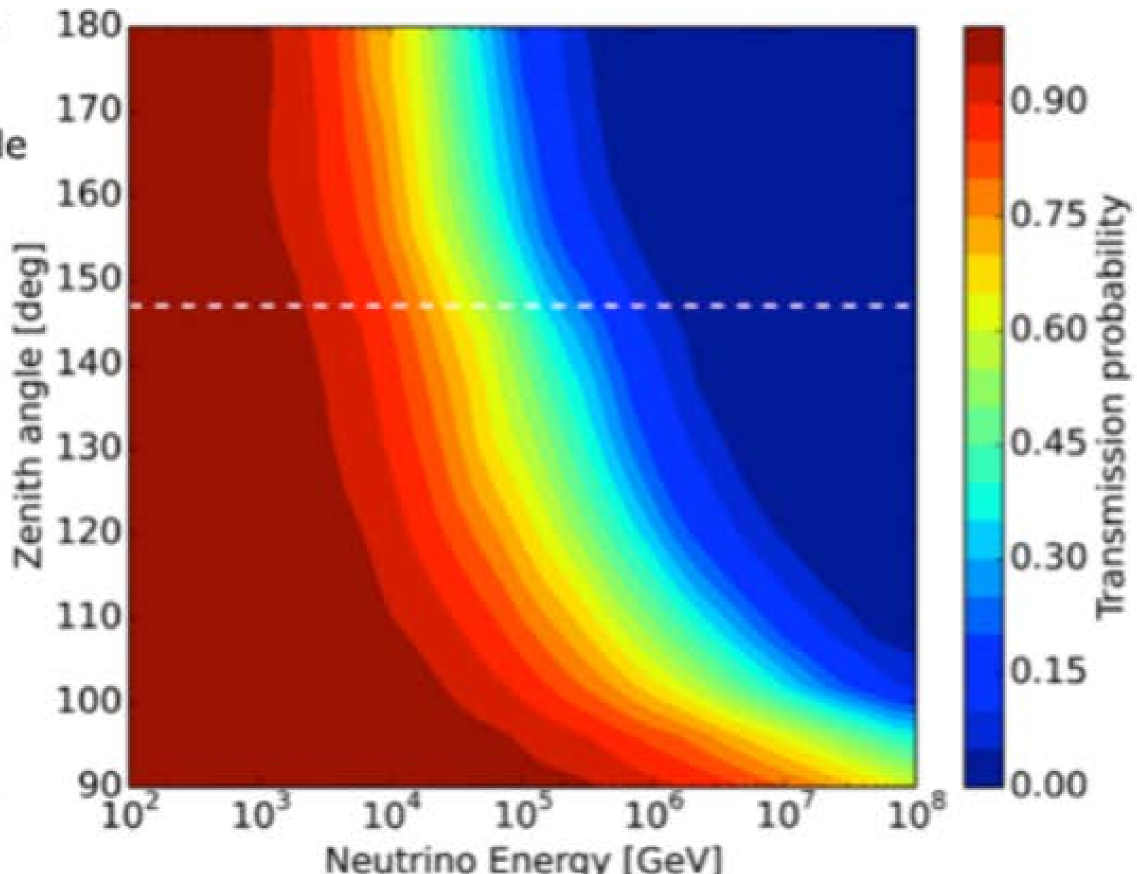
Neutrino Absorption Pattern

$$\text{Event rate} = V\Omega T \otimes N_A\sigma \otimes \phi \otimes \exp(-N_A\sigma X)$$

Aperture:Detector + Geometry $f(E_\nu,\theta)$ $\otimes$ Interaction $f(E_\nu)$ $\otimes$ Astro ν flux $f(E_\nu)$ $\otimes$ Absorption $f(E_\nu,\theta)$

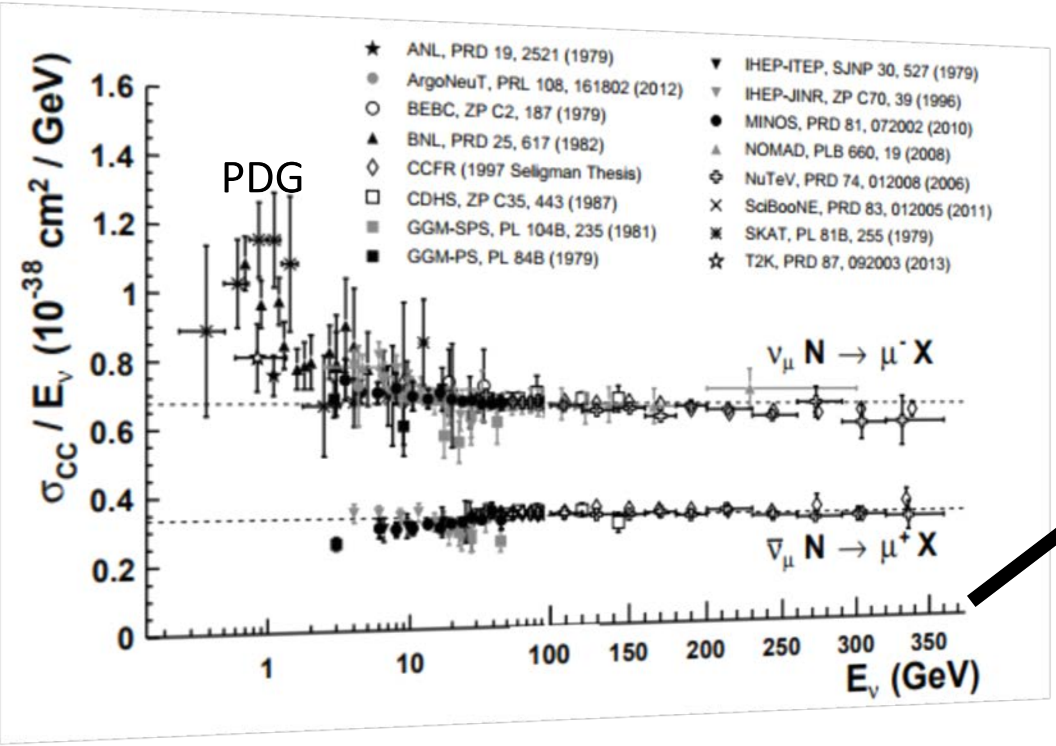
High energy neutrinos disappear because of neutrino-nucleon interaction in Earth

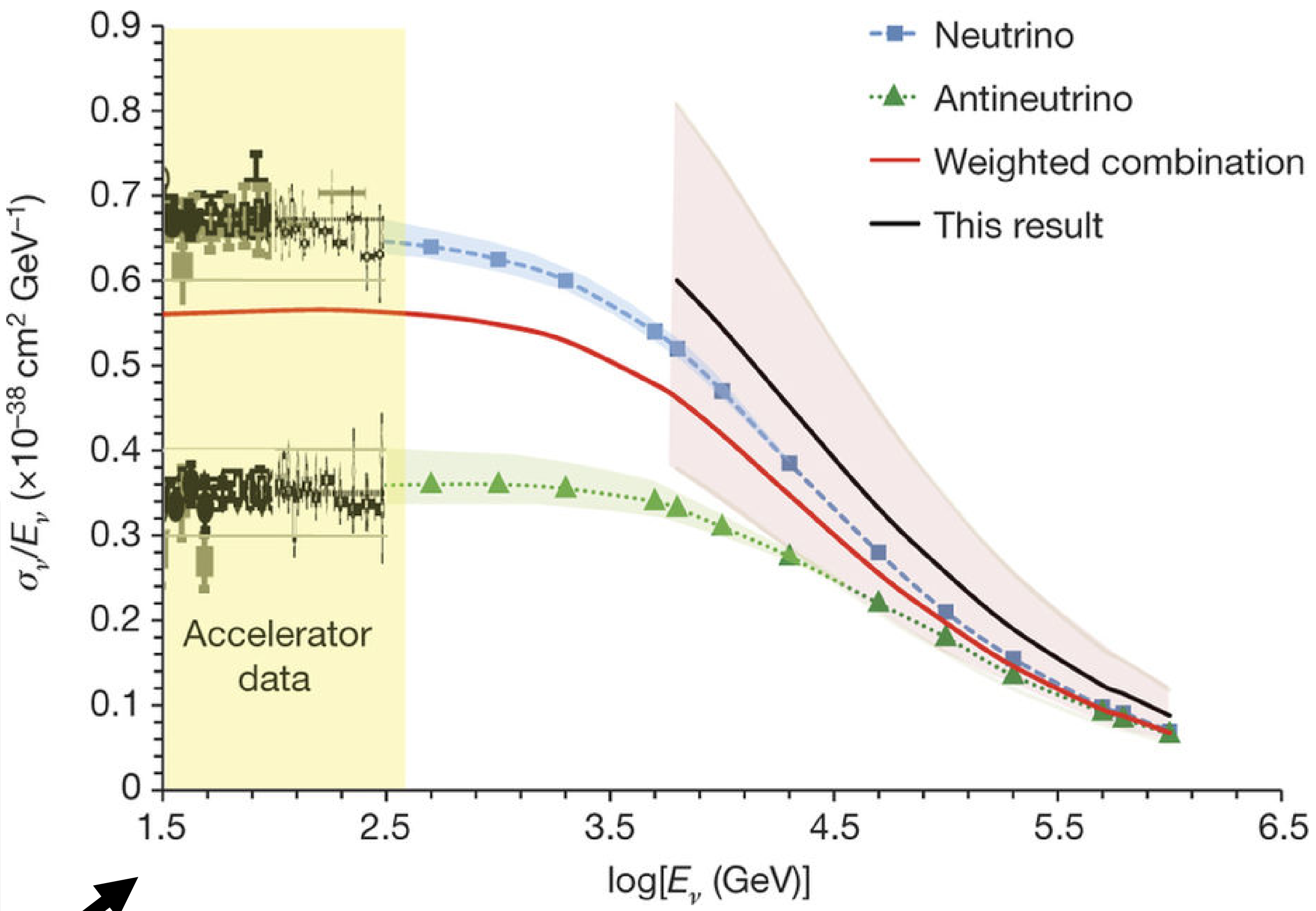




$\nu_\mu \to \nu_\mu$ Disappearance TeV Scale

Nature ***551*** *596 (2017)*





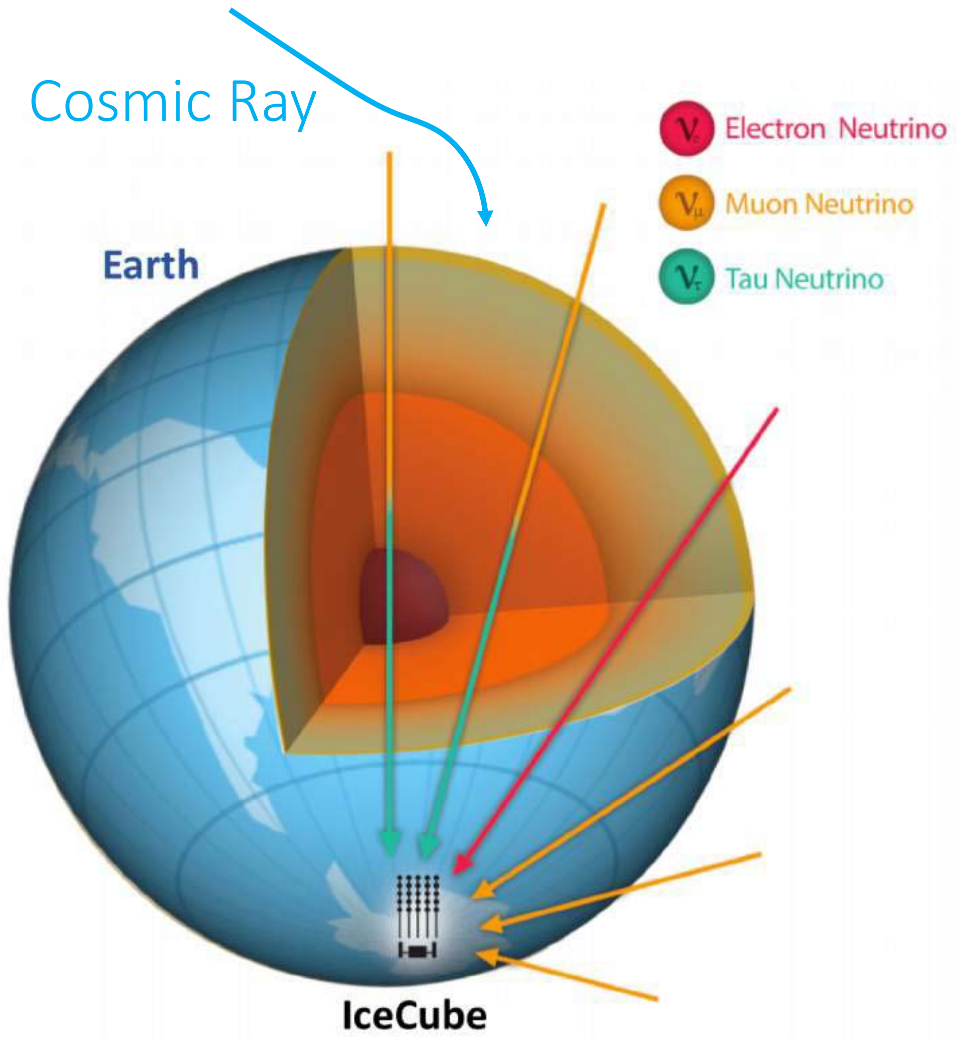
SM n_μ-N cross section scales by k factor

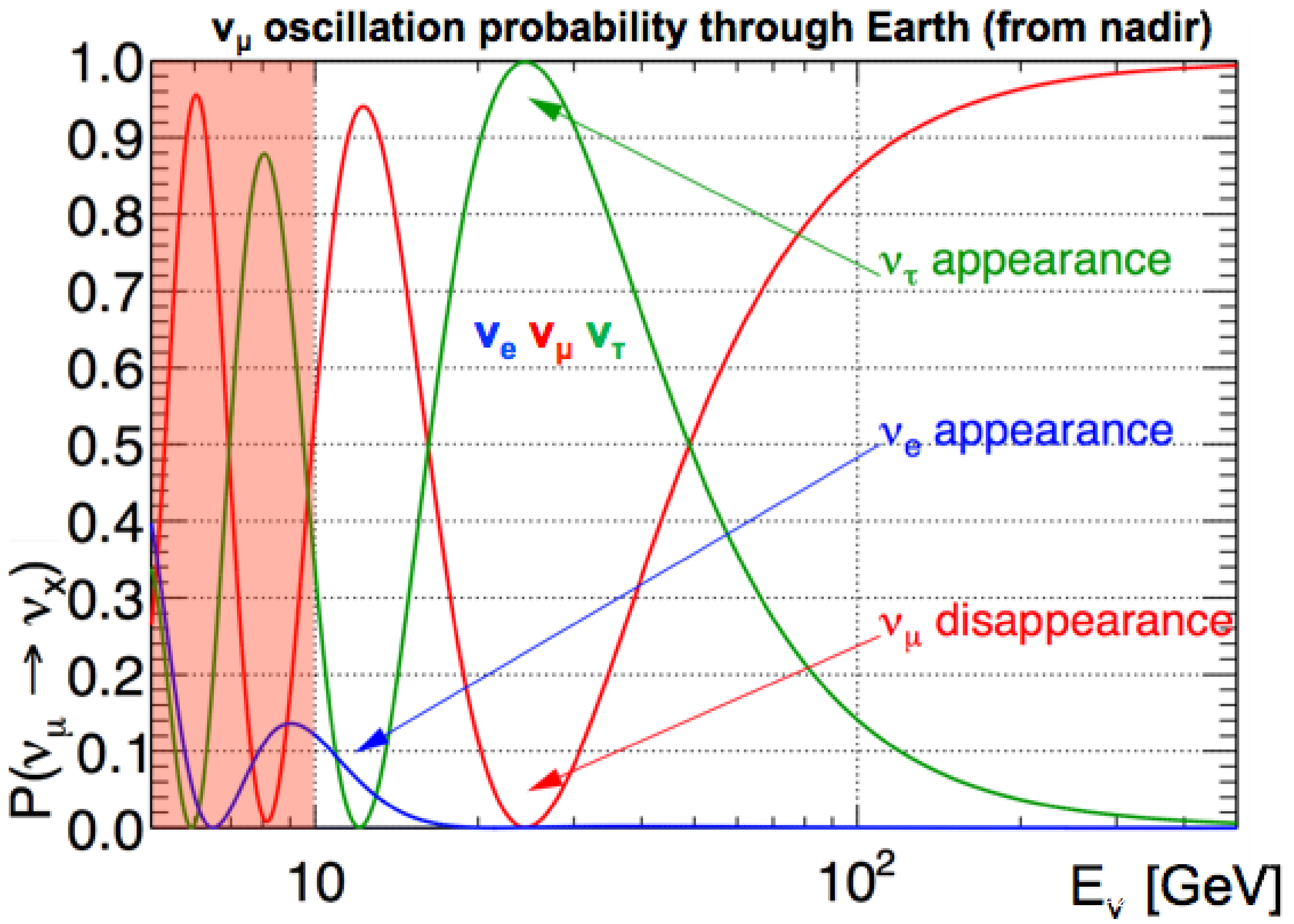
$$1.30^{+0.21}_{-0.19}\ (\text{stat.})\ ^{+0.39}_{-0.43}\ (\text{syst.})$$

CSMS: A. Cooper-Sarkar, P. Mertsch & S. Sarkar, JHEP 1108, 042 (2011)

Atmospheric ν Oscillations

- DeepCore has a multi-megaton effective mass
- Probes a large span of baselines and energy (L/E)

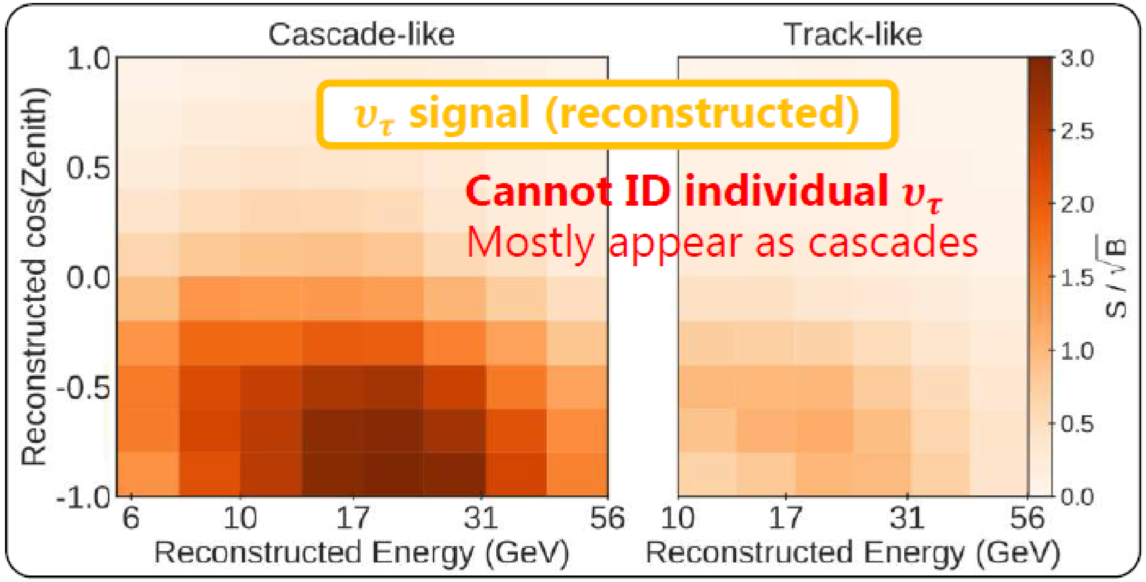




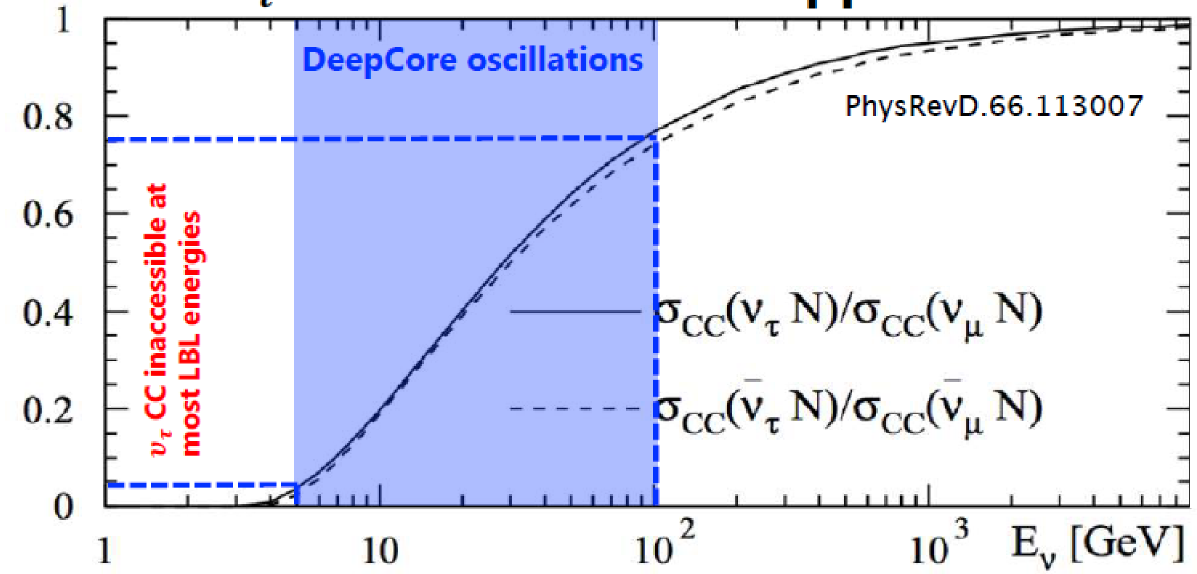
ν_τ Appearance with DeepCore

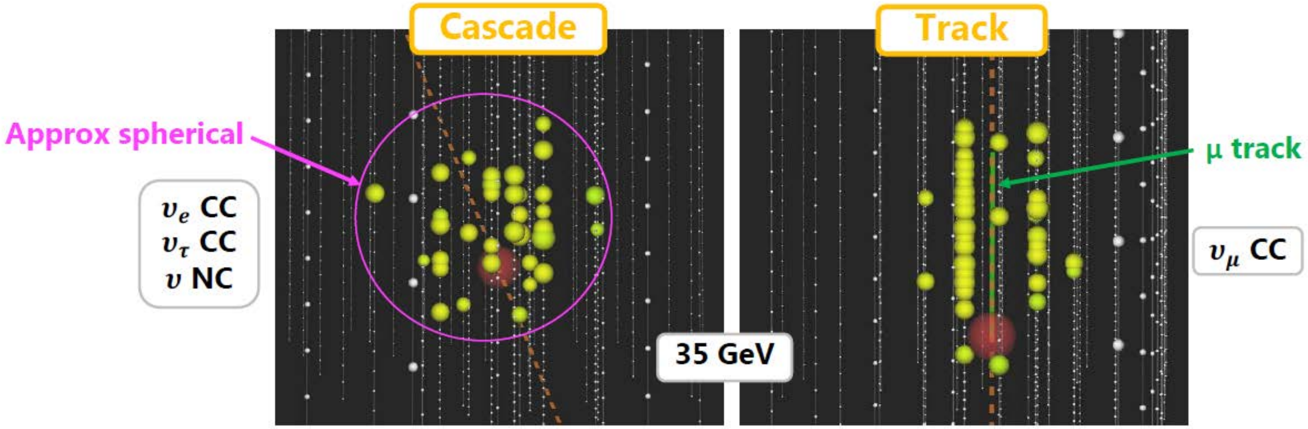
IceCube South Pole Neutrino Observatory

- Challenging measurement
  - CC cross section suppressed by τ mass
  - Produced τ decays ~instantly making PID difficult
- 3 measurements to date
  - Beam: **OPERA**
  - Atmospheric: **SuperK**, **DeepCore**



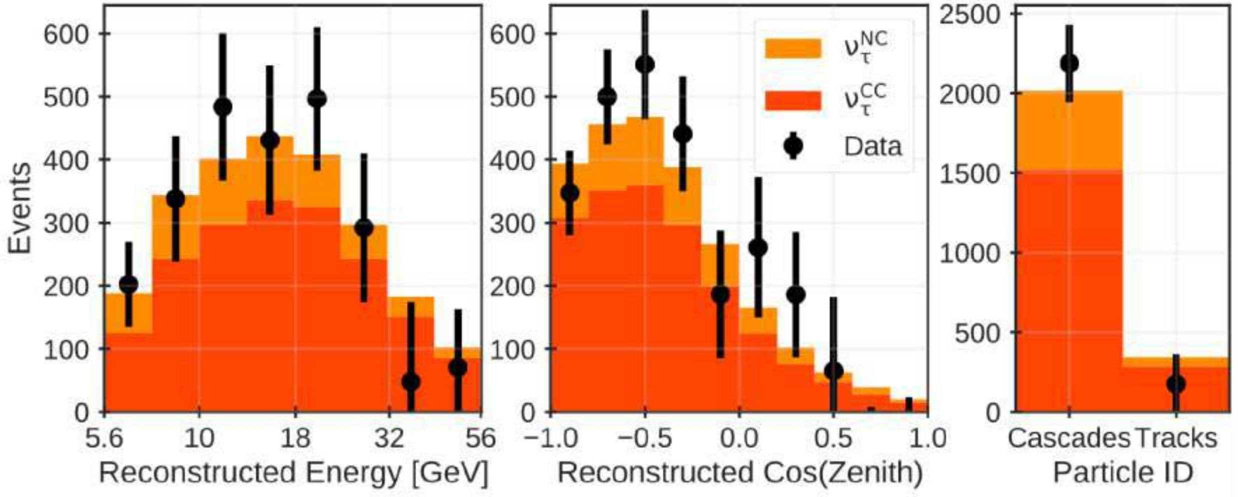
ν_τ CC cross section suppression

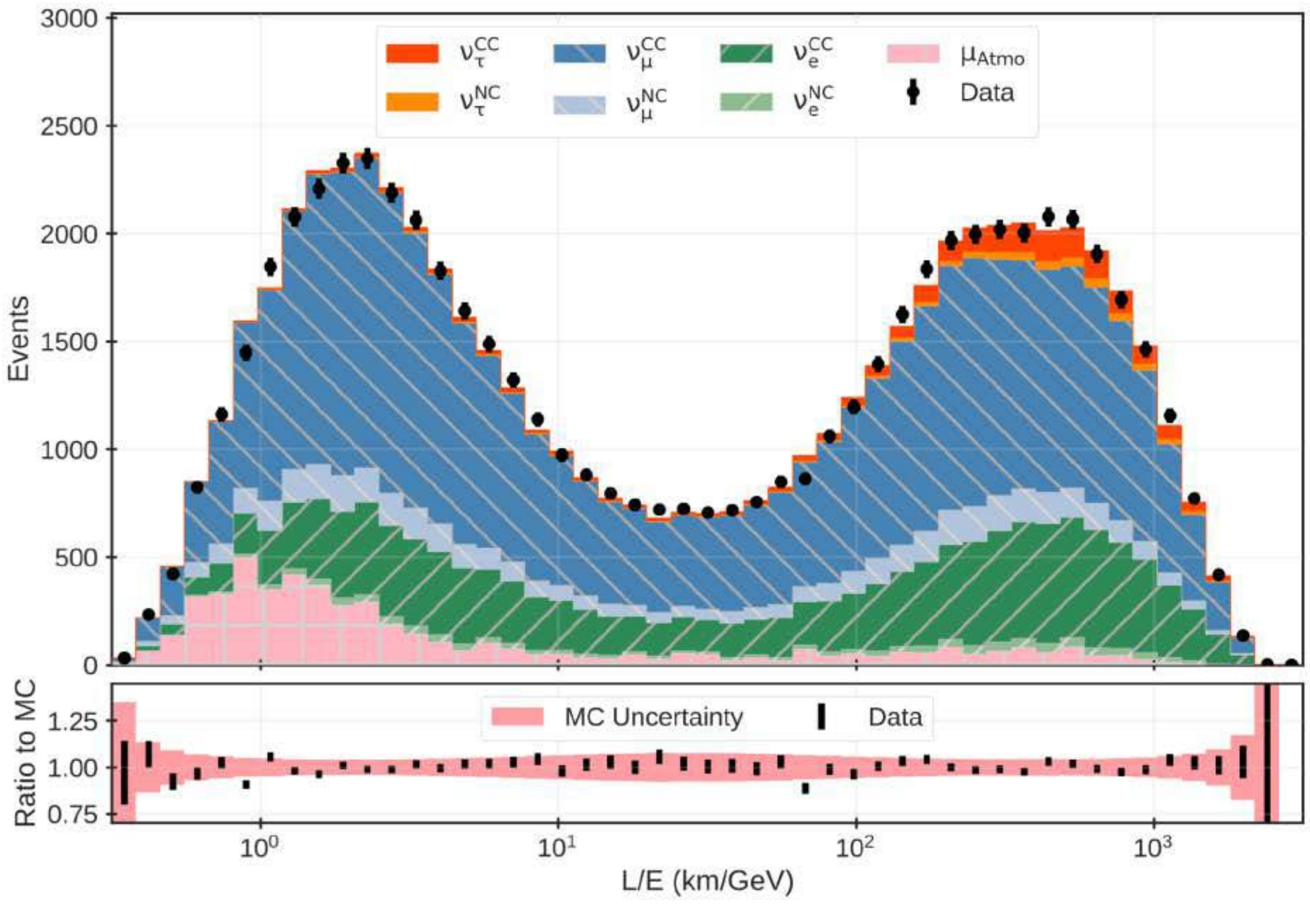




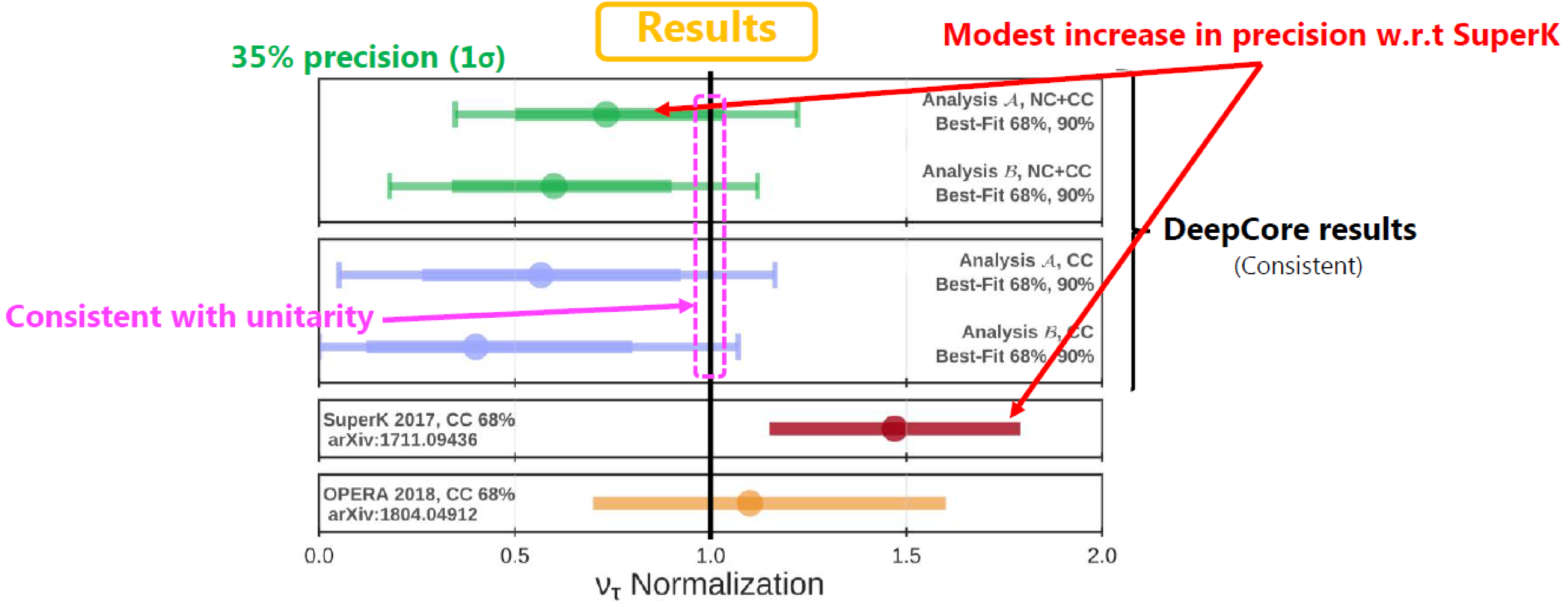
DeepCore ν_τ Appearance Results

- 2 analyses with 3 years of data [1901.05366]
- Fit energy, cos(zenith), and PID
- Look for 3D distortions in shape from MC predictions



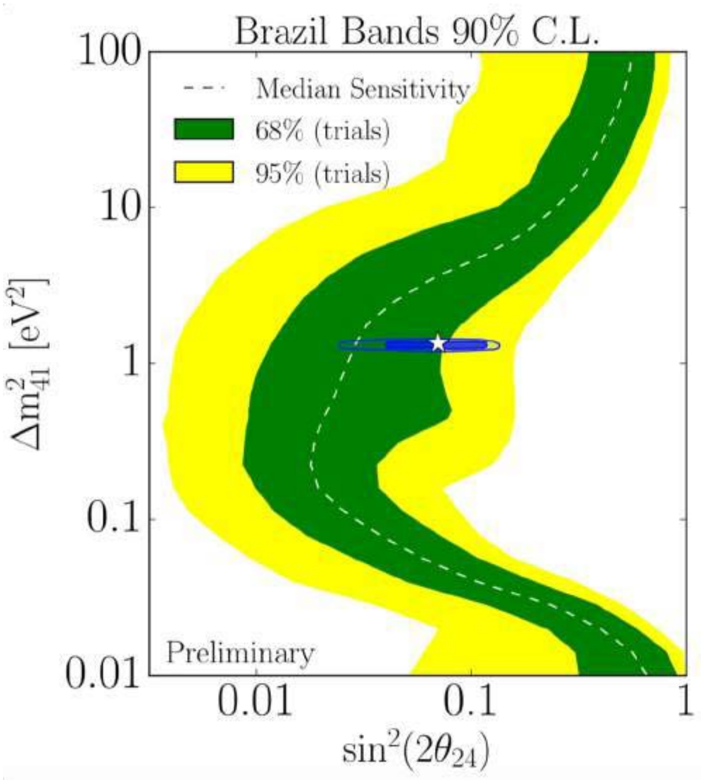


DeepCore ν_τ Appearance Results

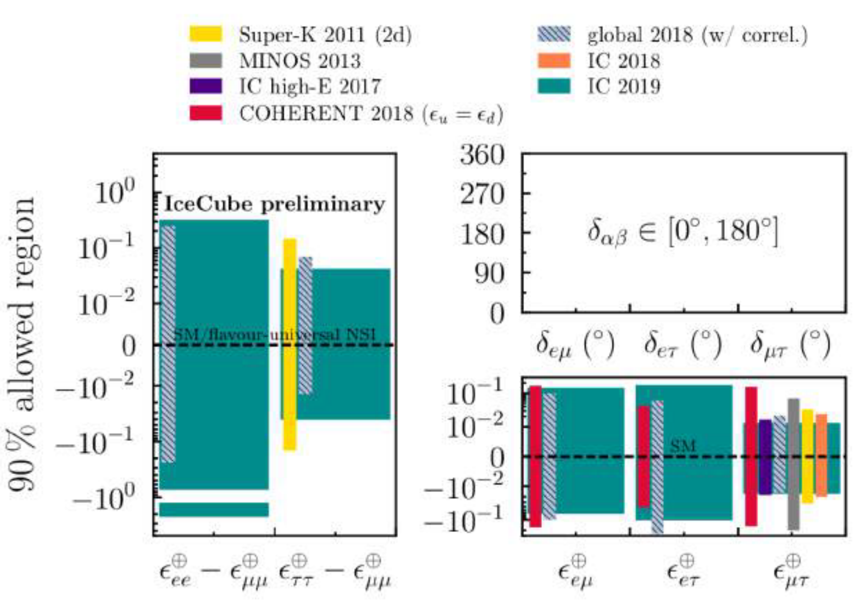


Other IceCube Beyond Standard Model Oscillation Studies

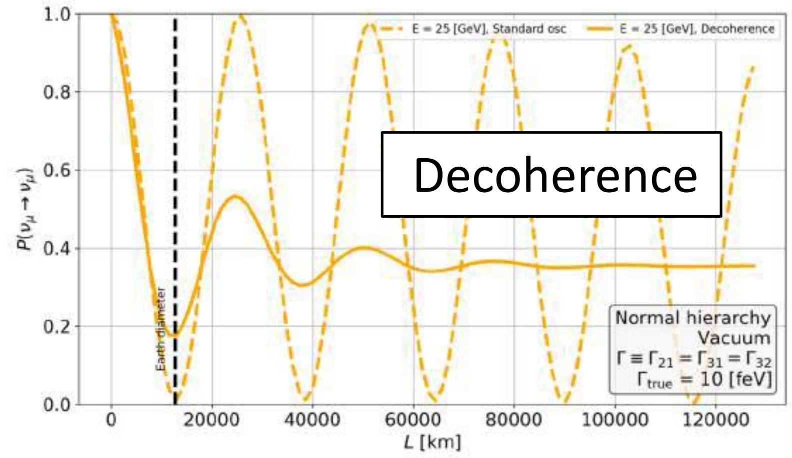
Sterile Neutrinos



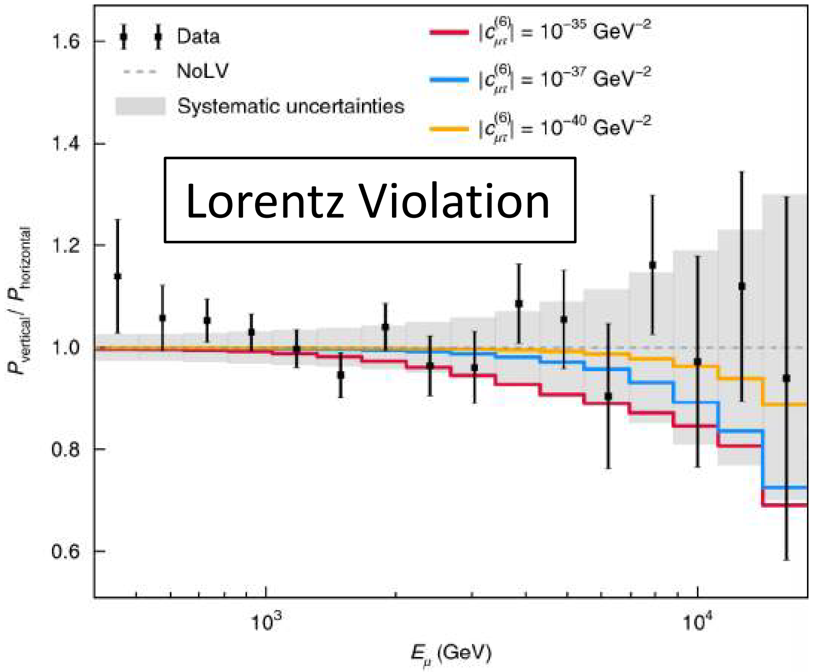
Nonstandard Interactions



Decoherence

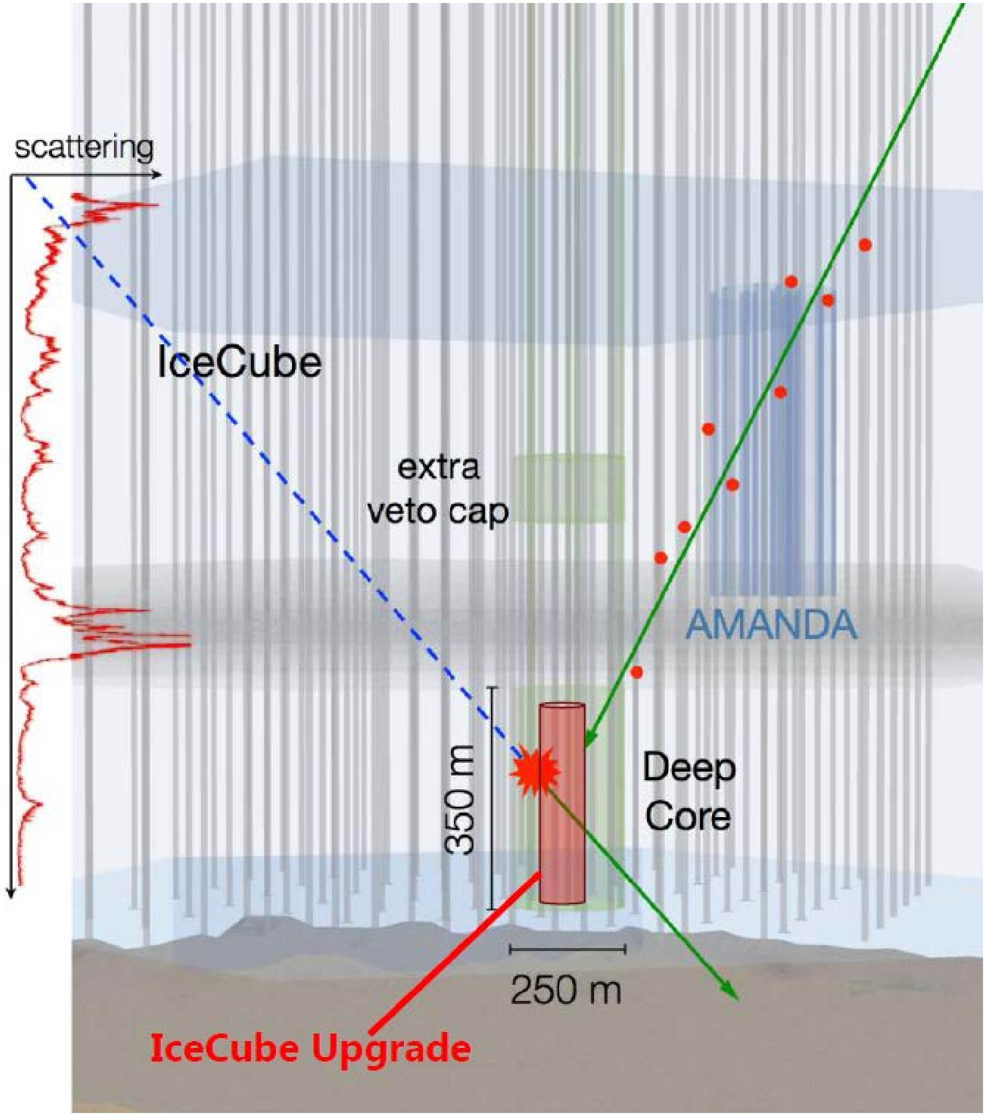


Lorentz Violation



Take Away Message

- DeepCore has world-leading ν_τ appearance measurement precision
- Result consistent with unitary 3x3 PMNS matrix
- Coming soon: New measurement with 5x statistics
- Success motivates IceCube Upgrade
    - 7 more densely instrumented strings
    - Large increase in photocathode density
    - Lower energy thresholds and improved calibrations extends capabilities



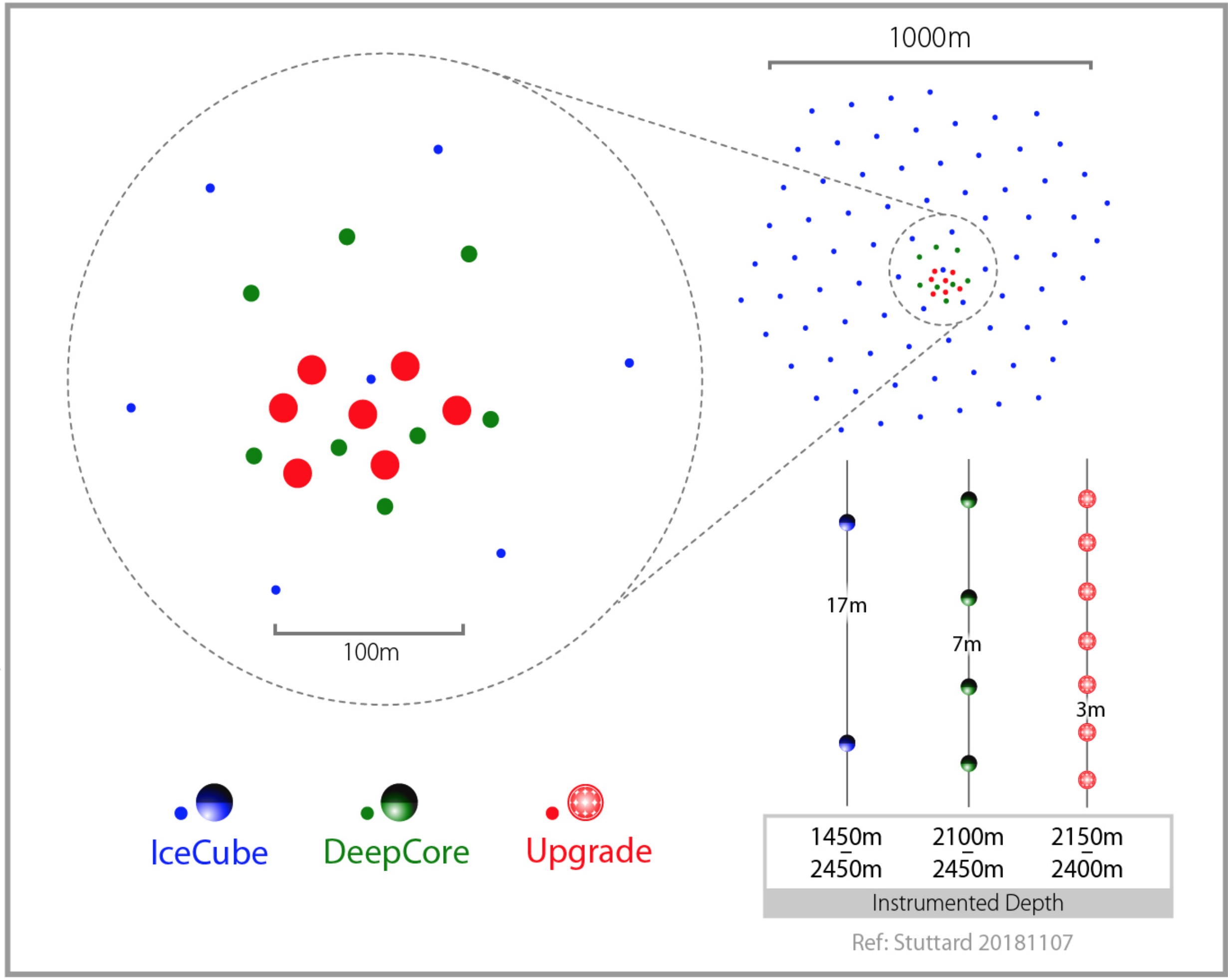
IceCube Upgrade

Fully funded first step to IceCube Gen2 underway

D-Egg

mDOM

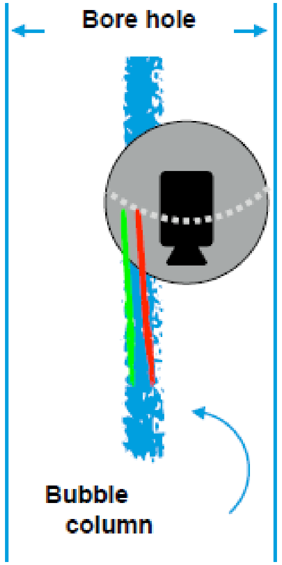
- Seven new strings of multi-PMT mDOMs in the DeepCore region
  - Inter-string spacing of ~22 m
- New calibration devices, incorporating lessons learned from a decade of IceCube calibration efforts
- Enhance IceCube's scientific of capabilities at both high and low energy

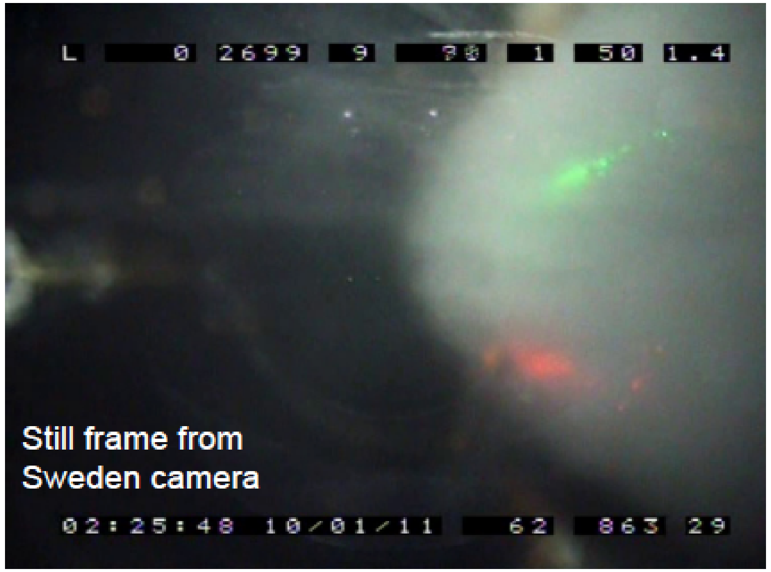


New, Better Calibration Devices

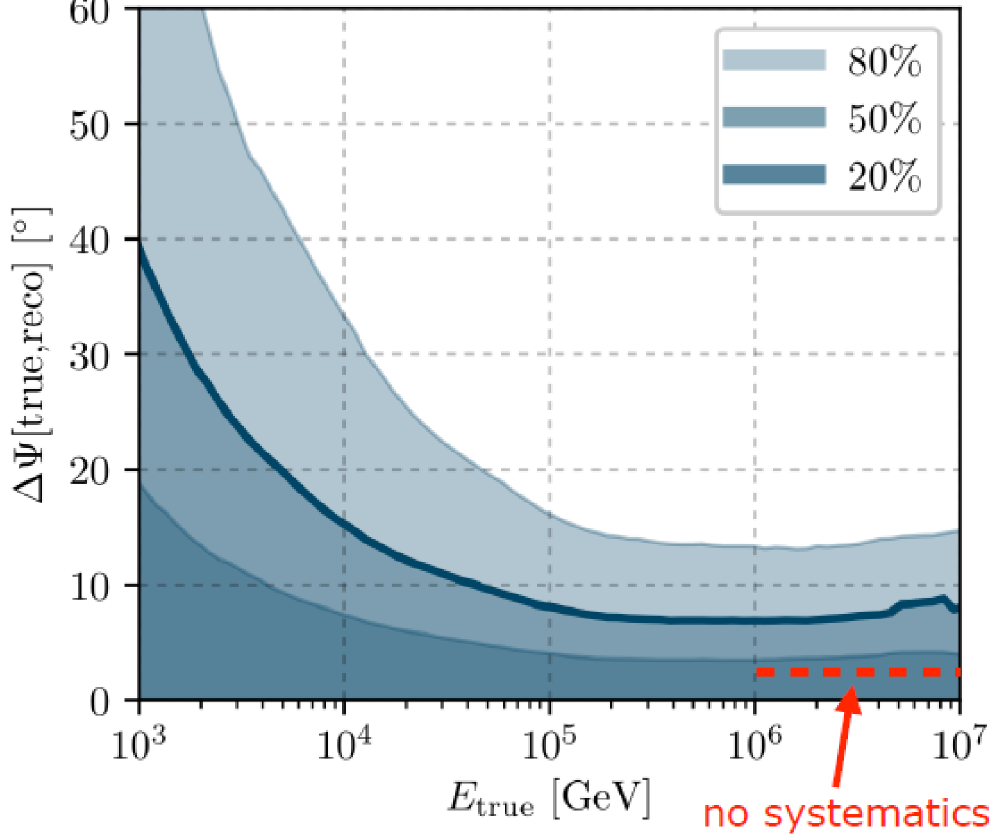
Enhance IceCube high-energy science

- Better control of systematics (in particular ice properties)
- Applicable to archival and future IceCube data
- Improved
  - angular/energy reconstruction
  - flavor ID for ν_τ





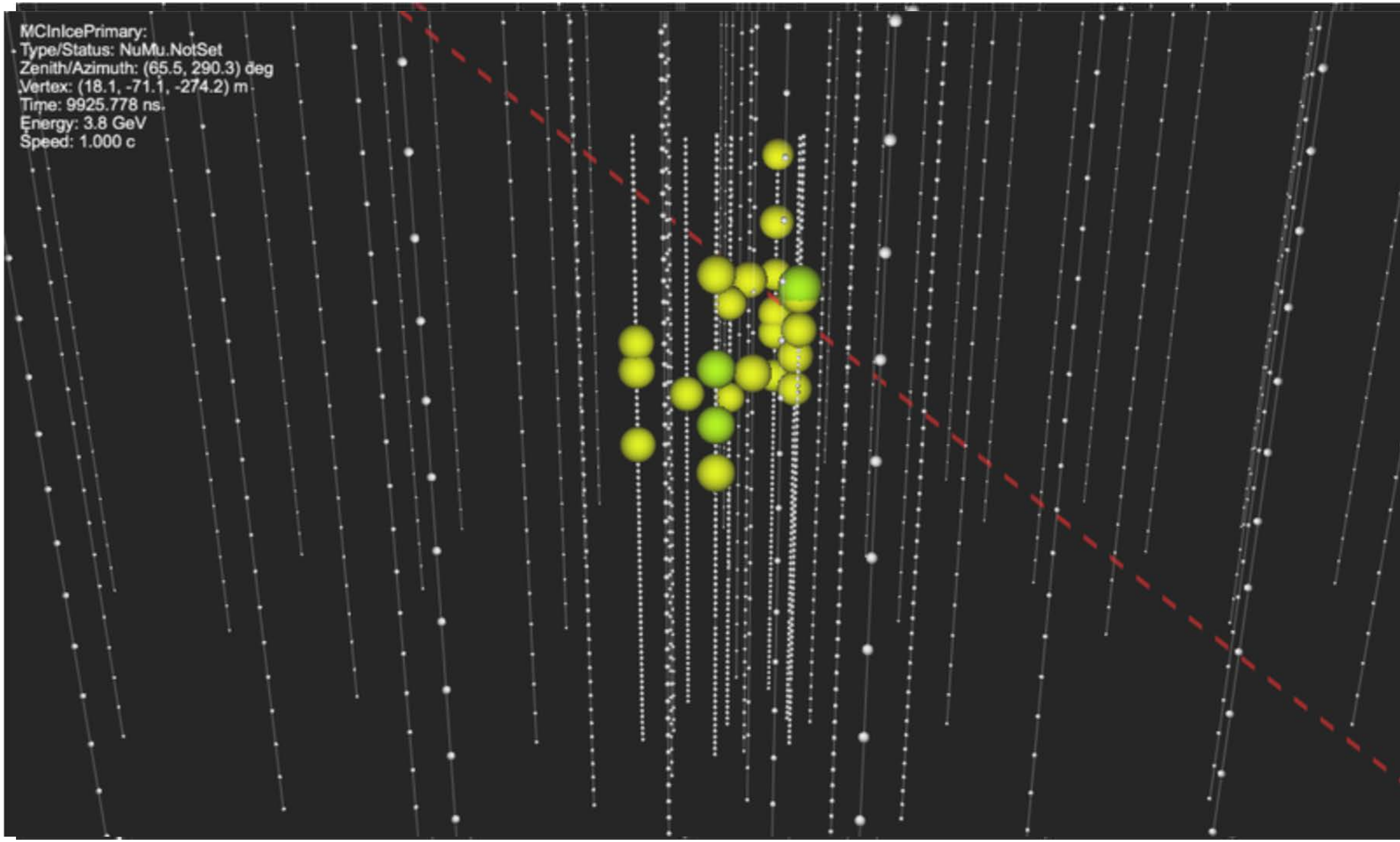
current cascade resolution incl. sys. (arXiv:1907.06714)



Lower Energy Threshold

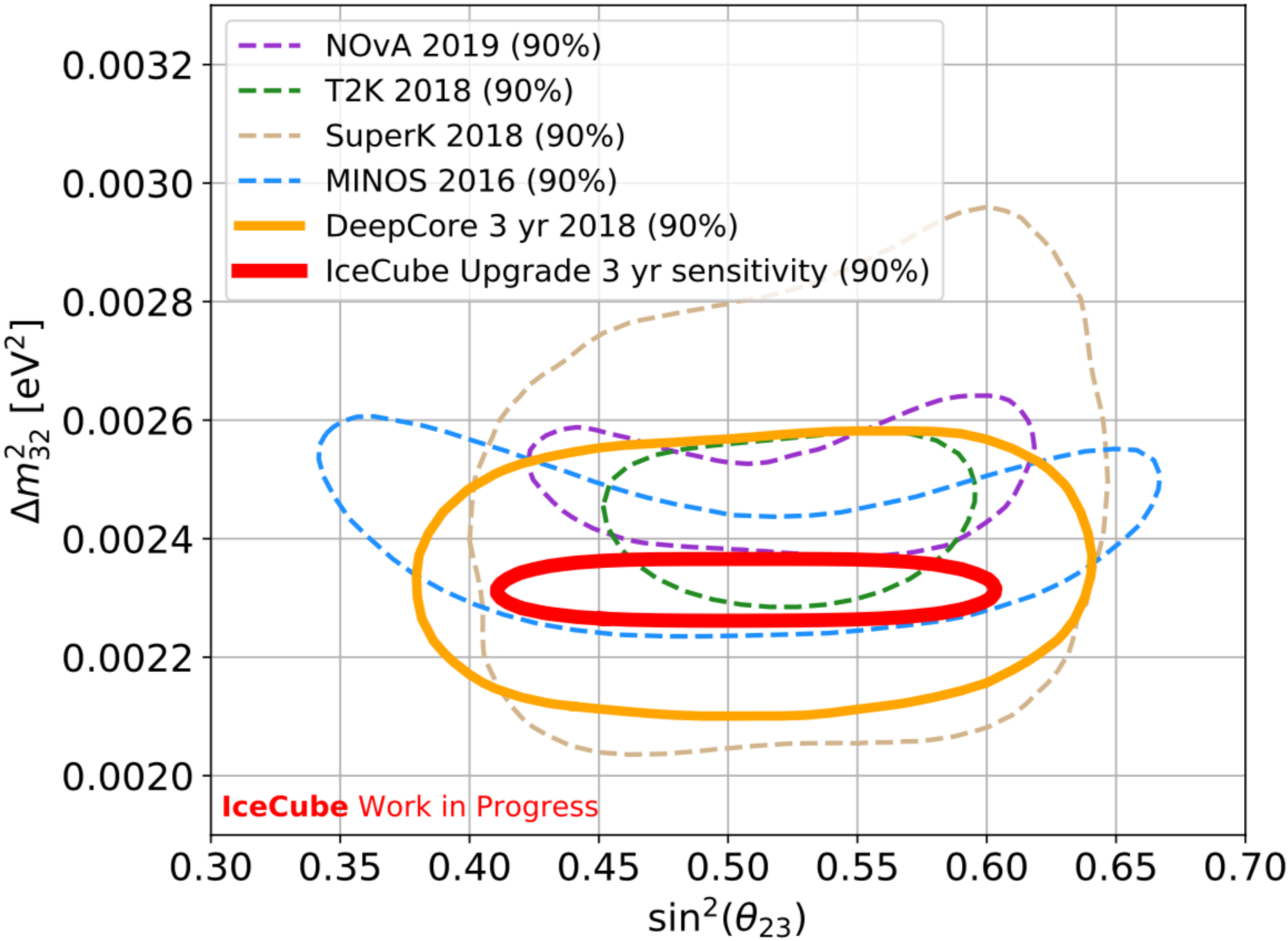
3.8 GeV muon neutrino

Would not trigger DeepCore but is both triggered and reconstructable with Upgrade



Precision ν_μ to ν_μ measurement

- Atmospheric mixing parameters
- Significantly improvement compared to DeepCore
- Comparable with results from other neutrino oscillation experiments
  - Probes different L/E and has different systematics
- Also sensitivity to mass ordering via combined fit with JUNO data.

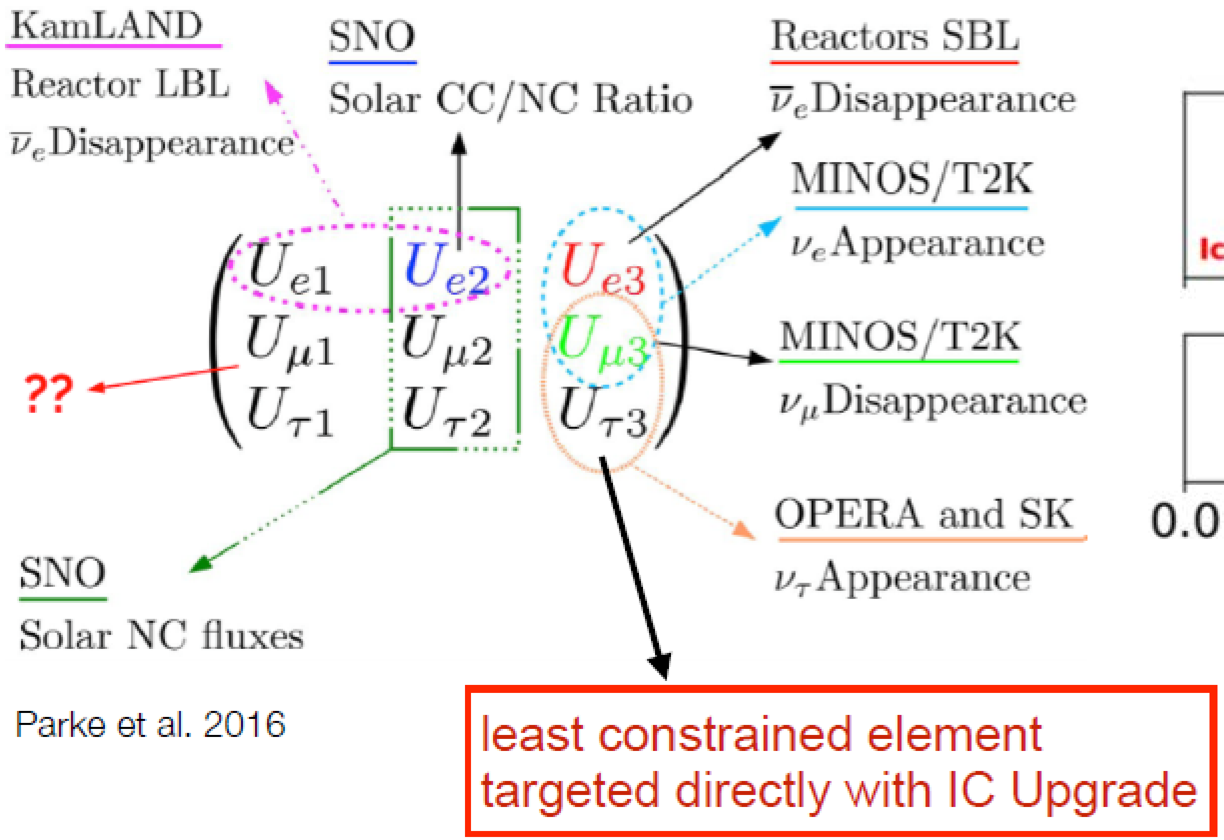


Precision ν_τ appearance

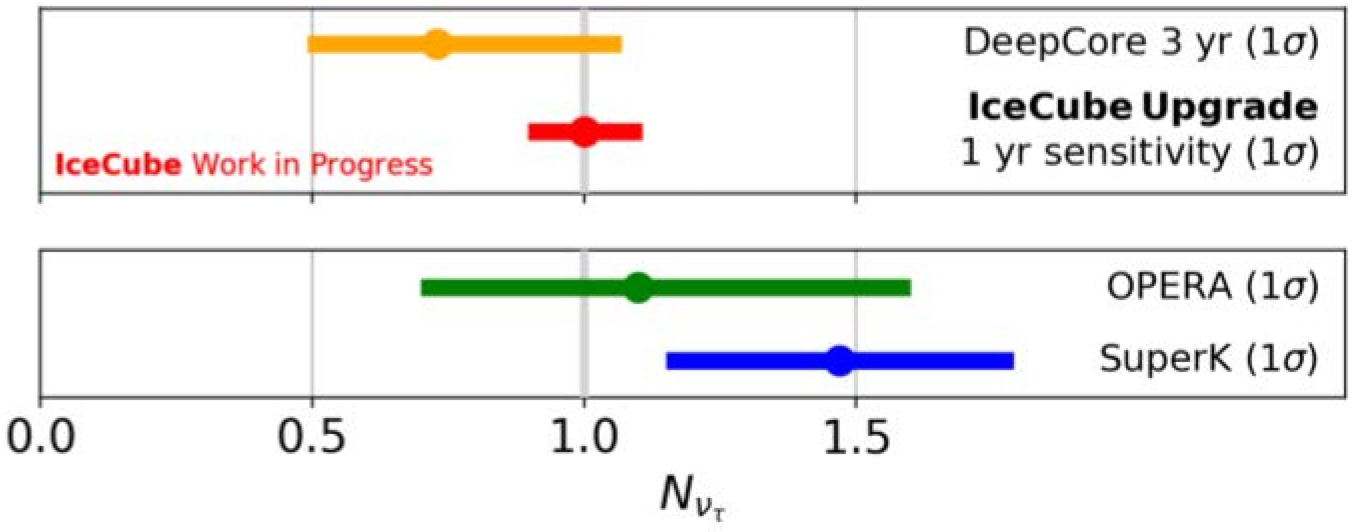
Testing unitarity of PMNS matrix

→ can achieve 10% ν_τ appearance precision after 1 year of data taking

- $N_{\nu\tau}$ =1 is unitary prediction

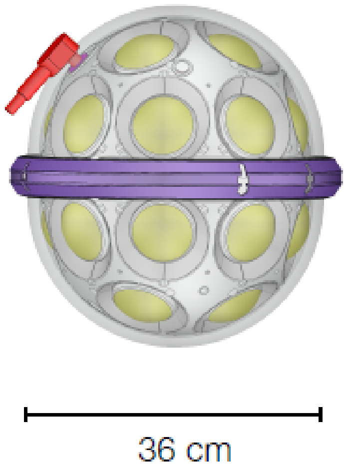


Parke et al. 2016



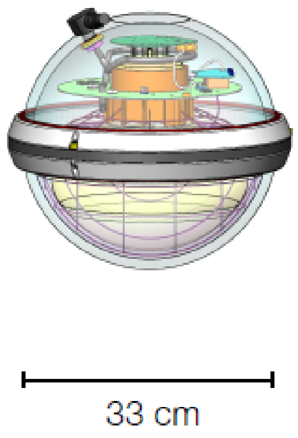
Instrumentation Research and Development

mDOM
(403 modules)



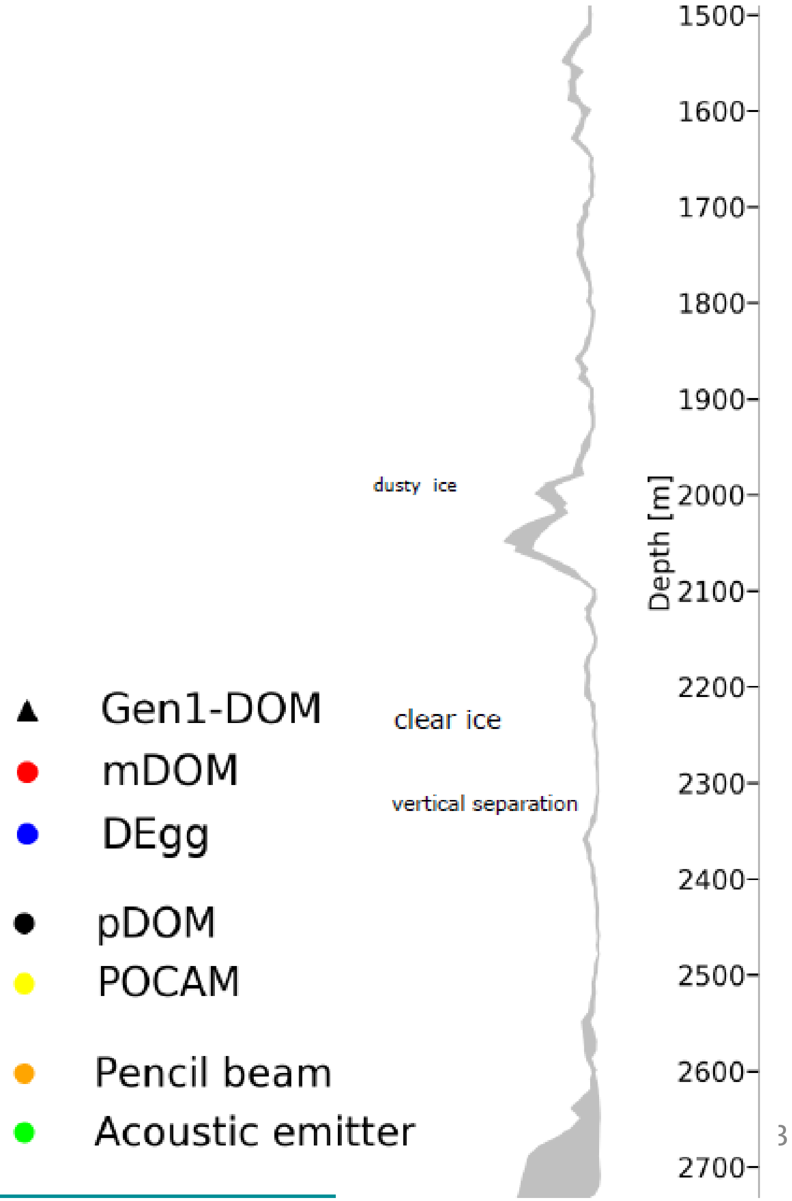
D-Egg
(277 modules)

PDOM
(14 modules)



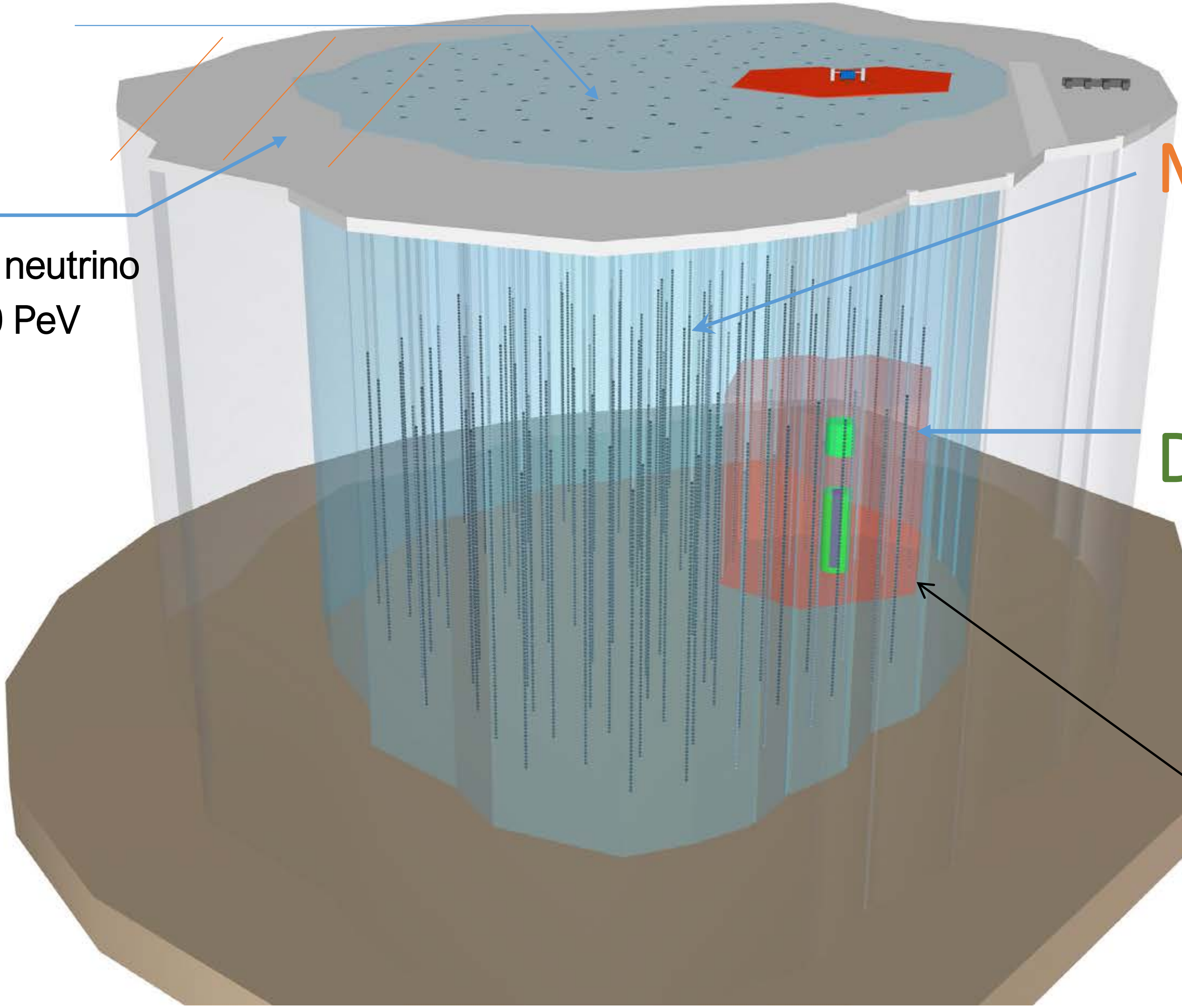
New sensor designs feature one or more of the following qualities

- Upgraded electronics
- Smaller diameter
- Increased UV sensitivity
- Larger and/or pixelated effective area



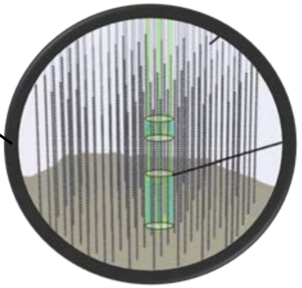
Future: IceCube-Gen2 Facility

- Surface array
  - muon veto
  - CR physics
- Radio array
  - cosmogenic neutrino
  - neutrino >10 PeV



Main array
- ≈100 strings
- ≈100 sensors/string
- ≈240m distance

Dense array
- 26 strings
- 125-192 sensors/string
- ≈25m distance



Upgrade/IceCube-Gen2 Timeline

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

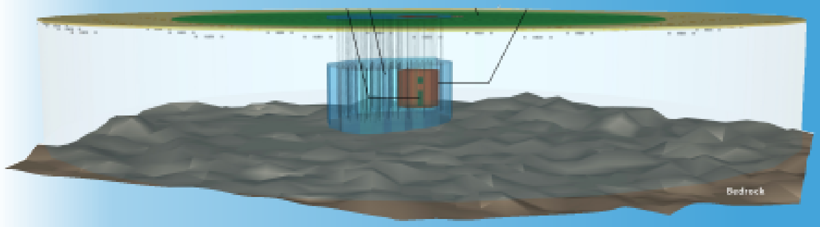
2019	2020	2021	2022	2023	2024	2025	2026	...	2033

IceCube Upgrade

Design — Production — Deployment

IceCube-Gen2

R&D — Design & Approval — Production — Deployment



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
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

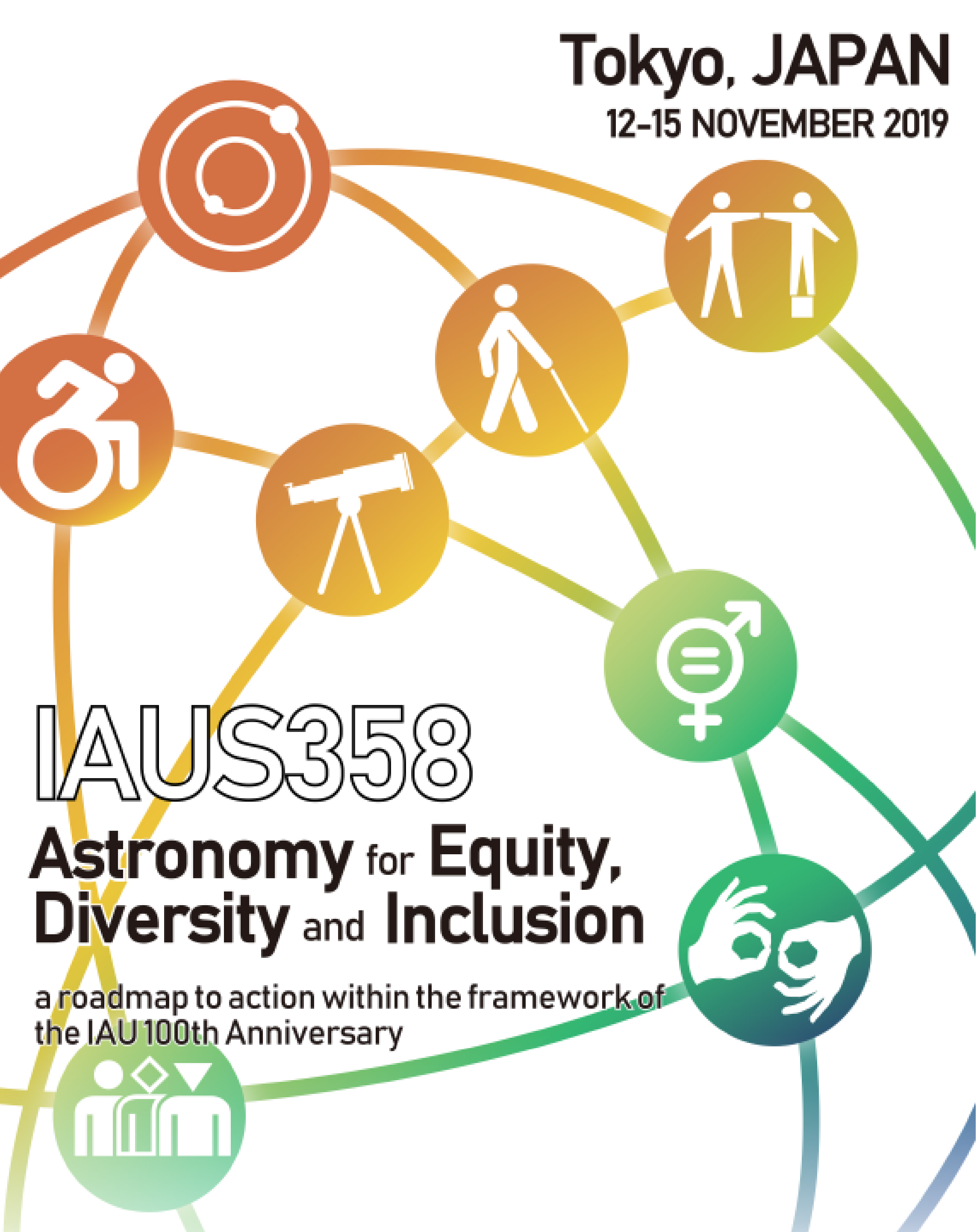
UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of California, Los Angeles
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 and 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
icecube.wisc.edu



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

Organisers
Platinum Sponsors
Golden Sponsor
Partners
Endorsers

Conclusions and Outlook

- IceCube sees neutrinos created in the atmosphere and the far Universe
- These neutrinos enable a wide range of particle physics and astrophysics studies
- IceCube has discovered high energy cosmic neutrinos, and evidence of the first cosmic neutrino source and thus evidence of an extragalactic cosmic-ray source
- The ongoing IceCube Upgrade followed by IceCube-Gen2 construction will deliver unprecedented exploration of the high energy Universe and probing of fundamental physics

Photo: Johannes Werthebach IceCube/NSF   August, 2018