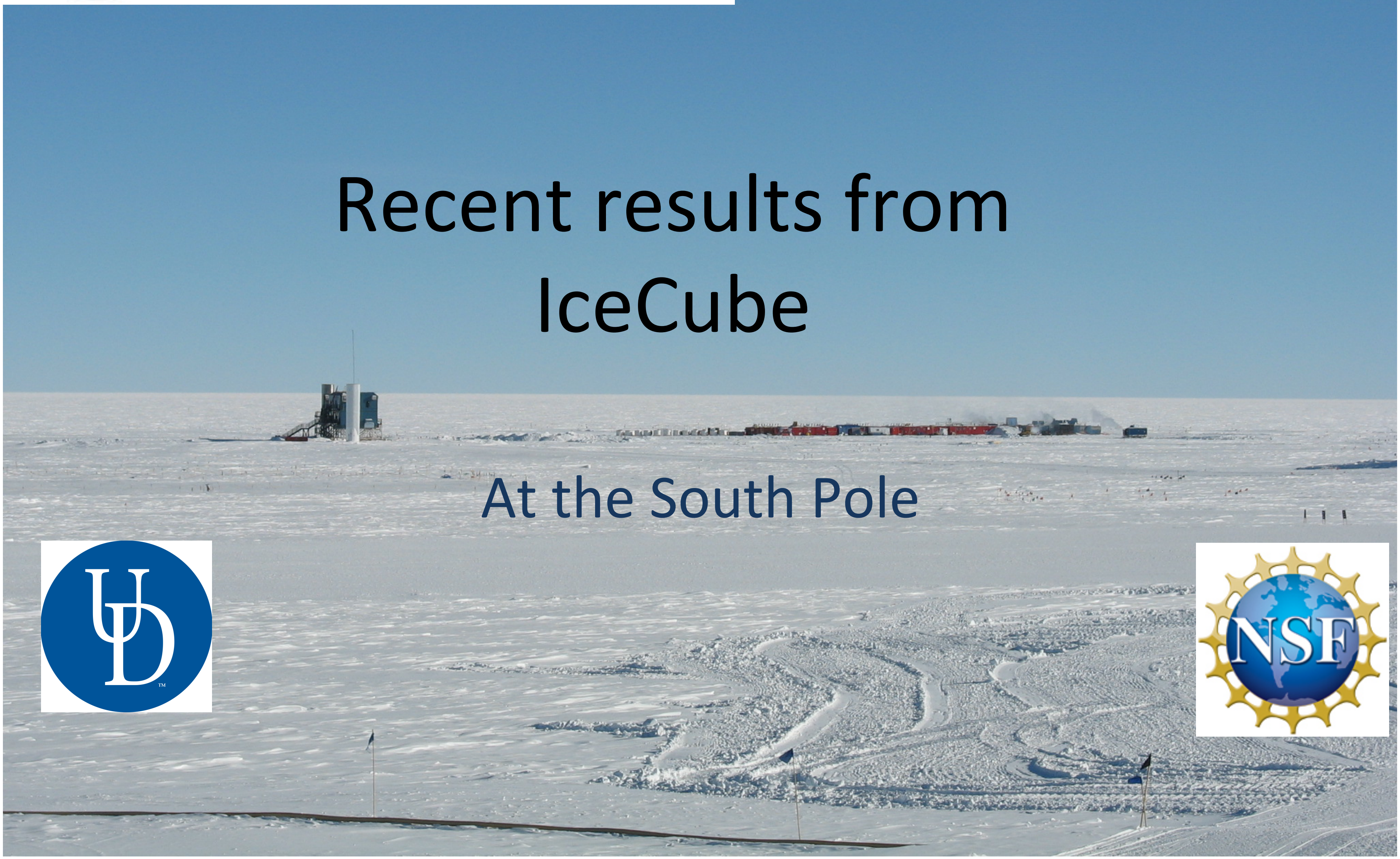
Recent results from IceCube



At the South Pole

Outline

1. The IceCube Observatory

2. Atmospheric and astrophysical neutrinos

3. Cosmic-ray physics with IceCube

4. Multi-messenger astrophysics and real time alerts

1. IceCube

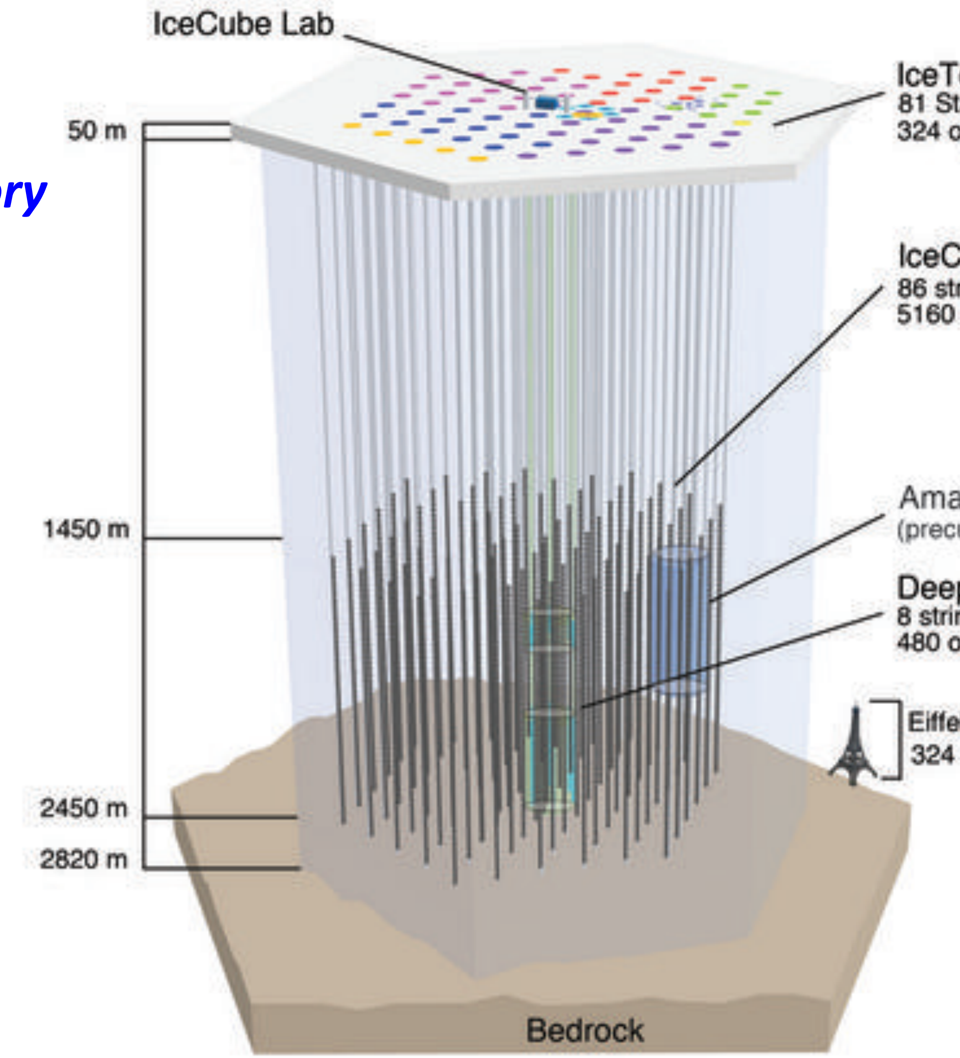
Deployment history

2002: proposal
2003-04 staging

2004-05	**1**	**4**
2005-06	**9**	**16**
2006-07	**22**	**26**
2007-08	**40**	**40**
2008-09	**59**	**59**
2009-10	**79**	**73**
2010-11	**86**	**81**

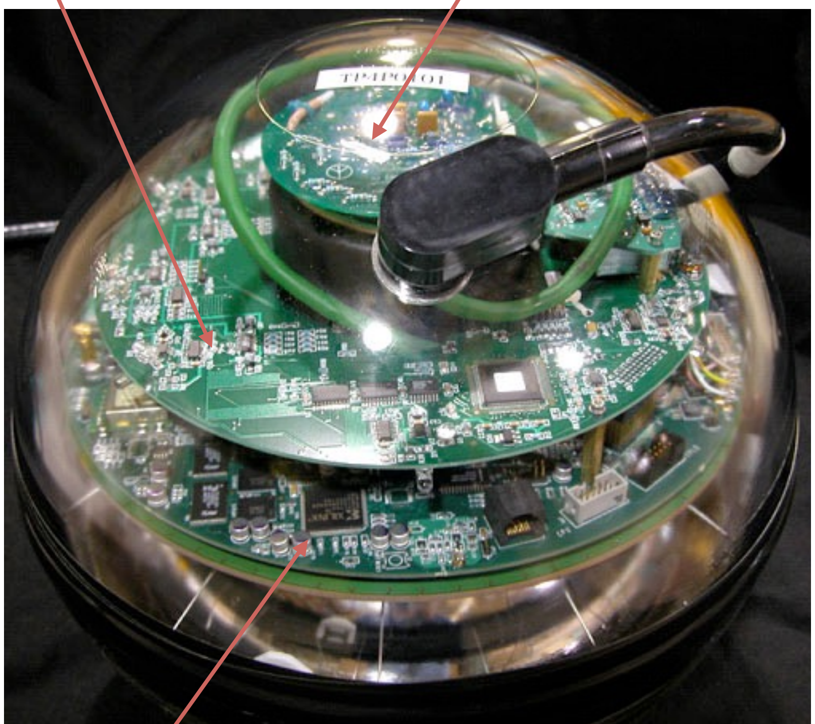
Deep strings

Surface stations



> 5400 Digital Optical Modules

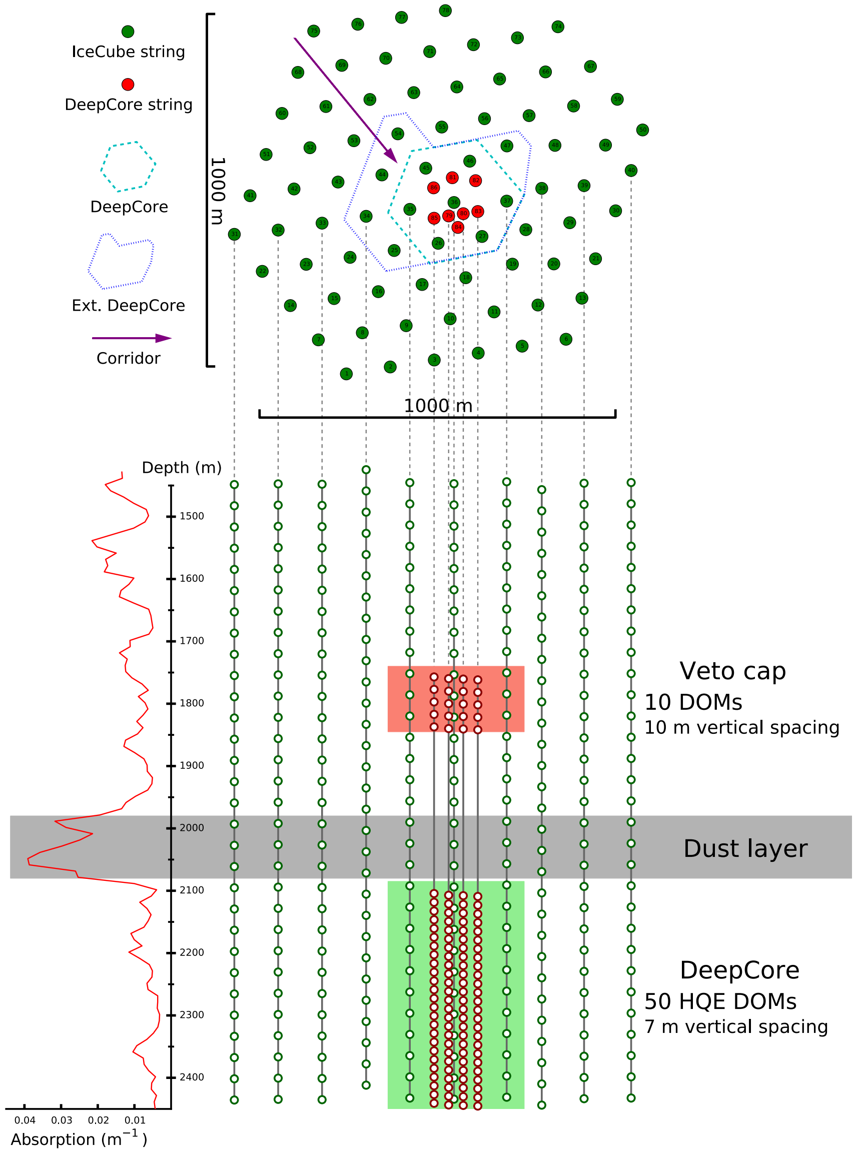
IceCube Digital Optical Module and deployment



IceCube Construction: 2004-2011

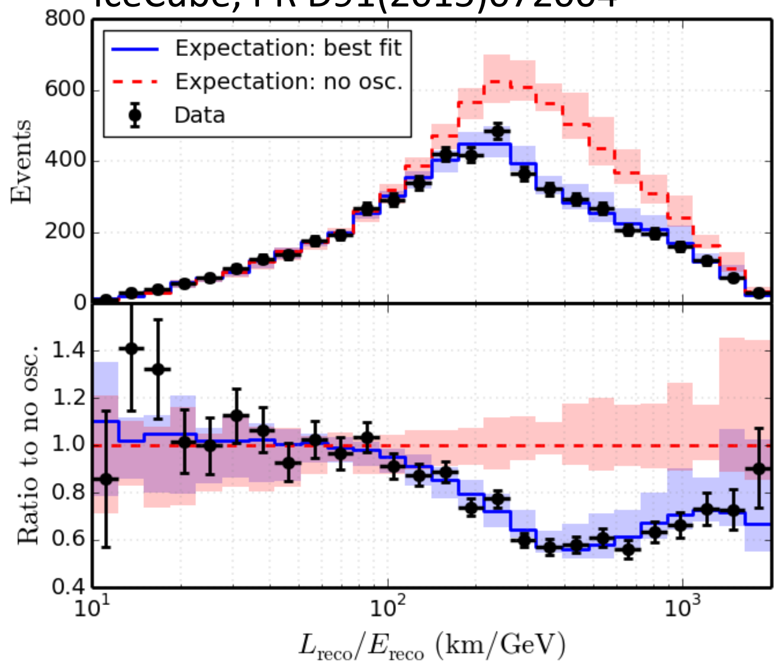
DeepCore subarray

- 8 strings with DOMs separated by 7 m
- Plus 7 standard strings
- Close spacing of strings lowers threshold from >100 GeV to <10 GeV
- Atmospheric neutrino oscillations studied near first oscillation maximum

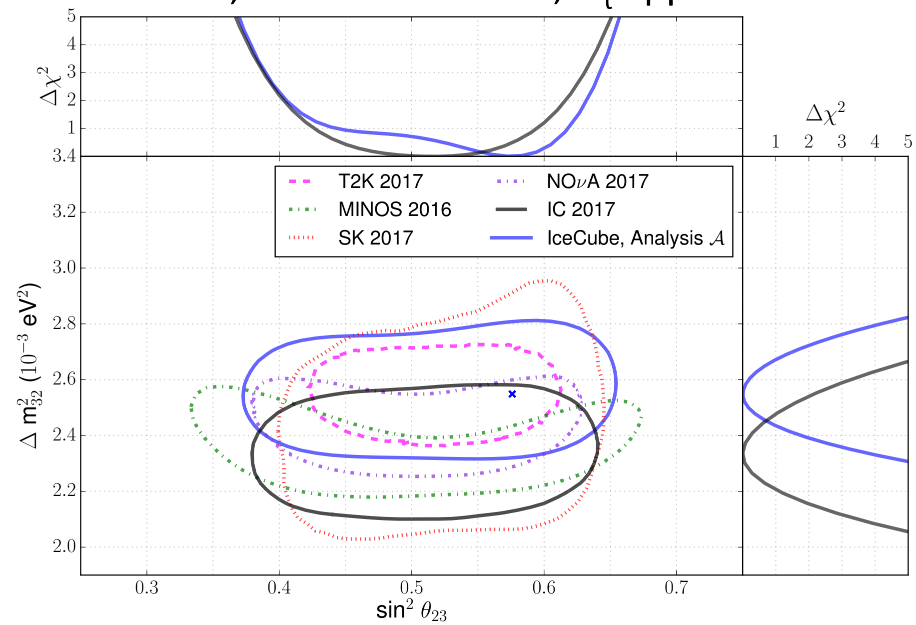


DeepCore oscillations results

IceCube, PR D91(2015)072004



IceCube, arXiv:1901.05366, ν_τ appearance



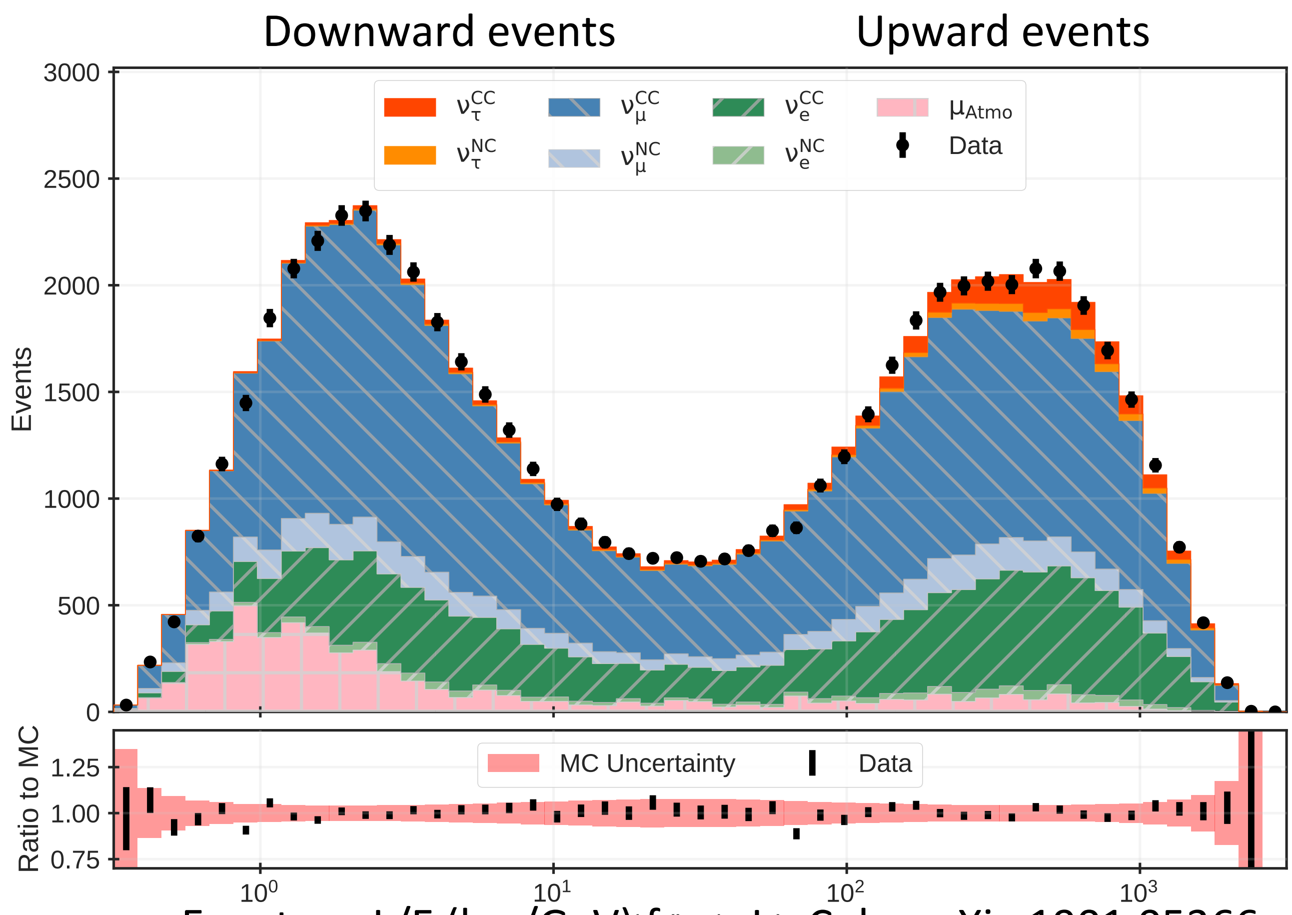
Neutrino oscillations: 3✕3 mixing matrix with main channel for $\nu_\mu \rightarrow \nu_\tau$

$$P_{\nu_\mu\rightarrow\nu_\tau} \approx \sin^2 2\theta_{23}\ \sin^2\left(1.27\frac{\delta m^2_{32}(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

Has a maximum at $E_\nu \approx 25$ GeV for $L \approx 10^4$ km, then goes to 0 for atmospheric ν as energy increases

Atmospheric ν_τ appearance

$$\nu_\tau \rightarrow \tau \begin{cases} \mu + \nu_\nu \\ e + \nu_e \\ q + \bar{q} \times 3 \end{cases}$$



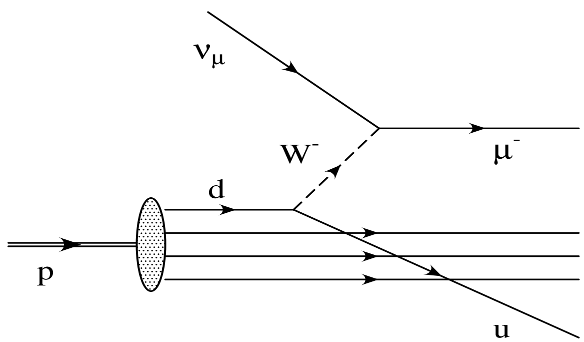
Events vs L/E (km/GeV) from IceCube arXiv:1901.05366

E_ν 5.6 to 56 GeV
$c\tau_\tau$ = 87 μm
m_τ = 1.777 GeV so
$\sigma(\nu_\tau) < \sigma(\nu_\mu) \approx \sigma(\nu_e)$

Astrophysical ν_τ appearance

P($\nu_\mu \rightarrow \nu_\tau$) averages to ½ over astronomical distances, so astrophysical neutrinos should include many ν_τ

Problem: they are difficult to distinguish in the detector



$$\nu_\mu \rightarrow \mu \rightarrow \text{ track}$$

Diagram for CC interaction of a ν_μ

Analogous diagrams for ν_e and ν_τ give

$$\nu_e \rightarrow e \rightarrow \text{ cascade}$$

$$\nu_\tau \rightarrow \tau \rightarrow \text{ short track} \rightarrow \text{cascade}$$

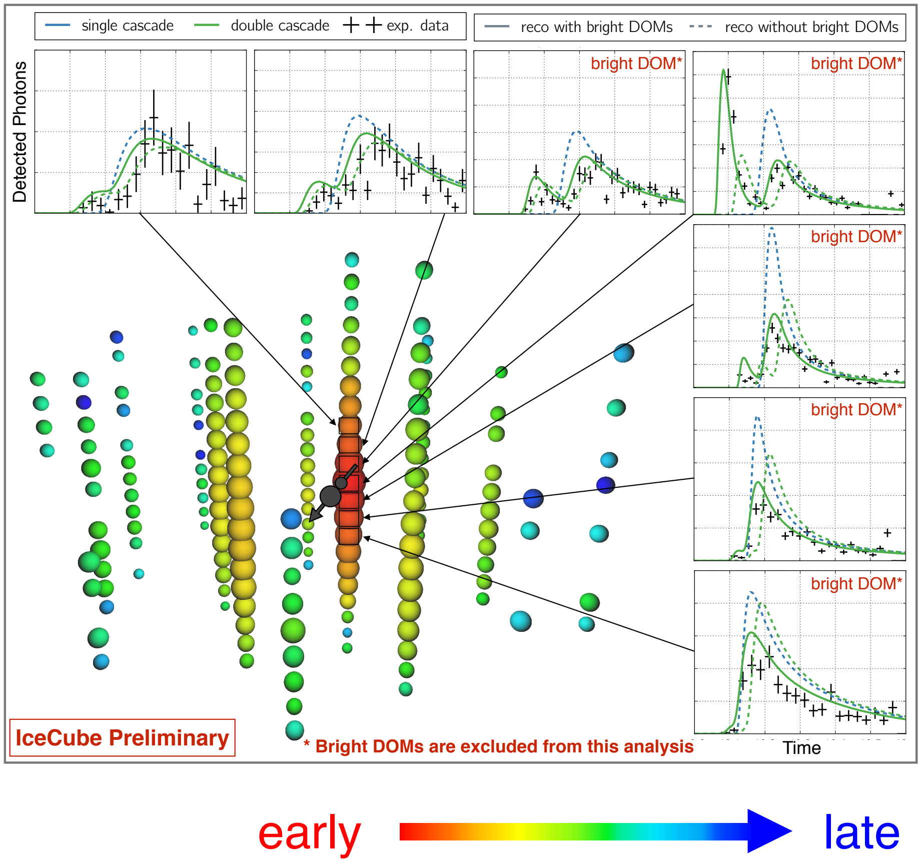
Double…………………………………………..bang

Learned & Pakvasa, Astropart. Phys. 3(1995)267

Problem: short lifetime of τ-lepton so event looks like a single cascade

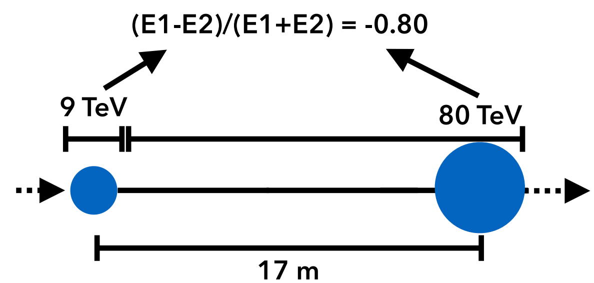
$$\gamma c\tau_\tau \approx 5\,m \times \frac{E_\tau}{100\,TeV}$$ compared to ≈ 10 m for em cascade from an electron

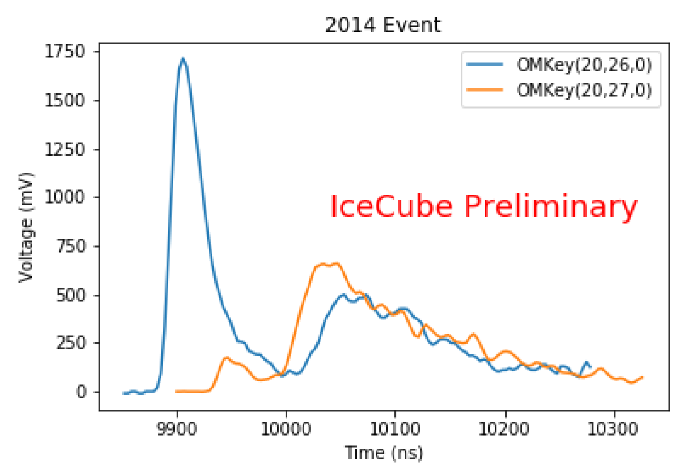
Astrophysical ν_τ candidate in IceCube



Double cascade analysis:

J. Stachurska for IceCube PoS(ICRC2019)1015





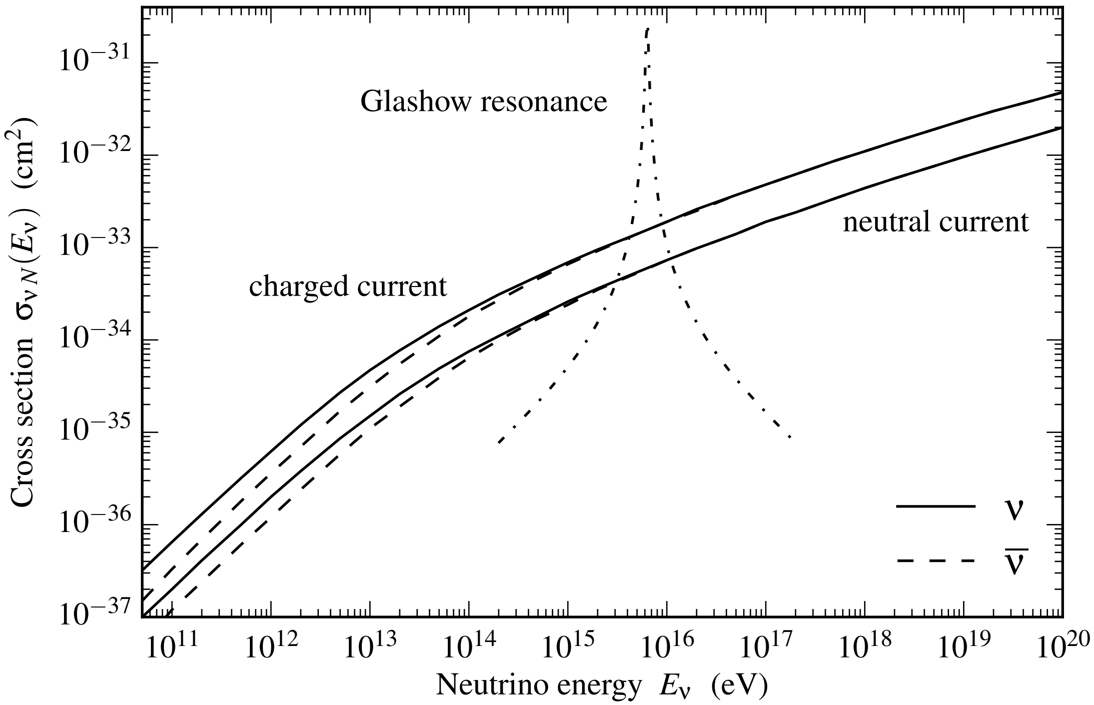
The same event is also found in two analyses that look for double peaked waveforms in bright DOMs:

Meier & Soedingrekso for IceCube PoS(ICRC2019)960

Wille & Xu for IceCube PoS(ICRC2019)1036

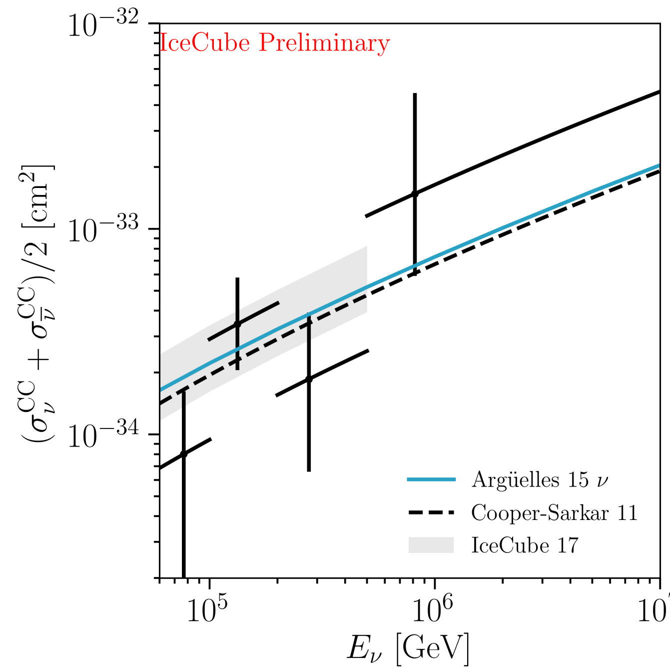
Neutrino cross sections

Figure from TG, Engel, Resconi book, 2016



Cross sections: CSMS, JHEP 1108 (2011) 042
Glashow Resonance, Phys. Rev. 118 (1960) 316

T. Yuan for IceCube
PoS(ICRC2019)1040 uses High Energy Starting Event sample directions through Earth and energies

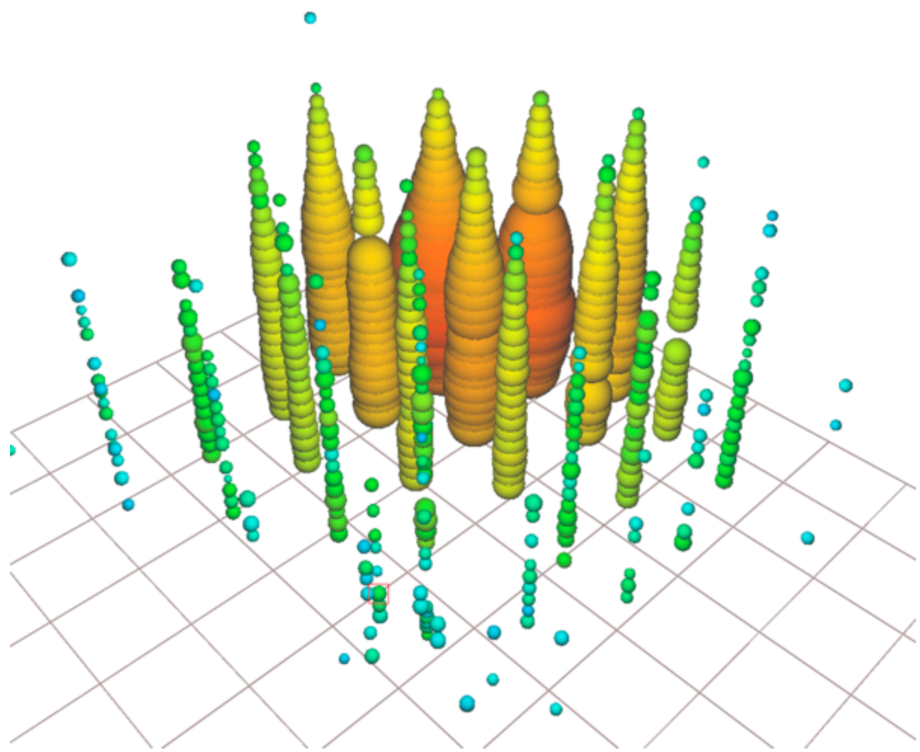


Glashow event candidate in IceCube

$$\overline{\nu}_e + e^- \to W^- \to \text{cascade}$$

- Discovered in a study of partially contained large cascades
- Visible energy consistent with the 6.3 PeV resonance energy
- PoS(ICRC2019)945

  Lu Lu for IceCube



Implications of small σ_ν

- Neutrinos reach Earth unabsorbed from cosmological distances
- The Earth starts absorbing up-going neutrinos only for $E_\nu > 10$ TeV
- Detector should be as large as possible:
  - The fraction of ν interacting 1 km of ice is small

$$1\,\mathrm{km\,ice} = 0.91 \cdot 6 \times 10^{23} \cdot 10^5 = 5 \cdot 10^{28}\,\mathrm{nucleons/cm}^2$$

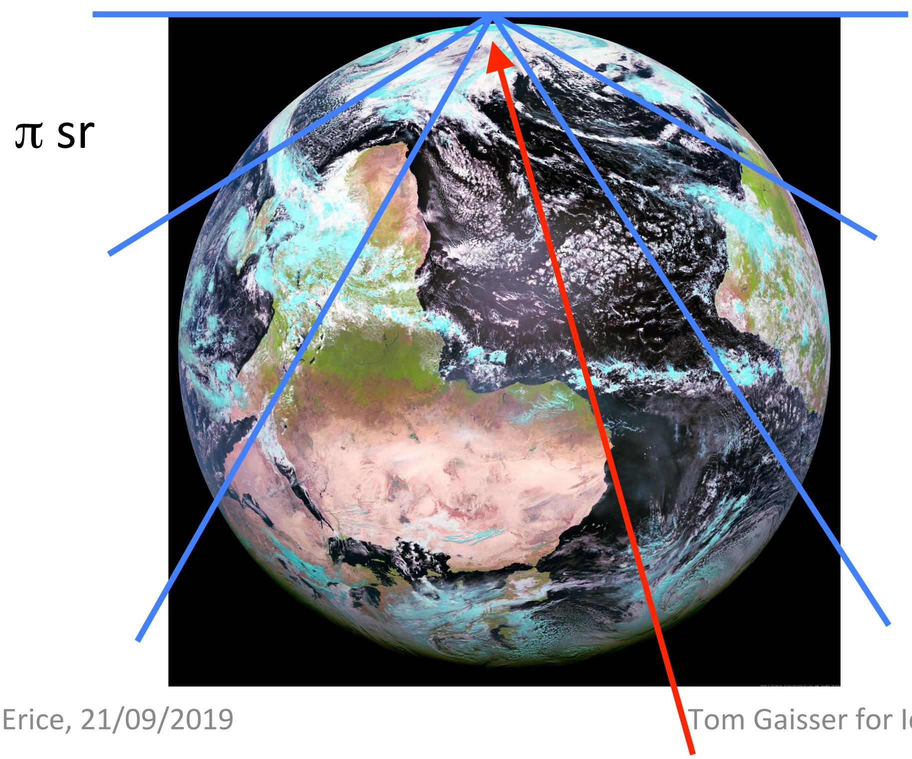
$$\sigma_\nu \approx 2.6 \cdot 10^{-34}\,\mathrm{cm}^2\ \mathrm{at}\,10^5\,\mathrm{GeV}$$

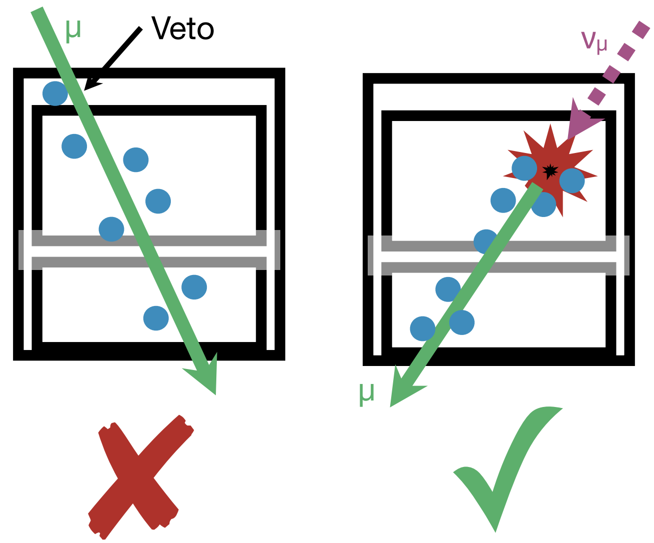
Product ≈ 10^{-5} is fraction of ν of this energy that interact in detector

2. IceCube high-energy neutrinos

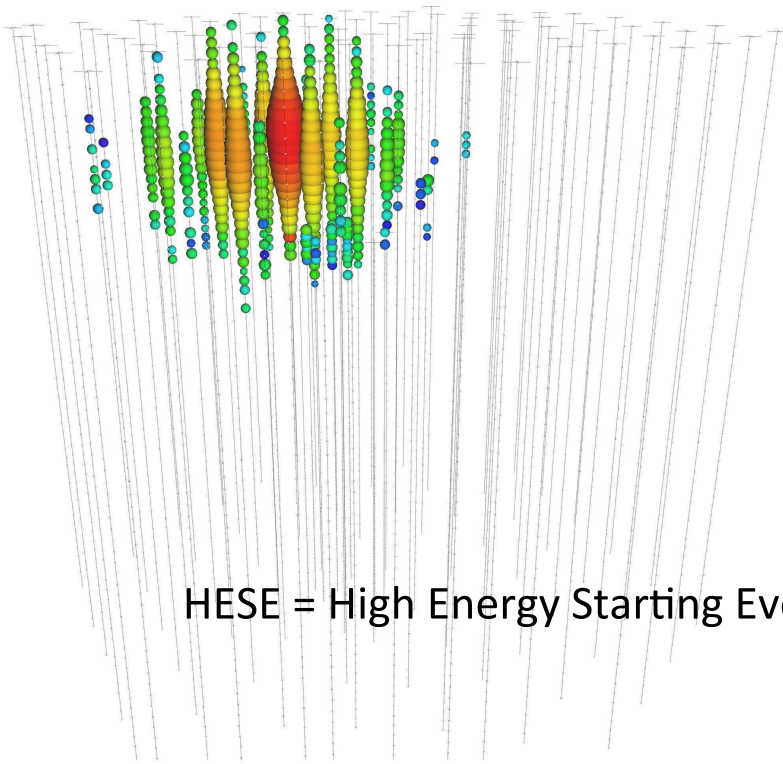
Two ways to identify neutrinos:

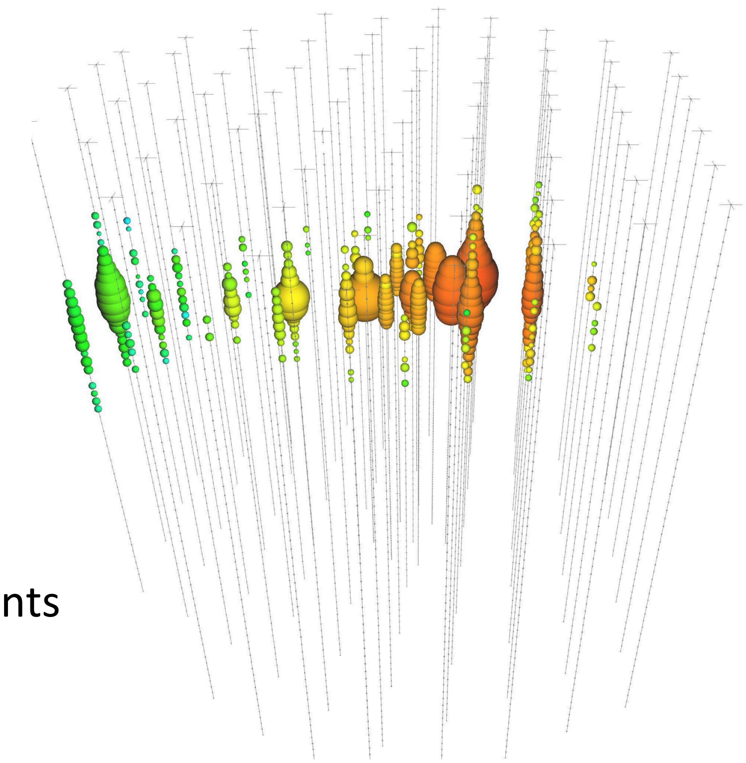
1. Upward using Earth as filter
2. Events start in detector





HESE event types in IceCube



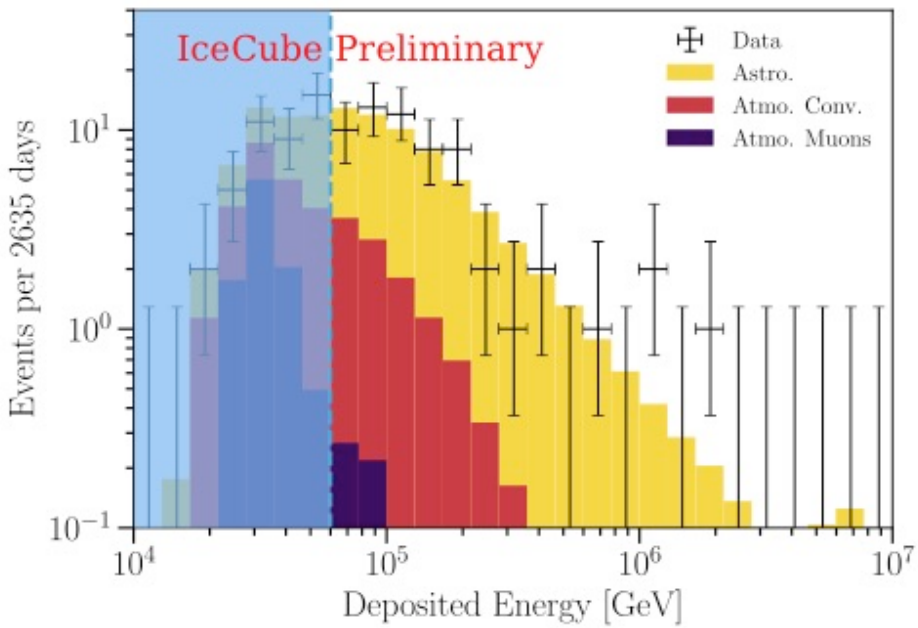


HESE = High Energy Starting Events

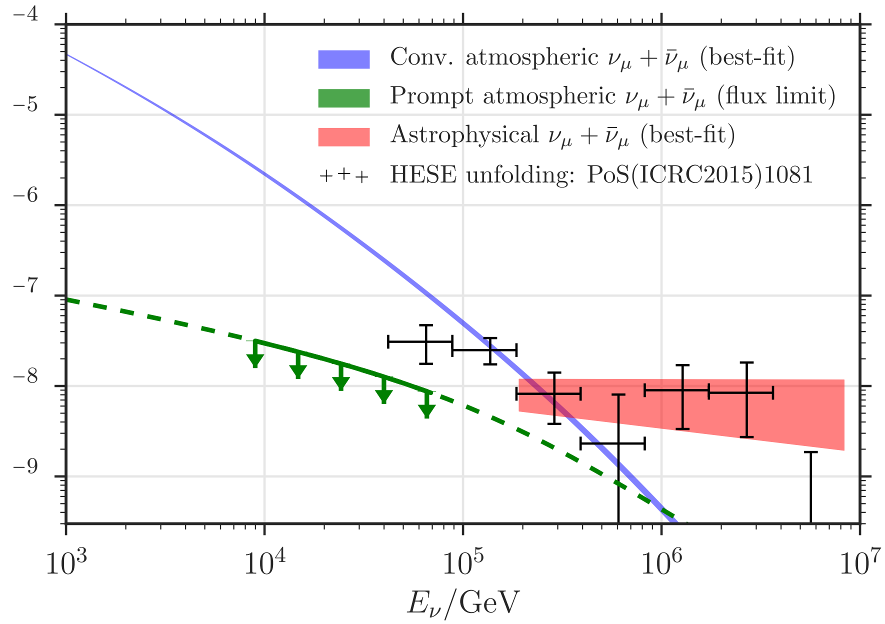
Cascade events:
CC interactions of ν_e and ν_τ
NC interactions of all flavors

Starting track: CC ν_μ
Note initial hadronic cascade

Astrophysical neutrinos



IceCube *7.5 year* HESE analysis
(HESE = High Energy Starting Event)
PoS(ICRC2019)1004

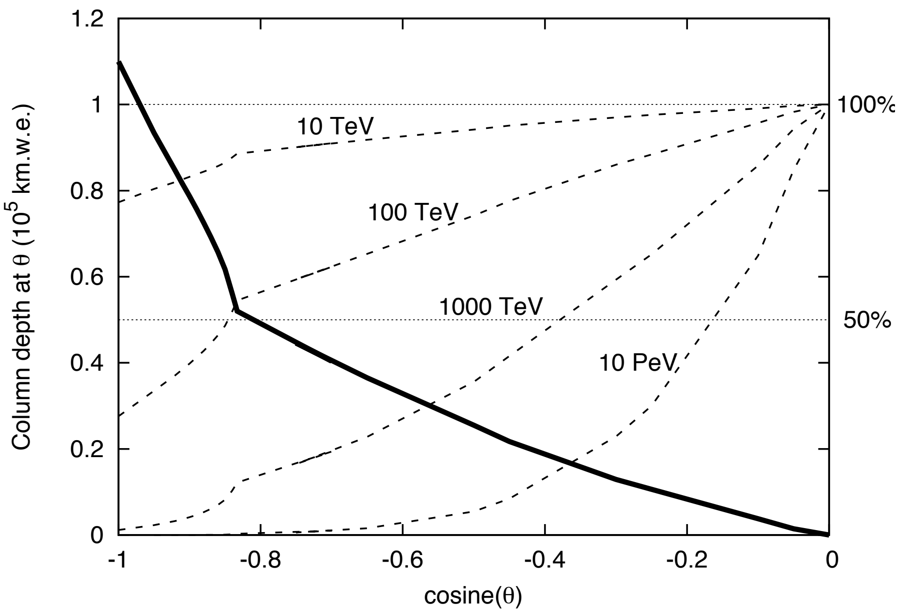


IceCube 6 year $\nu_\mu \rightarrow \mu$ analysis
arXiv:1607.08006, Ap.J. 833 (2016) 3

The astrophysical signal emerges above a steeply falling background of atmospheric neutrinos

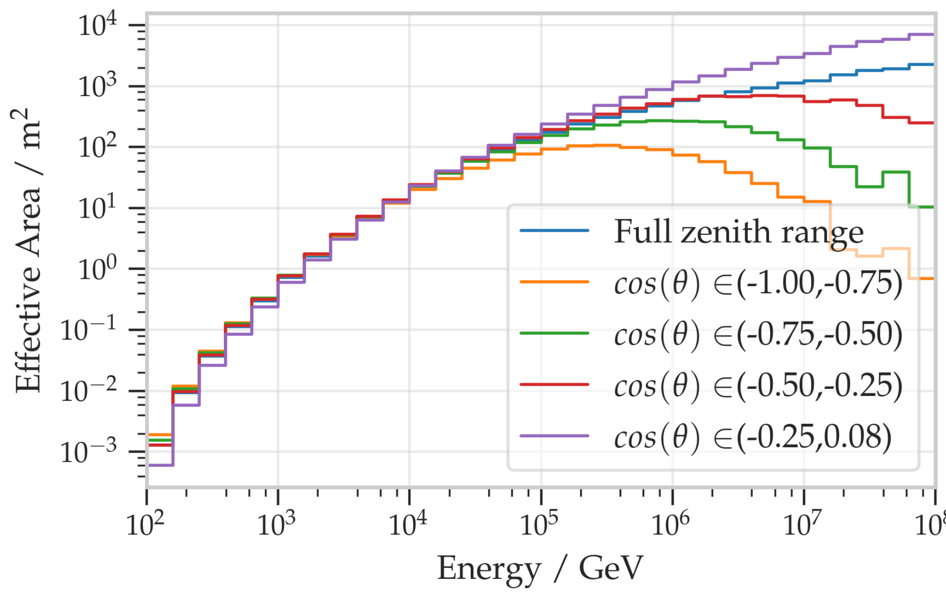
Shadow of the Earth

Affects both atmospheric and astrophysical neutrinos



Transparency of the Earth for neutrinos. Dashed line show passing fractions at four neutrino energies.

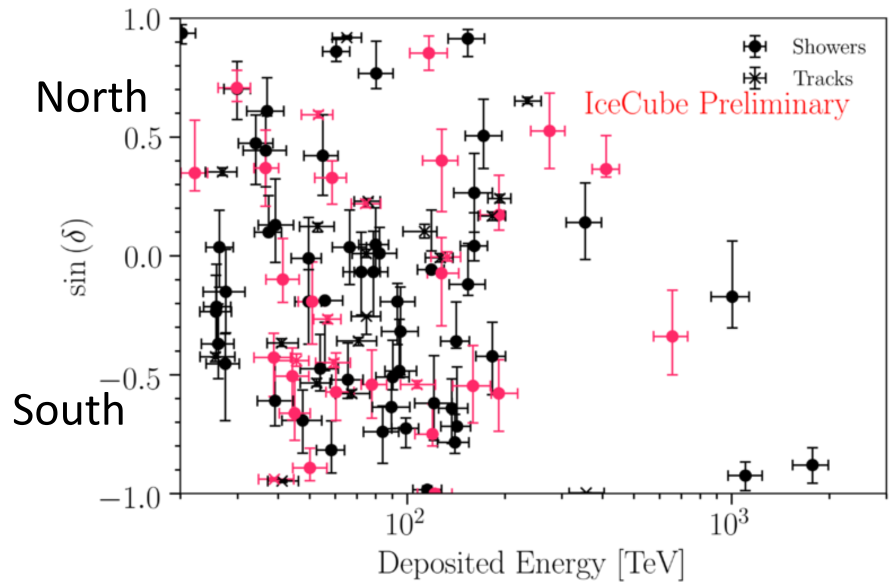
(Figure from *Atmospheric Neutrinos,* TG to appear in “Particle Physics with Neutrino Telescopes", C. Pérez de los Heros, editro, World Scientific.

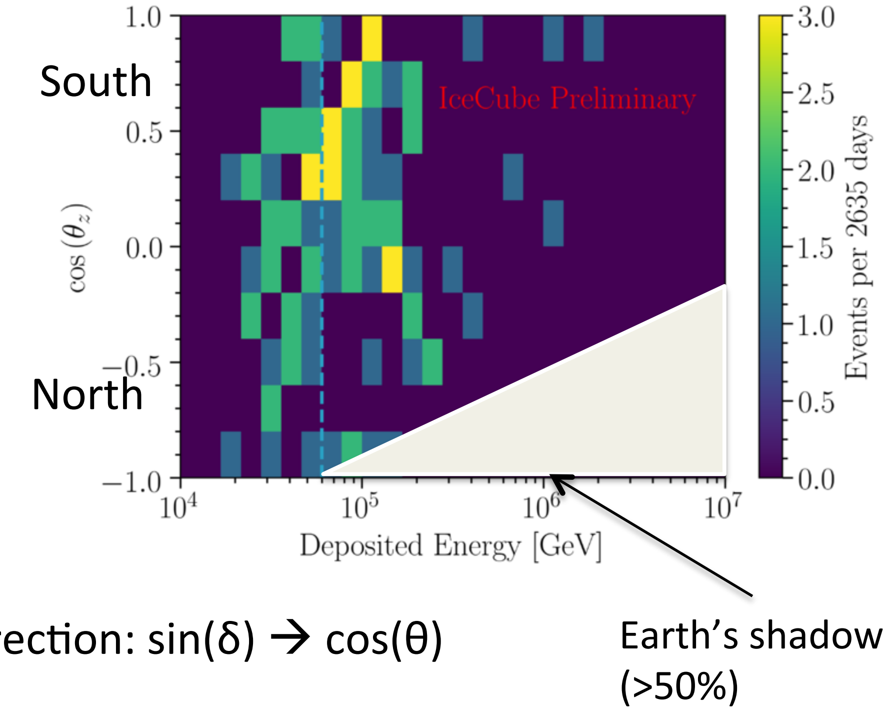


Effective areas for upward ν_μ in IceCube for the Northern hemisphere and for 4 directions below the horizon. Note the absorption of the Earth for high energies from large negative zenith angles.
(Fig. from PoS(ICRC2019)1017, J. Stettner for the IceCube collaboration.)

HESE 7.5 yrs

New reconstructions for all years with IceCube Pass 2



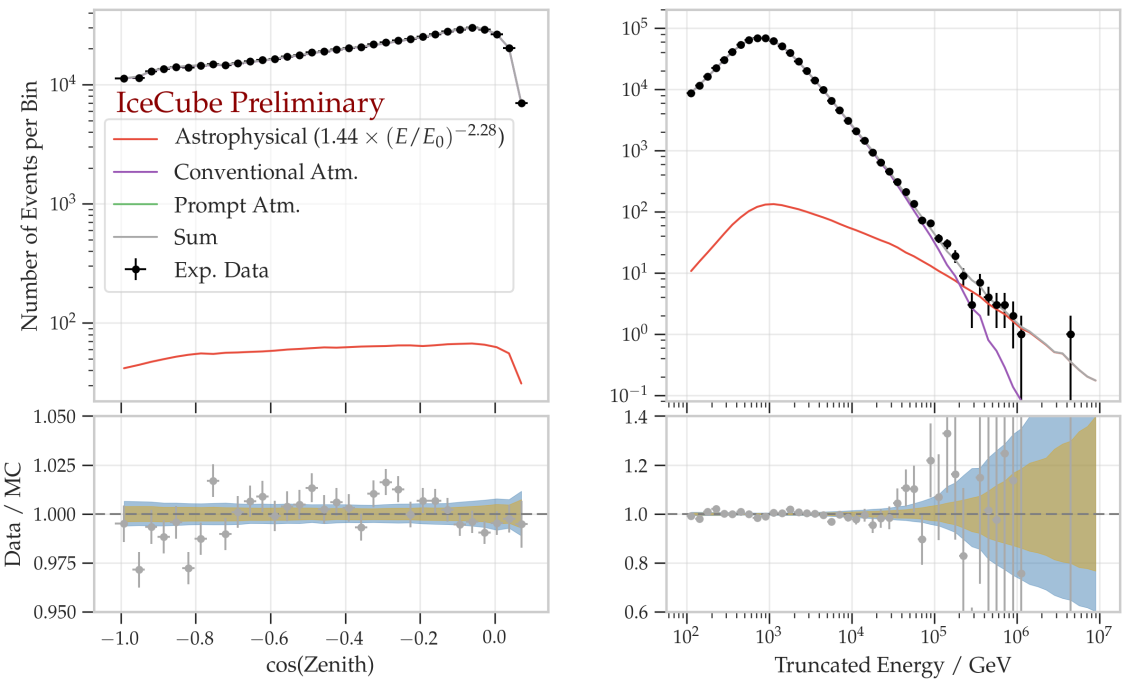


Note change in convention for direction: sin(δ) → cos(θ)

Work in progress reported at TeVPA 2018
(Austin Schneider for IceCube)

Upward ν_μ-induced muons (10 yrs)

- Red lines show astrophysical component
- Atmospherics dominate the angular distribution
- Signal emerges over background above 100 TeV

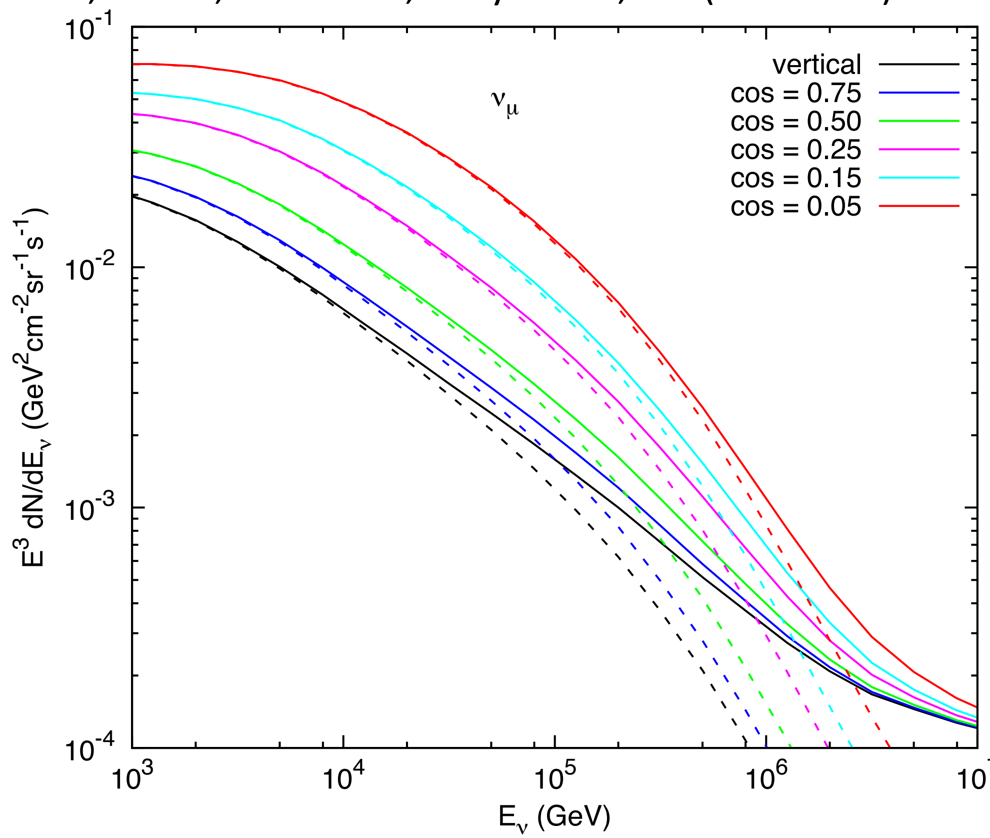


(Fig. from PoS(ICRC2019)1017, J. Stettner for the IceCube collaboration.)

Atmospheric ν_μ background

Fig. : TG, Soldin, Crossman, Fedynnitch, PoS(ICRC2019)893

- Flux increases near the horizontal
  - Decay of parent $K^\pm$, $\pi^\pm$ more likely
  - Most ν_μ are from $K^\pm$
- Prompt ν from charm dominate at high E:
  - above 100 TeV for vertical and
  - PeV for horizontal

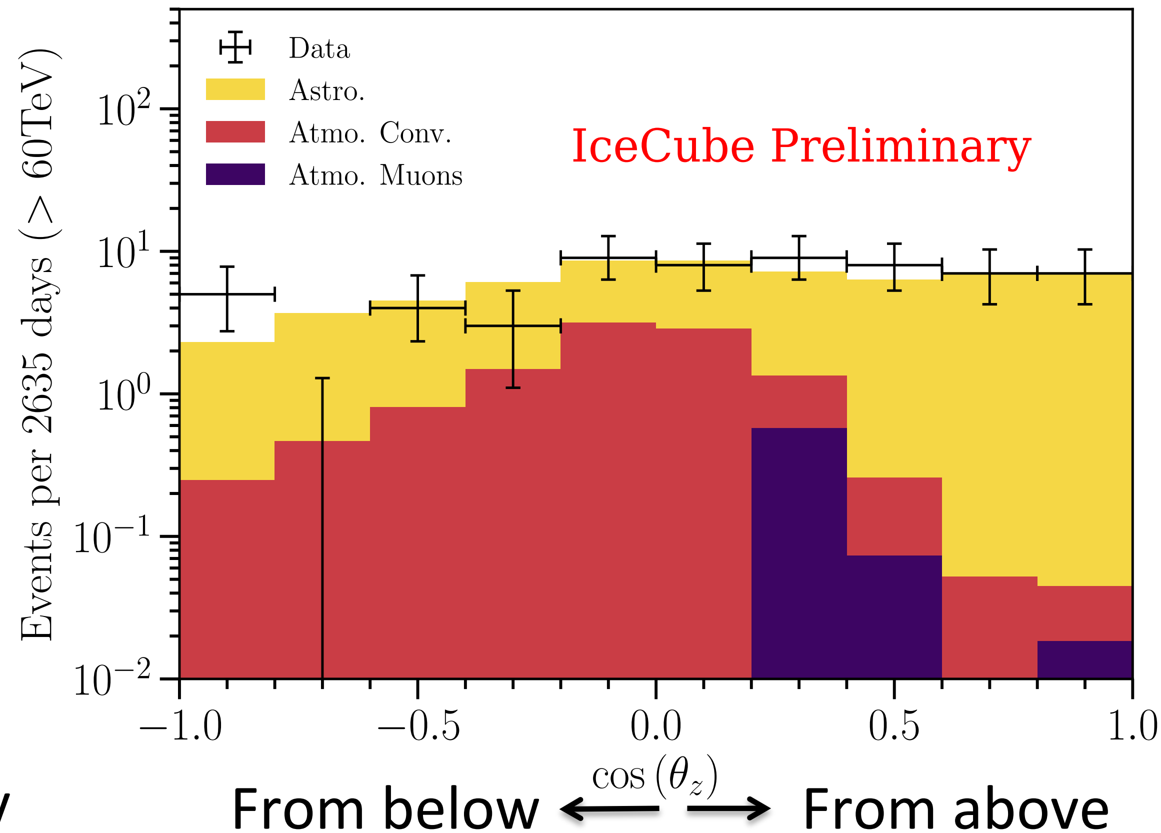


$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \sim \sum_{i=1,3} \frac{\mathcal{A}_{i\nu}}{1 + \mathcal{B}_{i\nu} \cos\theta E_\nu / \epsilon_i(T)}$$

$$\epsilon_{\pi^\pm} = 115\,\mathrm{GeV}$$
$$\epsilon_{K^\pm} = 857\,\mathrm{GeV}$$
$$\epsilon_{D^\pm} = 37\,\mathrm{PeV}$$
$$\text{for } T = 220^\circ K$$

HESE Angular distributions $E_{vis} > 60$ TeV

Fig. from PoS(ICRC2019) 1004, A. Schneider for IceCube



Angular dependence:

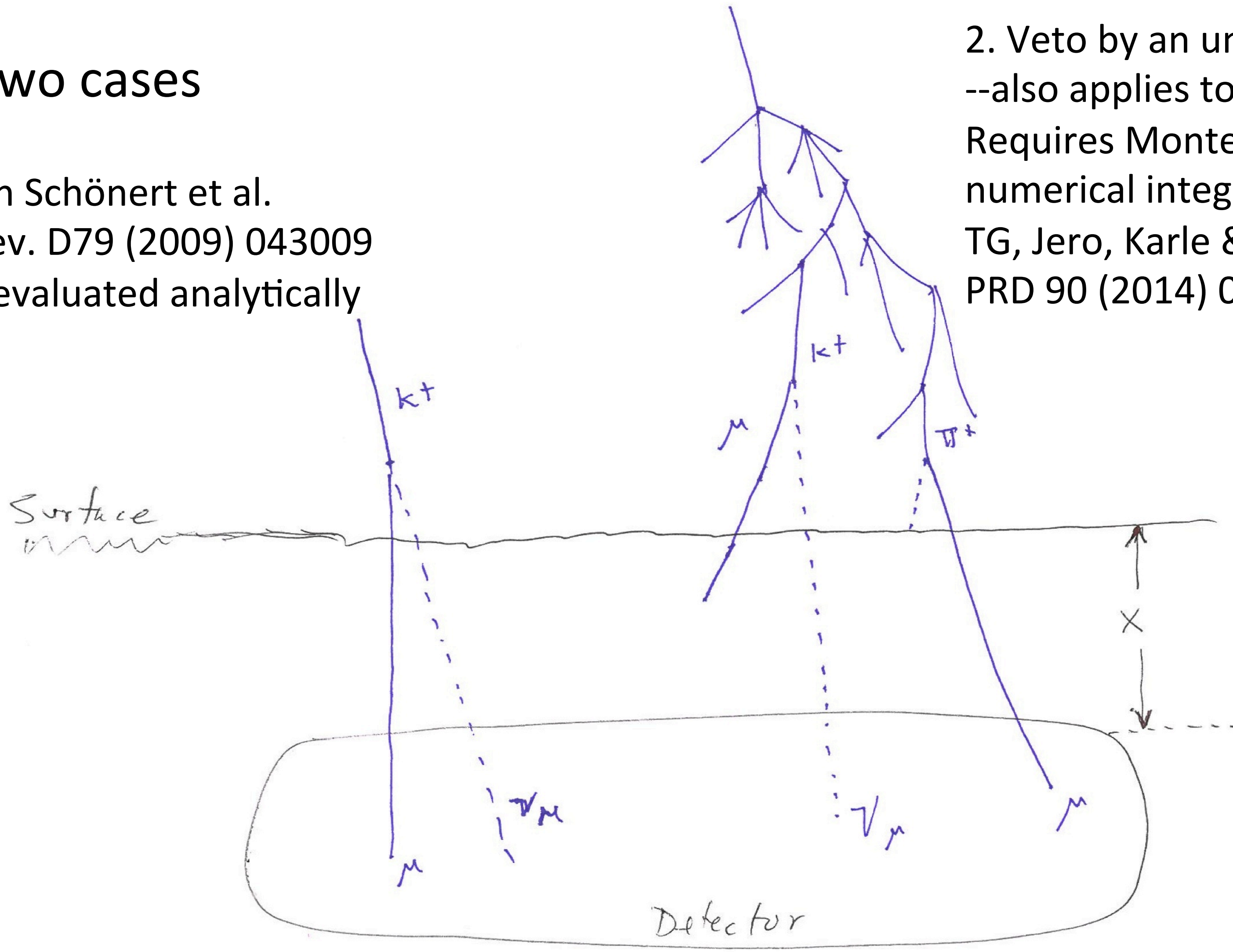
- From below:
  - absorption for signal
  - plus intrinsic excess for atmospheric ν near horizon
- From above:
  - self-veto of atmospheric ν by accompanying μ

Atmospheric neutrino self veto

Two cases

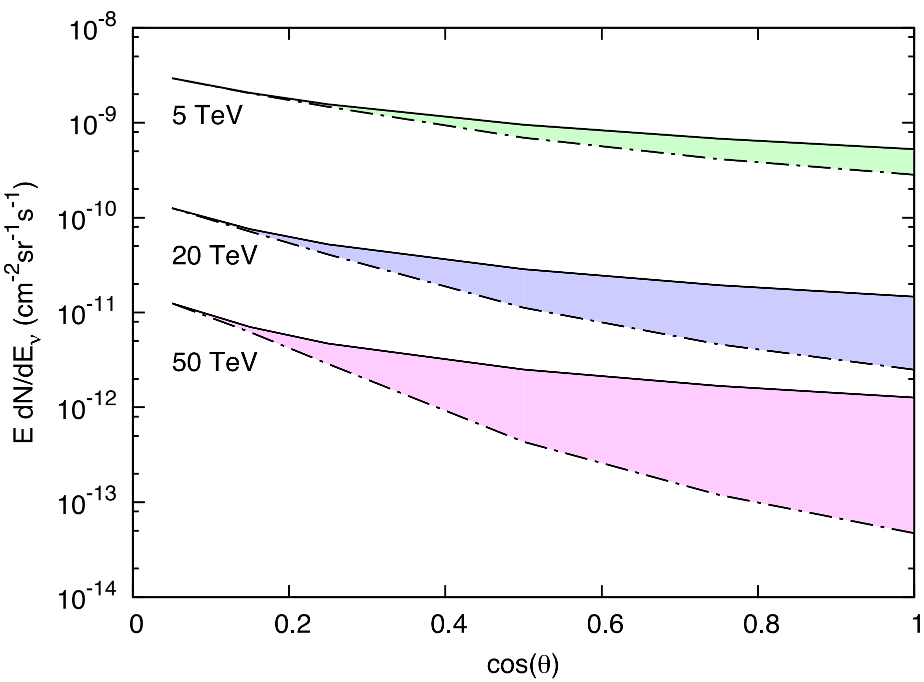
1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or numerical integration
TG, Jero, Karle & van Santen, PRD 90 (2014) 023009

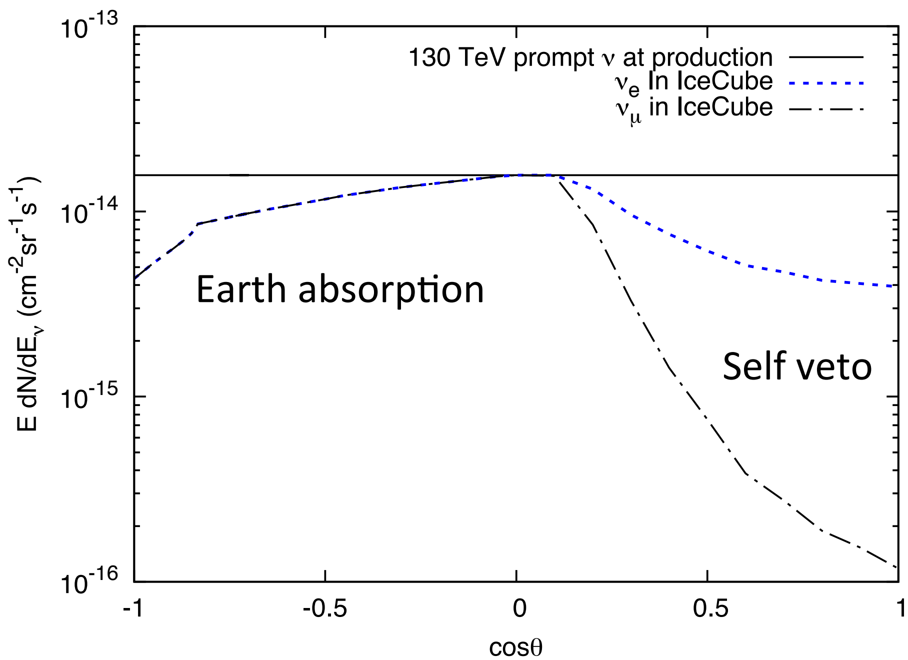


Neutrino self-veto updated*

Conventional ν_μ from above:
Peaked near horizon; veto probability increases with energy, more for vertical



Prompt ν at 130 TeV:
Isotropic at production,
Self veto stronger for ν_μ than for ν_e



Figures from TG chapter in World Scientific using updated veto*

* Arguelles, Palomares-Ruiz, Schneider, Wille, Yuan JCAP 1807 (2018) no.07, 047

High-energy astrophysical neutrinos

Cosmic-ray – gamma-ray – Neutrino connection

Astrophysical sources accelerate charged particles

Electrons produce photons e.g. by inverse Compton scattering, **but not neutrinos**

Protons produce mesons which produce **neutrinos** as well as photons

$$\pi^0 \to \gamma\,\gamma \qquad \pi^\pm \to \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$$

$$\mu^\pm \to e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$

Neutrinos have the potential to identify cosmic-ray sources

Galactic

Diffuse	Sources
C.R. + gas → ν	e.g. SNR near clouds

Extragalactic

Diffuse	Sources: Steady	Sources: Transient
p + CMB→π	SFG	GRB
p + EBL→ π	AGN	AGN
	SNRIIn	

Galactic fraction

- Of order 10%
- It is a guaranteed source
- Antares/IceCube limit is close to prediction (Ap.J.868 (2018) no. 2 L20)

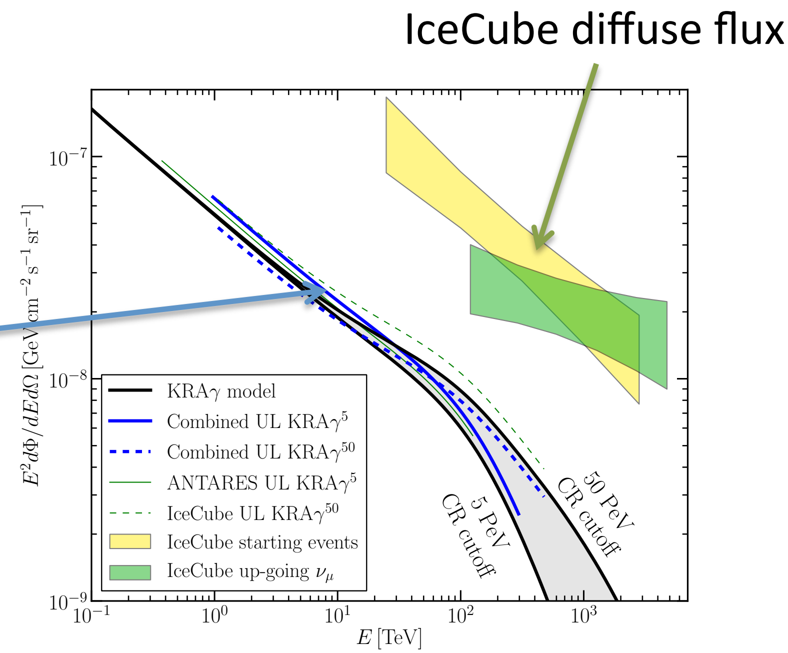
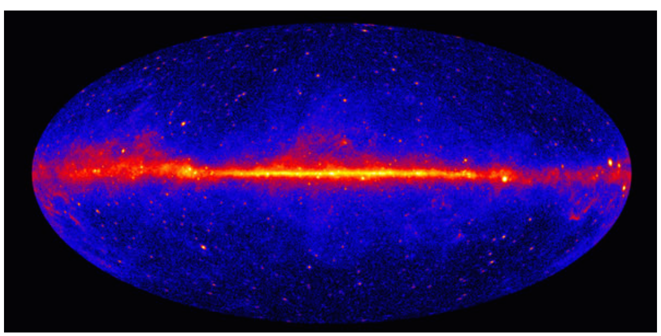


Figure 4. Combined upper limits (UL) at 90% confidence level (blue lines) on the three-flavor neutrino flux of the KRA$_\gamma$ model with the 5 and 50 PeV cutoffs (black lines). The boxes represent the diffuse astrophysical neutrino fluxes measured by IceCube using an isotropic flux template with starting events (yellow) and upgoing tracks (green).

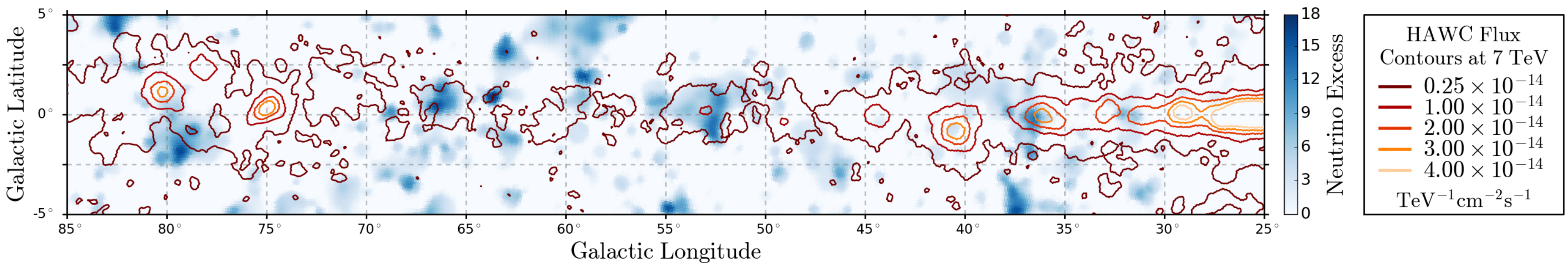


Fermi map of Gal. plane diffuse:

$$p + \text{gas} \rightarrow \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

Search for Galactic point sources (e.g. supernova remnants, pulsars)

Use HAWC high-energy γ measurements as a template.
Kheirandish & Wood for IceCube and HAWC Collaborations PoS(ICRC2019)



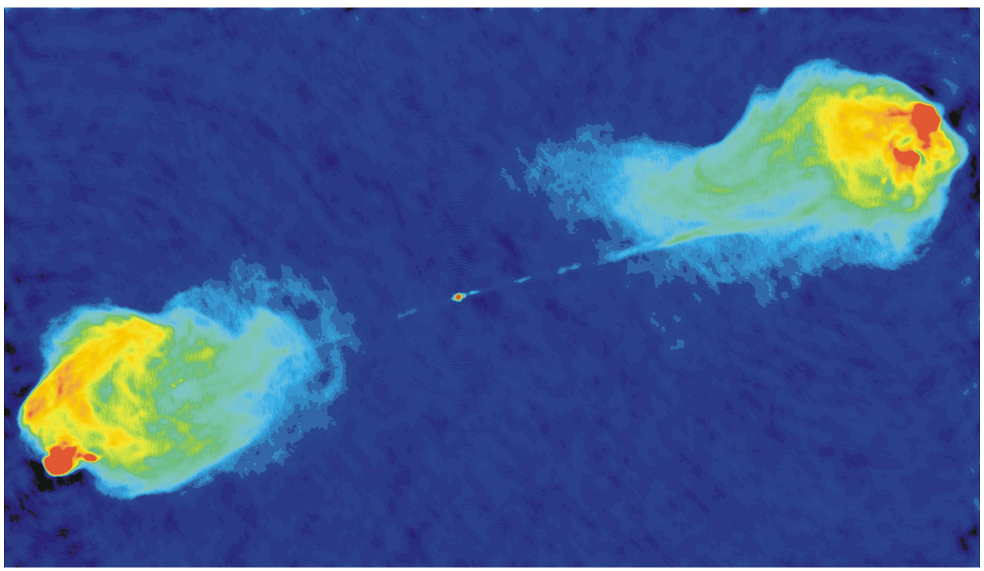
Map of IceCube ν excess (blue) superimposed on HAWC 7 TeV γ contours (red)

Search	Best Fit n_s	Sensitivity 10^{-13} [$TeV^{-1}cm^{-2}s^{-1}$]	Upper Limit (90% C.L.) 10^{-13} [$TeV^{-1}cm^{-2}s^{-1}$]	p-value
Stacking	15.4	0.7 (0.6)	1.5 (1.3)	0.09
Northern Plane	77.8	2.5 (0.4)	5.7 (0.8)	0.06
Cygnus Region	0.0	1.0 (0.6)	0.4 (0.2)	0.80
J1908+063 Region	12.0	0.7 (0.7)	1.3 (1.3)	0.14
J1857+027 Region	36.7	0.8 (1.2)	2.1 (3.2)	0.02

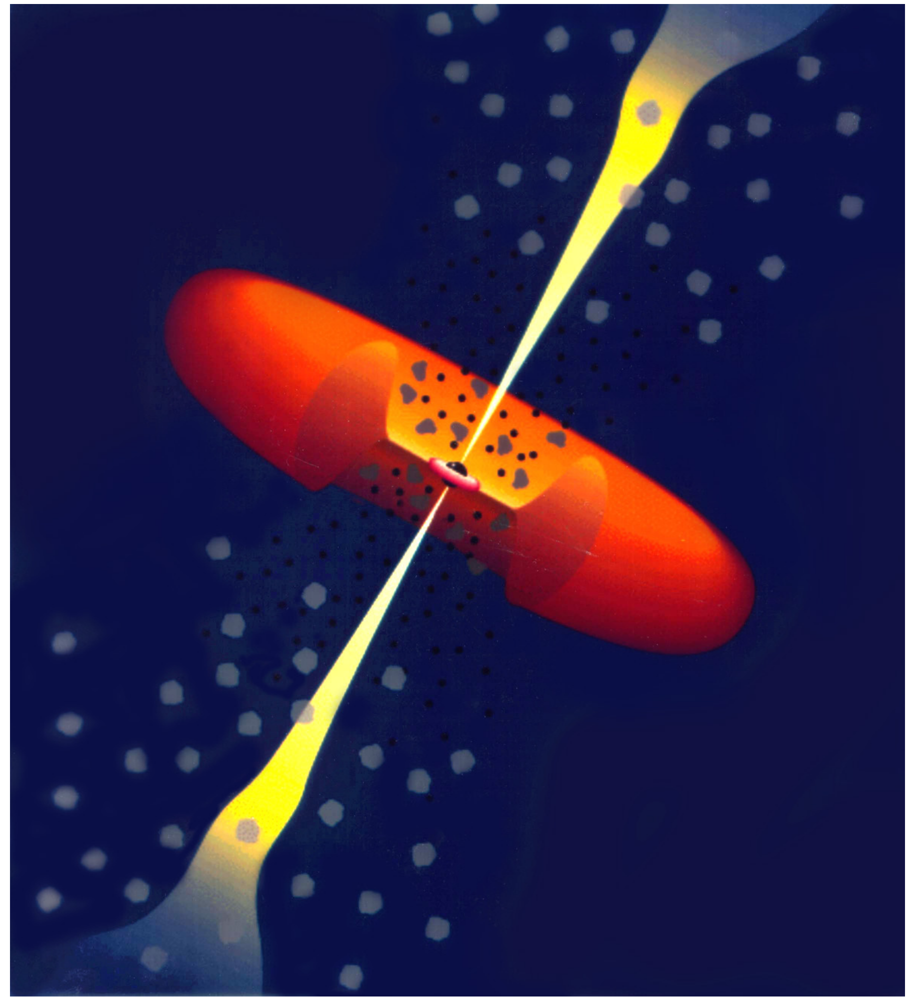
Active Galaxies as particle accelerators

A common phenomenon on both stellar & galactic scales:

- *Matter falls onto black hole or neutron star driving collimated, relativistic jets perpendicular to the disk*
- *Acceleration can occur both at remote termination shocks and at internal shocks near the central engine*
- *Neutrinos expected from central region but not from distant termination shocks*



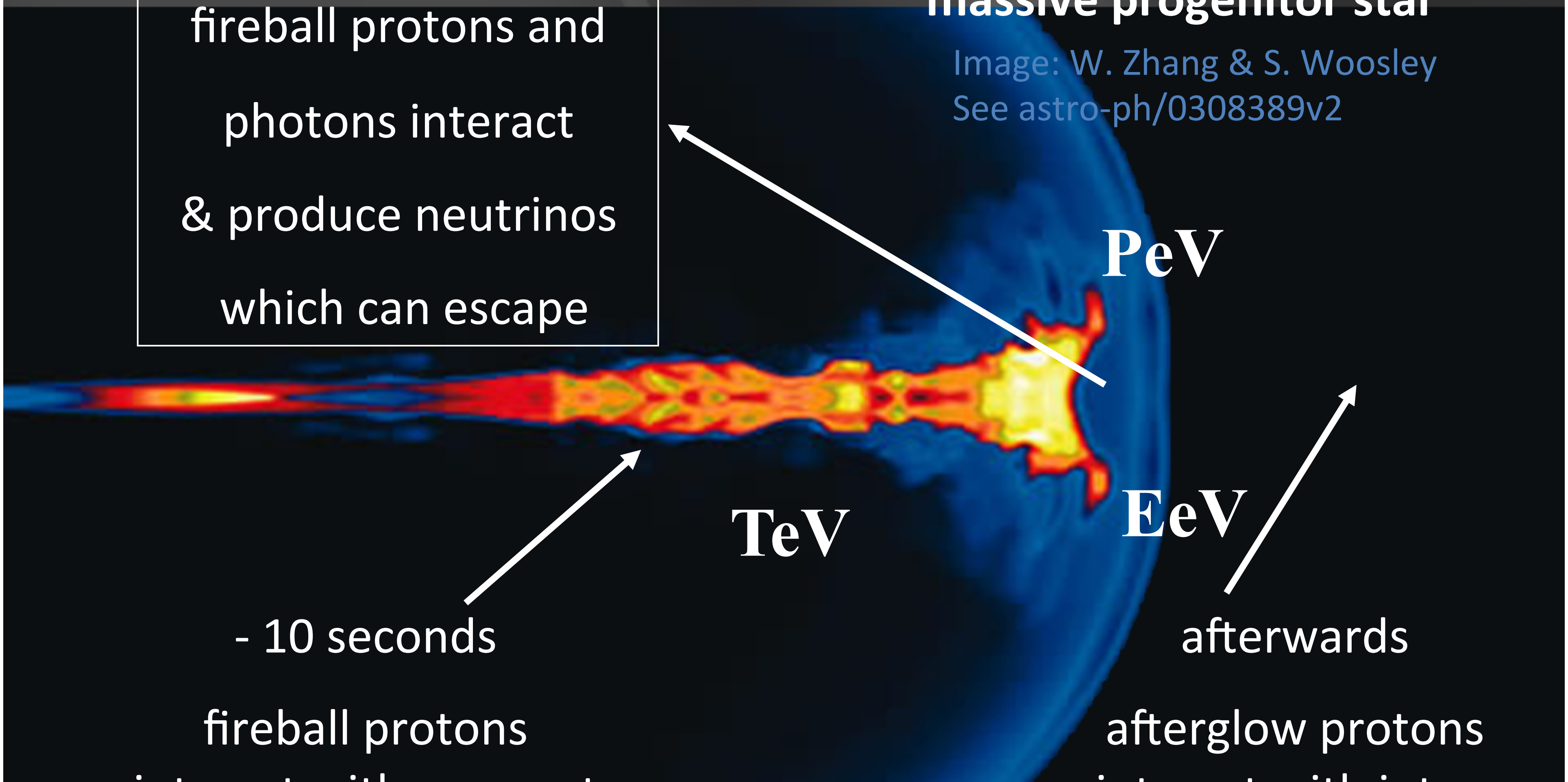
VLA image of Cygnus A
An active galaxy



M. Urry, astro-ph/0312545

Jet breakout in GRB following collapse of massive progenitor star

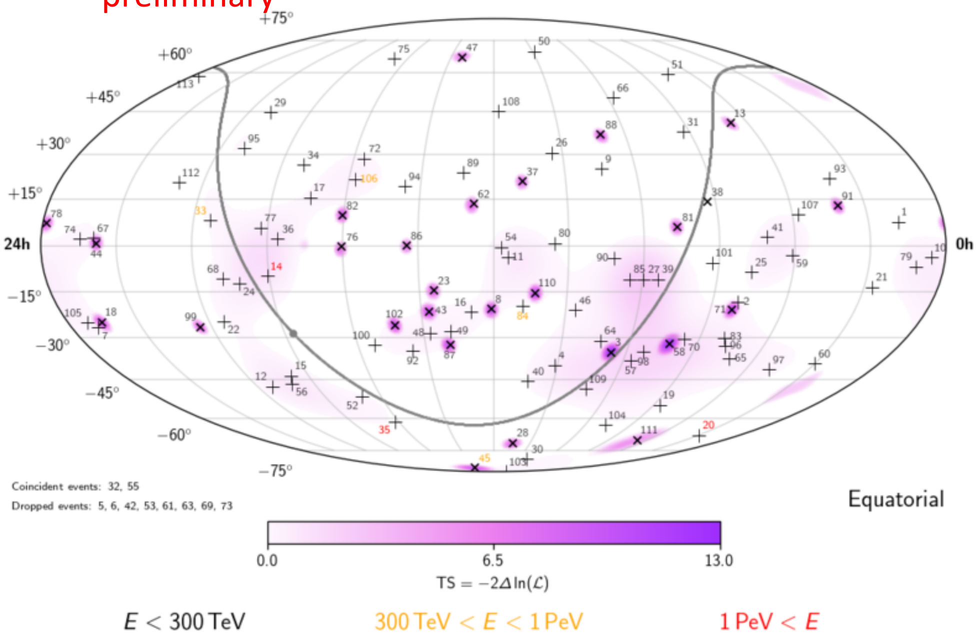
Image: W. Zhang & S. Woosley
See astro-ph/0308389v2



Halzen's summary of GRB, another potential source of extra-galactic CR

Sky maps of high-energy events

preliminary



IceCube HESE 7.5 year

IceCube 6 year $\nu_\mu \rightarrow \mu$ analysis
Ap.J. 833 (2016) 3 (E_μ > 200 TeV)

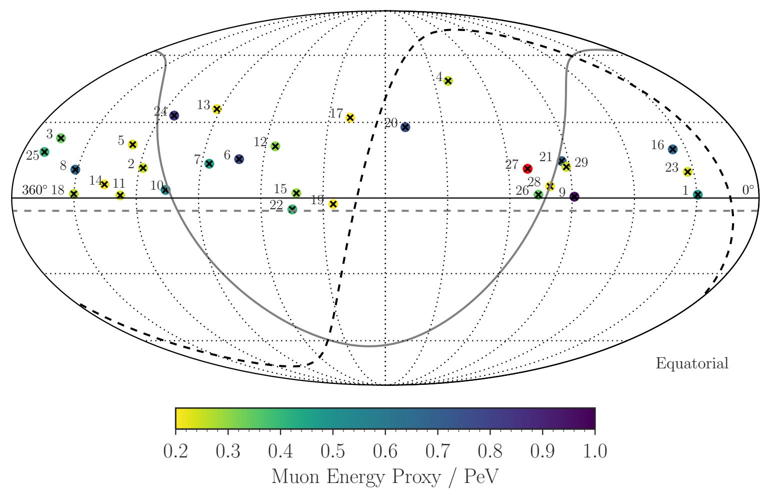


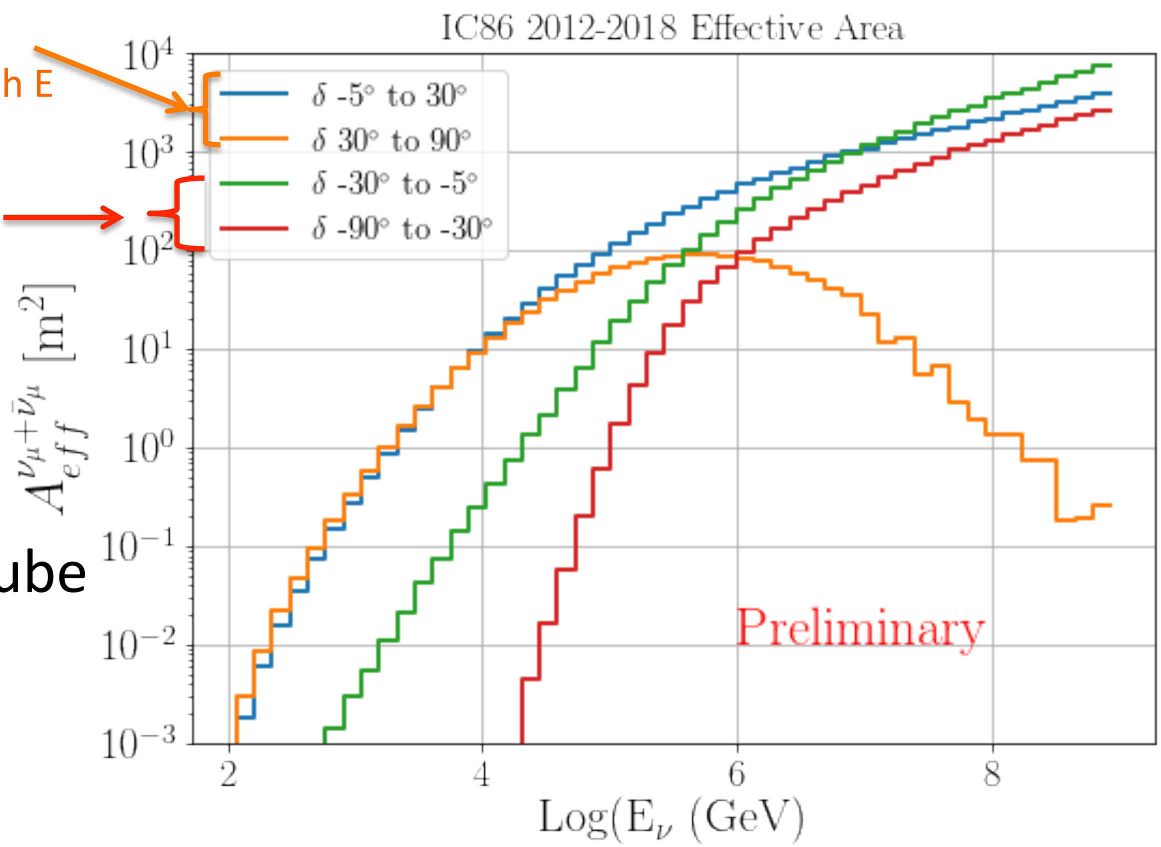
Figure 16. Arrival directions of events with a muon energy proxy above 200TeV. Given the best-fit spectrum the ratio of astrophysical to atmospheric events is about two to one. The horizontal dashed gray line shows the applied zenith angle cut of 85°. The curved gray line indicates the galactic plane and the dashed black line the supergalactic plane (Lahav et al. 2000). The multi-PeV track event is shown as a red dot and the energy proxy value listed in Tab. 4.

- *No steady point source is identified yet*
- *Isotropic distribution → mostly extragalactic*

Point source search – 10 yrs

From below: low background, low threshold + Earth absorption at high E

From above: high background, requires high threshold



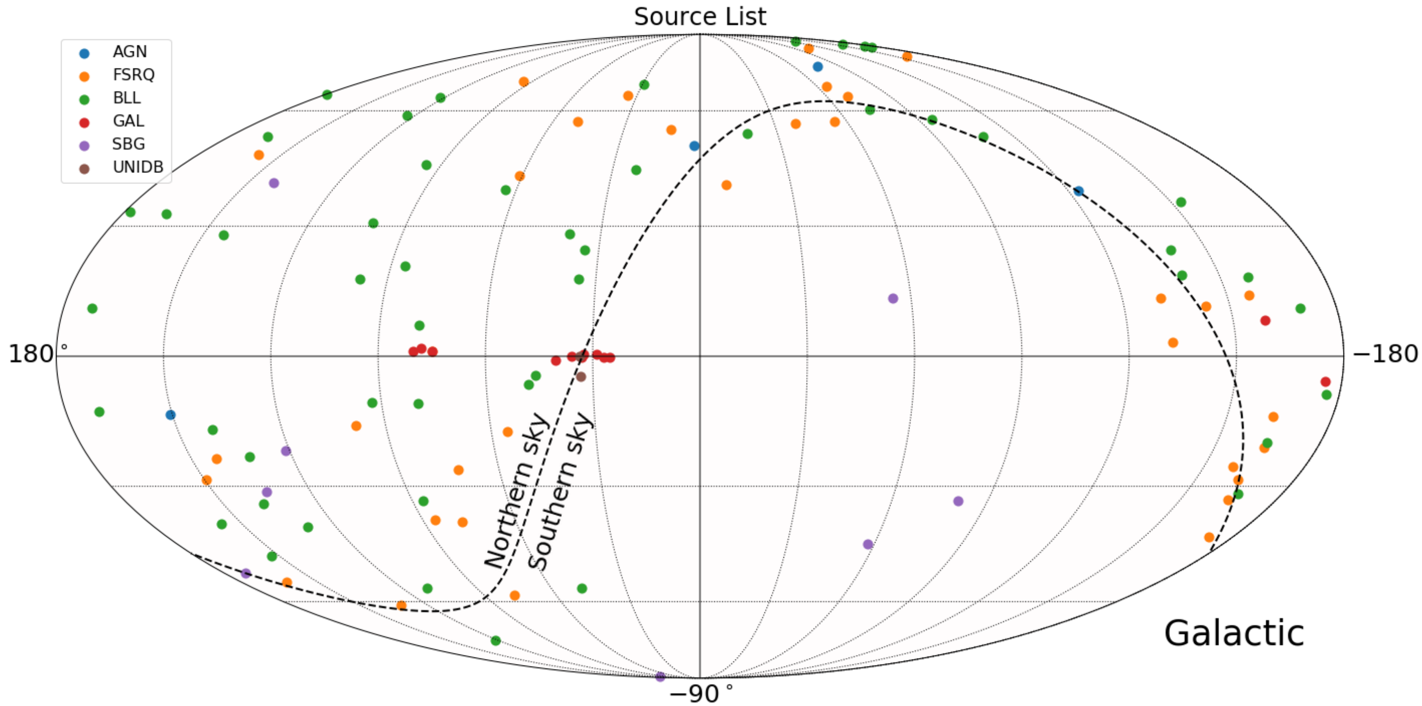
Effective areas for IceCube point source search

Tessa Carver for the IceCube Collaboration
PoS(ICRC2019)851

10 yr source list

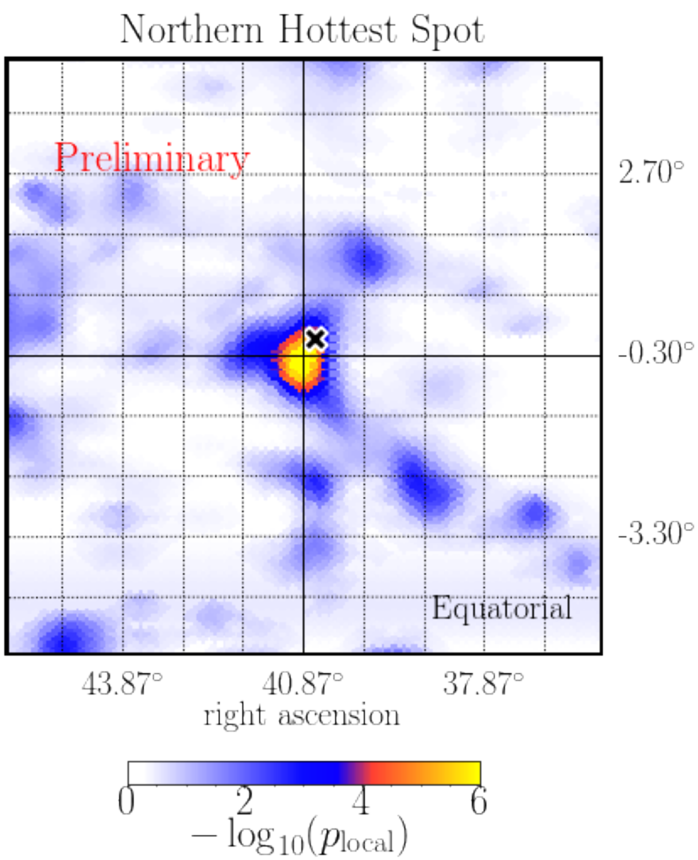
Galactic: 12

Extra-galactic: 98
AGN: 4
FSRQ: 35
Starburst gal: 8
Blazars: 50
UnID 2

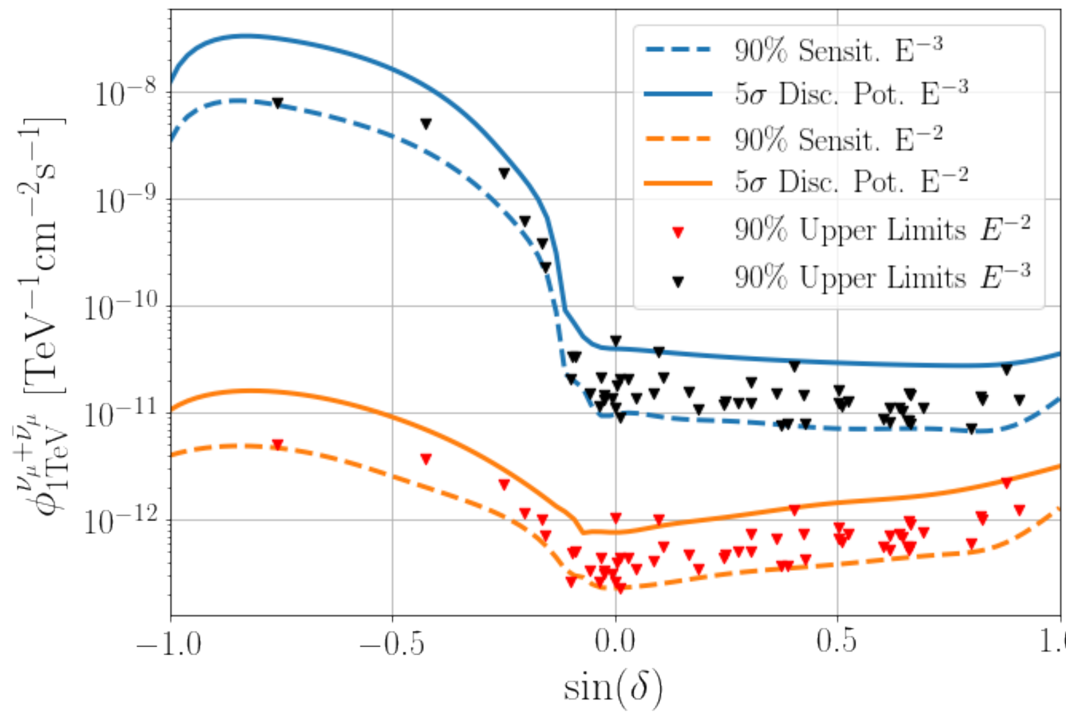


Sources chosen for potential visibility by IceCube on the basis of location and intensity of observed γ-ray flux

10 yr steady source search results



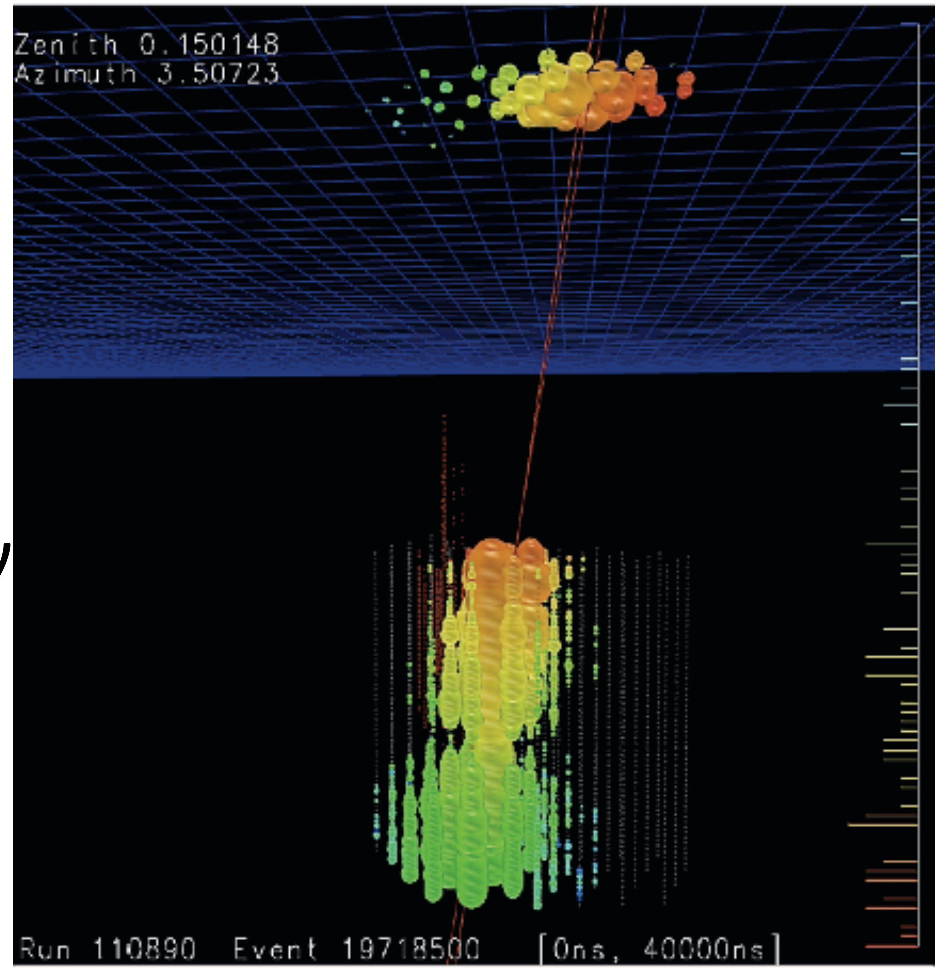
Local p-value map around NGC 1068, a starburst galaxy



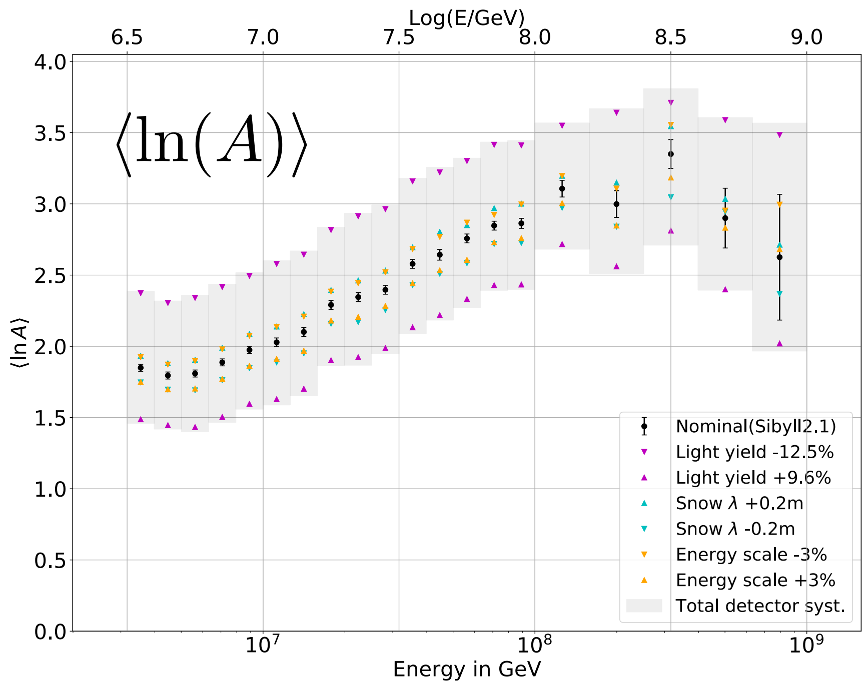
4 most significant sources:
NGC 1068 (starburst galaxy)
PKS 1424+240 (blazar)
GB6_J1542+6129 (blazar)
TXS0506+056 (blazar)

3. Cosmic-ray physics with IceCube

- Spectrum with IceTop
- Spectrum and composition with coincident events
- Anisotropy
- Seasonal variation μ & ν
- IceTop as a veto
  - To find neutrinos starting in the ice above IceCube



Composition from IceCube/IceTop ratio

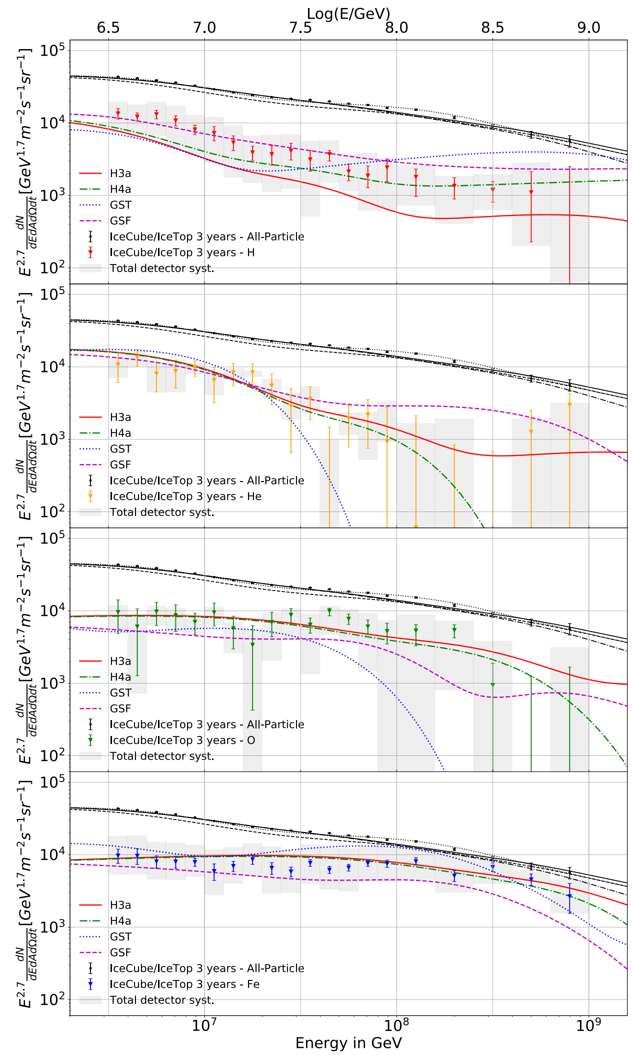


Protons

Helium

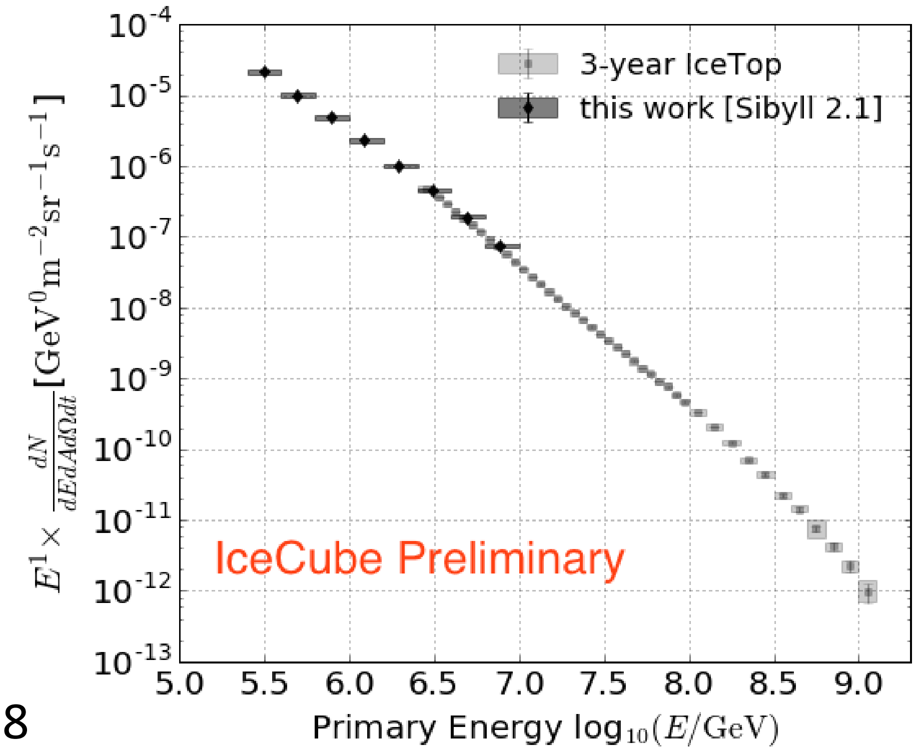
Oxygen

Iron

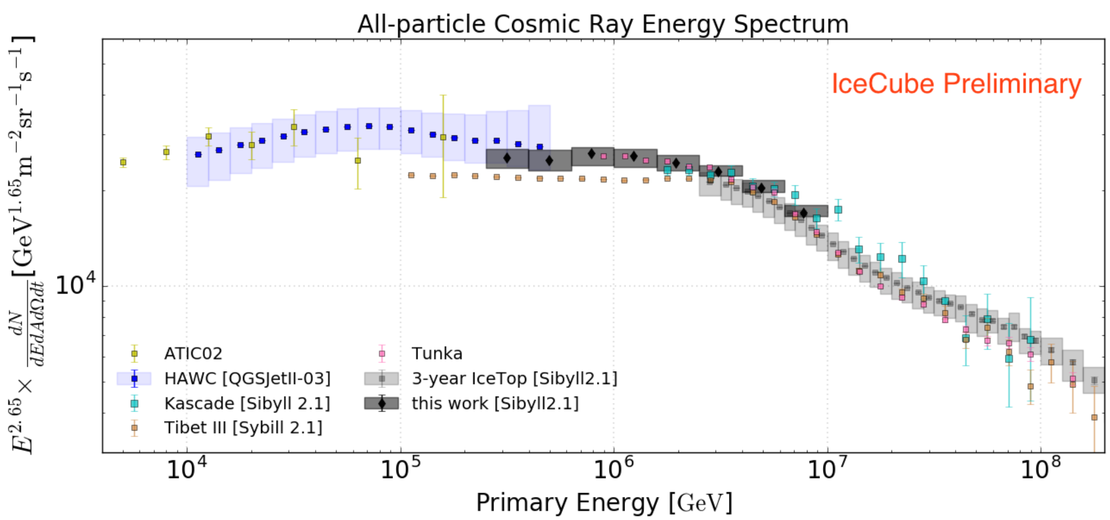


Phys. Rev. D (accepted)

Energy spectrum 250 TeV to EeV



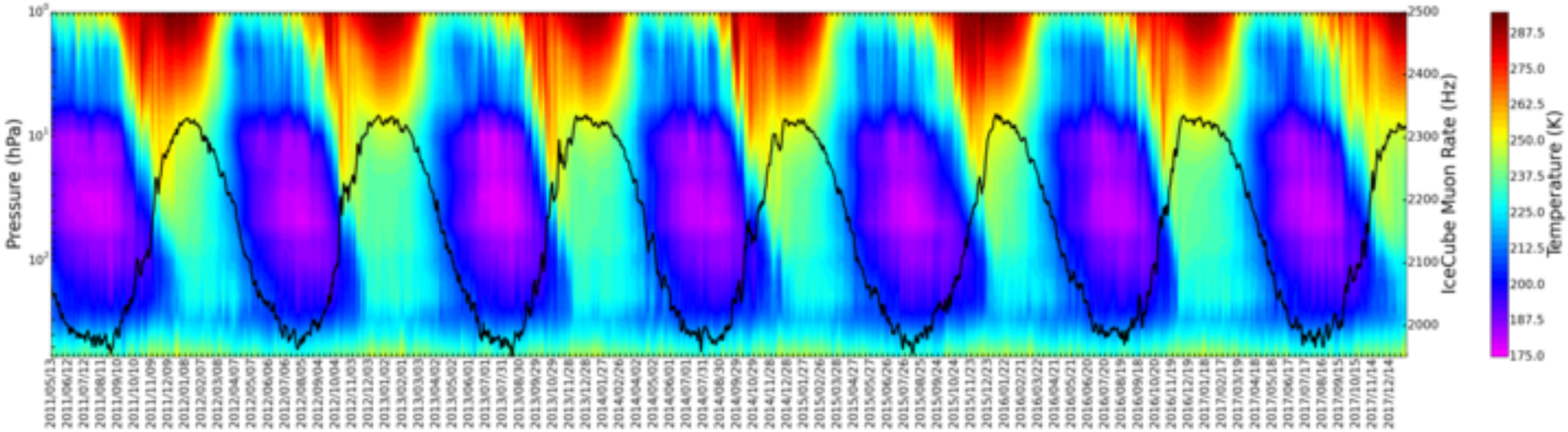
Low-energy extension:
R. Koirala for IceCube, PoS(ICRC2019)318



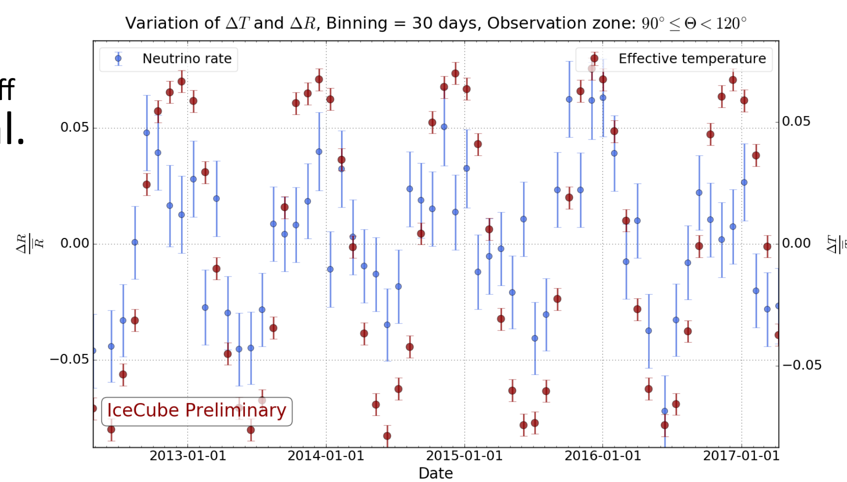
Comparison to HAWC and others

Seasonal variation of μ and ν

~ TeV muons seven years compared to T_{eff} (IceCube, PoS(ICRC2019)894, Tilav et al.)



~ TeV neutrinos five years compared to T_{eff} (IceCube, PoS(ICRC2019)465, Zöcklein et al.

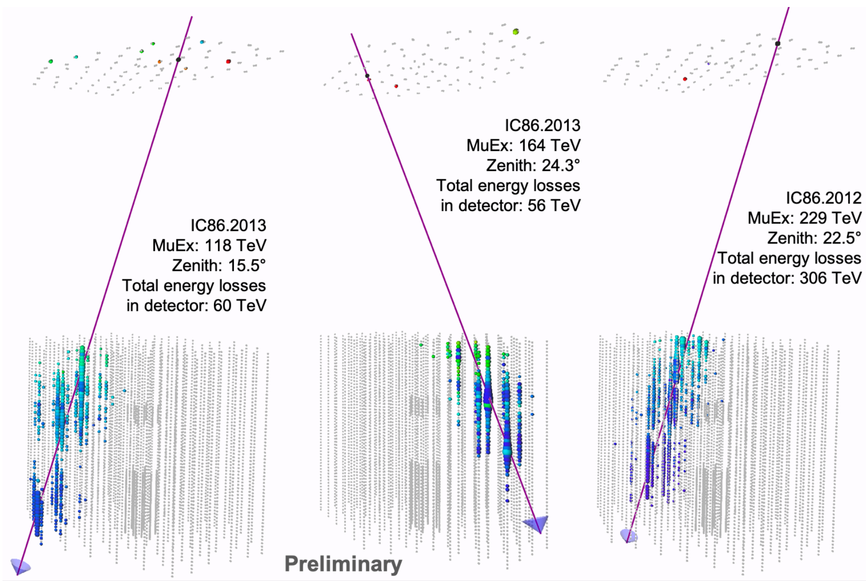


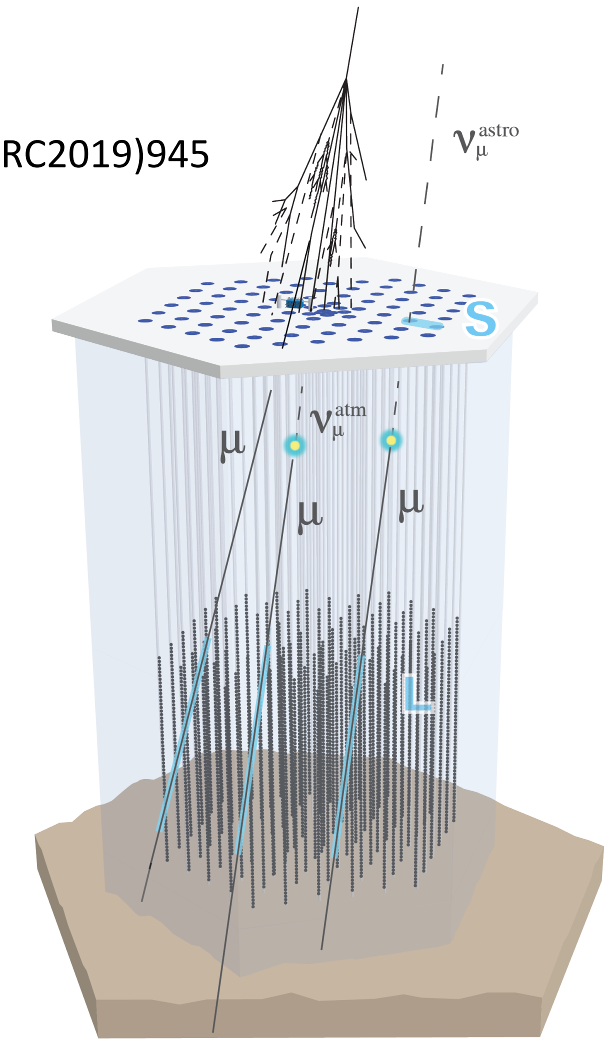
- μ mostly from decay of π, correlation coefficient ≈ 0.75
- ν mostly from decay of Kaons, correlation coefficient ≈ 0.42

IceTop as a veto

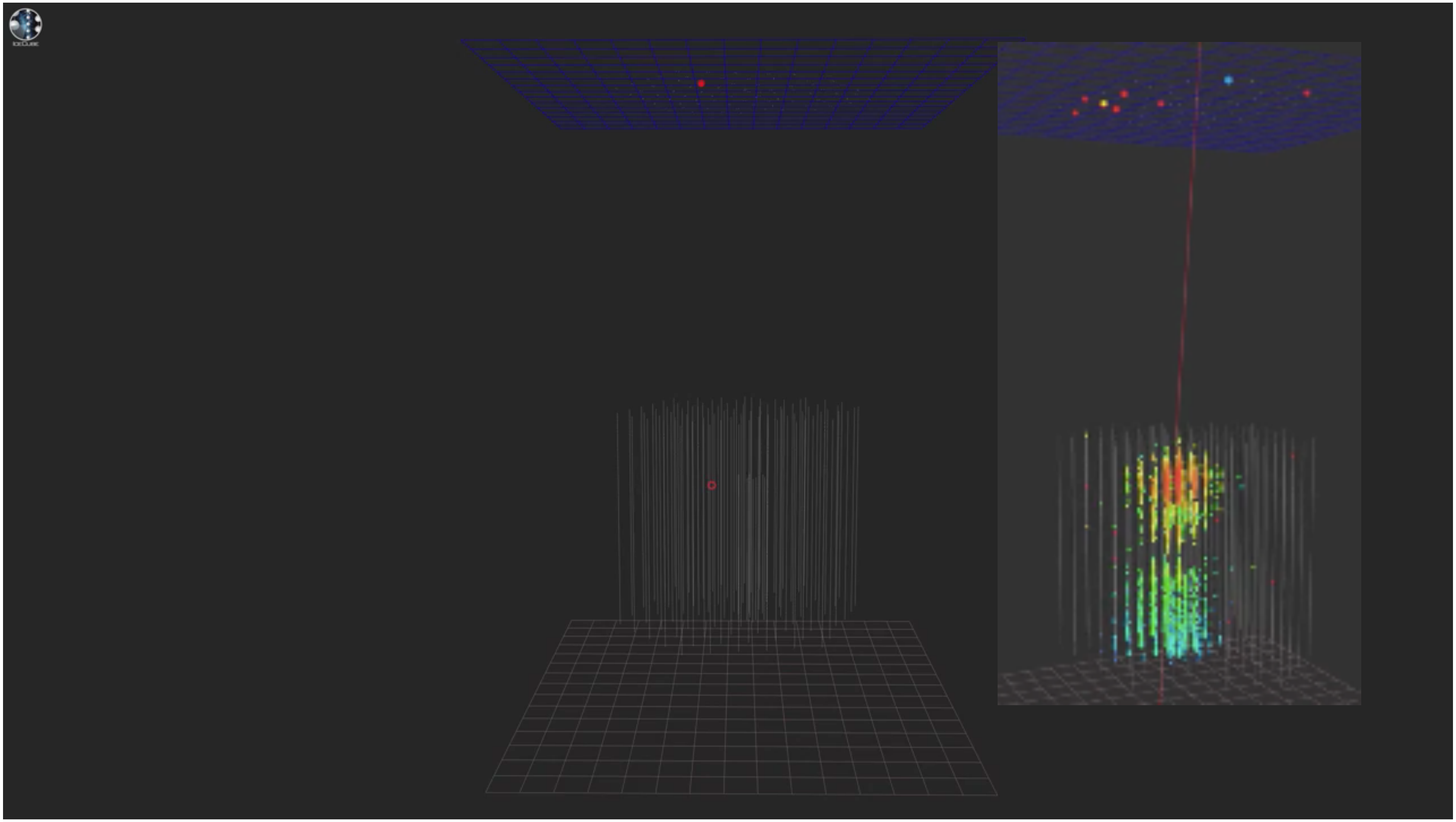
Tosi & Pandya PoS(ICRC2019)945

- Goal: include astrophysical ν_μ that interact above IceCube
- HESE Event #45 would have been vetoed if it started above IceCube
- Examples of interesting events





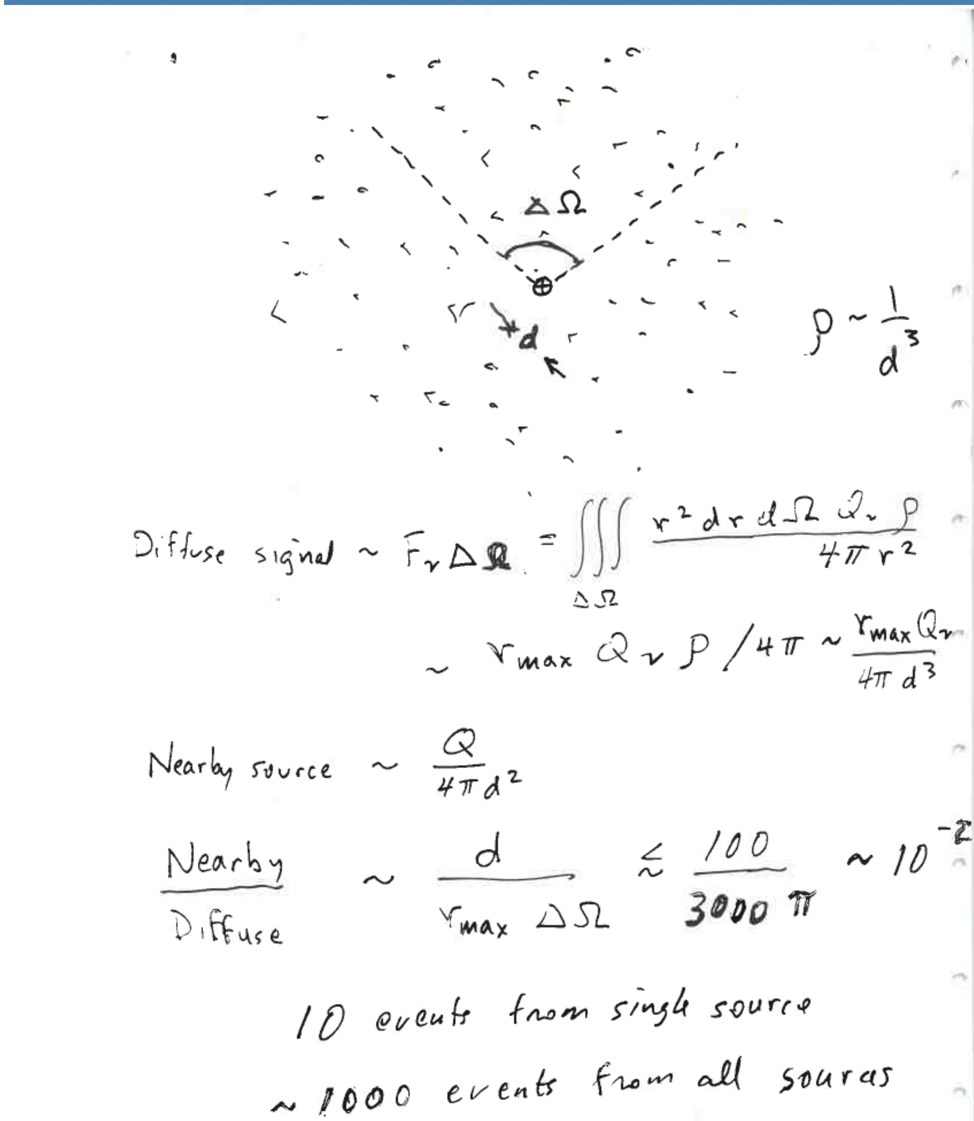
HESE Event #45 (430 TeV)



4. Multi-messenger astrophysics and real-time alerts

- The big question for neutrino astronomy:
  - How many neutrinos will we see from the whole sky before we find another nearby source
- Importance of the Real-time alert system
- Importance of multi-messenger follow-ups and coincidences

The big question for diffuse ν



Overhead from a planning meeting at UC Irvine 1997
IceCube has now measured F_ν

- IceCube diffuse signal:

$$F_\nu = \xi \frac{Q_\nu \rho \, R_H}{4\pi}$$

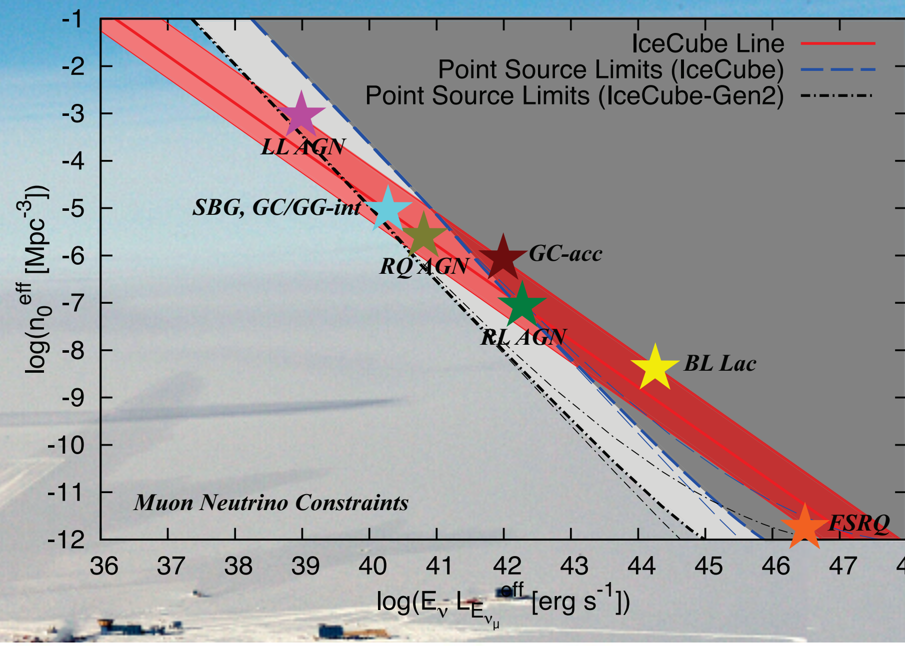
$$\sim 2.8 \times 10^{-8} \frac{\mathrm{GeV}}{\mathrm{cm^2 s\,sr}}$$

$$= 1.3 \times 10^{46} \frac{\mathrm{erg}}{\mathrm{Mpc^2 yr\,sr}}$$

$$\to \rho \, Q_\nu \sim 10^{43} \frac{\mathrm{erg}}{\mathrm{Mpc^3 yr}}$$

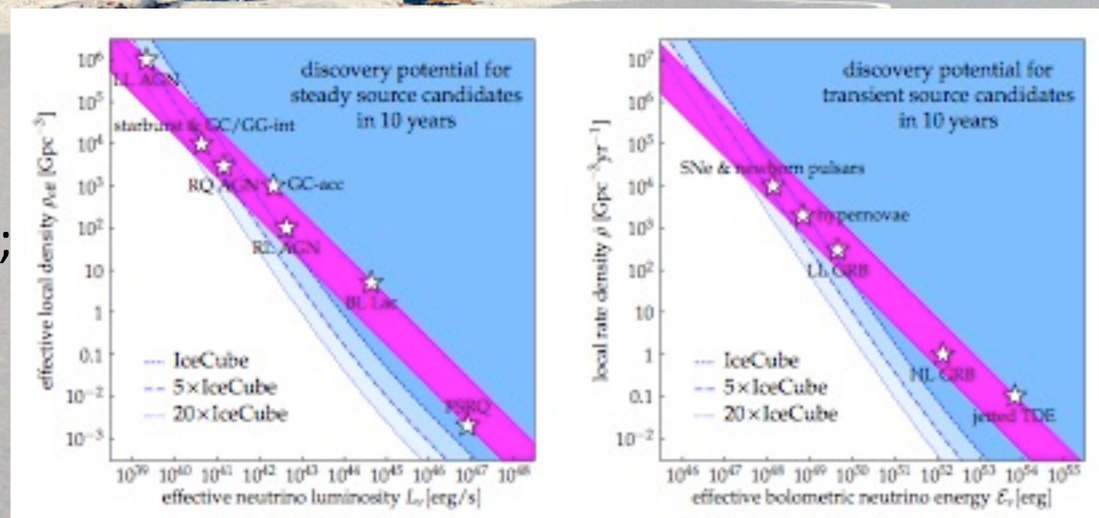
- Now plot source density vs source strength for various source classes

Murase & Waxman
PRD 94(2016)103006



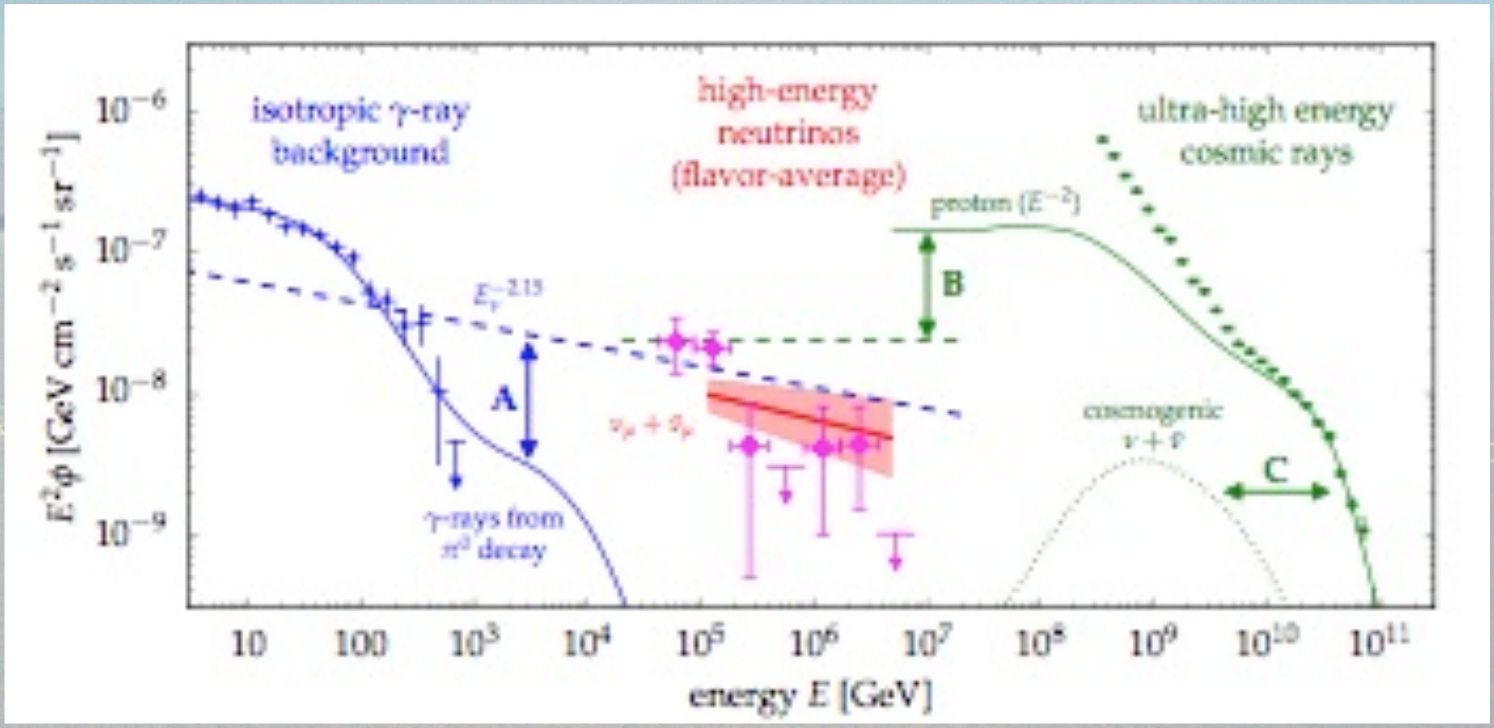
South Pole
2835 m.a.s.l.

Astrophysical Neutrino White Paper;
steady (l); transient (r)
arXiv:1903.04334



Connections to cosmic rays & diffuse γ

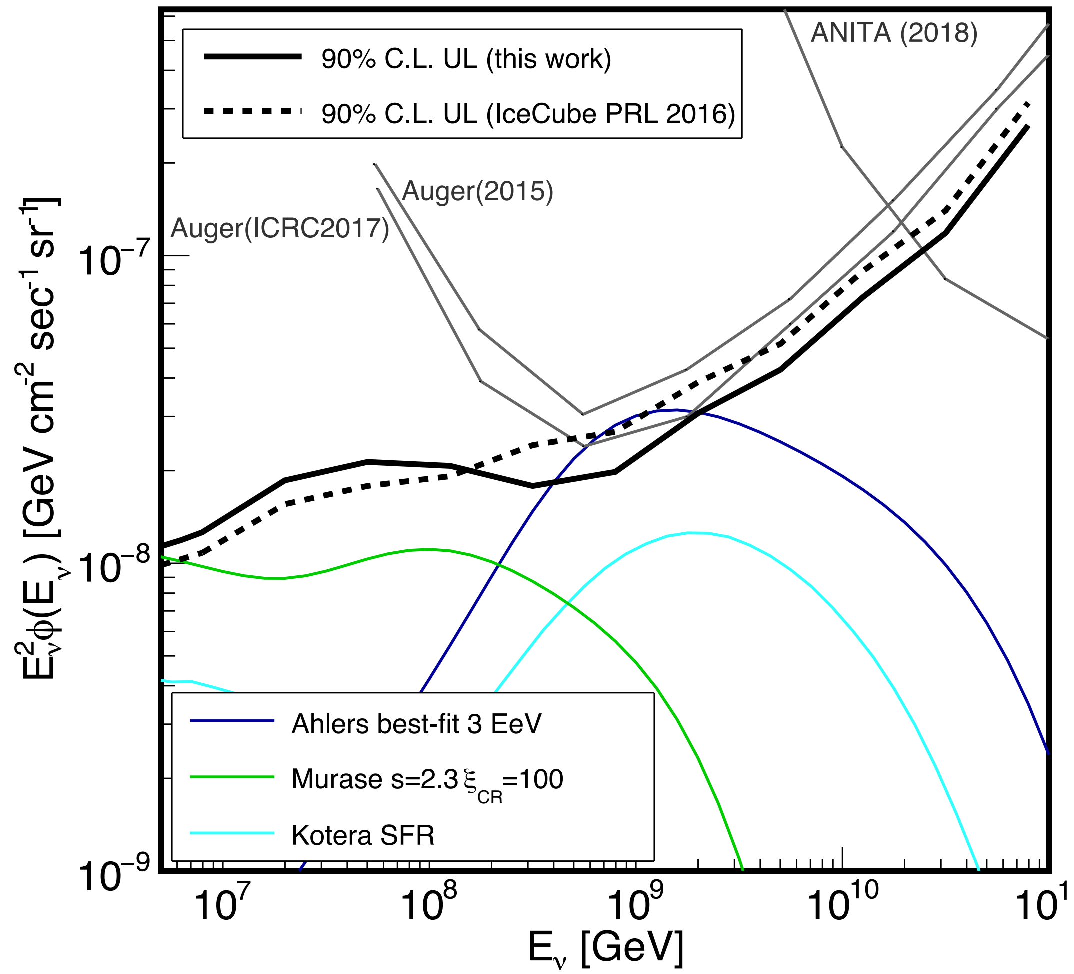
Astrophysical Neutrino White Paper; arXiv:1903.04334v2



A: γ – π – ν connection B: relation of ν and UHECR C: cosmogenic neutrinos

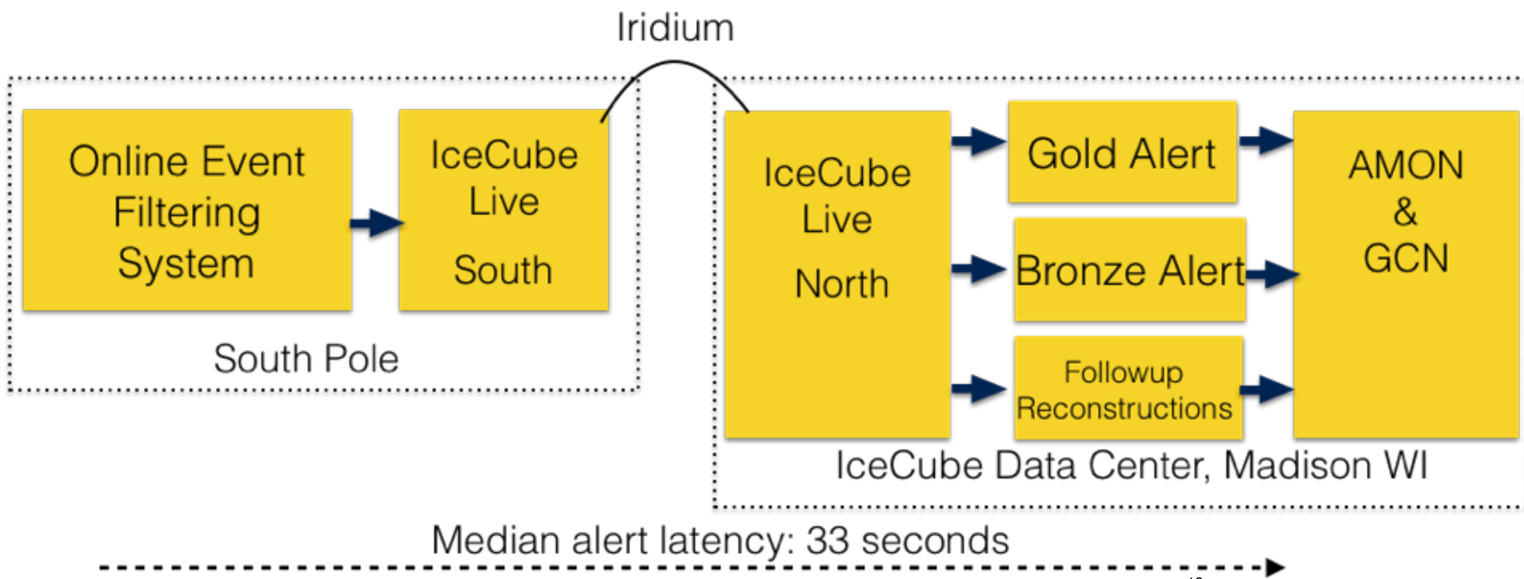
Cosmogenic (GZK) Neutrino limits

- Upper limits constrain models with UHECR = p
- Auger suggests heavy nuclei at highest energy
- Cosmogenic ν would be reduced
- Fraction of p in UHECR a current key question



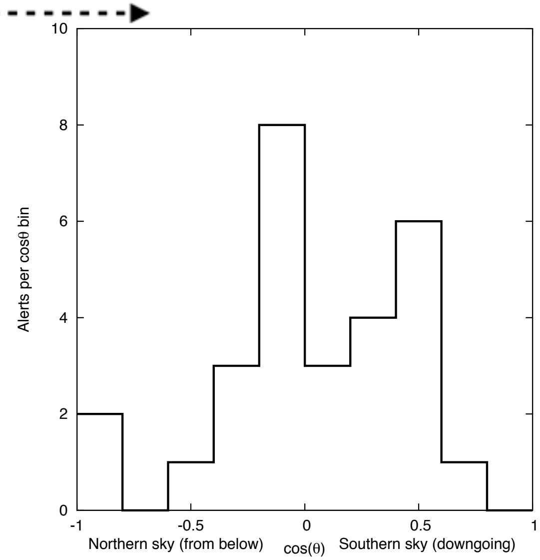
IceCube: PR D98 (2018) 062003

IceCube Realtime Alert System



Erik Blaufuss and IceCube Realtime Oversight Committee
PoS(ICRC2019)1021

- HESE: high-energy starting tracks
- EHE: high-energy tracks
- GFU: tracks for pt. src. Searches
- 25 Alerts since April, 2016



IceCube 170922A

Initial notice

From Bacodine <vxw@capella2.gsfc.nasa.gov>
Subject **[icecube-c] GCN/AMON_ICECUBE_EHE**
To nl_169_email_none@capella2.gsfc.nasa.gov

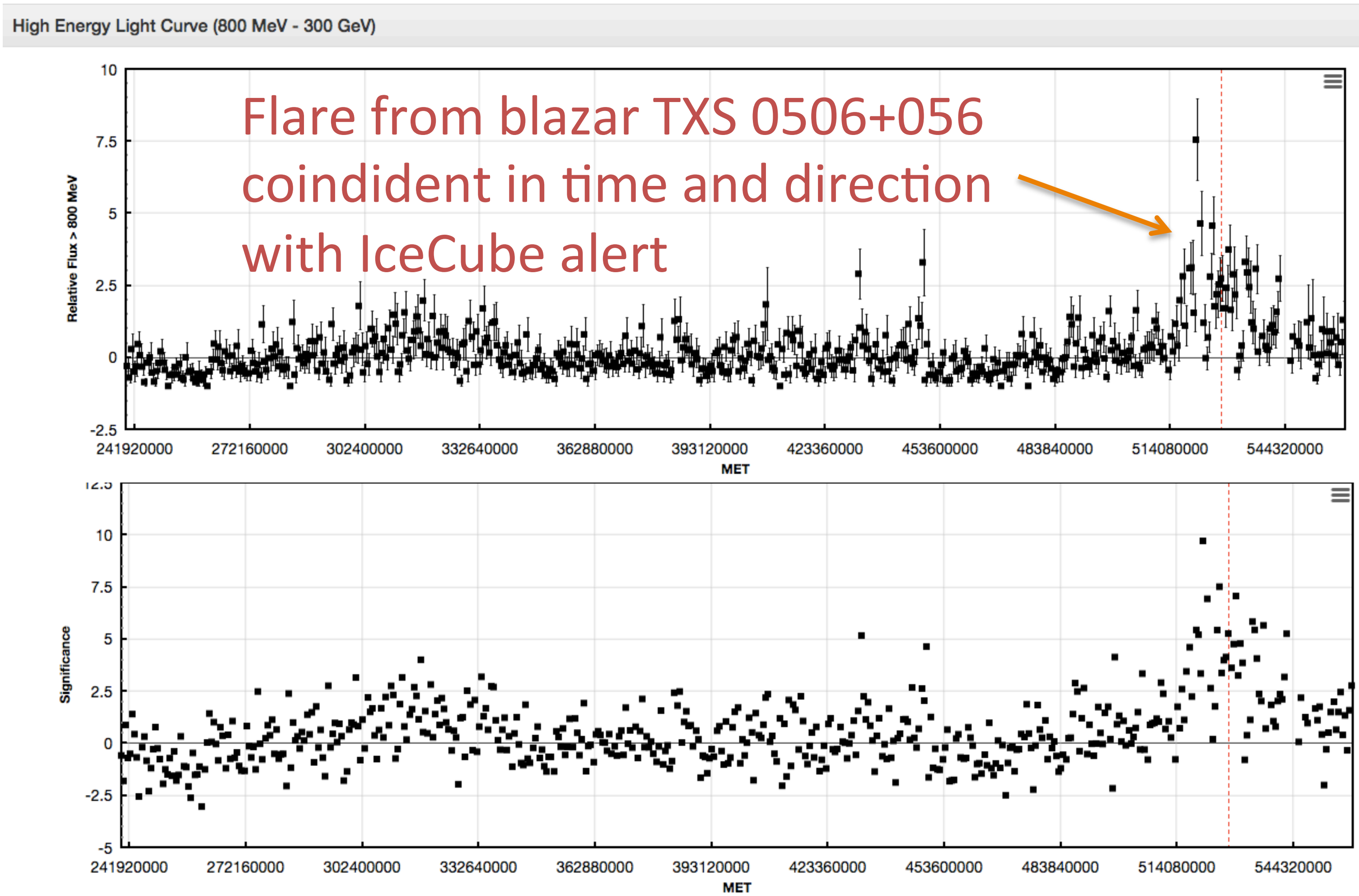
```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+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]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```

Signalness = 0.565

Follow up GCN 4 hours later

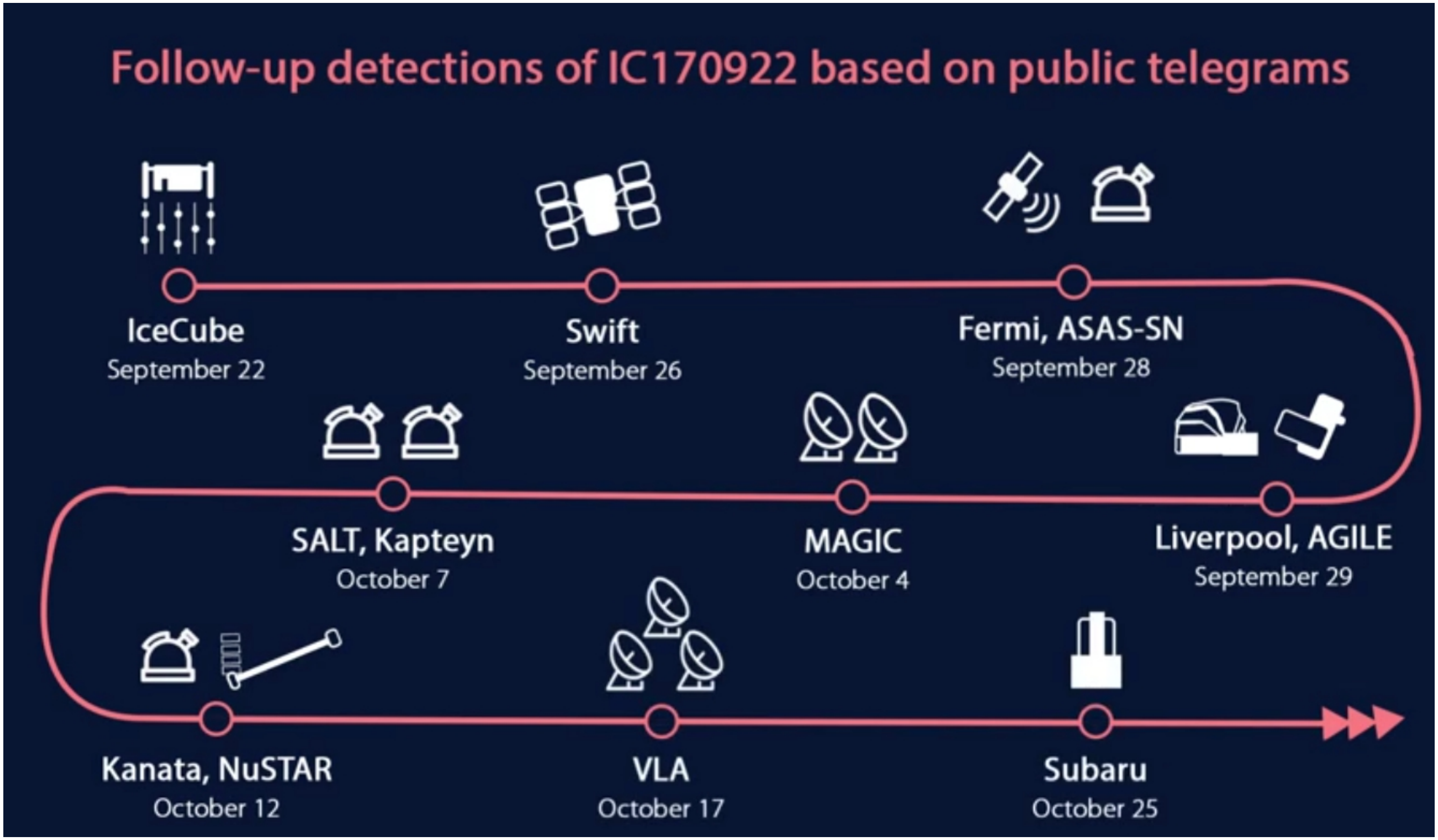
```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino
candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube  <blaufuss@icecube.umd.edu>

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 Atel 10791 (2017-09-28)



https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27

Multi-messenger astronomy

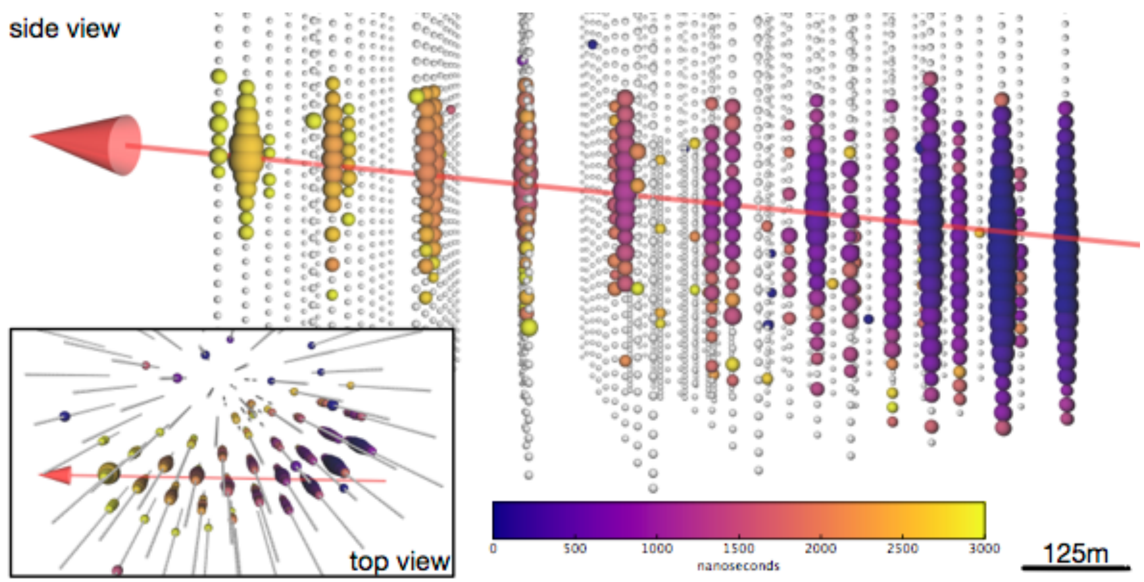


Graphic: Naoko Kurahashi Neilson

Publication in *Science,* 13 July 2018

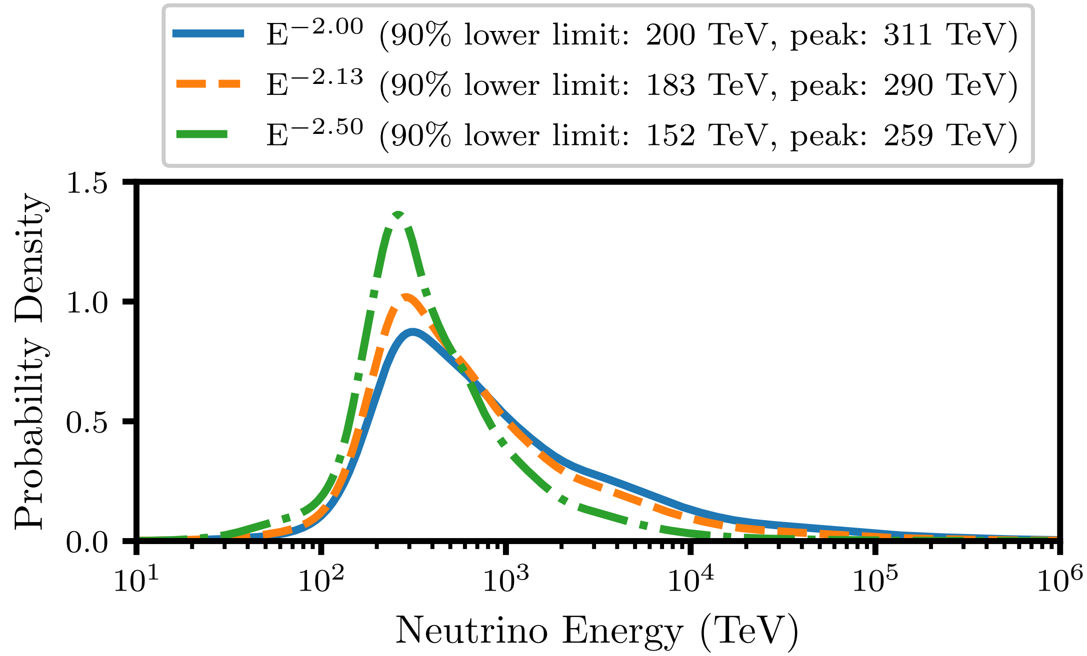
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *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*†



The IceCube Collaboration et al., Science 361, eaat1378 (2018) 13 July 2018

170922 neutrino energy ≈ 300 TeV

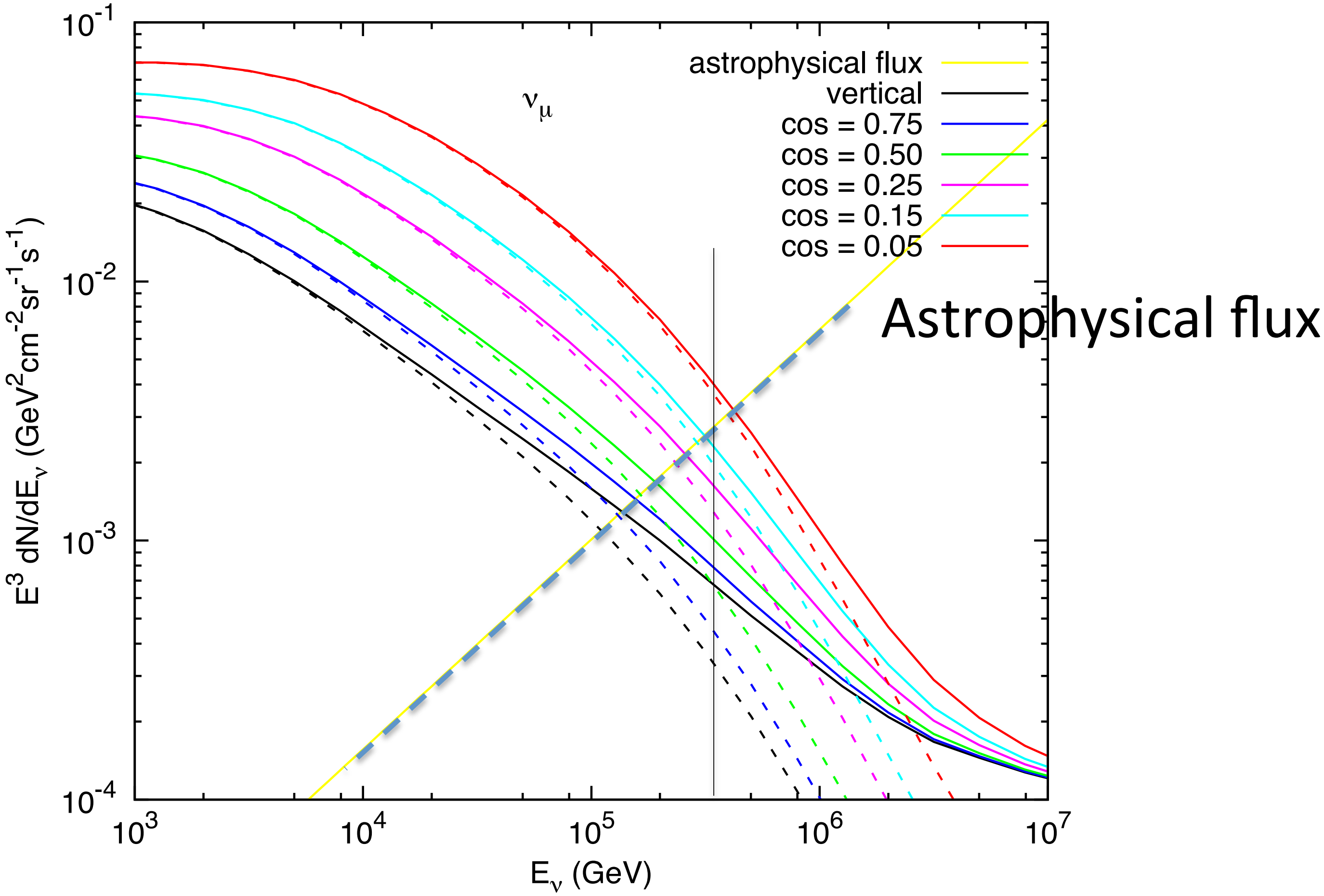


- Monte Carlo of ν_μ interaction, μ propagation
- Peak of distribution: 290 TeV with high energy tail
- 90% of area has E > 180 TeV

"Signalness" of 170922A

- Compare to the astrophysical spectrum of the upward ν_μ analysis (PoS(ICRC2017)1005):
  - At 100 TeV $E^2\phi_{\rm astro} \approx 1.01 \times 10^{-8}\,{\rm GeV\,cm^{-2}s^{-1}sr^{-1}}$
  - Fitted differential spectral index = -2.19
- Compare to atmospheric flux accounting for direction of the event
  - Declination = 5.72^{o}
  - Below horizon, so no atmospheric muons
  - Zenith angle = 95.72, cos(θ) ≈ -0.1, not absorbed by the Earth

170922A "signalness"



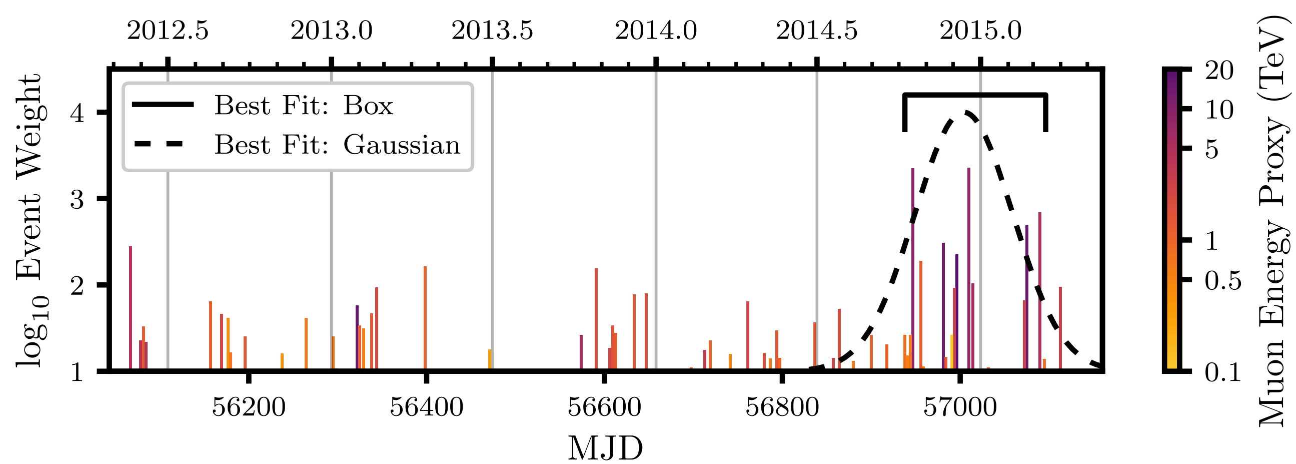
$E_\nu \approx$ 300 TeV, $\cos\theta \approx -0.1$

Is 170922A from TXS 0506+056 ?

- Chance coincidence ruled out at > 3 sigma
- Consistent with upper limit on ν from blazars*

***IceCube, Ap.J. 835 (2017) 45**

- Archival data shows a 3.5 sigma excess of neutrinos from TXS 0506 in 2014/15
  – But no corresponding flare in gamma-rays (!!)



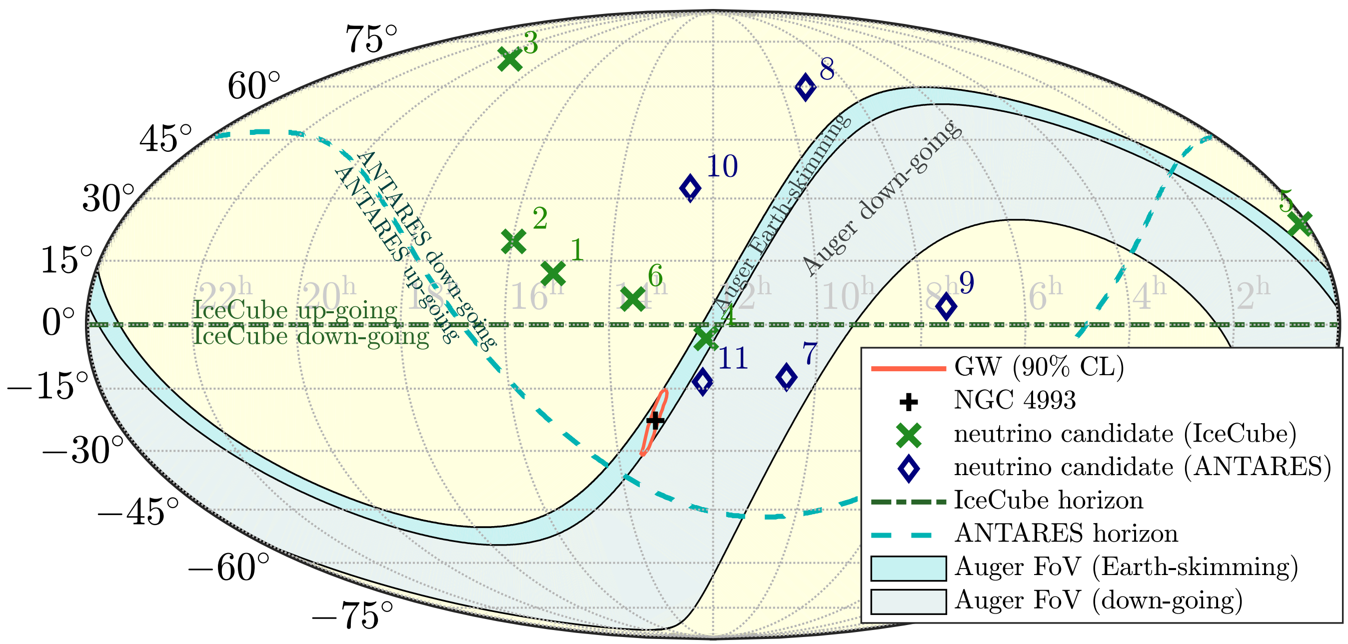
IceCube Collaboration, Science 361, 147–151 (2018) 13 July 2018

IceCube response to external alerts (some examples)

- Archival searches
  - Auger Events PoS(ICRC2019)842
  - Blazar catalogs PoS(ICRC2019)916
  - Gamma-ray bursts PoS(ICRC2019)859
  - IceCube alerts PoS(ICRC2019)929
- Fast response to
  - TeV gammas PoS(ICRC2019)841
  - Gravitational waves PoS(ICRC2019)918 and 930

Correlation of ν with GW from NS-NS merger ?

Search for neutrinos coincident with GW170817 by ANTARES, IceCube, Auger (arXiv:1710.05839v2, Ap.J. 850 (2017) L35)



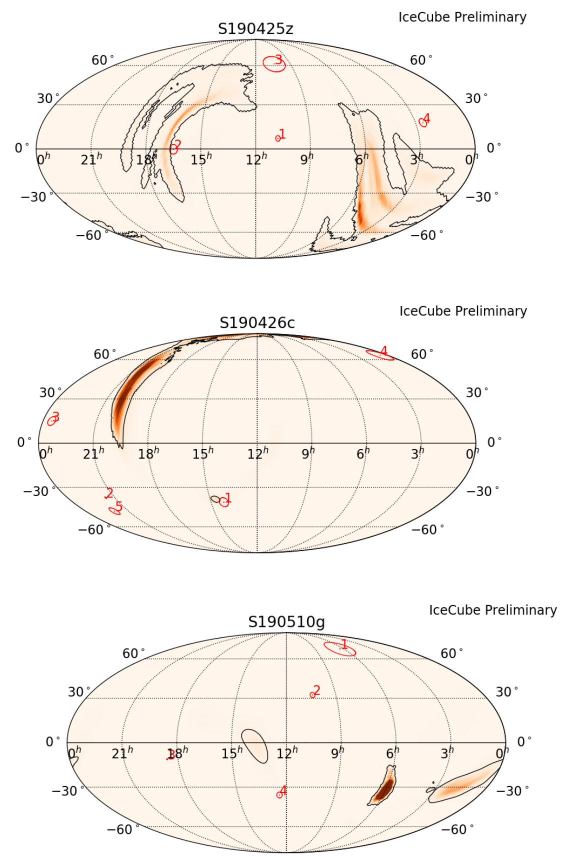
IceCube & LIGO-VIRGO 03

Gravitational-Wave + High-Energy Neutrino Searches   PoS(ICRC2019)930   Azadeh Keivani

No.	GW event	Possible Source (probability)	p-value (binary merger) [preliminary]
1	S190408an	BBH (>99%)	0.15
2	S190412m	BBH (>99%)	0.83
3	S190421ar	BBH (97%), Trs (3%)	0.62
4	S190425z	BNS (>99%)	–
5	S190426c	BNS (49%), NSBH (13%), Trs (14%), MG (24%)	–
6	S190503bf	BBH (96%), MG (3%)	0.29
7	S190510g	BNS (42%), Trs (58%)	–
8	S190512at	BBH (99%), Trs (1%)	0.51
9	S190513bm	BBH (94%), MG (5%)	0.74
10	S190517h	BBH (98%), MG (2%)	0.12
11	S190519bj	BBH (96%), Trs (4%)	0.16
12	S190521g	BBH (97%), Trs (3%)	0.19
13	S190521r	BBH (>99%)	0.16
14	S190602aq	BBH (>99%)	0.13

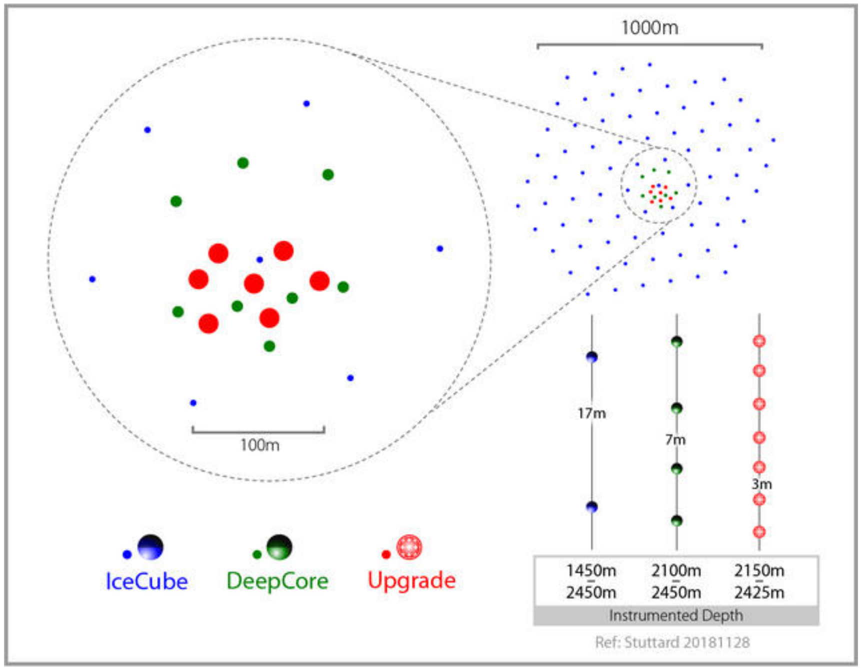
Table of events from first part of run 03 from PoS(ICRC2019)930
This analysis would send an alert when p-value of coincident neutrino is less than 0.01

Maps of possible BNS neutrinos withiin ±500 s



IceCube Upgrade

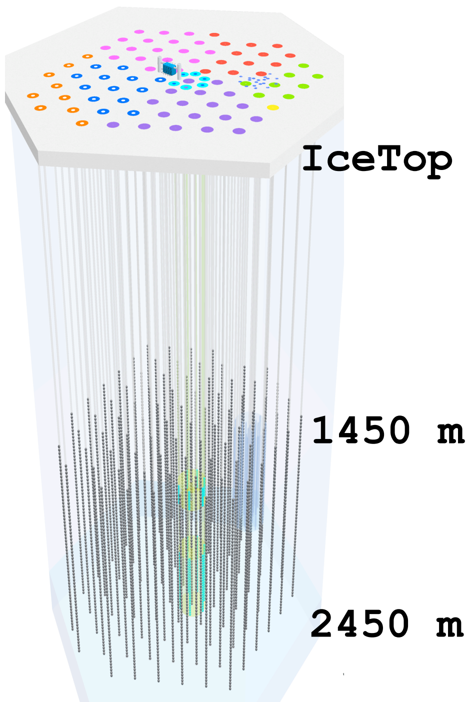
- Neutrino oscillation physics
  - ν_τ appearance
  - Mass hierarchy
- Improve calibration
  - To support improved reco of existing data
- Construction 2022/23
- Sets stage for IceCube Gen2

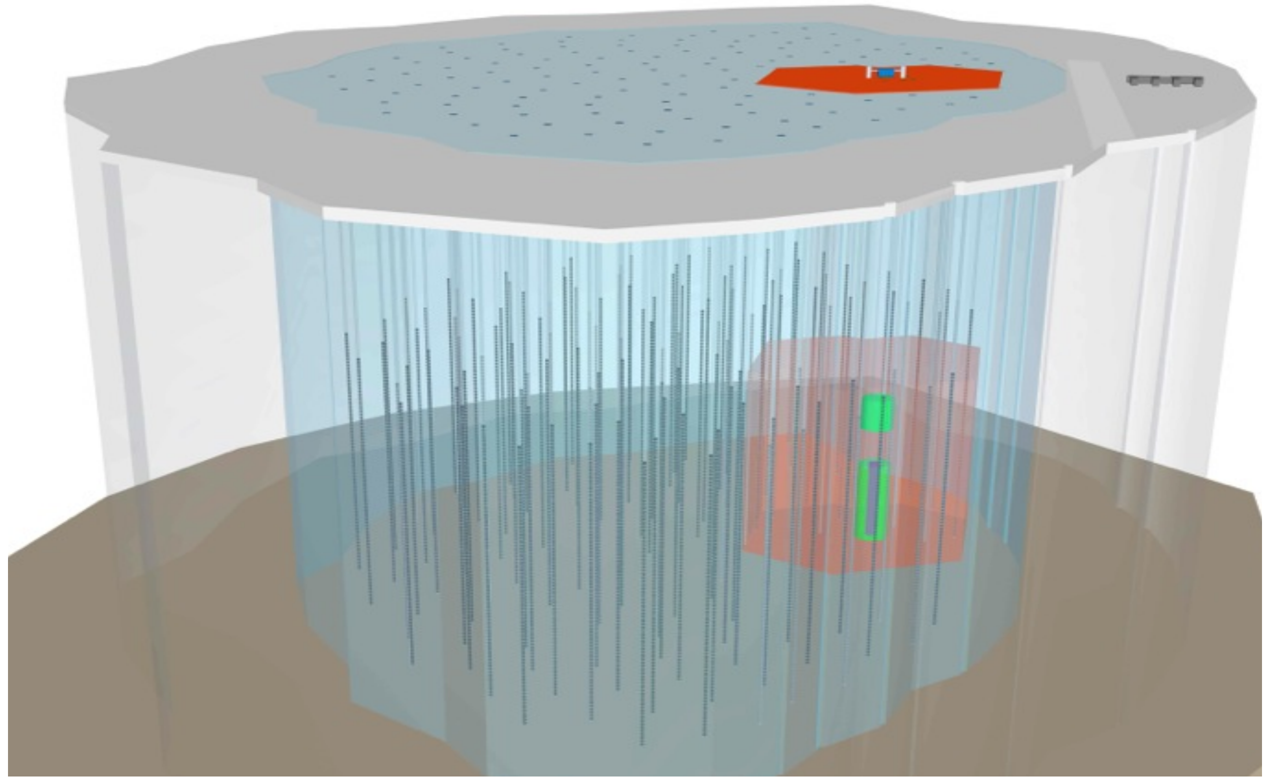


PoS(ICRC2019)1041

IceCube Gen2

0.26 km^2 sr → ~ 10 km^2 sr





A surface array over Gen2 increases the acceptance for veto by a factor of 40


THE ICECUBE COLLABORATION
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Universiteit Gent
Vrije Universiteit Brussel
CANADA
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University of Copenhagen
GERMANY
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The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)
ICECUBE
icecube.wisc.edu

References and backup

arXiv:1907.11699: The IceCube Neutrino Observatory, Contributions to the 36th International Cosmic Ray Conference
or directly at https://pos.sissa.it/358 and look up the paper number

Reviews:
Results from IceCube (D. Williams) PoS(ICRC2019)016

Recent results of Cosmic Ray Measurements from IceCube and IceTop (D. Soldin) PoS(ICRC2019)014

BACKUP:

UHECR composition: implications for cosmogenic neutrinos