Multimessenger Astronomy
francis halzen

- February 23, 1987
- August 17, 2017
- September 22, 2017
- ....

icecube.wisc.edu
supernova 1987a: 24 neutrinos, thousands of papers
• 20% of the Universe is opaque to the EM spectrum
• non-thermal Universe powered by cosmic accelerators
• probed by gravity waves, neutrinos and cosmic rays
The opaque Universe

$\gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^-$

photons interact with microwave photons before reaching our telescopes
Neutrinos? Perfect Messenger

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays after 105 years
- … but difficult to detect
• energy ~ [magnetic field B] x [accelerator’s size R]

• luminosity ~ a few percent of gravitational energy of...
supermassive black hole in active galaxy
Neutrino Beams: Heaven & Earth

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ \sim \text{cosmic ray} + \text{neutrino} \]
\[ \rightarrow p + \pi^0 \]
\[ \sim \text{cosmic ray} + \text{gamma} \]
IceCube

5160 PMs in 1 km$^3$

IceTop
81 Stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

DeepCore
8 strings spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m
photomultiplier tube - 10 inch
muon track: color is time; number of photons is energy
89 TeV

radius \sim \text{number of photons}

time \sim \text{red \rightarrow purple}
muon

• lattice of photomultipliers

neutrino

interaction

muon

neutrino
date: June 11, 2014
most probable energy: 9 PeV
topology: track
2.6 ± 0.3 PeV inside detector
neutron star-neutron star merger
buildup of magnetic fields near merger launches jet
very weak short GRB seen by Fermi (off axis?)

MeV neutrino emission:
- $\sim 0.01 \, M_{\text{sun}}$ material ejected
- $\sim$ supernova
off-axis jet  choked jet cocoon
high-energy neutrinos from internal shocks:

protons interact with photons
- from leakage of the collimation jet
- from bremsstrahlung by accelerated electrons to produce pions and neutrinos
TABLE II. Detection probability of neutrinos by IceCube and IceCube-Gen2

<table>
<thead>
<tr>
<th>model</th>
<th>IceCube-North</th>
<th>IceCube-South</th>
<th>Gen2-North</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>6.6</td>
<td>0.55</td>
<td>29</td>
</tr>
<tr>
<td>B</td>
<td>0.36</td>
<td>0.023</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Number of detected neutrinos from single event at 300 Mpc

<table>
<thead>
<tr>
<th>model</th>
<th>IceCube-North</th>
<th>IceCube-South</th>
<th>Gen2-North</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.12</td>
<td>$9.7 \times 10^{-3}$</td>
<td>0.52</td>
</tr>
<tr>
<td>B</td>
<td>$6.2 \times 10^{-3}$</td>
<td>$4.2 \times 10^{-4}$</td>
<td>0.027</td>
</tr>
</tbody>
</table>

GW+neutrino detection rate [yr$^{-1}$]

<table>
<thead>
<tr>
<th>model</th>
<th>IceCube</th>
<th>Gen2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.1</td>
<td>2.6</td>
</tr>
<tr>
<td>B</td>
<td>0.076</td>
<td>0.28</td>
</tr>
</tbody>
</table>
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IceCube

Icecube.wisc.edu
isolated neutrinos interacting inside the detector (HESE)

up-going muon tracks (UPMU)

total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.5°)
two methods are consistent
radiation and dust

black hole neutron star

accelerator is powered by large gravitational energy

p + \gamma \rightarrow n + (\pi^+)
\sim \text{cosmic ray + neutrino}

\rightarrow p + (\pi^0)
\sim \text{cosmic ray + gamma}

\nu and \gamma \text{ beams: heaven and earth}
gamma rays accompanying IceCube neutrinos interact with interstellar photons and fragment into multiple lower energy gamma rays that reach earth.
\[ \gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^- \]
\[
\pi^+ = \pi^- = \pi^0
\]

Fermi gammas

\[E^{-2.15}\]

pp scenario

SFR evolution

HESE (3yr)
arXiv:1410.1749
Fermi IGRB (2014)

cosmic neutrinos
• energy density of neutrinos in the non-thermal Universe is similar as that in gamma-rays
Fermi sources are mostly blazars common sources?

→ multimessenger astronomy
flux < 1% of astrophysical neutrino flux observed
Nature 484 (2012) 351-353
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!
We send our high-energy events in real-time as public GCN alerts now!

GCN notice for starting track sent Apr 27

We send rough reconstructions first and then update them.

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

43 seconds after trigger, GCN notice was sent

---

**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]
Fermi sky: mostly blazars
MAGIC
Many Messengers

Over three and a half weeks in 2017, astronomers observed the same celestial event—what they believe to be a flare-up from matter falling into a supermassive black hole—through multiple wavelengths of light, as well as particles called neutrinos. The combined observations offer scientists much more information about these mysterious phenomena than any measurement alone.

1. First, the IceCube Neutrino Observatory at the South Pole detected a high-energy neutrino and issued an alert.
2. The orbiting Swift x-ray telescope reported finding nine sources of x-rays coming from the same area of the sky as the neutrino.
3. Two days later the Fermi space telescope identified gamma rays coming from one of the same sources Swift found.
4. A network of ground-based optical telescopes called ASAS-SN announced that this source had been brightening over the past 50 days.
5. Another optical telescope found evidence that the source was a blazar—a huge black hole emitting jets as it swallowed mass.
6. The Very Large Array in New Mexico, observing in radio light, confirmed that the source of all these signals was a jet from a blazar.

Finkbeiner (Scientific American)
Further Observations I

- 17/09/23 09:31:27 GMT (GCN 21917), INTEGRAL, upper limit
- 17/09/24 19:34:55 GMT (GCN 21923), ANTARES, upper limit (+/-1h, +/-1d)
- 17/09/25 01:55:22 GMT (GCN 21924), HAWC, upper limit
- 17/09/26 14:34:30 GMT (GCN 21930), Swift (3.25h after the neutrino trigger, 800s per field, 19-point tiling), 9 sources identified
- 17/09/27 14:33 GMT (ATel 10787), HESS, observation 4h after neutrino trigger (for ~1h) and consecutive night (1h), no detection
- 17/09/28 10:10 GMT (ATel 10791), Fermi-LAT, known gamma-ray source TXS 0506+056 (3FGL J0509.4+0541) in error circle, in flaring state, redshift unknown
- 17/09/28 11:58:48 GMT (GCN 21941), further Swift observations, additional 5ks of TXS position, possible spectral evolution
- 17/09/28 18:00 GMT (ATel 10794): ASAS-SN finds enhanced optical flux of TXS 0506+056
- 17/09/29 13:00 GMT (ATel 10799): Liverpool telescope takes optical spectrum, no redshift measurement possible
- 17/09/29 15:41 GMT (ATel 10801): AGILE confirms gamma-ray flare
- 17/09/30 02:10 GMT (ATel 10802): HAWC, no detection in 12day window
Further Observations II

- 17/10/04 17:17 GMT (ATel 10817): MAGIC, VHE gamma-ray detection, 5 sigma detection above 100 GeV was achieved after 12 h of observations from Sept. 28th till Oct. 3rd

- 17/10/07 13:26 GMT (ATel 10830): SALT-HRS, optical spectrum, no redshift measurement possible

- 17/10/07 18:58 GMT (ATel 10831): Kapteyn optical telescope, decline of the flare reported from ASAS-SN data continues

- 17/10/09 22:32 GMT (ATel 10833): VERITAS, observations started 12.2h after neutrino trigger, total time of 5h, no detection

- 17/09/11 02:36 GMT (ATel 10838): MAXI/GSC, no significant X-ray enhancement

- 17/09/11 08:44 GMT (ATel 10840): VLT/X-Shooter spectrum, no lines, non-detection of Lyman alpha absorption $\rightarrow z<1.6$

- 17/09/12 15:50 GMT (ATel 10844): Kanata optical follow-up, intrinsic polarization

- 17/09/12 16:54 GMT (ATel 10845): Joint Swift and NuSTAR observations, Jointly analyzed, the spectra are not consistent with any single power-law fit

- 17/09/17 14:08 GMT (ATel 10861): VLA radio observations, significant variability, radio spectrum is typical of emission from a compact jet

- 17/09/25 04:36 GMT (ATel 10890): Subaru/FOCAS, spectrum, no redshift measurement possible
Multi-wavelength observations of a flaring blazar coincident with an IceCube high-energy neutrino

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

• neutrino: time 22.09.17, 20:54:31 UTC
  energy 290 TeV
  direction RA 77.43° Dec 5.72°

• Fermi-LAT: flaring blazar within 0.1°

• MAGIC: TeV source in follow-up observations

• ...

• → IceCube archival data (without look-elsewhere effect)

• → Fermi-LAT archival data
we identified a source of high energy cosmic rays:

the active galaxy (blazar) TXS 0506+056 at a distance of 1.8 Gpc (redshift of 0.33)

extensive multiwavelength campaign will allow us to study the first cosmic accelerator
THE REDSHIFT OF THE BL LAC OBJECT TXS 0506+056.

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ABSTRACT

The bright BL Lac object TXS 0506+056 is a most likely counterpart of the IceCube neutrino event EHE 170922A. The lack of this redshift prevents a comprehensive understanding of the modeling of the source. We present high signal-to-noise optical spectroscopy, in the range 4100-9000 Å, obtained at the 10.4m Gran Telescopio Canarias. The spectrum is characterized by a power law continuum and is marked by faint interstellar features. In the regions unaffected by these features, we found three very weak (EW ~ 0.1 Å) emission lines that we identify with [O II] 3727 Å, [O III] 5007 Å, and [NII] 6583 Å, yielding the redshift $z = 0.3365 \pm 0.0010$.

Keywords: galaxies: BL Lacertae objects: individual (TXS 0506+056) – distances and redshifts – gamma rays: galaxies – neutrinos

→ although at 10 times larger redshift than nearby blazars (like the Markarian sources), TXS 0506+056 has the same flux → probably special subclass
• flare buildup ~100 days
• neutrinos emitted during period of
• rapid variation ~days

⇒ previous evidence?
AGILE DETECTION OF A CANDIDATE GAMMA-RAY PRECURSOR TO THE ICECUBE-160731 NEUTRINO EVENT

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TANAMI blazars in the IceCube PeV neutrino fields

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ABSTRACT

The IceCube Collaboration has announced the discovery of a neutrino flux in excess of the atmospheric background. Owing to the steeply falling atmospheric background spectrum, events at PeV energies most likely have an extraterrestrial origin. We present the multiwavelength properties of the six radio-brightest blazars that are positionally coincident with these events using contemporaneous data of the TANAMI blazar sample, including high-resolution images and spectral energy distributions. Assuming the X-ray to \( \gamma \)-ray emission originates in the photoproduction of pions by accelerated protons, the integrated predicted neutrino luminosity of these sources is high enough to explain the two detected PeV events.

Key words. neutrinos – galaxies: active – quasars: general
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- the future is now

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