IceCube's Observation of Cosmic Neutrinos

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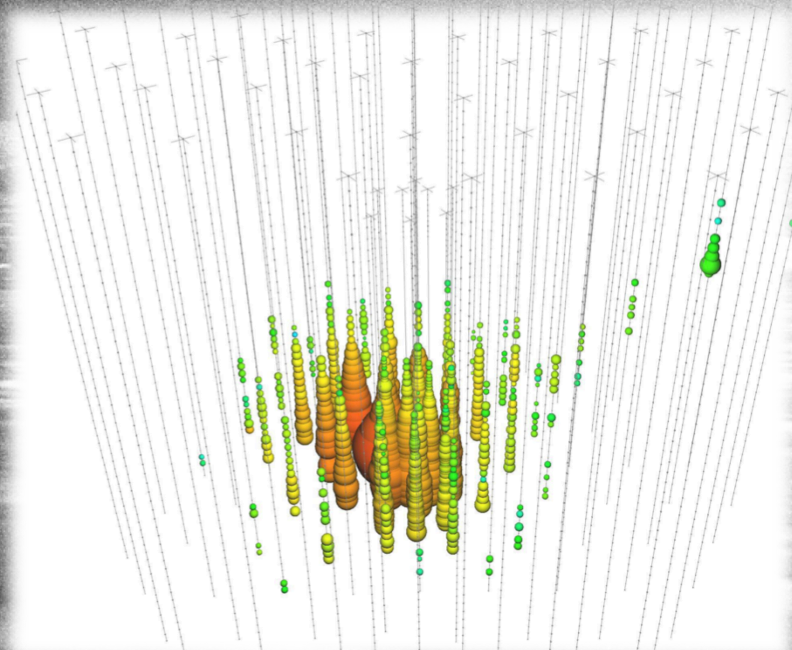
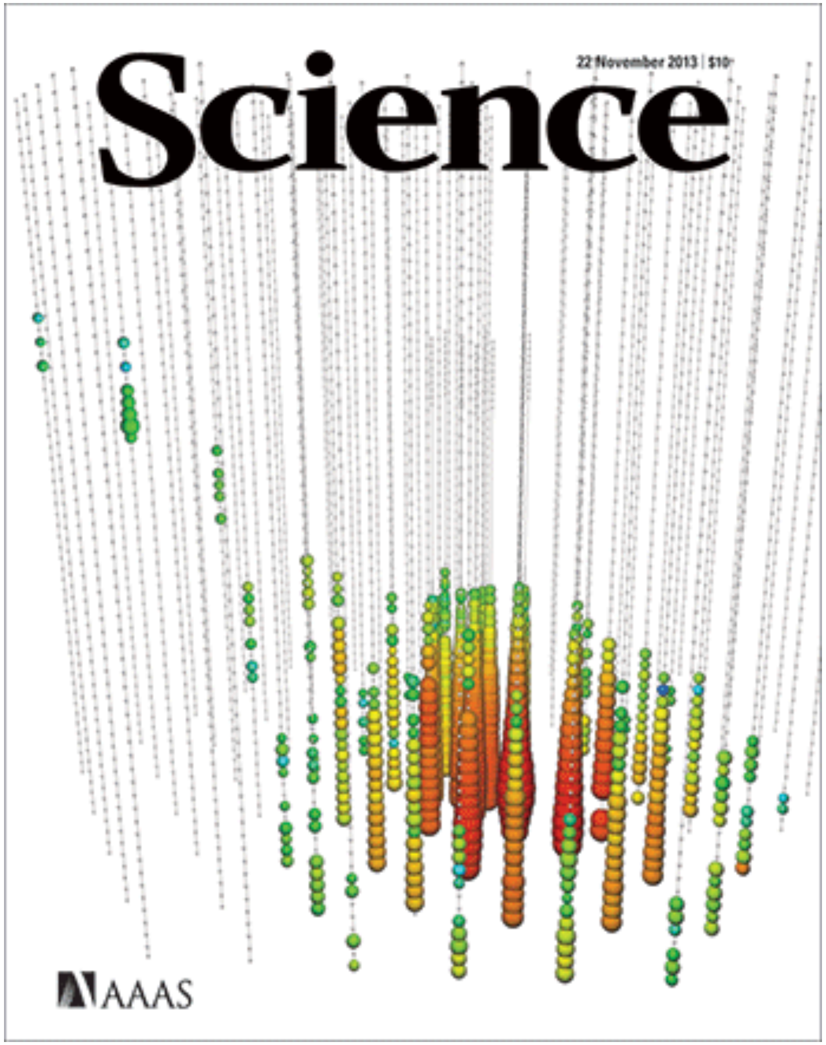
South Pole Sunday Science Lecture
December 22, 2013



IceCube in the News



Cosmic neutrinos named Physics World 2013 Breakthrough of the Year

Dec 13, 2013 8 comments

The *Physics World* award for the 2013 Breakthrough of the Year goes to "the IceCube South Pole Neutrino Observatory for making the first observations of high-energy cosmic neutrinos". Nine other achievements are highly commended and cover topics ranging from nuclear physics to nanotechnology

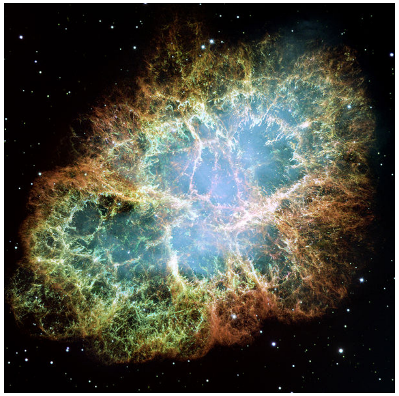
Celebrating the completion of IceCube at the South Pole

A 100-Year-Old Mystery...

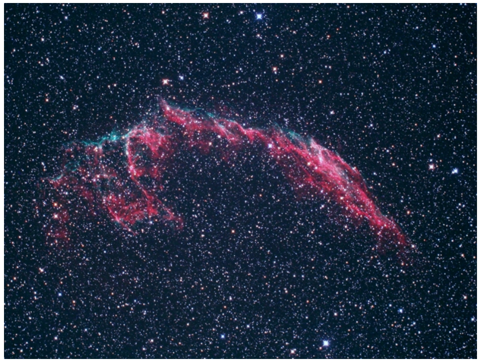
V. Hess balloon flights, 1911-12

- Cosmic rays: charged particles coming from everywhere in the sky
- Energies up to 10^{20} eV (16 J)
- What are they and where do they come from?
- How do they reach such enormous energies?
- What can we learn about particle physics at such extremes?
- Can we do astronomy with particles?

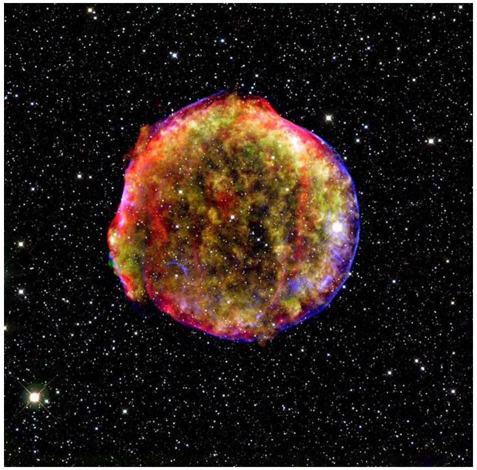
Nature's Accelerators: SNRs?



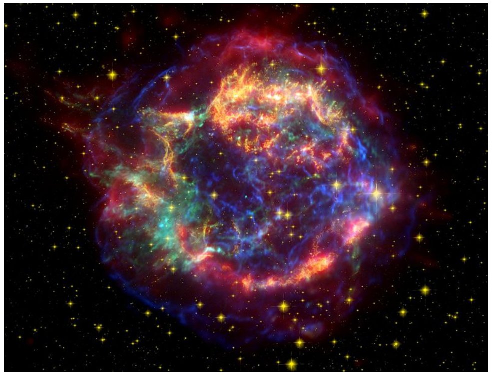
Crab nebula (M1)
Hubble, false color



Veil nebula
(NGC6992, etc.)
optical



Tycho (SN1572 / B Cas)
X-ray / infrared

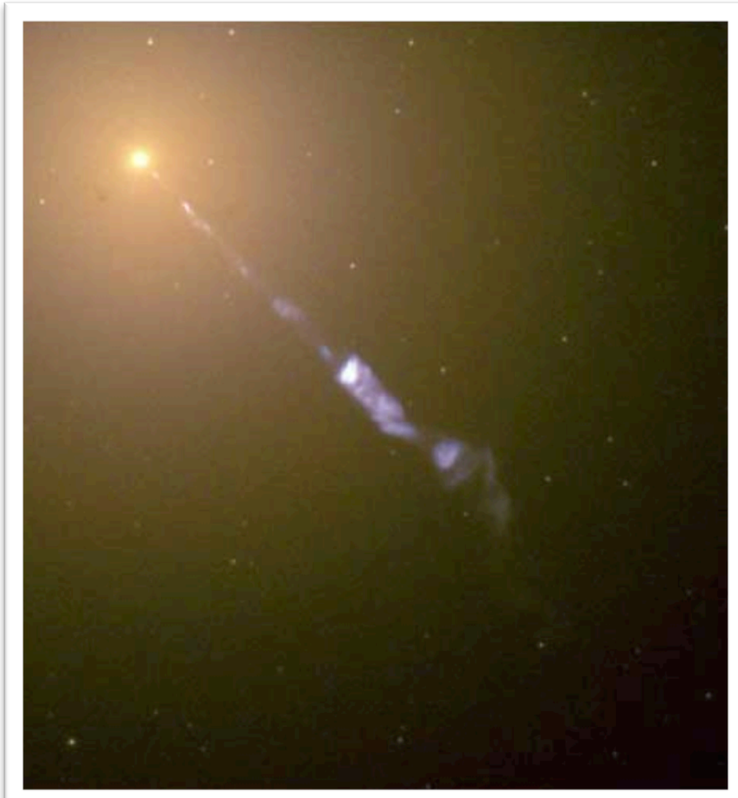


Cassiopeia A
X-ray / optical / infrared

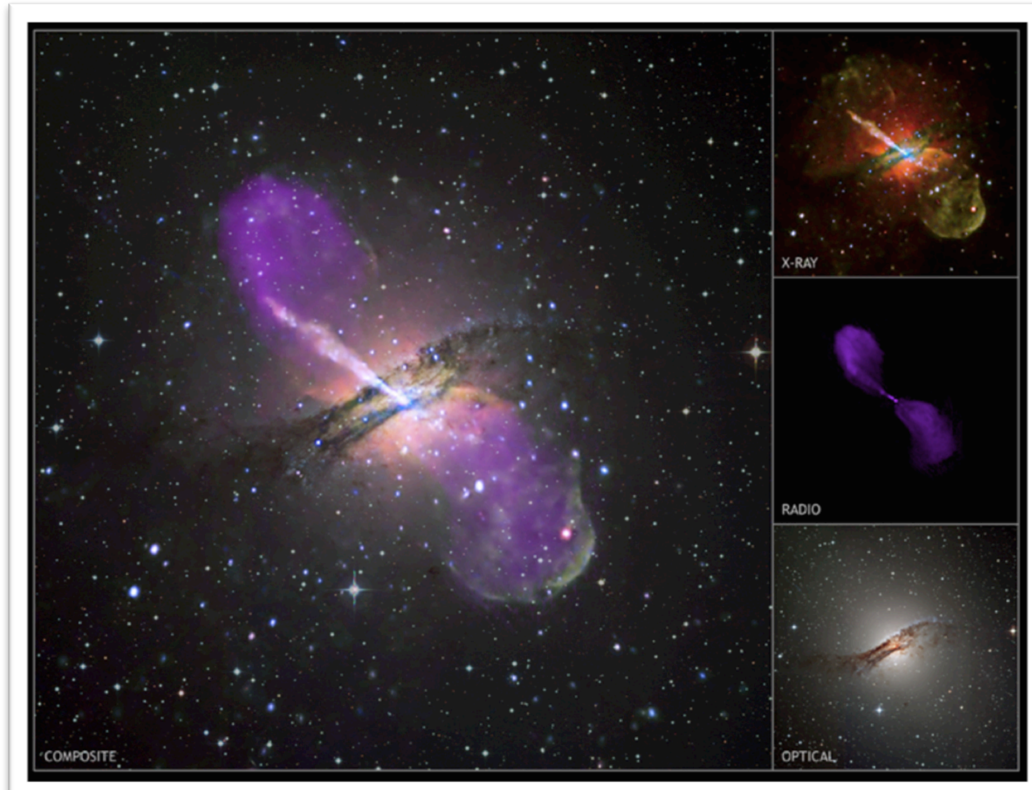
several supernova remnants (SNR) in our Galaxy

Nature's Accelerators: AGN?

M87

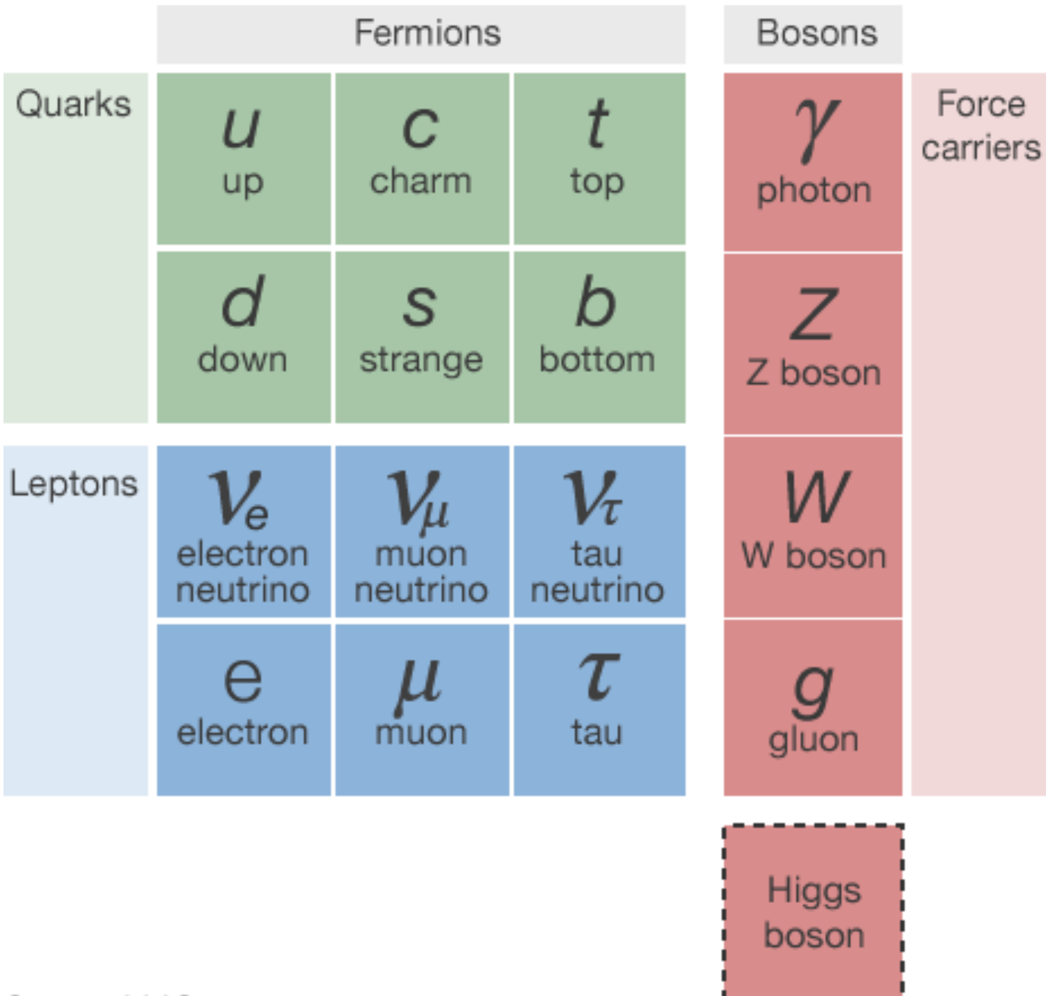


Centaurus A (NGC 5128)



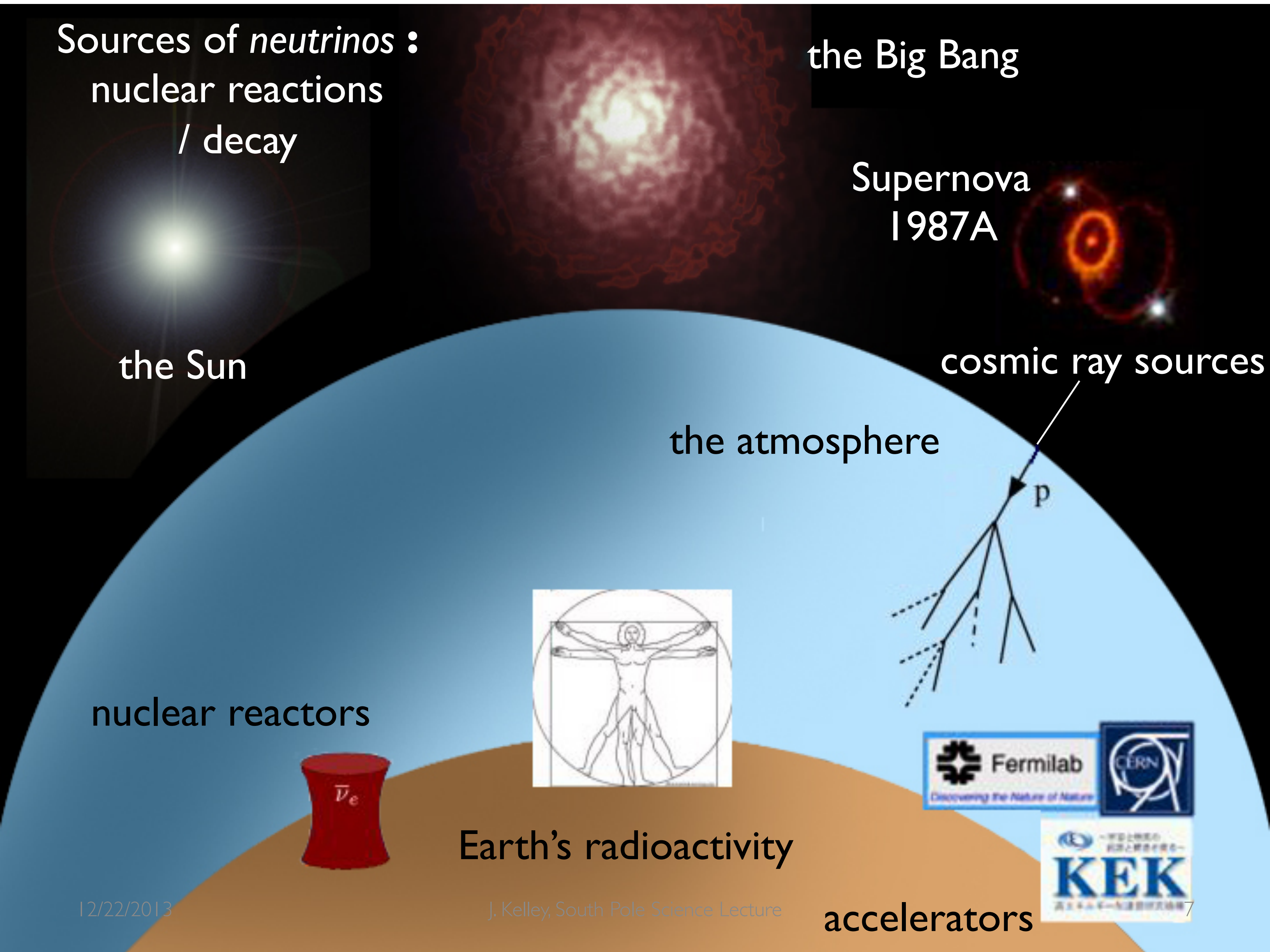
composite images of two active galactic nuclei (AGN)

Particle Physics Primer



Source: AAAS

- Everyday matter: up, down quarks and electrons
- Three types or "flavor" of neutrino
  - no electric or color charge
  - small, unknown masses
  - can oscillate / change flavor
- Flavors related to the three charged leptons
  - certain interactions can produce electron, muon, tau


Sources of *neutrinos* :
nuclear reactions
/ decay
the Big Bang
Supernova
1987A
the Sun
cosmic ray sources
the atmosphere
p
nuclear reactors
$\bar{\nu}_e$
Earth's radioactivity
Fermilab
Discovering the Nature of Nature
CERN
KEK
accelerators

Different Locations, Same Particle Physics

$$p+\gamma \to p+\pi^0, n+\pi^+$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

High-energy proton collides with anything: pions!

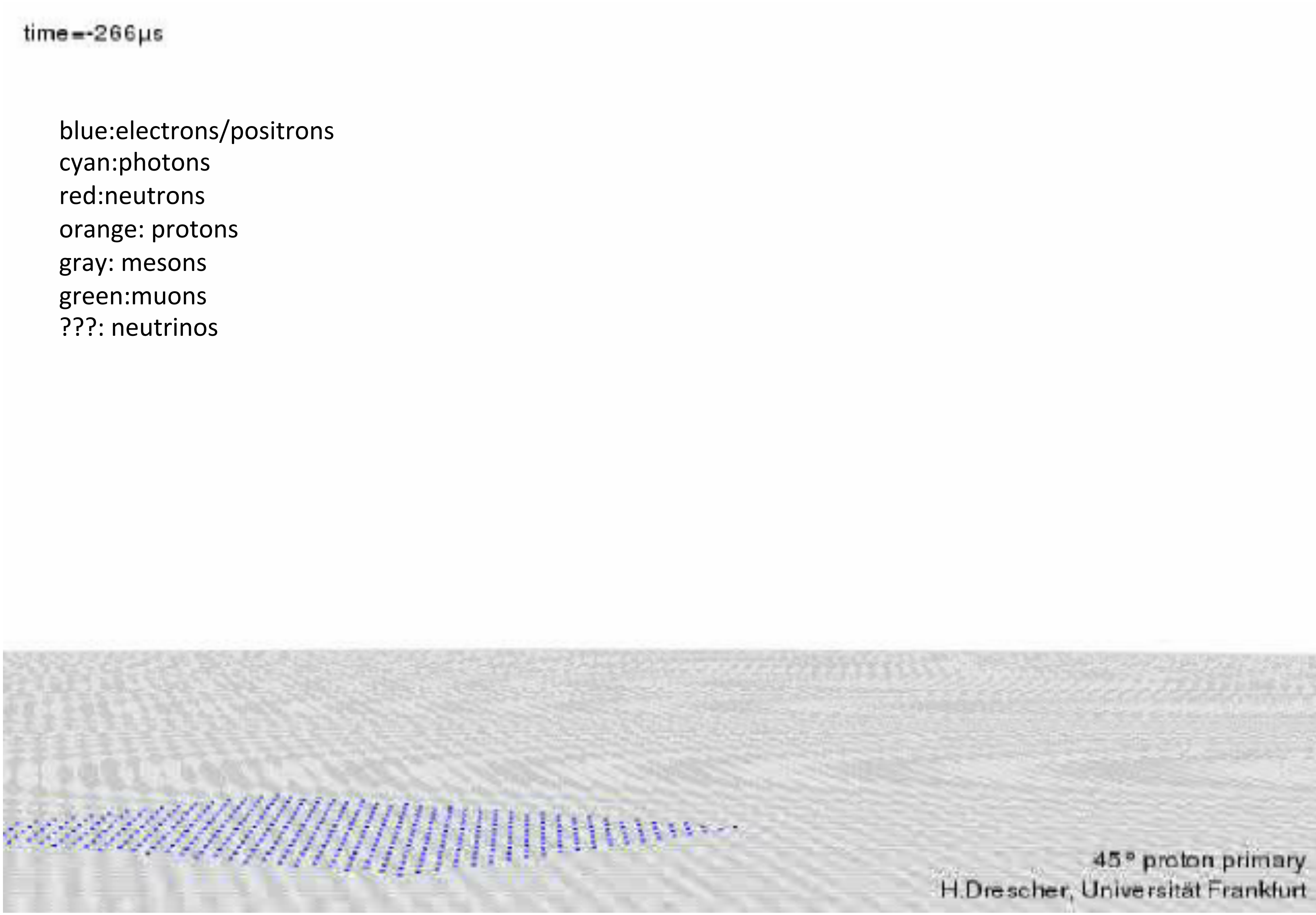
Decay to gamma-rays, muons, neutrinos, etc.

Similar processes happening in:

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

Cosmic rays and neutrinos are closely connected

Cosmic Ray Air Shower Simulation



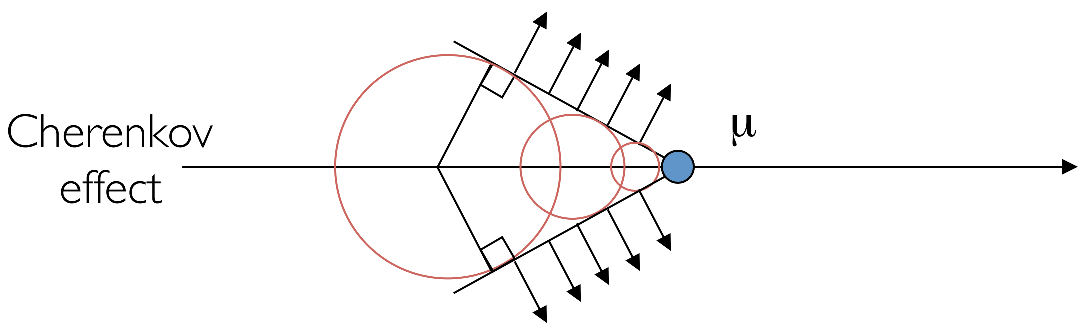
blue:electrons/positrons
cyan:photons
red:neutrons
orange: protons
gray: mesons
green:muons
???: neutrinos

How Do We Detect ν?

1. With difficulty! Most neutrinos pass completely through Earth.

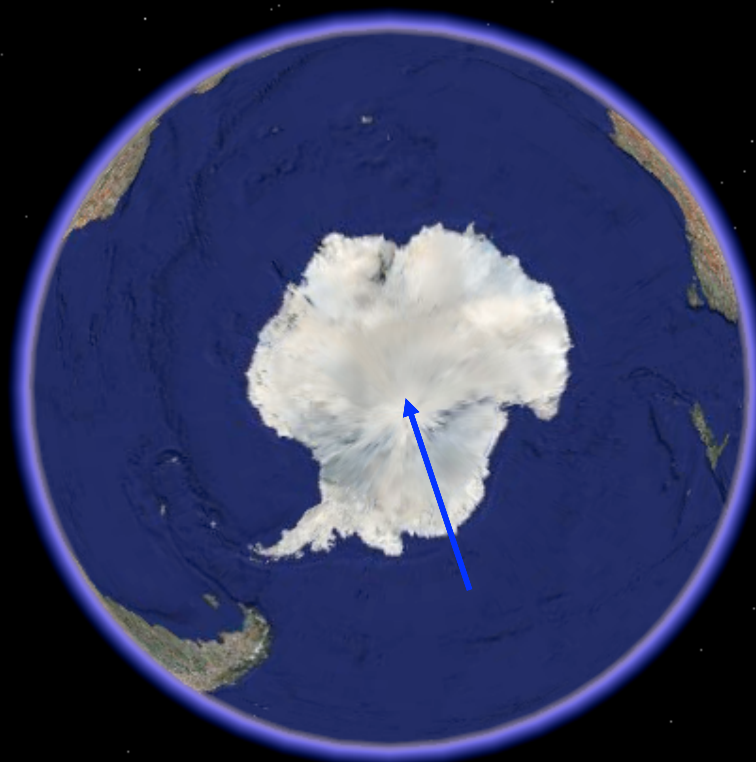
2. Need to wait for an interaction / collision — necessitates a big target

3. Then detect the collision debris, i.e. other, more visible particles, using the light emitted



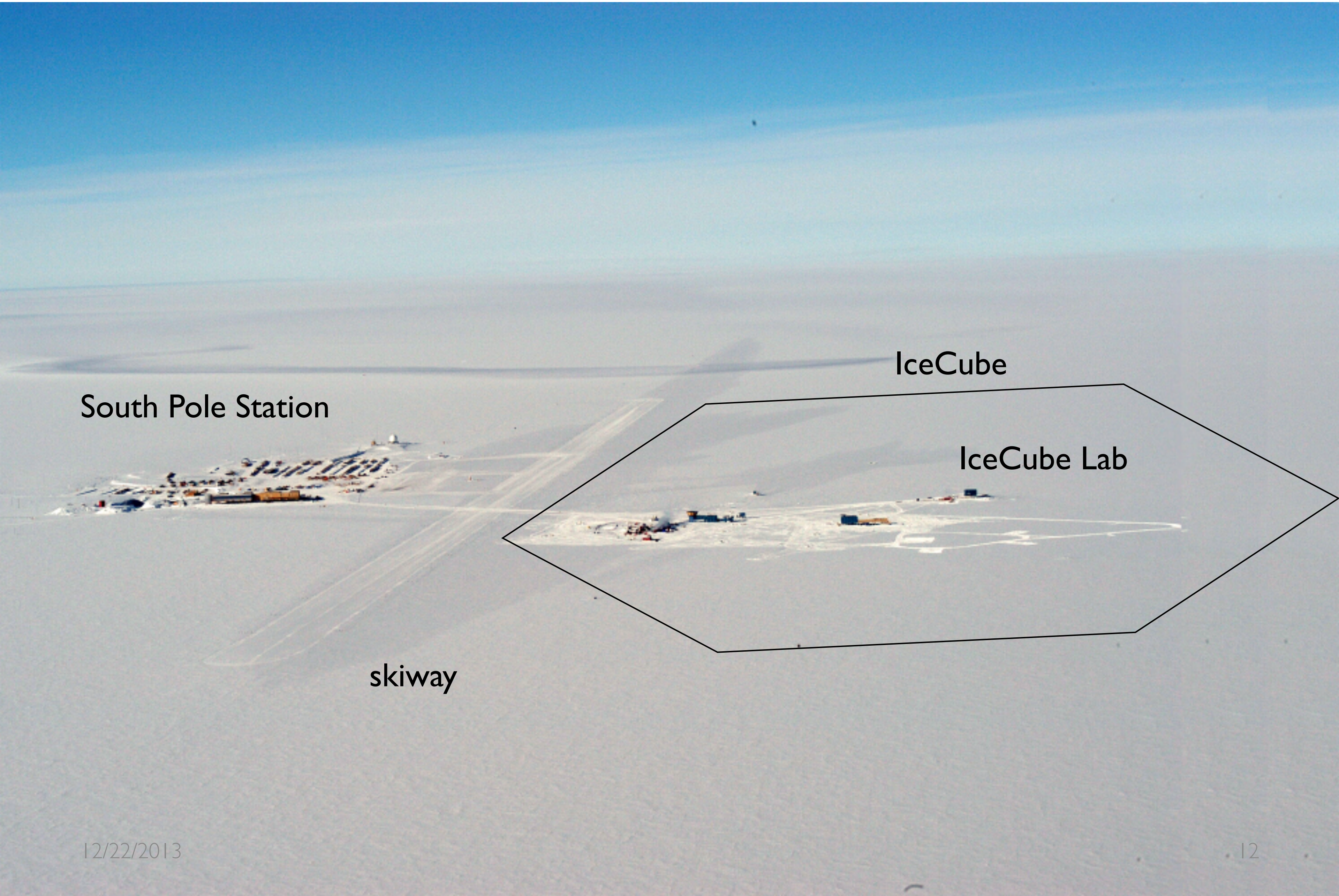
Earth's Transparent Medium: H_2O

Mediterranean,
Lake Baikal

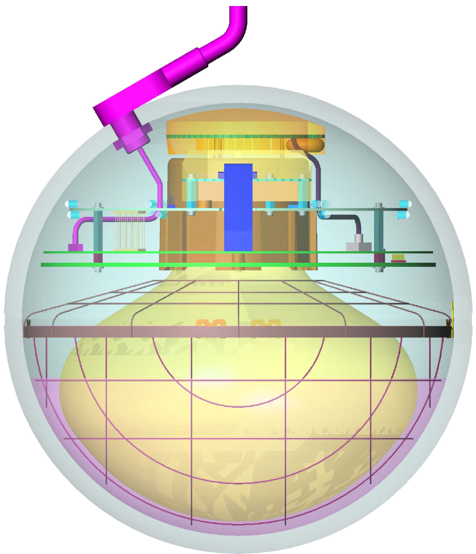


Antarctic ice sheet

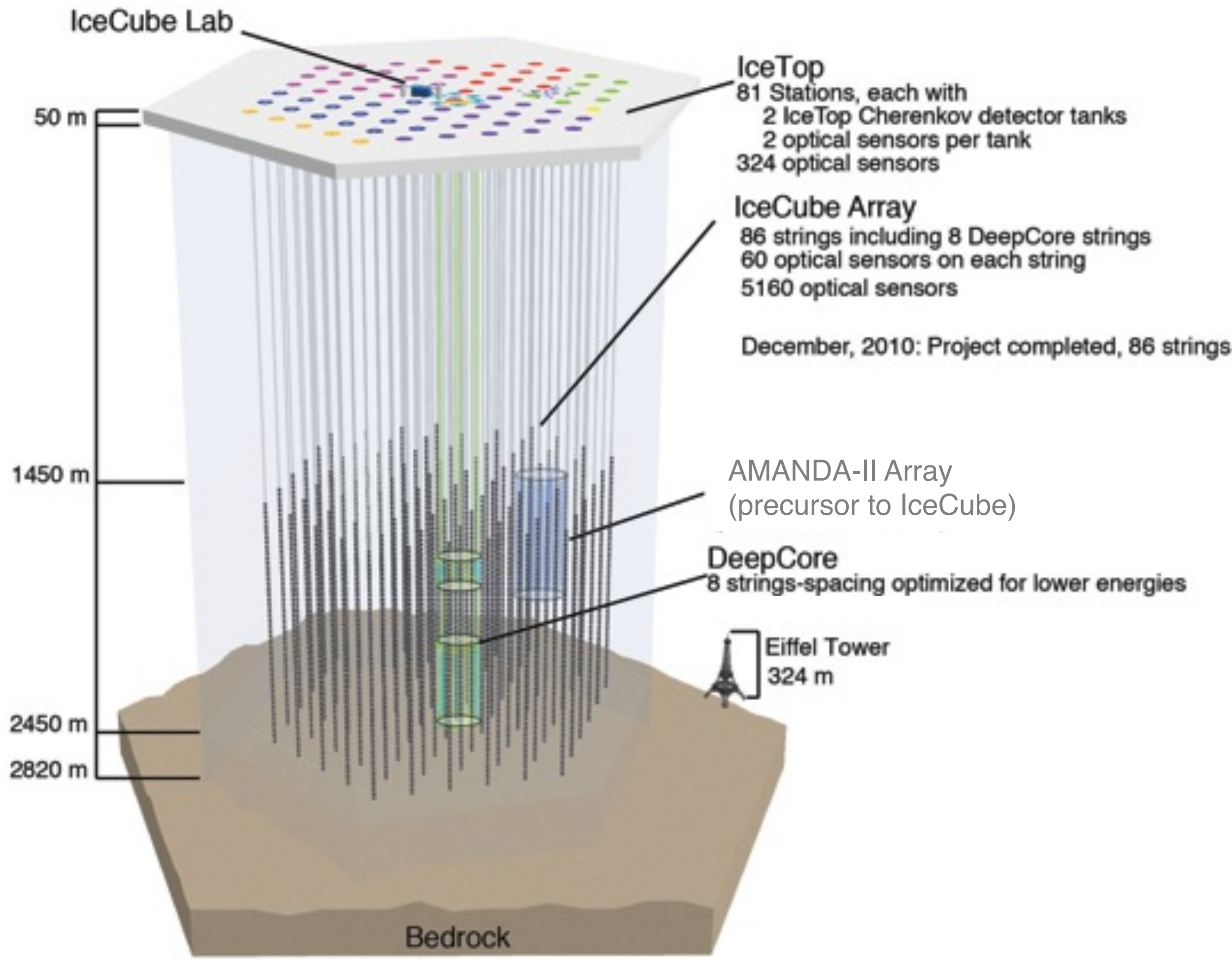
IceCube from the Air



The IceCube Detector

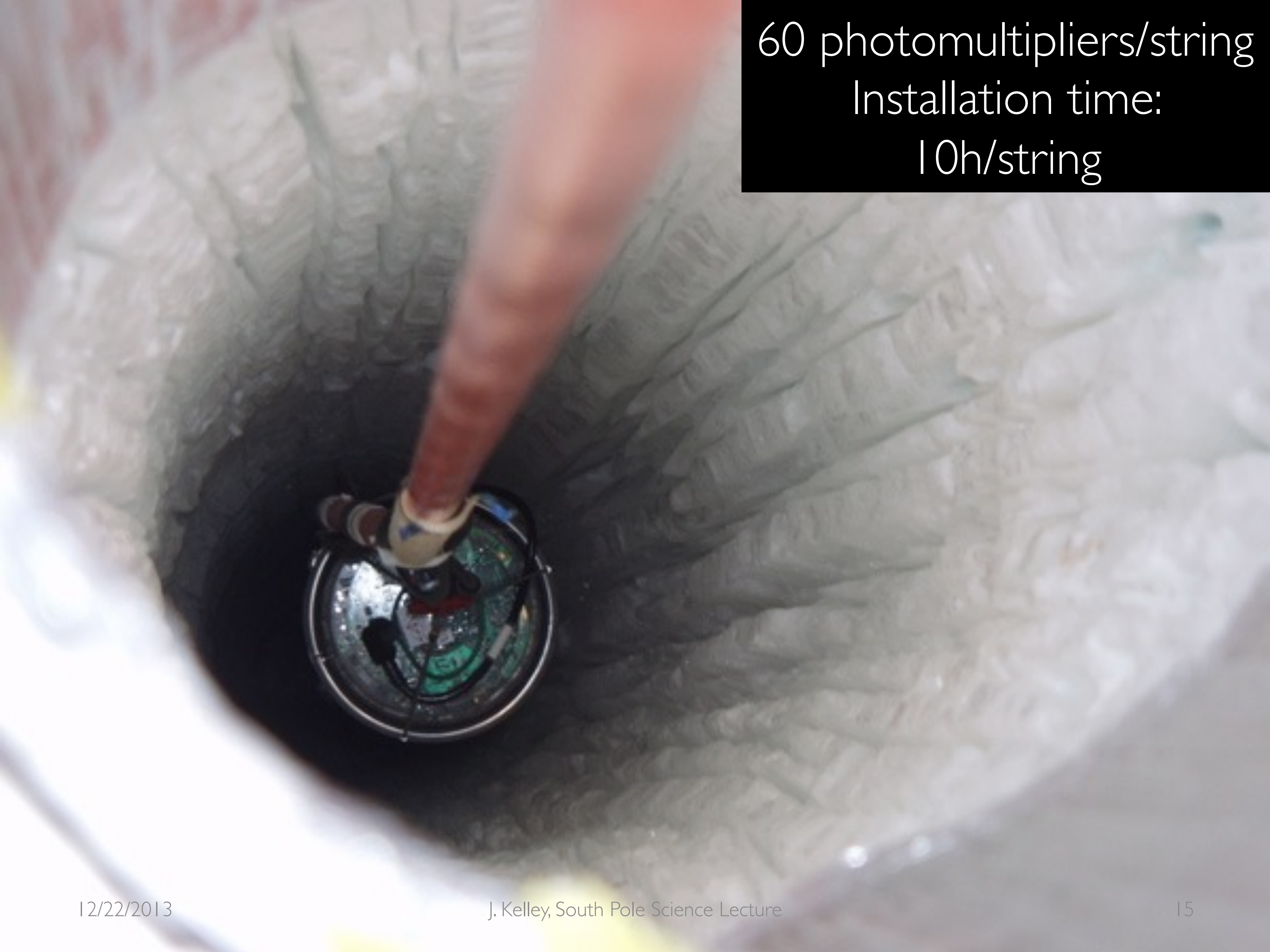


digital optical module (DOM)

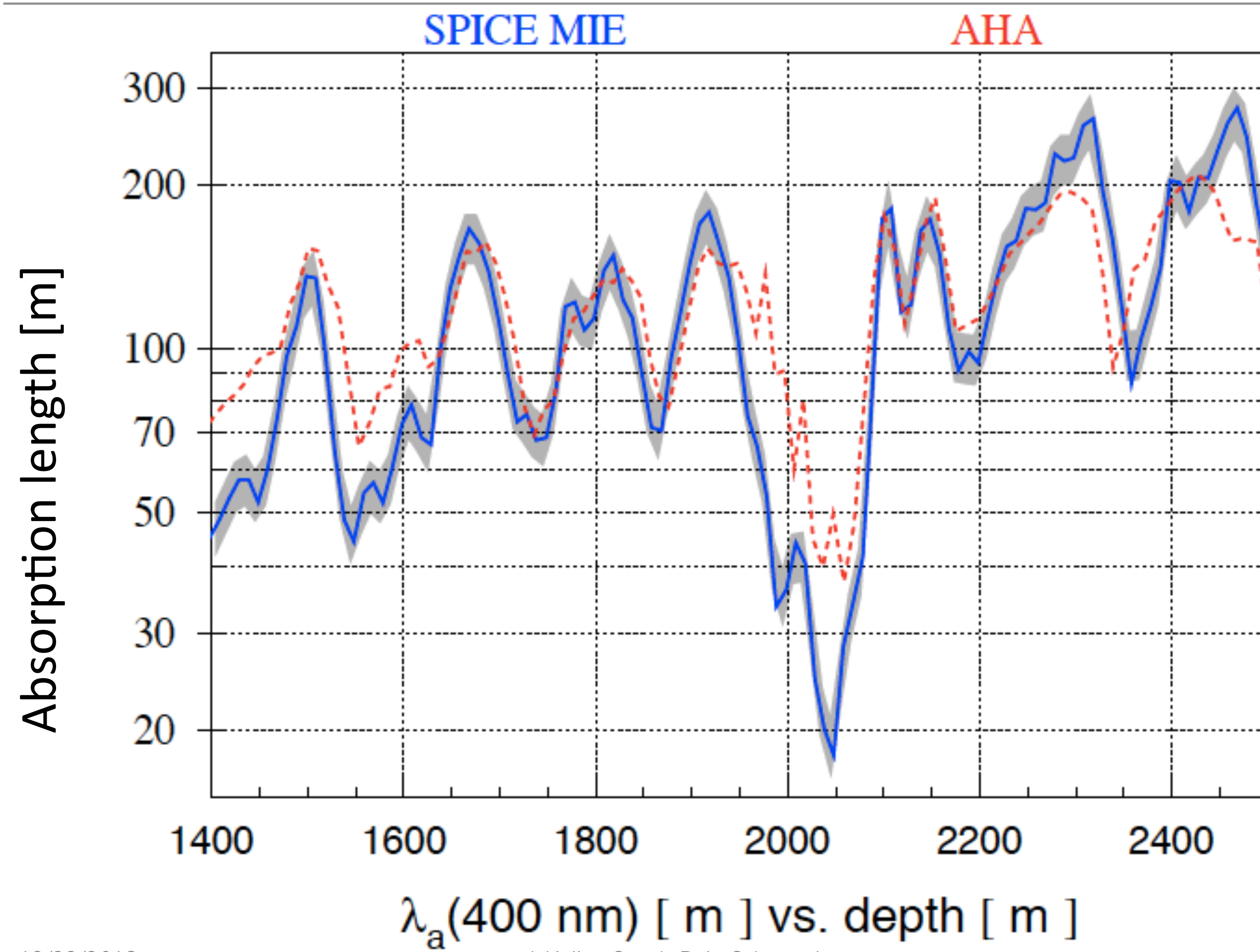


Hot water drilling

60 photomultipliers/string
Installation time:
10h/string

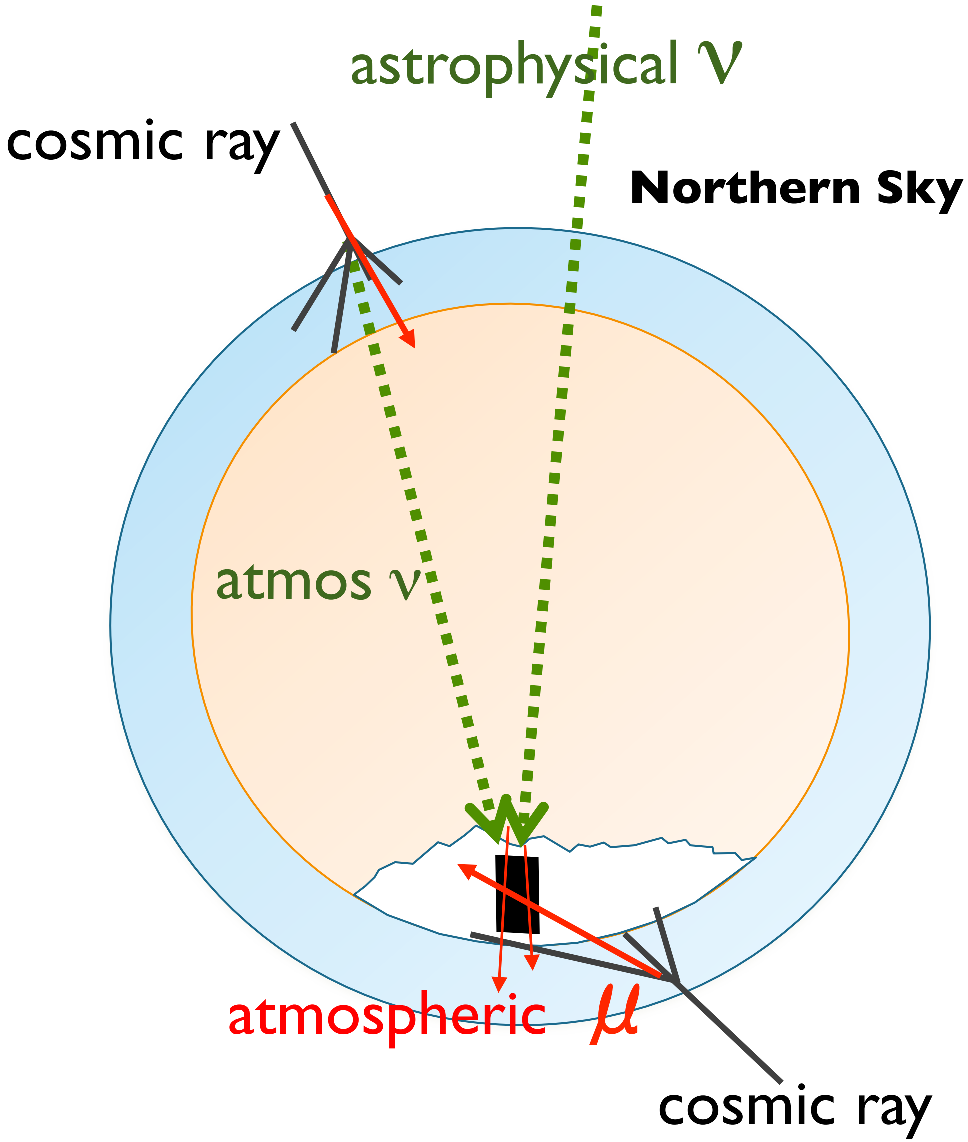


Deep Ice is Extremely Clear



Dec 18, 2010: final DOM deployed

What IceCube Sees



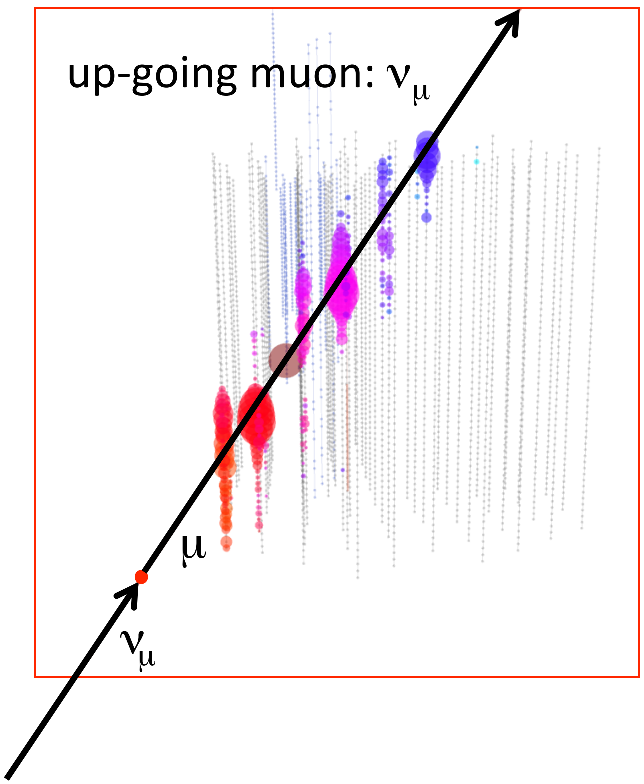
Cosmic-ray muons:
~3000 / second!

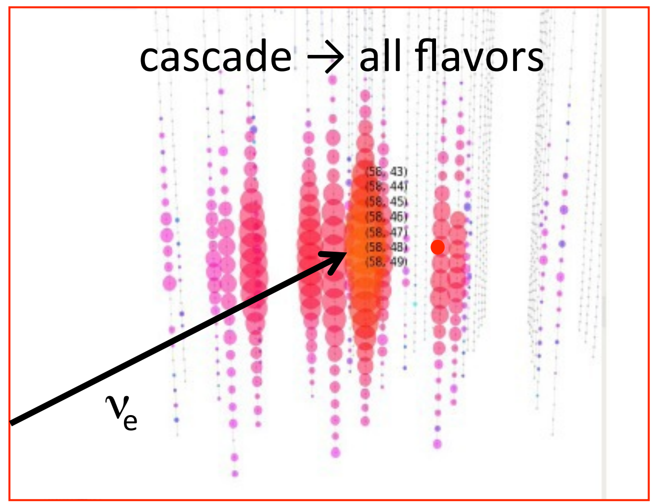
Atmospheric neutrinos:
~1 / 10 minutes

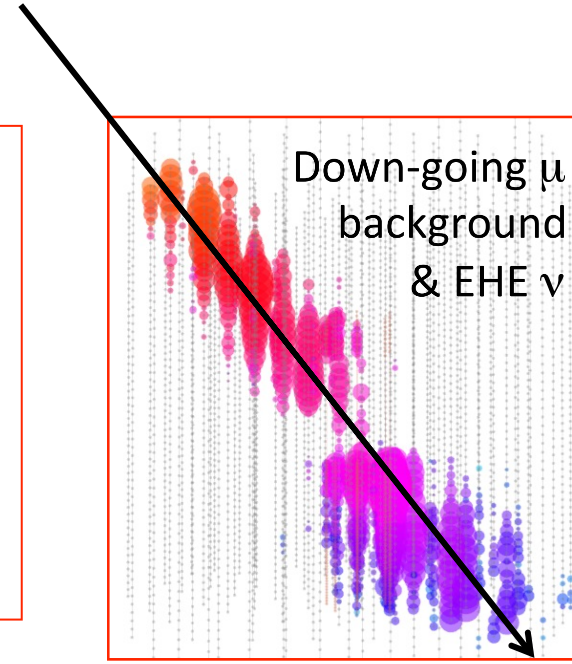
Astrophysical neutrinos: ???

Event Signatures

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



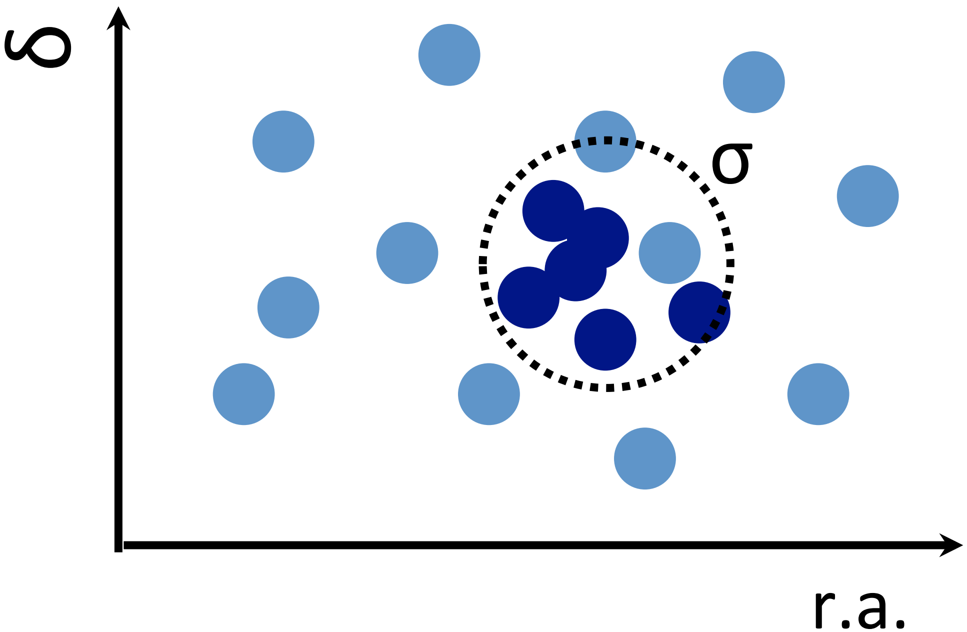




"Tracks": good direction, not-so-good energy determination

"Cascades", or "showers": good energy determination, not-so-good direction

Neutrino Point Source Searches



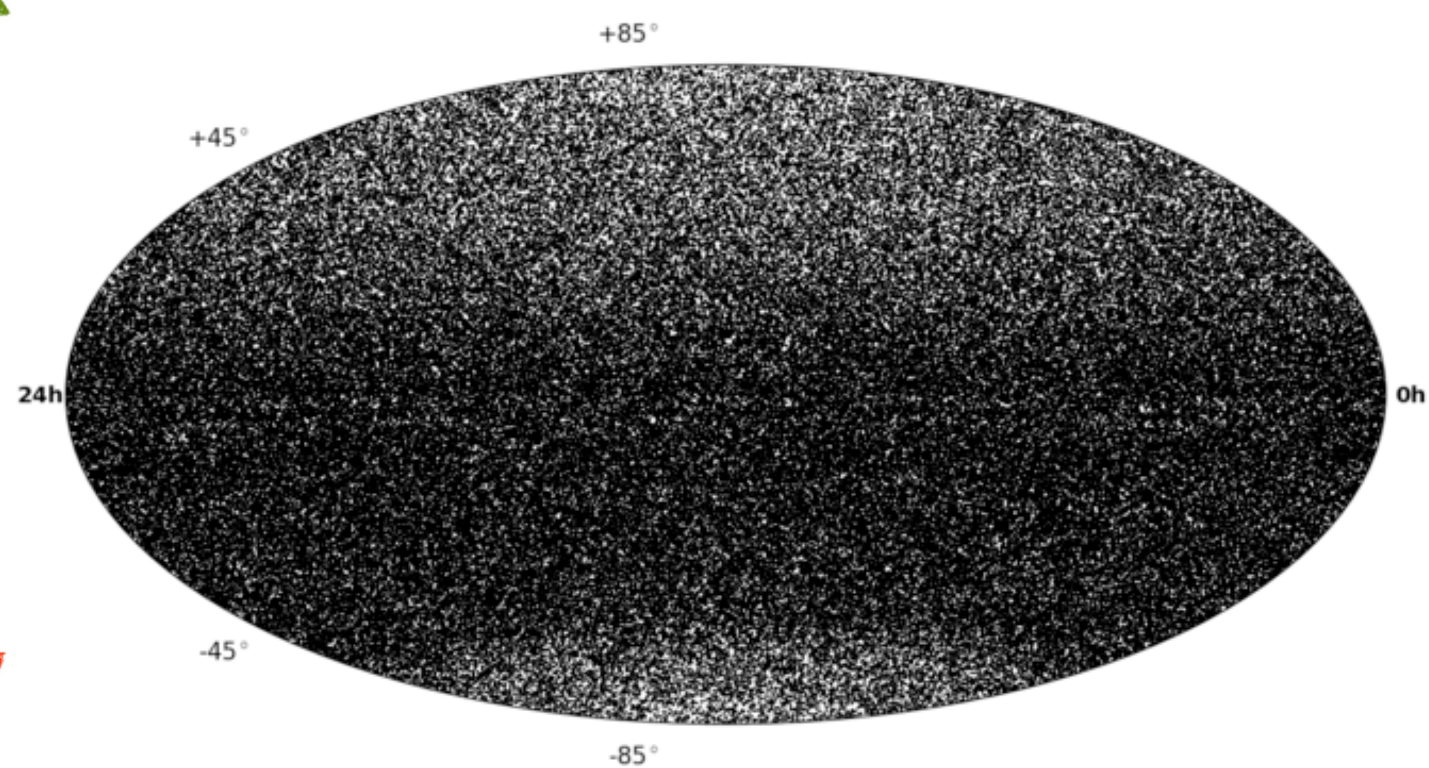
- Basic idea: use track events, and look for clusters in the sky (atmospheric neutrinos and muons don't cluster)
- Unbinned likelihood search
- Covers both hemispheres (different backgrounds, energy regimes)

IceCube 3-year Neutrino Sky

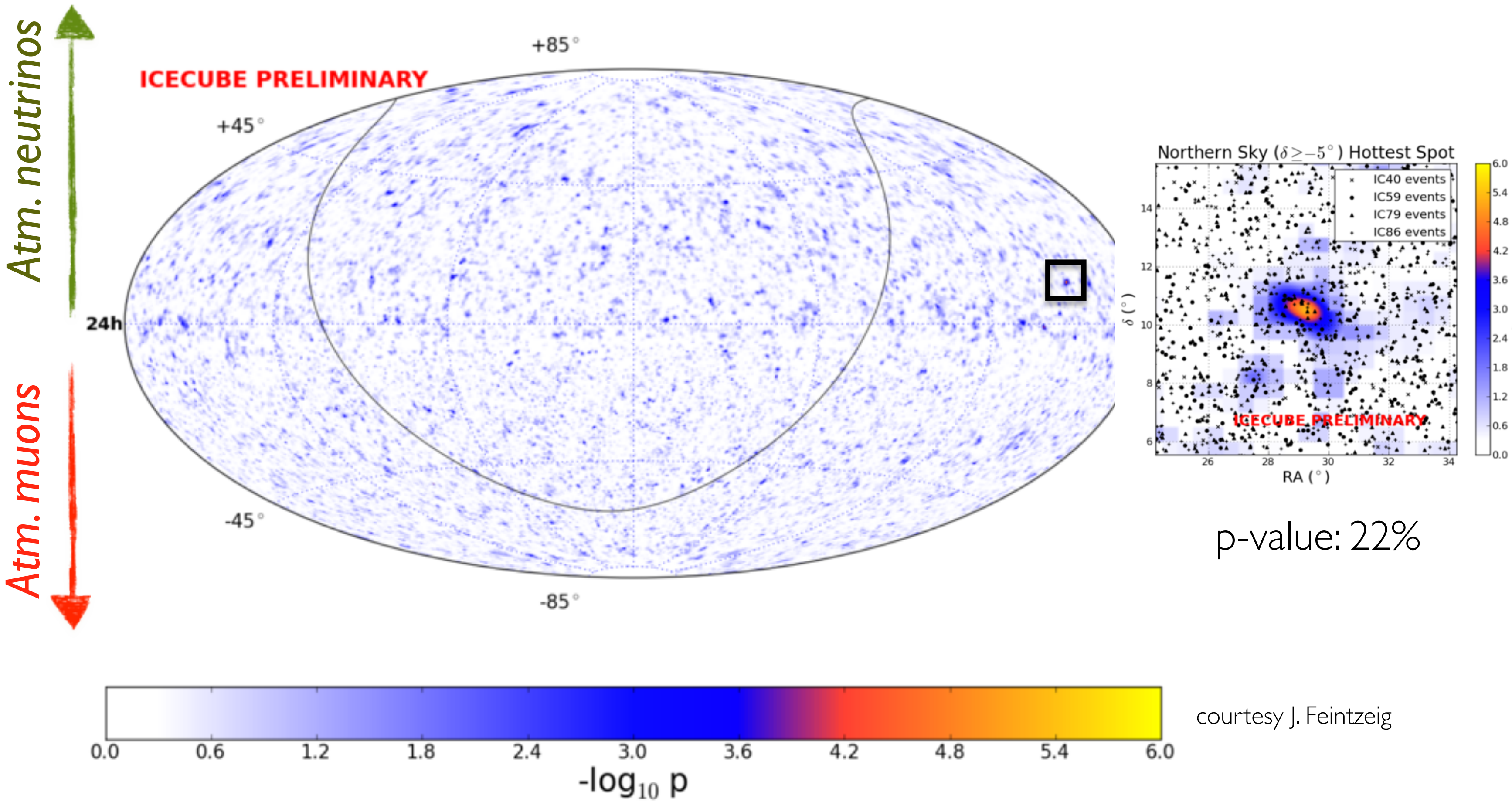
- *Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)*
- *Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)*

Atm. neutrinos

Atm. muons



IceCube 4-year Neutrino Sky



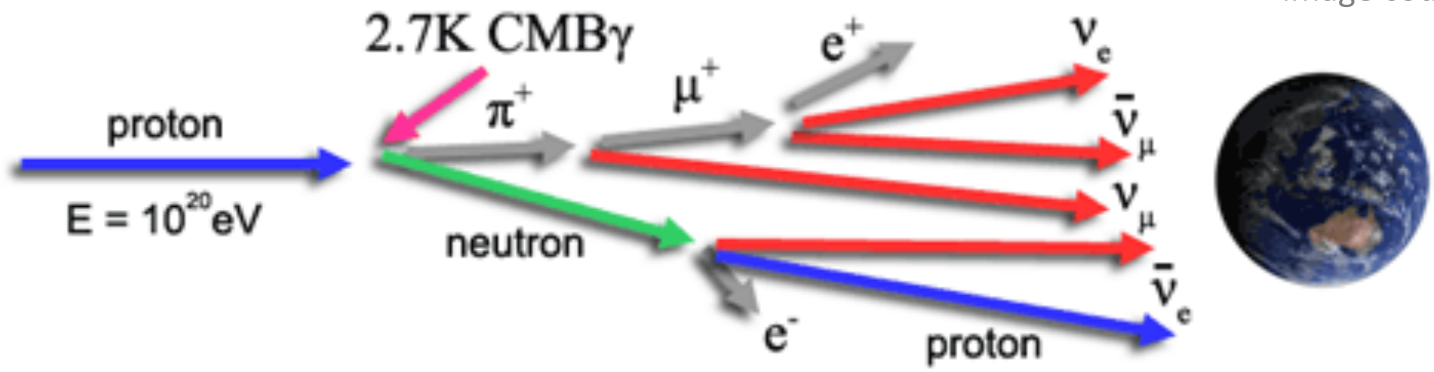
p-value: 22%

courtesy J. Feintzeig

No significant cluster found yet (or correlation with source list)

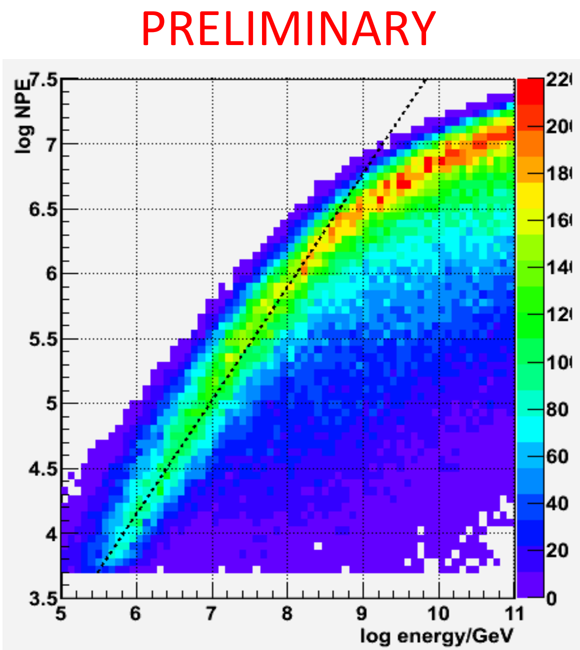
Ultra-high Energy Neutrino Search

image courtesy JEM-EUSO

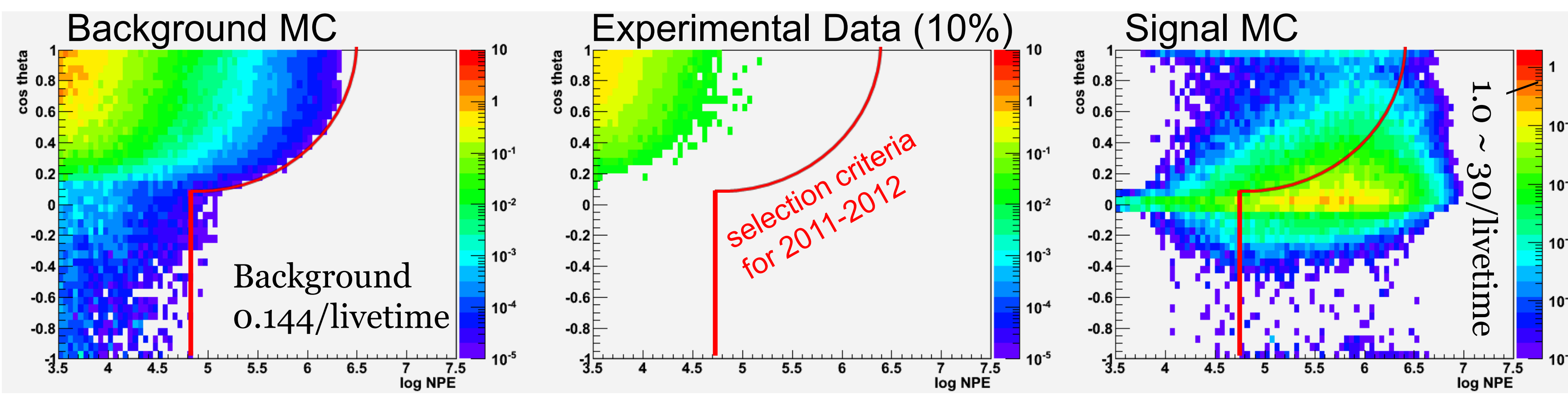


- Interaction of UHE cosmic rays with cosmic microwave background (GZK effect)
- Also produces UHE neutrinos ("cosmogenic", "GZK", "BZ")

IceCube EHE Neutrino Search



- May 2010 – May 2012 (672.7 days livetime)
- Primary selection criterion: high "NPE" / brightness
- Expected background: 0.14 events

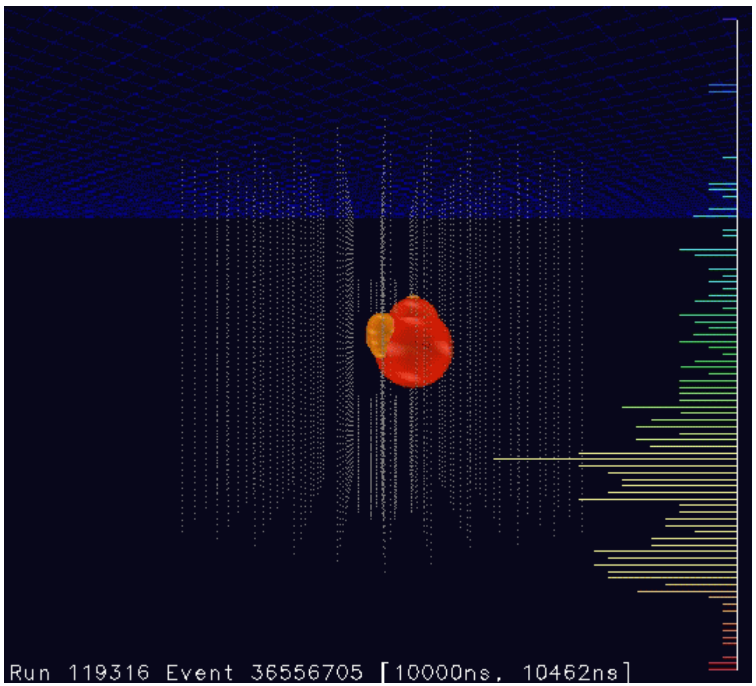


see also first IceCube upper limits: Phys. Rev. D 82, 072003 (2010)

Highest-energy Neutrinos Ever Observed

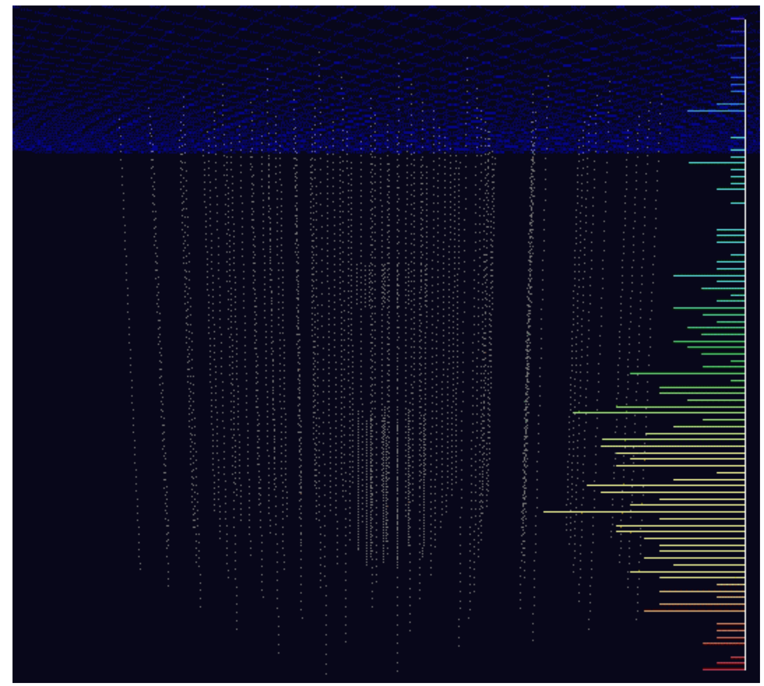
Two cascade events in unblinded data sample
(background estimation: 0.14 events; 2.8 σ, P = 0.29%)

9 Aug. 2011: 70k PE, 354 DOMs



"Bert" ~1100 TeV

3 Jan 2012: 96k PE, 312 DOMs

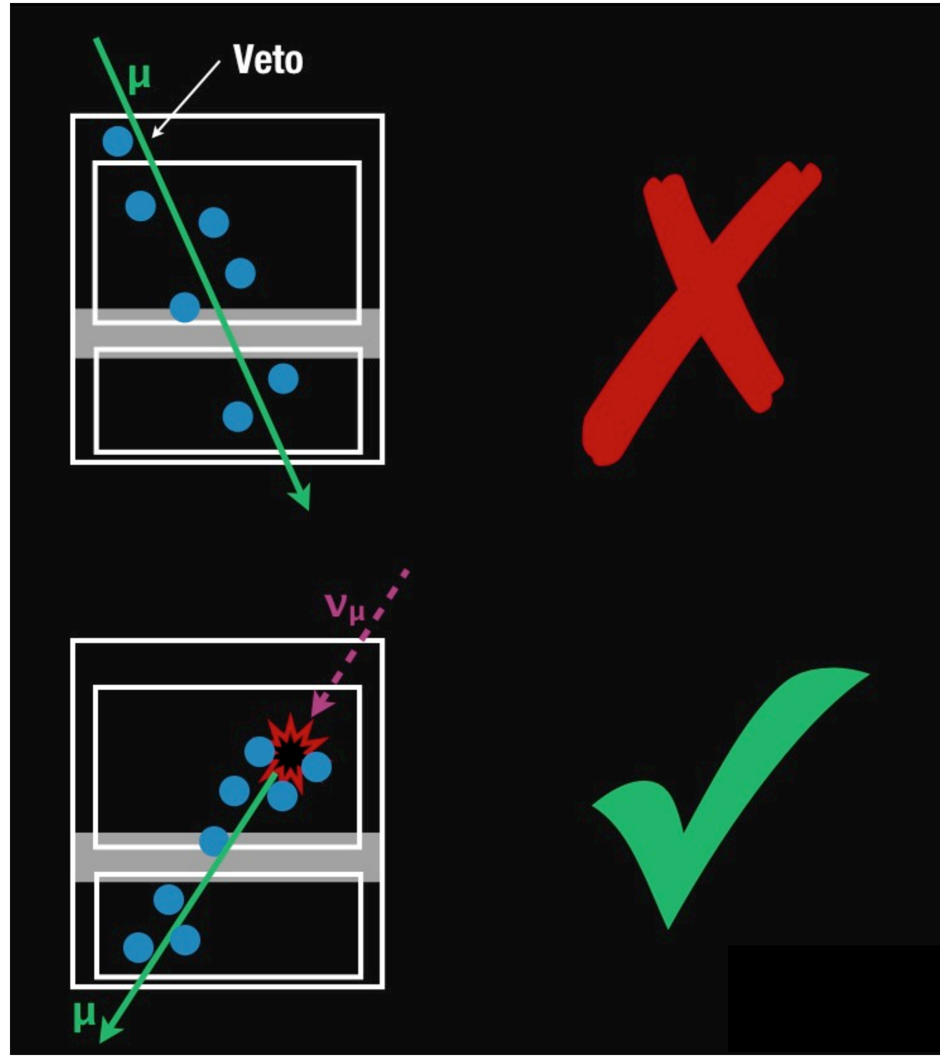


"Ernie" ~1300 TeV

Phys. Rev. Lett. 111, 021103 (2013)

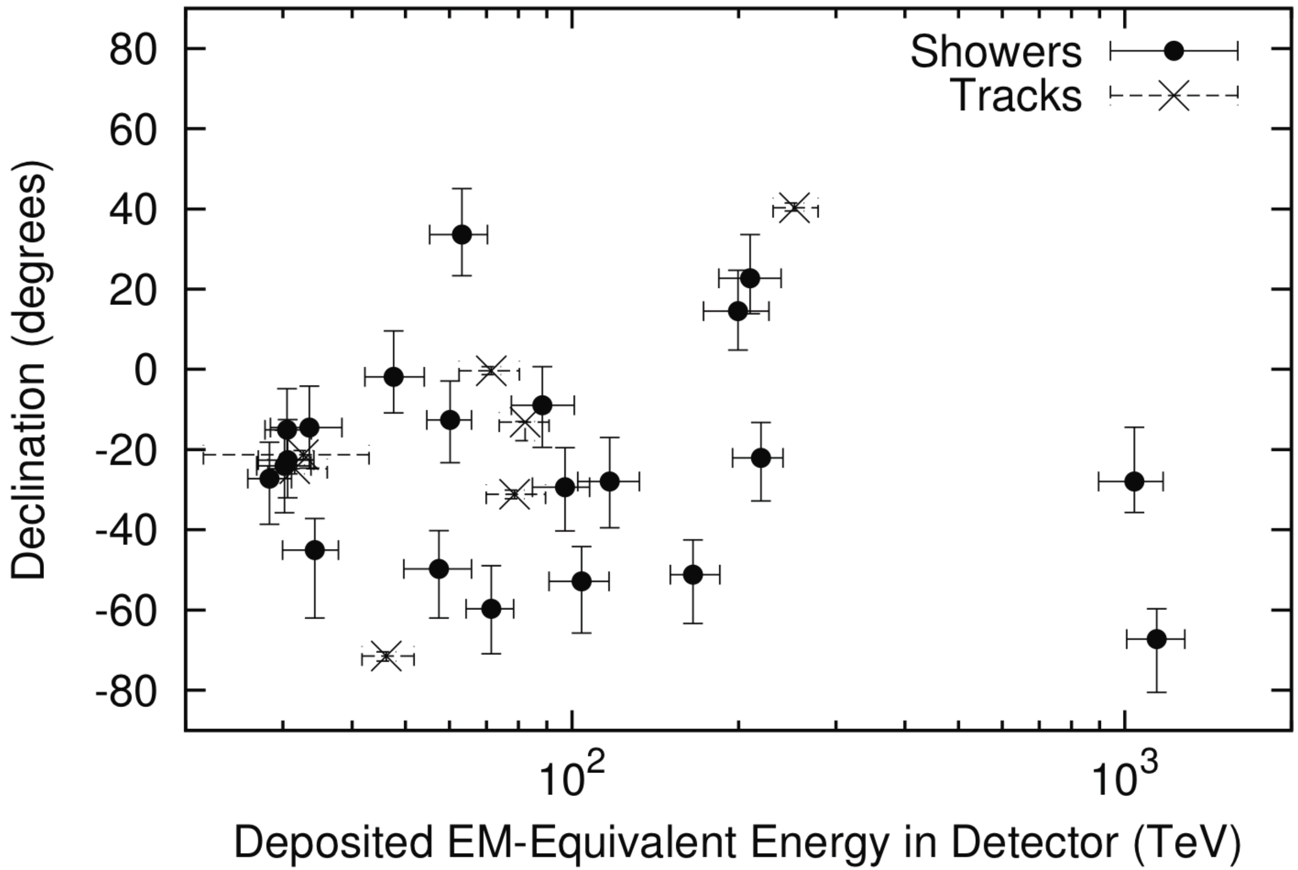
How to find more?

- High-energy starting event search (May 2010 to May 2012)
- Veto layer excludes atmospheric muons and some atmospheric neutrinos
- Sensitive to showers and tracks
- Sensitive in all directions



courtesy C. Kopper

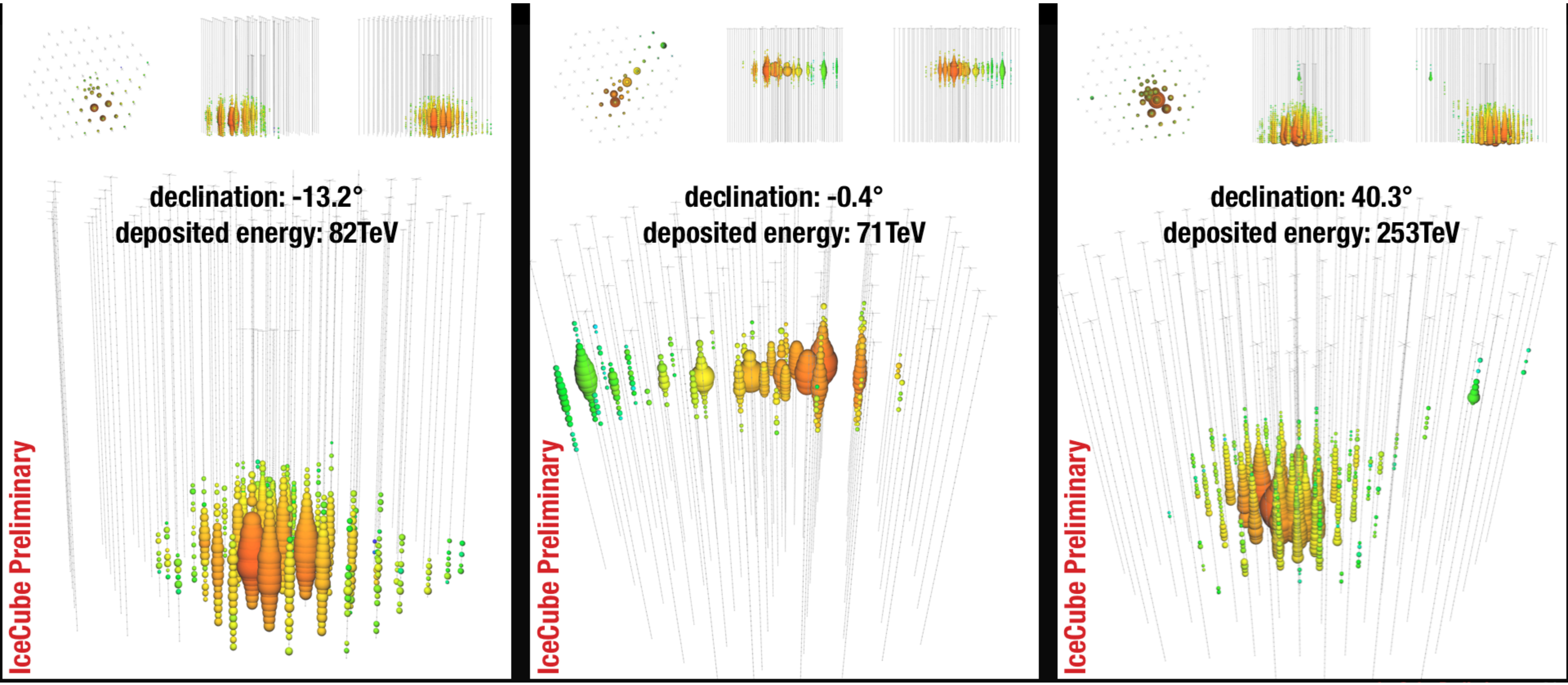
Results: 26 more events



28 events (7 with visible muons, 21 without) on background of $10.6^{+5.0}_{-3.6}$

Science 342, 1242856 (2013)

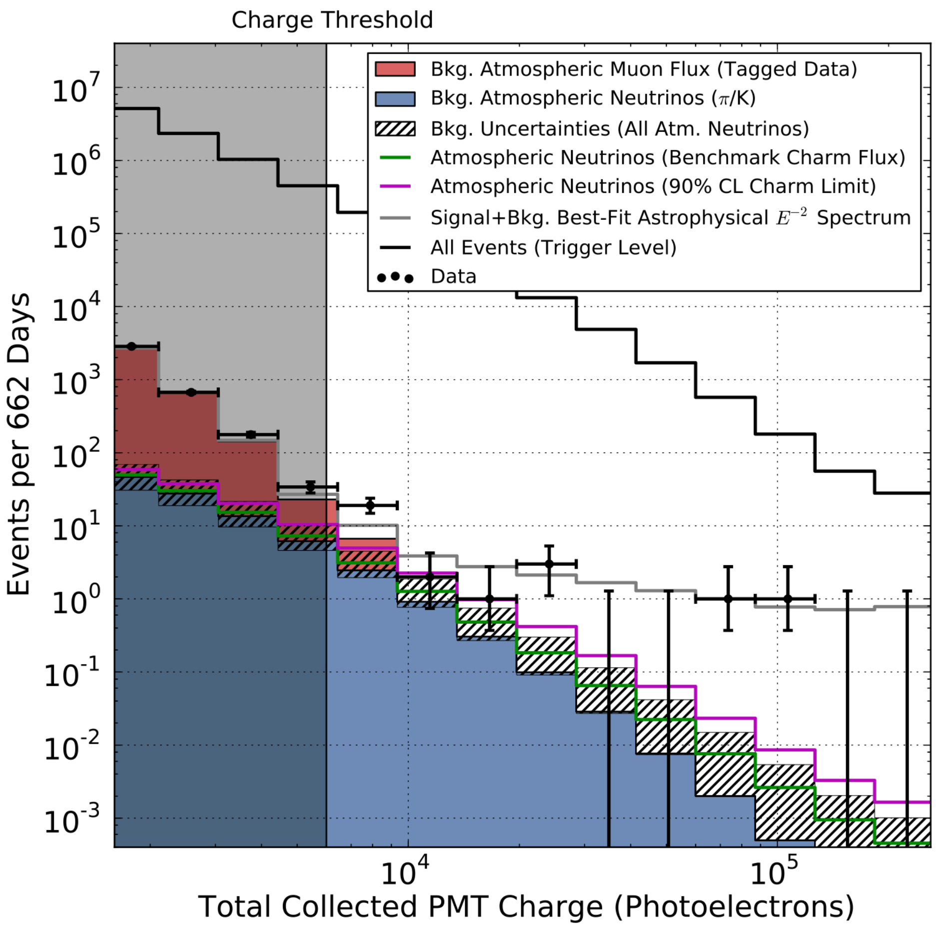
A Few Events


declination: -13.2°
deposited energy: 82TeV
IceCube Preliminary
declination: -0.4°
deposited energy: 71TeV
IceCube Preliminary
declination: 40.3°
deposited energy: 253TeV
IceCube Preliminary

What Are They?

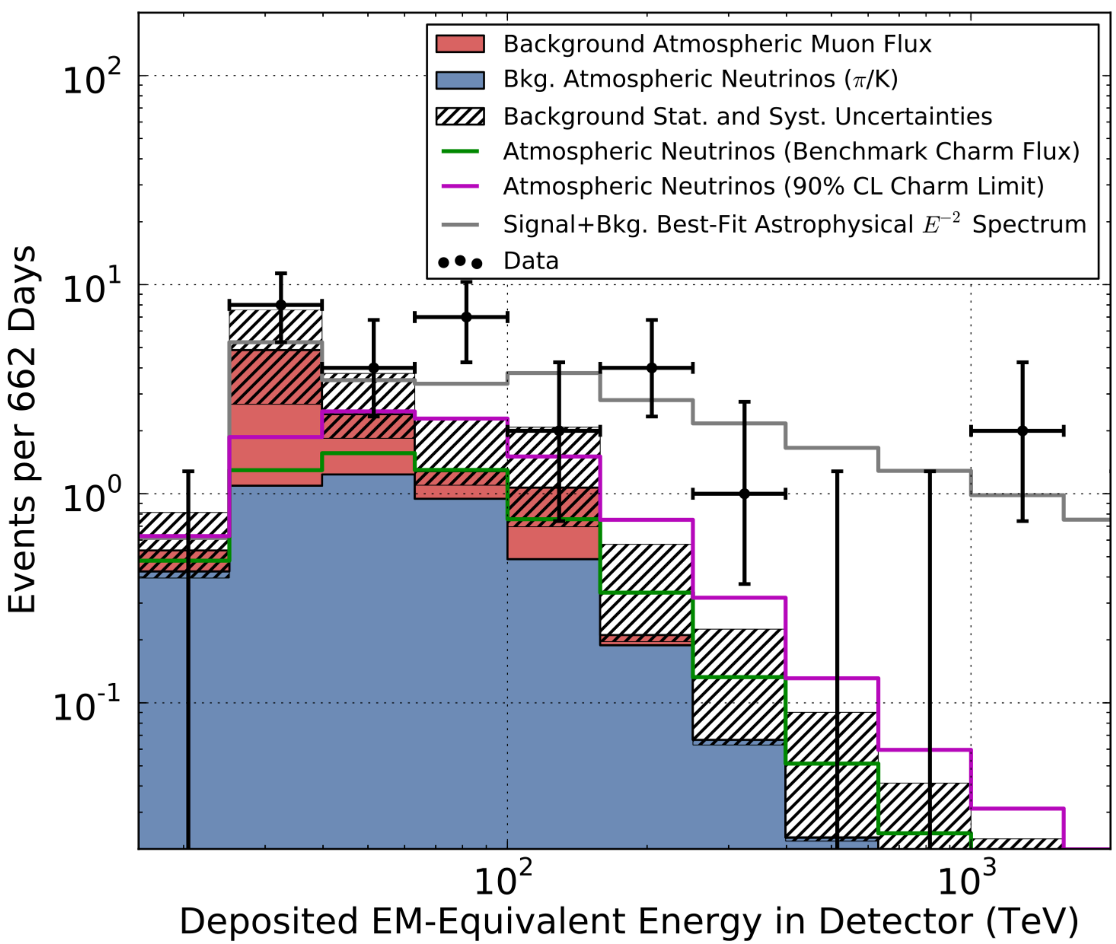
Signal	Background	Data
✔ Cascade-dominated ($\sim$ 80%) from oscillations	✘ Track-like from CR muons and atmospheric ν_μ	• 21/28 are cascades
✔ High energy? Typically assume E^{-2}	✘ Soft spectrum ($E^{-3.7}$), $\lesssim 1$ event/year $>$ 100 TeV	• Energies to above 1 PeV, 9 above 100 TeV
✔ Mostly (2/3) in southern sky from Earth absorption	✘ Muons in south, atmospheric neutrinos in north	• 24/28 from South, mostly cascades

Charge (Brightness) Distribution



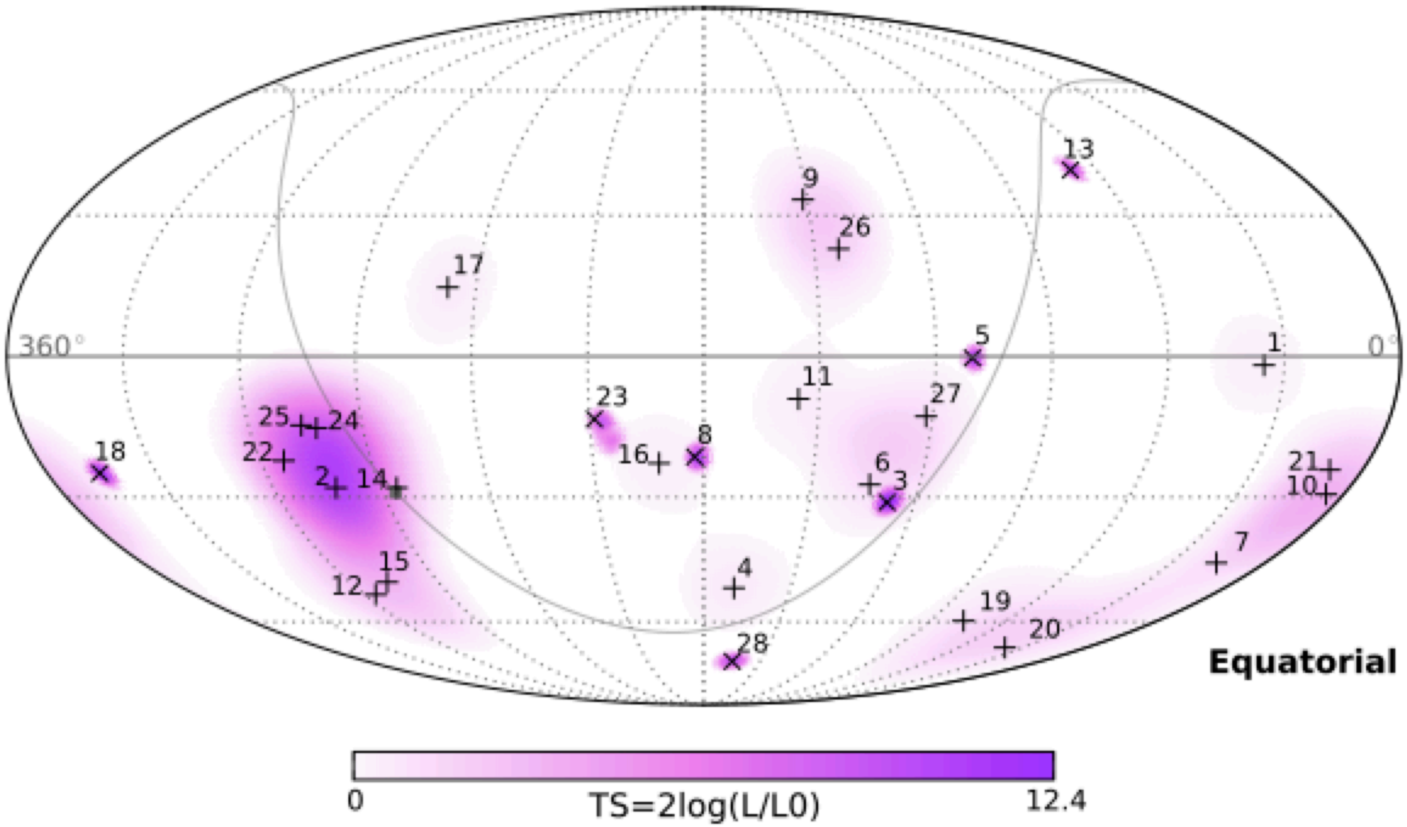
- Fits well to background estimates below charge threshold
- Hatched region: uncertainties in atmospheric neutrino flux
- Significance of excess: 4.1σ (P = 0.004%)

Deposited Energy Spectrum



- Compatible with benchmark E^{-2} astrophysical model
- Potential cutoff at 2-5 PeV
- Best-fit neutrino flux: $1.2 \pm 0.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

Skymap of the Event Directions

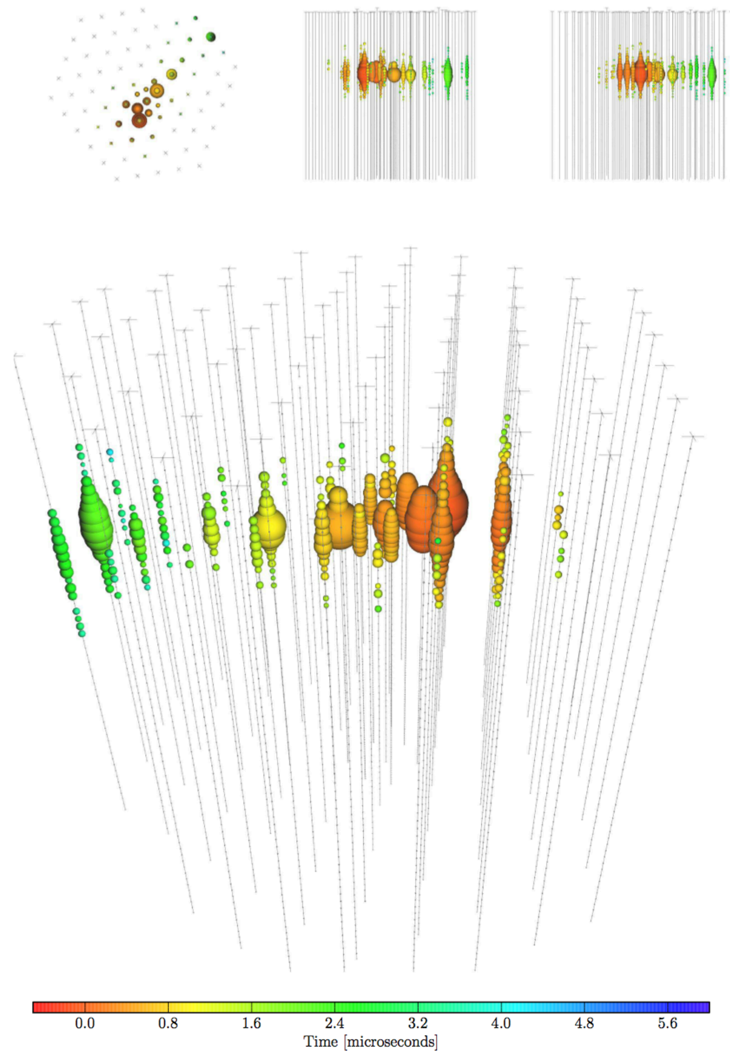


Skymap is compatible with a diffuse "glow" of high-energy cosmic neutrinos, but we can't say yet what the sources are

Why is this Interesting?

- First observation of high-energy cosmic neutrinos
  - only other astrophysical neutrinos observed from the Sun, SN1987A

- We hope it is the beginning of neutrino astronomy
  - find sources of cosmic rays (after 100 years!)
  - understand the most violent objects in the Universe
  - measure fundamental properties of neutrinos



This Season: Major ICL Computing Upgrade

server upgrade

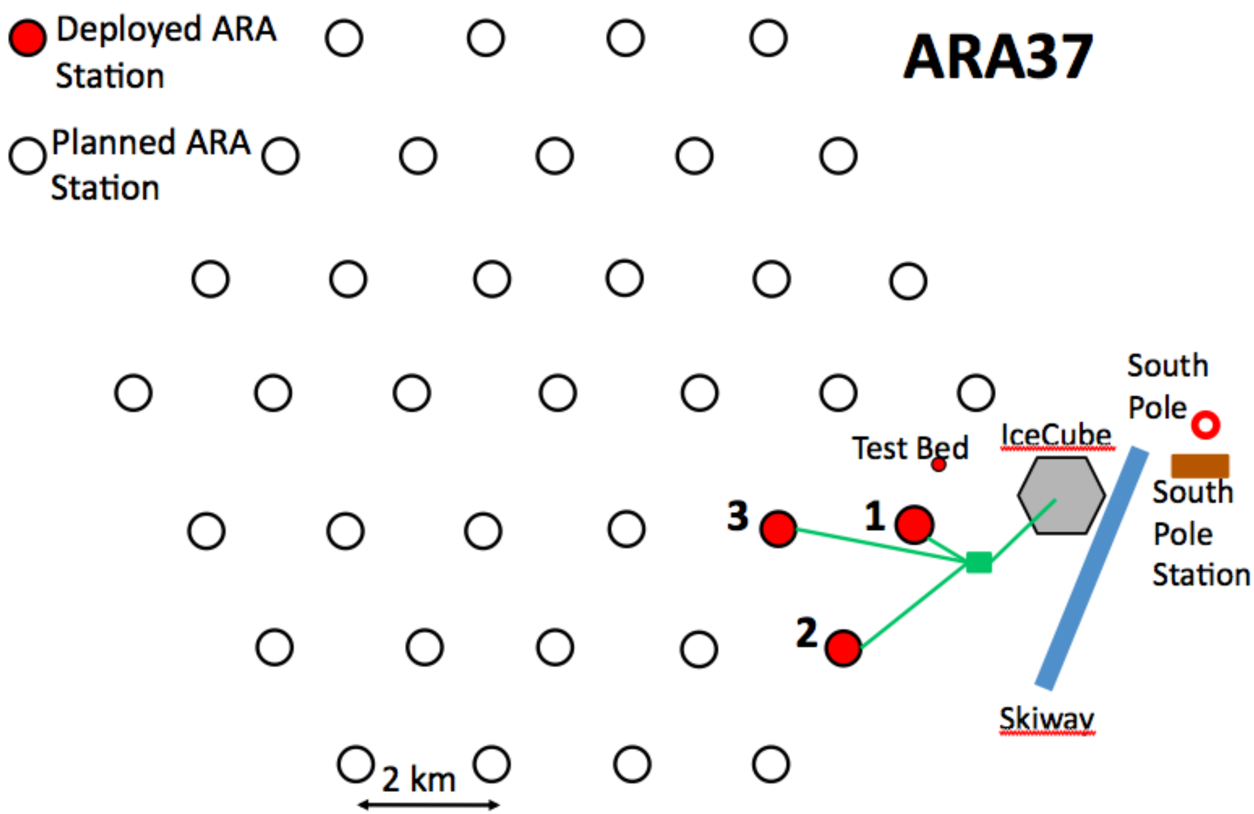
UPS upgrade

DOMHub upgrade

plus standard maintenance and calibration

Other Neutrino Experiments at SP

ARA (Askaryan Radio Array): 200-km^2 ultra-high-energy neutrino detector

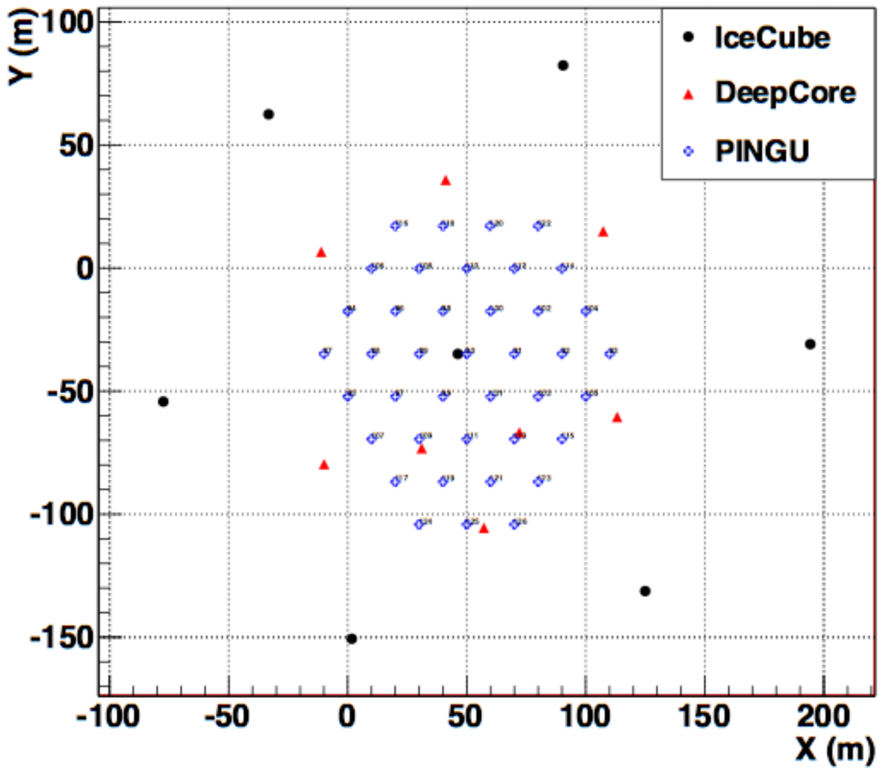


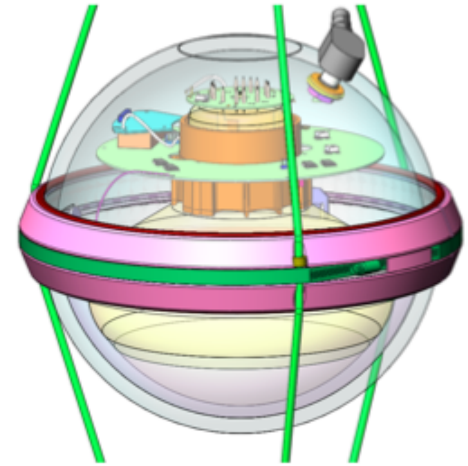
STATUS: testbed + 3 stations deployed; proposal to continue construction

What's Next?

PINGU: low-energy extension to determine neutrino mass hierarchy

- 40 strings
- 60 PDOMs* per string
- Bottom center of IceCube
  - in-fills DeepCore
  - in clearest ice



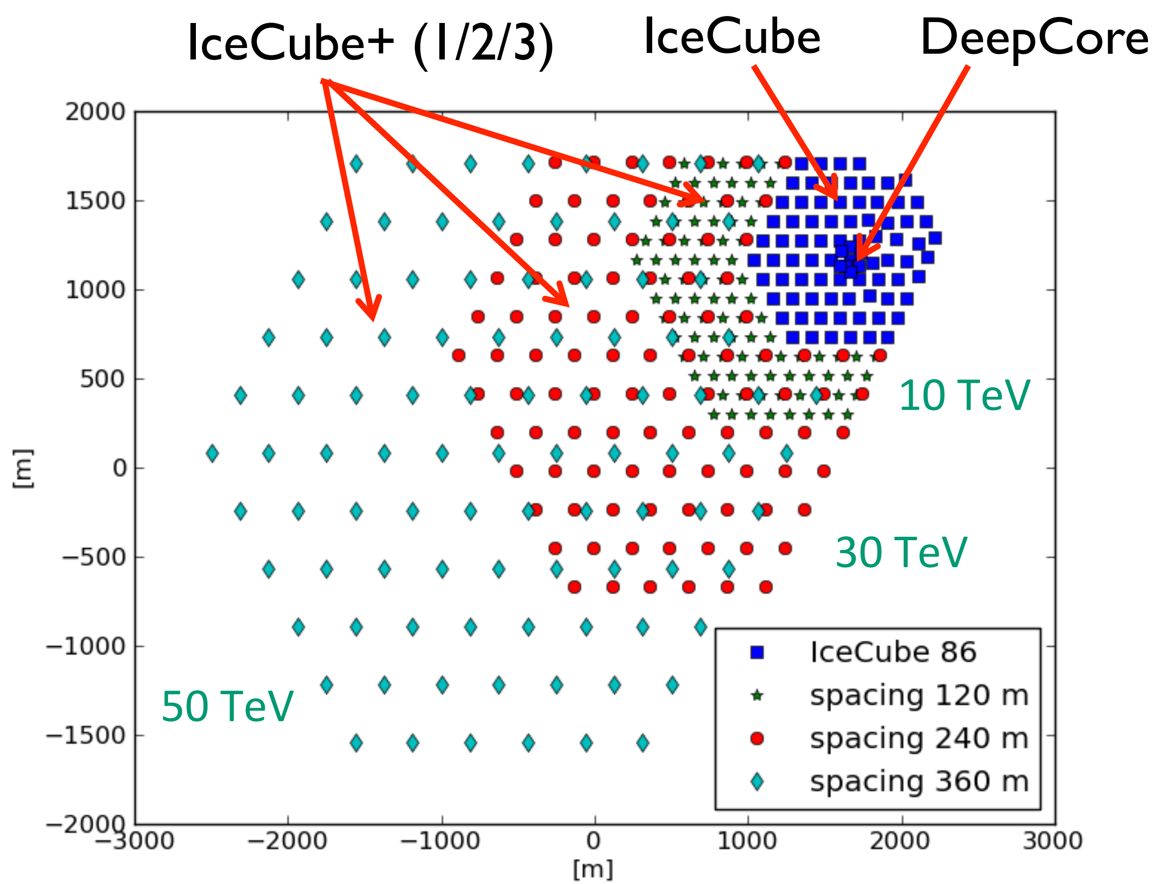


*PINGU Digital Optical Module: HQE PMT, electronics, pressure vessel, supporting hardware; very similar to IceCube DOM.

STATUS: Letter of Intent available in a few weeks; hardware prototyping

What's After That?

IceCube high-energy extension: next leap forward in neutrino astronomy



Spacing 1 (120m):
- IceCube (1 km^3)
- \+ 98 strings (1,3 km^3)
- = 2,3 km^3

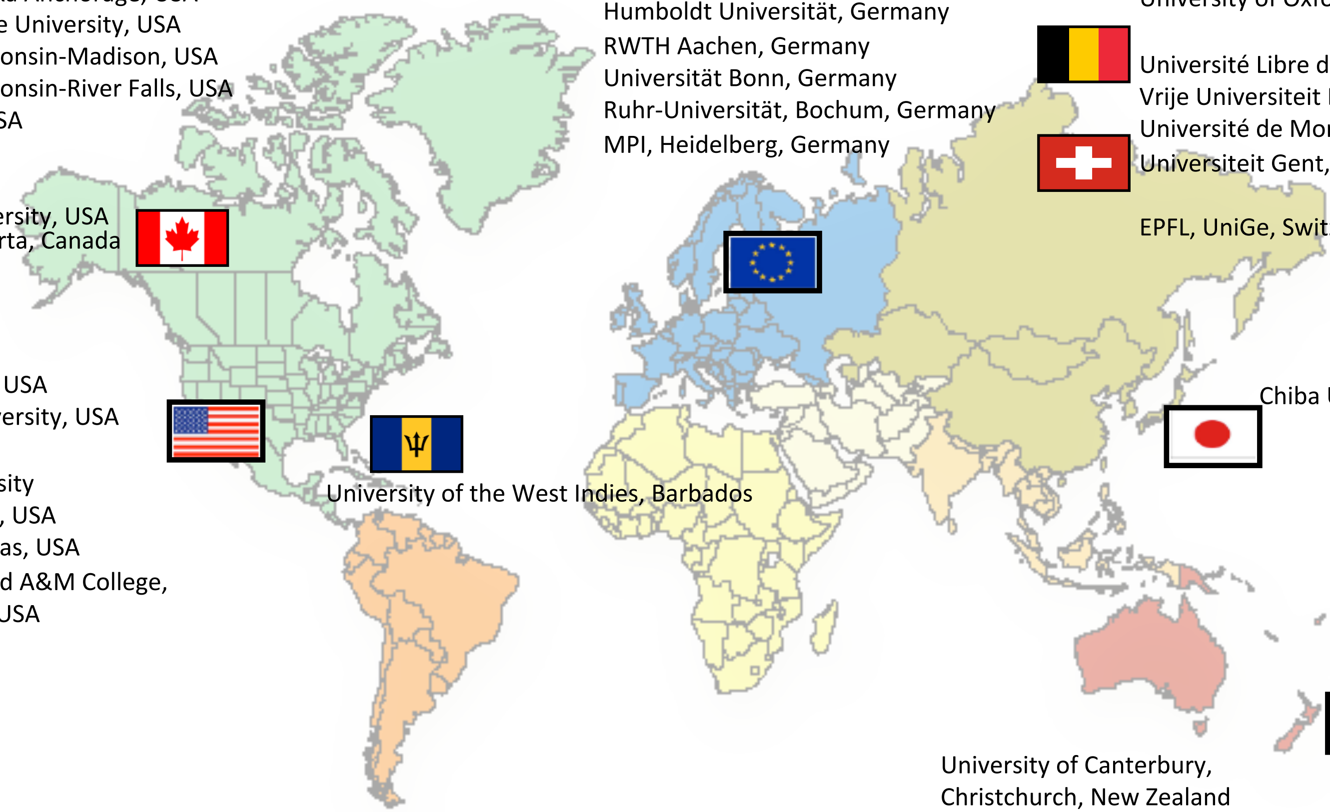
Spacing 2 (240m):
- IceCube (1 km^3)
- \+ 99 strings (5,3 km^3)
- = 6,3 km^3

Spacing 3 (360m):
- IceCube (1 km^3)
- \+ 95 strings (11,6 km^3)
- = 12,6 km^3

STATUS: detector design simulations underway

ICECUBE COLLABORATION

10 countries, 40 institutions, ~260 collaborators



Bartol Research Inst, Univ of Delaware, USA
University of Alaska Anchorage, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA
Stony Brook University, USA
University of Alberta, Canada

Univ. of Alabama, USA
Clark-Atlanta University, USA
Georgia Tech
Ohio State University
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA

University of the West Indies, Barbados

Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany
Humboldt Universität, Germany
RWTH Aachen, Germany
Universität Bonn, Germany
Ruhr-Universität, Bochum, Germany
MPI, Heidelberg, Germany

Uppsala Universitet, Sweden
Stockholm Universitet, Sweden

Imperial College, London, UK
University of Oxford, UK

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons, Belgium
Universiteit Gent, Belgium

EPFL, UniGe, Switzerland

Chiba University, Japan

University of Canterbury, Christchurch, New Zealand

ICECUBE COLLABORATION

10 countries, 40 institutions, ~260 collaborators

Bartol Research Inst, Univ of Delaware, USA
University of Alaska Anchorage, USA
Pennsylvania State University, USA
University of \
University of \
LBNL, Berkele
UC Berkeley, U
UC Irvine, USA
Stony Brook U
University of A

Univ. of Alabama, USA
Clark-Atlanta University, USA
Georgia Tech
Ohio State University
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA

University of the West Indies, Barbados

Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany
Humboldt Universität, Germany
RWTH Aachen, Germany

Uppsala Universitet, Sweden
Stockholm Universitet, Sweden

Imperial College, London, UK
University of Oxford, UK

ité Libre de Bruxelles, Belgium
iversiteit Brussel, Belgium
ité de Mons, Belgium
iteit Gent, Belgium

niGe, Switzerland

Chiba University, Japan

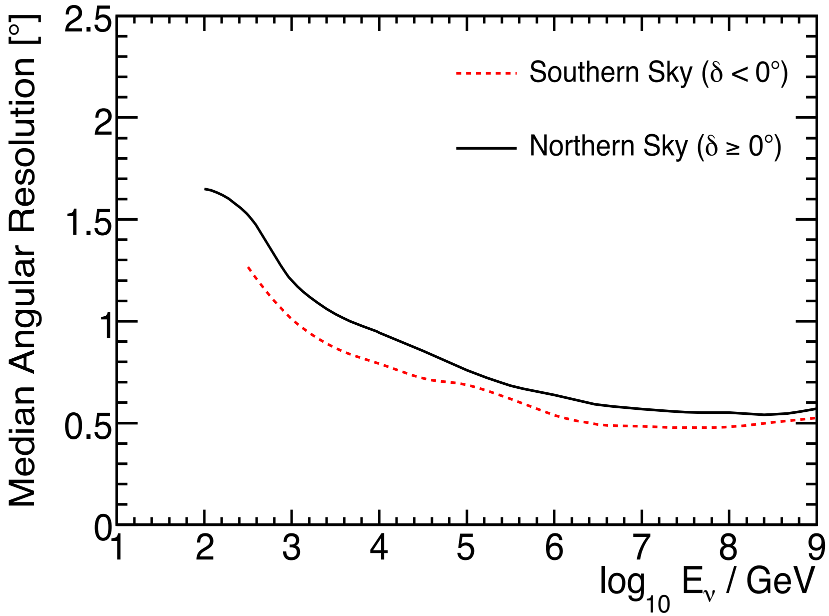
University of Canterbury, Christchurch, New Zealand

Thanks from all of us!

Backup Slides

Detector Performance

Simulated tracks

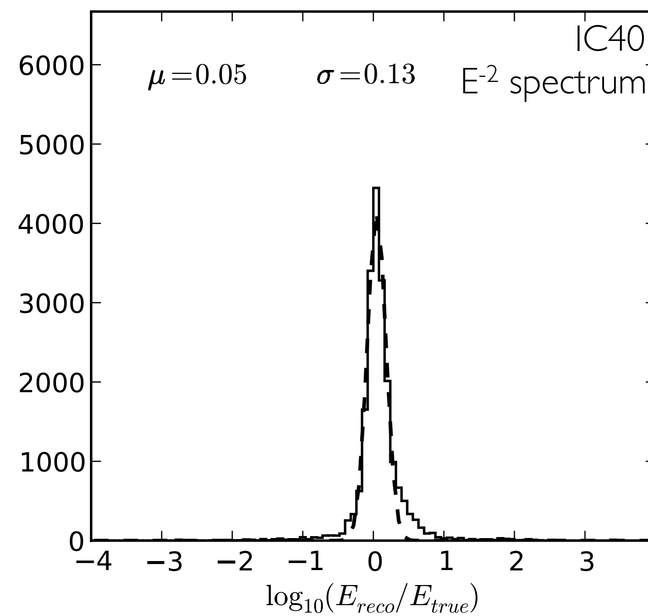


angular resolution: ~1°

μ energy estimation via dE/dx

~30% in $\log_{10}$(E)

Simulated cascades

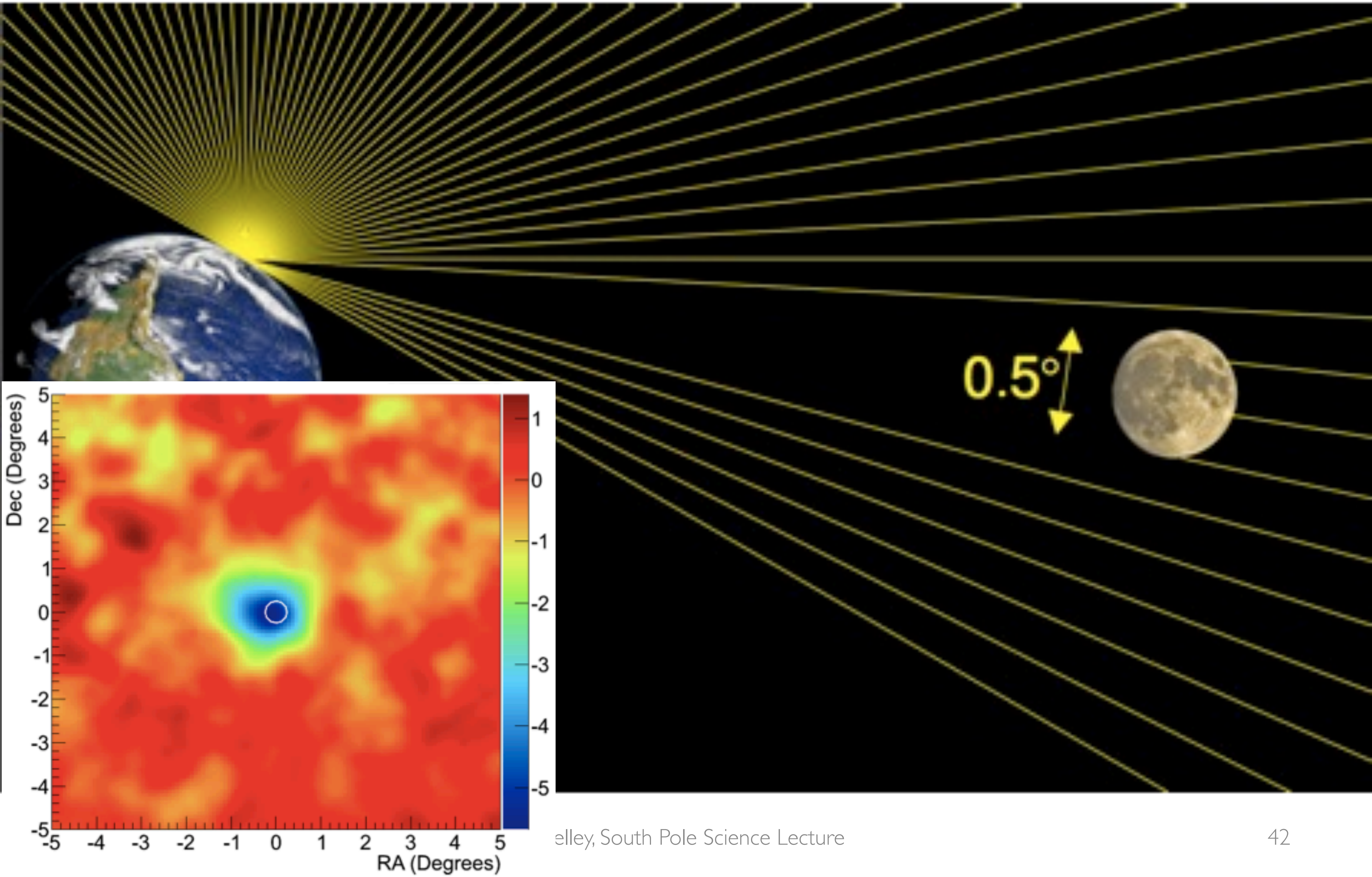


energy resolution: ~35%

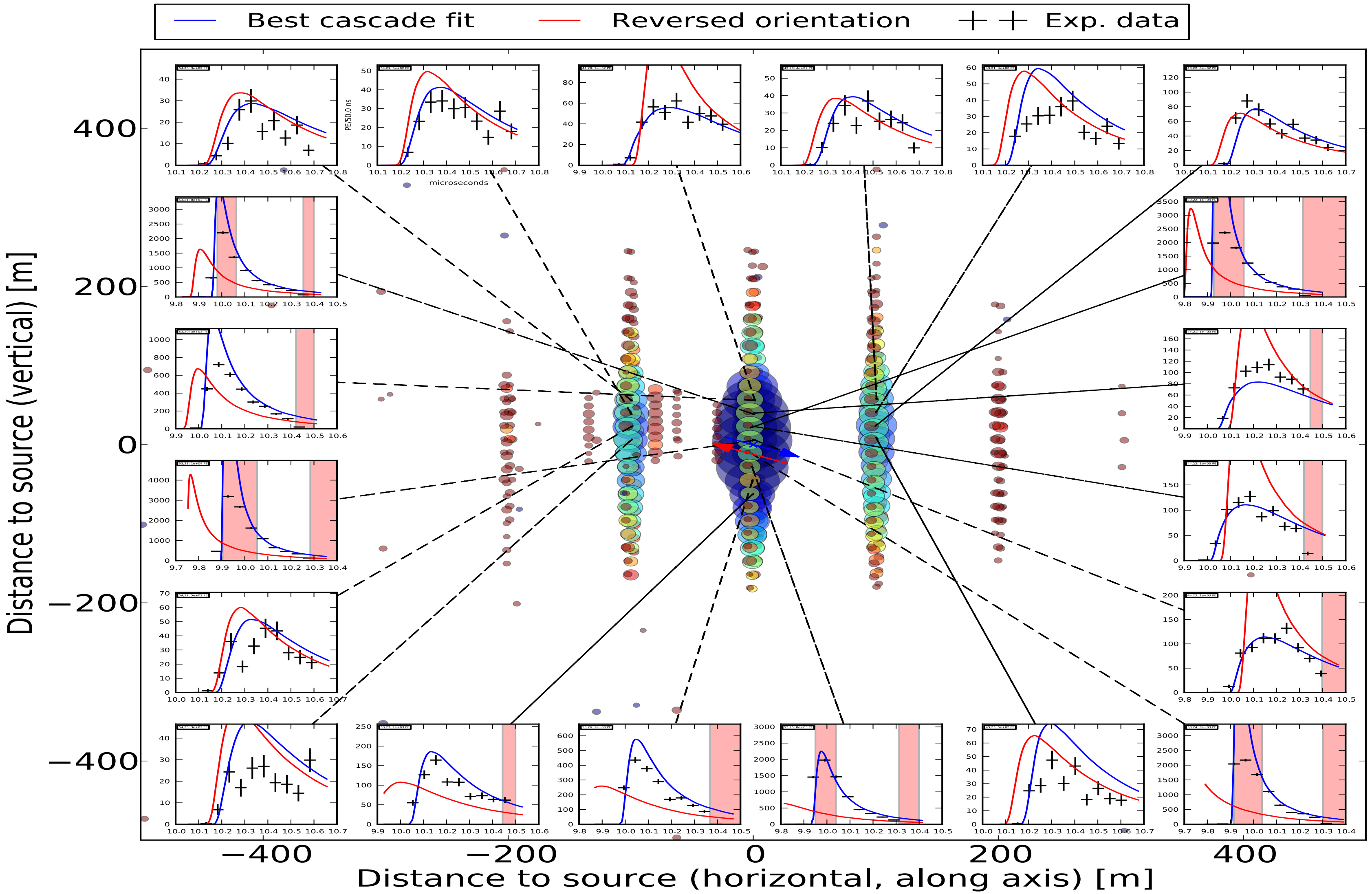
angular resolution: ~10-30°

Continual time synchronization to ~2 ns; ice calibration with in-situ flashers

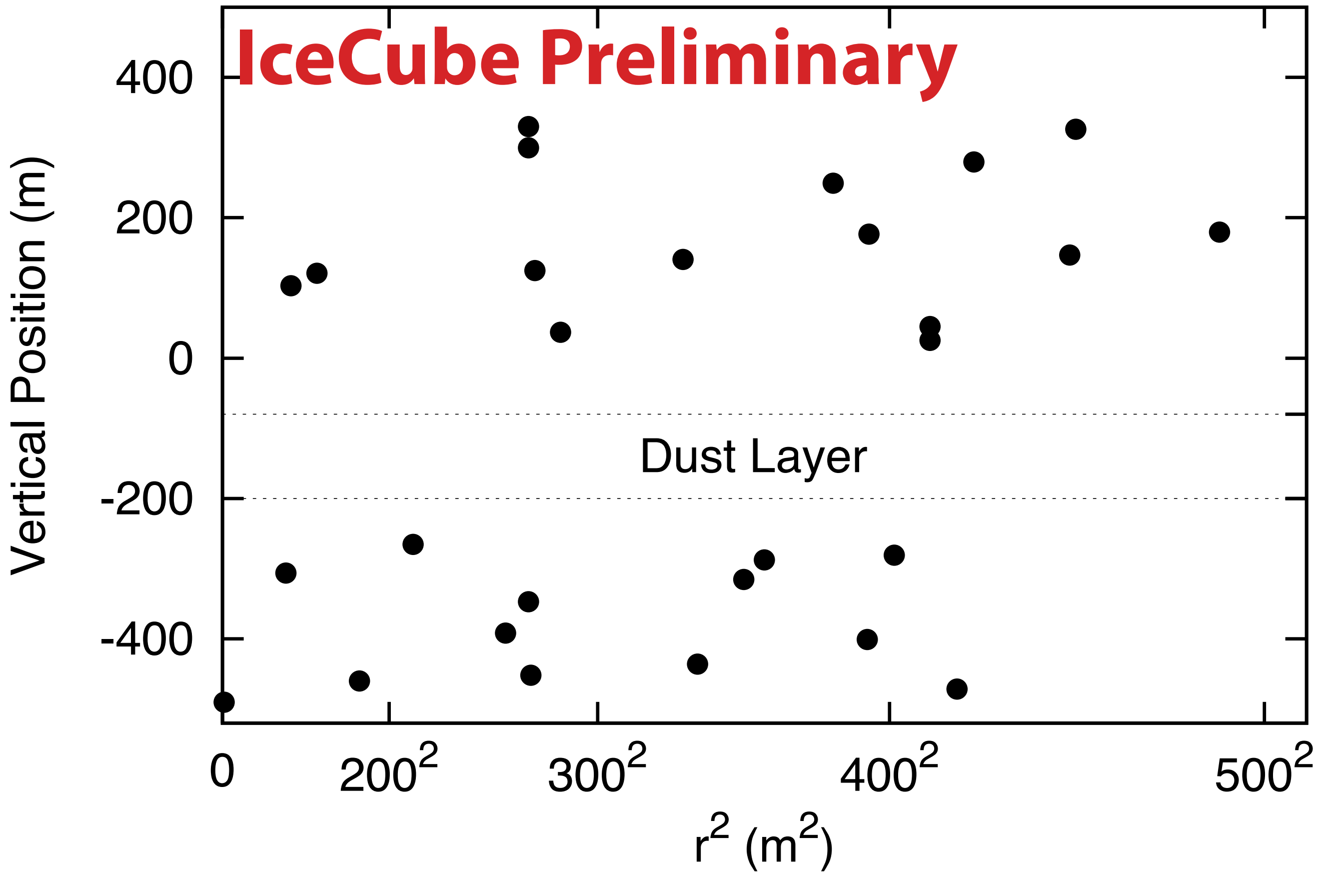
Shadow of the Moon



Cascade Directional Reconstruction



Location in Detector



Uniform in fiducial volume

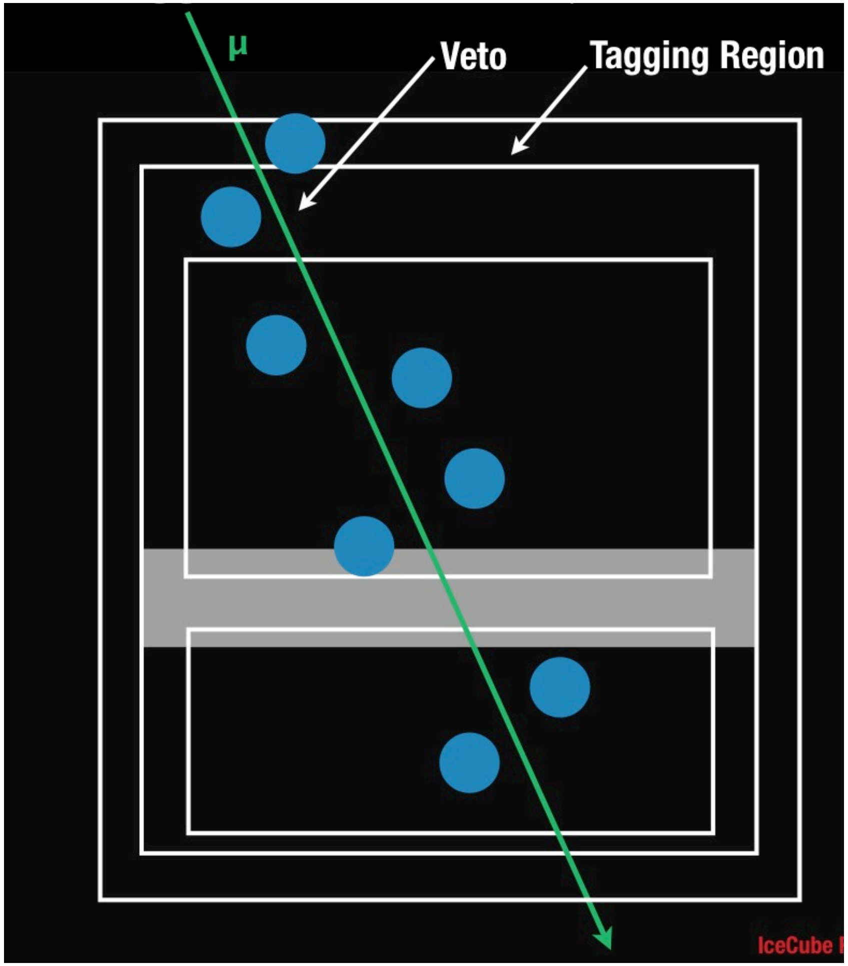
Muon Background Estimation From Data

- Add one layer of DOMs to "tag" known background events
  - use these to evaluate veto efficiency

- Can be checked at lower energies where background dominates

- Estimated muon background:
  - 3 ± 1.5 events / year

- Remaining background is atmospheric neutrinos
  - $2.3^{+1.9}_{-0.6}$ events / year



IceCube Data Flow