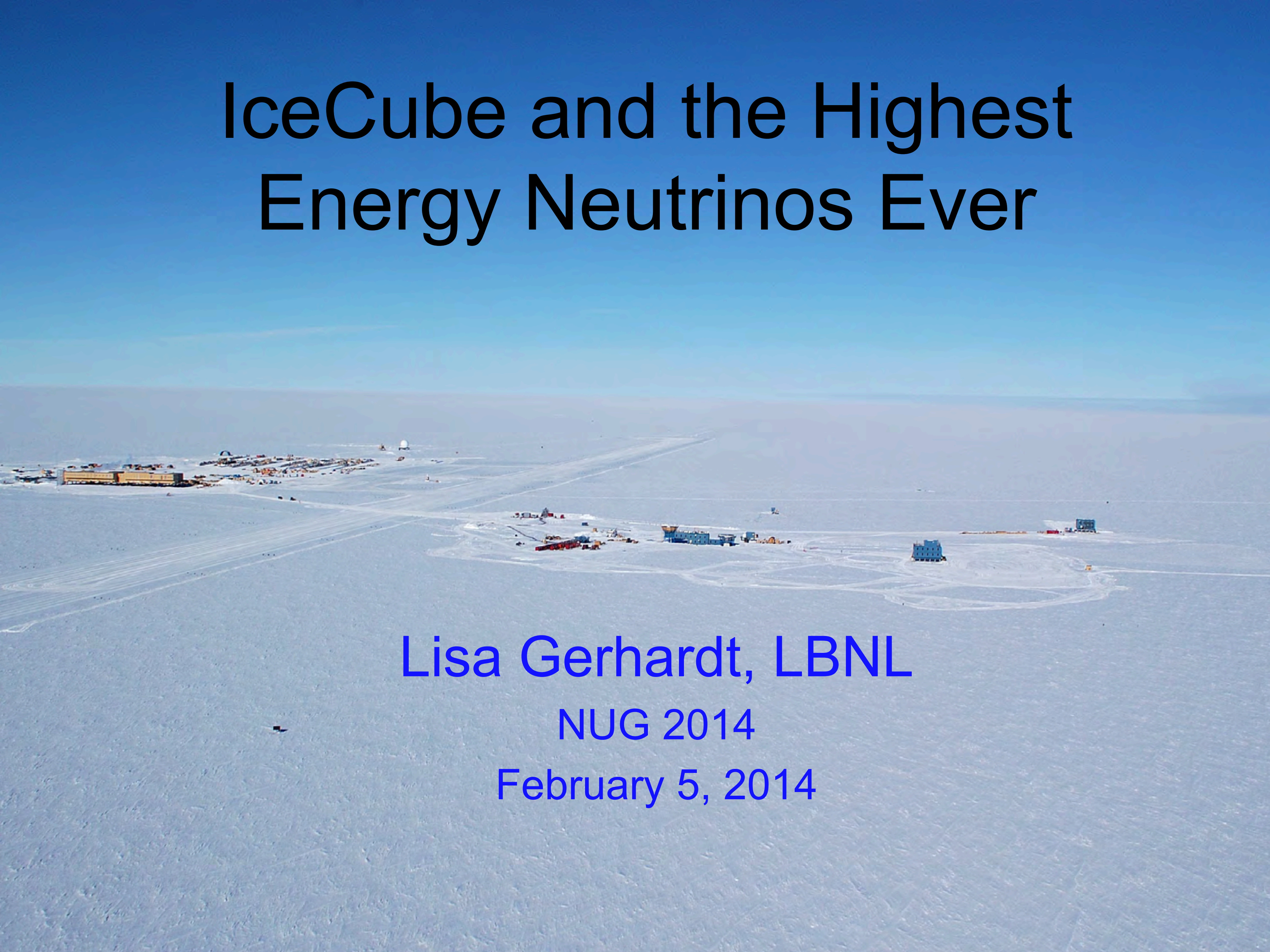


IceCube and the Highest Energy Neutrinos Ever

Lisa Gerhardt, LBNL

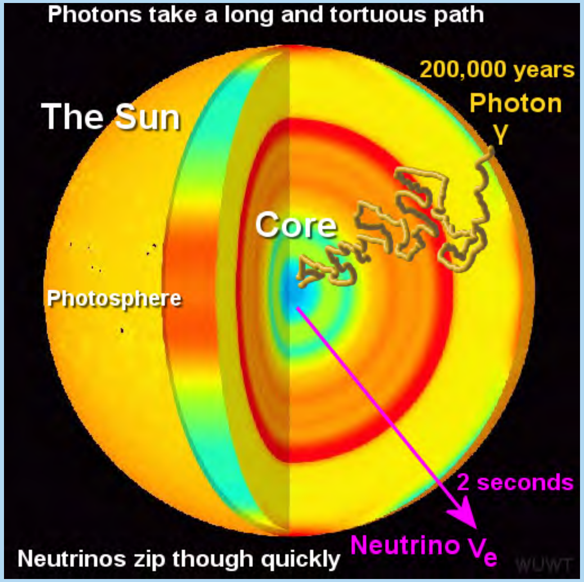
NUG 2014

February 5, 2014

Neutrinos

"Small neutral one"
Fundamental particle
Three Flavors

"Ghost Particle"



Neutrinos are produced locally in Sun, nuclear reactors, and cosmic ray interactions in atmosphere

Why neutrinos?

Three particles to observe the universe

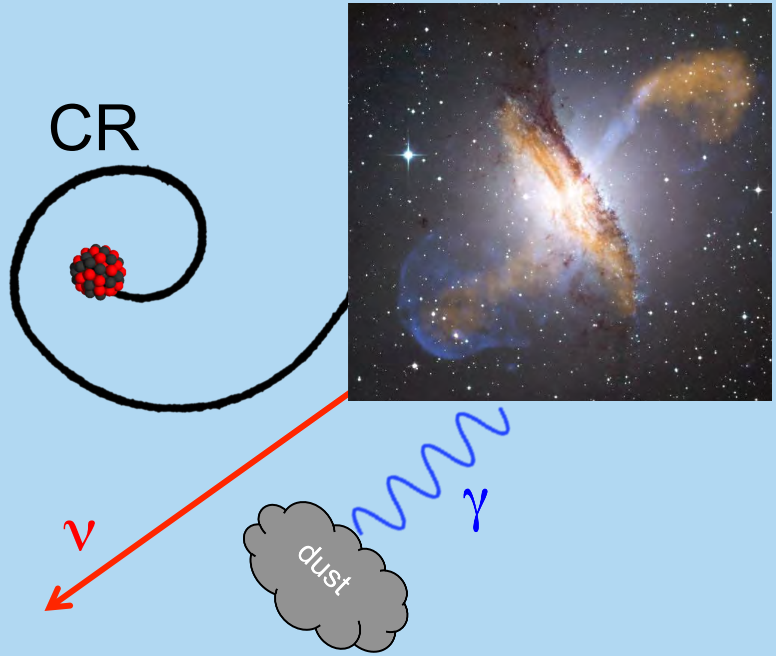
– Photons, cosmic rays, and neutrinos

High energy photons are absorbed by dust, other photons

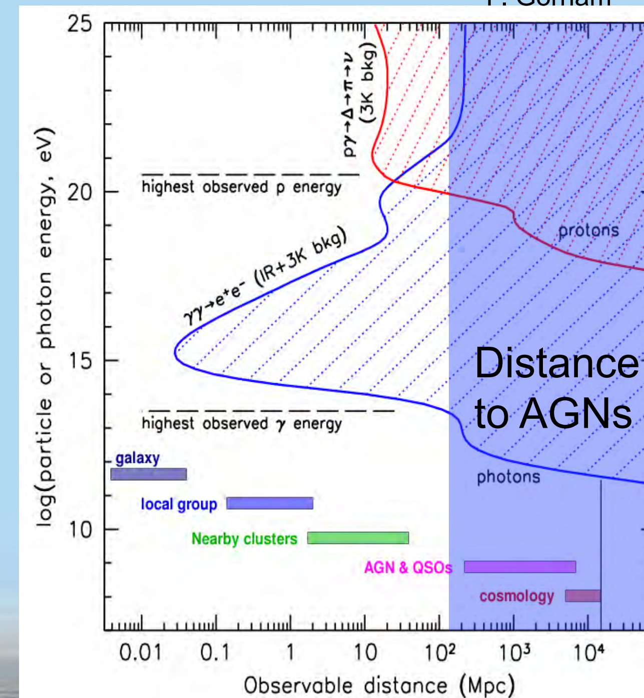
Cosmic rays are bent by magnetic fields

– "Big" so easy to interact

Neutrinos are a unique probe of distant astronomical objects

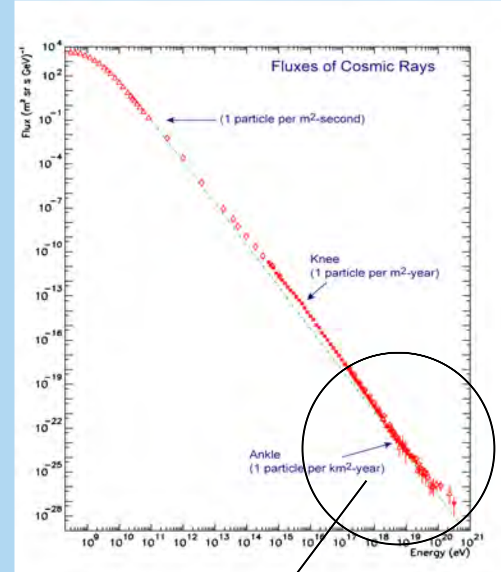


P. Gorham



(A Few) Neutrino Sources

Gamma Ray Bursts



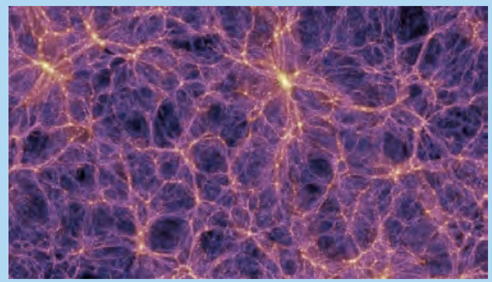
GZK ν

$$p + \gamma_{CMB} \rightarrow \Delta^{\pm} \rightarrow \pi^{\pm} + n$$

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

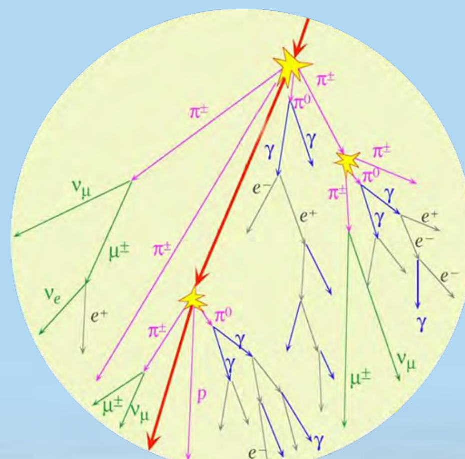
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

Active Galactic Nuclei



Dark Matter

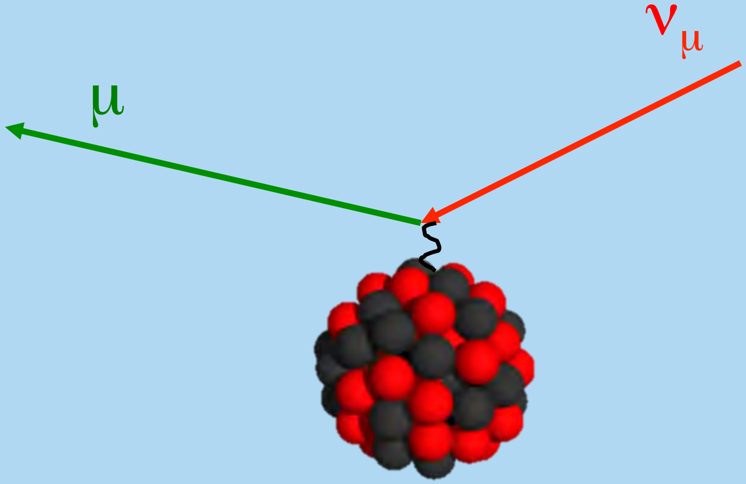
Supernovae

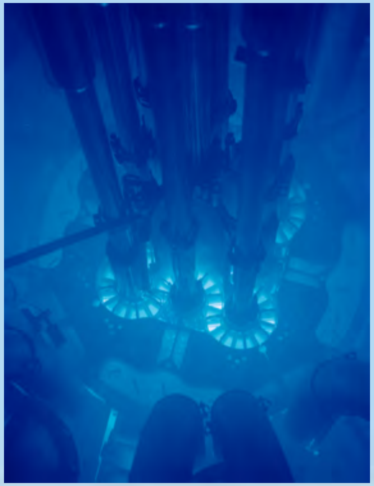


CRs: atm ν

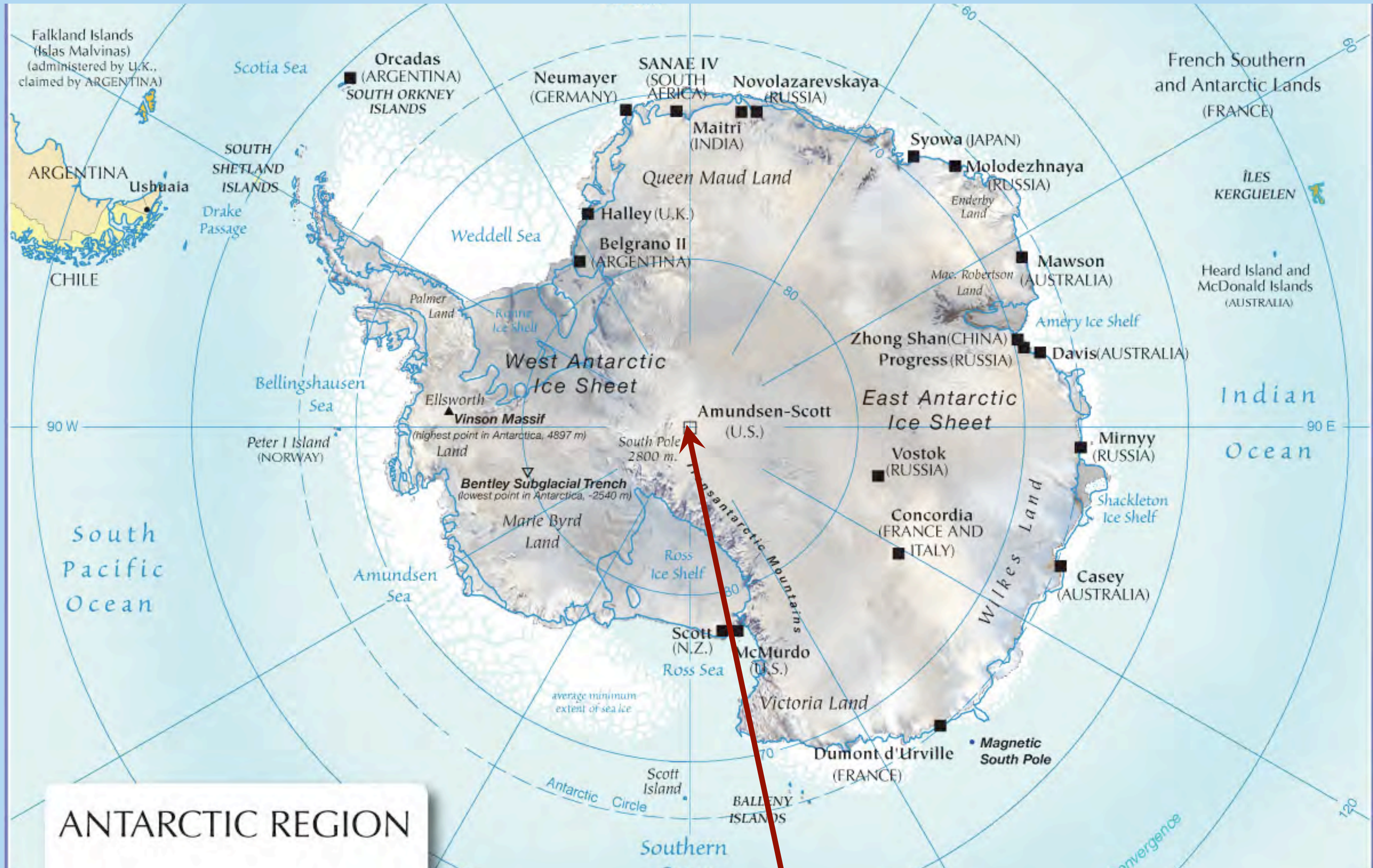
Neutrino Detection

- Neutrino interacts and produces charged particle
- Muon is traveling faster than speed of light in ice
- Emits Cherenkov light (cone 41°)
- Light is detected by Digital Optical Module (DOM)



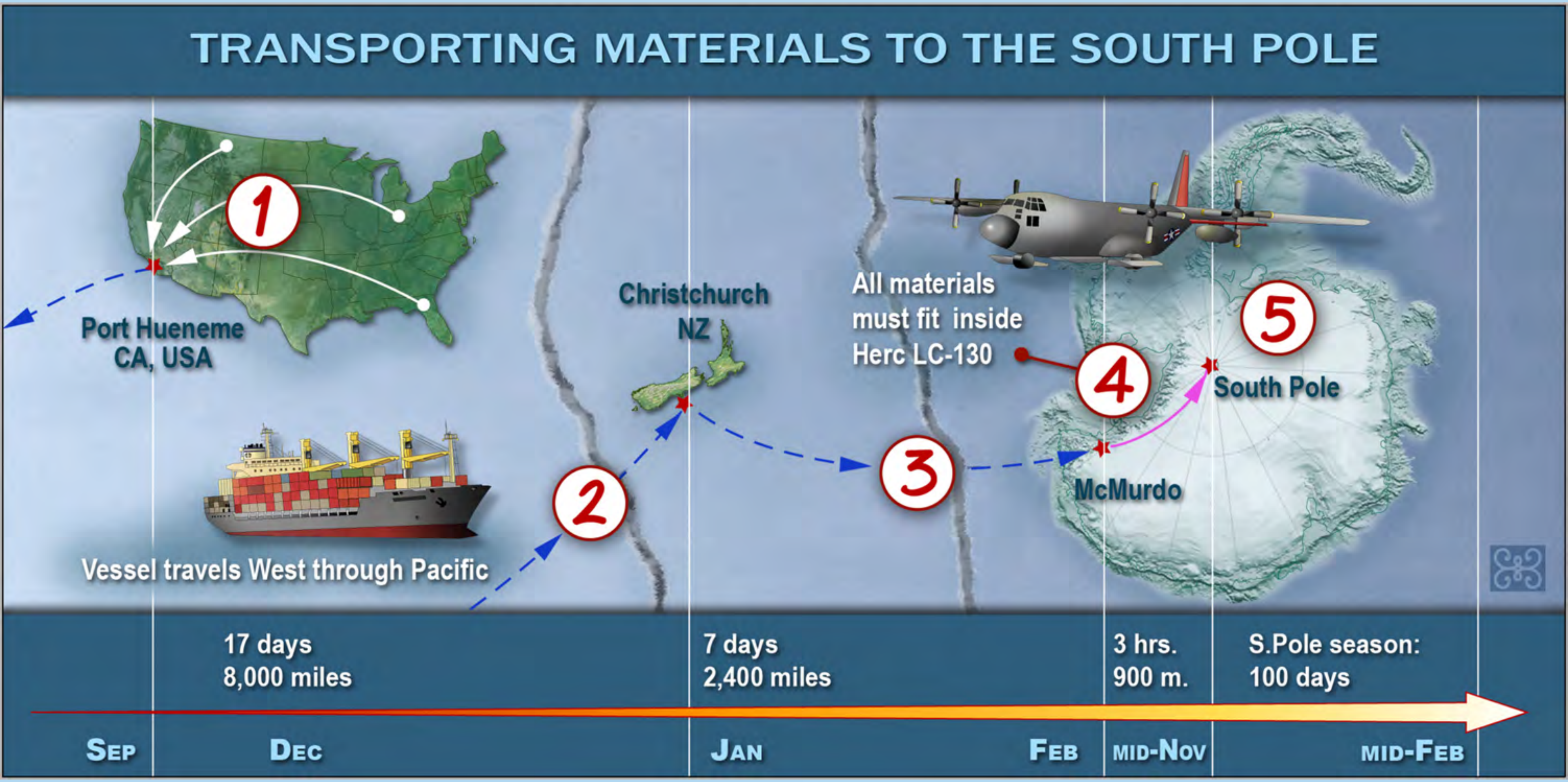


Big Ice



South Pole

A Long Trip


TRANSPORTING MATERIALS TO THE SOUTH POLE
1
Port Hueneme
CA, USA
Vessel travels West through Pacific
2
Christchurch
NZ
3
All materials
must fit inside
Herc LC-130
4
McMurdo
5
South Pole
17 days
8,000 miles
7 days
2,400 miles
3 hrs.
900 m.
S.Pole season:
100 days
SEP
DEC
JAN
FEB
MID-NOV
MID-FEB

McMurdo

IceCube

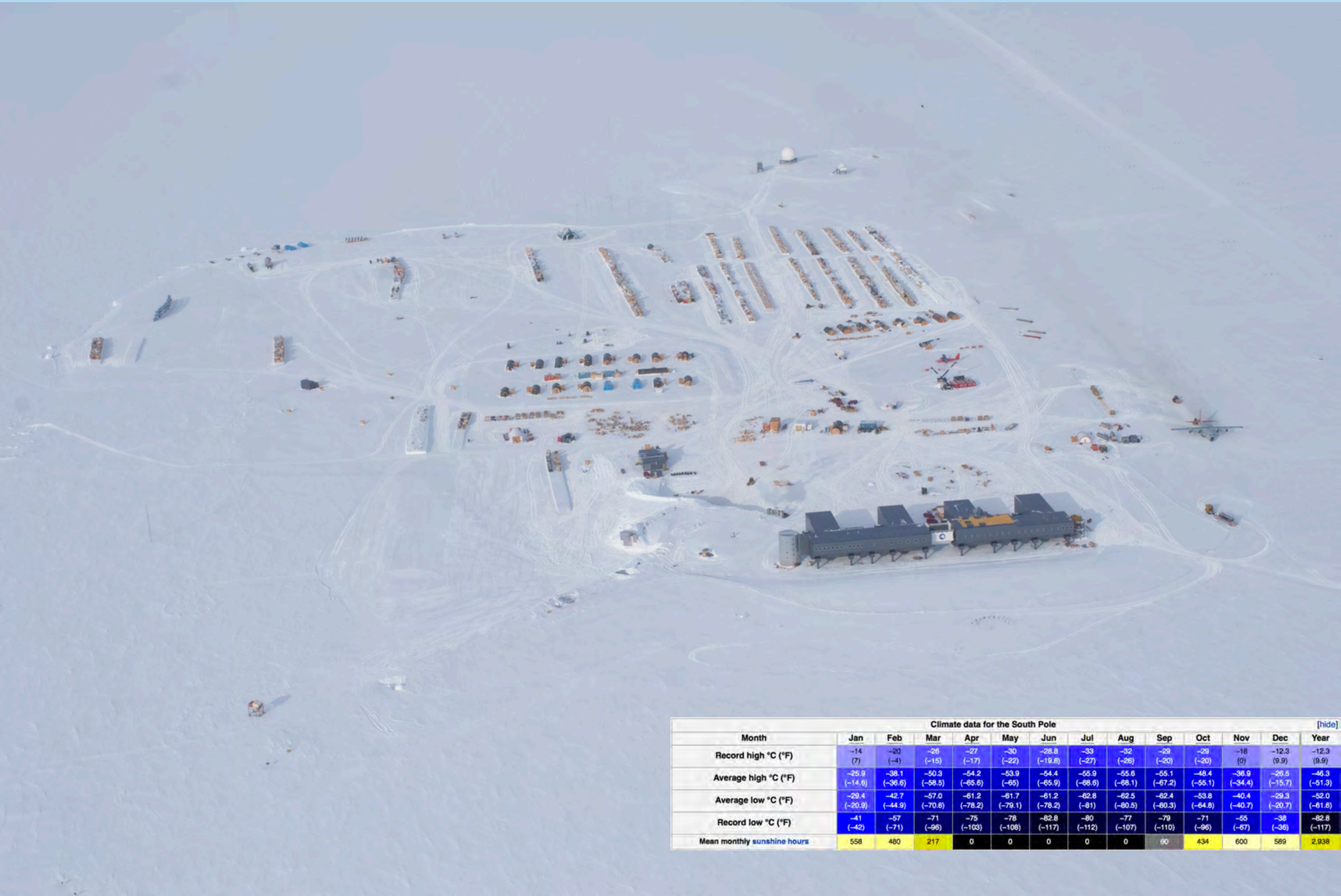
BERKELEY LAB

Logistics

IceCube

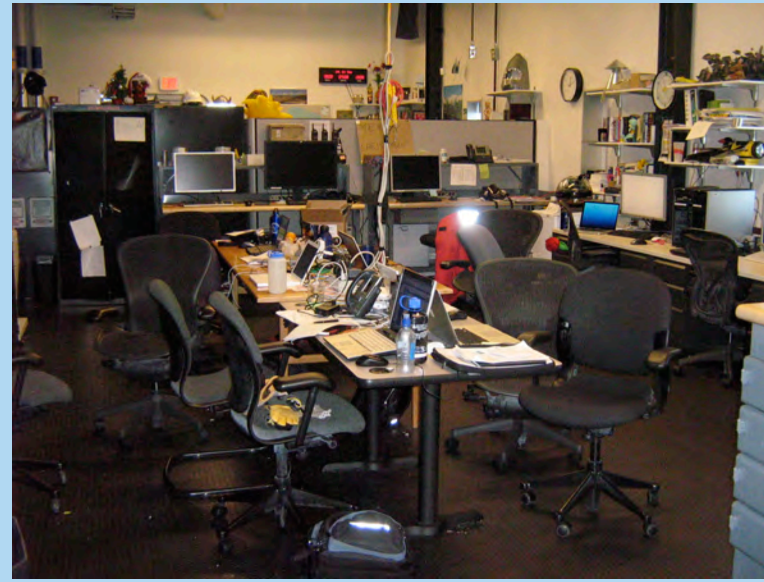
BERKELEY LAB

South Pole

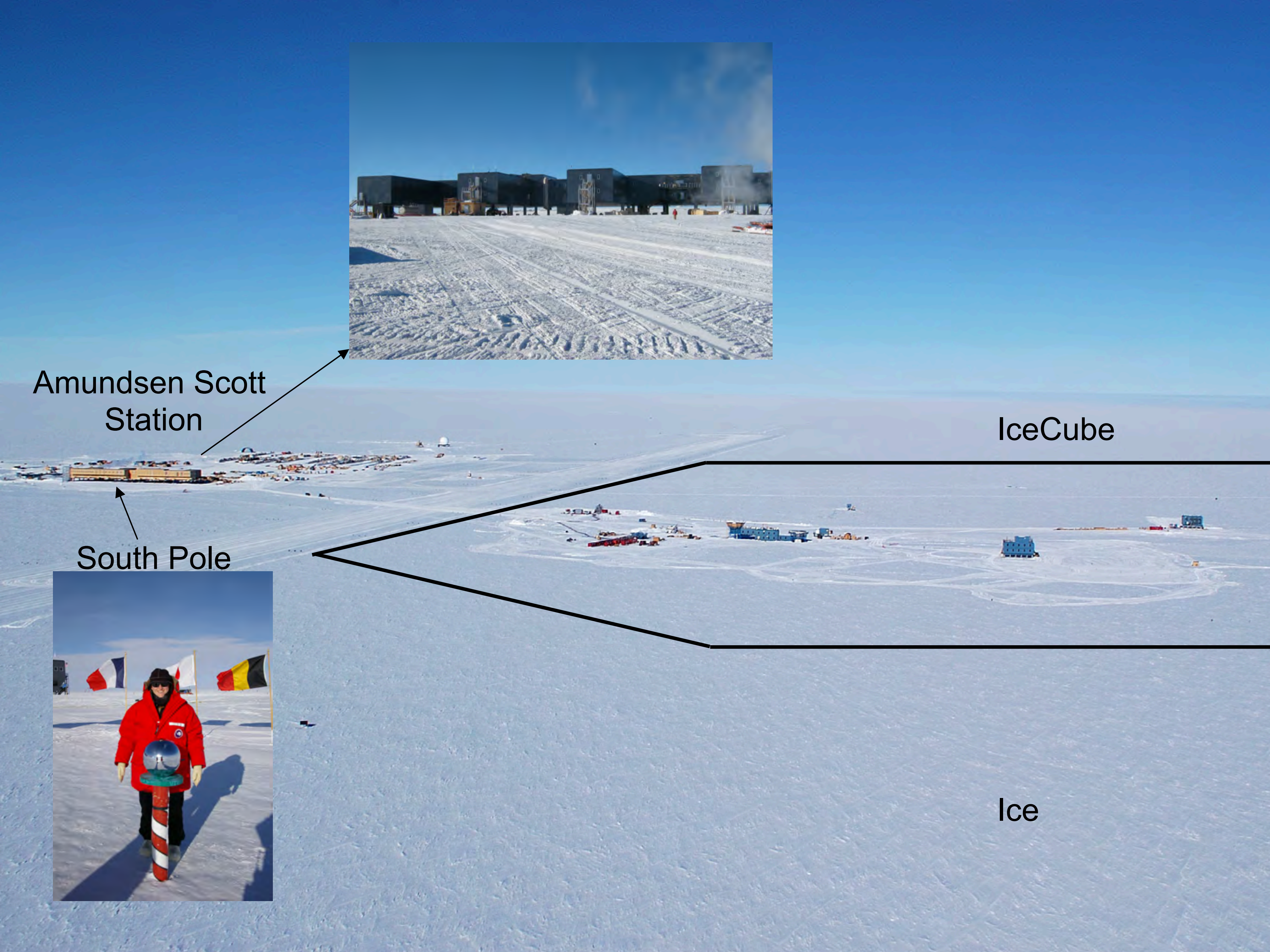


Climate data for the South Pole													[hide]
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	−14 (7)	−20 (−4)	−26 (−15)	−27 (−17)	−30 (−22)	−28.8 (−19.8)	−33 (−27)	−32 (−26)	−29 (−20)	−29 (−20)	−18 (0)	−12.3 (9.9)	−12.3 (9.9)
Average high °C (°F)	−25.9 (−14.6)	−38.1 (−36.6)	−50.3 (−58.5)	−54.2 (−65.6)	−53.9 (−65)	−54.4 (−65.9)	−55.9 (−68.6)	−55.6 (−68.1)	−55.1 (−67.2)	−48.4 (−55.1)	−36.9 (−34.4)	−26.5 (−15.7)	−46.3 (−51.3)
Average low °C (°F)	−29.4 (−20.9)	−42.7 (−44.9)	−57.0 (−70.6)	−61.2 (−78.2)	−61.7 (−79.1)	−61.2 (−78.2)	−62.8 (−81)	−62.5 (−80.5)	−62.4 (−80.3)	−53.8 (−64.8)	−40.4 (−40.7)	−29.3 (−20.7)	−52.0 (−61.6)
Record low °C (°F)	−41 (−42)	−57 (−71)	−71 (−96)	−75 (−103)	−78 (−108)	−82.8 (−117)	−80 (−112)	−77 (−107)	−79 (−110)	−71 (−96)	−55 (−67)	−38 (−36)	−82.8 (−117)
Mean monthly sunshine hours	558	480	217	0	0	0	0	0	60	434	600	589	2,938

Amundsen Scott Station

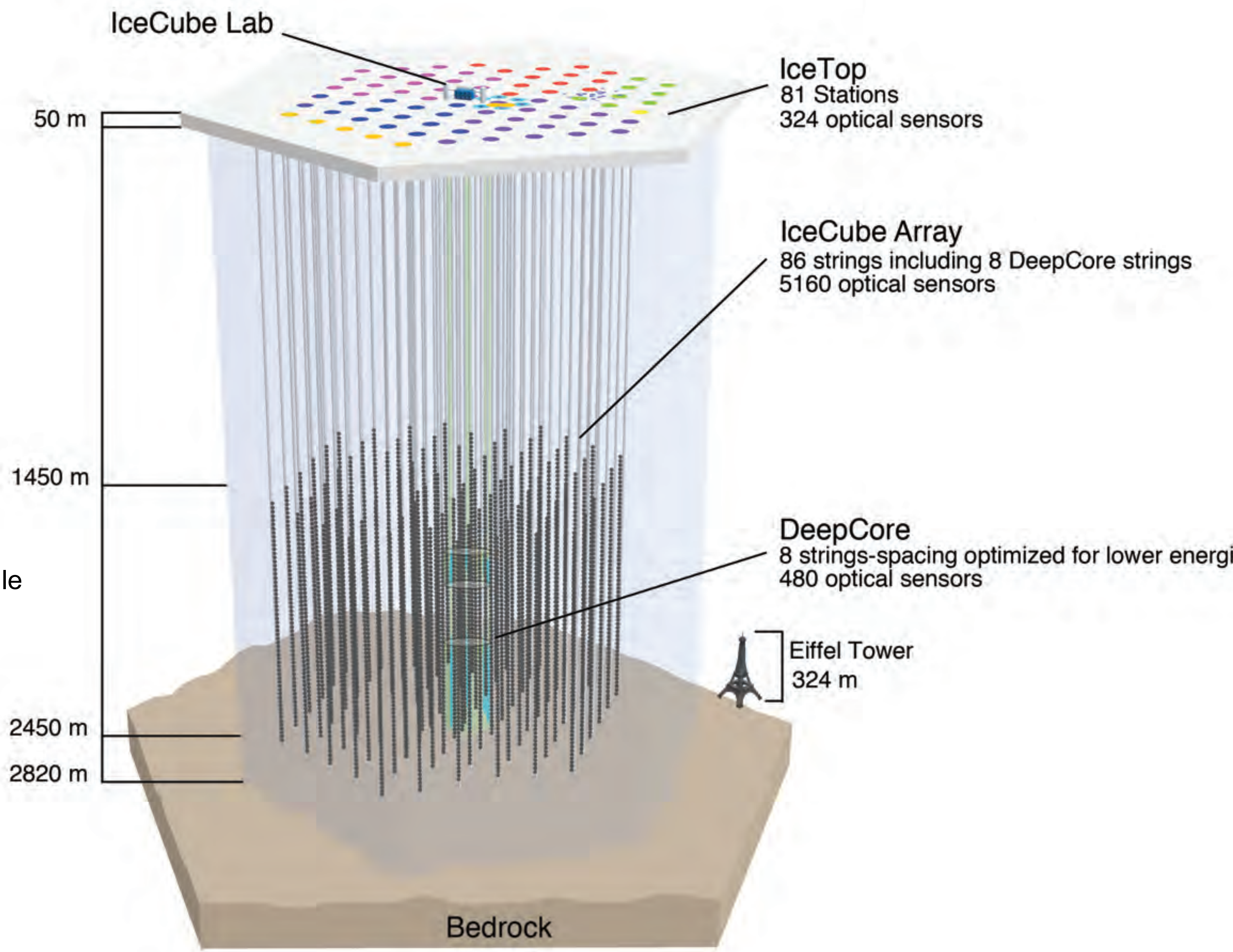


IceCube


Amundsen Scott Station
IceCube
South Pole
Ice

IceCube

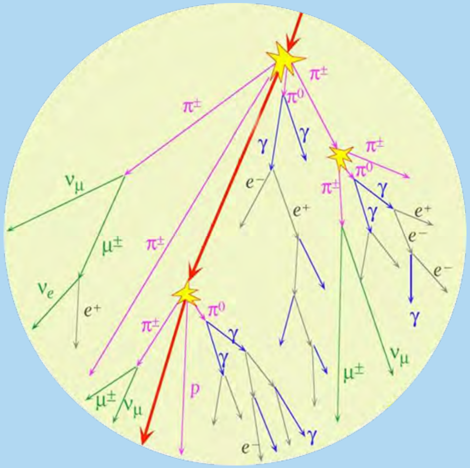
DOM: Digital Optical Module
Designed at LBNL

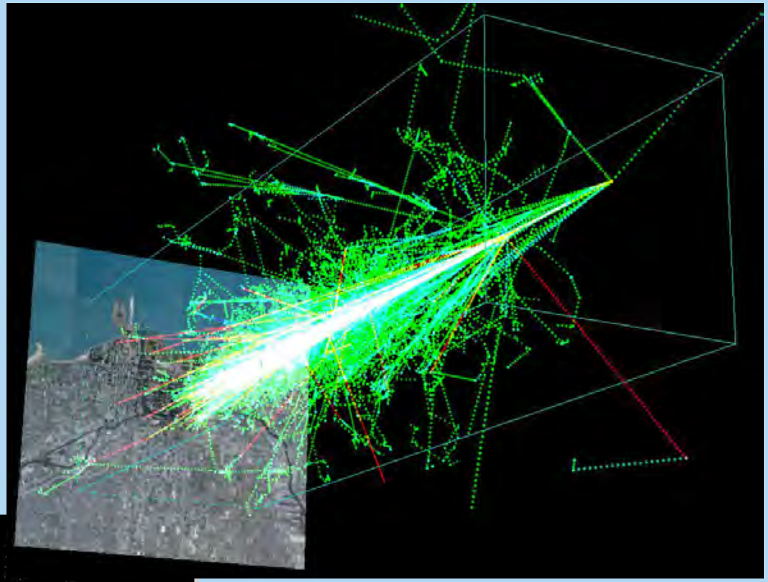


IceCube Data

Surface DAQ
400 CPUs
TDRSS satellite
1 TB / day, only 105 GB / day over satellite

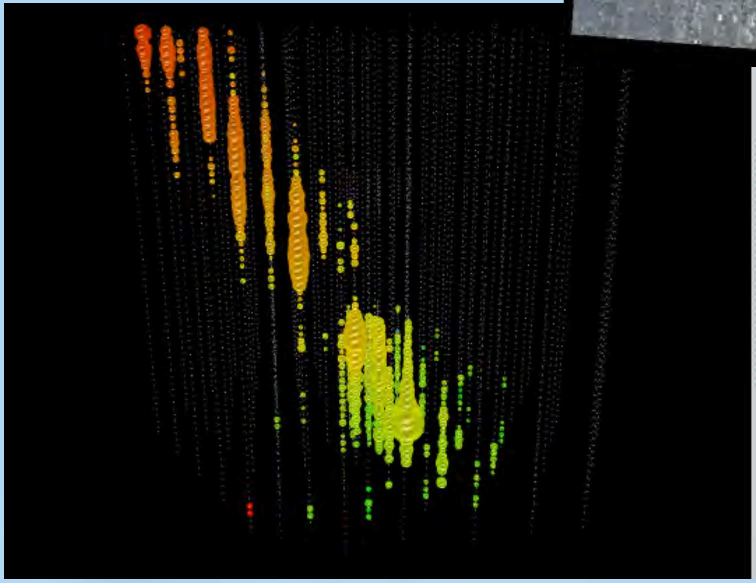
IceCube’s Background





Not just background!

Lots of interesting CR physics, too.



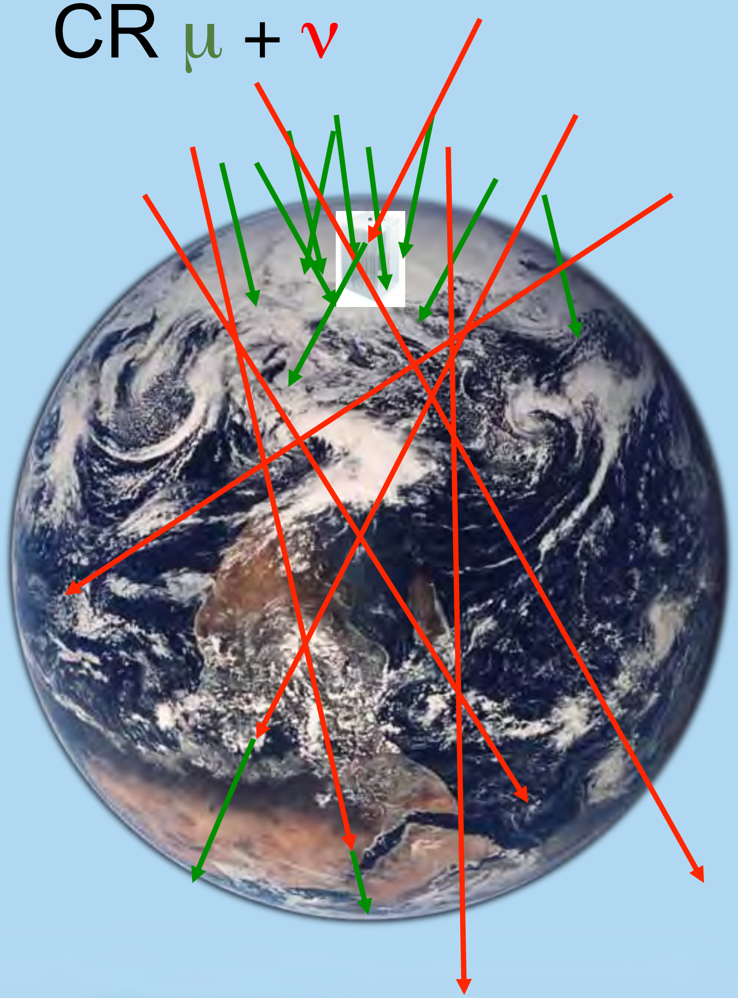
Cosmic rays: 2800 Hz

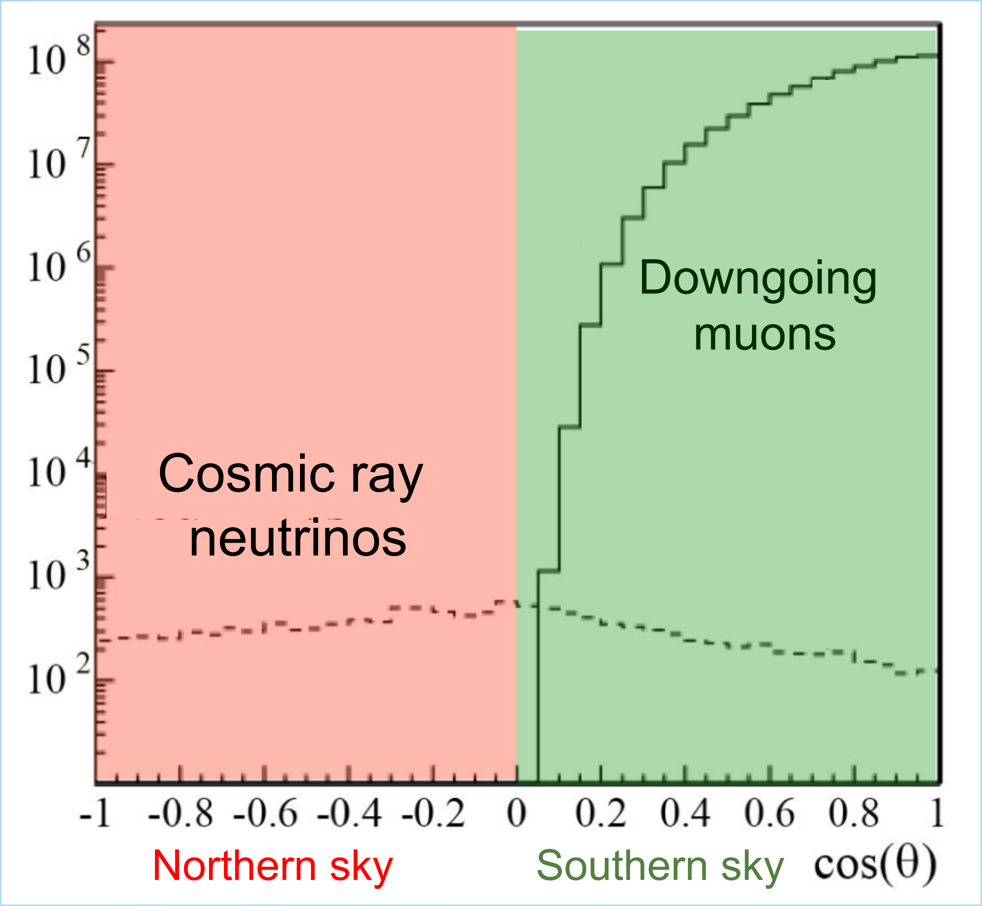
- Nuclei on nuclei at 100 x LHC energy
- Hadron rain
- Produce 10’s to 10,000’s μ’s and ν’s

90 billion CRs, looking for a handful of neutrinos

Separate by Direction

CR μ + ν





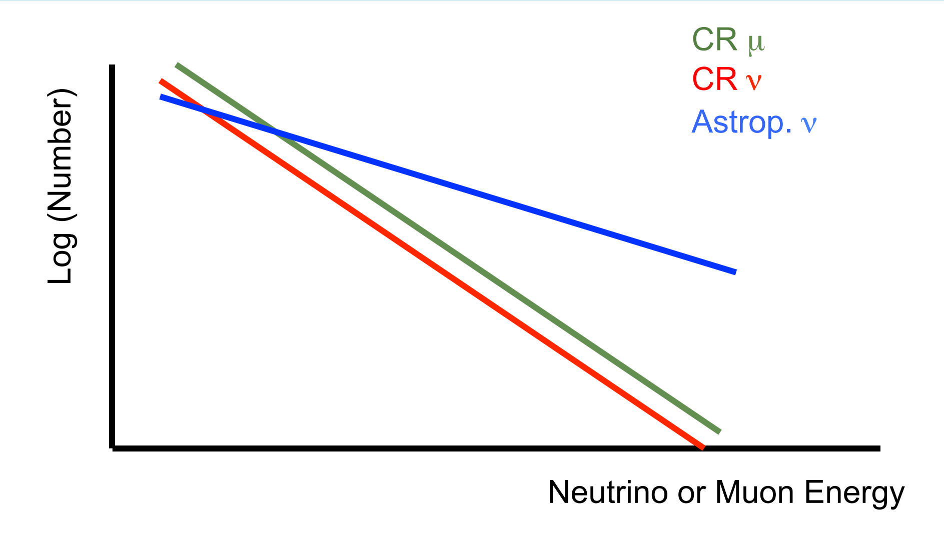
Separate by Energy

- Looking for astrophysical neutrinos

$$p + \gamma / p \rightarrow \text{hadrons} \rightarrow \nu + \text{stuff}$$

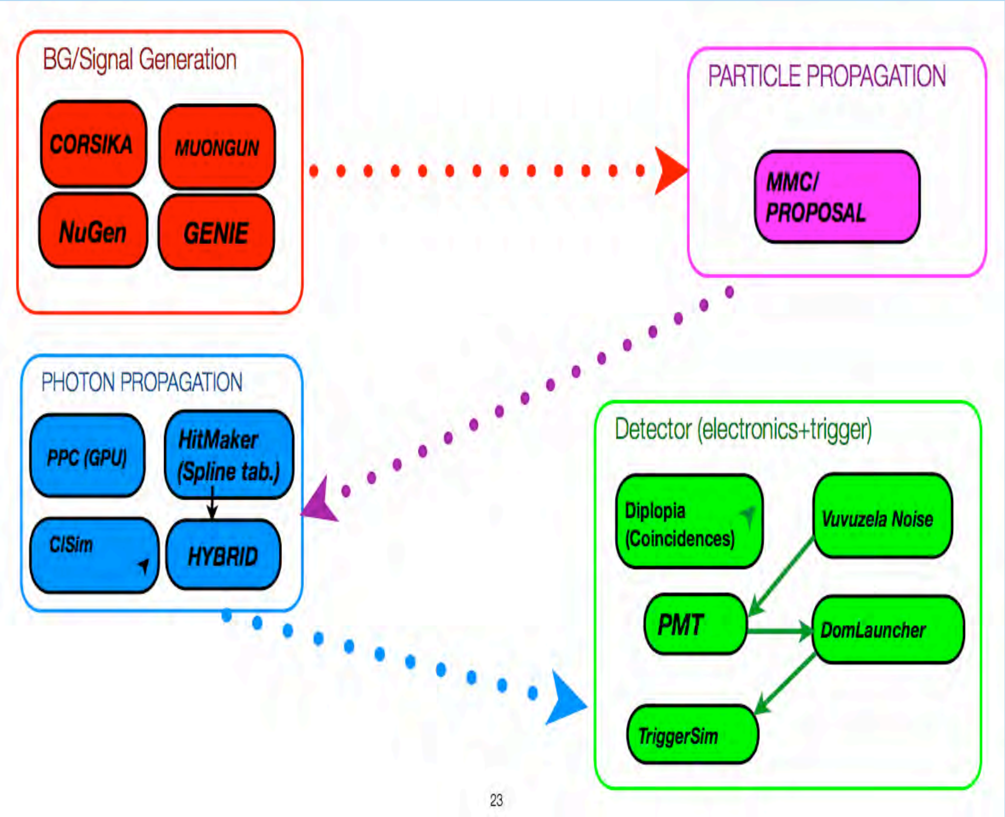
- Against cosmic ray neutrino background

$$p + p \rightarrow \text{hadrons} \rightarrow \text{hadrons} \rightarrow \text{hadrons} \rightarrow \nu + \text{stuff}$$



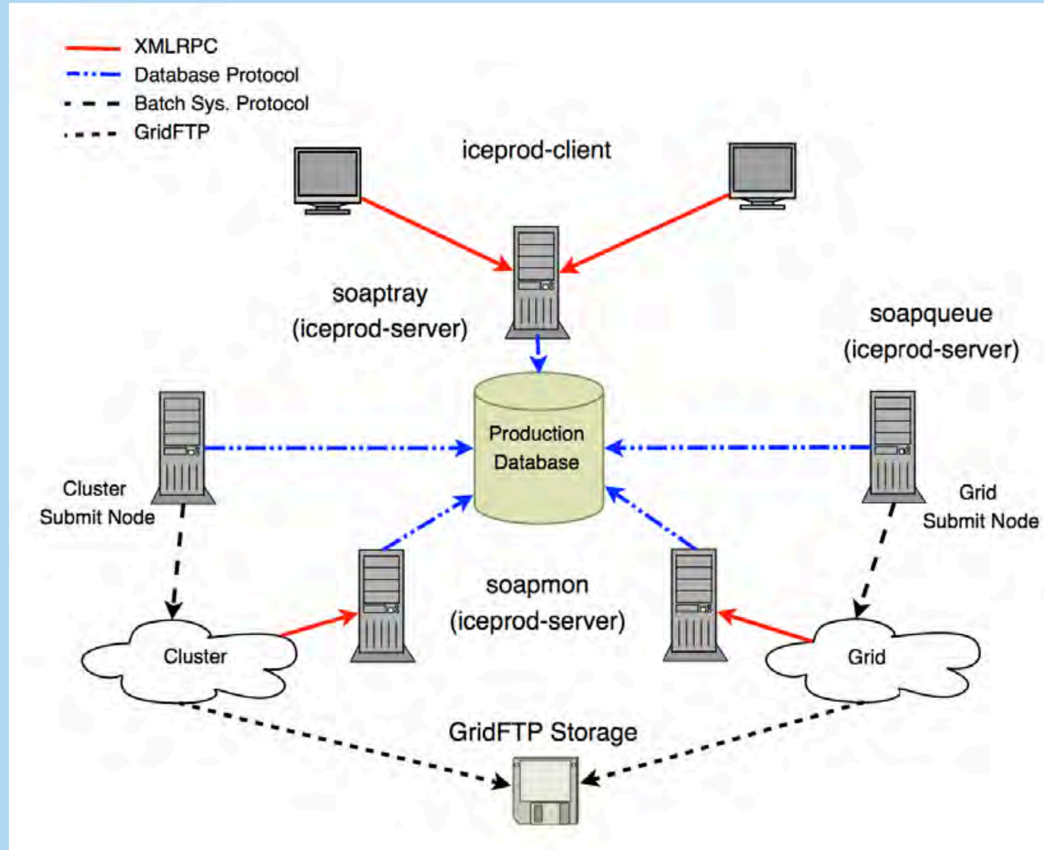
Simulation Is Critical

- 'Pleasantly parallel' simulation
- Modeling particle interactions in the atmosphere or the ice
- Rare processes
    - Doing the same thing over and over
- Primarily C++ and python, some java



IceCube Production Framework

- Uses resources distributed throughout the collaboration
  - –Heterogeneous collection of clusters and grids
  - –Different batch system/middleware
  - –Different OS systems/platforms
- Coordinated by IceProd
  - –Based on Python, XMLRPC, GridFTP
  - –Runs on top of batch queuing systems or grid middleware



WestGrid

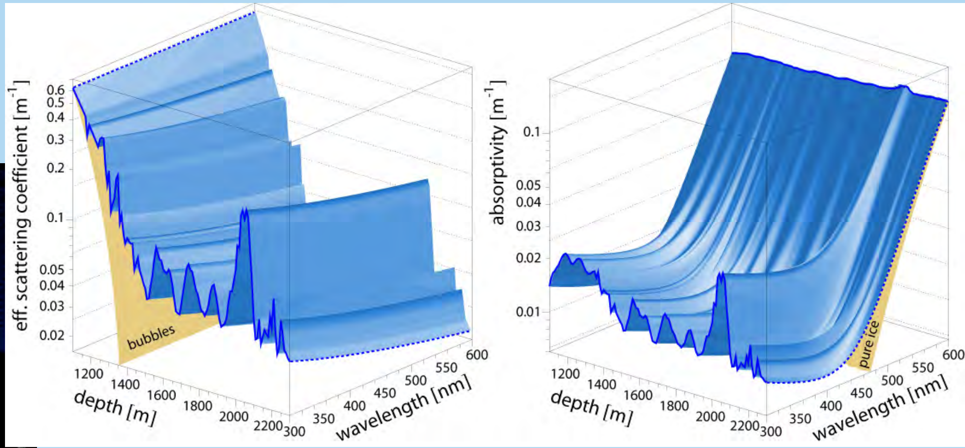
GRID ENGINE

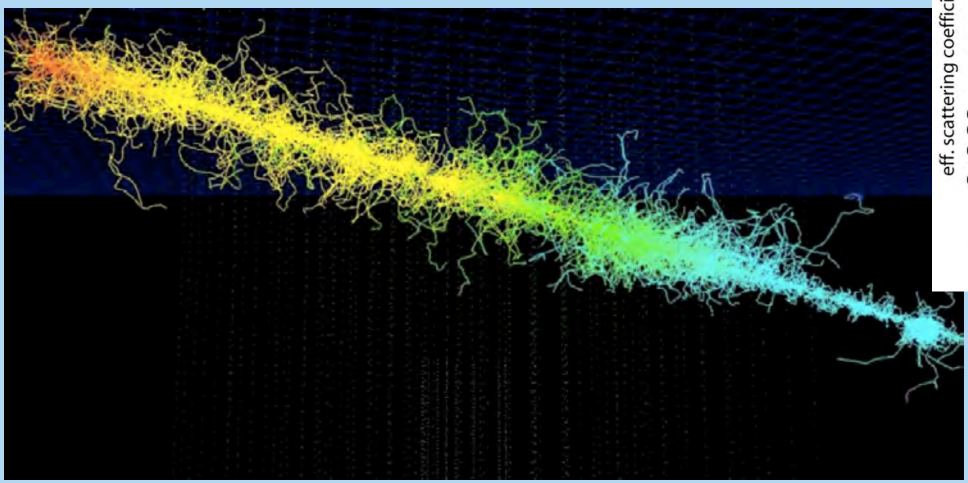
NORDUGRID
Grid Solution for Wide Area Computing and Data Handling

CONDOR
high throughput computing

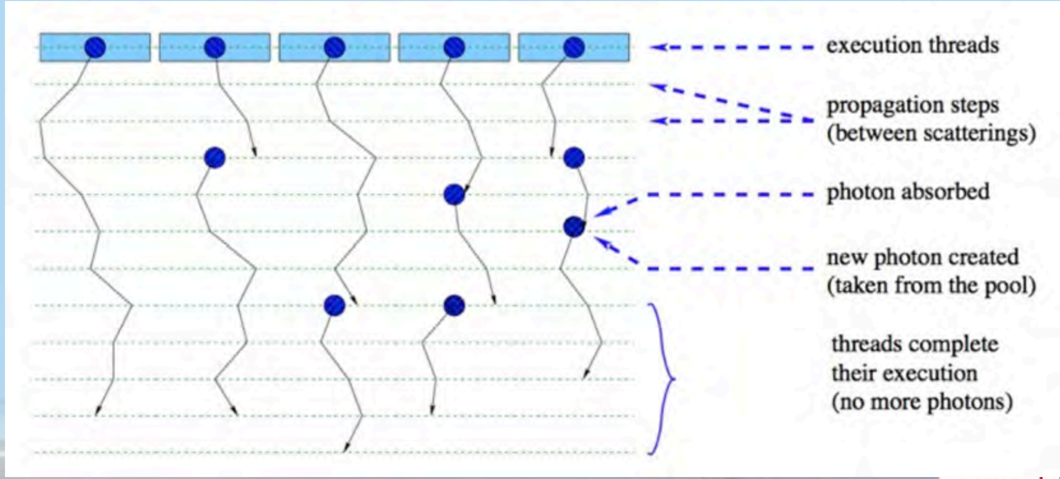
GPUs are Essential

- Absorption and scattering of light in ice changes



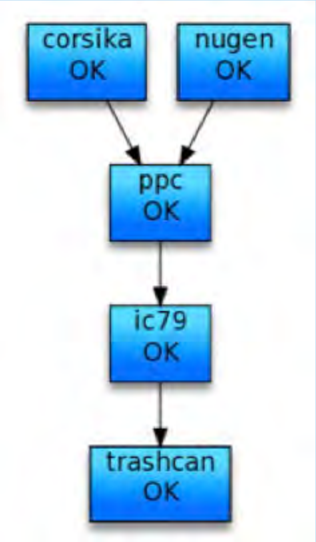


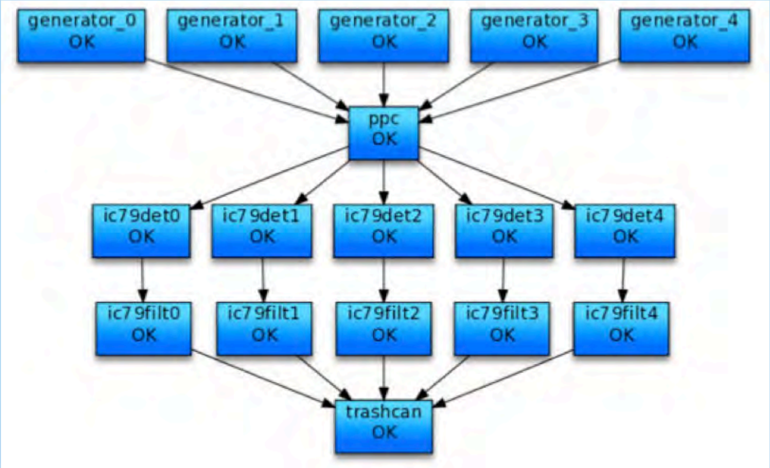
- Use individual photon tracking
- Dirac GPU cluster essential for this
- IceCube bought GPU cluster of 48 Tesla M2070 GPUs

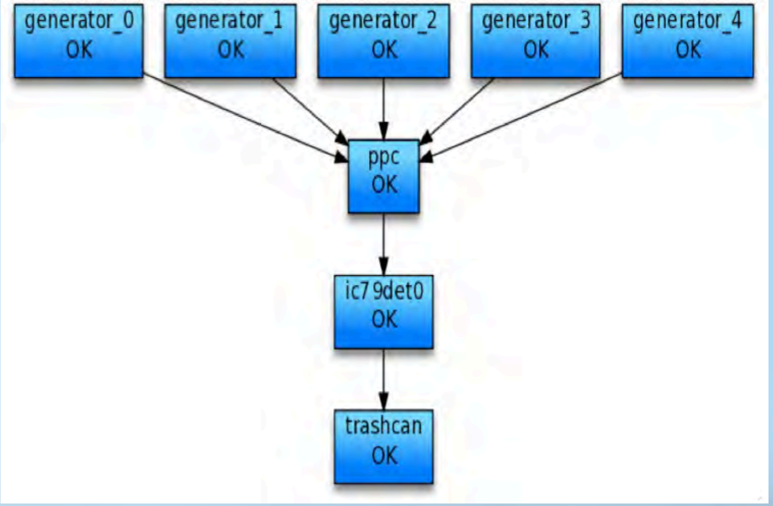


DAGs Keep the GPUs Fed

- Only photon propagation needs GPUs
- The rest are CPU only
- Ratio of CPU / GPU needed changes depending on the simulation type
- IceProd breaks simulation up into chunks, sends CPU-intensive tasks to CPU clusters through out the collaboration

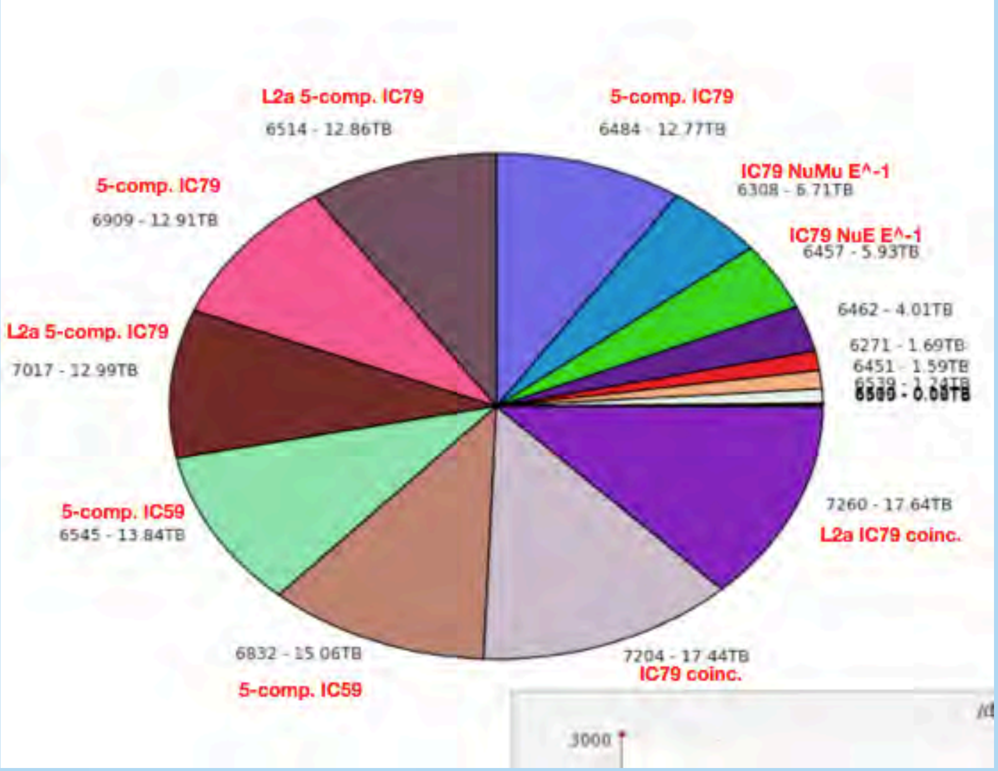






Collaboration Effort

- Spread over 38 different institutions
- Peak 11,000 cores, average 4,000 cores
  - ~10% was done at PDSF and Carver
- 135 TB of data
- Used to fuel >30 papers and ~50 analyses in 2011 / 2012



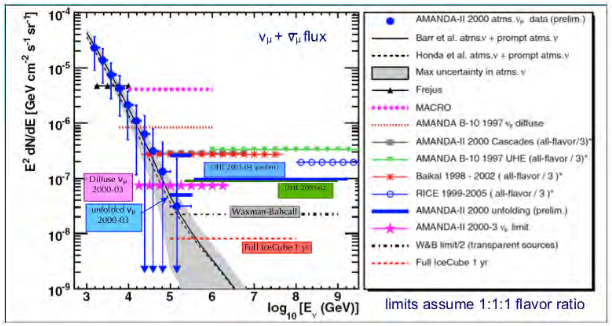
A Wealth of Science

AGNs, p+ accelerators

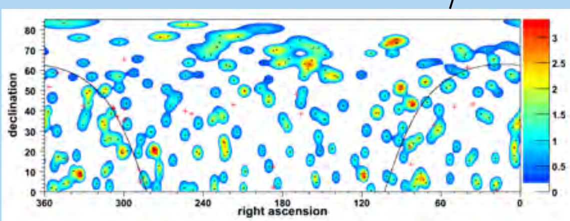
GRBs

γ

ν



Diffuse Sources

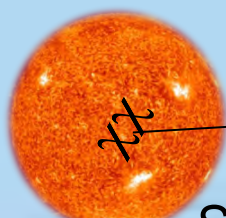


Point Sources

$\chi\chi$

?

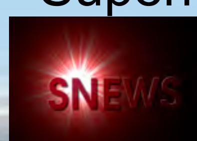
GZK/UHE ν



$\chi\chi$

Solar WIMPs

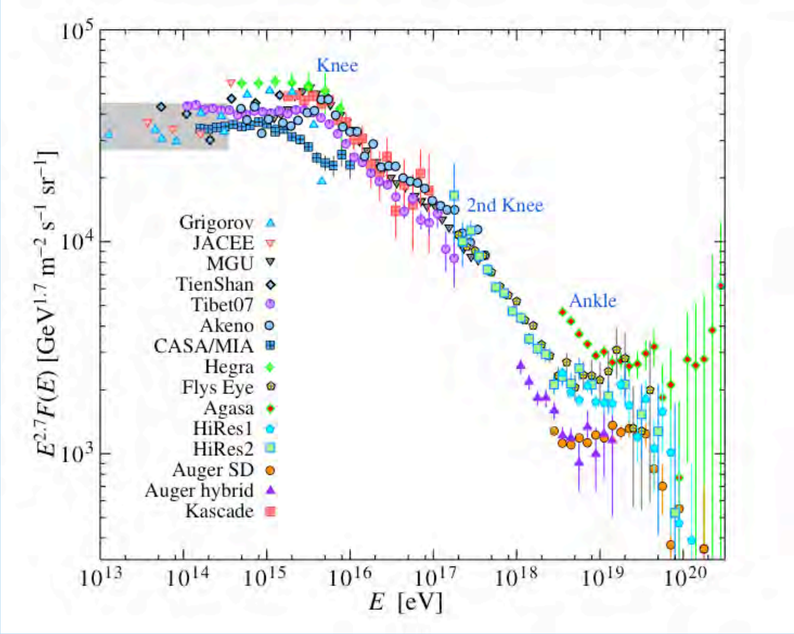
Supernovae

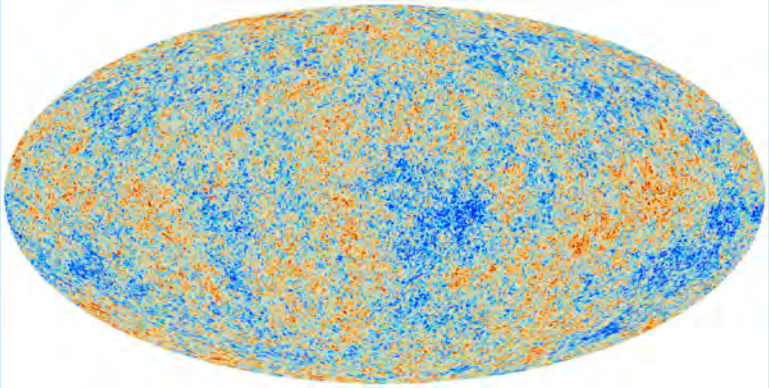


CRs

Search for the Highest Energy Neutrinos

- Highest energy cosmic rays + cosmic microwave background => highest energy neutrinos
  - "Guaranteed" source



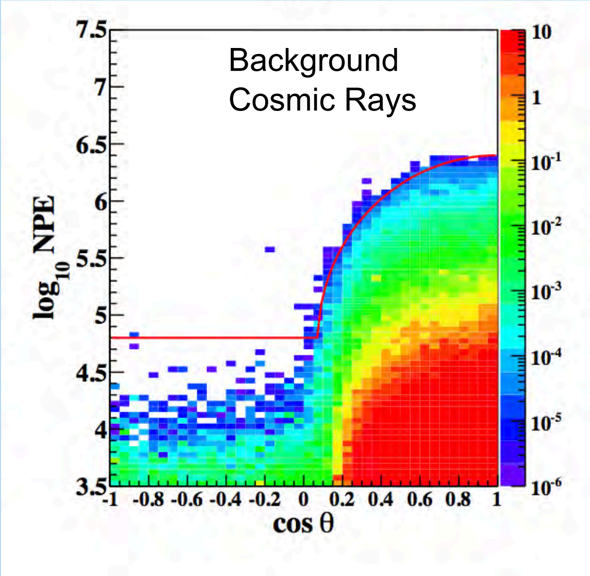


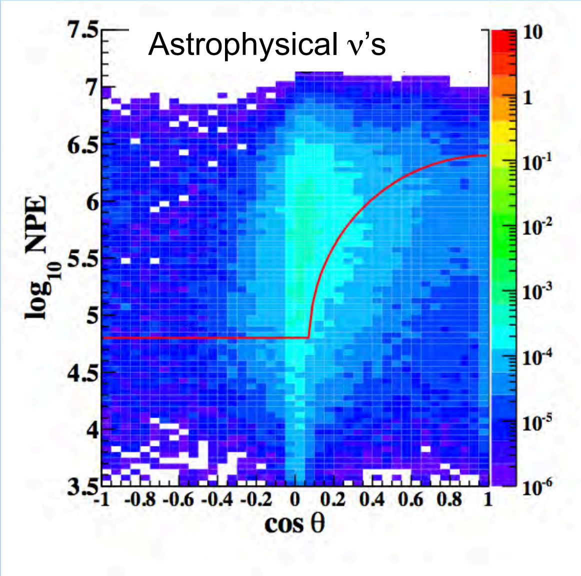
IceCube

BERKELEY LAB

Search for the Highest Energy Neutrinos

- Highest energy cosmic rays + cosmic microwave background => highest energy neutrinos
  - “Guaranteed” source
- Used number of photons as a proxy for energy



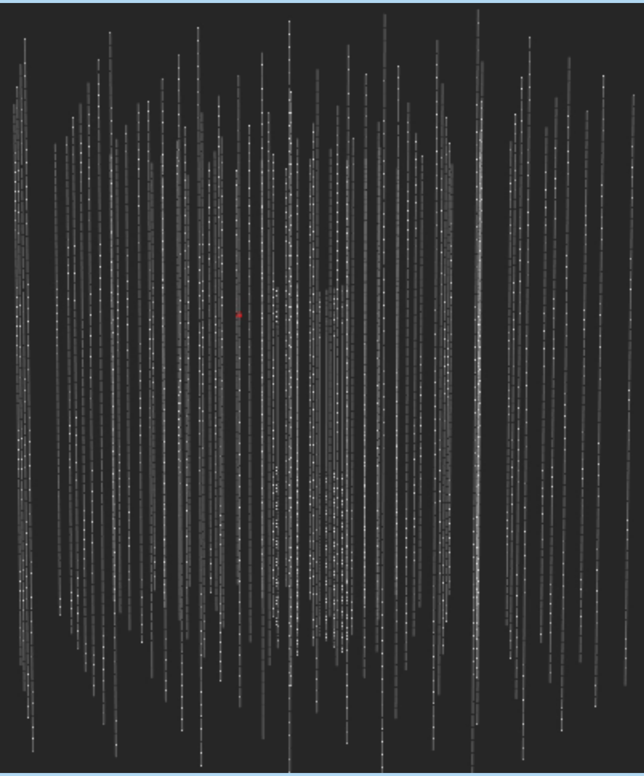


- Looked at two years of data, found two surprises

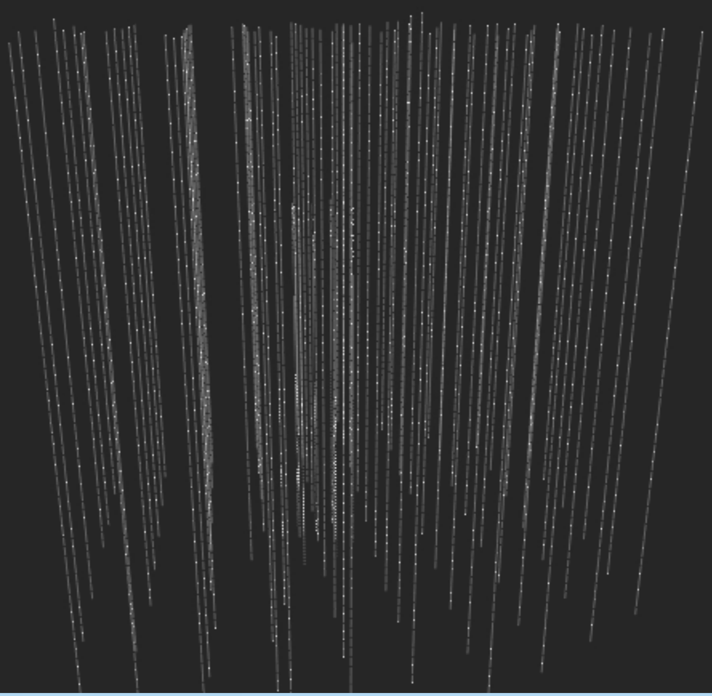
Bert and Ernie

Energies are 1.0 and 1.1 PeV

July, 2013

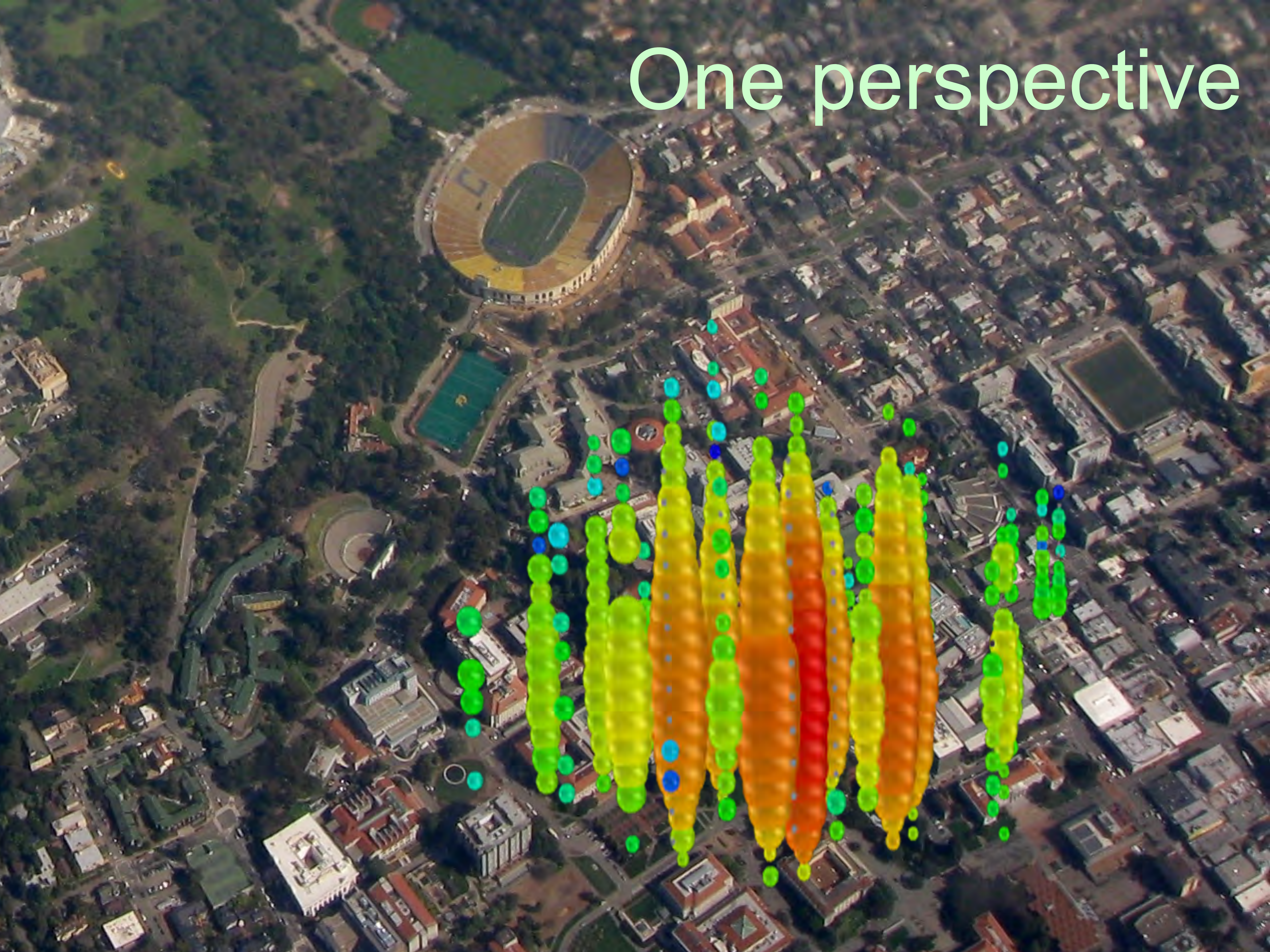


72,907 photons

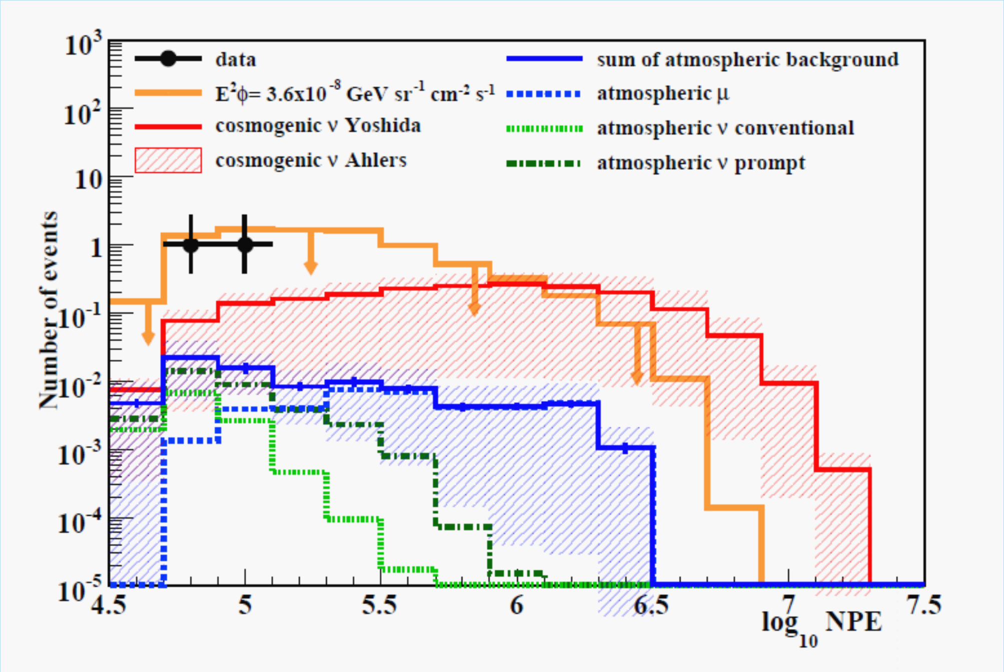


107,898 photons

One perspective

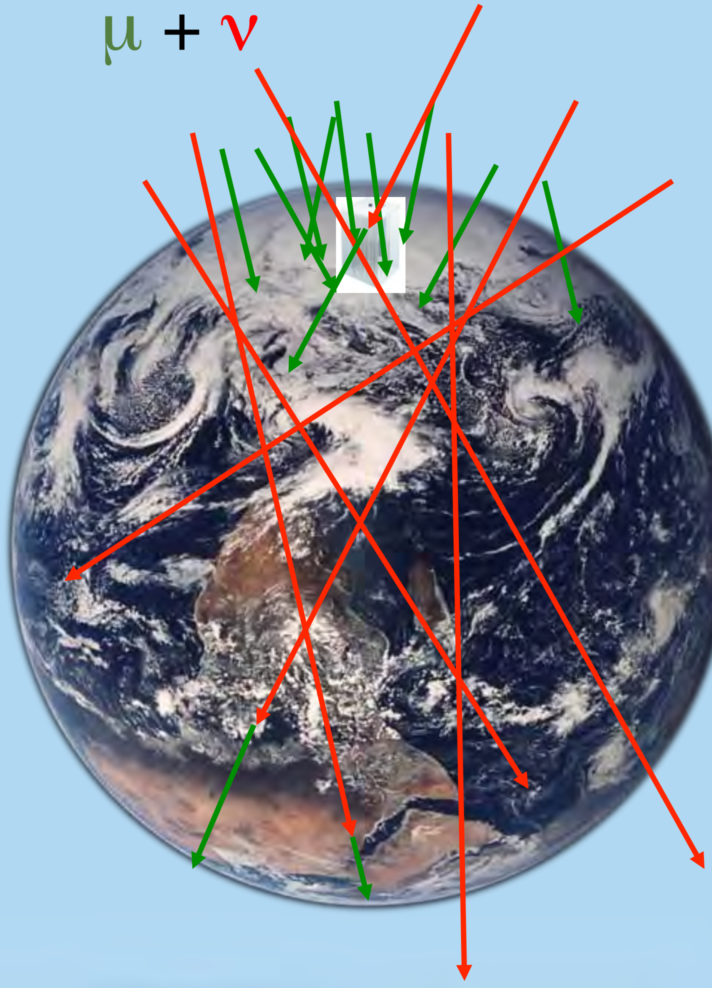


Lonely at the Top

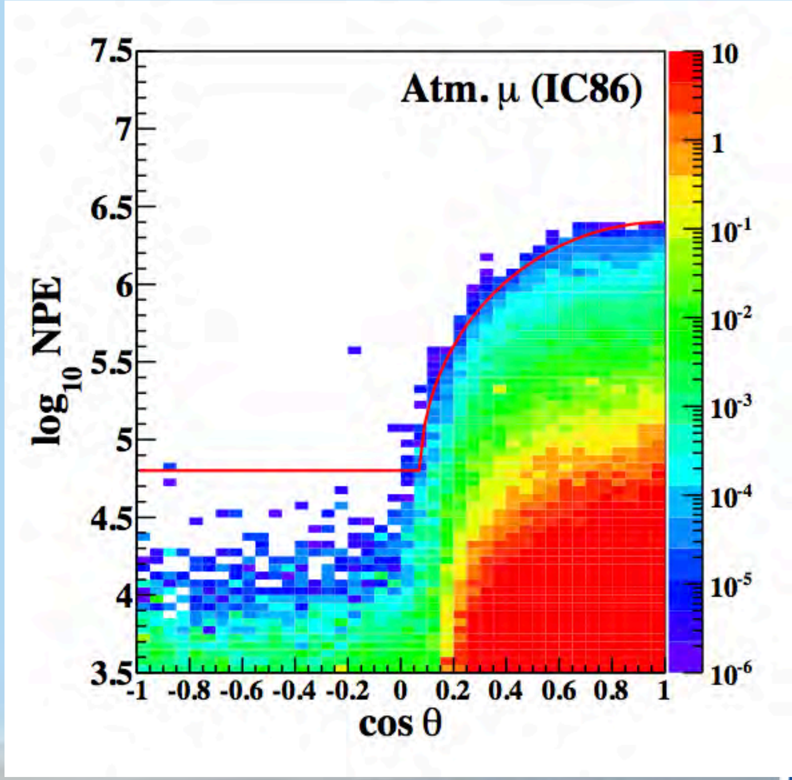


- Two perfect cascades
- Not a good match for theoretical predictions
- Need more data!
- Rate is 1 event / year: sooo long
- But then some IceCubers had an idea

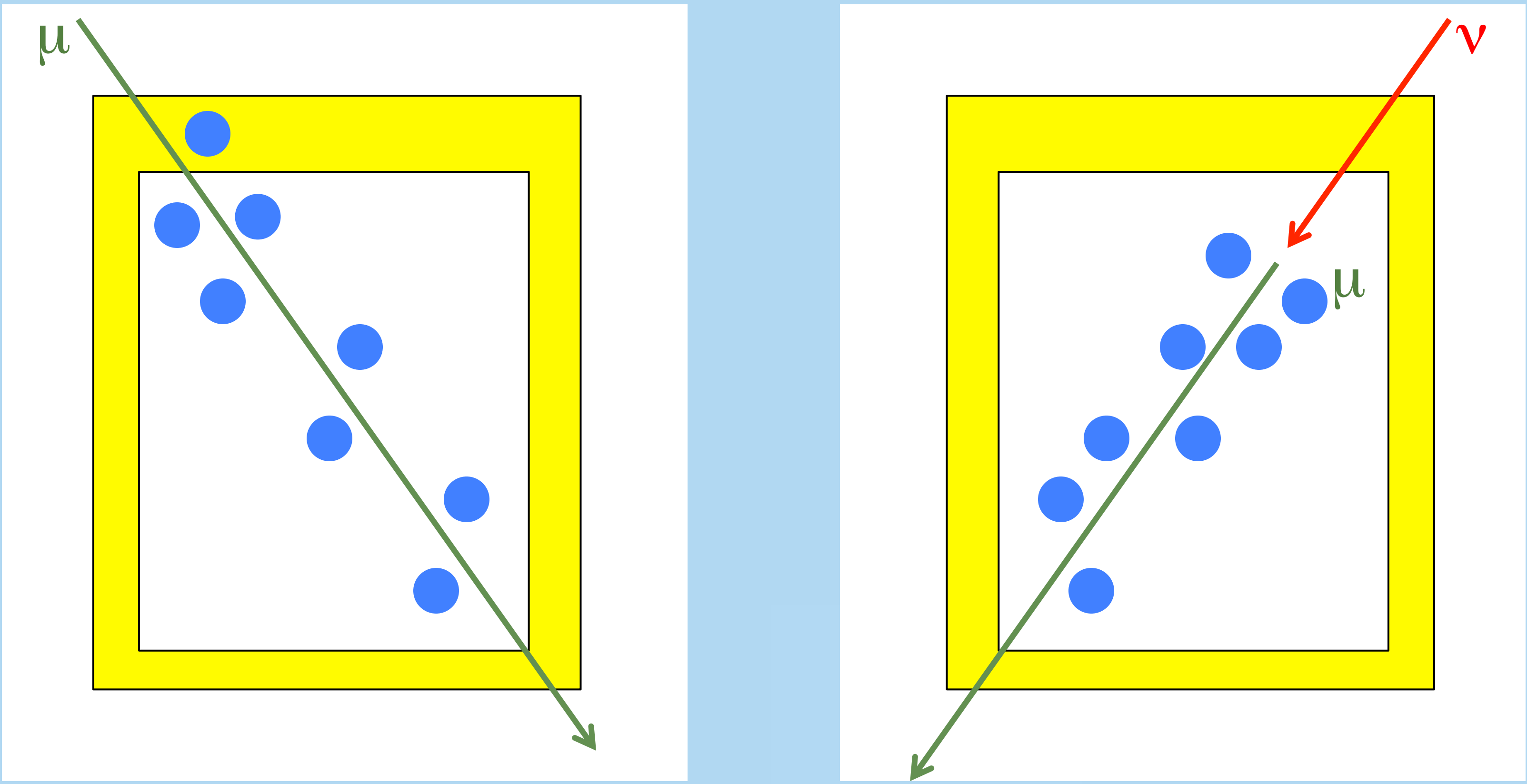
Muon Veto



If we can identify atmospheric muons from the Southern hemisphere, we can lower the energy threshold and get more events



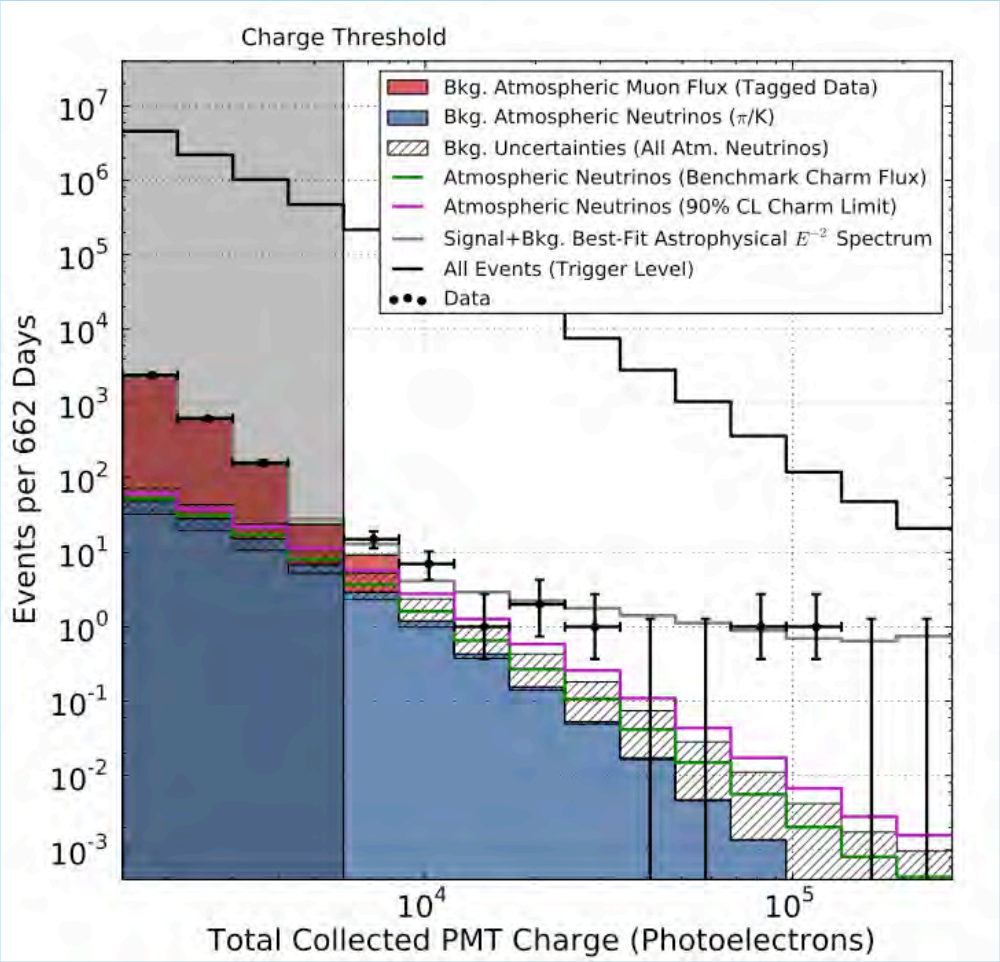
Separate by Topology



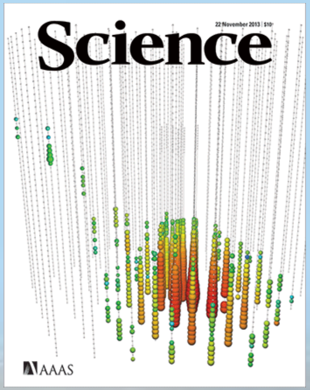
Starting Track Events

- Vetoes atmospheric muons
  - Pay a price in detector size, but more than worth it
- Added lower energy cut to get above atmospheric neutrinos
- Re-searched two years of data
- Went from 2 events to 28 events

The Evidence Is In



- Data agrees with background prediction at low energies
- Clear excess at high energies
- 4 sigma deviation from pure background expectation



November 22nd, 2013

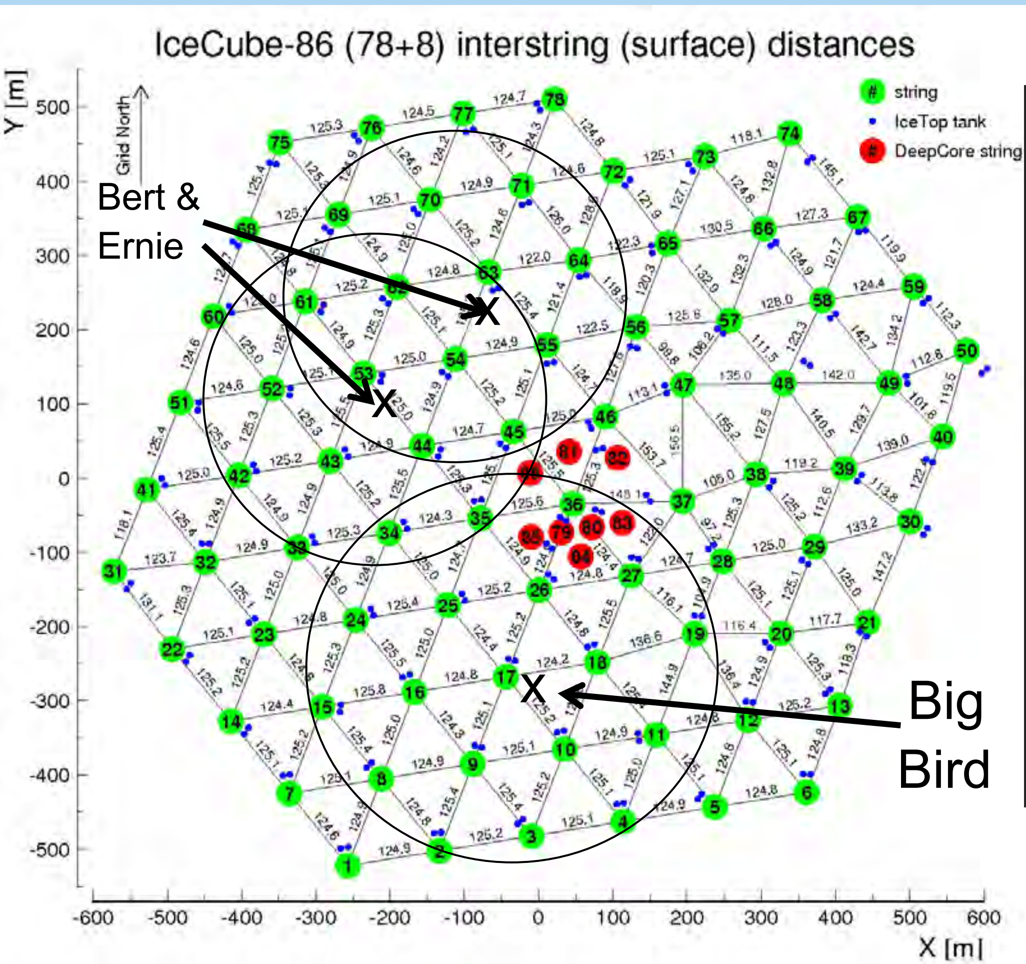
Now What?

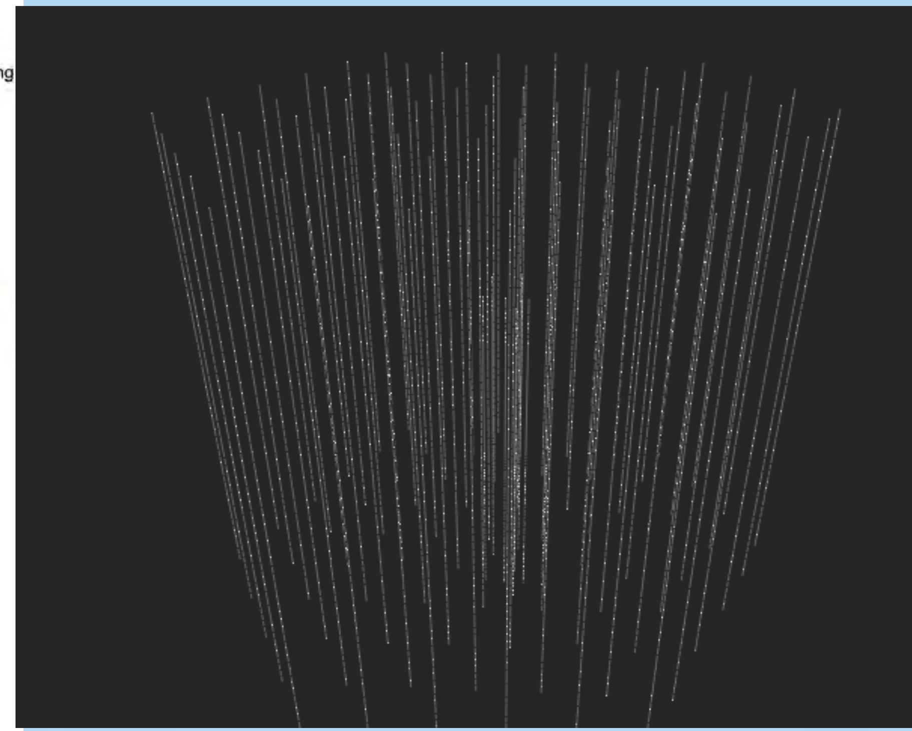
- Keep Looking!
  - Found these events in only two years of full IceCube data
  - Have another year and a half in the can
- Earlier this year we searched 10% of another year of data
  - Improved analysis, focused in on cascade shaped events

Big Bird

Energy is CENSORED

Deposited 127,065 photons into 378 DOMs





Conclusions

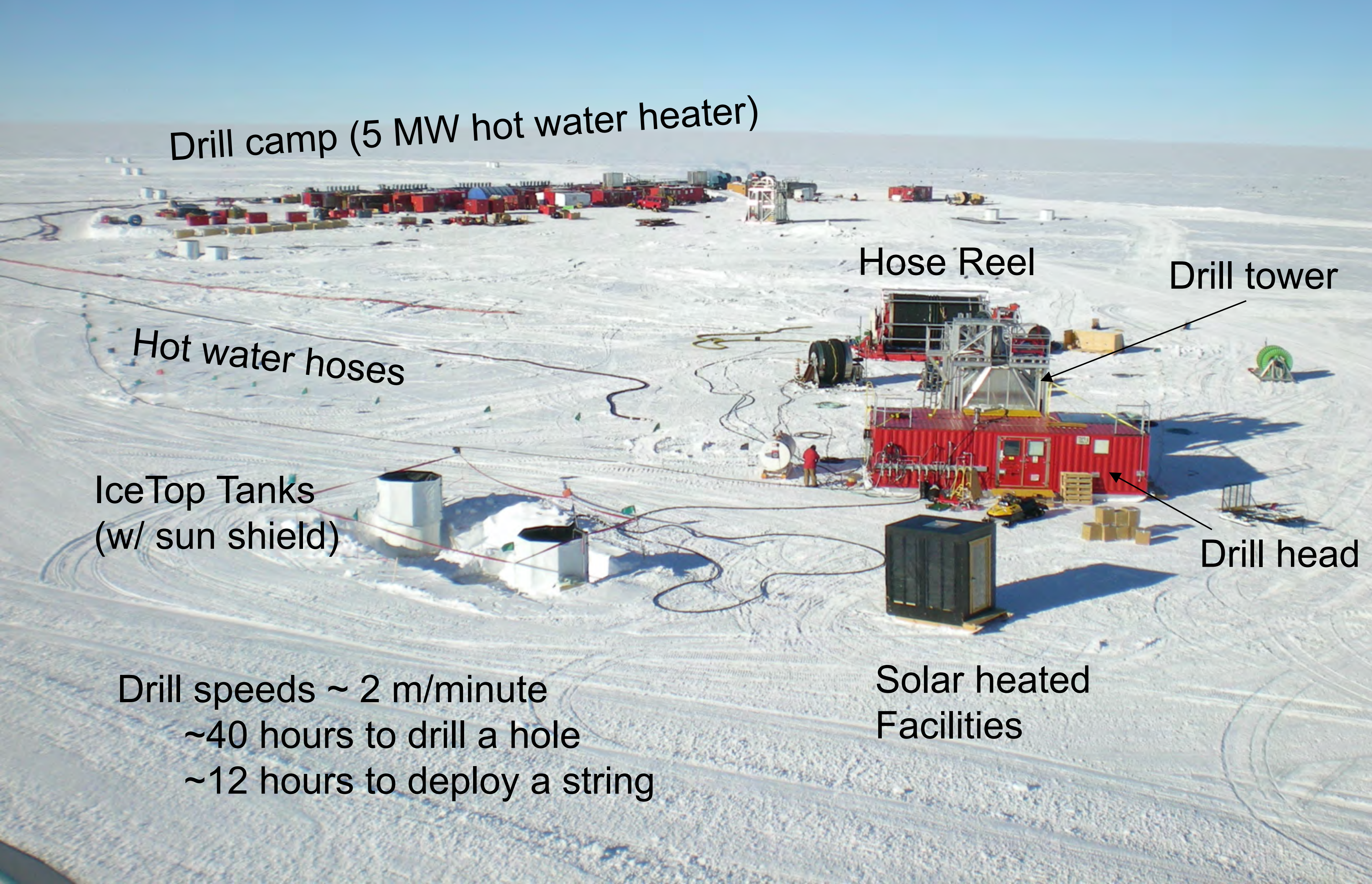
- IceCube has seen the first evidence of astrophysical neutrinos
  - Origin still unclear
- Made possible through use of computing resources at NERSC and other locations
- Plan to take data until 2022
- Beginning of a new era of neutrino astronomy

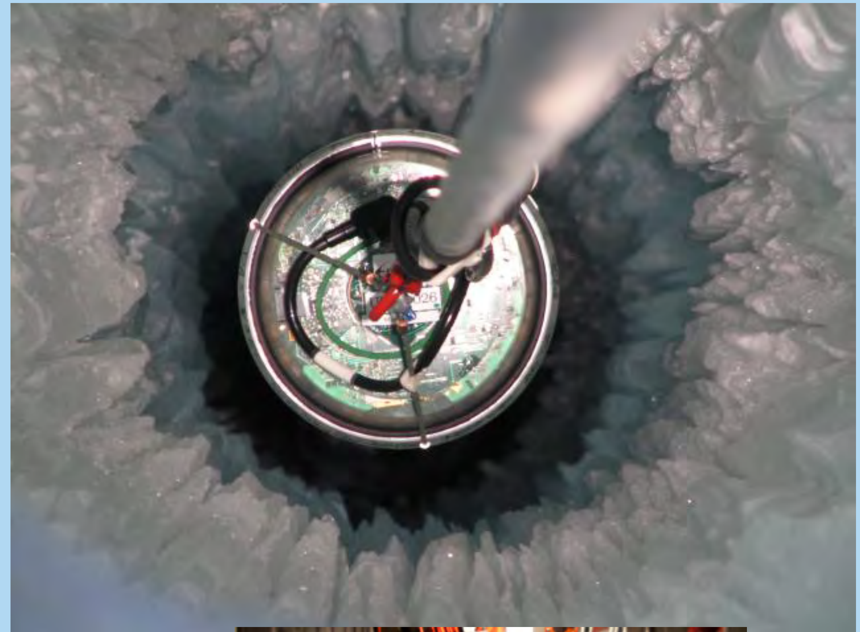
The IceCube Collaboration

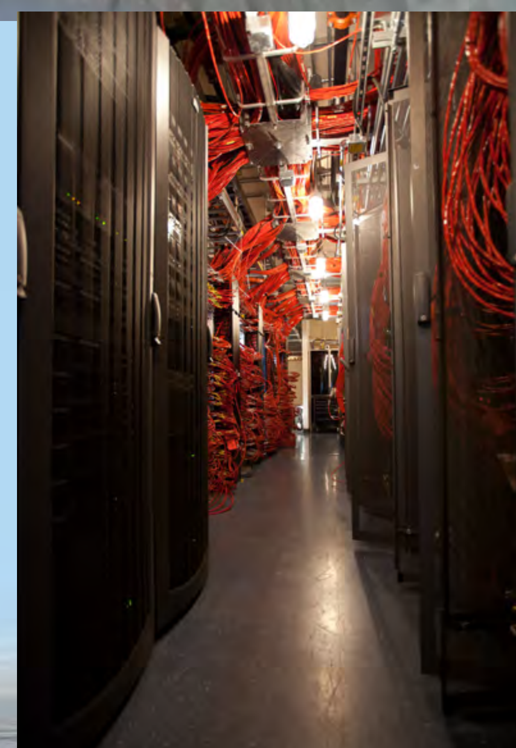
International Funding Agencies

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)
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)

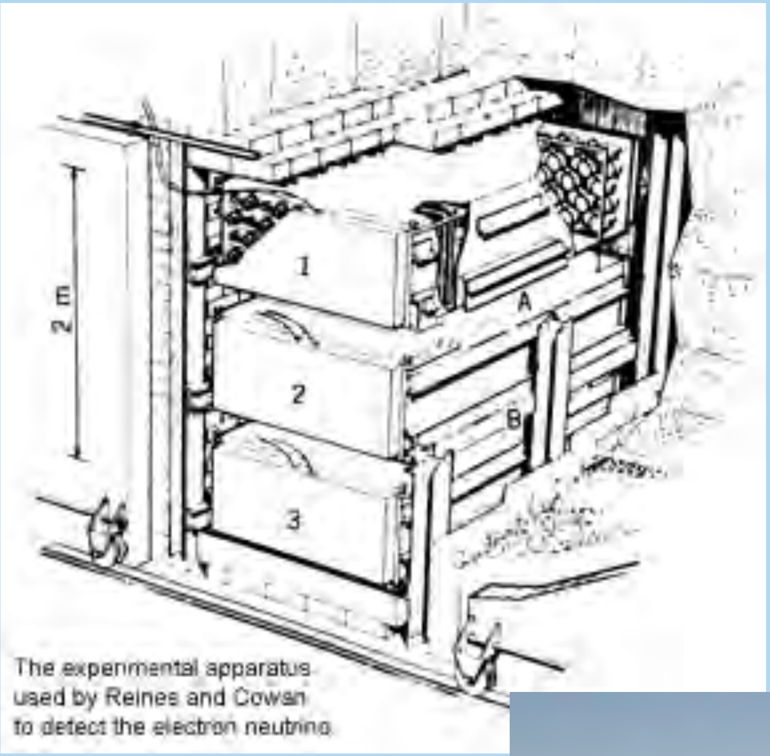
The IceCube Hot Water Drill



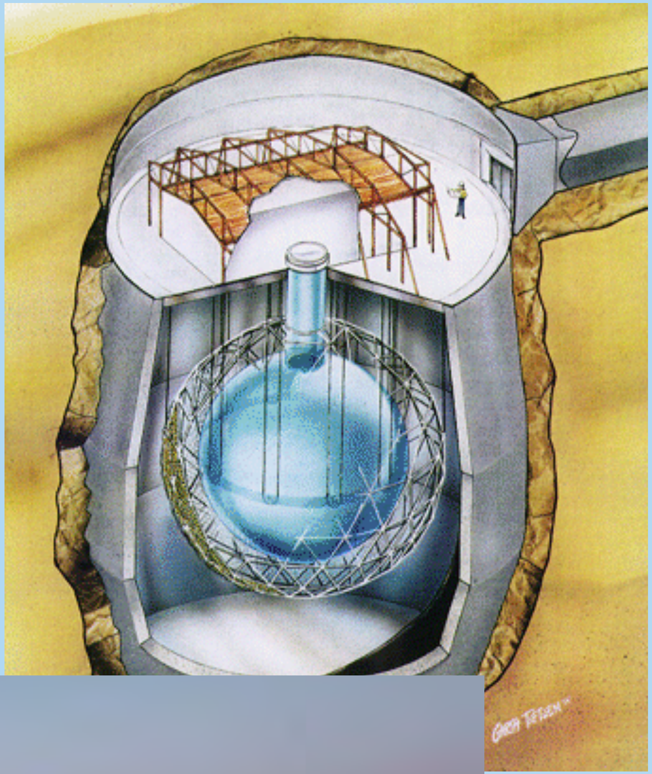




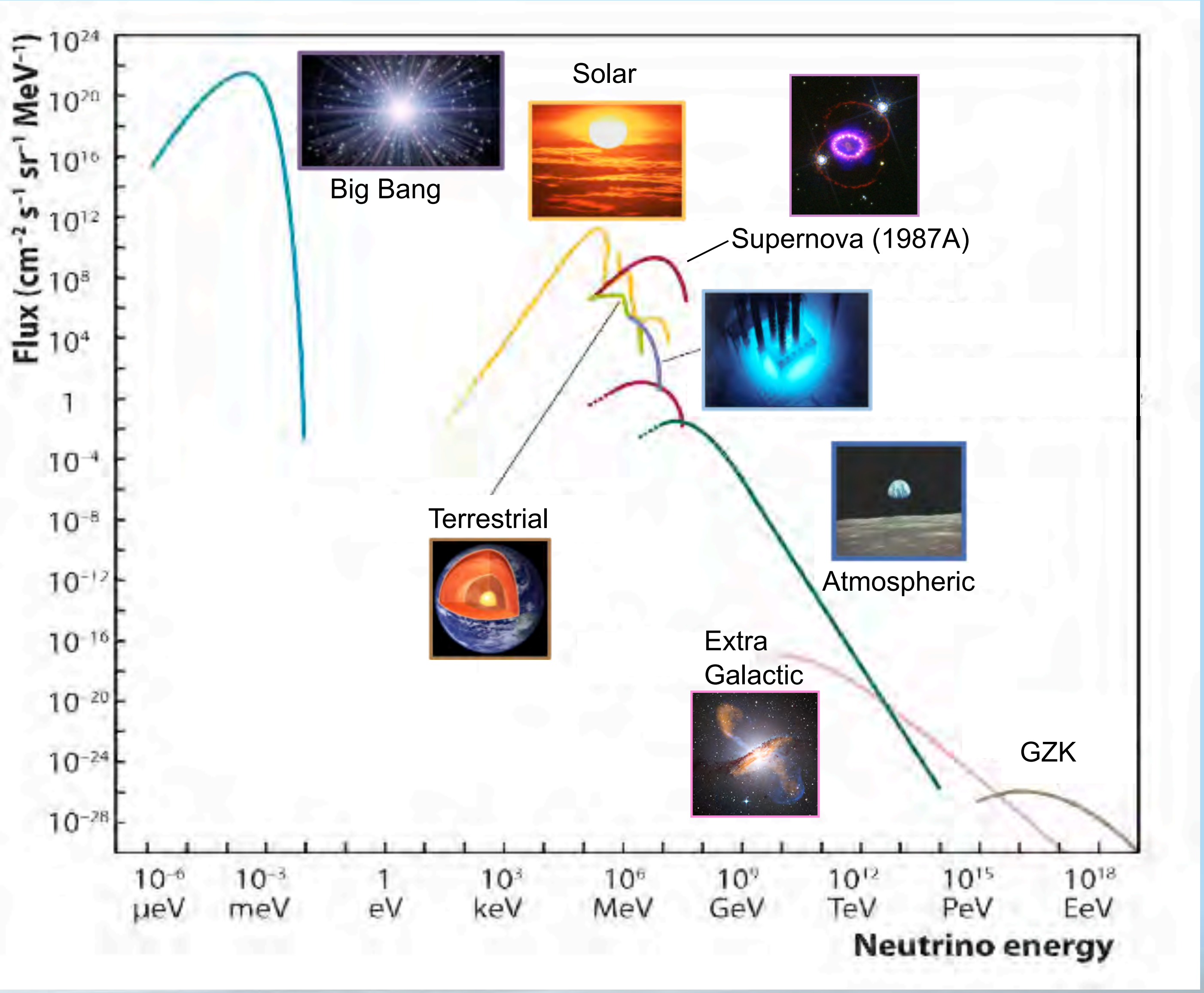
Big Water



The experimental apparatus used by Reines and Cowan to detect the electron neutrino

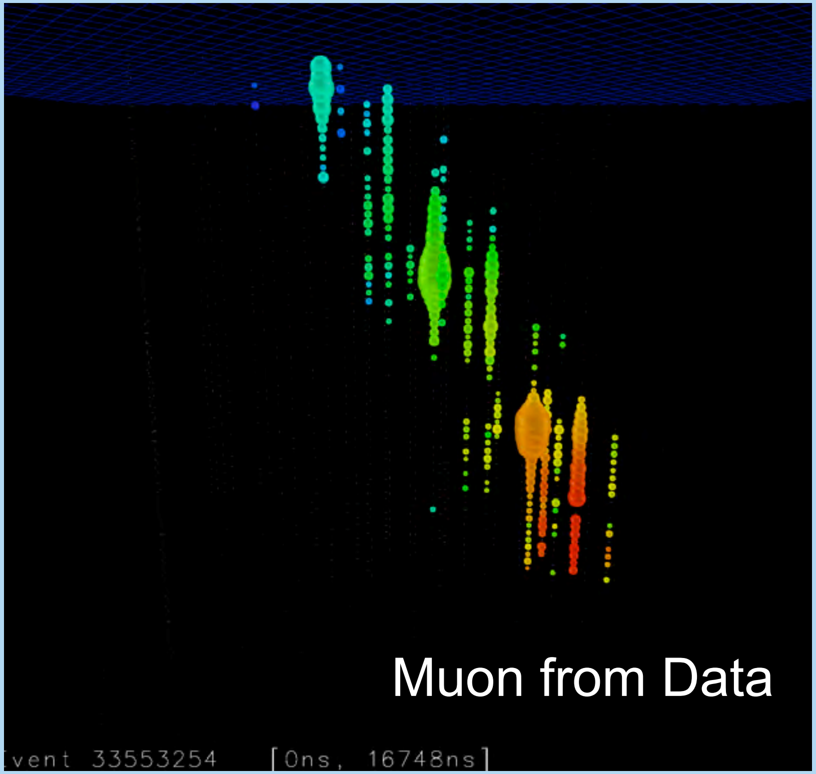


Neutrinos in The Wild



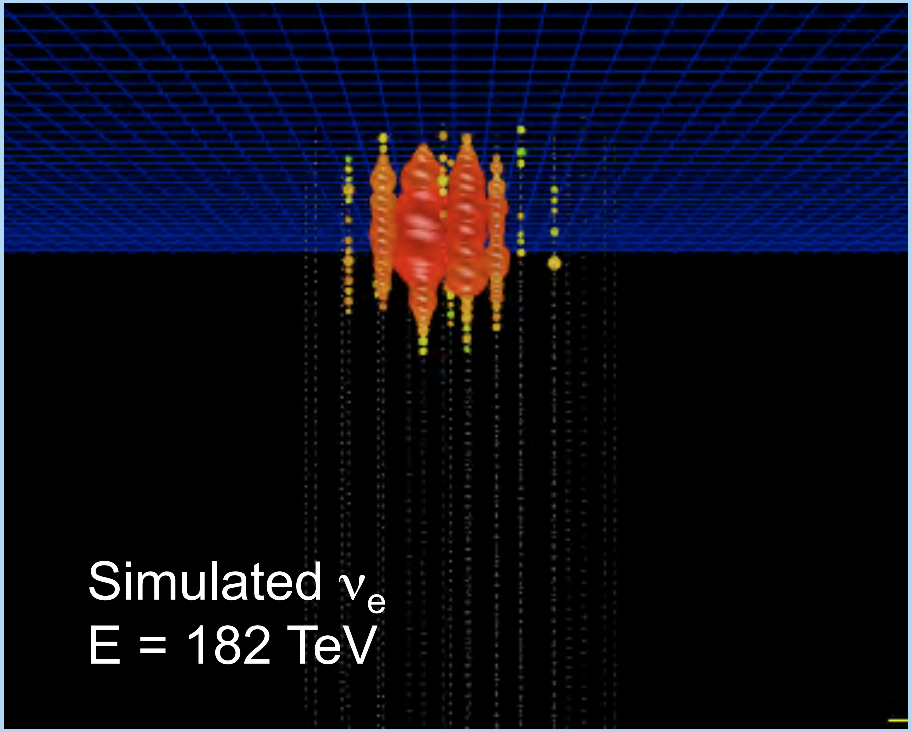
Neutrino Flavor Identification

Tracks



- Muons and taus
- Long tracks length ~1 km

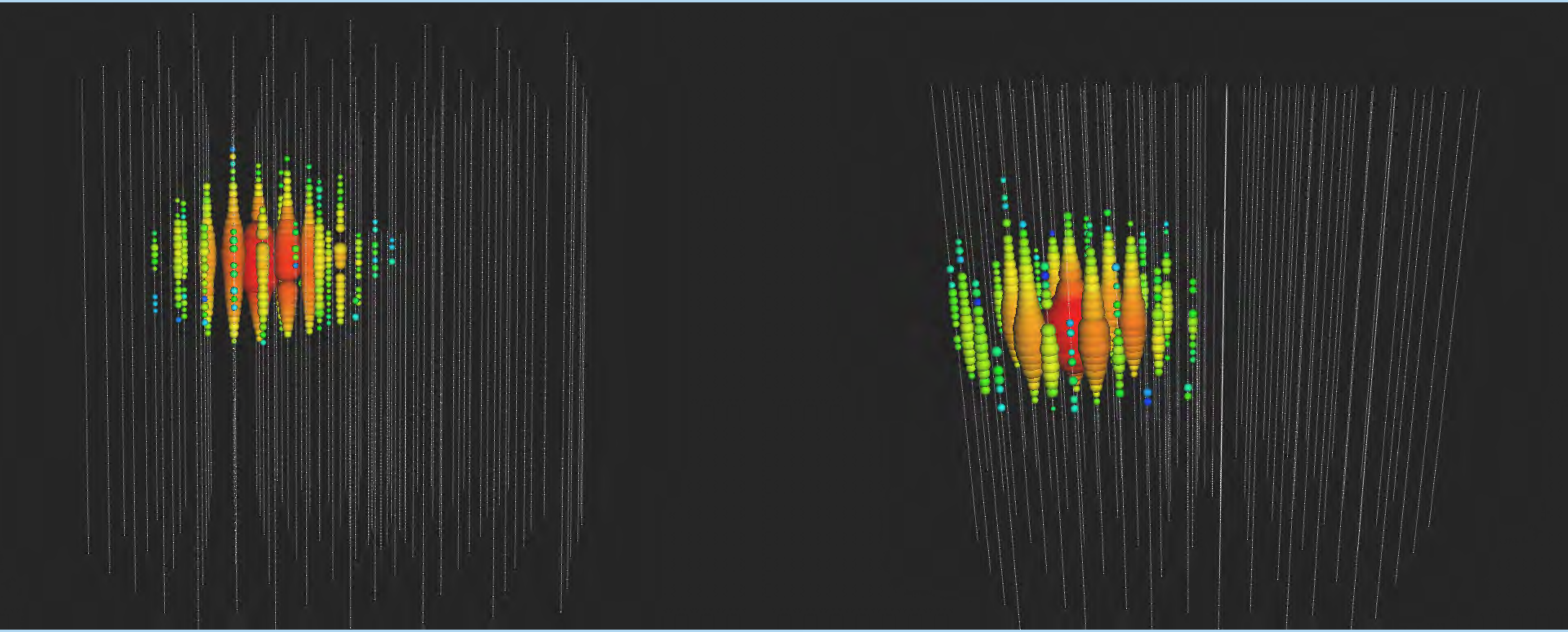
Cascades



- ν_e, ν_τ, and NC also make cascades
- "Point" sources O(10 m)
- Electron kicks out many other electrons

Bert and Ernie

Energies are 1.0 and 1.1 PeV

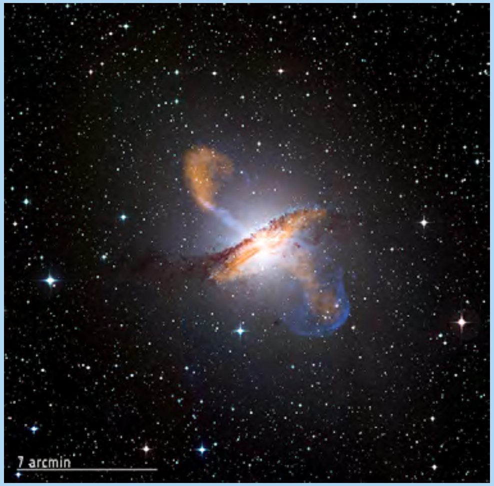


72,907 photons

107,898 photons

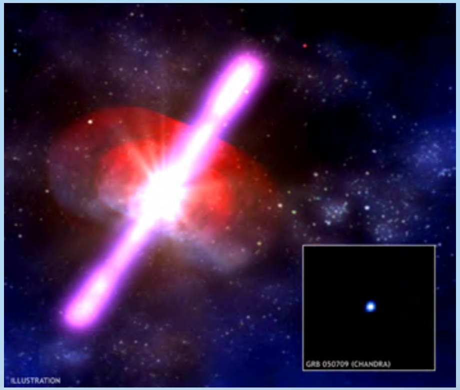
Fantastic Accelerators

Large radius



AGNs:
B field 1 G,
size 10^{12} km

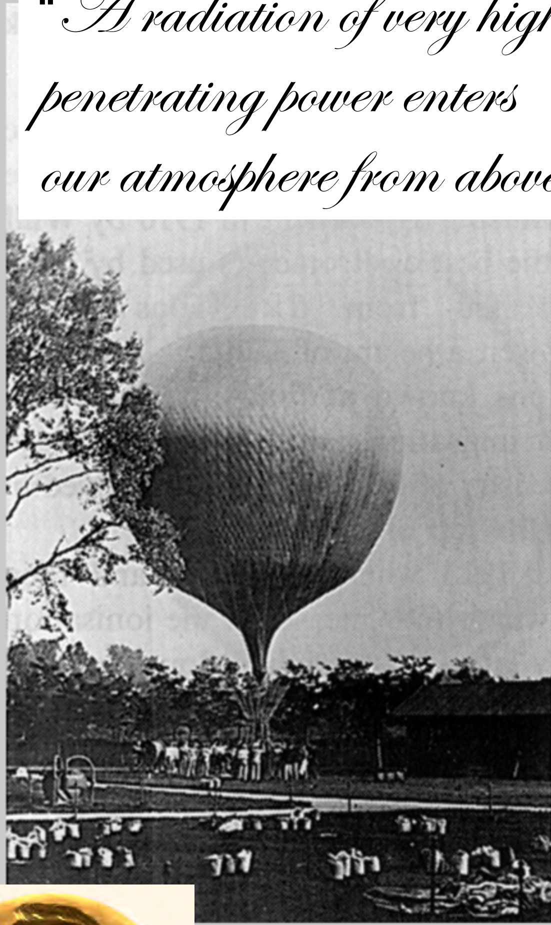
Large magnetic field

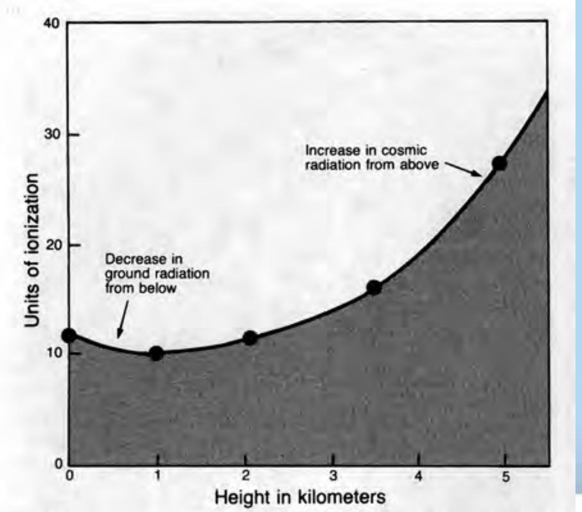


GRBs:
B field 10^9 G,
size 10^5 km

Radiation From Space

"A radiation of very high penetrating power enters our atmosphere from above."

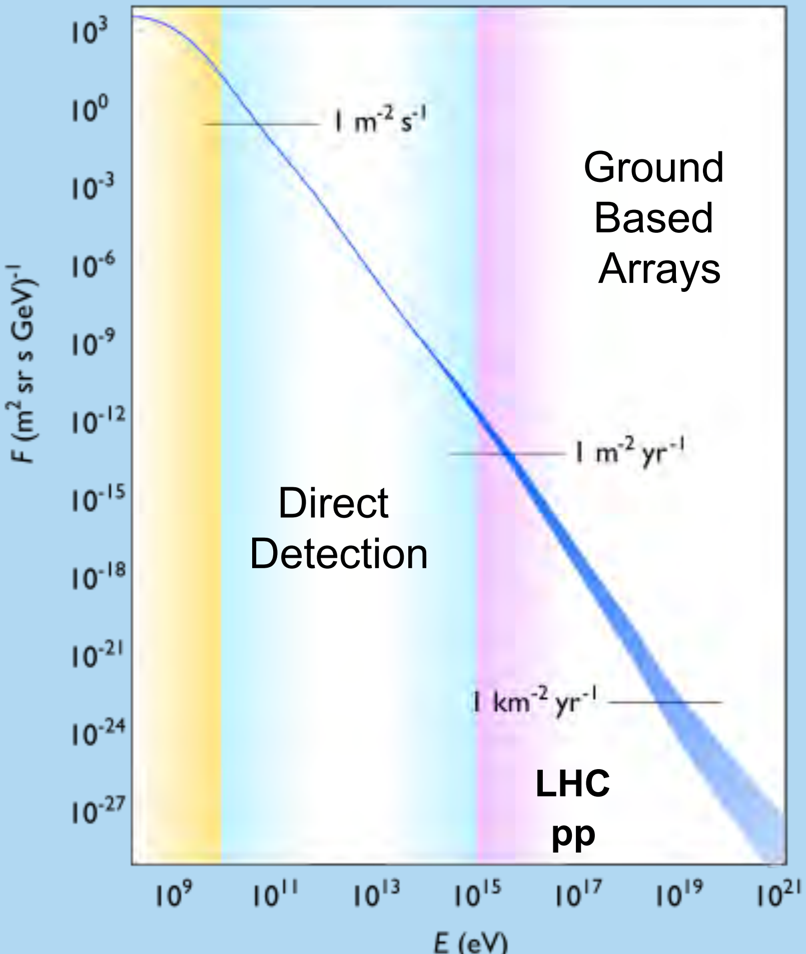




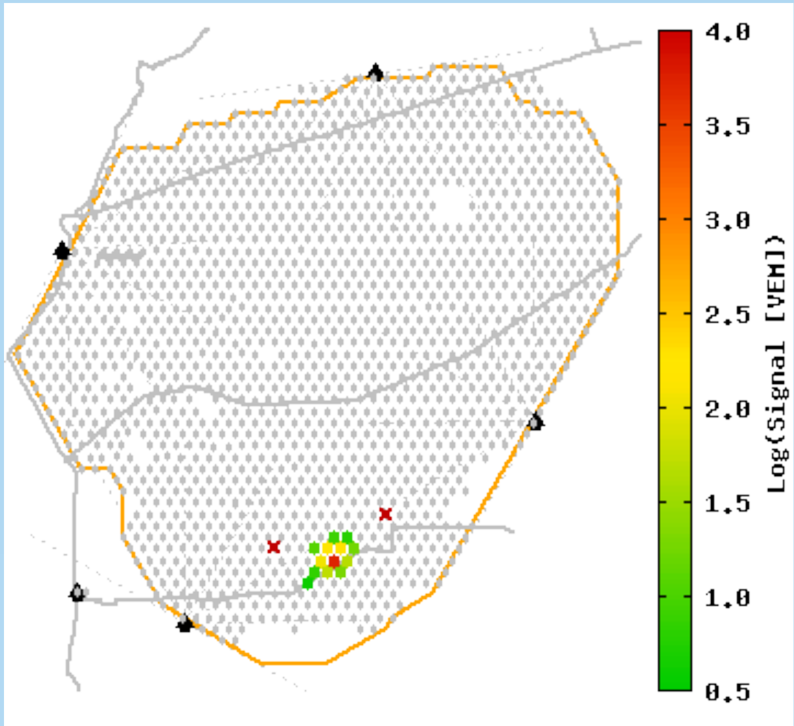
- Measured by Victor Hess in 1912
- Nobel Prize 1936

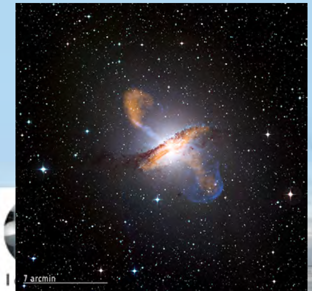
100 Years After Hess

S. Lafebre



- Falls as $E^{-2.7}$
- Cosmic rays energies span 13 orders of magnitude up to 10^{20} eV





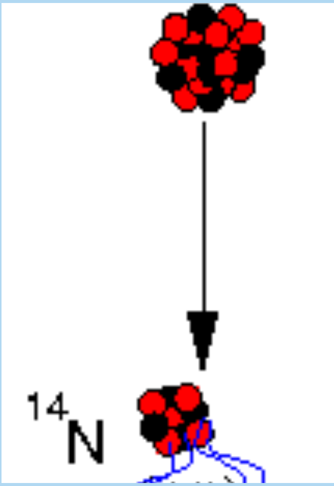
Highest energy CR so far: 3×10^{20} eV
Footprint 6 km diameter
(city of Berkeley)
10,000 muons at center

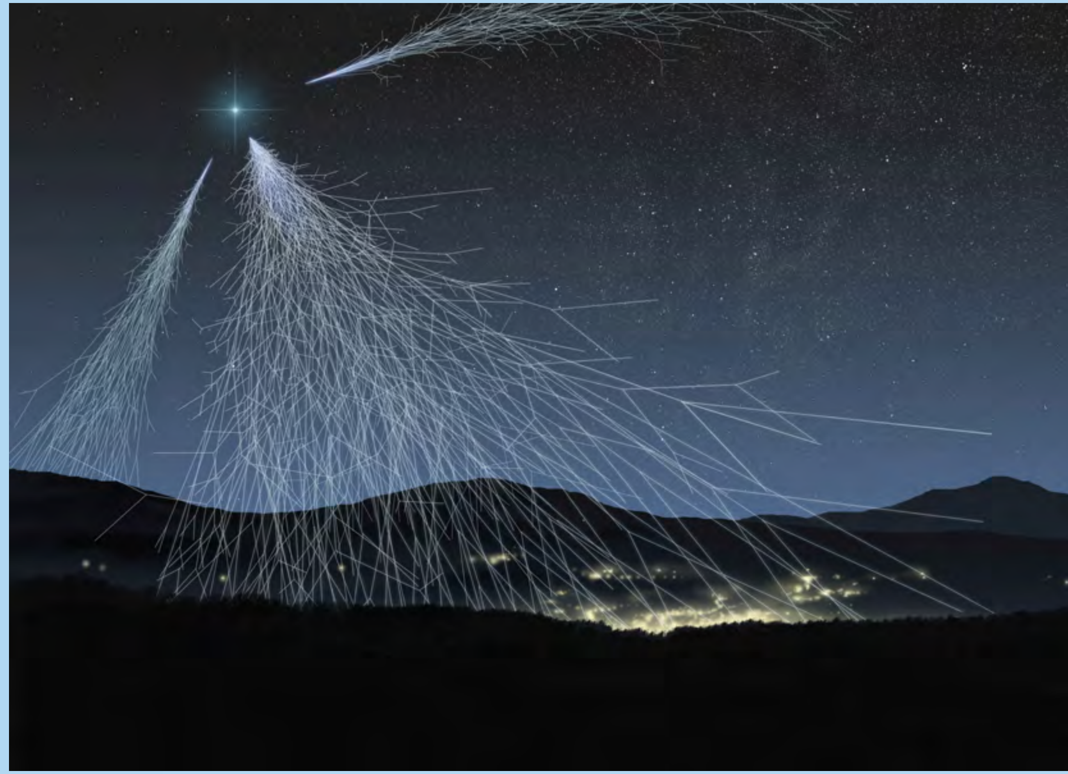
A Special Kind of Place

IceCube

BERKELEY LAB

Massive Cascades

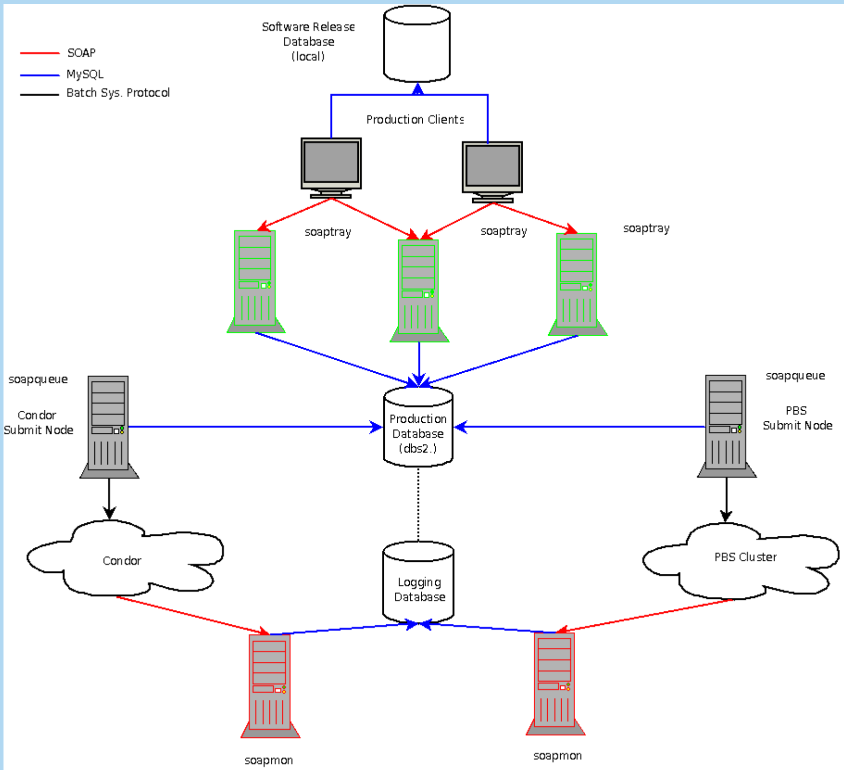


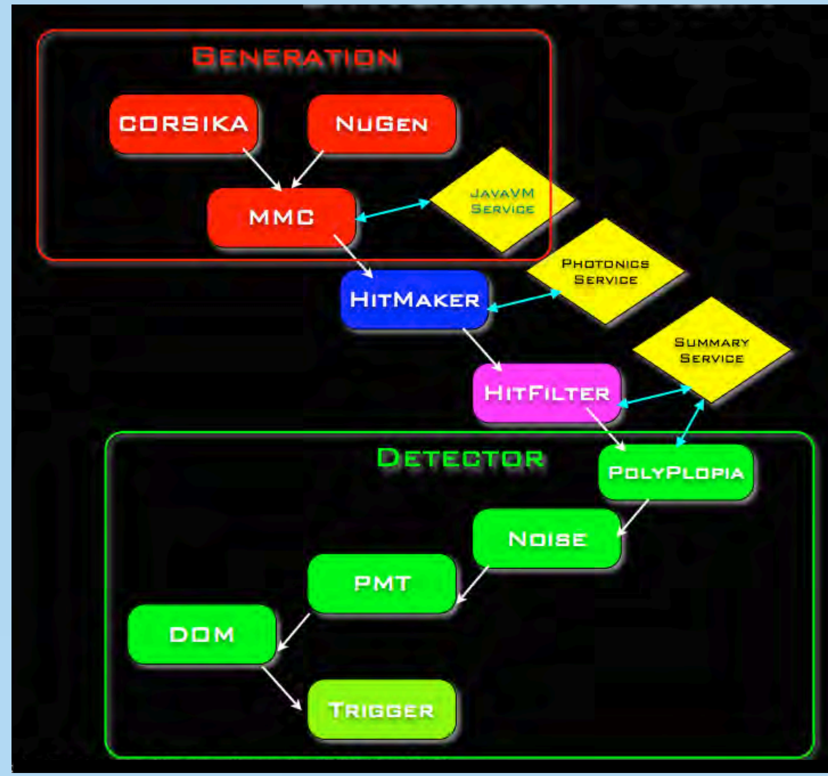


Particle Zoo

- p + N_2 ➔ $\pi^{\pm}$, π^0, $K^{\pm}$, K^0, p, n, Λ, D, etc.
- π^0 ➔ $\gamma\gamma$ ➔ showers of e^+/e^-
- Low energy $\pi^{\pm}$, $K^{\pm}$ decay to μ, ν. High energy interact and make more π
- Bulk of energy and particles are in electromagnetic component
- Tens to 10 of thousands of penetrating muons and neutrinos

Simulation Management

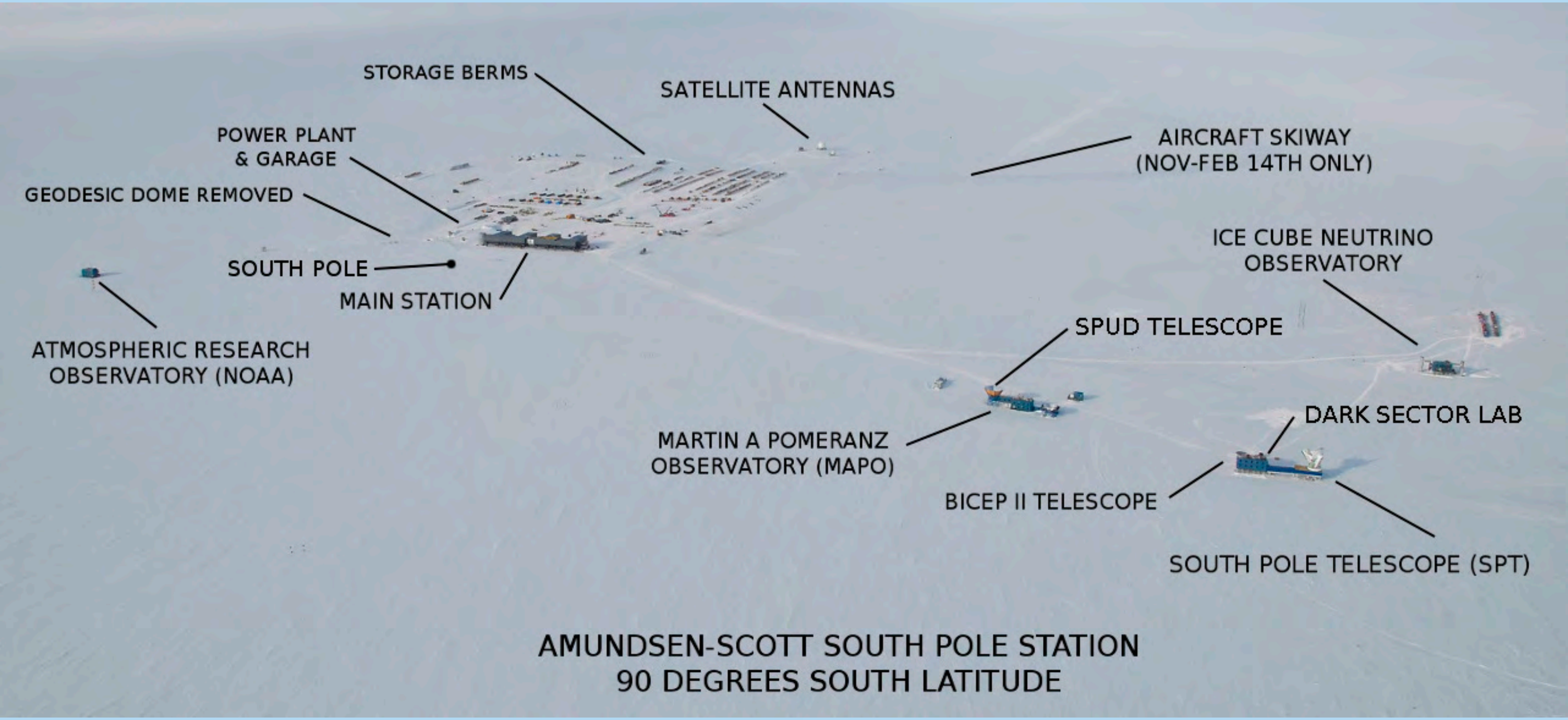




IceProd
Python code
Uses SOAP xml
Collected using GridFTP

Jamesways

Science at Antarctica



Cosmic Ray Backgrounds

$$CR + \text{nucleus} \rightarrow \Delta^{\pm} \rightarrow \pi^{\pm} + n$$

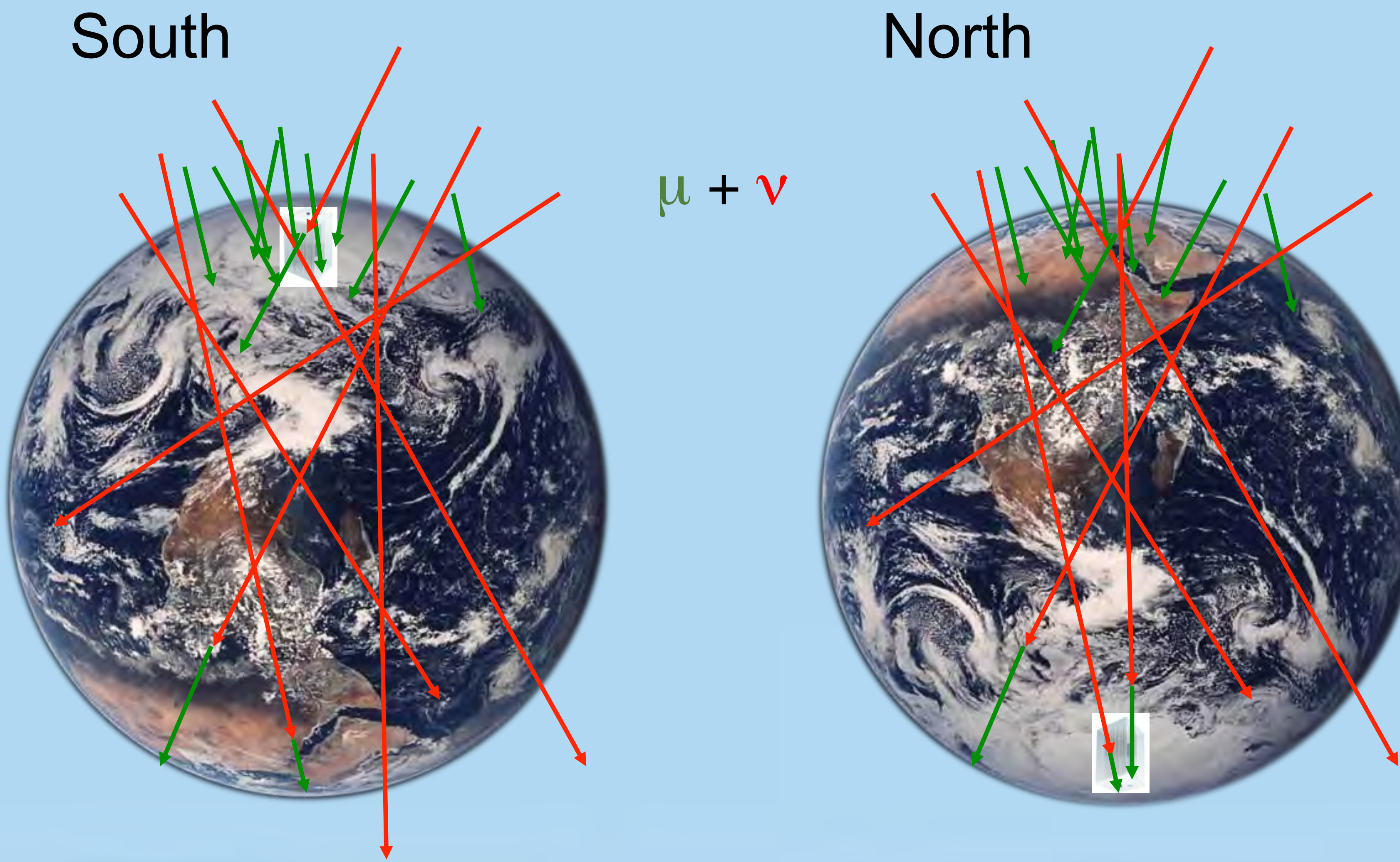
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e} + \nu_{\mu}$$

- Atmospheric neutrinos
  - Interact in the ice and produce muons / electrons
  - Essentially the same as astrophysical neutrino
- Atmospheric muons
  - Astrophysical neutrino make electrons / muons too
  - All muons / electrons make light in ice
- DOMs are democratic
  - See photons, regardless of origin

Not just background!

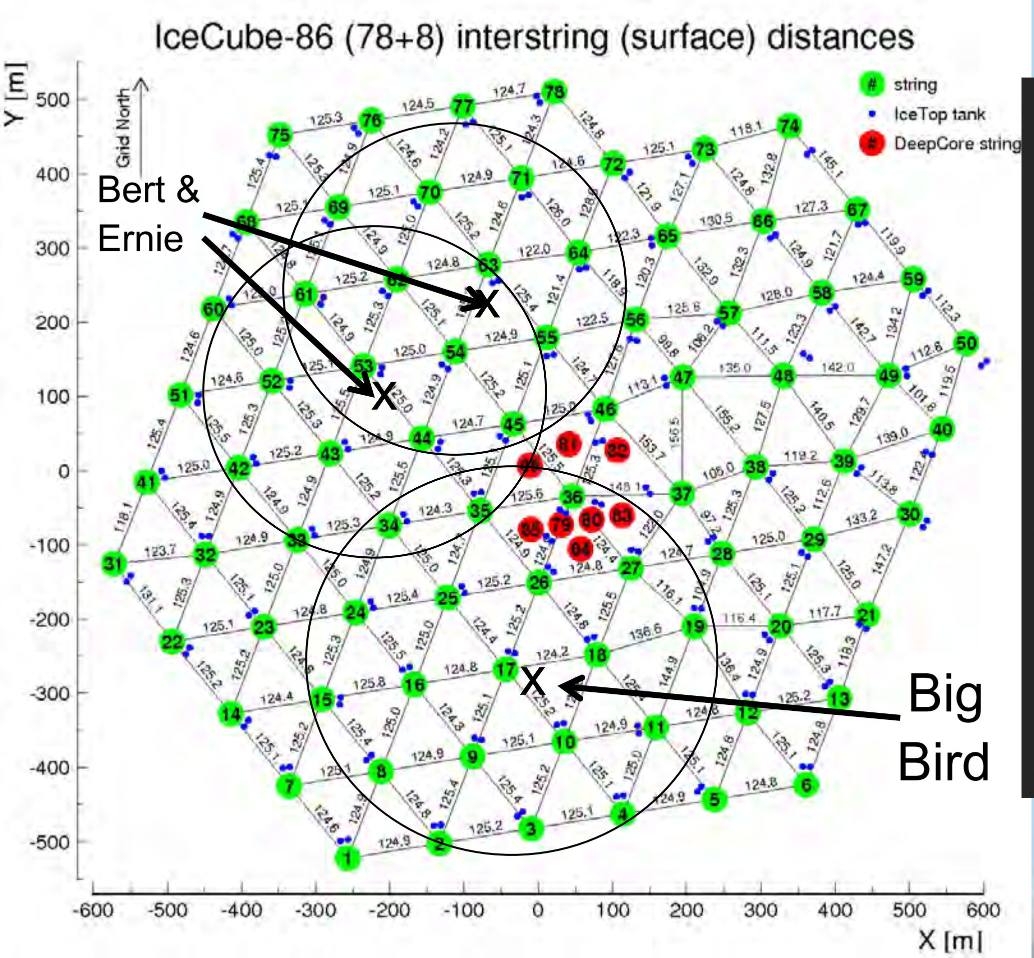
Lots of interesting CR physics, too.

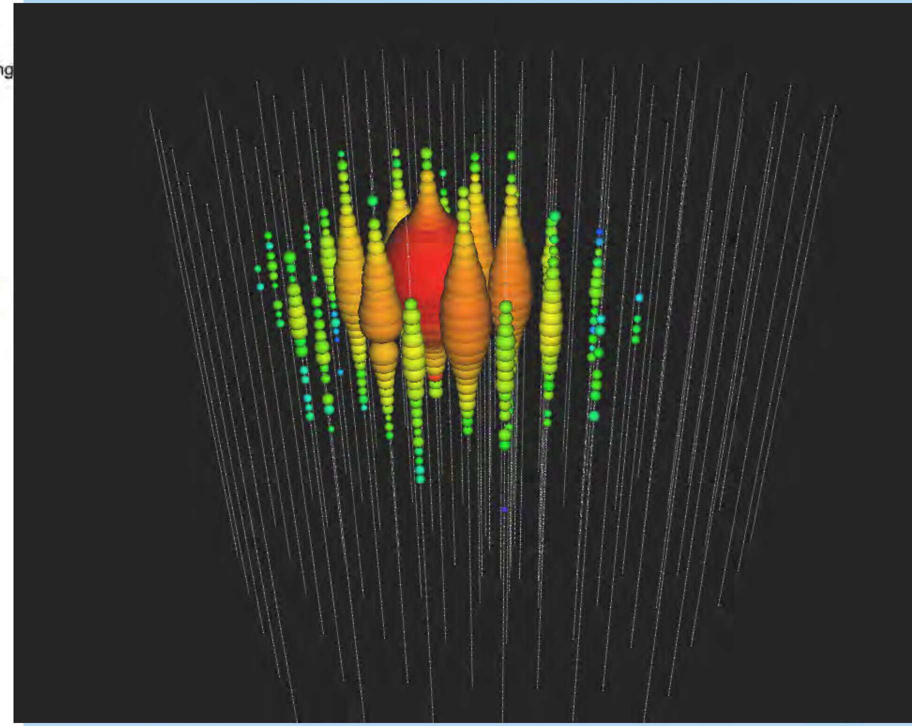
A Matter of Perspective



Big Bird

Energy is 2.2 PeV, deposited
127,065 photons into 378 DOMs





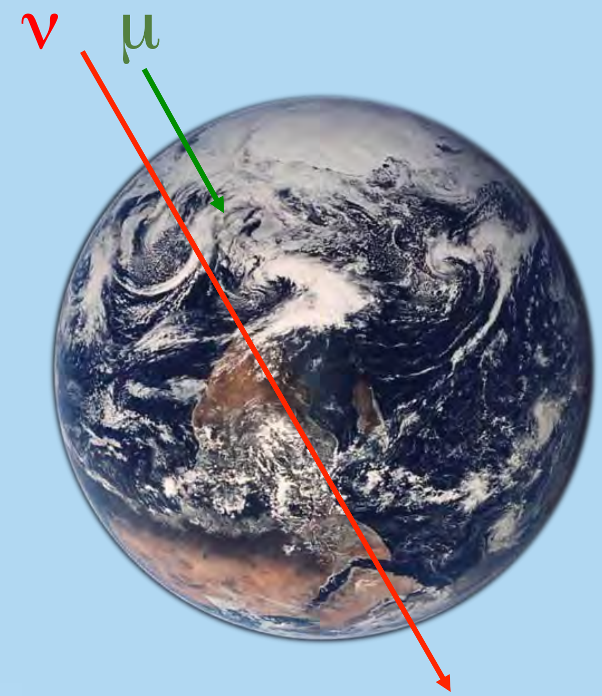
History of neutrinos

- 1956: First detector of nuclear reactor neutrinos
- 1965: First atmospheric neutrino detection
- 1968: First solar neutrino detection
- 1976: DUMAND
- 1987: Only neutrinos from outside of the solar system detected from 1987 Supernova
  - 3 simultaneous detections within 13 seconds
- 1995: AMANDA drilled into Antarctic Ice
- 2005: IceCube construction began
- 2013: IceCube finds first evidence for high energy astrophysical neutrinos

Cosmic Ray Backgrounds

$$CR + \text{nucleus} \rightarrow \Delta^{\pm} \rightarrow \pi^{\pm} + n$$

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



Atmospheric neutrinos
- –Separate by energy

Atmospheric muons
- –Separate by direction

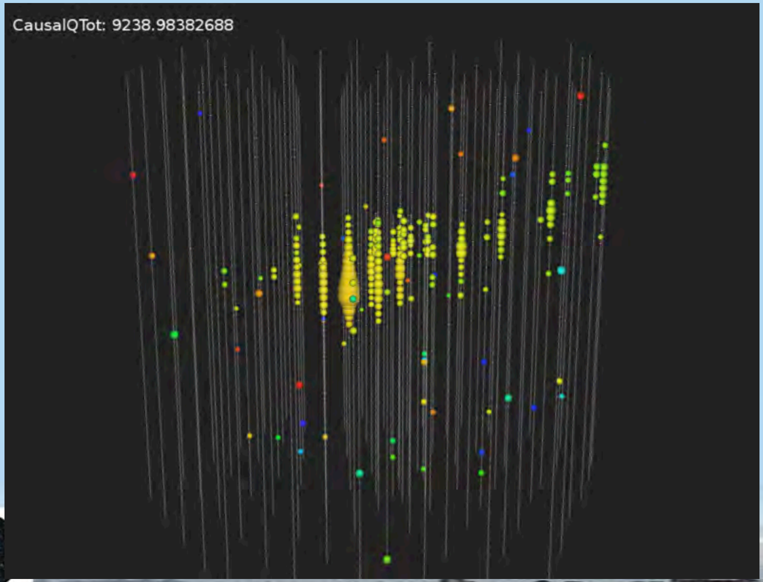
'Traditional' IceCube analyses
- –Southern Direction: Energy threshold
- –Northern Direction: Earth Shield, lower energy threshold

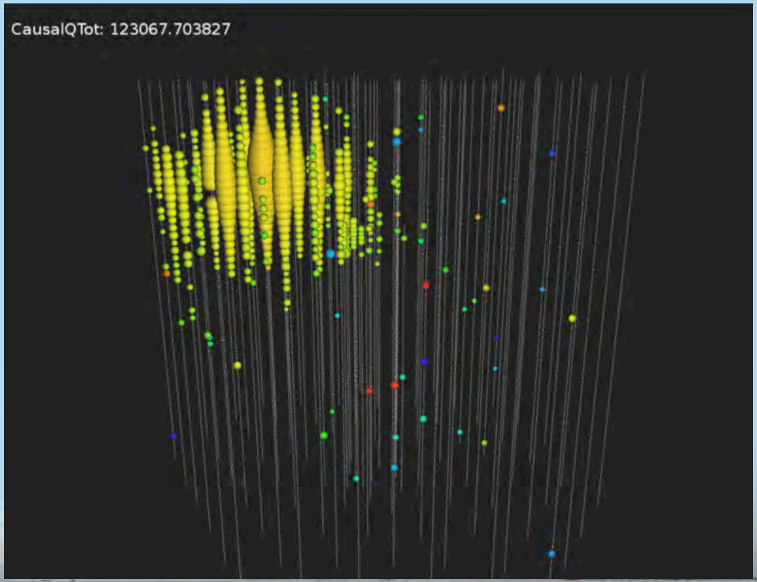
Evidence of What?

Leading candidate for source of these neutrinos is AGNs

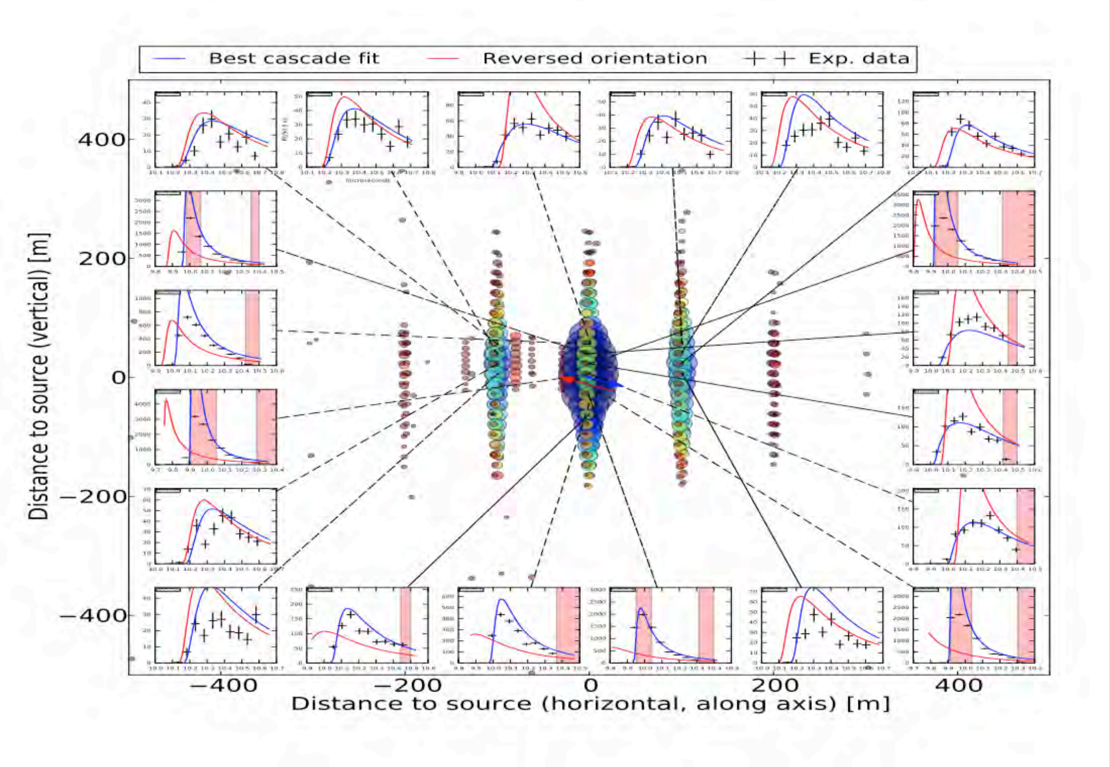
Reconstruct direction and see if they're pointing back to anything interesting

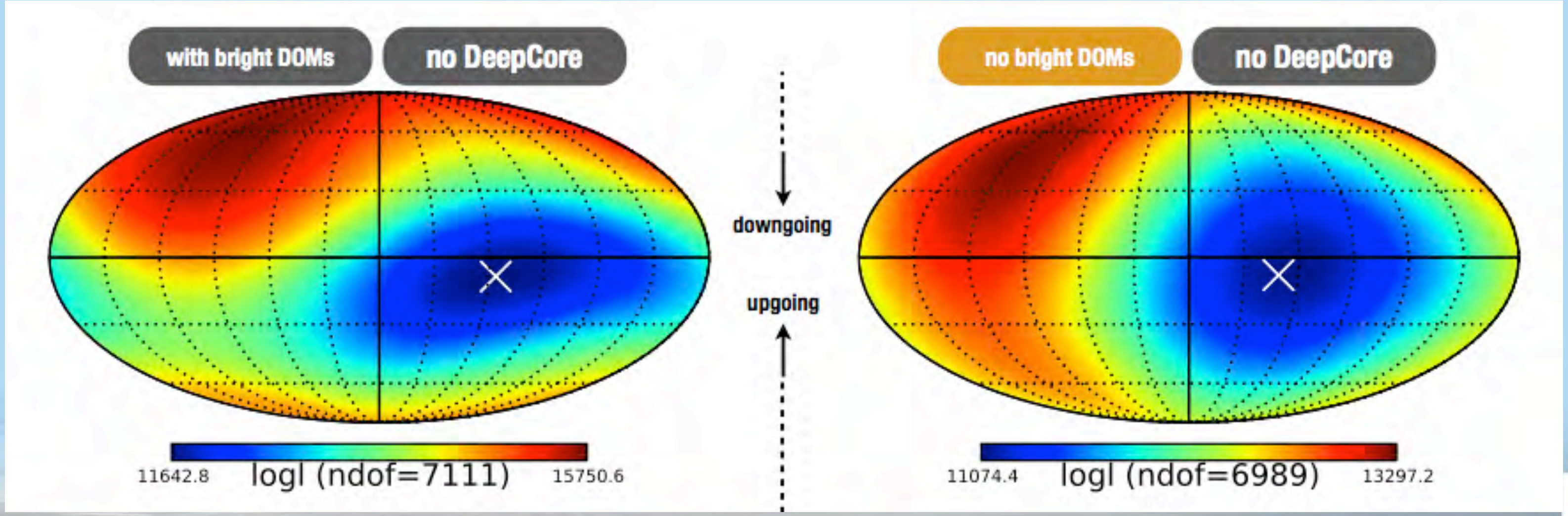
21 cascades and 7 tracks



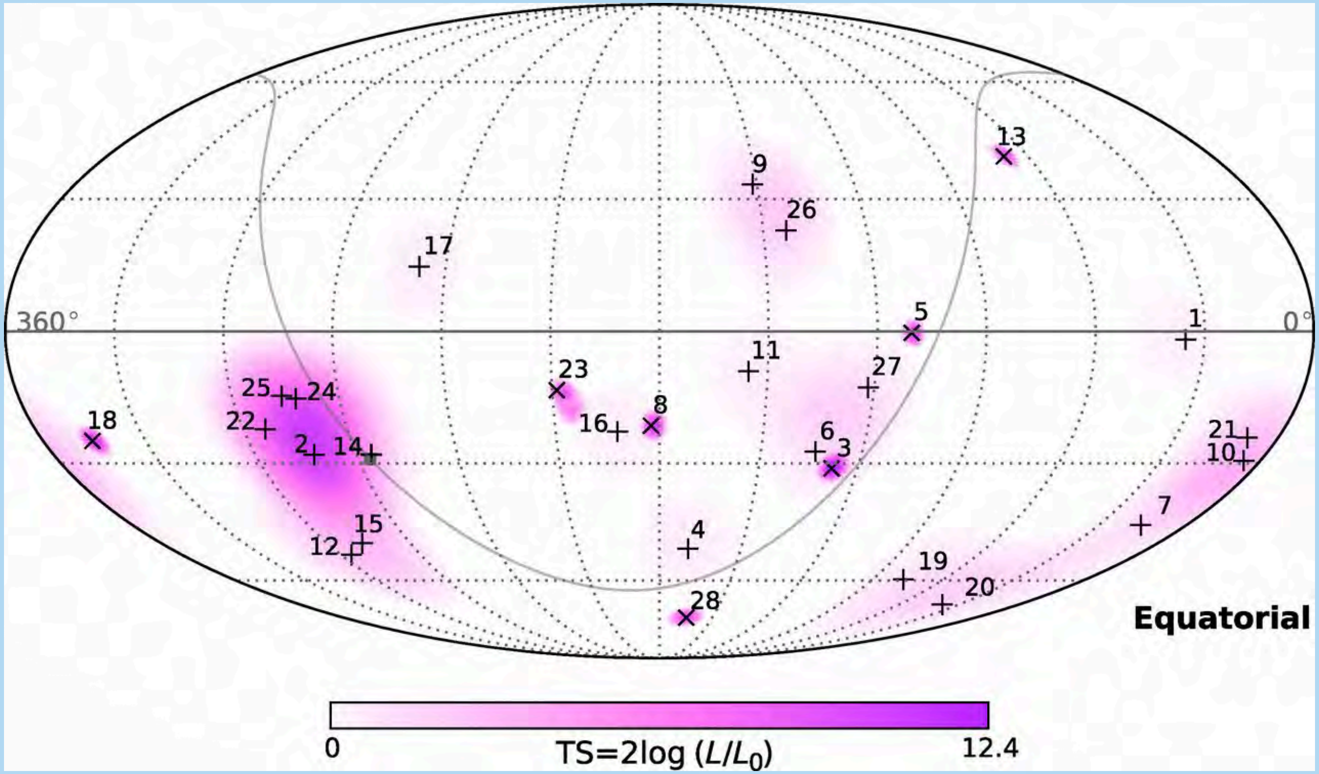


Reconstructing Cascade Direction





Sky Map of Neutrinos



No significant clustering found