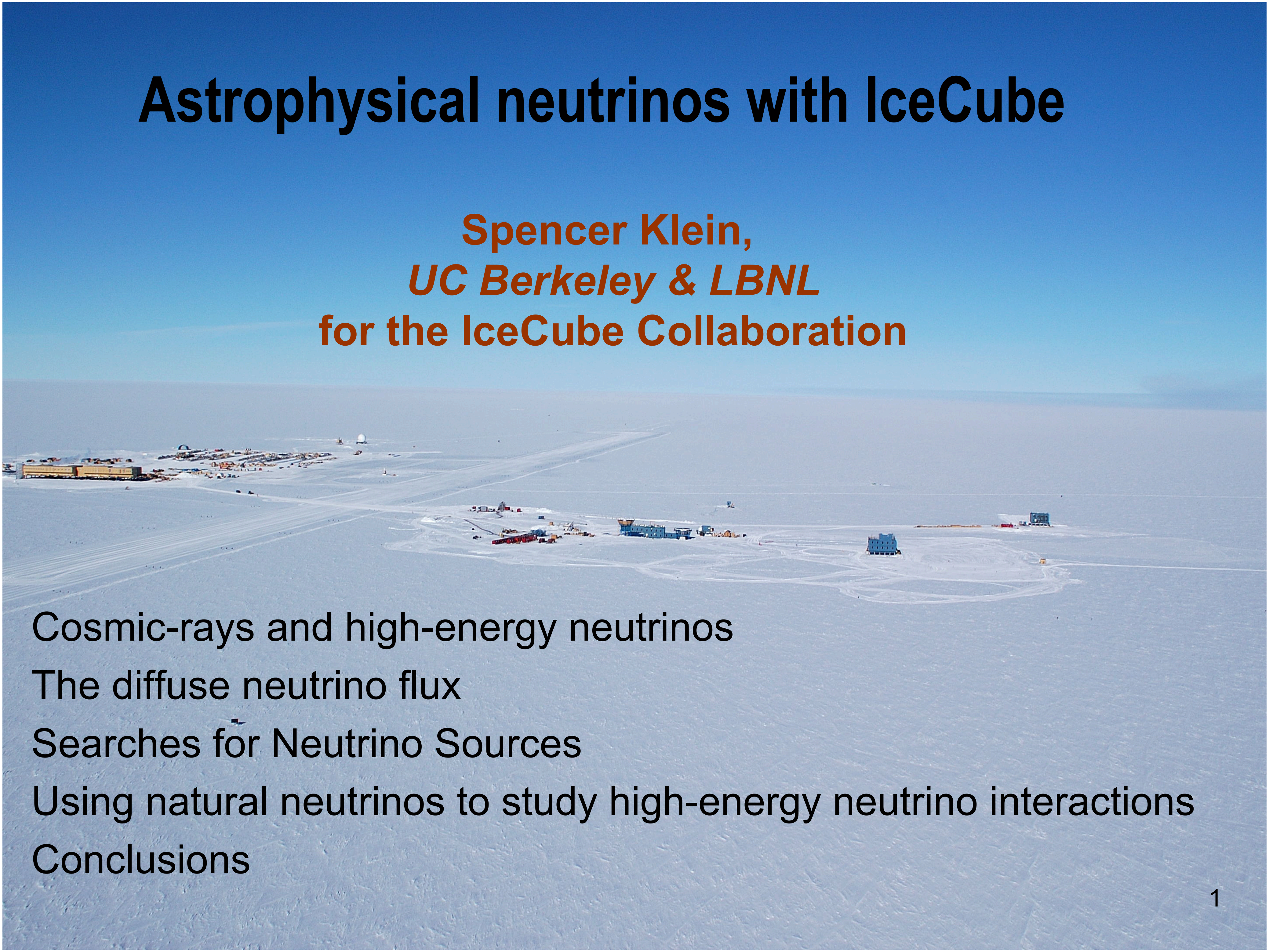


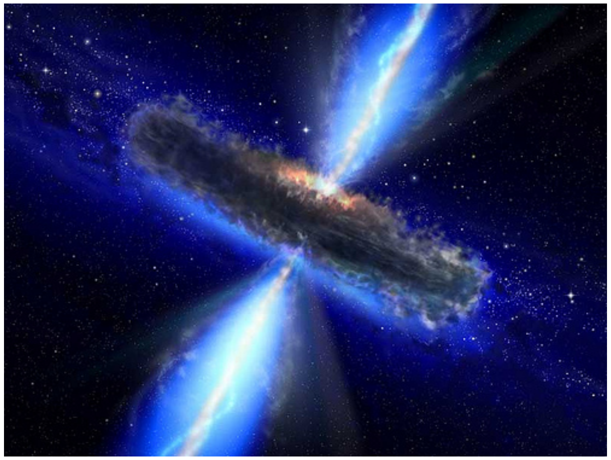
Astrophysical neutrinos with IceCube

Spencer Klein,
UC Berkeley & LBNL
for the IceCube Collaboration

Cosmic-rays and high-energy neutrinos
The diffuse neutrino flux
Searches for Neutrino Sources
Using natural neutrinos to study high-energy neutrino interactions
Conclusions

Cosmic-rays and high-energy neutrinos

- We observe cosmic-rays with energies up to $3*10^{20}$ eV (50 Joules)
- Below $10^{15\pm1}$ eV, most cosmic-rays probably come from supernova remnants
  - Composition, gamma-ray spectra…
- Beyond that, we don't know
  - Cosmic-rays are bent by magnetic fields, so don't point back to their sources
  - Active galactic nuclei are popular sources
    - Galaxies with supermassive black holes which accrete matter, emitting jets along the galaxies axis.
- We need a new probe … neutrinos
  - Produced by beam-gas or beam-photon interactions in/near their production sites, or in-transit

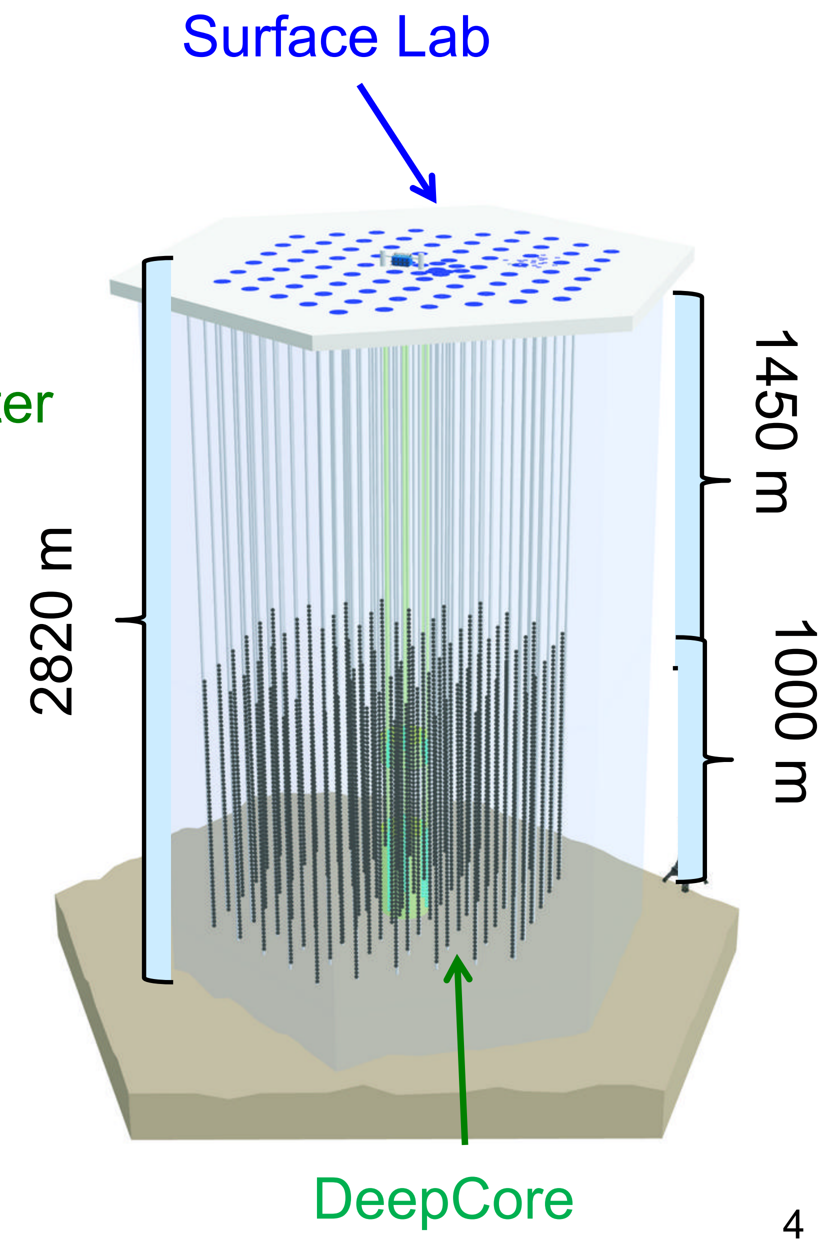


Two approaches to the astrophysical neutrino fluxes

- (1) Known cosmic-ray flux, and assumed beam gas/photon density
  - Maximum density corresponds to opacity=1, so cosmic-rays just barely escape from the accelerators.
  - Waxman-Bahcall bound - optically thick source
- (2) Measured photon flux, assuming that photons come from π^0, and the expected π^0:$\pi^{\pm}$ ratio
  - Electron accelerators may only produce synchrotron radiation
  - Sign of hadronic acceleration: 70 MeV γ from π^0 decay at rest
  - Optically thin source
- Both calculations indicate that a 1 km^3 detector is needed to see astrophysical neutrinos

IceCube

- 1 km^3 neutrino observatory
- 5160 digital optical modules (DOMs)
  - 10" phototube in a 13" sphere
  - 86 strings with 60 modules
    - 78 on a 125 m hexagonal grid
    - 8 denser "DeepCore" strings in center
  - 1450 to 2450 m deep
- 160 station - 1 km^2 surface array
- Completed in December, 2010
- 98% of DOMs working perfectly
- >99% live time
  - No physicists around to mess with hardware.



The IceCube Collaboration

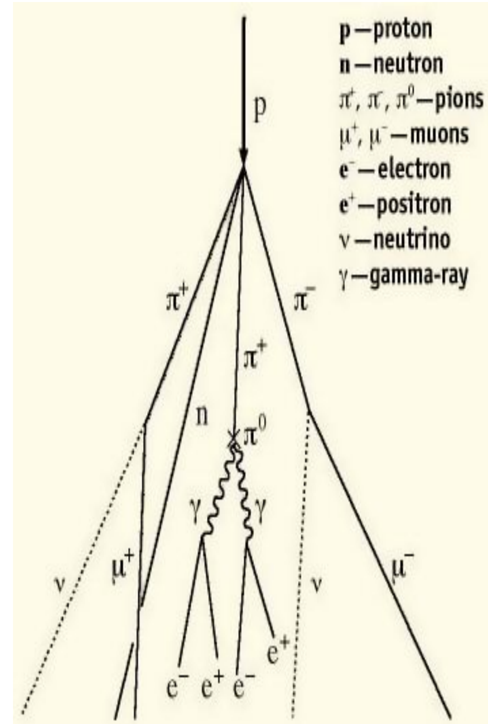
310 collaborators from 52 institutions in 11 countries

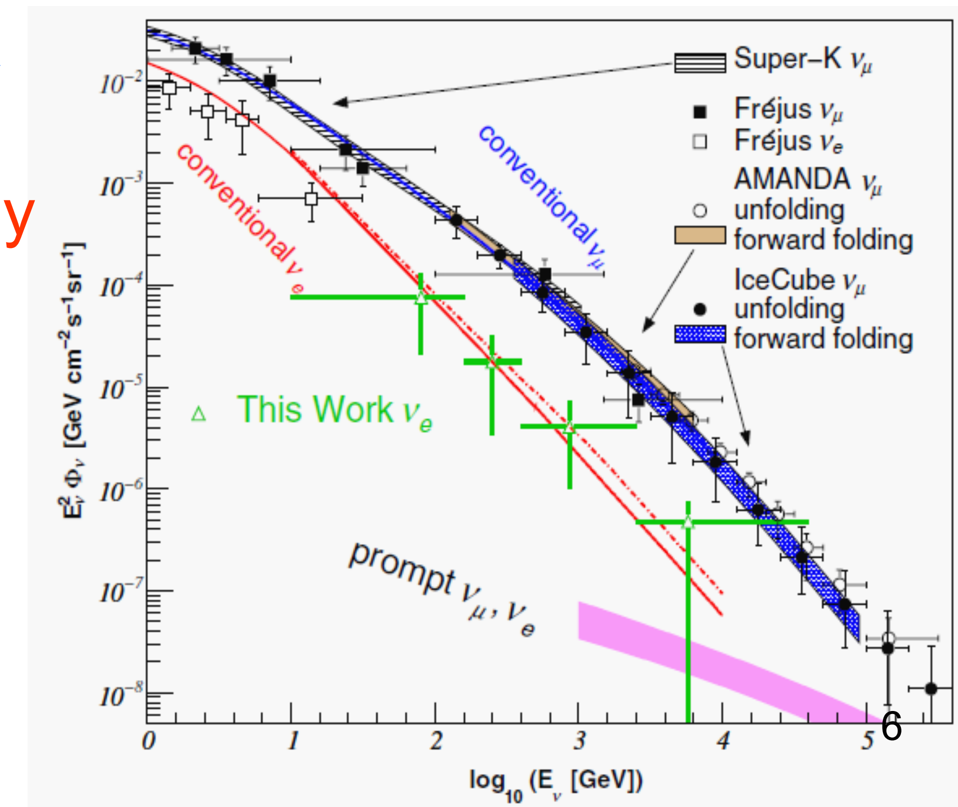
Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Backgrounds: atmospheric μ and ν

- Produced when cosmic-rays interact in the upper atmosphere, producing hadronic showers
- IceCube sees ~ 2800 Hz of μ from π/K decay
  - Huge background for downward-going searches
- Conventional ν from π/K/μ decay
  - Mostly ν_μ ***
  - Competition between π/K decay & interaction softens spectrum.
- Prompt ν from charm/bottom decay
  - 50% ν_μ, 50% ν_e
  - Follows cosmic-ray spectrum
  - Not yet observed

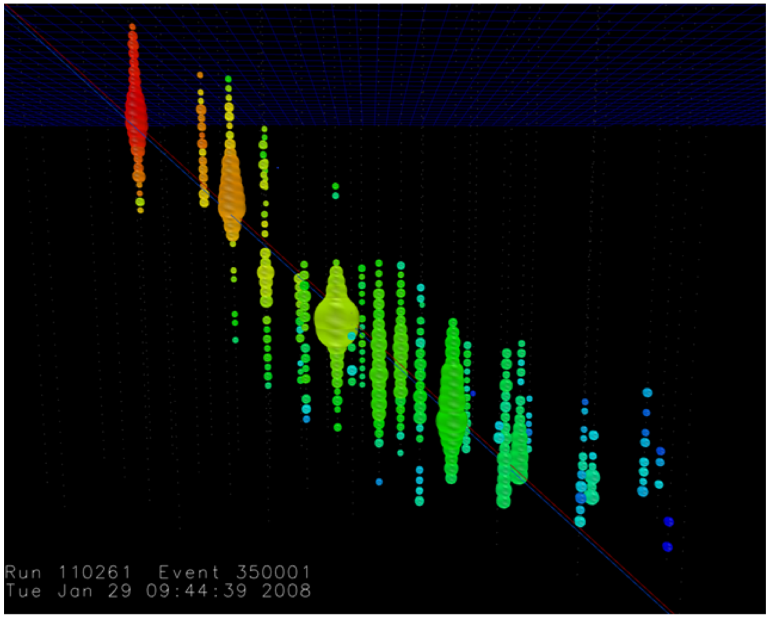




*** Neutrino telescopes cannot generally distinguish between $\nu/\overline{\nu}$; so I will lump them together

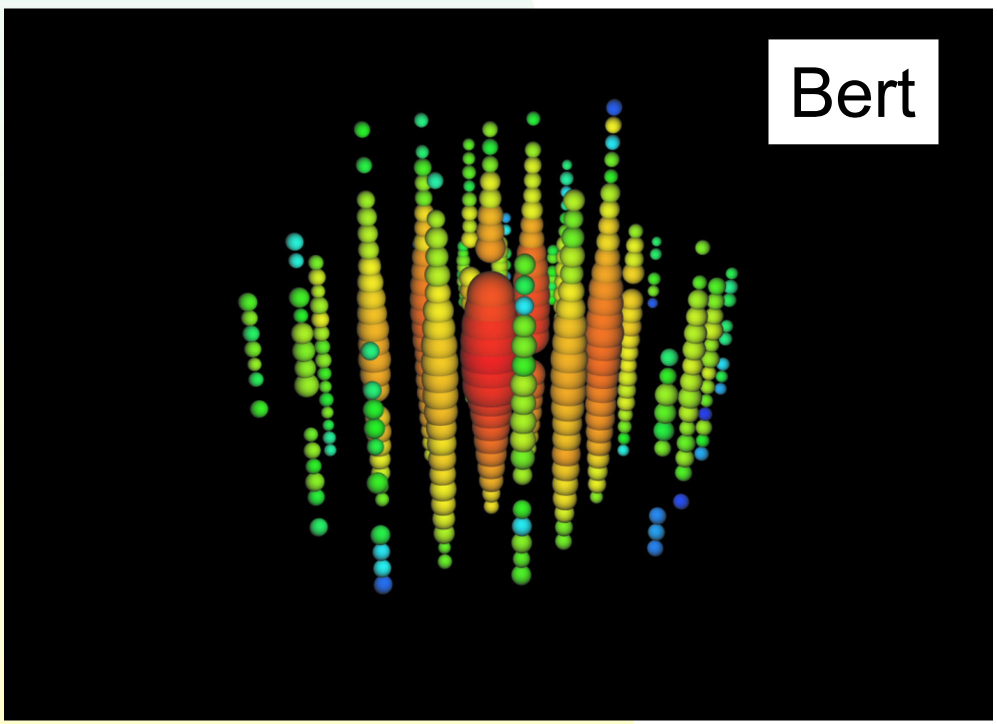
Extra-terrestrial ν search strategies

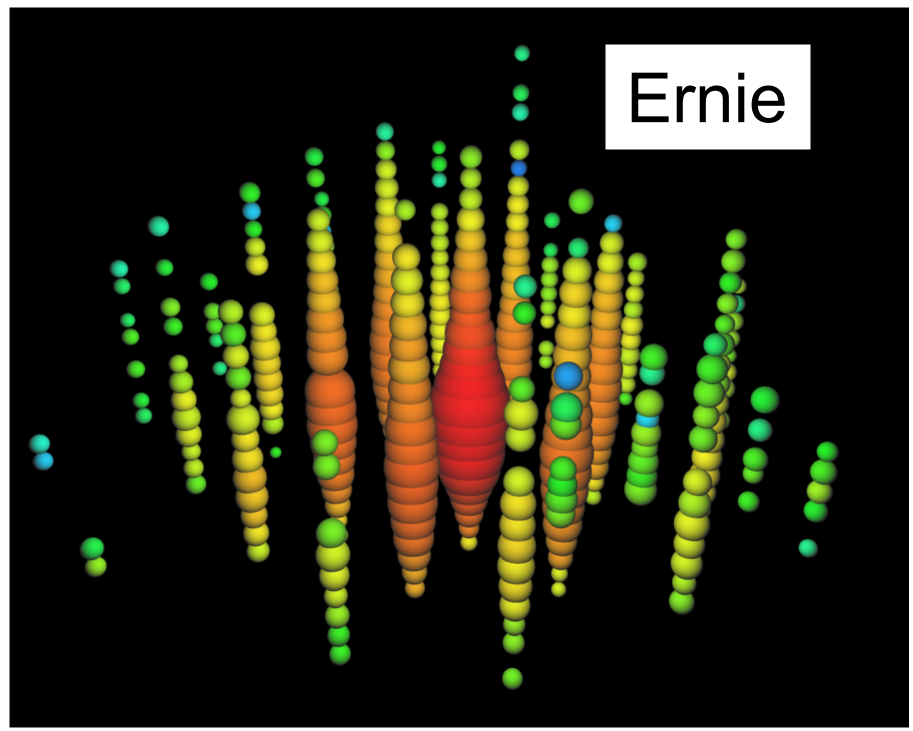
- Backgrounds are large
  - Downgoing atmospheric μ
    - 500:00 μ: 1 ν
  - Atmospheric ν
    - Ratio depends on energy
- Separation strategies
  - Point sources
  - Energy spectra
    - Harder than atmospheric (?)
  - Upward-going vs. downward-going
    - N.b. downward-going have large μ background, but atmospheric ν may self-veto
  - ν flavor ratio – atmospheric ν_τ flux ~ 0
    - No ν_τ signal seen so far



Bert & Ernie

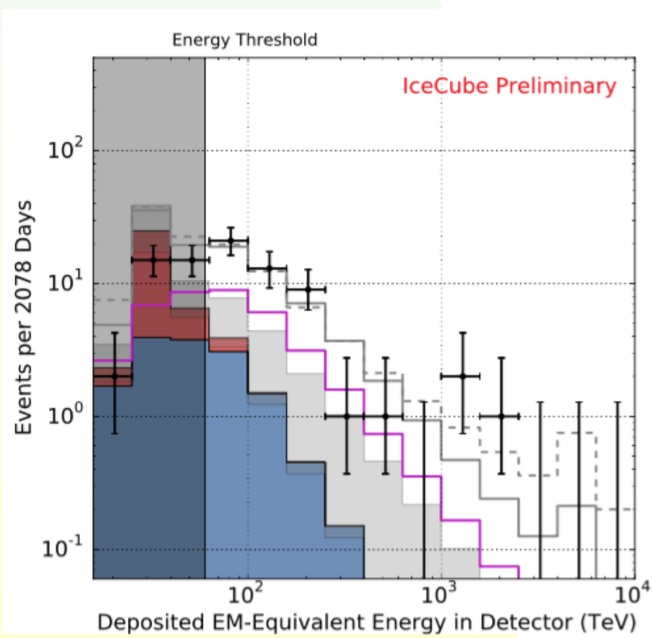
- The first clear evidence for extra-terrestrial neutrinos came from a search for extremely high-energy neutrinos
- Both have E ~ 1 PeV ;too low to be from GZK neutrinos
- Both events are ‘golden’ cascades, well contained in the detector with well reconstructed energies
- Atmos. Background: 0.082 ± 0.004 (stat.) $^{+0.06}_{-0.04}$ (syst.) events

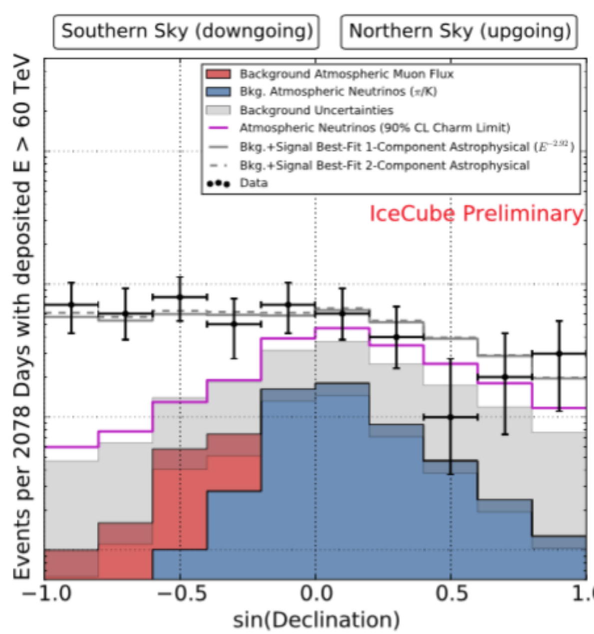




Contained event search

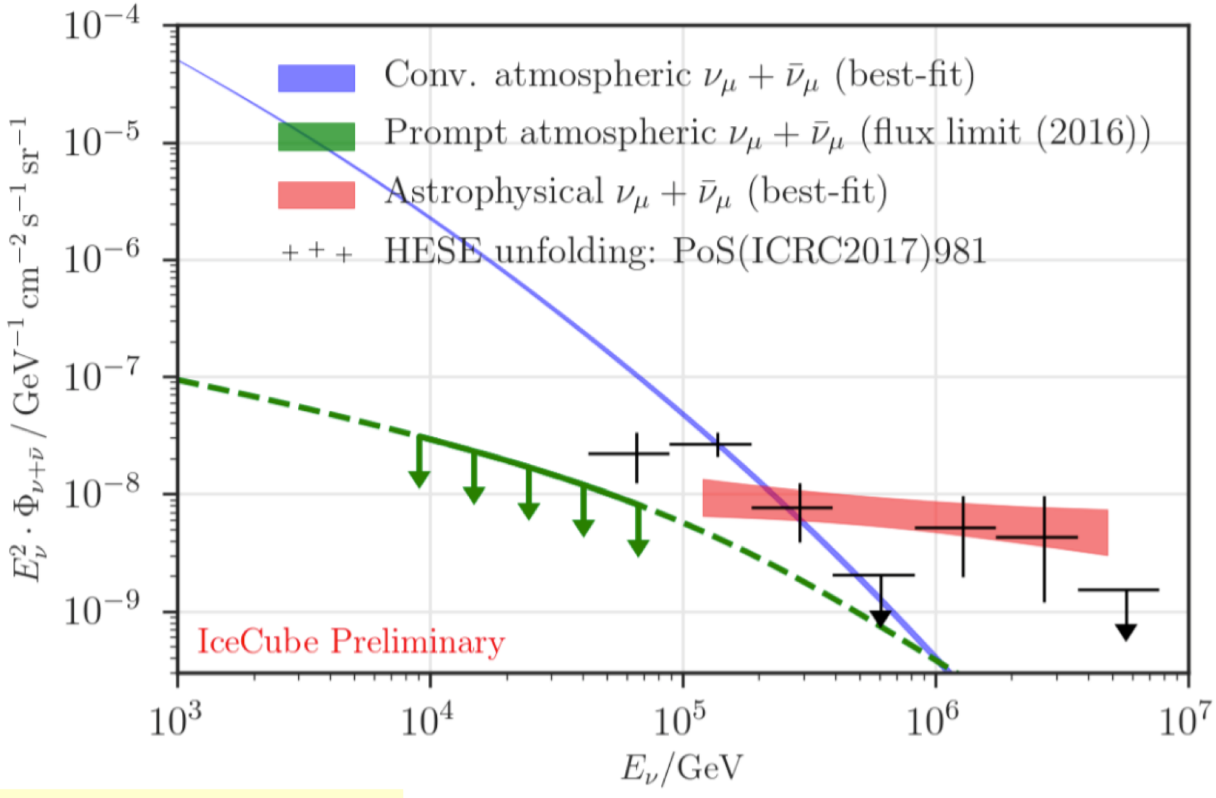
- Bert and Ernie inspired the "HESE" high-energy starting event search, which led to the discovery of astrophysical n
- Today: HESE 6 year sample: 82 events in 2078 live-days
  - 2 obvious background events excluded
  - Expected atmospheric μ background 25 ± 7 events
    - Estimated from data using double-wall veto study
  - Estimated atmospheric ν background 16^{+11}_{-4} events
- Best fit dN/dE ~ $E^{-2.92 \pm 0.3}$ in range 60 TeV < $E_{deposited}$ < 10 PeV





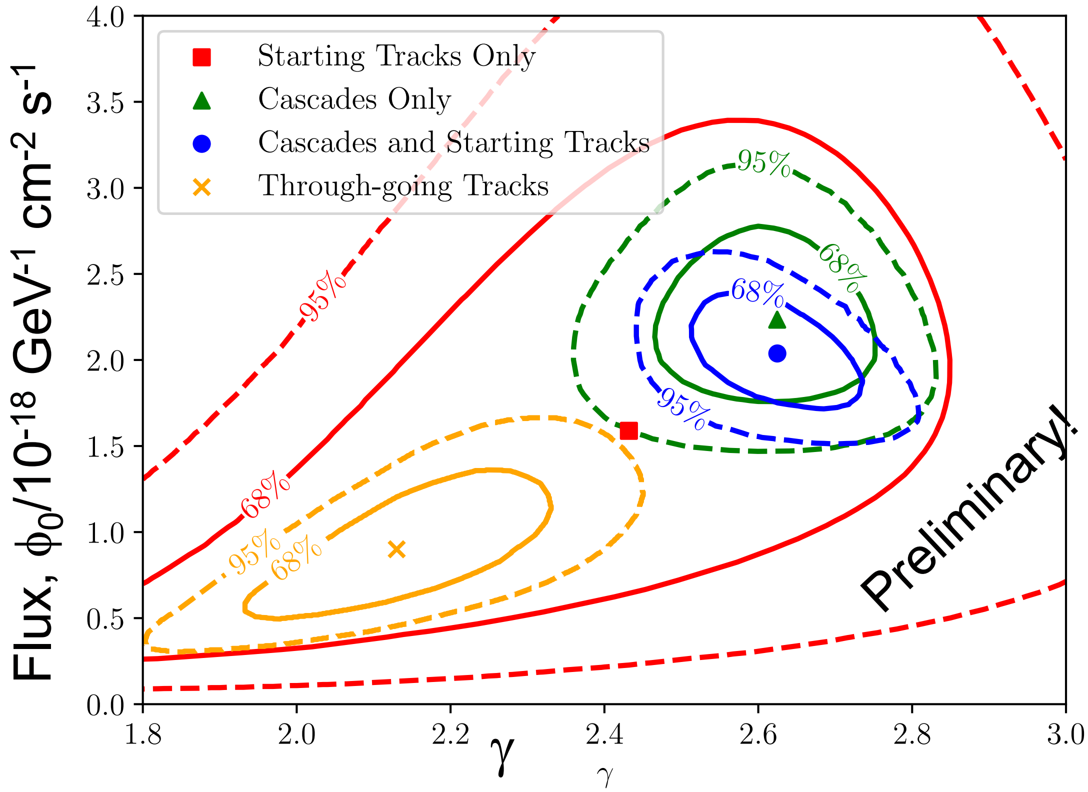
Through-going ν

- Upward-going through-going tracks in 8 years of data
  - Fit to conventional + prompt + atmospheric ν mixture
- Best fit dN/dE ~ $E^{-2.2 \pm 0.1}$
  - Spectral index is in tension with the contained event study, but centered at considerably higher neutrino energies
  - Flux agrees in overlap region



Are astrophysical ν_μ and ν_e different?

- Astrophysical flux has been fit by a single power law $dN/dE \sim E^{-\gamma}$
- IceCube observes tension between different classes of analyses
  - Contained event (mostly cascades) studies find γ ~2.5-3.0
  - Throughgoing μ studies find $\gamma \sim 2.1 \pm 0.1$, at much higher energies
- Here: fit starting track and cascade components separately
  - Probe similar energy ranges



Spectral Indices $dN/dE \sim E^{-\gamma}$

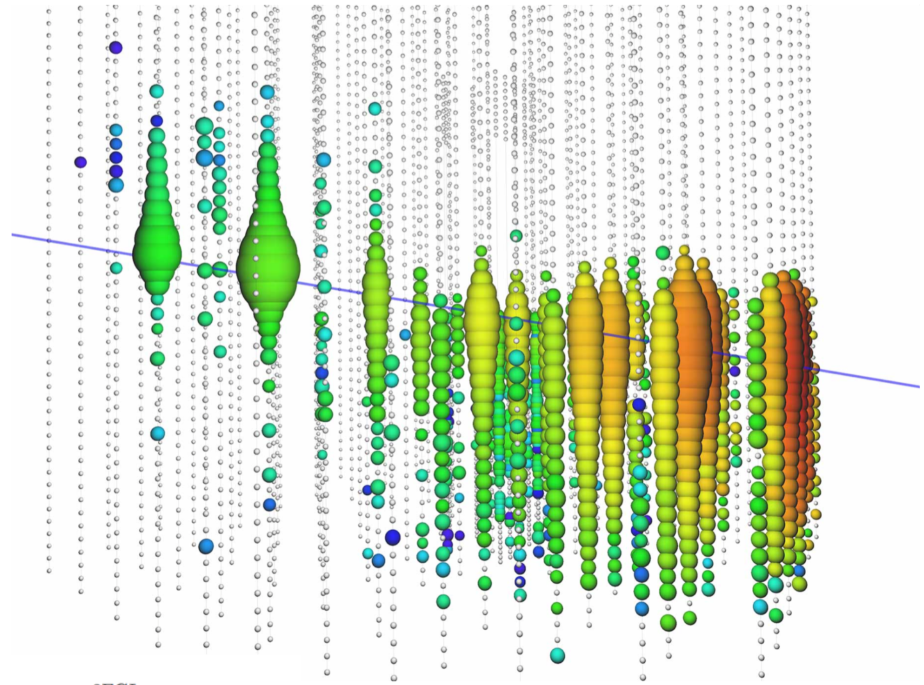
$\gamma_{casc} = 2.62 \pm 0.08$

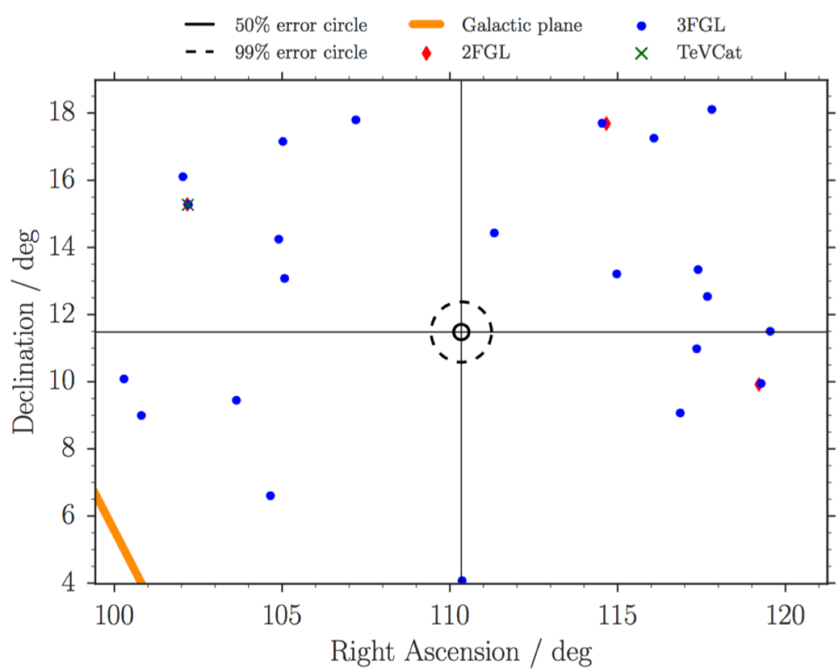
$\gamma_{track} = 2.43^{+0.28}_{-0.30}$

γ_{track} is between cascades & throughgoing μ results.

Where do these neutrinos come from?

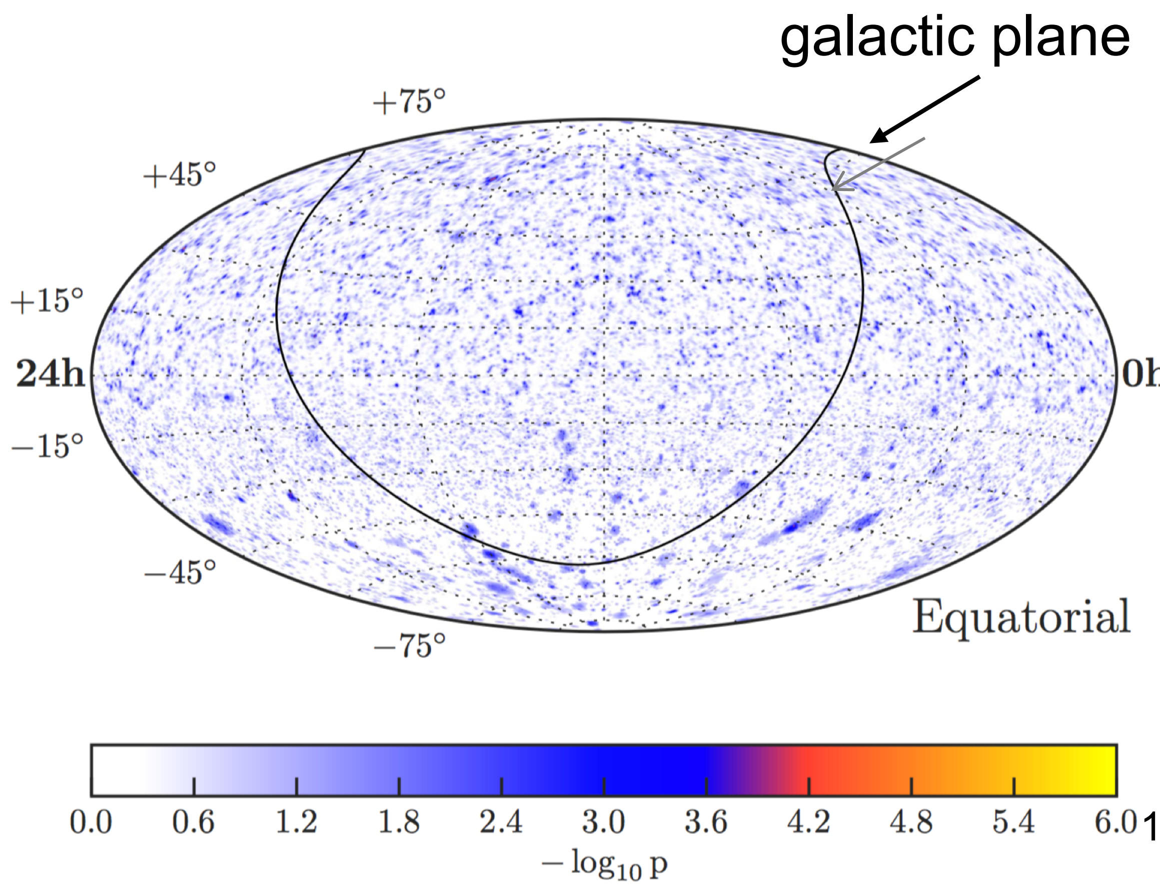
- Big event seen June 11, 2014
  - 2.6 PeV deposited in detector
  - E_μ likely ~ 3-5 PeV
  - E_ν likely ~ 5-10 PeV
- Direction known to ~ 0.3°
  - Nothing obviously interesting from that direction





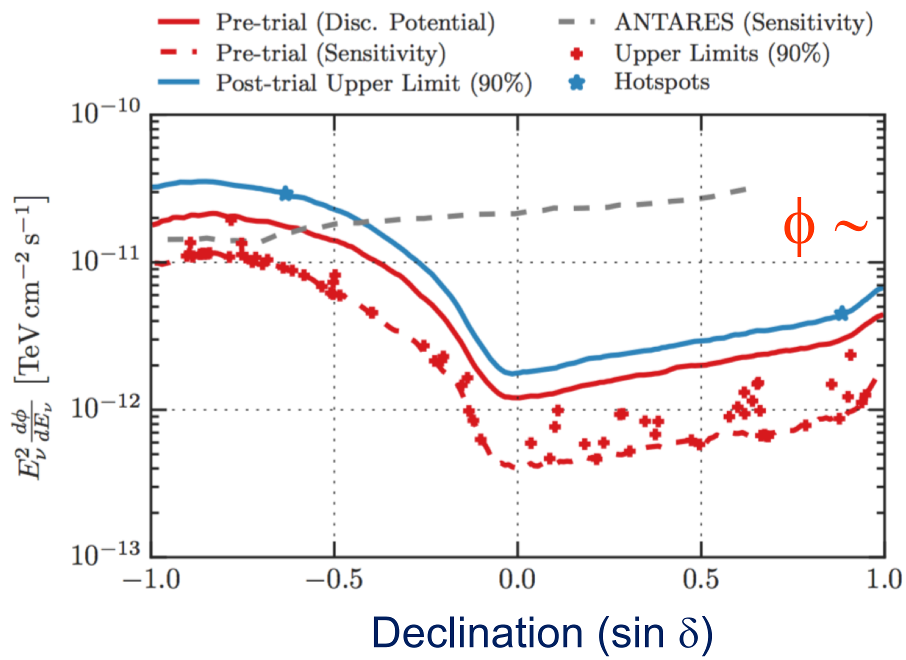
7 year neutrino sky map

- Using all neutrino events is much more sensitive than just using starting events
- 2431 live days, with 711,000 events
- Throughgoing muons, mostly lower energy
  - ~90% ν purity in Northern Hemisphere; mostly μ in South
- No significant excesses



Backgrounds are derived from data at similar zenith angle, but with scrambled azimuthal angle.

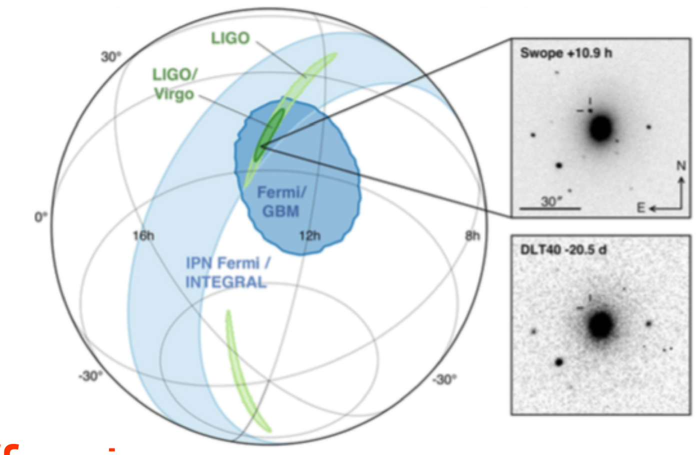
Point source searches



- Flux limits calculated for assumed E^{-2} energy spectrum
  - Limits depend on declination
    - == zenith angle in IceCube
  - $E^2\phi \sim 10^{-12}$ TeV cm^{-2} s^{-1} constrain many older theory predictions
    - ~ Comparable to photon flux
- All-sky survey, pre-selected sources and source class stacking
  - e.g. blazars, supernova remannts, etc.
- Searches for gamma-ray bursts, using GRB position/times determined from photon observations
- Periodic/flaring sources
  - Triggered (by other observations) and untriggered
  - LIGO gravity wave events

GW170817 and gamma-ray bursts

- A ‘classic’ merger of two neutron stars to form a black hole.
- 100 second long gravitation waves seen by LIGO
  - Distance =40 ± 8 Mpc



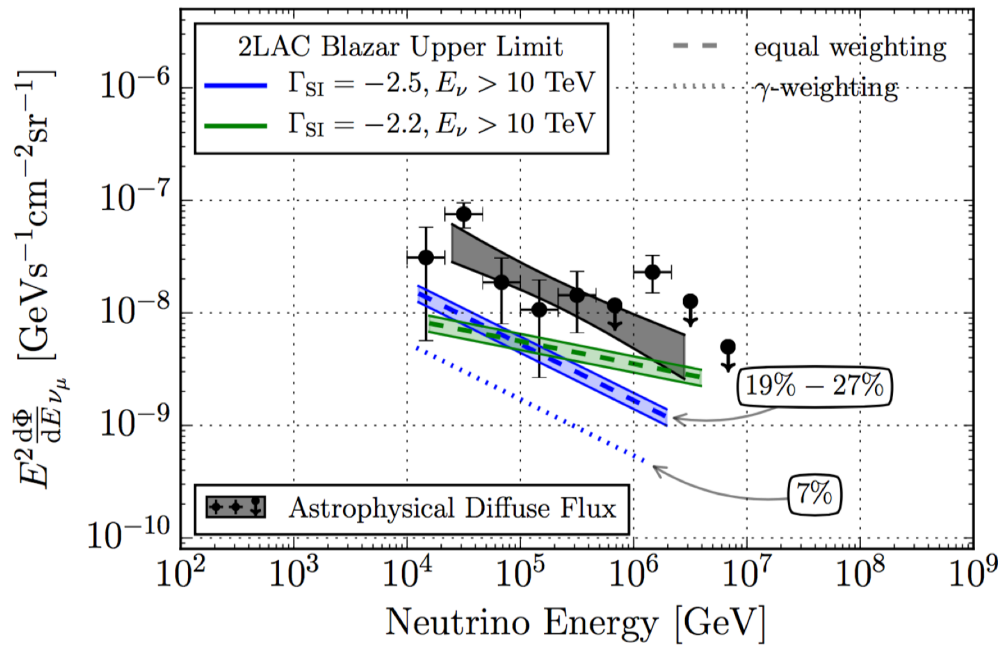
- Classic long GRB, but jets were slightly off axis.
- No neutrinos seen
  - Off-axis geometry is sub-optimal for high-energy neutrinos
- A larger (previous) search by IceCube looked for neutrinos from 1172 gamma-ray bursts seen by the Gamma-ray Coordinates Network (GCN)
  - No signals were seen.
  - GRBs are responsible for less than 1% of the diffuse flux seen by IceCube

Other source Classes

- Autocorrelation analyses find that a large number of sources must contribute to the observed flux.
  - Disfavors very source classes where objects are very rare.
- A combined IceCube/Fermi γ-ray telescope study finds that star forming galaxies can contribute at most ~20% of the observed diffuse flux.
- Studies of the galactic plane show that there may be a small contribution to the flux coming from our galaxy, but most of the flux is not.

Blazar search

- Stacked search of blazars seen by the Fermi-LAT gamma-ray telescope
  - Sum signal from 862 blazars (and, separately, by some sub-categories)
    - Equal weighting, or weighting by gamma-ray flux
- No excess seen
- For an $dN/dE \sim E^{-2.5}$ neutrino spectrum, blazars produce <27% of the diffuse flux seen by IceCube
  - If spectrum is $E^{-2.2}$, limit loosens to 50% of observed flux



Multi-messenger astronomy: AGN in outburst?

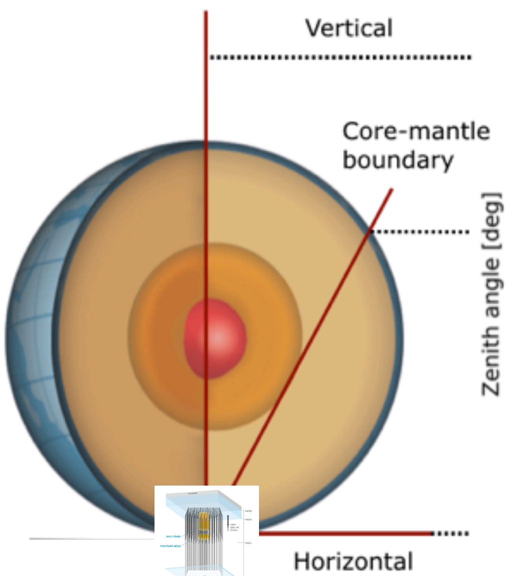
- On Sept. 22, 2017, IceCube observed a single high-energy probable-neutrino track-like event
  - Triggered follow-up observations
  - Fermi/LAT satellite & Magic Cherenkov telescope observe γ-rays from 800 MeV to > 100 GeV
  - Multiple radio & optical observations
- Location consistent with a known blazar TXS 0506+056
  - Optical emission and γ-rays enhanced during that period
    - It was ‘flaring’
- Redshift measured (post-ν) $z=0.3365 \pm 0.0010$
  - Photons with E> ~ 300 GeV are attenuated by absorption

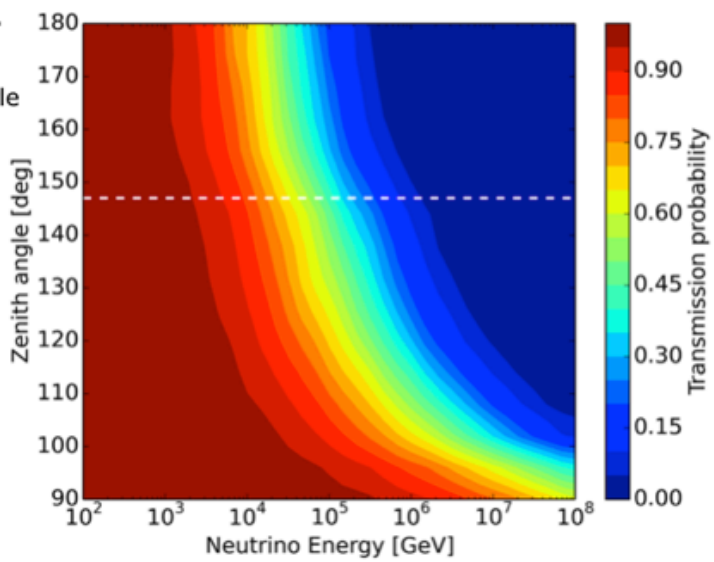
Situation still in flux…
arXiv:1802.01939, GCN Circular 21916, Atel 10791 & 10,817

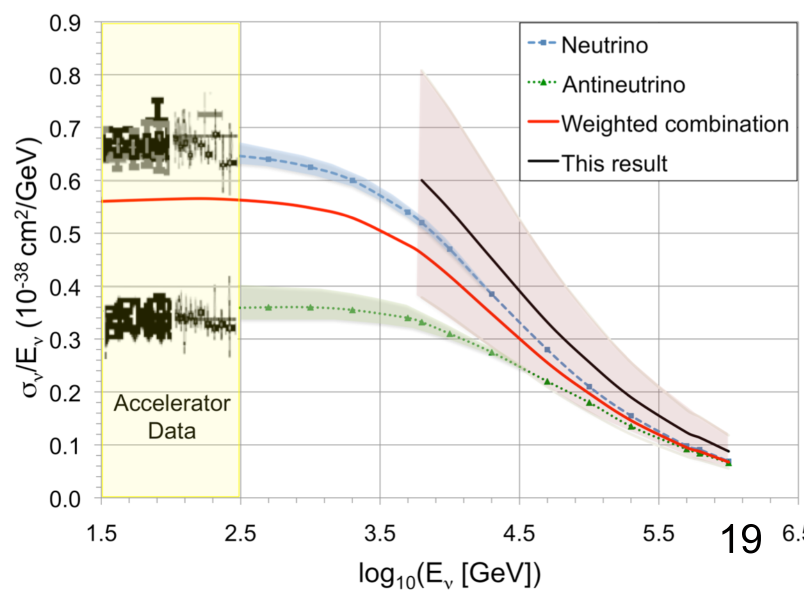
$\sigma_{\nu N}$ measurement

- At energies above 30 TeV, the Earth absorbs neutrinos
- 1 year of up-going ν_μ data was binned in (E_μ, $\cos(\theta_z)$)
  - Fit to standard cocktail, with absorption allowed to vary
  - Cross-section is a multiple ("R") of standard model cross-section
  - Neutral-current included; reduces neutrino energy

$R=1.30\ ^{+0.21}_{-0.19}\,(\text{stat})\ ^{+0.39}_{-0.43}\,(\text{syst.})$ $\qquad$ $6.3\ \text{TeV} < E_\nu < 980\ \text{TeV}$

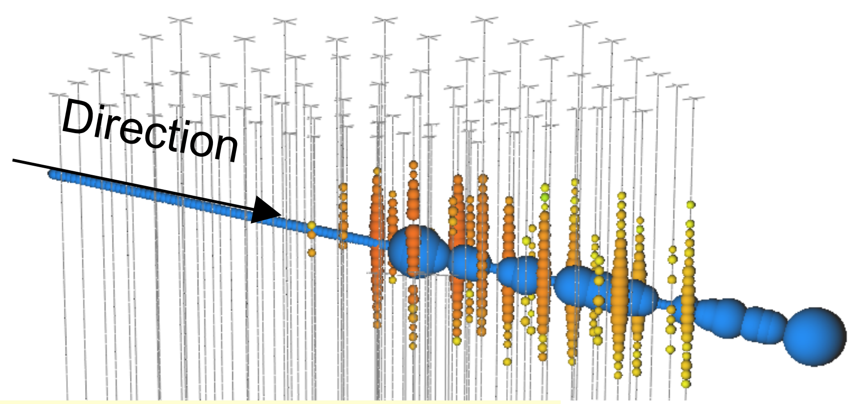






Inelasticity in contained events

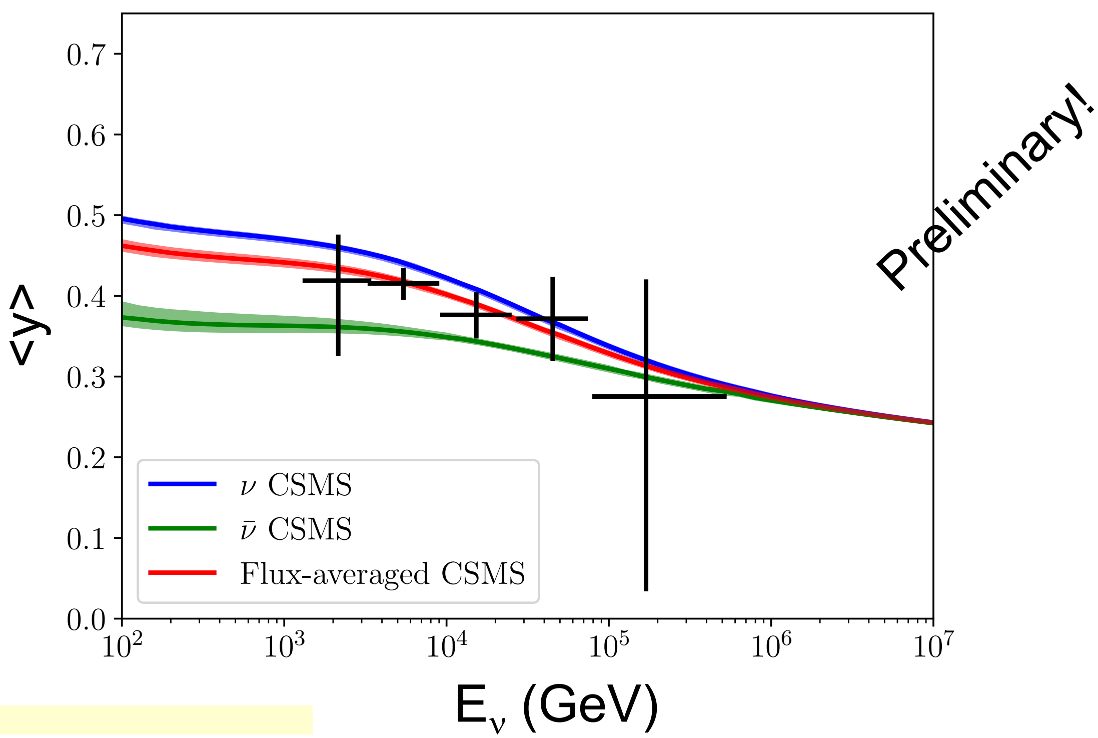
- Inelasticity $y = E_{hadronic\ shower}/E_\nu$
  - Predicted by standard weak interaction model
  - Inelasticity distributions are different for ν, $\overline{\nu}$ for $E_\nu < 10$ TeV
- Analysis uses 2650 starting track events (ν_μ) in 5 years of data, selected by a machine learning approach
  - 965 similarly-selected cascades used in some global fits
- A second machine finds $E_{cascade}$, E_μ, y_{vis}
  - y_{vis} ~ y, but accounts for missing energy



A starting track event with
E_{casc} =64 TeV
E_μ = 724 TeV
y_{vis}=0.08

Mean inelasticity <y>

- Parameterize $d\sigma/dy \sim (1+\varepsilon(1-y)^2)y^{\lambda-1}$
  - Motivated by low-x region, where $xq(x,Q^2) \sim x^{-\lambda}$
- ε, λ are heavily correlated, so fit for <y> and λ
  - <y> decreases with energy, as expected
  - In agreement with CSMS calculation
  - Used to measure atmospheric $\bar{\nu}/\nu$ ratio and to observe charm production in ν interactions from 1.5 to 340 TeV



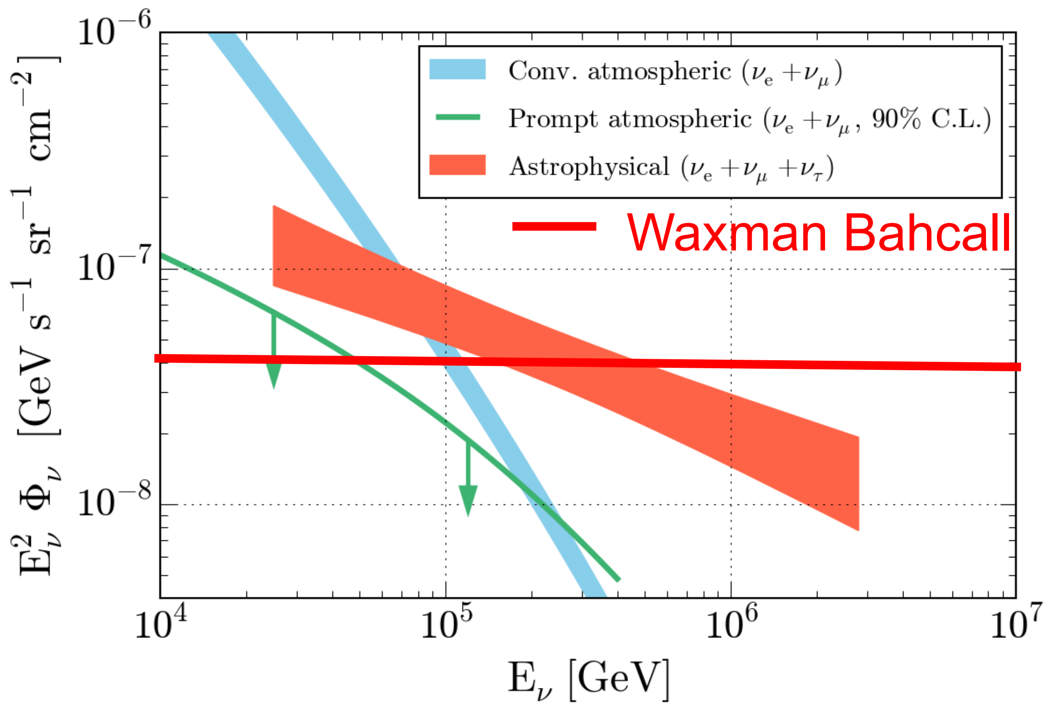
Conclusions

- IceCube has observed a flux of diffuse astrophysical neutrinos with a significance well above 5σ.
  - For a single power law fit, $dN/dE \sim E^{-2.0-3.0}$
  - Tension between different spectral measurements -> more complex spectrum?
- The flux level is roughly around the maximum expected level
  - Opacity=1?
- We have not observed any clear continuous or episodic point sources, and have put significant constraints on many interesting classes of sources.
- There are reports of an interesting coincidence between a high-energy IceCube event and enhanced gamma-ray activity from Fermi, detection of > 100 GeV gamma rays from the Magic telescopes, from a flaring BL Lac (Blazar) object.
  - Stay tuned…

Extra/backup

The ν flux is nearly saturated

- The flux is near (or above) the 'Waxman-Bahcall bound, which corresponds to opacity=1
  - Different spectral indices complicate comparison
  - Cosmic-rays just escape from the source
- For most ν prediction models, one must push parameters upward to explain the observed flux
  - It should be easy to find the sources.



Letting the flavor ratio float

- Based on inelasticity study, to be described later
- 11 TeV < $E_{cascade}$ < 410 TeV
- 8.6 TeV < $E_{CC\ evt}$ < 207 TeV
- Much closer match than combined fit w/ throughgoing tracks
  - Results still valid for complex spectra
- 100% ν_e & 100 ν_μ excluded
- Not yet sensitive to different standard acceleration models
- Other studies find similar results