Next Steps in Neutrino Astronomy with IceCube



John Kelley for the IceCube Collaboration

SCAR 2016 Kuala Lumpur, Malaysia August 23, 2016

Cosmic Ray Acceleration and Neutrino Production



Fermi shock acceleration: $dN/dE \sim E^{-2}$

$$p + \gamma \rightarrow p + \pi^{0}, n + \pi^{+}$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

1:2:0 flavor ratio at source

Similar processes (incl.p+p) happening in:

- cosmic ray sources (ambient light, gas)
- outer space (cosmic microwave background)
- Earth's atmosphere (N, O, etc. nucleus)

astrophysical source neutrinos cosmogenic neutrinos atmospheric neutrinos

IceCube from the Air



The IceCube Detector



Detection Principle





Cosmic-ray muons: ~3000 / second Atmospheric neutrinos: ~1 / 5 minutes Astrophysical neutrinos: ~1 / month

Event Topologies

Positions, times, and amplitudes of Cherenkov light deposition: <u>neutrino direction + energy</u>



track (data)

factor of ≈ 2 energy resolution < 1° angular resolution at high energies



shower (data)

- ≈ ±15% deposited energy resolution
 ≈ 10° angular resolution
- (at energies ≥ 100 TeV)



''double-bang''(≩10 PeV) and other signatures (simulation)

```
(not observed yet)
```

High-Energy Starting Event Search

- High-energy starting event (''HESE'') search
- Veto layer excludes atmospheric muons and some atmospheric neutrinos
- Sensitive to all flavors, all directions



Latest Results (2010–2014 data)

• 54 events in 1347 days

arXiv:1510:05223 update of PRL (2014), Science (2013)

- Estimated backgrounds:
 9.0^{+8.0}_{-2.2} atm. neutrinos
 12.6±5.1 atm. muons
- Significance over background-only hypothesis: ~7σ



Deposited EM-Equivalent Energy in Detector (TeV)

Highest-energy HESE Event



2 PeV — "Big Bird"

Skymap (HESE)



No significant clustering found, including around Galactic plane

SCAR 2016

Point-source Search Skymap



What are the Sources?



- ¹ IceCube collab., Ap.J.Lett. 2014
 ² Bechtol et al., arXiv:1511.00688
 ³ IseCube collab. submitted to Ap
- ³ IceCube collab., submitted to Ap.J.

- No resolved neutrino point source yet
- No source-class correlation observed yet
- Constrained: – flux < ~1% GRBs¹ < ~15% starburst galaxies² < ~30% blazars³
- Unconstrained so far:
 - radio AGN
 - supernovae
 - "choked" source models

Multi-messenger Neutrino Follow-up



- Neutrino candidates identified with South Pole online system
- Partner observatories alerted
- Public GCN via AMON for HESE track-like + EHE (extremely high-energy) events

From DOMs to Neutrino Alert



Looking Forward: The IceCube–Gen2 Facility

- IceCube–Gen2 High-Energy Array
 - high-statistics energy spectrum
 - high-energy track events to pinpoint sources
- PINGU
 - low-energy infill of DeepCore
 - precision oscillation and mass hierarchy
- Extended surface detector + veto
- Additional radio detection technology



Streamlined Drilling & Logistics



- Next-generation Enhanced Hot Water Drill
 - reduced footprint
 - smaller crew
- Transport equipment and fuel using South Pole Traverse
 - fewer flights needed
- May also reduce hole diameter
 - reduced fuel usage

IceCube–Gen2Target Sensitivity

Baseline Gen2 DOM

• updated electronics

New technologies

- more PMTs
- wavelength shifters
- narrow profile
- better glass, gel







Summary



- IceCube has observed a diffuse flux of high-energy astrophysical neutrinos
 - "first light" for neutrino astronomy
- No evidence of anisotropy
 - likely partially extragalactic
 - no point source found yet
- Stacking analyses limit contribution from GRBs, blazars
- Robust multi-messenger campaigns in progress
- Design of new IceCube–Gen2 facility underway



The IceCube Collaboration

USA

Canada University of Alberta–Edmonton University of Toronto

Clark Atlanta University Drexel University Georgia Institute of Technology Lawrence Berkeley National Laboratory Marquette University Massachusetts Institute of Technology **Michigan State University Ohio State University** Pennsylvania State University South Dakota School of Mines & 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 Delaware **University of Kansas** University of Maryland University of Rochester University of Wisconsin-Madison University of Wisconsin-River Falls Yale University

University of Copenhagen, Denmark

Chiba University, Japan

Sungkyunkwan University, Korea

University of Oxford, UK -

Belgium Université Libre de Bruxelles Université de Mons Universiteit Gent Vrije Universiteit Brussel Sweden Stockholms universitet Uppsala universitet

Germany

Deutsches Elektronen-Synchrotron Friedrich-Alexander-Universität Erlangen-Nürnberg Humboldt-Universität zu Berlin Ruhr-Universität Bochum RWTH Aachen Technische Universität Dortmund Technische Universität München Universität Mainz Universität Münster Universität Wuppertal

Université de Genève, Switzerland

University of Adelaide, Australia

University of Canterbury, New Zealand

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)