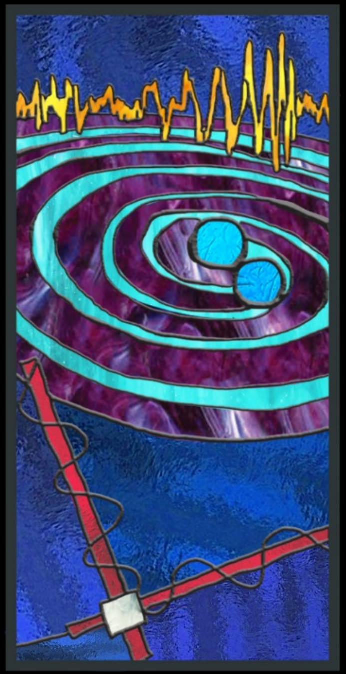
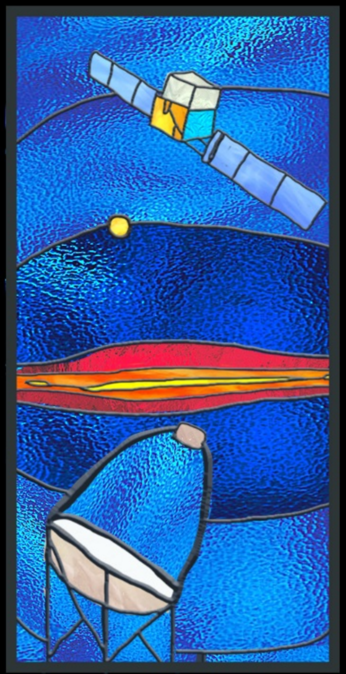




Multimessenger Astronomy with Neutrinos at the South Pole

IceCube and Future Observatories in the Ice

Kael Hanson

Director, Wisconsin IceCube Particle Astrophysics Center (WIPAC)
University of Wisconsin – Madison

COSMO 2018 | Daejeon, South Korea

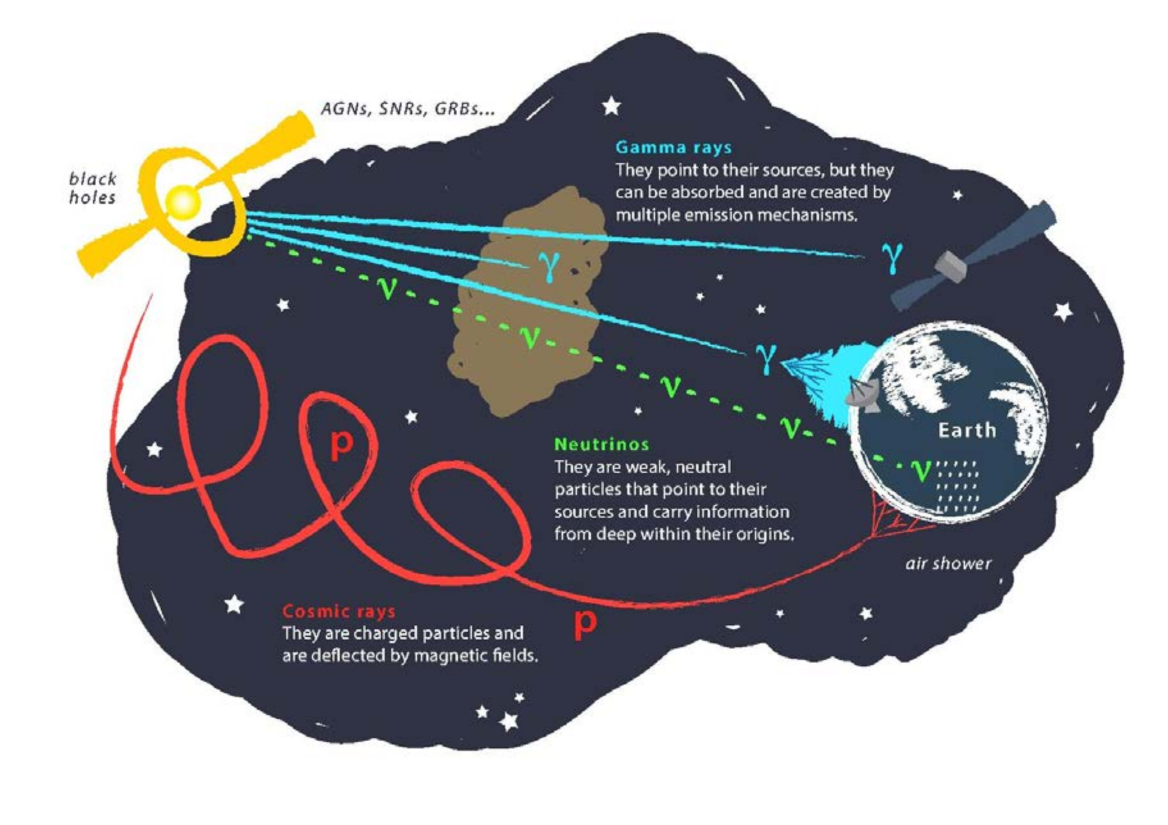
August 31st 2018

ICECUBE GEN2

The Case for Multimessenger Astronomy

Take all you are given

High energy astrophysical acceleration sites are likely emitters of gammas, charged ions, and neutrinos. Each particle used as a messenger particle has it own strengths and weaknesses – we can push our knowledge deeper by combining them.



Gamma rays: point back to sources and easily detectible but there is problem of interactions in dense sources or in transit over not-so-long distances. PeV and above constrained to intergalactic-scale distances. EM and hadronic production possible and often difficult to discriminate.

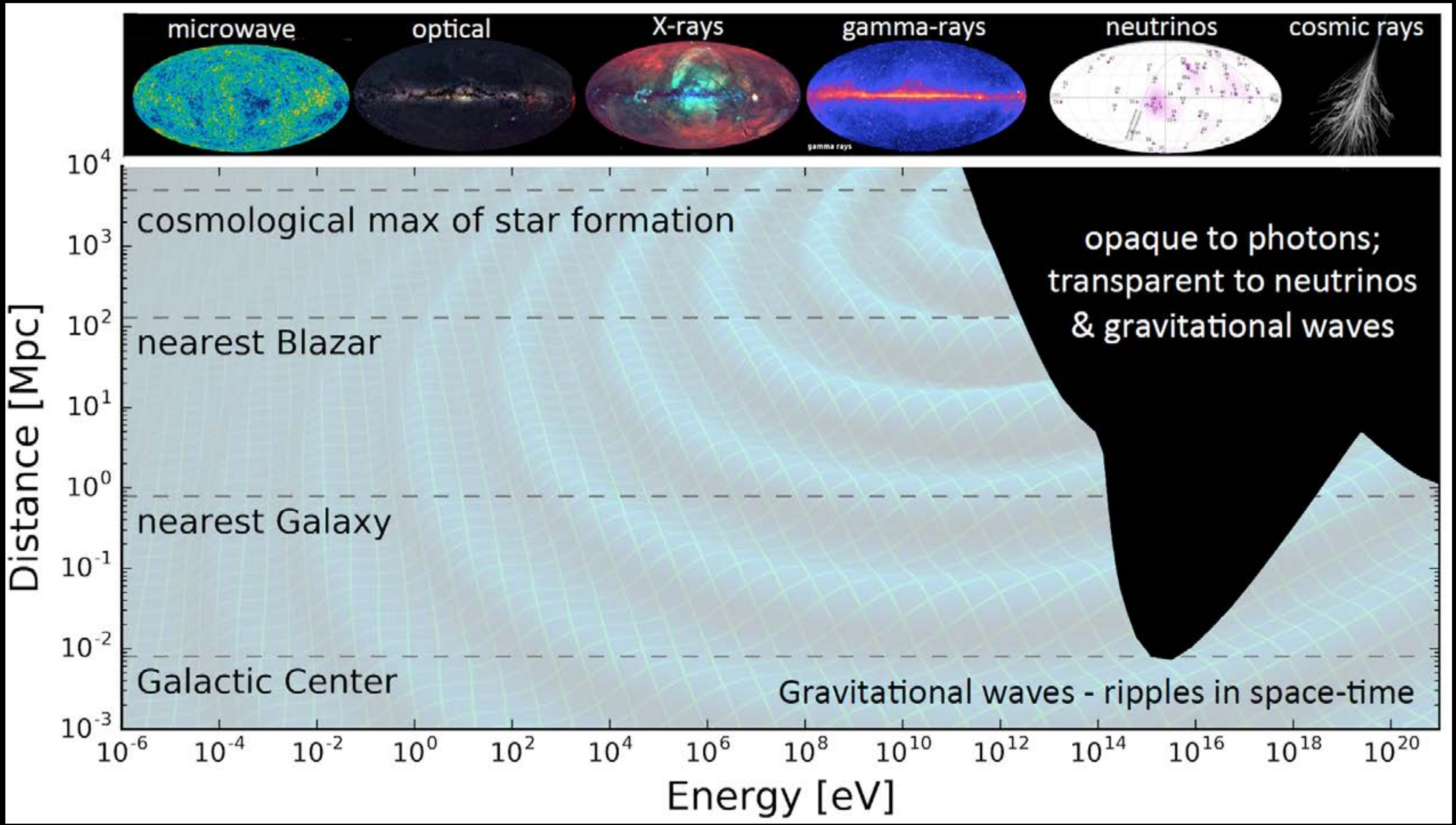
Cosmic rays: and up to 10^{19} eV travel over cosmological distances. Not impossible but difficult to trace back to source due to deflection in GMF/IGMF. UHE detection requires large ground arrays.

Neutrinos: point back to sources and offer pristine look even deep into compact objects; no horizon – a good thing overall but has implications in point-source searches; require large, expensive underground or underwater (ice) detector facilities; radio is however promising economical technique at UHE.

Challenge / Opportunity: Cosmic Horizons

Neutrinos are alone the only astronomical messengers capable of directly imaging the extreme energy sky. Photons interact with EBL and already at 100's of TeV are limited to Mpc scales.

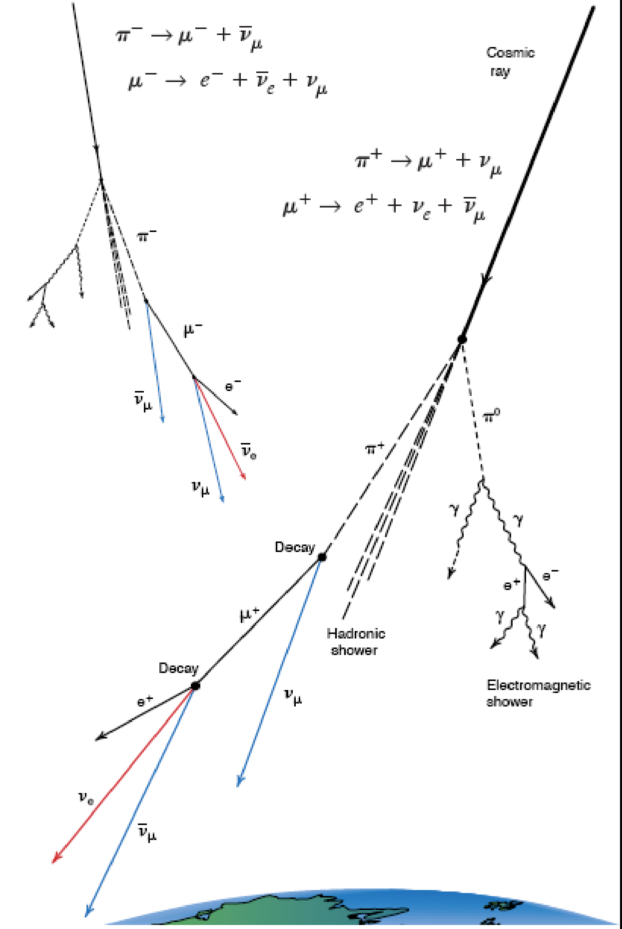
Charged cosmic rays processed by galactic and inter-galactic magnetic fields as well as galactic diffusion: energy and angles at observation no longer follow source.

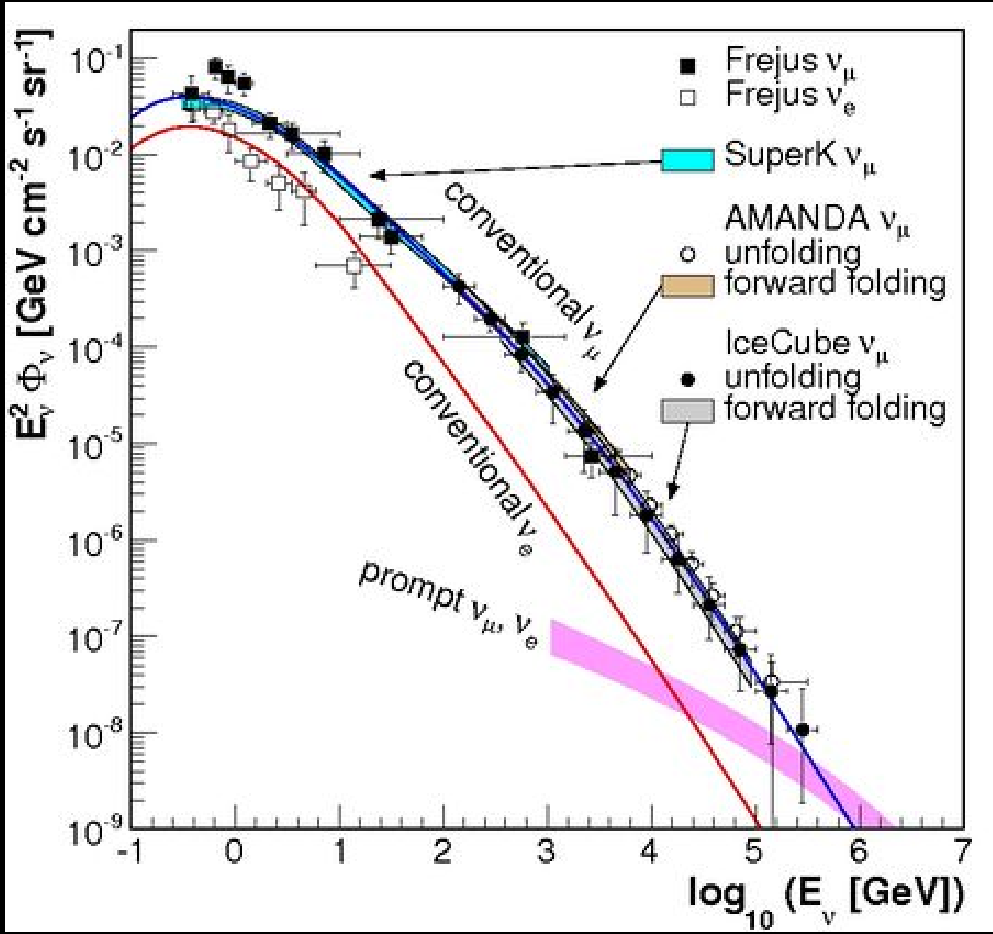


Atmospheric Neutrino "Backgrounds"

Neutrinos are also produced in quantity by cosmic ray interactions in the Earth's atmosphere: decaying mesons yield muons, ν_e, and ν_μ (not ν_τ however). These form a nearly irreducible background for astrophysical neutrinos (IceCube detects 1 every 5 minutes vs 1/week for astrophysical ν).

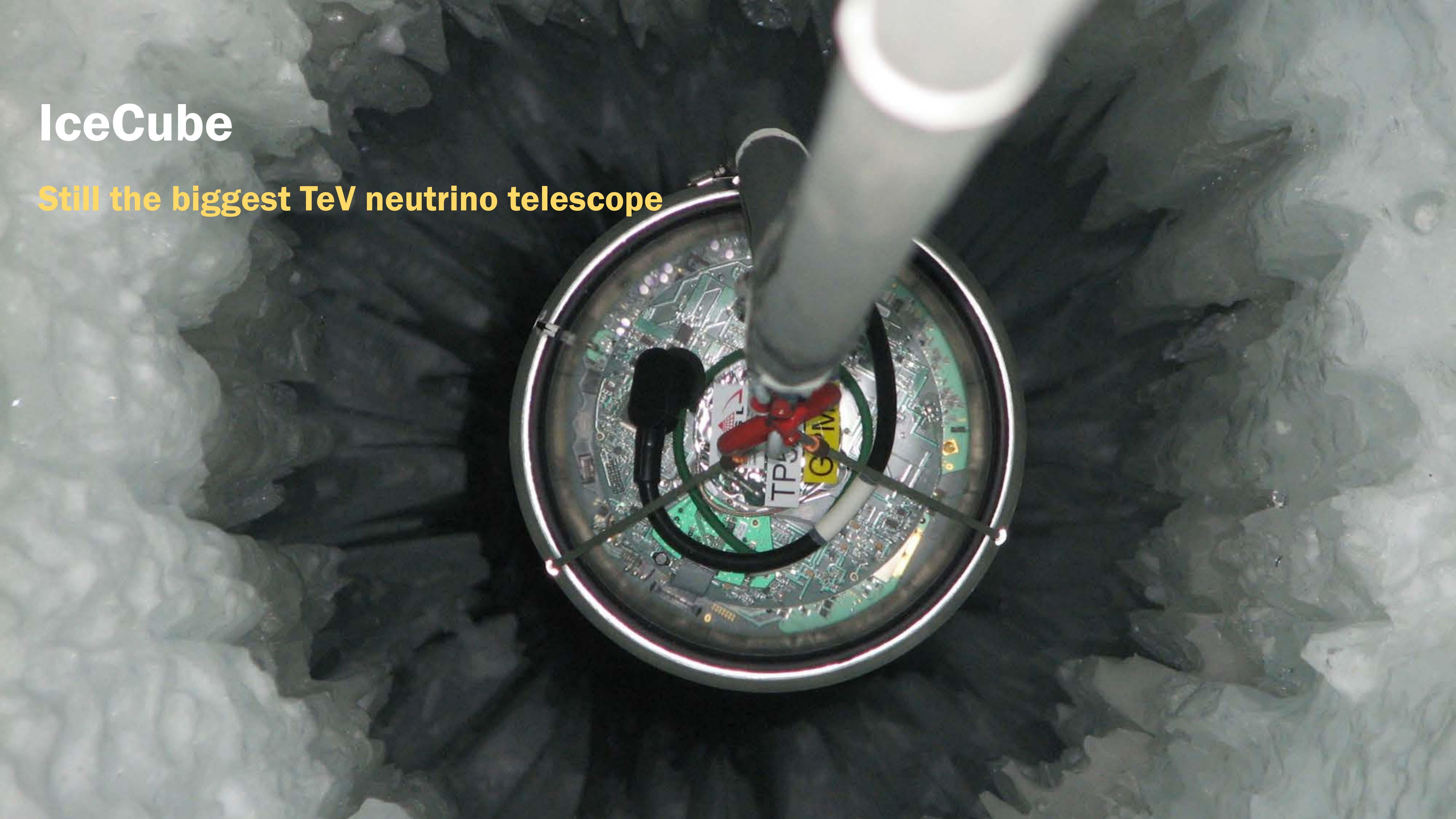
The handle is the energy: because mesons lose energy in the atmosphere the flux of atmospheric neutrinos is approx. power law with spectral index -3.7.





IceCube

Still the biggest TeV neutrino telescope



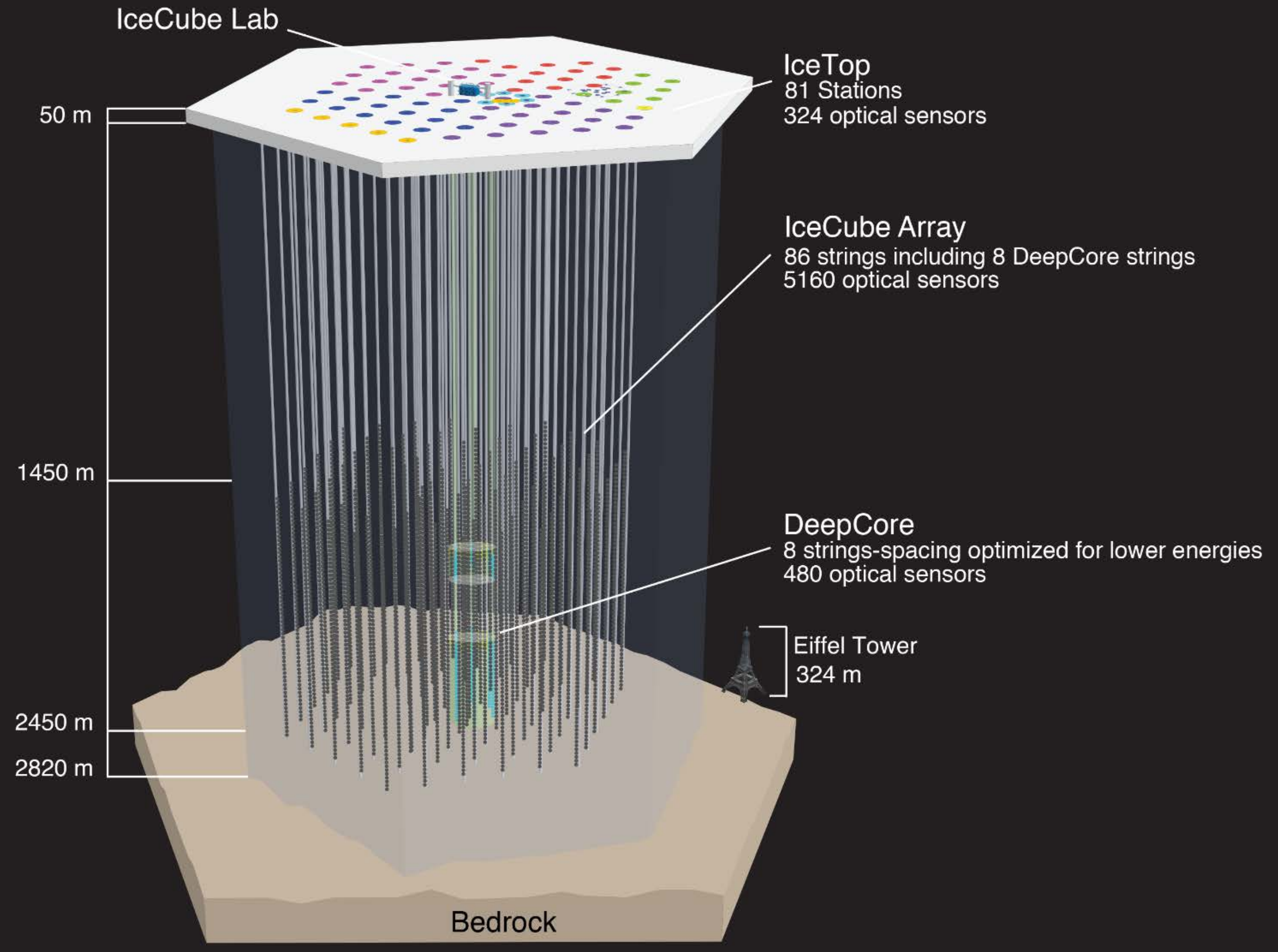
C Rott - SKKU

The IceCube Collaboration includes > 300 researchers from 47 institutes in 12 countries.

IceCube is one of the NSF's large facilities (LIGO, LSST, ... 2 dozen others).

The Operations and Management of the facility is handled by WIPAC at UW-Madison. In addition to having a large science group, our center supports the technical aspects: computing, data storage, detector maintenance, ...

The IceCube Neutrino Observatory



IceCube construction began in 2002 with design and procurement of the drill. The first string to be deployed was in Jan 2005. Over the next 6 season 85 more strings were deployed with the last string being "tied off" on December 17, 2010. Full 86 string data taking started May 2011.

TPC: $279M USD - $40M non-US

The South Pole site was chosen

(A) Because there is a lot of ice;

(B) Logistic support: 5 million lbs. of cargo were delivered and 77 person-years of effort on-ice it took to make IceCube. Everything was at that time airlifted inside LC-130 Hercules aircraft.

The IceCube Digital Optical Module (DOM)

Optical

- **Large Area Photocathode** 10” 10-stage Hamamatsu R7081-02 PMT (*QE* 24% @ 420 nm); High QE variant (*QE* 35% @ 420 nm) used in DeepCore DOMs
- **Low noise** 500 Hz bkg count rate in-ice @ 0.25 pe threshold.
- **Glass / Gel** 0.5” thick Benthos pressure housing rated to 10,000 psi. Better transmission in 330 - 400 nm relative to AMANDA OM. Low radioactivity glass.
- **Optical calibration** Each DOM calibrated ε(λ, T) in the lab to about 7%; *in-situ* flashers additionally permit in-ice optical measurements

Communicatons / Timing

- Comunications is digital at rate of 1 Mbit/s shared by 2 DOMs on a single copper pair.
- The DOMs each timestamp PMT pulses using a local XO. Nevertheless, 1 ns time resolution is achieved through automatic clock synchronization protocol

Digitizer

IceCube adopted waveform readout of PMT pulses to deal with complex scattering of photons in ice. There are two digitizers:

- 300 MSPS ASIC 14-bit effective resolution but limited to ~500 ns
- 40 MSPS pipelined ADC capture to 6.4 μs

Smart Sensor

FPGA + ARM CPU SoC. 4k-hit deep memory buffer stores hits until readout over 1 Mbit digital link to surface.

Power

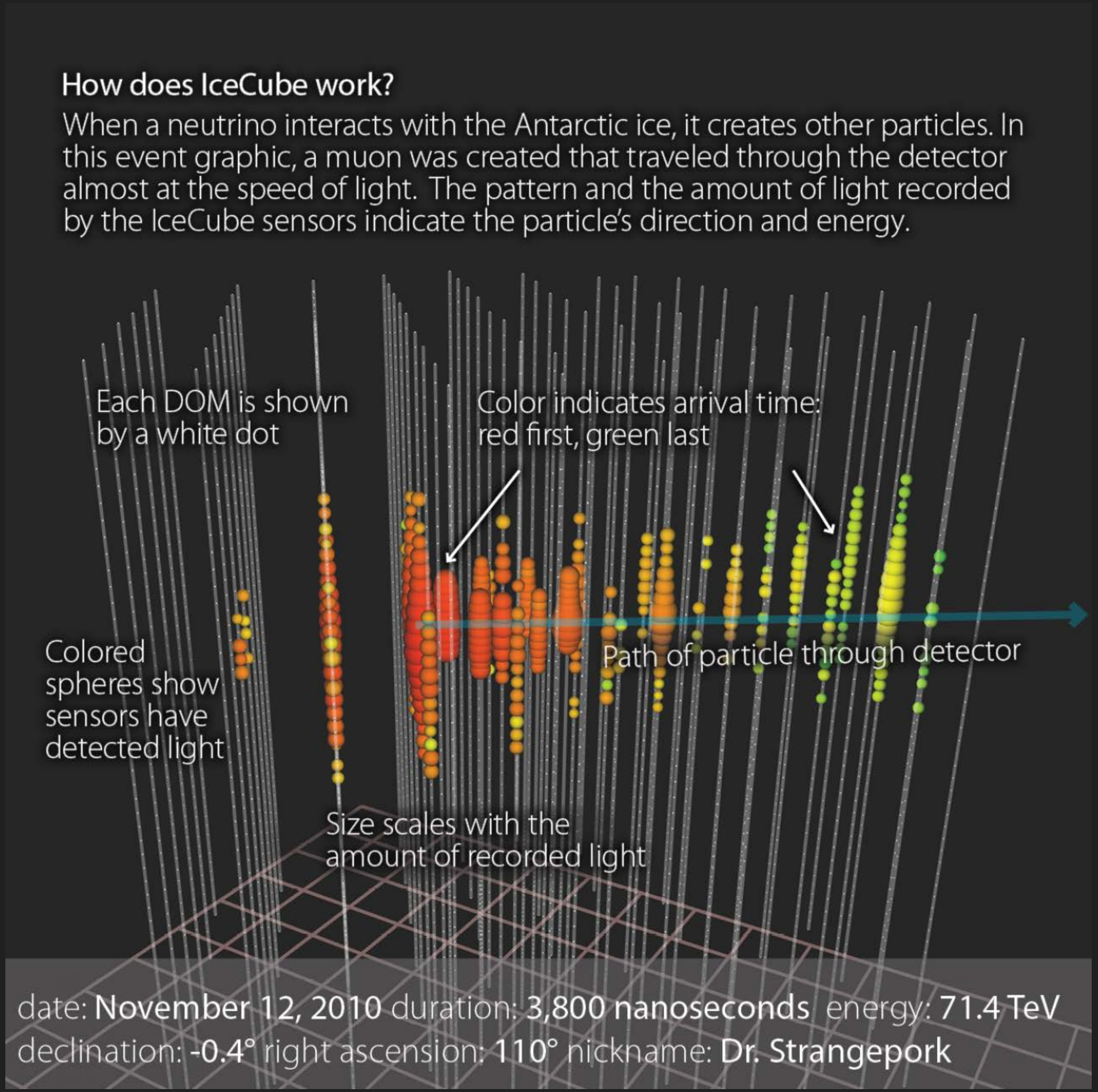
Power supplied by 18 AWG Cu pair to surface (3.5 km). 96 V, 3.75 W per channel (DOM)

Detecting Neutrinos in the Ice

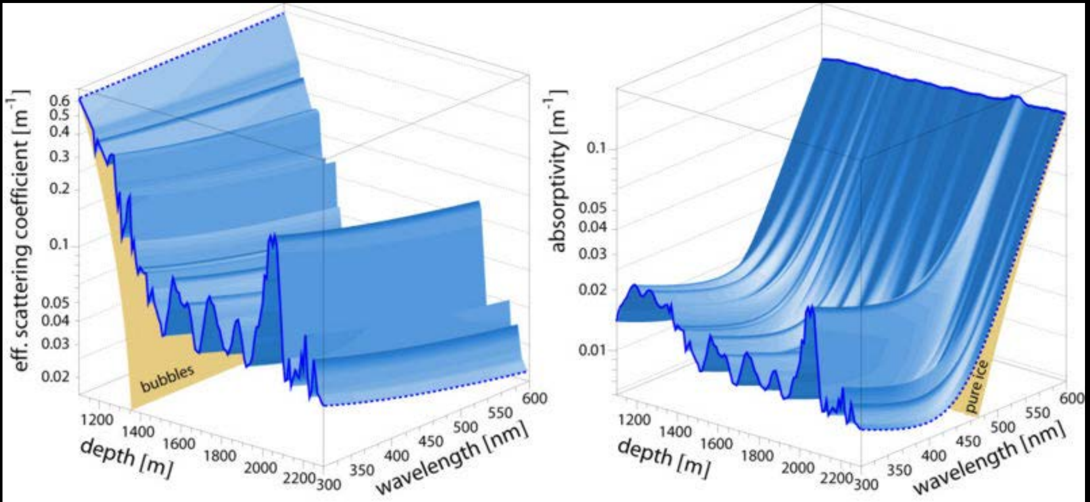
IceCube is "water" Cherenkov detector: we detect the charged ultrarelativistic secondaries which are produced in neutrino scattering in ice or detect CR muons and their stochastic secondaries.

Ice is a good calorimetric medium: we can get 10% resolution on E (dE/dX for muons).

Scattering and non-uniformity is problematic both for precision reconstruction and for simulation of the detector. Still we are able to obtain O(½) degree angular resolution for tracks.



Ice

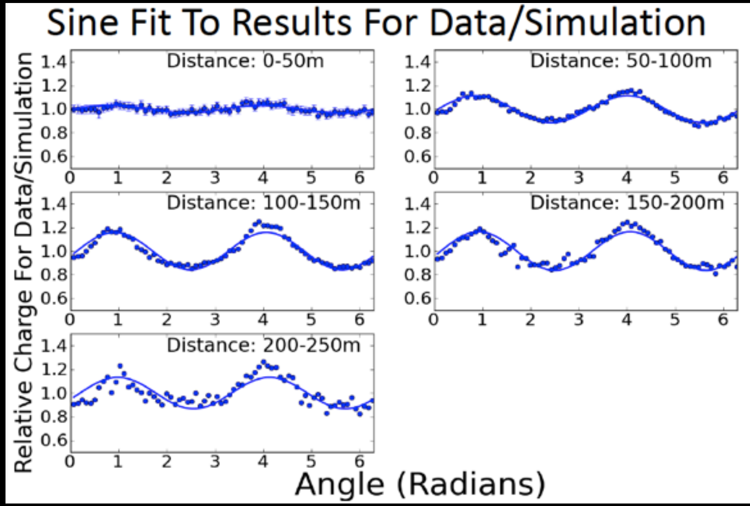


The complex ice structure deposited over 100 k-yr contains much structure and is prominent challenge for IceCube:

- Simulation of 10^{10} photons or more for high energy events now possible with GPU acceleration
- Not only is there z structure, there is tilt and directional anisotropy!

Ice properties measured with in-ice calibration sources:

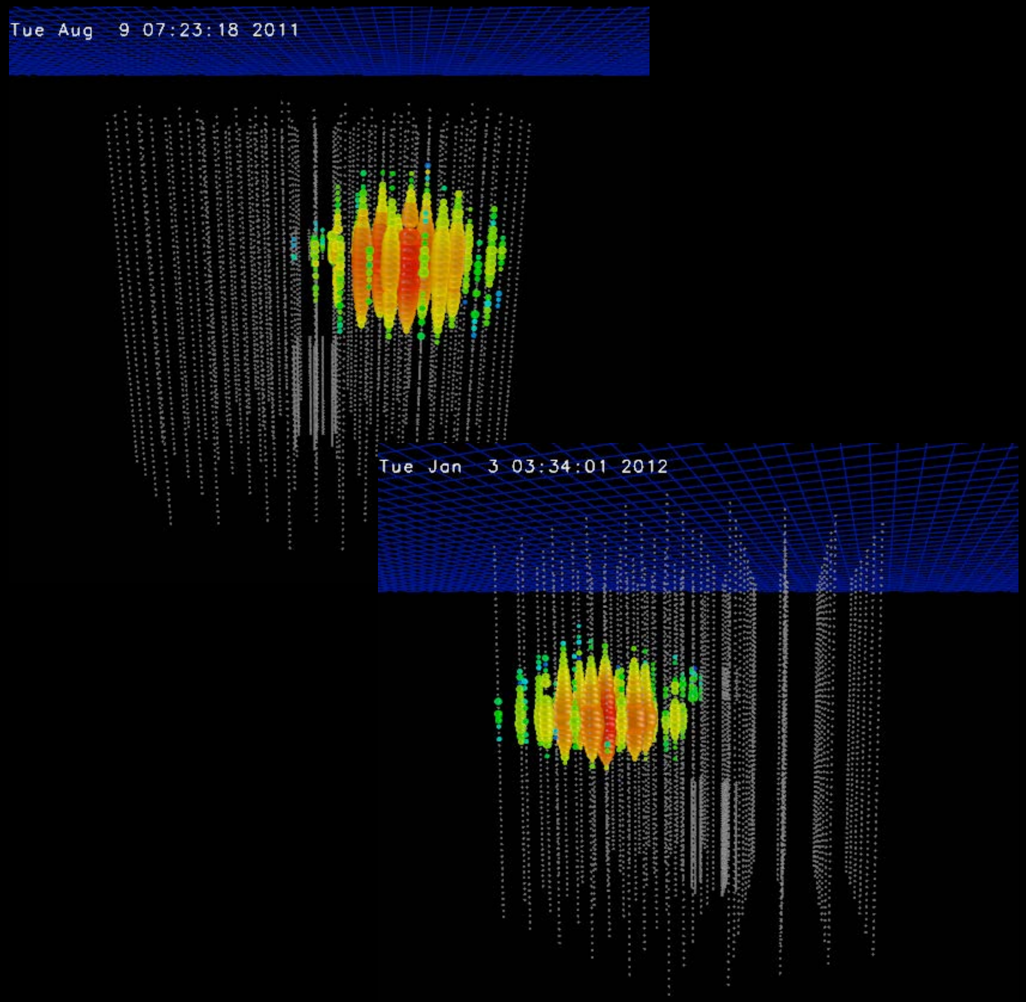
- 12 high brightness 400 nm LEDs per DOM – a few DOMs have different colors;
- Handful of special calibrated sources;
- Dedicated dust logging of boreholes – IceCube also contains a few glaciologists.



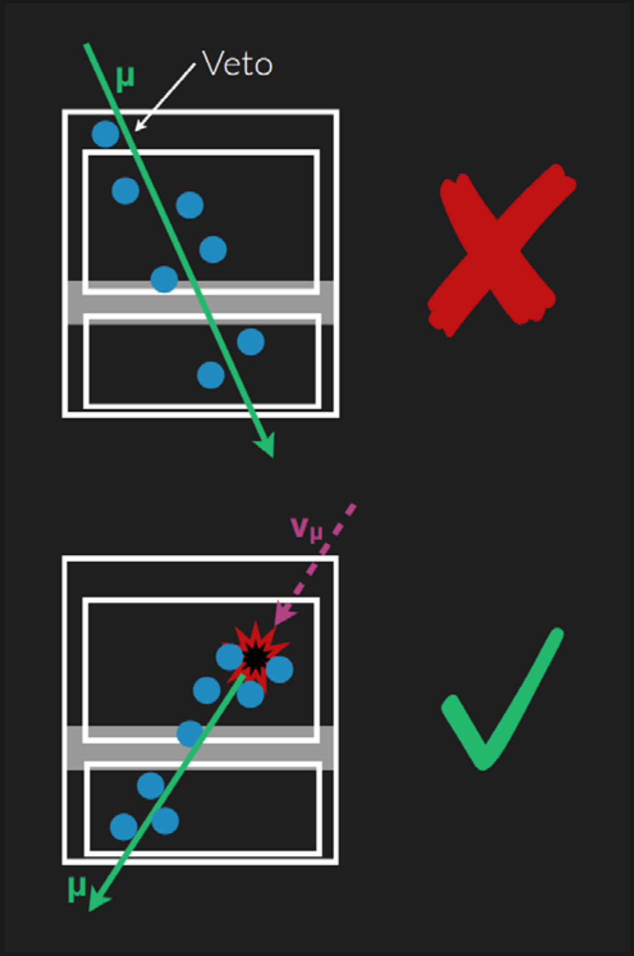
It started with 2 muppets: Bert and Ernie

Quite by accident, while looking for extremely high energy neutrinos from the GZK interacting protons, we found two events in the first year of full IC86 data that didn't look like any background: they were clear cascade-like events which started inside the detector just like a neutrino should.   And they had extremely high energy: 1.05 PeV and 1.15 PeV, each had nearly 100,000 detected photo-electrons!

Now that we had seen real, unmistakable signal events with our "eyes", we knew how to proceeed:



High-Energy Starting Event (HESE) Analysis

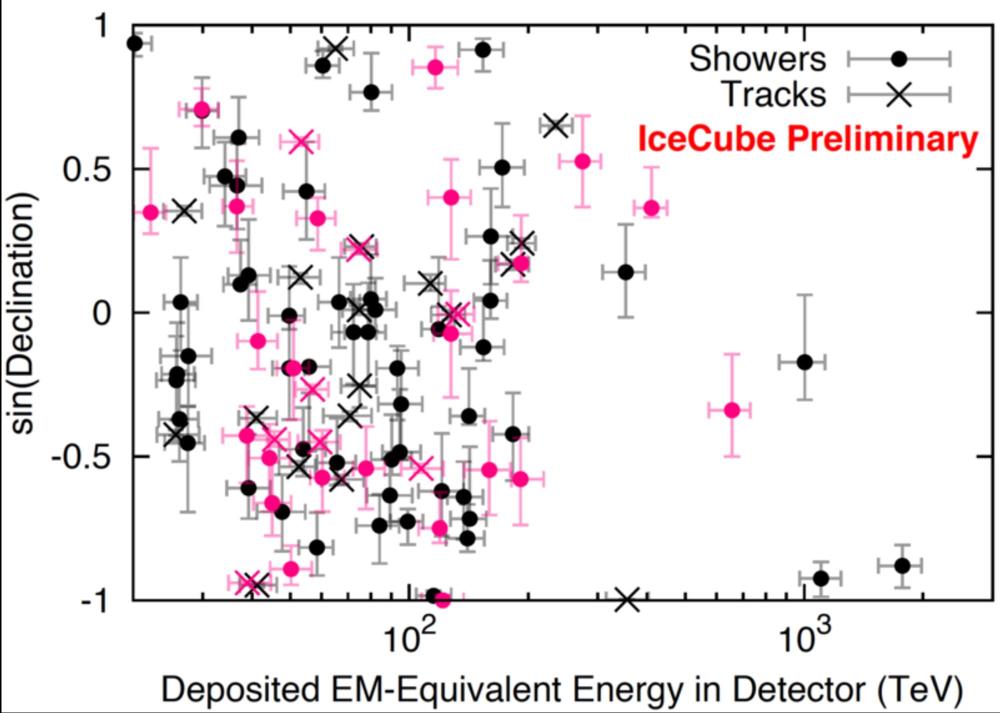


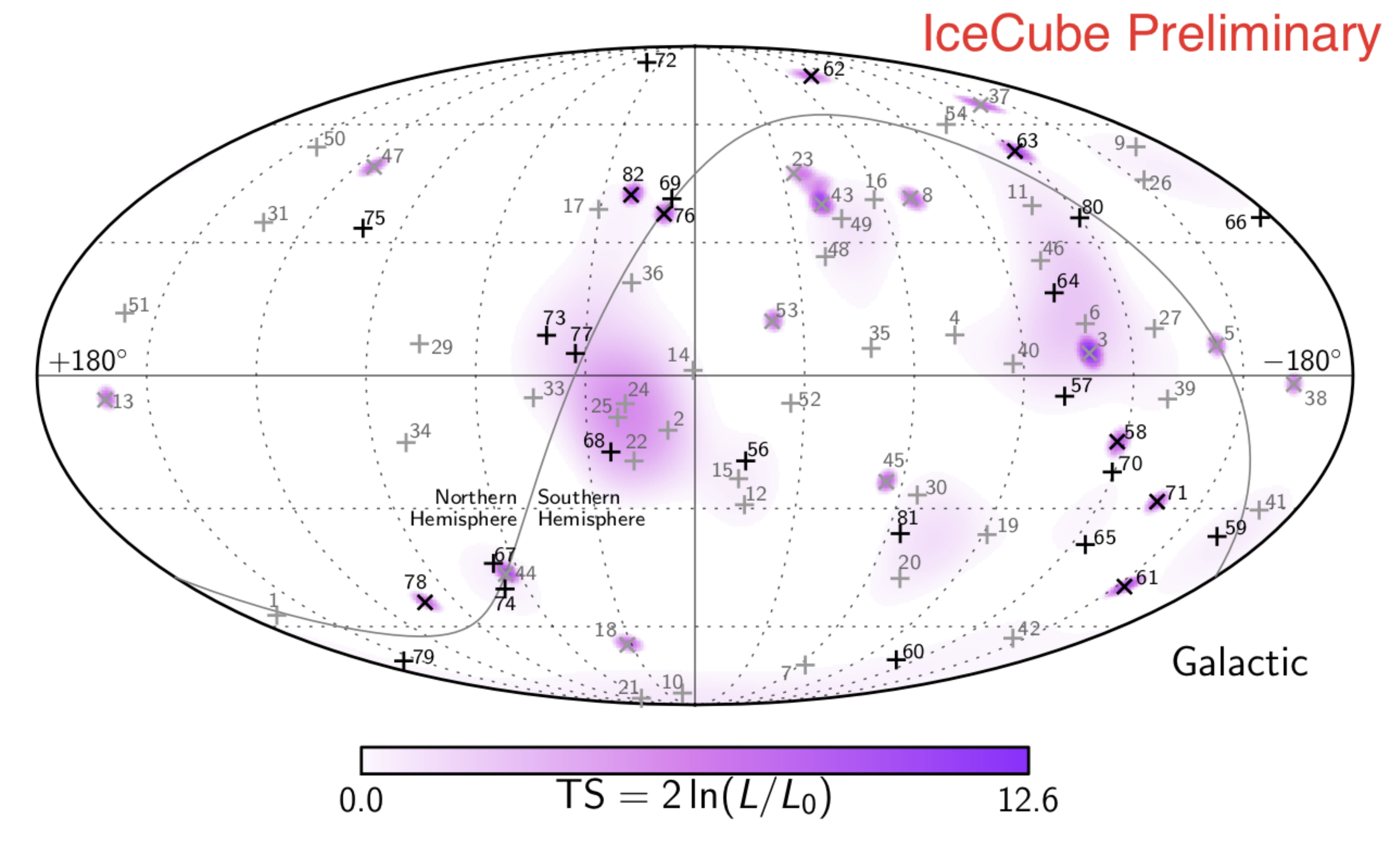
Strategy: focus on high-energy events (2 > PeV events in 1 year, either we got really lucky or the ice is full of them). The very simple cut developed (it is now running in real time at Pole) is this:

- Qtot > 6000 p.e. : this will setup an energy threshold of approx. 30 TeV, but, again, there should be *many* events out there based on the two observations;
- Use part of IceCube's outer shell as a veto. It's OK if hits occur in the veto as the particle exits (PC muons will do this) but *not* OK if the first hits occur in the veto region.
- It is also possible to use data to check the veto performance

The HESE analysis was then sensitive to all flavors above about 60 TeV (muons are penalized slightly because some energy escapes); background could be estimated from data. The effective volume of the search was 400 Mton – about 40% efficient.

HESE 6-year Results



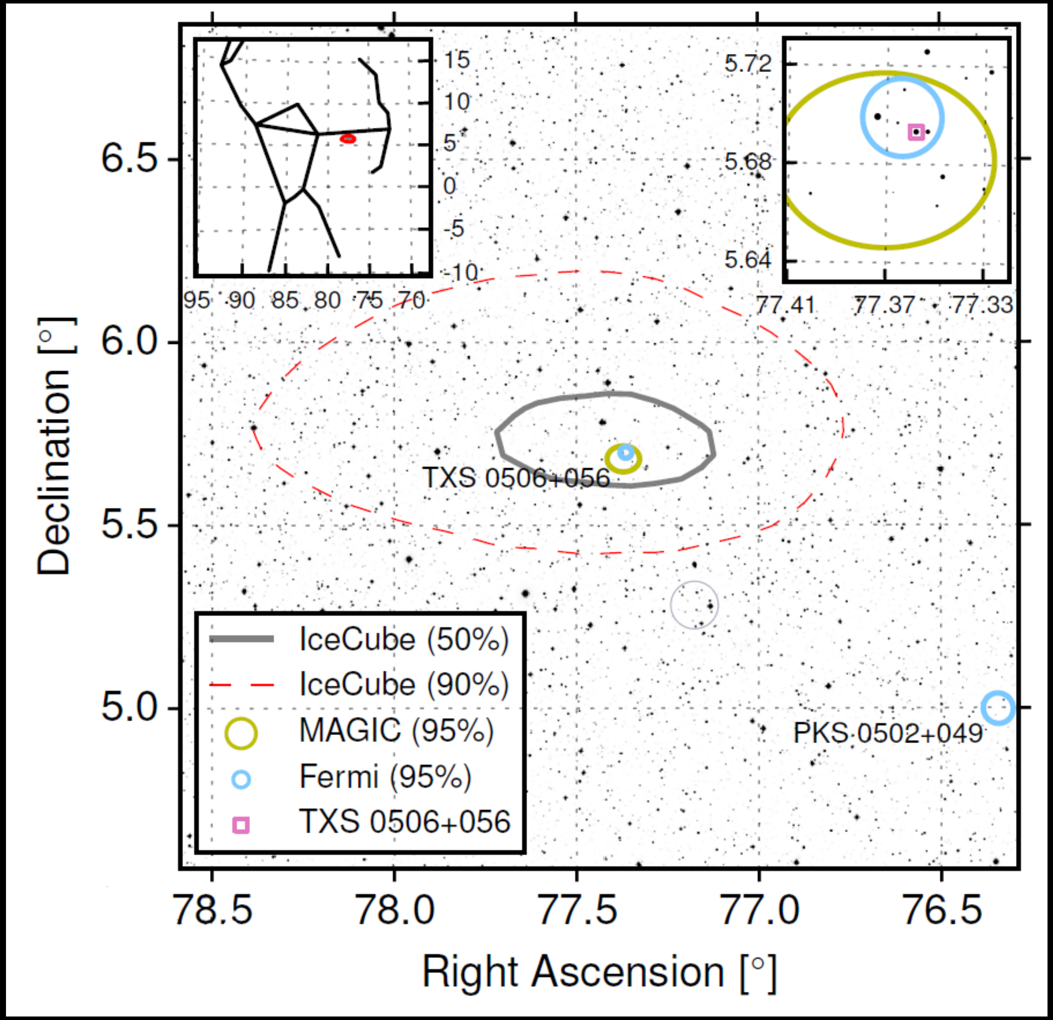


TXS 0506+056

First Observation of Astrophysical Source in EM and Neutrinos

I've seen things you people wouldn't believe. Attack ships on fire off the shoulder of Orion. I watched C-beams glitter in the dark near the Tannhäuser Gate. All those moments will be lost in time, like tears in rain …

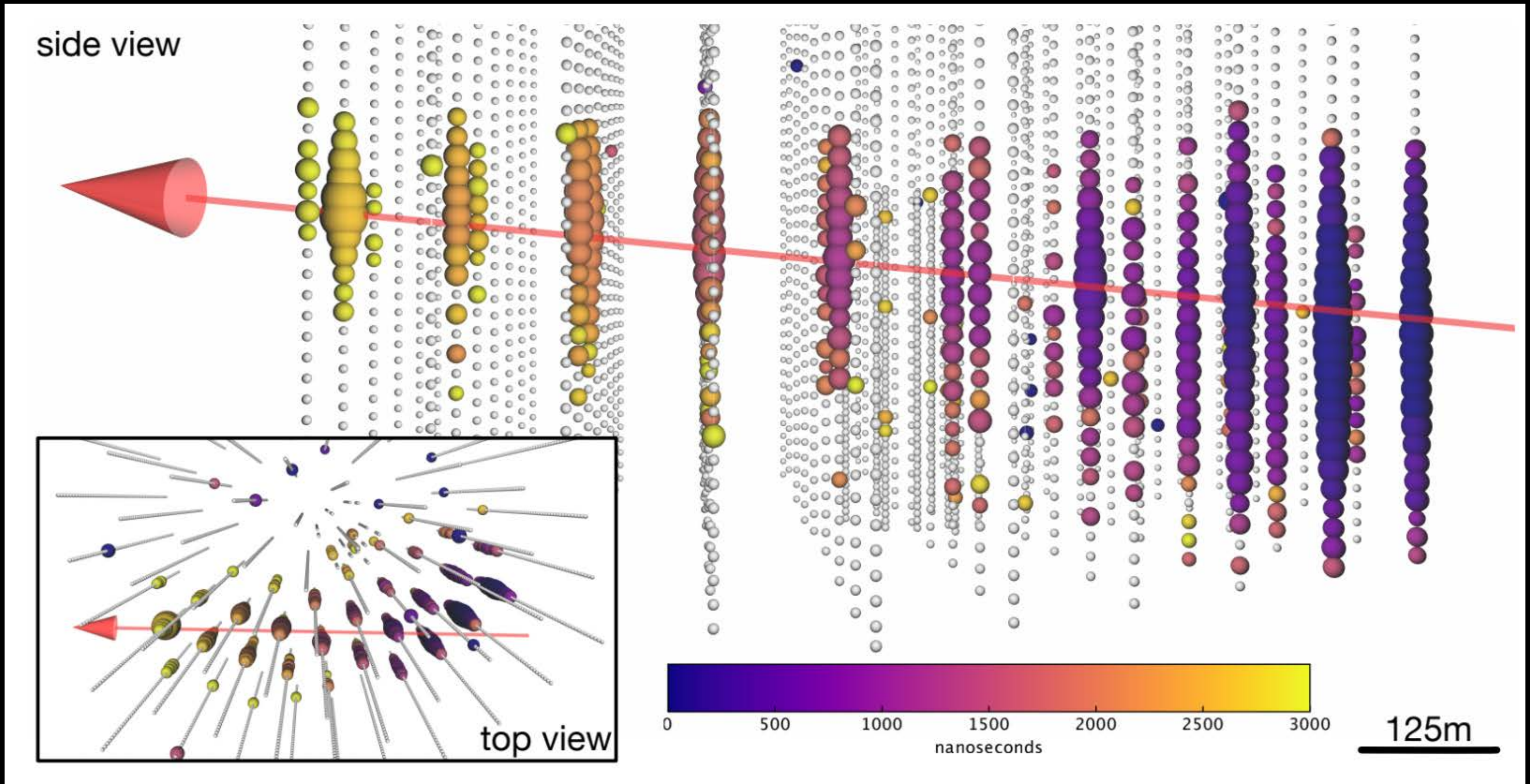
– Roy Batty (Rutger Hauer) *Blade Runner (1982)*



The IceCube Realtime System

- IceCube operates largest data center on continent
- Digital data packets from sensors sent to surface and processed by software trigger and readout system (IceCube DAQ) – 3 kHz trigger rate (mostly cosmic ray muons from above) yields about 10 MB/sec written to disk with ~ 5 sec latency.
- Online compute farm performs event reconstructions.
- High significance events sent via Iridium satellite link to Northern Hemisphere where automated GCN alerts sent out.
- IceCube has been sending RT alerts several years but high-energy tracks sent only since Spring 2016 – about 10/yr.
- On 22 Sept 2017 at 20:54:30.43 UTC alert IC170922 issued
- 43 seconds elapsed between event in ice and GCN alert dissemination on network.

The IceCube HE Muon Event



Event was high energy through-going muon event: ~25 TeV energy deposited in detector with most probable neutrino energy ~ 300 TeV.

Muon track reconstruction to within 0.1° of TXS 0506.

Realtime HE Neutrino Candidate IC170922

AGILE confirmation of gamm
IceCube-170922A

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OA Verrecchia (SSDC/ASI and INAF/OAR), M. Tavani (I A. Bulgarelli (INAF/IASF-Bo), P. Munar-Adrover, Vercellone (INAF/OA-Brera), I. Donnarumma (ASI Striani (CIFS and INAF/IAPS), M. Cardillo (INAF/O Trifoglio (INAF/IASF-Bo), A. Giuliani, S. Mereghett A. Chen (Wits University), A. Argan, E. Costa, E. I Lazzarotto, I. Lapshov, L. Pacciani, P. Soffitta, S. Sab M. Rapisarda (ENEA-Frascati), G. Di Cocco, F. Fus (INAF/IASF-Bo), A. Pellizzoni, M. Pilia, A. Trois Vallazza (INFN Trieste), F. Longo (Univ. Trieste an (INFN and Univ. Roma Tor Vergata), M. Prest (Univ. and Univ. Roma Sapienza), P. W. Cattaneo, A. Ra (INAF/OAR and Wits University), Ferrari (Univ. Torino and CIFS), A. Antonelli (SSDC/ASI), P.*

Credential Certification

Subjects: Gamma Ray, >GeV, Neutr

Referred to by ATel #: 10817, 1083

Tweet | Recommend 4

Following the IceCube observation T0 = 17/09/22 20:54:30.43 UT (ht increased gamma-ray activity fron J0509.4+0541) in the IceCube-1709 GRID data acquired in the days be gamma-ray excess above 100 MeV error regions.

On a 3-day integration starting fro analysis yields a detection at about 0.5) x 10^-6 ph cm^-2 s^-1, centere stat. c.l.) +/- 0.1 deg (syst.) (R.A., D IceCube centroid and from the po within the Fermi-LAT reported peric

A preliminary search for a peak flux occurs between one or two days b found by AGILE, regarding the dete HESE event, IceCube-160731 (Luca

Gamma-ray activity from this regior

This measurement was obtained wit Multifrequency observations of the

VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

ATel #10861; *A. J. Tetarenko, G. R. Sivakoff (UAlberta), A. E. Kimball (NRAO), and J. C.A. Miller-Jones (Curtin-ICRAR)*
on 17 Oct 2017; 14:08 UT
Credential Certification: Alexandra Tetarenko (tetarenk@ualberta.ca)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino
candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss (University of
Maryland) report on behalf of the IceCube Collaboration
(http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event
with a high probability of being of astrophysical origin. The event was
identified by the  Extremely High Energy (EHE) track event selection. The
IceCube detector was in a normal operating state. EHE events typically
have a neutrino interaction vertex that is outside the detector, produce
a muon that traverses the detector volume, and have a high light level (a
proxy for energy).

After the initial automated alert
(https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more
sophisticated reconstruction algorithms have been applied offline, with
the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help
identify a possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector
operating at the geographic South Pole, Antarctica. The IceCube realtime
alert point of contact can be reached at roc@icecube.wisc.edu
```

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

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430

Tweet | Recommend 3

We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL J0509.4+0542), is located inside the IceCube error region. The FAVA (Fermi All-sky Variability Analysis) light curve at energies above 800 MeV shows a flaring state recently (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27). Indeed, the LAT 0.1--300 GeV flux during 2018 September 15 to 27 was (3.6+/-0.5)E-7 photons cm-2 s-1 (errors are statistical only), increased by a factor of ~6 compared to the 3FGL flux, with nearly the same power-law index of 2.0+/-0.1. We strongly encourage multiwavelength observations of this source. We also encourage optical spectroscopy for this source, because the redshift is still unknown. According to NED, the R-band magnitude is reported as 15.1 (Healey et al. 2008, ApJS 175, 97). Radio observations show that this blazar has had increasing flux during the past year: http://www.astro.caltech.edu/ovroblazars/data.php?page=data_query, http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/0506+056.shtml.

Because Fermi operates in an all-sky scanning mode, regular gamma-ray monitoring of this source region will continue. For this source the Fermi-LAT contact person is Yasuyuki T. Tanaka (ytanaka@astro.hiroshima-u.ac.jp). The Fermi-LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and Sweden.

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

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

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet | Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B. Fox (PSU), D. F. Cowen (PSU), J. P. Osborne (U. Leicester), and F. E. Marshall (GSFC) report on behalf of the Swift-IceCube collaboration:*
on 28 Sep 2017; 11:57 UT
Credential Certification: Phil Evans (pae9@star.le.ac.uk)

Subjects: X-ray, Quasar, Variables

Referred to by ATel #: 10794, 10799, 10817, 10830, 10838, 10840, 10844, 10861

Tweet | Recommend 2

Fermi-LAT has reported a gamma-ray source (blazar), TXS 0506+056 (3FGL J0509.4+0541 / 3FHL J0509.4+0542) which is located inside the IceCube-170922A event error region (Kopper & Blaufuss, GCN #21916) and is flaring above 800 MeV (Tanaka et al., ATEL #10791). This source is also observed in our Swift-XRT follow-up of IceCube-170922A (Source 2, 1SXPS J050925.9+054134 in the 1SXPS catalogue), reported previously by Keivani et al. (GCN #21930).

We conducted a further 5 ks observation of this Source with Swift, beginning at 2017 Sep 27 at 18:52 UT (4.95 d after the neutrino event). In these data the X-ray source has brightened since we the original observations. The current spectral photon index (Γ) is 2.50 [+0.23, -0.12], similar to the historical value in 1SXPS: Γ = 2.32 [+0.33, -0.29] (http://www.swift.ac.uk/1SXPS/1SXPS%20J050925.9%2B054134; Evans et al. 2014). In our initial observations following the neutrino trigger, Γ was marginally harder but with large uncertainty: 1.9 [+0.8, -0.7]. The hardness ratio light curve of the observations taken since the neutrino trigger also shows evidence for spectral softening between the two epochs, suggesting that the source is undergoing spectral evolution.

“Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A,” The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams, Science 361, eaat1378 (2018).

“Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert,” IceCube Collaboration: M.G. Aartsen et al. Science 361, 147-151 (2018).

“The blazar TXS 0506+056 associated with a high-energy neutrino: insights into extragalactic jets and cosmic ray acceleration,” The MAGIC Collaboration: M. L. Ahnen et al, Accepted for publication in The Astrophysical Journal Letters.

“Dissecting the region around IceCube-170922A: the blazar TXS 0506+056 as the first cosmic neutrino source,” P. Padovani, P. Giommi, E. Resconi, T. Glauch, B. Arsioli, N. Sahakyan, and M. Huber, Accepted for publication in Monthly Notices of the Royal Astronomical Society.

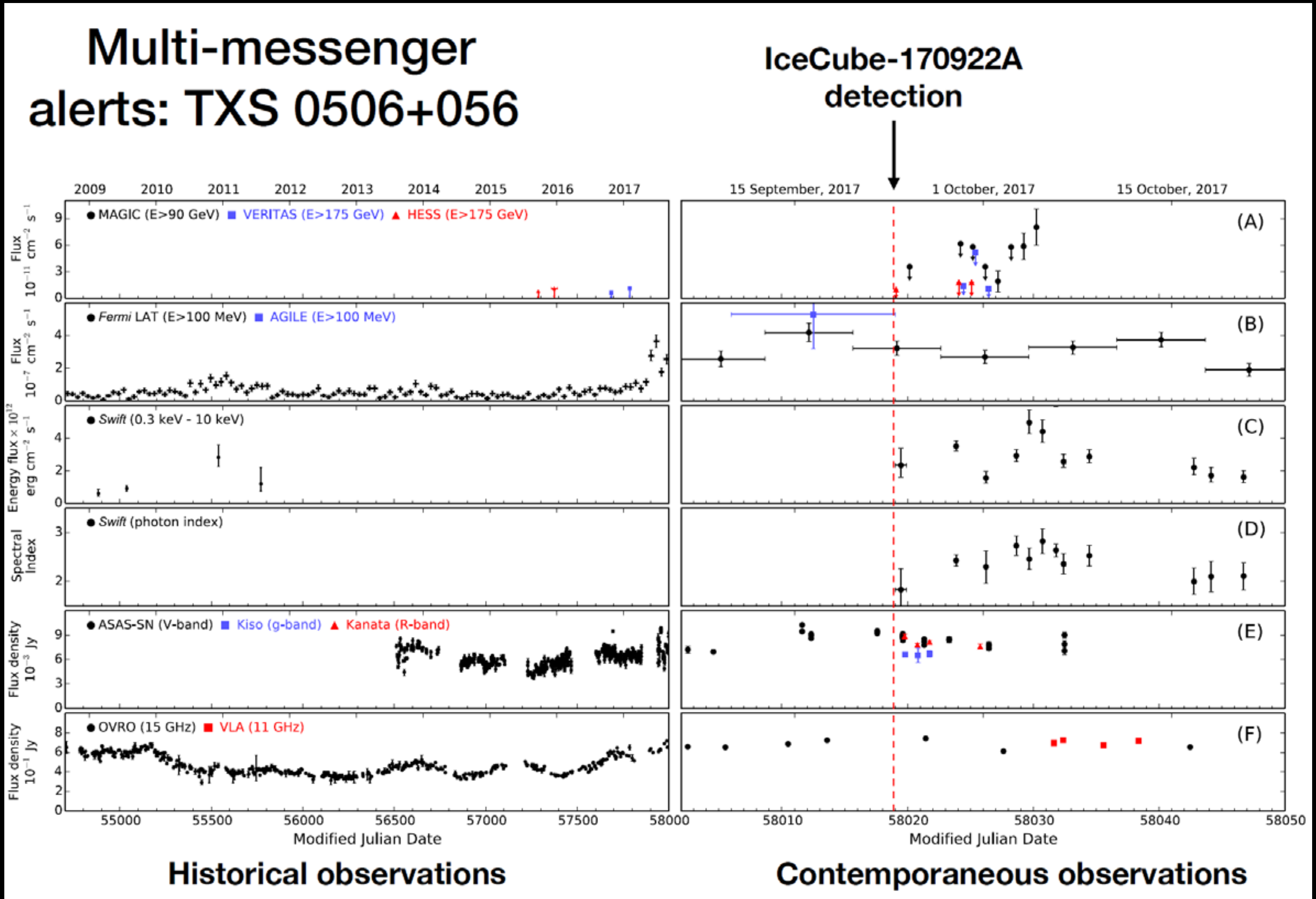
“VERITAS Observations of the BL Lac Object TXS 0506+056,” VERITAS Collaboration: Abeysekara et al. The Astrophysical Journal Letters (2018).

“A Multimessenger Picture of the Flaring Blazar TXS 0506+056: Implications for High-Energy Neutrino Emission and Cosmic Ray Acceleration,” A. Keivani, K. Murase, M. Petropoulou, D. B. Fox, S. B. Cenko, S. Chaty, A. Coleiro, J. J. DeLaunay, S. Dimitrakoudis, P. A. Evans, J. A. Kennea, F. E. Marshall, A. Mastichiadis, J. P. Osborne, M. Santander, A. Tohuvavohu, and C. F. Turley, Submitted to The Astrophysical Journal.

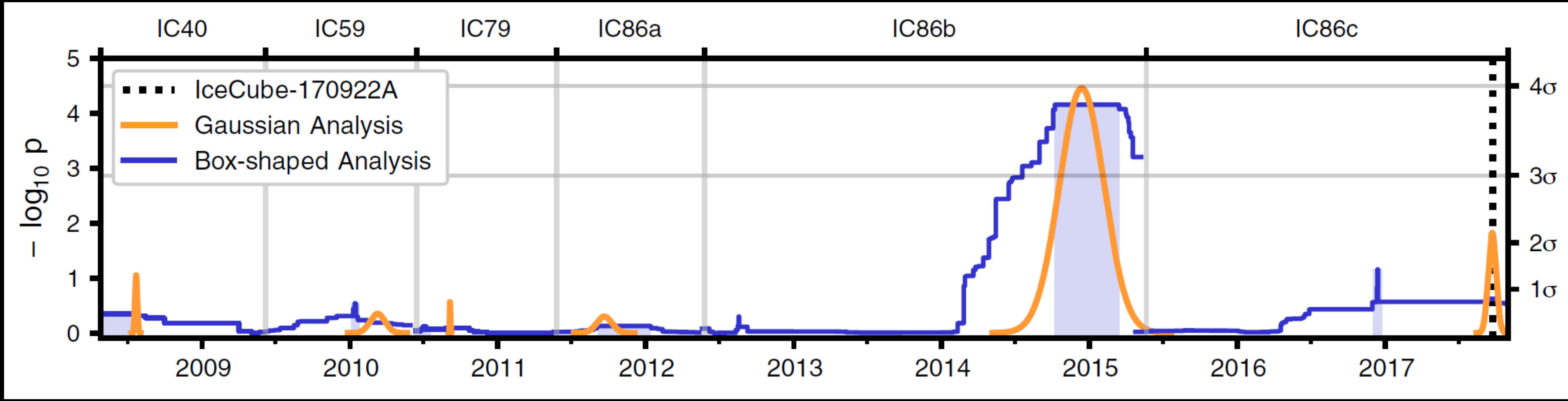
“Search for neutrinos from TXS 0506+056 with the ANTARES telescope,” ANTARES Collaboration: A. Albert et al, Submitted to The Astrophysical Journal Letters.

See https://icecube.wisc.edu/pubs/neutrino_blazar for up-to-date information

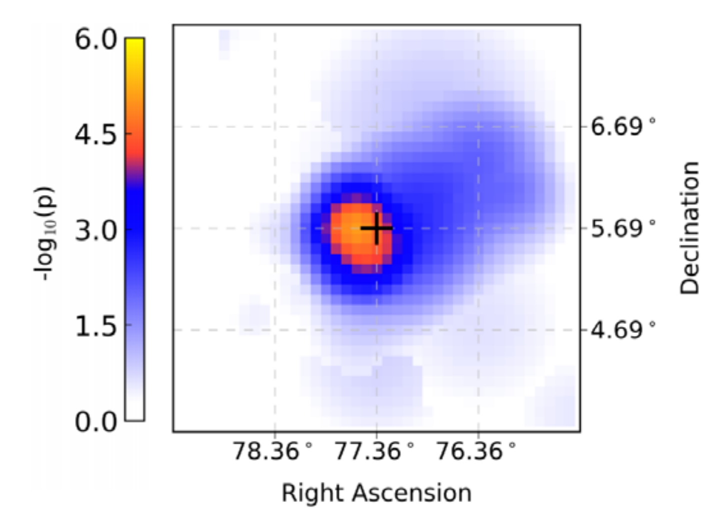
Multi-messenger Follow-Up Observations



IceCube Archival Search – Neutrino "Flare"



- Observations divided into 6 periods of differing run configurations.
- One period contains significant excess – 19 events on background of 6.
- Gaussian time window centered at 13 Dec 2014 with full width of 110 days.
- Spectral index of 2.1.
- 3.5 σ rejection of background hypothesis.



What is TXS 0506 and What Are Implications?

- Known source in EM – z = 0.3365 (GTC Oct 2017) giving distance of 4 Glyr
- Blazar (AGN with jet pointed at observer)
- Radio, optical, x-ray, and gamma all indicate blazar was in flaring state for weeks / months leading up to the Sep 2017 neutrino alert.
- Source had never been considered as likely source of detectable neutrino flux – without MMA observations its presence in IceCube skymaps overshadowed by hotter spots on sky.
- Among 50 brightest gamma ray sources in Fermi-LAT catalog → one of most luminous objects, 10x more luminous than Markarians.
- This result consistent with previous IceCube analysis giving upper limit of 27% contribution of AGNs to HE diffuse neutrino flux.
- Discrimination of acceleration models at source, see https://arxiv.org/abs/1807.04537, hybrid lepton/hadron + multi-zone.

IceCube Upgrade

High Energy Array

Cosmic Ray Array

Radio Array

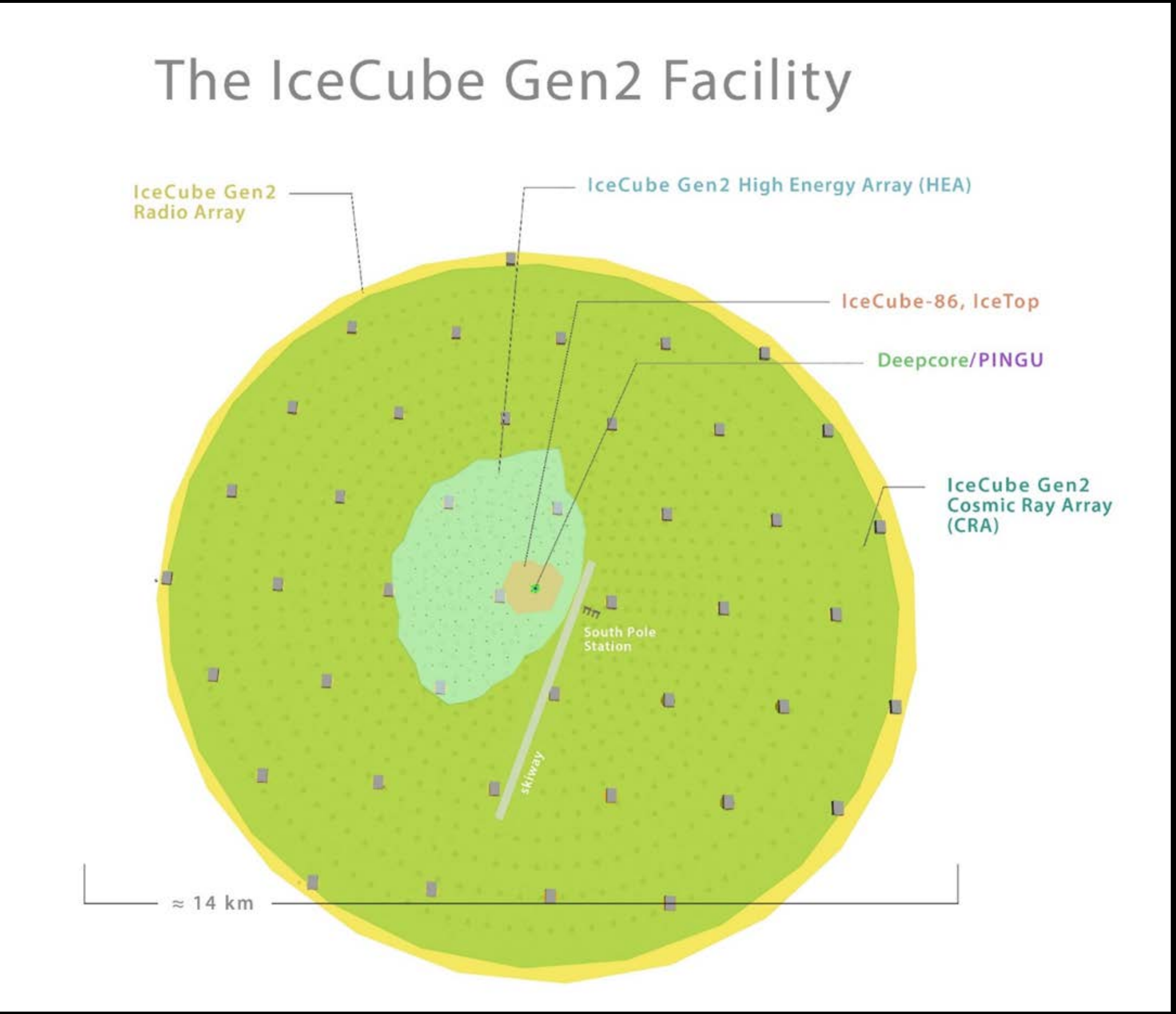
IceCube Gen2 – The Future of Neutrino Astronomy

IceCube Gen2 White Paper:
arXiv: 1412.5106v2

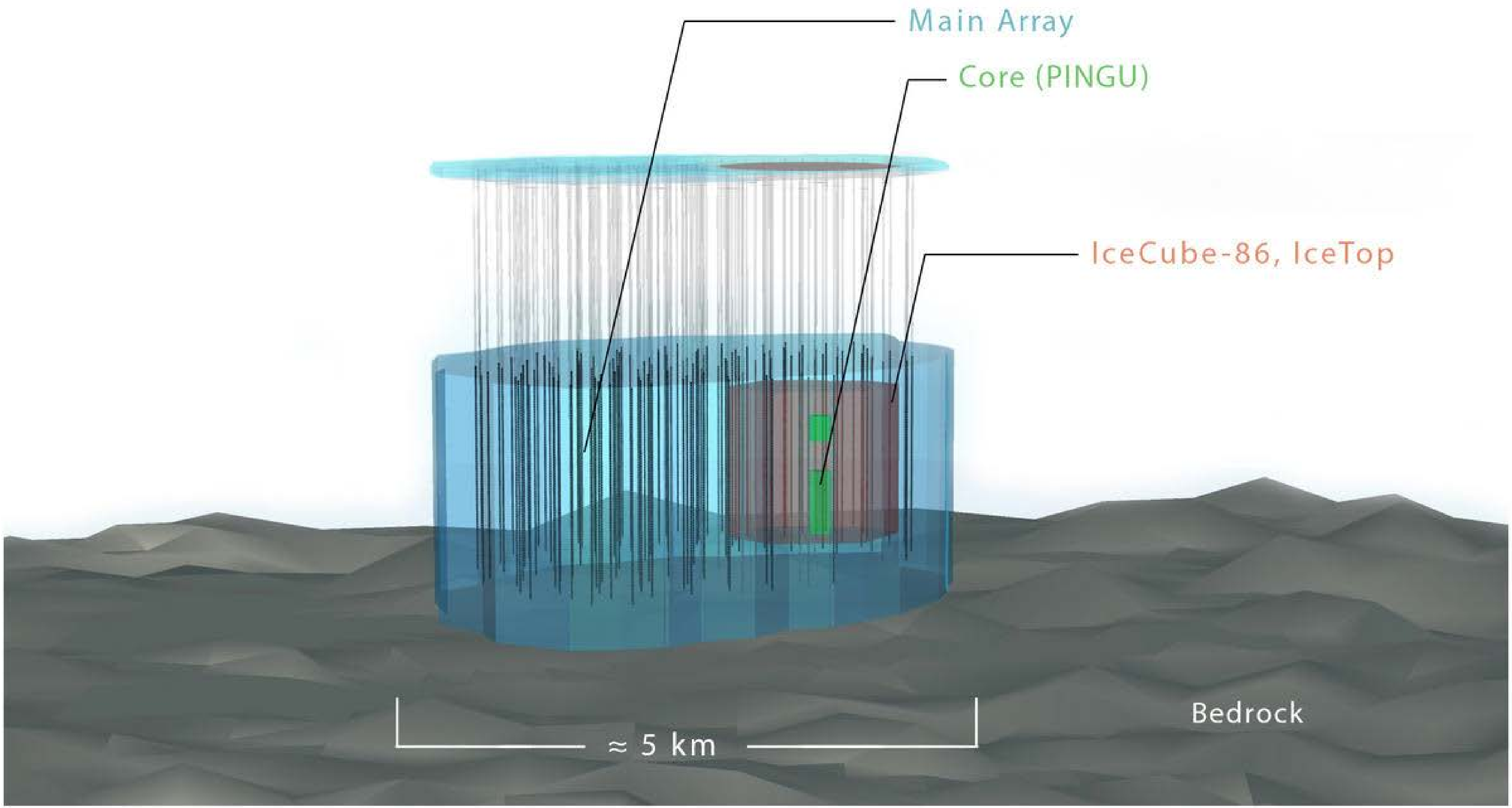
Conceptual Design

A conceptual drawing of the IceCube Gen2 Facility is shown at right. Specific points of design are likely to evolve quite a bit. However salient points are the multiple sub-detectors spanning energy range of ~ GeV to EeV:

- Upgrade: low energy, tau neutrinos, precision calibration of ice;
- High Energy Array (HEA) – 100 TeV+ neutrino detector using optical sensors evolved from IceCube
- Cosmic Ray Array (CRA) – veto array for HEA as well as exploration of cosmic ray physics
- Radio Array (RA) – ARA-like or perhaps much denser array of RF power envelope detectors. Overtakes optical in region 100 PeV+

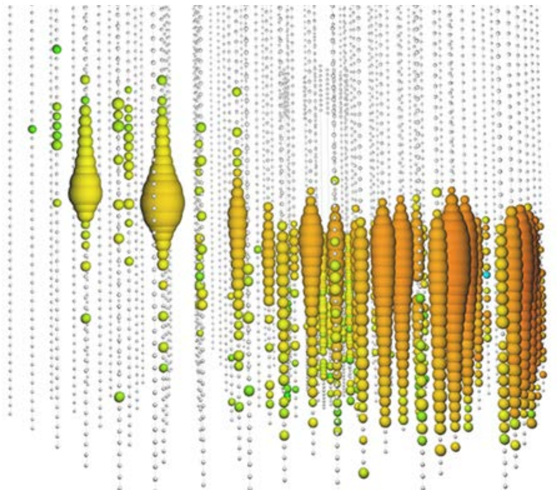


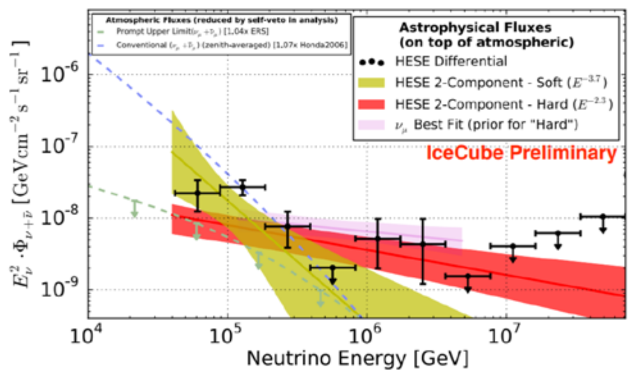
The IceCube Gen2 Facility



PeV-Scale Neutrinos

2.6 PeV ν_μ. The parent neutrino's energy is in the range 5-10 PeV.





Region above 100 TeV is sweet spot for neutrino astrophysics:

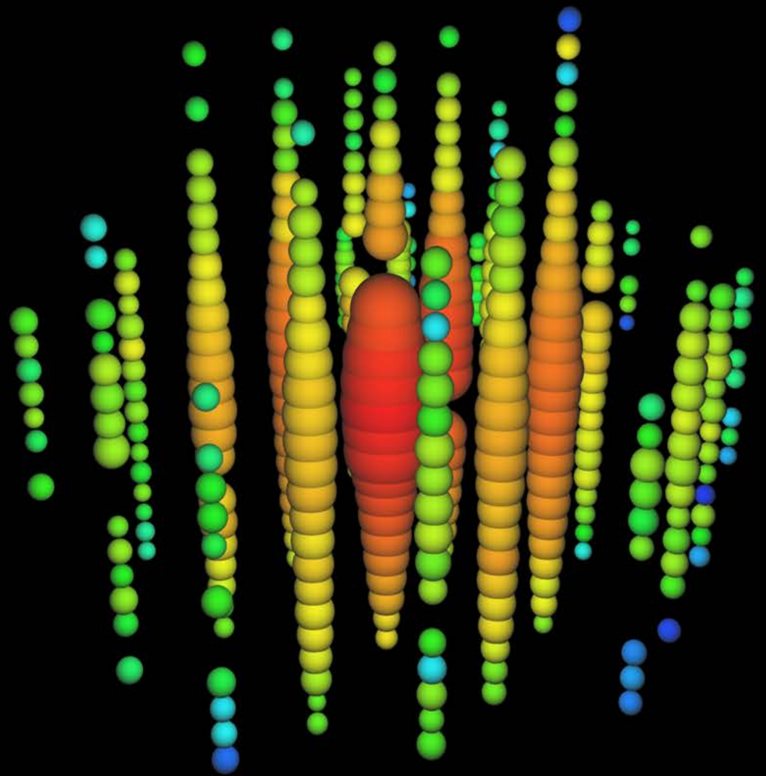
- Background-free region for study of
  - Point sources
  - Correlation studies
  - Energy spectra
- Gen2/HEA would deliver O(10) events per year above 1 PeV
- At PeV scales new phenomena arise which help disentangle flavors providing information on source physics:
  - Tau double bangs – separated – O(1-2) per year in IceCube Gen2/HEA
  - Glashow resonance events [arXiv:1108.3163 Battacharya, et al] have pure muon, tau lollipop signatures – discrimination of pp versus pγ at source.
- Recent TXS 0506 source → 10x IceCube detect several new blazars (an other source classes or exclude?) per year!

PeV neutrinos don't need dense detector

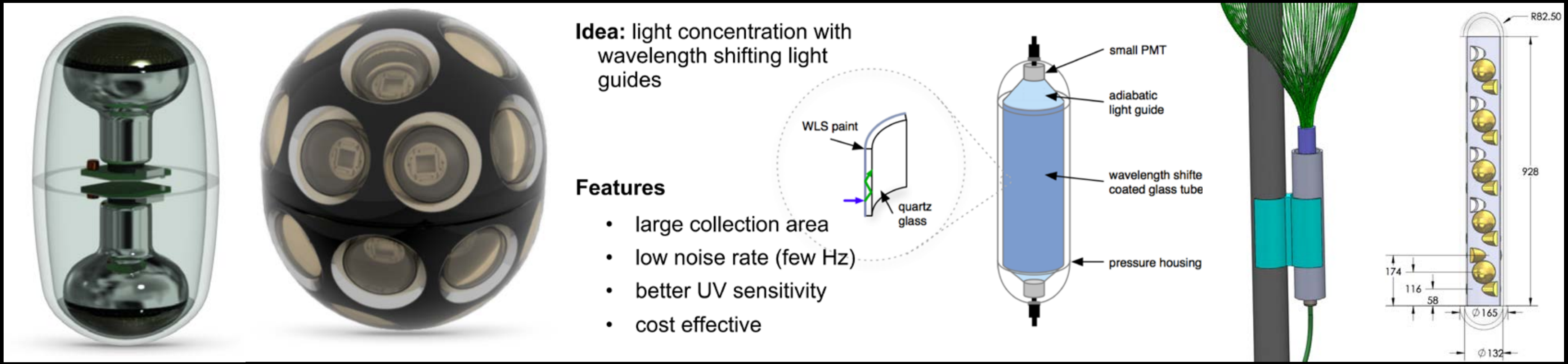
Take Bert – one of the two original ~ 1 PeV neutrinos found in IceCube data.

Study reconstruction of this event with *real* sparse detector: IceCube with strings removed to simulate wider spacing. With 20 strings separated by 250 m

Vertex resolution	12 m
Angular resolution	30°
Energy resolution	10%

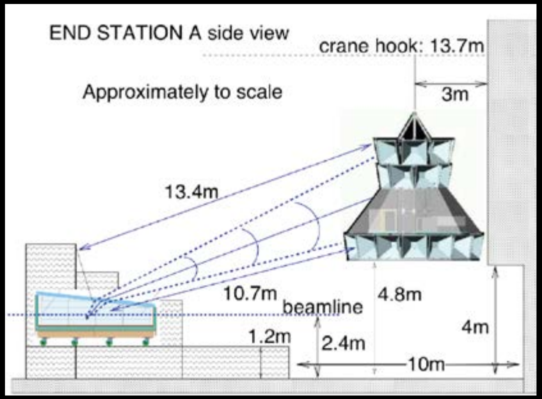


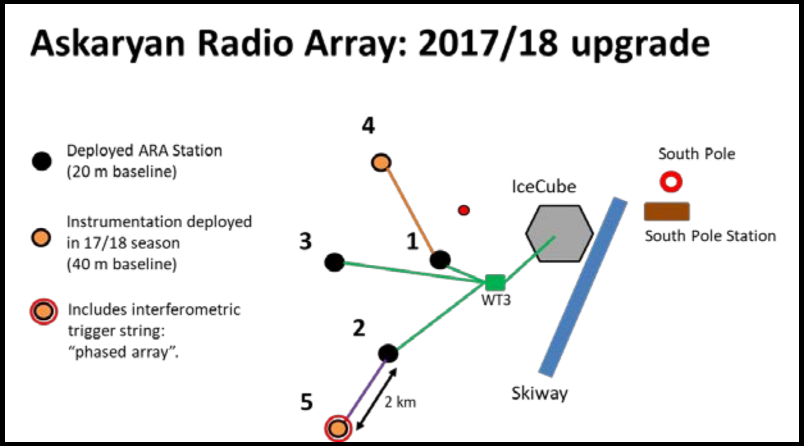
Gen2 Sensor Designs

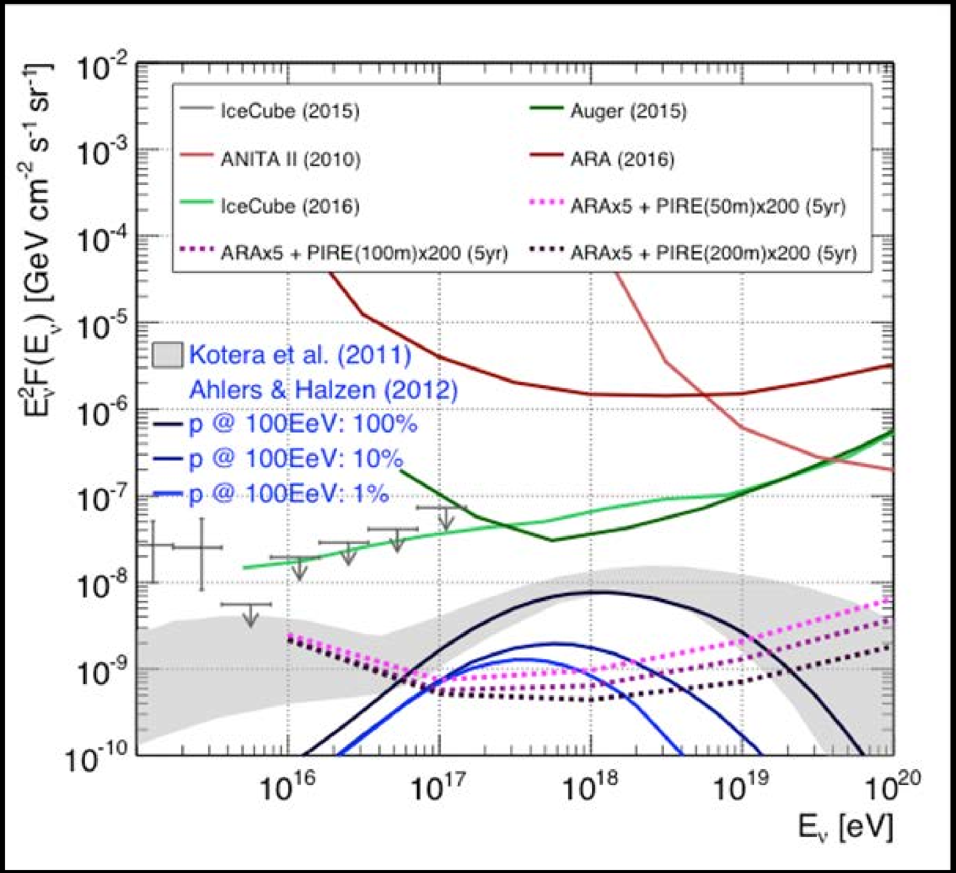


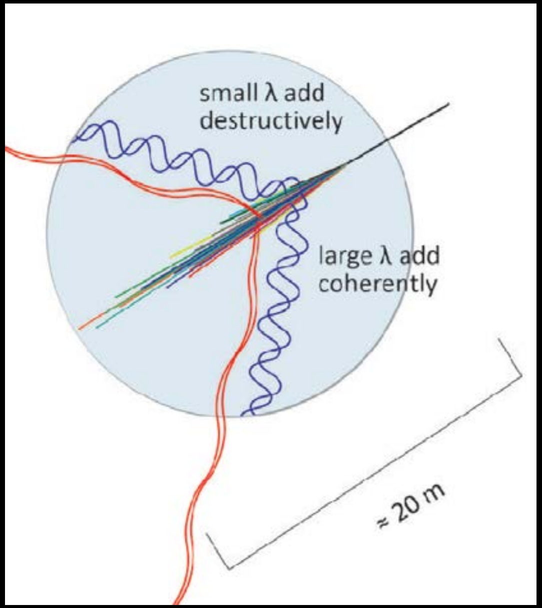
- Name of the game is photon effective collection area:
- Several new sensors under consideration for Gen2: D-Egg and mDOM will be utilized in the Phase I Upgrade. Other sensor technologies require more R&D. Profit from availability of drill holes to deploy future instrumentation and retire risk early.

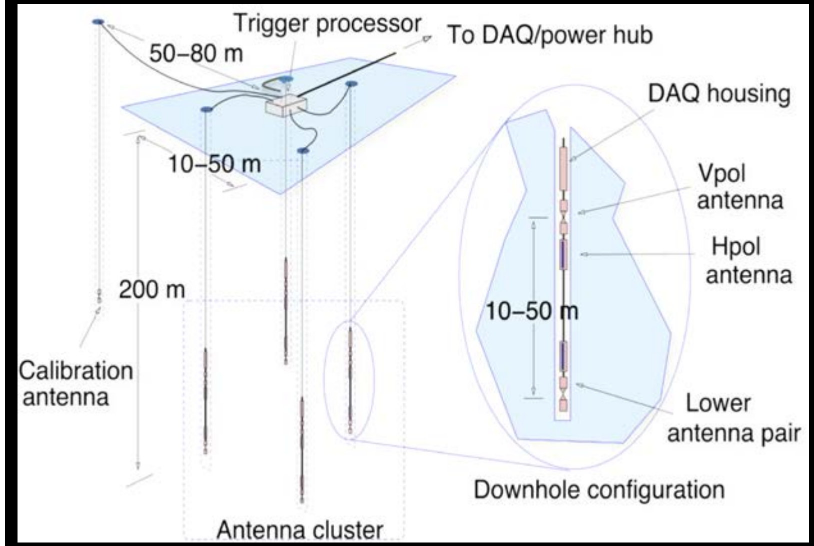
Radio Detection of Neutrinos









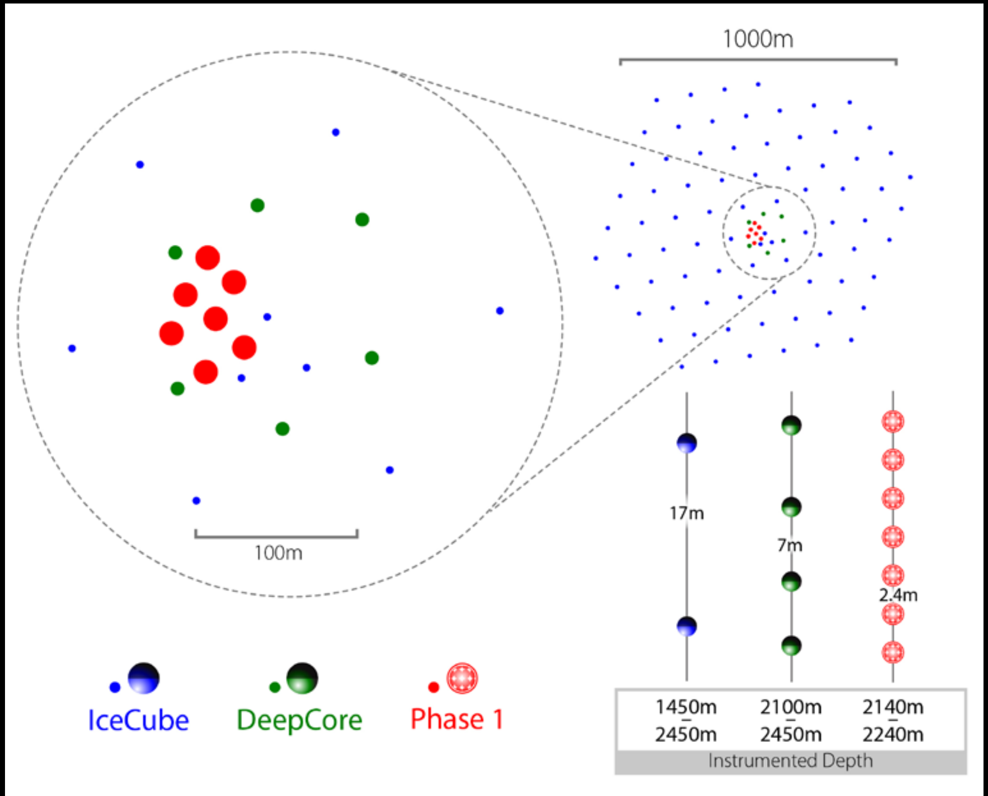


Radio technique high threshold – 10's of PeV – but 10x more cost effective at UHE.

The IceCube Phase I Upgrade

Gen2 Phase 1: First Steps

Science goals:
(a) Probe unitarity of PMNS matrix
(b) Improve calibration and characterization of ice for improved HE multimessenger neutrino astronomy

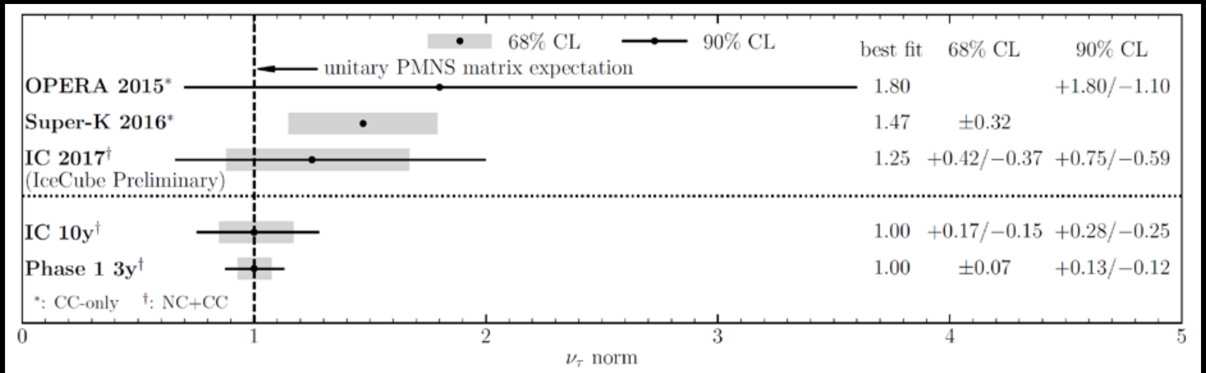


7 strings (US 3 | JP 2 | DE 2) densely populated with next generation, high performance photodetectors:
- Integrates with existing IceCube: data acquisition, event filtering, simulation will require extension;
- No significant increase in steady-state operations;
- Negligible increase in data rate
- +3 kW power (+5% increase relative to IceCube)

Proposed project leverages significant effort already invested by US/Non-US IceCube groups to develop instrumentation and infrastructure for next-generation neutrino detector at South Pole.

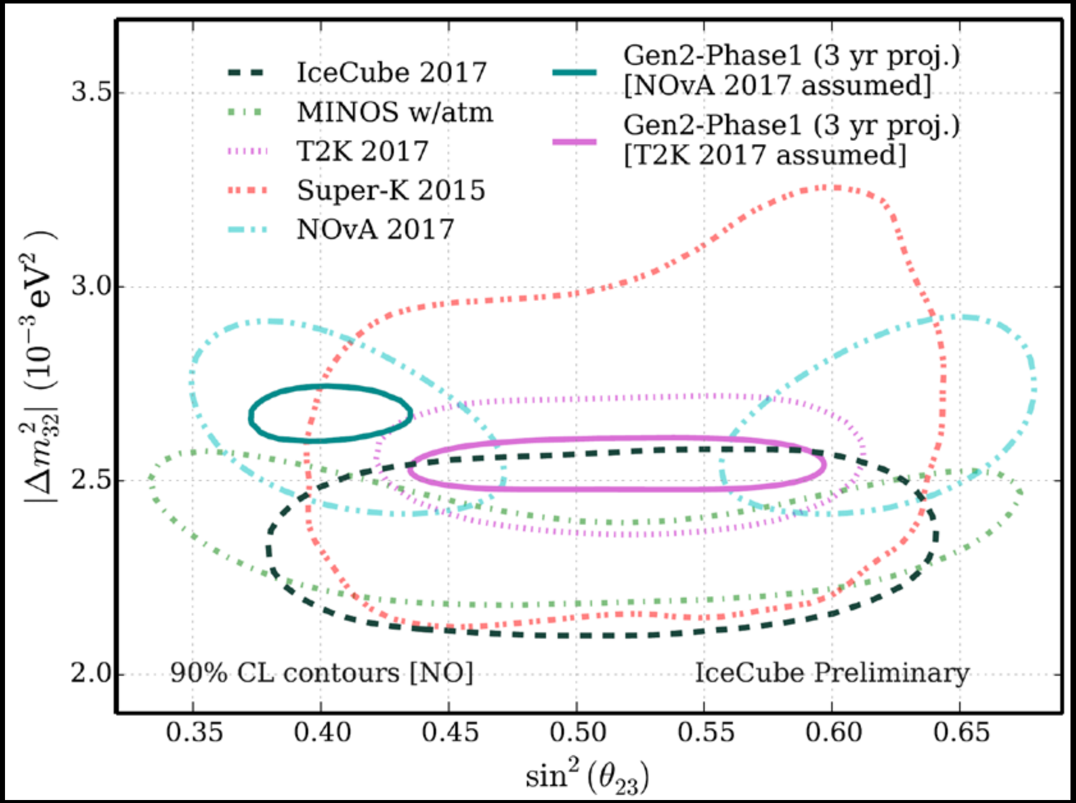
Array	String Spacing	Module Spacing	Modules per String
IceCube	125 m	17 m	60
DeepCore	75 m	7 m	60
Phase 1	20 m	2 m	125

Neutrino Mixing



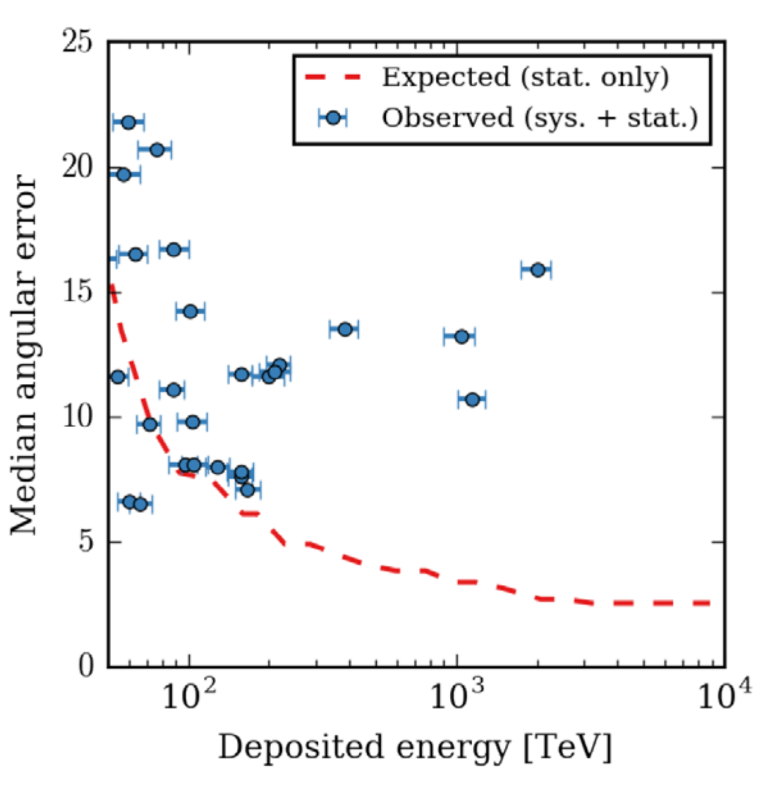
With only 7 but densely instrumented strings …

- Expect 2500 CC+NC tau neutrino events per annum. Statistically measure taus based on energy and angle.
- Will exlude no-tau appear w 14 sig after 3 years.
- Best constraints on atmospheric mixing parameters (maximal mixing / octant for ATMNU).



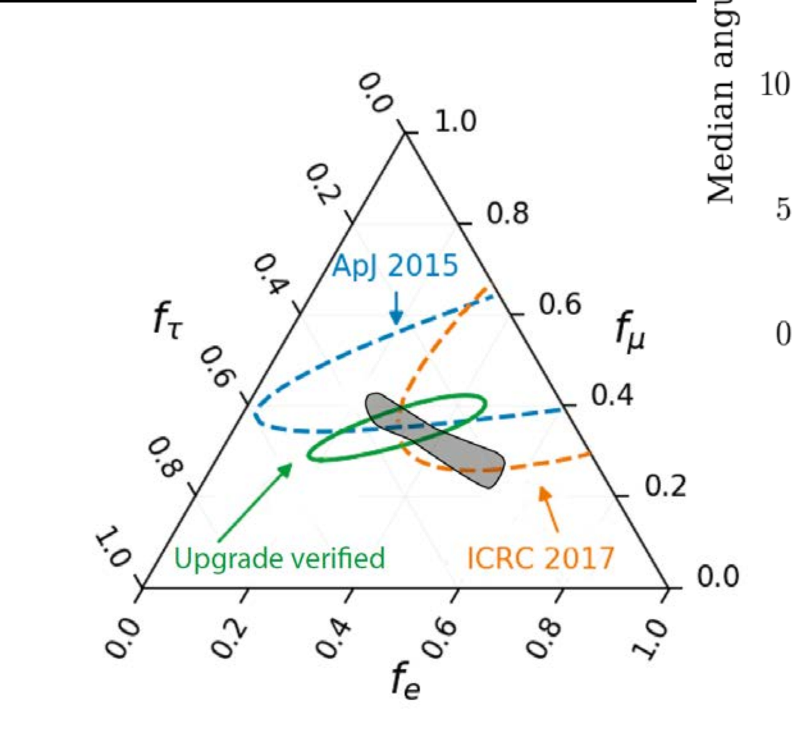
Improving IceCube Reconstructions

Lack of precision knowledge of ice limits angular reconstructions – in particular bad at high energy where, contrary to expectation, the reconstruction gets worse. Cascade reconstruction (right) at PeV has median ang. res of 15° but would be improved to 3-5° with better ice characterization. This applies to muon reconstructions as well with improvements to 0.1 - 0.2 ° foreseen.



Obvious benefit to MMA is improved source localization: HESE-160427a, a 140 TeV track coincident with Pan-STARRS SN PS16cgx.

Improved flavor ID for tau neutrinos to better constrain source physics. This is currently limited by ice anisotropy uncertainty: tau double-pulse harder than PeV double bang.



Improved calibrations are retroactively applicable to 10+ years IceCube archival data!

Timeline

- IceCube Upgrade Proposal (nee Phase 1 Upgrade) submitted 2016 receives excellent reviews. Submitted to NSF mid-scale program.
- NSF FY19 budget request includes allocation for “Big Ideas” which include multi-messenger astronomy ($30 million) and mid-scale infrastructure ($60 million).
- Gen2 scale, O(300) million USD must be MREFC project → multiple years in design phases.

Time	IceCube Upgrade Milestone
2019Q1	Preliminary Design Review; drill recon season @ Pole
2019	Preparation for final design; long lead procurement
2020Q1	Final Design Review
20/21 Pole Season	Drill generators ship to Pole; refurb drill structures @ Pole
21/22 Pole Season	Firn drilling; drill IV&T
22/23 Pole Season	Deploy 7 strings

Time	Gen2 Milestone
2020	Concept Design Review
2021	Preliminary Design Review
2022	Final Design Review; begin production
2025-2031	Deployment 120 HEA deep ice strings

Conclusions

- Neutrinos are going to play a key role in MMA from now and through the 2020's. They allow us to reach into the ultrahigh-energy sky and peer deep into exotic high energy phenomena. TXS 0506 first source identified in neutrinos and EM.
- Need next generation instrument to study source physics at TXS and to identify other neutrino souces - but this is still a long way off. New Gen2 facility not likely to be fully operational until ~ 2030.
- In the short term, with a modest investment, we can improve our knowledge of the ice and get better multimessenger astronomy from IceCube going forward and going backwards too with Phase I Upgrade.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THE END