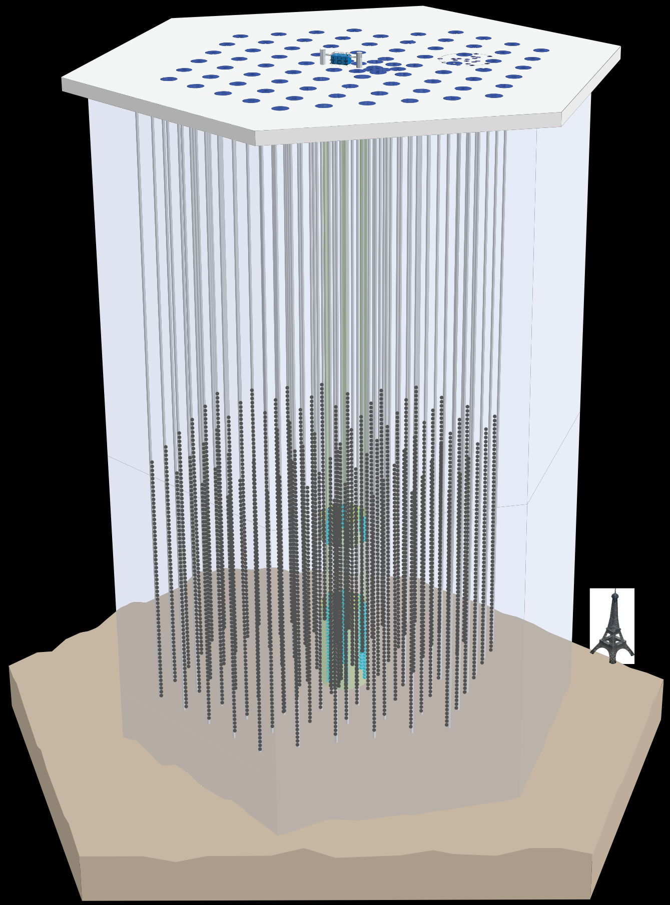
Astrophysical neutrinos and the search for their origins

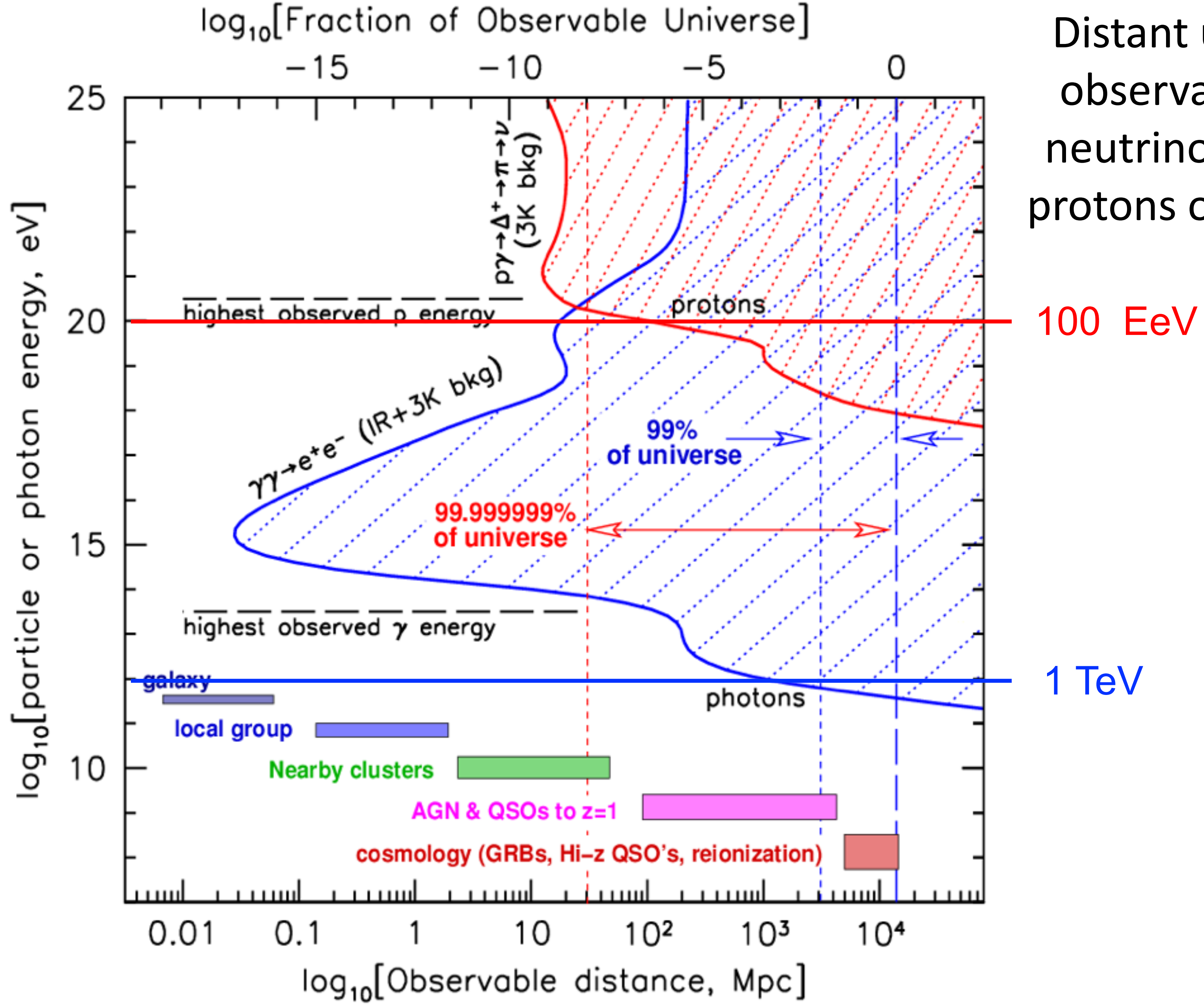


Justin Vandenbroucke (University of Wisconsin)

for the IceCube Collaboration

Surveying the Fast-Changing Multi-wavelength Sky with SVOM

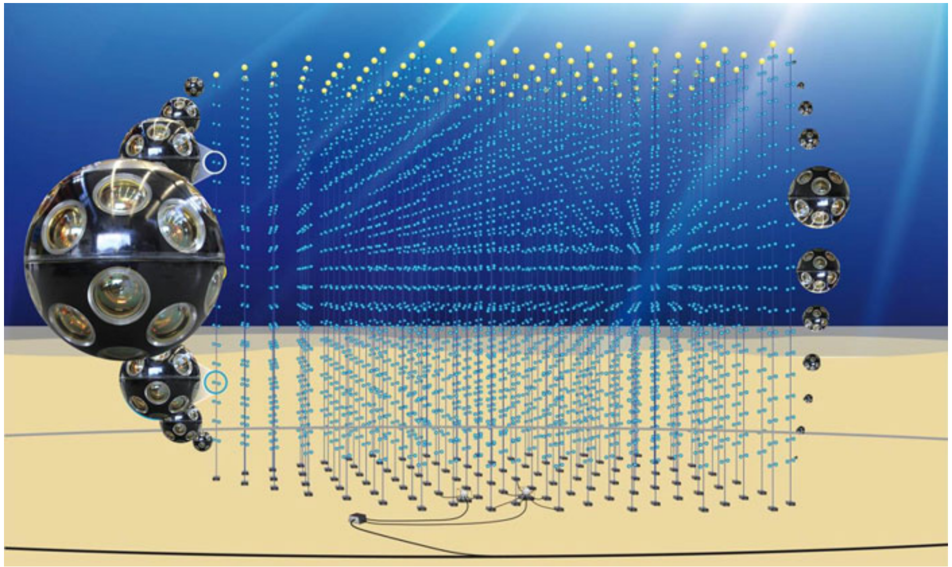
Qiannan, Guizhou province, China, April 24, 2017



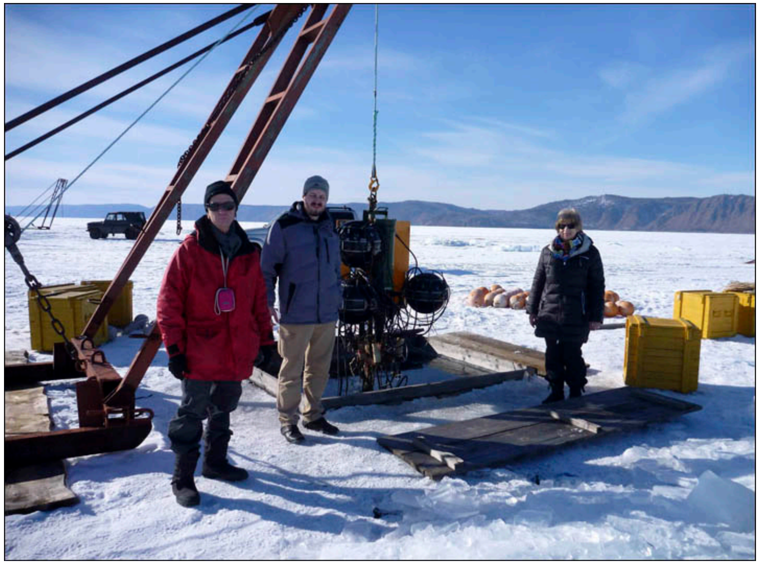
Distant universe: observable with neutrinos but not protons or gammas

Neutrino telescopes around the world

ANTARES & KM3NeT (Mediterranean)

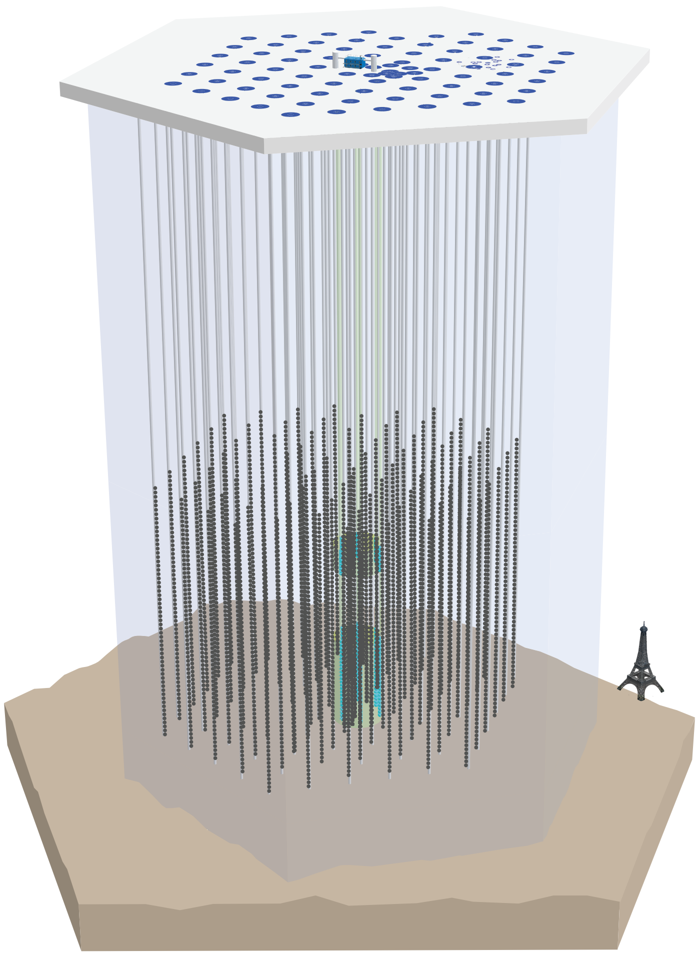


Baikal & GVD (Russia)



The IceCube Neutrino Observatory

completed 2011



IceTop (surface array): 81 stations

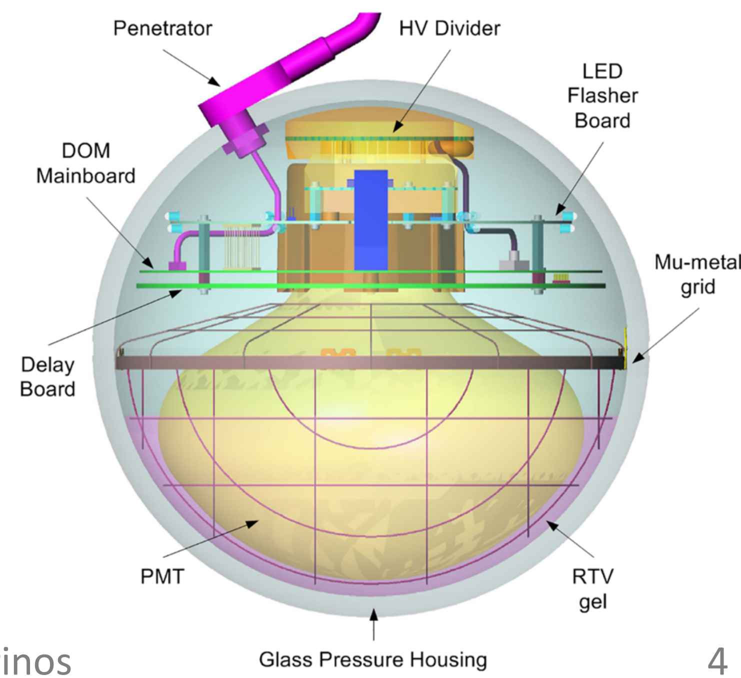
IceCube: 86 strings

5160 optical sensors over 1 km^3 volume

17 m vertical spacing

125 m horizontal spacing

DeepCore (low energy threshold)

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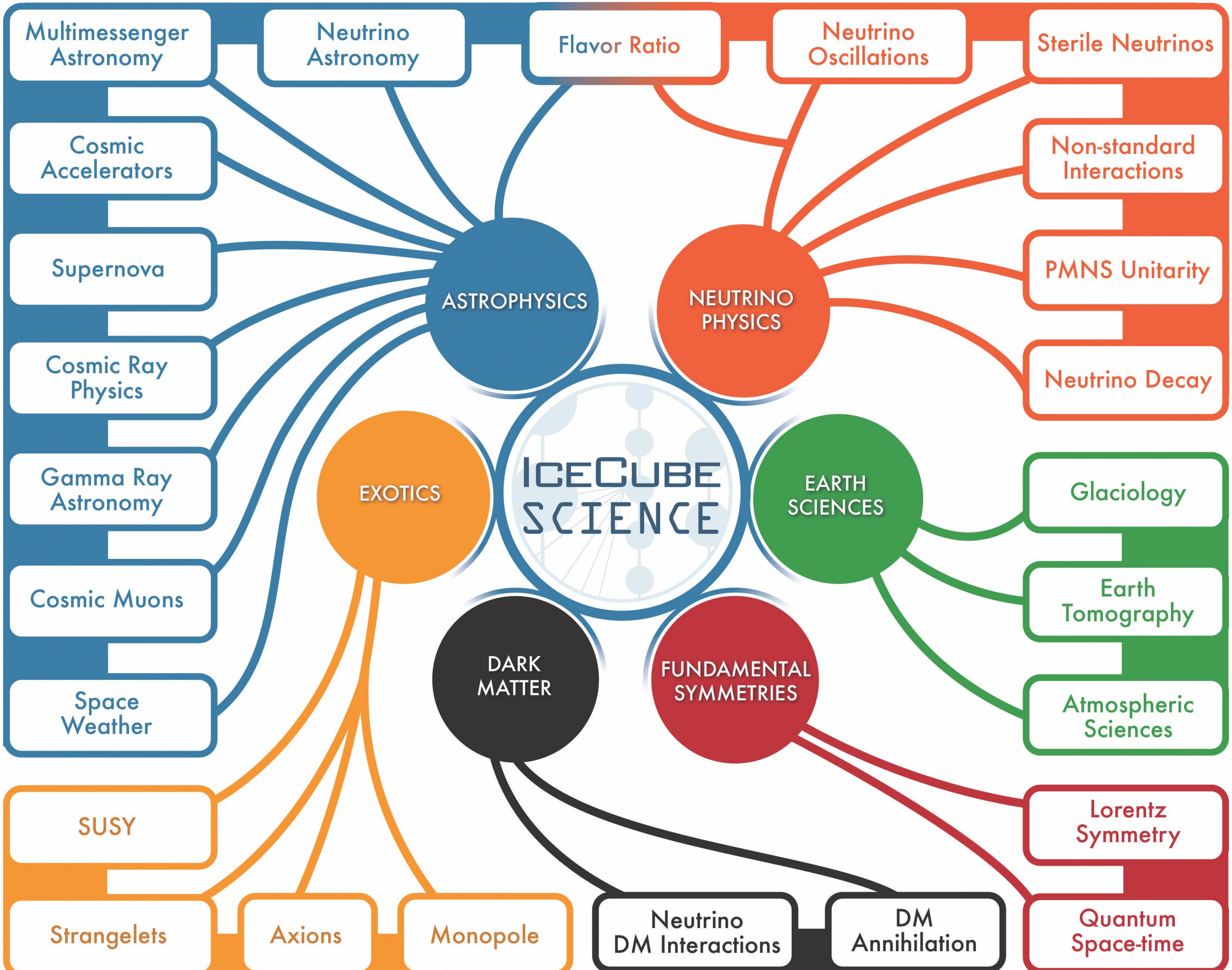

Multimessenger Astronomy
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Sterile Neutrinos
Cosmic Accelerators
Non-standard Interactions
Supernova
PMNS Unitarity
ASTROPHYSICS
NEUTRINO PHYSICS
Neutrino Decay
Cosmic Ray Physics
Gamma Ray Astronomy
EXOTICS
ICECUBE SCIENCE
EARTH SCIENCES
Glaciology
Cosmic Muons
Earth Tomography
DARK MATTER
FUNDAMENTAL SYMMETRIES
Space Weather
Atmospheric Sciences
SUSY
Lorentz Symmetry
Strangelets
Axions
Monopole
Neutrino DM Interactions
DM Annihilation
Quantum Space-time

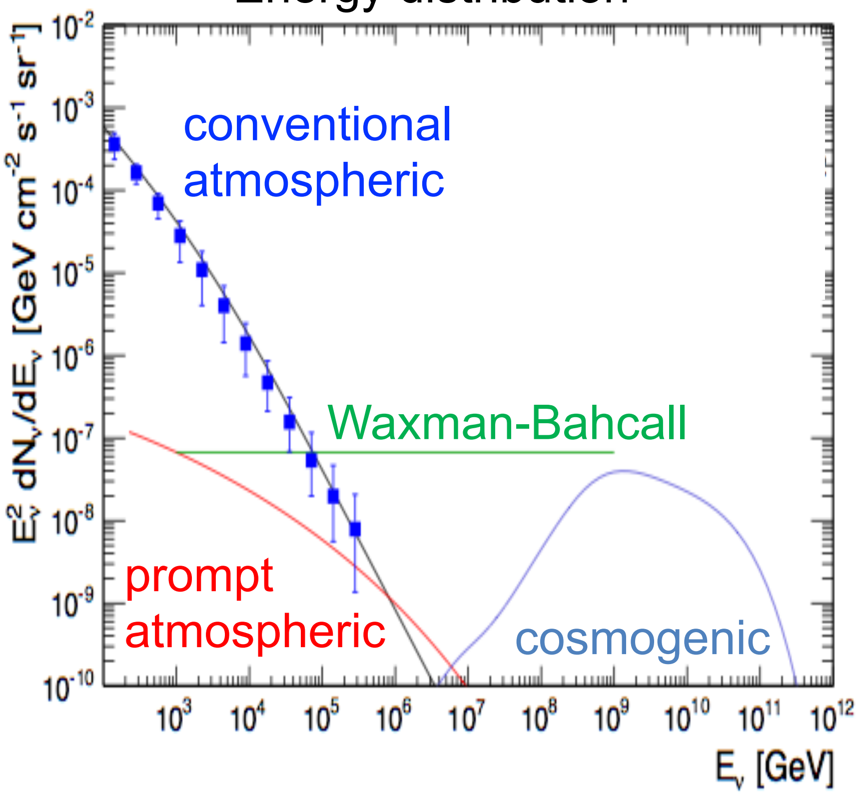
IceCube signals and backgrounds

Most events detected by IceCube are not astrophysical neutrinos

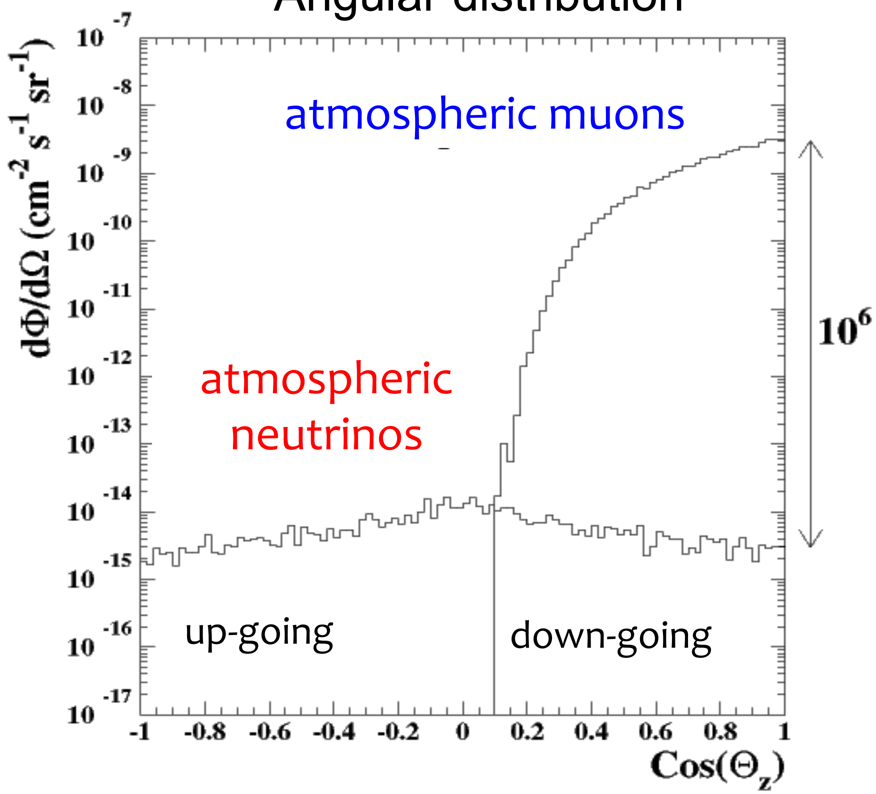
• atmospheric	μ	~7×10^{10}/year
• atmospheric	$\nu_\mu \rightarrow \mu$	~8×10^{4}/year
• astrophysical	$\nu_\mu \rightarrow \mu$	~10/year above 200 TeV

Background and signal differ in spectrum and angular distribution

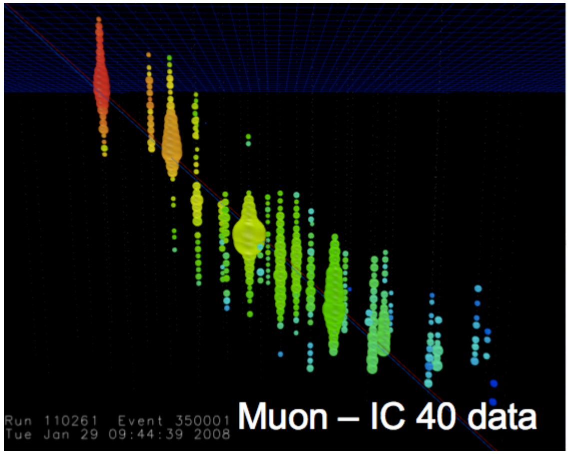
Energy distribution

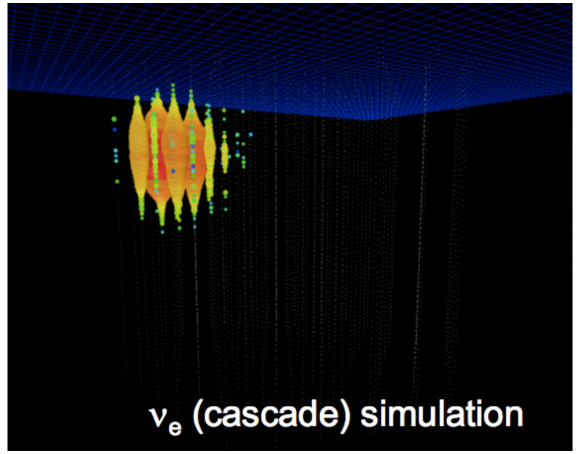


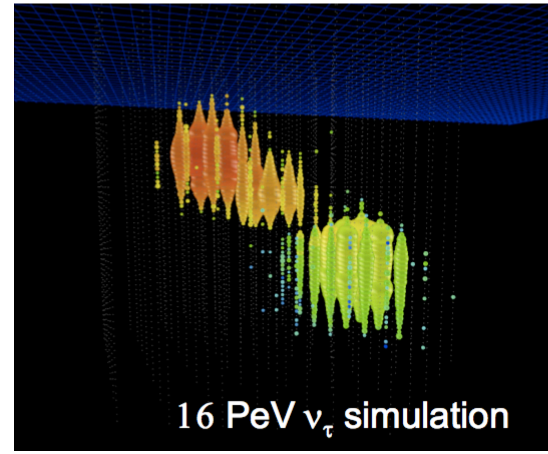
Angular distribution



Neutrino interaction channels and flavor identification







Muon neutrino:

+ Straight track,
  points to neutrino source,
  angular resolution ~1°
- Cosmic-ray muon background

Electron neutrino:

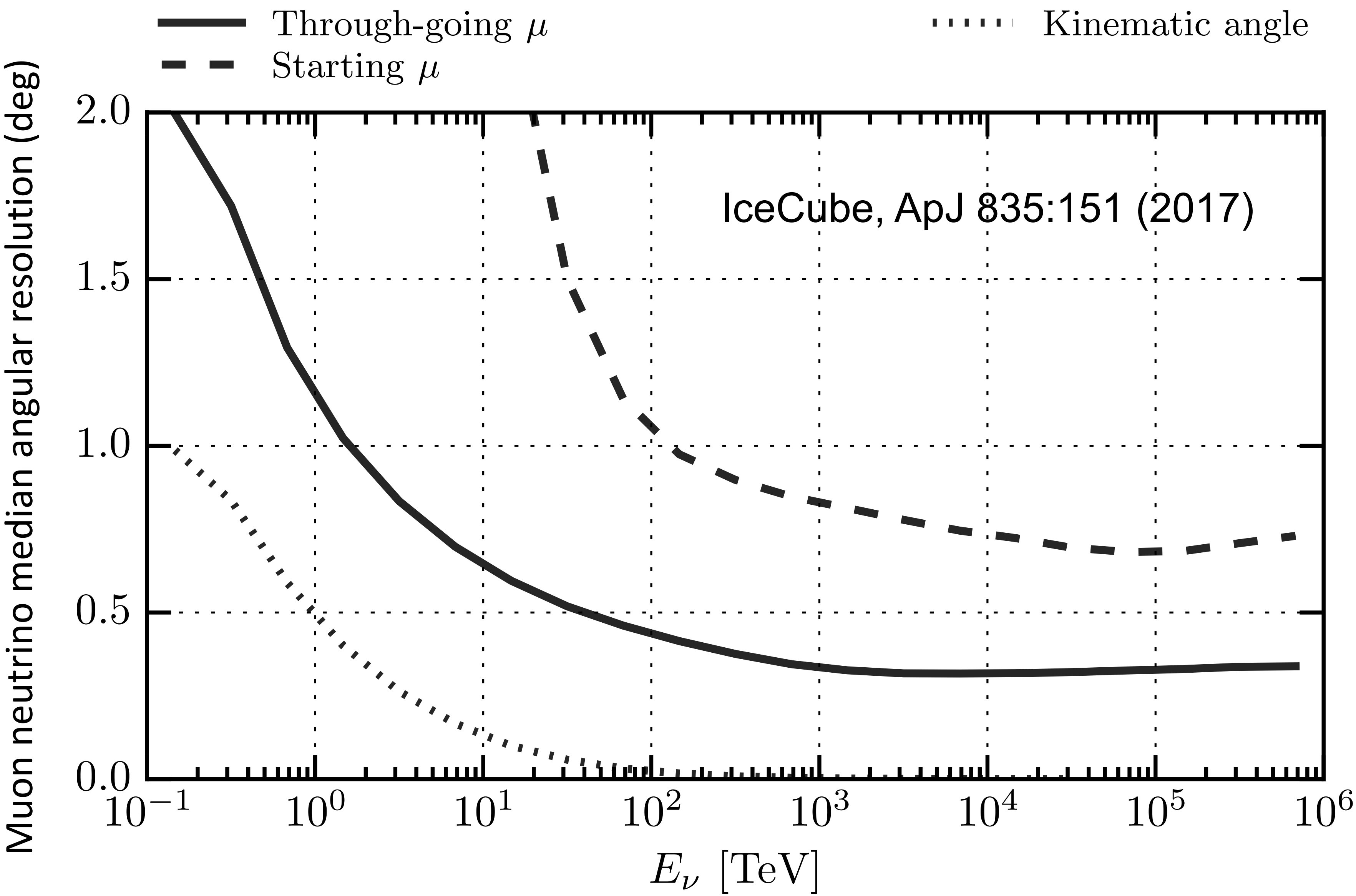
- Cascade, must be in detector
- Poor angular resolution
+ Good energy measurement

Tau neutrino:

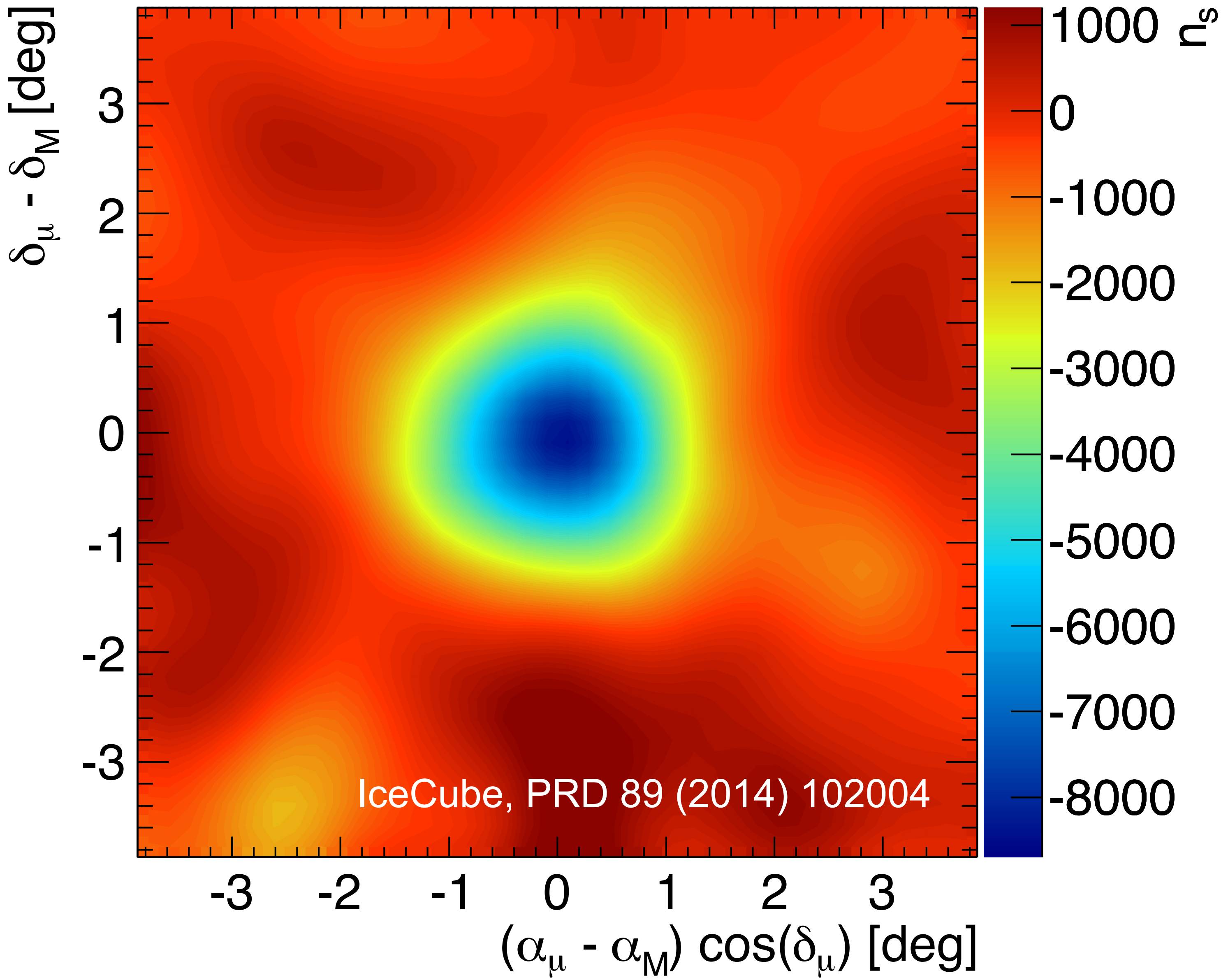
+ Double bang signature,
  low background
+ Pointing capability

- Tracks: ~1° angular resolution
- Cascades/showers: ~15° angular resolution

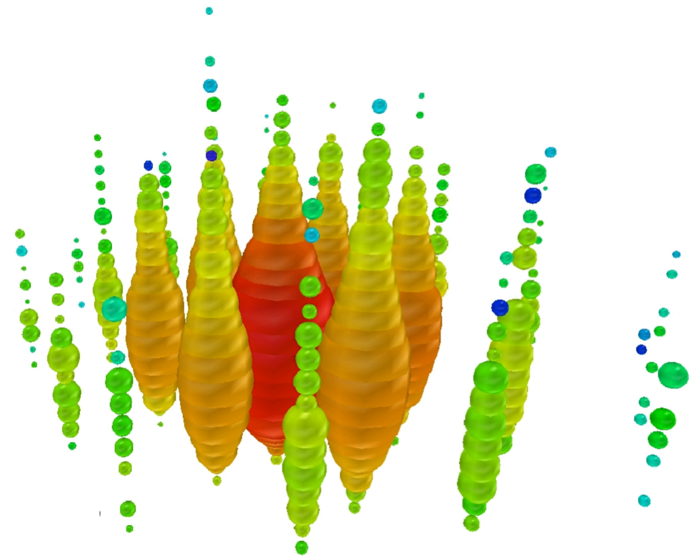
Angular resolution (muon neutrino tracks)



Validation of direction reconstruction with Moon shadow



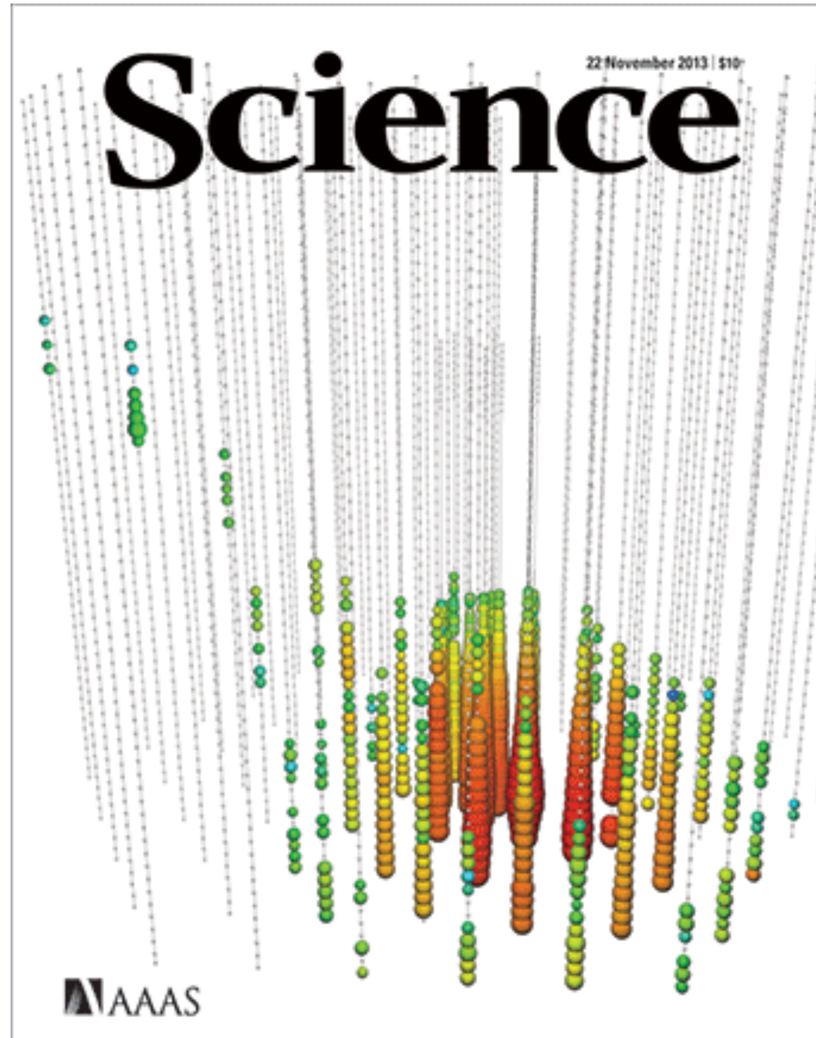
Two PeV events detected in two years of data

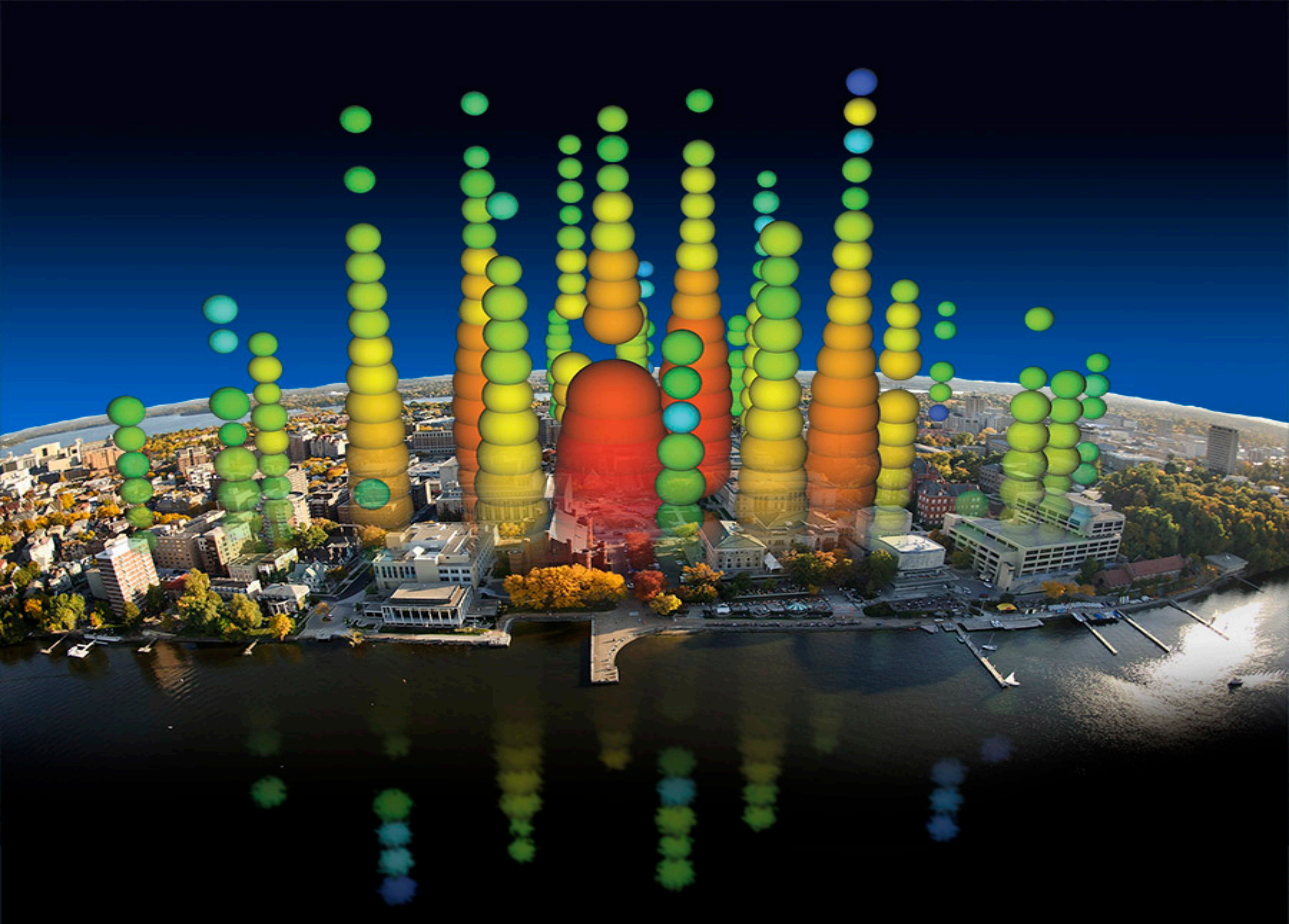


- One year with 79 strings + one year with 86 strings
- This analysis was optimized for extremely high energy (GZK) neutrinos
- Each event is a contained neutrino-induced shower with at least 1 PeV deposited in detector (lower limit on neutrino energy)
- First hint of astrophysical neutrinos (atmospheric events unlikely to produce this many events at this high energy): 2.8 σ significance

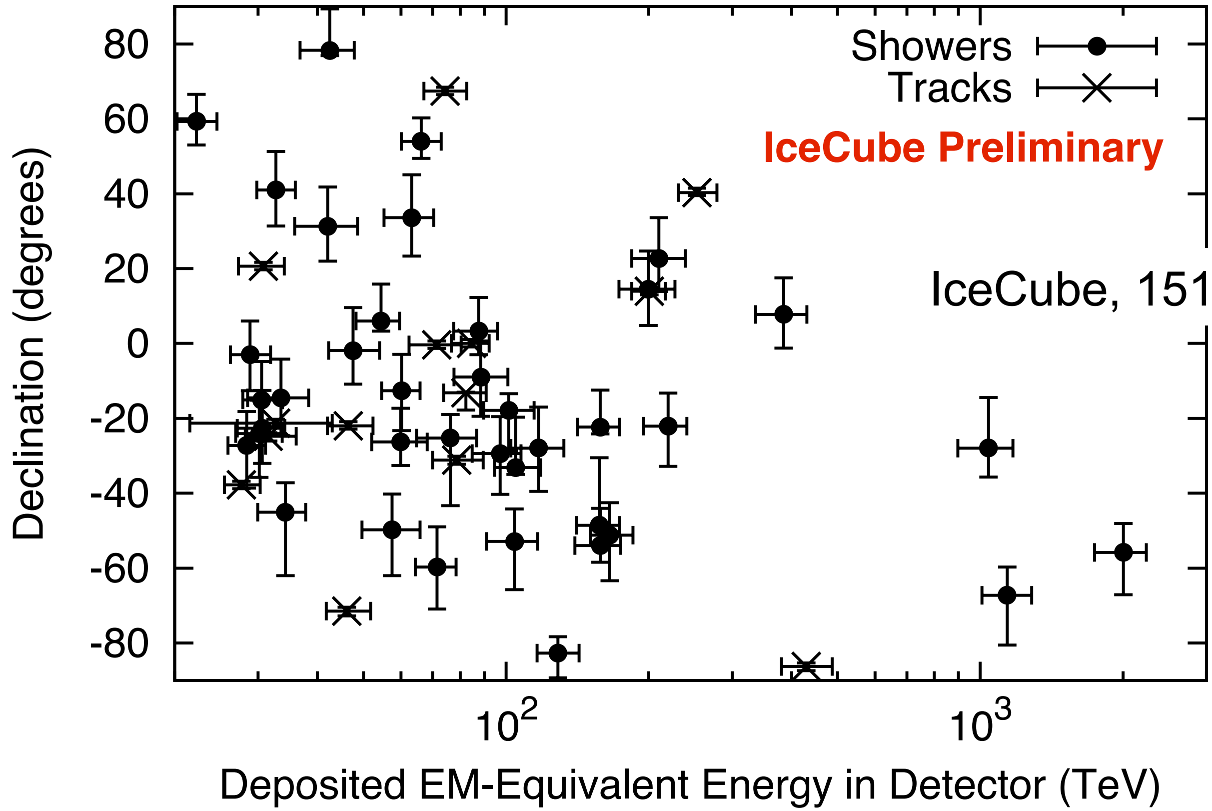
Evidence for astrophysical neutrinos in two years of data

- Same two years of data (IC79 and IC86) as first two PeV events
- Follow-up analysis using starting events to reduce energy threshold and detect both tracks and showers from full sky
- 26 additional events (28 total)
- Inconsistent with purely atmospheric origin at 4.1 σ significance





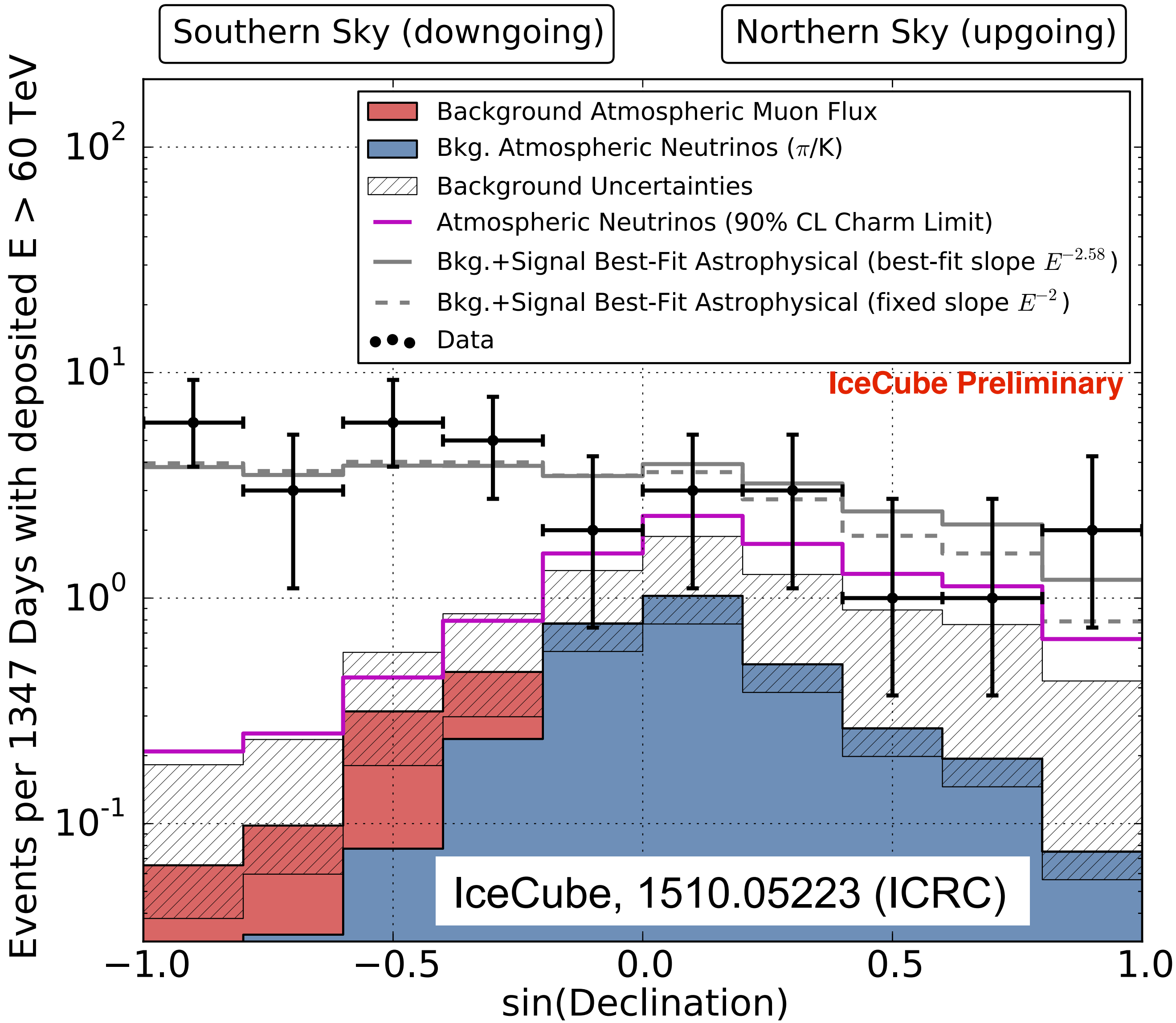
High energy starting events in four years of data



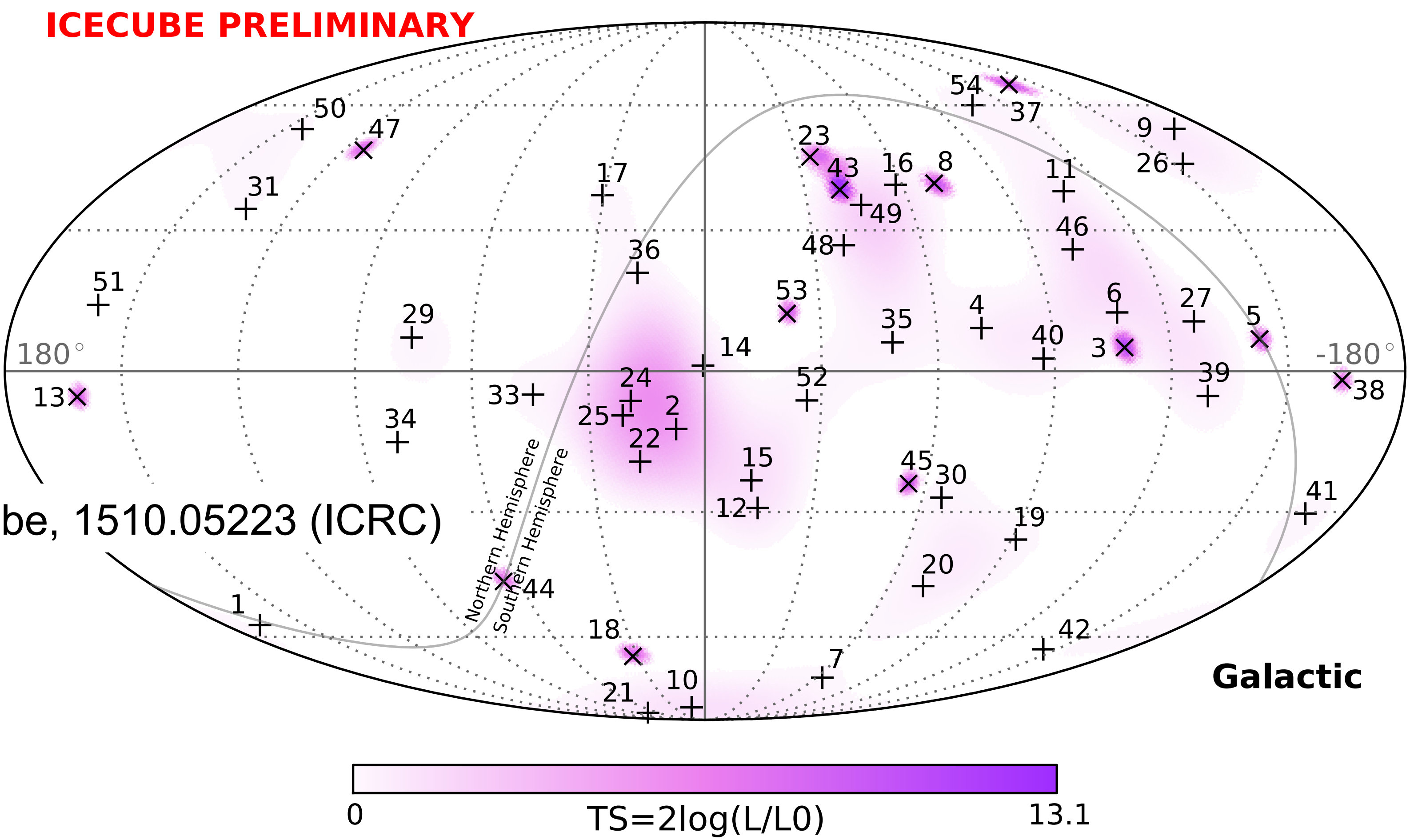
IceCube, 1510.05223 (ICRC)

- 54 total events in IC79 plus three years IC86
- Fraction of astrophysical events (above atmospheric background) increases with energy
- Three events with E > 1 PeV (highest energy neutrinos ever detected)
- At high energy, Earth absorption blocks Northern hemisphere events

Declination distribution of starting events (four years)



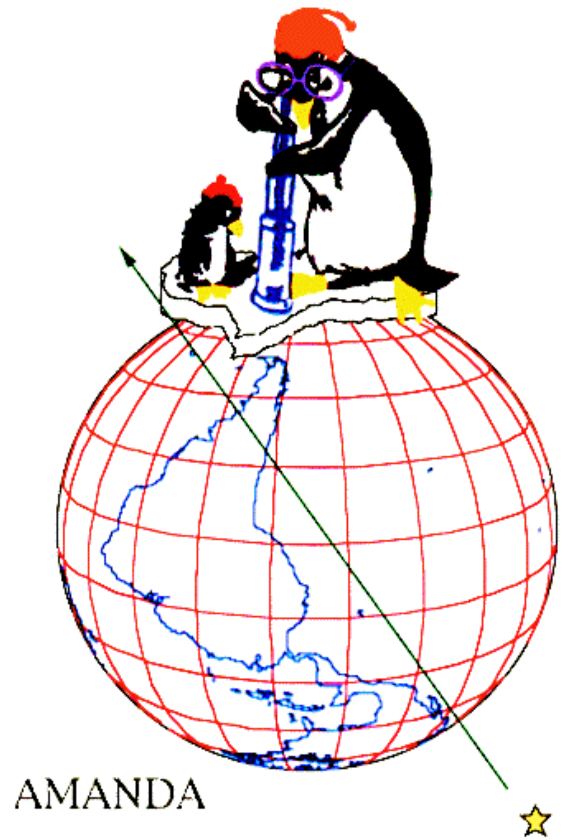
Sky map of starting events from four years



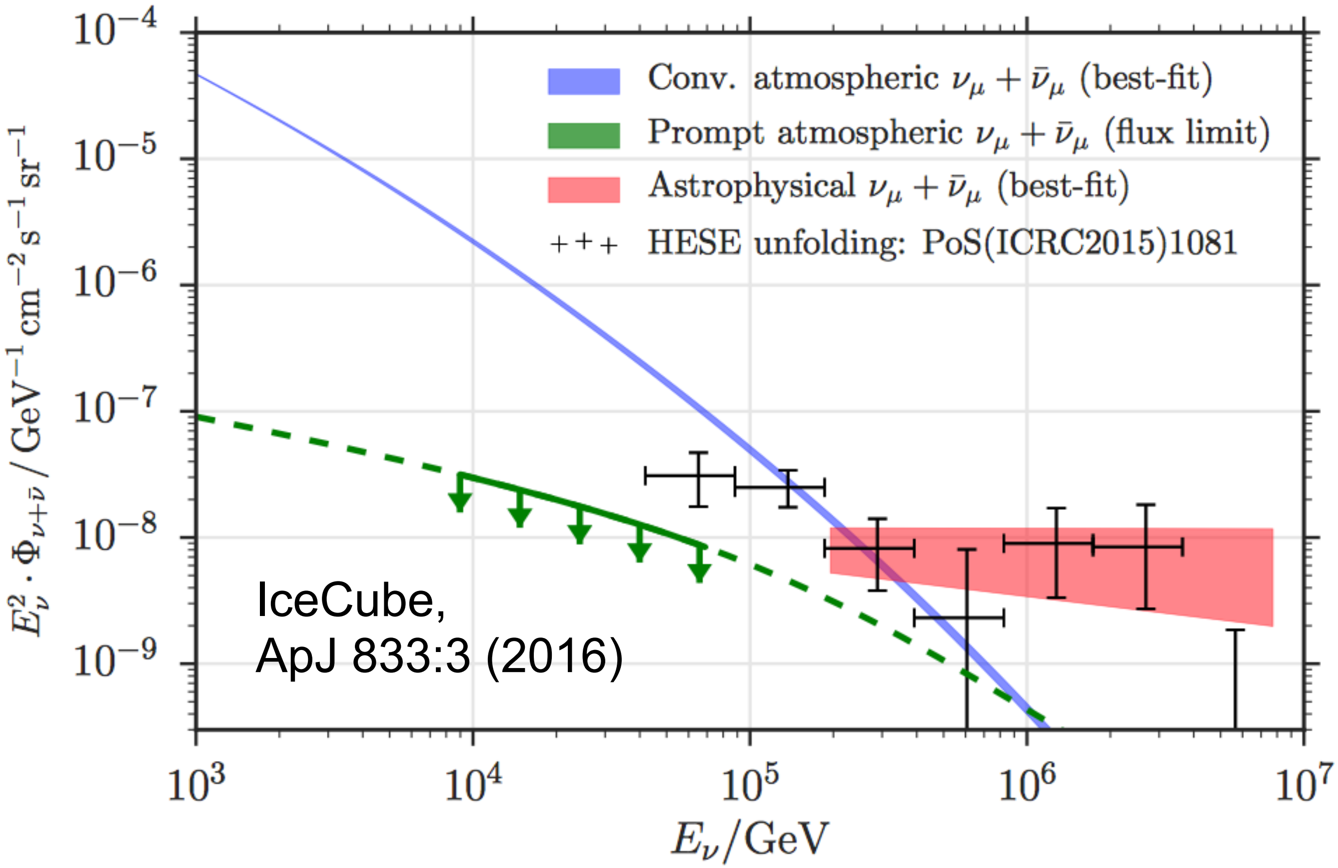
IceCube, 1510.05223 (ICRC)

No significant clustering observed (54 high energy starting events)

A more traditional search: up-going muon neutrinos from the Northern hemisphere



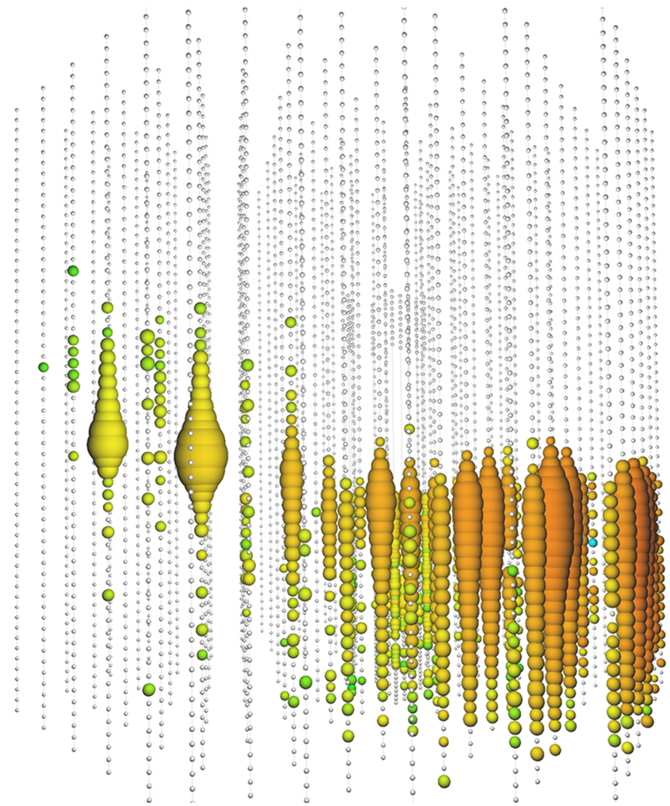
Confirmation of the discovery with Northern muon neutrinos



- Detected by two independent interaction and detection methods
- Consistent with isotropic
- Likely extragalactic (could be partially but not all Galactic)

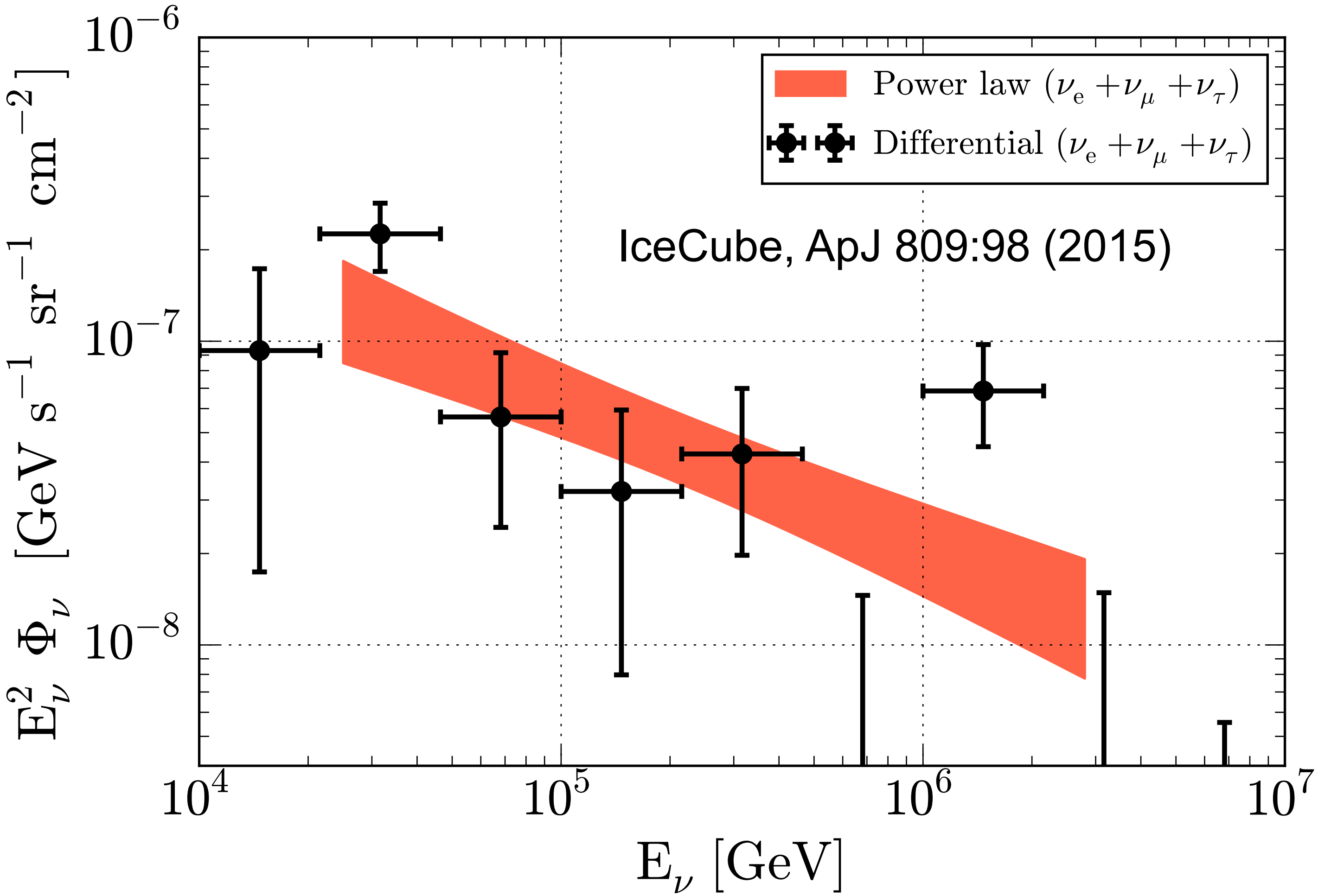
An up-going muon neutrino track depositing several PeV

ATel #7856



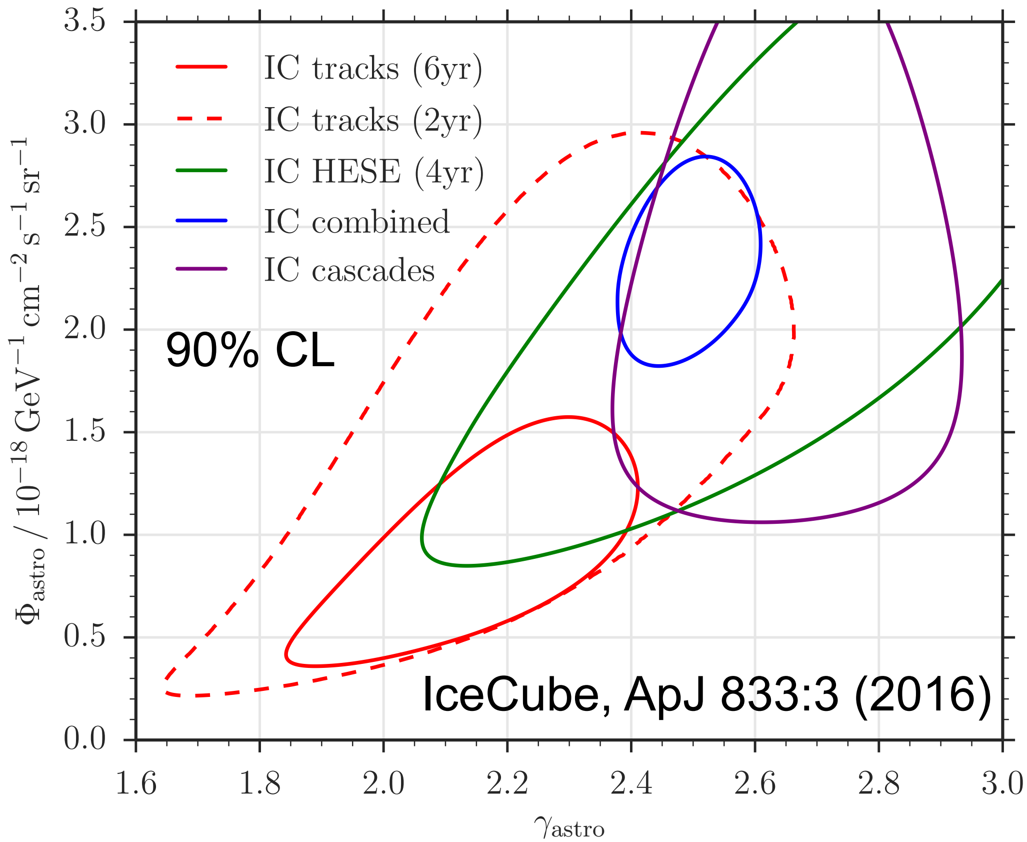
- Track with <1° angular resolution
- Discovered in six-year (2009-2015) astrophysical muon neutrino analysis
- Deposited 2.6 PeV (June 11, 2014)
- Neutrino energy likely several times larger
- Less than 0.01% chance of being atmospheric background

Global fit of multiple IceCube channels and data samples



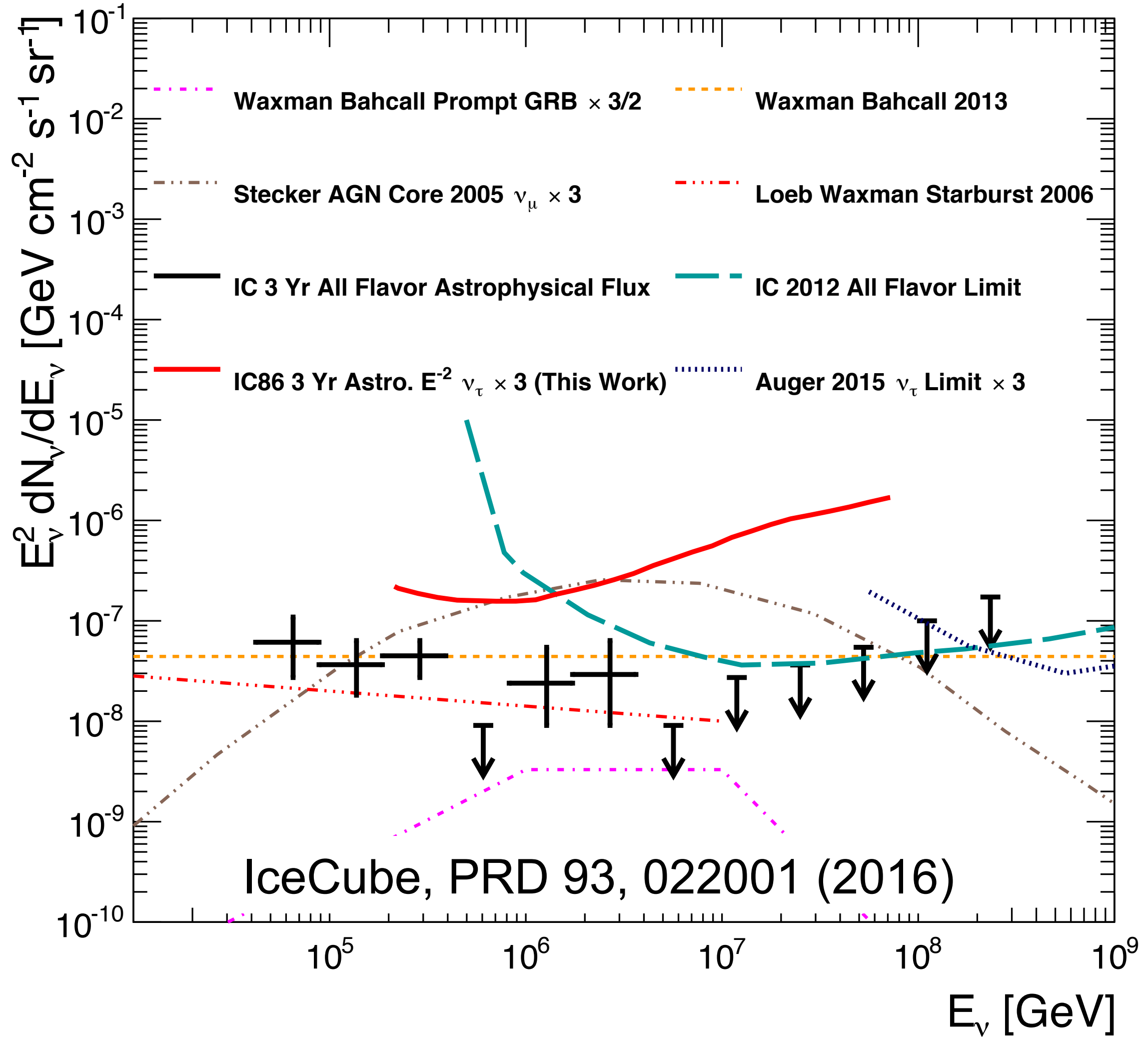
- Showers and tracks, 2008-2013
- Fit well by unbroken power law with index 2.50 ± 0.09
- E^{-2} disfavored at 3.8 σ

Measuring the diffuse astrophysical neutrino spectrum



Analysis	Index	Normalization @ 100 TeV	Significance (σ)	Energy range
HESE 4 yr	2.58 ± 0.25	2.2 ± 0.7	6.5	
Northern tracks 6 yr	2.13 ± 0.13	0.90 +0.30 -0.27	5.6	191 TeV to 8.3 PeV
Cascades 2 yr	2.67 ± 0.13	2.3 +0.7 -0.6	4.7	10 TeV to 1 PeV
Global fit	2.50 ± 0.09	6.7 +1.1 -1.2		25 TeV to 2.8 PeV

Tau neutrino upper limit from three years of 86-string data

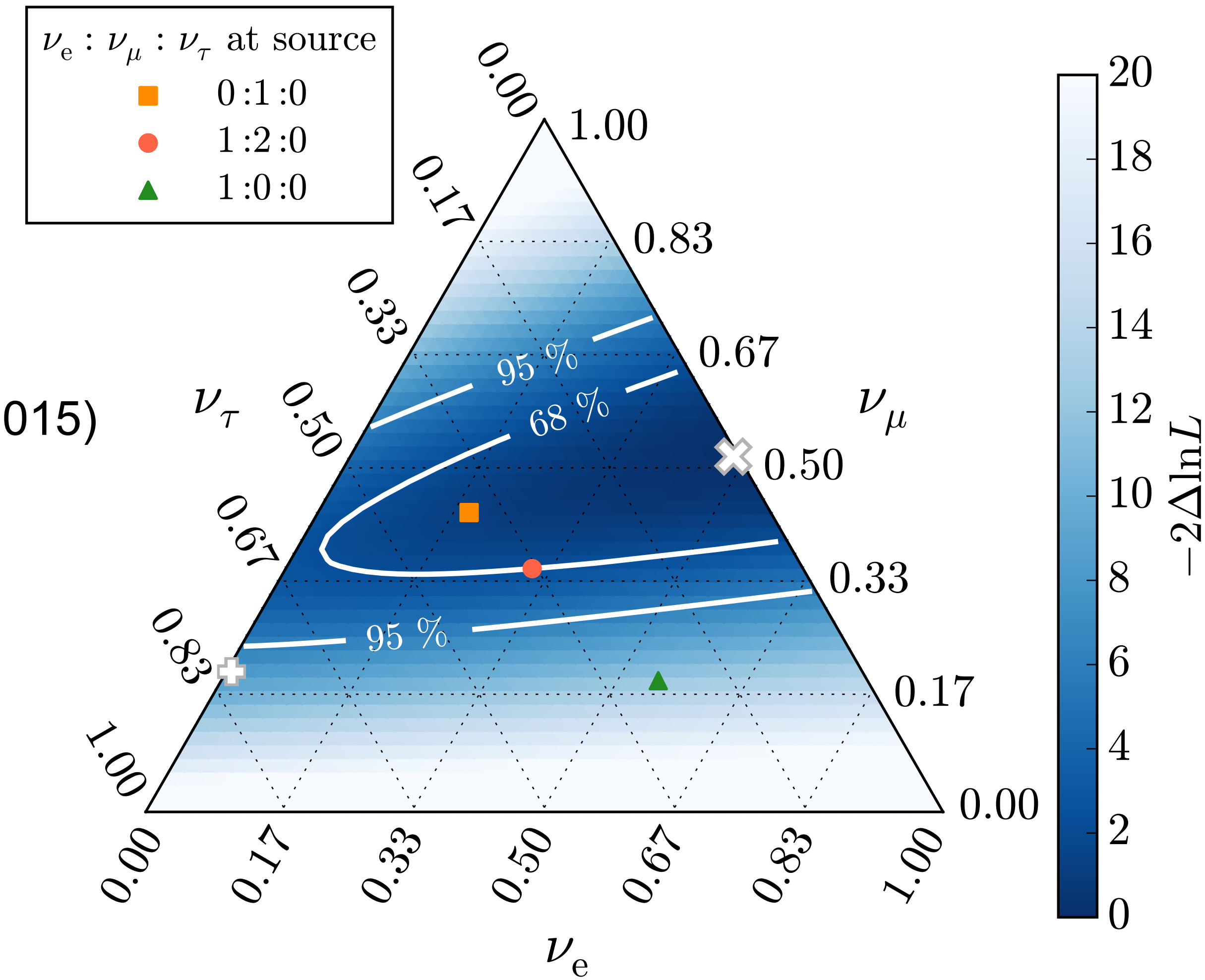


Reached >2 orders of magnitude lower energy than previous (Pierre Auger) tau neutrino searches

Astrophysical neutrino flavor ratio

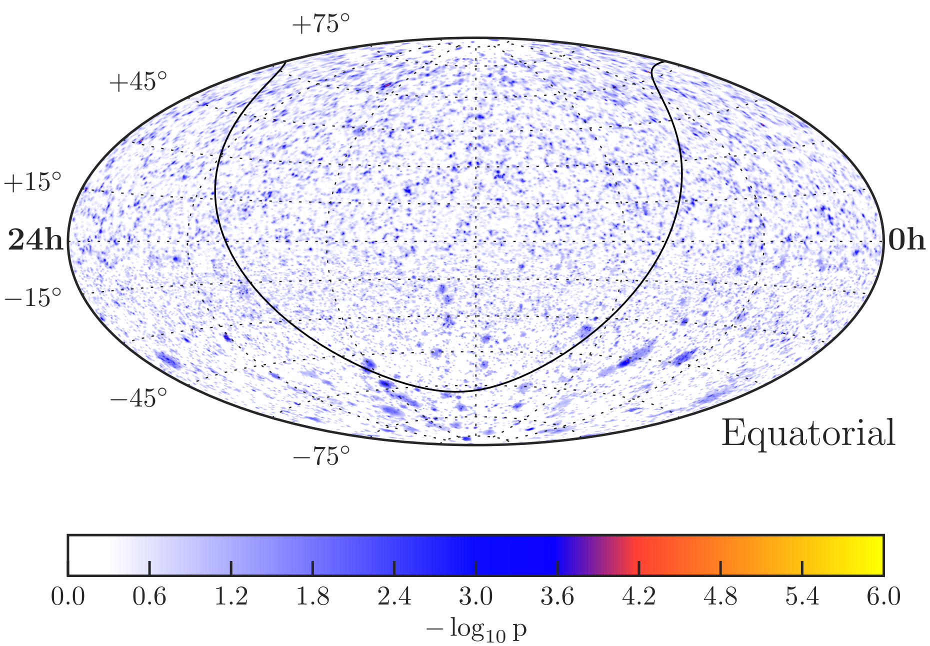
Muon damped
Standard π production
Neutron decay

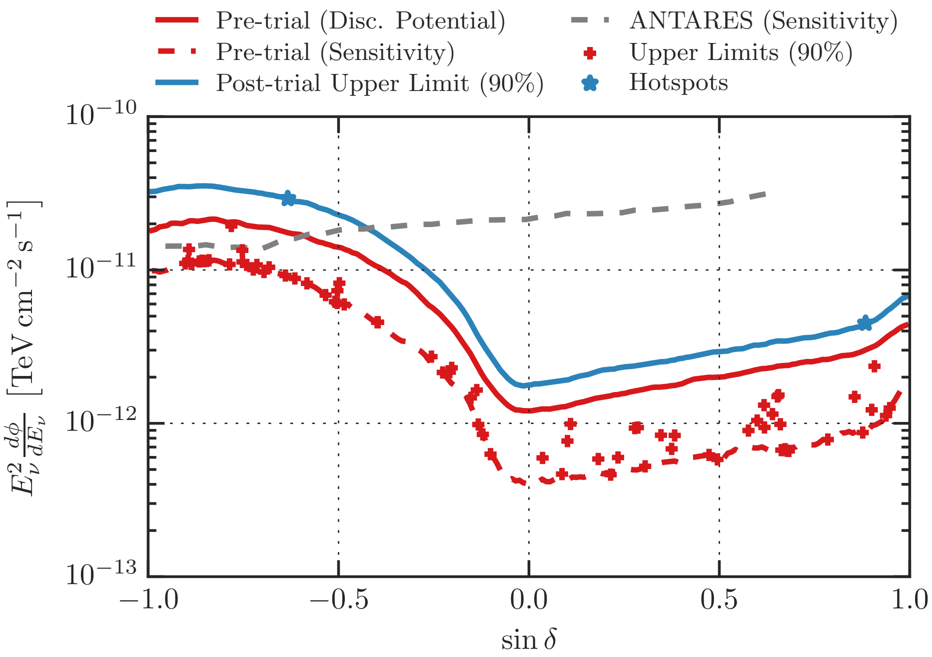
IceCube, ApJ 809:98 (2015)



Production of purely electron neutrinos at the source (from neutron decay) rejected at 3.6 σ significance

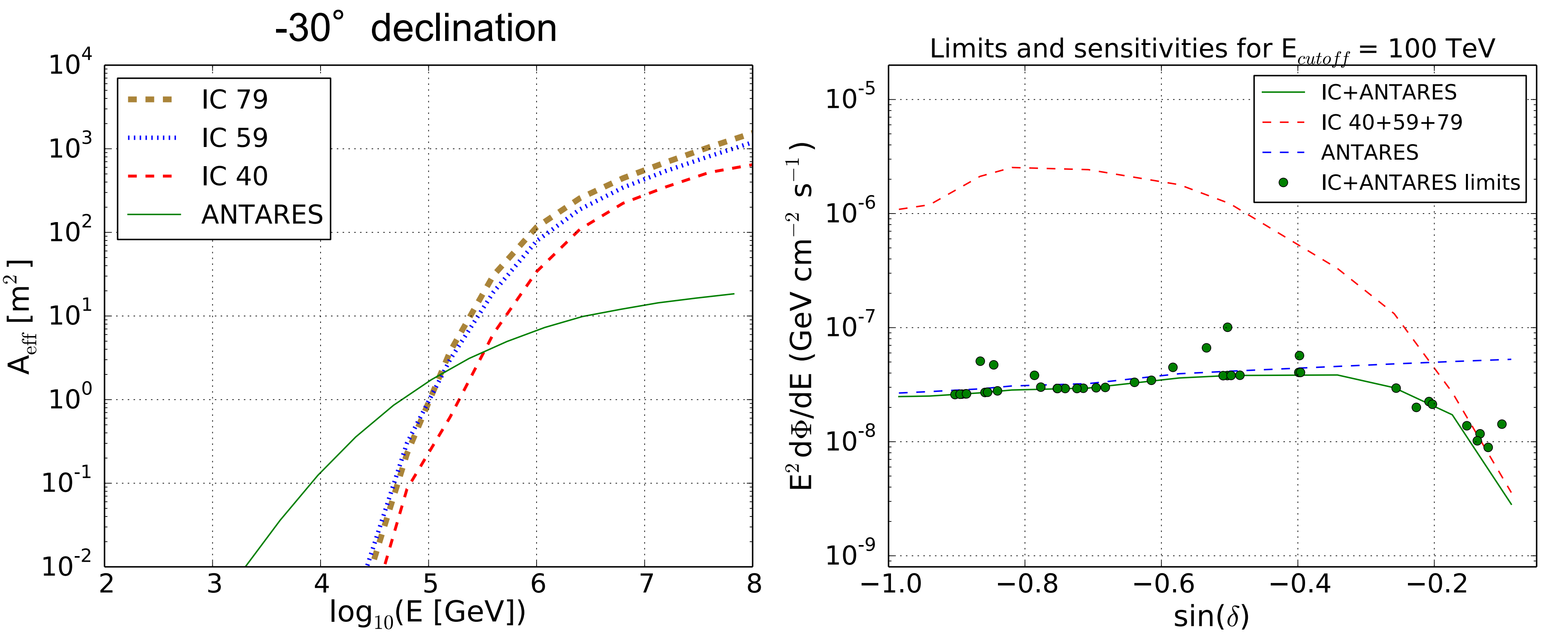
Despite a bright diffuse flux, no discrete sources detected yet (steady or transient)





IceCube, ApJ 835:151 (2017)

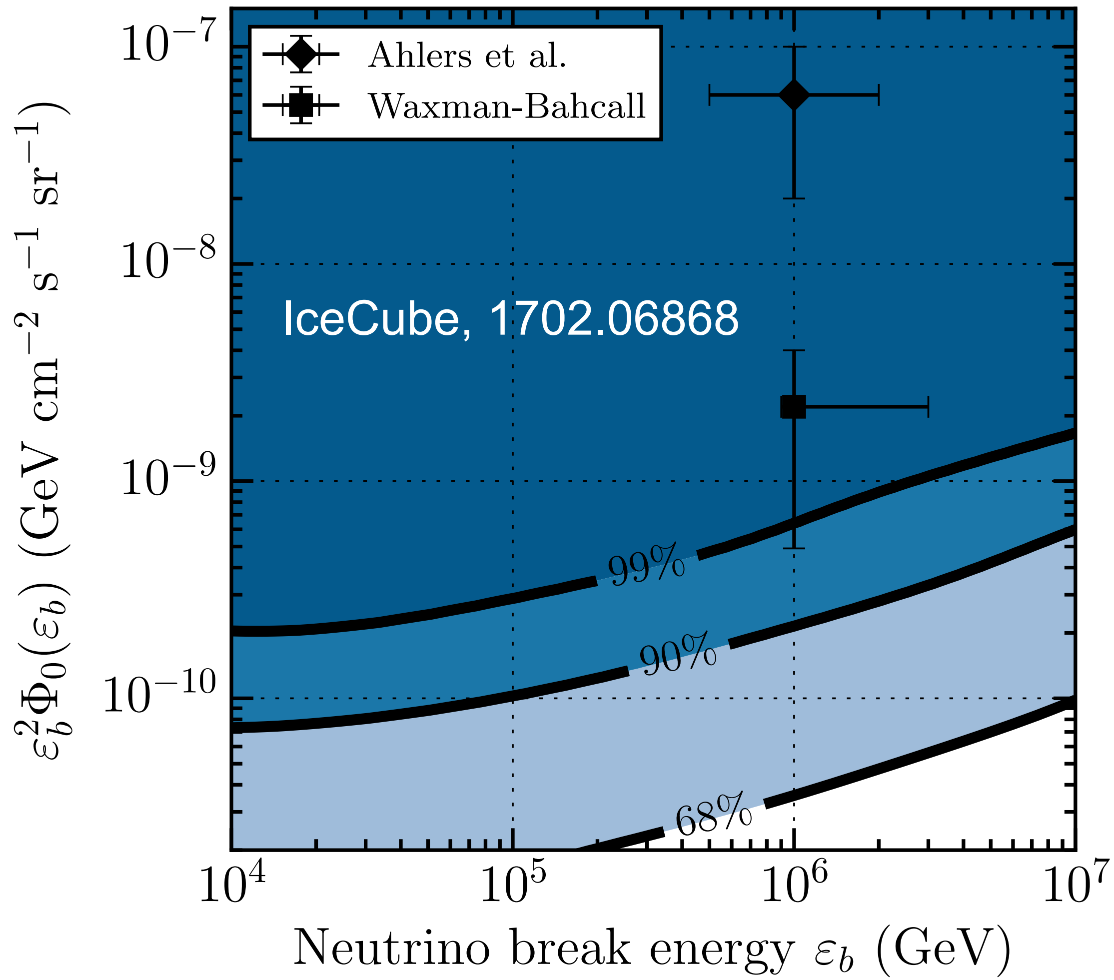
Combined ANTARES-IceCube search for Southern point sources



ANTARES & IceCube, ApJ 823:65 (2016)

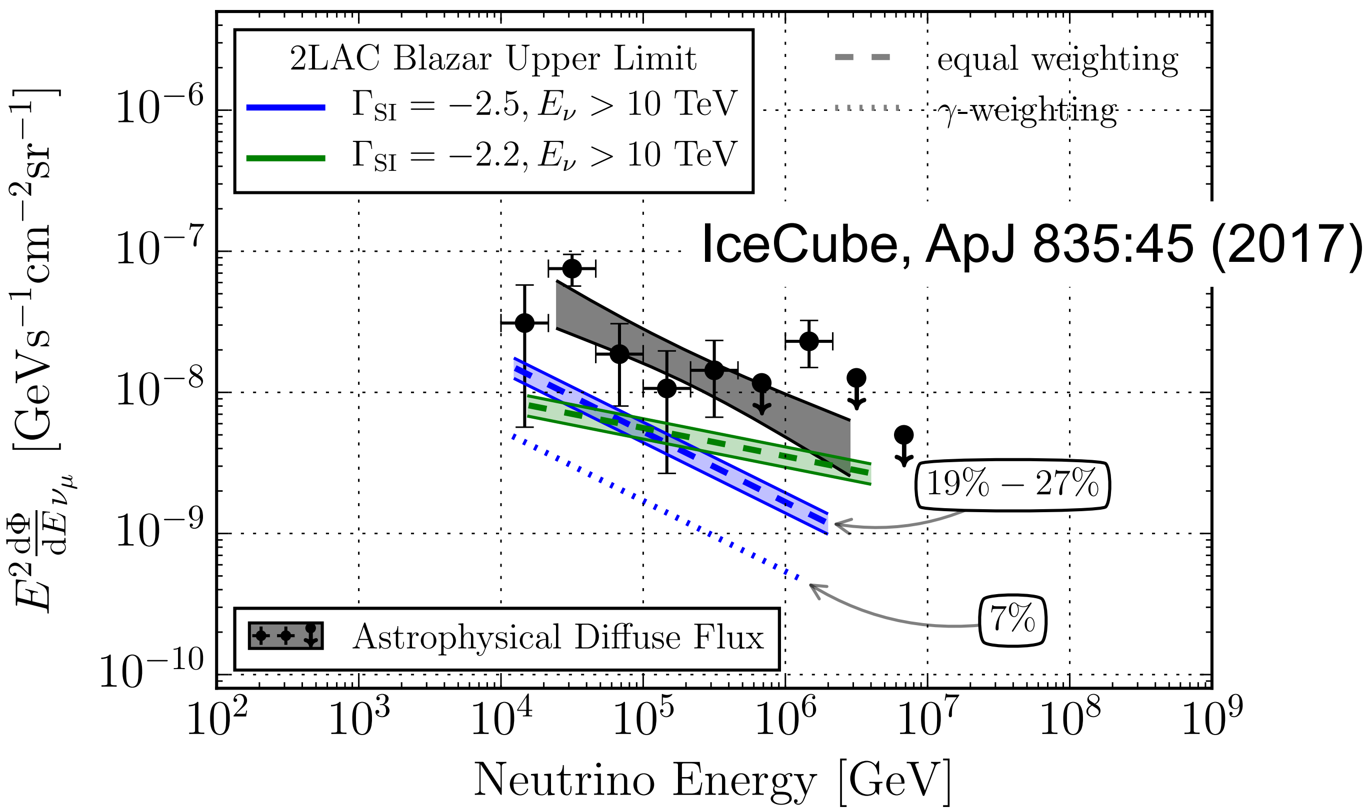
- ANTARES more sensitive than IceCube for soft Southern hemisphere sources
- Combining events provides better sensitivity than either detector alone

The neutrinos are not produced by gamma-ray bursts



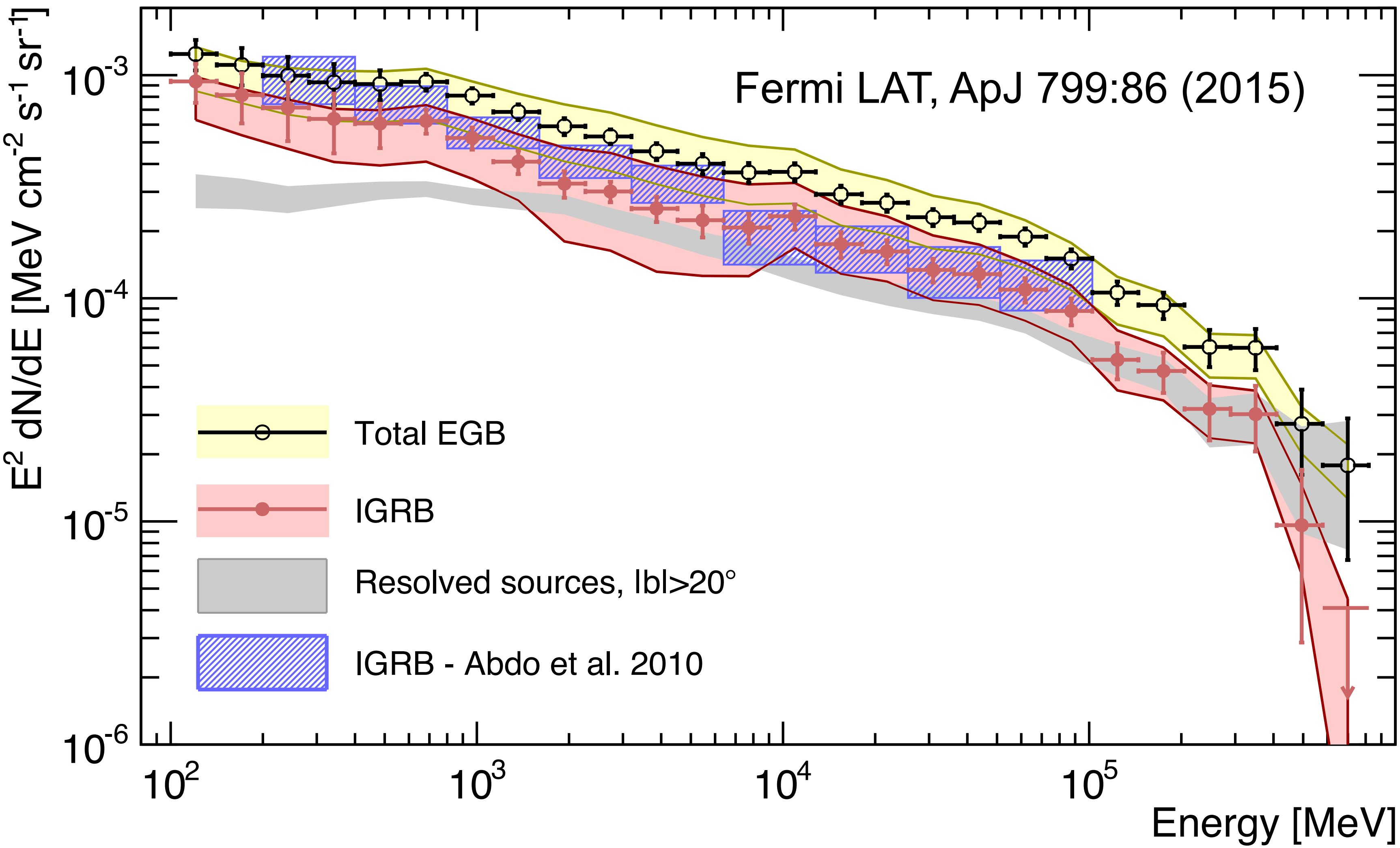
- 1172 satellite-detected GRBs
- Five years of muon neutrino track events
- Conclusion: <1% of astrophysical neutrino flux is produced by GRBs

The neutrinos are not produced (predominantly) by steady blazar emission

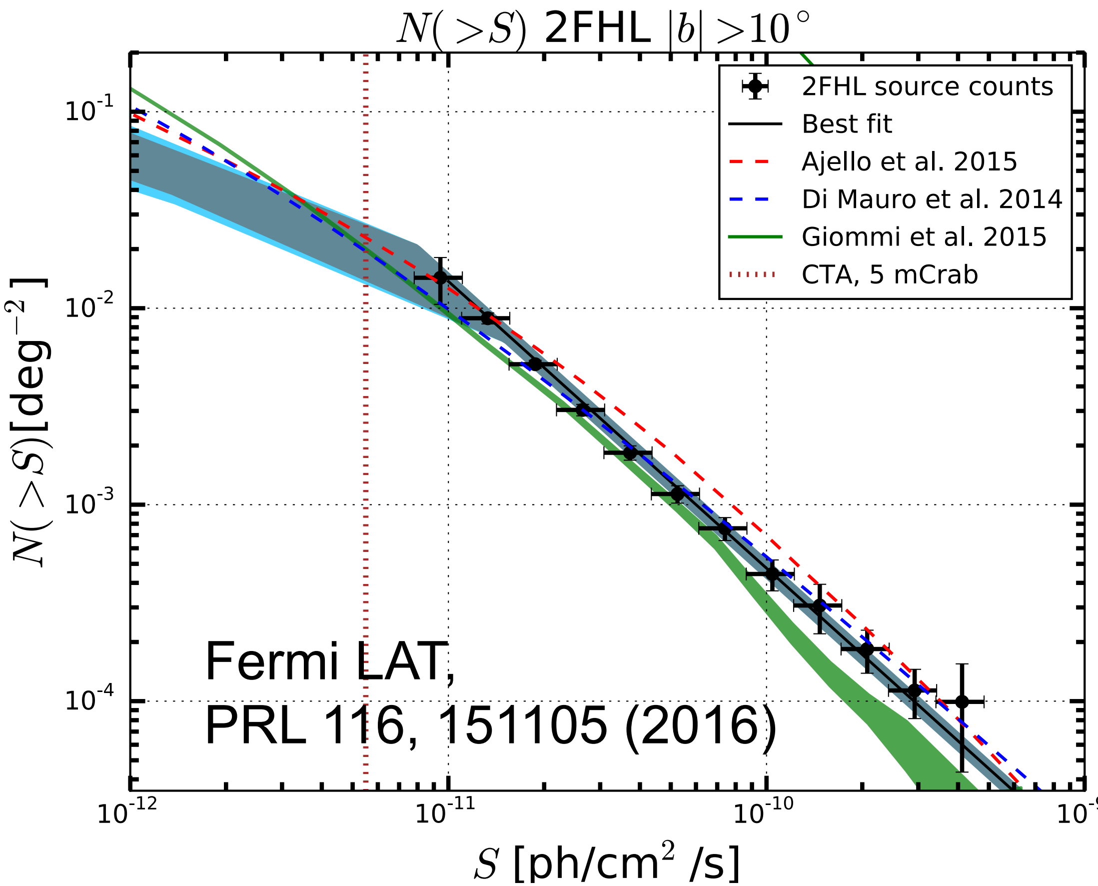


- Search for correlation between IceCube neutrinos and GeV blazars
- Fermi 2LAC sample: 862 blazars
- Lack of detection constrains contribution of 2LAC blazars to at most
  - 27% of neutrino signal assuming equal weighting among blazars
  - 7% of neutrino signal assuming neutrino flux proportional to gamma flux

Fermi Large Area Telescope measurement of extra-galactic gamma-ray background and its isotropic component

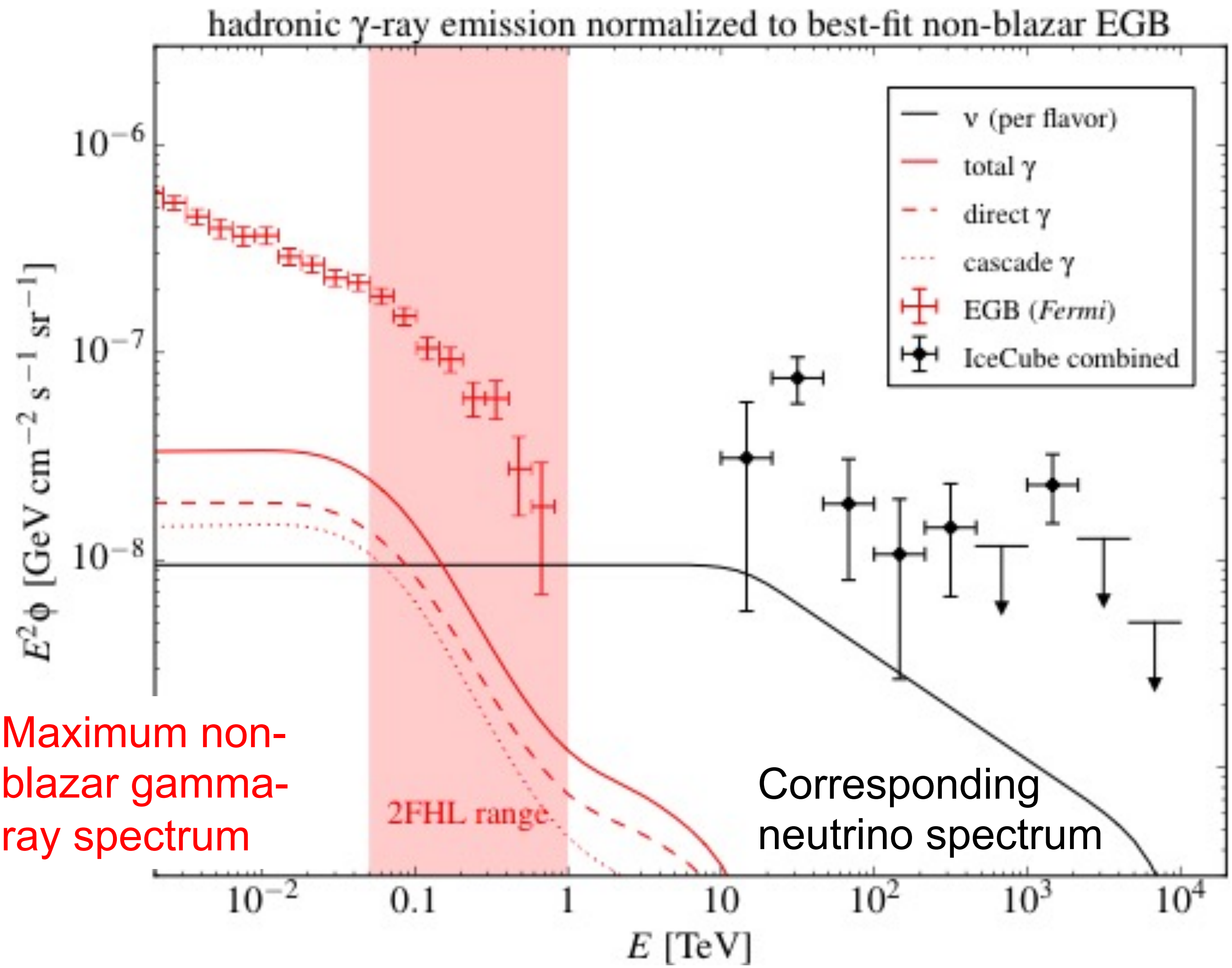


Fermi LAT source count distribution above 50 GeV



- Euclidean (index 2.5) source count distribution in LAT hard source catalog (2FHL)
- Photon statistics used to constrain source count distribution below individual source detection threshold and detect break
- Integrating this resolves 86% of extragalactic gamma-ray background into sources
- Consistent with single population (blazars)

The neutrinos are not produced by star-forming galaxies

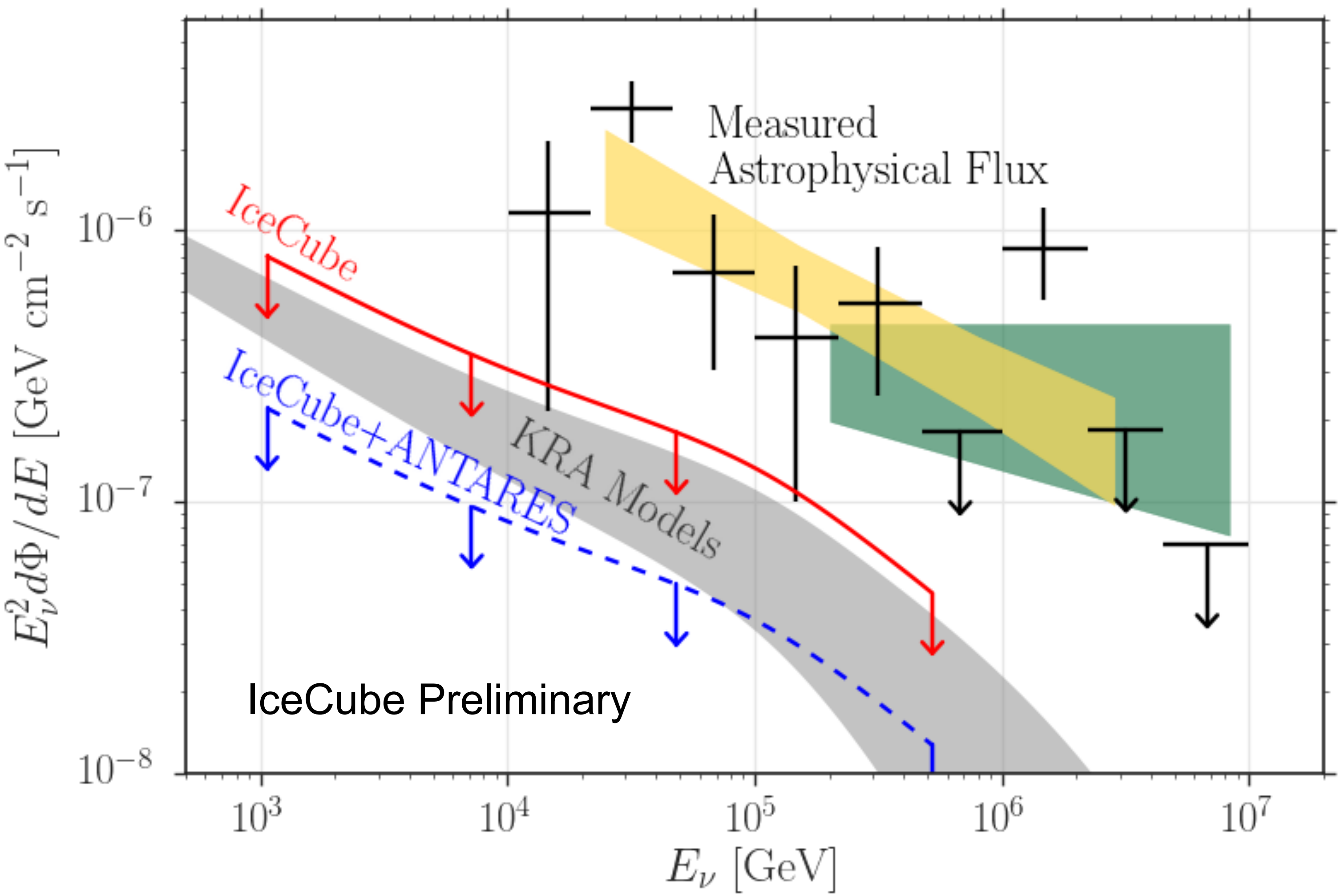


Maximum non-blazar gamma-ray spectrum

Corresponding neutrino spectrum

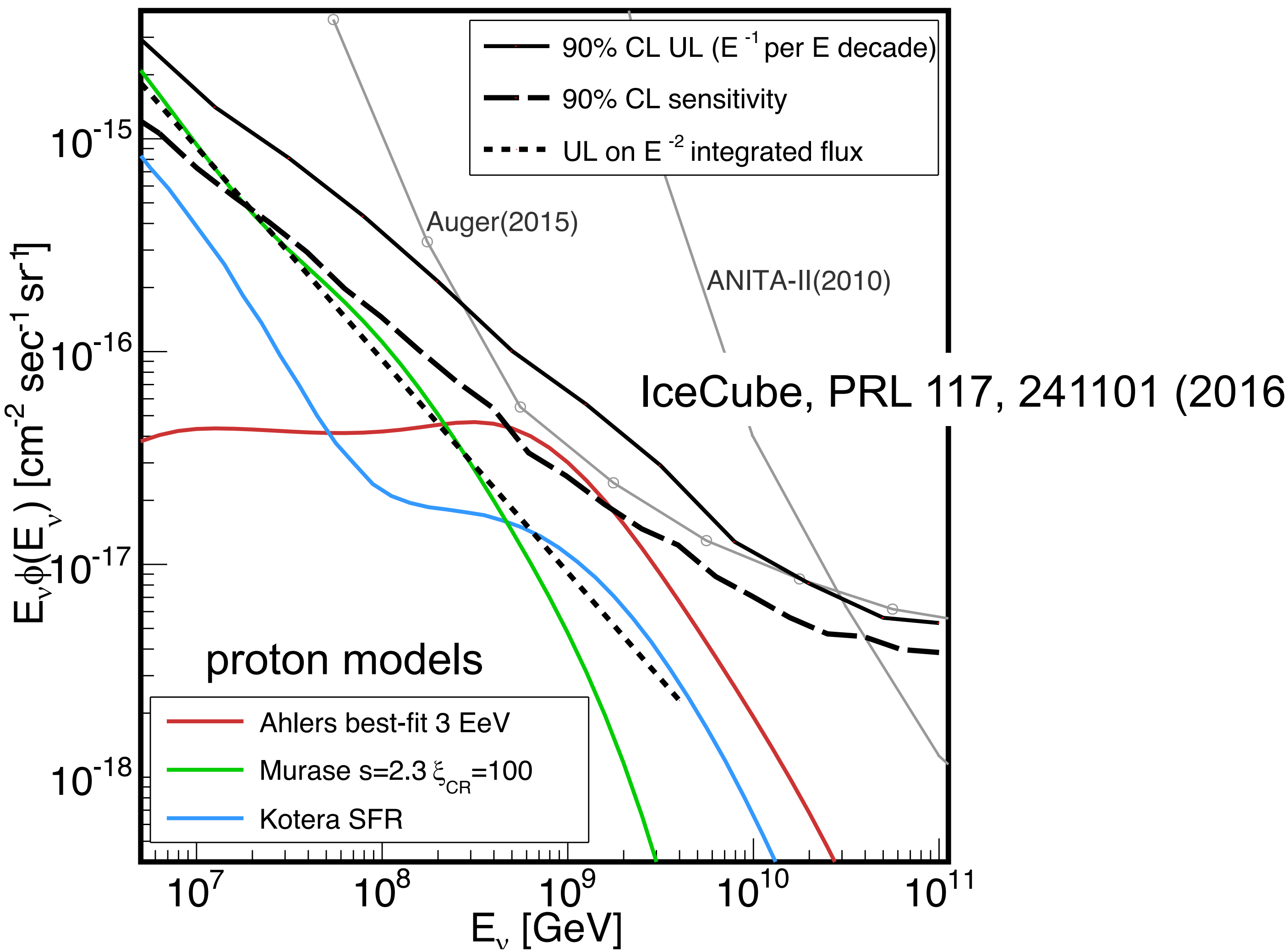
Bechtol, Ahlers, Di Mauro, Ajello, Vandenbroucke, ApJ 836:47 (2017)

Search for Galactic neutrinos



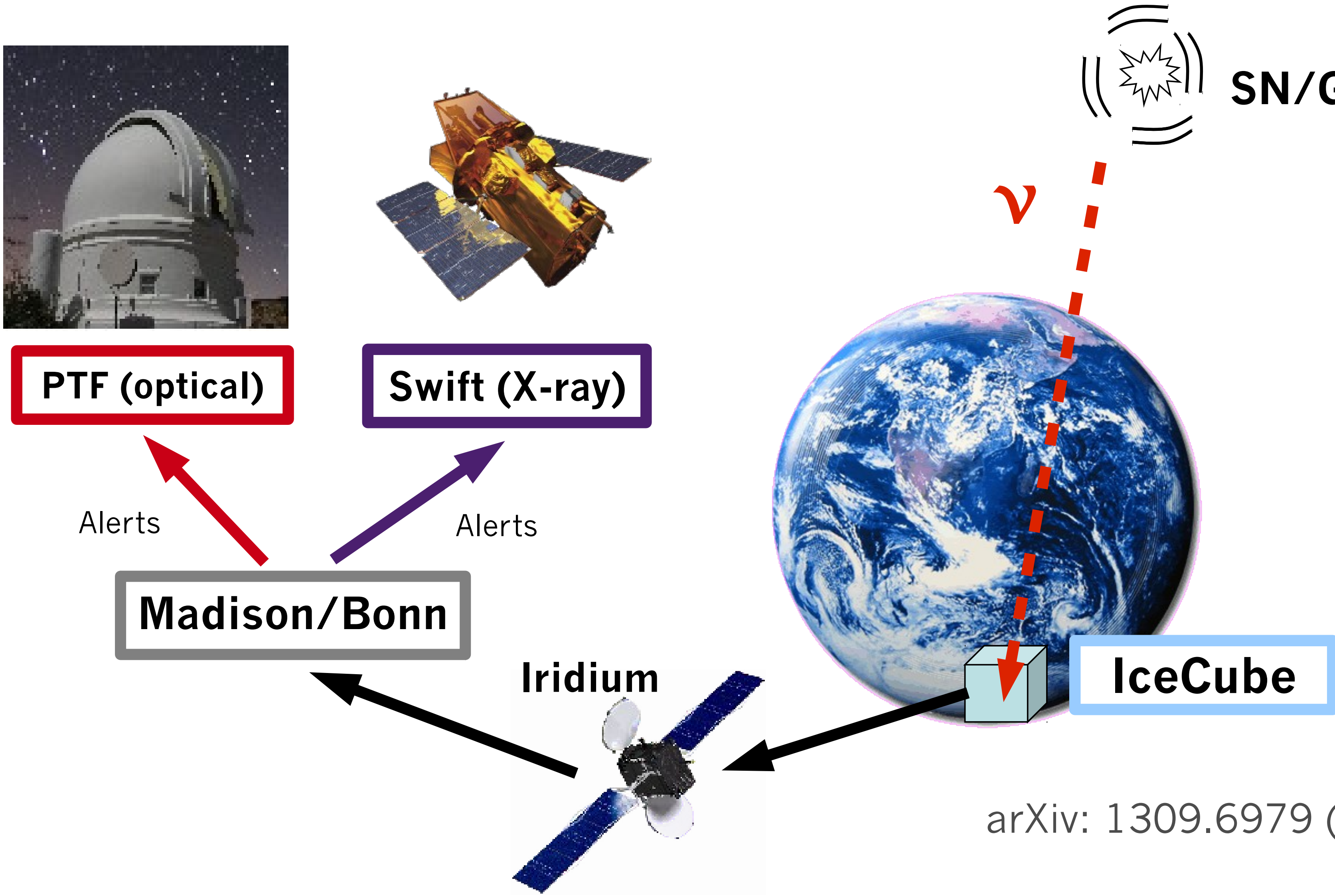
- Galactic neutrinos are expected from both diffuse emission and discrete sources
- KRA models: D. Gaggero et al. ApJL 815, L25 (2015)

Search for cosmogenic (GZK) neutrinos



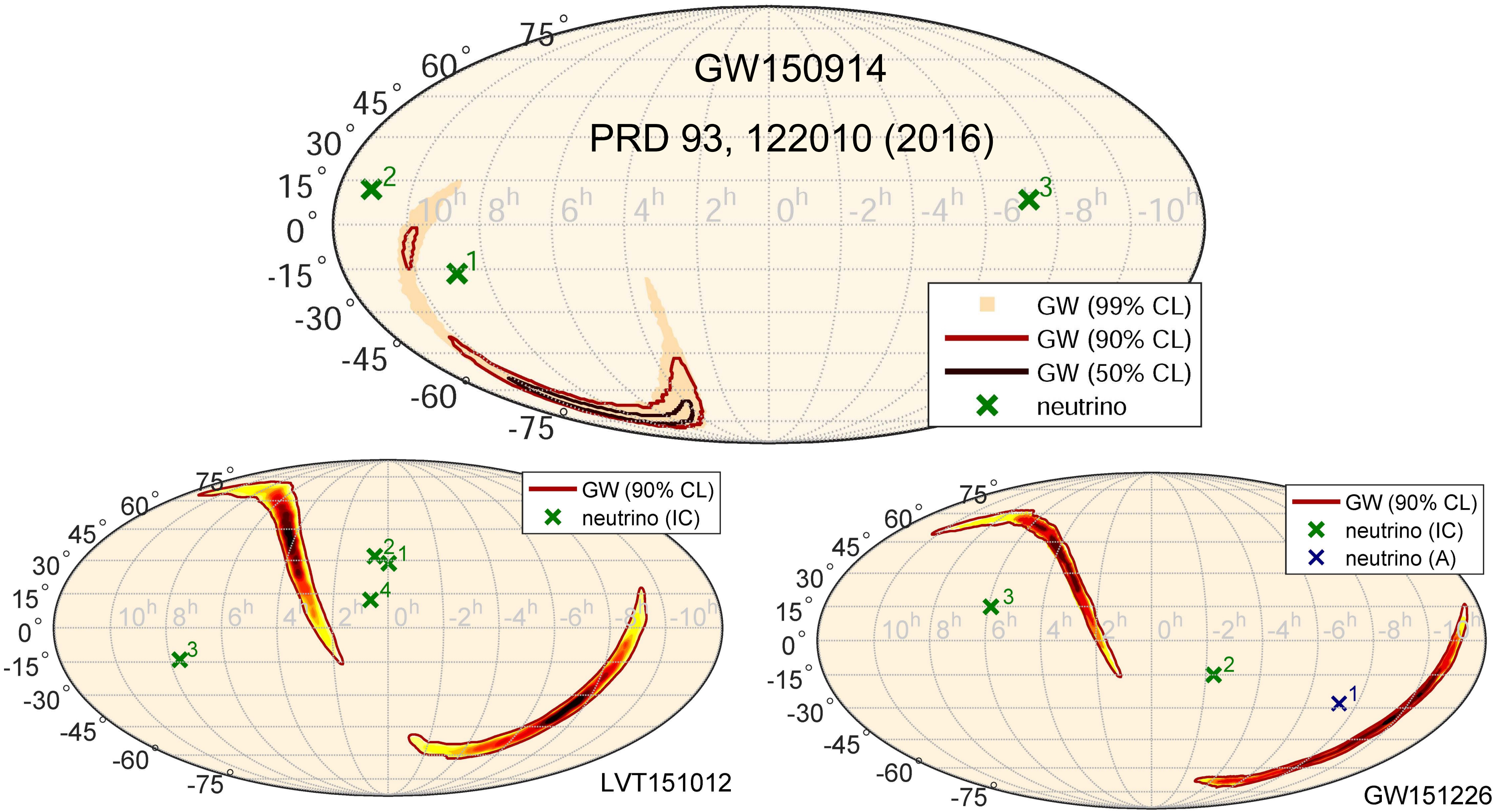
- Non-detection in 6 years of data (including 3 years of IC86)
- Beginning to disfavor proton UHECR models in favor of heavier composition

IceCube alerts optical, x-ray, and gamma-ray observatories where and when to point



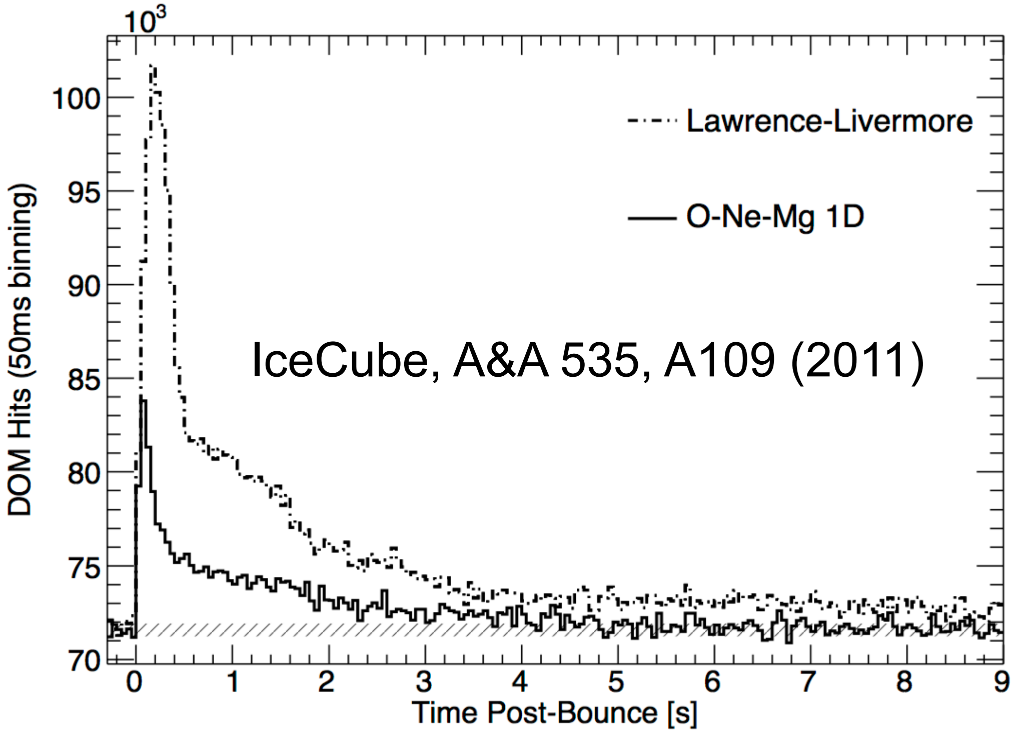
arXiv: 1309.6979 (p.40)

Multi-messenger astrophysics without electromagnetic messengers



1703.06298

MeV neutrino detection with IceCube, for supernovae and other transients



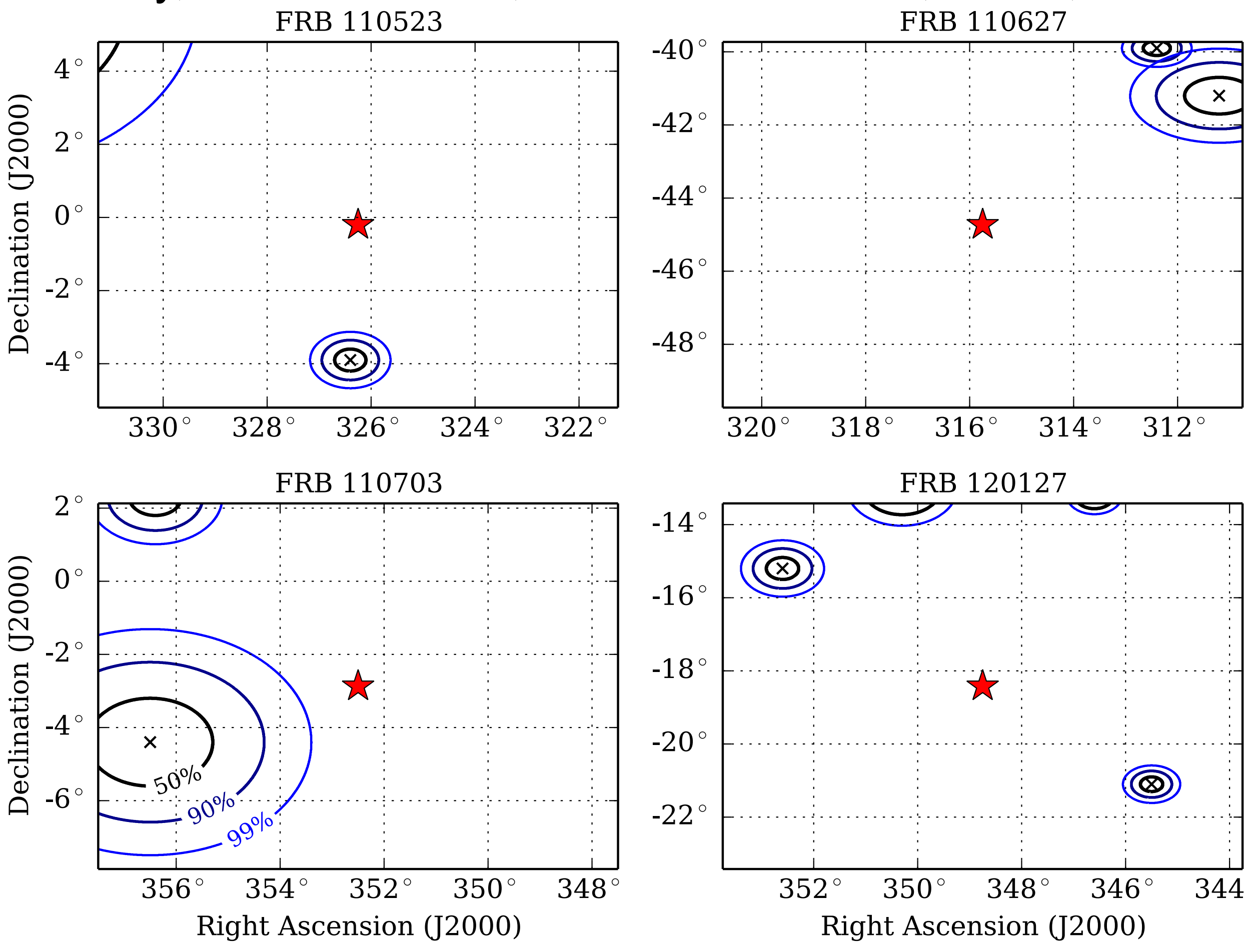
- Above 1.8 MeV, electron anti neutrinos undergo inverse beta decay, producing a neutron and a positron
- Positron produces Cherenkov photons before annihilating
- Each photomultiplier tube can detect a local sphere of neutrino interactions
- A burst of MeV neutrinos is detectable as a cumulative rise in the photon rates across many photomultiplier tubes
- Useful for detecting supernova neutrinos and other MeV neutrino bursts

Searching for neutrinos from fast radio bursts (FRBs)

- Discovery of a neutrino-FRB association would be a major breakthrough for two outstanding mysteries in astrophysics
- Neutrinos indicate hadronic or exotic rather than leptonic processes
- Compared to radio telescopes, effective area of IceCube is small
- However, field of view (4π) and observing time (>99%) are enormous: unlike most observatories, we were / are / will be observing on source and on time for nearly every FRB
- We can search our archival data set for neutrinos coincident in time and direction with FRBs
- We can quickly search FRBs announced in real time

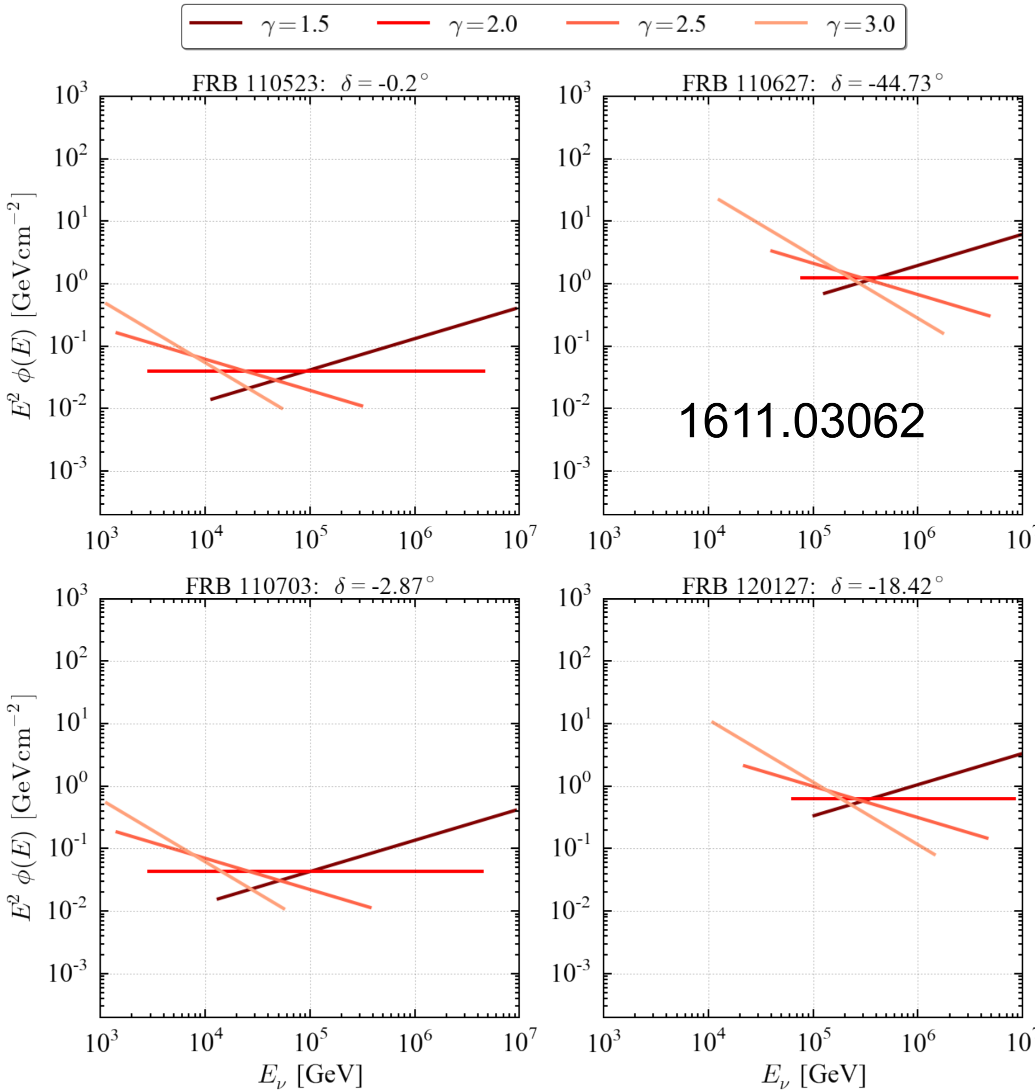
Results from analysis of 1 year of data and 4 FRBs

S. Fahey, A. Kheirandish, J. Vandenbroucke, D. Xu, 1611.03062



No FRB has an IceCube event coincident in direction (within estimated 99% error radius) and time on one day time scale

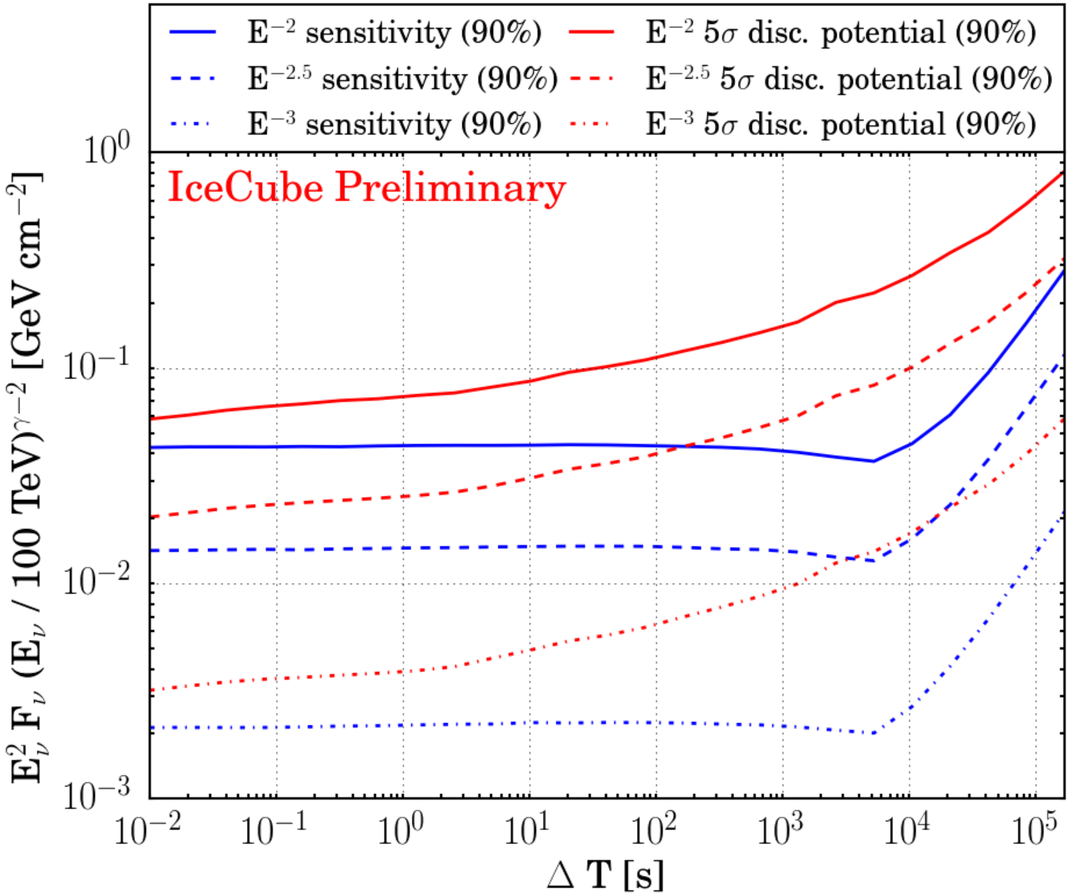
Interpretation of non-detection: 90% upper limits on FRB neutrino fluence assuming power law spectrum



Search for neutrinos from 13 FRBs in four-year IceCube data

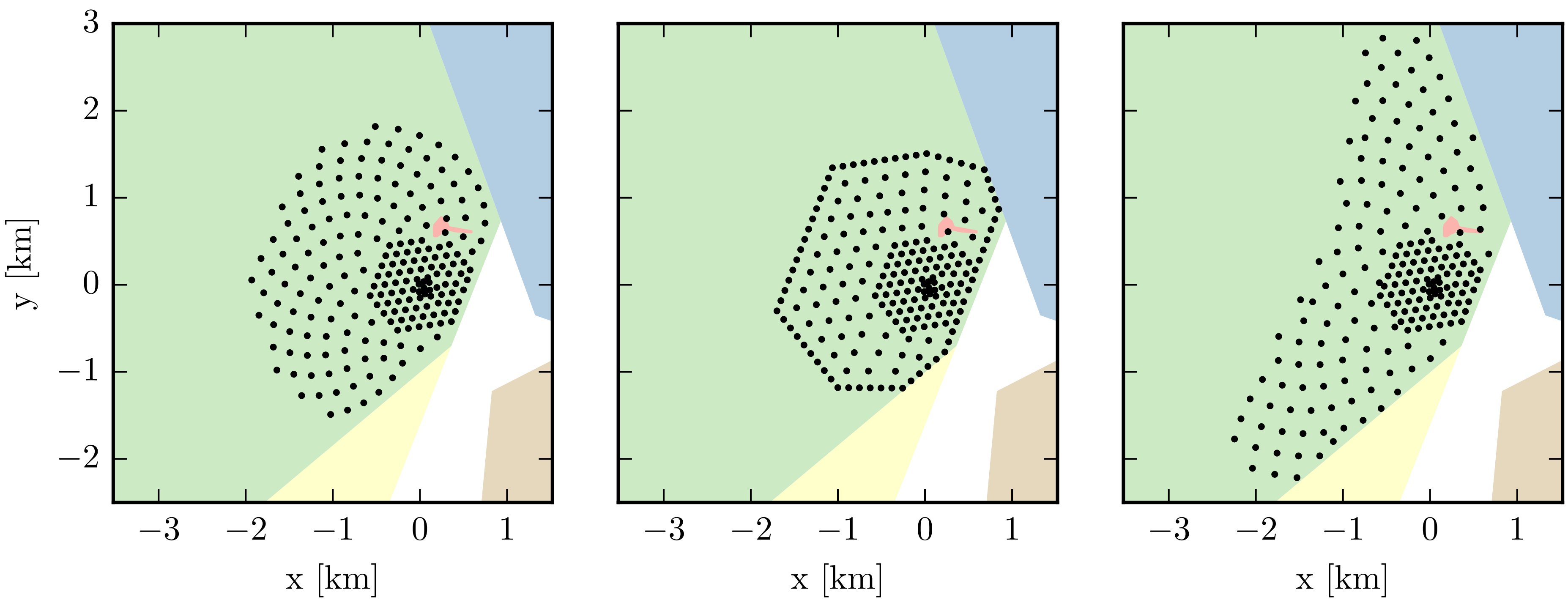
- "Southern" (dec < -5°) analysis: May 2010 to May 2015
  - 9 Parkes FRBs from 110220 through 150418
  - Did not include 150807 or 3 bursts from 2001 or 1 from 2009
- "Northern" (dec > -5°) analysis: May 2011 to May 2016
  - 110523 (Green Bank)
  - 110703 (Parkes)
  - 130628 (Parkes)
  - 121102 (Arecibo and VLA): 17 bursts from repeater, Nov 2012 through Dec 2015
  - Did not (yet) include more recent repeater bursts

Search for neutrinos from 13 FRBs in four-year data set



- Sensitivity to stacked bursts with declination > -5°
- Background free at short times, small background at long times

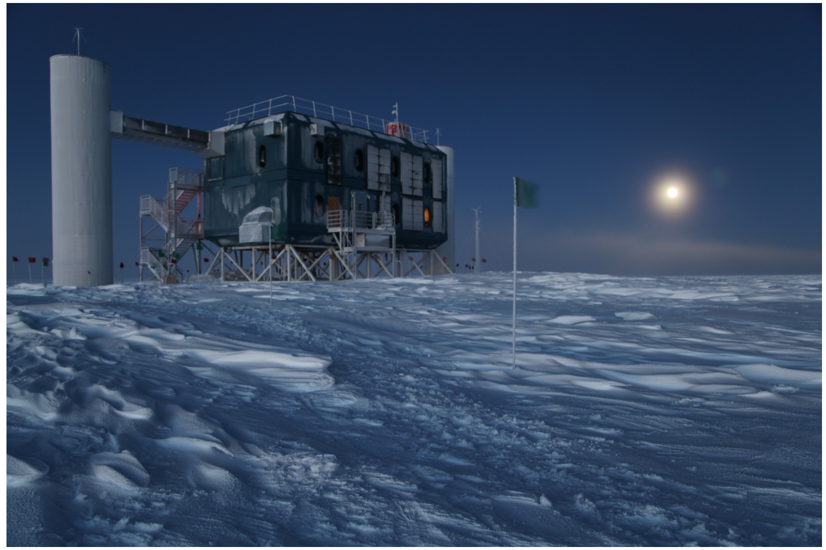
IceCube-Gen2: the next generation



- High energy extension: Instrument ~10 km³ (sparsely with ~120 new strings) to increase sensitivity to high energy (0.1-10 PeV) muon and cascade events
- Surface array for increased southern sky sensitivity and cosmic-ray physics
- Identify neutrino sources and study them with multiple messengers
- Dense inner core for neutrino physics including mass hierarchy
- Askaryan Radio Array for 10^{18} eV neutrinos

IceCube, 1401.2046
IceCube, 1412.5106

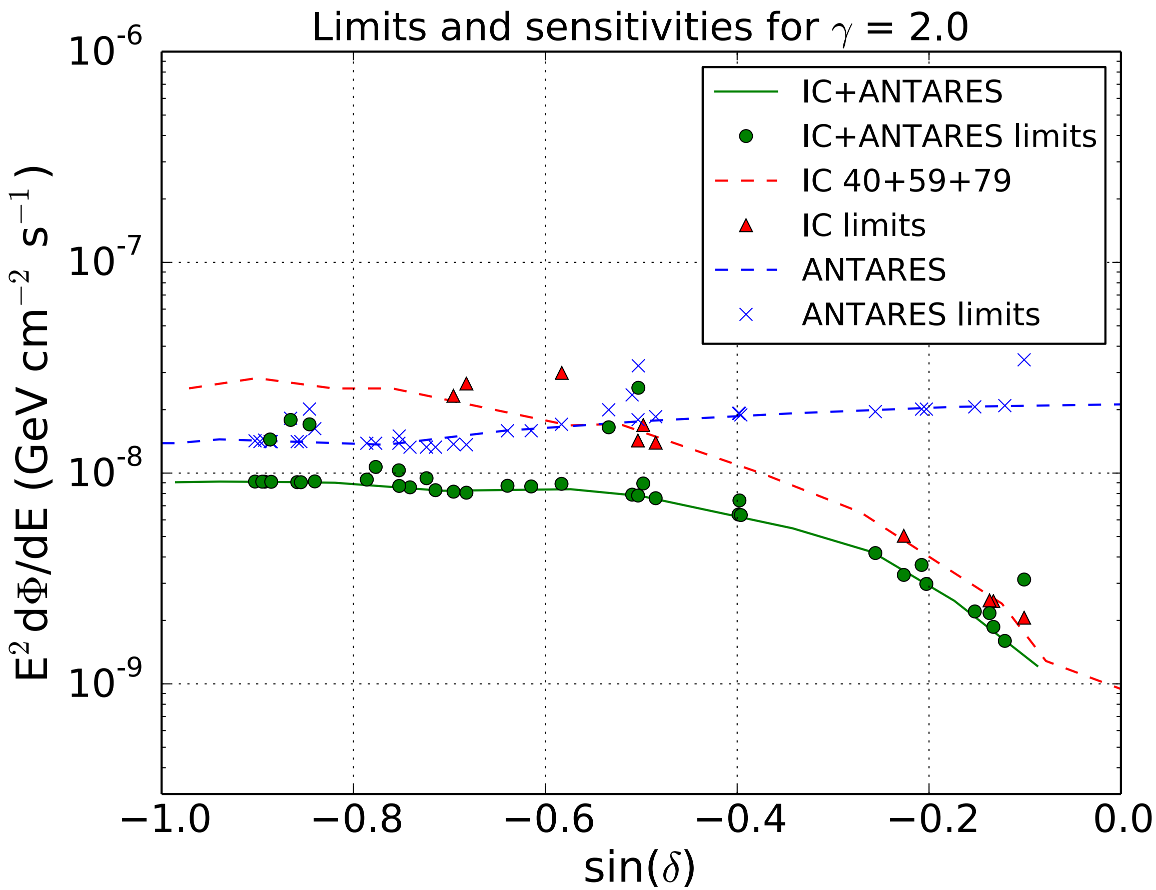
Conclusion and outlook



- A diffuse astrophysical neutrino flux (TeV to PeV) has been discovered by IceCube
- The origin is still a mystery: no discrete sources identified yet
- Multi-messenger studies are providing strong constraints on source classes
- Real-time follow-up in place through coordination with other observatories: radio, optical, X-ray, gamma-ray, gravitational wave
- Public alerts released in real time: starting events, high energy events, doublets
- KM3NeT will provide excellent sensitivity to soft Southern (inc. Galactic) sources
- IceCube-Gen2 upgrade under development

Additional slides

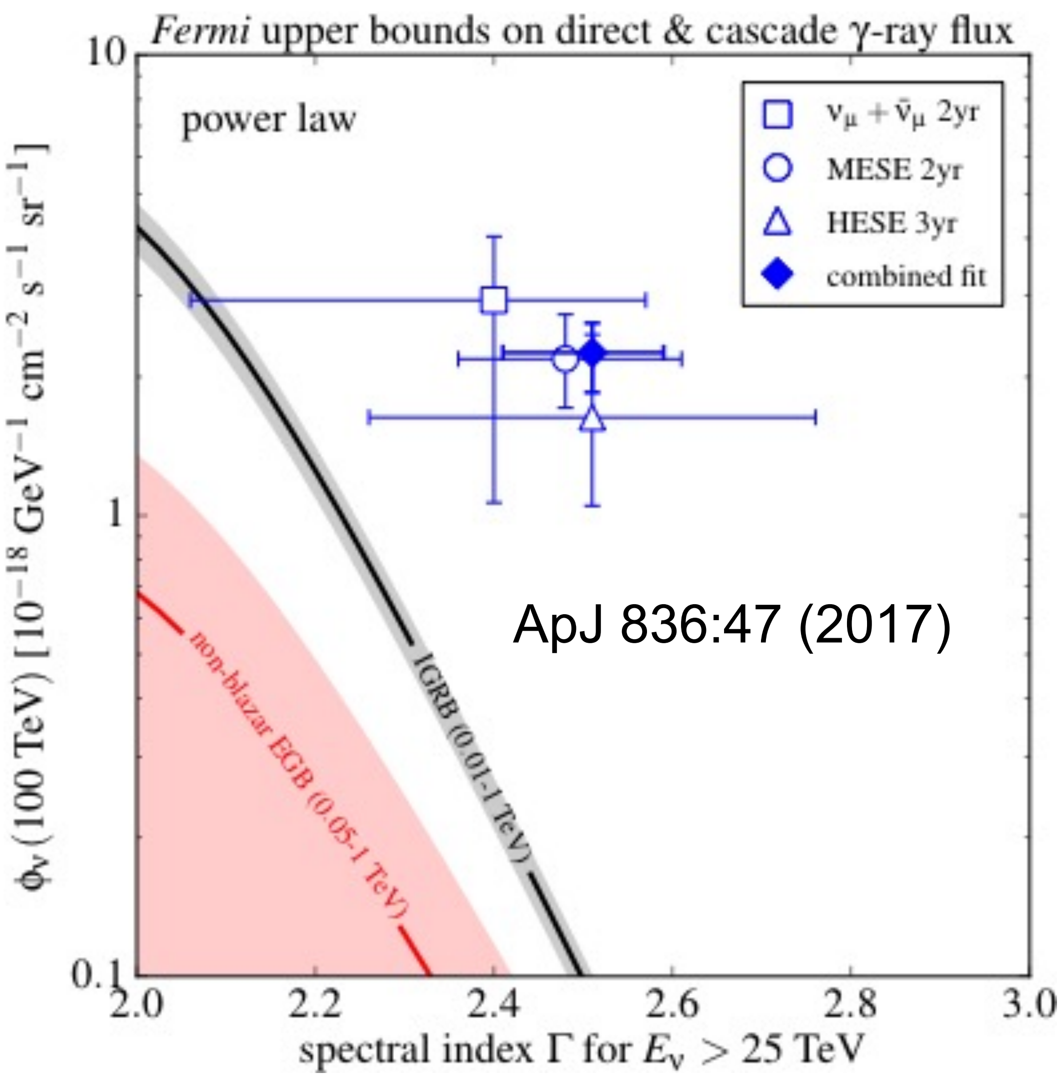
Combined ANTARES-IceCube search for Southern E^{-2} point sources



ANTARES & IceCube, ApJ 823:65 (2016)

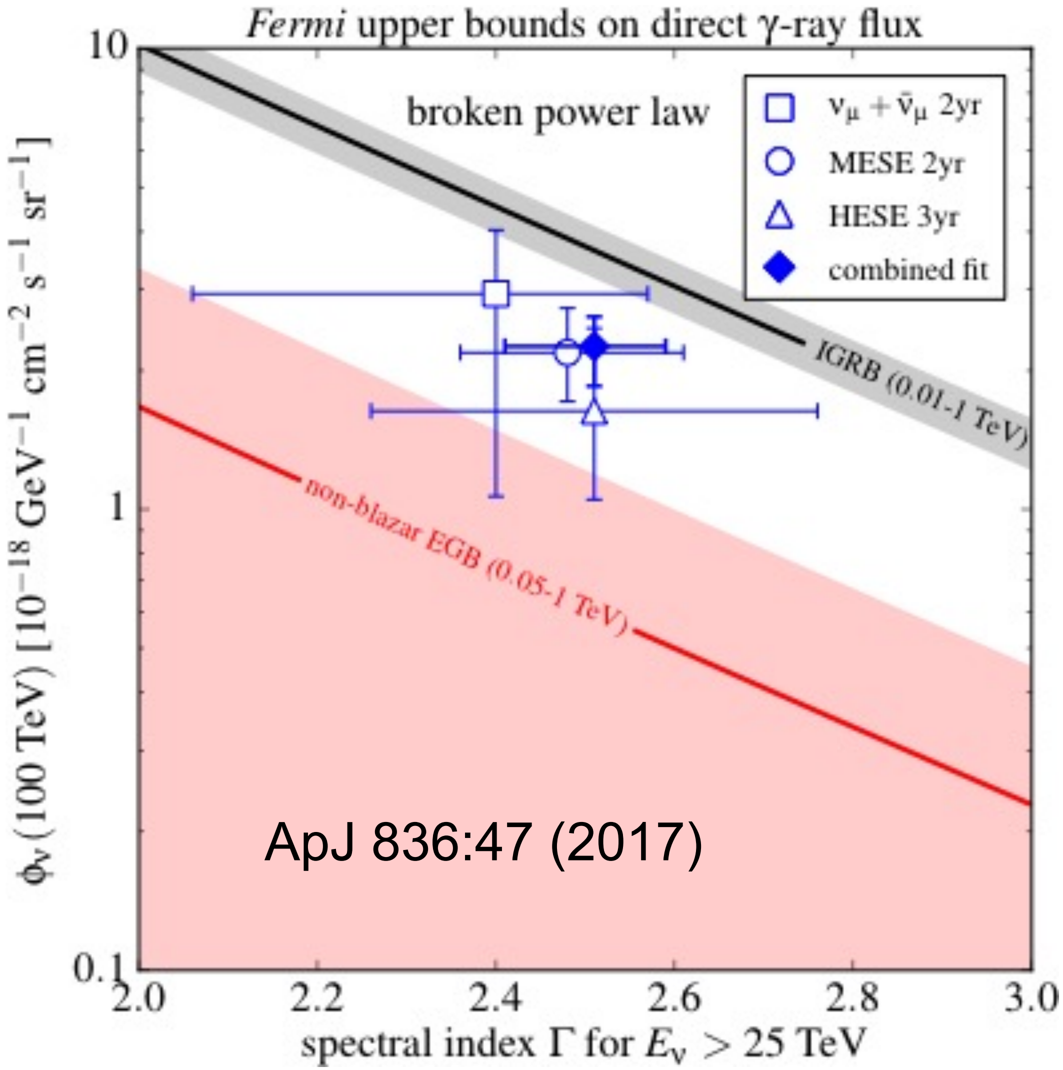
- ANTARES more sensitive than IceCube for soft Southern hemisphere sources
- Combining events provides better sensitivity than either detector alone

The neutrinos are not produced by star-forming galaxies

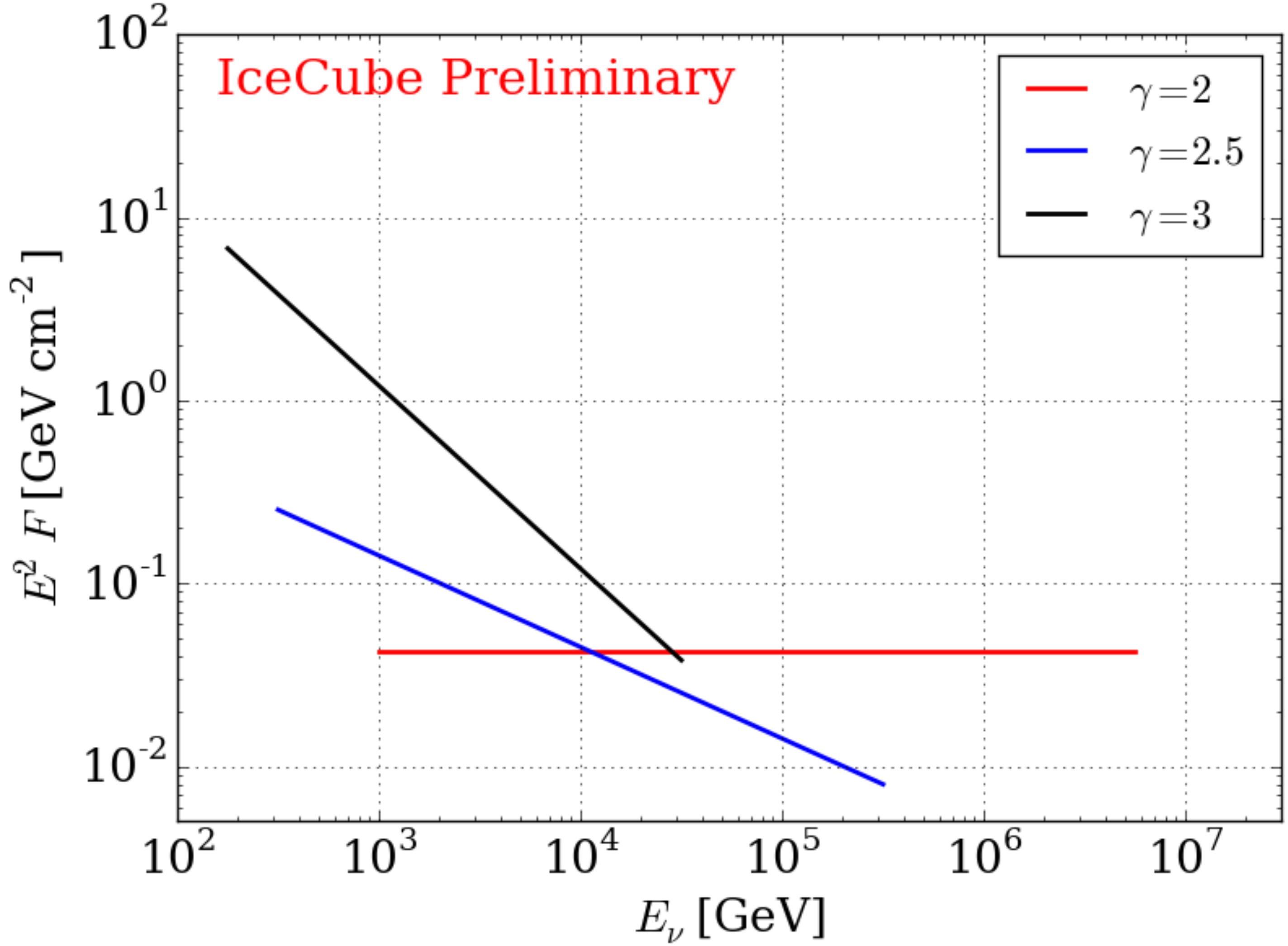


ApJ 836:47 (2017)

The neutrinos are not produced by star-forming galaxies

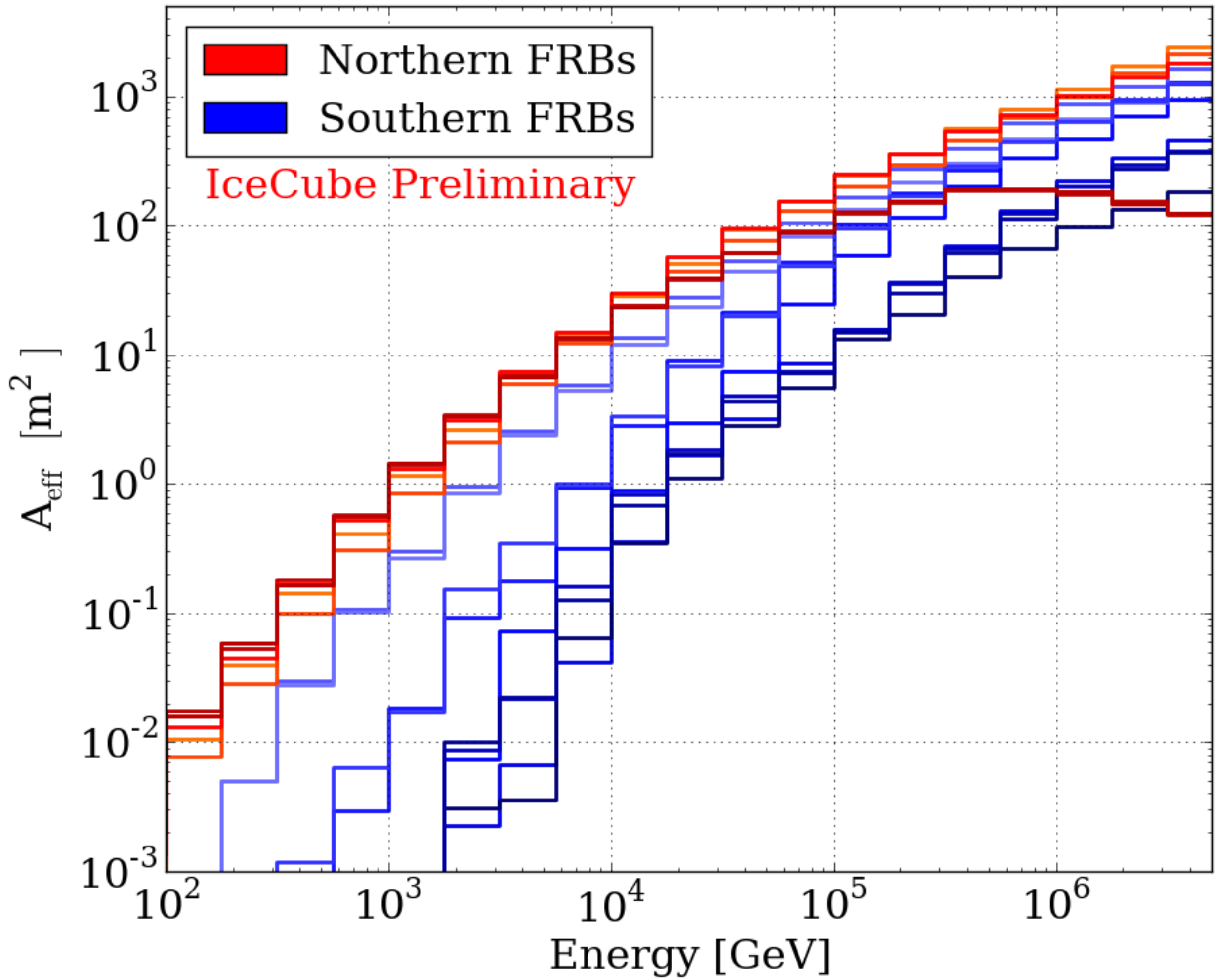


FRB neutrino fluench sensitivity on short time scale (±5 ms)



4 stacked FRBs at declination > -5°

Effective area in direction of each FRB analyzed

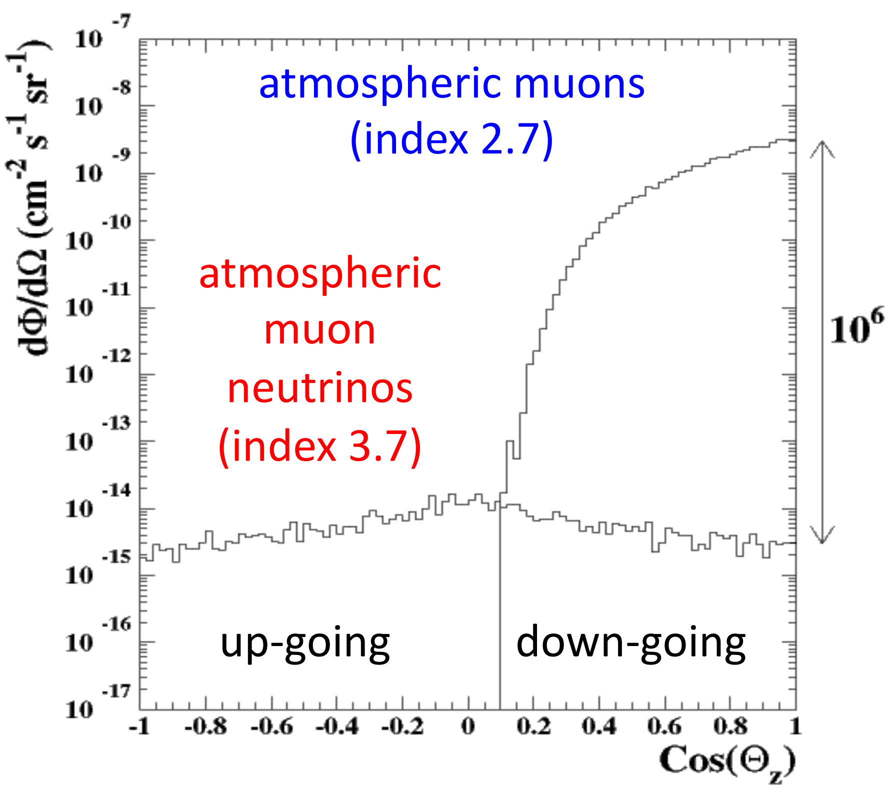


IceCube signals and backgrounds

Most events detected by IceCube are not astrophysical neutrinos

• atmospheric	μ	~7×10^{10}/year
• atmospheric	$\nu_\mu \rightarrow \mu$	>8×10^{4}/year
• astrophysical	$\nu_\mu \rightarrow \mu$	~10/year

Background and signal differ in spectrum and angular distribution



Field of view: 4π
Track angular resolution: ~1°

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Analysis #1: One-year simple analysis

- Use one year of IceCube data (May 2011 to May 2012) to analyze four FRBs (110523, 110627, 110703, 120127)
- Perform simple search for association in direction and time on one day time scale
- S. Fahey, A. Kheirandish, J. Vandenbroucke & D. Xu, submitted (1611.03062)

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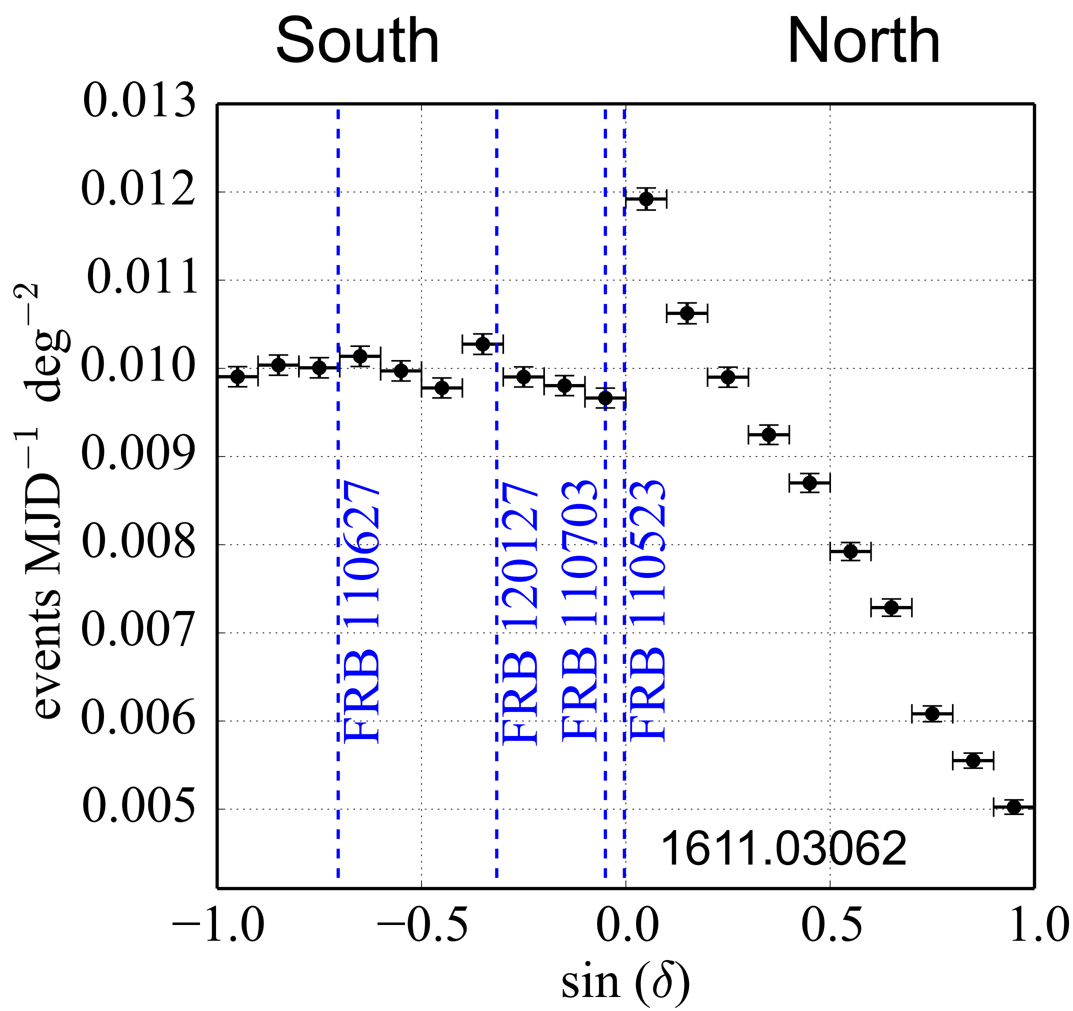
Background event rate



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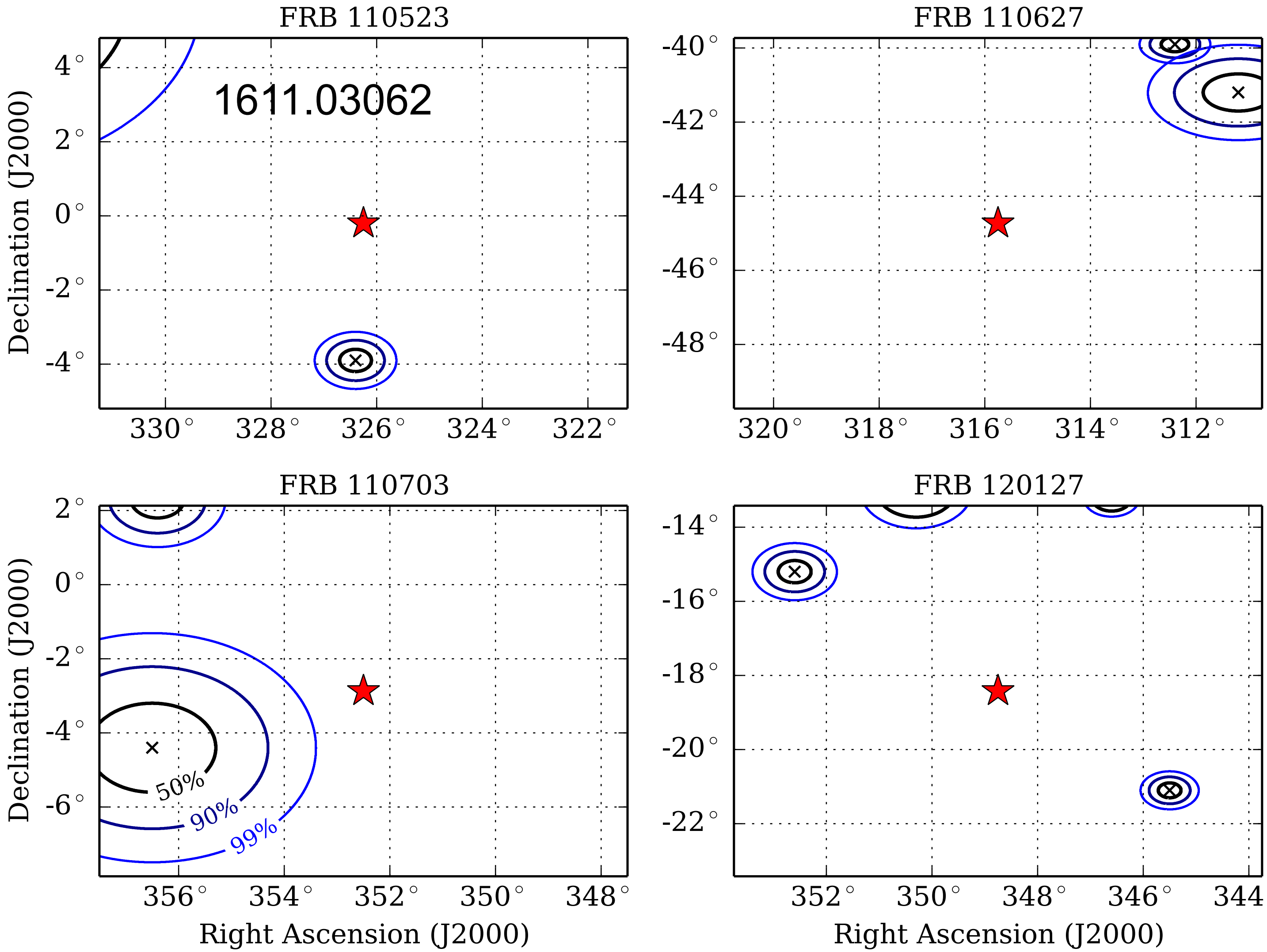
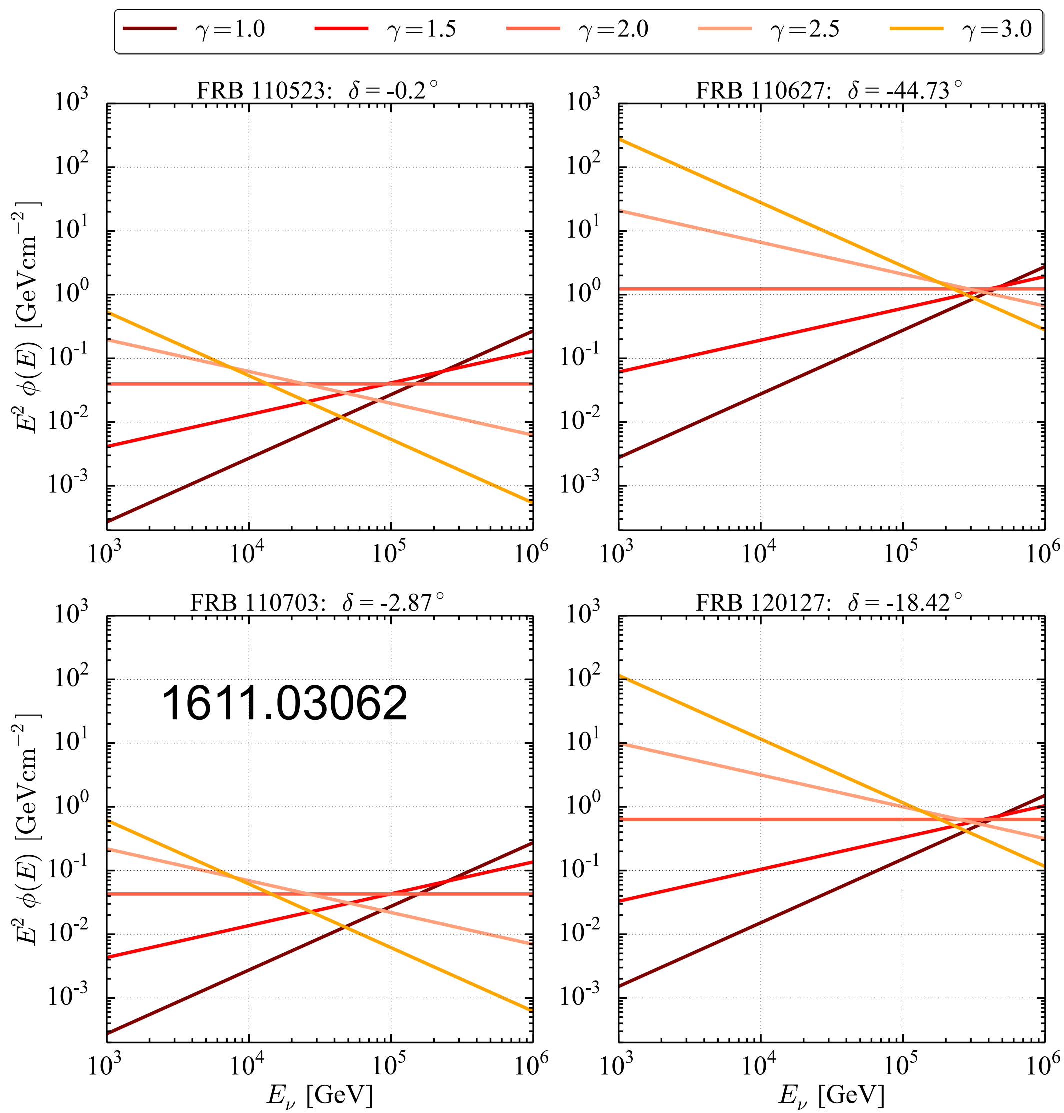
Results from analysis of 1 year of data and 4 FRBs



No FRB has an IceCube event coincident in direction (within estimated 99% error radius) and time on one day time scale

Interpretation of non-detection: 90% upper limits on neutrino fluence assuming power law spectrum



Analysis #2: four-year analysis with increased sensitivity and short time scales

- Use loose event selection with high effective area
- For model independence, search within a set of time windows expanding in factors of 2 from ±5 ms to ±23.3 hr (25 windows)
- Analyze 4 years of data from each hemisphere and all published FRBs within the time range
- Analyze two “hemispheres” (boundary at -5° declination) separately due to very different rate of atmospheric muon background
- Two methods: (A) search for single significant association (B) stack FRBs

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FRBs analyzed in four-year data set

- “Southern” (dec < -5°) analysis: May 2010 to May 2015
  - 9 Parkes FRBs from 110220 through 150418
  - Did not include 150807 or 3 bursts from 2001 or 1 from 2009
- “Northern” (dec > -5°) analysis: May 2011 to May 2016
  - 110523 (Green Bank)
  - 110703 (Parkes)
  - 130628 (Parkes)
  - 121102 (Arecibo and VLA): 17 bursts from repeater, Nov 2012 through Dec 2015
  - Did not (yet) include more recent repeater bursts

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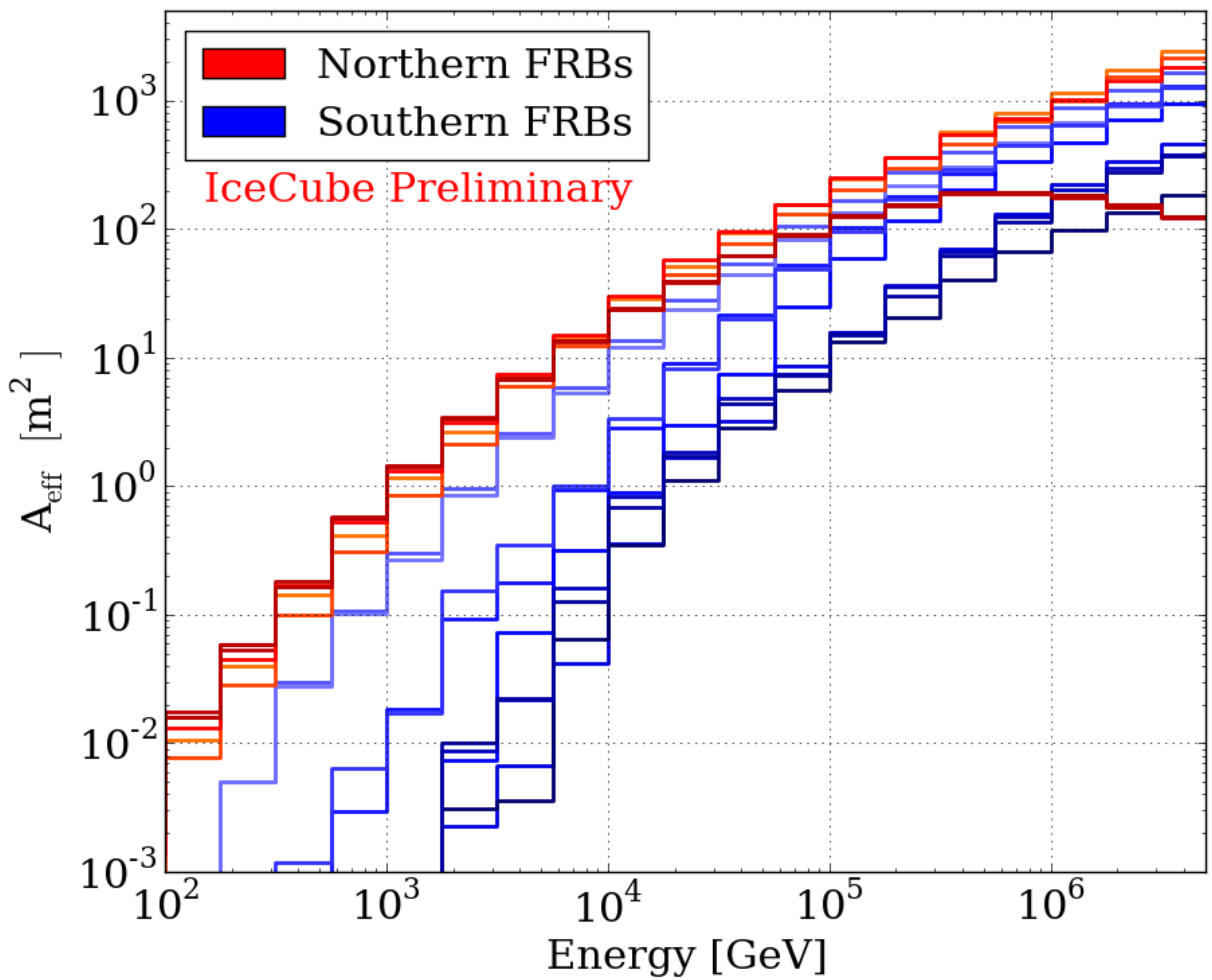
Effective area in direction of each FRB analyzed



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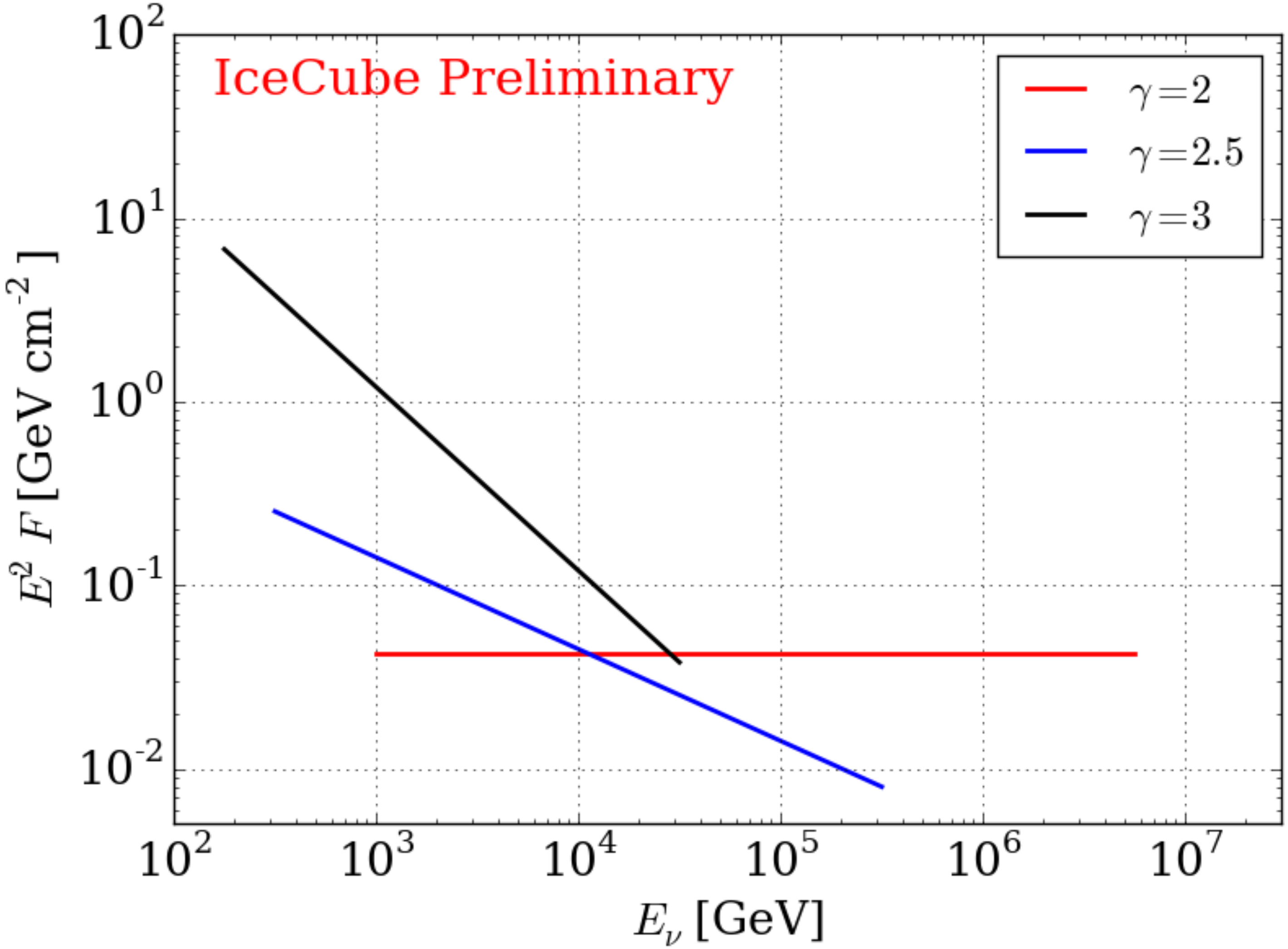
Example sensitivity for shortest time scale (±5 ms)



Stacked northern FRBs

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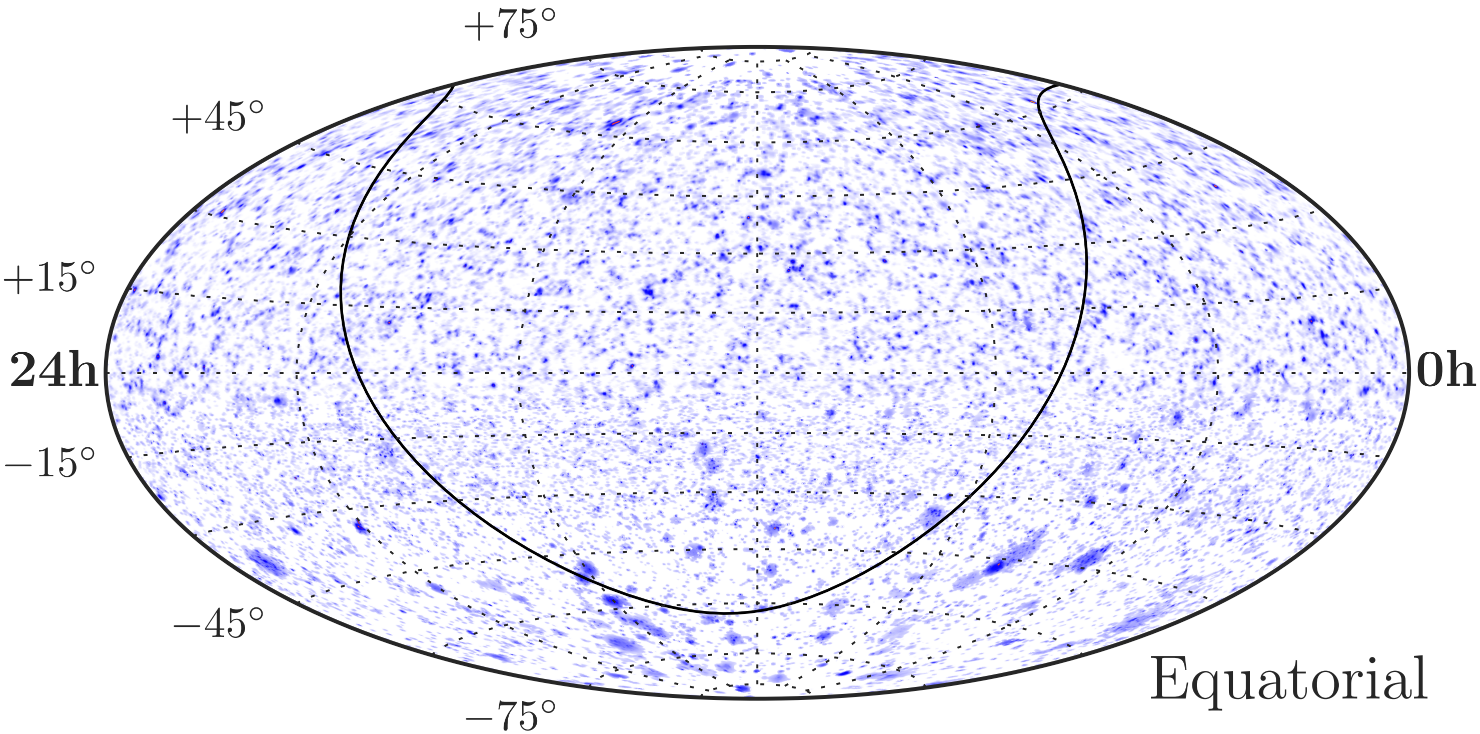
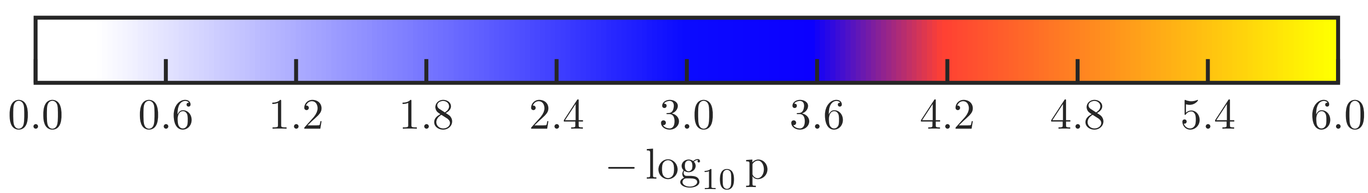
Searching for a TeV gamma-ray FRB counterpart with VERITAS

- VERITAS is an atmospheric Cherenkov array in Arizona
  - Effective area: 10^5 m^2
  - Background: 1 event/minute within 0.1° of point source
  - Instrumental deadtime: 30μs
- Sensitive to gamma rays from 85 GeV to 30 TeV
- 3.5° field of view implies one FRB is observed every few nights. A blind search of 10,000 hours of archived observations is underway
- Contemporaneous observations of FRB 121102 with Arecibo are taking place this season
- Keen to coordinate with other telescopes/ programs
  - Jamie Holder, University of Delaware: jholder@udel.edu

Despite measuring a bright unresolved flux, no discrete sources detected yet (steady, variable, or transient)



ApJ 835 (2017) no. 2, 151



Obvious source classes (GRBs, star-forming galaxies, average blazar emission) cannot explain most of the signal

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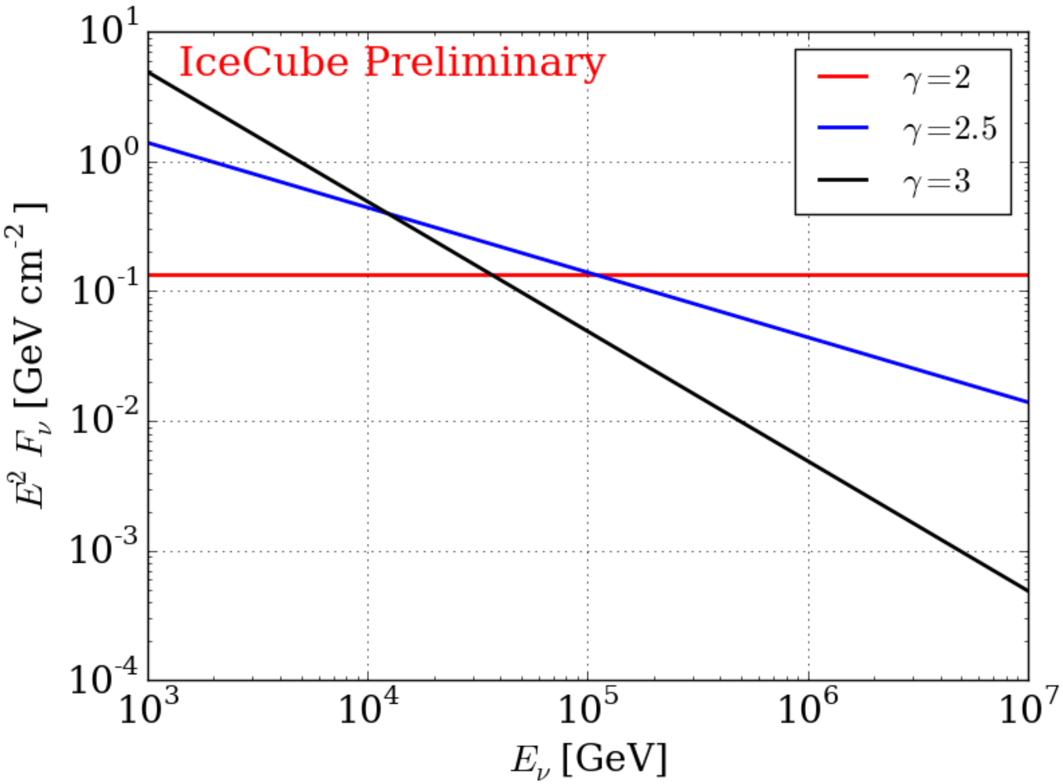
Example sensitivity for shortest time scale (±5 ms)



Stacked northern FRBs

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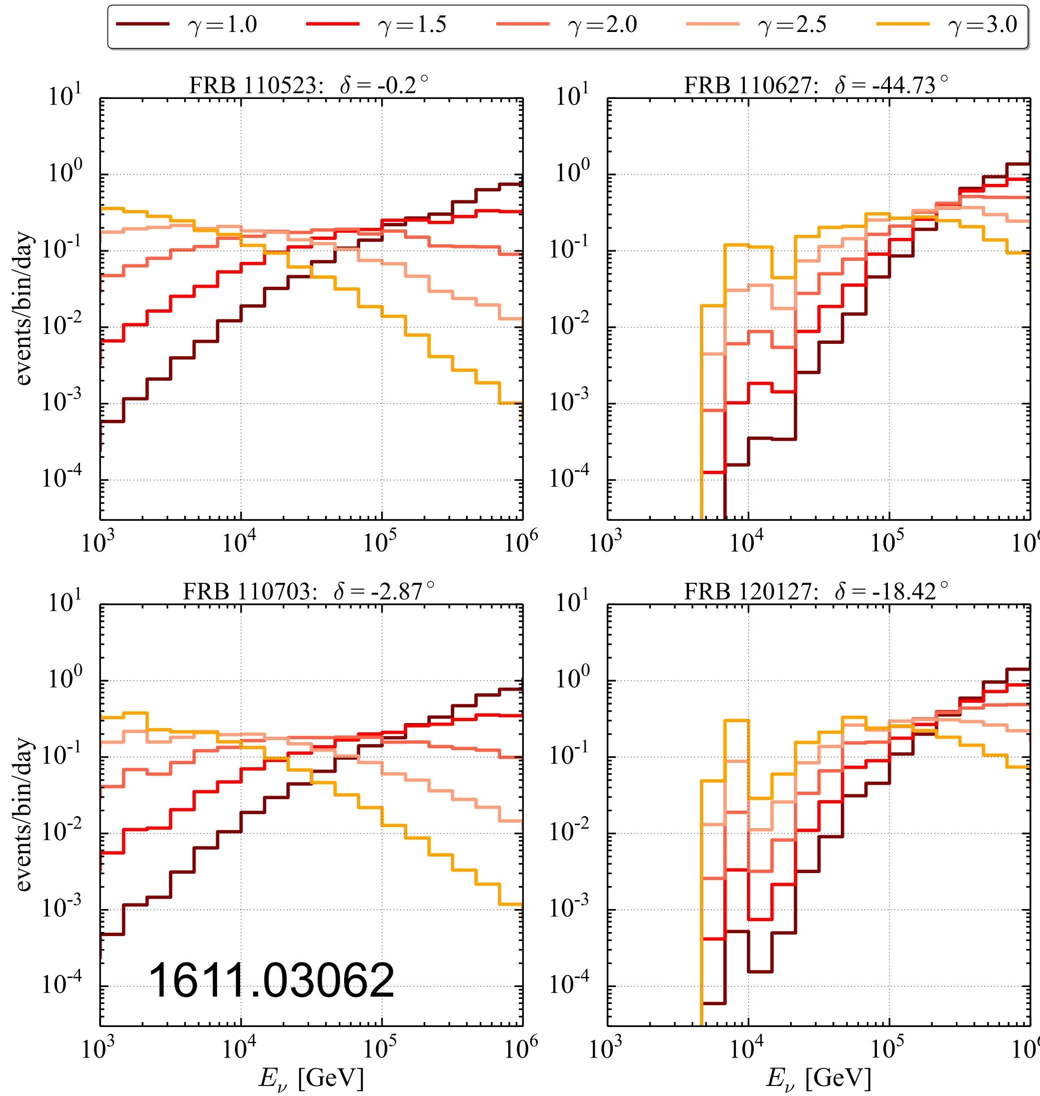
Interpretation of non-detection: energy distribution of events that would be detected given a power law input spectrum



Normalized to 2.3 events

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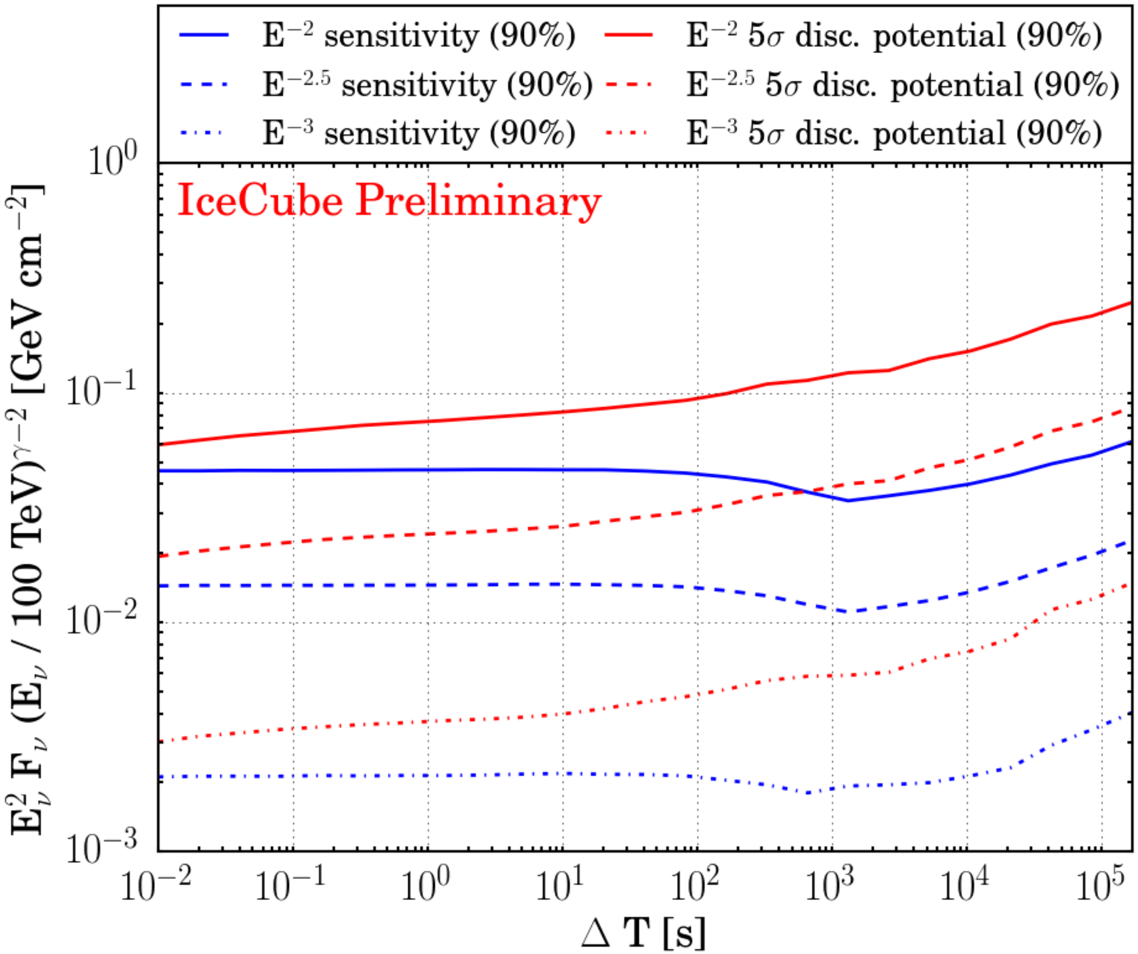
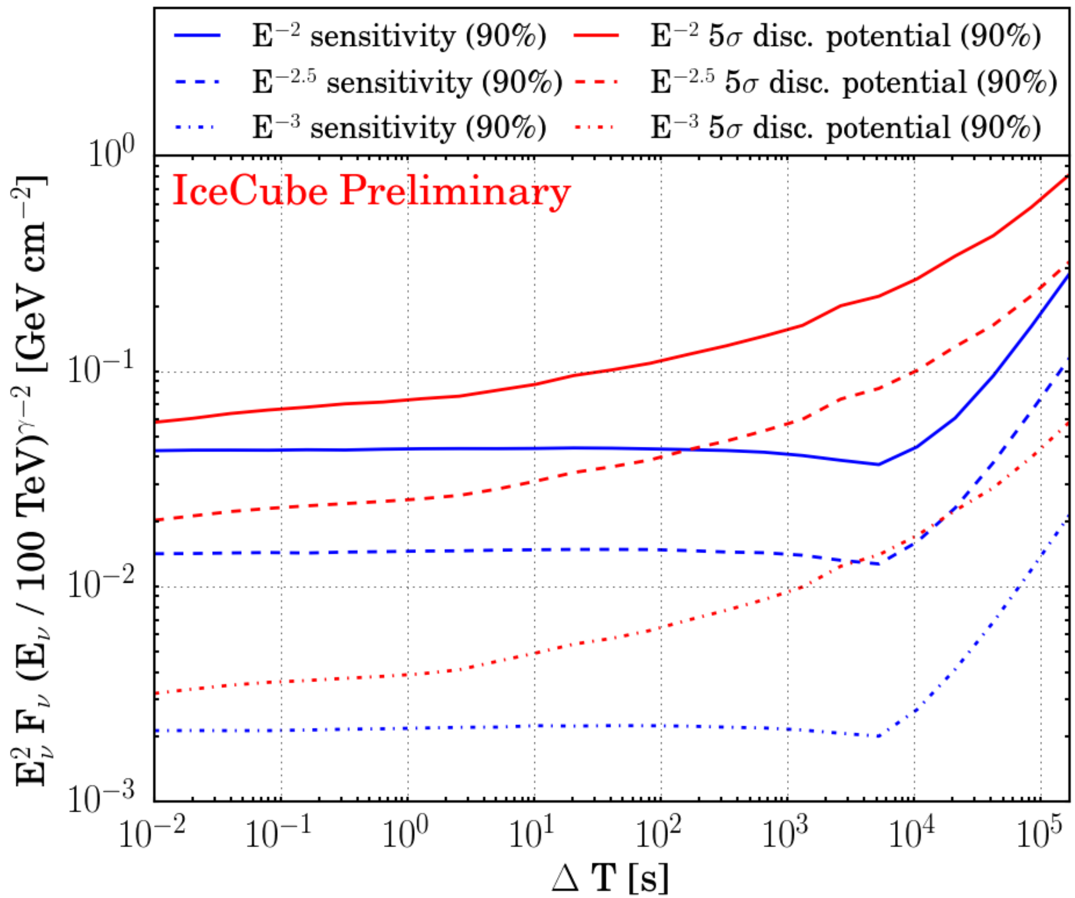
Sensitivity as a function of search time window size



- Example Northern analysis with maximum-burst method
- Background free at short times, small background at long times

Sensitivity as a function of search time window size



- Example Northern analysis with stacking method
- Background free at short times, small background at long times

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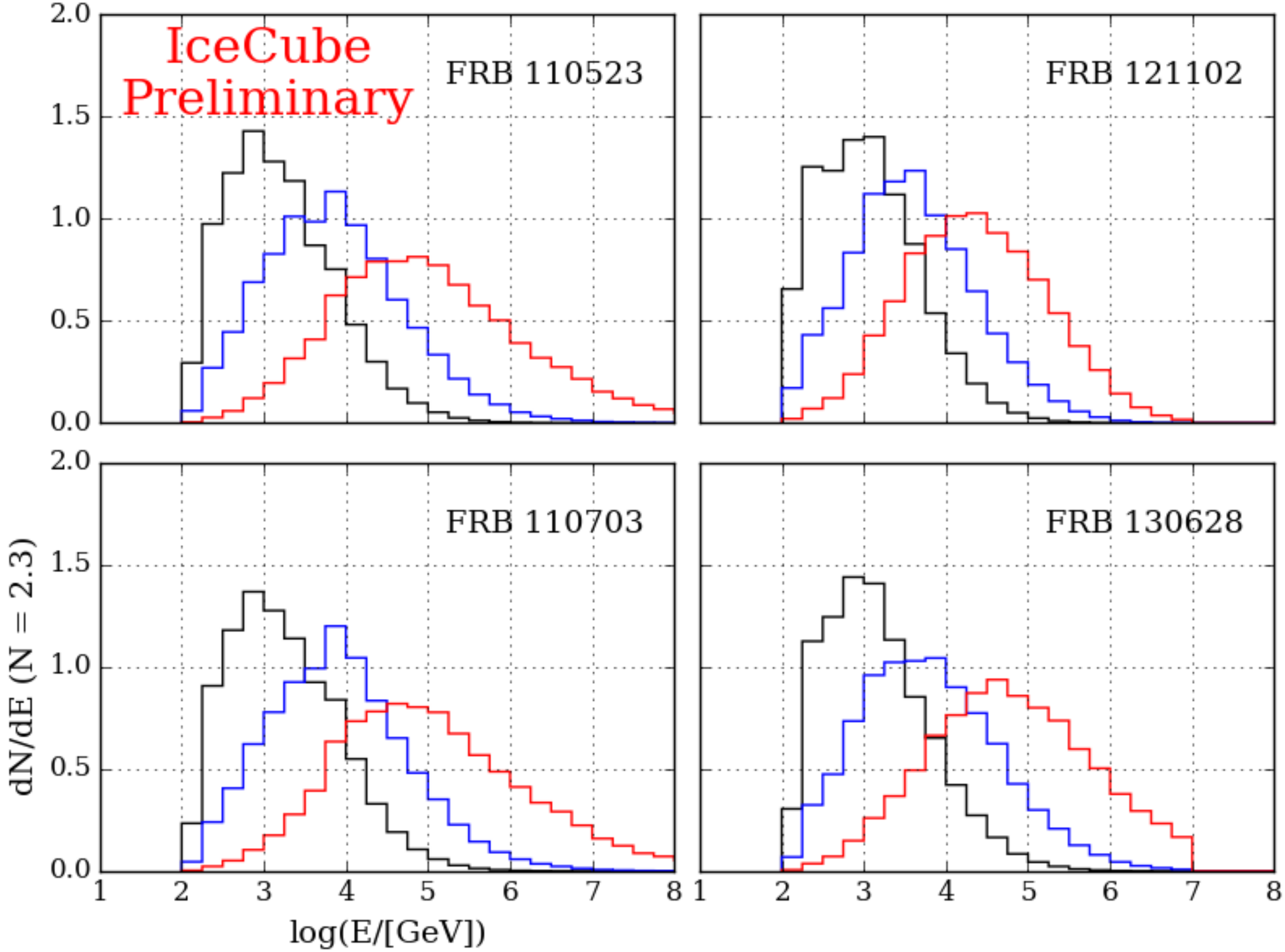
Astrophysical neutrinos

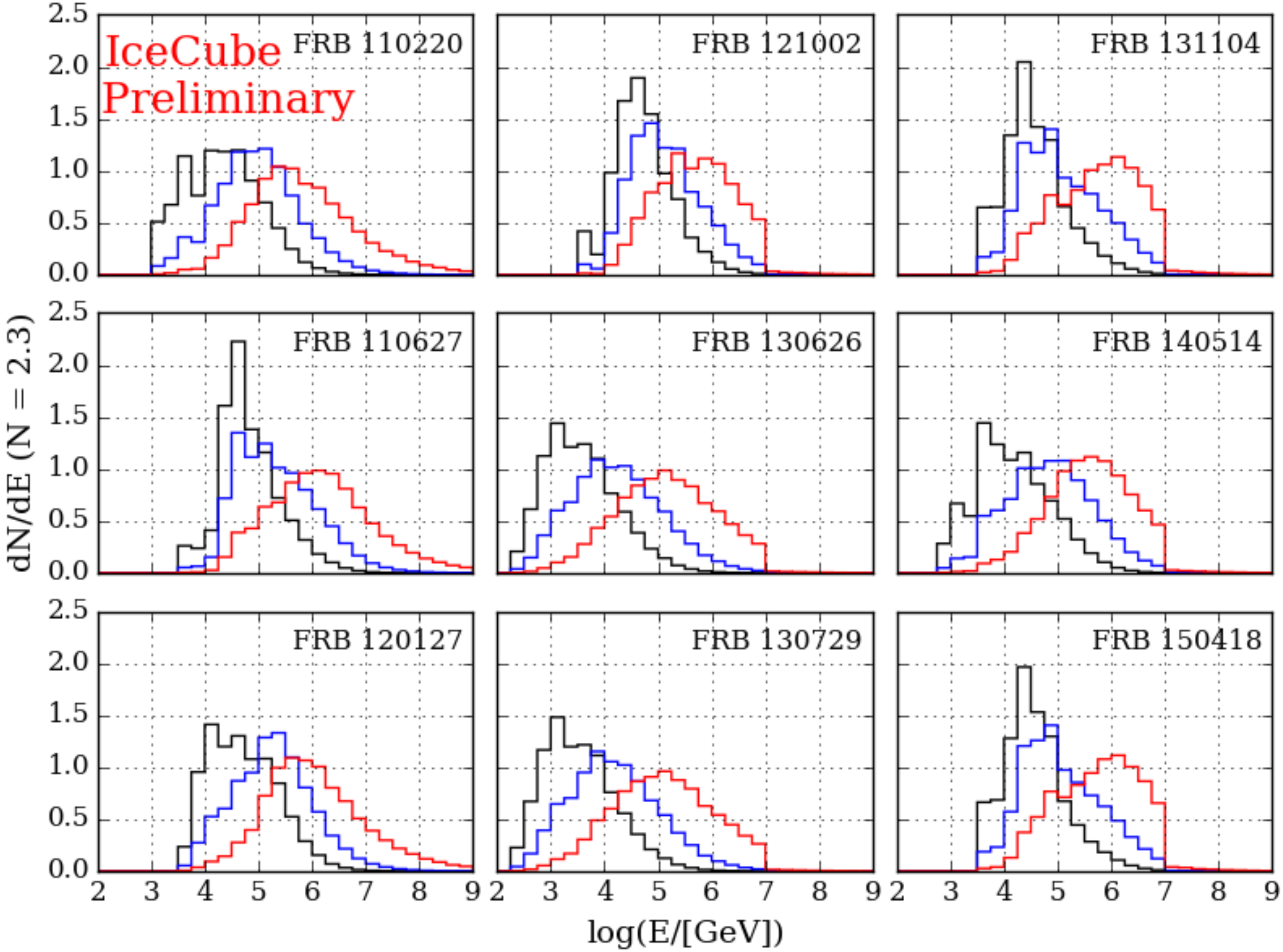
IceCube event sample and background rate

Northern Sample	Livetime (days)	N_events	90% containment radius	90% area (sqr. deg.)	Events in area (ΔT = 0.01 s)	Events in area (ΔT = 167772.16 s)
IC86-1	341.9	107,612	2.13°	14.25	2.31e-8	0.388
IC86-2	332.2	157,754	2.68°	22.56	5.53e-8	0.928
IC86-3	362.2	193,320	2.79°	24.45	6.74e-8	1.130
IC86-4	369.8	197,311	2.79°	24.45	6.73e-8	1.130
IC86-5	356.8	186,600	2.83°	25.16	6.79e-8	1.139
Southern Sample	**Livetime (days)**	**N_events**	**90% containment radius**	**90% area (sqr. deg.)**	**Events in area (ΔT = 0.01 s)**	**Events in area (ΔT = 167772.16 s)**
IC79	314.6	67,474	1.02°	3.30	4.35e-9	0.073
IC86-1	359.6	58,982	1.10°	3.77	3.80e-9	0.064
IC86-2	328.6	91,485	1.05°	3.44	5.89e-9	0.099
IC86-3	358.6	100,820	1.04°	3.43	5.77e-9	0.097
IC86-4	350.7	60,500	1.04°	3.42	3.63e-9	0.061

Energy distribution of detected events (if any) given an



Energy distribution of detected events (if any) given an



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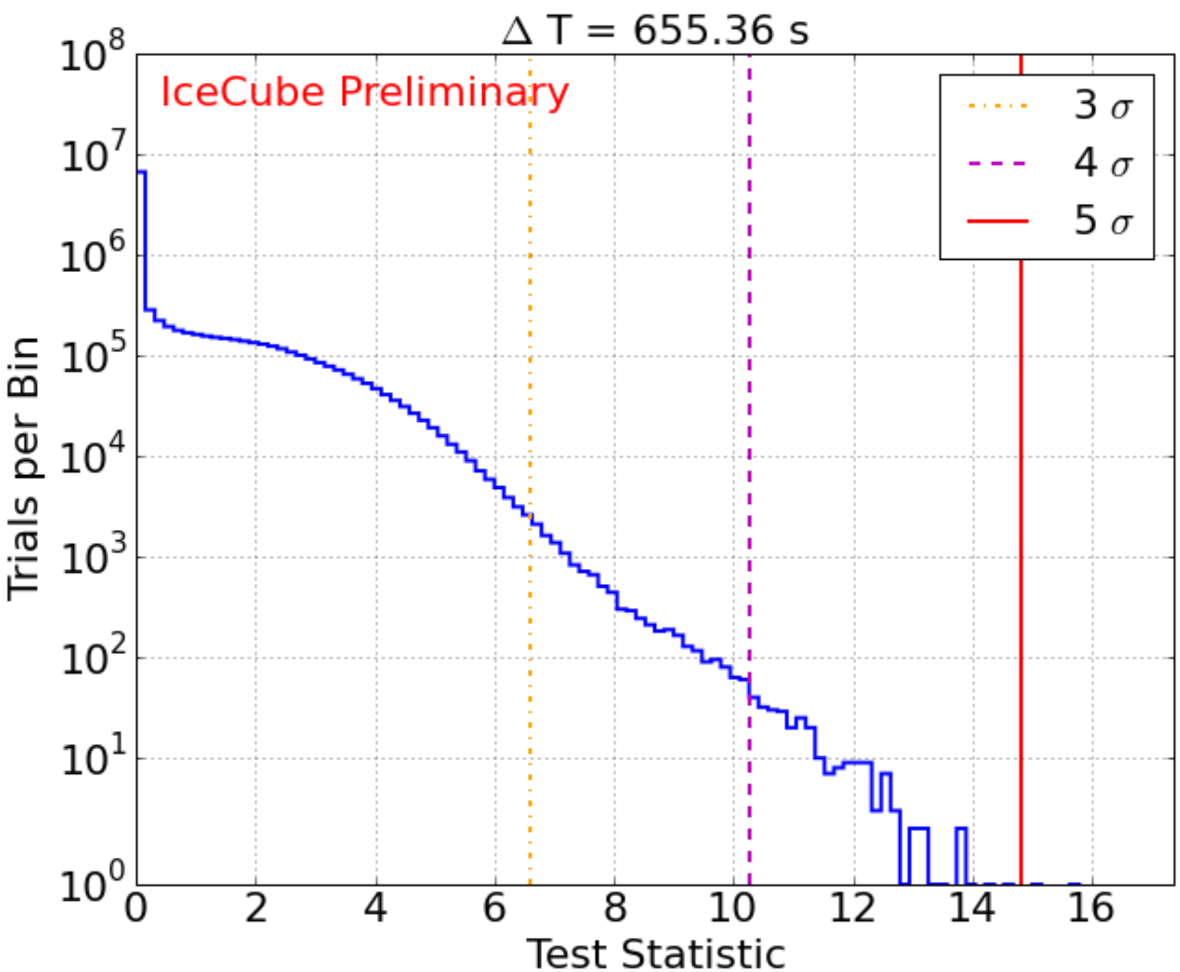
Test statistic distribution



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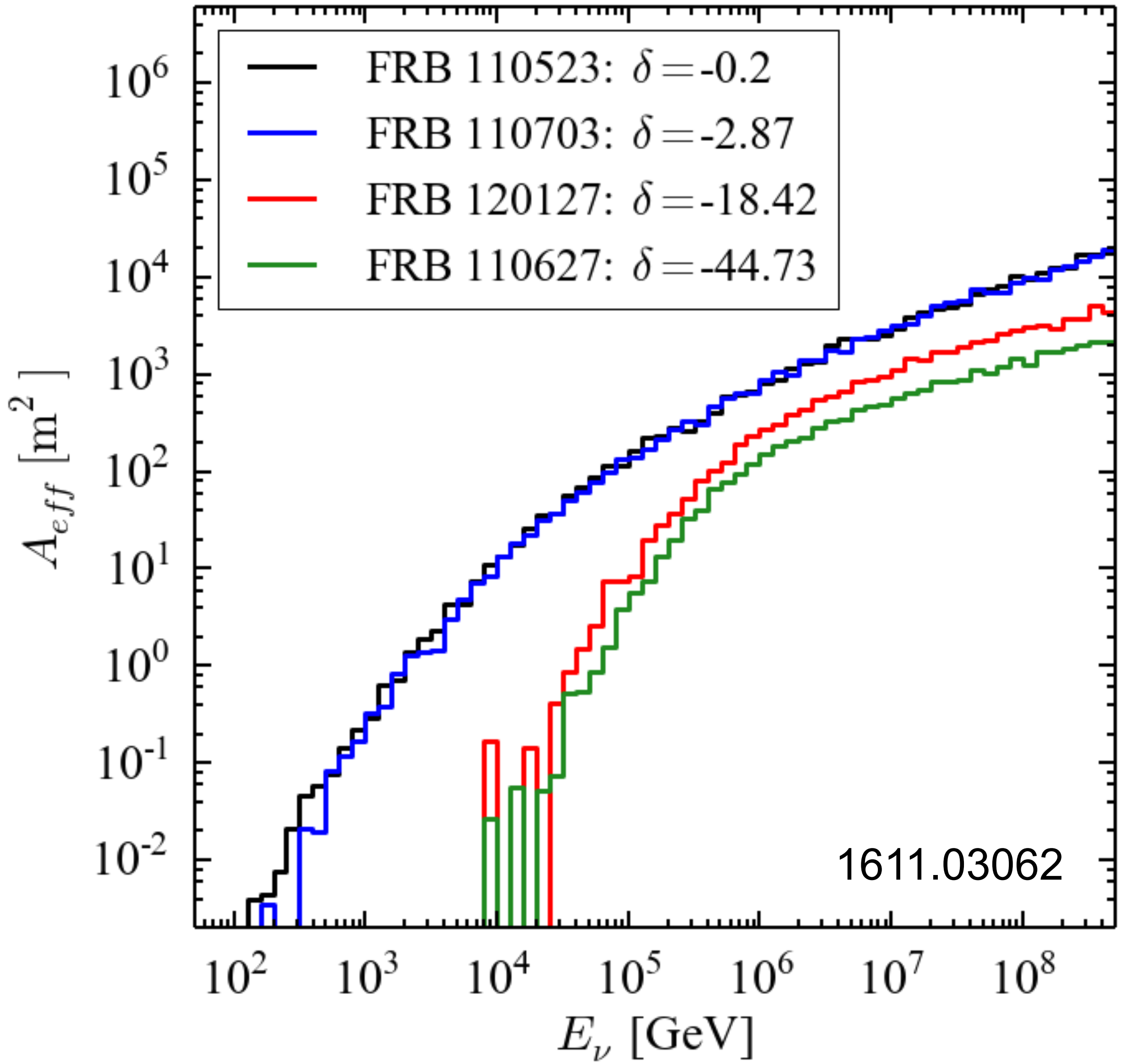
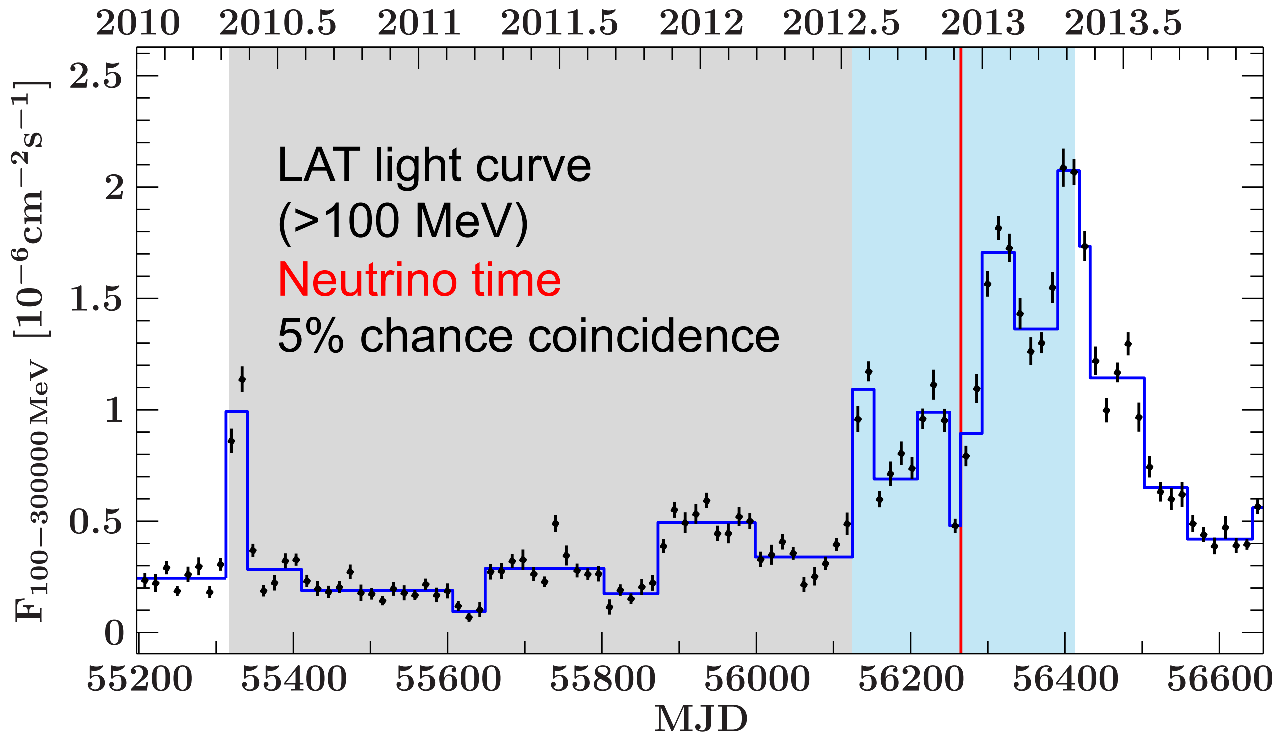
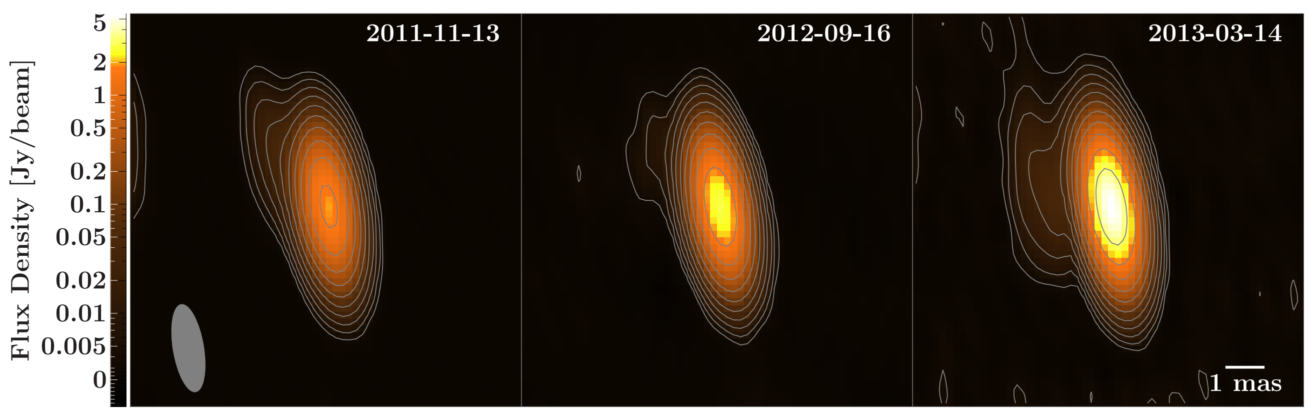
Effective area of analysis #1



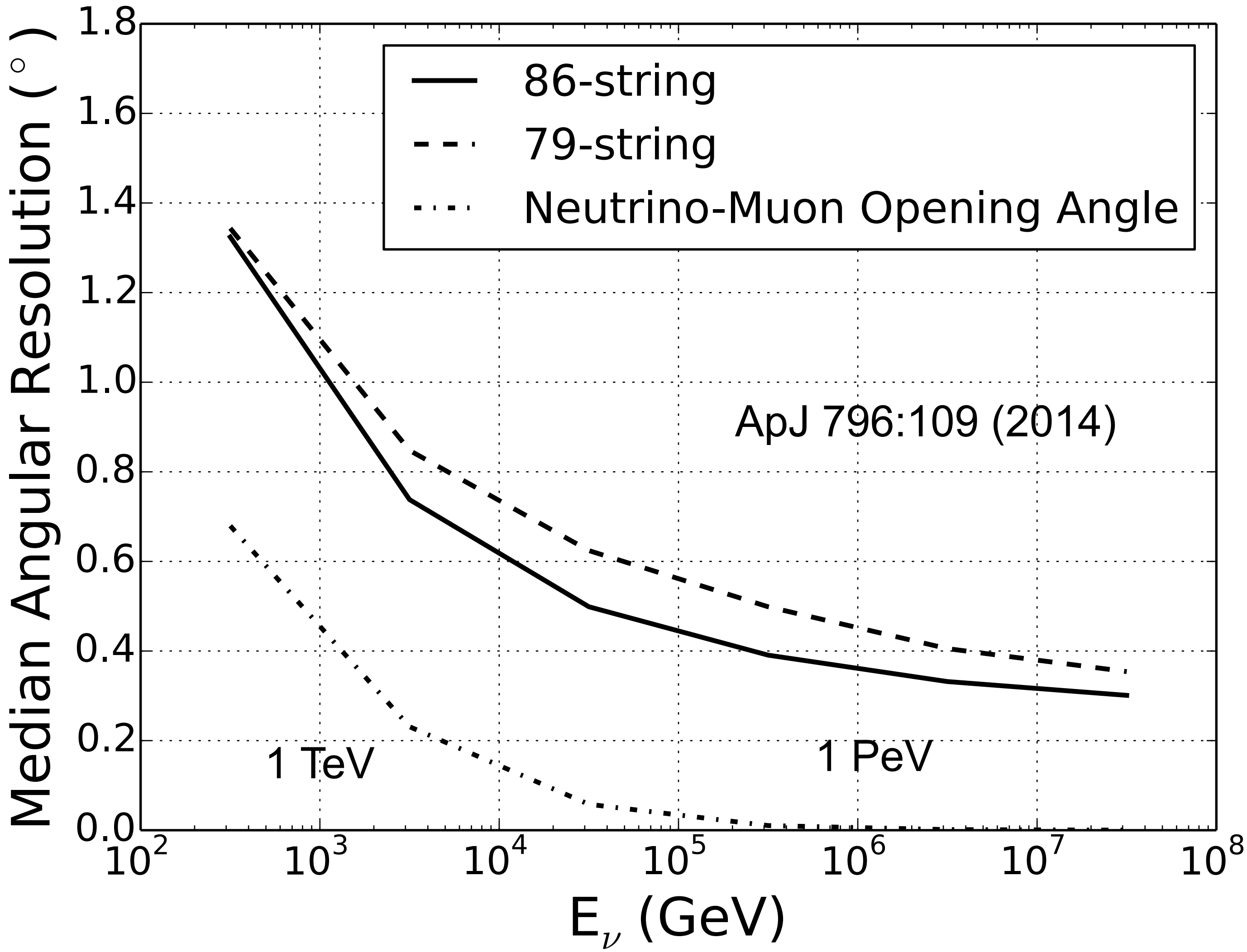
Coincidence between PKS B1424-418 blazar flare and PeV ν





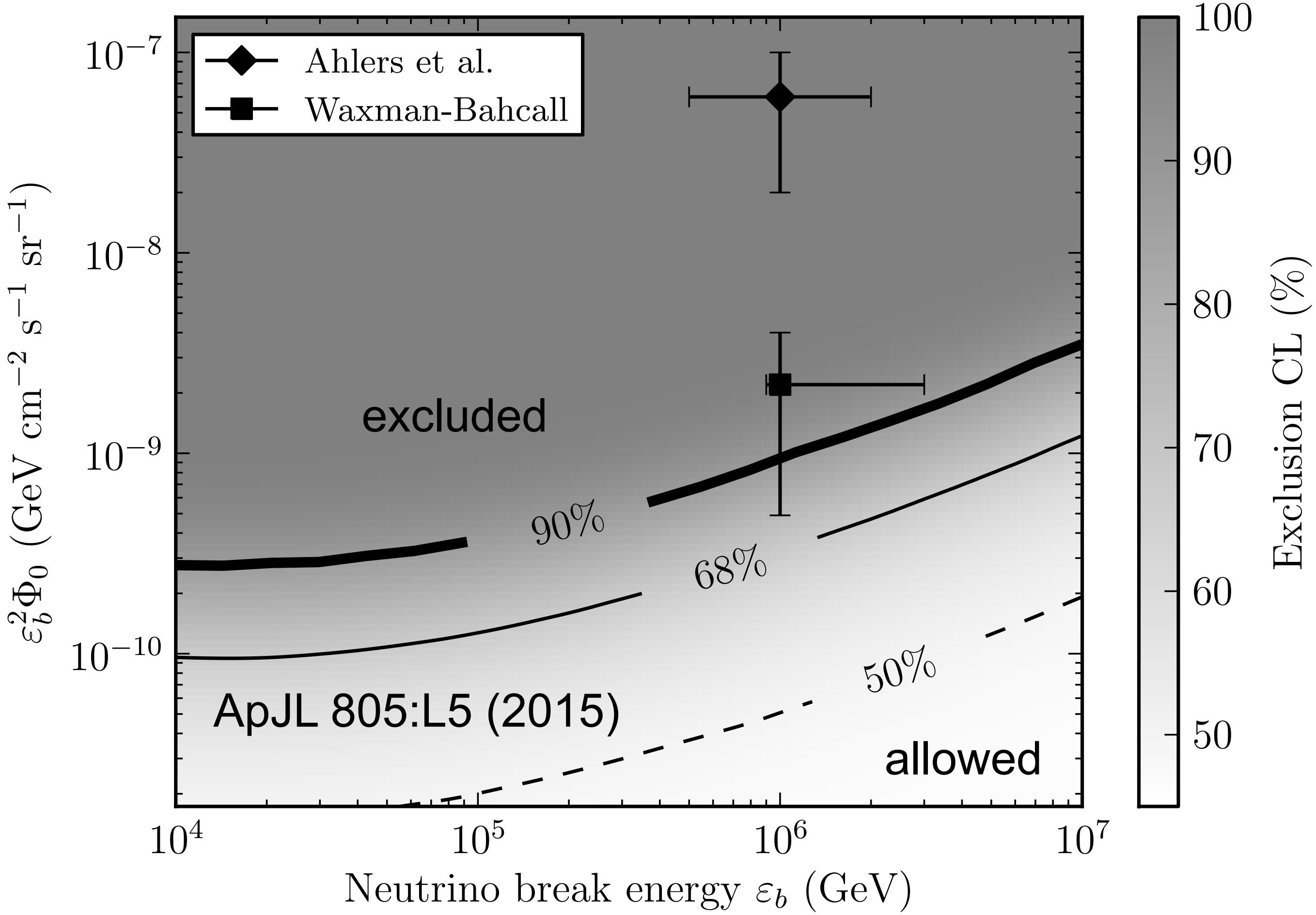
Kadler et al. 1602.02012

Angular resolution



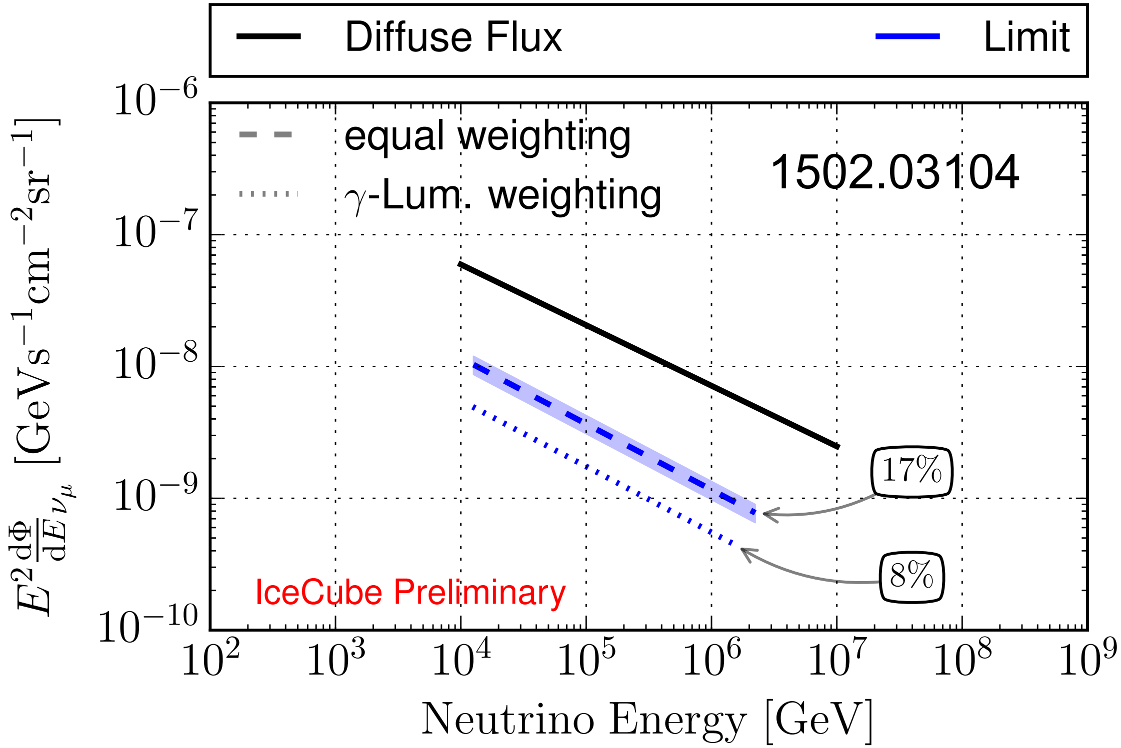
Muon neutrino angular resolution

The neutrinos are not produced by gamma-ray bursts



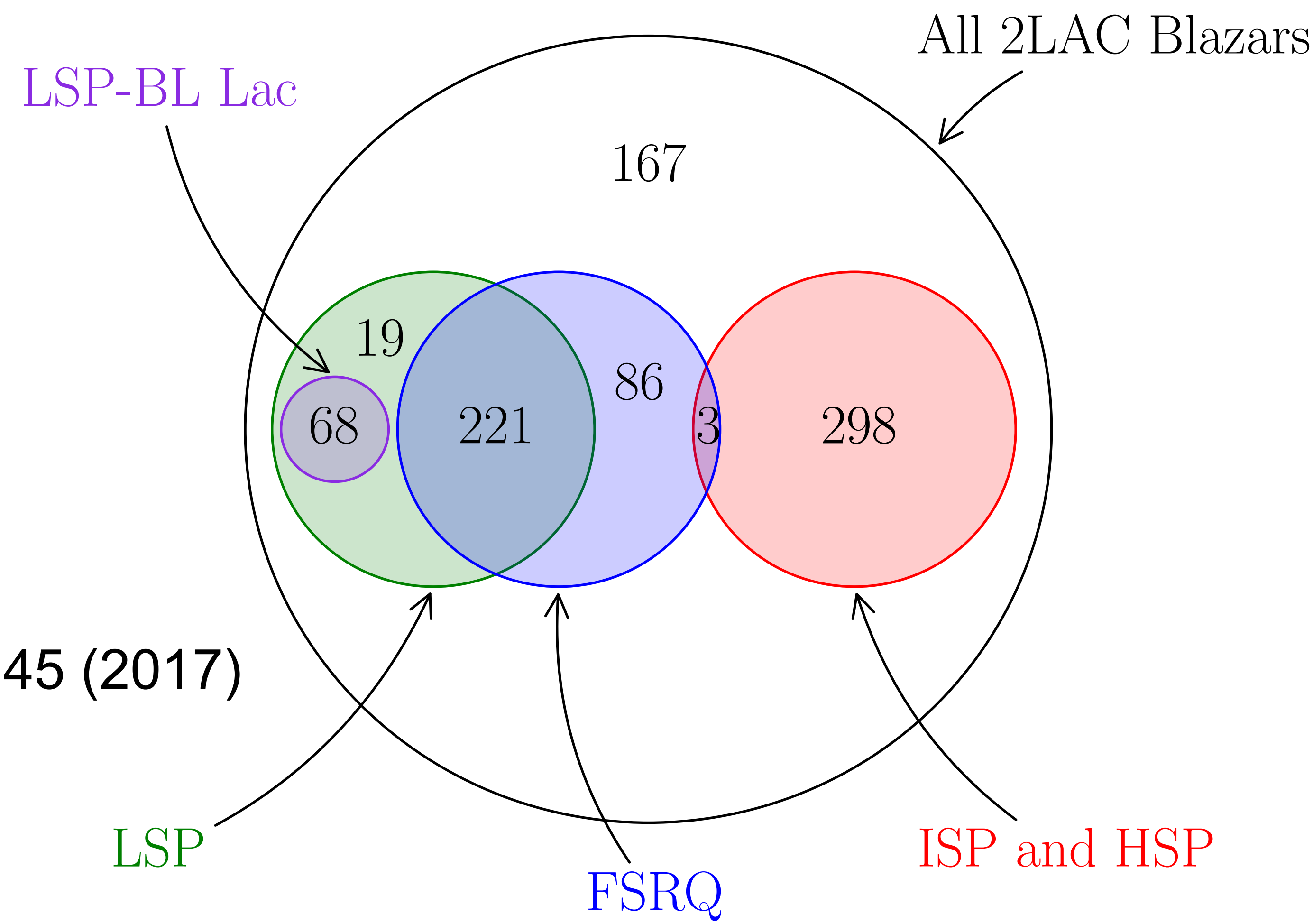
- Four years of data (40, 59, 79, 86 strings) and 506 bursts
- One low-significance event detected
- <1% of astrophysical neutrino signal produced by GRBs
- Models of GRBs as source of UHECR ruled out

The neutrinos are not produced (predominantly) by steady blazar emission



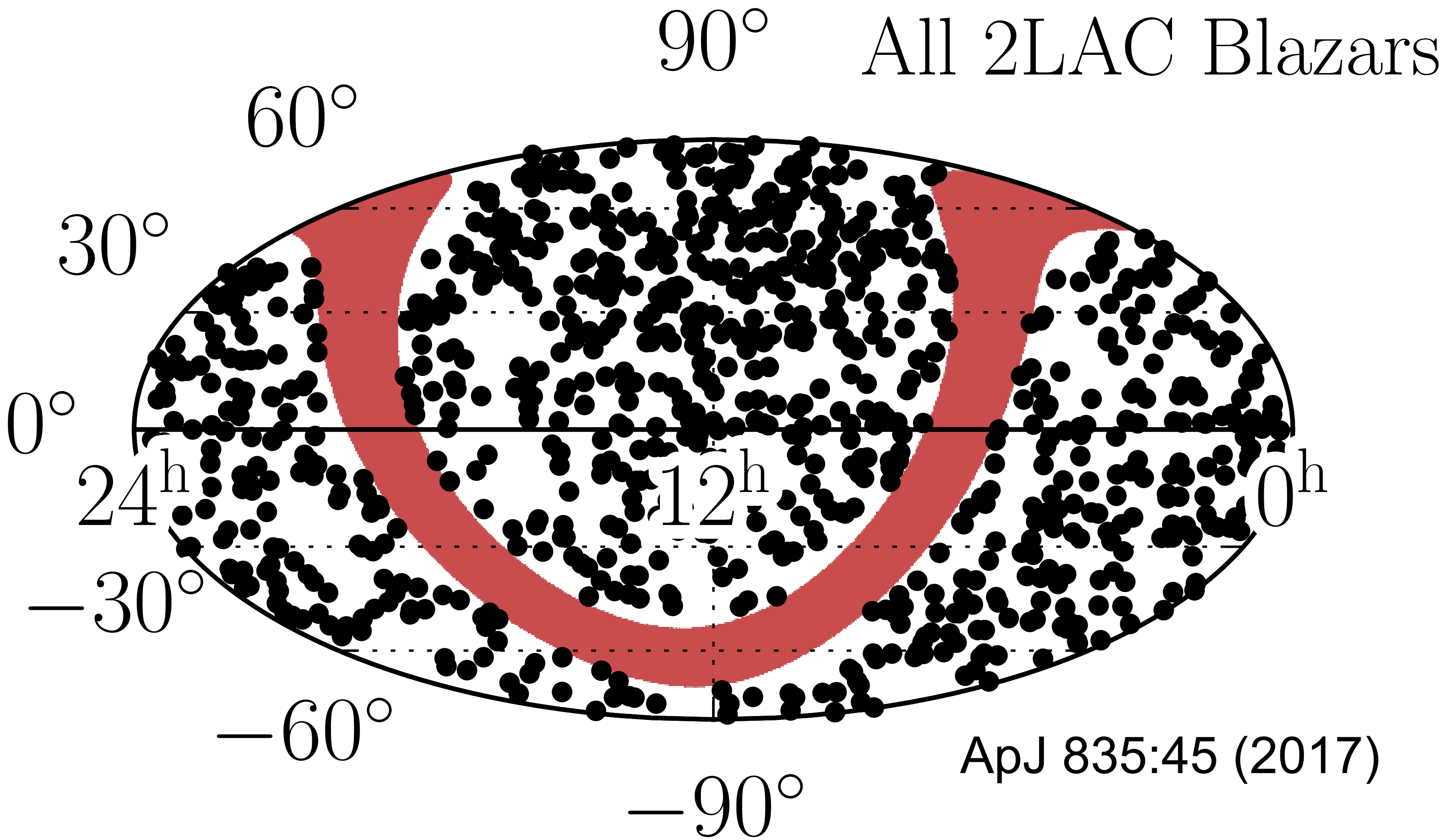
- Search for correlation between IceCube neutrinos and GeV blazars
- Fermi 2LAC sample: 862 objects
- Lack of detection constrains contribution of 2LAC blazars to at most
  - 17% of neutrino signal assuming equal weighting among blazars
  - 8% of neutrino signal assuming neutrino flux proportional to gamma flux

The neutrinos are not produced (predominantly) by steady blazar emission



ApJ 835:45 (2017)

The neutrinos are not produced (predominantly) by steady blazar emission



ApJ 835:45 (2017)