Astronomical Neutrino Sources
- (selected) Latest IceCube High Energy $\nu$ Results

Joanna Kiryluk
Stony Brook University

for the IceCube Collaboration

29$^{\text{th}}$ International Symposium on Lepton Photon Interactions at High Energies (LP20019)
5-10 August 2019, Toronto (Canada)
Open Question: Origin of Cosmic rays at Ultra-High Energies

- Starburst galaxies (SN, GRB’s)
- Galaxy clusters
- AGN

New/update from this ICRC 2019:
- HAWC and Tibet p+HE
- IceCube mass composition
- All-particle spectra from IceTop, Tunka-133, TA, Auger
- DAMPE, NUCLEON-KLEM, CALET

Direct measurements pre ICRC 2019:
- p
- He
- O*
- Fe*
- Total

H. Dembinski; details in PoS(ICRC2017)533
Breakthrough in Multi-Messenger Astronomy: IceCube Neutrinos Point to Long-Sought Cosmic Ray Accelerator

A blazar emitting very high energy neutrinos and gamma rays
Introduction: astronomical sources
Multi-messenger Astronomy
- opening a new window to the Universe

1 pc ~ 3 lyr

γ(E~TeV/PeV) + γ_{EBL/CMB} → e^+ + e^−

Credit: Bartos & Kowalski 2017
Multi-messenger Astronomy
- opening a new window to the Universe

1 pc ~ 3 lyr

- Radio/microwave
- Infrared/optical
- X-rays
- Gamma-rays
- Neutrinos
- Cosmic-rays

TXS 0506+056 (blazar)

Distance [Mpc]

Blazar TXS 0506+056
Credit: DESY/Science lab
Possible Sources of Accelerated Cosmic Rays
[Observed by EM telescopes/detectors]

\[ E_{\text{max}} = 10^{18} eV Z \beta \left( \frac{R}{\text{kpc}} \right) \left( \frac{B}{\mu G} \right) \]

Hillas plot

Source classes as function of the magnetic field strength B and their characteristic size R

Credit: E. Bernardini (HEP-EPS, 2019)
Possible Sources of Accelerated Cosmic Rays
[Observed by EM telescopes/detectors]

\[ E_{\text{max}} = 10^{18} eV Z \beta \left( \frac{R}{\text{kpc}} \right) \left( \frac{B}{\mu G} \right) \]

Hillas plot

- Galactic
- Extra-Galactic
  
  \( z \) dependence

- Steady
- Transient

- Compact
- Extended

Credit: E. Bernardini (HEP-EPS, 2019)
EM energy spectrum and corresponding physics processes

Examples of single π production exclusive processes in pp

\[ \text{pp} \rightarrow \text{np} + \pi^+ \]
\[ \text{pp} \rightarrow \text{pp} + \pi^0 \]
\[ \text{pp} \rightarrow \text{d} + \pi^+ \]
The first detection of $\pi^0$ decay feature in $\gamma$-ray spectra of IC443 by **Fermi-LAT** provides direct evidence that cosmic-ray protons are accelerated in SNRs. Should be neutrino (galactic) sources.
Pulsars and surrounding Pulsar Wind Nebula (PWN): (Galactic & Extended Source) of VHE γ’s

Pulsar:
- a highly magnetized rotating neutron star. Emits a beam of em radiation.
- generates pulsar winds (charged particles/plasmas accelerated to relativistic speeds by rapidly rotating B fields of $10^8$ T) which power surrounding Supernova Remnants = PWN

- Vela: Spectral Energy Distribution strongly favors a two-component leptonic model
- Hadronic model is disfavored

Microquasar SS 433 and its Jets:
(Galactic) Source of VHE $\gamma$ rays
$E_\gamma > 100$ TeV

- SS433: its jets distort the SNR shell
- First direct observation of particle acceleration in jets
- $\gamma$ rays are not Doppler boosted, origin in lobes, not central Black Hole
- Model of PeV electrons + B of 16 mG matches the data
Neutron Stars Merger
Confirmed Source (Transient & Compact) of gravitational waves GW170817 and (short) gamma ray bursts GRB 170817A

NS-merger: possible neutrino production source
No \( \nu \) observed so far.

Credit: Illustration: NASA/CXC/M.Weiss
TXS 0506+56 blazar (AGN+Jets)  
(Extra Galactic) Source of (VHE) $\gamma$'s and $\nu$'s

Example Model:
- One spherical radiation zone model

X-ray and VHE $\gamma$-ray data sensitive to (sub-dominant) hadronic contributions

W. Winter et al (ICRC2019)
Neutrino Fluxes

- CR spectrum formation
- CR acceleration
  - Fermi mechanism: $\gamma_{CR} \sim 2$
- CR propagation
- $\nu$ benchmark model: $\gamma_{\nu} \sim 2$
  - [Fermi acceleration at shock fronts]
- Waxman-Bahcall bound
  - $E_\nu^2 \Phi_{WB} \approx 3.4 \times 10^{-8}$ GeV/cm$^2$sr s

Two neutrino production mechanisms at source:
- $pp$ (hadro-production)
- $p\gamma$ (photo-production)

Benchmark “model”: pion and muon decays, e.g.
- $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow (e^+ + \nu_e + \bar{\nu}_\mu) + \nu_\mu$

Resulting $\nu$ flux flavor composition:
- At Source $(f_e : f_\mu : f_\tau)_S = (1:2:0)_S$
- At Earth $(f_e : f_\mu : f_\tau)_E = (1:1:1)_E$

Require large detection volumes: $\sim 1$ km$^3$ or more
IceCube n telescope
Atmospheric muons and neutrinos: how many?

Events detected per year:

- **atmospheric** $\mu \sim 10^{11}$
  2700 per second

- **atmospheric** $\nu \sim 10^5$
  1 every 6 minutes

- **cosmic** $\nu \sim 10$
  1 every month

Cosmic neutrinos / cosmic rays background:

1 / 10000000000

Credit: IceCube
IceCube: Event Signatures

Tracks:
- through-going muons
- energy resolution ~ factor of 2
- pointing resolution <1°

Cascades:
- e-m and/or hadronic cascades
- cascades contained in detector, resolutions:
  - visible energy ~ 10%
  - angular ~ 10°- 40°

Composites
- starting tracks
- tau “double cascades” (τ hadronic decay)
Cosmic Neutrino (diffuse) Flux
Discovery of Cosmic Neutrinos with IceCube

"ν_µ + ν_e + ν_τ All-Sky High Energy Starting Events" (HESE) analysis

Contained Cascades + Starting Tracks


- Background Atmospheric Muon Flux
- Bkg. Atmospheric Neutrinos (τ/K)
- Background Stat. and Syst. Uncertainties
- Atmospheric Neutrinos (90% CL Charm Limit)
- Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
- Data

3 events
E ~ PeV
IceCube Highest Energy PeV Neutrinos

Muon Neutrino (track) PoS(ICRC2015) 1079

June 2014
deposited energy:
2.6 ± 0.3 PeV
DEC=11.42° RA=110.63°

Median muon energy: 4.5 ± 1.2 PeV
Median ν energy: 8.7 PeV

deposited energy: 5.9±0.18 PeV

Double cascade & double pulse, tau neutrino candidate
deposited energy 90 TeV

J. Stachurska (ICRC2019)
J. Soedingrekso, L. Wille (ICRC2019)
IceCube Diffuse Neutrino flux Measurements and characteristics

A. Schneider PoS(ICRC2019) 1004
H. Niederhausen PoS(ICRC2017) 968
J. Stettner PoS(ICRC2019) 1017

Fig. From F. Halzen (ICRC2019)
IceCube Diffuse Neutrino flux Measurements and characteristics

A. Kappes, D. Williams (ICRC2019)

Single power law (unbroken) describes data well, IceCube continue to observe PeV $\nu$ events
Cascades diffuse flux measurement and characteristics

Beyond single power-law

Fit with two component flux model describes cascade data well, however fit with single power law flux is preferred.
Neutrino, $\gamma$-rays and cosmic rays connection

Cosmic Rays “reservoirs”:
Starburst galaxies (SN, GRB’s, )
Galaxy clusters

Figs from: A.Kappes, K. Murase (ICRC2019)
Cosmic Neutrino (Point) Sources
On 22 September 2017 IceCube detected a ~290-TeV neutrino from a direction, as reported by Fermi-LAT on September 28 2017, consistent with the flaring γ-ray blazar TXS 0506+056.

Multi-wavelength photon follow up observations
Evidence of the first $\nu$ source: TXS 0506+056

- $\nu_\mu$-flare found in archival IceCube data
  10/2014 - 03/2015

Identification of a blazar as a source of HE $\nu$’s and CR’s
Significance: 3.5 sigma (2 / 10000)

Science 361, eaat1378 (2018)
Science 361, 146 (2018)
**IceCube All-Sky Point Source Search**

- All-Sky search (10yrs): Search for excess of astro ν from a common direction over the bg of atm. ν (Northern Sky) or μ / ν (Southern Sky).
- Assumed time integrated emission of ν’s and E–γ energy spectrum.

---

**Hottest Point in South**: δ < -5°
- RA = 350.18°, Dec = -56.45°
- $n_{\text{signal}} = 17.8$, $γ = 3.3$, $TS = 20.0$
- $-\log_{10}(p_{\text{val}}) = 5.37 \Rightarrow 75\%$ post-trial

**Hottest Point in North**: δ ≥ -5°
- RA = 40.87°, Dec = -0.30°
- $n_{\text{signal}} = 61.5$, $γ = 3.4$, $TS = 25.3$
- $-\log_{10}(p_{\text{val}}) = 6.45 \Rightarrow 9.9\%$ post-trial

T. Carver et al (ICRC2019)
IceCube All-Sky Point Source: Catalog List Search

- New source candidates list of 110 Galactic & Extra-galactic sources
- Results: Northern Sources (87 extra-galactic, 10 Galactic)
  Southern Sources (11 extra-galactic, 2 Galactic)

- Most significant source from list NGC1068 (2.9σ post trial)
- 4 most significant sources 3.3σ post trial (2.2σ without TXS 0506)

T. Carver et al (ICRC2019)
• New source candidates list of 57 Galactic & Extra-galactic sources
• 7yrs IceCube data + 9years Antares data

No significant evidence of cosmic neutrino sources has been found
IceCube All-Sky Source Search with Cascades (7yrs)

1907.06714 [astro-ph]

- Median cascade resolution $< 10^0$ above 40 TeV with deep learning
- The most significant source was RX J1713.7-3946 (Supernova Remnant, SNR)

SNR stacking analysis results

<table>
<thead>
<tr>
<th>Catalog</th>
<th>7yr Cascades</th>
<th>7yr Tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity</td>
<td>p-value</td>
</tr>
<tr>
<td>SNR with mol. cloud</td>
<td>9.9</td>
<td>0.12</td>
</tr>
<tr>
<td>SNR with PWN</td>
<td>6.3</td>
<td>1</td>
</tr>
<tr>
<td>SNR alone</td>
<td>7.5</td>
<td>0.082</td>
</tr>
</tbody>
</table>

Table 1. Sensitivity and results of the SNR stacking analyses, compared to the previous analysis with tracks (Aartsen et al. 2017b). Sensitivity and ULs are given as $E^2 \cdot (E/100\text{TeV})^{0.5} \cdot dN/dE$ in units $10^{-12} \text{ TeV cm}^{-2} \text{s}$. 

Combined ANTARES, IceCube, PAO and TA search for common origin between high energy neutrinos and cosmic rays

Three searches:

1. Neutrino/UHECR cross-correlation
2. Search for neutrino clusters in direction of UHECR
3. Search for UHECR clusters in direction of neutrinos

No significant correlation seen
Neutrino- Nucleon Cross Section Measurements

TeV-PeV Neutrino absorption in Earth

IceCube: Nature 551 (2017) 596

SM $\nu_\mu$-N cross section scales by $\kappa$ factor

$1.30^{+0.21}_{-0.19}$ (stat.) $+0.39$ (syst.)
HE Neutrino- Nucleon Cross Section Measurements

TeV-PeV neutrinos of all flavors
Cross section consistent with Standard Model
(Optical) Neutrino Observatories: Future to address the unresolved origin of astrophysical neutrinos

- Baikal-GVD, Km3Net – ARCA under construction coming online ICRC2019 first results
- P-ONE Ocean Network Canada conceptual phase

- IceCube-Gen2: proposed multi-cubic-kilometer neutrino detector
- Designed to be sensitive to 5x fainter sources
- Wide-band neutrino observatory with optical and radio detectors, surface array
Era of km$^3$ neutrino astronomy has begun

IceCube Discovery $\rightarrow$ Measurements $\rightarrow$ Models testing

Diffuse signal $\rightarrow$ First source $\rightarrow$ Catalog!

Astrophysical neutrinos have been discovered
Diffuse flux characteristics - unbroken power law
Interpretation challenging
Evidence of neutrino source: flaring blazar
M77/NG1068 stands out in the latest source search (catalog and all sky search)
Cosmic accelerator source searches continue ….

Large(r) detectors needed on BOTH Northern and Southern hemisphere

Other complementary techniques (not covered here): $\nu$’s radio detection

Stay tuned!
THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Lab
Marquette University
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of California, Los Angeles
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and 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)