Exploring the Universe with "Icebound" Neutrinos

Donglian Xu

(WIPAC, UW-Madison)

EPD Seminar, IHEP

April 10, 2018

Beijing, China

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

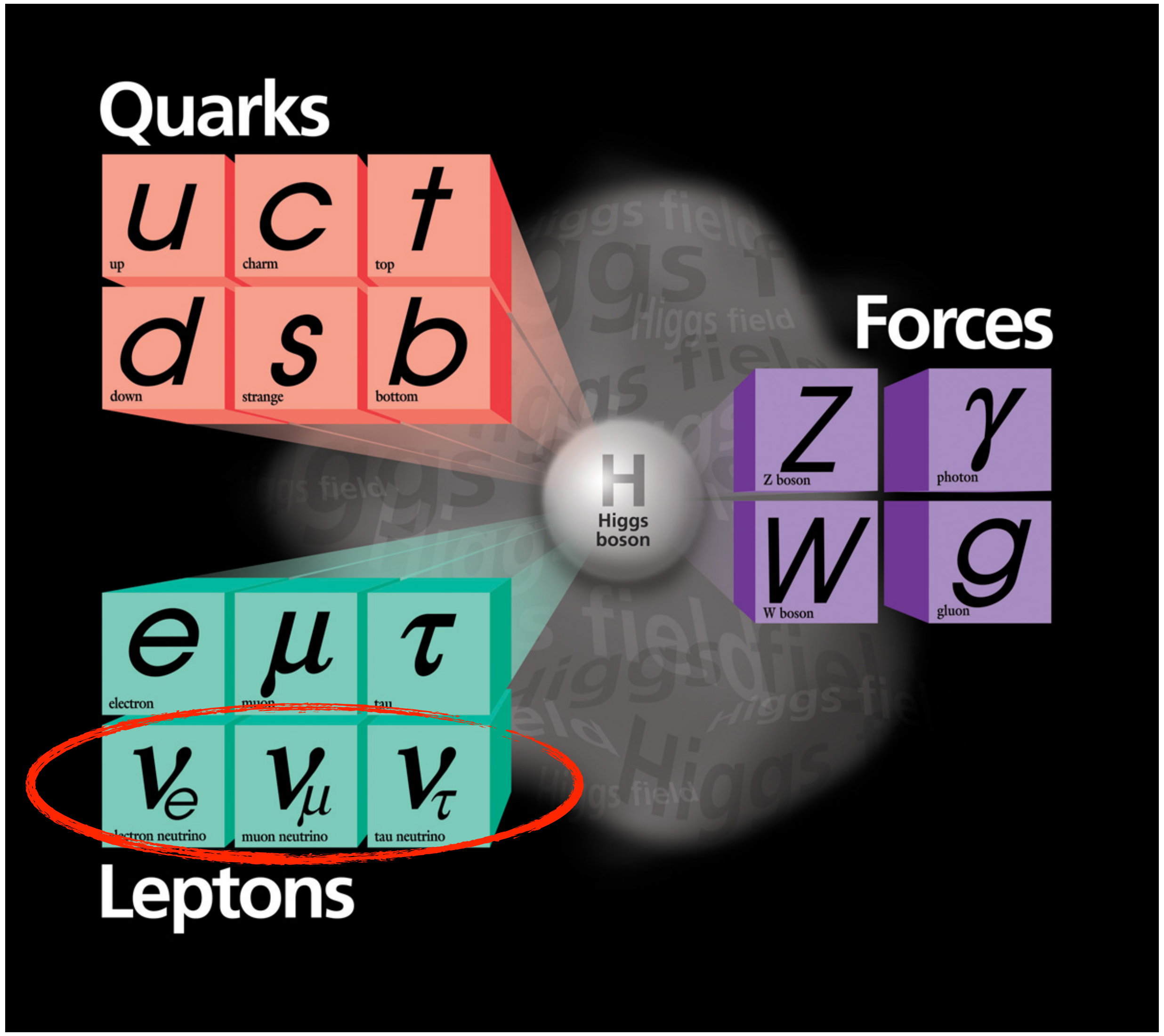
Email: dxu@icecube.wisc.edu

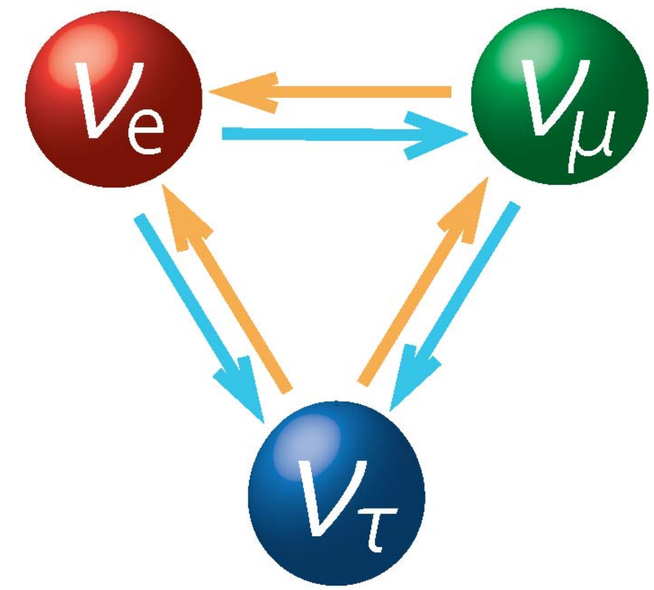
Outline

- ✦ **Neutrinos and neutrinos as cosmic messenger**
- ✦ **Cosmic rays and multi-messenger astronomy**
- ✦ **Neutrino astronomy:**
  - ✓ **Neutrino telescopes**
  - ✓ **(Some) recent results from IceCube**
    - ➡ **Search for astrophysical tau neutrinos**
    - ➡ **Hunting for neutrino sources**
  - ✓ **The Future: IceCube-Gen2**

Neutrinos:
A Unique Astronomical Messenger

Neutrinos





http://j-parc.jp/Neutrino/en/intro-t2kexp.html

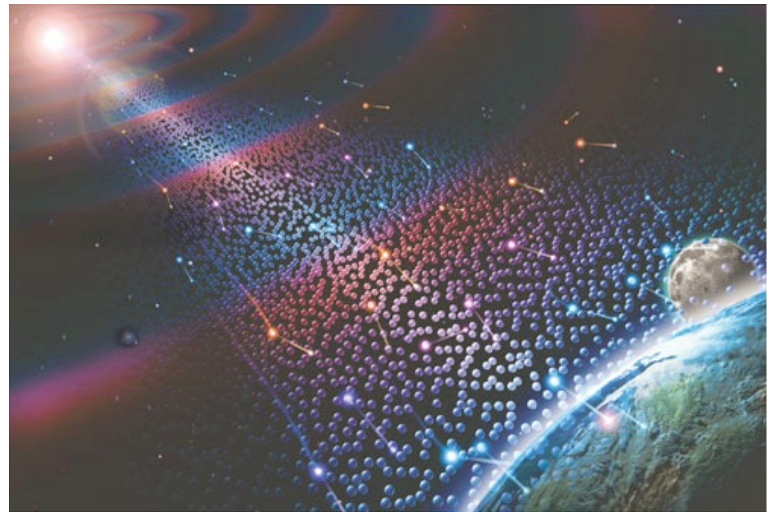
Neutrinos: neutral, weakly interacting
=> hard to detect

- First hypothesized by Wolfgang Pauli in 1930 to explain missing energy and momentum in the beta decay

- **First detection by Reines and Cowan in 1956**

Neutrinos have small mass

Neutrinos from Space



• **Solar neutrino problem:** only 1/2-1/3 of predicted ν_e were detected.

Neutrinos Oscillate

In the Large Magellanic Cloud, ~168,000 light years away

• Solar neutrino experiments:
Homestake, GALLEX, SAGE, Kamiokande/Super-Kamiokande, SNO, ...

• SN 1987A detection:
- Kamiokande-II (11 $\bar{\nu}_e$)
- IMB (8 $\bar{\nu}_e$)
- Baksan (5 $\bar{\nu}_e$)

$\boxed{\text{MeV neutrinos}}$

"…for the detection of cosmic neutrinos" (2002)

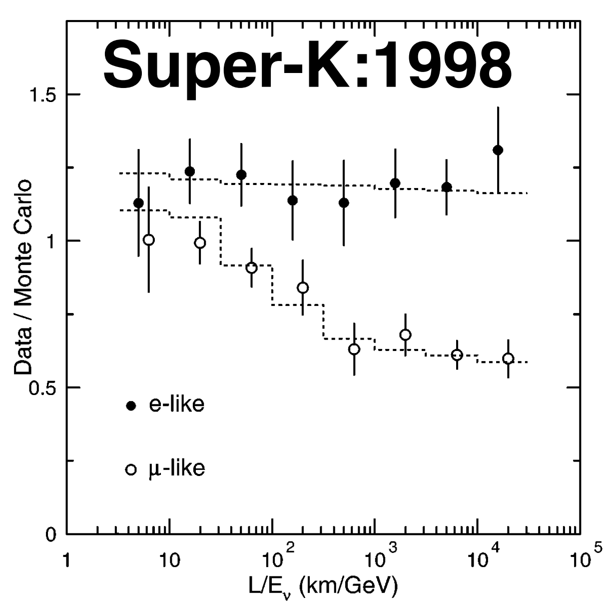
Neutrino Oscillation

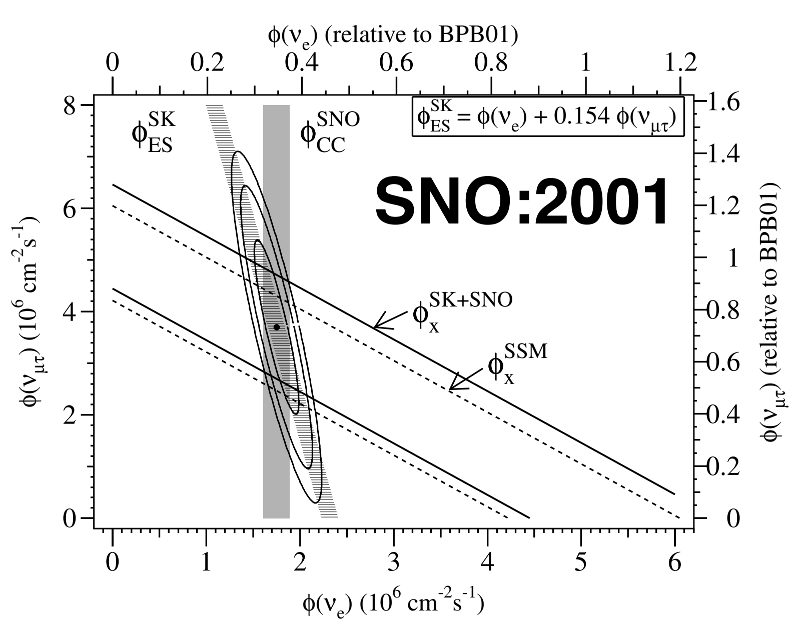
- **Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric sector}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar sector}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

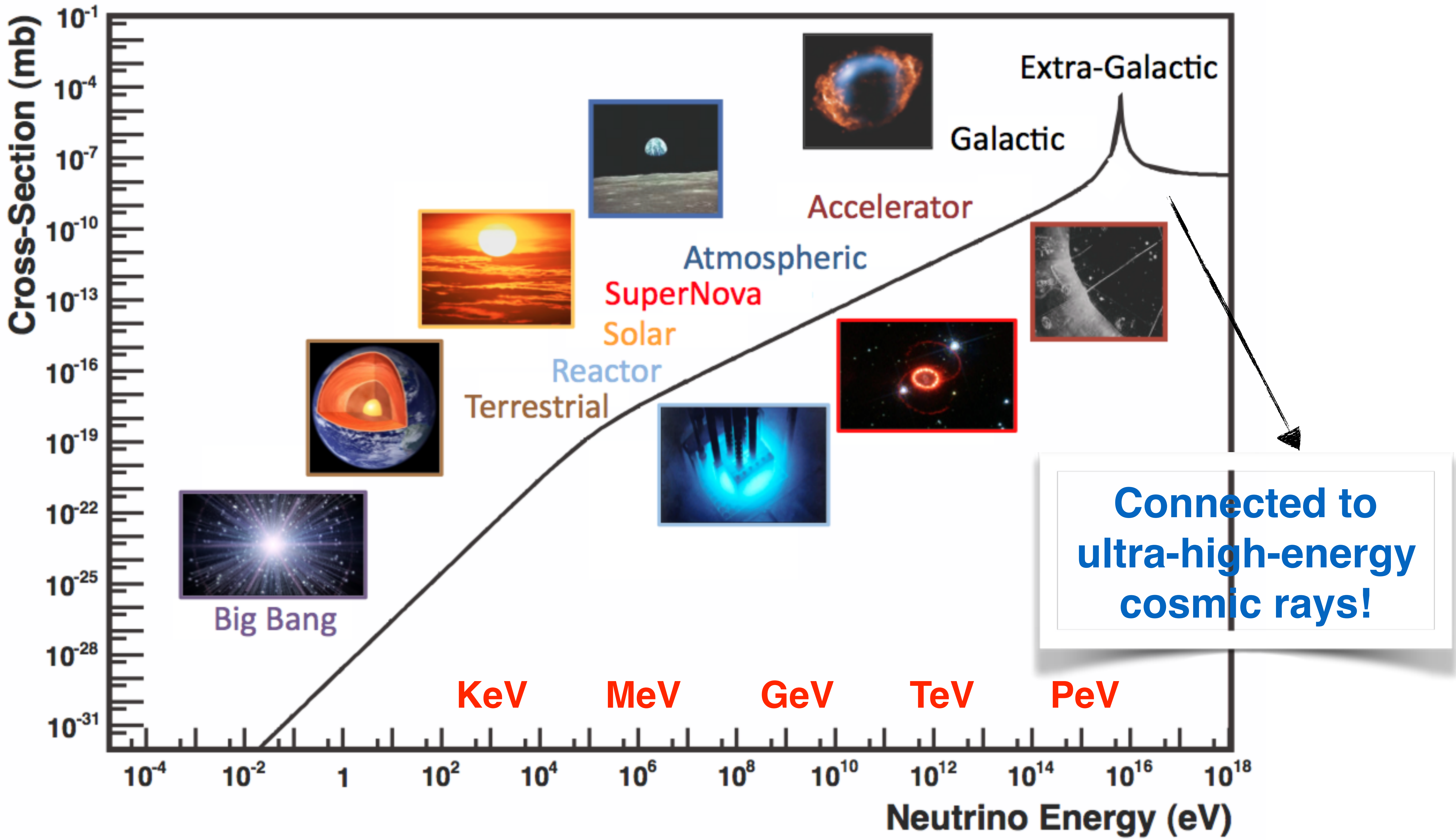
- **Oscillation probabilities (two flavor):**

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right) \text{ (natural units)}.$$



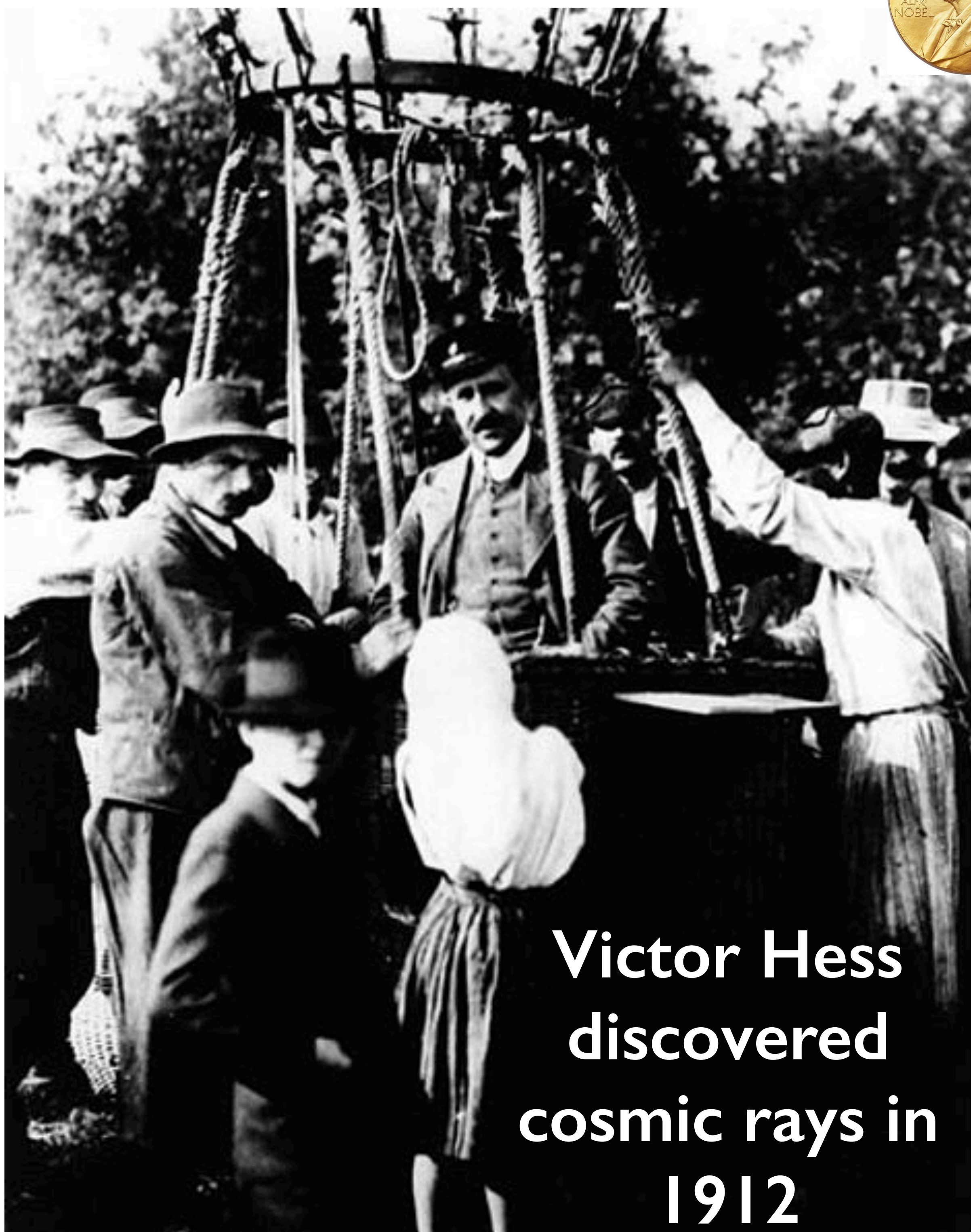


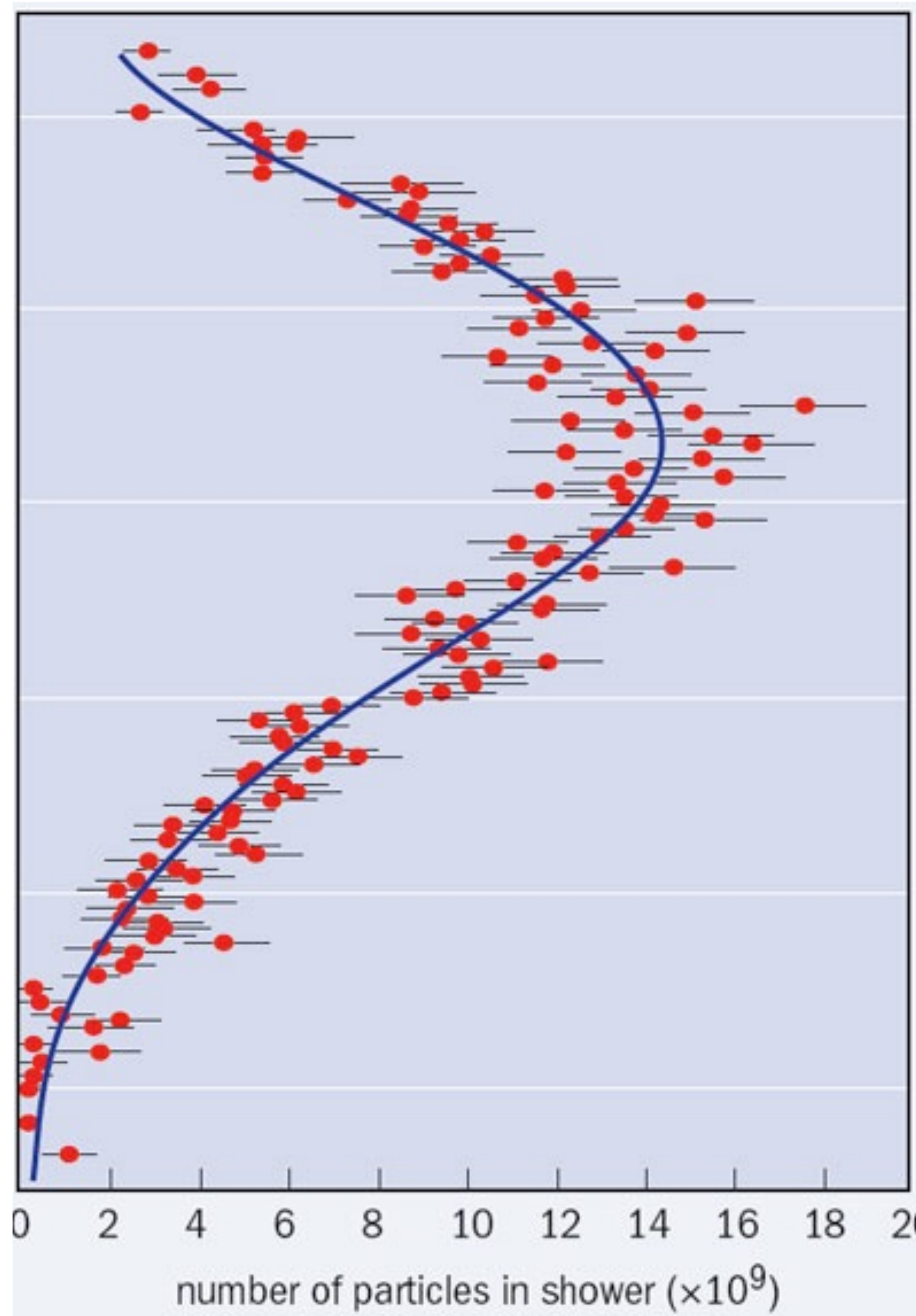
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"(2015)


Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang
Connected to ultra-high-energy cosmic rays!
KeV
MeV
GeV
TeV
PeV
Cross-Section (mb)
10-1
10-4
10-7
10-10
10-13
10-16
10-19
10-22
10-25
10-28
10-31
10-4
10-2
1
102
104
106
108
1010
1012
1014
1016
1018
Neutrino Energy (eV)

Cosmic Rays &
Multi-messenger Astronomy

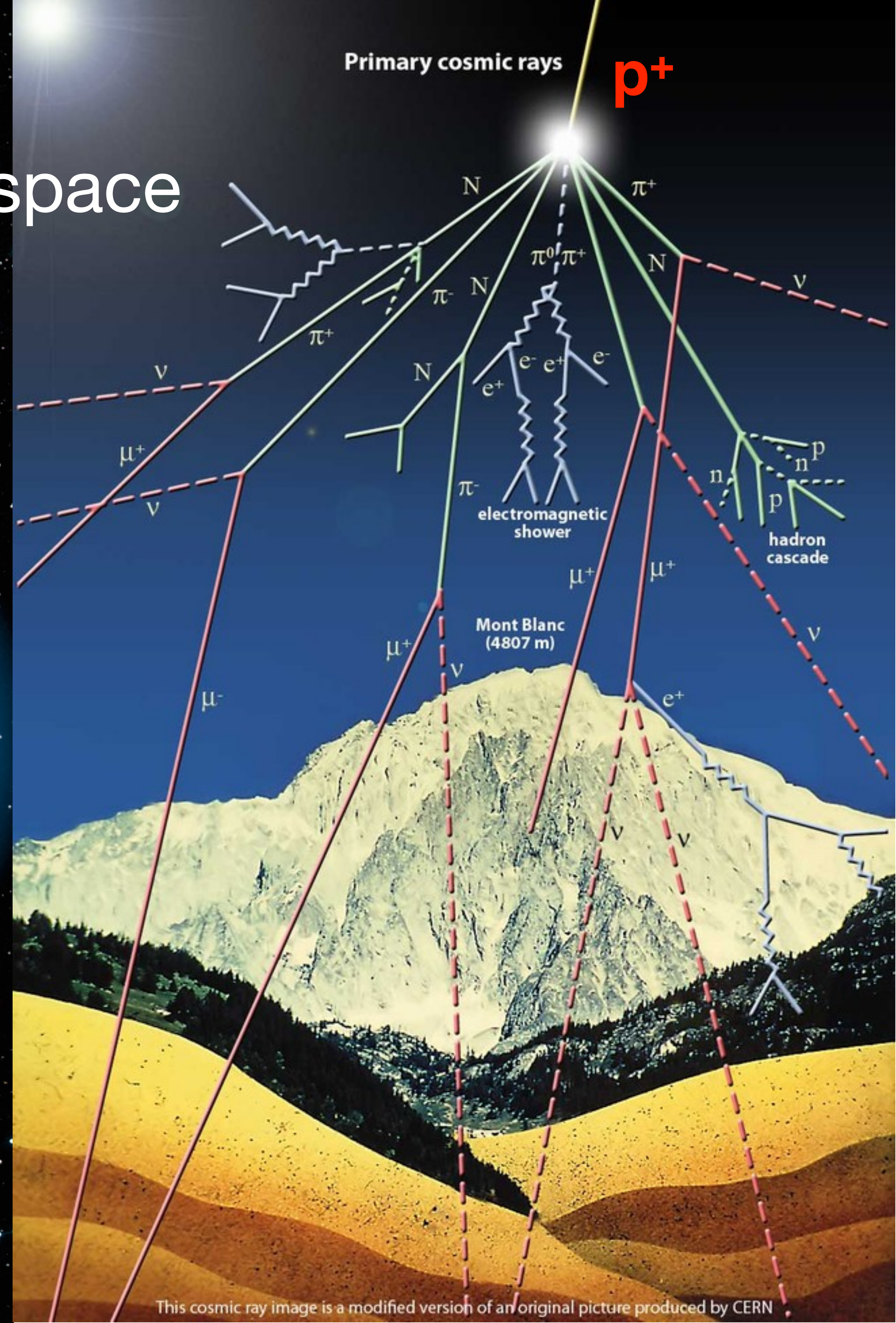
Cosmic Rays


Victor Hess discovered cosmic rays in 1912


0
2
4
6
8
10
12
14
16
18
20
number of particles in shower (×10^9)

cosmic rays
bombarding Earth from space

Earth atmosphere as particle detector



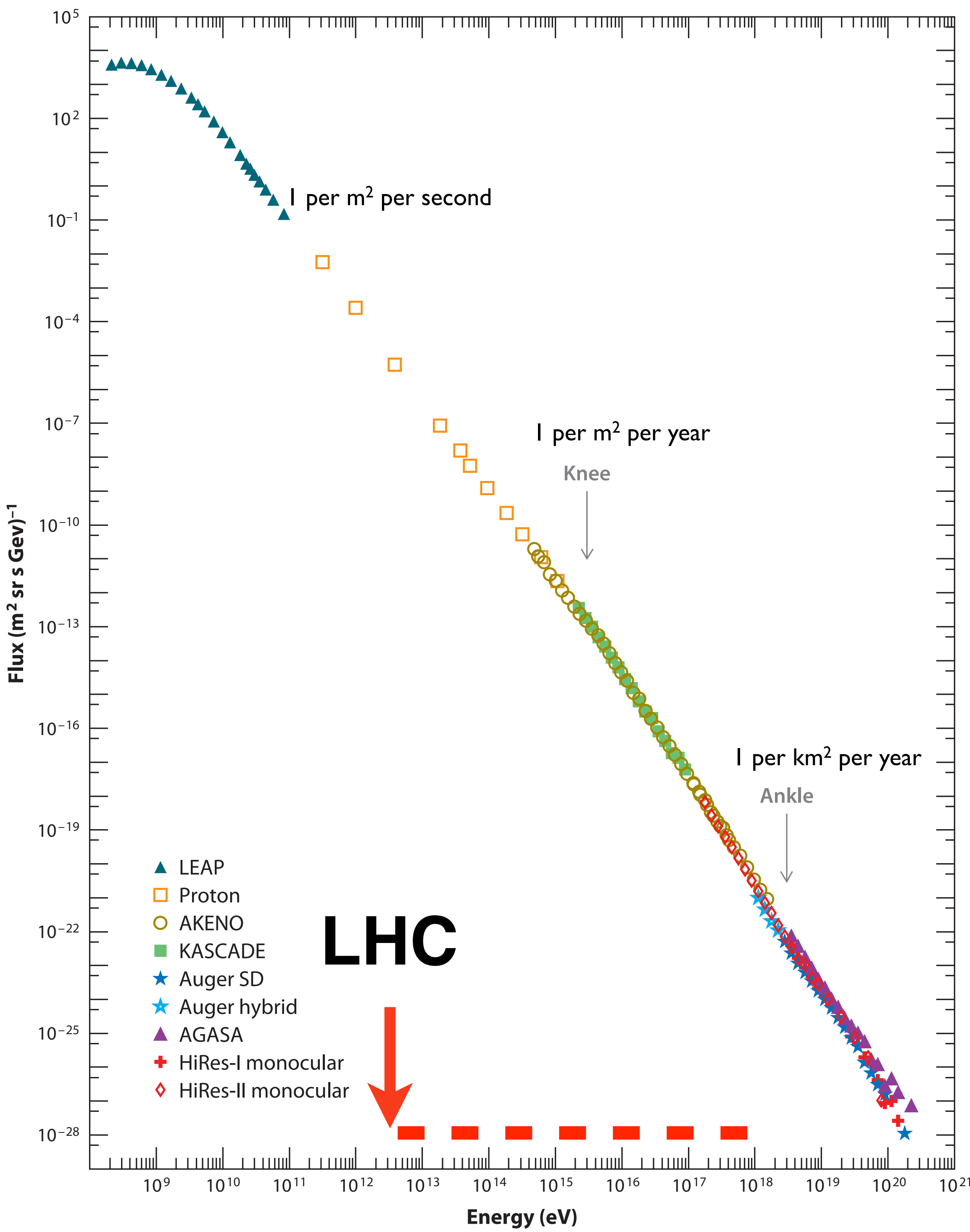
Cosmic Rays: the Oh-My-God Particle

- The Oh-My-God particle was detected by the Fly's Eye detector in 1991 in Utah
- Energy ~3x10^{21} eV

That is, **50 joules** of kinetic energy. Roughly equivalent to a **baseball** kinetic energy thrown at **100 km/h.**

But, all contained in an atomic scale volume!

Cosmic Rays & Neutrinos



All particle cosmic ray energy spectrum

J. Beatty and S. Westerhoff, Ann. Rev. Nucl. Par. Sci. **59** (2009)

$$pp \rightarrow pp\pi^0$$
$$p\gamma \rightarrow \Delta^+ \rightarrow p\pi^0$$
$$\pi^0 \rightarrow \gamma\gamma$$

$$pp \rightarrow pn\pi^+$$
$$p\gamma \rightarrow \Delta^+ \rightarrow n\pi^+$$
$$\pi^+ \rightarrow \mu^+\nu_\mu$$
$$\mu^+ \rightarrow e^+\nu_e\bar{\nu_\mu}$$

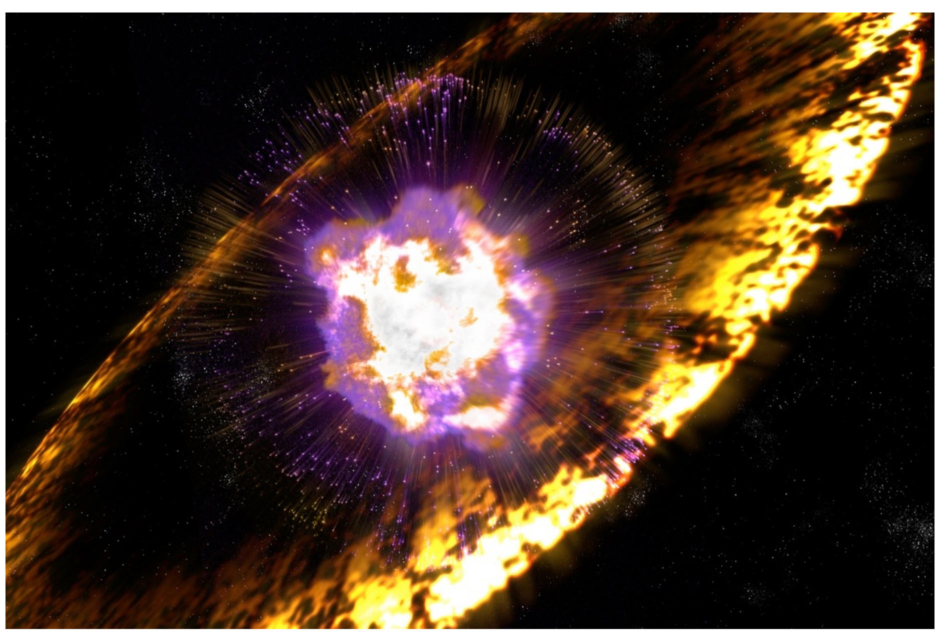
$$(\nu_e : \nu_\mu : \nu_\tau)^S \simeq (1:2:0)$$

- The production of high-energy cosmic rays should also lead to the production of gamma rays and neutrinos
- Acceleration of cosmic rays in astrophysical shocks leads to E^{-2} energy spectrum (Fermi acceleration)

Candidate Cosmic Ray Acceleration Sites

Active Galactic Nuclei (AGNs)

Gamma Ray Burst (GRB)



Supernovae

- **Fermi acceleration:**

$$\frac{dN}{dE} \sim E_\nu^{-2}$$

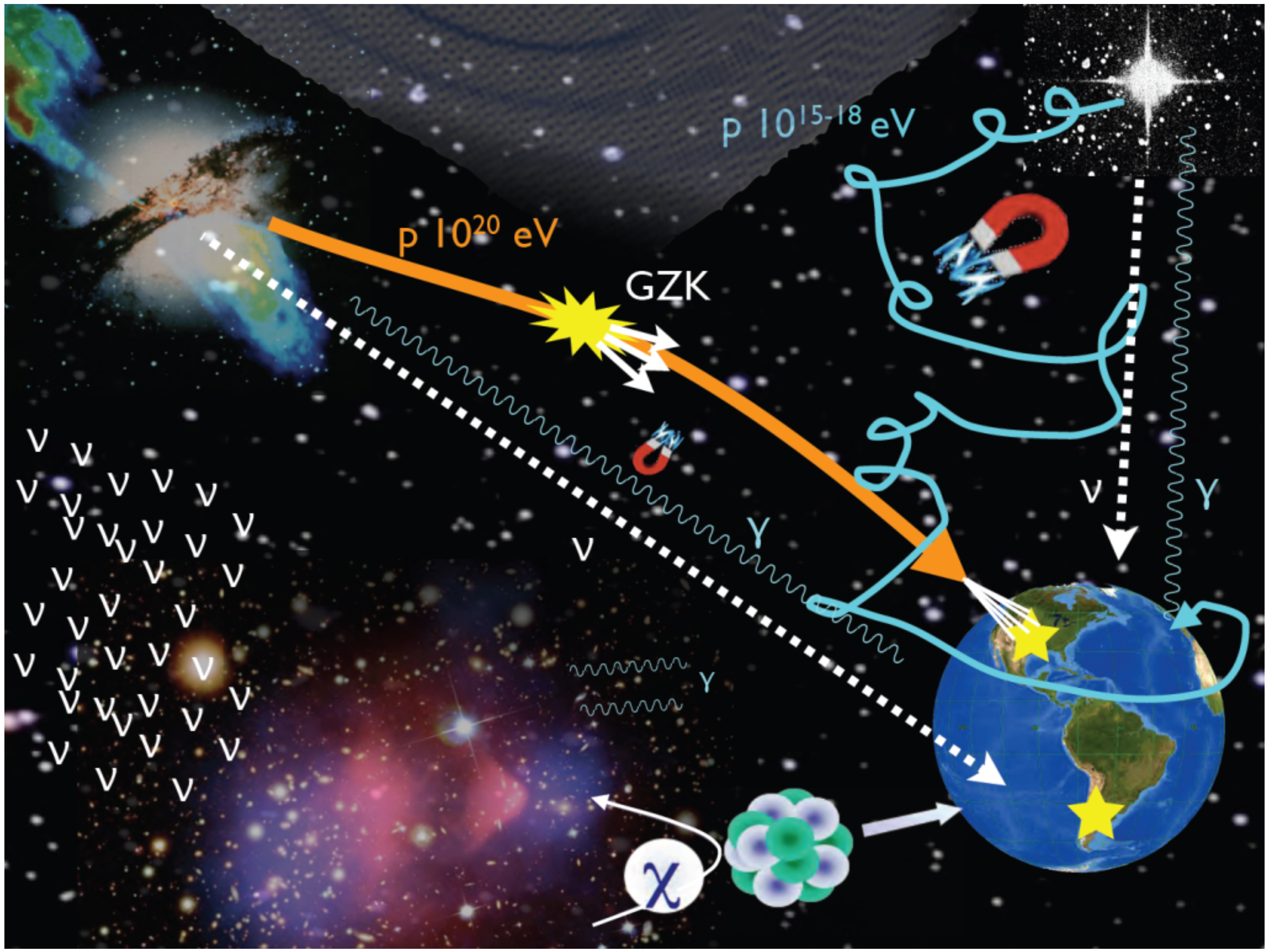
If cosmic rays interact before decaying, spectrum is softer

- **At Earth's surface:**

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

Expected astro. ν flux at Earth $E^2\phi_\nu \sim 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} (TeV-PeV)

Multi-messenger Astronomy with Neutrinos



Source: http://web.physik.rwth-aachen.de/~wiebusch/Research.html

Cosmic Rays:

- Abundant
- Origin unknown
- Charged, trajectory deflected
- At highest energy, absorbed by CMB

Gamma Rays:

- Interact with CMB
- absorbed by infrared background

Neutrinos:

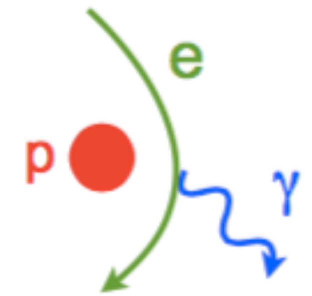
- Weakly interact
- Point back to source

Unique messenger from the high-energy Universe!

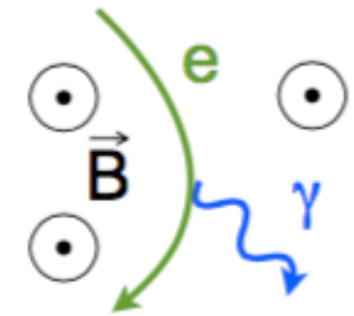
WIPAC Wisconsin IceCube Particle Astrophysics Center
IceCube South Pole Neutrino Observatory

Hadronic vs Leptonic Processes

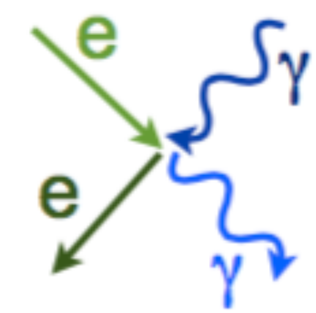
Leptonic processes:
no neutrino production



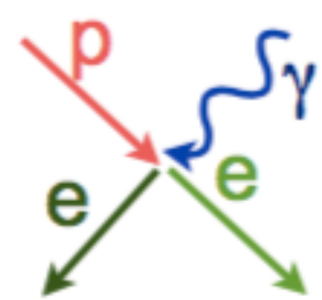
Bremsstrahlung



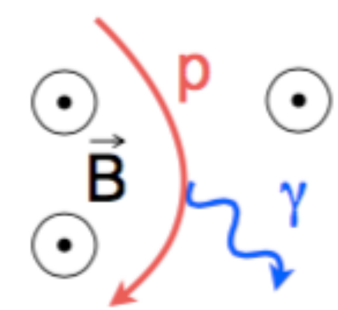
Synchrotron



Inverse Compton

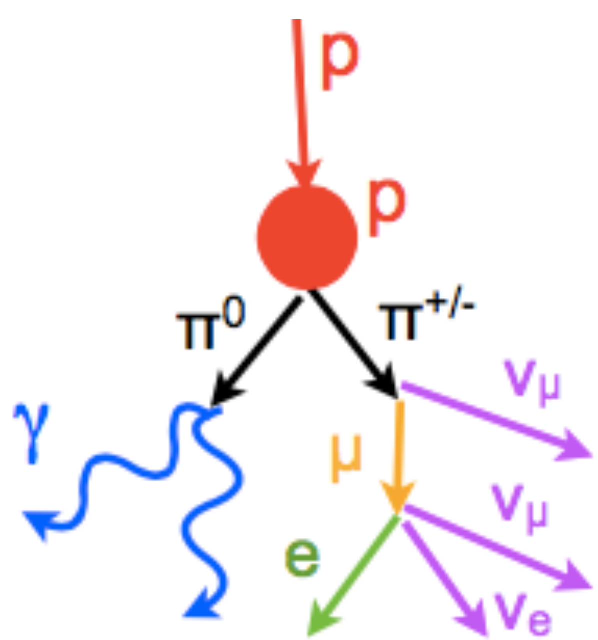


Pair production



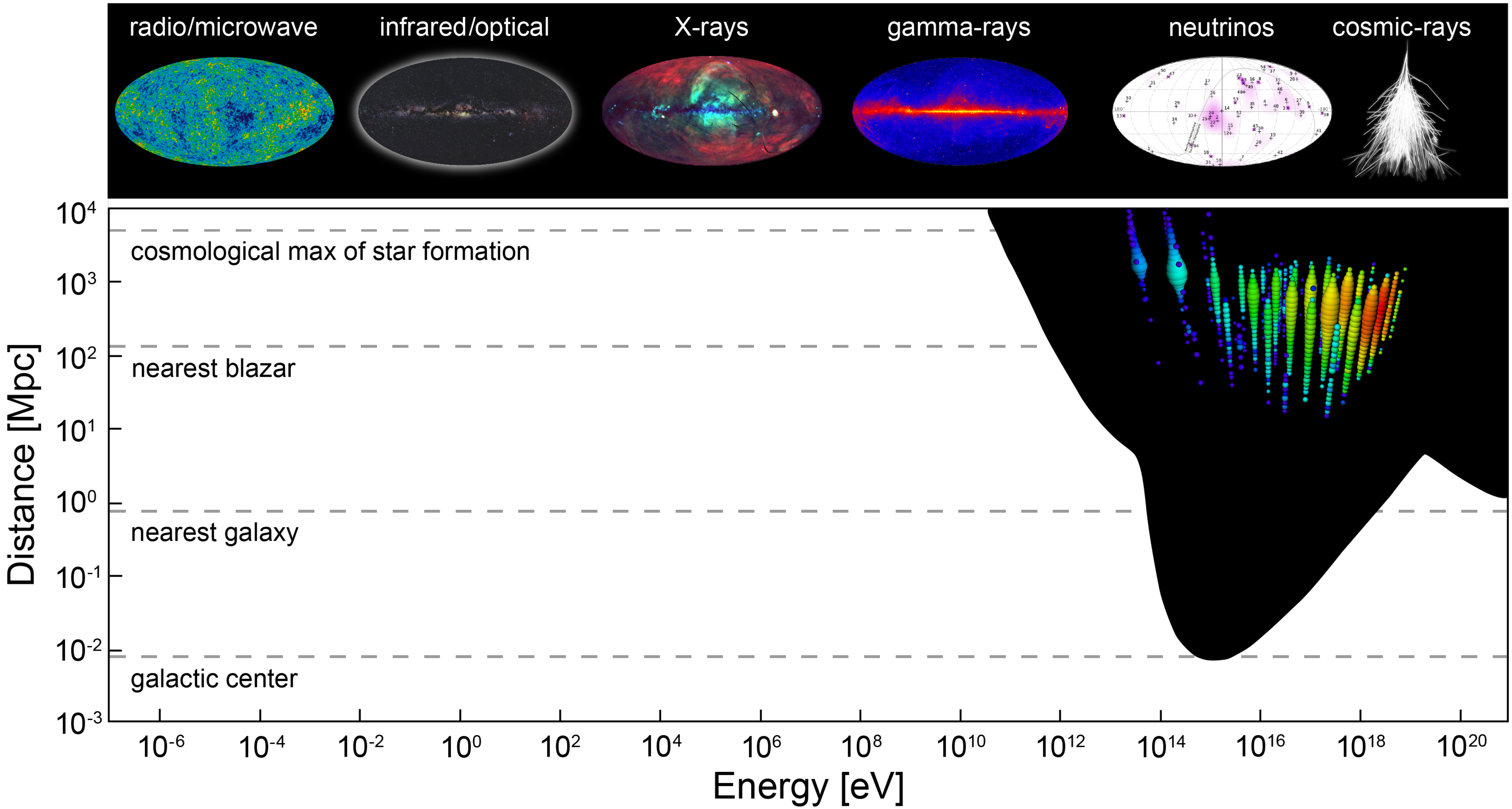
p - Synchrotron

Hadronic processes:
neutrino production



Neutrinos are a diagnostic for hadronic interactions

Multi-messenger Astronomy



The Universe is opaque to EM radiation for ¼ of the spectrum, i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.

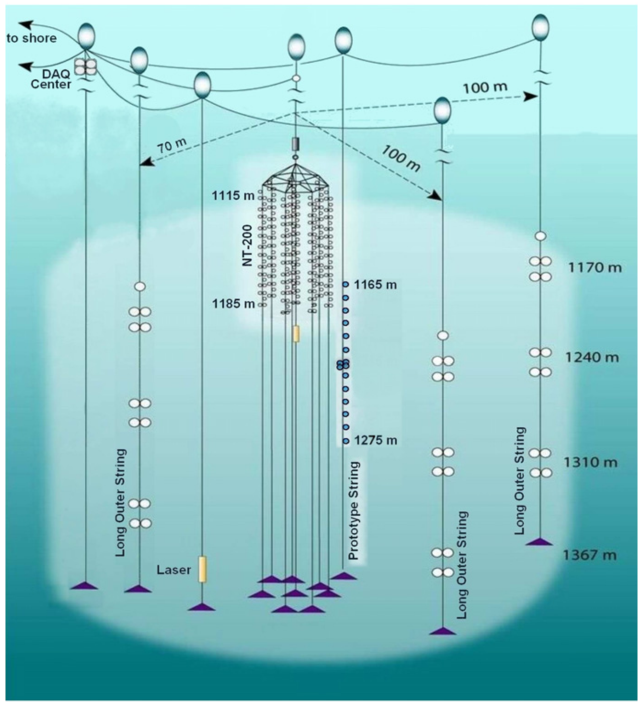
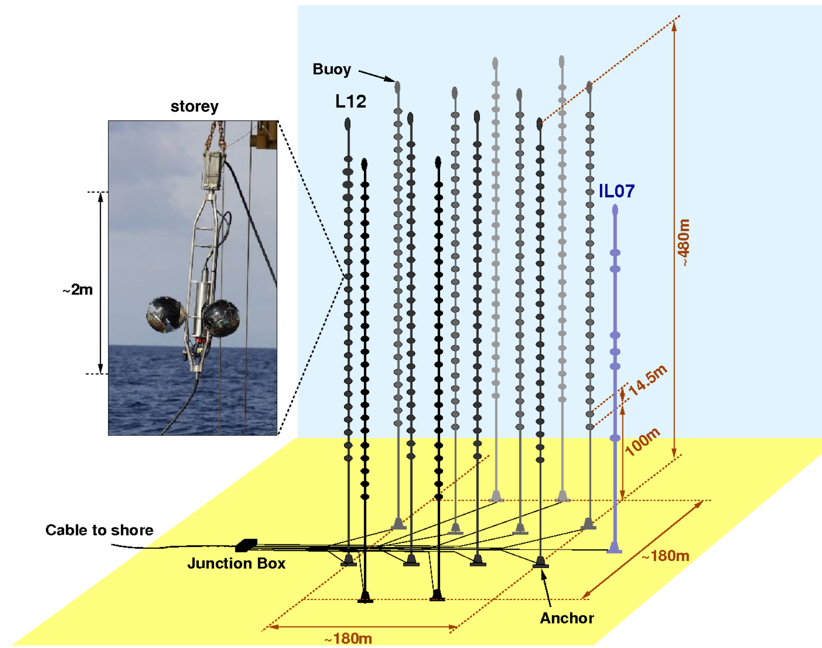
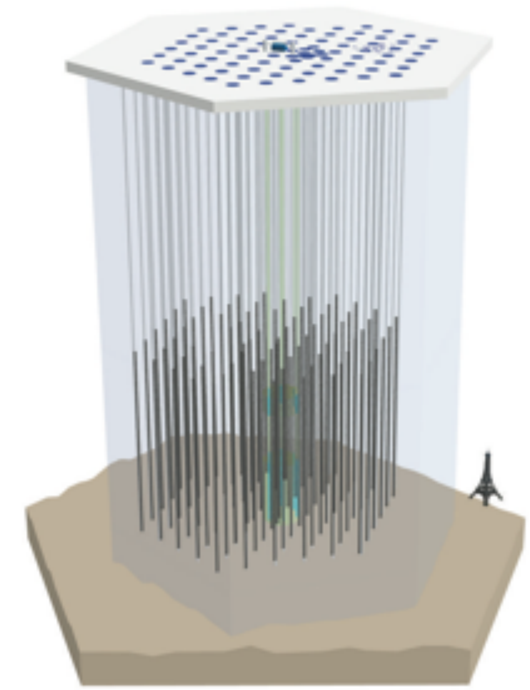
Neutrino Astronomy:

1. Neutrino Telescopes

2. (Some) Recent Results from IceCube

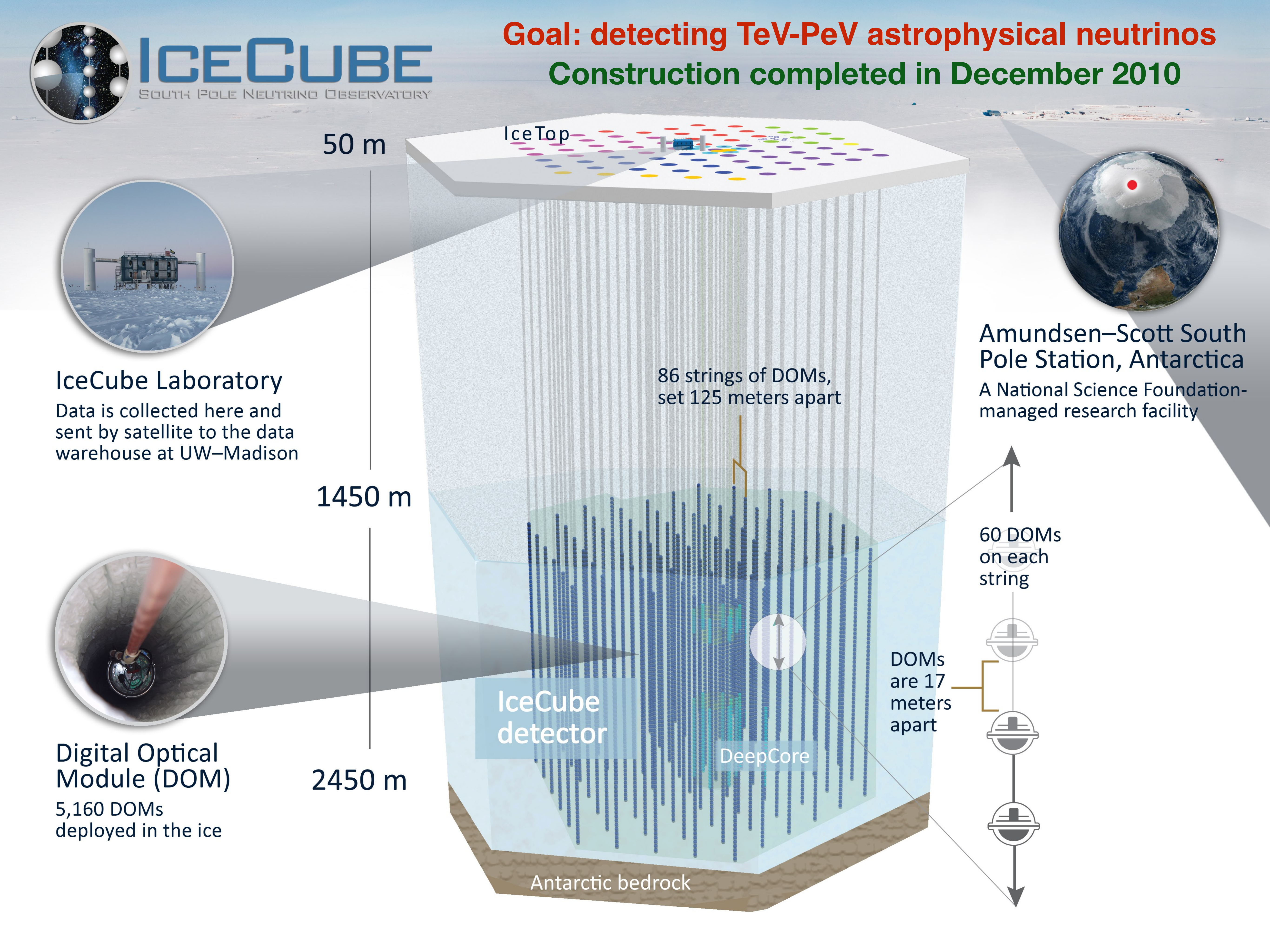
3. The Future: IceCube-Gen2

The World's Existing Neutrino Telescopes

NT-200+	ANTARES	IceCube
		

NT-200+	ANTARES	IceCube
•Lake Baikal	•Mediterranean Sea	•South Pole glacier
•1/2000 km^3	•1/100 km^3	•1 km^3
•228 PMTs	•885 PMTs	•5160 PMTs

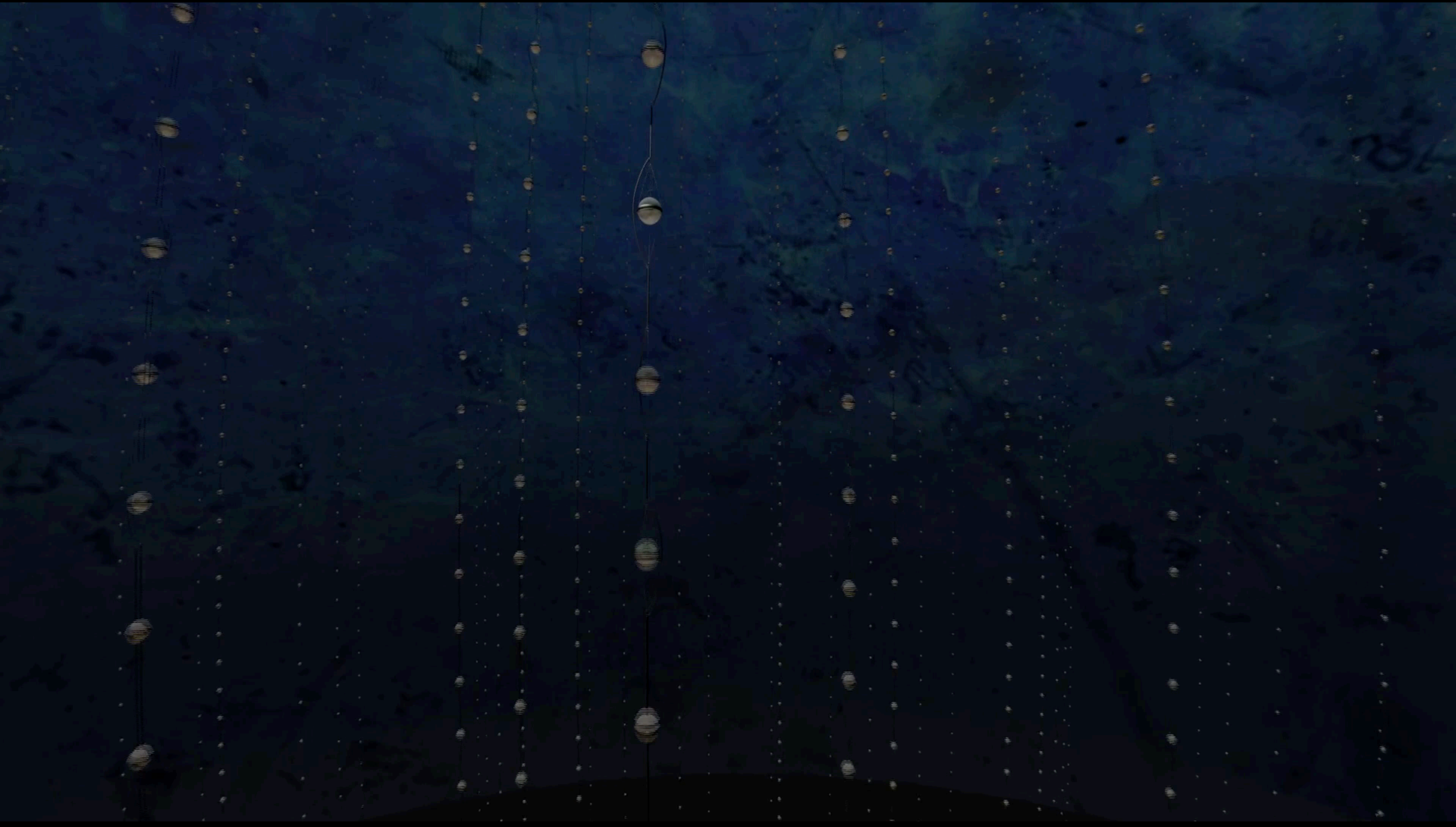
Larger, sparser → higher energies



ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
Goal: detecting TeV-PeV astrophysical neutrinos
Construction completed in December 2010
IceTop
50 m
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
IceCube detector
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart

Light Detection Sensor - DOM

5160 DOMs buried in the ice

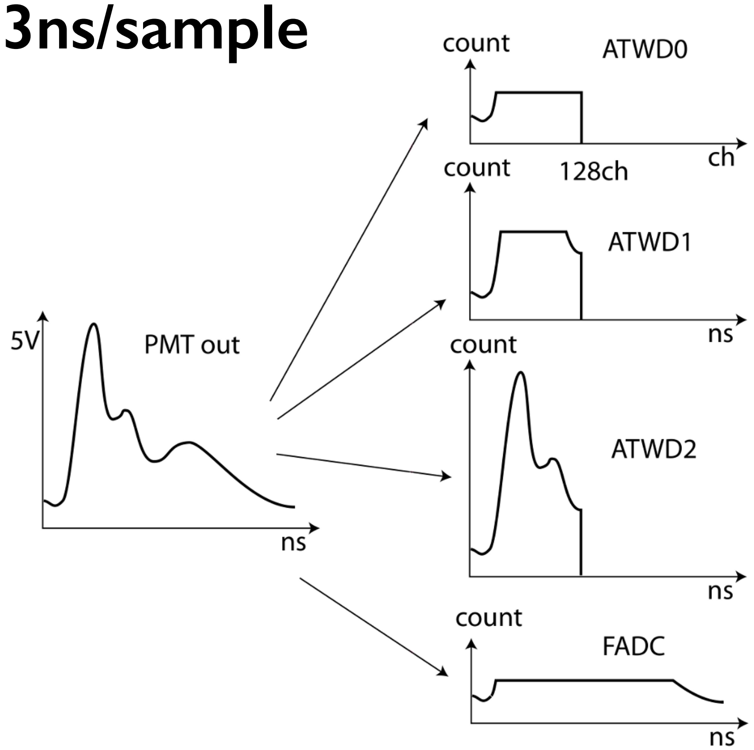


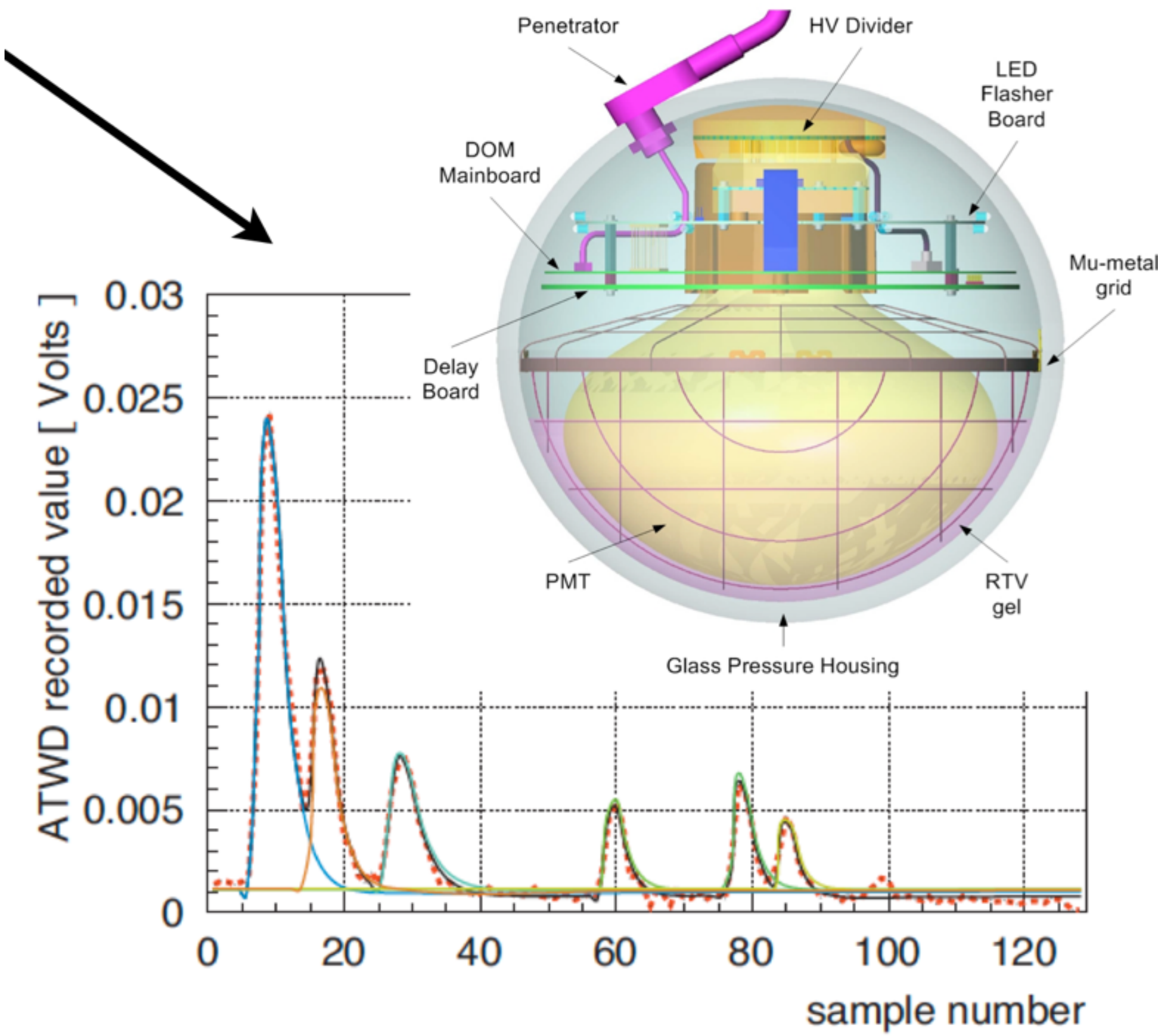
IceCube DOMs and Waveforms

Digitization of PMT waveforms in ice, with ns precision time stamps

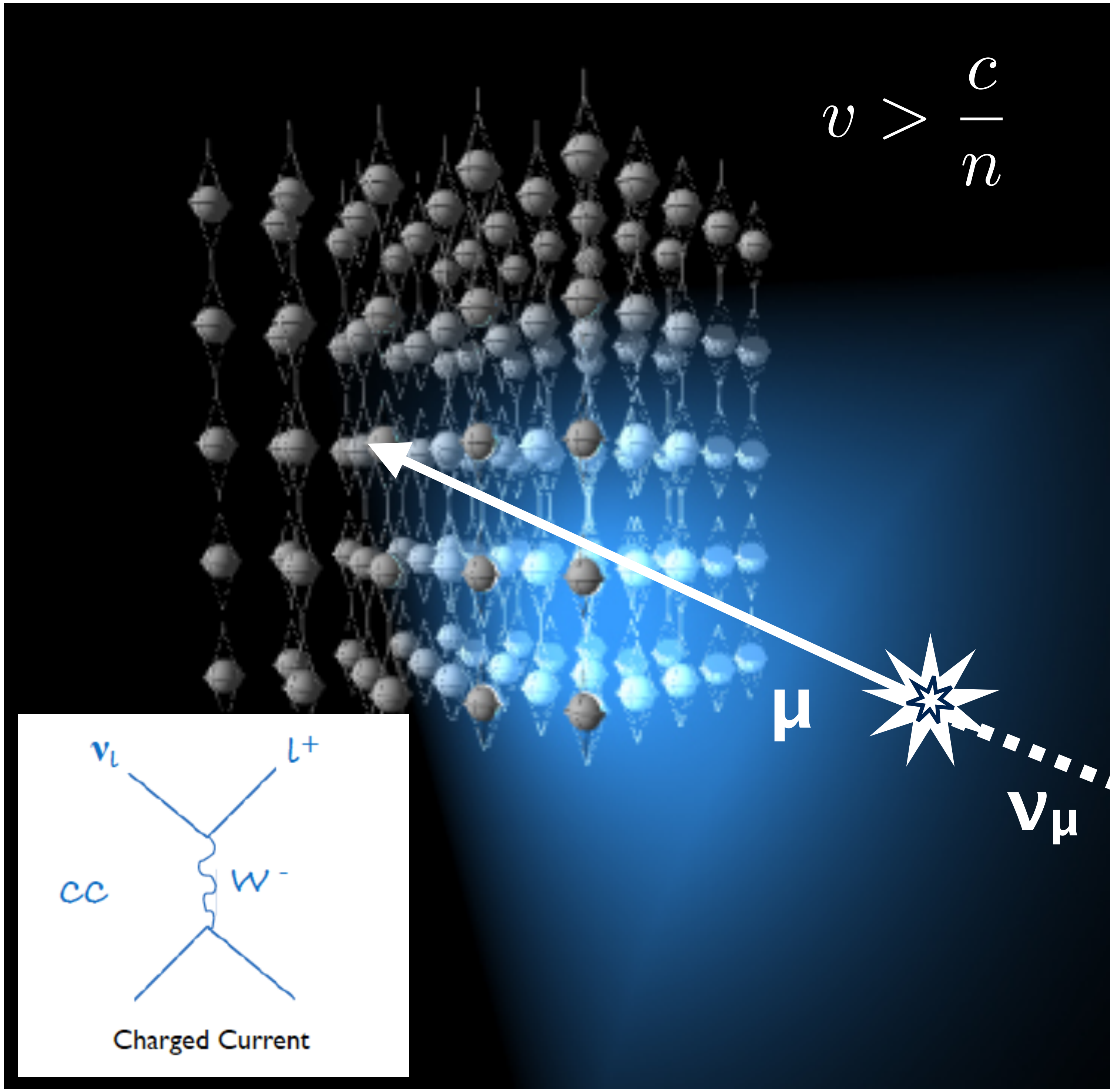
Analog Transient Waveform Digitizer (ATWD) waveform:

- Three channels with (16x, 2x, 0.25x) of nominal gain 10^7
- Time window: 422.3 ns, 128 samples with 3.3ns/sample



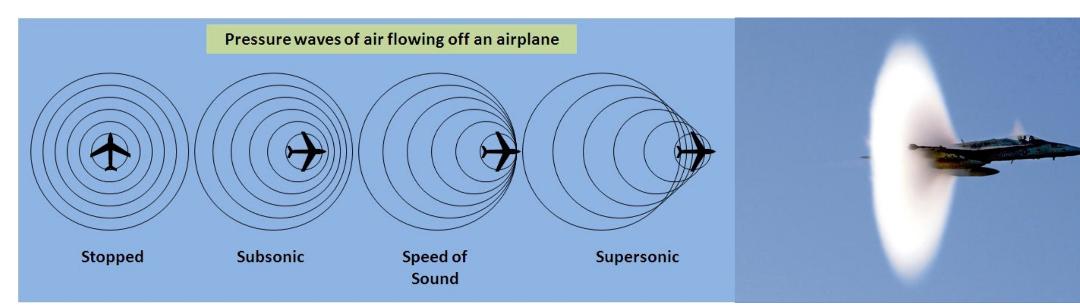


Detection Principle - Cherenkov Radiation



“light boom” - the Cherenkov effect

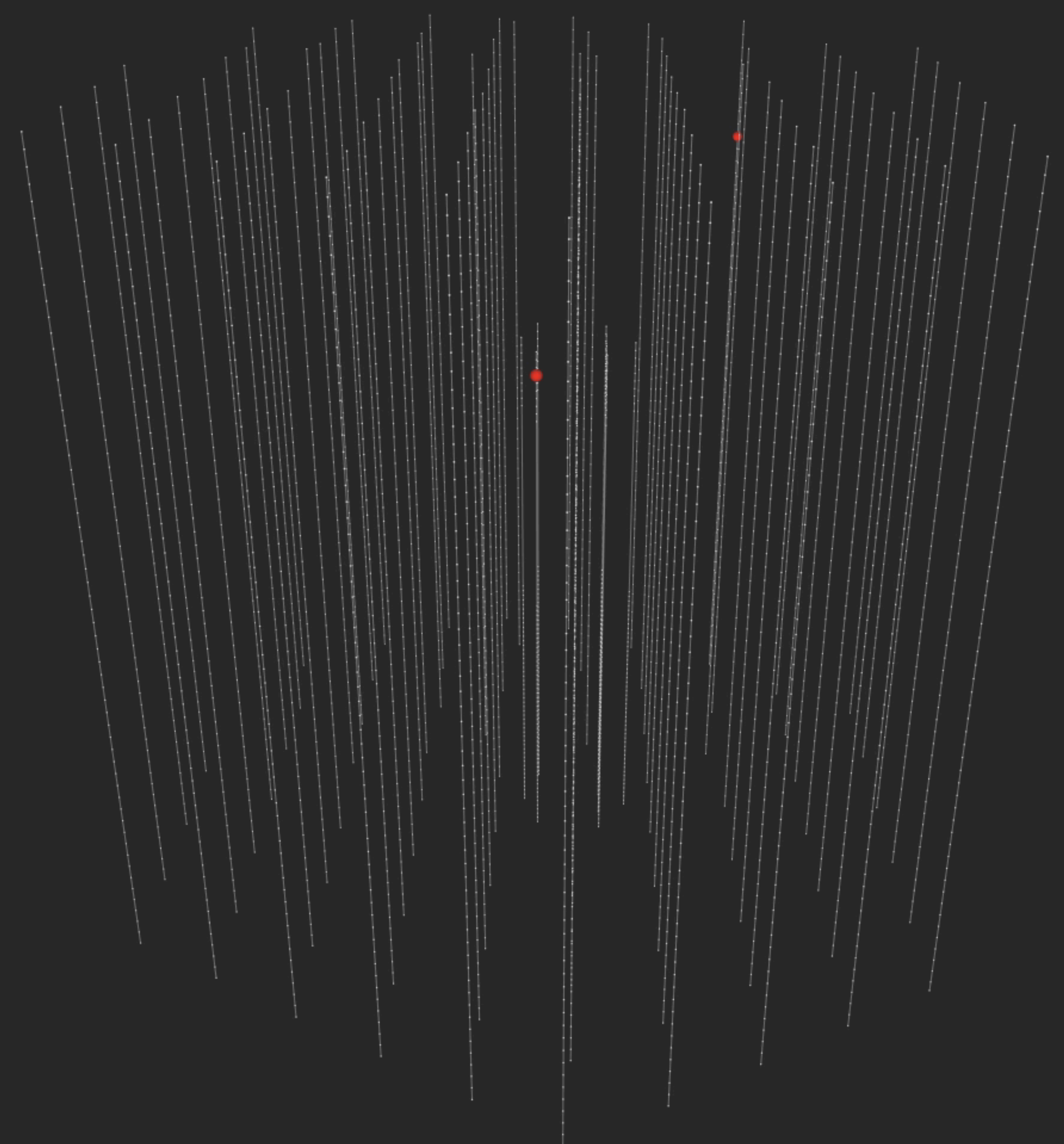
- Neutrinos cannot be detected directly
- Detecting light from neutrino interactions with the ice nuclei (DIS)
- Sensitive to single photon



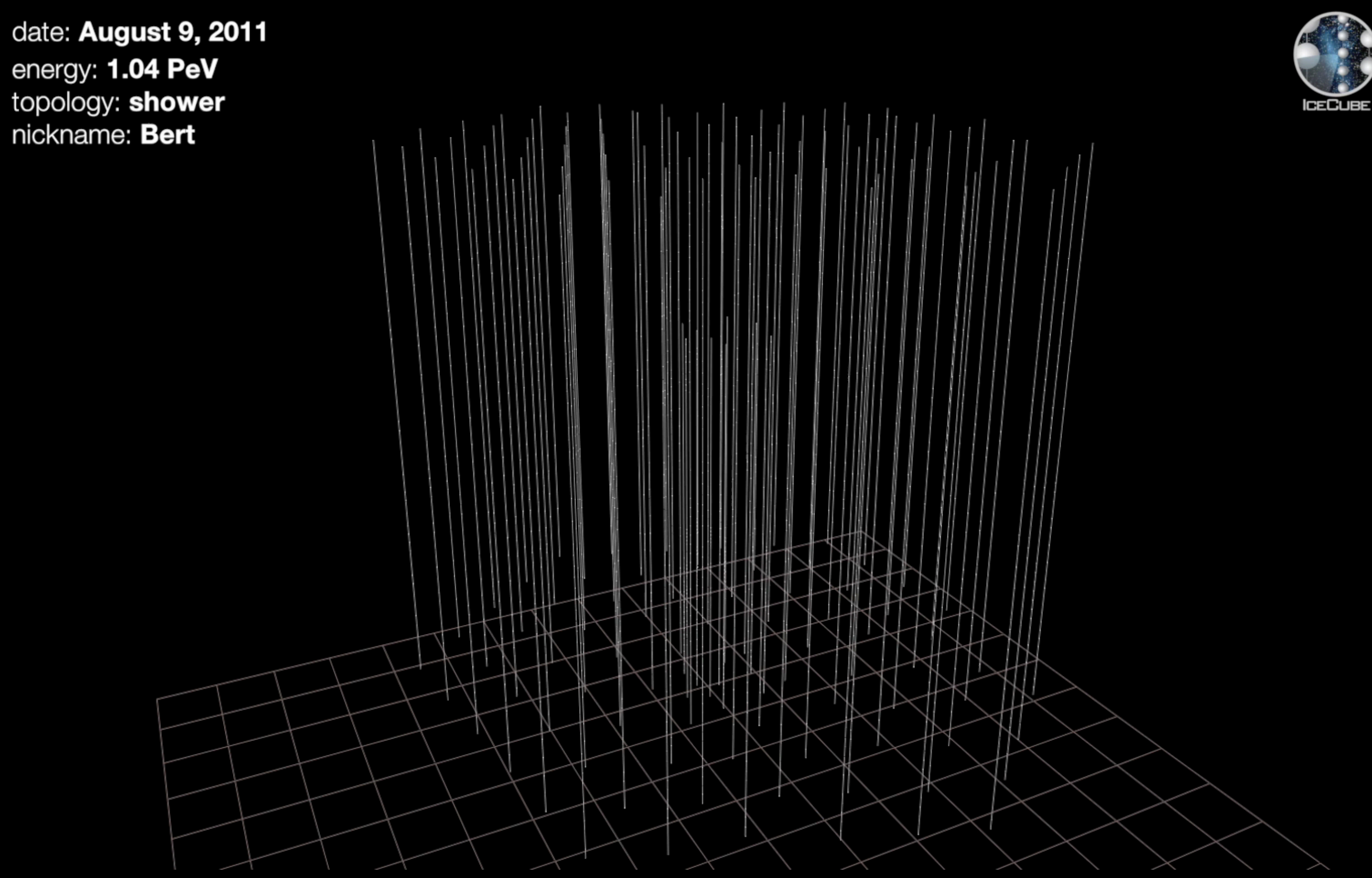
sonic boom

Event Topology - “Track”

Muon



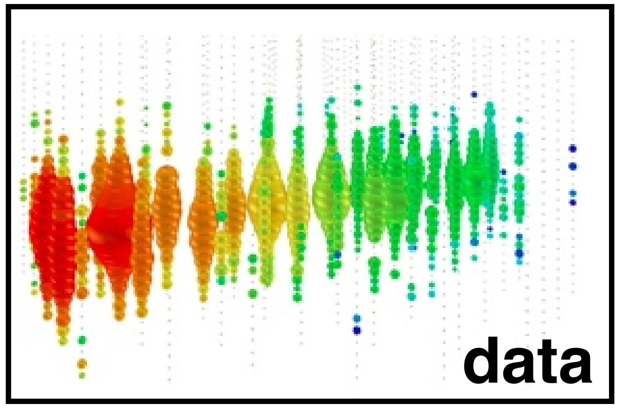
Event Topology - “Cascade”



Neutrino Signatures in IceCube

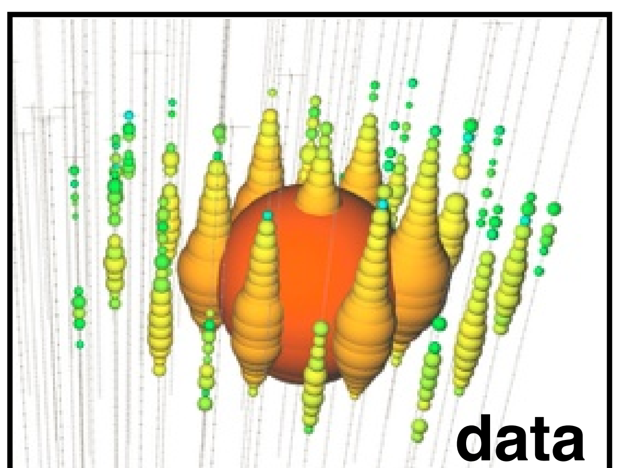
(1) Track: charged current ν_μ

- <1º Angular resolution
- Factor ~ 2 energy resolution

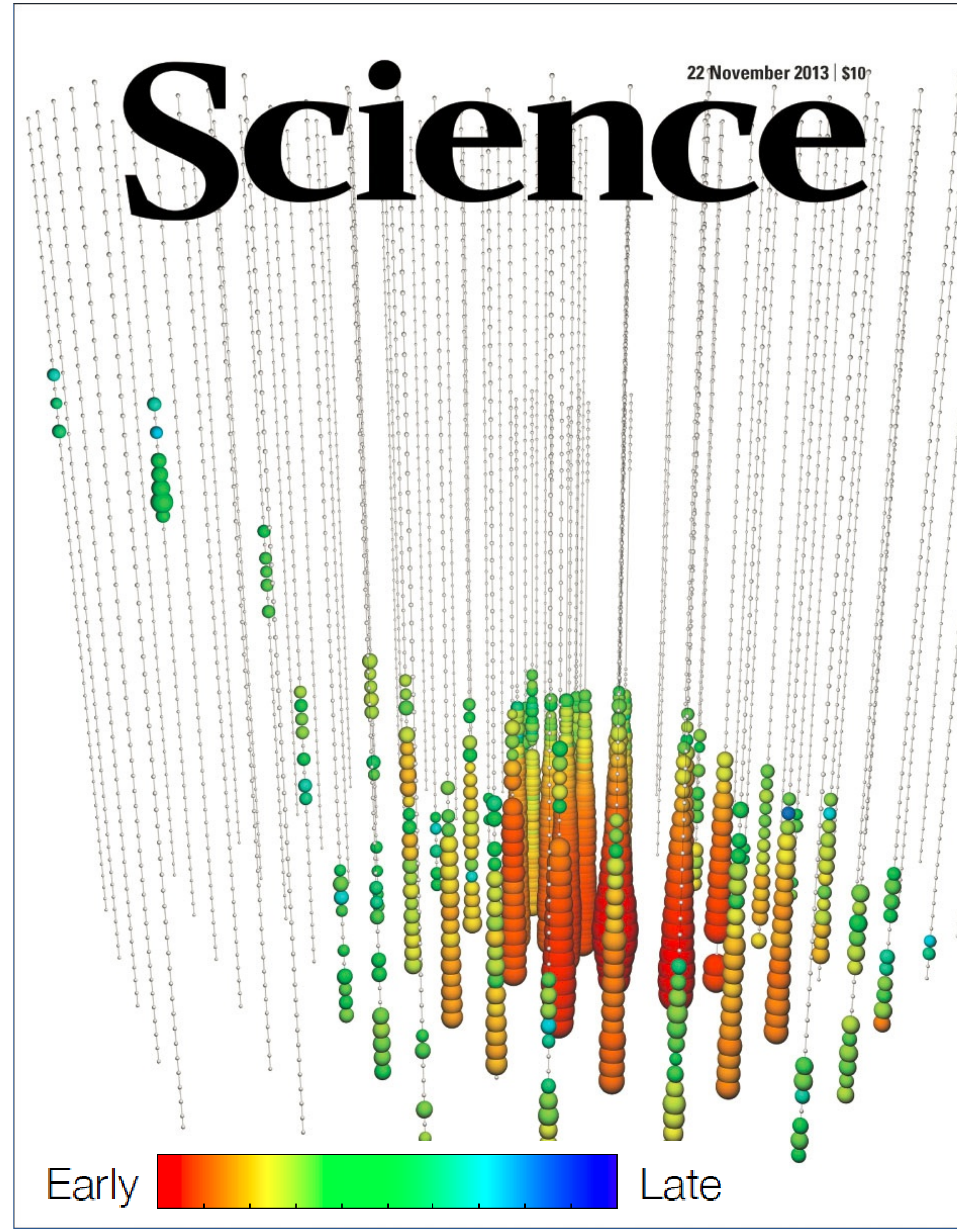


(2) Cascade / Shower: all neutral current, charged current ν_e, low-E charged current ν_τ

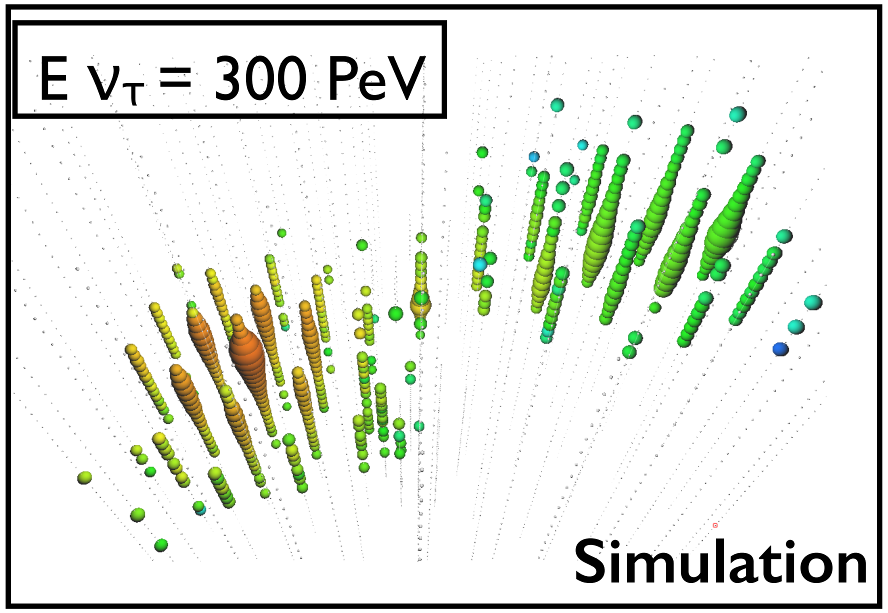
- 10º Angular resolution above 100 TeV
- 15% energy resolution on deposited energy

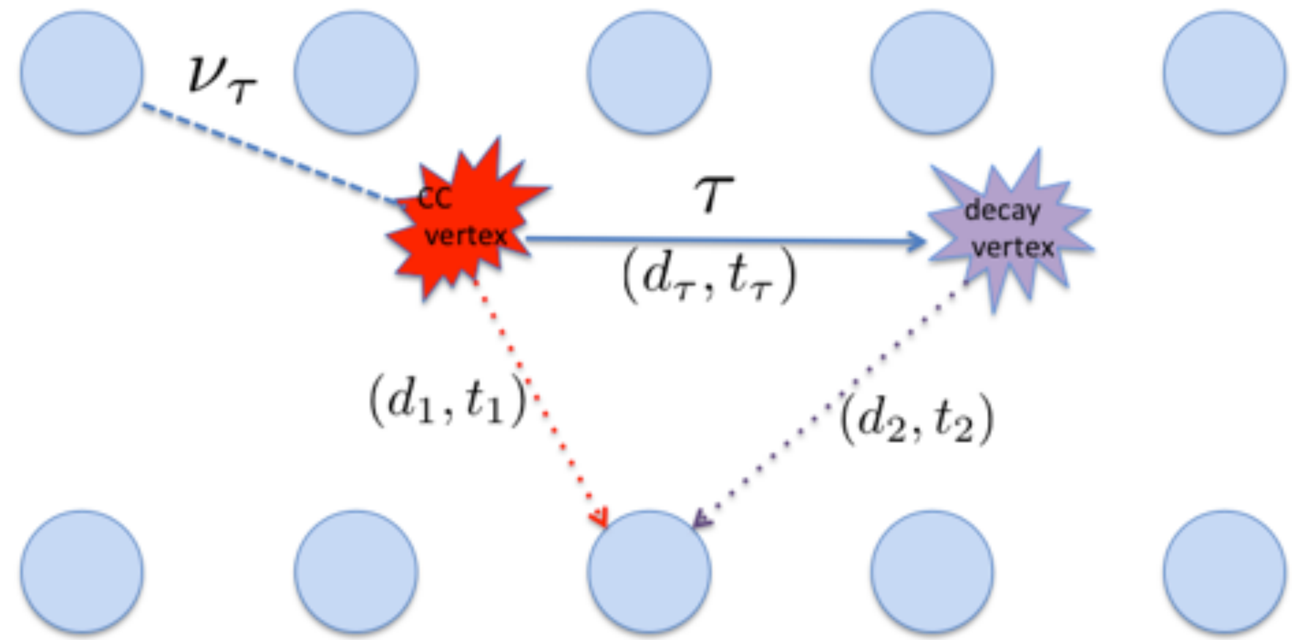


"high degeneracy"



(3) Double Cascades:
High-E ν_τ charged current





- **Tau decay length scales ~ 1PeV / 50m**
- **Not yet detected: active search ongoing**

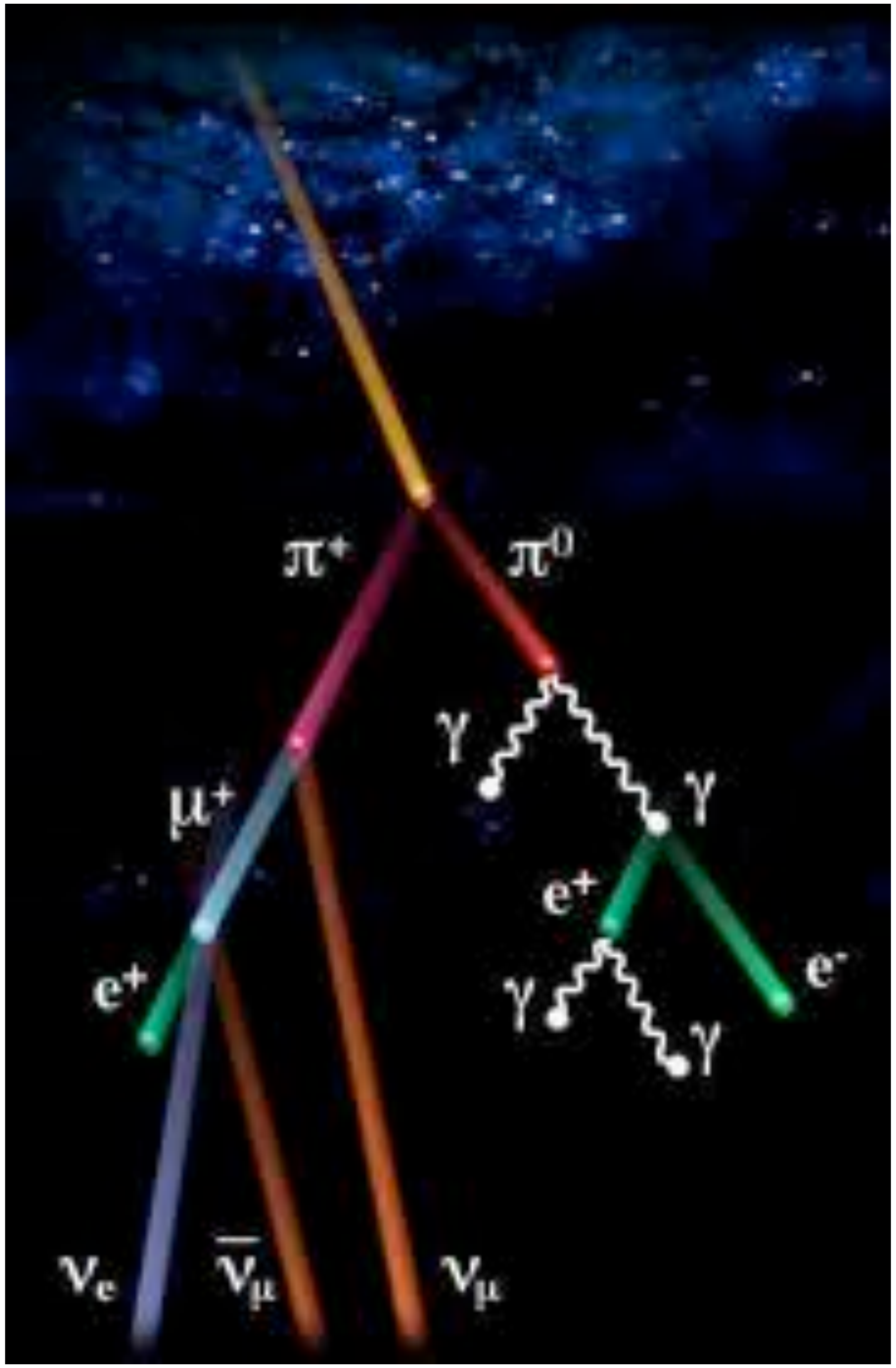
$$\nu_\tau + N \rightarrow \tau^- + X$$

$$\tau^- \rightarrow \nu_\tau + hadrons \quad (64.8\%)$$

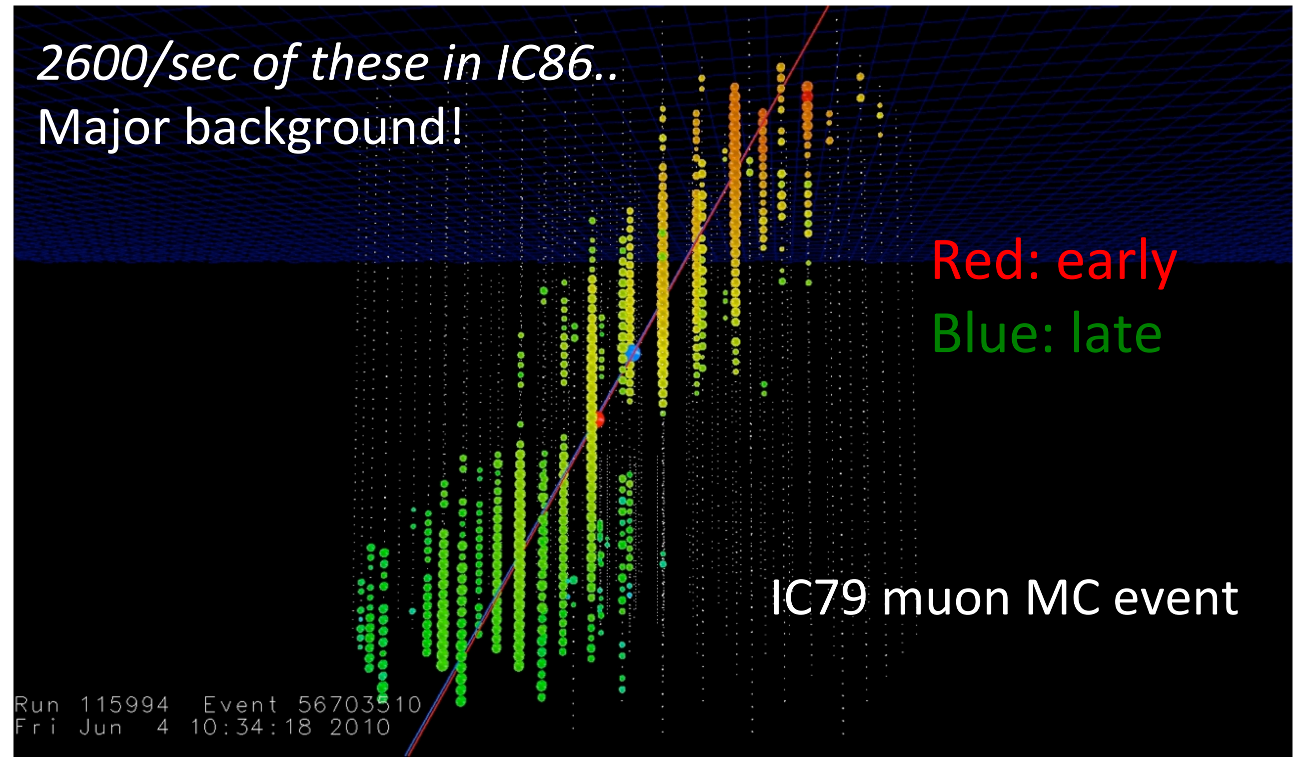
$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^- \quad (17.8\%)$$

$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^- \quad (17.4\%)$$

Background — Atmospheric Muons & Neutrinos



neutrino : muon ~ 1 : 10^6



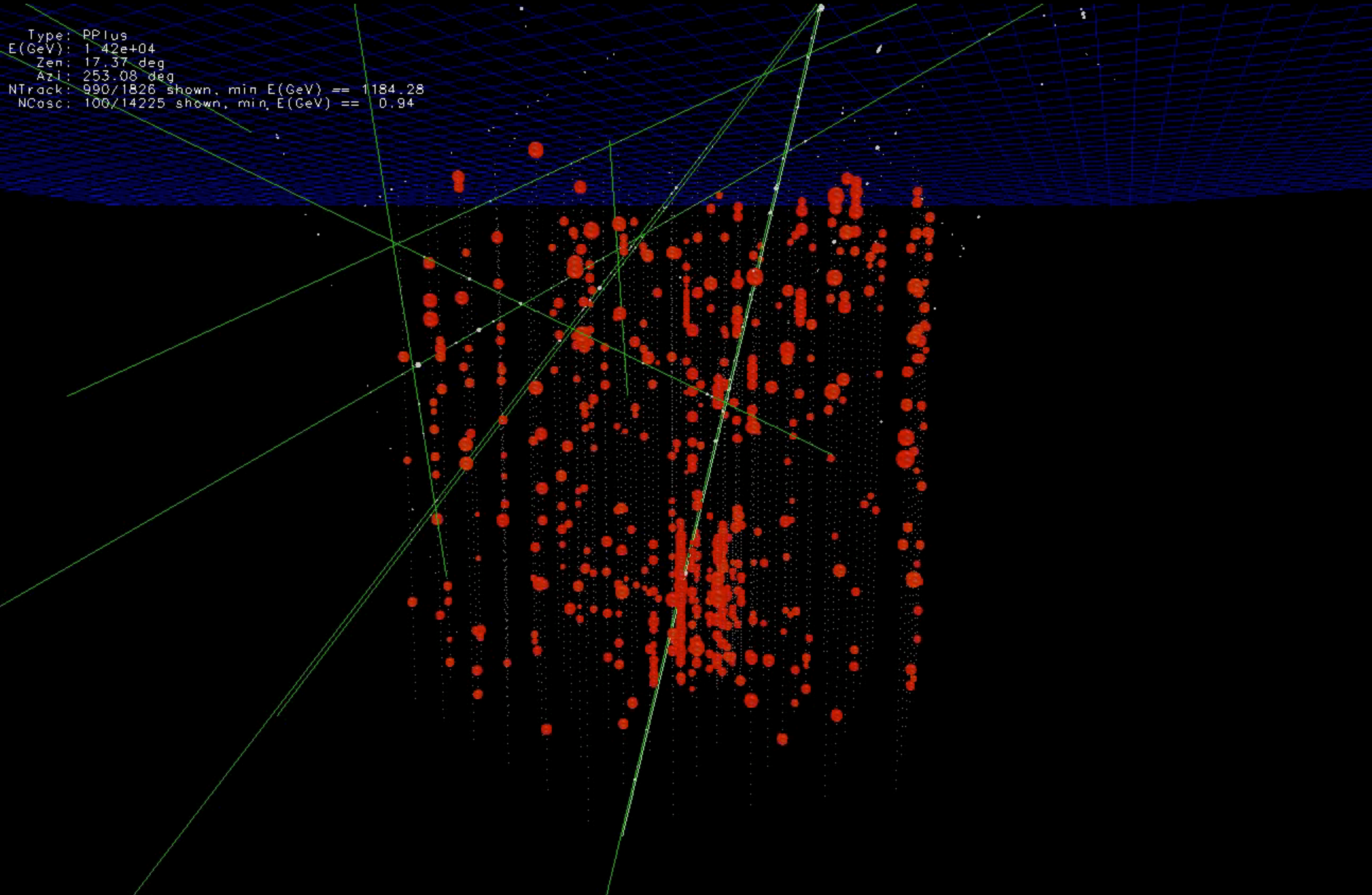
- Conventional: $\frac{dN}{dE_\nu} \sim E_\nu^{-3.7}$

  $\nu_e : \nu_\mu \simeq 1 : 2$

- Prompt: $\frac{dN}{dE_\nu} \sim E_\nu^{-2.7}$ $\nu_e : \nu_\mu \simeq 1 : 1$

Atmospheric prompt ν_τ is ~10 times lower than ν_μ and ν_e

IceCube Collecting Data - What happens in 10 milliseconds?



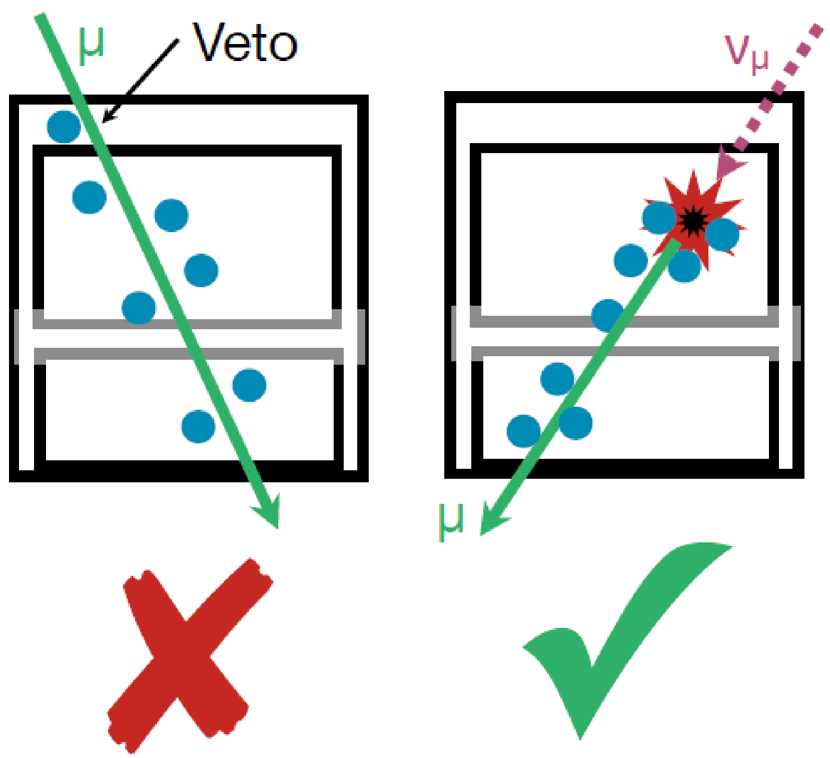
Muons Detected per Year in IceCube

- **Atmospheric μ** **7×10^{10} (3000/s)**
- **Atmospheric ν $\longrightarrow$ μ** **$>8\times10^{4}$ (1/6 minuts)**
- **Cosmic ν $\longrightarrow$ μ** **~ 10**

Finding astrophysical neutrinos is like.. finding a needle in a bunch of haystacks!

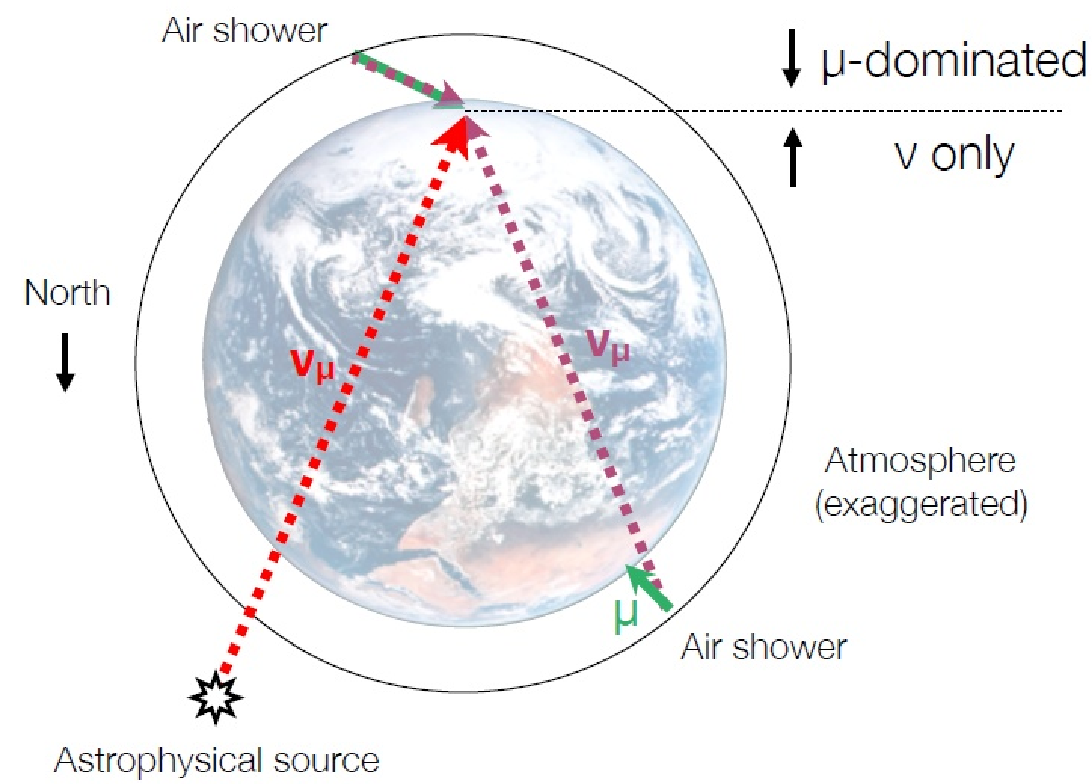
Diffuse Astrophysical Neutrinos: Detection Strategy

(1) Veto method: all sky, all flavor, starting events



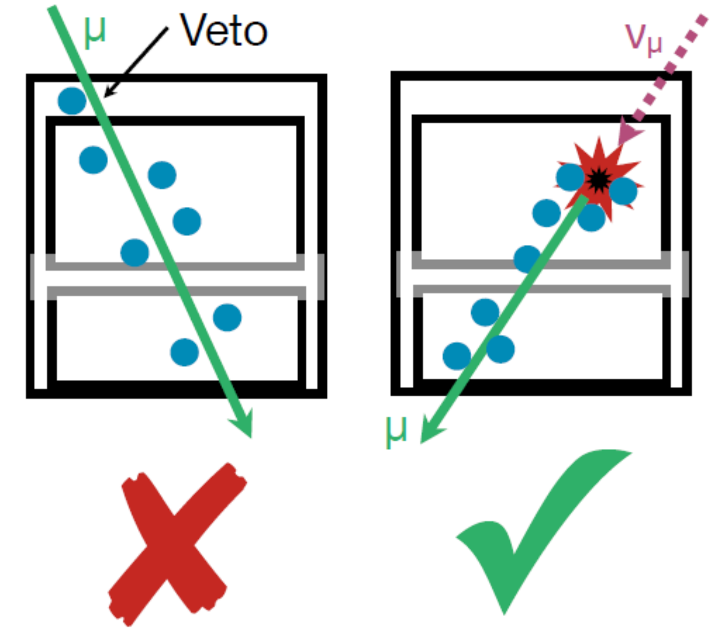
- **Containment required, effective volume smaller than detector**

(2) Through-going events: northern sky, ν_μ CC and muonically decay ν_τ CC events



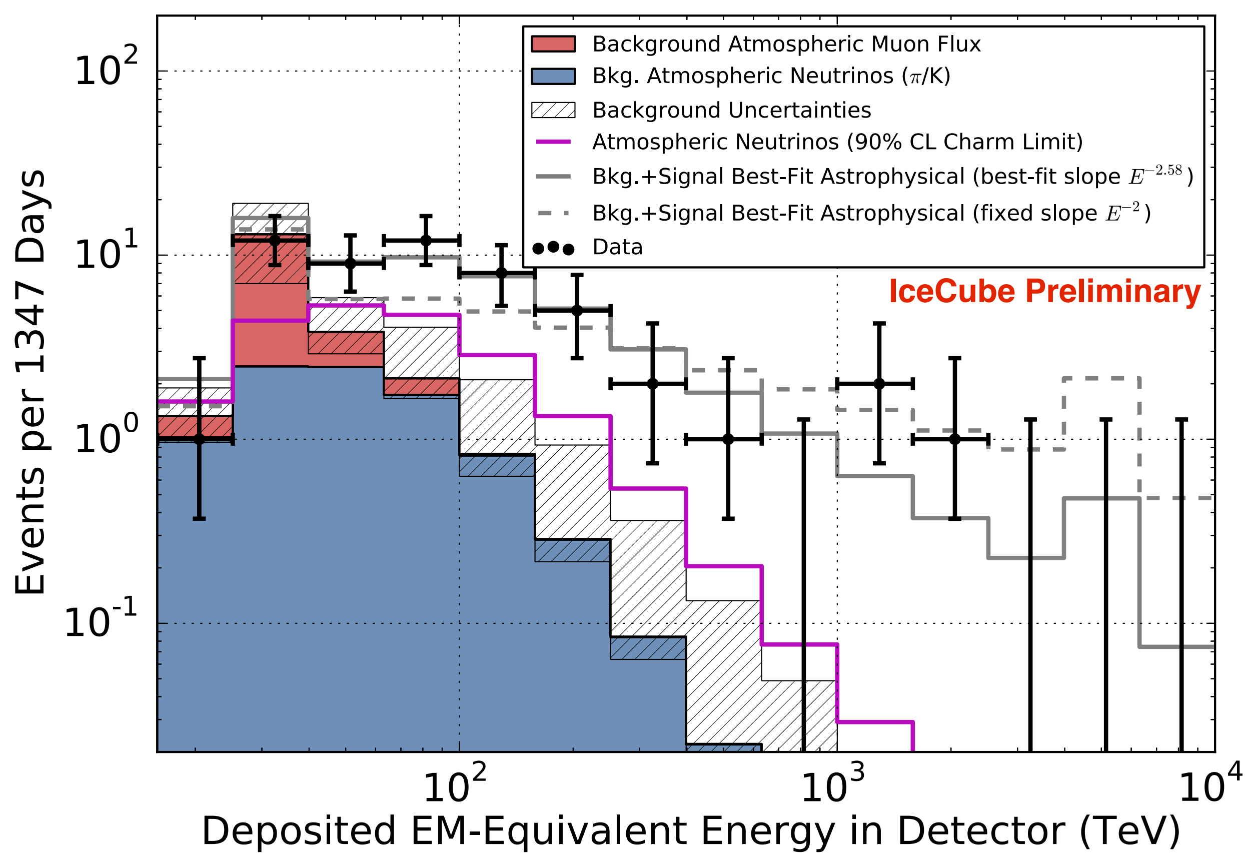
- **No containment required, effective volume larger than detector**

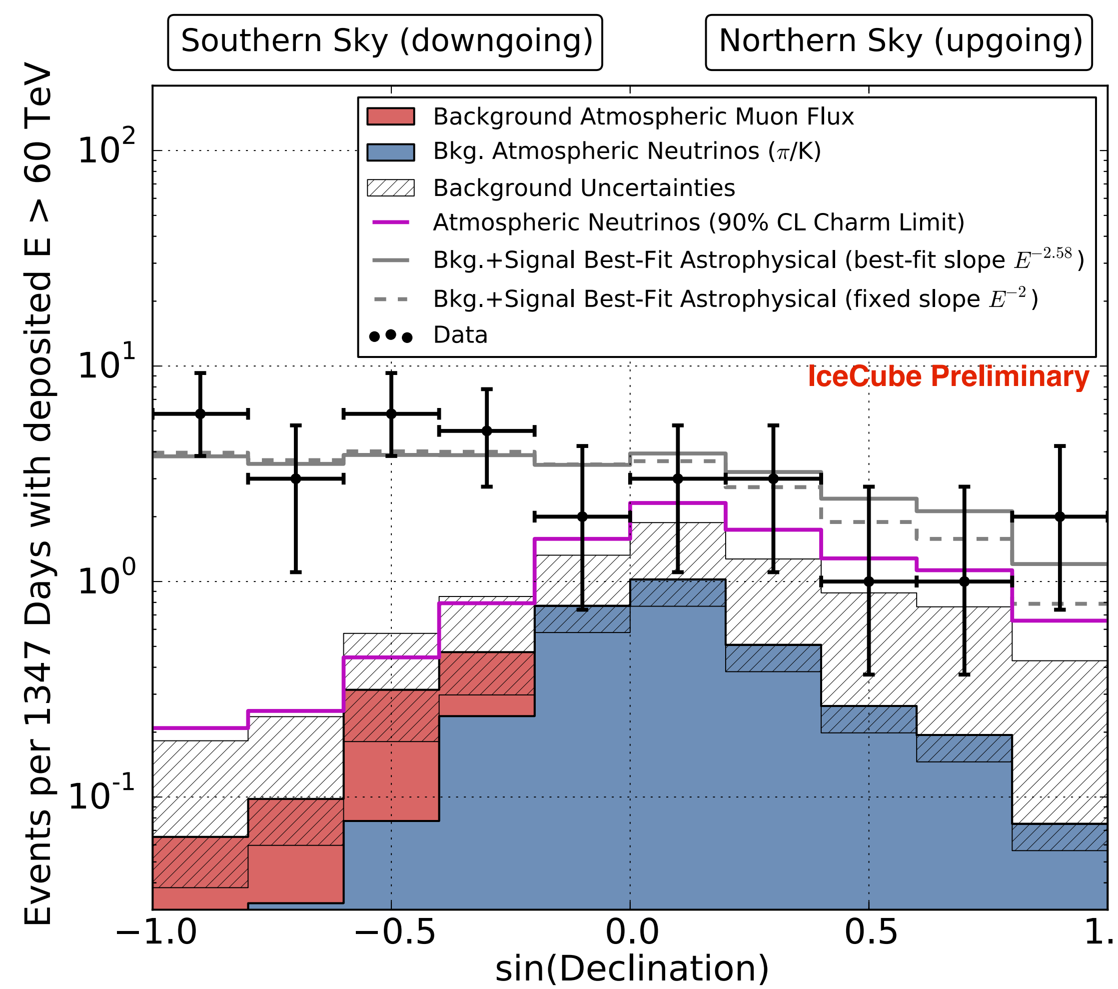
High Energy Starting Event Search



- **54 events in 1347 days, highest 2 PeV cascade**
- **Expected atmo. bg: $21.6^{+9.5}_{-5.6}$**
- **Reject pure atmo. origin at ~ 7σ**
- **Best fit astro. flux:**

$$E^2\Phi(E) = 2.2 \pm 0.7 \times 10^{-8}\left(\frac{E}{100\,\mathrm{TeV}}\right)^{-0.58}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

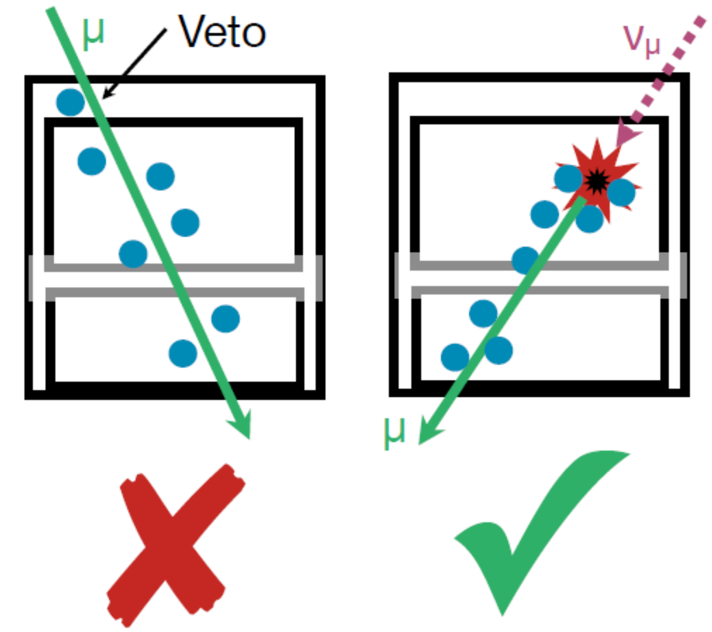


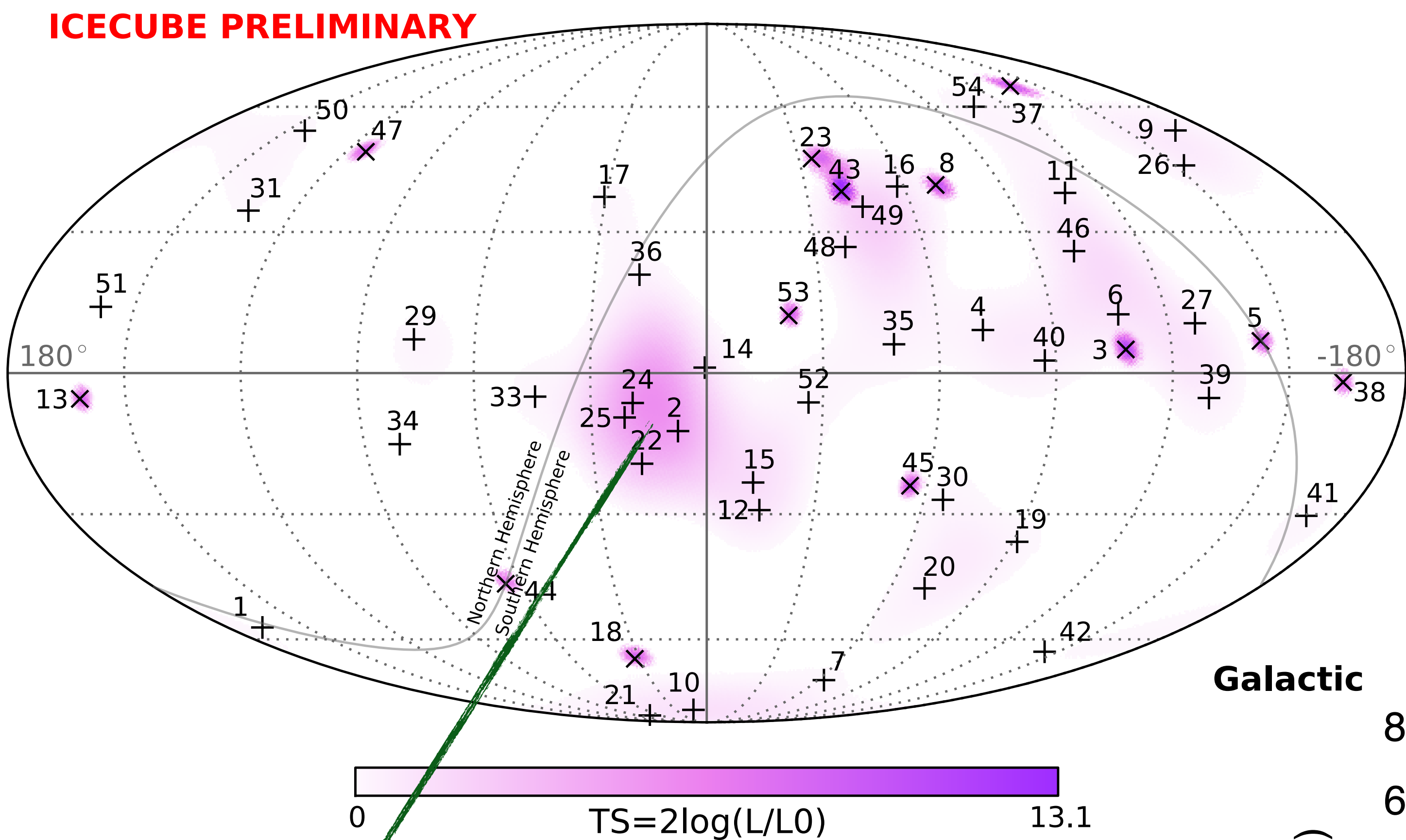


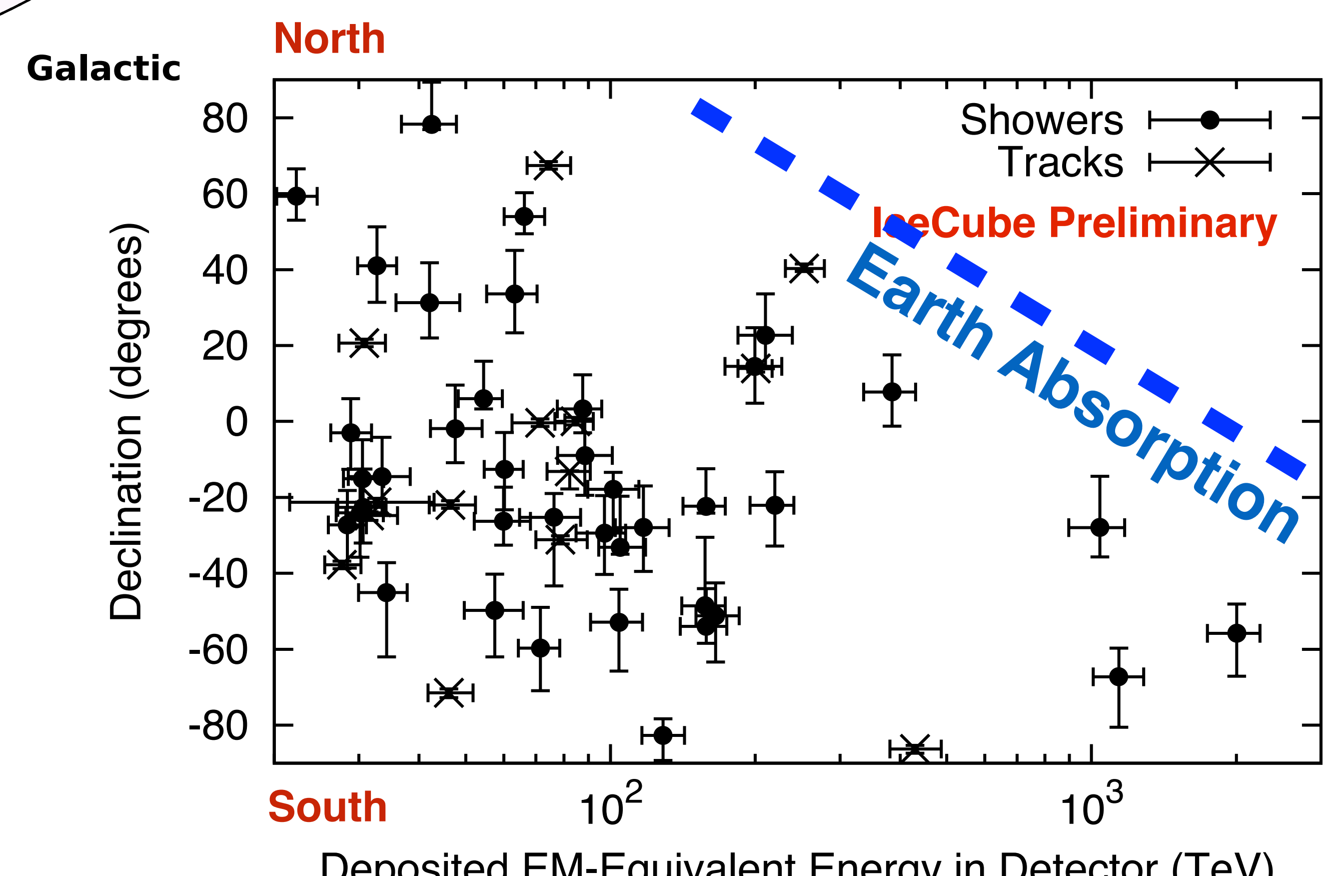
Science 22 Nov 2013:Vol. 342, Issue 6161 (2-yr)
Phys. Rev. Lett. 113, 101101 (3-yr)
PoS(ICRC2015)1081 (4-yr)

WIPAC
Wisconsin IceCube Particle Astrophysics Center
ICECUBE
South Pole Neutrino Observatory

High Energy Starting Event Search





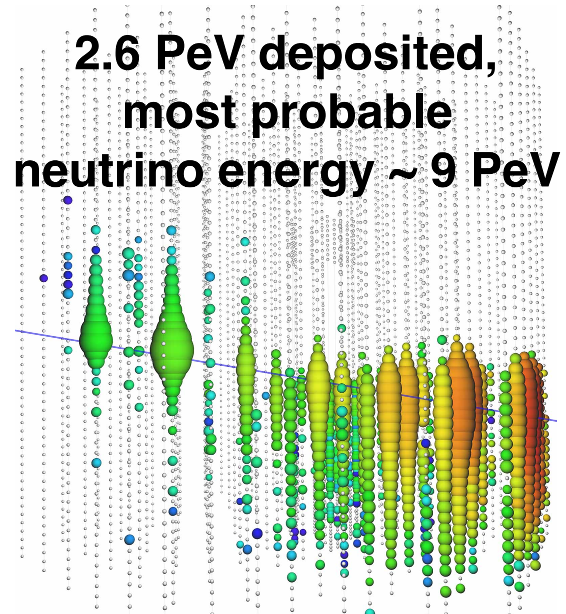


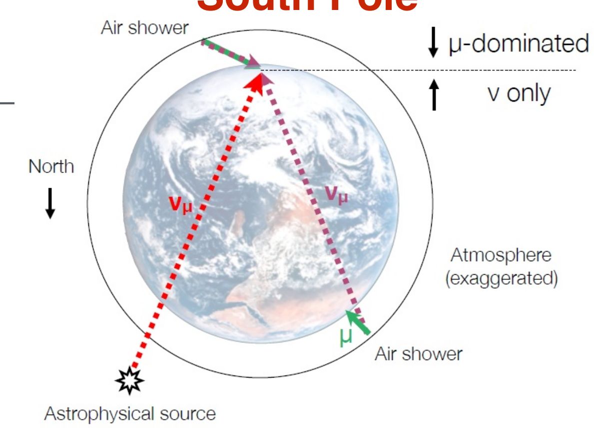
All sky post trial p-value: 58%

Science 22 Nov 2013:Vol. 342, Issue 6161 (2-yr)
Phys. Rev. Lett. 113, 101101 (3-yr)
PoS(ICRC2015)1081 (4-yr)

6 Year Through-going Tracks

- **352, 294 events, highest 2.6 PeV**
- **Reject pure atmo. origin at 5.6σ**
- **No point sources, no clustering**
- **Astro. flux best fit:**

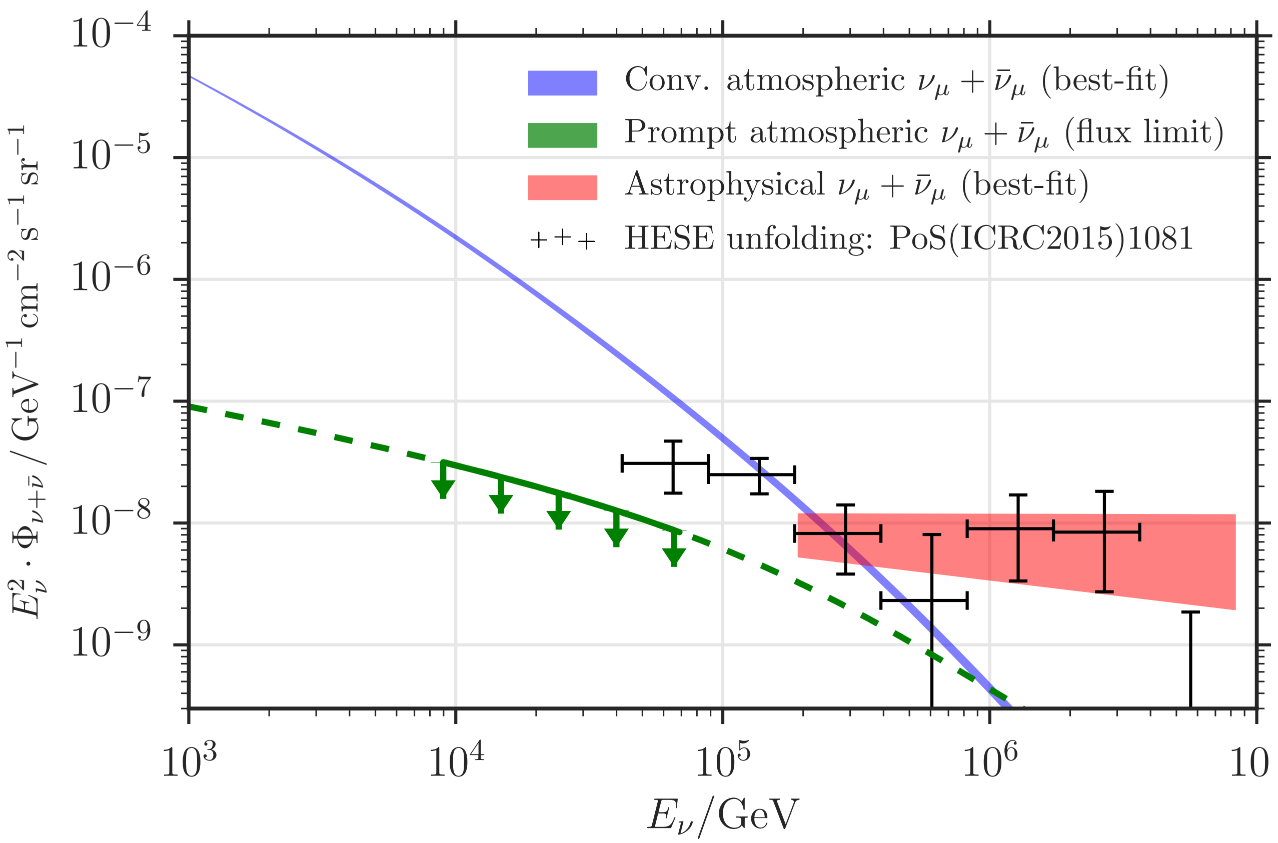


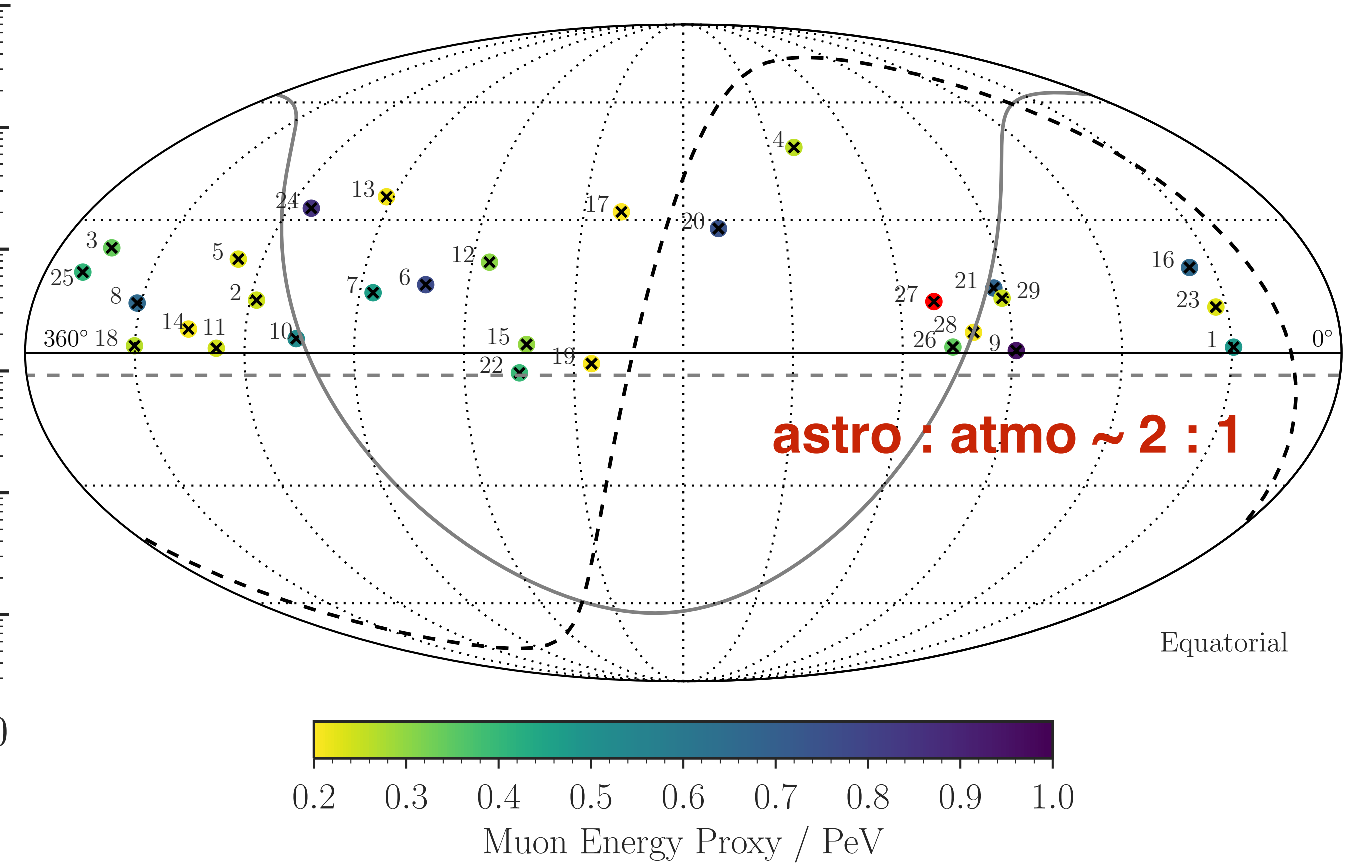


Using the Earth as a shield for cosmic-ray induced muons

$$\Phi_{\nu+\bar{\nu}} = (0.90^{+0.30}_{-0.27}) \cdot \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-(2.13\pm0.13)} \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

29 events > 200 TeV





Phys. Rev. Lett. 115, 081102 (2 yr)
Astrophys.J. 833 (2016) no.1, 3

What about the astrophysical tau neutrinos?

Impact of Tau Neutrino Identification

arXiv.org > astro-ph > arXiv:1707.01982

(H

Astrophysics > High Energy Astrophysical Phenomena

No Tau? No Astronomy!

Daniele Fargion, Pietro Oliva

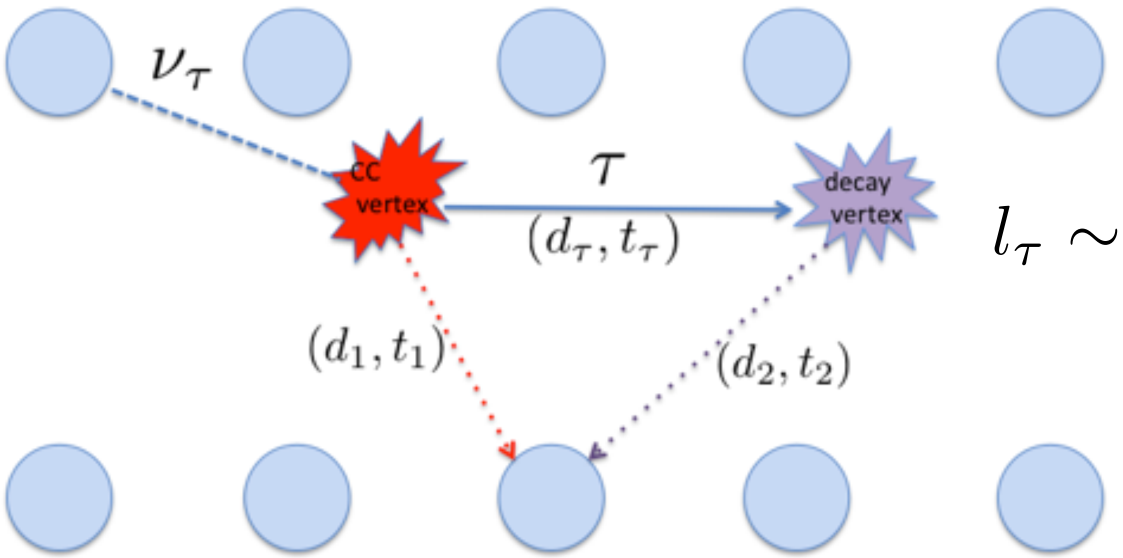
(Submitted on 6 Jul 2017 (v1), last revised 13 Jul 2017 (this version, v3))

Since 2013 IceCube cascade showers sudden overabundance have shown a fast flavor change above 30-60 TeV up to
energy. This flavor change from dominant muon tracks at TeVs to shower events at higher energies, has been indebt
new injection of a neutrino astronomy. However the recent published 54 neutrino HESE, high energy starting events,
as the 38 external muon tracks made by trough going muon formed around the IceCube, none of them are pointing t
expected X-gamma or radio sources: no one in connection to GRB, no toward active BL Lac, neither to AGN source in
catalog. No clear correlation with nearby mass distribution (Local Group), nor to galactic plane. Moreover there have
any record (among a dozen of 200 TeV energetic events) of the expected double bang due to the tau neutrino birth a
decay. An amazing and surprising unfair distribution in flavor versus expected democratic one. Finally there is not a
consistence of the internal HESE event spectra and the external crossing muon track ones. Moreover the apparent suc
astrophysical neutrino flux rise at 60 TeV might be probably also suddenly cut at a few PeV in order to hide the (unob
yet) Glashow resonance peak at 6.3 PeV. A more mondane prompt charmed atmospheric neutrino component may ex
most of the IceCube puzzles. If this near future, 2017-2018, it does not shine tau neutrino signals somewhere (by ta
airshowers in AUGER, TA, ASHRA or double bang in IceCube) there are a list of consequences to face. These missing
correlations and in particular the tau signature absence force us to claim : No Tau? No neutrino Astronomy.

WIPAC WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

3 Year Astrophysical Tau Neutrino Double Cascades

Schematic ν_τ CC interaction in IceCube



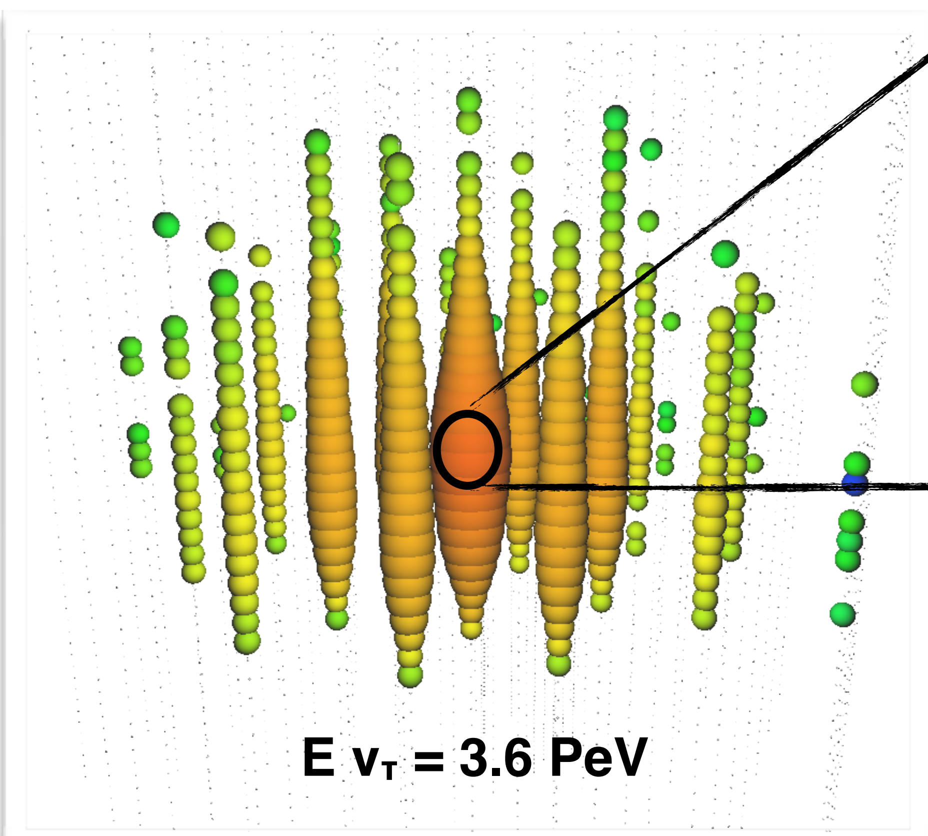
$$l_\tau \sim \frac{50\ \mathrm{m}}{\mathrm{PeV}}$$

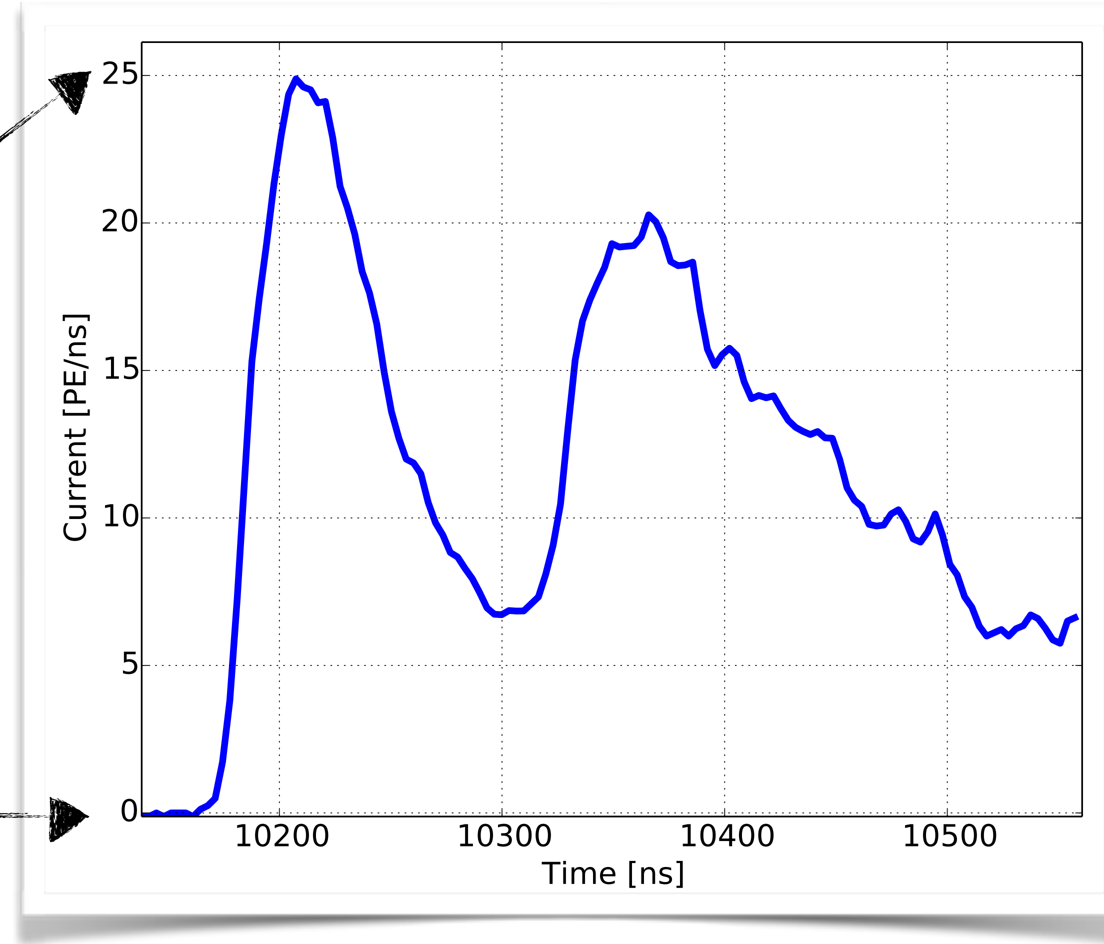
$$\nu_\tau + N \rightarrow \tau^- + X$$

$\tau^- \rightarrow \nu_\tau + hadrons$ (64.8%) ✓

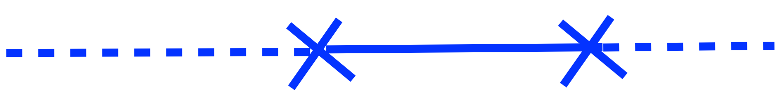
$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^-$ (17.8%) ✓

$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^-$ (17.4%)



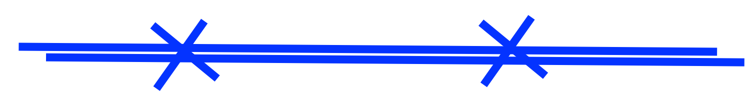


Signal

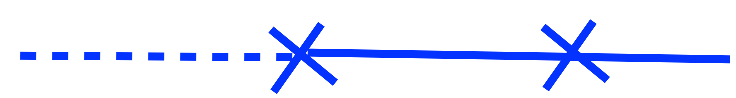


ν_τ

Backgrounds



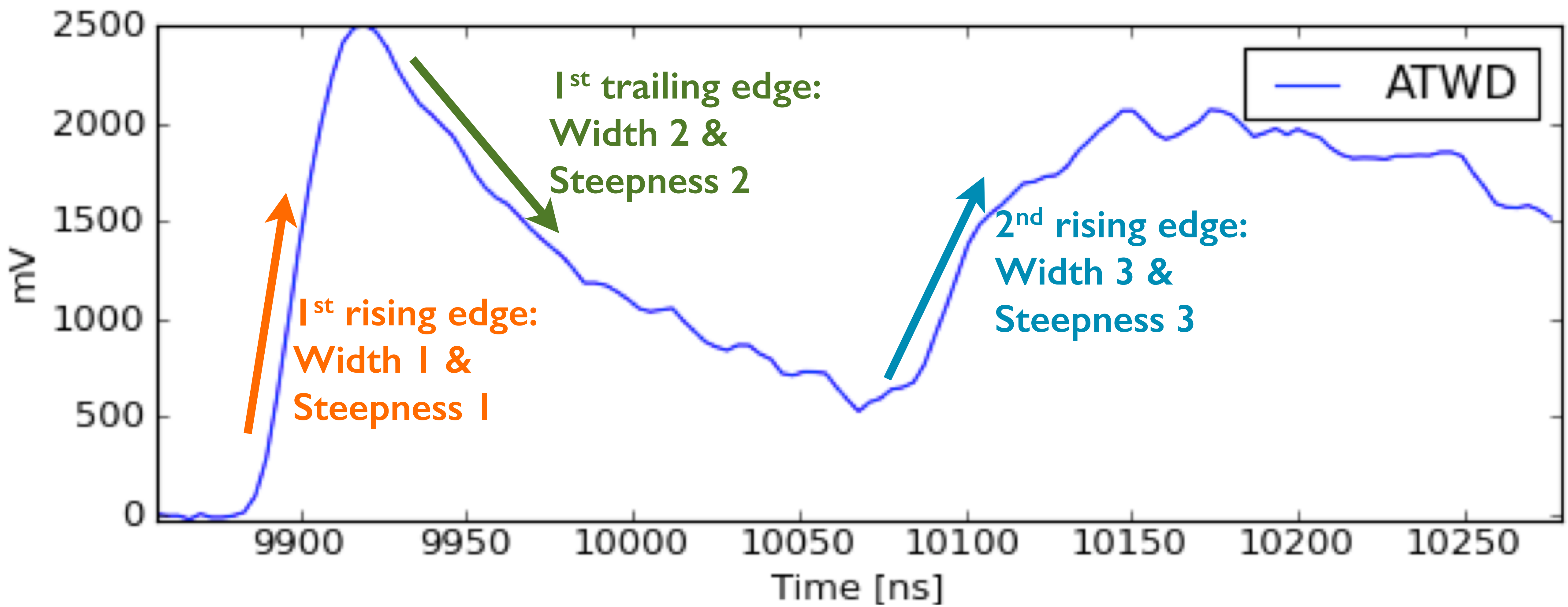
Muons



ν_μ

TeV-scale stochastic losses ~O(10) meters near some DOM

Double Pulse Algorithm (DPA)

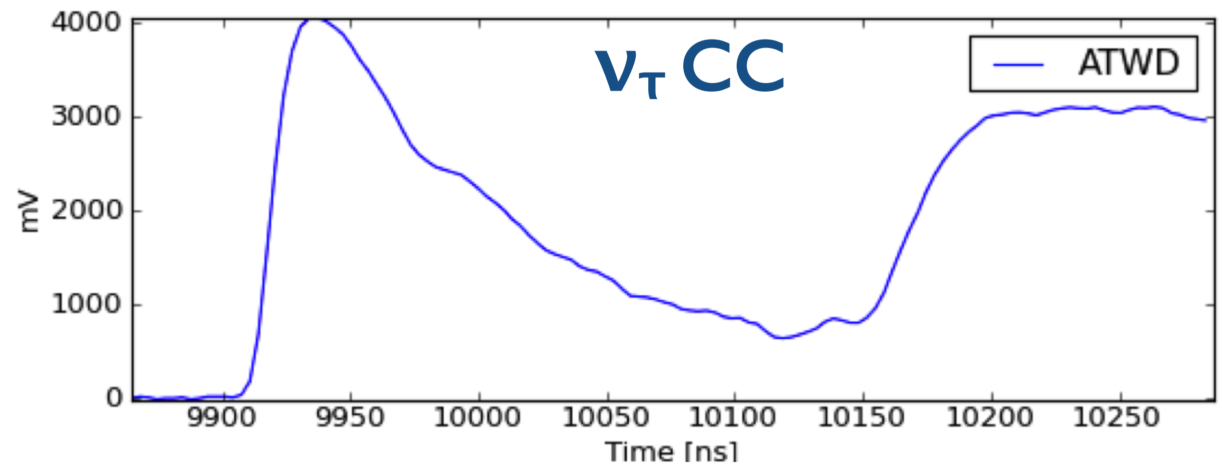


Note: DPA only runs on ATWD waveforms with accumulated charge > 432 PE

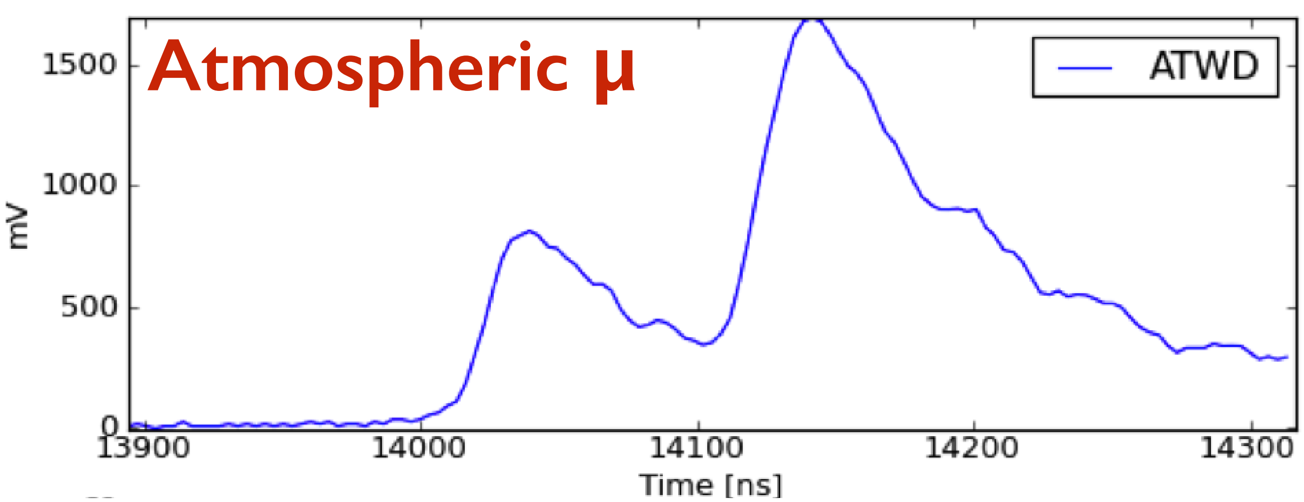
ICRC2013 poster: "Detecting Tau Neutrinos in IceCube with Double Pulses"
[arXiv:1309.7003]

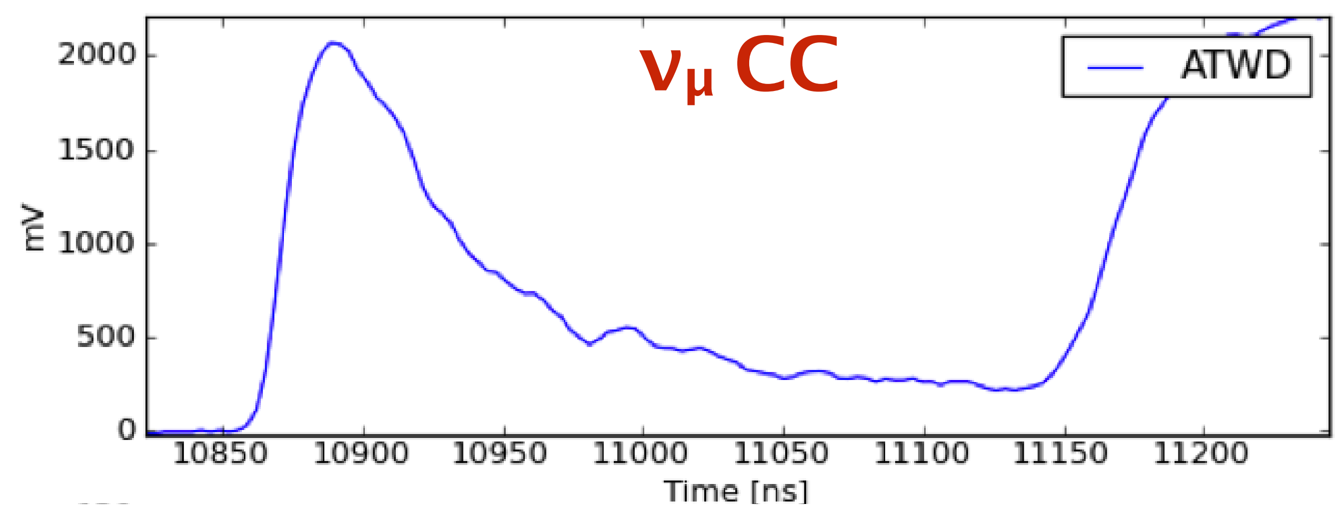
Identified Double Pulse Waveforms

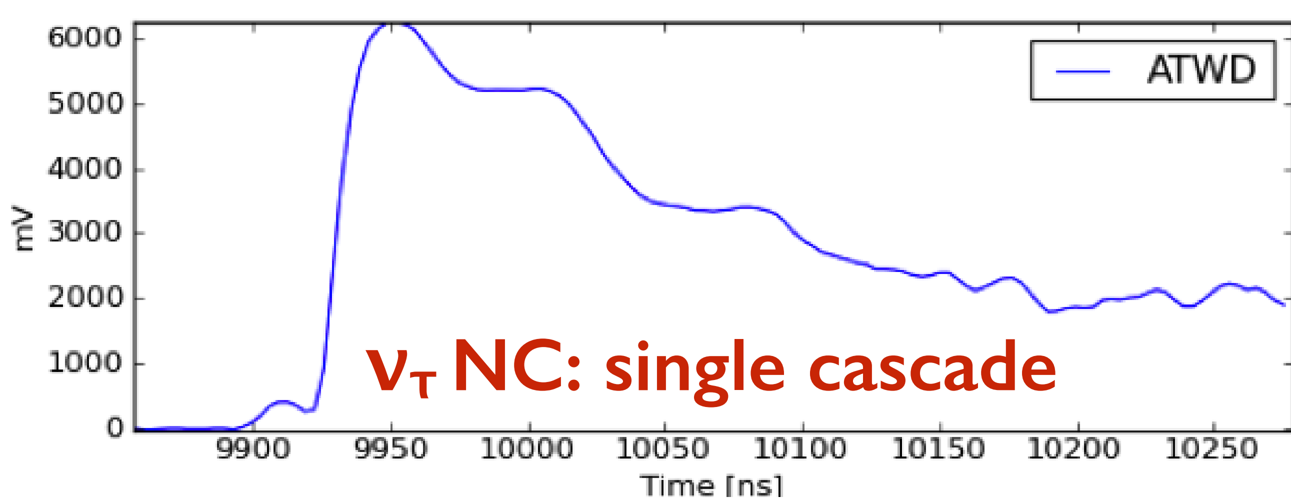
Signal:



Background:





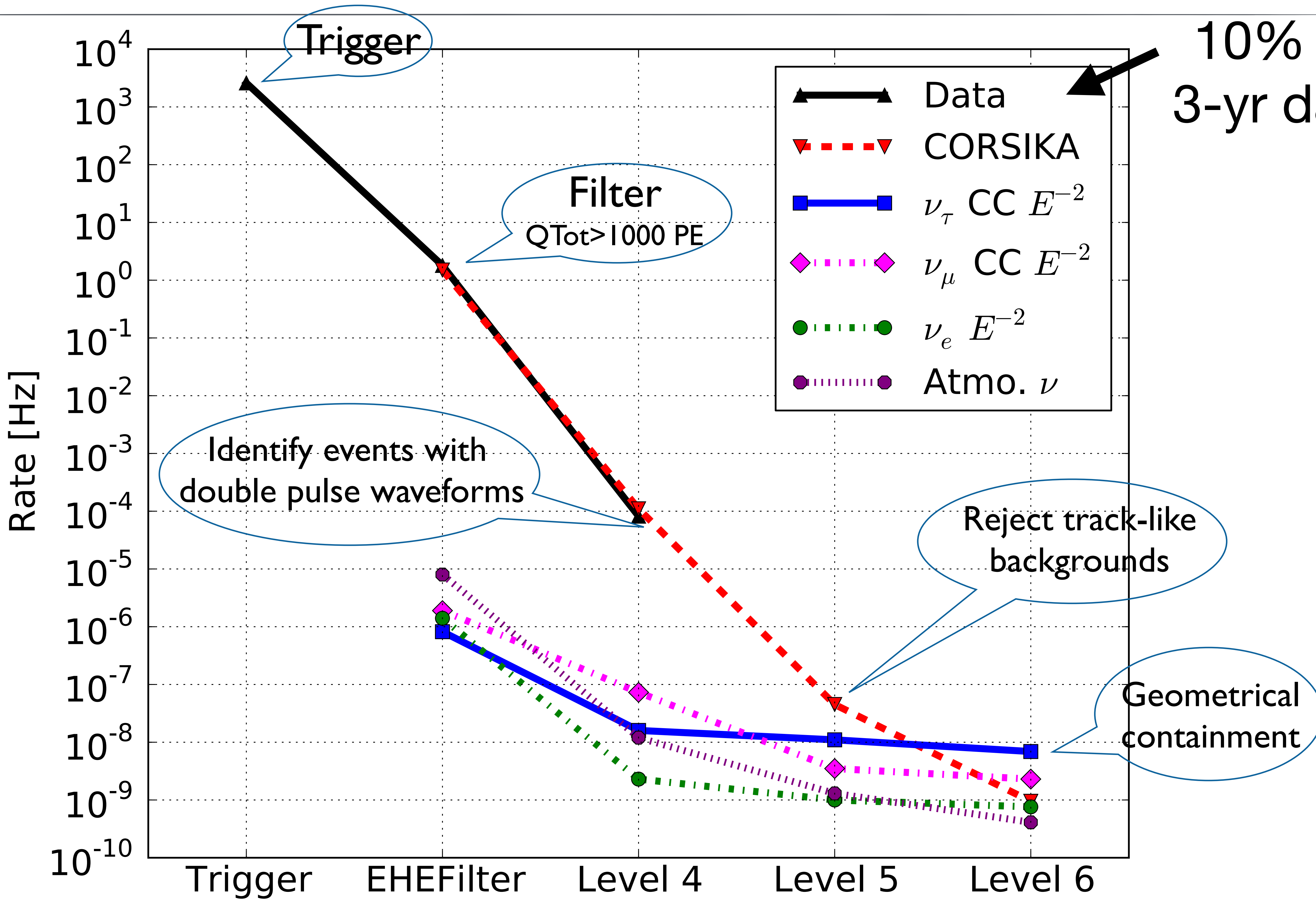


Most important to reject at waveform level

WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Event Selection and Cut Efficiency



10% of 3-yr data

Phys. Rev. D 93, 022001 (3-yr)

Sensitivity and Results

Sensitivity:

	In 914.1 days
Signal	**0.54±0.01**
Total background	**0.35±0.06**

- Sensitivity: 5.1 $\times 10^{-8}$ GeV cm^{-2} sr^{-1}s^{-1}
  - Flux per flavor: 1.0 $\times 10^{-8}$ GeV cm^{-2} sr^{-1}s^{-1} (Phys. Rev. Lett. **113**, 101101)
- Middle 90% signal energy range: 214 TeV - 72 PeV

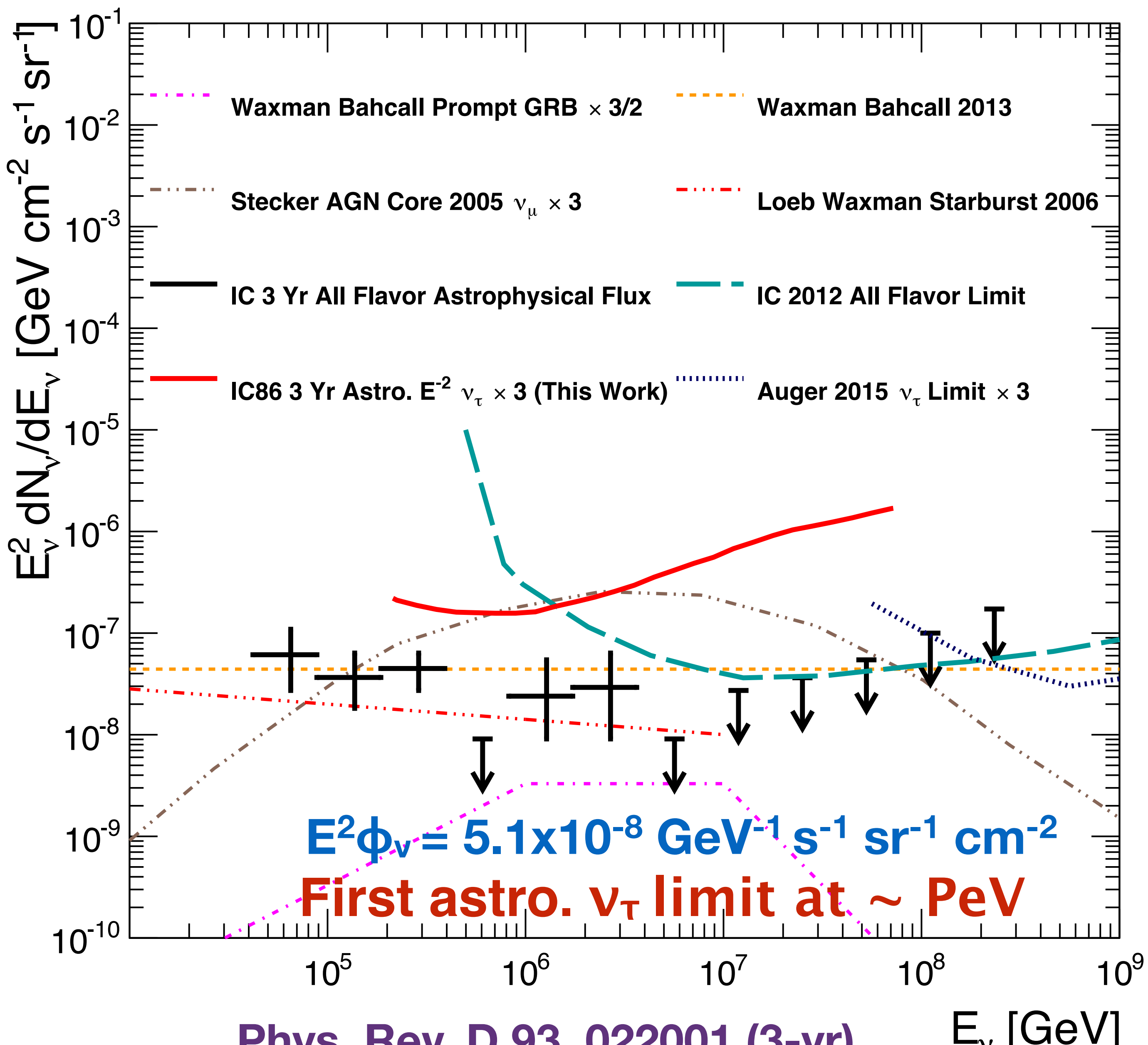
Unblinding Results:

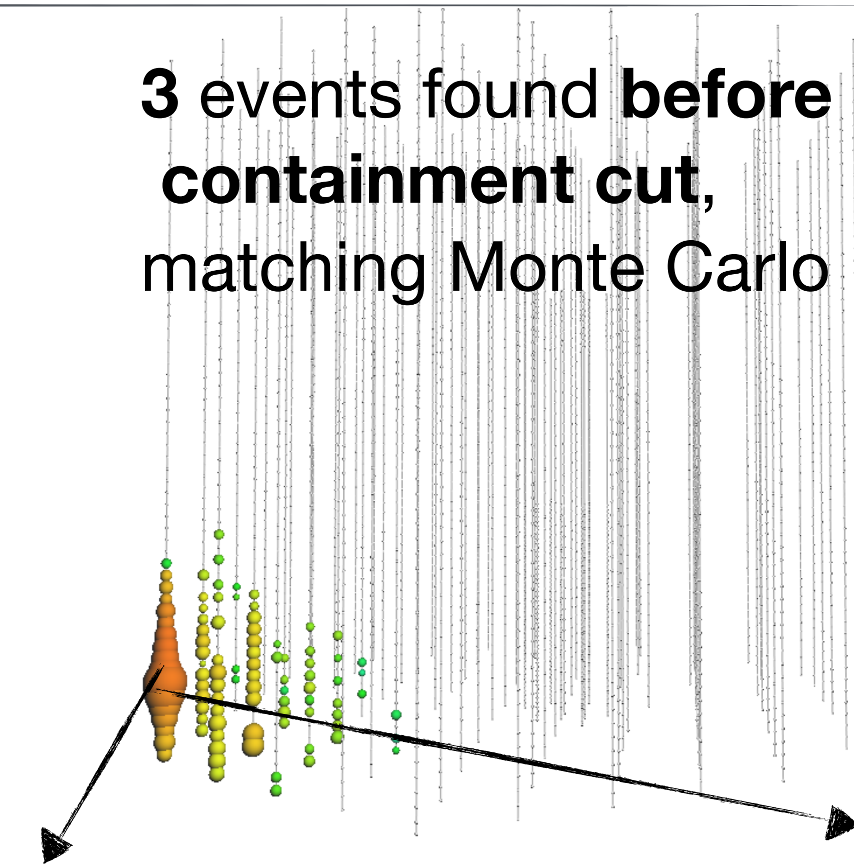
Rates in 914.1 days	L5	L6
CORSIKA	3.5±3.4	0.08±0.06
Blind Sample	**3±2**	**0**

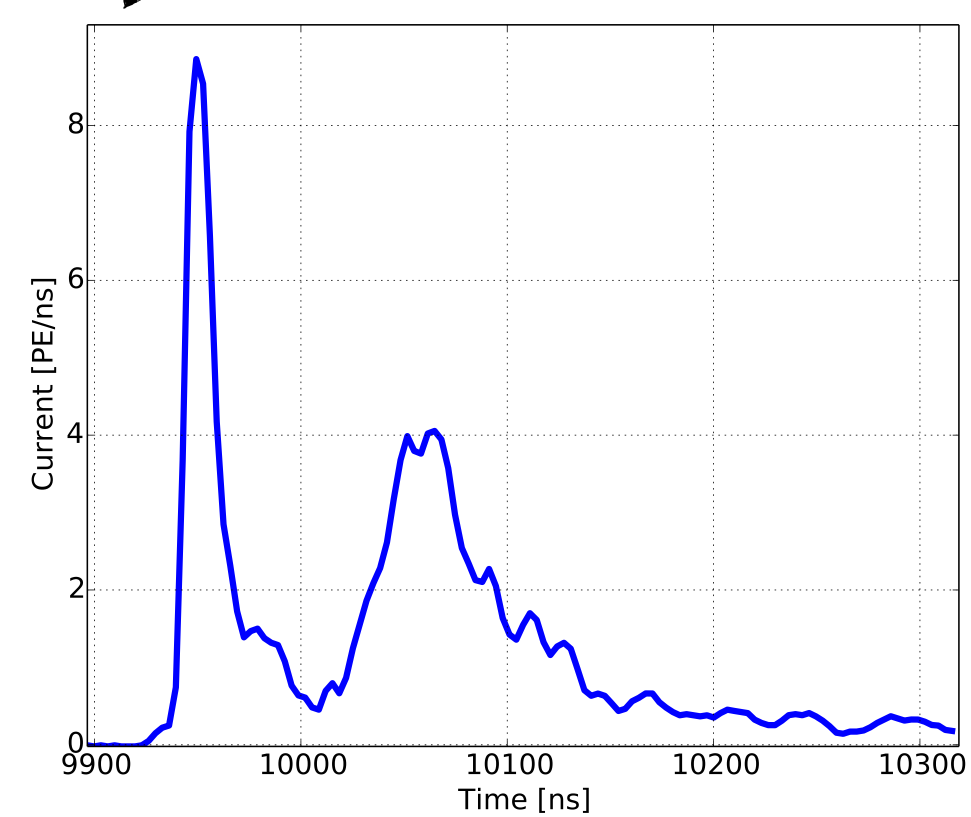
3 Year Astrophysical Tau Neutrino Search: Results

- **0.54 signal, 0.35 bg expected in 914 days**
- **Zero events found at final cut**

3 events found **before containment cut**, matching Monte Carlo







Phys. Rev. D 93, 022001 (3-yr)

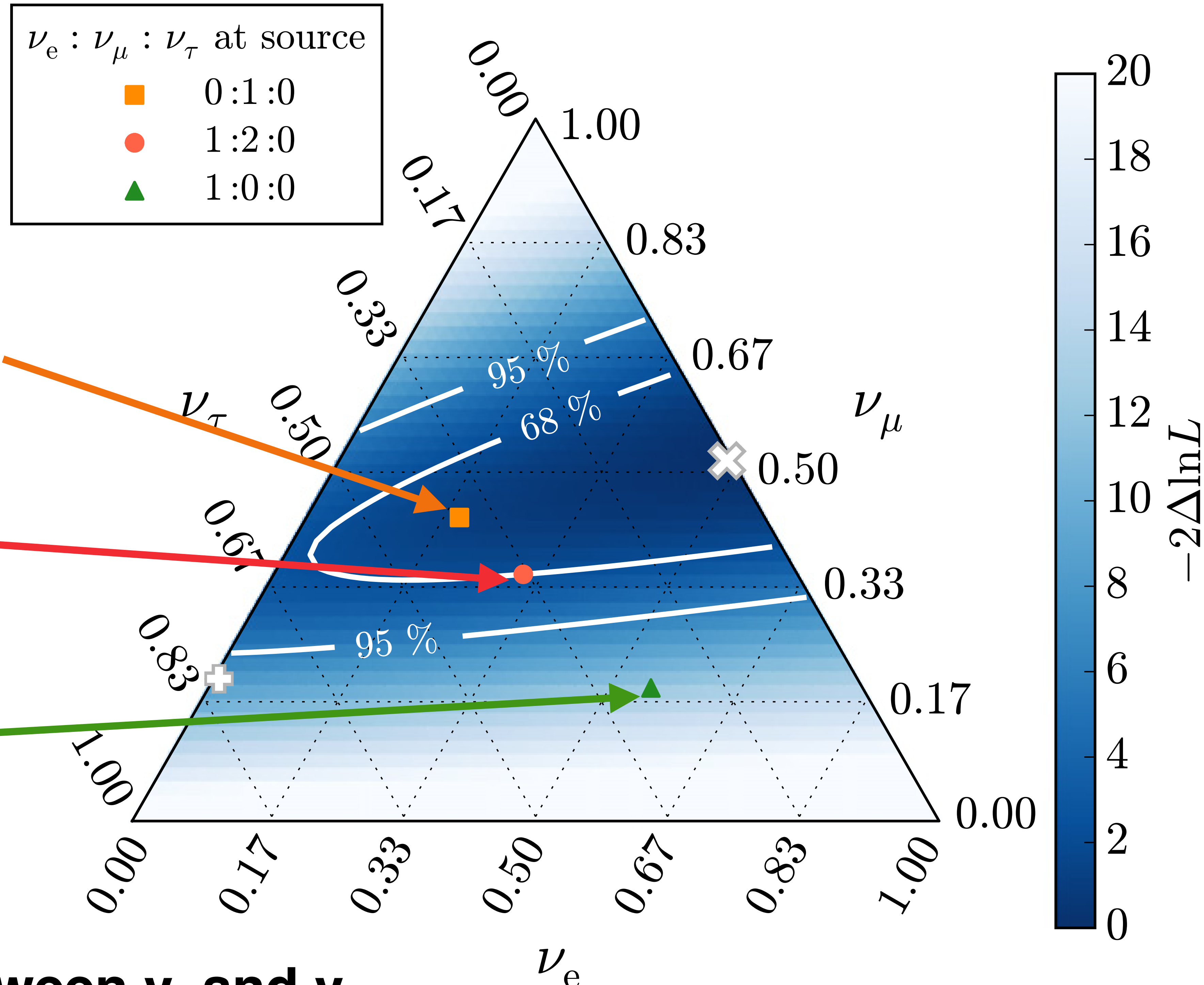
WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Astrophysical Neutrino Flavor Composition

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

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



muon-damped pion decay: allowed

Pion decay: allowed

Neutron decay only: disfavored at 3.7σ

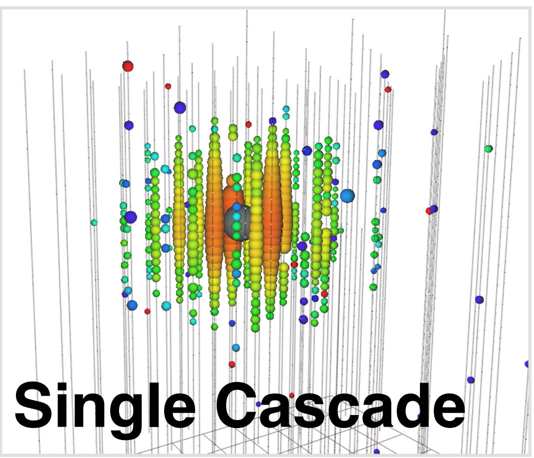
High degeneracy between ν_τ and ν_e in the cascades

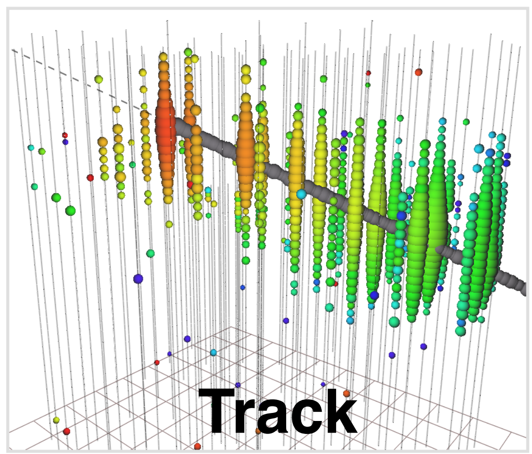
ApJ 809, 98 (2015)
Phys. Rev. Lett. 114, 171102

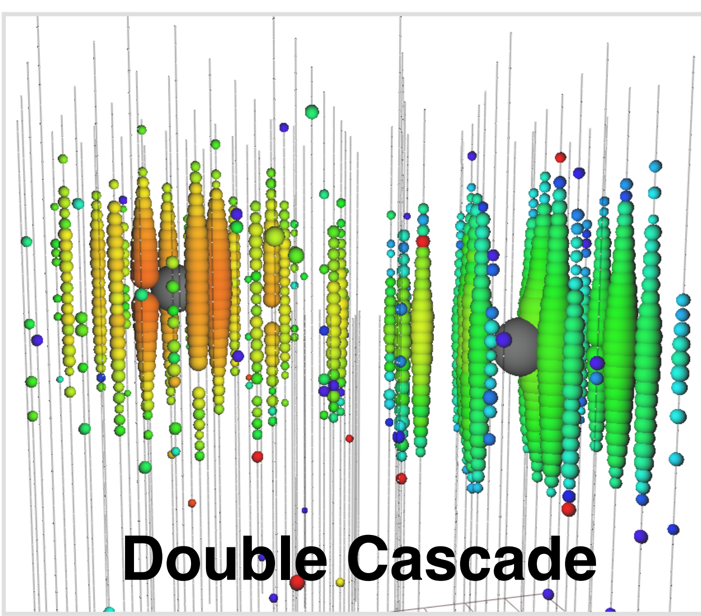
6-Year Astrophysical Tau Neutrino Search with HESE

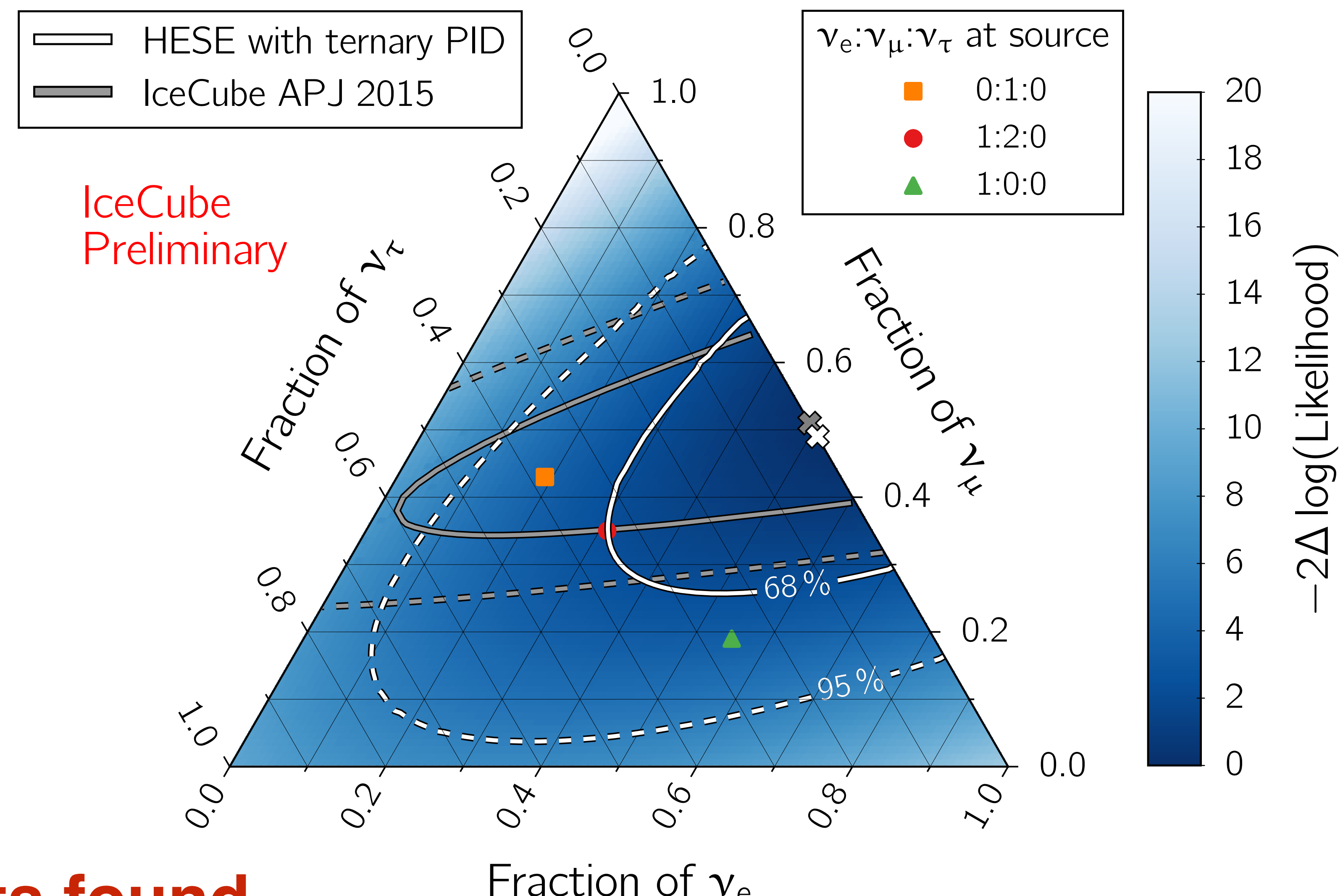
- Dedicated reconstruction to resolve double cascades

- Maximum likelihood method to fit for astrophysical tau neutrino flux







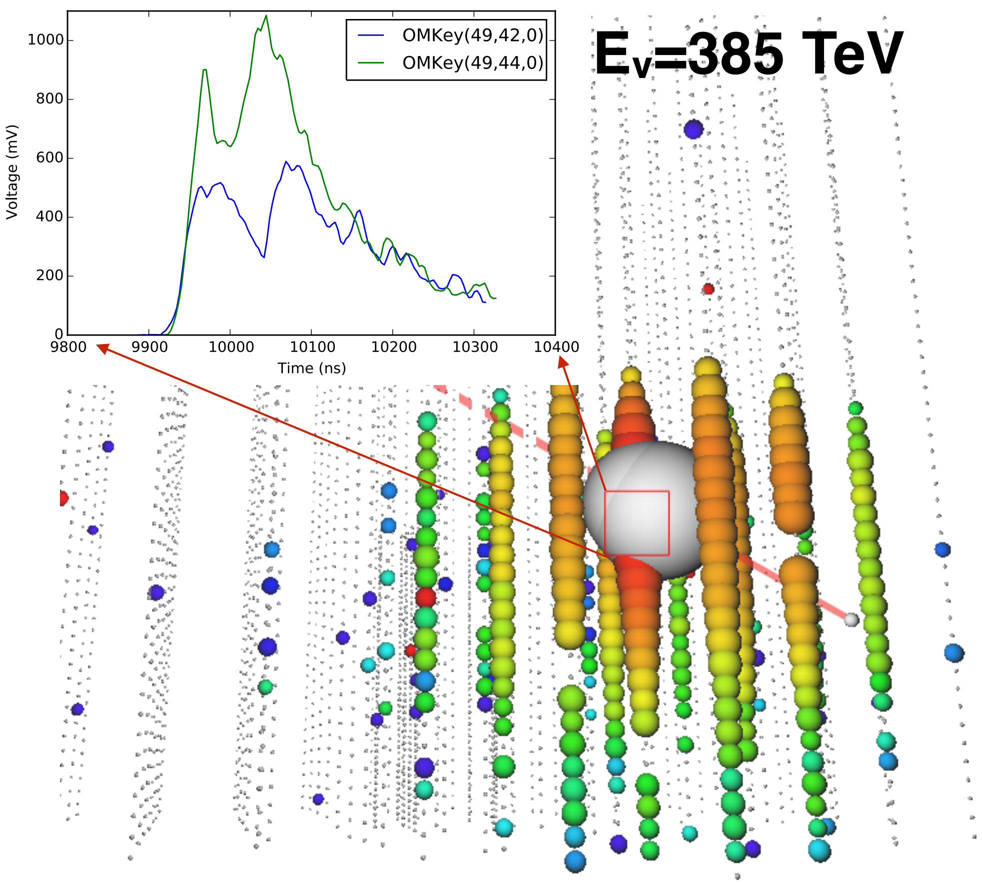


Zero Double Cascade events found

(p=9% to reject no tau hypothesis)

PoS(ICRC2017)974

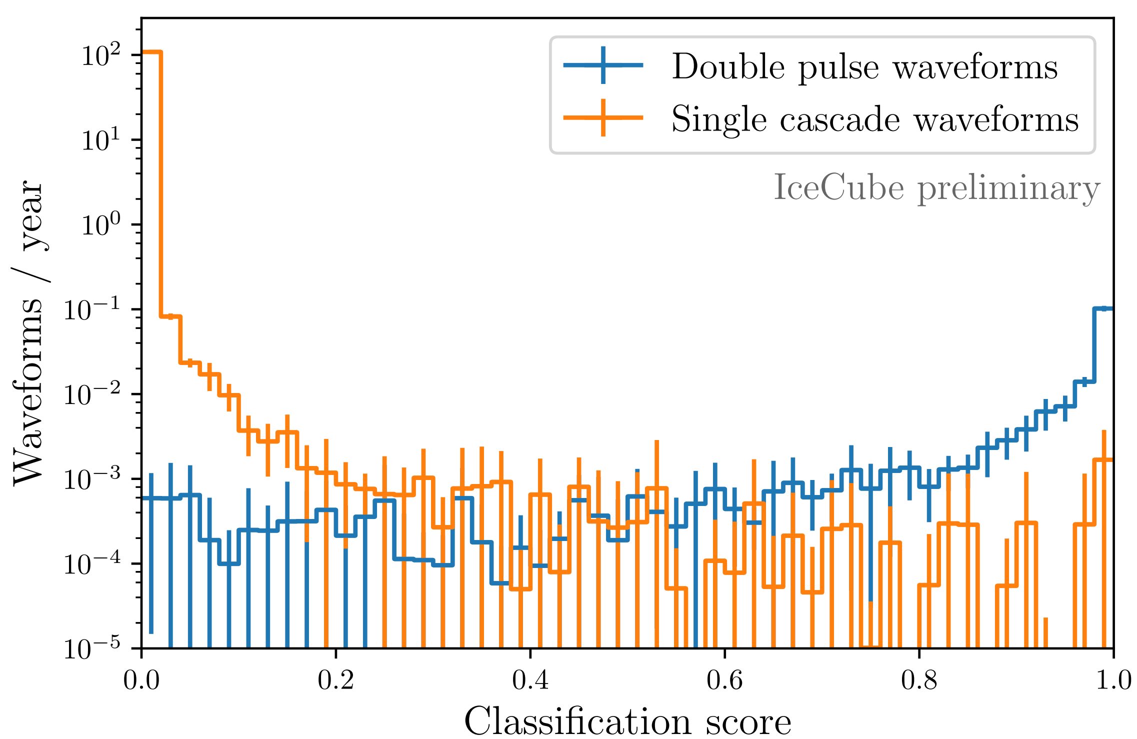
8-Year Astrophysical Tau Neutrino Search with Waveforms

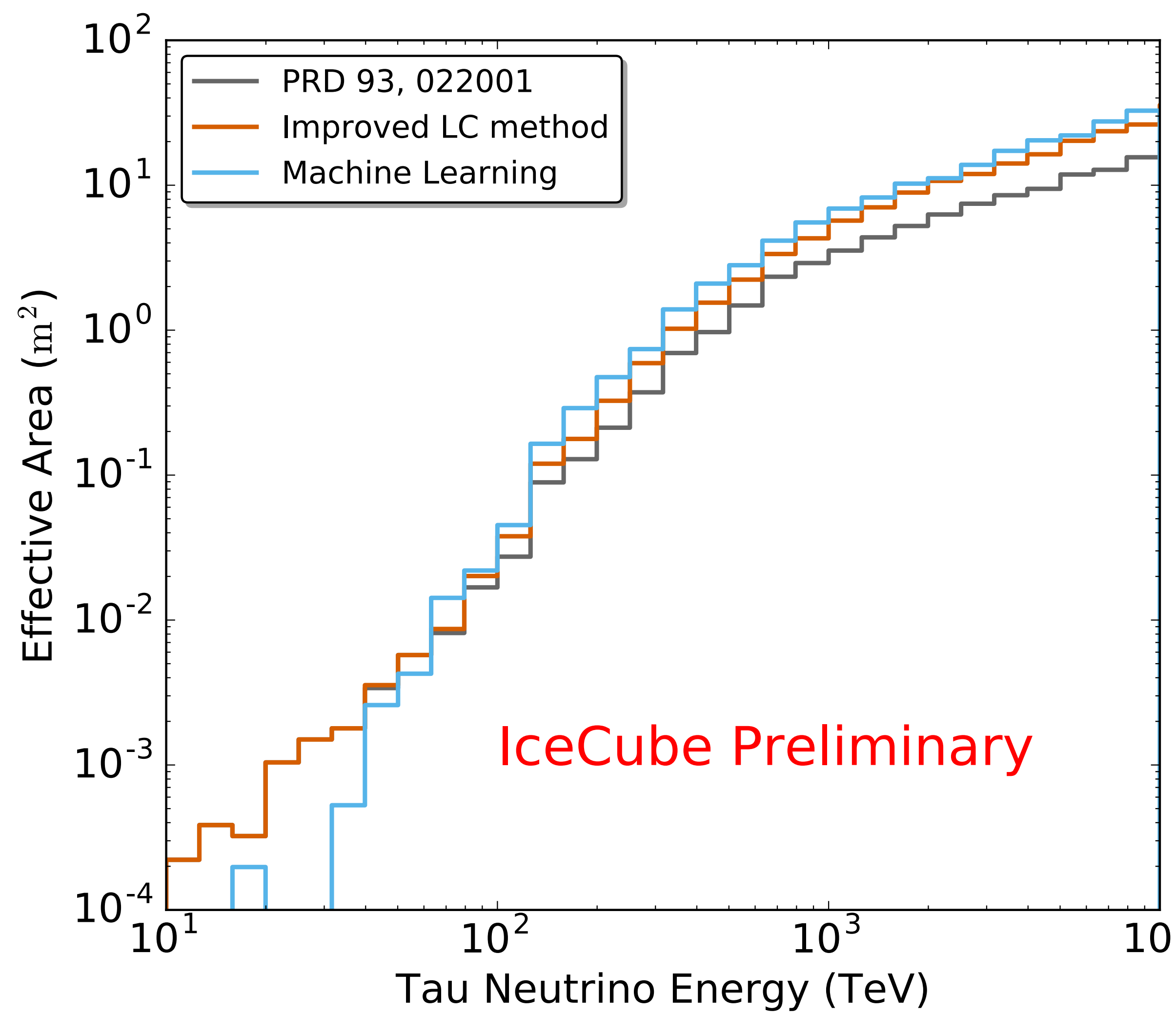


Signal efficiency increases by 50%:

- Lowering double pulse waveform parameter thresholds by requiring local coincidence (LC)
- Machine learning

Expect ~ 2-3 events in 8 years, stay tuned!



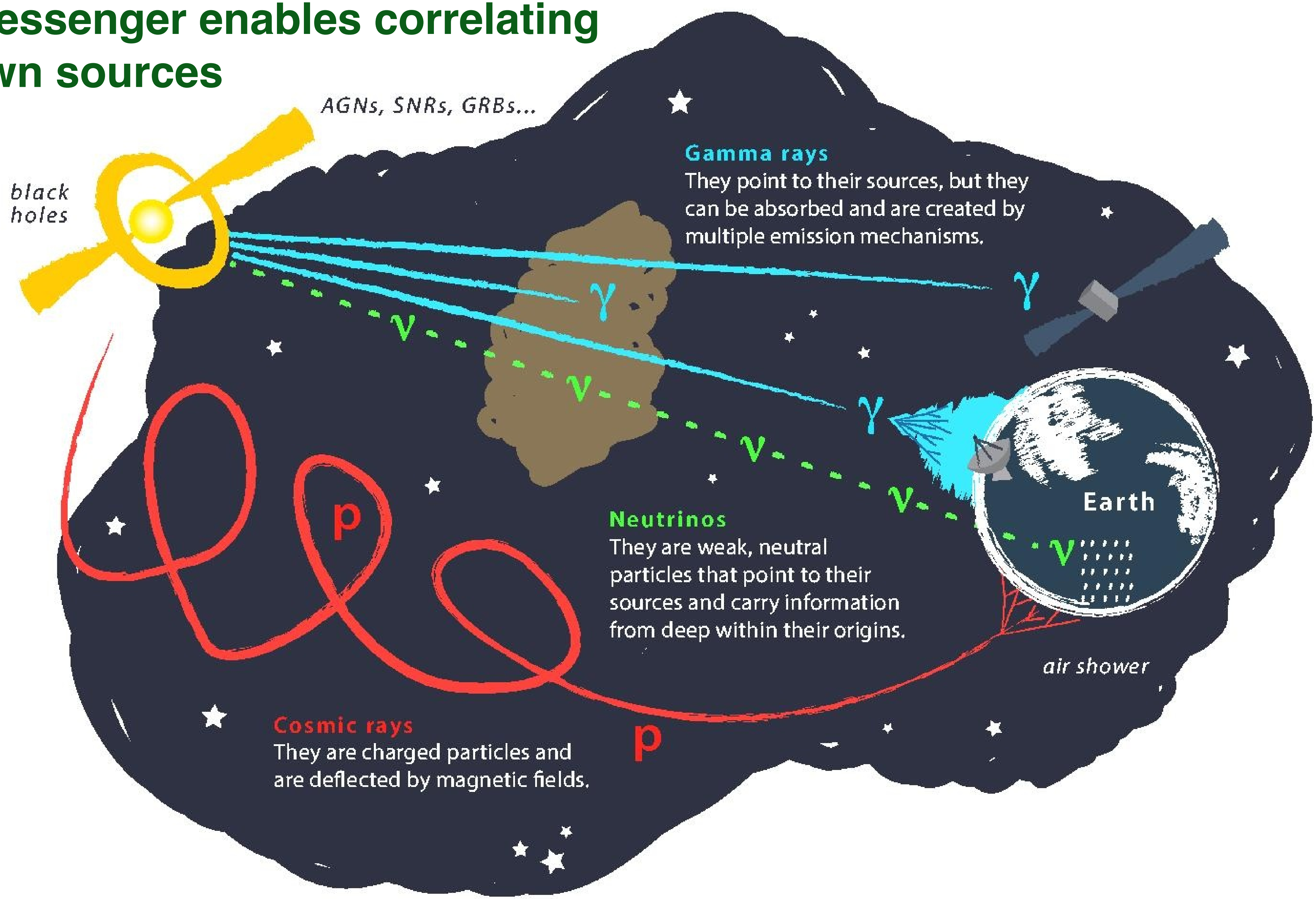


PoS(ICRC2017)1009

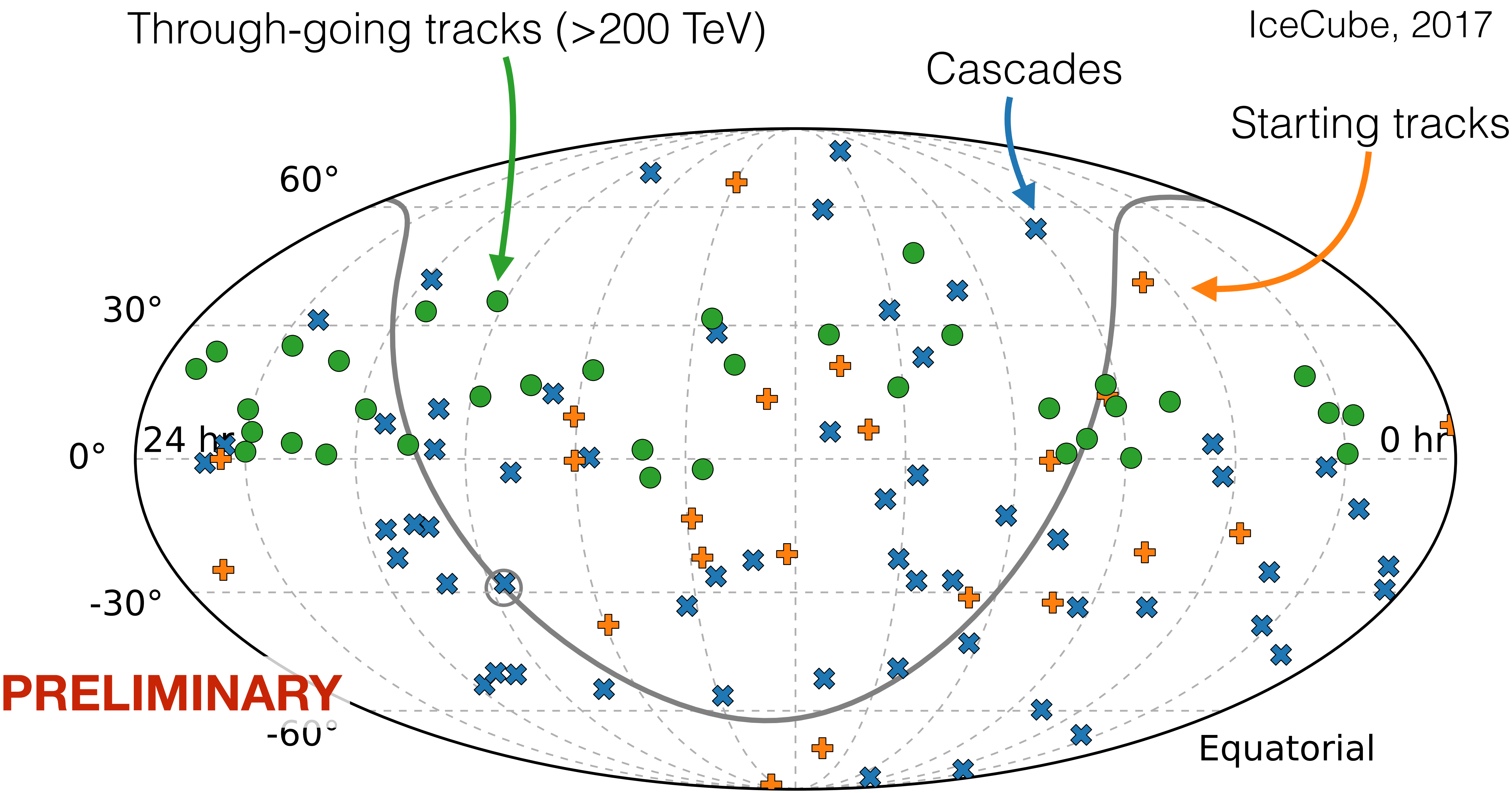
Where Do They Come From?

Source identification requires good angular resolution

Multi-messenger enables correlating to known sources



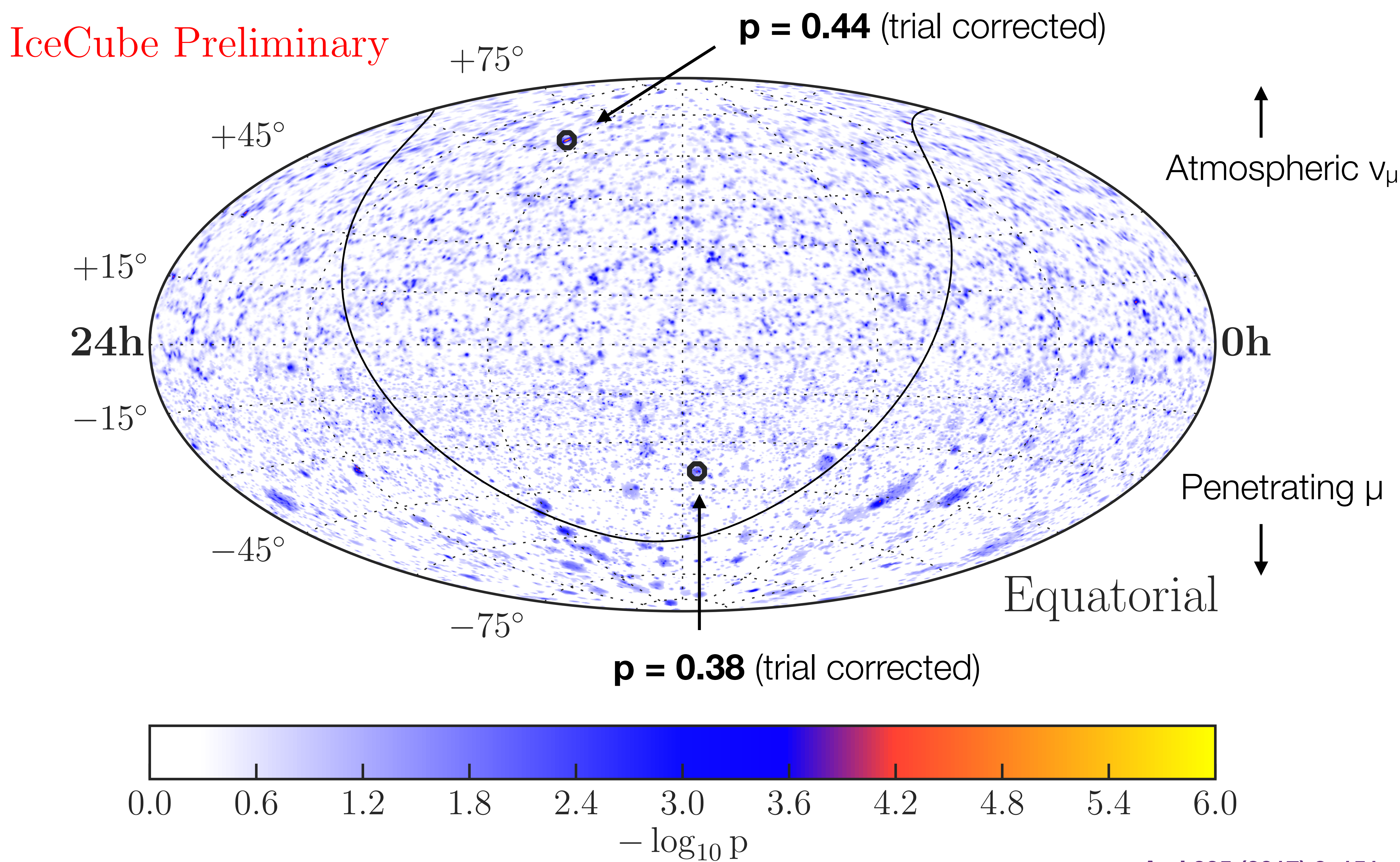
High-energy Neutrinos on the Sky Observed by IceCube



Event numbers: brightest point source vs all

$$\mathbf{N_{ps} \sim 10^{-2}\ (n/10^{-7}\ Mpc^{-3})^{-1/3}\ x\ N_{diff}}$$

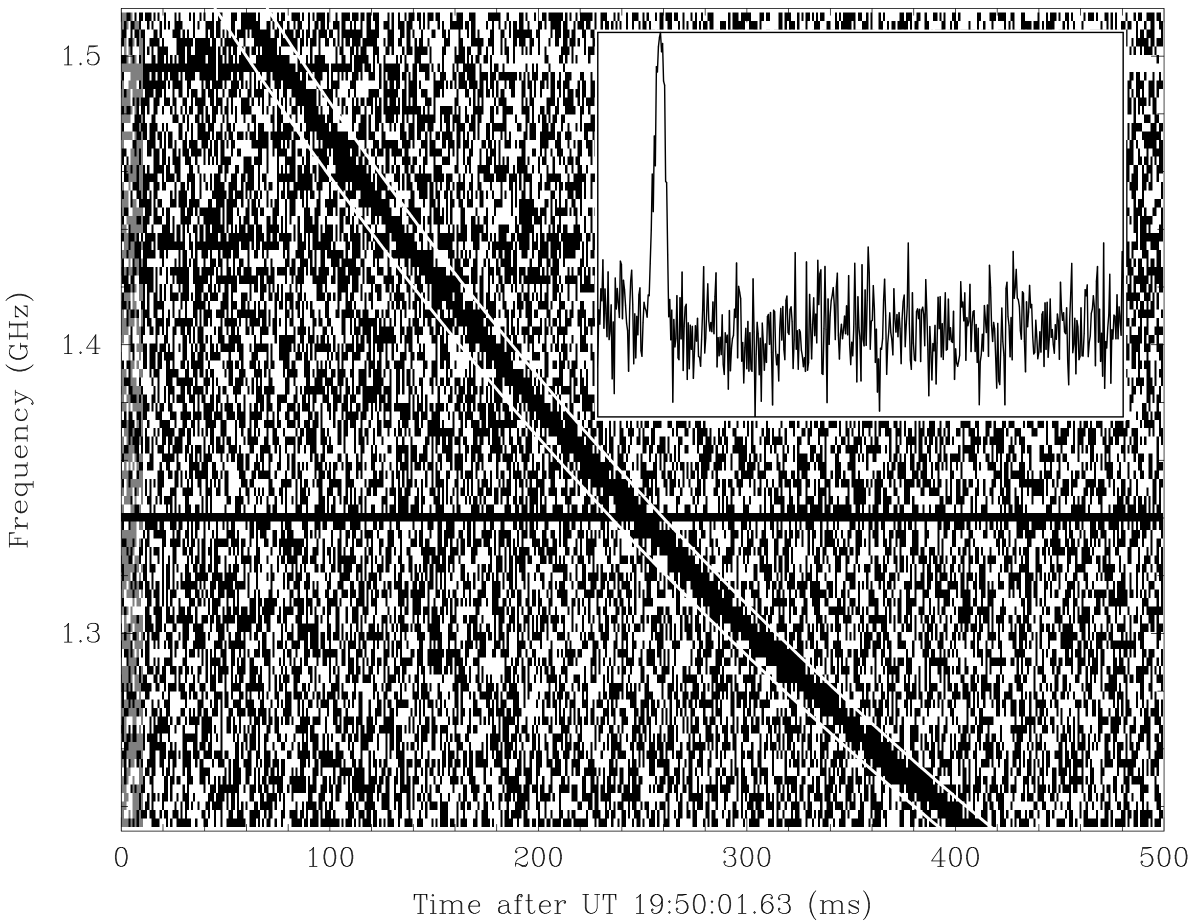
7-Yr All-sky Integrated Point Source Search



ApJ 835 (2017) 2, 151

Transient Population Studies: Fast Radio Bursts (FRBs)

*Lorimer et al.,**Science** 318 (5851): 777-780*

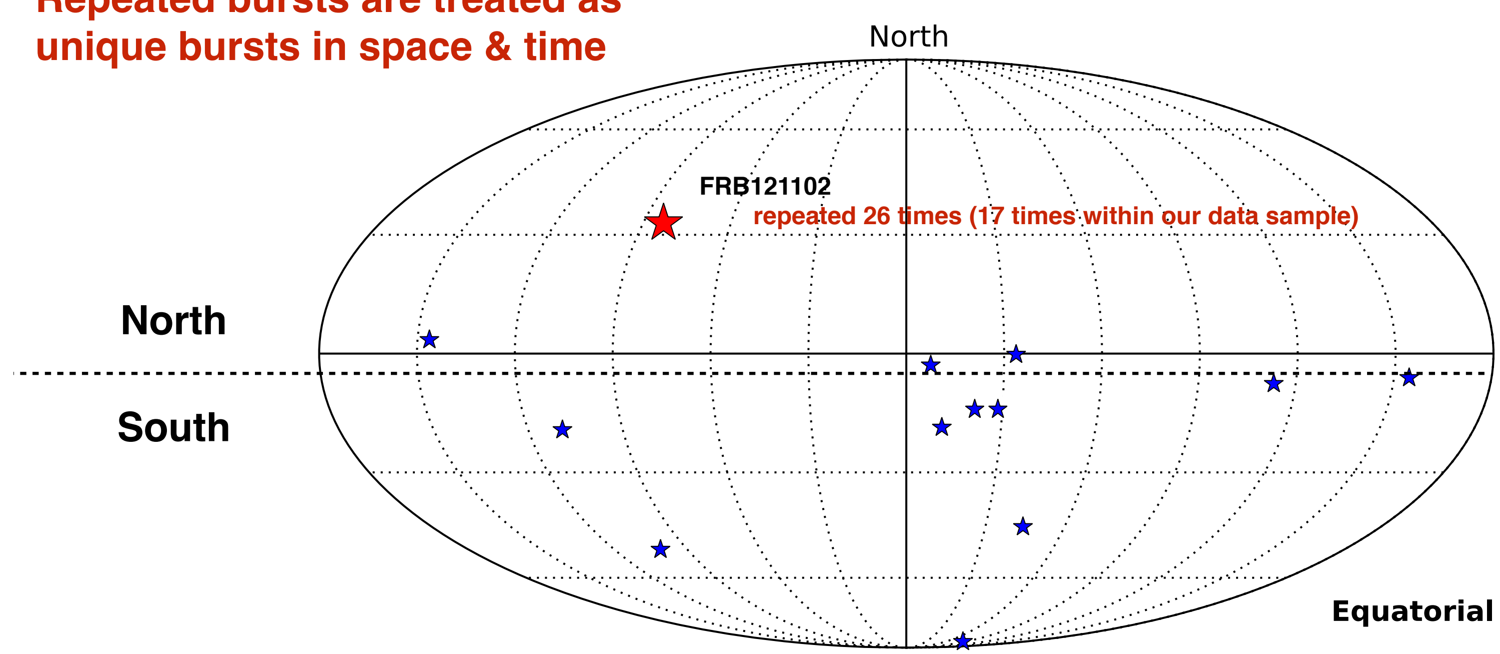


FRBs

- ***O*** **(ms) radio bursts**
- **non-thermal, extragalactic**
- **rate ~10% of core-collapsed SNe**

- Burst times cover IceCube data taking seasons from 2010 to 2015 (6 years)
- A total of **29** FRBs (**11** unique locations).

Repeated bursts are treated as unique bursts in space & time

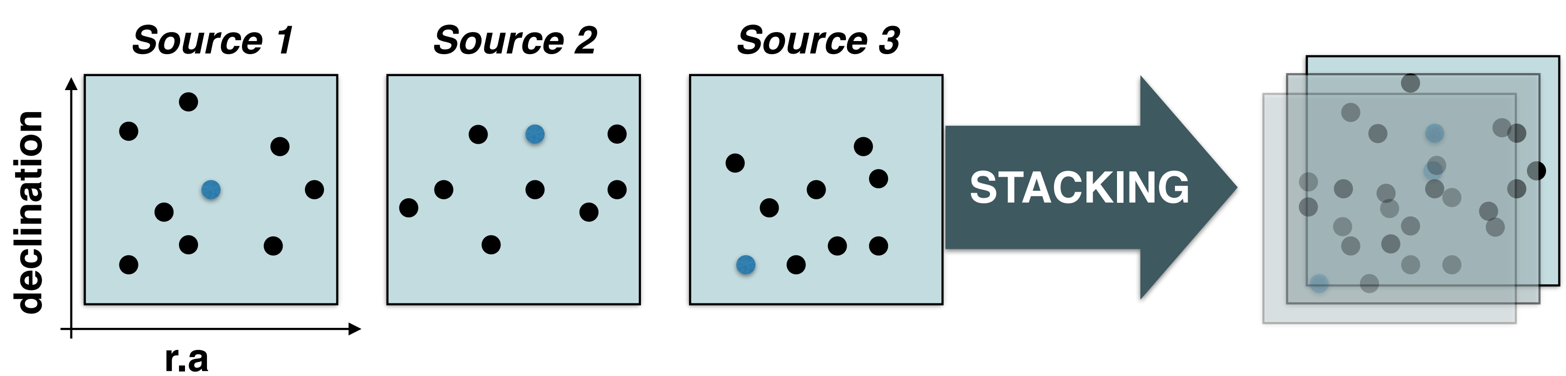


Fast Radio Bursts Search - Analysis Methods

- **Unbinned maximum likelihood (Poisson-based)**

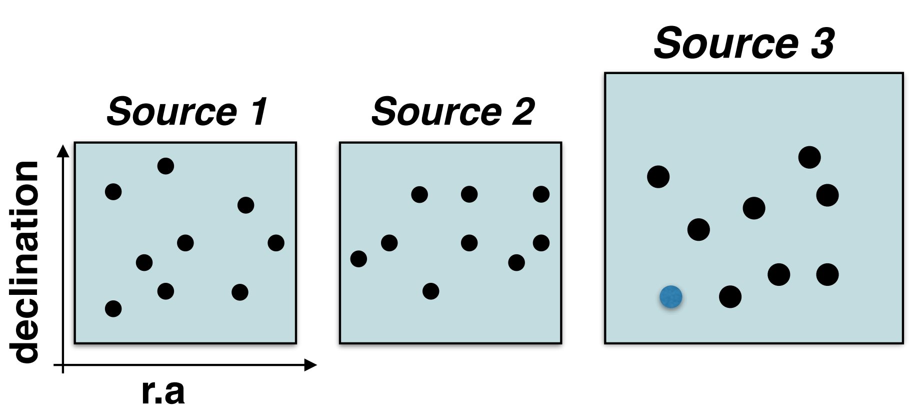
$$\textit{Test statistics} \quad T := -\hat{n}_s + \sum_{i=1}^{N} \ln\left(1 + \frac{\hat{n}_s S_i}{< n_b > B_i}\right)$$

- **Stacking** "Distributed fluence test"



- **Max-burst**

"Single bright neutrino source test"



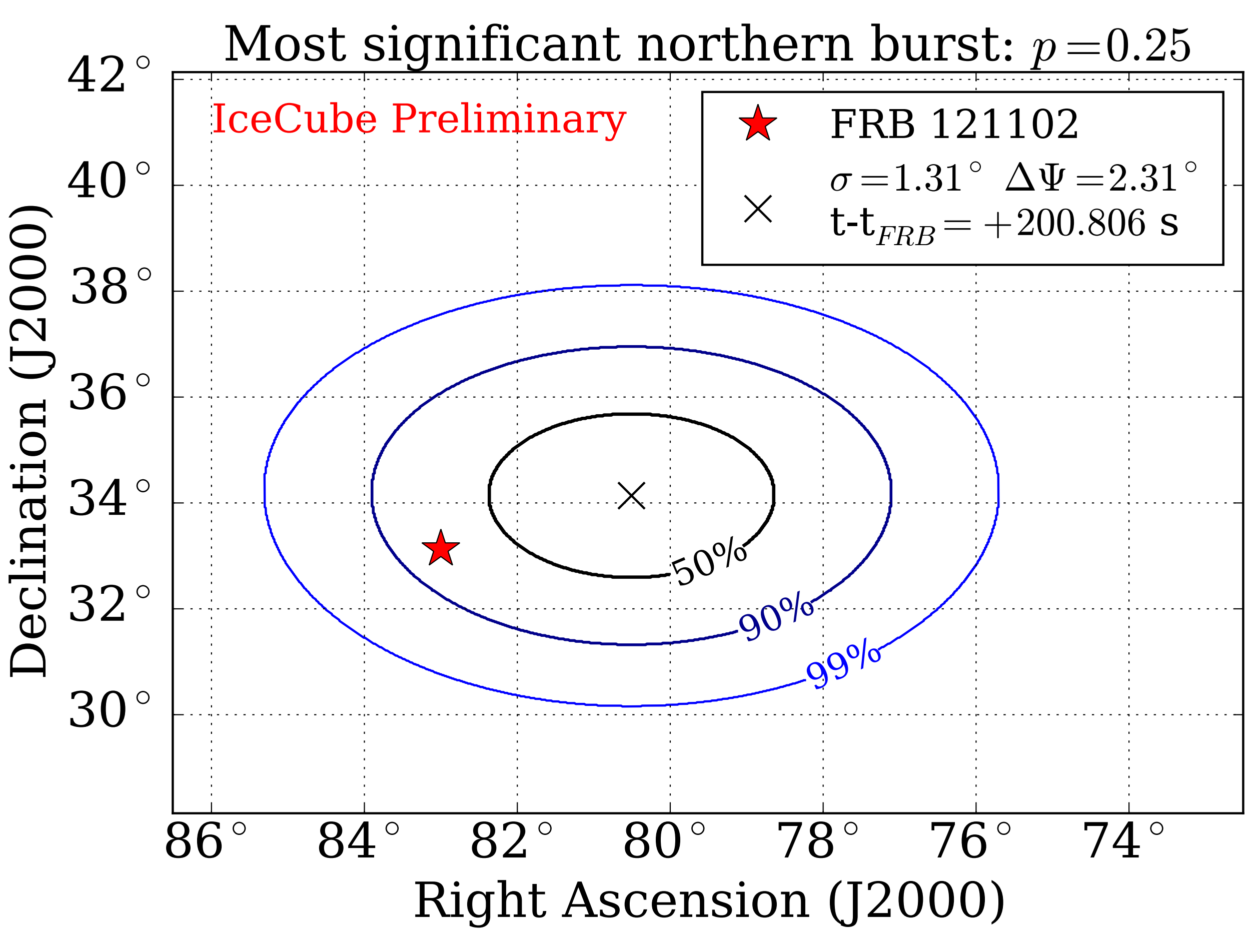
- ▸ **Model independent**
- ▸ **Expanding time windows centered at burst times**
- ▸ **25 time windows from 10 ms to 2 days, expanding as 2^ix10 ms (i =0, …, 24)**

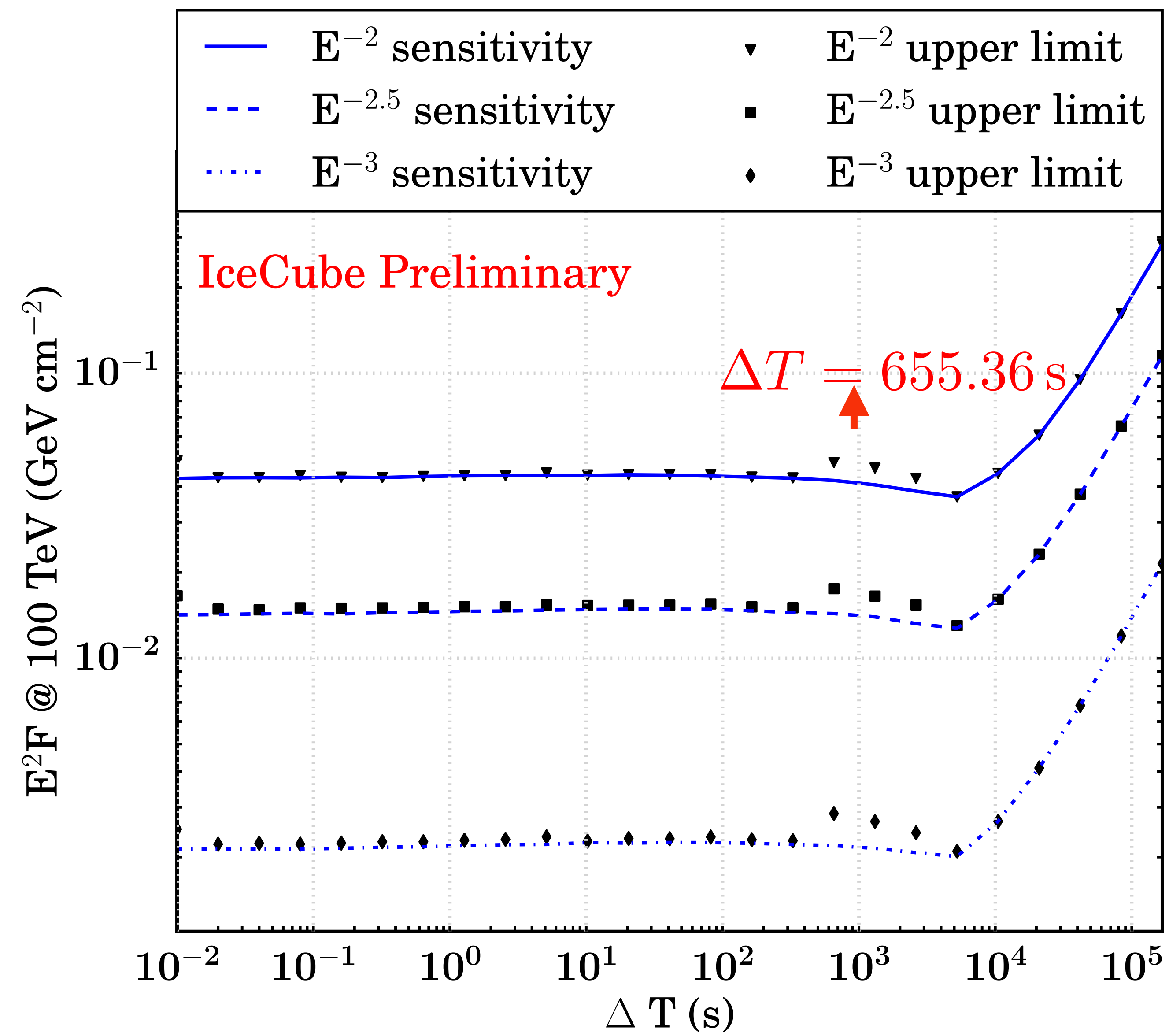
Transient Population Studies: Fast Radio Bursts

A total of 1.2 million events from all-sky in 6 years

Most optimal time window:

$$\Delta T = 655.36\,\mathrm{s}$$





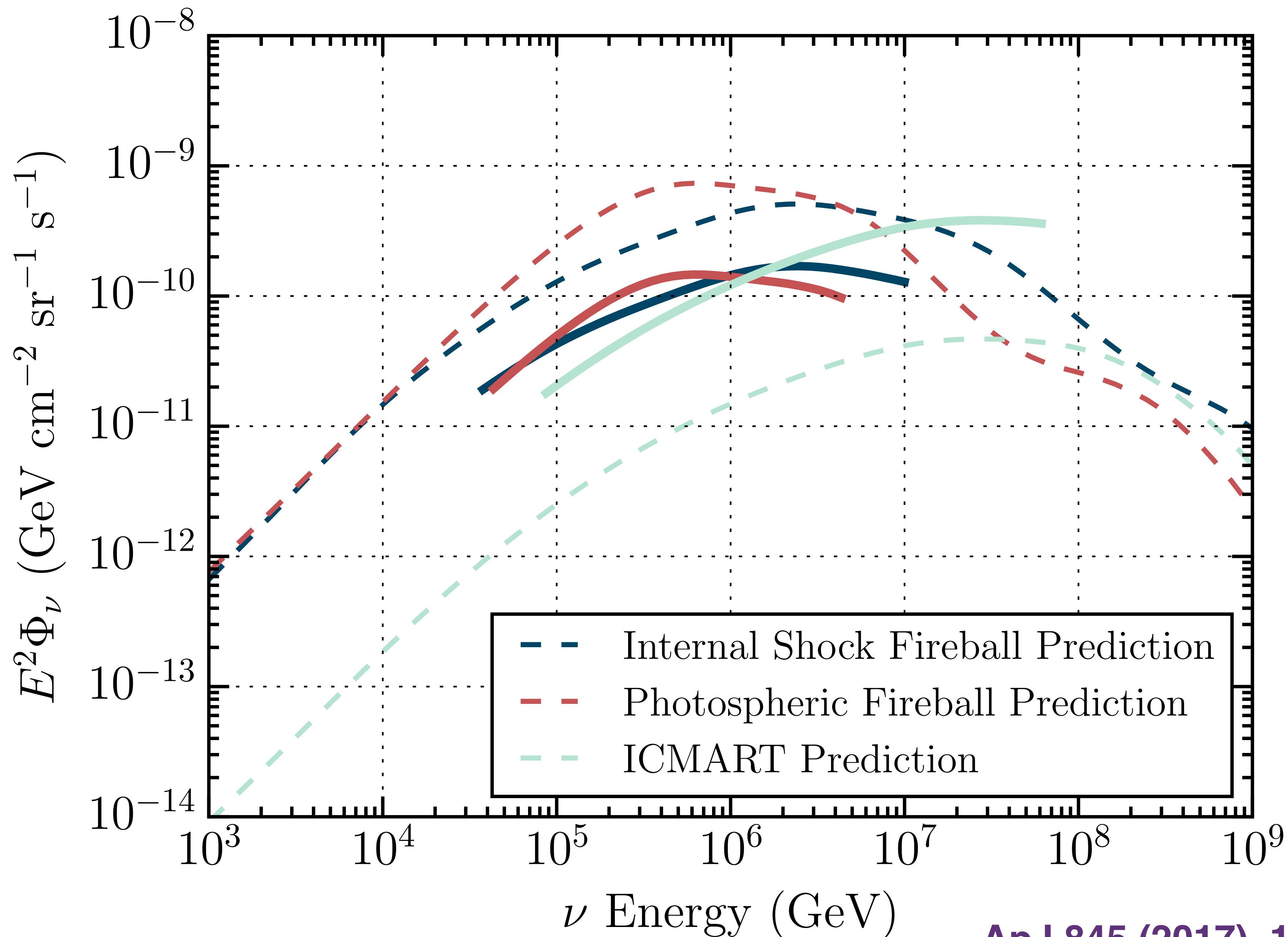
Most stringent limits on neutrino fluence (E^{-2}) from FRBs ~ 0.04 GeV cm^{-2}

S. Fahey, A. Kheirandish, J. Vandenbroucke, **DX**, ApJ 845 (2017) 1, 14

IceCube Collaboration, arXiv:1712.06277 (accepted for publication in ApJ)

Catalog stacking

North + South combined

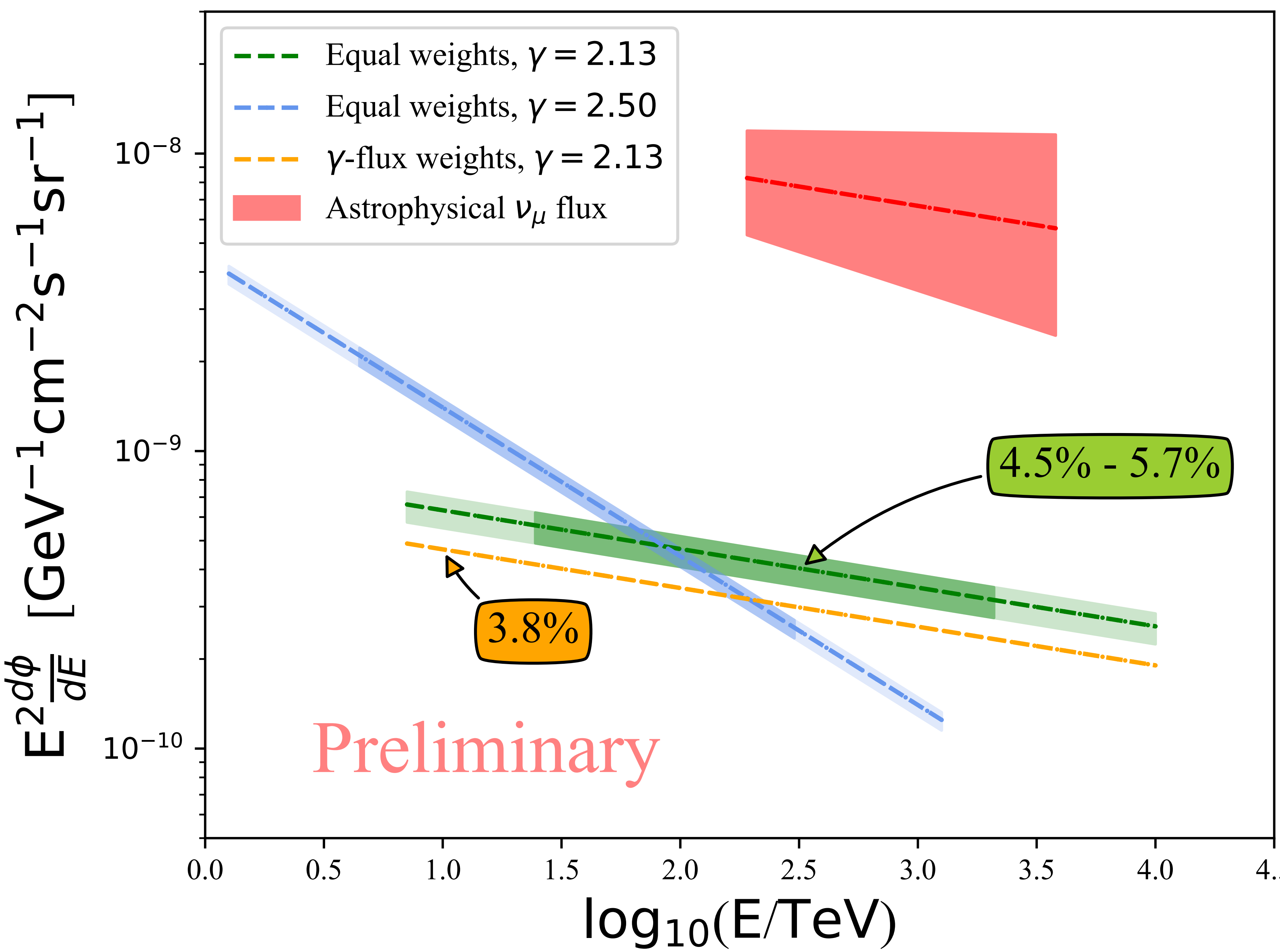


ApJ 845 (2017), 1, 14

Prompt emission from GRBs can produce <1% of the observed neutrino flux.

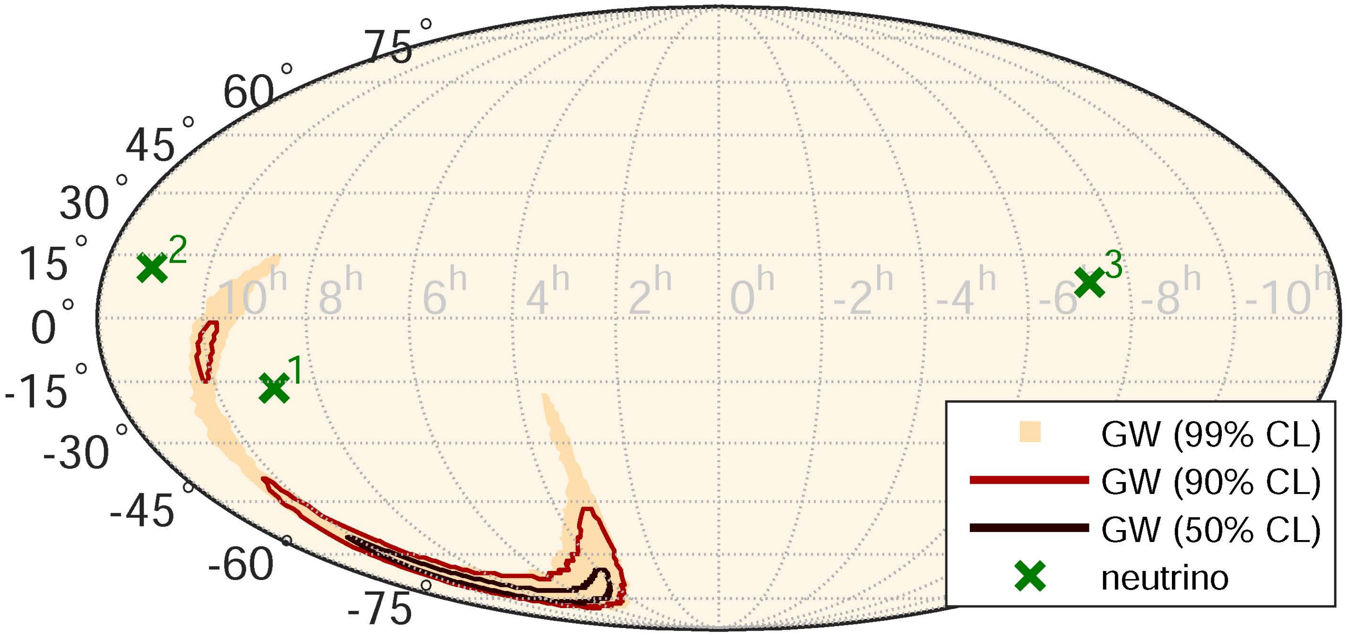
Blazars account for:
85% of the extragalactic γ background
< 6% of the IceCube neutrino flux

See: ICRC2017: M. Huber, NU043
Fermi-LAT PRL 116(15) 151105
Astrophys.J. 835 (2017) no.1, 45



Multi-messenger Correlation with non-EM Partners

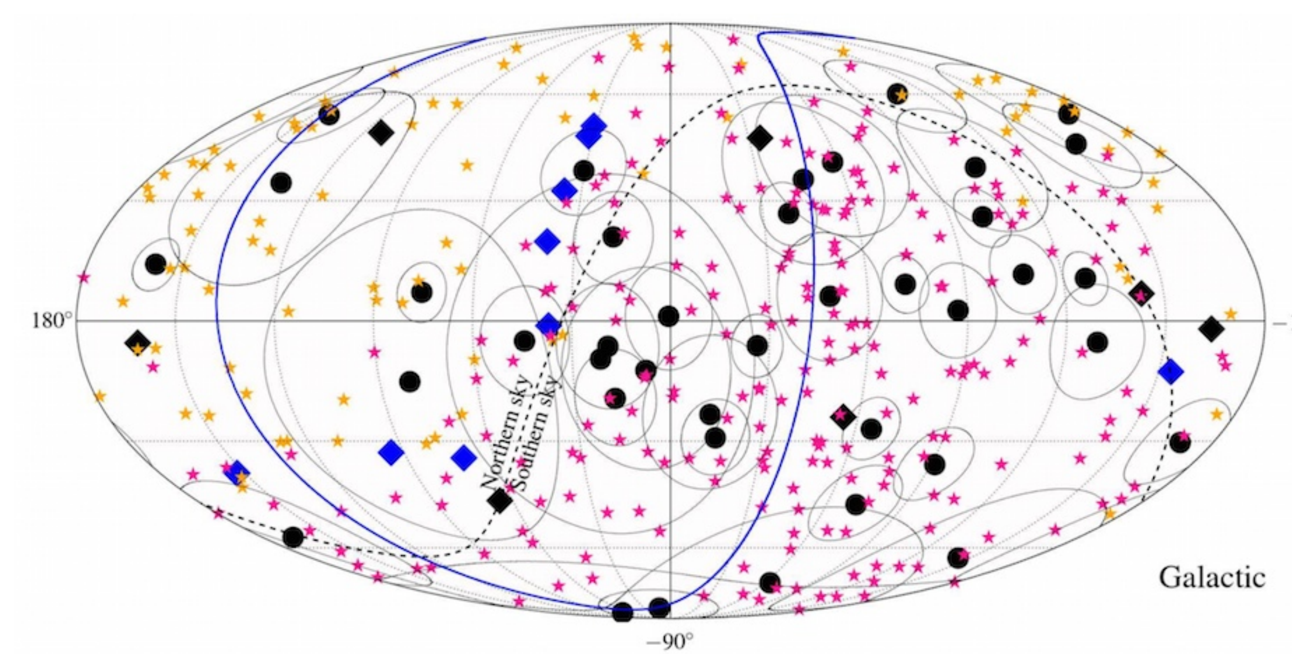
Gravitational Waves



- **Correlate neutrinos with the LIGO event GW150914 within +/-500s**
- **Observed 3 events, consistent with atmospheric background**

https://arxiv.org/pdf/1602.05411v3.pdf

Ultra-high-energy cosmic rays (UHECRs)



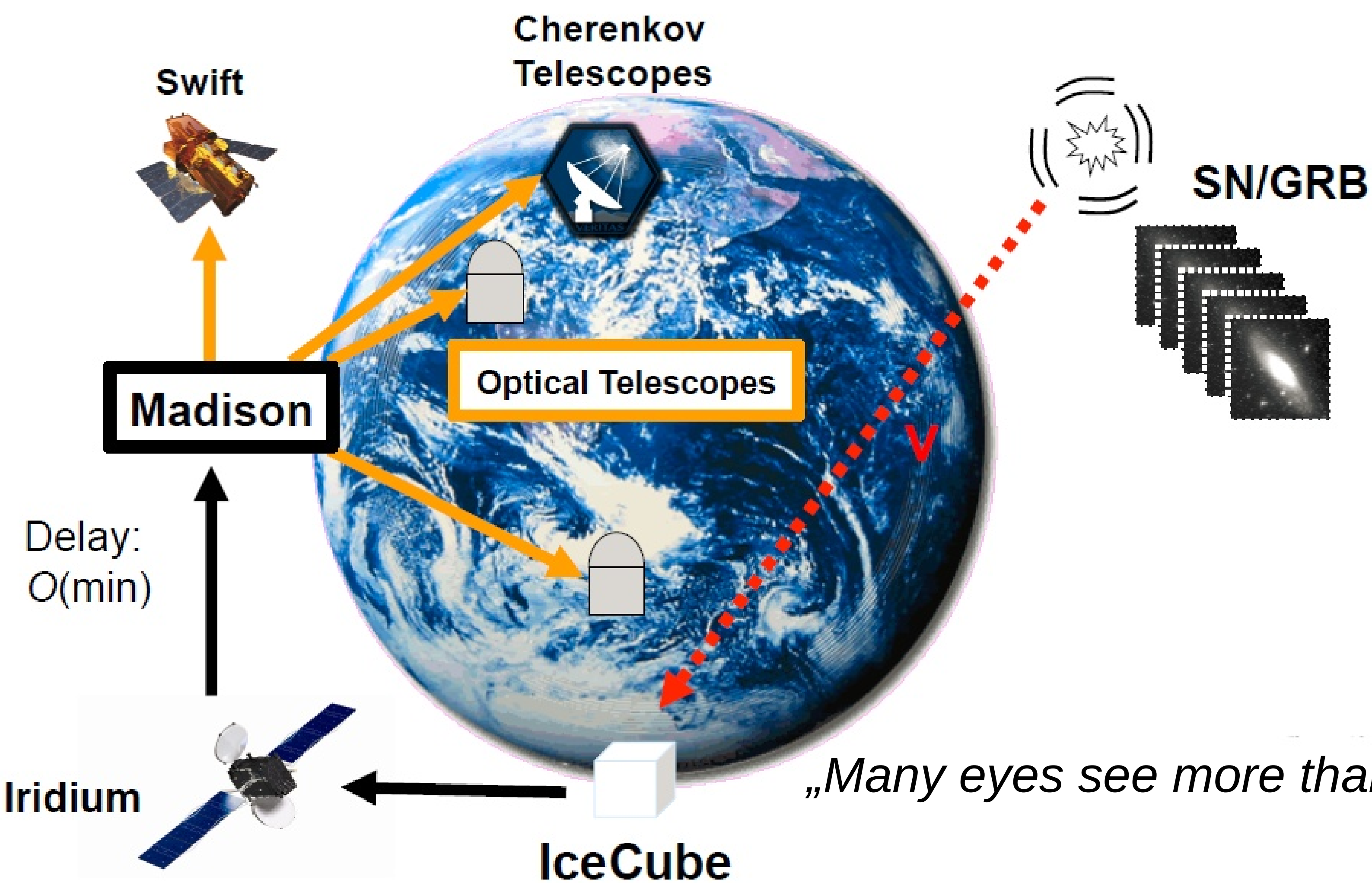
- **Cross correlate HE neutrinos with ~300 UHECRs > 50 EeV**
- **No significance over 3.3σ**

JCAP 1601 (2016), no. 01, 037

Realtime Alert Systems

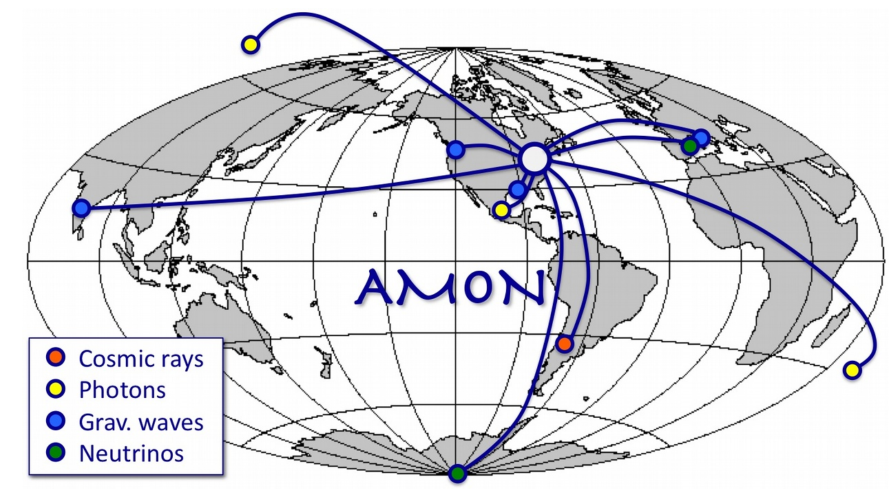
Correlating to other observatories:

- **Single high-significance neutrinos**
- **Lower-significance multiplets**



„Many eyes see more than two.“

Public alert network



The Astrophysical Multimessenger Observatory Network:
FACT, VERITAS, MASTER, LMT, ASAS-SN, LCOGT

Individual MOU partners

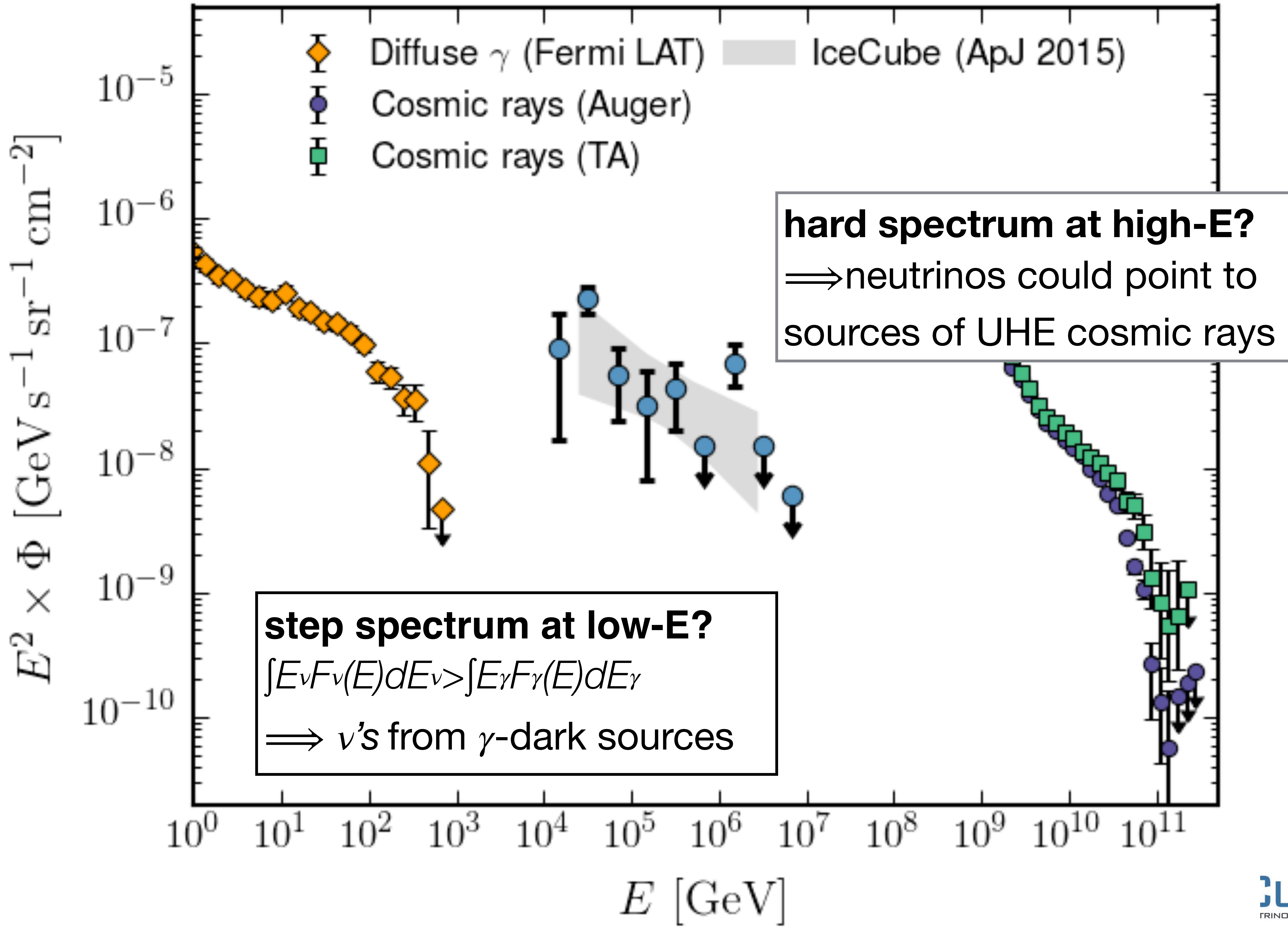
Swift XRT, PTF, VERITAS, Magic HESS, HAWC, MWA LIGO/VIRGO

Followups communicated via:

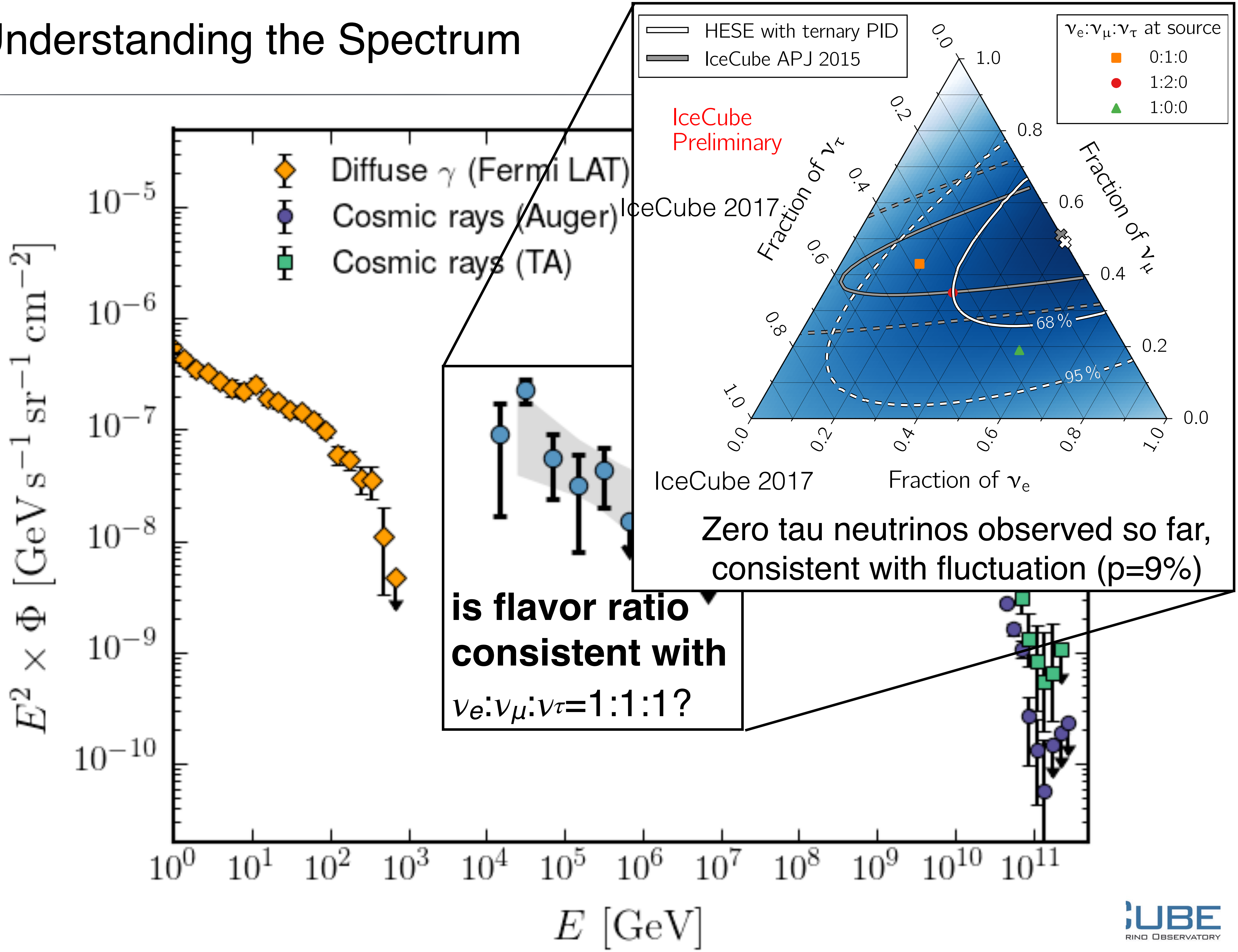
The Gamma-ray Coordinates Network

The Astronomer's Telegram

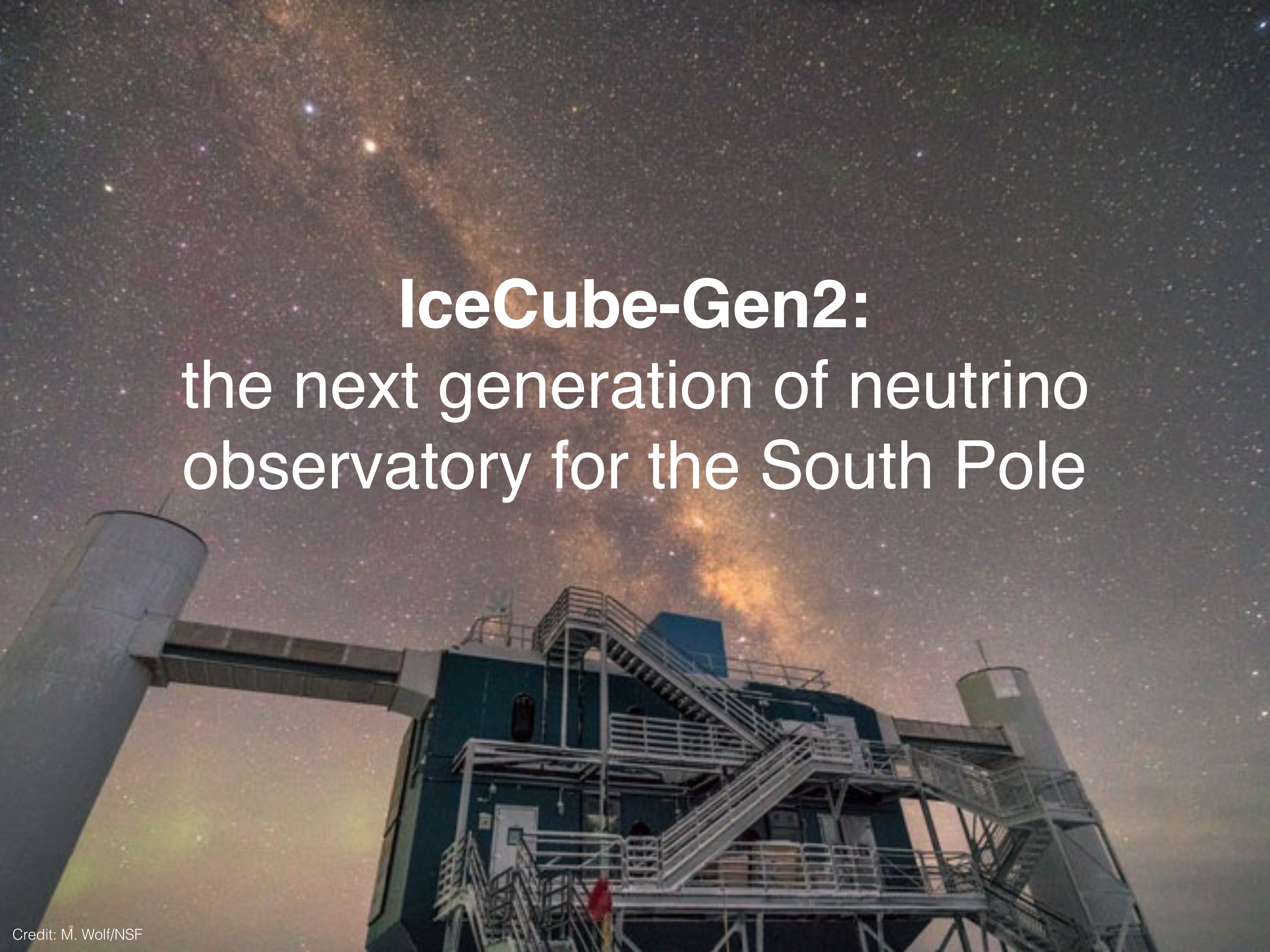
Understanding the Spectrum



Understanding the Spectrum



IceCube-Gen2:
the next generation of neutrino observatory for the South Pole

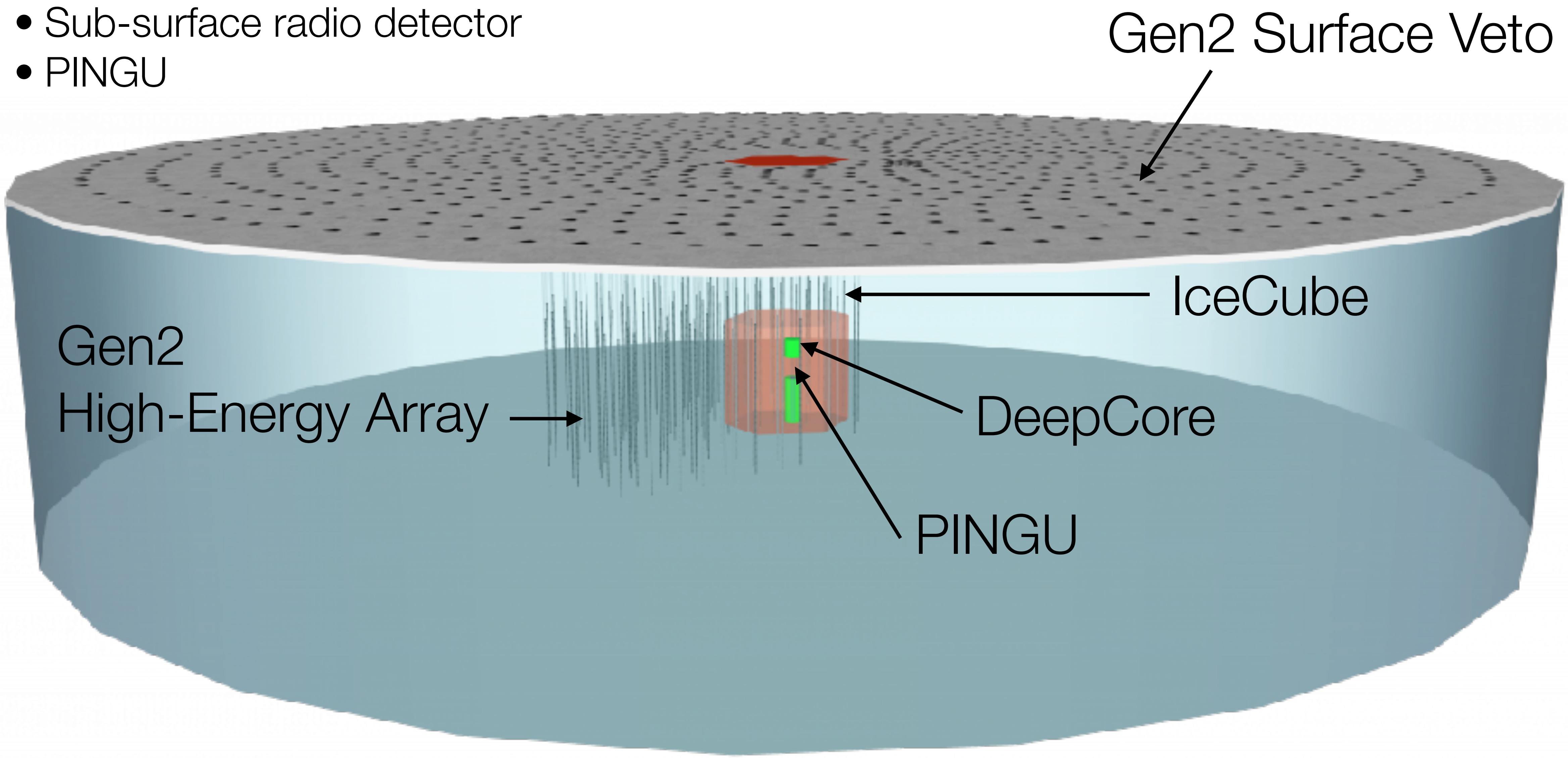


Credit: M. Wolf/NSF

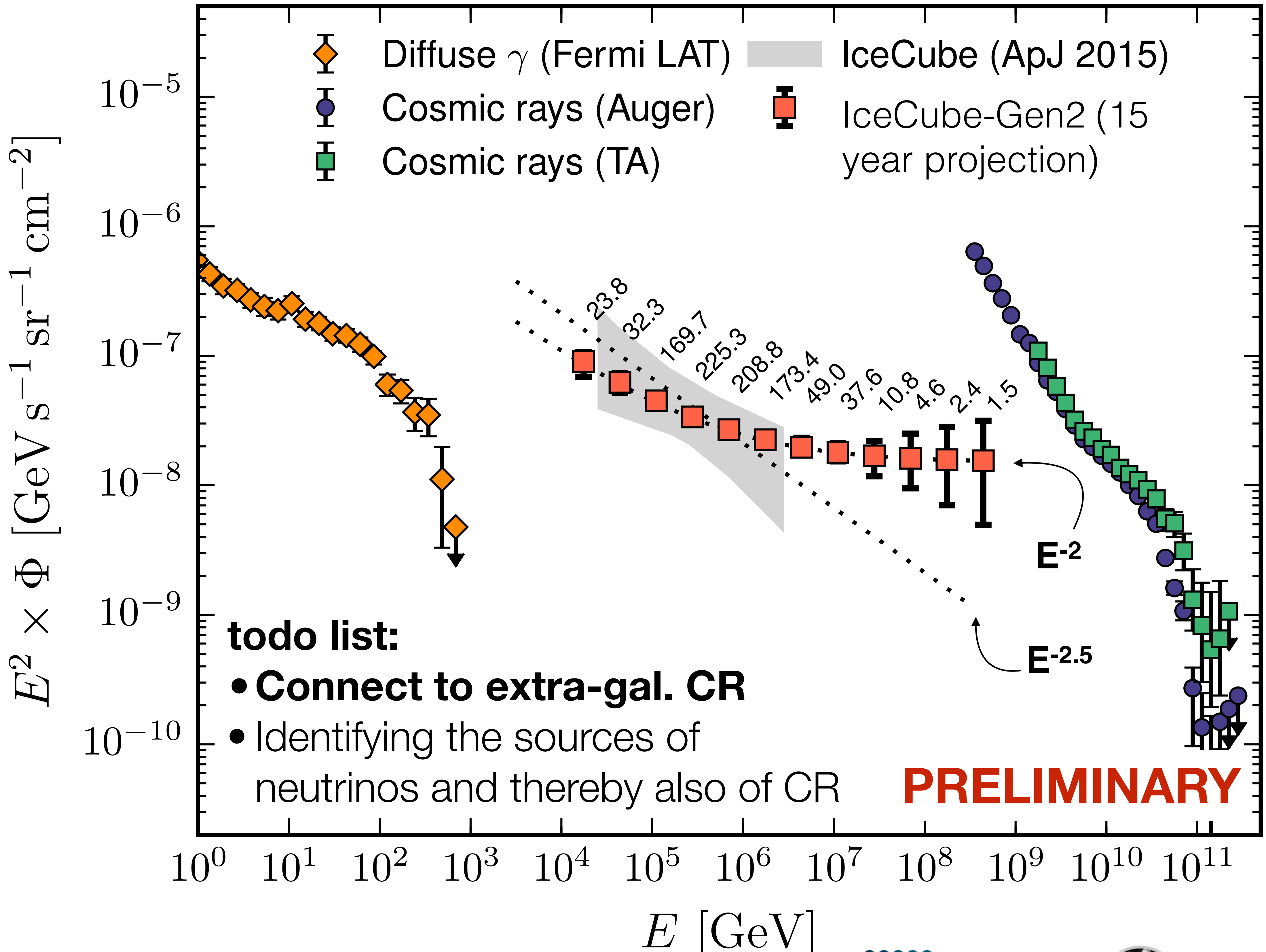
- **Resolve the sources of IceCube's high energy astrophysical neutrinos**
- **Identify the sources of the highest energy cosmic rays**
- Decipher the production mechanisms of high energy cosmic particles
- Obtain a unique multi-messenger view into the explosion of stars and the evolution of stellar remnants
- Explore active galaxies and the very high-energy Universe when it was most active
- Study of galactic and extra galactic propagation of CR with neutrinos as tracers
- Test nuclear, neutrino and BSM physics

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

Multi-component observatory:
- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU



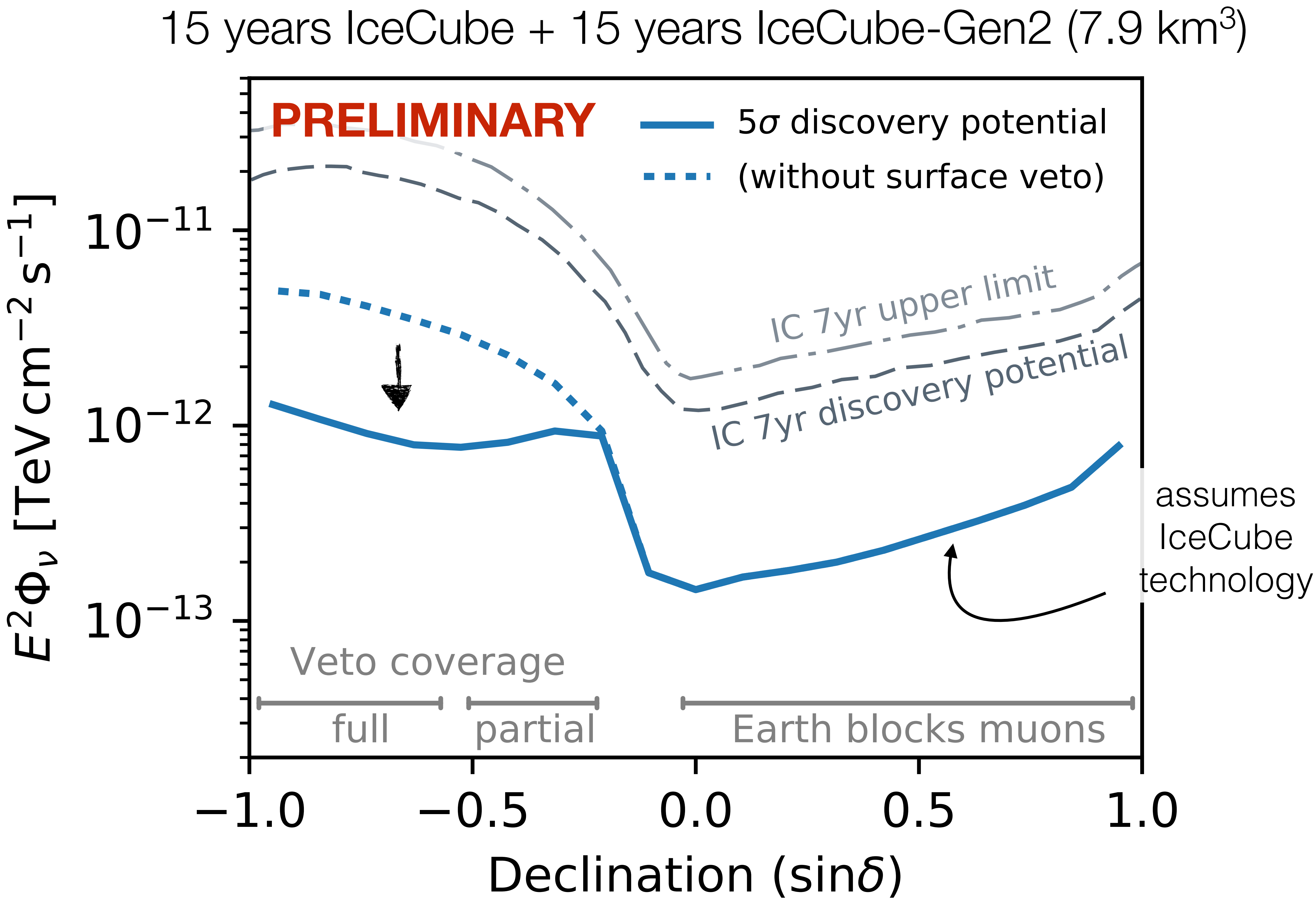
IceCube-Gen2 Sensitivity



todo list:

- **Connect to extra-gal. CR**
- Identifying the sources of neutrinos and thereby also of CR

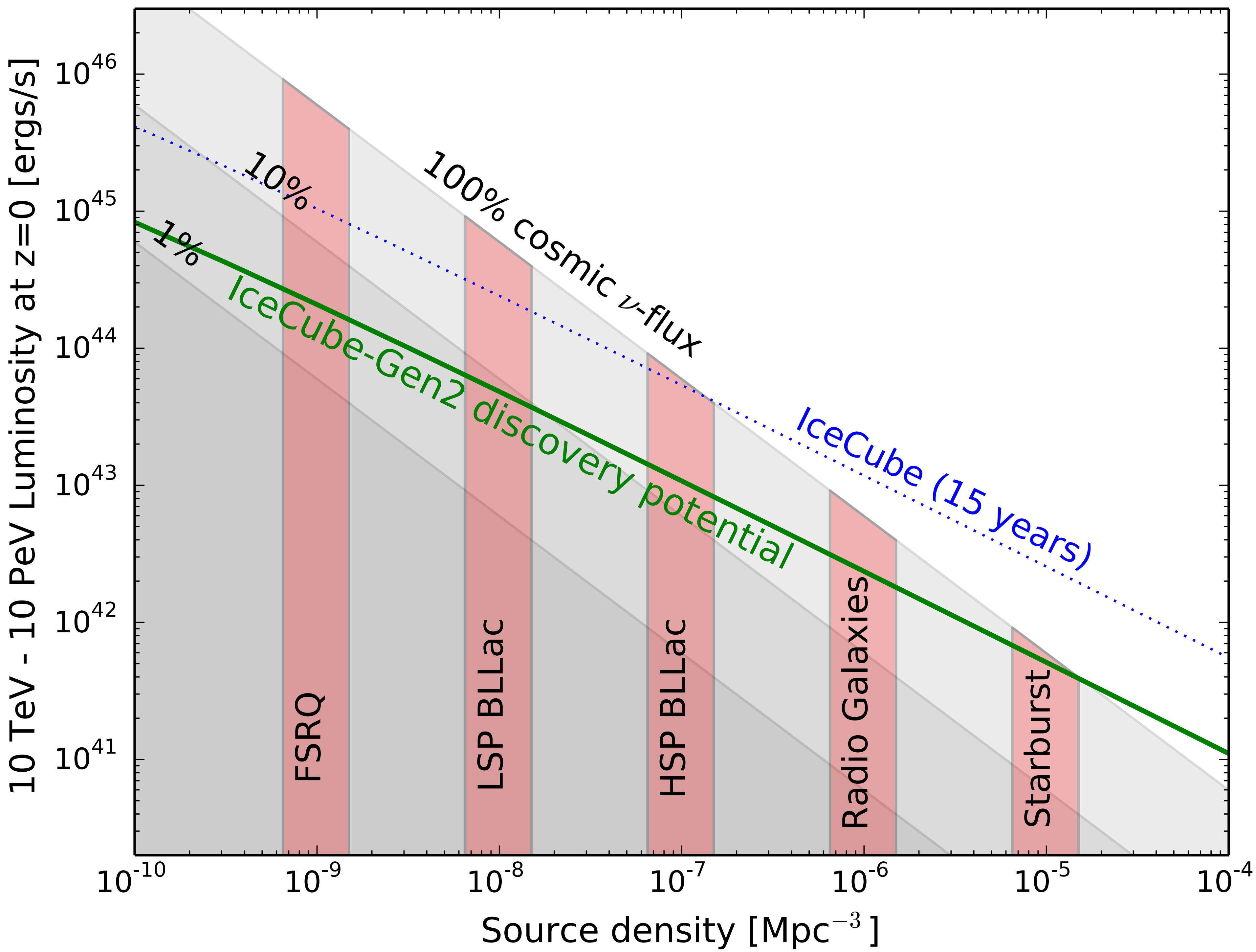
IceCube-Gen2 Point Source Sensitivity



WIPAC Wisconsin IceCube Particle Astrophysics Center

IceCube South Pole Neutrino Observatory

Identifying the Sources of IceCube Neutrinos



IceCube-Gen2 will have sufficient sensitivity to detect all reasonable source scenarios

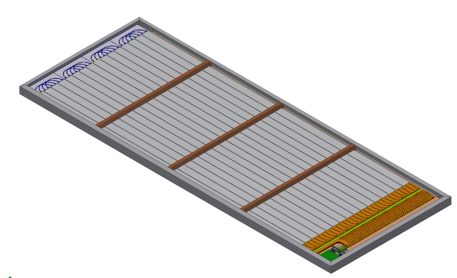
IceCube-Gen2 R&D

D-Egg: dual-PMT optical module
ICRC2017: A. Ishihara, NU073; A. Stoessl, NU111

mDOM: multi-PMT optical module
ICRC2017: L. Classen, NU082

WOM: wavelength-shifting optical module
ICRC2017: P. Peiffer, NU053

Optical modules: more photons per unit cost, more information per photon



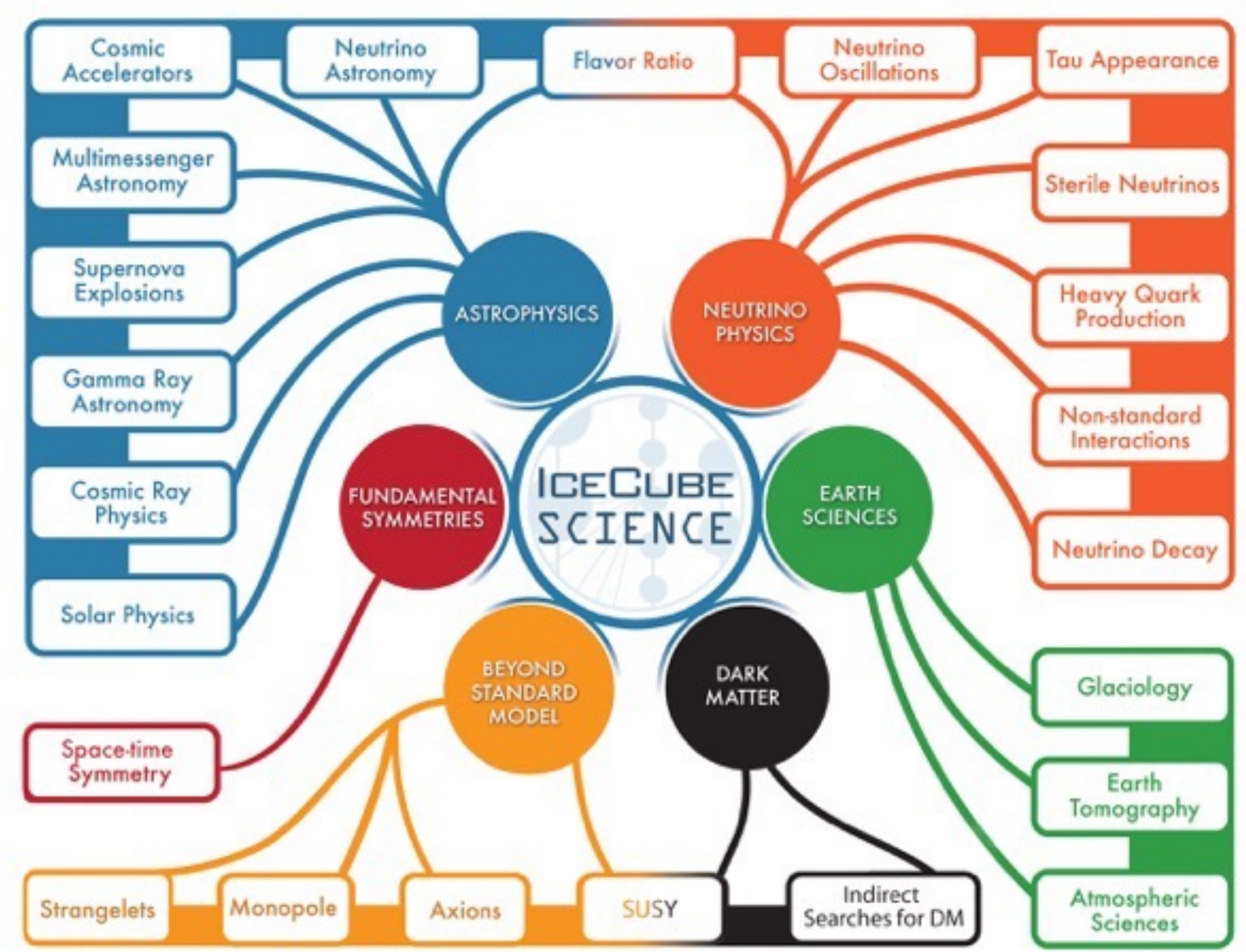
IceTop scintillator upgrade
ICRC2017: S. Kunwar, CRI148

IceACT: low-threshold air shower veto
ICRC2017: J. Auffenberg, NU041

Surface detector: threshold vs. duty cycle

Summary

- **Neutrino is a unique astronomical messenger: can point back to distant sources**
- **IceCube has discovered astrophysical neutrinos; dawn of neutrino astronomy**
- **Astrophysical tau neutrinos is still elusive, but should be expected around the corner**
- **Astrophysical neutrino point sources are yet to be discovered. The campaign for neutrino point sources is ON**
- **IceCube-Gen2 with upgrade planning for both low and high energies will have up to an order of magnitude increase in sensitivity**


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

2016

- **265 scientists**
- **47 institutions**
- **12 countries**

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

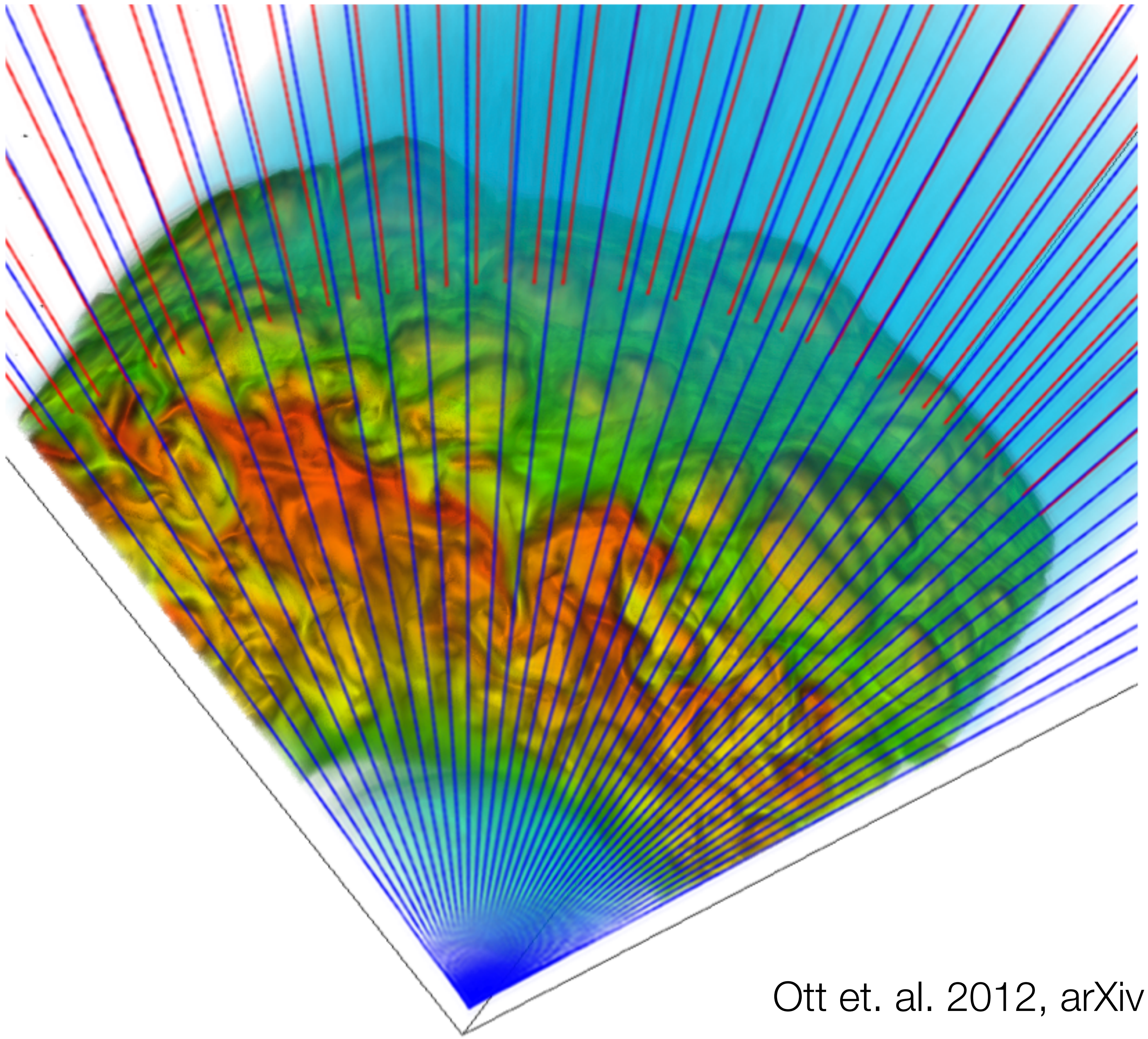
UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
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 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)

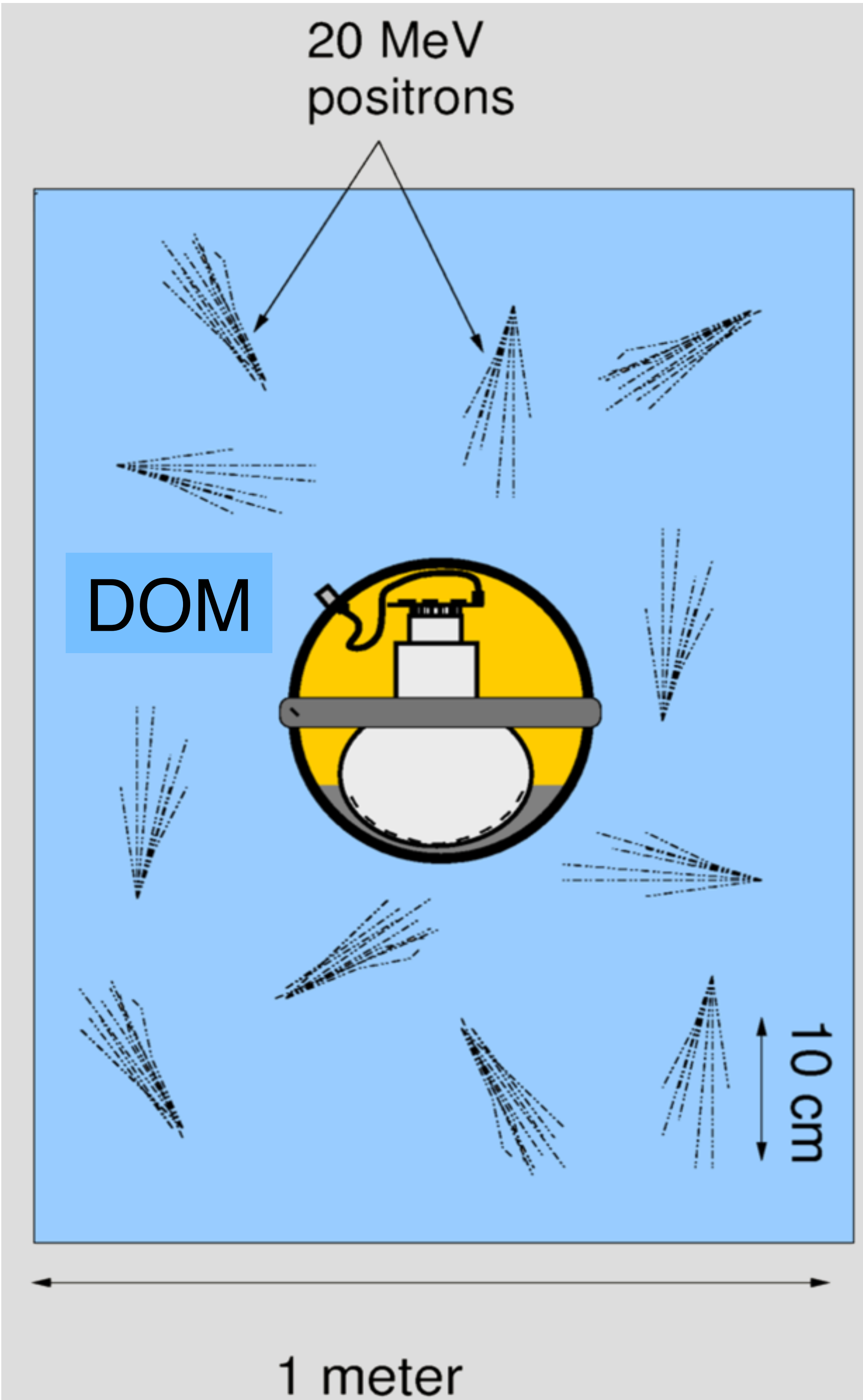
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

Backup Slides



Ott et. al. 2012, arXiv 1204.0512v1

Supernova Neutrinos in IceCube



- Supernova
  - Uniform illumination in the ice, ~0.5 to 1×10^6 events in 10 seconds
  - A statistical significant increase in the detector noise: DOM-to-DOM correlated increase in detector noise
- IceCube advantage
  - Low PMT noise - ~300 Hz
  - High statistics - 0.25% error
  - 2 ms time resolution
- Challenges: No pointing, individual events, or energy information

Supernova Neutrinos in IceCube - Loglikelihood Analysis

$$\mathcal{L}(\Delta\mu) = \prod_{i=1}^{N_{\mathrm{DOM}}} \frac{1}{\sqrt{2\pi\sigma_i}} \exp\left\{ -\frac{1}{2} \left(\frac{r_i - (\mu_i + \epsilon_i \Delta\mu)}{\sigma_i} \right)^2 \right\}$$

$\Delta\mu$ - Increase in detector noise rate

ϵ_i - Efficiency parameters

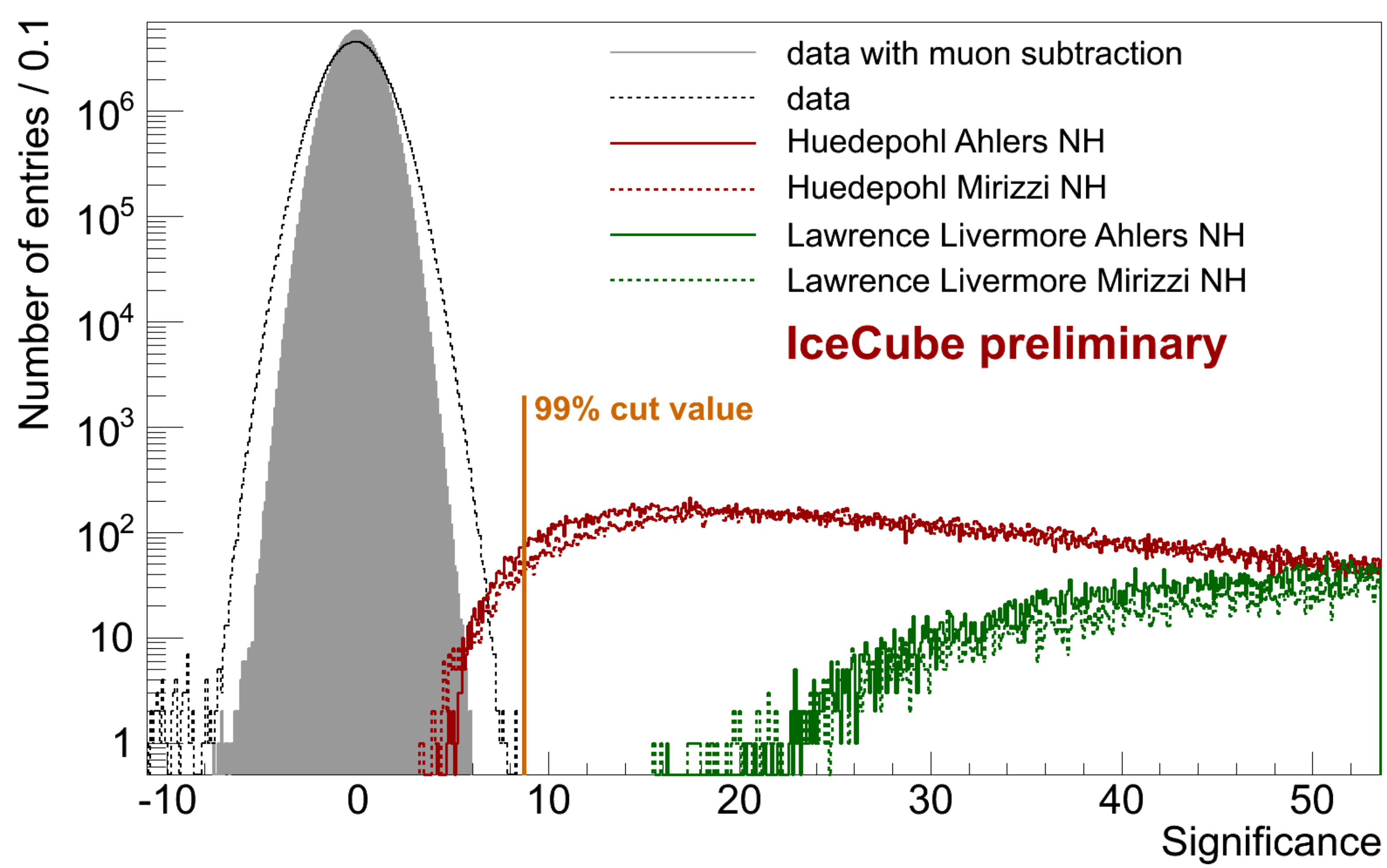
μ_i - Mean background rate

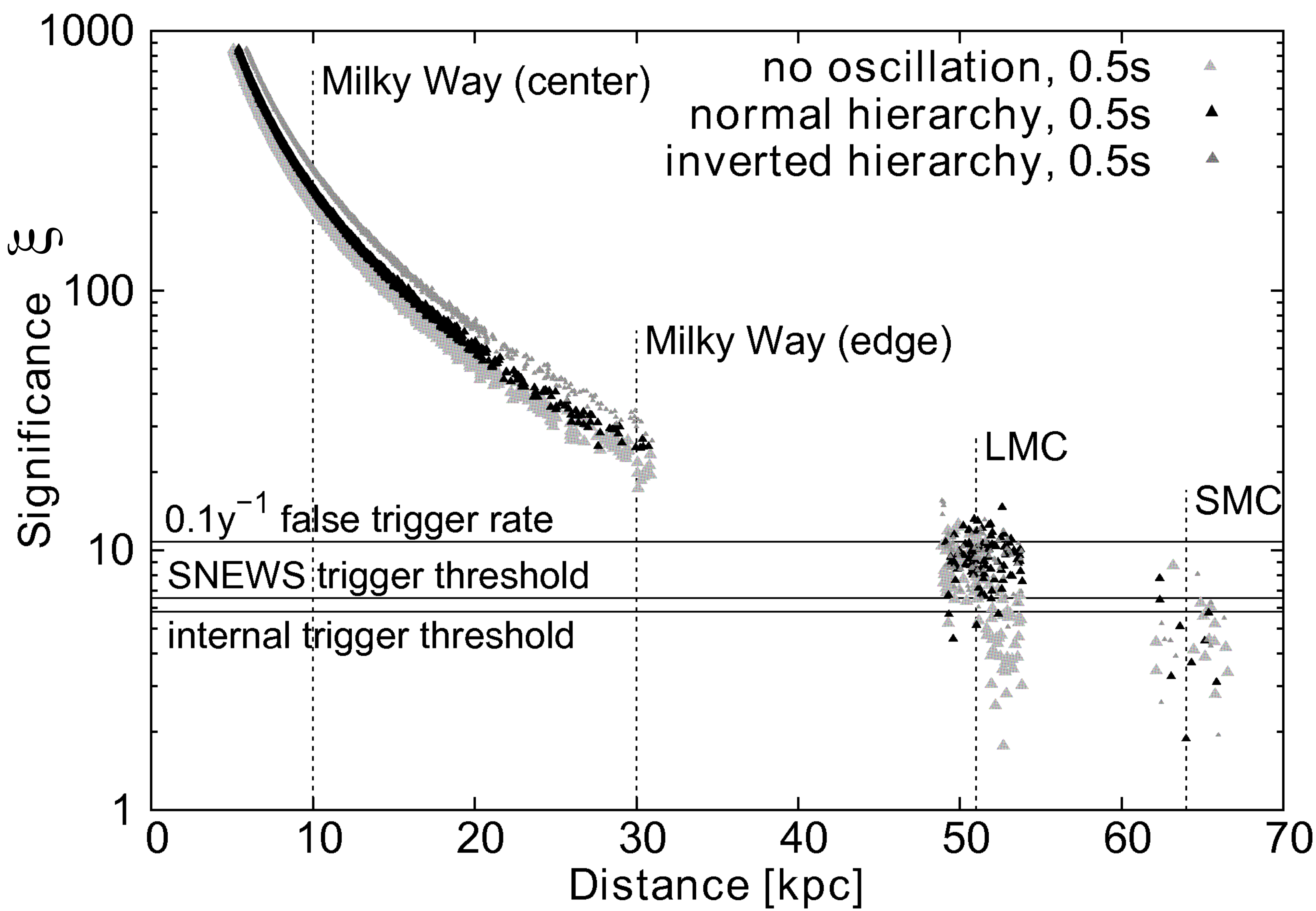
σ_i - Error on background rate

r_i - Rate in signal bin

Significance (ξ) = $\dfrac{\Delta\mu}{\sigma_{\Delta\mu}}$

ξ ≥ 6 alert sent to working group




1000
100
10
1
Significance ξ
0
10
20
30
40
50
60
70
Distance [kpc]
no oscillation, 0.5s
normal hierarchy, 0.5s
inverted hierarchy, 0.5s
Milky Way (center)
Milky Way (edge)
LMC
SMC
0.1y⁻¹ false trigger rate
SNEWS trigger threshold
internal trigger threshold