

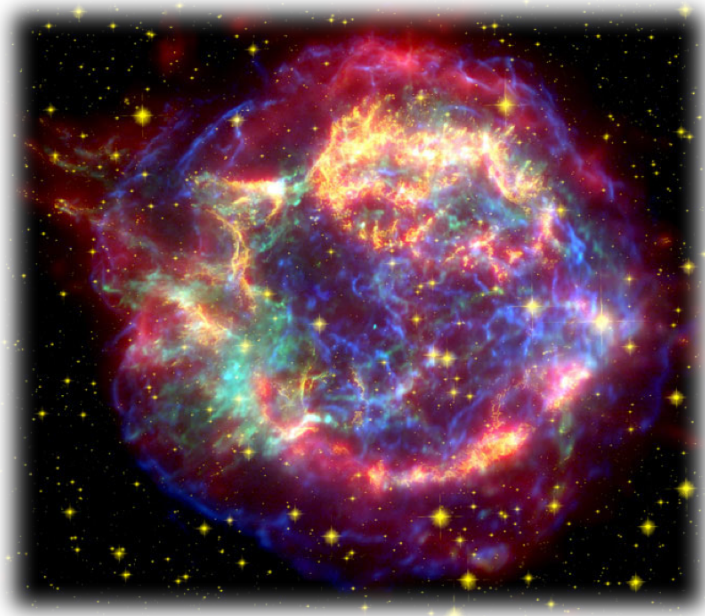
# Next Steps in Neutrino Astronomy with IceCube



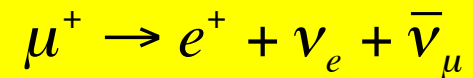
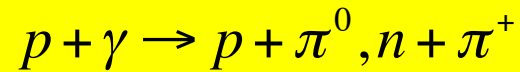
John Kelley for the IceCube Collaboration

SCAR 2016  
Kuala Lumpur, Malaysia  
August 23, 2016

# Cosmic Ray Acceleration and Neutrino Production



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



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)

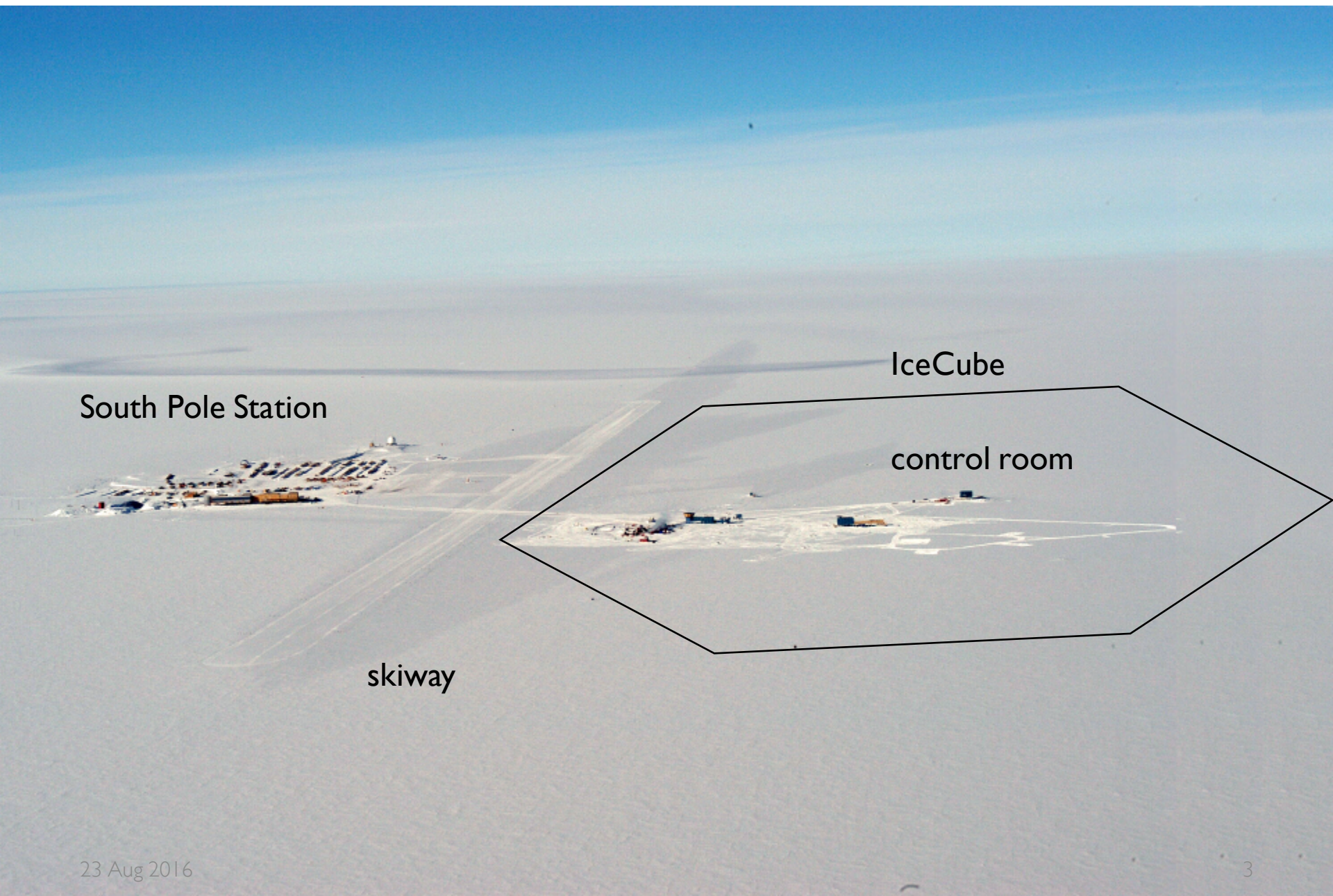
astrophysical source

neutrinos

cosmogenic neutrinos

atmospheric neutrinos

# IceCube from the Air



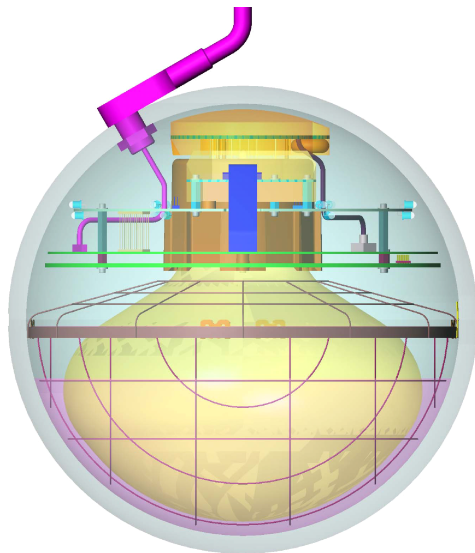
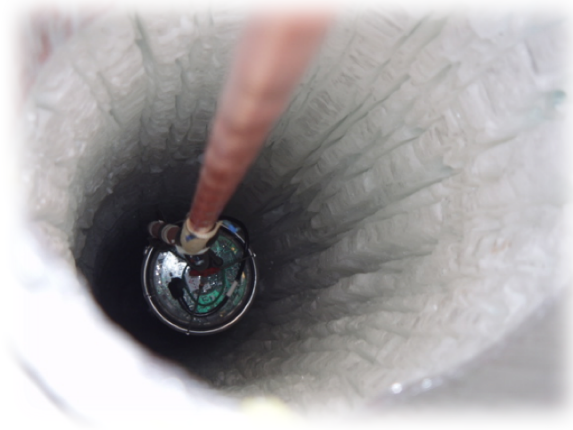
South Pole Station

IceCube

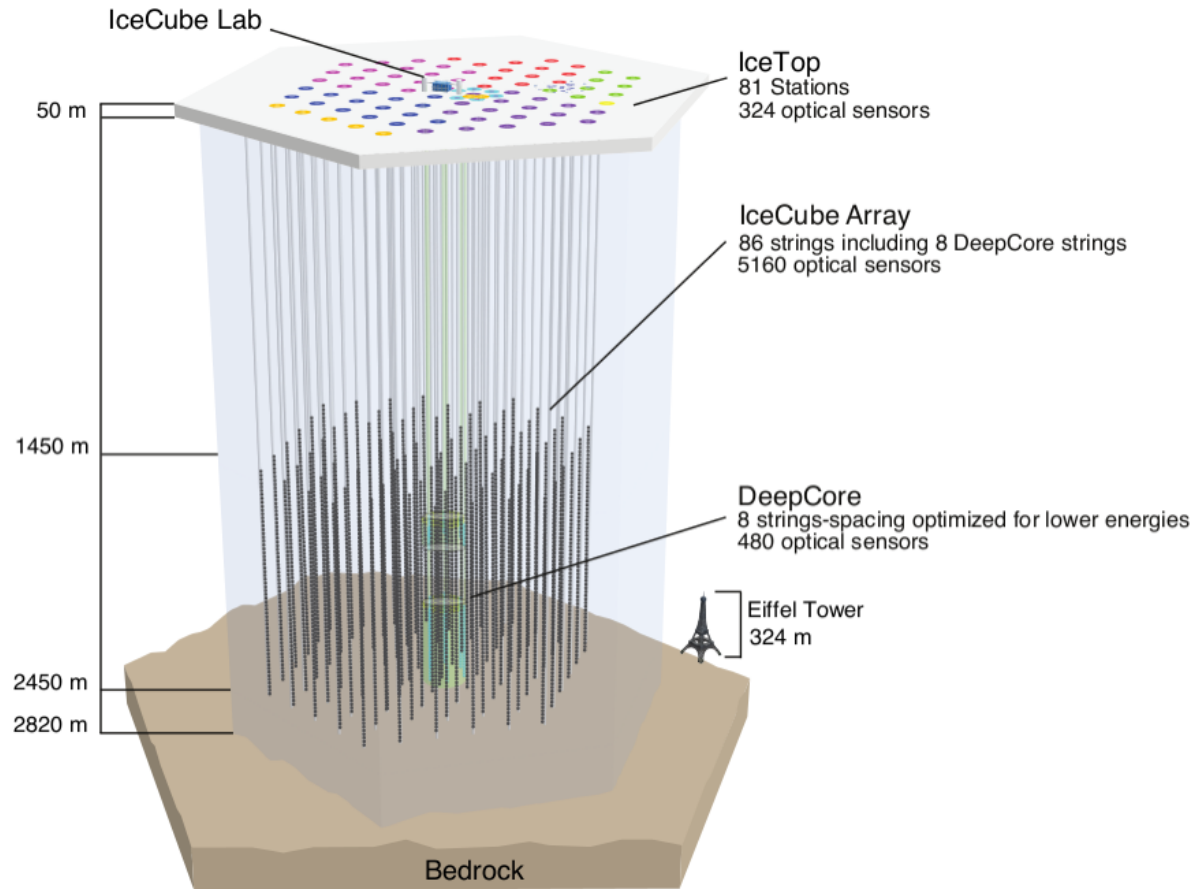
control room

skiway

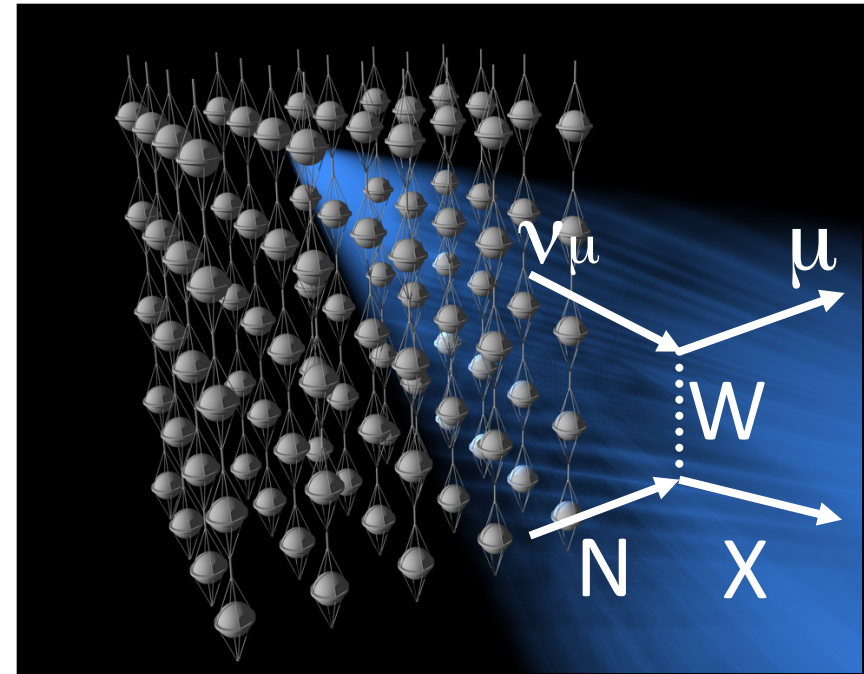
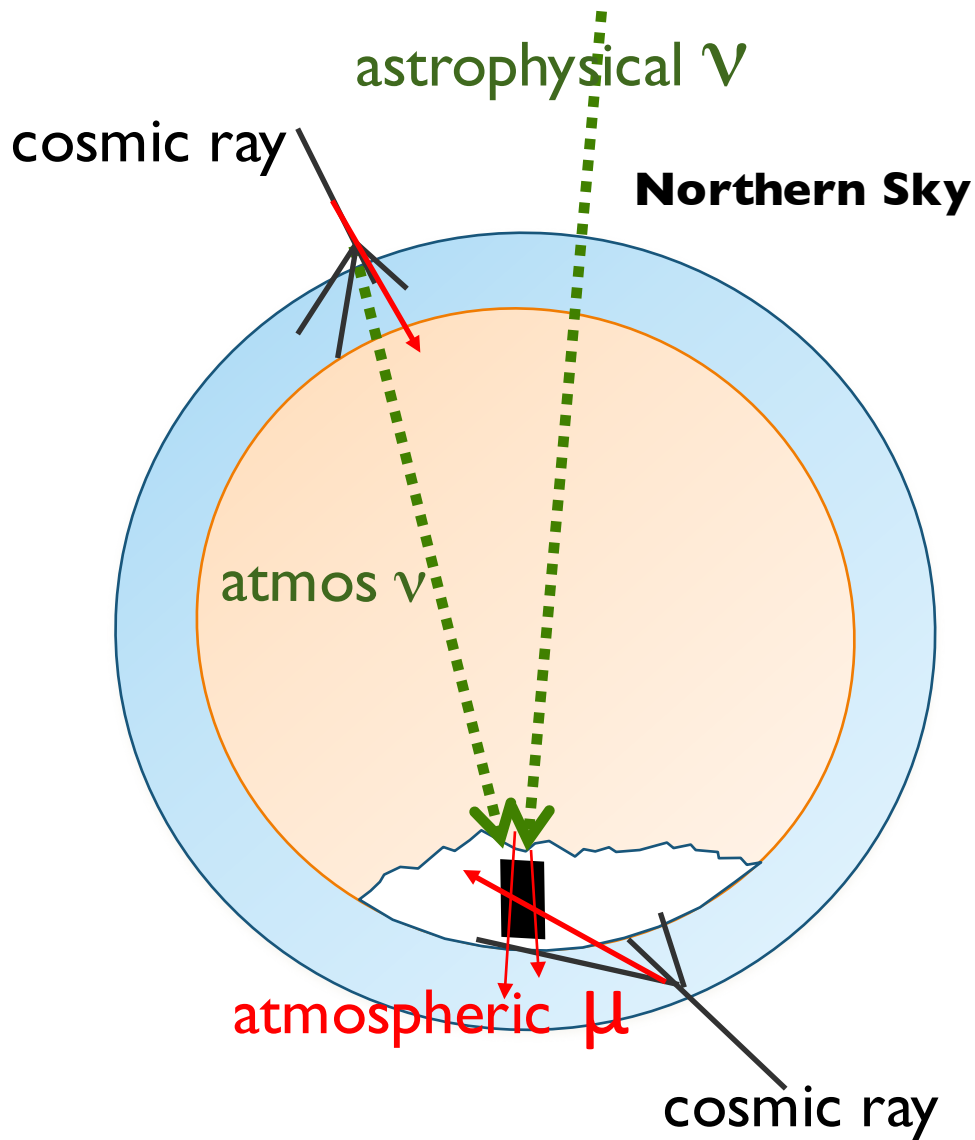
# The IceCube Detector



digital optical module (DOM)



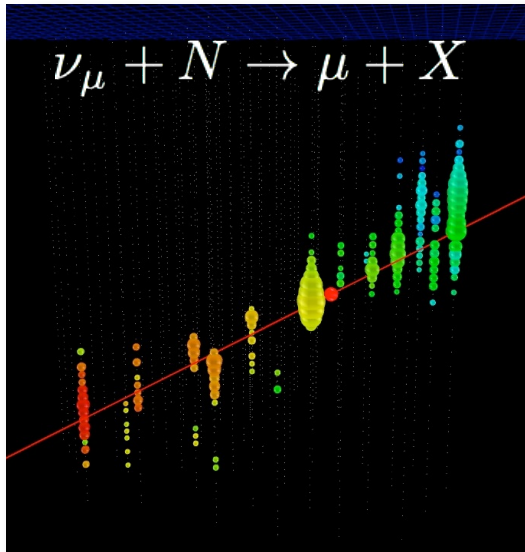
# Detection Principle



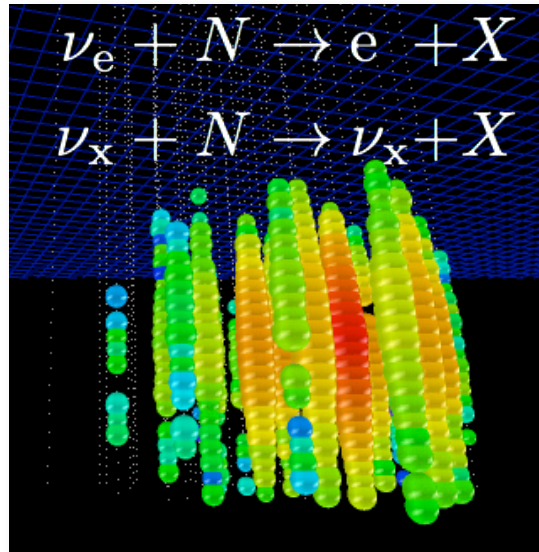
Cosmic-ray muons:  $\sim 3000$  / second  
Atmospheric neutrinos:  $\sim 1$  / 5 minutes  
Astrophysical neutrinos:  $\sim 1$  / **month**

# Event Topologies

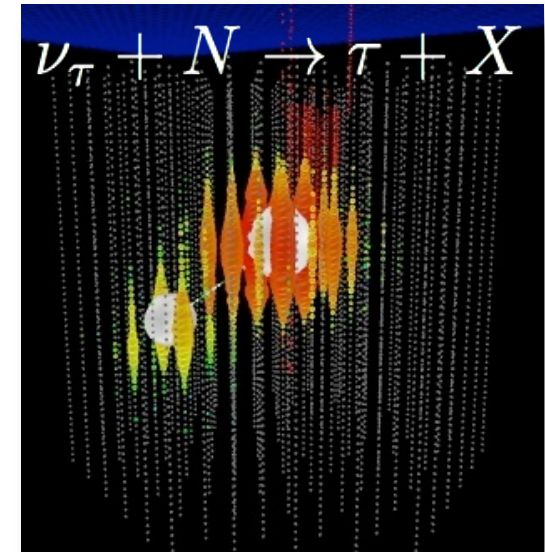
Positions, times, and amplitudes of Cherenkov light deposition: neutrino direction + energy



track (data)



shower (data)



"double-bang" ( $\gtrsim 10$  PeV)  
and other signatures  
(simulation)

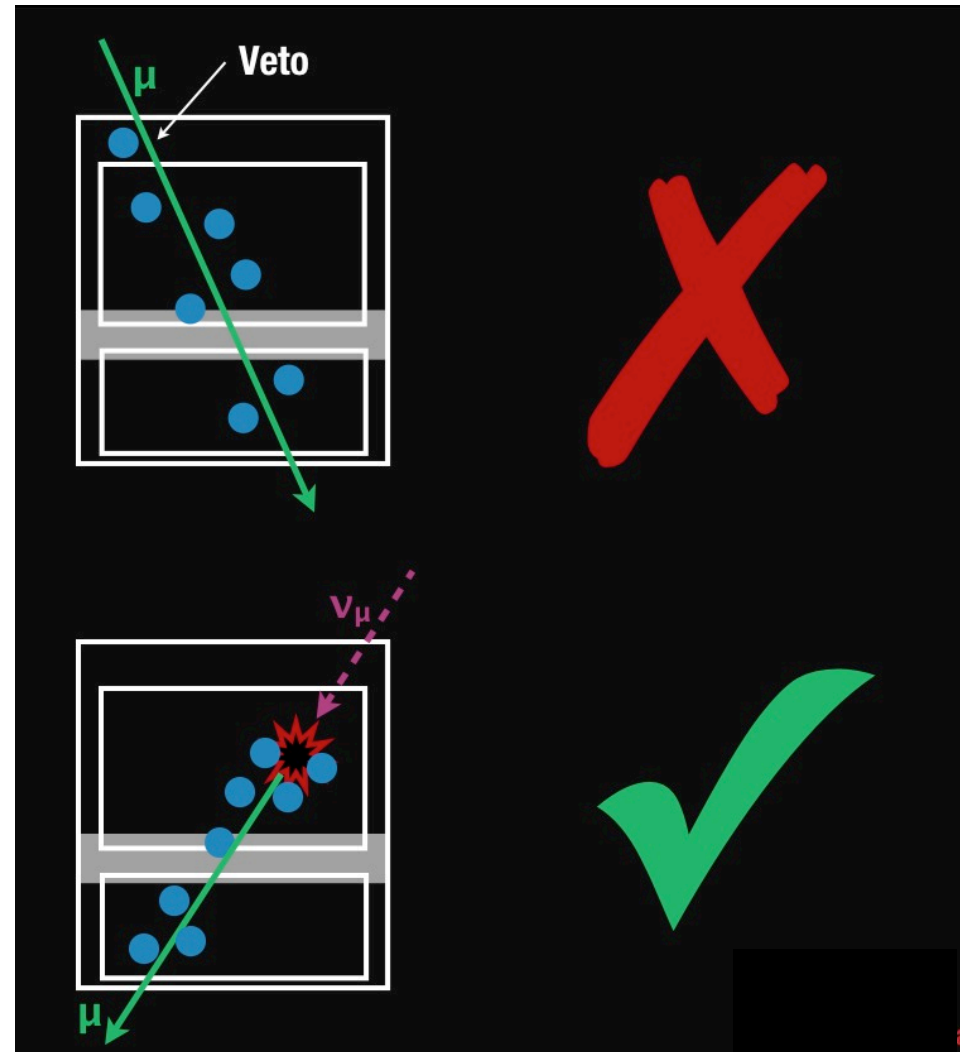
(not observed yet)

factor of  $\approx 2$  energy resolution  
<  $1^\circ$  angular resolution at high  
energies

$\approx \pm 15\%$  deposited energy  
resolution  
 $\approx 10^\circ$  angular resolution  
(at energies  $\gtrsim 100$  TeV)

# 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



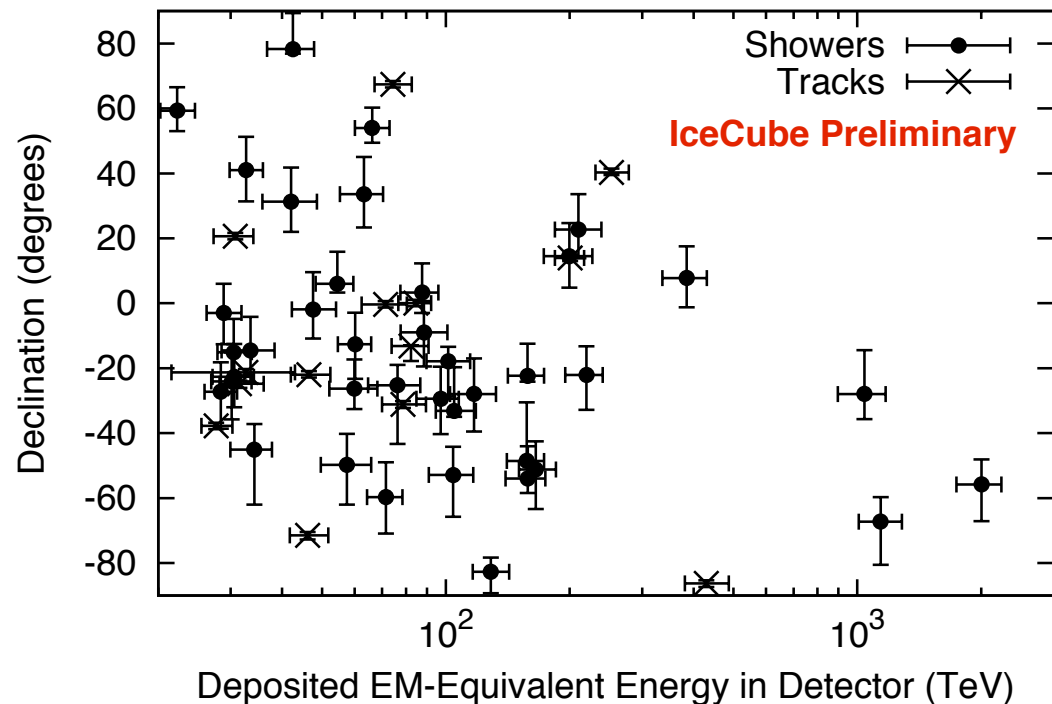
courtesy C. Kopper

# Latest Results (2010–2014 data)

arXiv:1510:05223

update of PRL (2014), Science (2013)

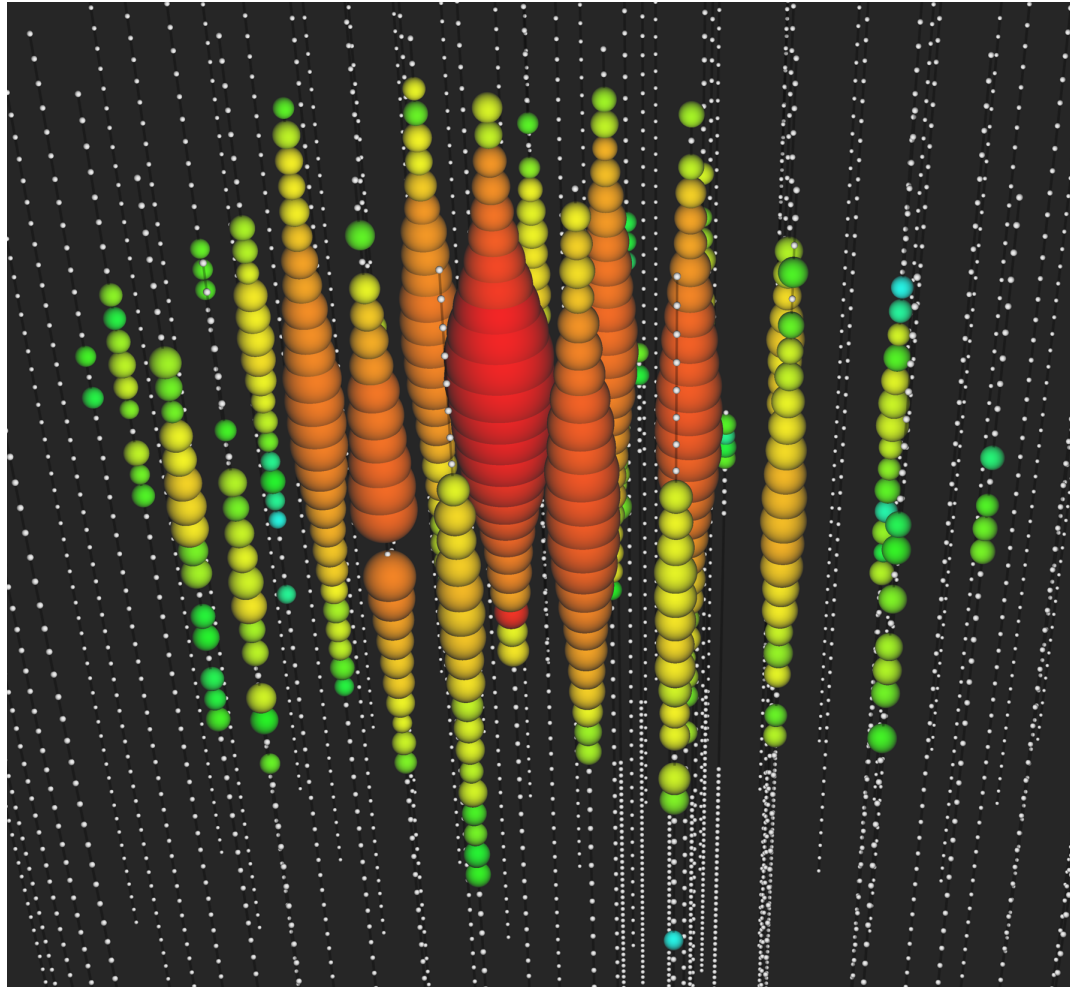
- 54 events in 1347 days
  - $9.0^{+8.0}_{-2.2}$  atm. neutrinos
  - $12.6 \pm 5.1$  atm. muons
- Estimated backgrounds:
  - $9.0^{+8.0}_{-2.2}$  atm. neutrinos
  - $12.6 \pm 5.1$  atm. muons
- Significance over background-only hypothesis:  $\sim 7\sigma$





# Highest-energy HESE Event

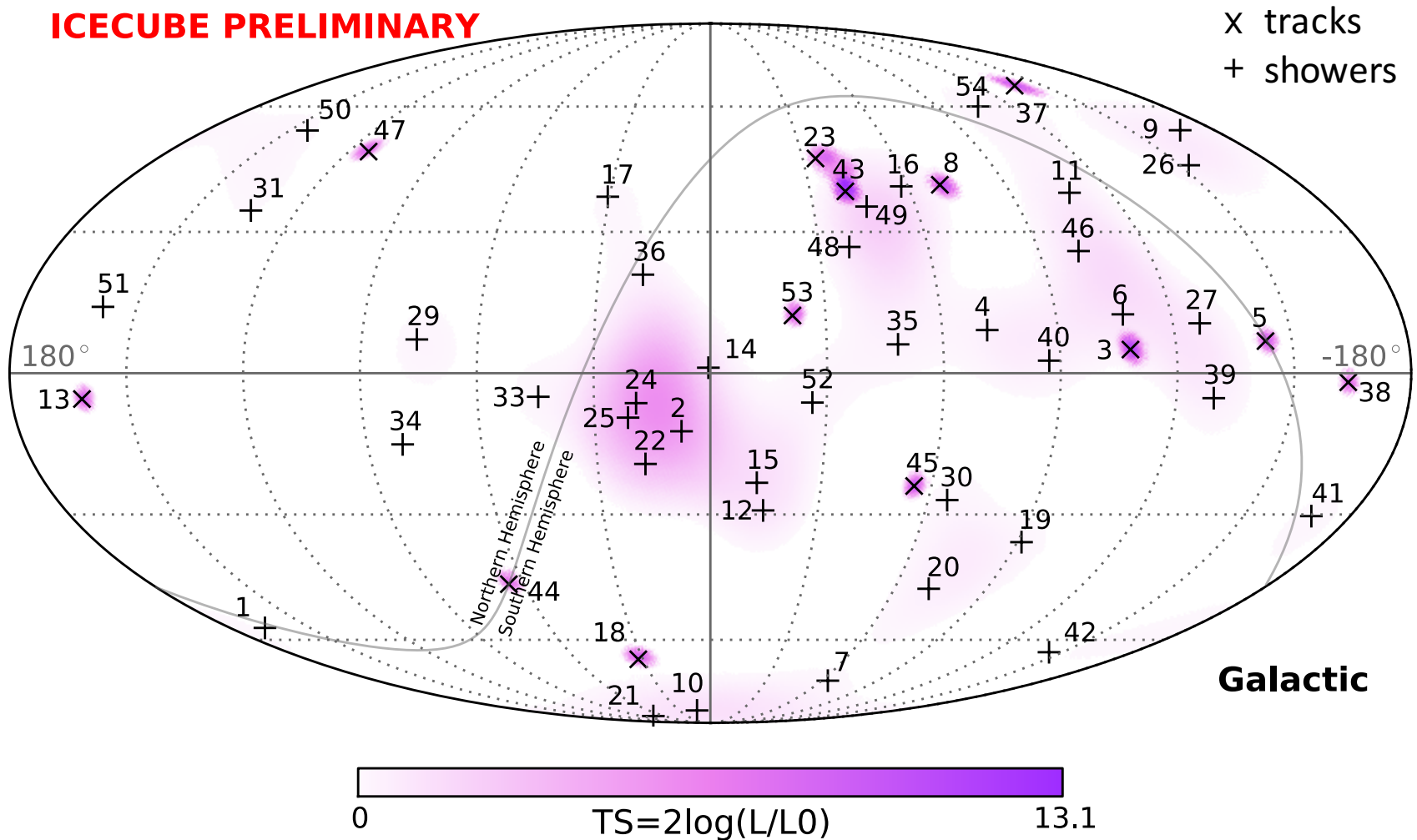
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2 PeV — “Big Bird”

# Skymap (HESE)

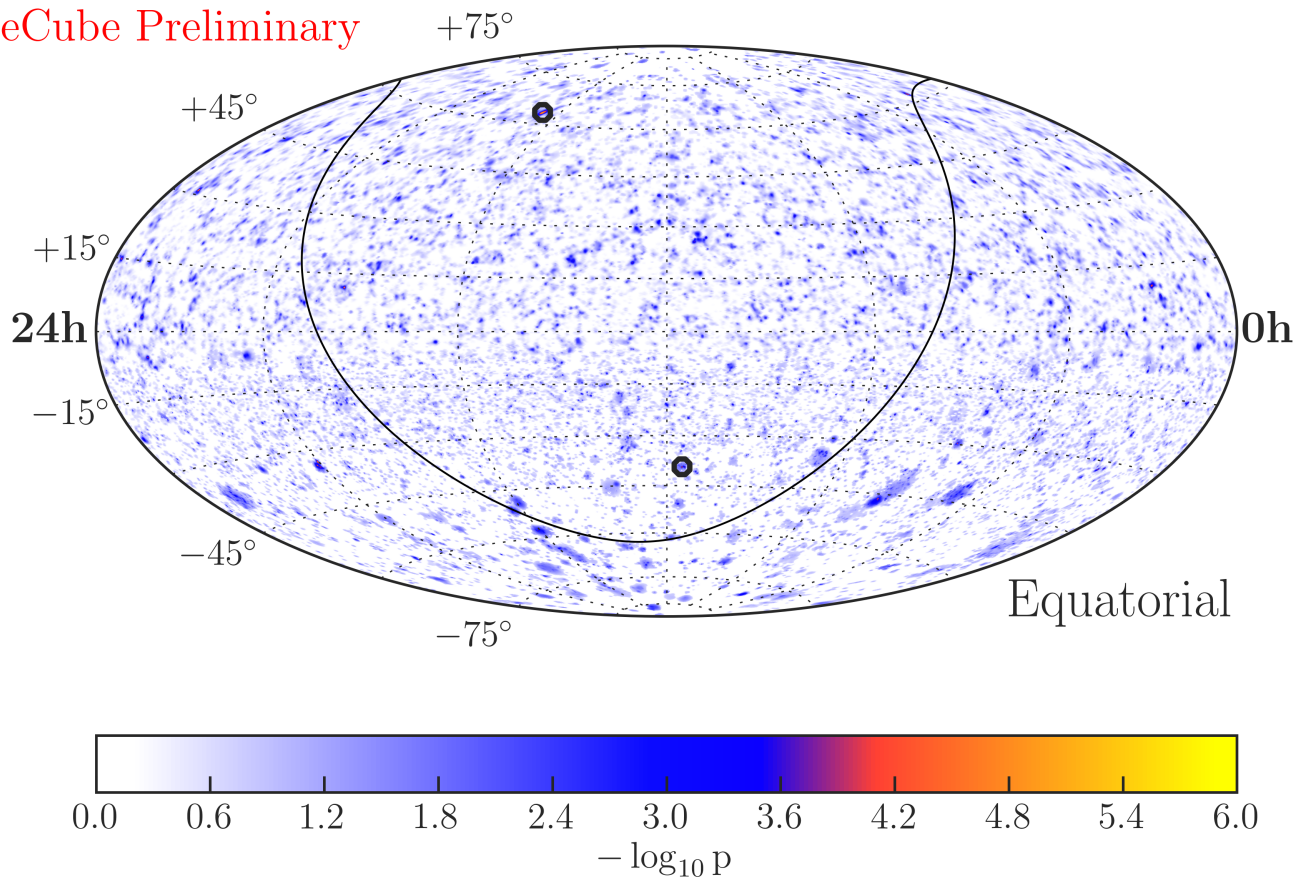
**ICECUBE PRELIMINARY**



No significant clustering found, including around Galactic plane

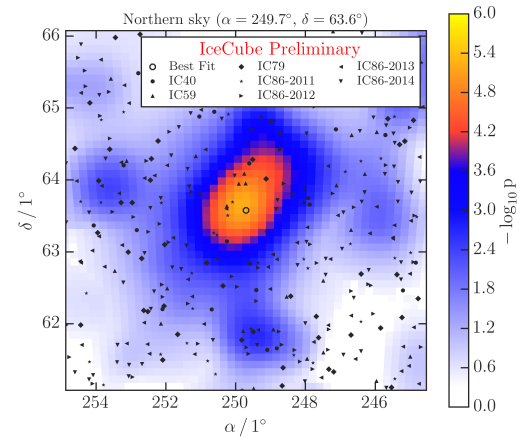
# Point-source Search Skymap

IceCube Preliminary

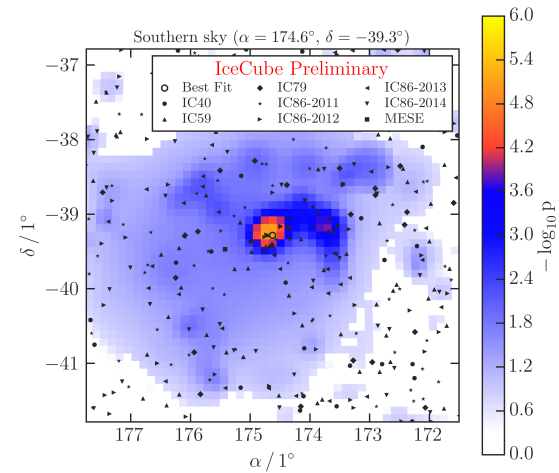


No point source found (7 years of data)

Northern sky:  $N_{\text{source}} > O(10^3)$



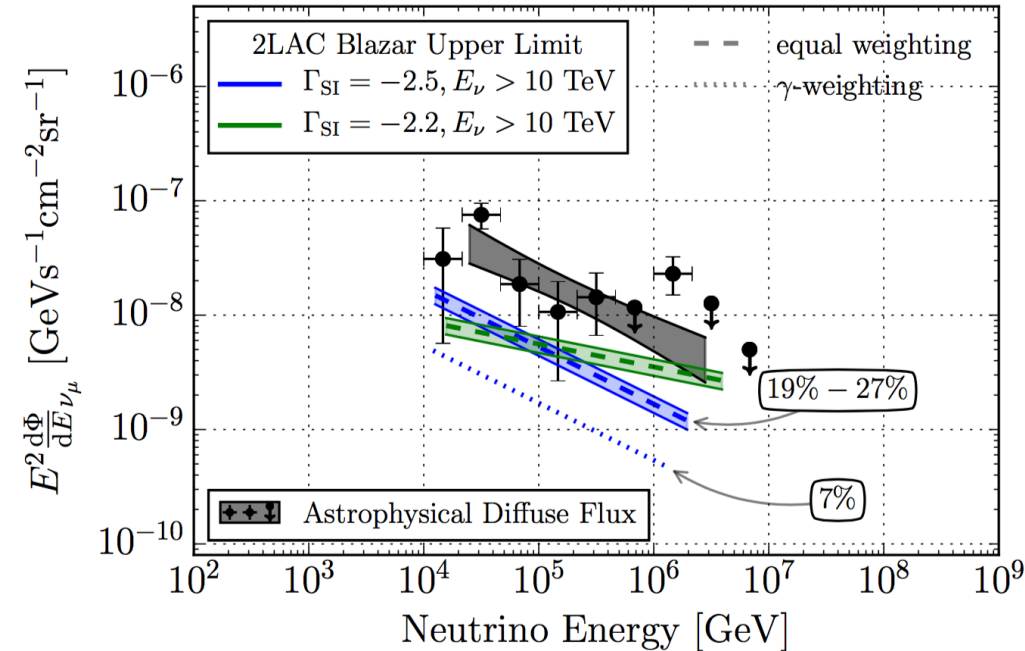
p-value: 44%



p-value: 39%

# What are the Sources?

## Blazar stacking flux limit



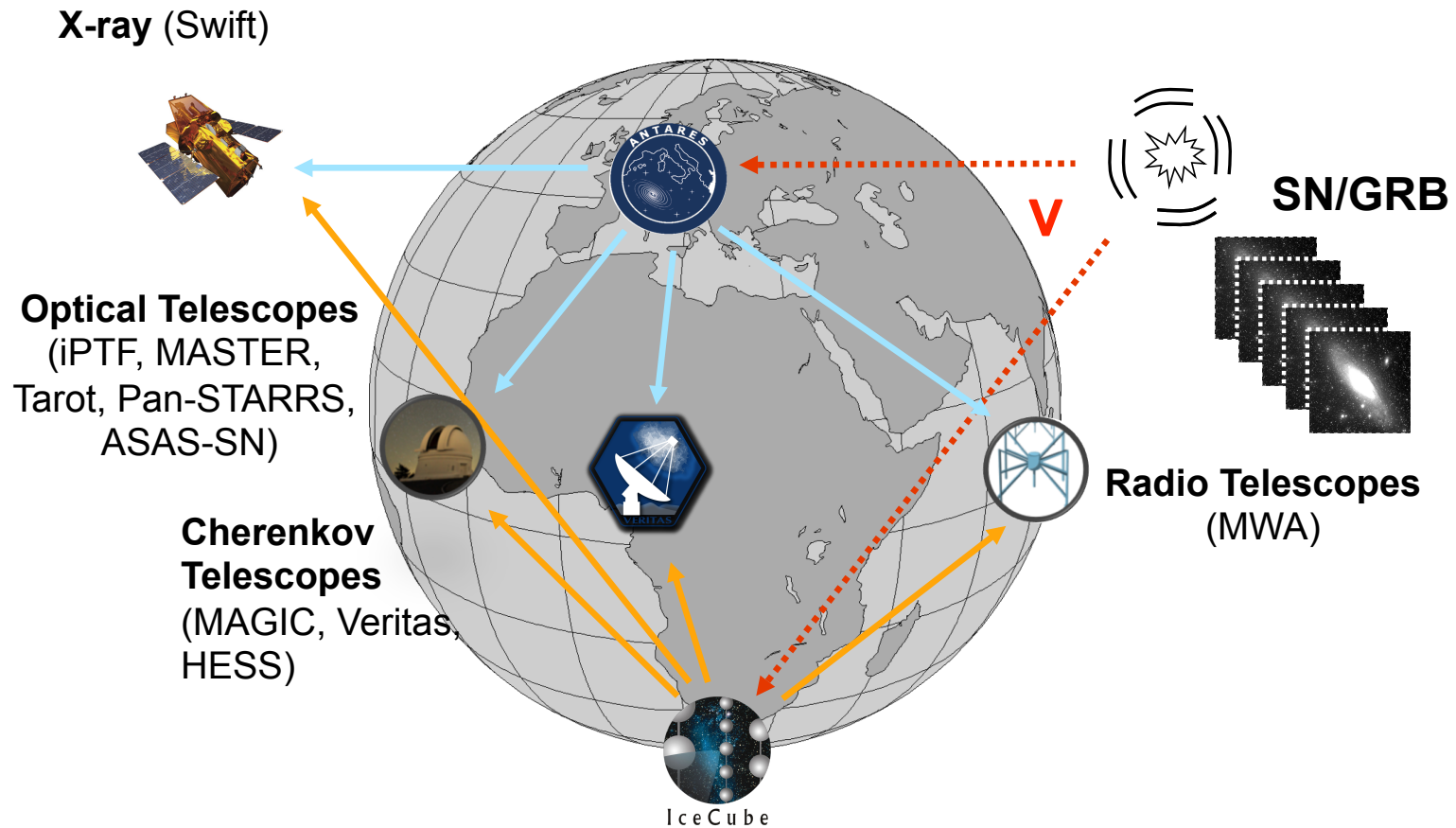
- No resolved neutrino point source yet
- No source-class correlation observed yet
- Constrained:
  - flux  $< \sim 1\%$  GRBs<sup>1</sup>
  - $< \sim 15\%$  starburst galaxies<sup>2</sup>
  - $< \sim 30\%$  blazars<sup>3</sup>
- Unconstrained so far:
  - radio AGN
  - supernovae
  - “choked” source models

<sup>1</sup> IceCube collab., Ap.J.Lett. 2014

<sup>2</sup> Bechtol et al., arXiv:1511.00688

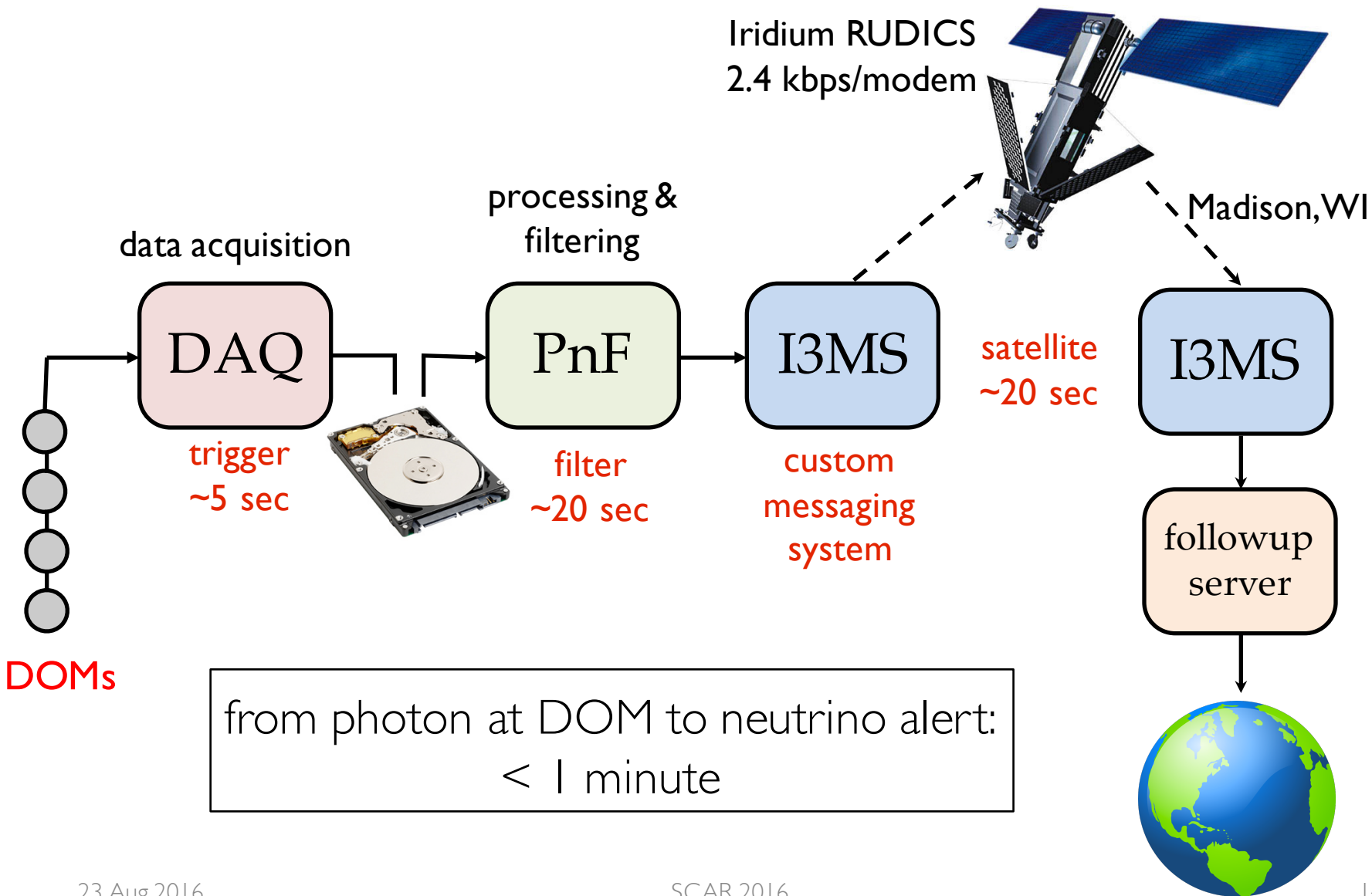
<sup>3</sup> IceCube collab., submitted to Ap.J.

# 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

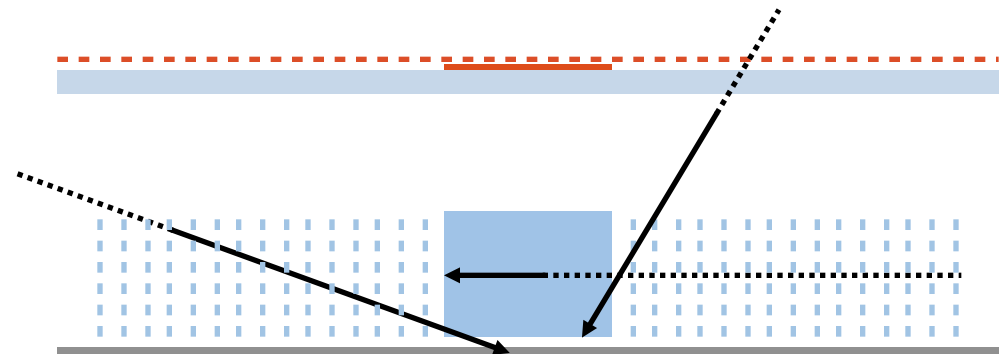
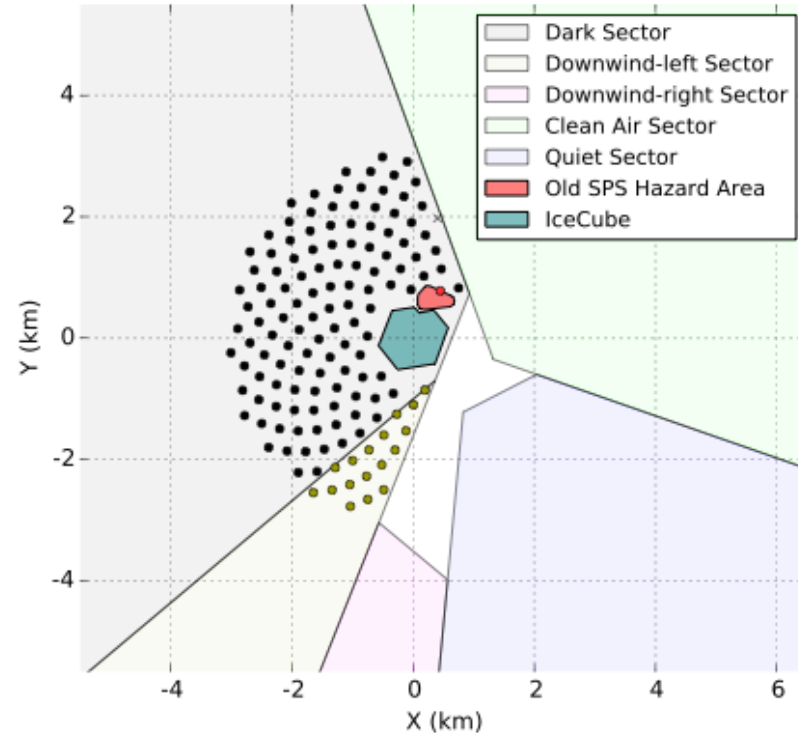
# From DOMs to Neutrino Alert



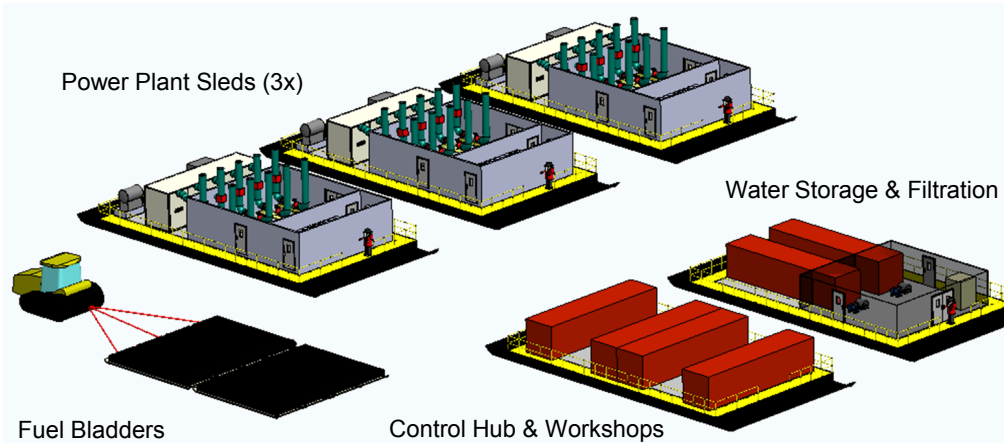
# Looking Forward: The IceCube–Gen2 Facility

- 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

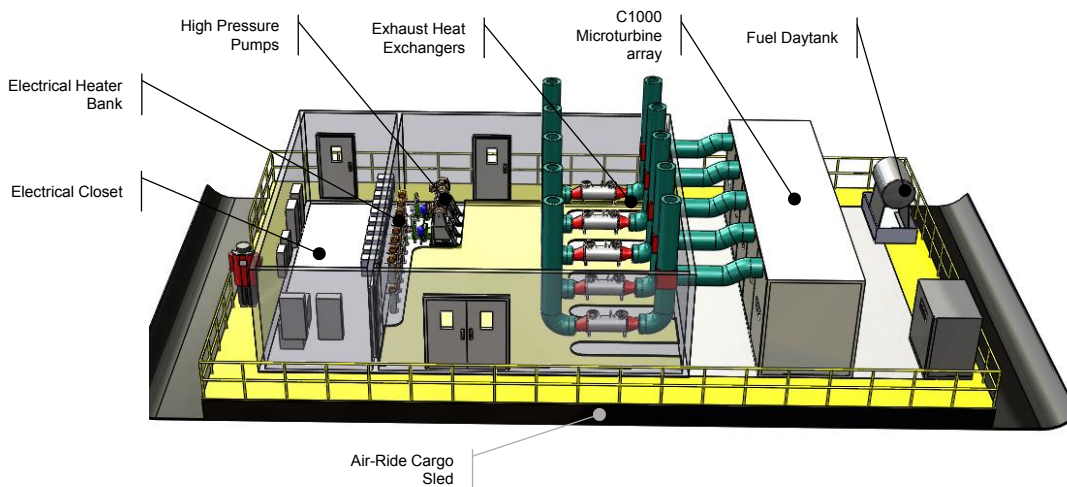
HE layout for  $s = 183.30$  m,  $N = 120 + (17 \text{ downwind, } 1 \text{ edge, } 1 \text{ hazard})$  in IceCube (X,Y) coordinates



# 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

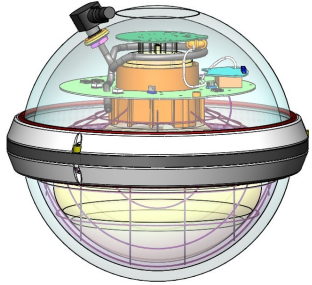




# IceCube–Gen2 Target Sensitivity

## Baseline Gen2 DOM

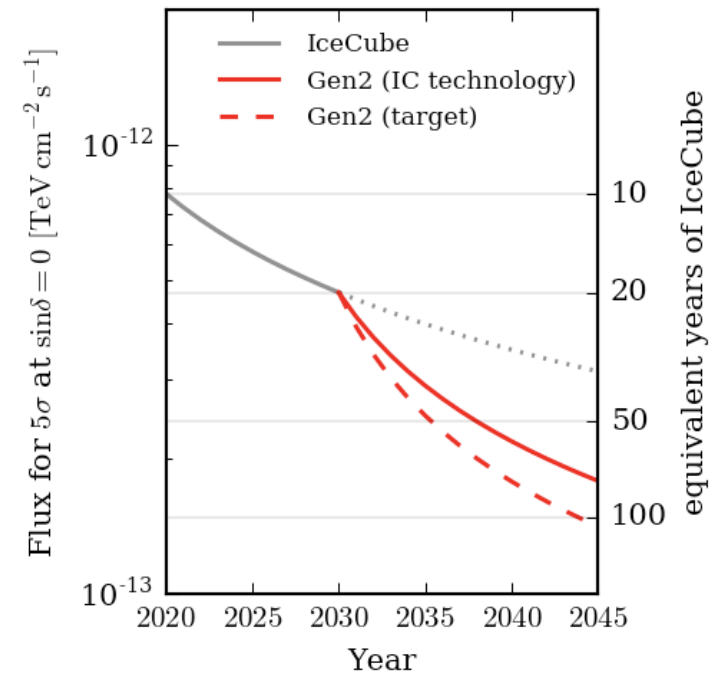
- updated electronics



## New technologies

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

## Point source sensitivity

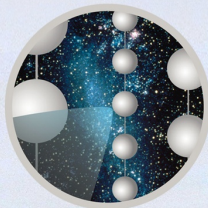


# Summary

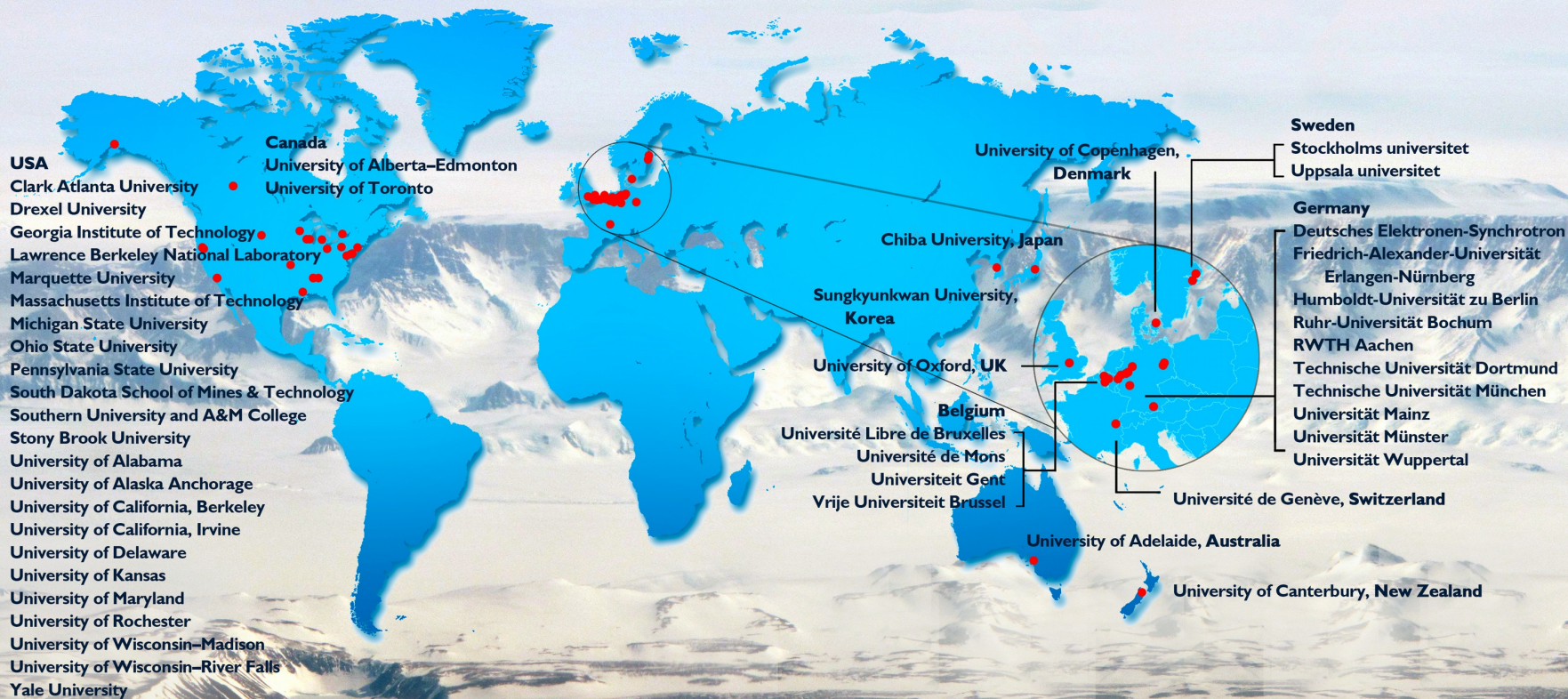
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- IceCube has observed a diffuse flux of high-energy astrophysical neutrinos
  - “first light” for neutrino astronomy
- No evidence of anisotropy
  - likely partially extragalactic
  - no point source found yet
- Stacking analyses limit contribution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



# The IceCube Collaboration



## 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)