

ICECUBE

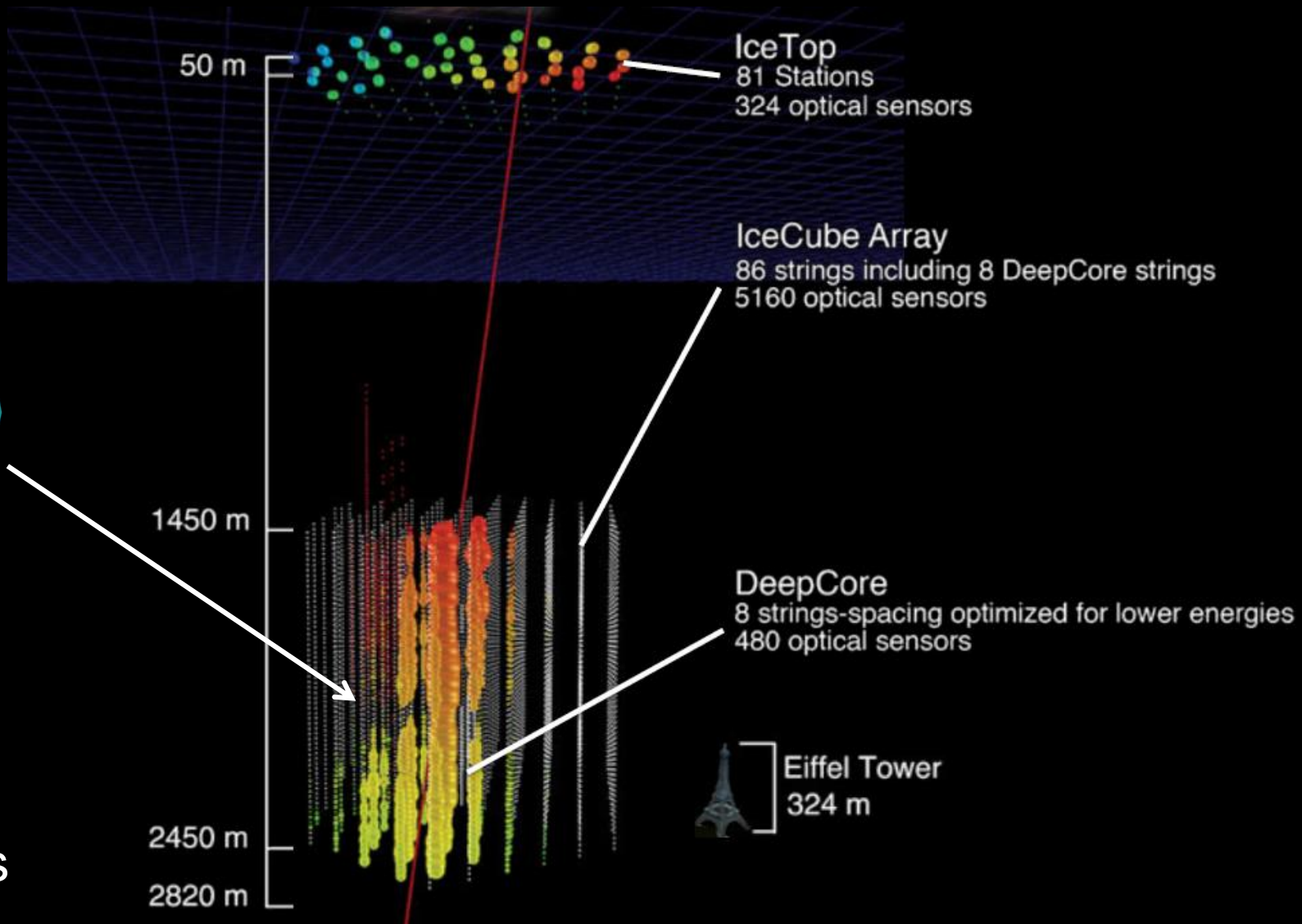


IceCube:
francis halzen

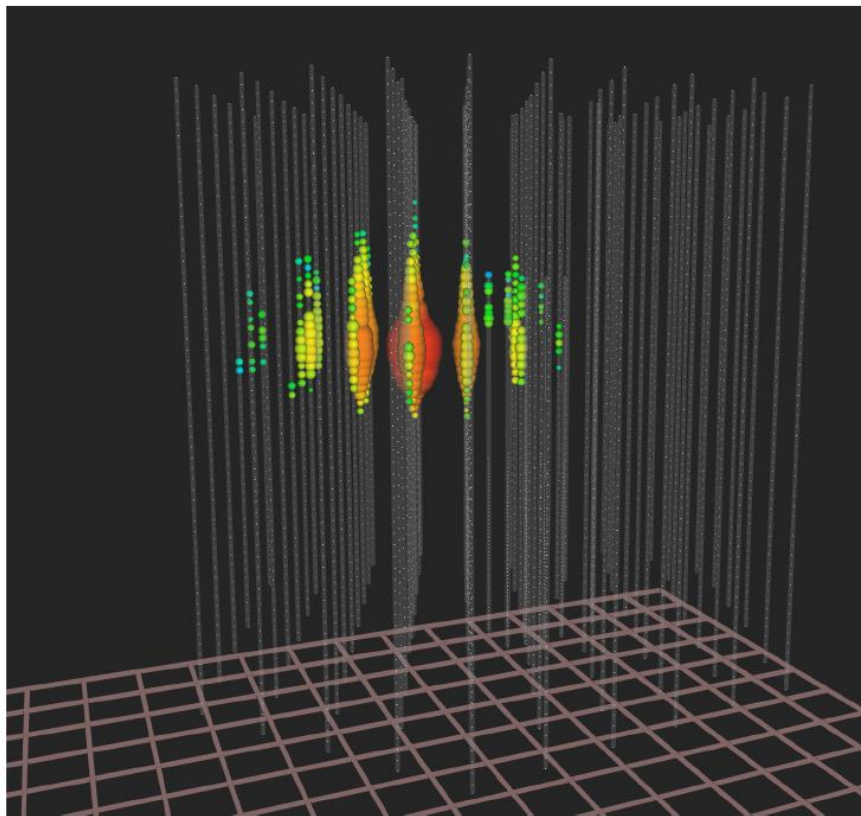
- IceCube
- PeV: cosmic neutrinos and the first high-energy cosmic ray accelerator
- > 10 GeV: oscillations, tau appearance
- $> \text{TeV}$: sterile neutrinos
- next: generation 2-phase 1

IceCube

5160 PMs
in 1 km³

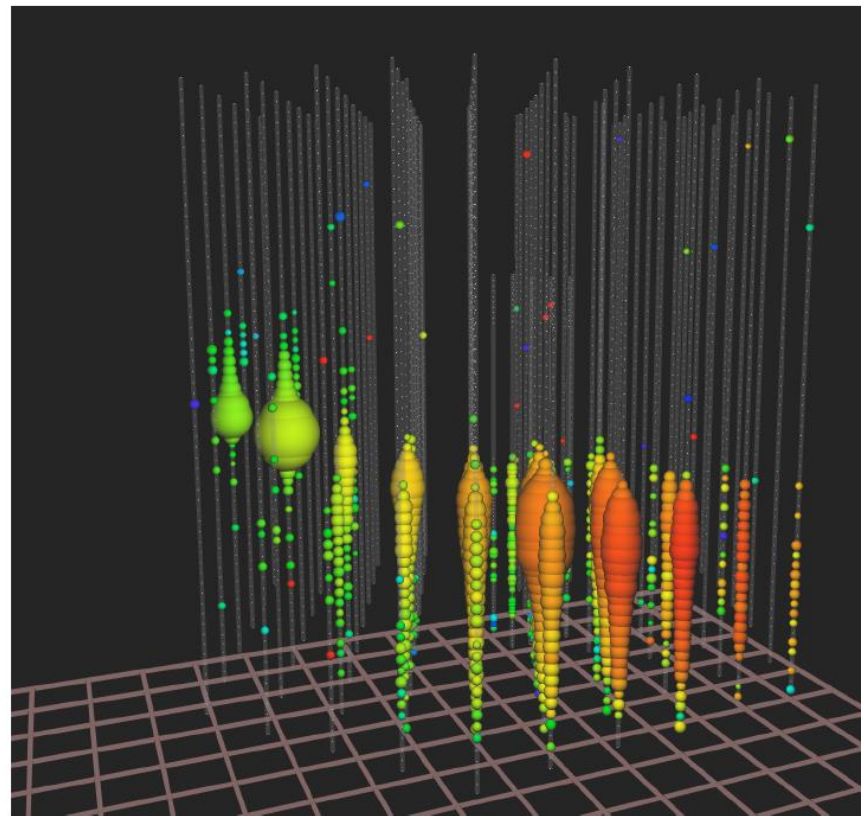


isolated neutrinos interacting
inside the detector



total energy measurement
all flavors, all sky

up-going muon tracks
(through the Earth)



astronomy: angular resolution
superior ($<0.4^\circ$)

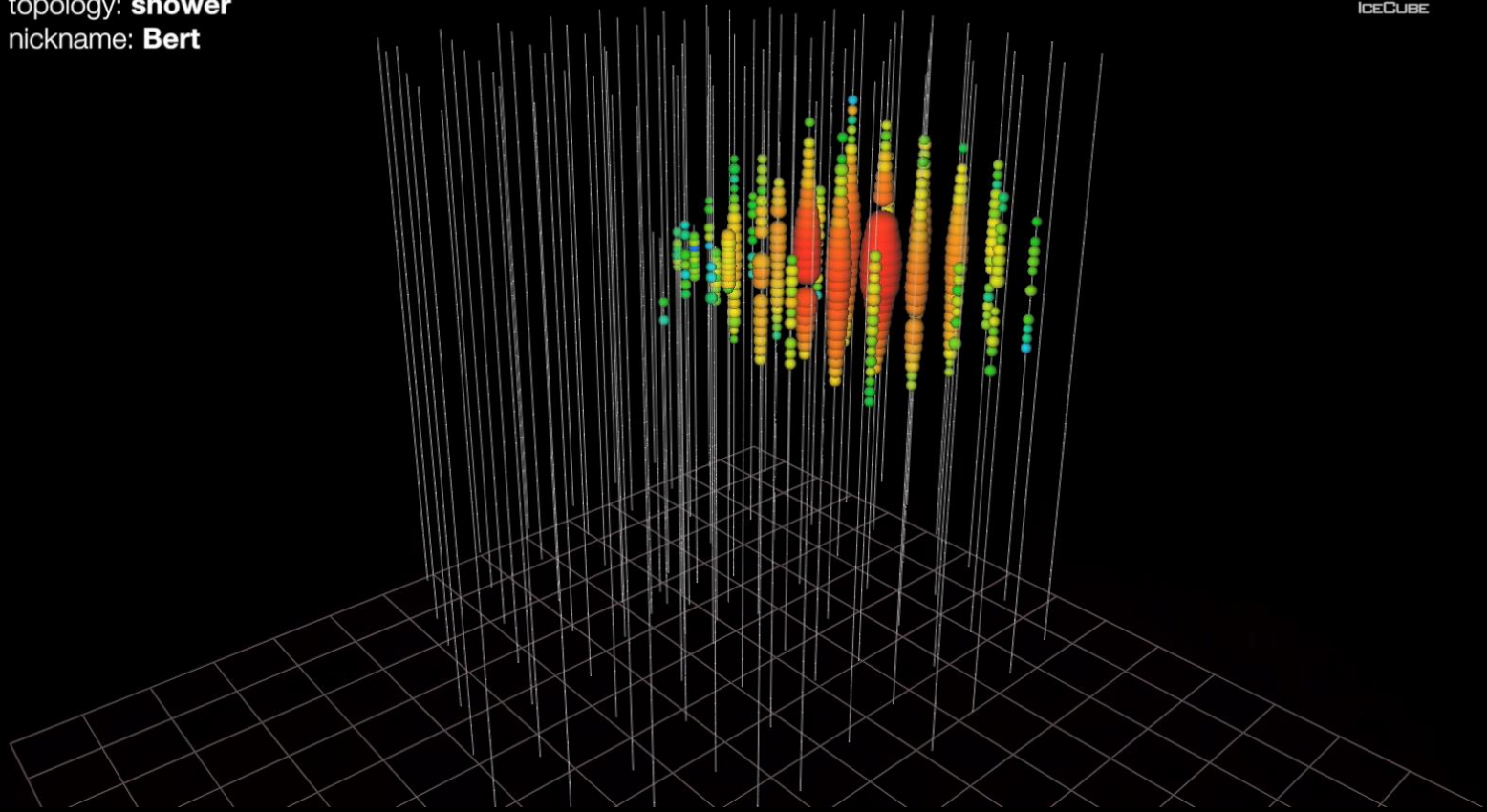
GZK neutrino search: two neutrinos with $> 1,000$ TeV

date: **August 9, 2011**

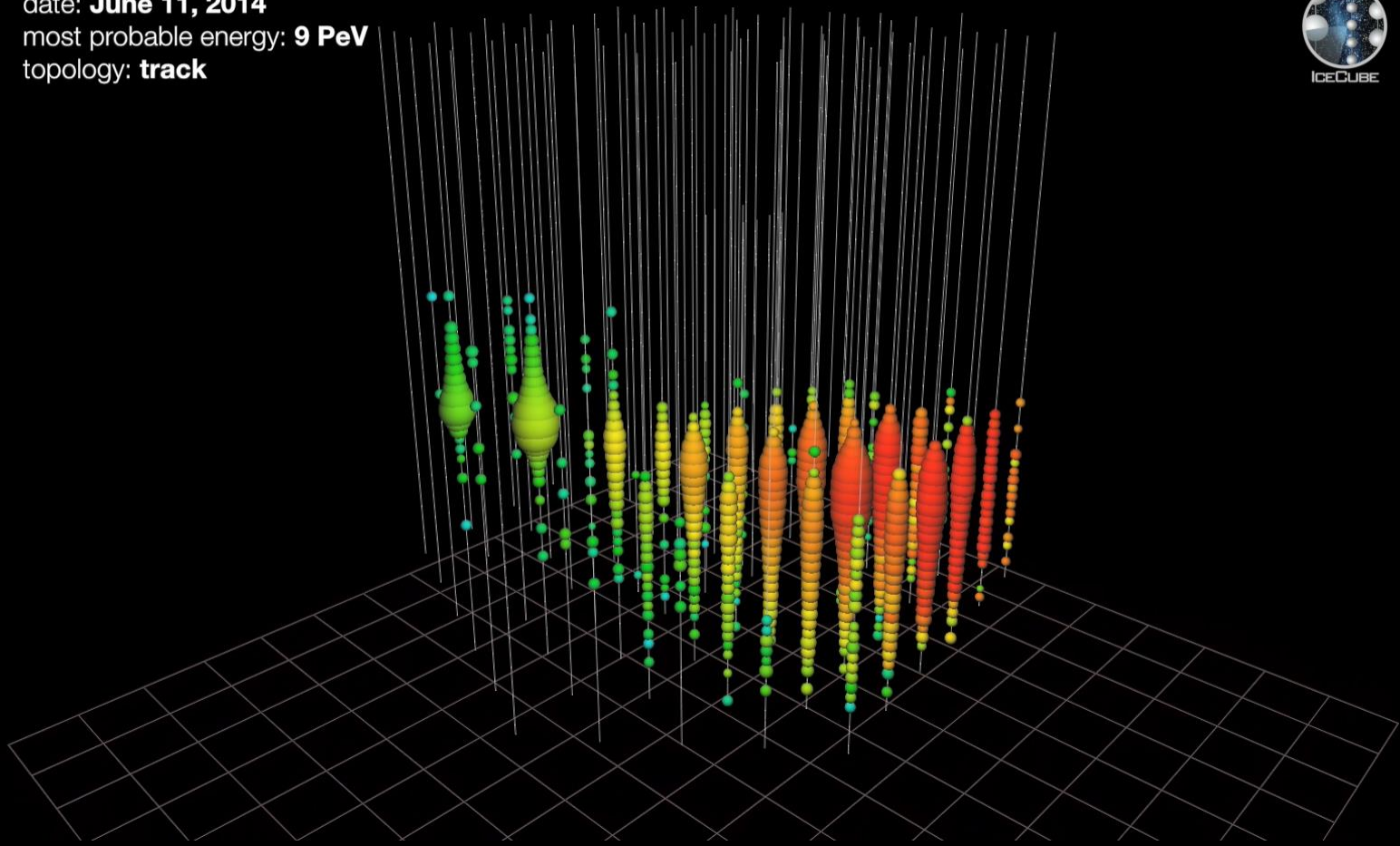
energy: **1.04 PeV**

topology: **shower**

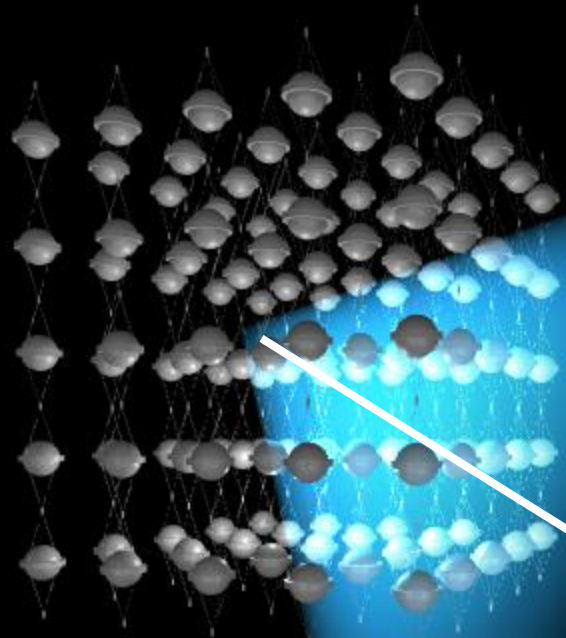
nickname: **Bert**



date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**



- speed of light in water $< c$
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track

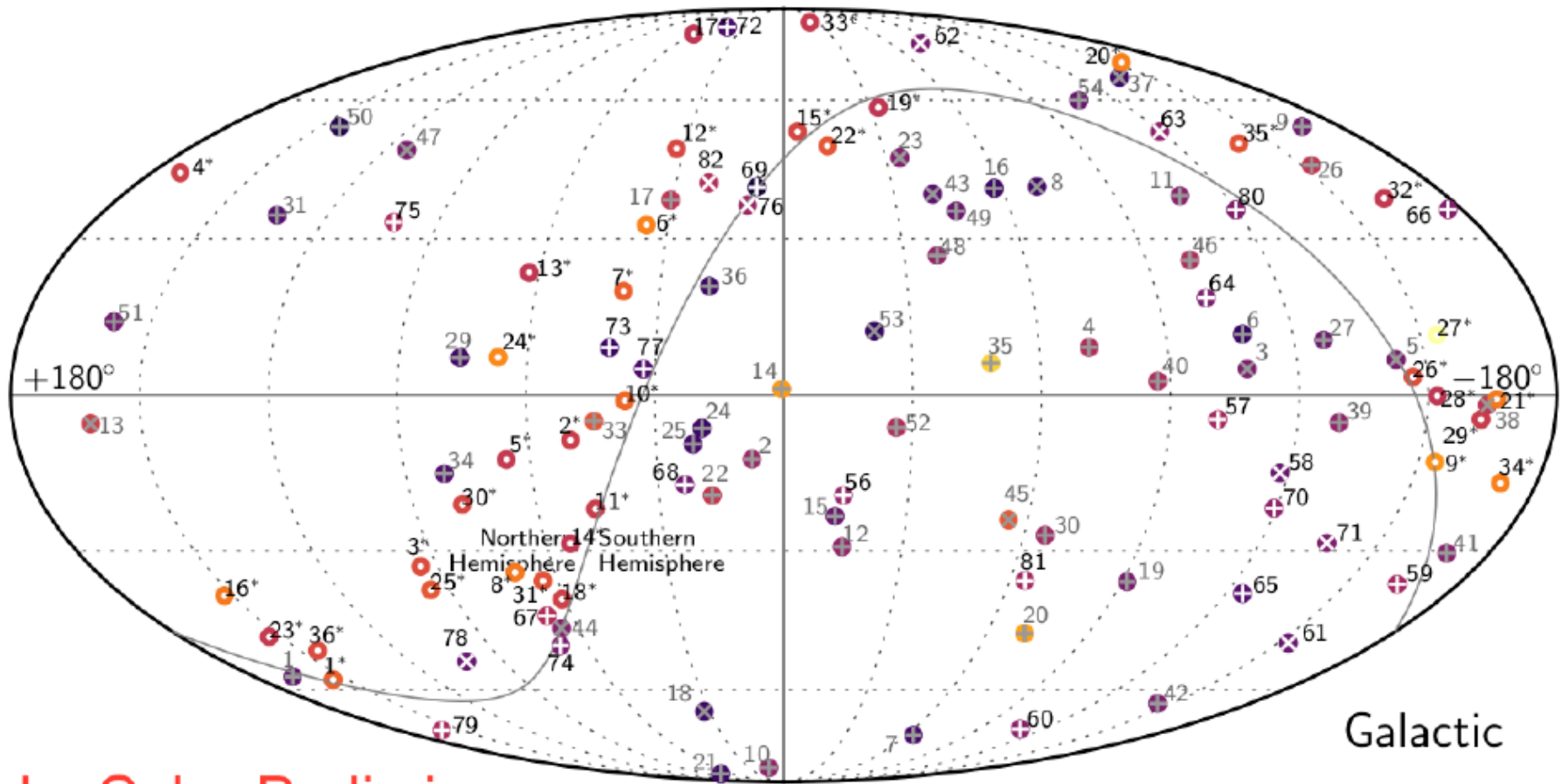


muon

interaction

neutrino

- lattice of photomultipliers



IceCube Preliminary

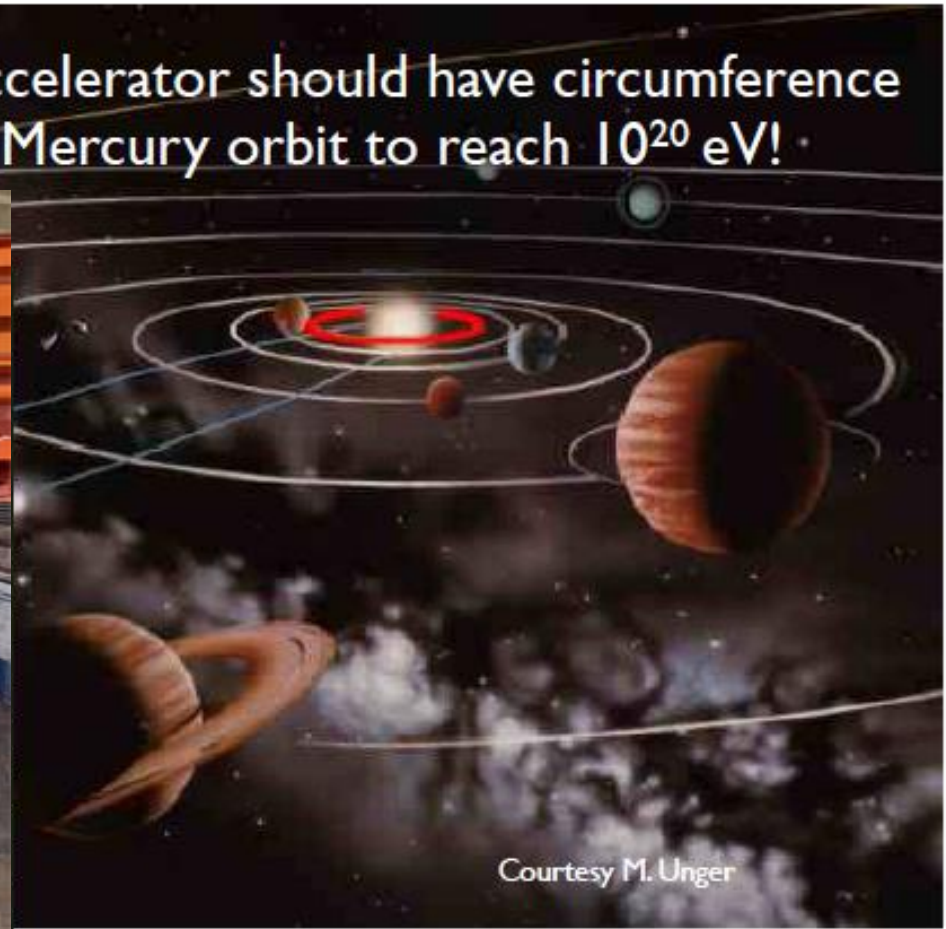


Deposited Energy or Muon Energy Proxy [TeV]

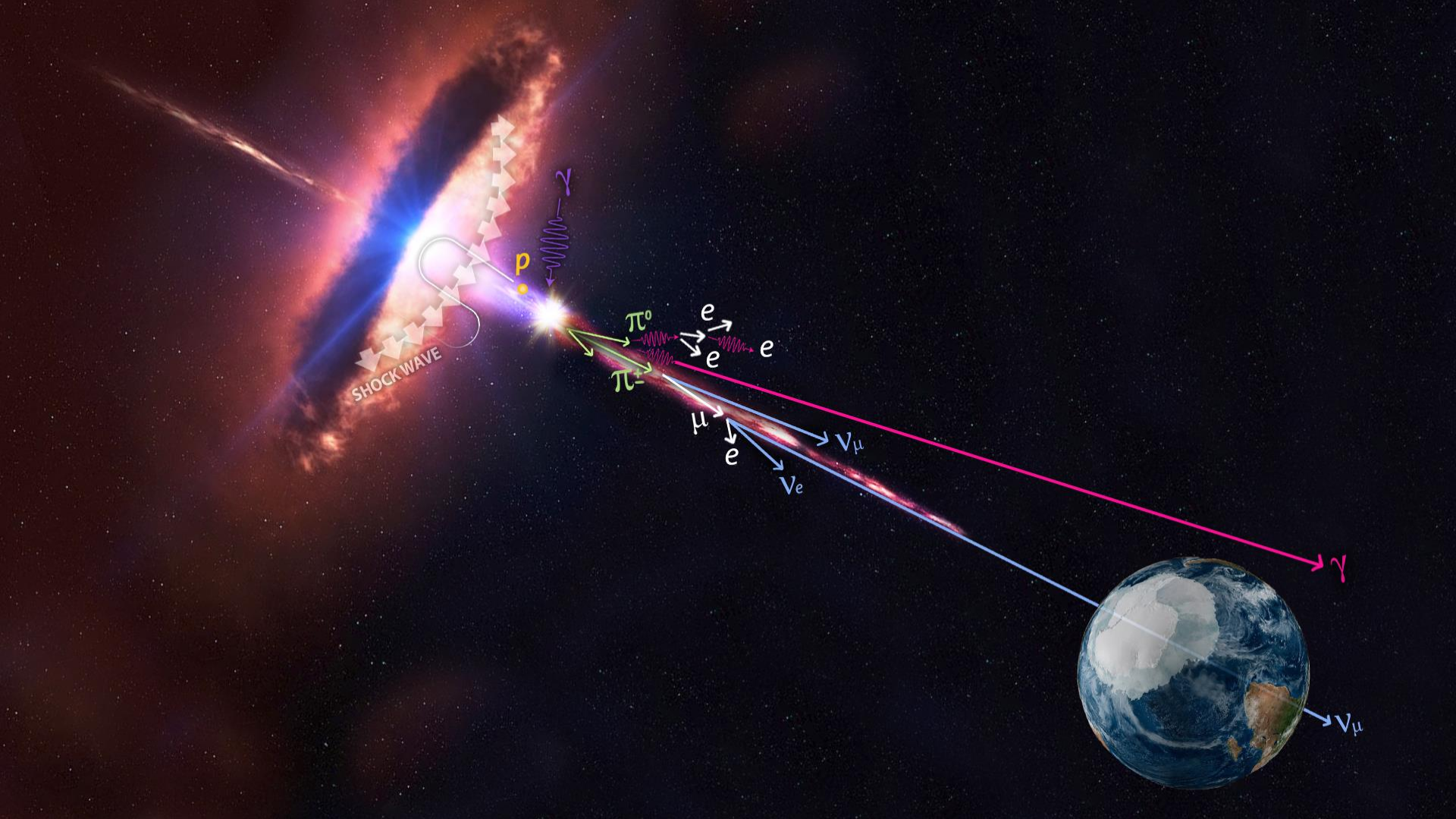
- ⊗ N New Starting Tracks
- ⊗ N Earlier Starting Tracks
- ⊕ N New Starting Cascades
- ⊕ N Earlier Starting Cascades
- N^* Throughgoing Tracks

- energy \sim [magnetic field B] x [accelerator's size R]

LHC accelerator should have circumference of Mercury orbit to reach 10^{20} eV!



- luminosity \sim a few percent of gravitational energy of...





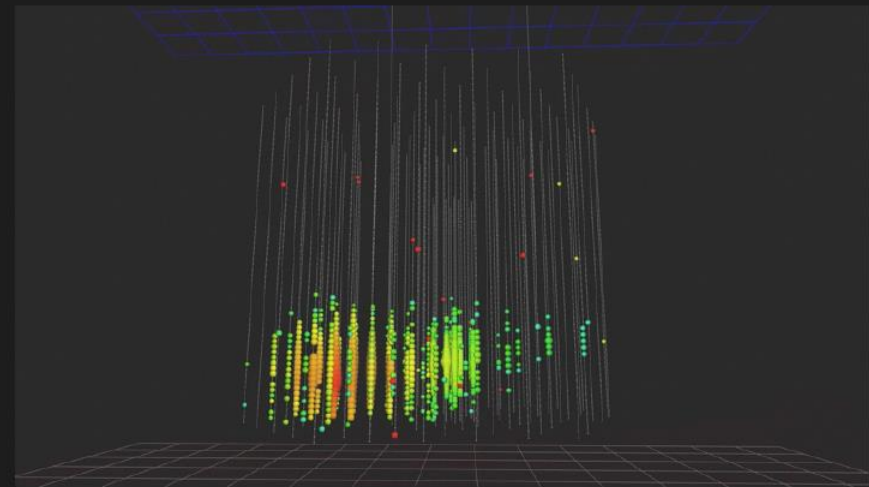
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!

TITLE: GCN/AMON NOTICE
NOTICE_DATE: Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE: AMON ICECUBE HESE
RUN_NUM: 127853
EVENT_NUM: 67093193
SRC_RA: 240.5683d {+16h 02m 16s} (J2000),
240.7644d {+16h 03m 03s} (current),
239.9678d {+15h 59m 52s} (1950)
SRC_DEC: +9.3417d {+09d 20' 30"} (J2000),
+9.2972d {+09d 17' 50"} (current),
+9.4798d {+09d 28' 47"} (1950)
SRC_ERROR: 35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50: 0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE: 17505 TJD; 118 DOY; 16/04/27 (yy/mm/dd)
DISCOVERY_TIME: 21152 SOD {05:52:32.00} UT
REVISION: 2
N_EVENTS: 1 [number of neutrinos]
STREAM: 1
DELTA_T: 0.0000 [sec]
SIGMA_T: 0.0000 [sec]
FALSE_POS: 0.0000e+00 [s⁻¹ sr⁻¹]
PVALUE: 0.0000e+00 [dn]
CHARGE: 18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN: 35.75d {+02h 23m 00s} +14.21d {+14d 12' 45"}

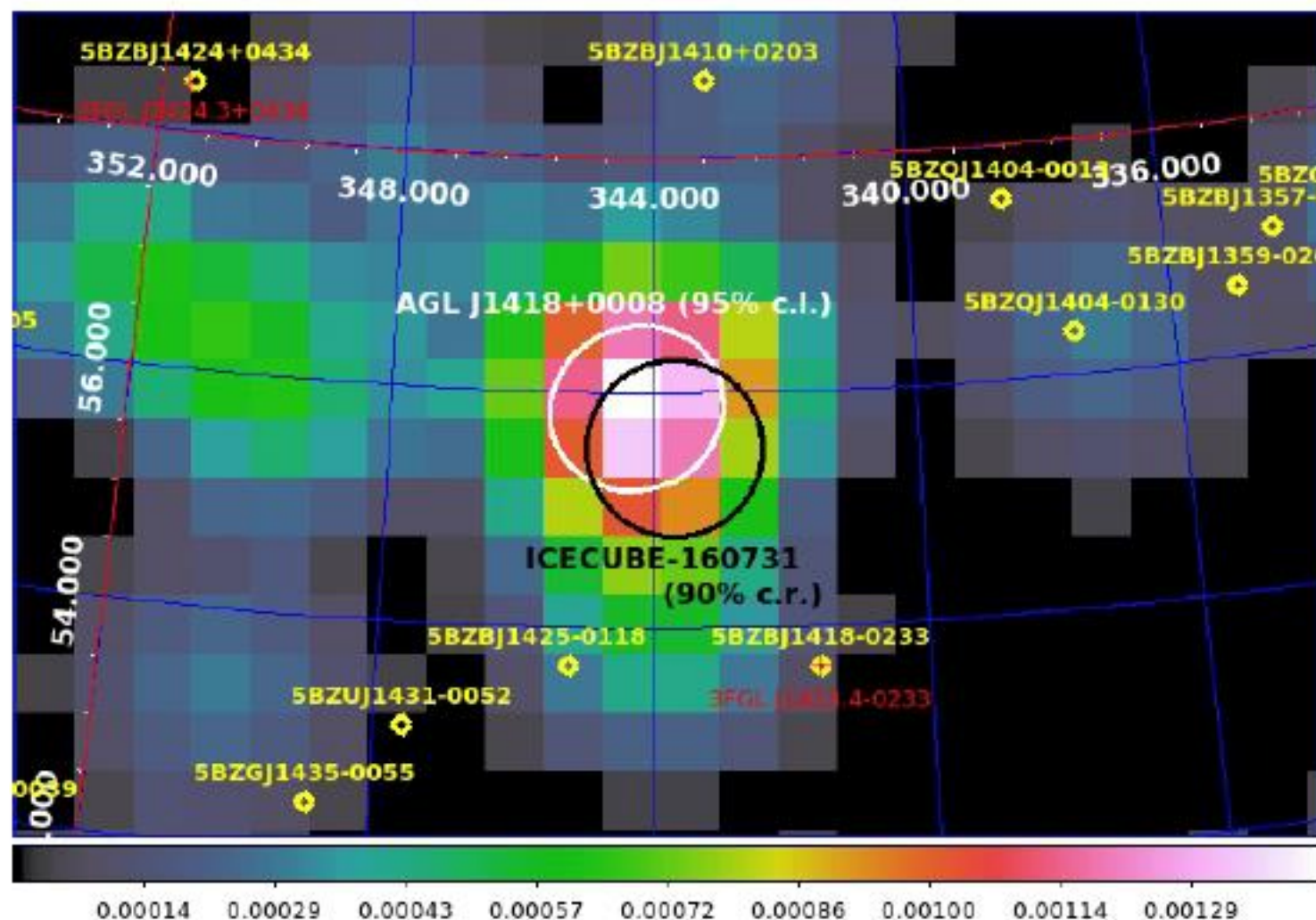
GCN notice for starting track sent Apr 27

We send rough reconstructions first and then update them.



AGILE DETECTION OF A CANDIDATE GAMMA-RAY PRECURSOR TO THE ICECUBE-160731 NEUTRINO EVENT

F. LUCARELLI,^{1,2} C. PITTORI,^{1,2} F. VERRECCHIA,^{1,2} I. DONNARUMMA,³ M. TAVANI,^{4,5,6} A. BULGARELLI,⁷ A. GIULIANI,⁸
L. A. ANTONELLI,^{1,2} P. CARAVEO,⁸ P. W. CATTANEO,⁹ S. COLAFRANCESCO,^{10,2} F. LONGO,¹¹ S. MEREGHETTI,⁸
A. MORSELLI,¹² L. PACCIANI,⁴ G. PIANO,⁴ A. PELLIZZONI,¹³ M. PILIA,¹³ A. RAPPOLDI,⁹ A. TROIS,¹³ AND S. VERCELLONE¹⁴



Corresponding author: Fabrizio Lucarelli
fabrizio.lucarelli@asdc.asi.it

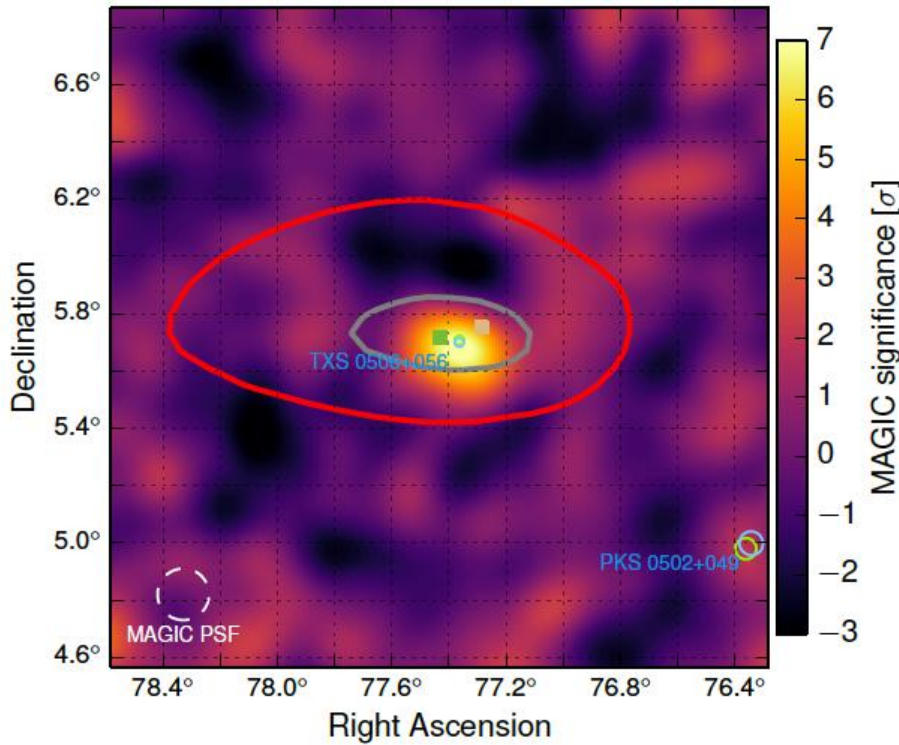
IceCube Trigger

43 seconds after trigger, GCN notice was sent

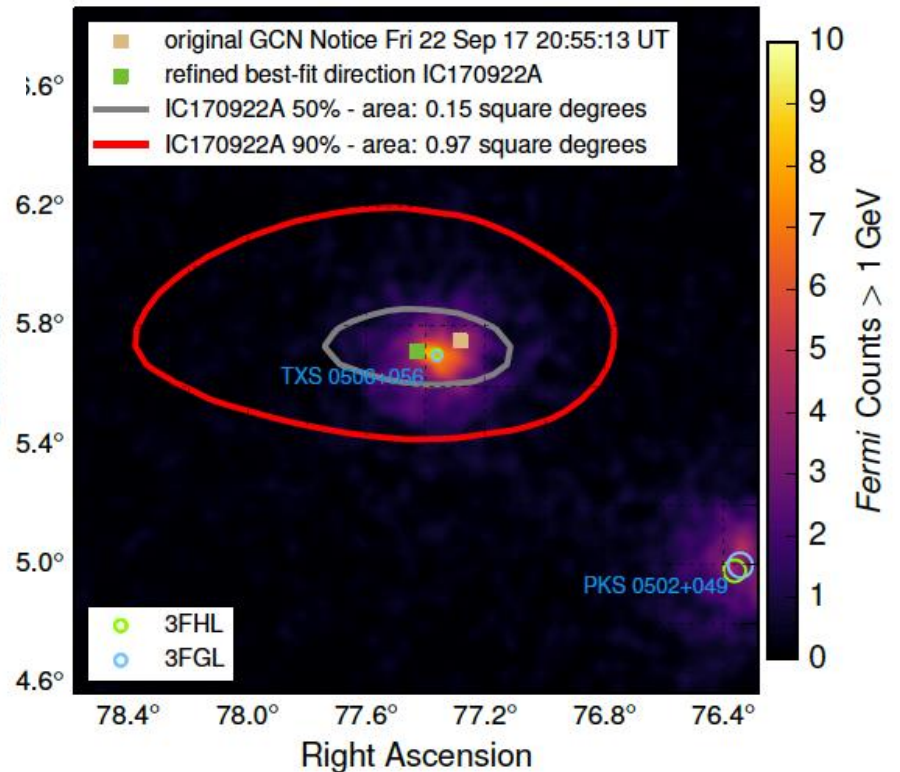
```
////////////////////////////////////  
TITLE:                GCN/AMON NOTICE  
NOTICE_DATE:          Fri 22 Sep 17 20:55:13 UT  
NOTICE_TYPE:          AMON ICECUBE EHE  
RUN_NUM:              130033  
EVENT_NUM:            50579430  
SRC_RA:               77.2853d {+05h 09m 08s} (J2000),  
                     77.5221d {+05h 10m 05s} (current),  
                     76.6176d {+05h 06m 28s} (1950)  
SRC_DEC:              +5.7517d {+05d 45' 06"} (J2000),  
                     +5.7732d {+05d 46' 24"} (current),  
                     +5.6888d {+05d 41' 20"} (1950)  
SRC_ERROR:            14.99 [arcmin radius, stat+sys, 50% containment]  
DISCOVERY_DATE:       18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)  
DISCOVERY_TIME:       75270 SOD {20:54:30.43} UT  
REVISION:              0  
N_EVENTS:              1 [number of neutrinos]  
STREAM:                2  
DELTA_T:              0.0000 [sec]  
SIGMA_T:              0.0000e+00 [dn]  
ENERGY :              1.1998e+02 [TeV]  
SIGNALNESS:           5.6507e-01 [dn]  
CHARGE:                5784.9552 [pe]
```

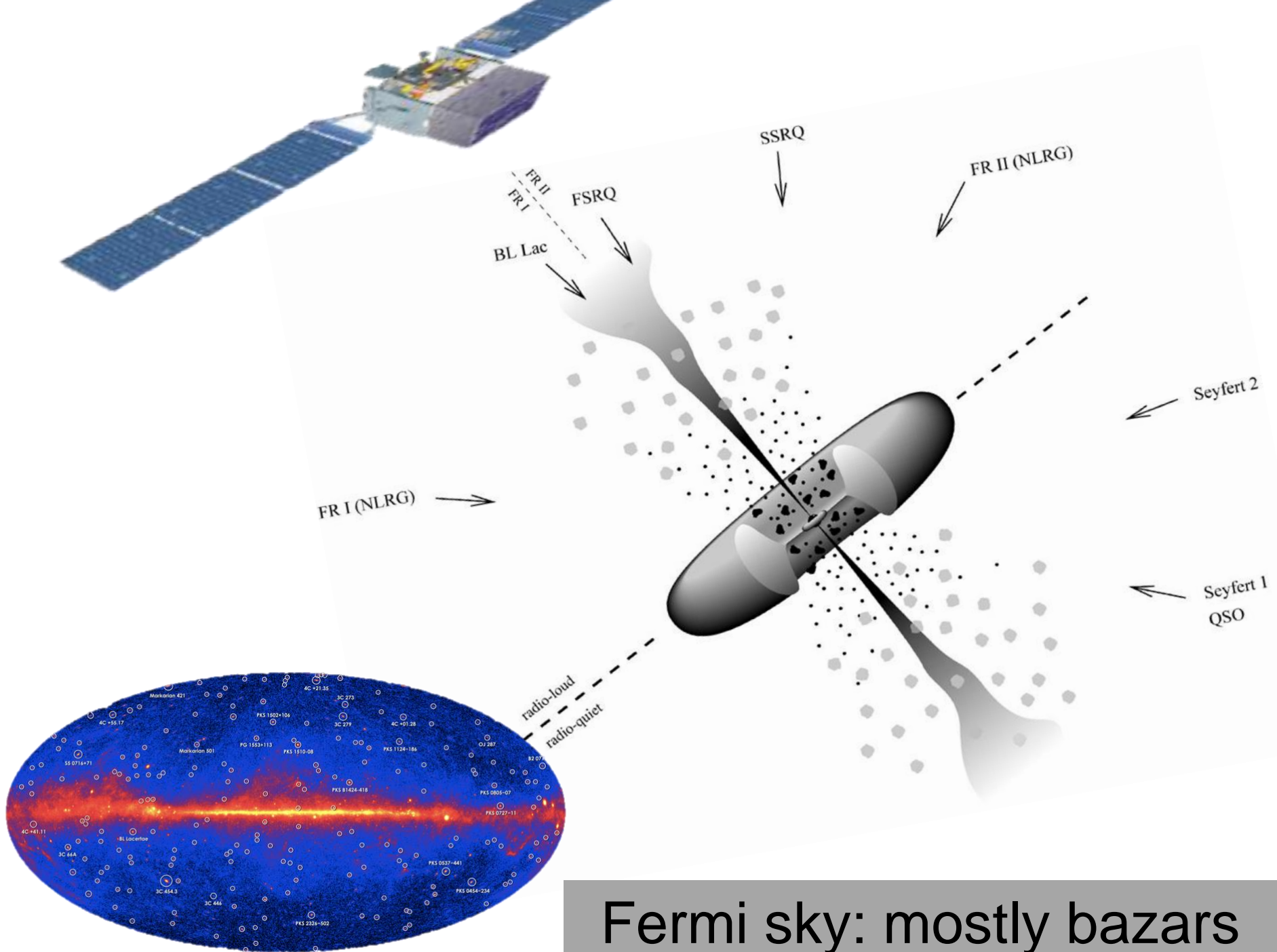
IceCube 170922

Fermi
detects a flaring
blazar within 0.1°



MAGIC
detects emission of
> 100 GeV gammas





Fermi sky: mostly bazars

MAGIC atmospheric Cherenkov telescope



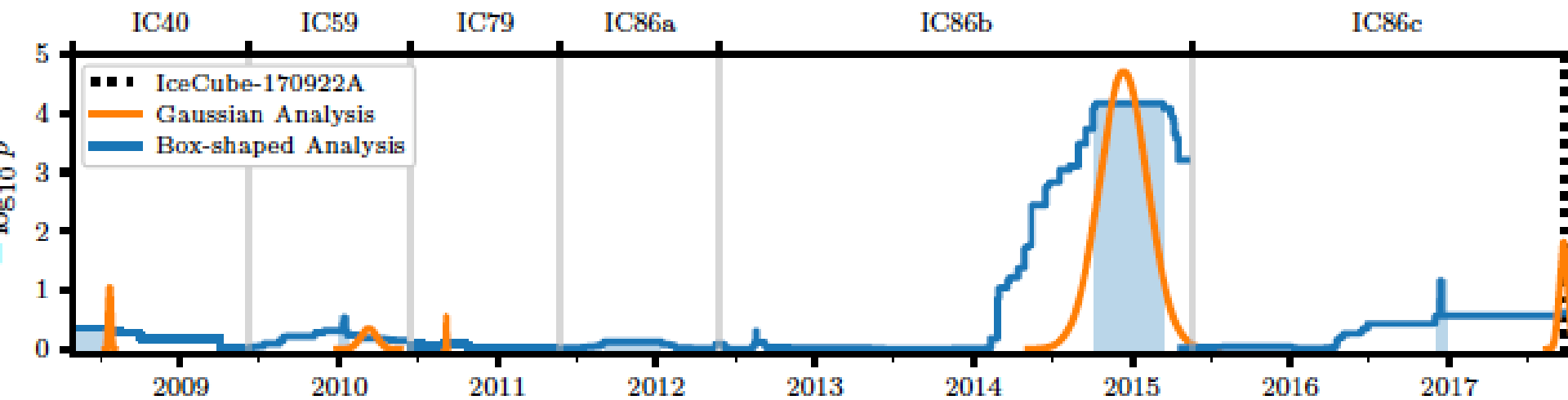
Follow-up detections of IC170922 based on public telegrams



multiwavelength campaign launched by IC 170922

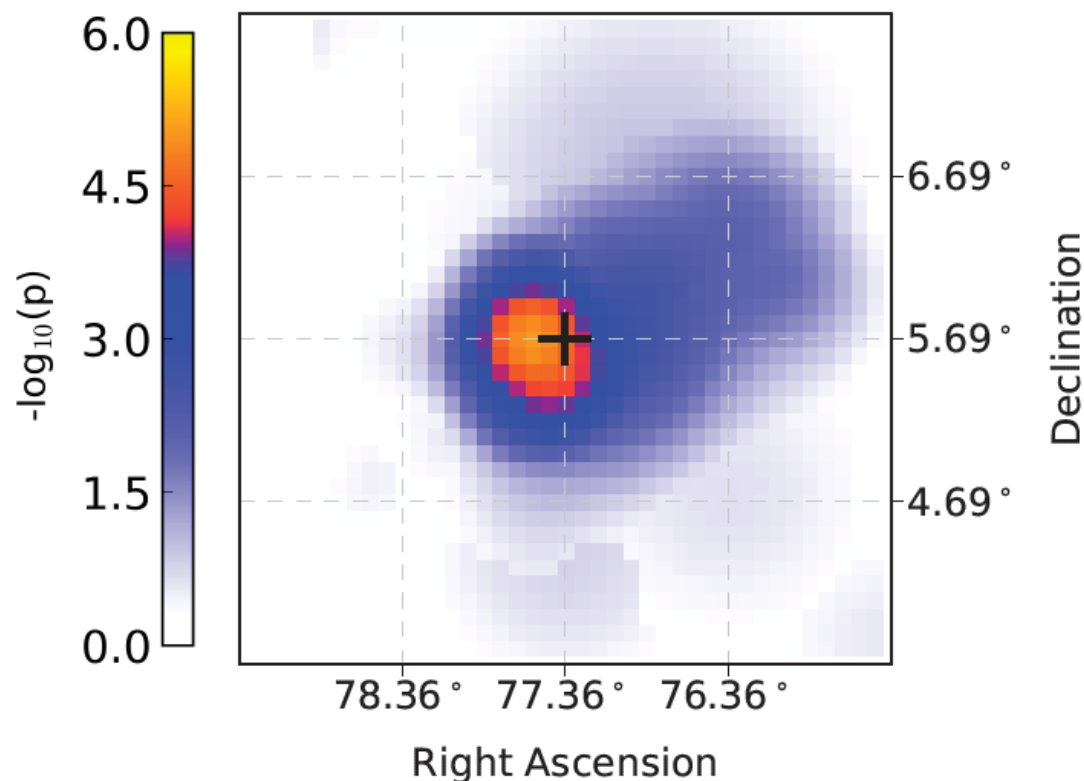
IceCube, *Fermi* –LAT, MAGIC, Agile, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, KISO, Liverpool, Subaru, *Swift*, VLA, VERITAS

- neutrino: time 22.09.17, 20:54:31 UTC
energy 290 TeV
direction RA 77.43° Dec 5.72°
- Fermi-LAT: flaring blazar within 0.1° (6x steady flux)
- MAGIC: TeV source in follow-up observations
- follow-up by 12 more telescopes
- → IceCube archival data (without look-elsewhere effect)
- → Fermi-LAT archival data



search in archival IceCube data:

- ~100 day flare in December 2014
- accompanied by hardening of the Fermi spectrum



IceCube Neutrino Flare

2014 - 2015



we identified a source of high energy cosmic rays:

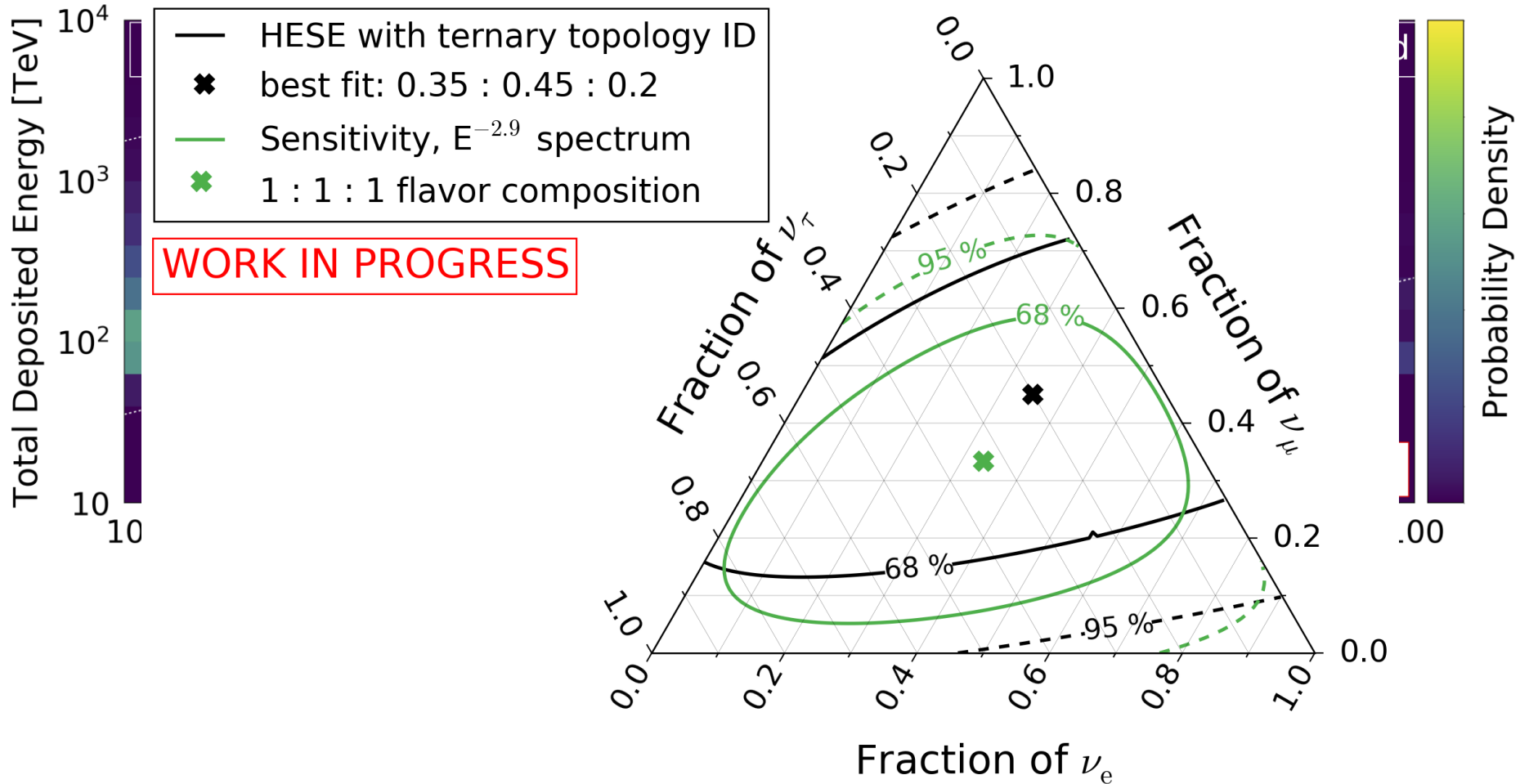
the active galaxy (blazar) TXS 0506+056 at a
redshift of 0.33

extensive multiwavelength campaign will allow us
to study the first cosmic accelerator

Victor Hess 1912



high-energy starting events – 7.5 yr

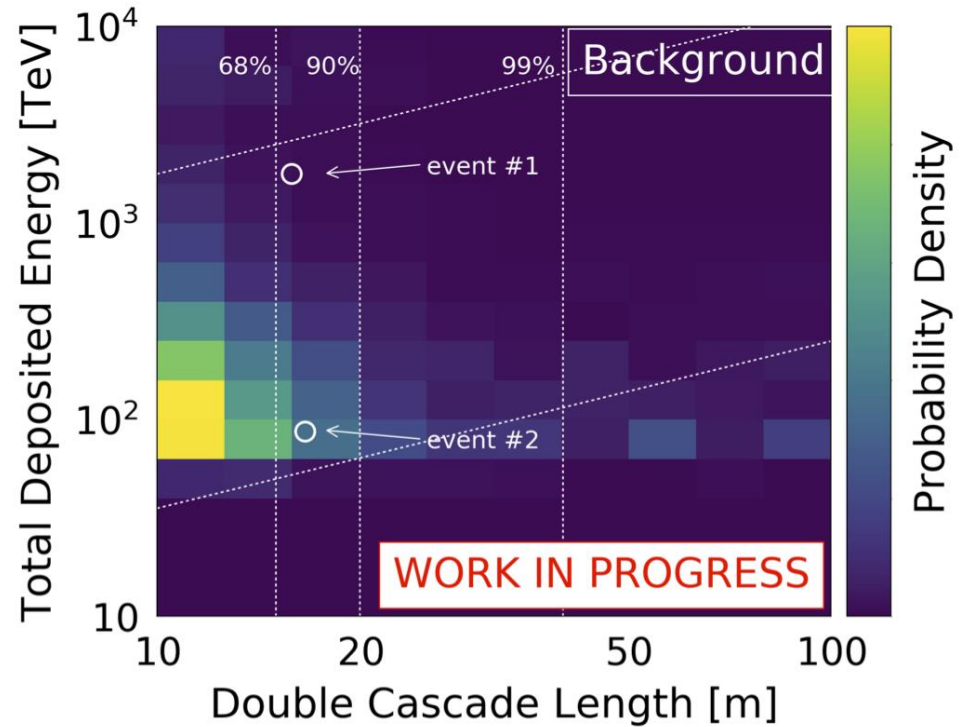
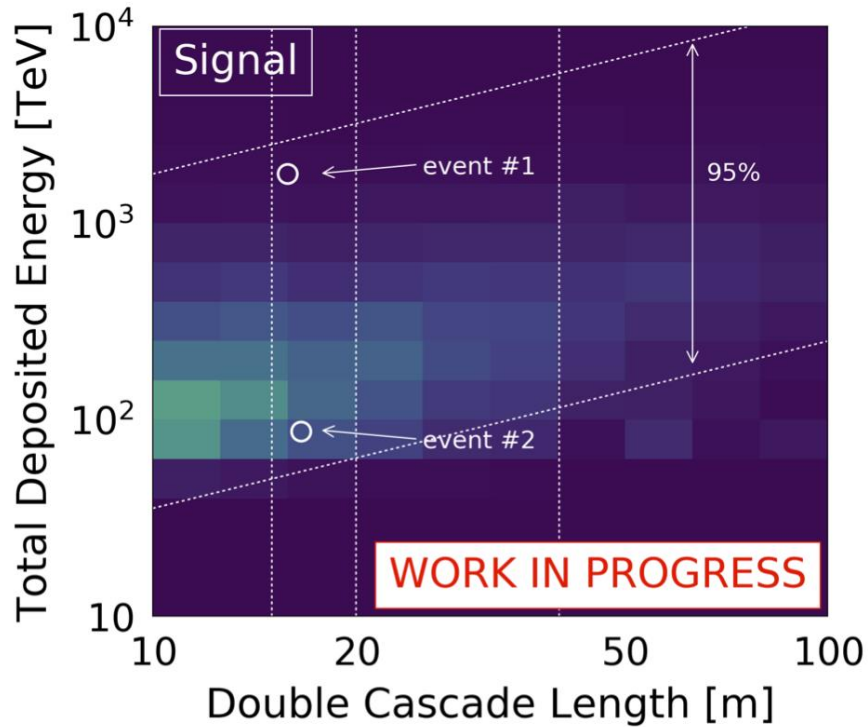


oscillations of PeV neutrinos over cosmic distances to 1:1:1

high-energy starting events – 7.5 yr

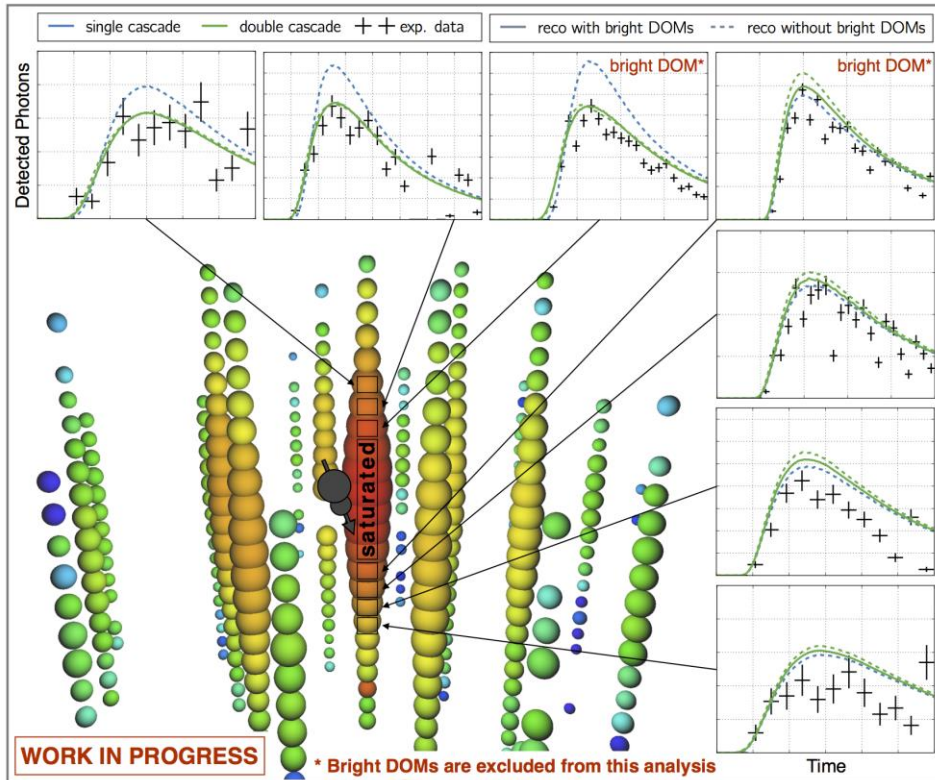
— HESE with ternary topology ID

$\frac{0}{0}$

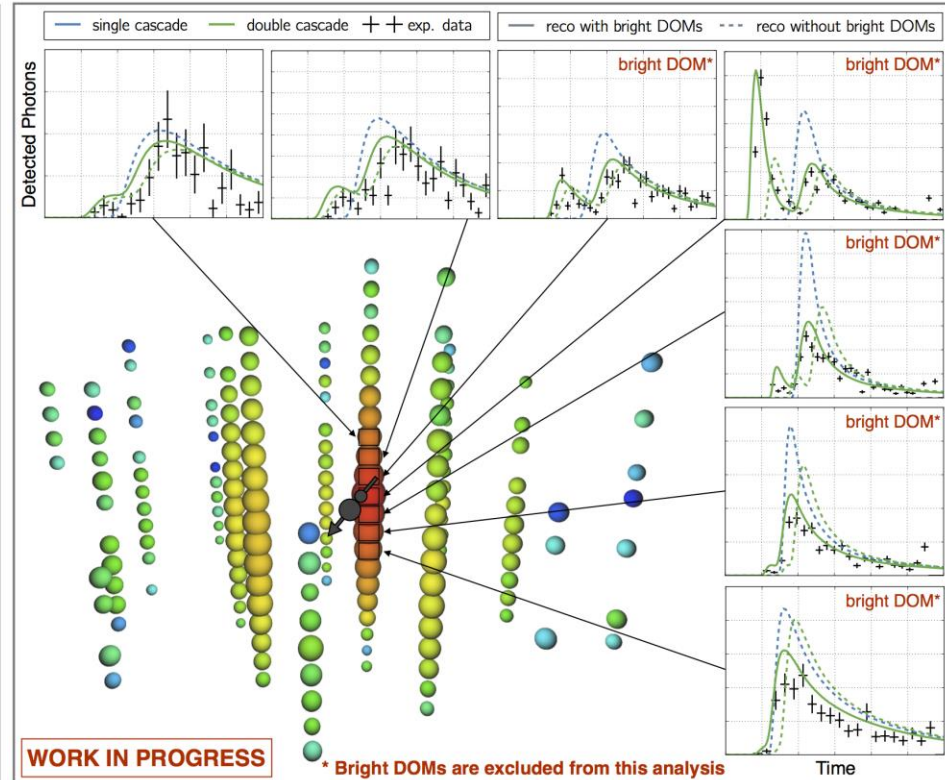


Fraction of ν_e

high-energy starting events (starting) – 7.5 yr



Double cascade Event #1



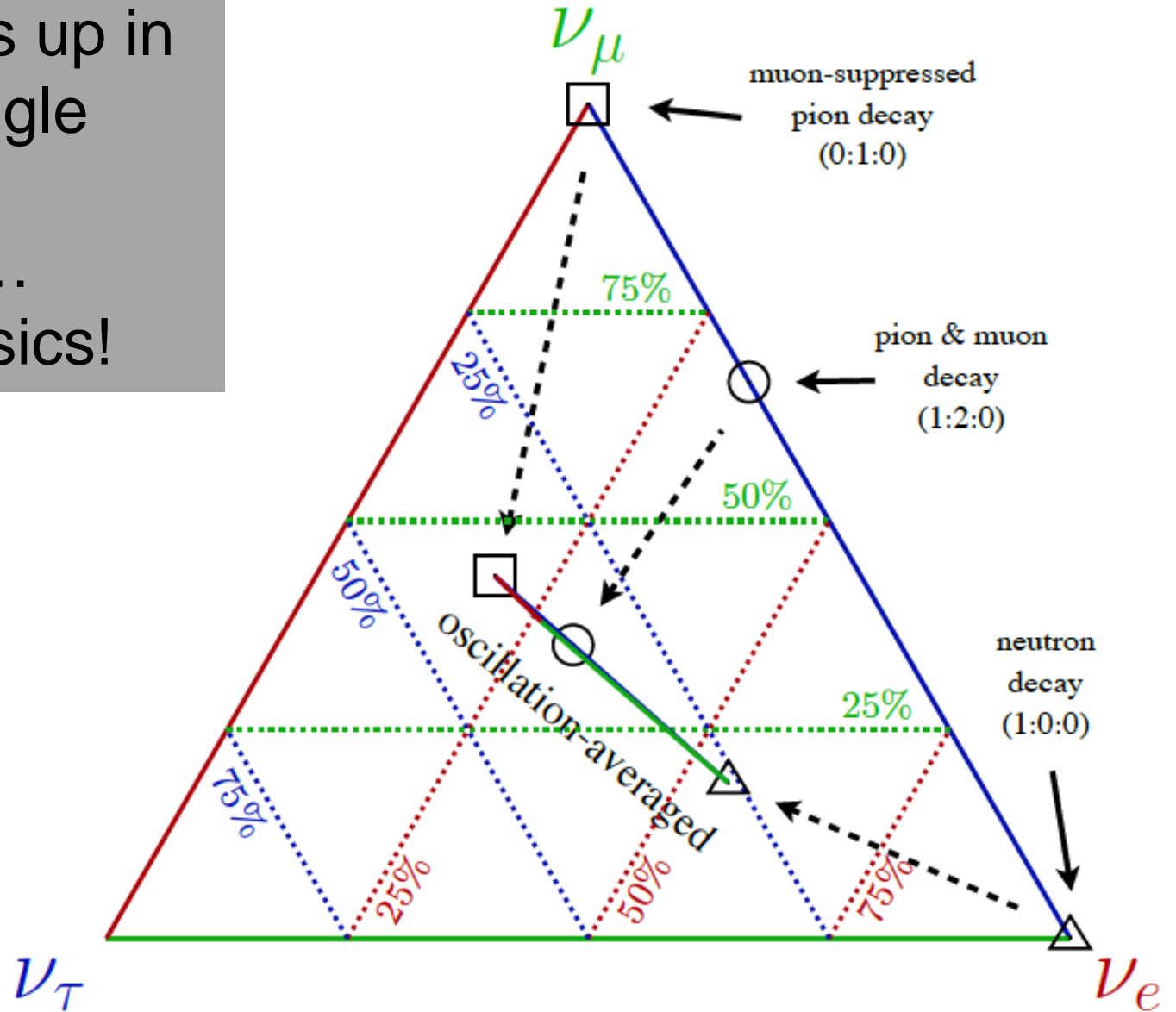
Double cascade Event #2

“Bright” DOMs not used in reconstruction

Direction and two reconstructed cascades shown in dark gray

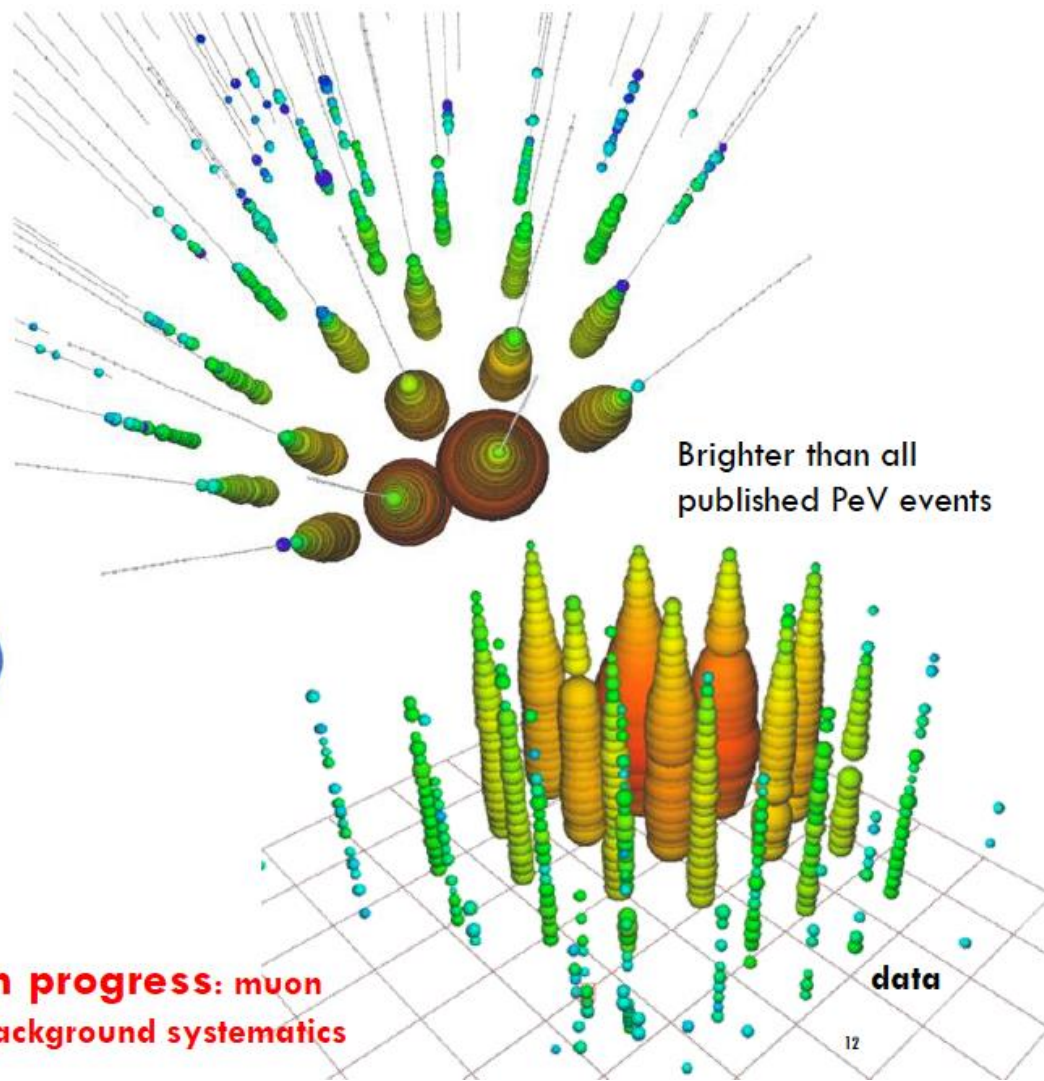
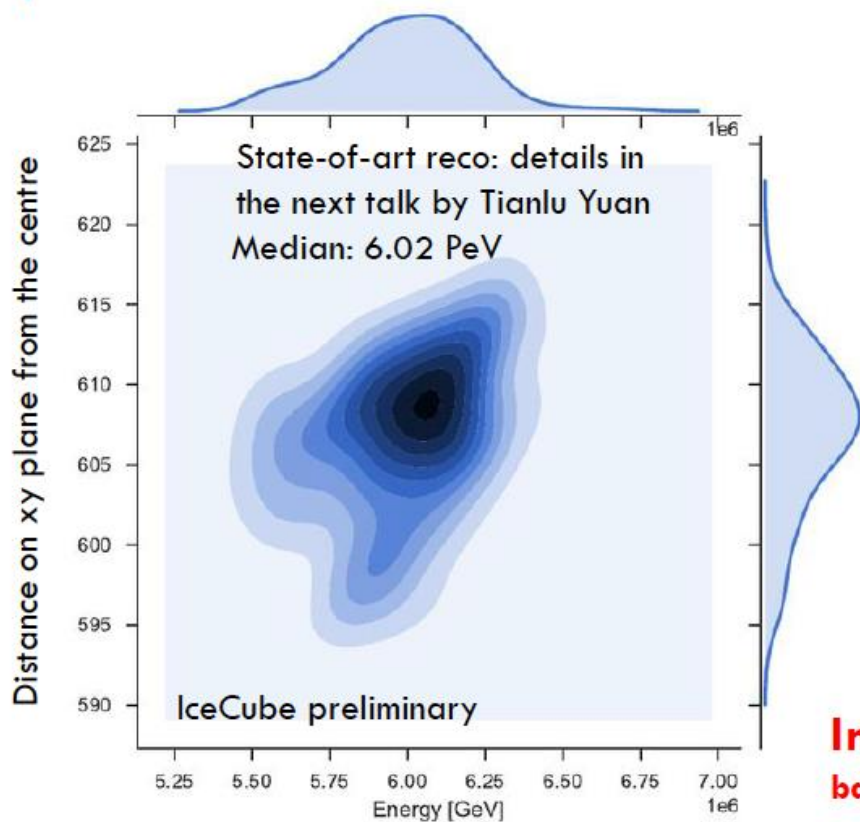
every astrophysical
model ends up in
the triangle

if not...
new physics!

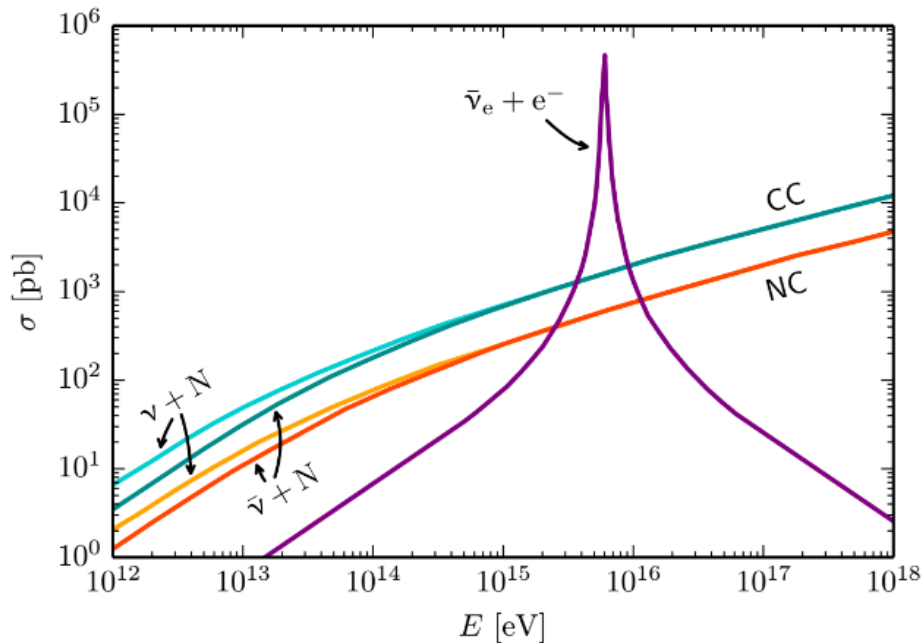
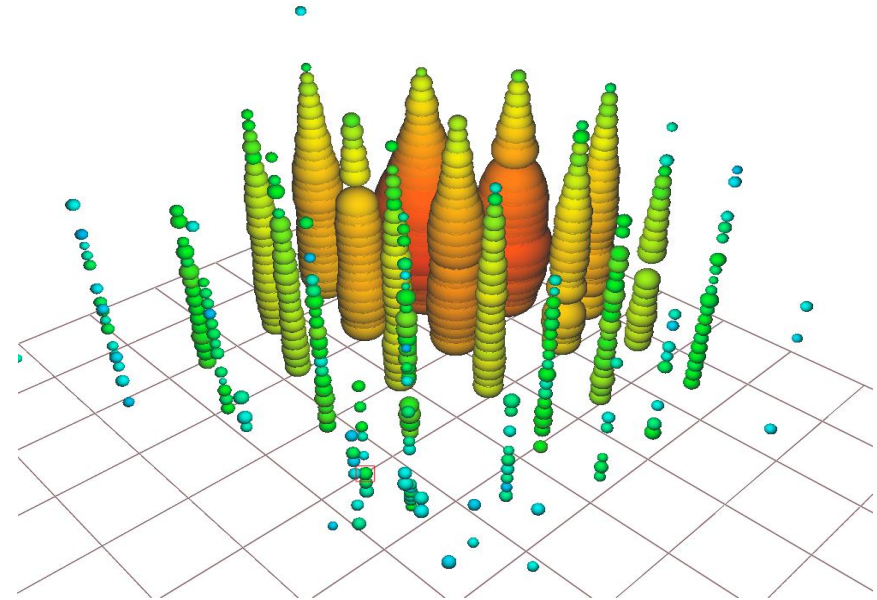
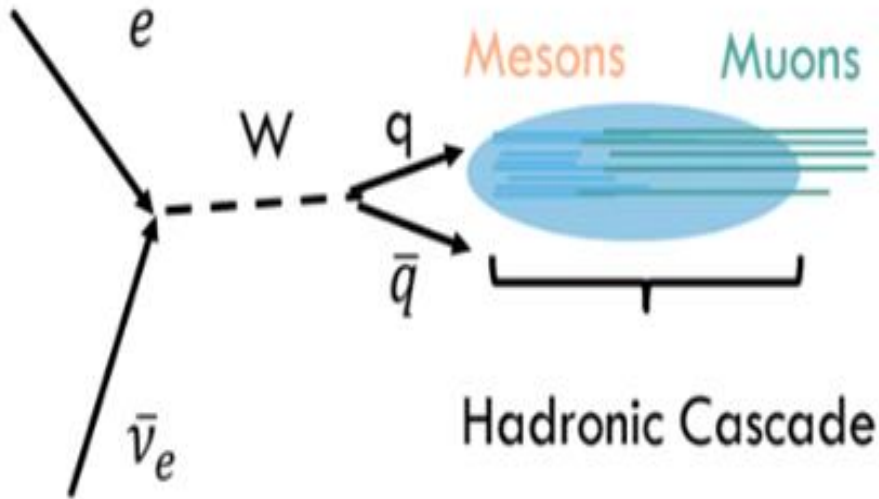


Partially contained event with energy 5.9 PeV

HIGHEST-ENERGY NEUTRINO CANDIDATE



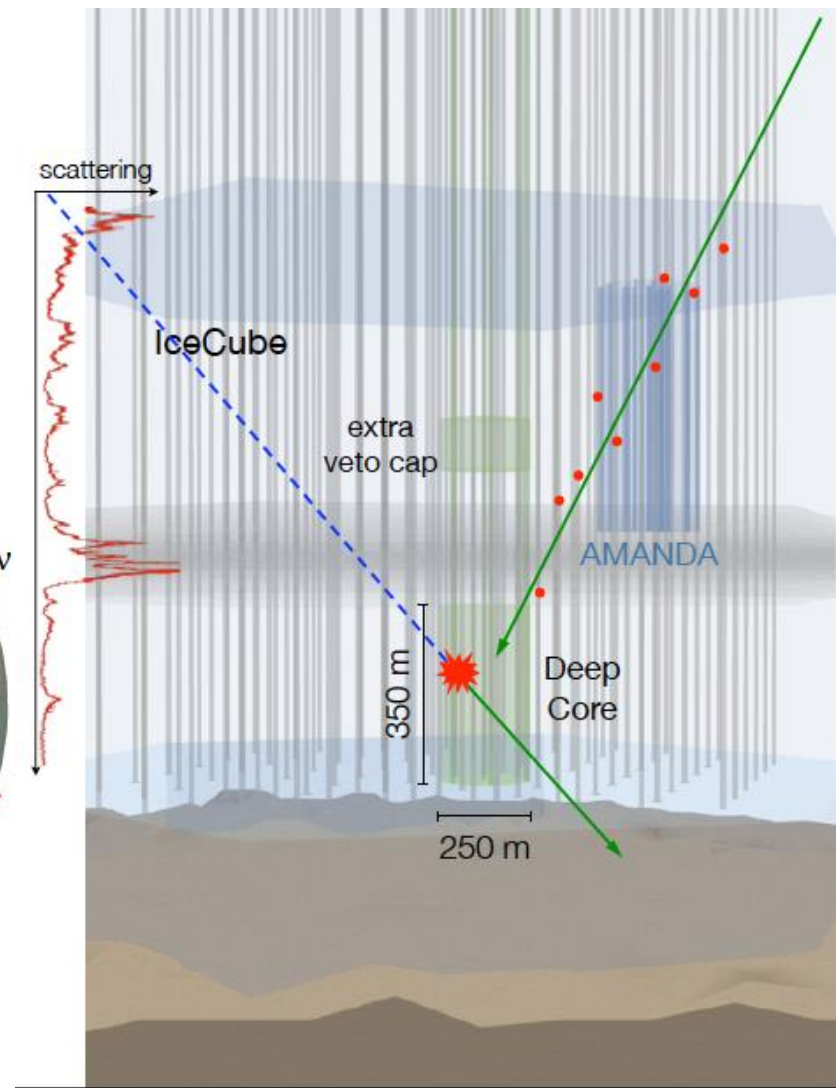
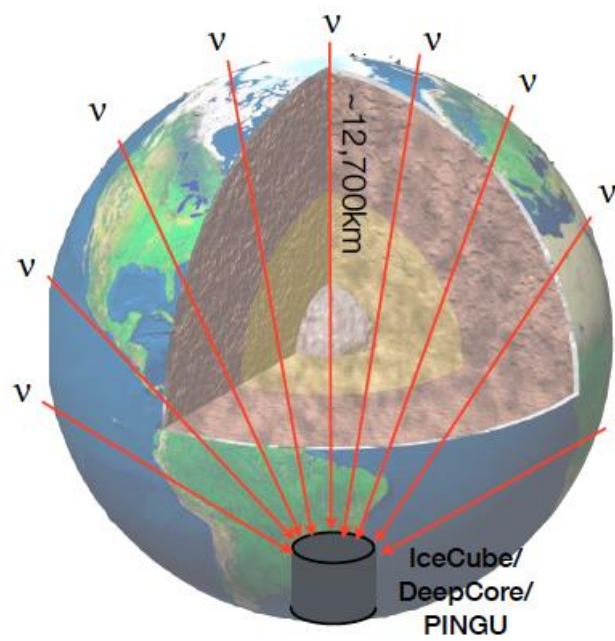
Glashow resonance: anti- $\nu_e + \text{atomic electron} \rightarrow \text{real } W$



- partially-contained PeV search
- deposited energy: 5.9 ± 0.18 PeV
- typical visible energy is 93%
- \rightarrow resonance: $E_\nu = 6.3$ PeV

work on-going

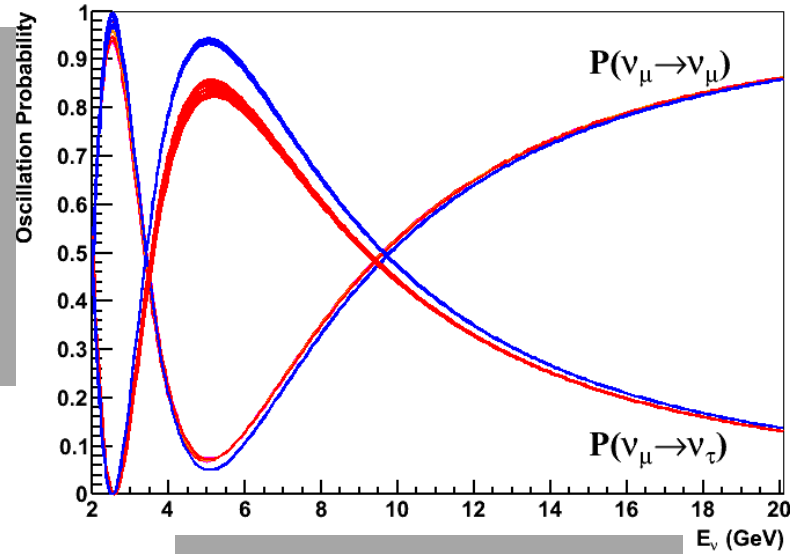
one million
atmospheric
neutrinos...



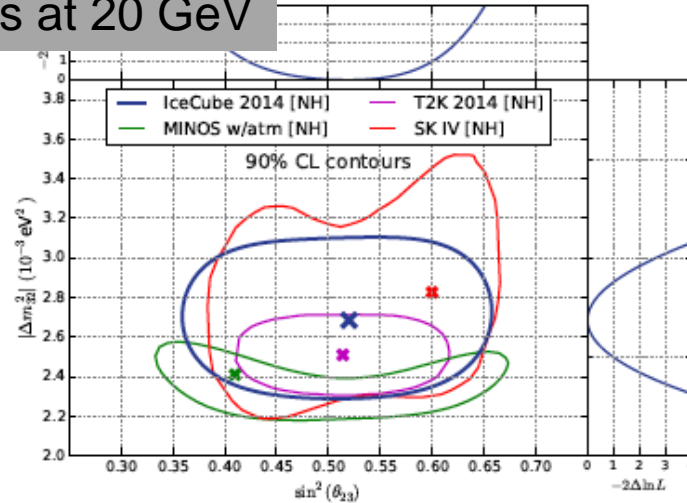
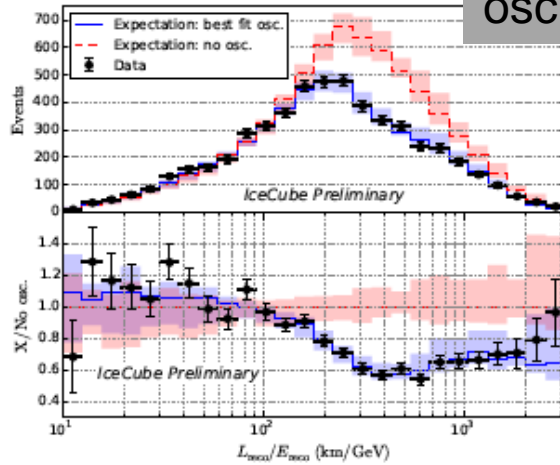
IceCube

DeepCore

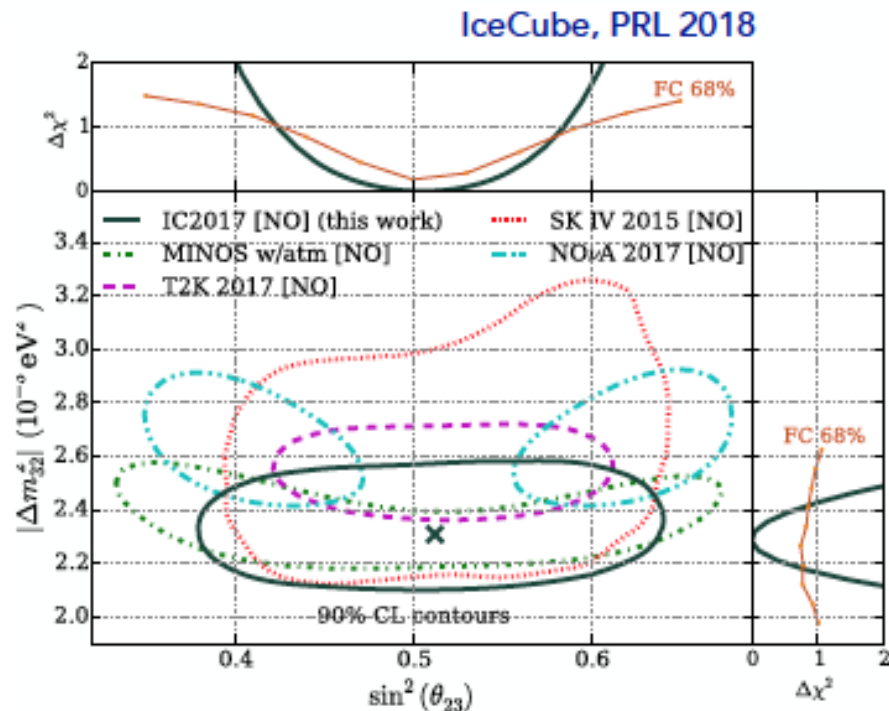
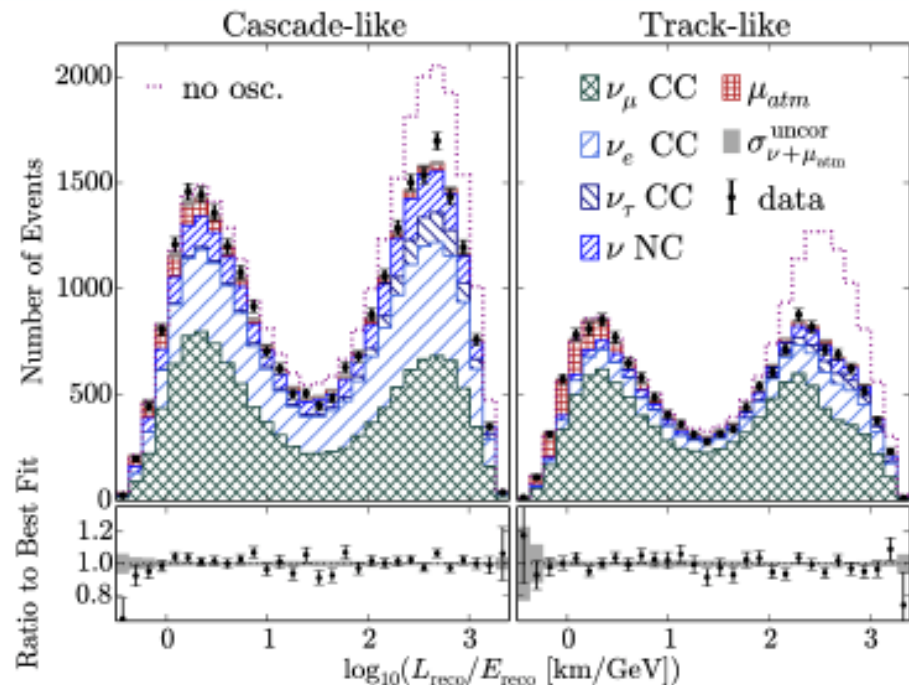
PINGU



oscillations at 20 GeV



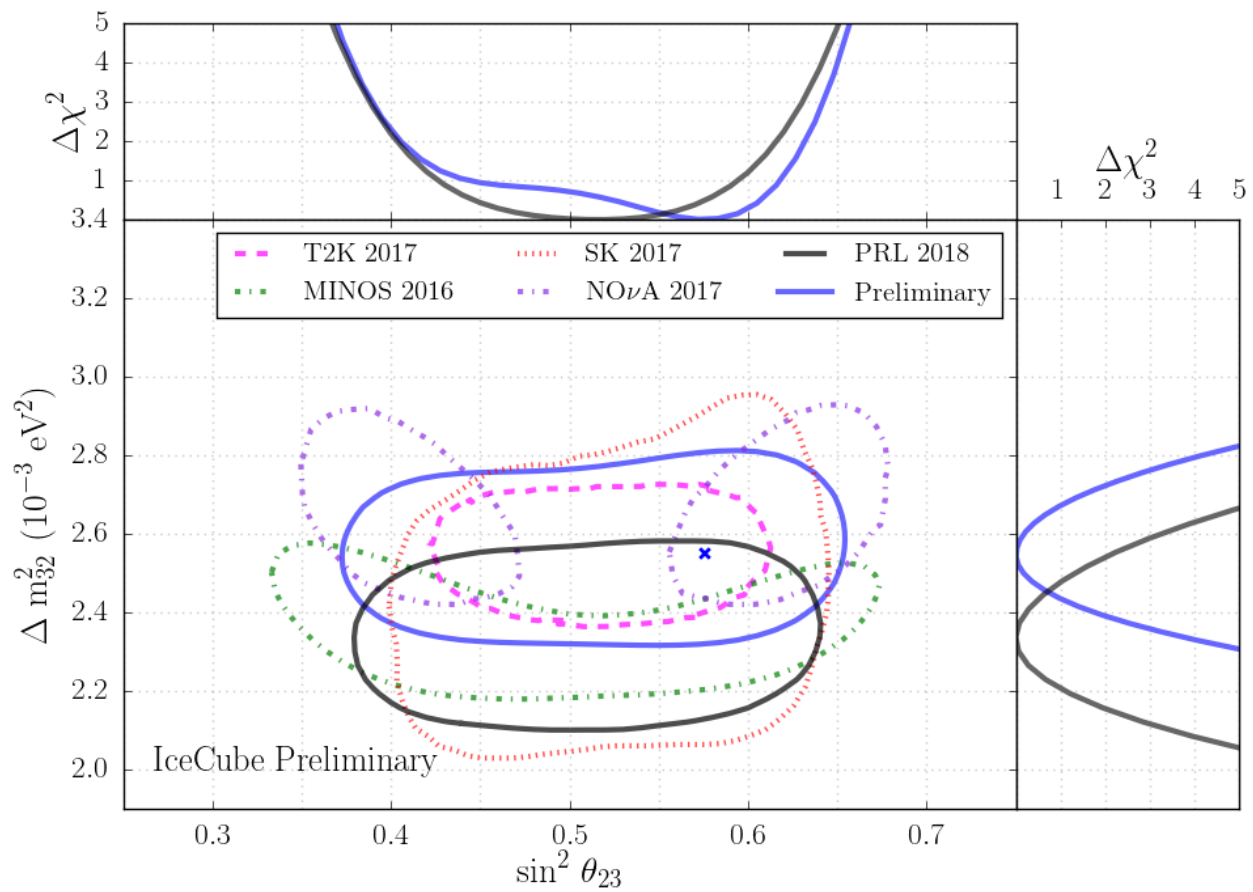
Neutrino Oscillation



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

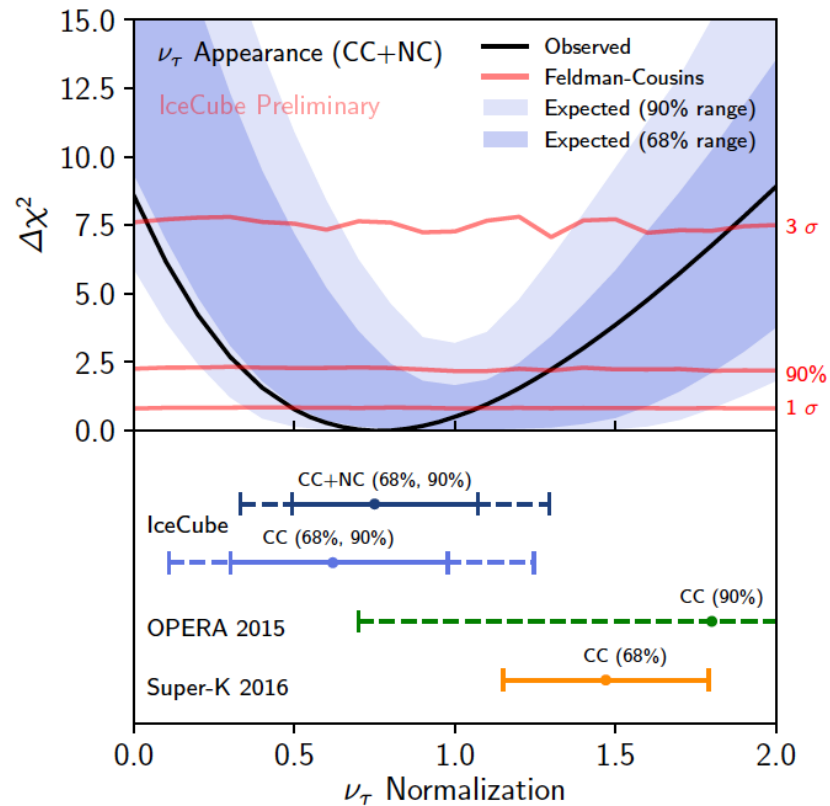
$$\Delta m_{32}^2 = 2.31^{+0.11}_{-0.13} \times 10^{-3} \text{eV}^2$$

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



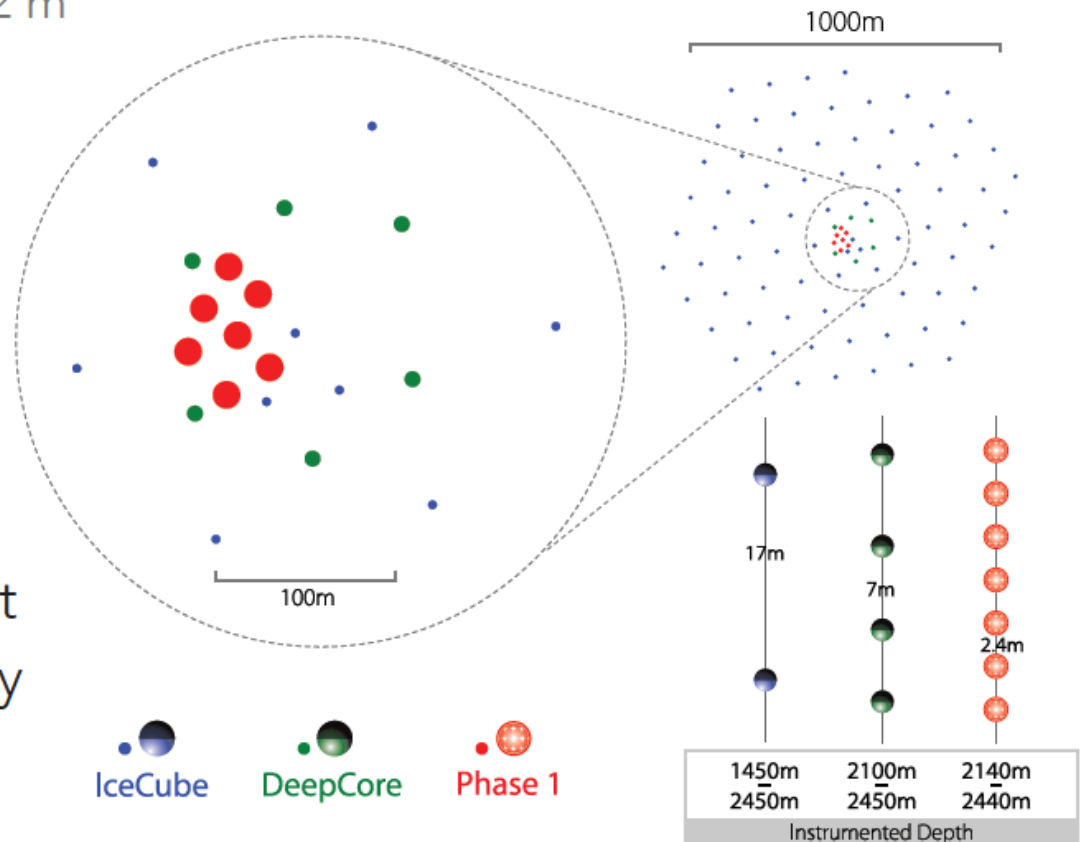
Tau Appearance and PMNS Unitarity

- 3-yr DeepCore result competitive with 15-yr Super-K measurement
 - Analysis improvements and additional data will improve precision
- IceCube Upgrade will achieve $\pm 7\%$ in 3 years
 - $\sim 10\%$ precision needed for real tests of unitarity of PMNS mixing matrix



Next Step: the IceCube Upgrade

- Seven new strings of multi-PMT mDOMs in the DeepCore region
 - Inter-string spacing of ~ 22 m
- Suite of new calibration devices to boost IceCube calibration initiatives
- Improve scientific capabilities of IceCube at both high and low energy

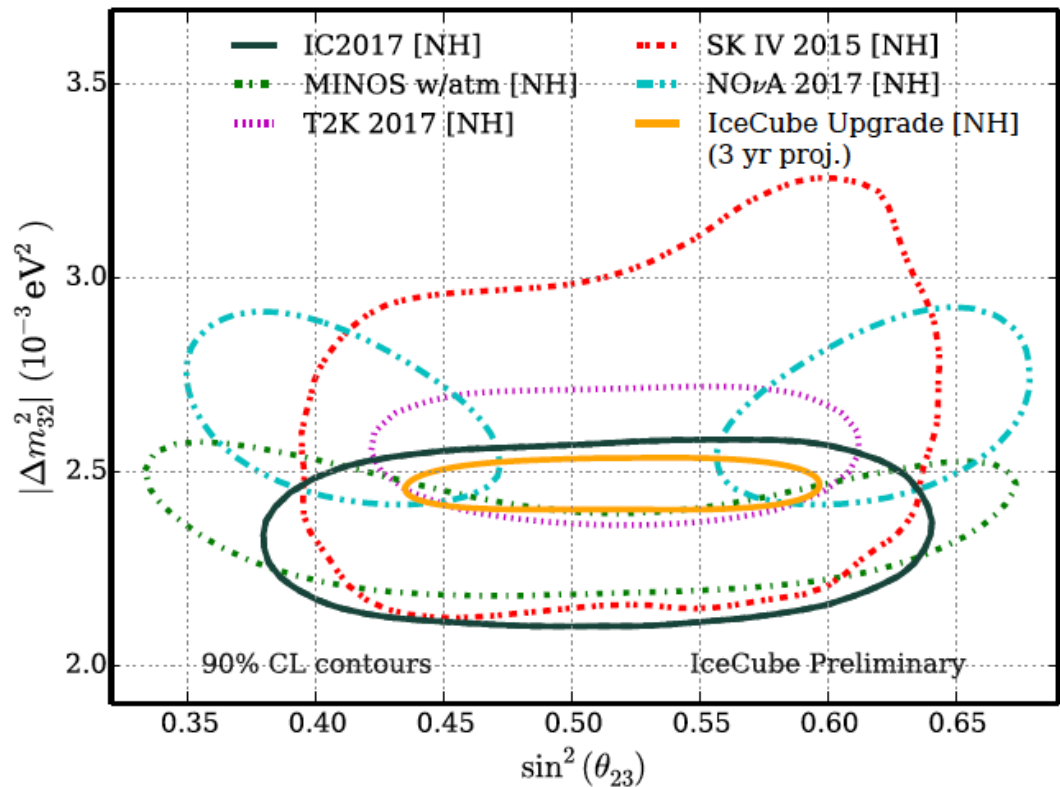


Atmospheric Oscillation Parameters

- Currently unclear whether $\sin^2 \theta_{23}$ is maximal

- 3rd mass state made up of equal parts ν_μ, ν_τ
- Evidence of new symmetry?

- T2K and IceCube prefer maximal mixing, NOvA disfavors maximal at $2.6\sigma^*$

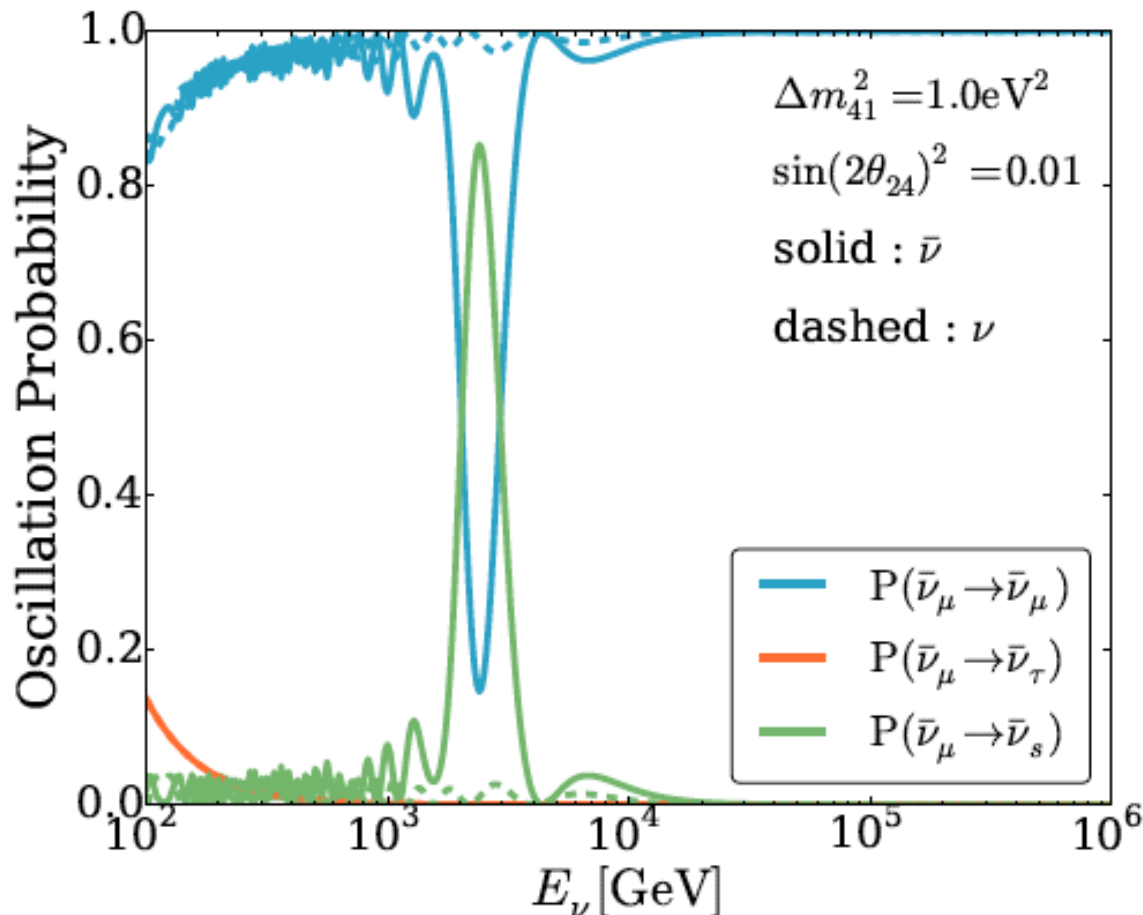


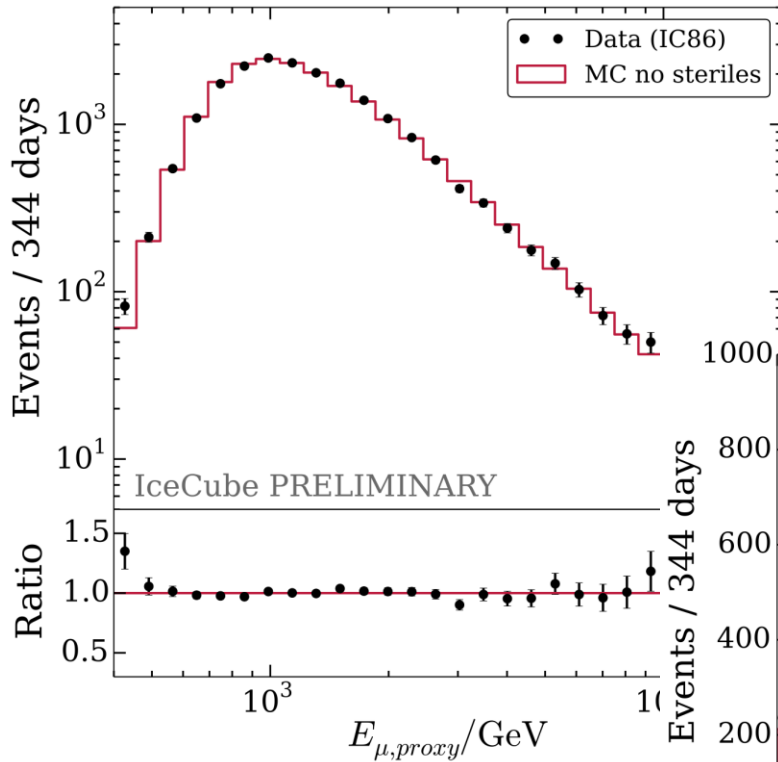
- Higher energy range of IceCube also permits octant determination via matter resonance (99.93% CL expected at NOvA 2017 best fit)

eV sterile neutrino \rightarrow Earth MSW resonance for TeV neutrinos

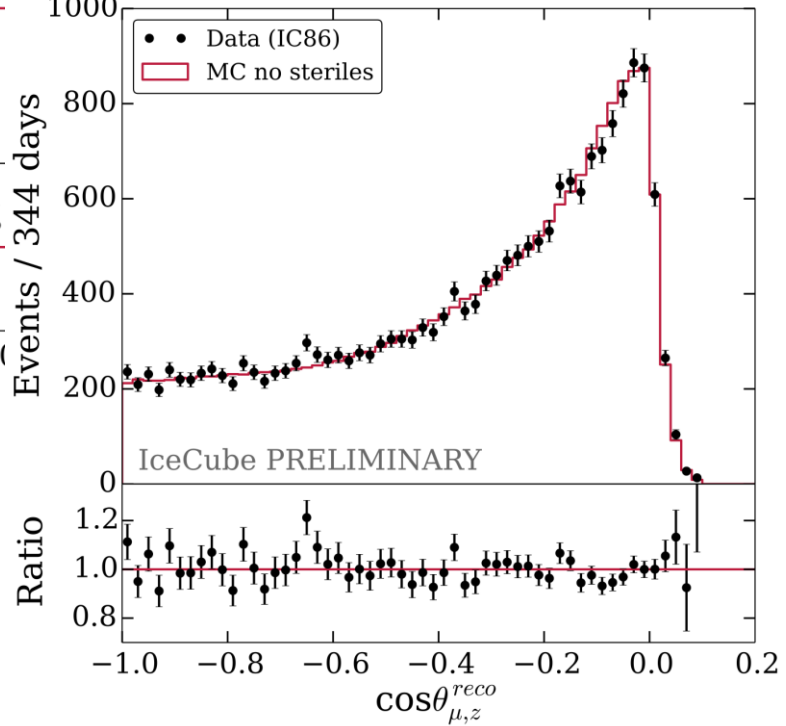
In the **Earth** for sterile neutrino $\Delta m^2 = O(1eV^2)$ the MSW effect happens when

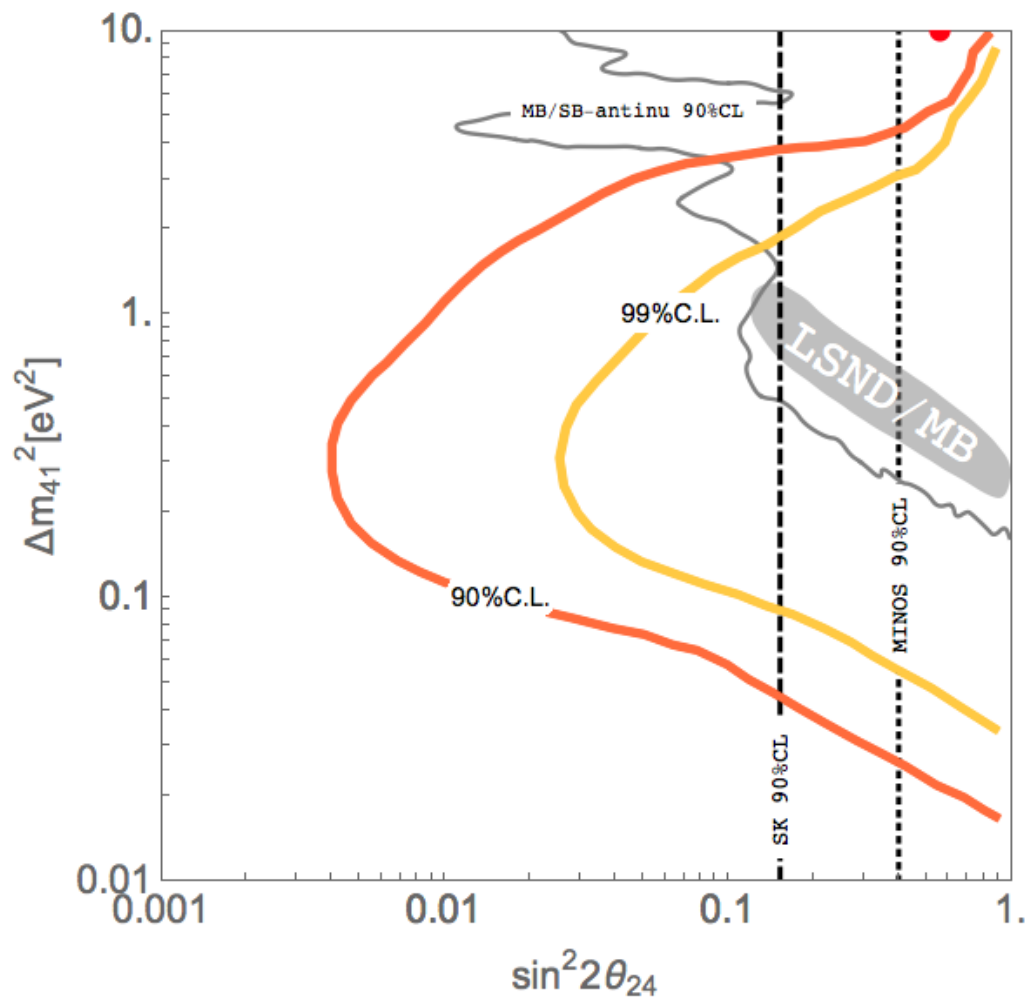
$$E_\nu = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F N} \sim O(\text{TeV})$$



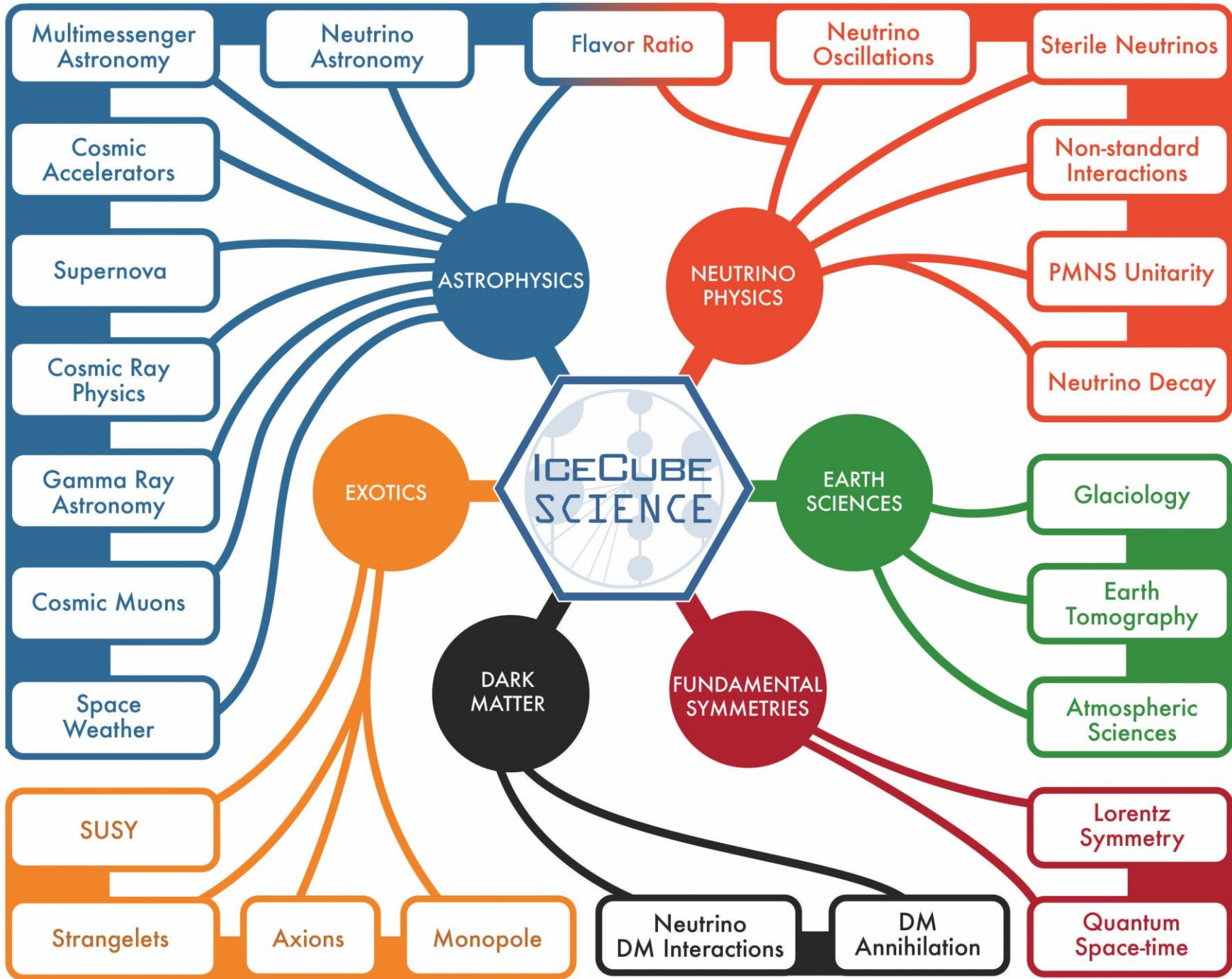


no telltale structure
in the zenith angle
distribution





from 1 \rightarrow 7 years of data soon



THE ICECUBE COLLABORATION



AUSTRALIA 1

UNITED KINGDOM 1

UNITED STATES 25

