Recent Results from IceCube

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for the IceCube Collaboration

September 22nd, 2016

Tau 2016, Beijing, China

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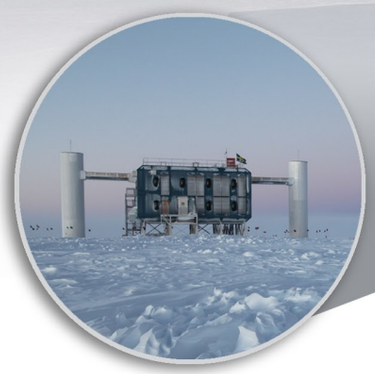
IceCube South Pole Neutrino Observatory

IceCube
South Pole Neutrino Observatory

Goal: detecting TeV-PeV astrophysical neutrinos
Construction completed in December 2010



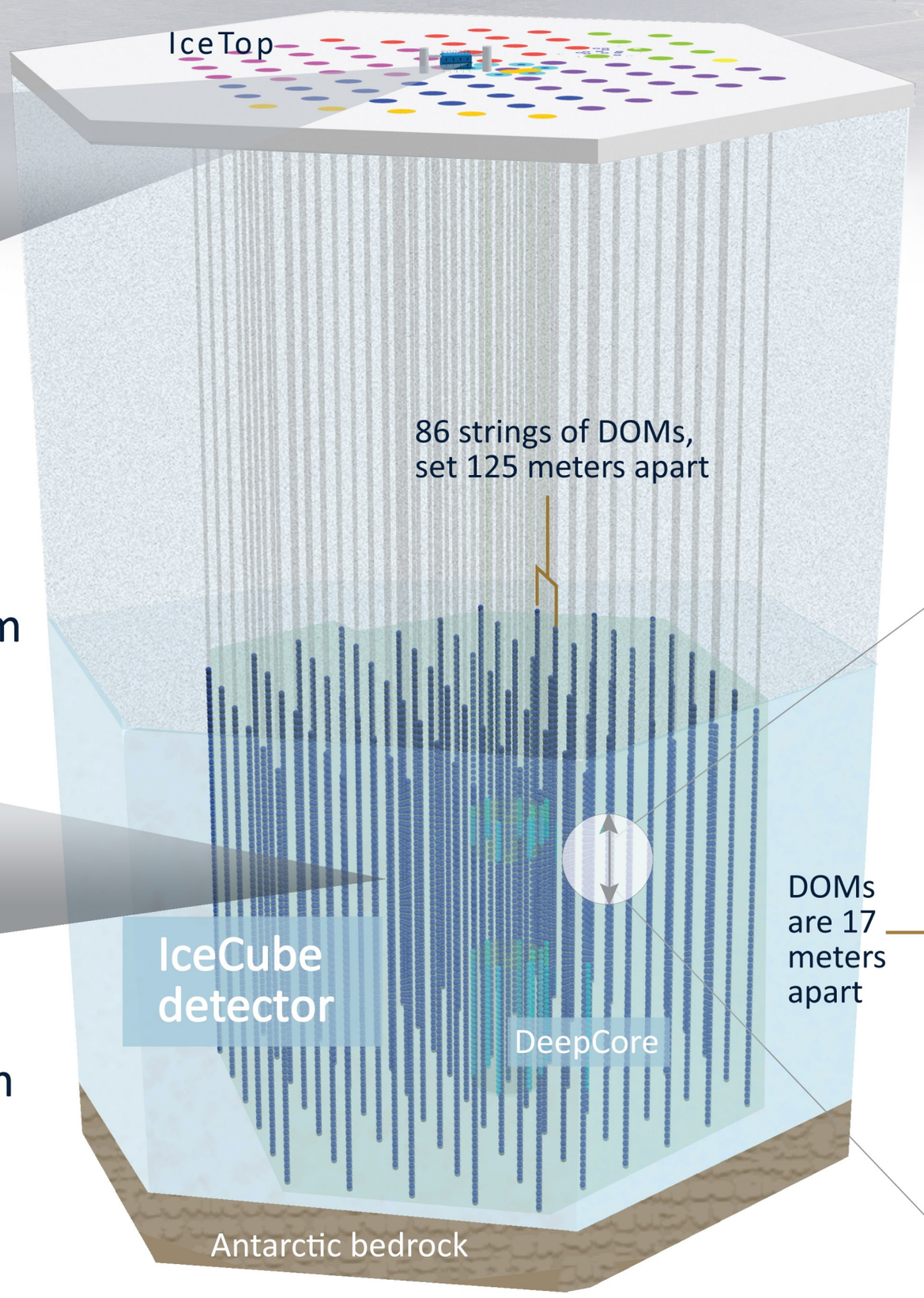
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison

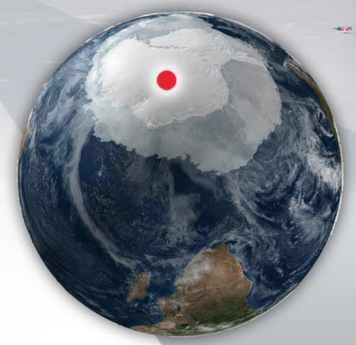
50 m

1450 m

Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

2450 m



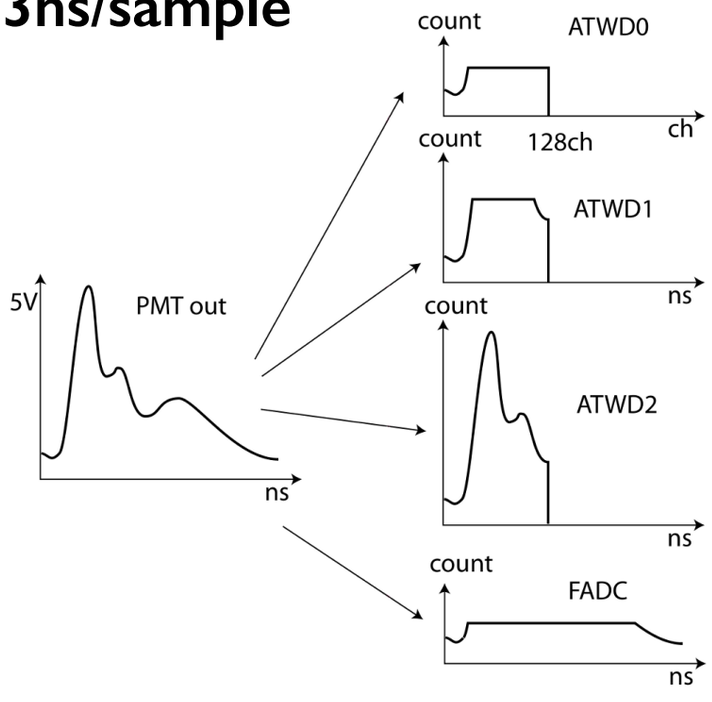


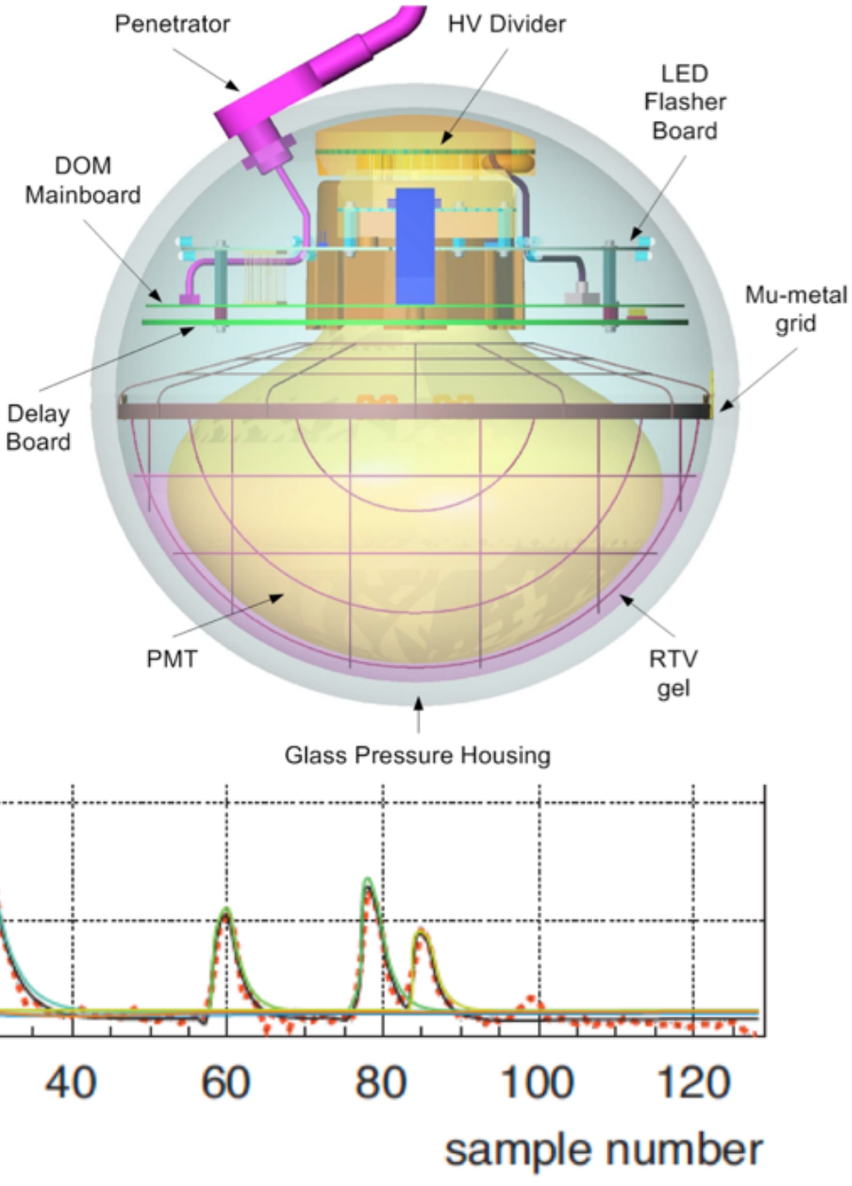
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility

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





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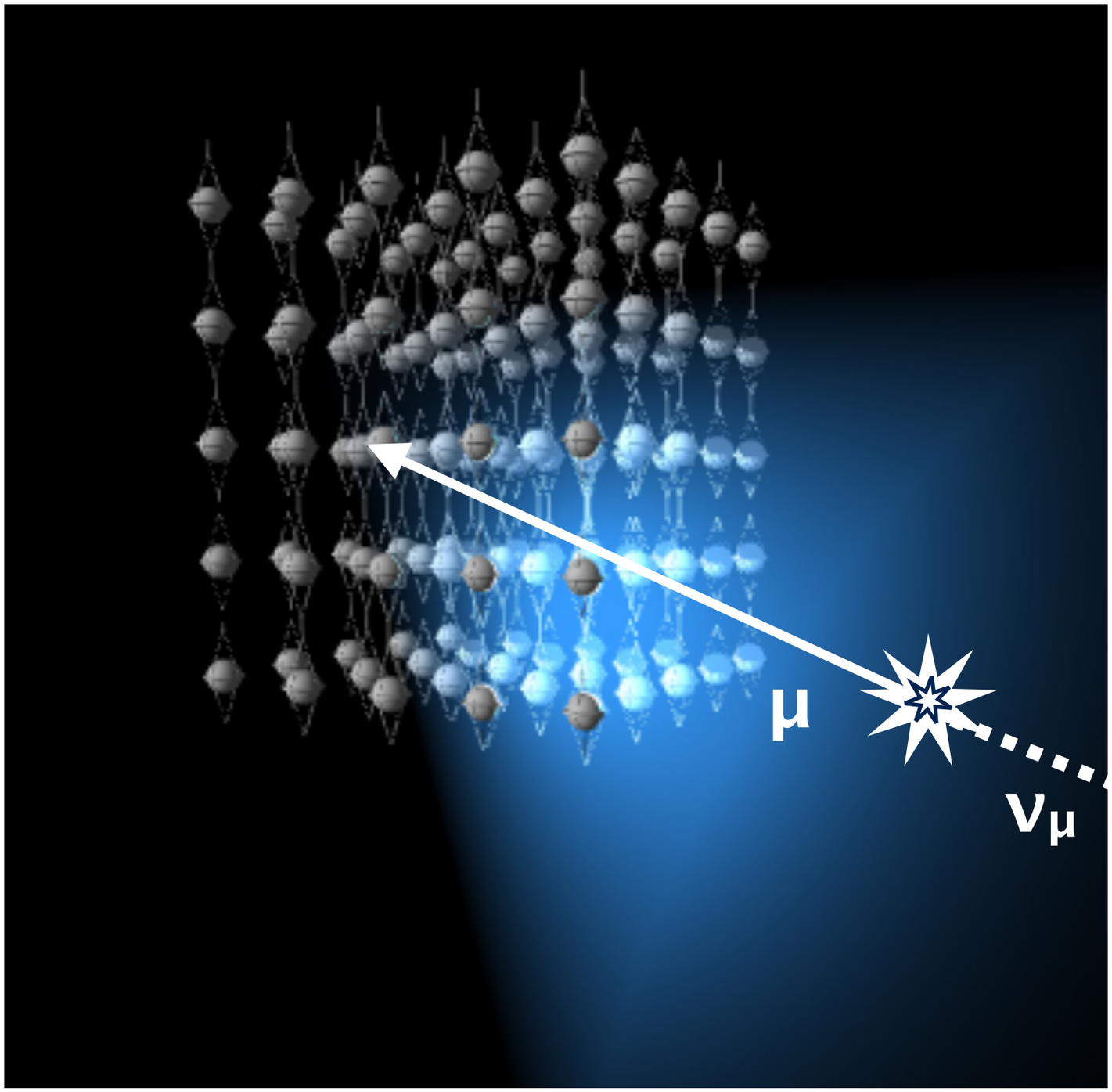
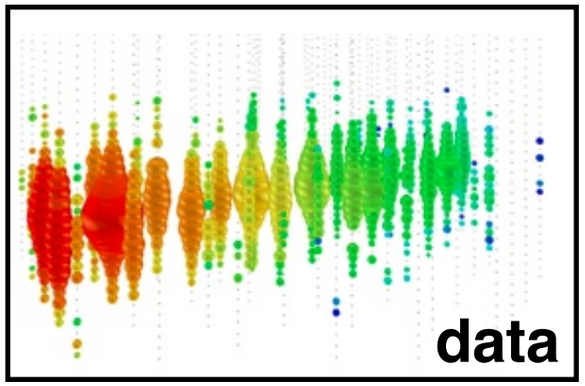
Detection Principle - Cherenkov Radiation



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

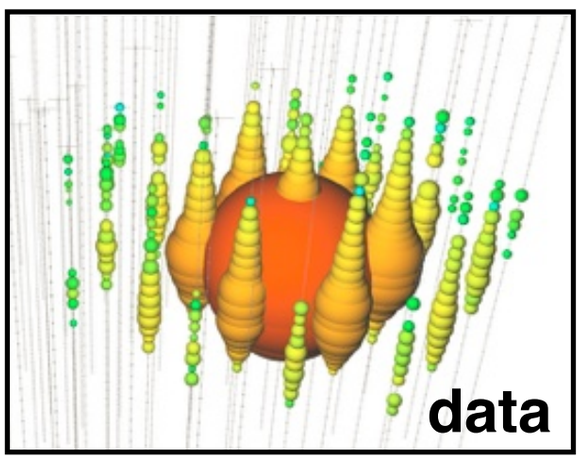
(1) Track: charged current ν_μ

- **<1° Angular resolution**
- **Factor ~ 2 energy resolution**

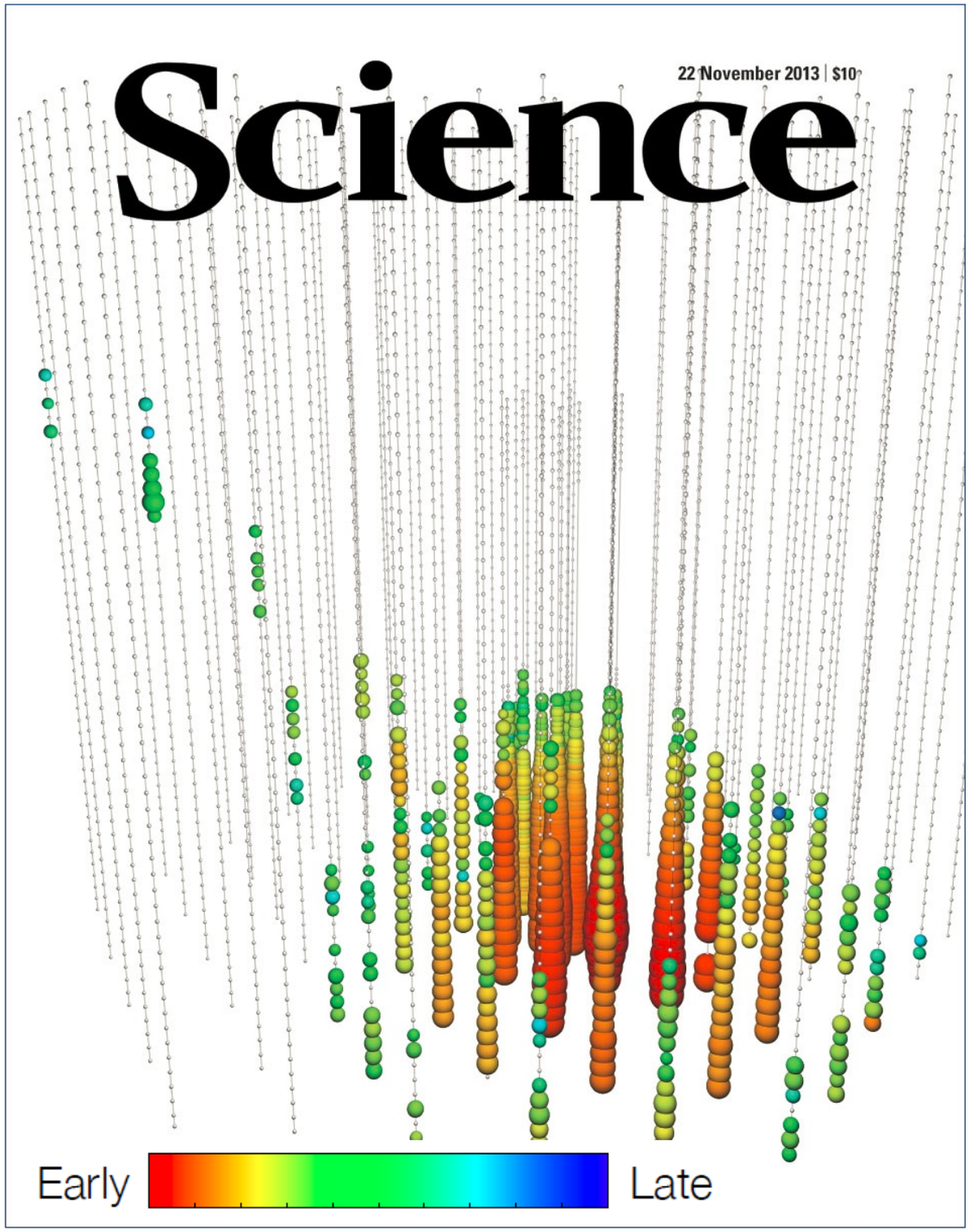


(2) Cascade / Shower: all neutral current, charged current ν_e, low-E charged current ν_τ

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



"high degeneracy"



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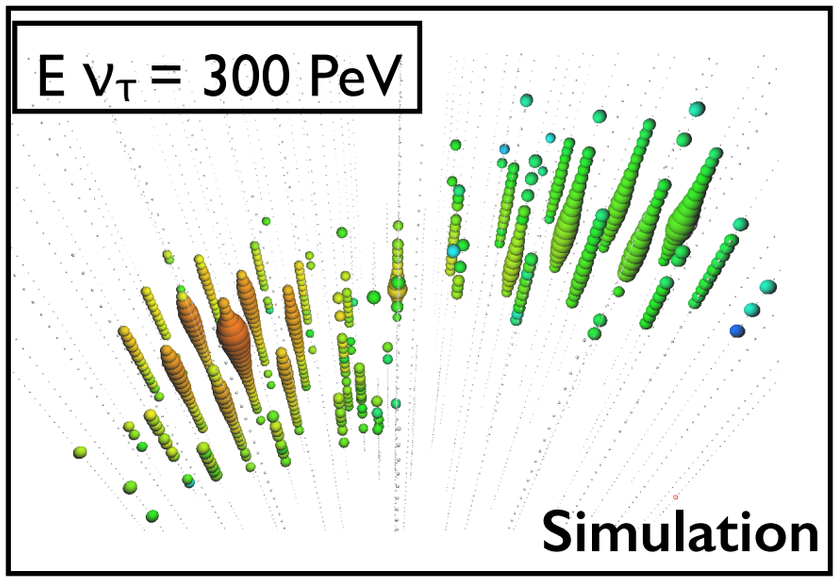
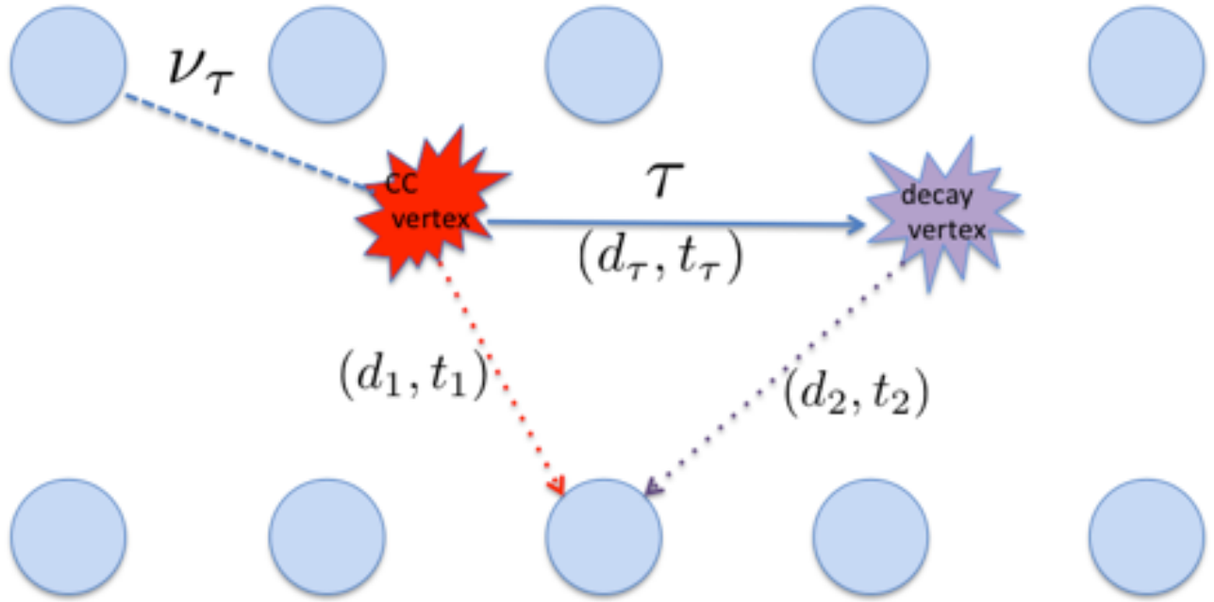
(3) Double Cascades: High-E ν_τ charged current





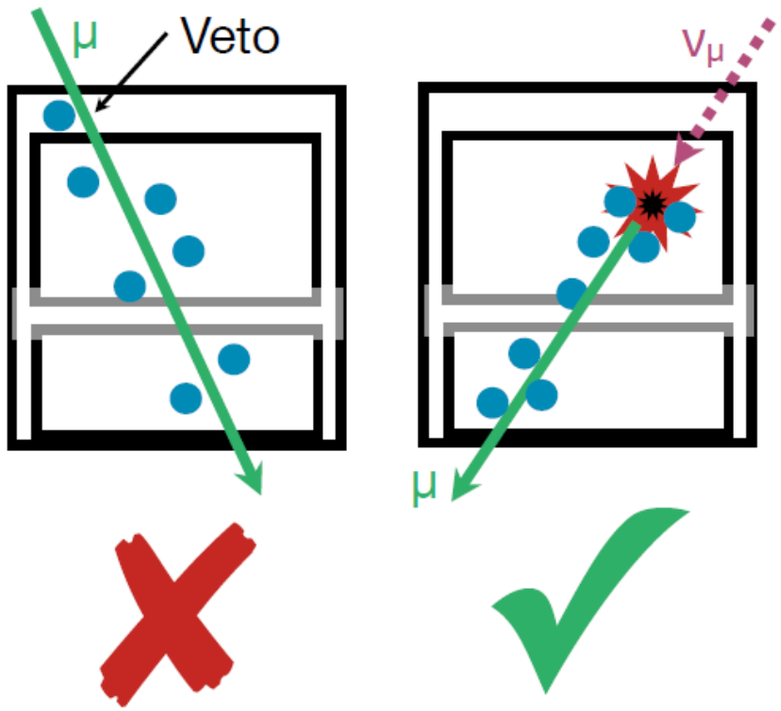
- **Tau decay length scales ~ 1PeV / 50m**
- **Not yet detected: active search ongoing**

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

$$\tau^- \rightarrow \nu_\tau + hadrons \quad (64.8\%)$$
$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^- \quad (17.8\%)$$
$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^- \quad (17.4\%)$$

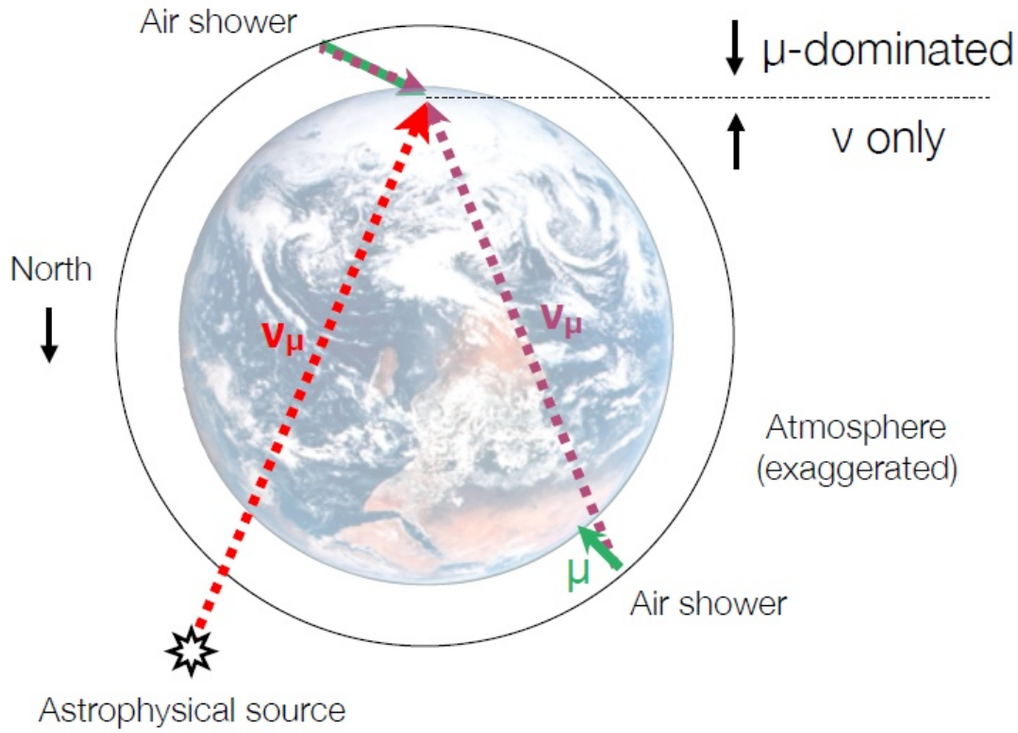
Diffuse Astrophysical Neutrinos: Detection Strategy

(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

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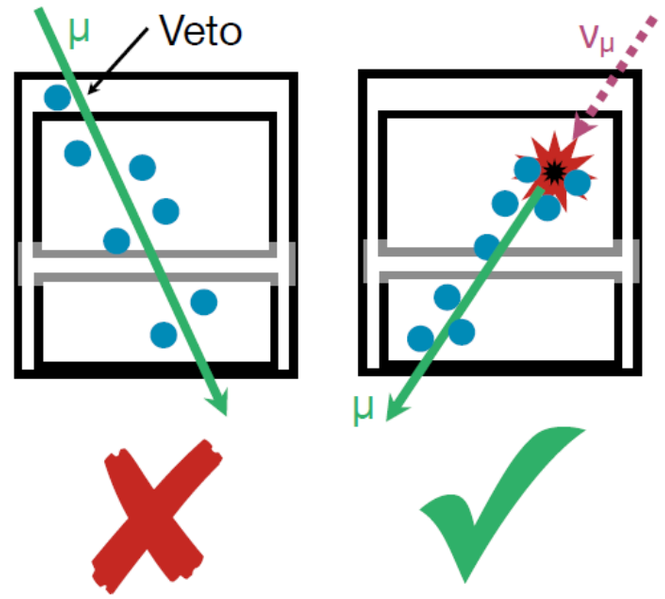
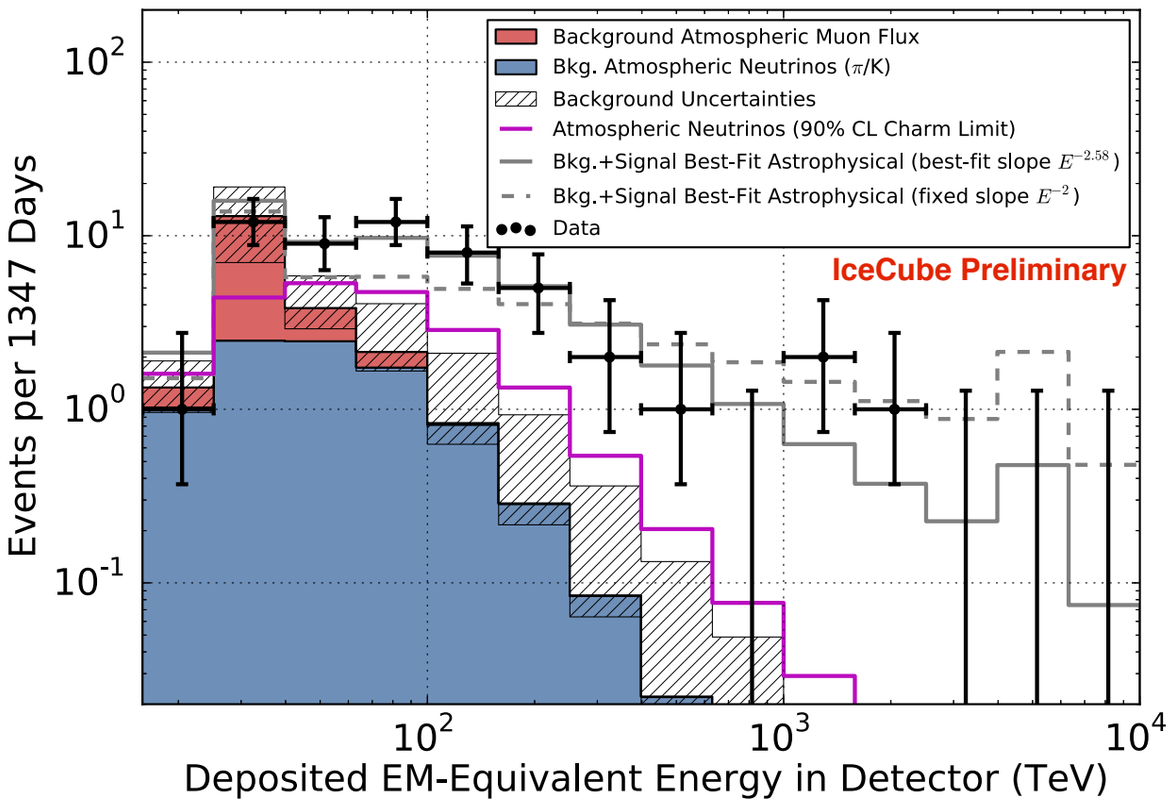
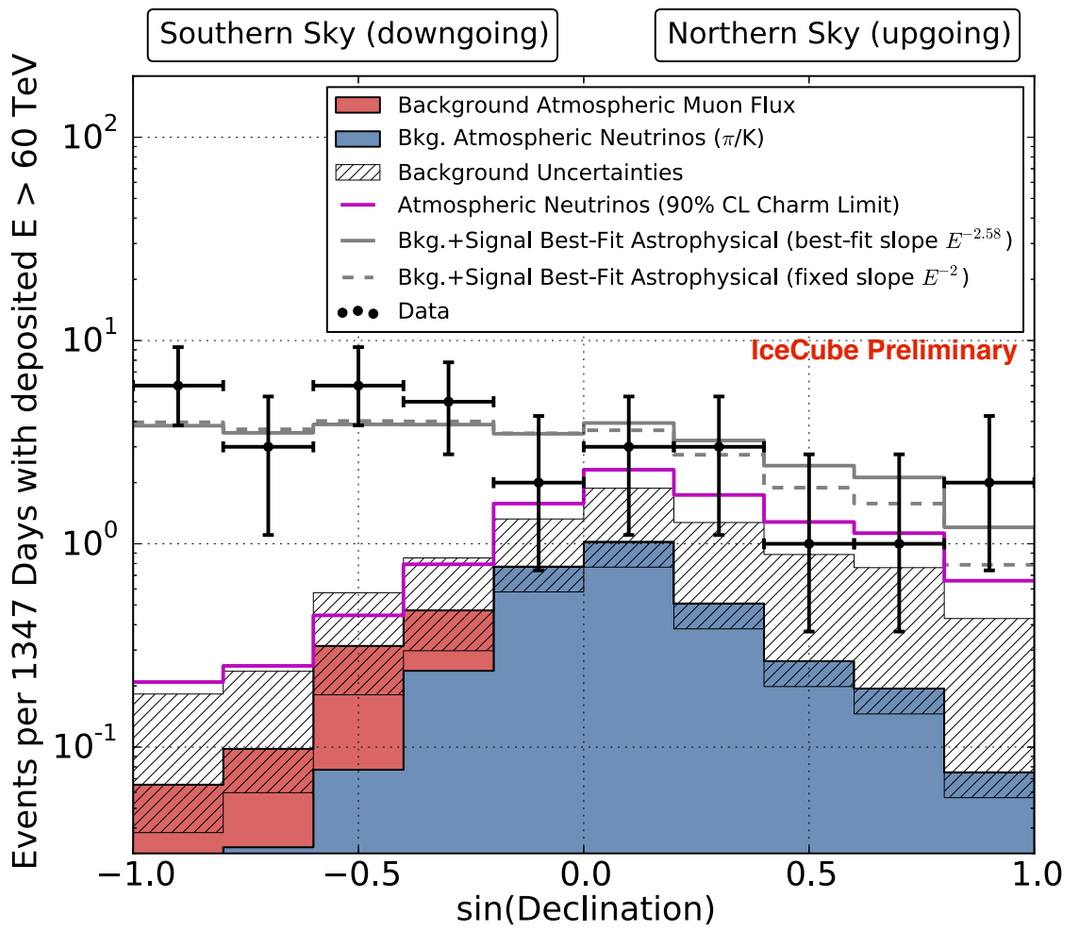
High Energy Starting Event Search



- **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)

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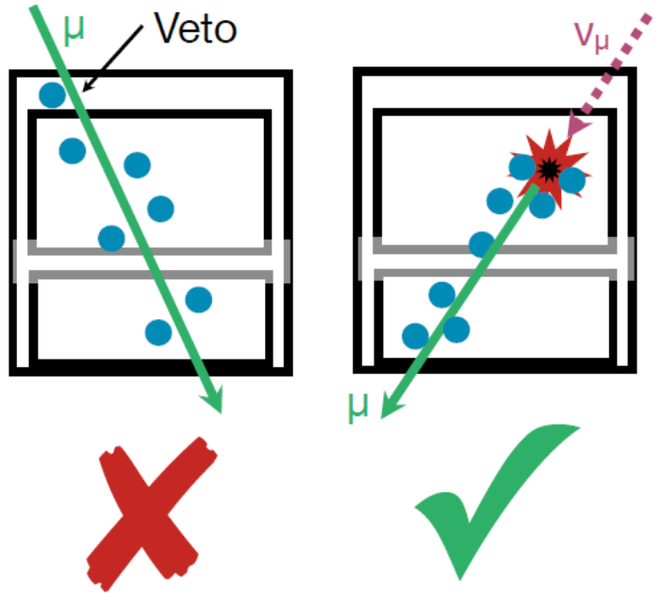
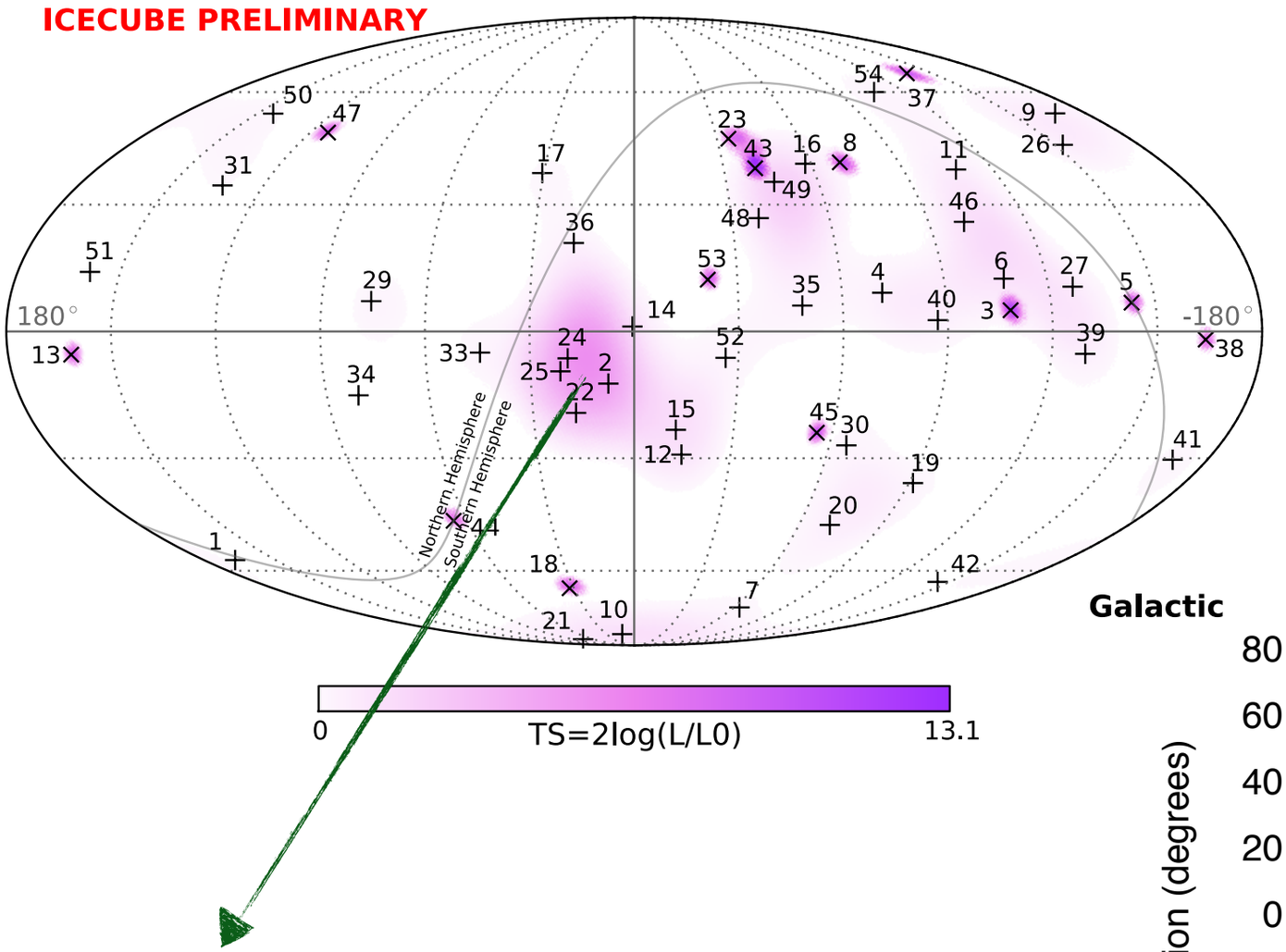
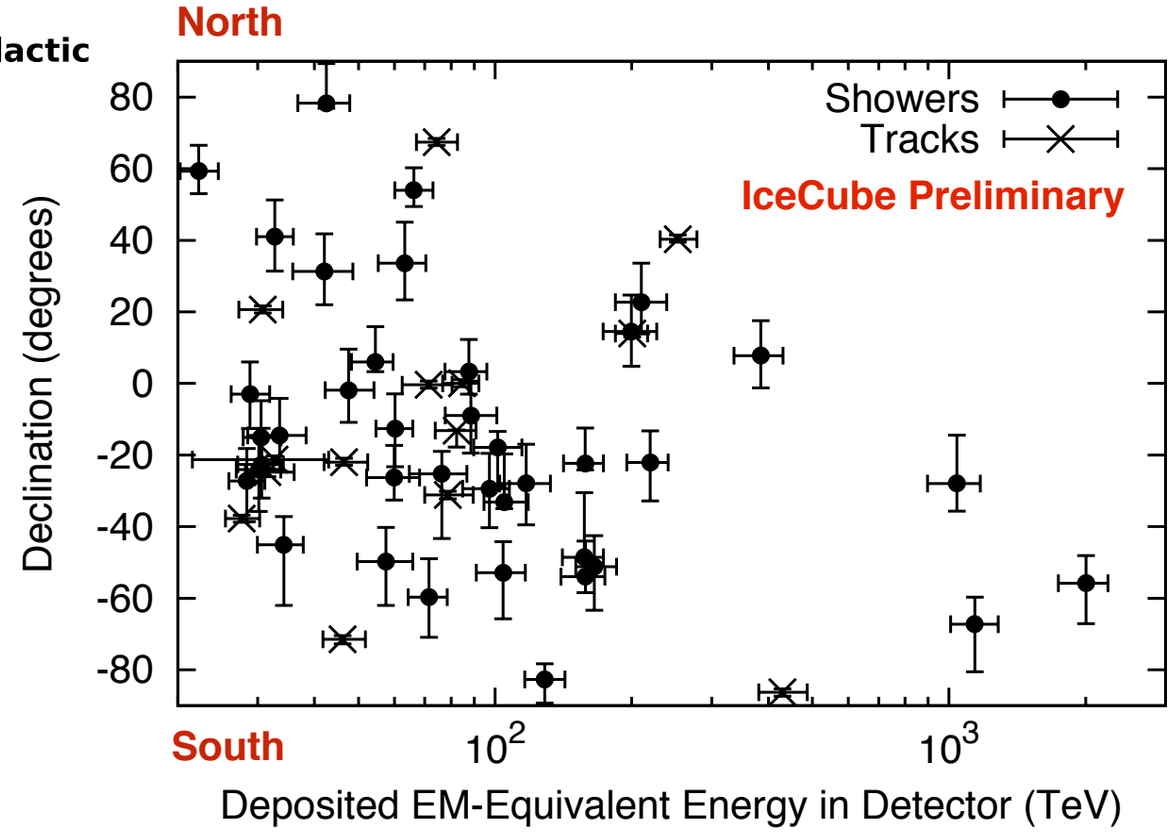
High Energy Starting Event Search





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)

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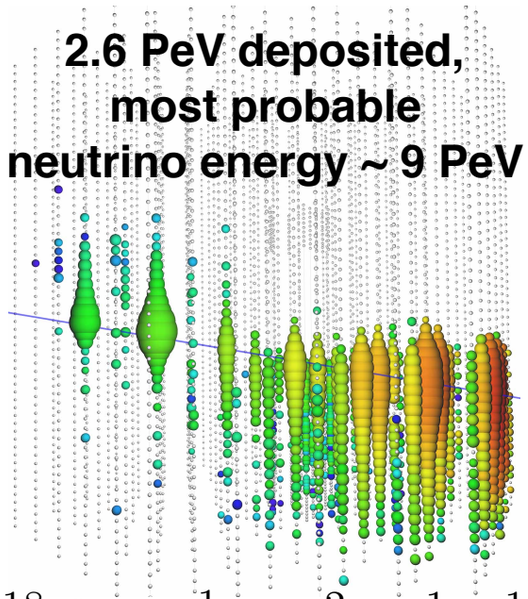
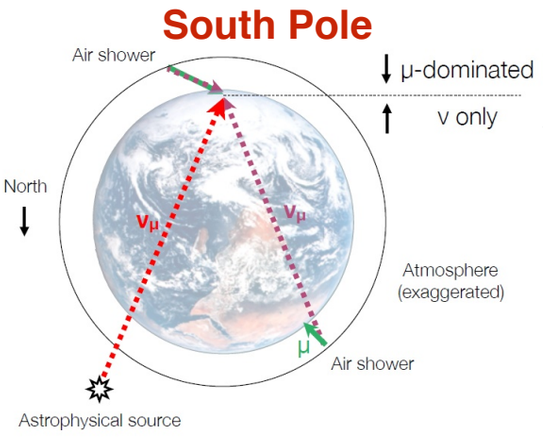
6 Year Through-going Tracks

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

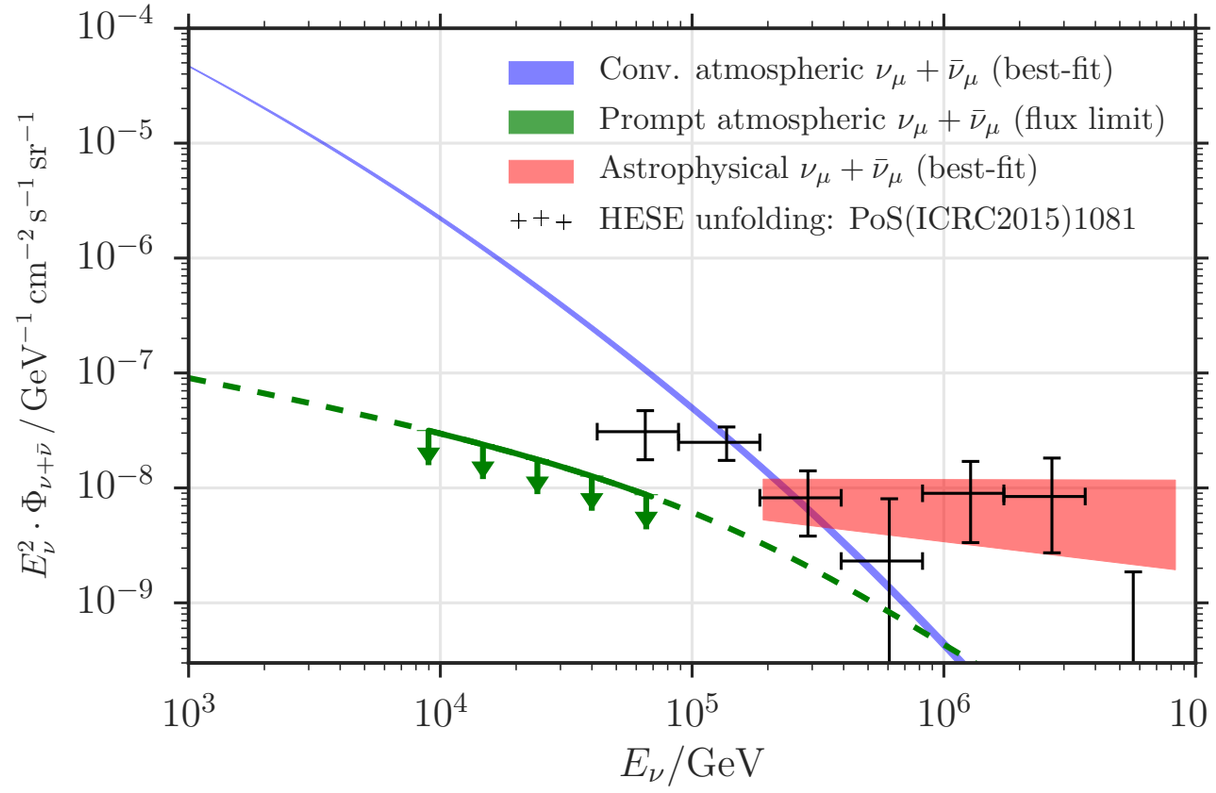
$$\Phi_{\nu+\bar{\nu}} = (0.90^{+0.30}_{-0.27}) \cdot \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-(2.13\pm0.13)} \cdot 10^{-18}\,\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

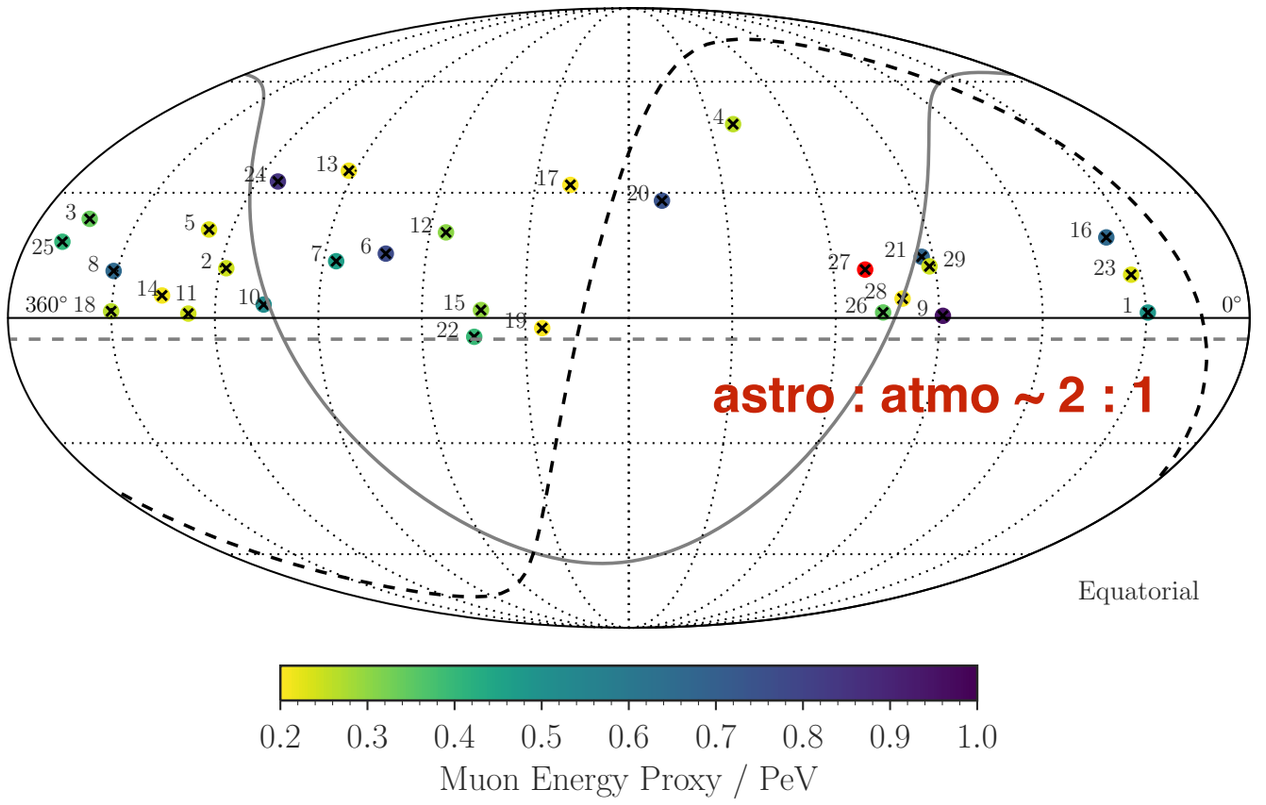




Using the Earth as a shield for cosmic-ray induced muons

29 events > 200 TeV





Phys. Rev. Lett. 115, 081102 (2 yr)
https://arxiv.org/abs/1607.08006 (6 yr)

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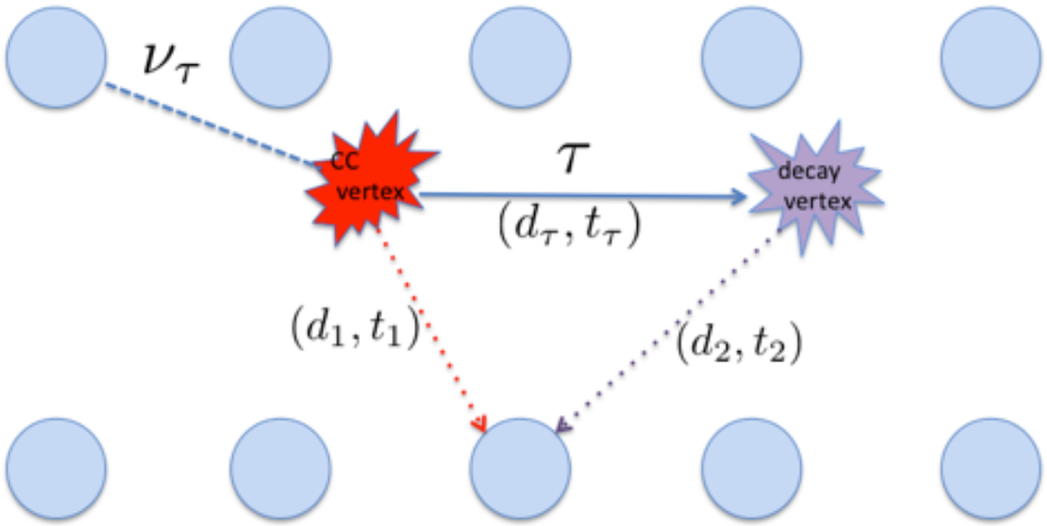
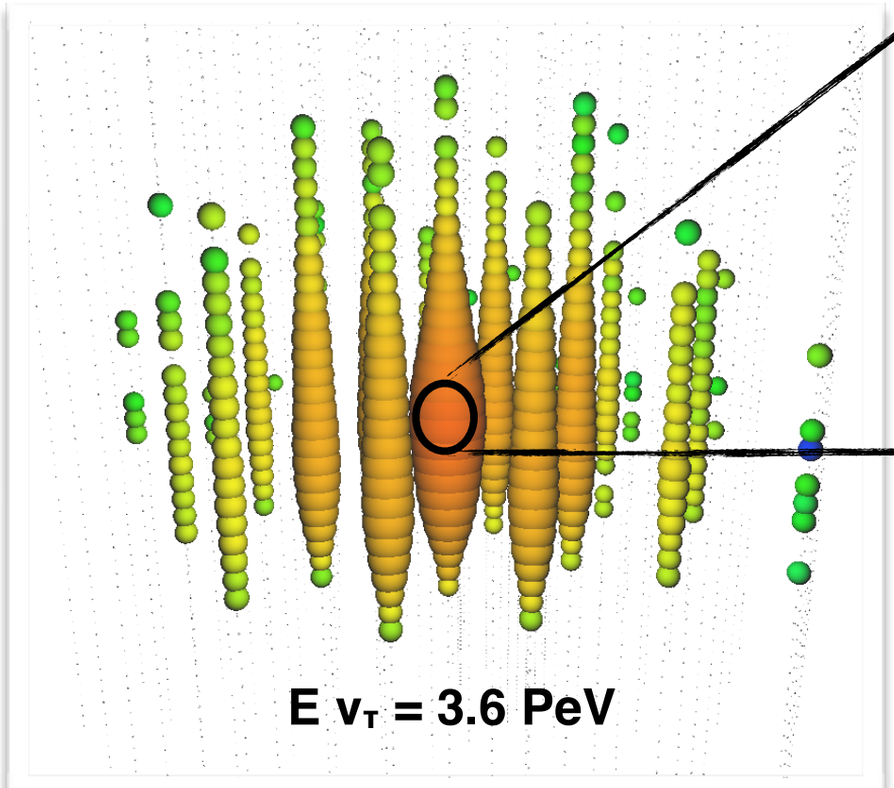
3 Year Astrophysical Tau Neutrino Double Cascades

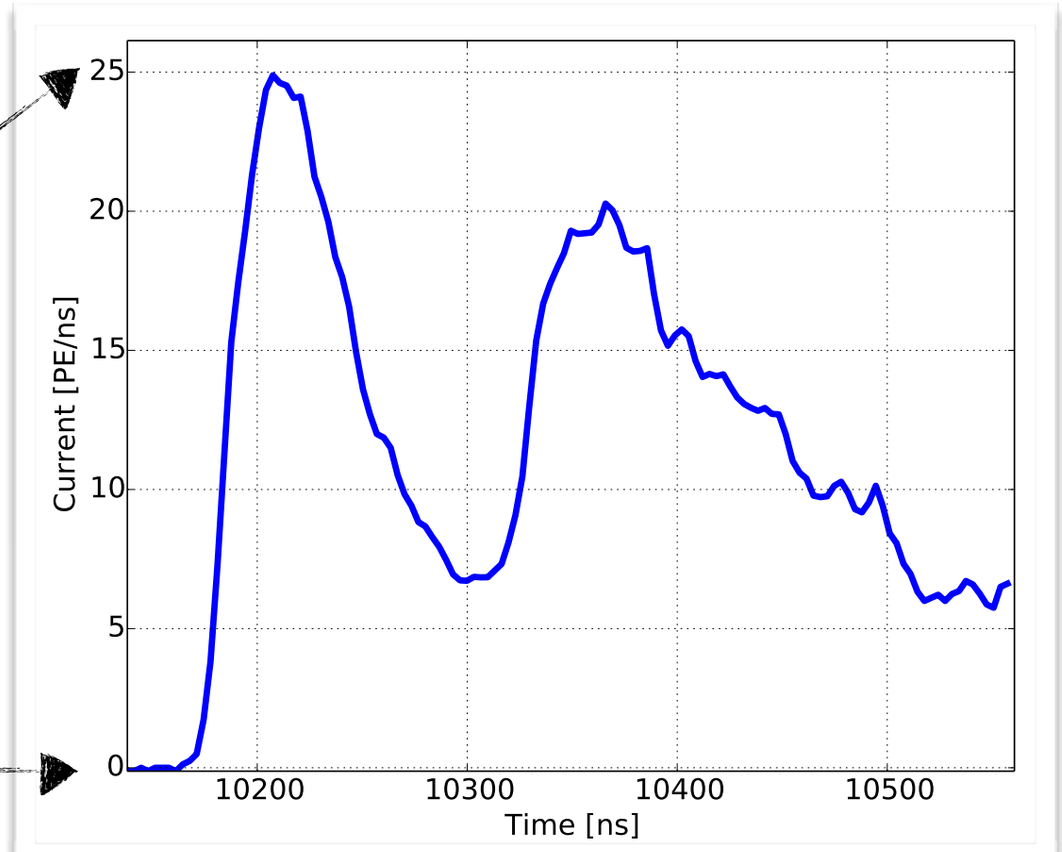
Schematic ν_τ CC interaction in IceCube



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

$$\tau^- \rightarrow \nu_\tau + hadrons \quad (64.8\%) \checkmark$$
$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_e + e^- \quad (17.8\%) \checkmark$$
$$\tau^- \rightarrow \nu_\tau + \bar{\nu}_\mu + \mu^- \quad (17.4\%)$$





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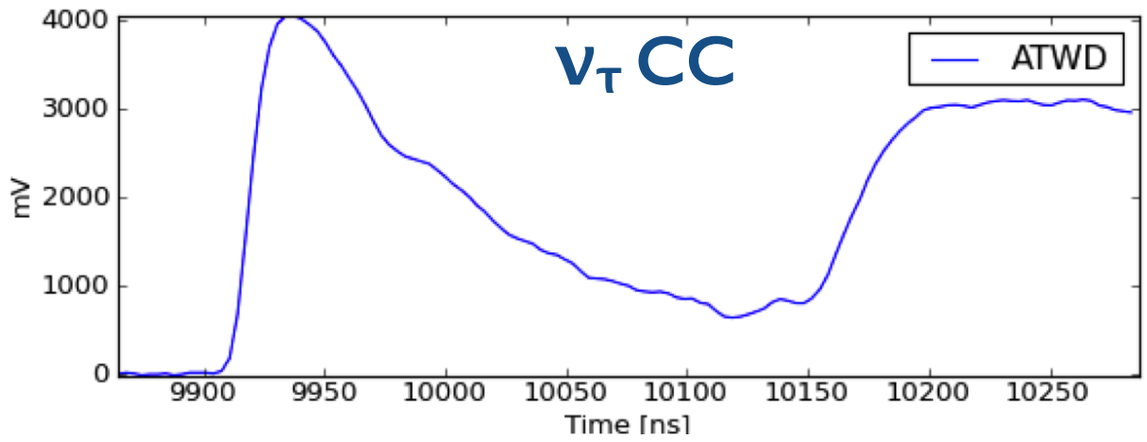
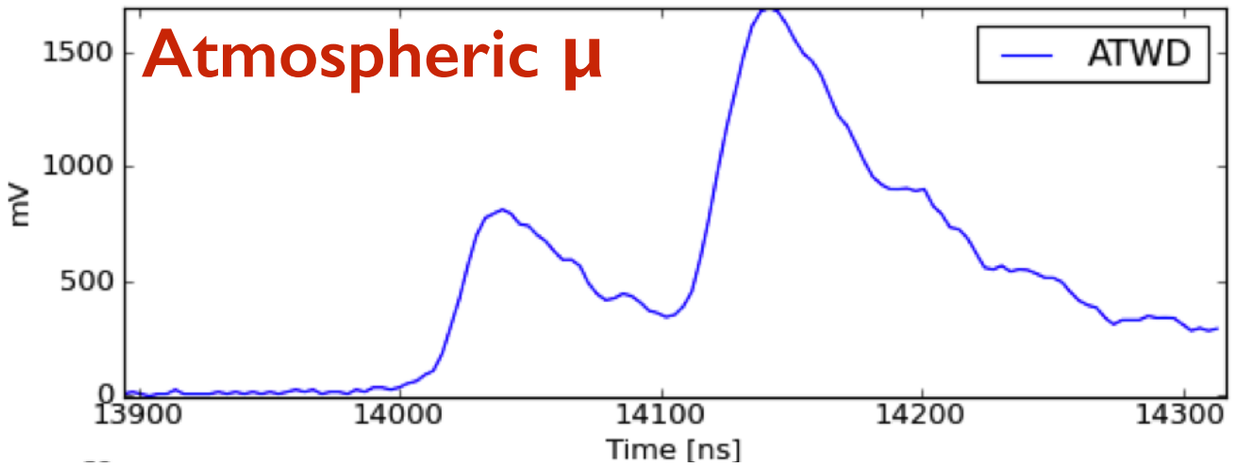
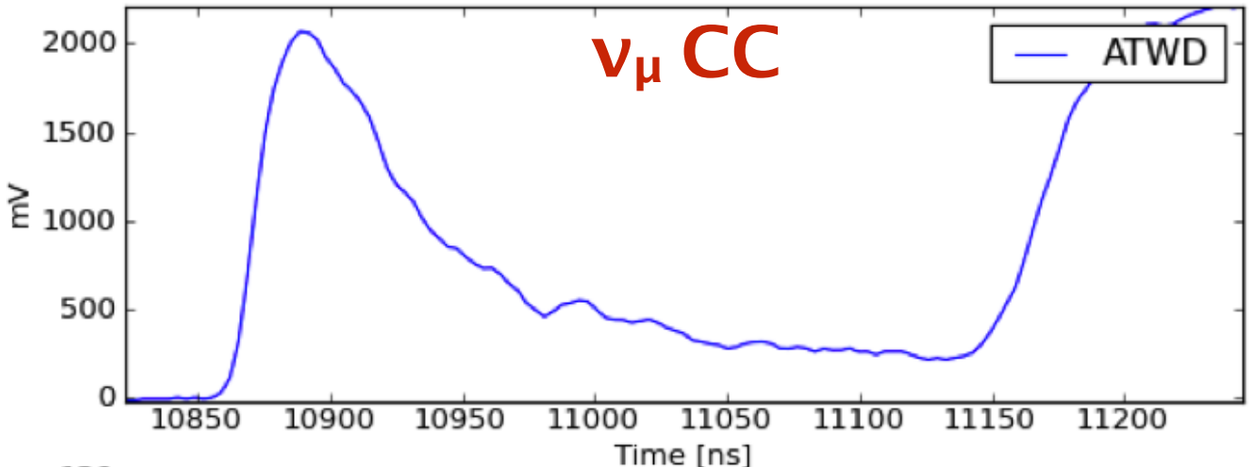
Identified Double Pulse Waveforms

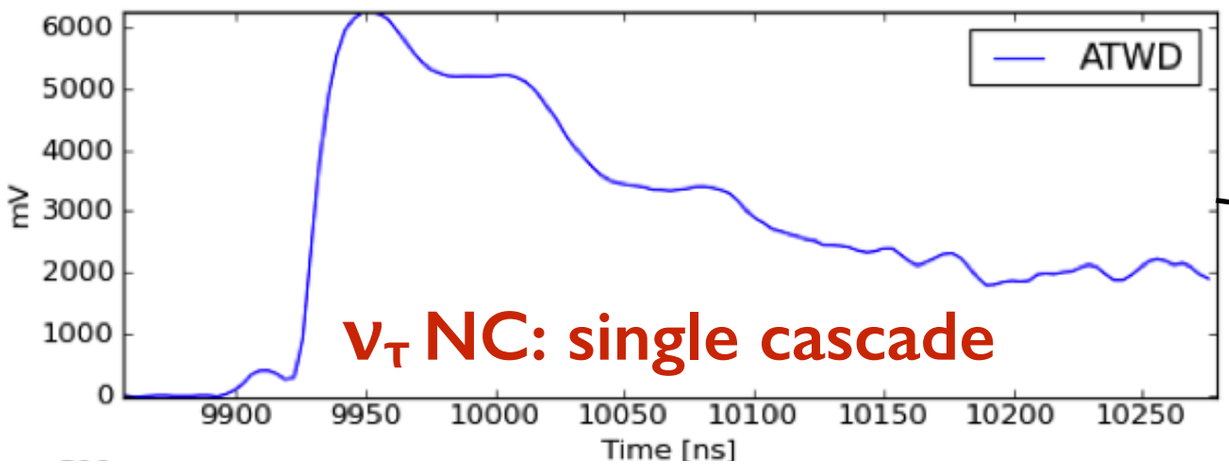
Signal:



Background:







Most important to reject at waveform level

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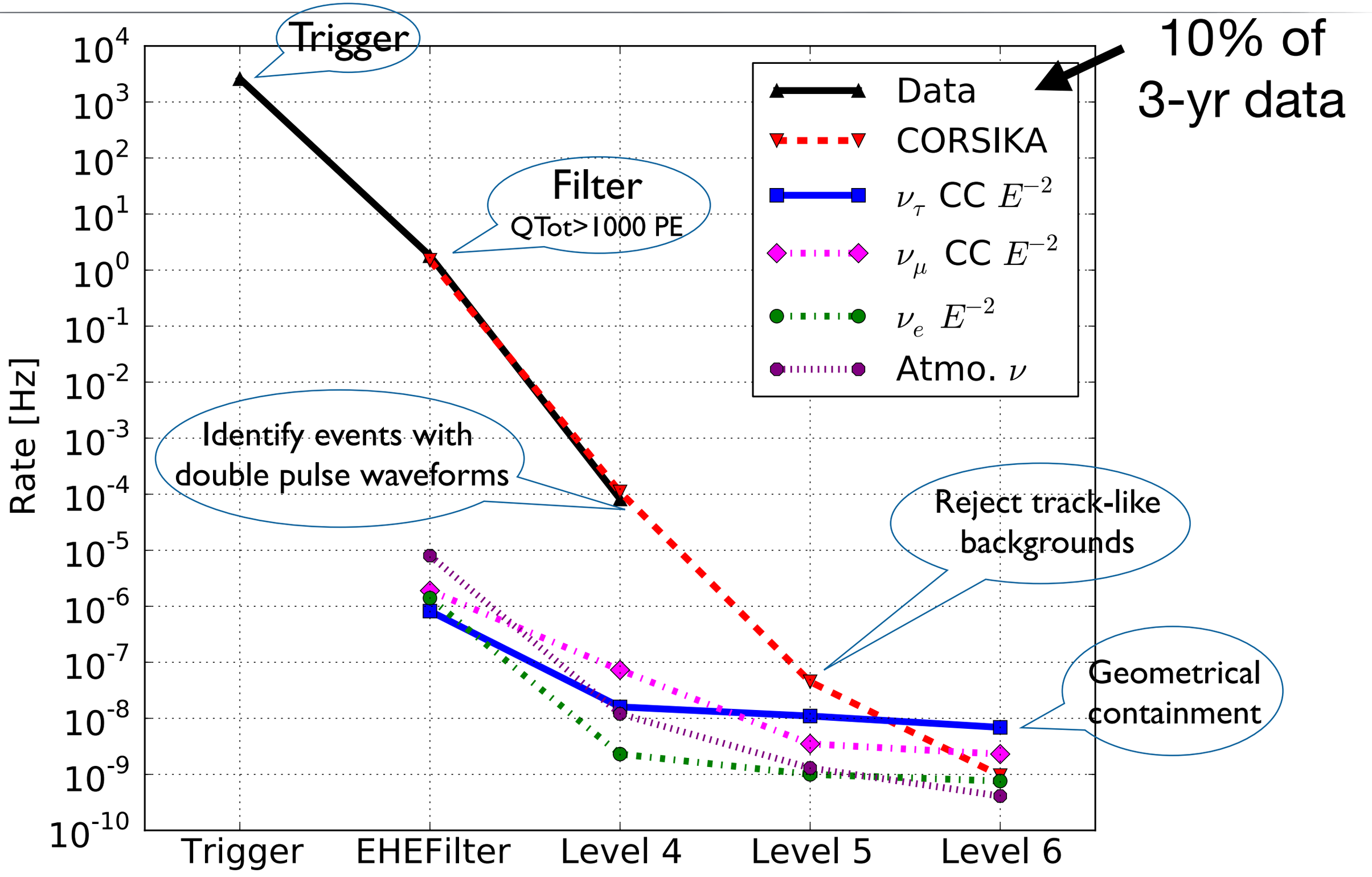
Event Selection and Cut Efficiency



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

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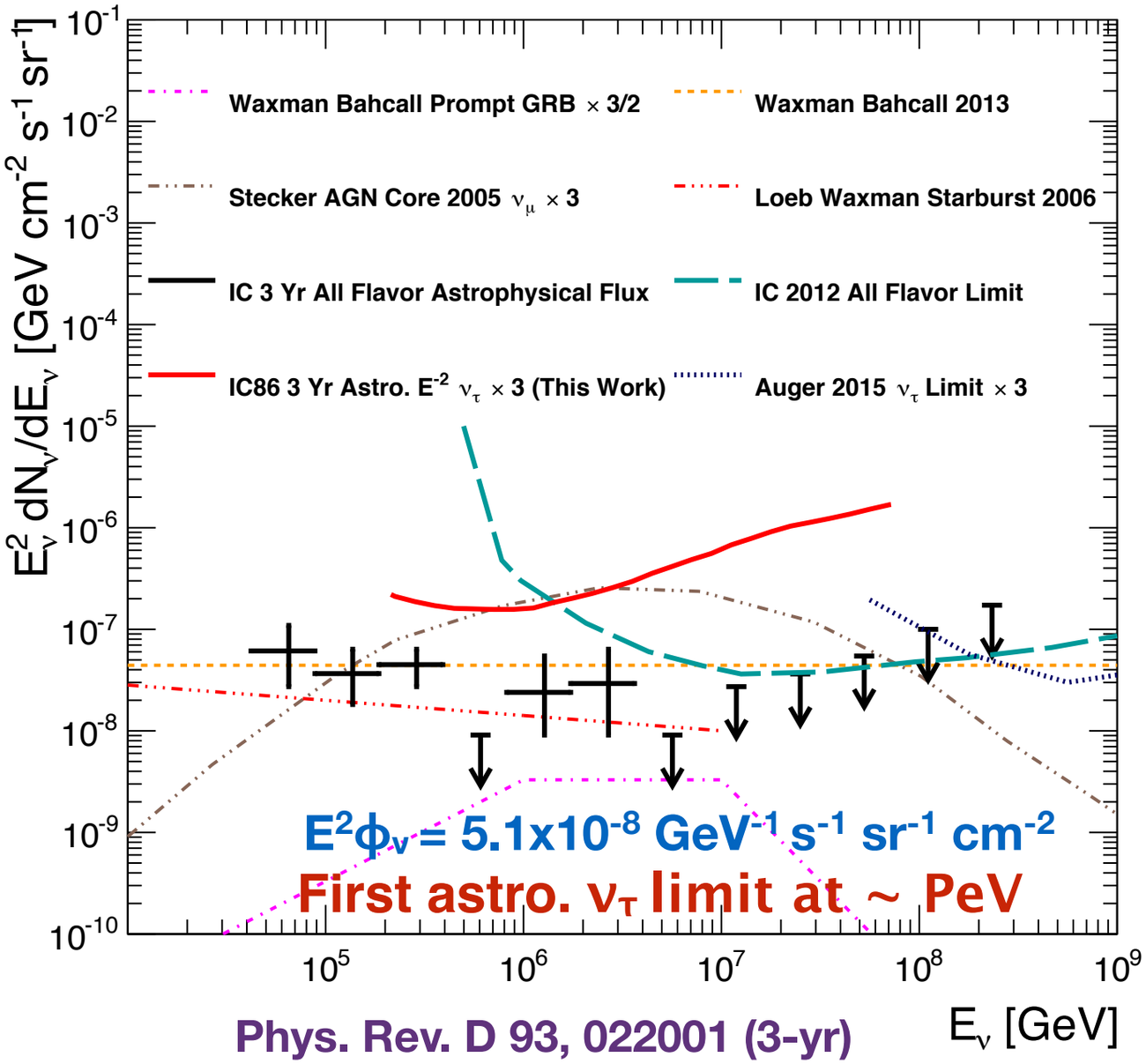
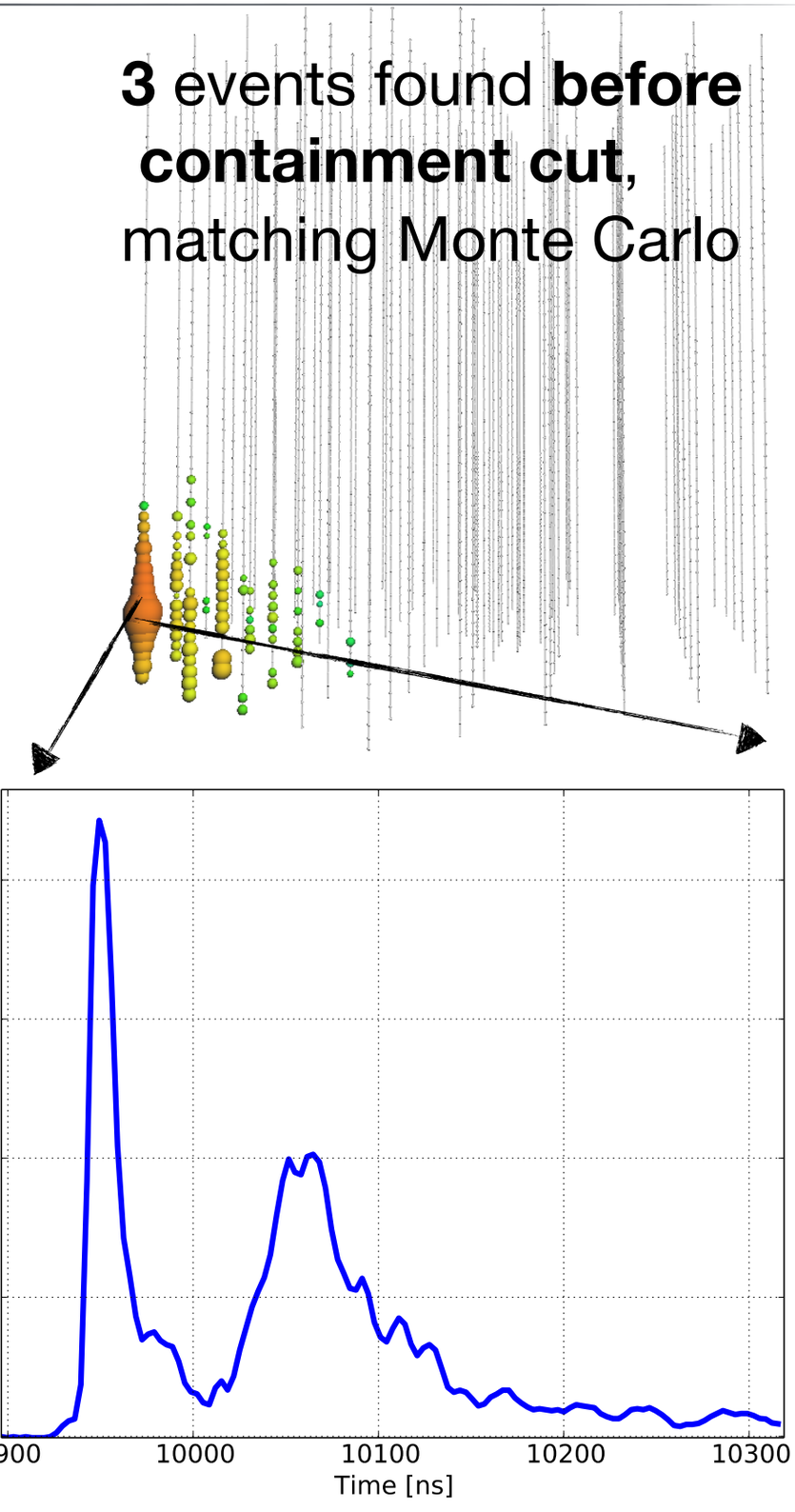
3 Year Astrophysical Tau Neutrino Search: Results

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



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

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



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Astrophysical Neutrino Flavor Composition

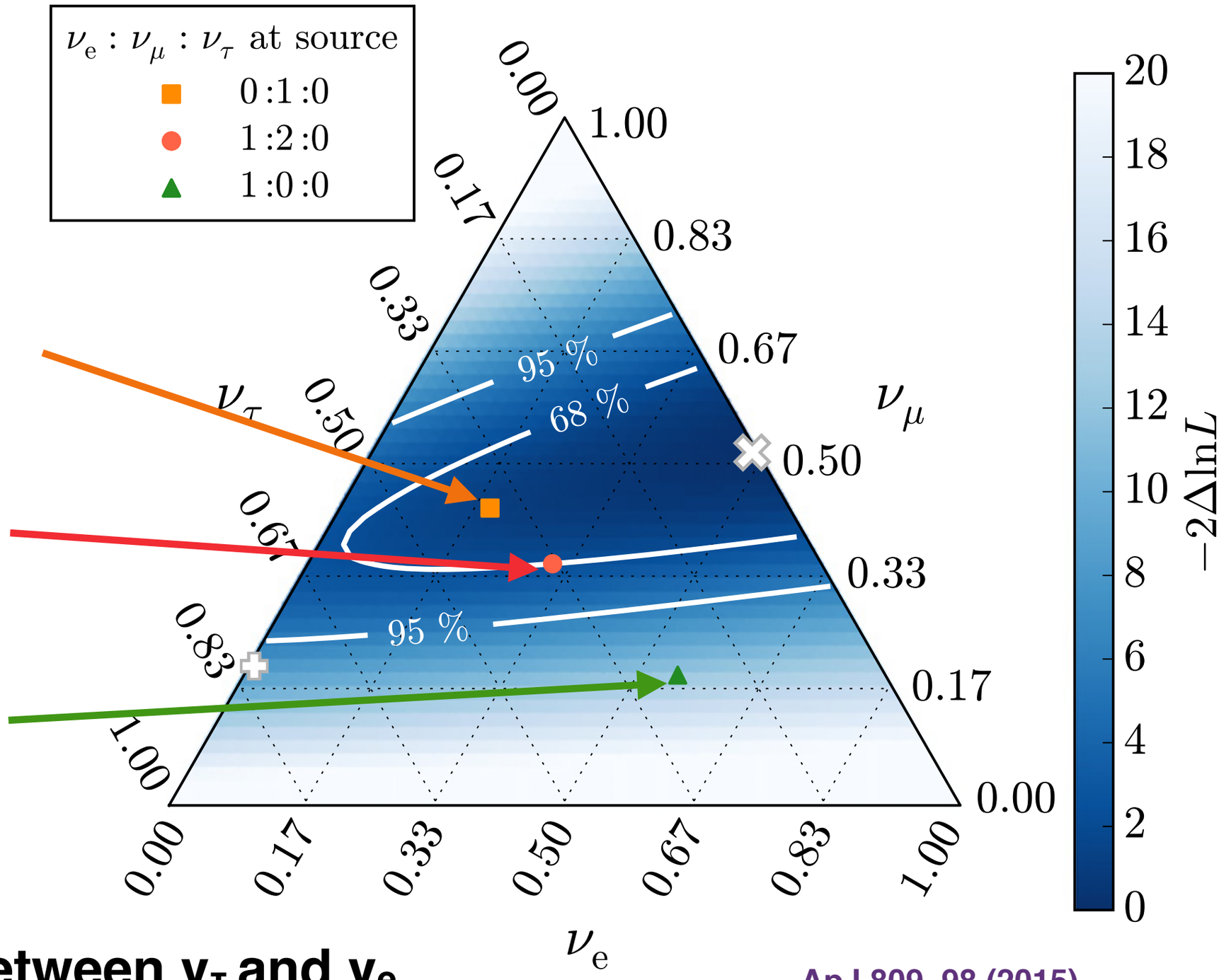
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

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

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

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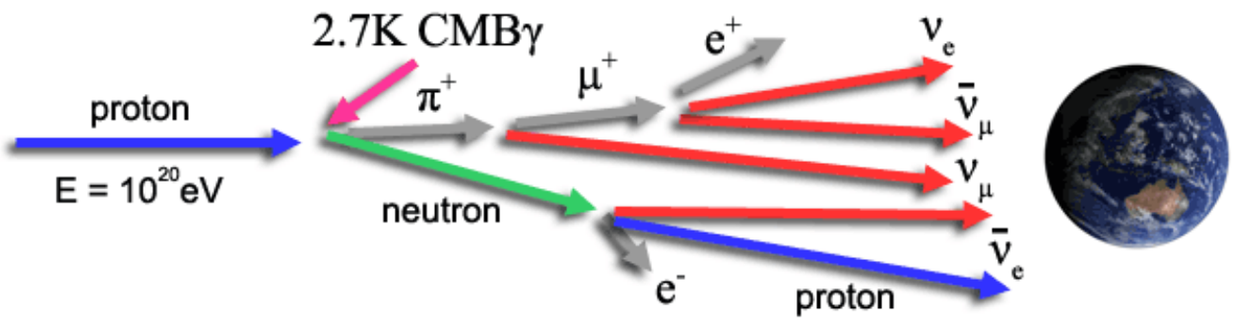
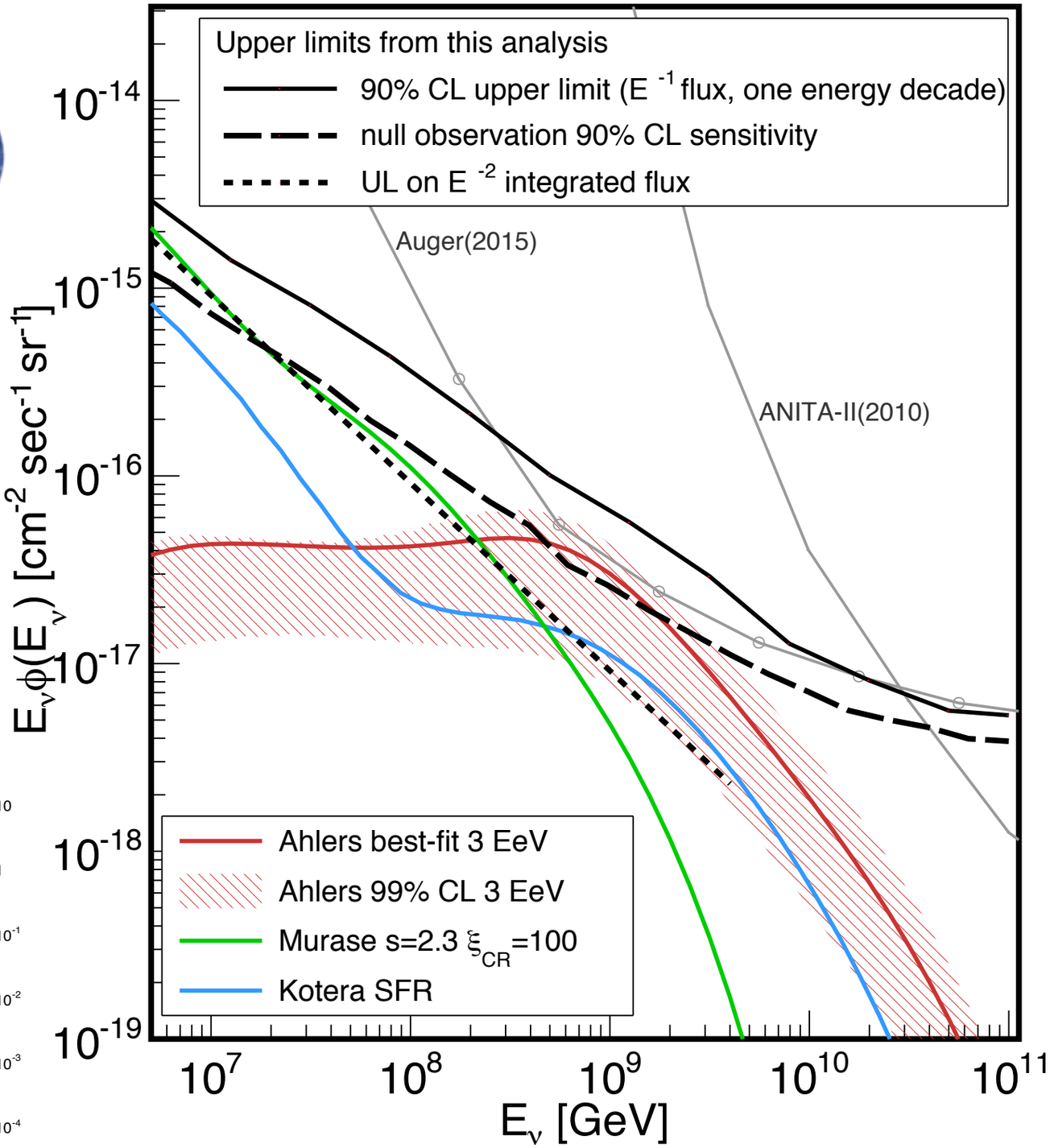
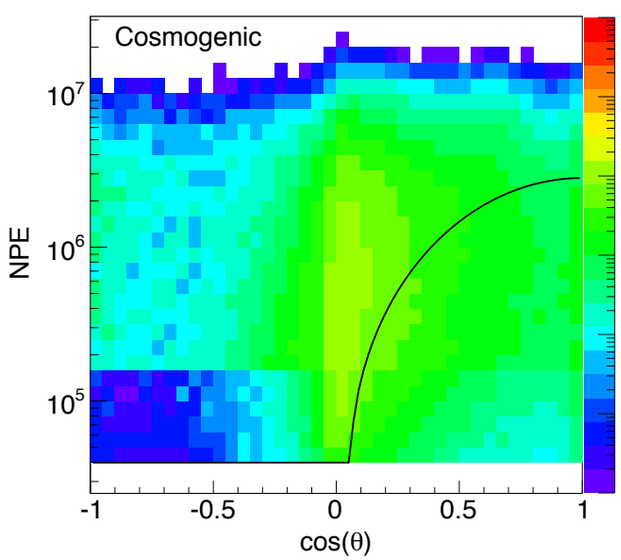
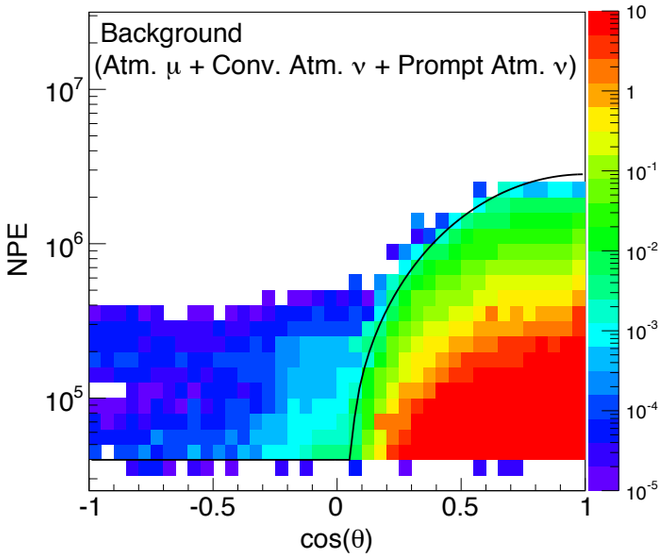
7-Year EHE Neutrinos Search



- **GZK neutrino searches > 10 PeV**
- **Null result —> constraints on GZK neutrino models**







https://arxiv.org/pdf/1607.05886v1.pdf
(submitted to PRL)

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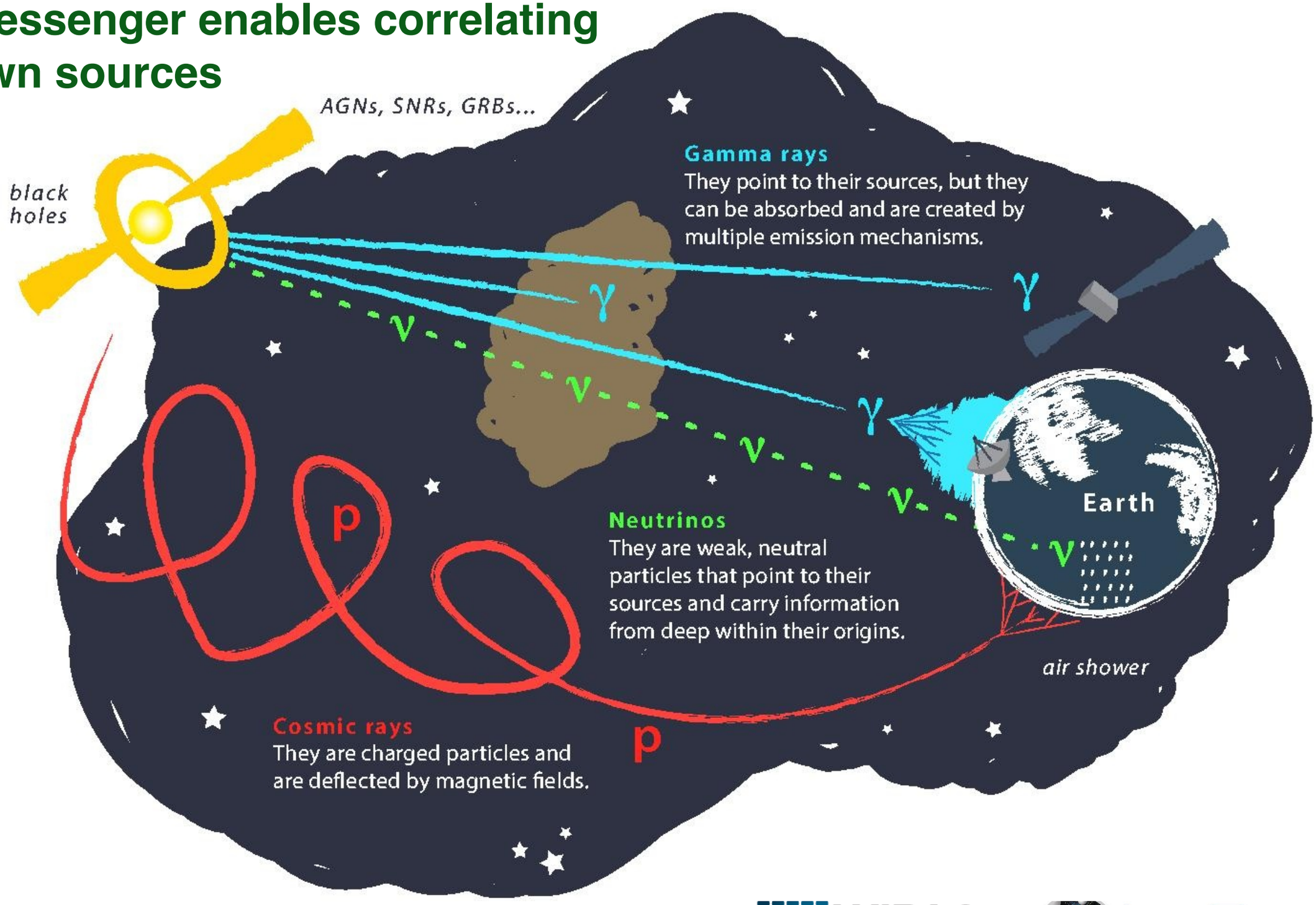
Where Do They Come From?

Source identification requires good angular resolution

Multi-messenger enables correlating to known sources



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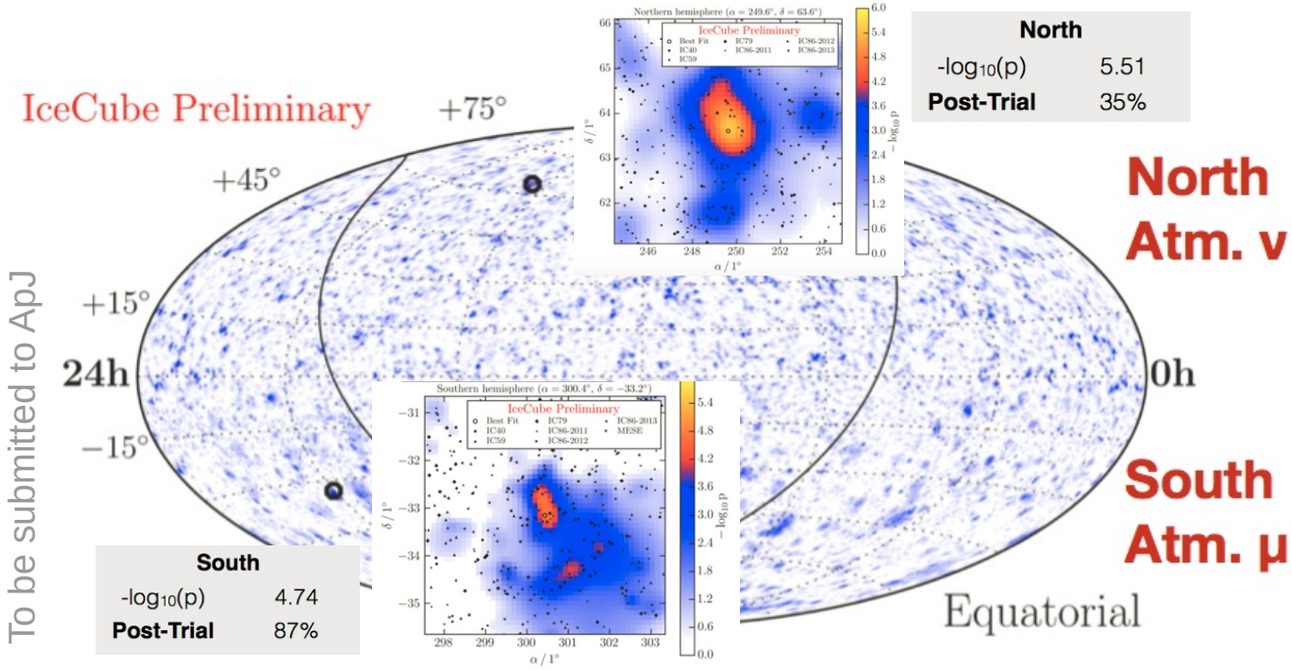
Where Do They Come From?

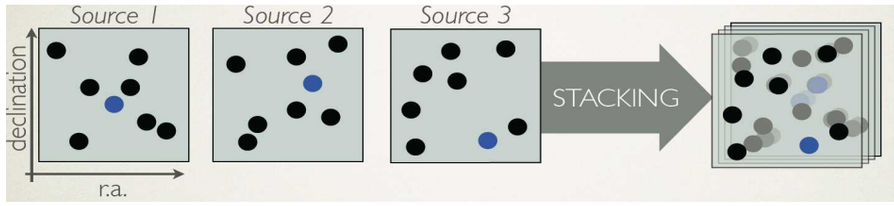
7 Year Point Source Search



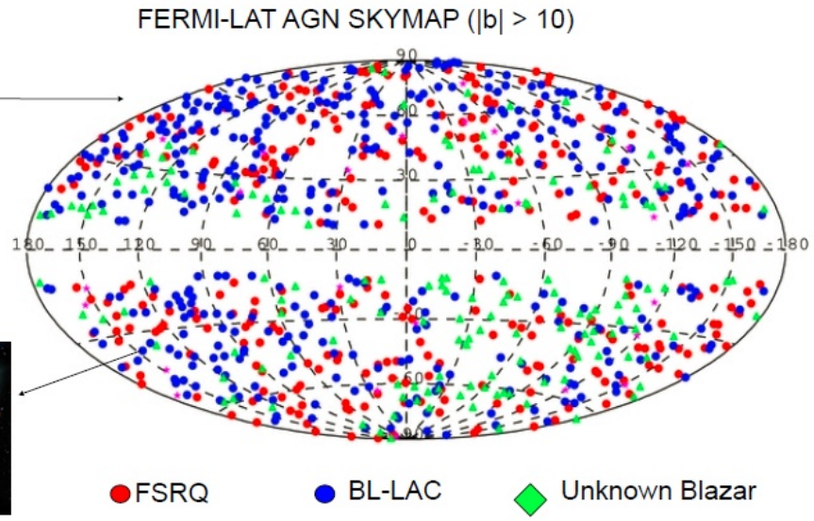
North	
-log10(p)	5.51
Post-Trial	35%

South	
-log10(p)	4.74
Post-Trial	87%

Blazars Stacking



Total sources: ~ 900



- All sky & with catalog
- Time-integrated unbinned search for hot spots

- Correlate astro. neutrinos with 862 known GeV-Blazars
- No significance (1.6σ)

So, no TeV neutrino sources yet

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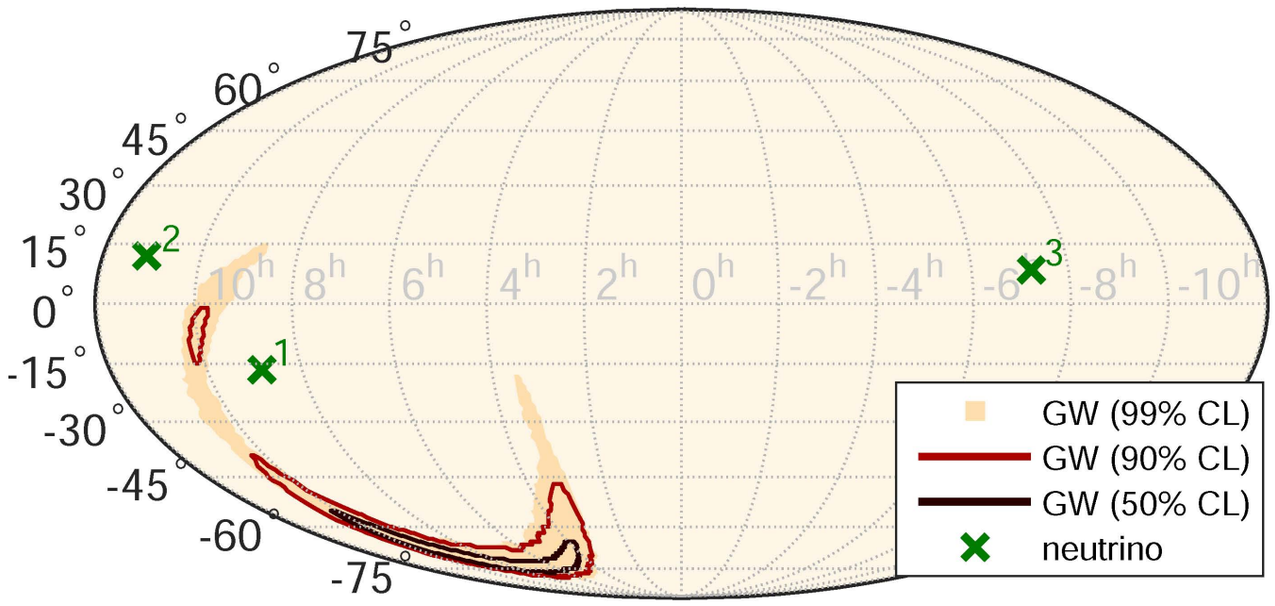
Multi-messenger Correlation with non-EM Partners

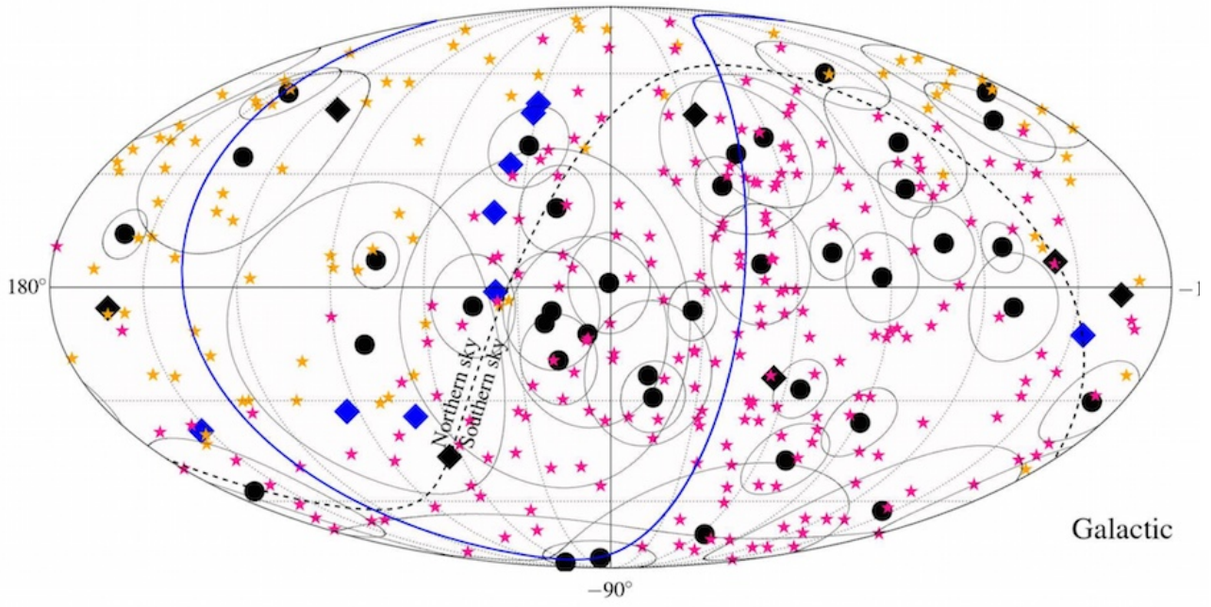
Gravitational Waves



- **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

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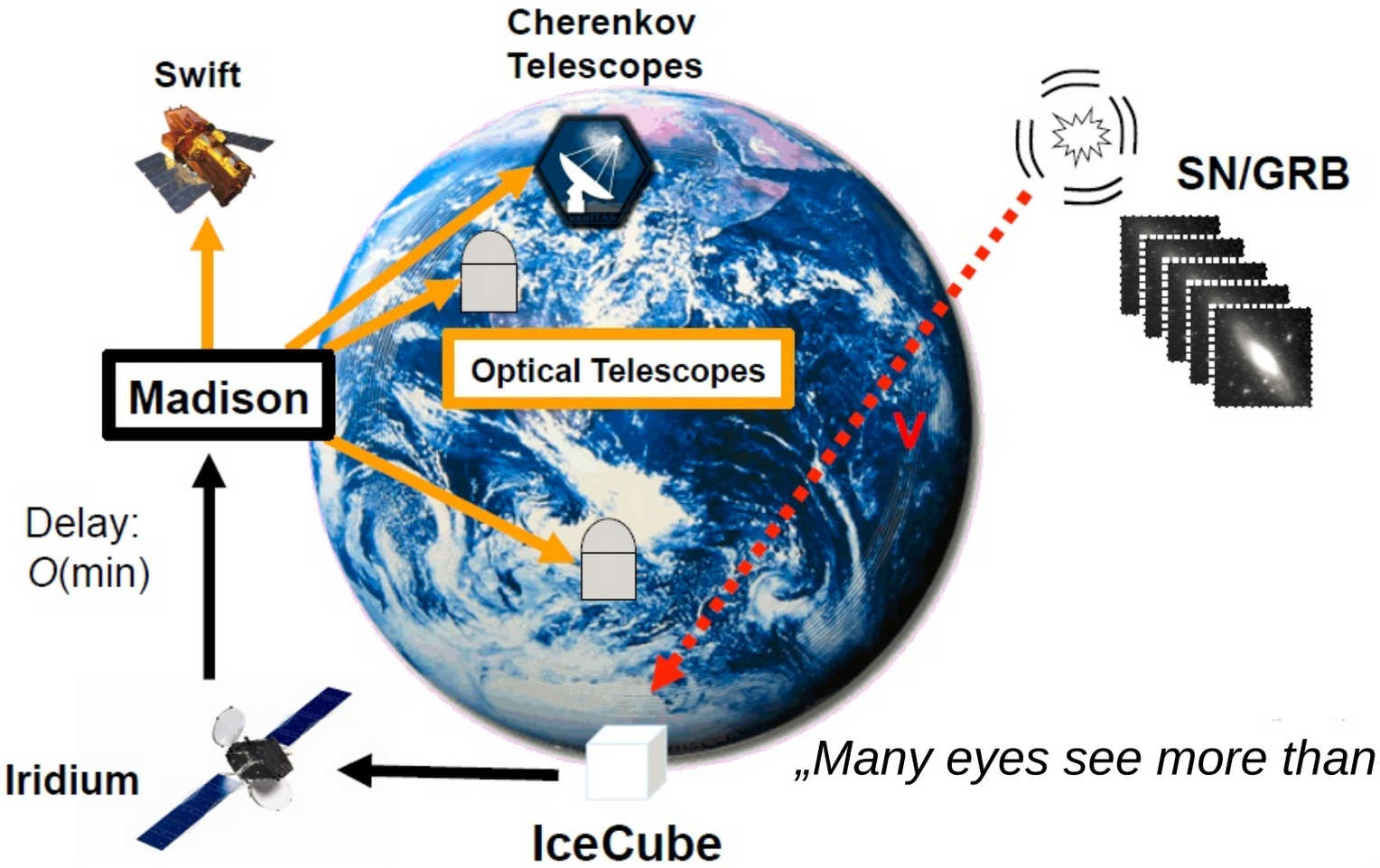
Realtime Alert Systems

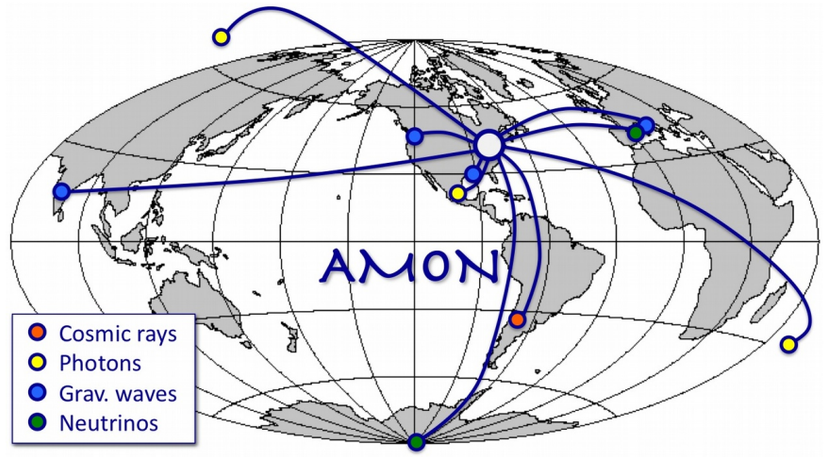
Correlating to other observatories:

- **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 Astronomer's Telegram

The Gamma-ray Coordinates Network

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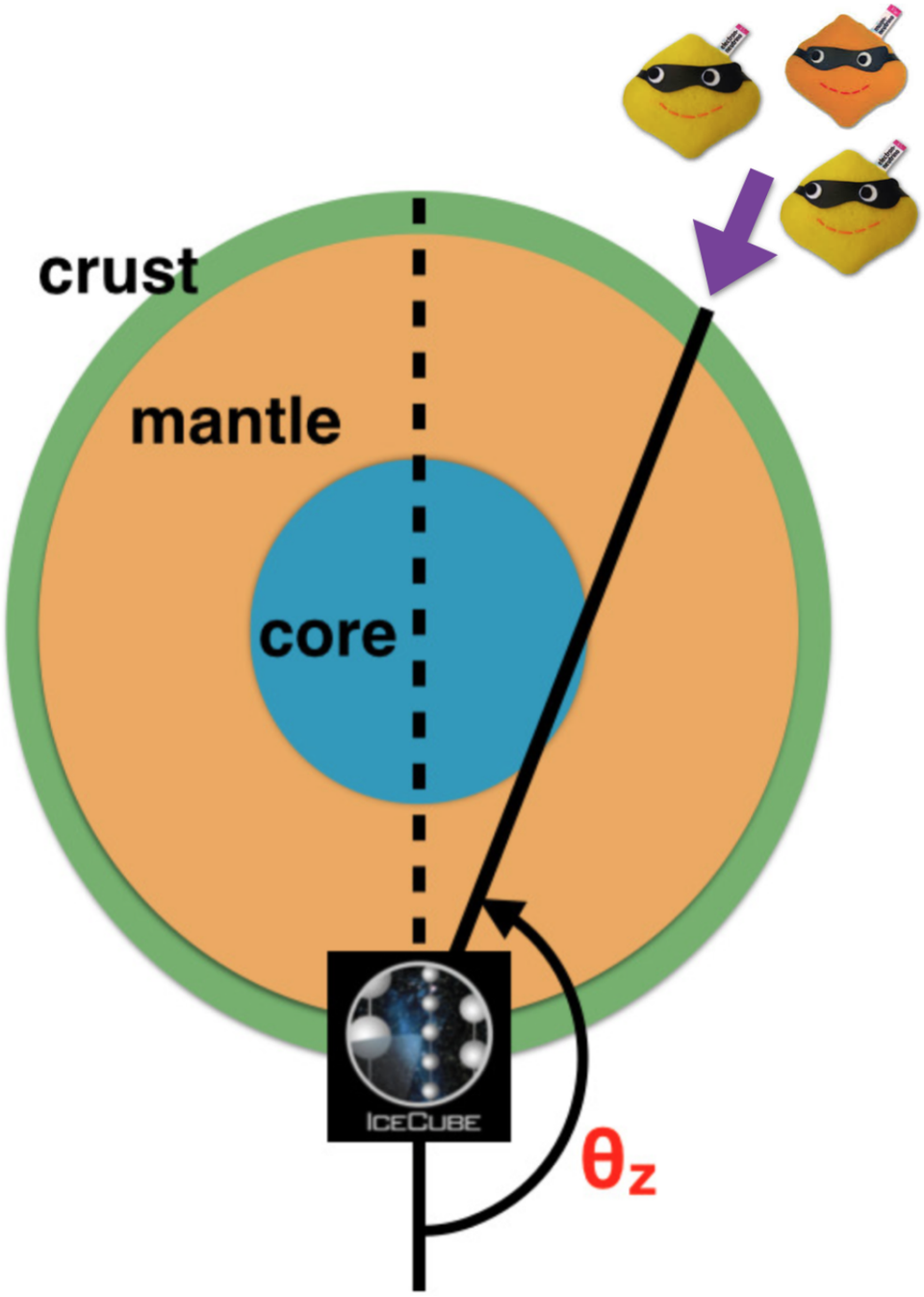
Neutrino Oscillations through the Earth

The neutrinos come from different zenith angles (θ_z) traversing different layers of the Earth



core :

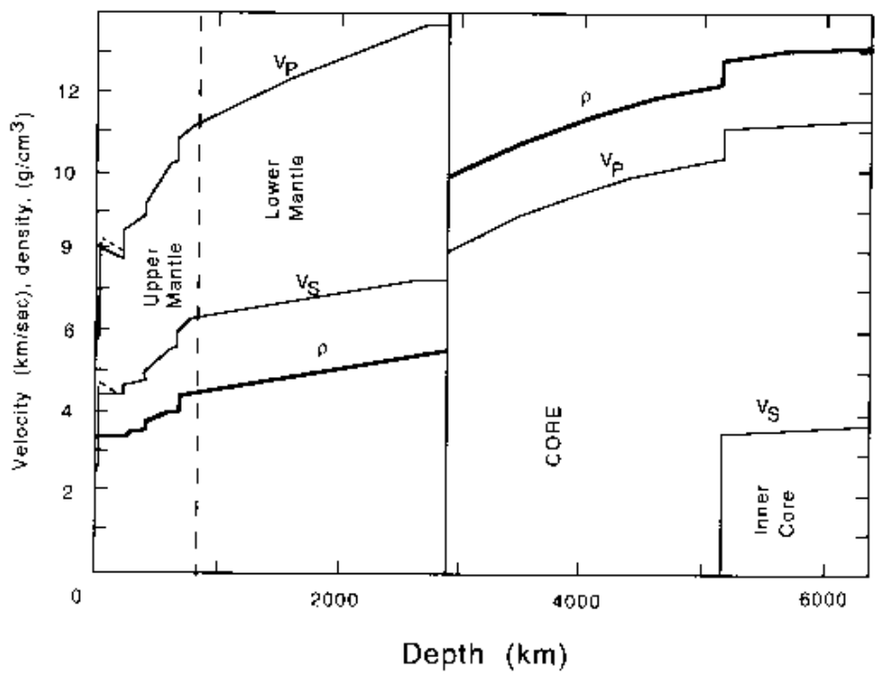
$\cos\theta_z \sim [-1, -0.8]$

mantle :

$\cos\theta_z \sim [-0.8, -0.1]$

crust :

$\cos\theta_z > -0.1$



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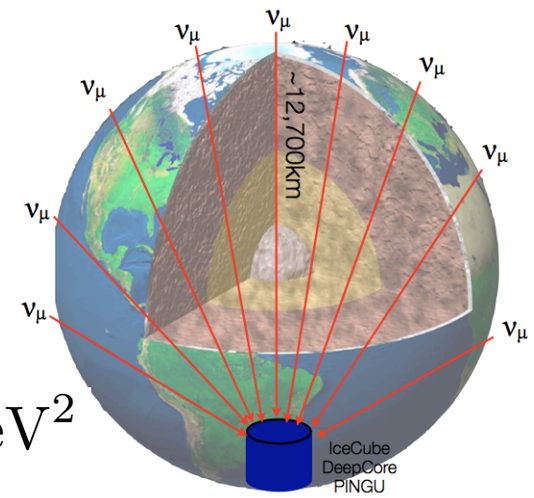
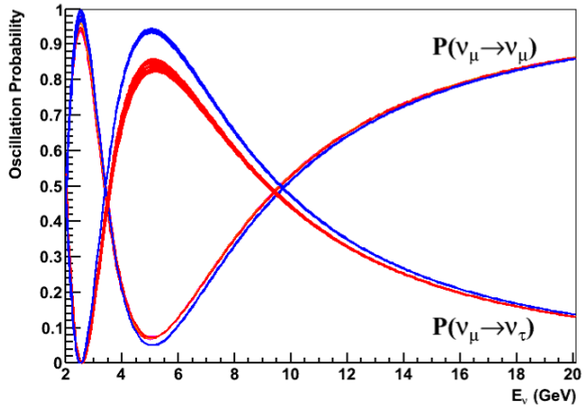
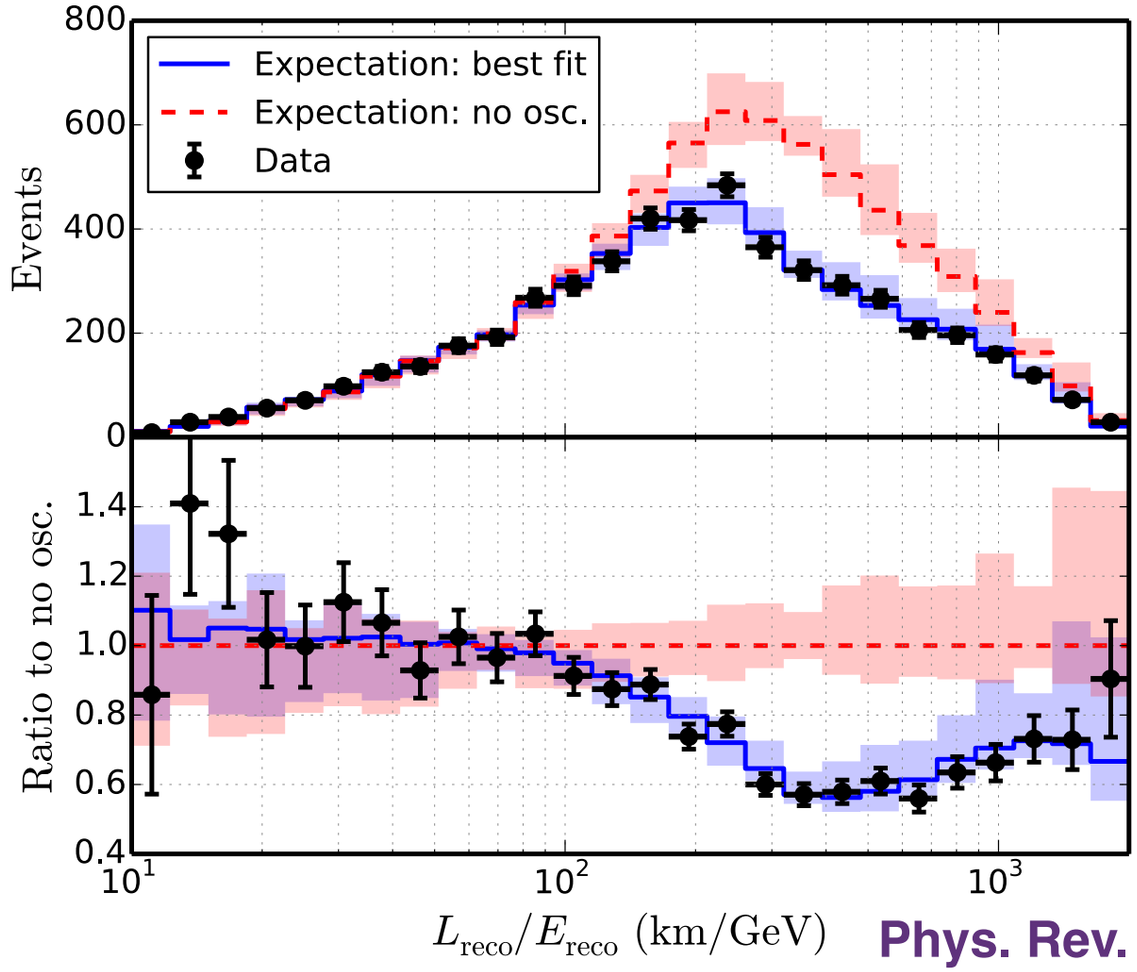
Atmospheric Muon Neutrino Disappearance

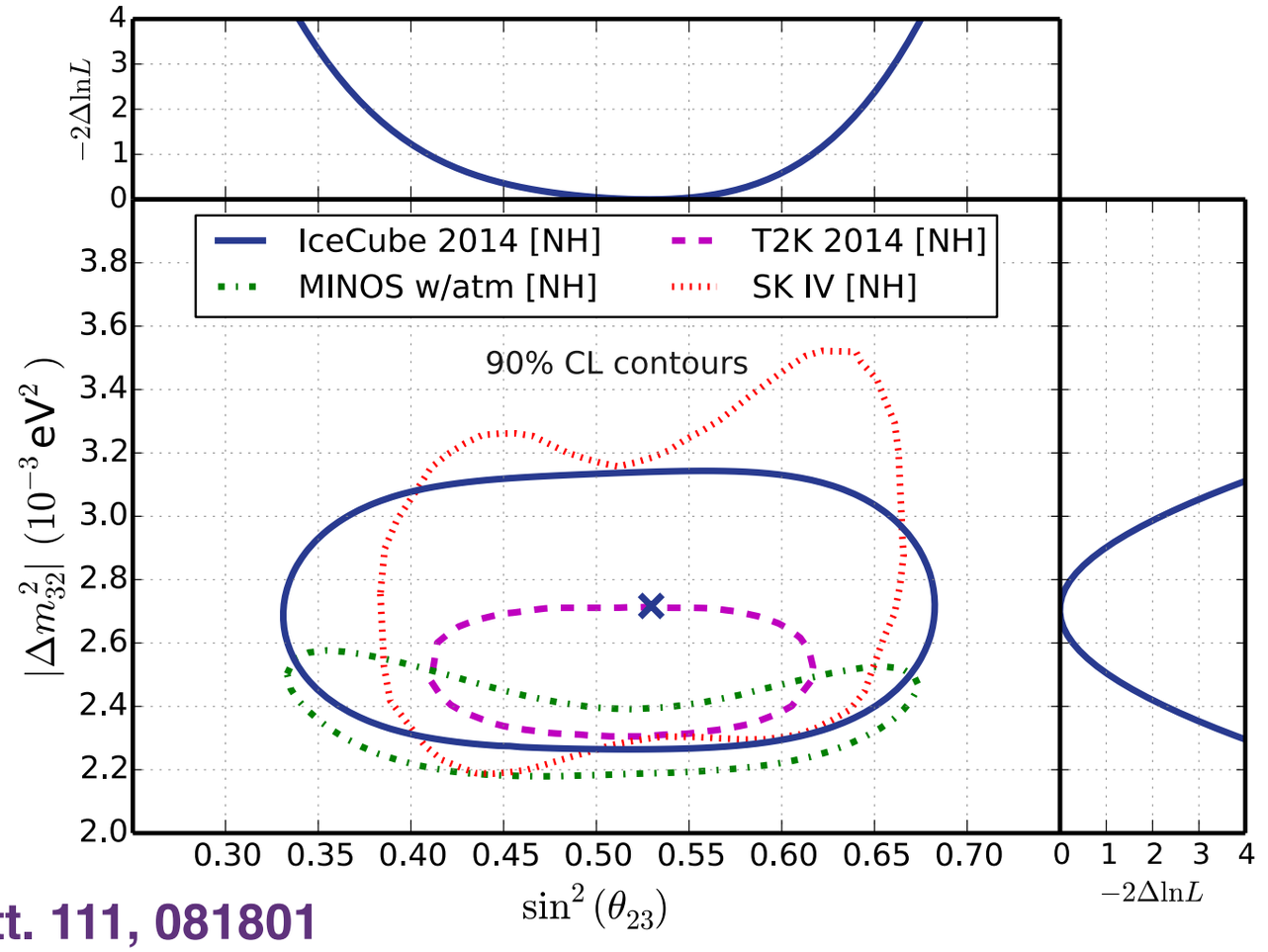
- **5293 high quality events in 953 days**
- **10 - 100 GeV (DeepCore)**
- **Best fit oscillation parameters:**

$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$ and $|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\mathrm{eV}^2$









Phys. Rev. Lett. 111, 081801
Phys. Rev. D 91, 072004

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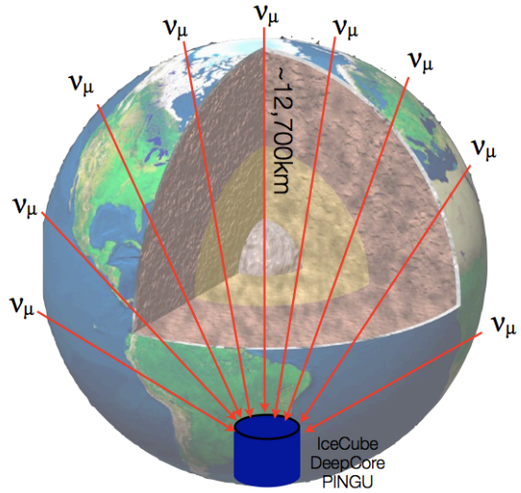
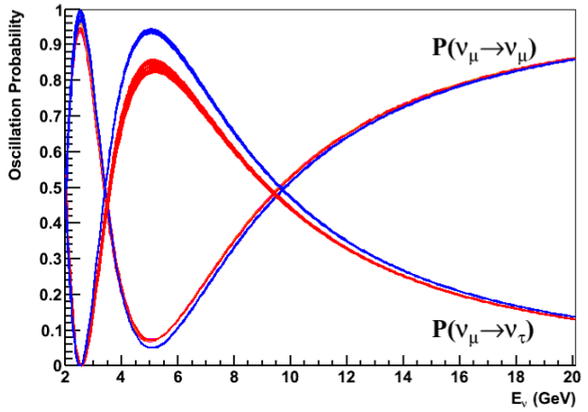
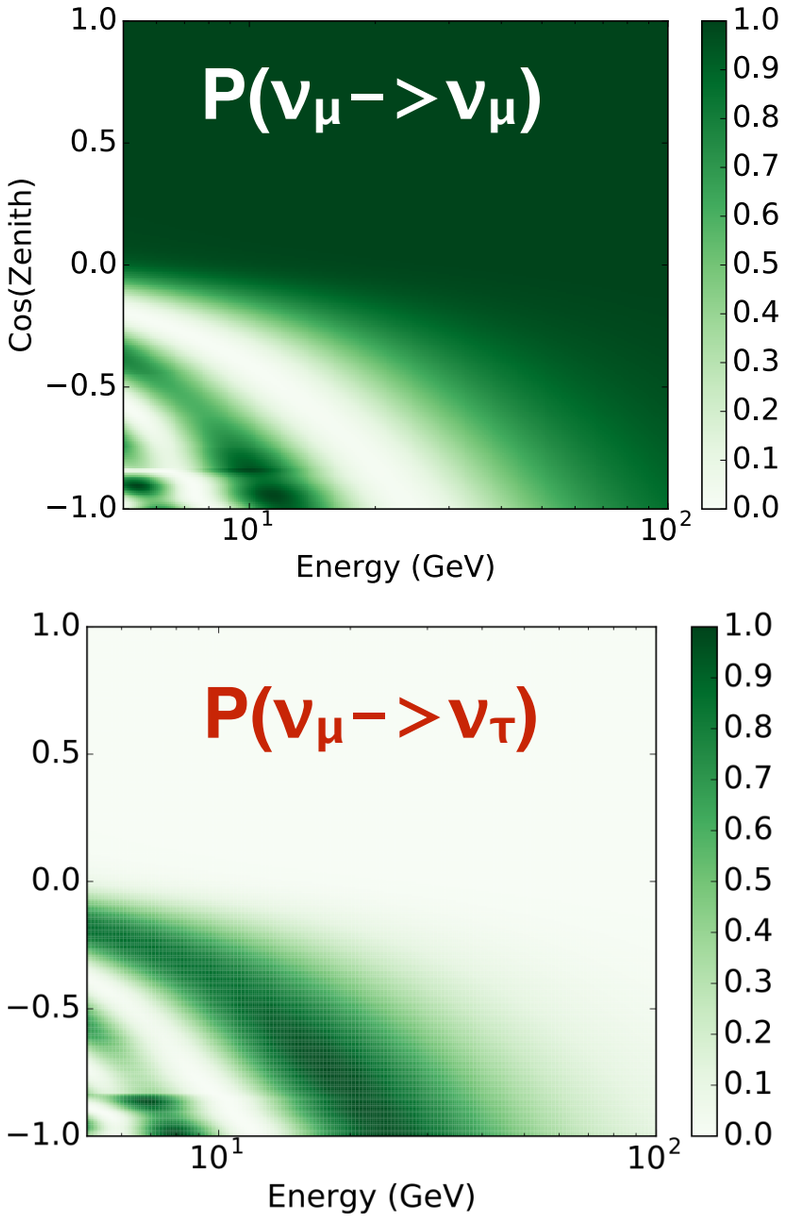
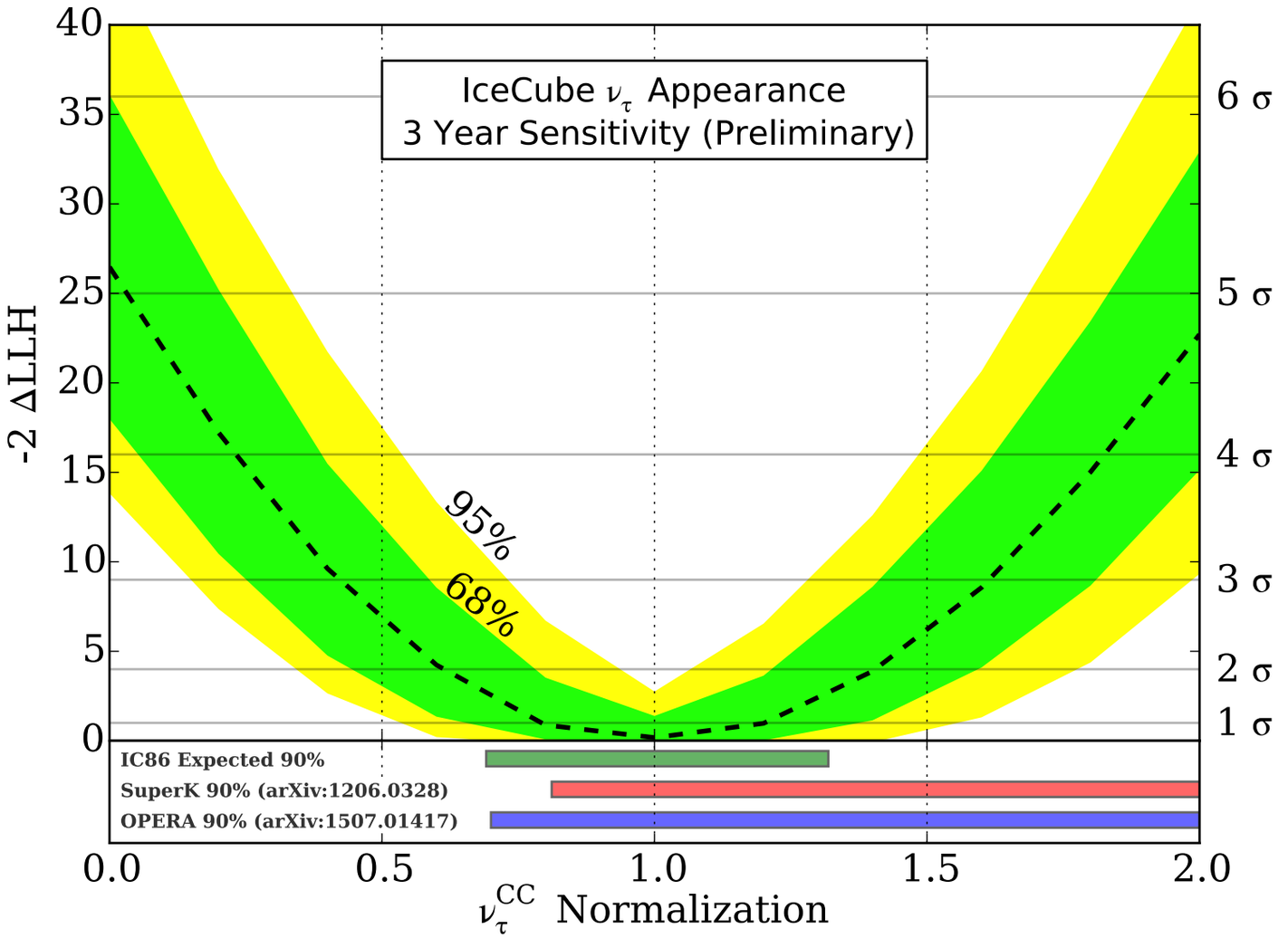
Atmospheric Tau Neutrino Appearance

- **Measure tau appearance in terms of cascade excess**
- **High statistics sample**









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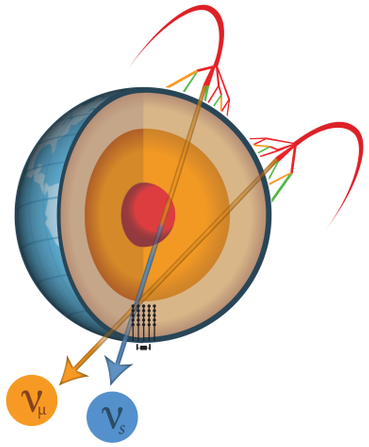
Atmospheric Neutrinos Oscillating to Sterile Neutrinos

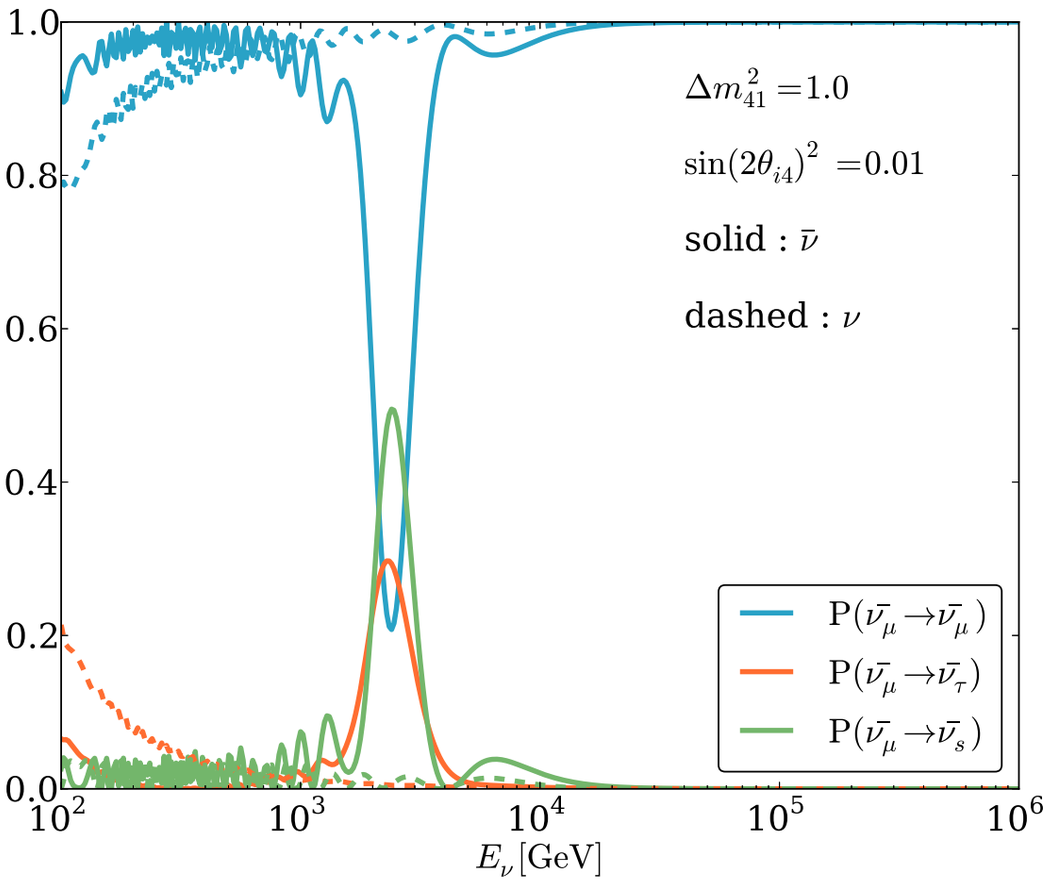
For sterile neutrinos with

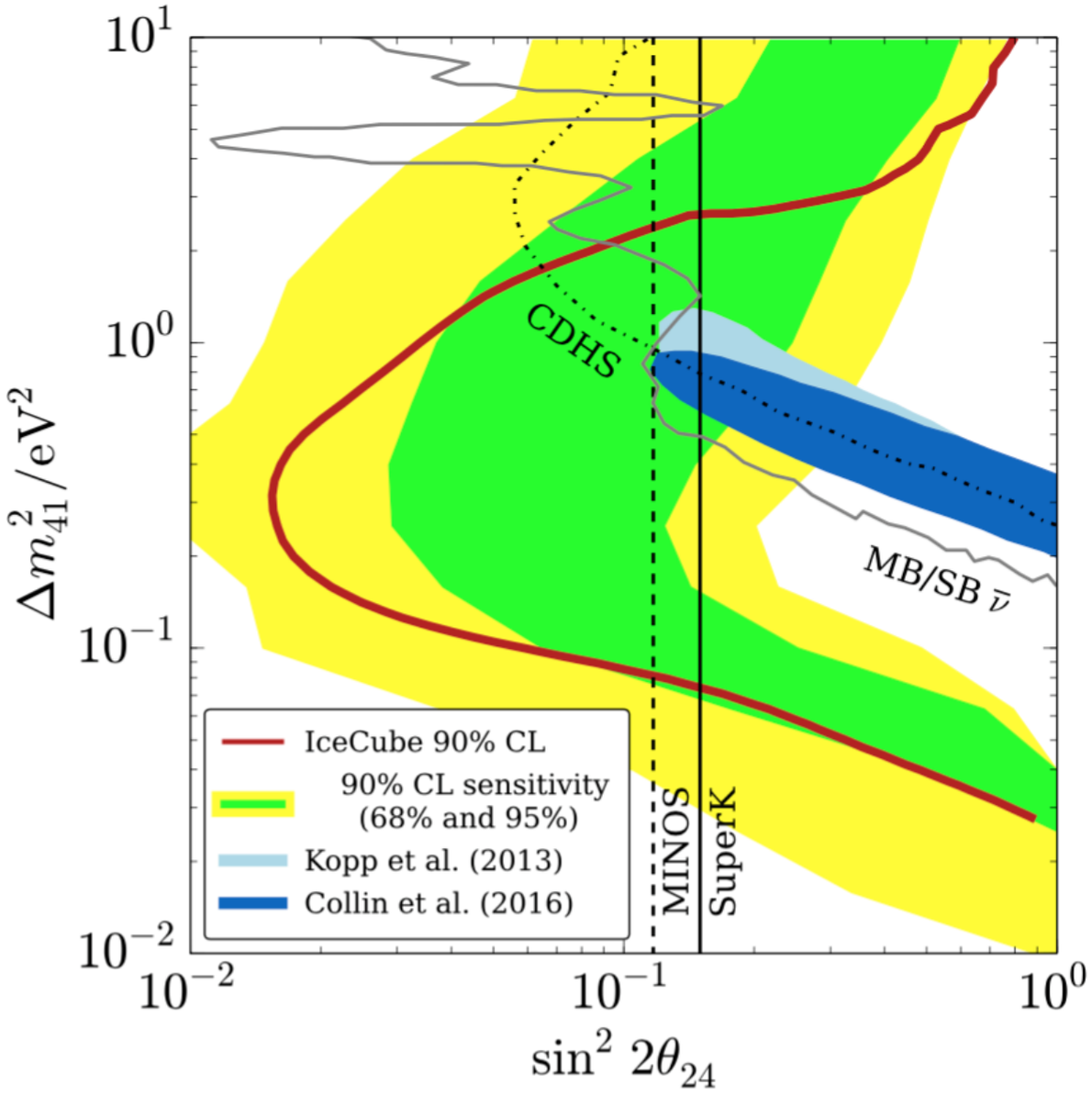
$$\Delta m^2 = O(1eV^2)$$

$$E_\nu^{res} = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F N} \sim O(TeV)$$



- **~ 20,000 events in 344 days**
- **Minimal 3+1 model**
- **LSND/MB region excluded at ~ 99% CL**





Nunokawa et al. PLB, B562, 279 (2003).
arXiv:hep-ph/0302039

Phys. Rev. Lett. 117, 071801

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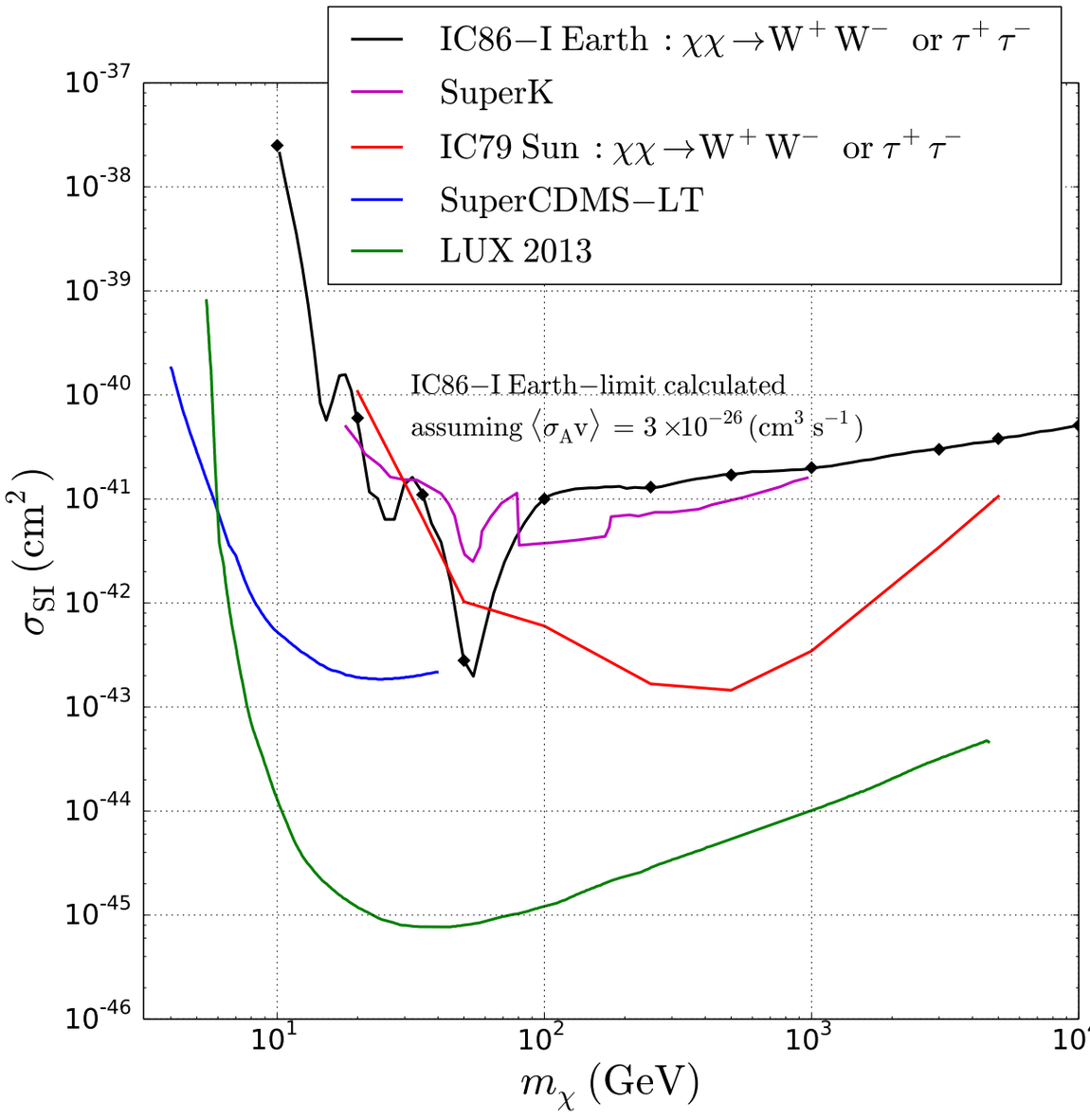
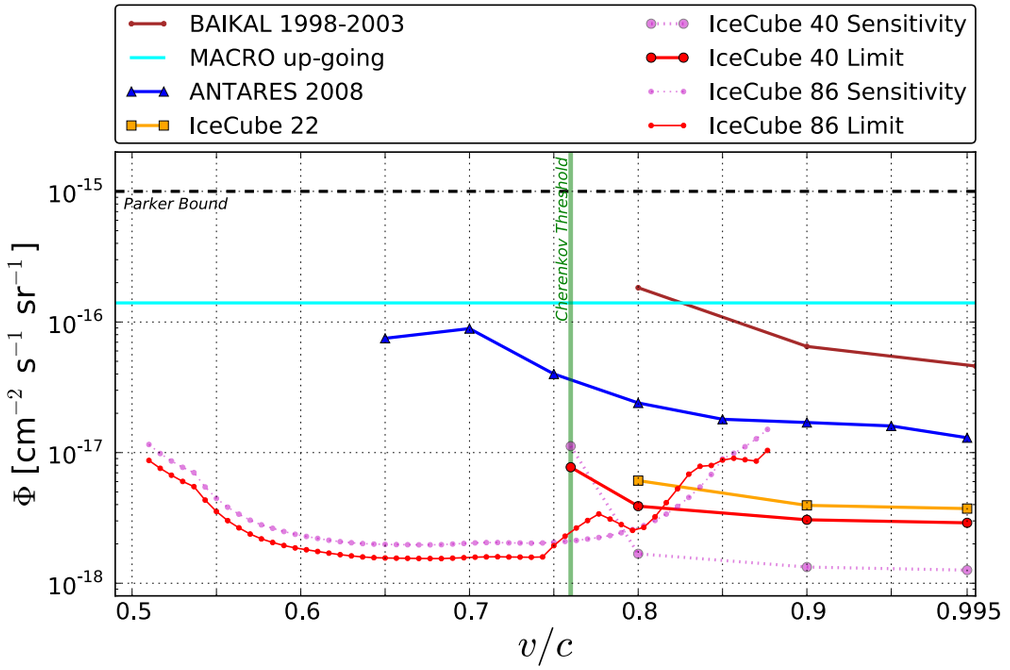
Other Physics Reach by IceCube (incomplete)

A very versatile detector ..

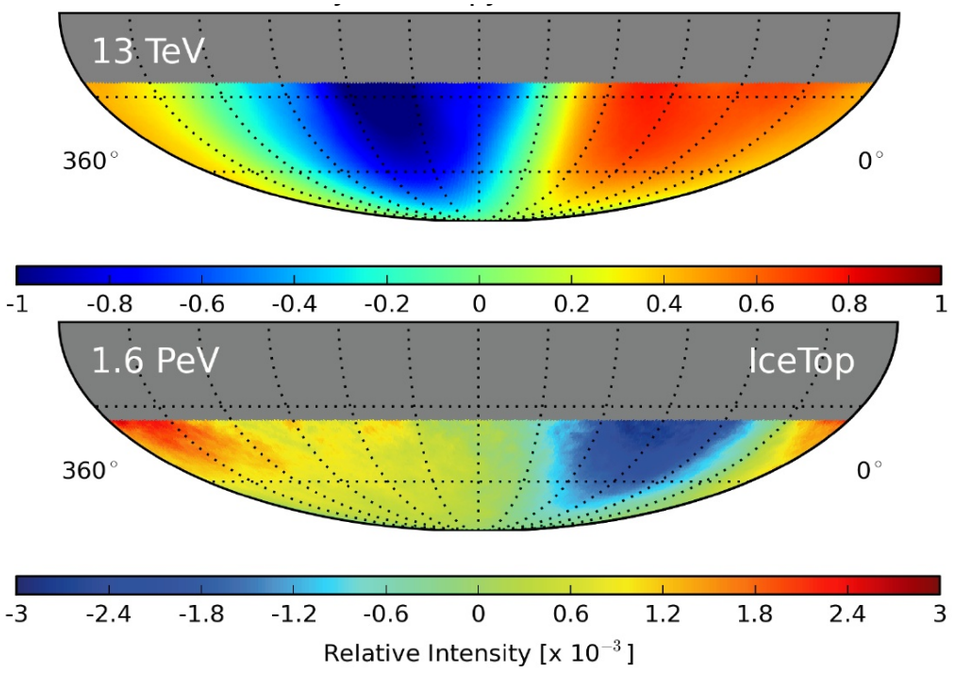
Earth WIMP: arXiv:1609.01492



Magnetic Monopole: EPJ C76 (2016) 133



Cosmic-ray anisotropy: arXiv:1603.01227



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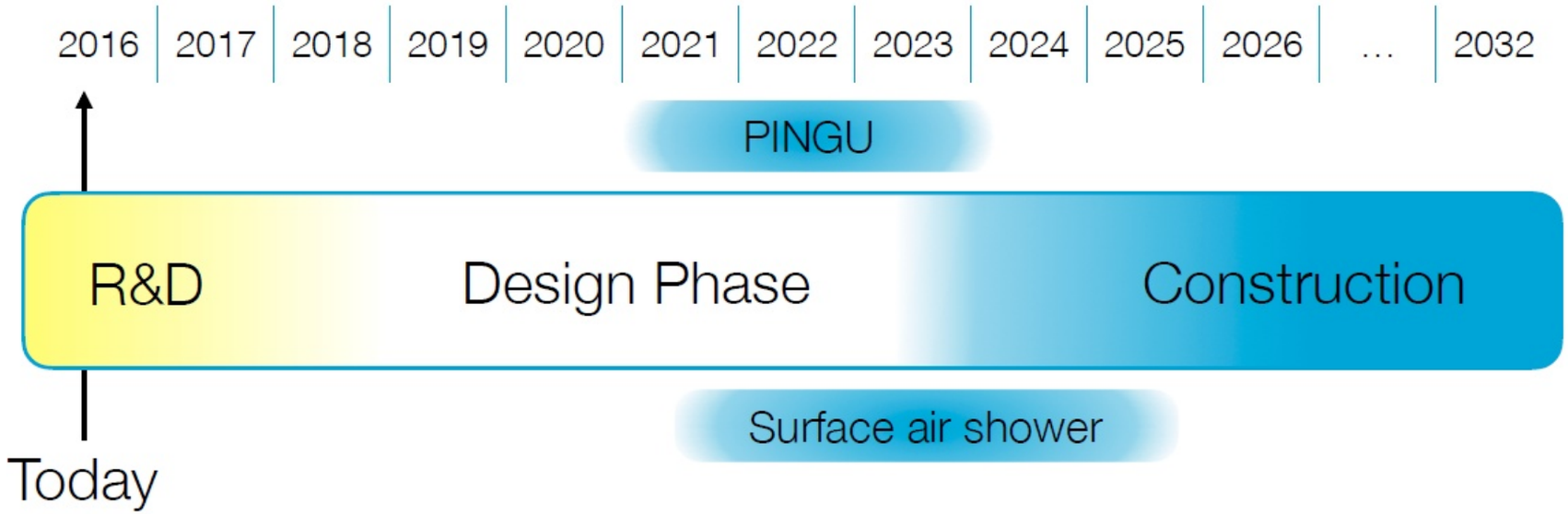
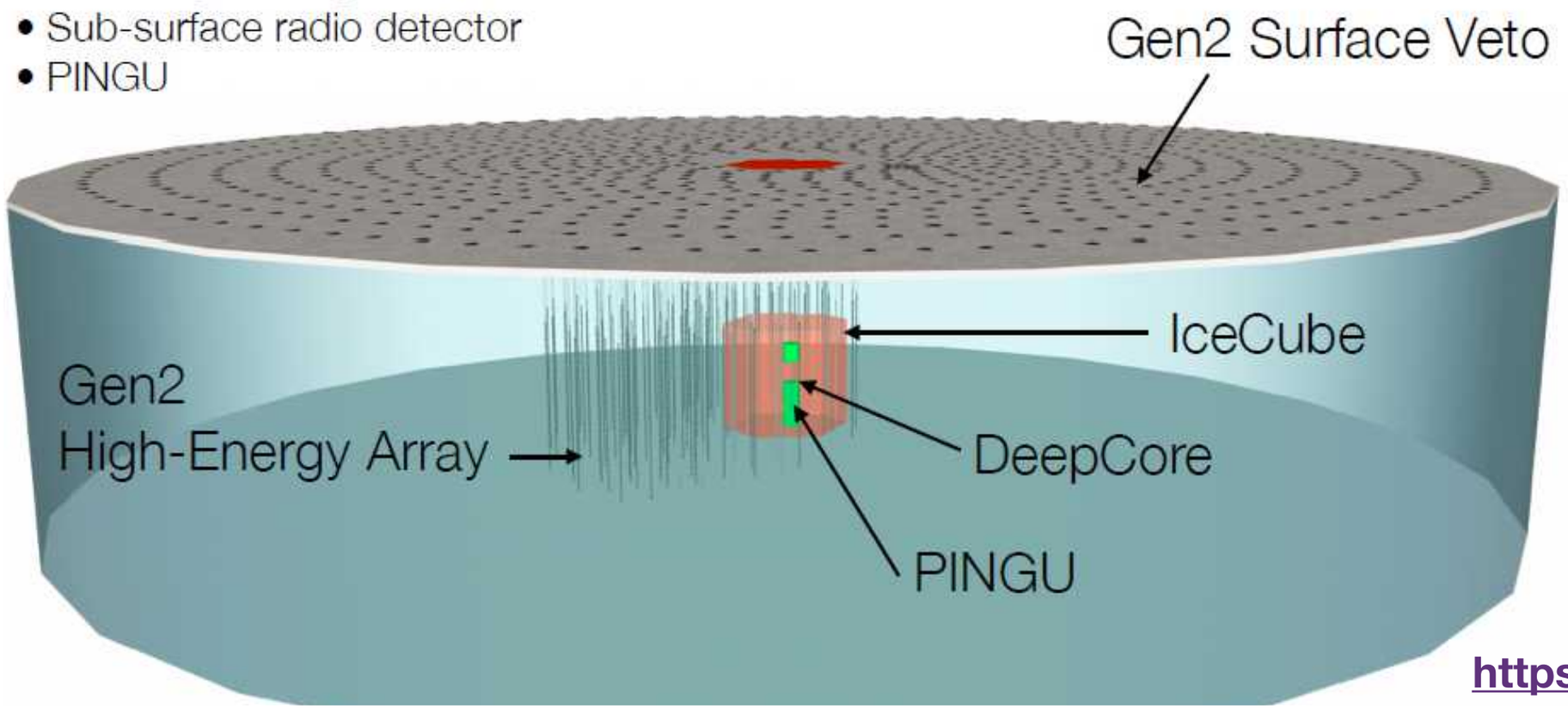


Multi-component observatory:

- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU



https://arxiv.org/abs/1412.5106

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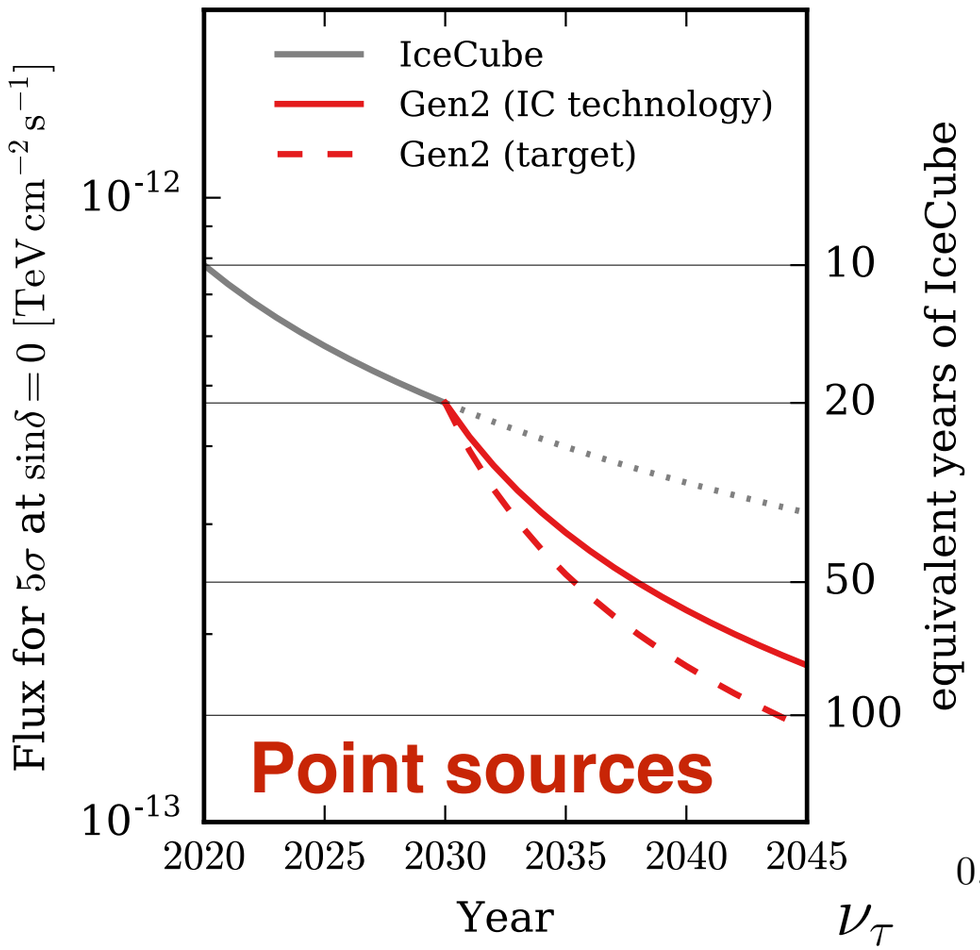
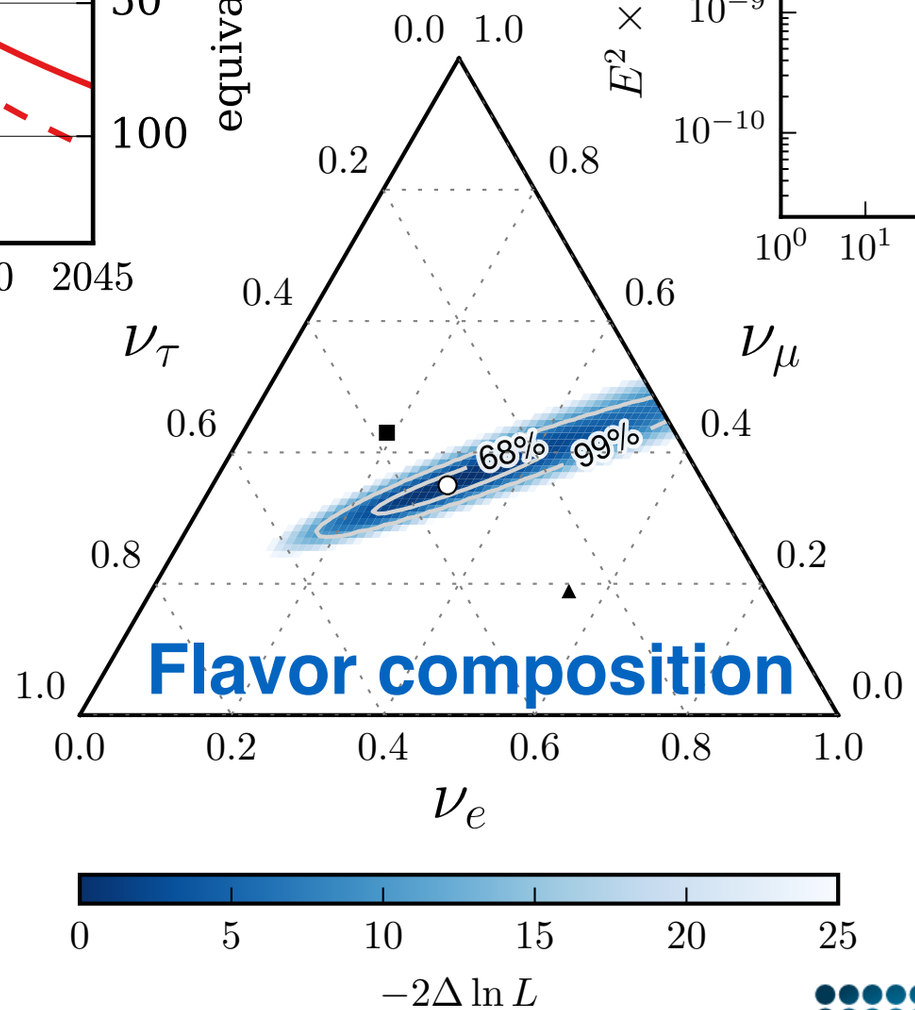
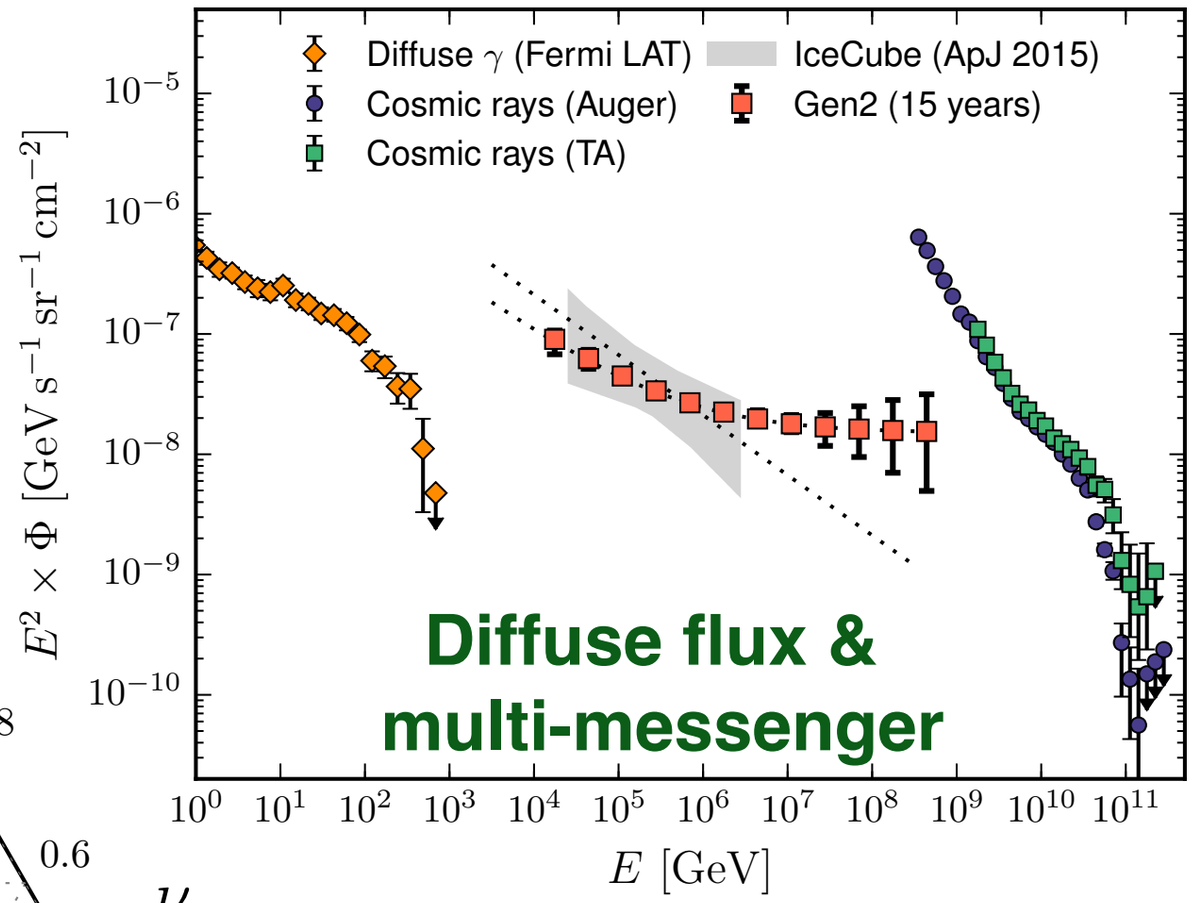
IceCube-Gen2: Science Case







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Summary

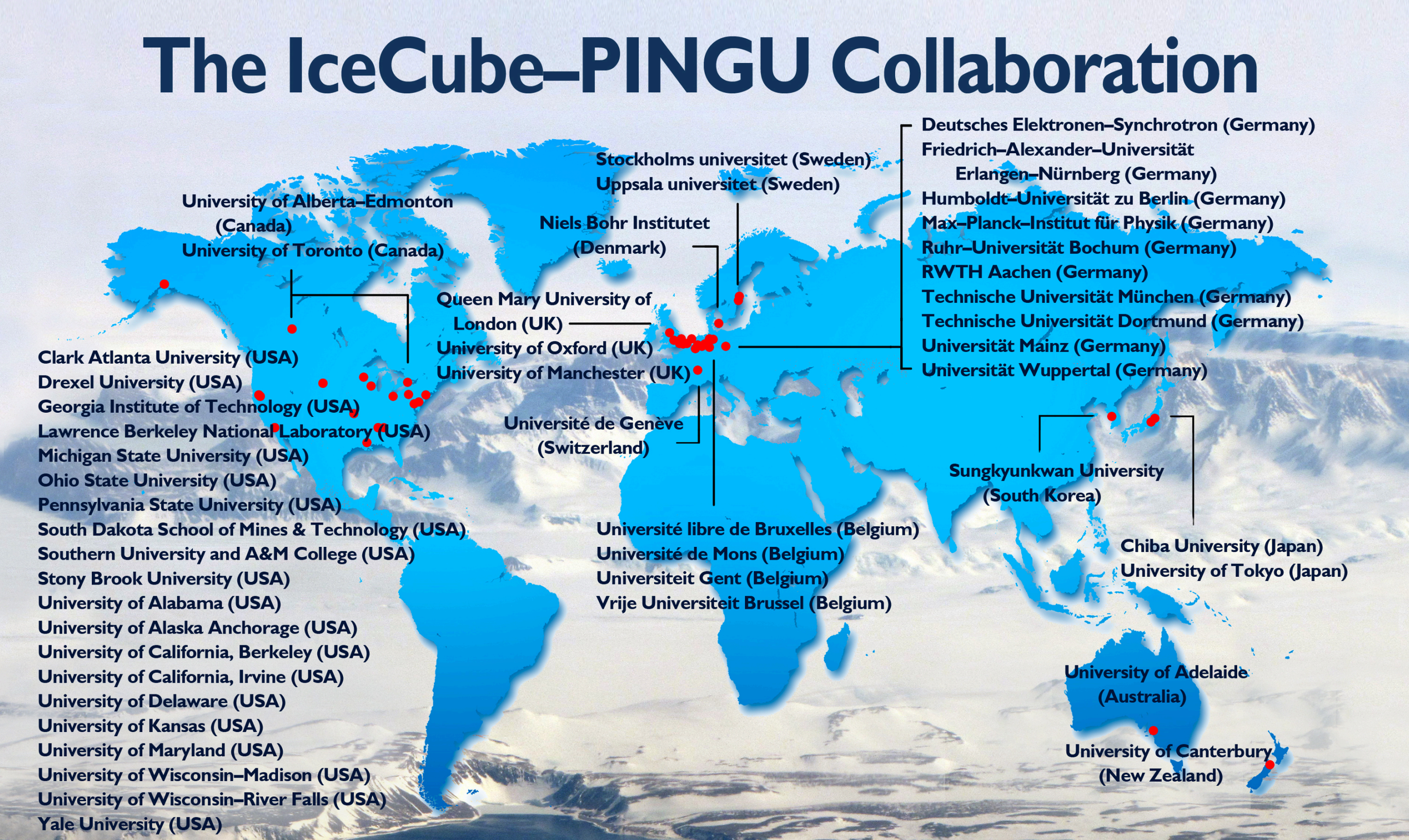
- **IceCube has discovered astrophysical neutrinos; dawn of neutrino astronomy**

- **Six years of smooth operation since completion with >99% uptime. Many exciting physics topics are ongoing and more to come**

- **Astrophysical neutrino point sources are yet to be discovered. The campaign for neutrino point sources is ON**

- **IceCube-Gen2 will have up to an order of magnitude increase in sensitivity**

The IceCube–PINGU Collaboration



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