Cosmic Rays and High Energy Neutrinos

J. Beatty

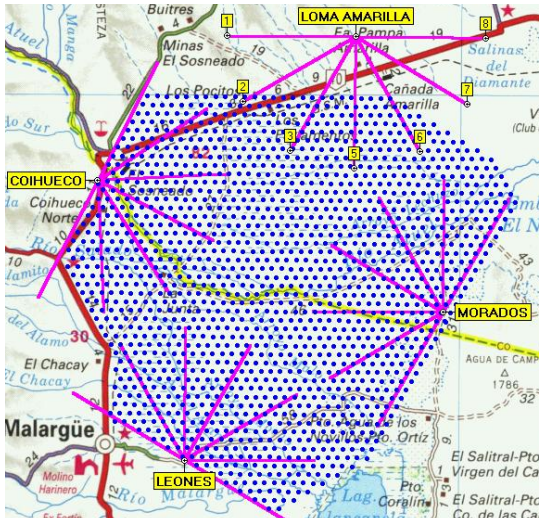
A. Nelson, A. Olinto, G. Sinnis

Results from Current Ultra High Energy Cosmic Ray Experiments

Hybrid Fluorescence/Surface Detector Experiments

Auger

3000 km^2 in Argentina

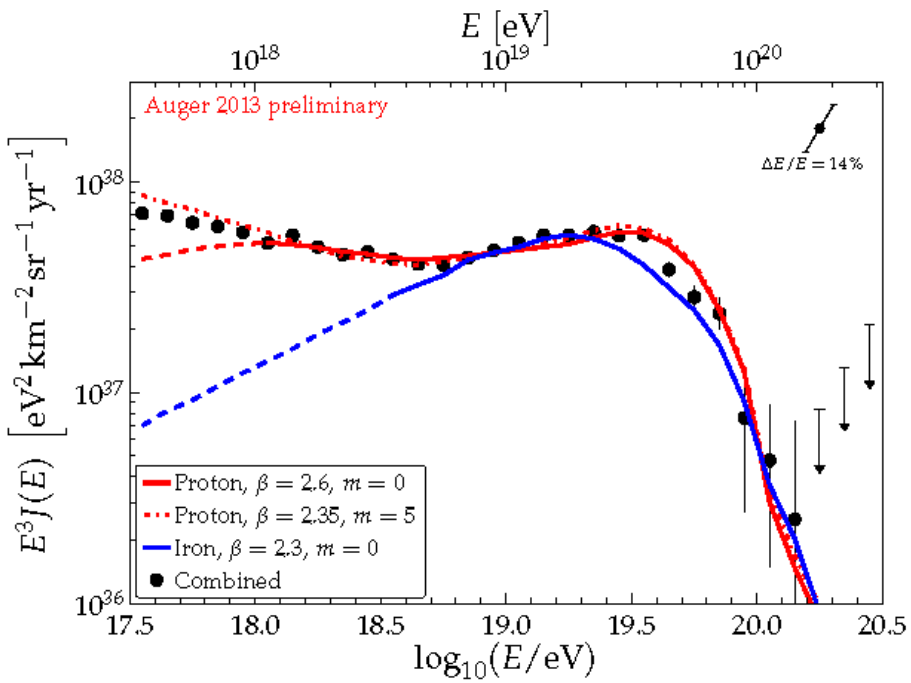


Telescope Array

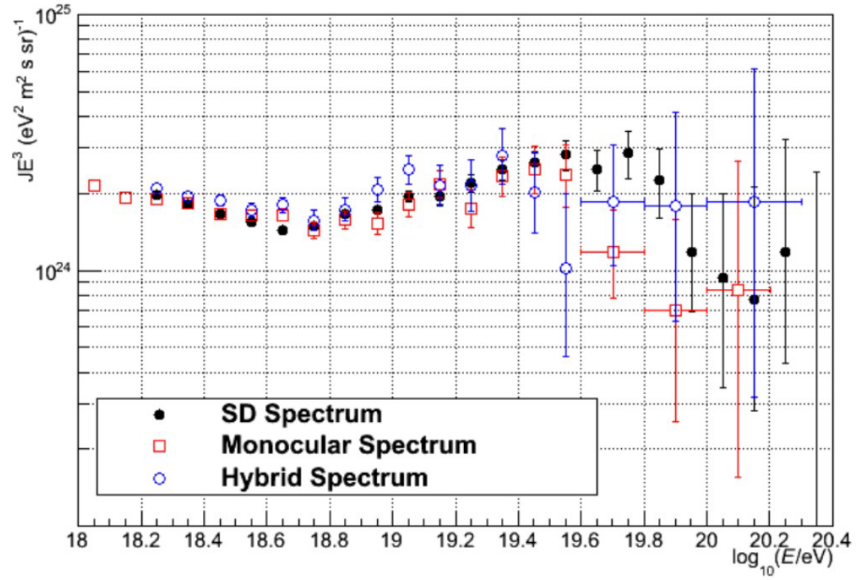
700 km^2 in Utah

Evidence for GZK-like Suppression

Auger

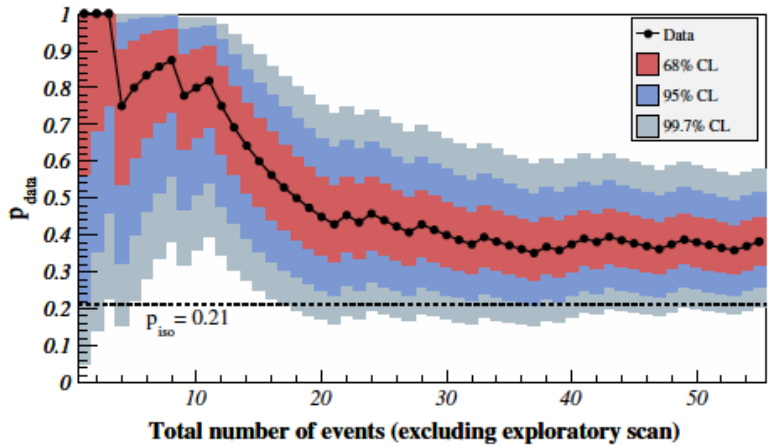


Telescope Array

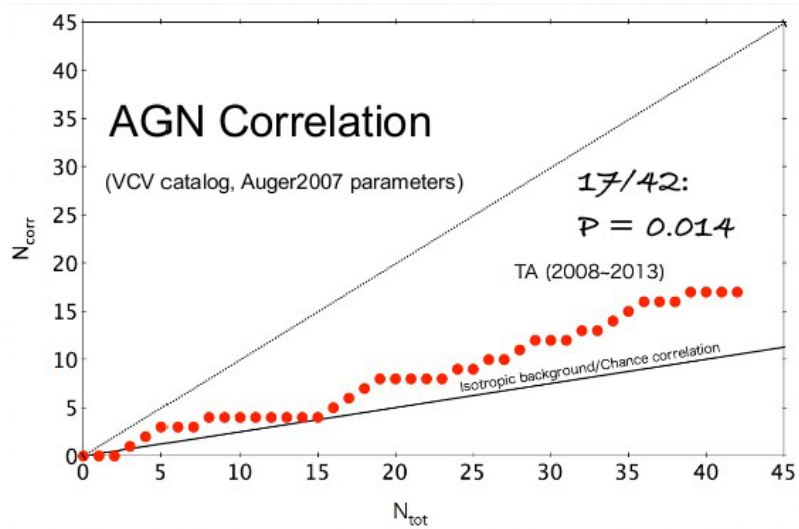


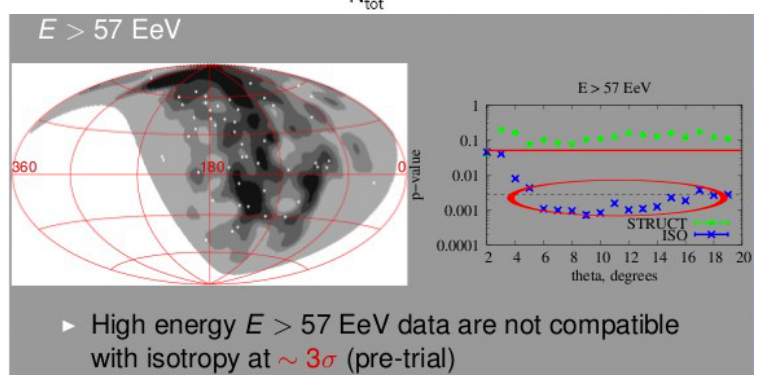
Anisotropy

Auger



Telescope Array





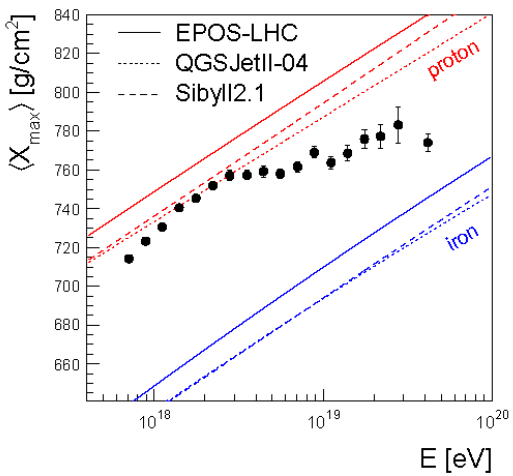
Hints of correlation with local distribution of matter from both experiments, but more data needed.

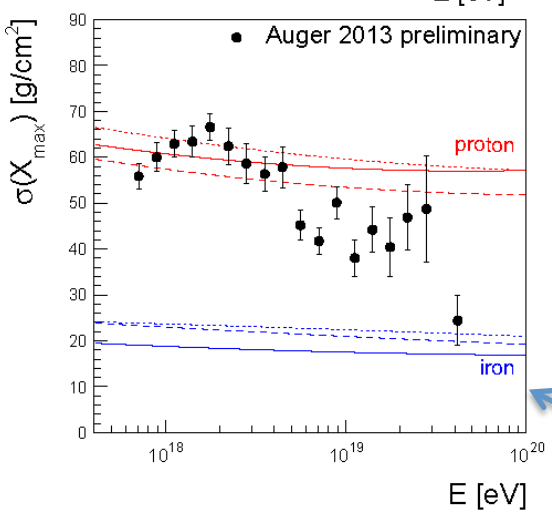
Including composition information may strengthen correlations.

Prescription-based searches and joint global analyses are underway.

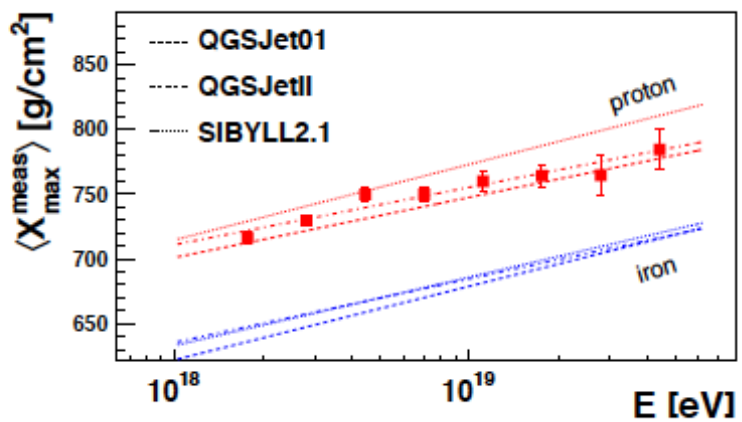
Composition and Interactions

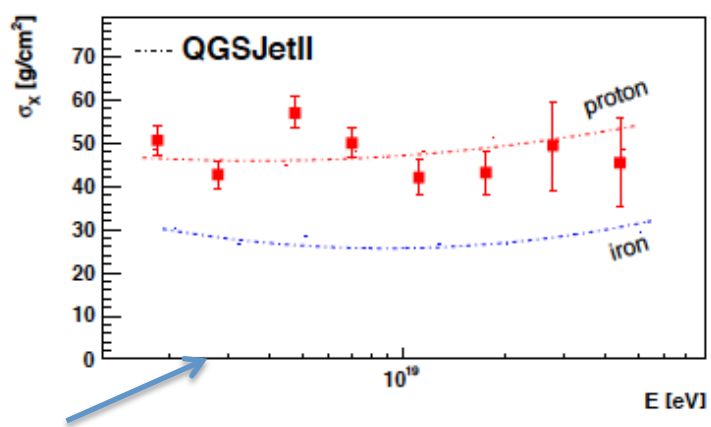
Auger





HiRes



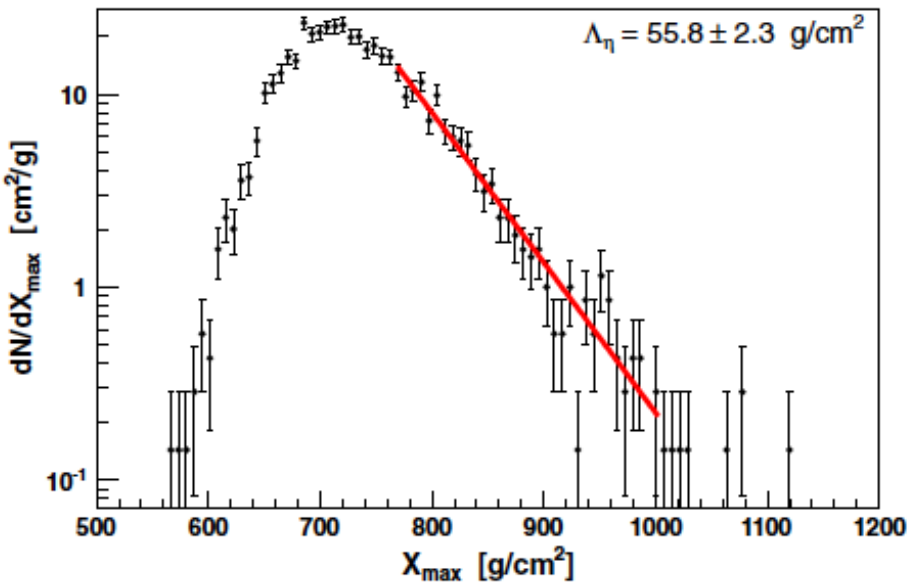


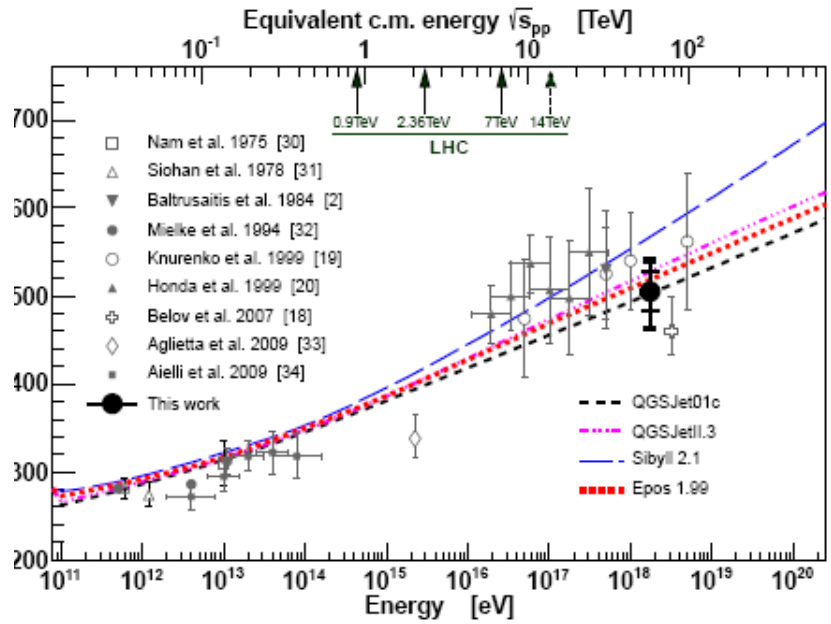
Different estimators and selections

Some observations

- "Composition" is a convenient way of describing changes in shower development, which is what is actually being measured.
- An alternative hypothesis is that interactions rather than beam particles are changing.
- Well-motivated theoretical models describe many features of the data.
  - arXiv 1307:2322 (Farrar and Allen)
    Restoration of chiral symmetry in QCD

Particle Physics from Astrophysics: p-Air Cross Section at sqrt(s)=57 TeV

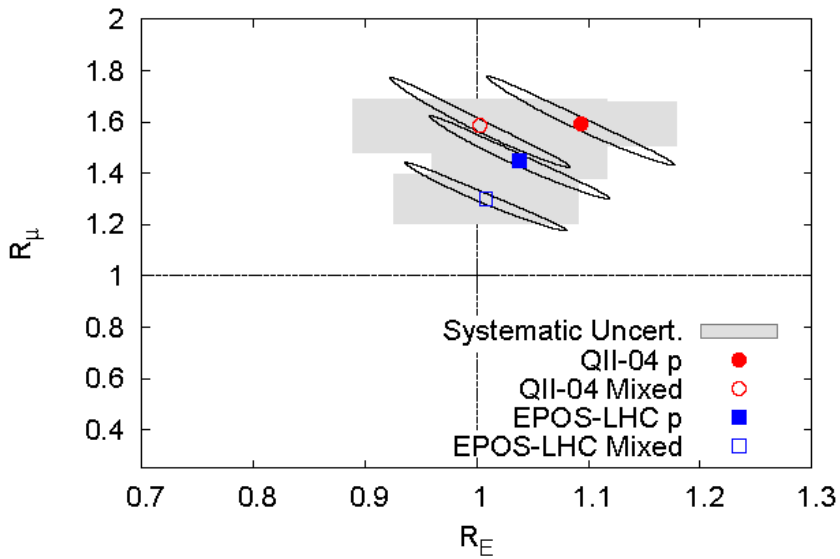




Low energy extensions (e.g. TALE) can cross-calibrate with LHC

Showers are not well-described by models tuned at LHC

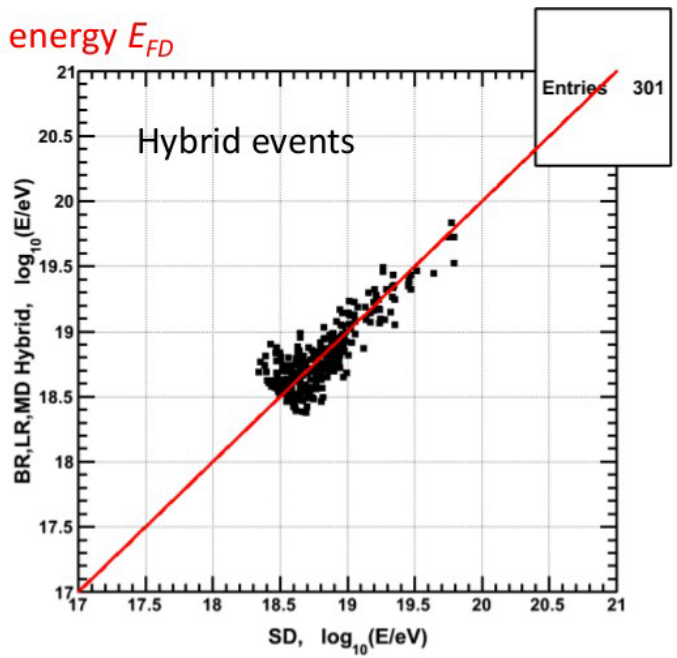
Auger



muon excess

Telescope Array

FD energy E_{FD}



SD energy E_{SD}
(scaled to FD energy)

$$E_{SD} = E'_{SD}/1.27$$

Mismatch between calorimetric and MC energies

What have we learned?

There is a flux suppression near the energy expected for the GZK suppression

But accelerators are also reaching their limits.

There are hints of anisotropy

But not enough statistics to identify sources.

There are changes in the characteristics of showers in this energy region

Could be a composition change…

…or evidence for a change in interactions (e.g. chiral symmetry restoration in QCD)

What next?

- Better handles on composition and interactions
  - Event-by-event compostion diagnostics are the goal.
  - Muon identification is key
- Larger aperture for more statistics
  - Determine anisotropy and identify sources
  - Extend spectrum beyond GZK region

Surface Array Upgrades and Expansions

Enhanced muon identification and increased dynamic range helps in unfolding the details of shower development for composition and interaction studies

Auger plans to propose an upgrade consisting of:

- Increased FADC speed and dynamic range (improves muon ID and reconstruction)
- Extended Dynamic Range with an additional small PMT
- Muon detection enhancements of the surface array (technology TBD)
- Increased fluorescence duty cycle

TA could be expanded to match the size of Auger In the northern hemisphere.

There are discussions of a new large ground array project by European groups, but no definite proposal.

High Statistics from Space Based Observations

Auger+TA	3700 km^2	25 events/yr >60EeV
Earth	$5x10^8$ km^2	$3.4x10^6$ events/yr >60EeV
JEM-EUSO	$4x10^4$ km^2	250 events/yr >60EeV

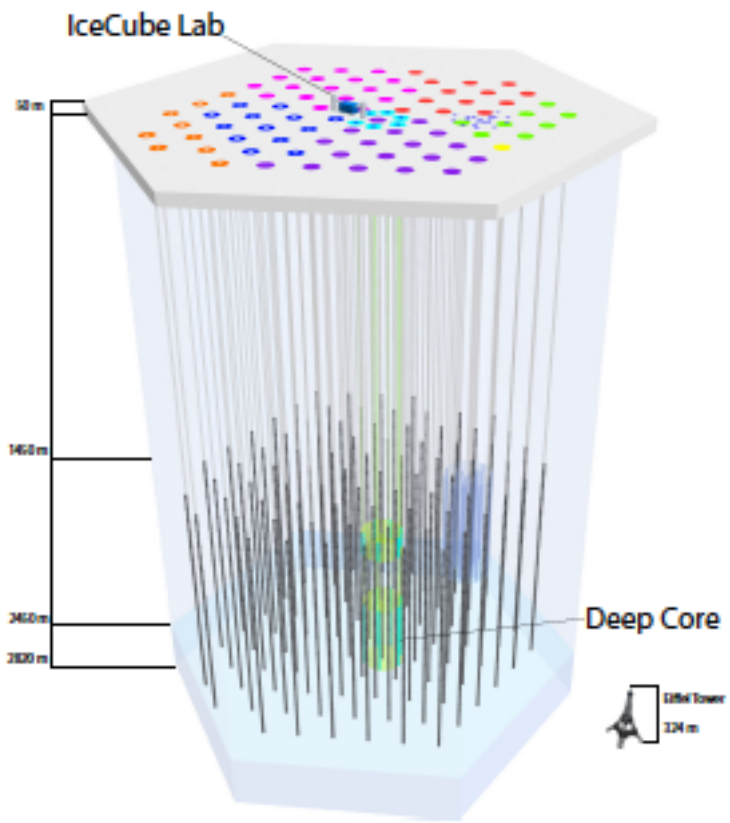
(20% duty cycle, nadir mode)

JEM-EUSO

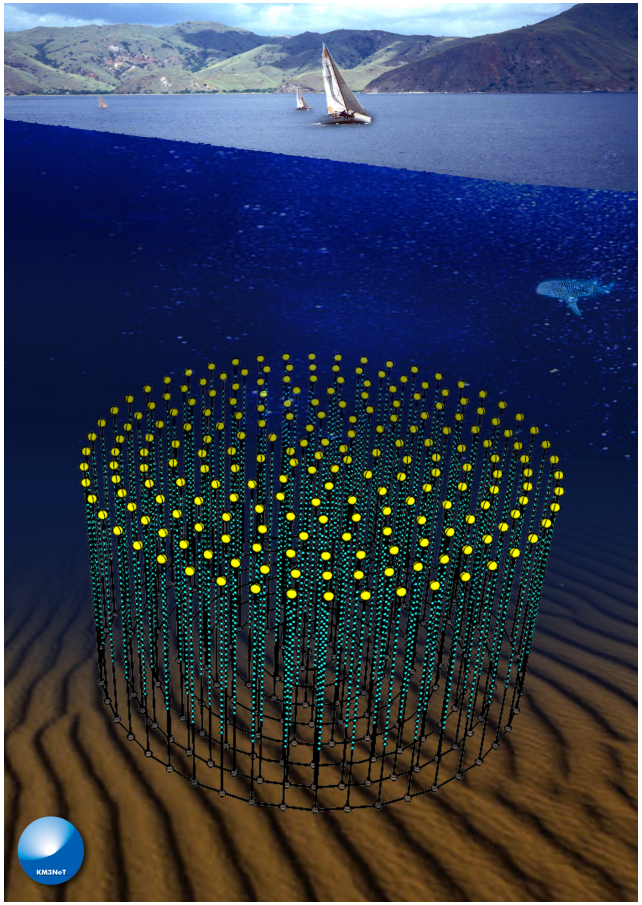
Other concepts: SWORD (radio),…

Current High Energy Neutrino Experiments

Kilometer^3-scale detectors

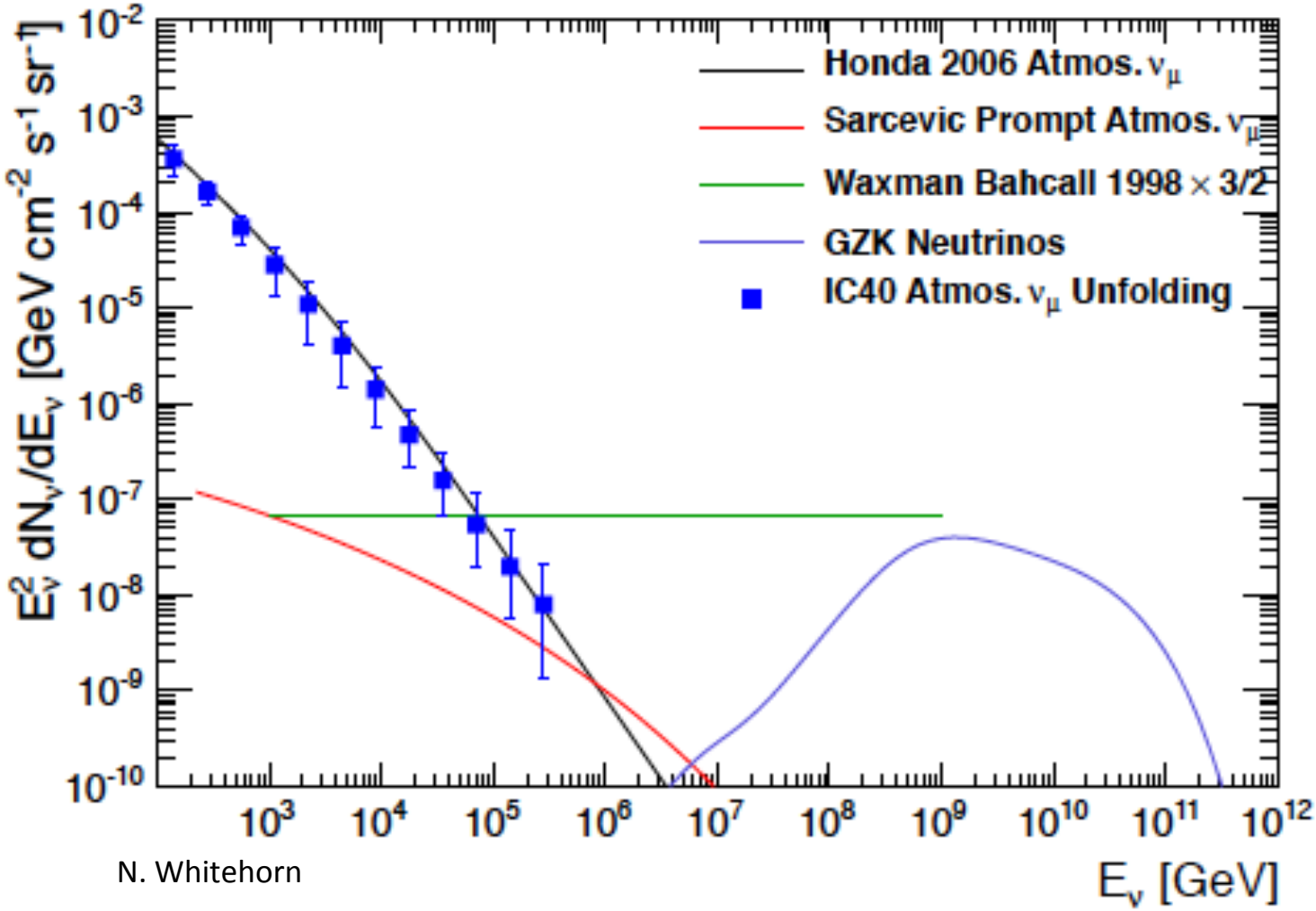


IceCube



Antares, Baikal, KM3NET (future)

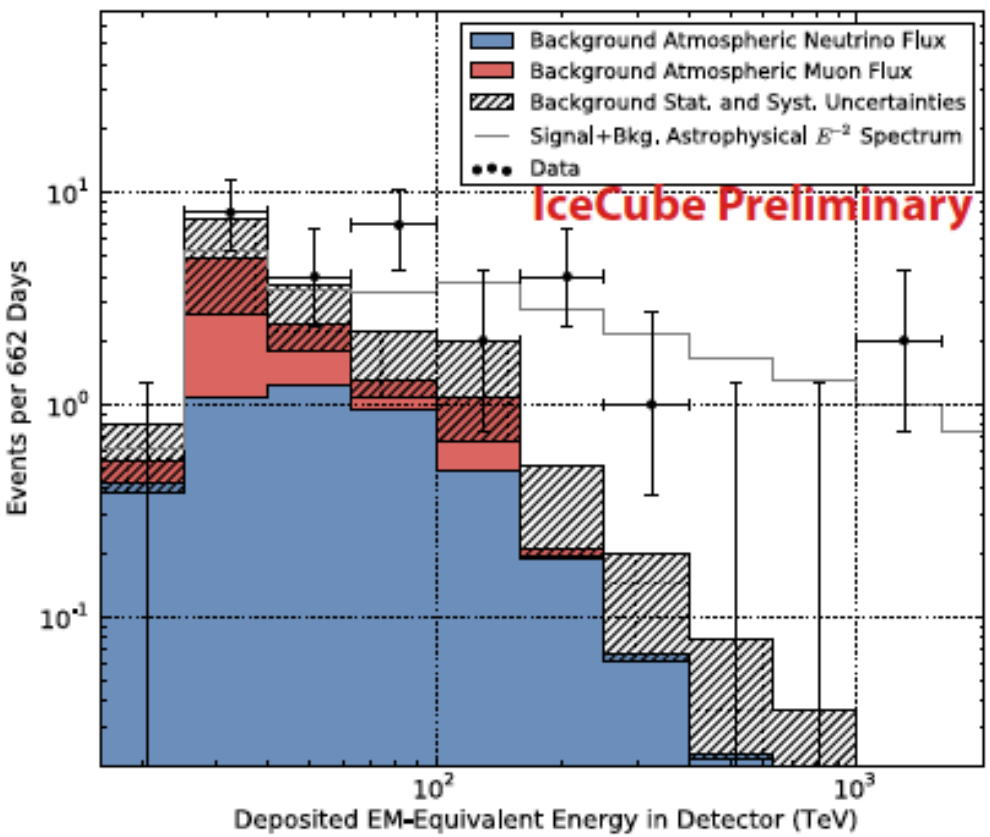
Neutrinos Above 1 TeV



N. Whitehorn

π/K Atmospheric ν Charm Astrophysical (E^{-2}) GZK

Have the first High Energy Astrophysical Neutrinos been observed by IceCube?



28 events with a spectrum harder than that expected for any atmospheric backgrounds.

Cascade-dominated as expected.

Southern events more abundant as expected due to Earth anttenuation

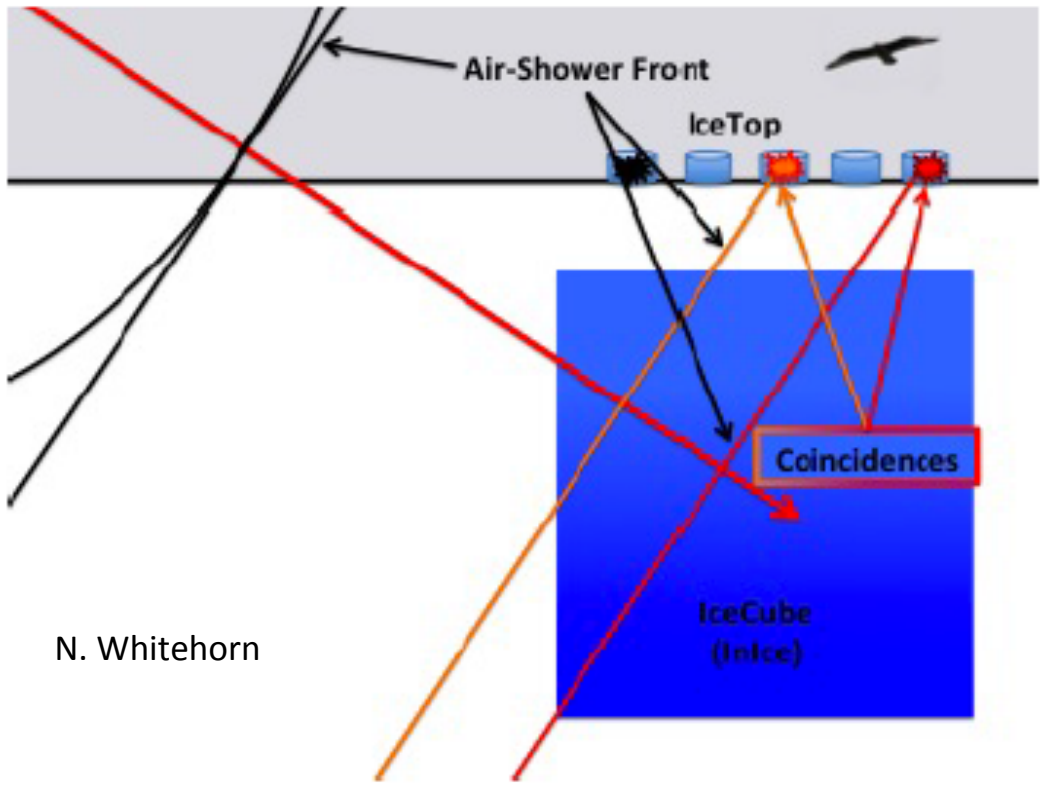
Spectrum slightly softer than E^{-2}

Insufficient statistics to identify sources; currently compatible with isotropy.

More to come as IceCube runs…

High Energy IceCube Extensions

Expanded surface array
to reject atmospheric ν over wider geometry

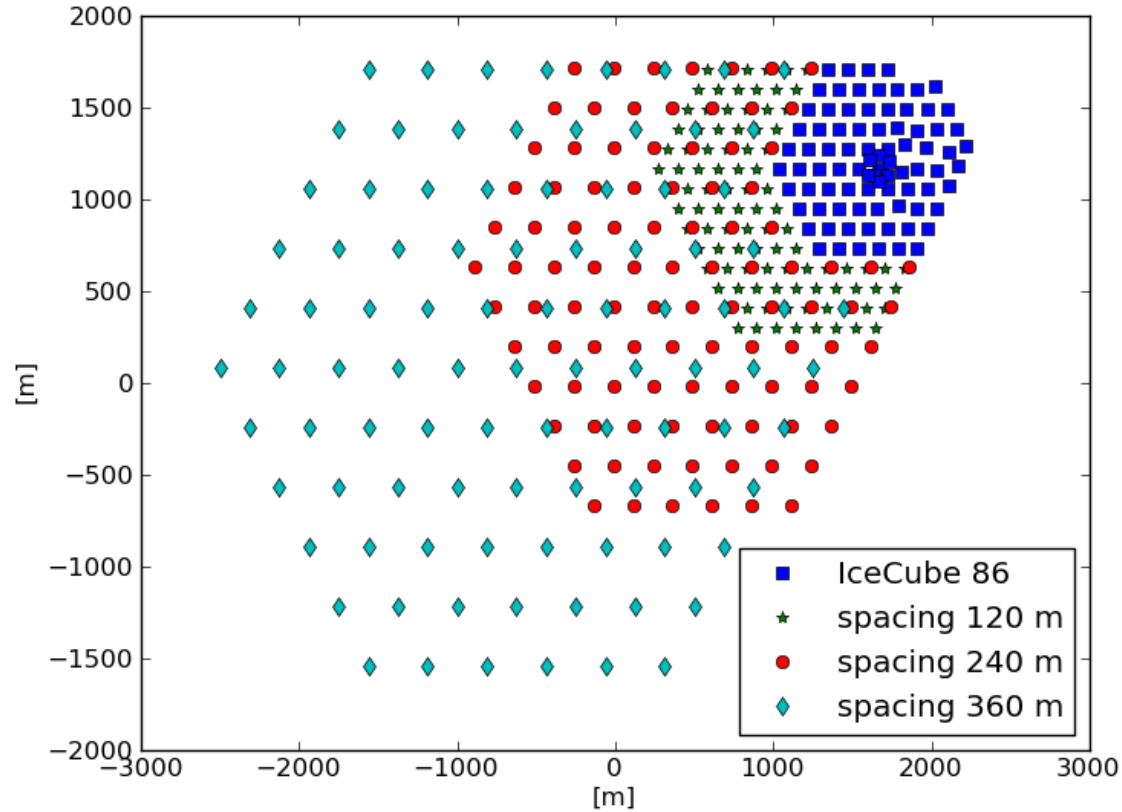


N. Whitehorn

Possible factor 3-5 increase in southern ν_μ acceptance

High Energy IceCube Extensions

IceCube++: Options for ~10 km^2 extensions optimized for PeV neutrinos



PINGU: A Low Energy IceCube Extension

PRECISION ICECUBE NEXT GENERATION UPGRADE

40 high density strings with IceCube as a veto, optimized for low threshold (few GeV).

Targeted at
ν mass hierarchy

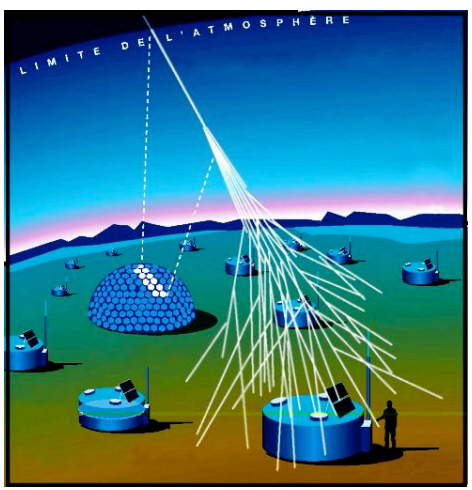
See Gus Sinnis talk.

Neutrino Production: The GZK Process

GZK process: Cosmic ray protons (E> $10^{19.5}$ eV) interact with CMB photons

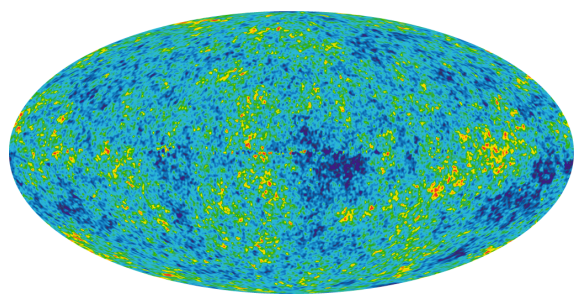
$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\rightarrow \mu^+ + \boxed{\nu_\mu}$$
$$\rightarrow e^+ + \boxed{\bar{\nu}_\mu + \nu_e}$$

cosmic rays

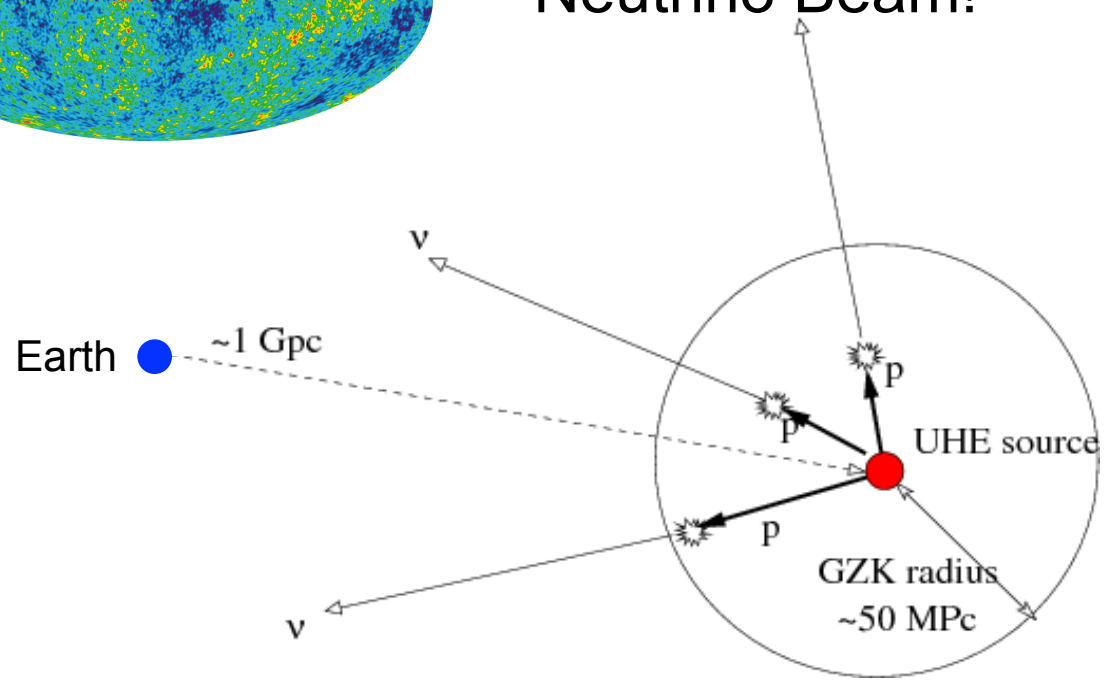


+

CMB



= Neutrino Beam!



Discover the origin of high energy cosmic rays through neutrinos?

GZK Neutrino Experiments using the Askaryan Effect

Electromagnetic cascades result in an evolving population of electrons, positrons, and photons as showers develop.

- Positrons are depleted by in-flight annihilation.
- Additional electrons are upscattered from the medium.
- The net effect is a negative charge excess (~20%) in the shower, moving relativistically.

Dominant RF mechanism in solids (ice, salt, regolith).

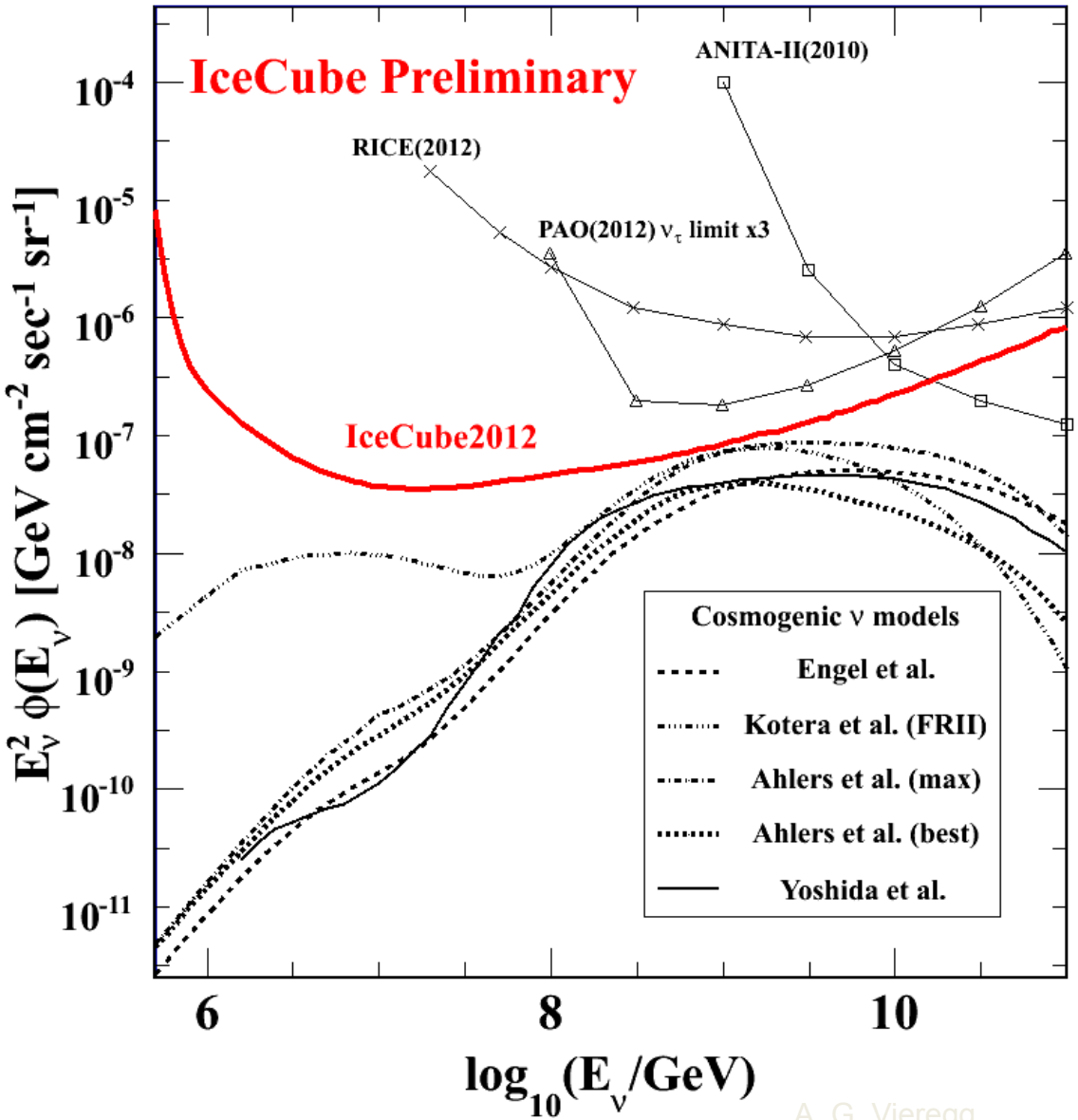
Coherent Cherenkov Radiation at long wavelengths!

Signal scales as E^2 => for typical detector parameters, higher sensitivity than optical detectors above ~10^{18}eV

Ice is a particularly suitable medium

(~km attenuation lengths)

IceCube Sensitivity to UHE Neutrinos



Best current limit

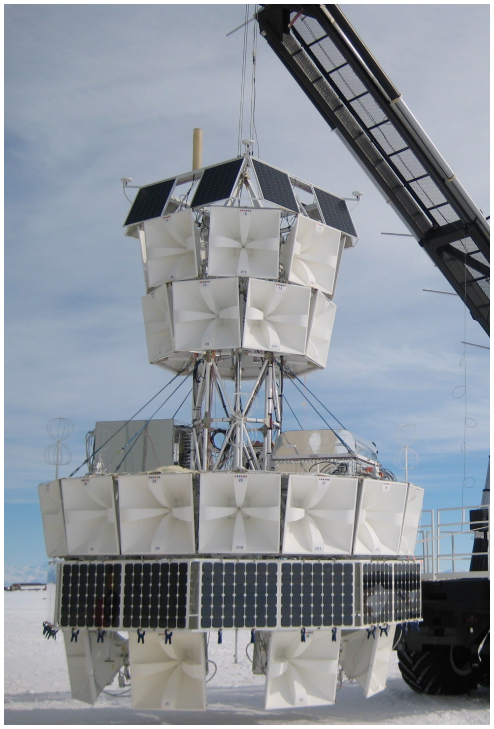
$<10^{19}$ eV

ANITA-I & ANITA-II: Best Limit > 10^{19} eV

NASA Long Duration Balloon, launched from Antarctica

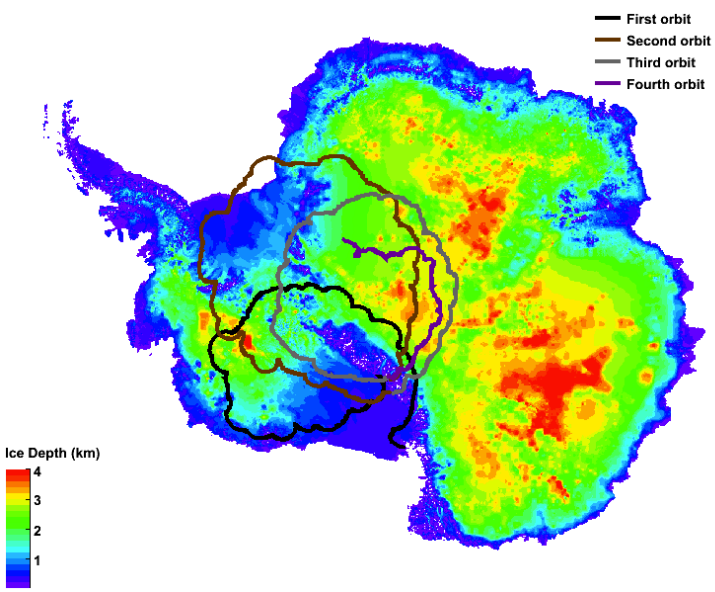
ANITA-I: 35 day flight 2006-07

ANITA-II: 30 day flight 2008-09



Instrument Overview:

- 40 horn antennas, 200-1200 MHz
- Direction calculated from timing delay between antennas
- In-flight calibration from ground
- Threshold limited by thermal noise

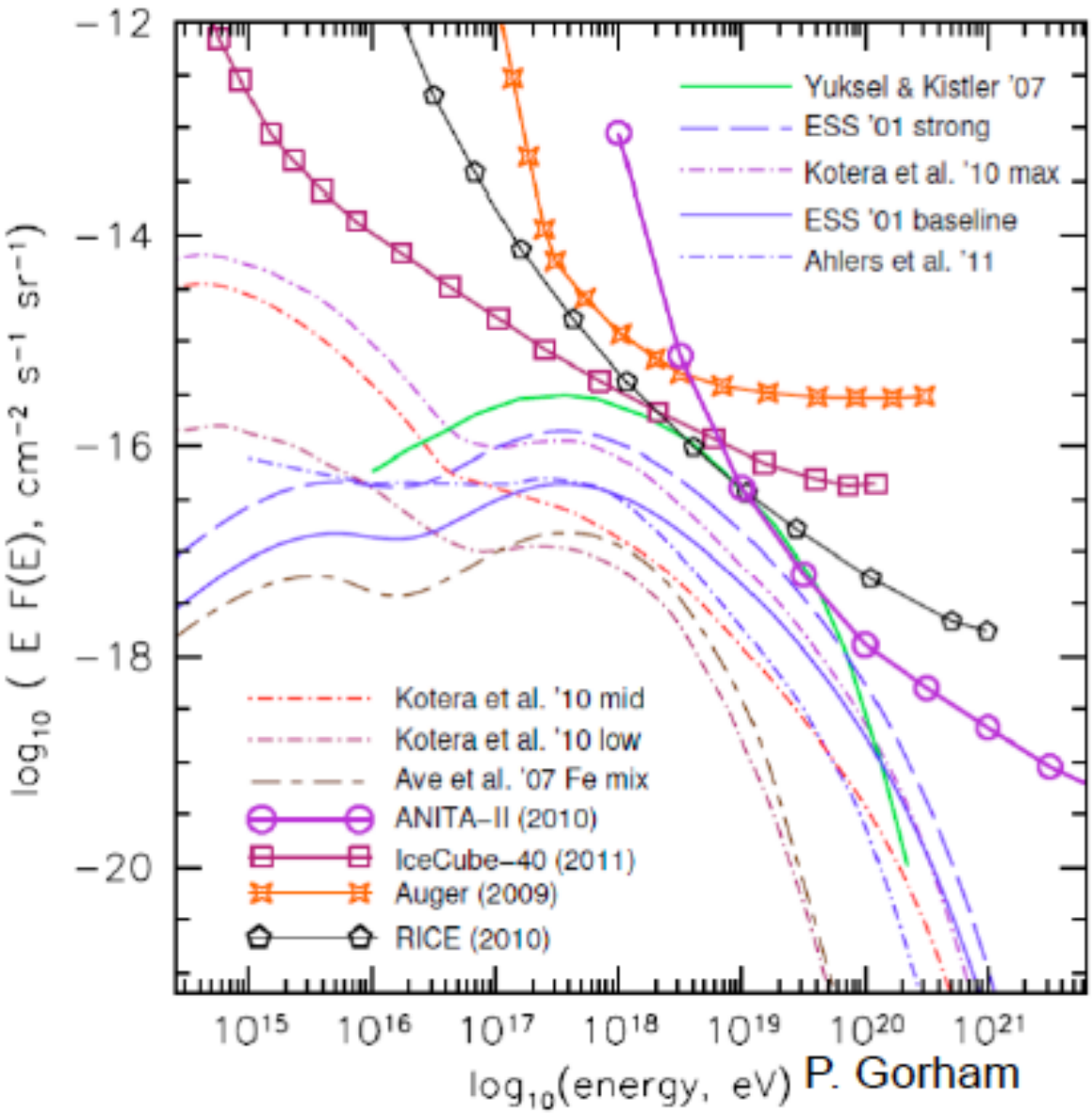


UHE Neutrino Search Results:

	ANITA-I	ANITA-II
Neutrino Candidate Events	1	1
Expected Background	1.1	0.97 +/- 0.42

24

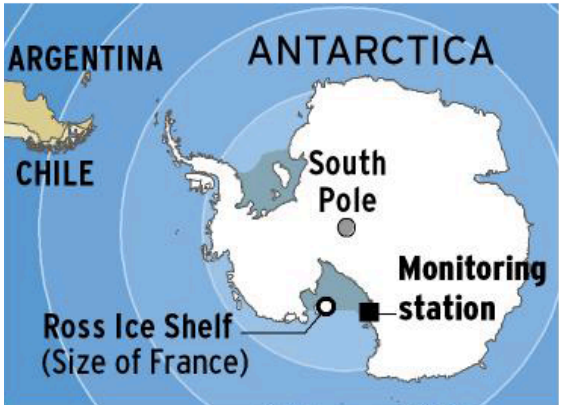
Current Limits and Theoretical Expectations



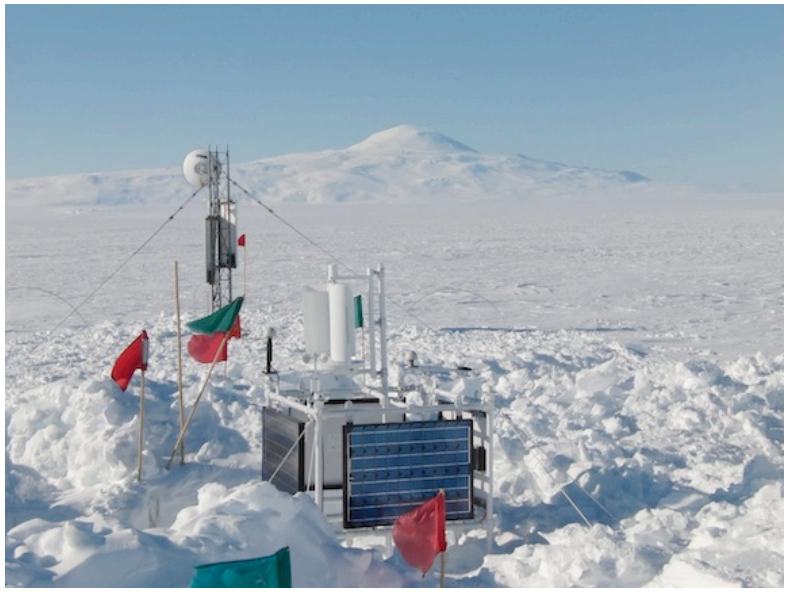
Next Generation Askaryan Experiments

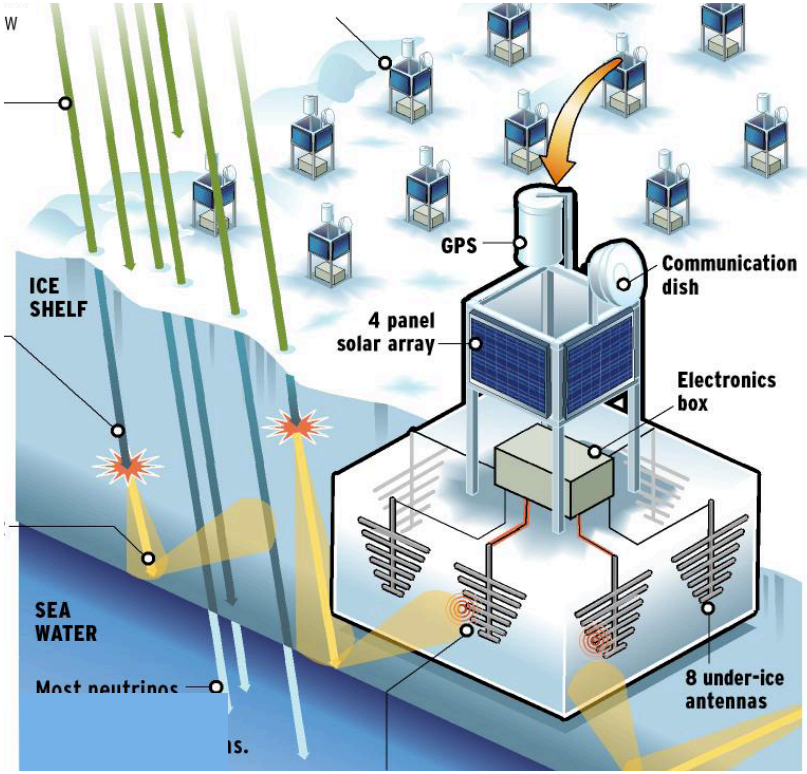
ARIANNA

Ground-based array of antennas on the surface of the Ross Ice Shelf



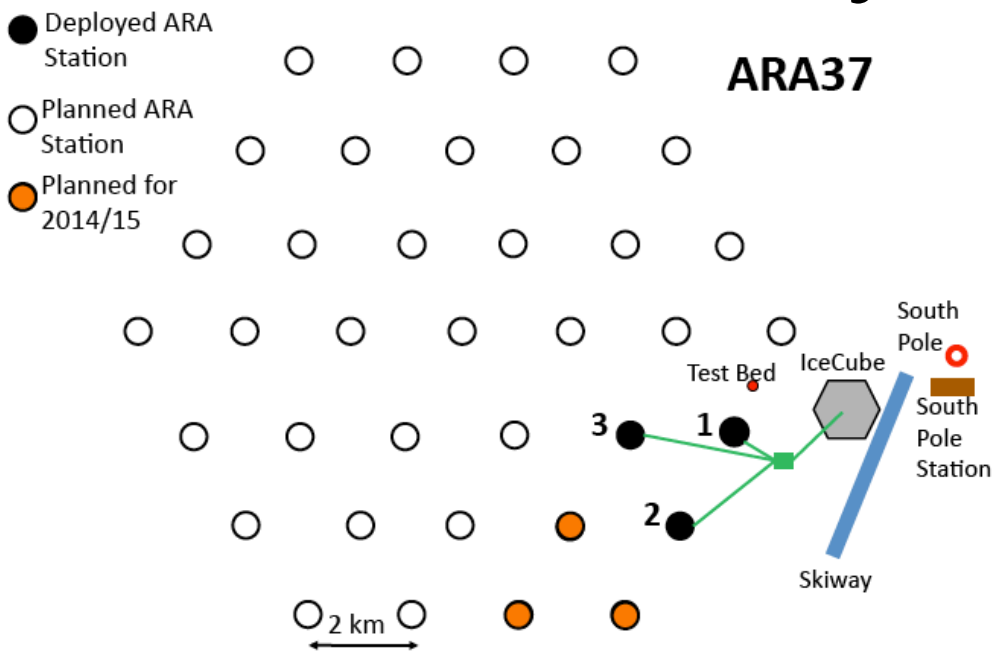
Ice-seawater interface reflects emission from downward-going events





ARIANNA Coll. See arXiv:1207.3846

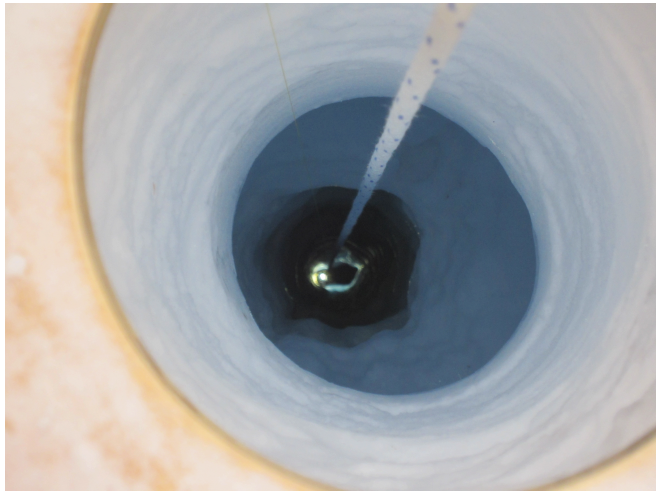
ARA: Askaryan Radio Array



37-string array of antennas buried 200m below the surface at the South Pole

V Pol Antennas

H Pol Antennas

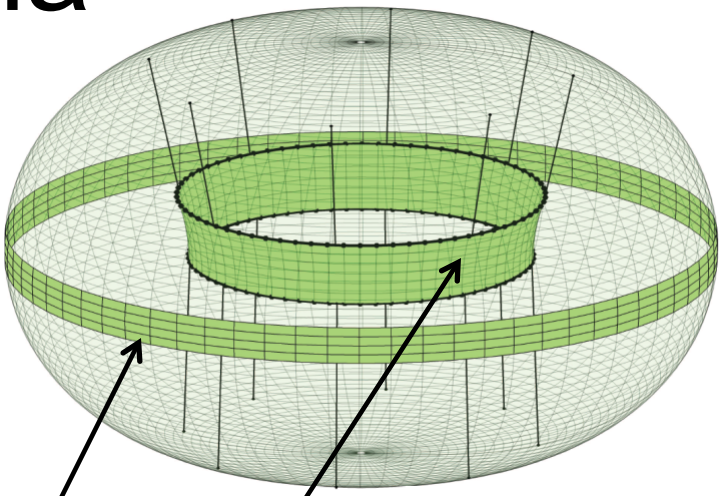


ARA Collaboration. Astropart. Phys. (2012)

EVA: ExaVolt Antenna

NASA super pressure balloon incorporates an antenna

Similar sensitivity to 3-year ARA, and ARIANNA



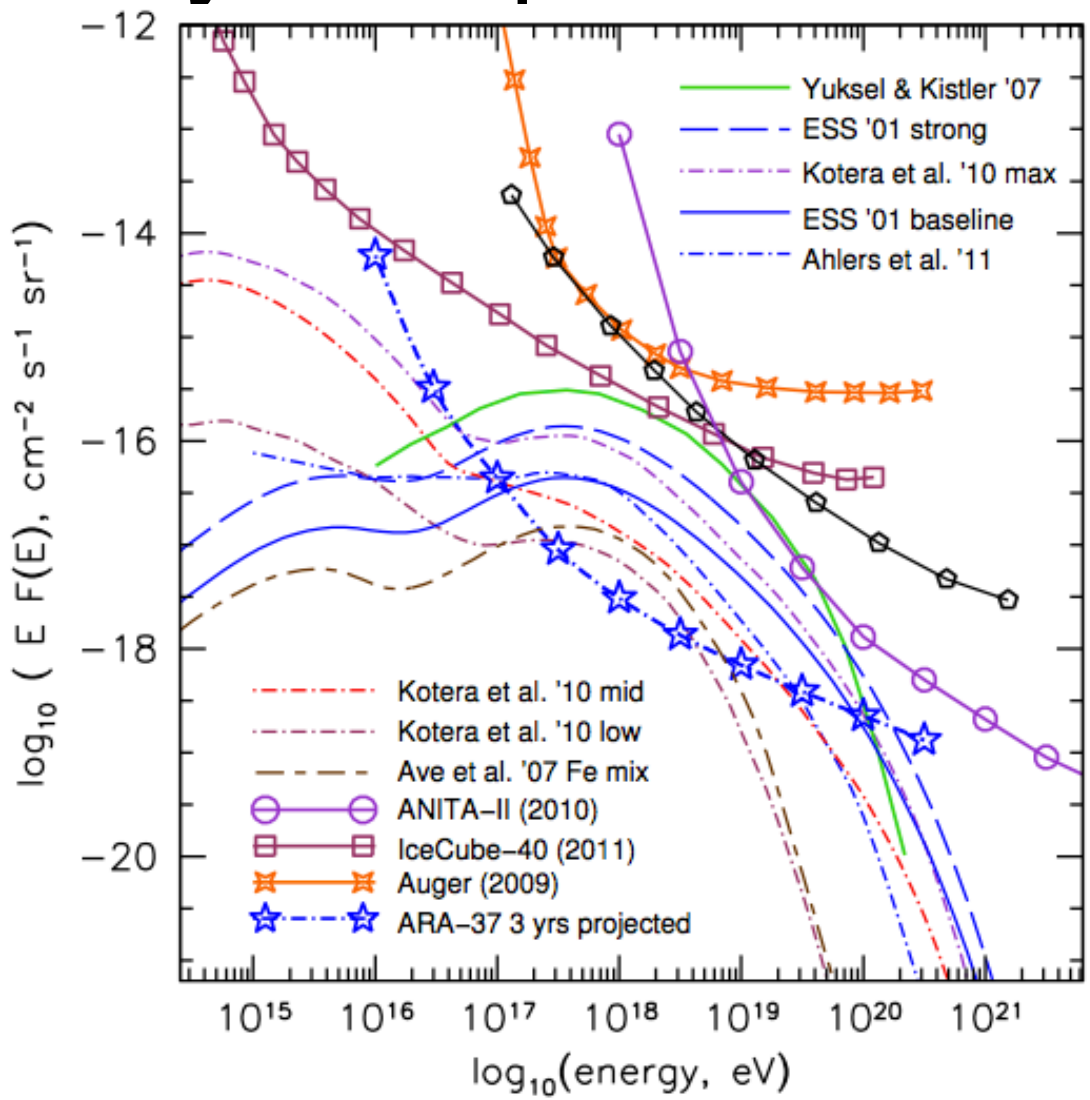
Gorham et al. (2011)

→ Feed design: dual-polarization, broadband, sinuous antennas on inner membrane

Neutrino Sensitivity of Next-Generation Askaryan Experiments

What the sensitivity of a next-generation UHE neutrino detector looks like:

→ With tens of events per year, we'll have a real high-energy neutrino observatory for particle physics and astrophysics

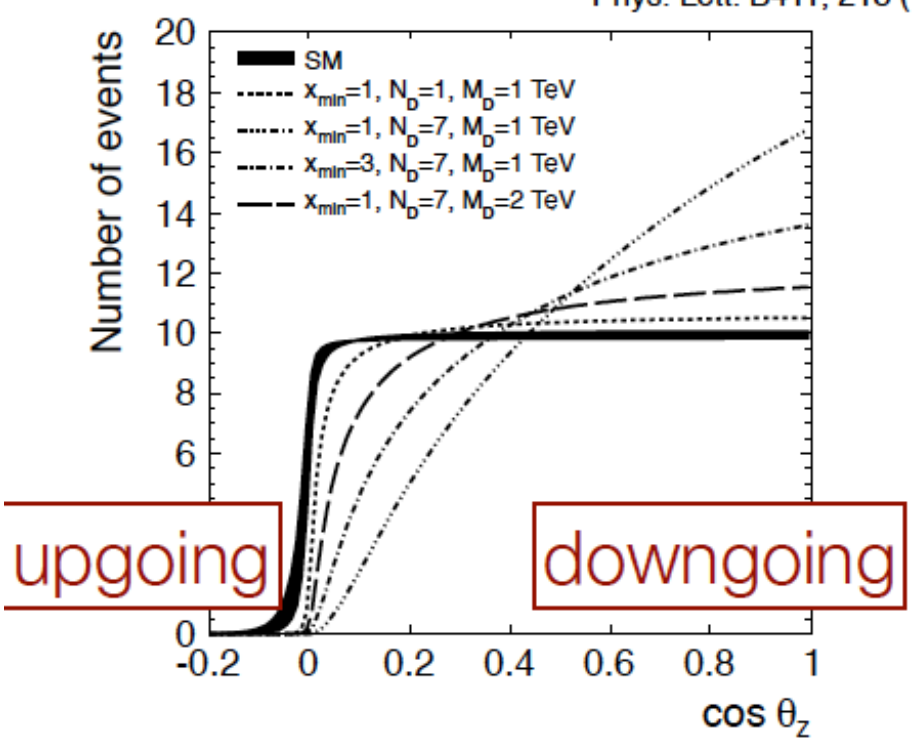


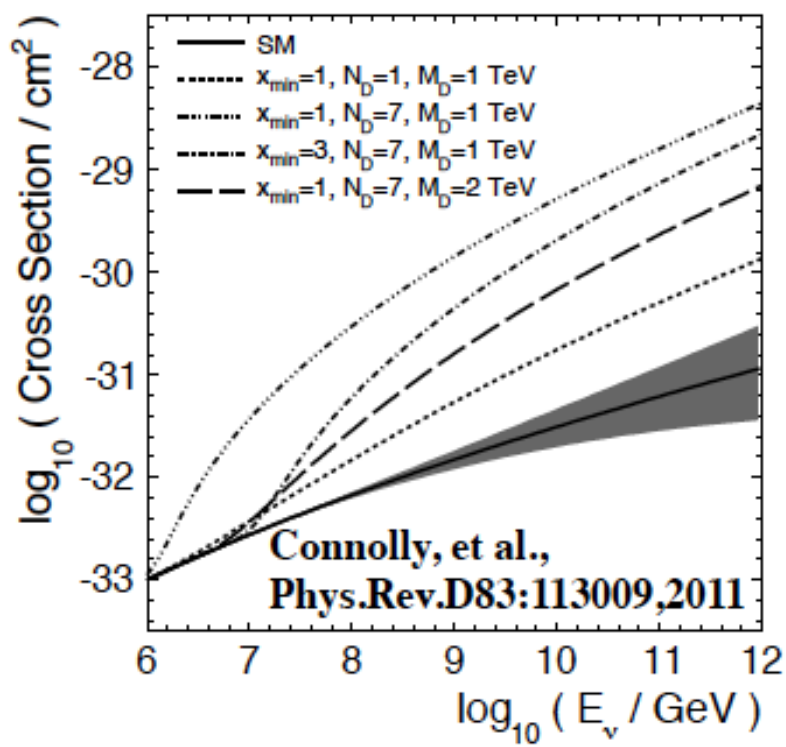
ARA Coll. arXiv:1105.2854

Particle Physics from Astrophysics: UHE Neutrino Cross Sections

If UHE neutrinos are detected, their intensity as a function of zenith angle provides a measurement of the νN cross section.

J. Alvarez-Muniz and E. Zas, Phys. Lett. B411, 218 (1997)





Synergies

- Trans GZK cosmic rays sample the nearby universe (<~100 Mpc)
- GZK neutrinos travel over cosmological distances, and their flux depends both on composition and on the redshift evolution of the sources.

Combining cosmic ray and neutrino data can potentially yield a rich harvest.