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Neutrino Particle Astrophysics



Ryan Nichol

Outline

- History
- Motivation
- IceCube
- ANITA & ARA
- PINGU

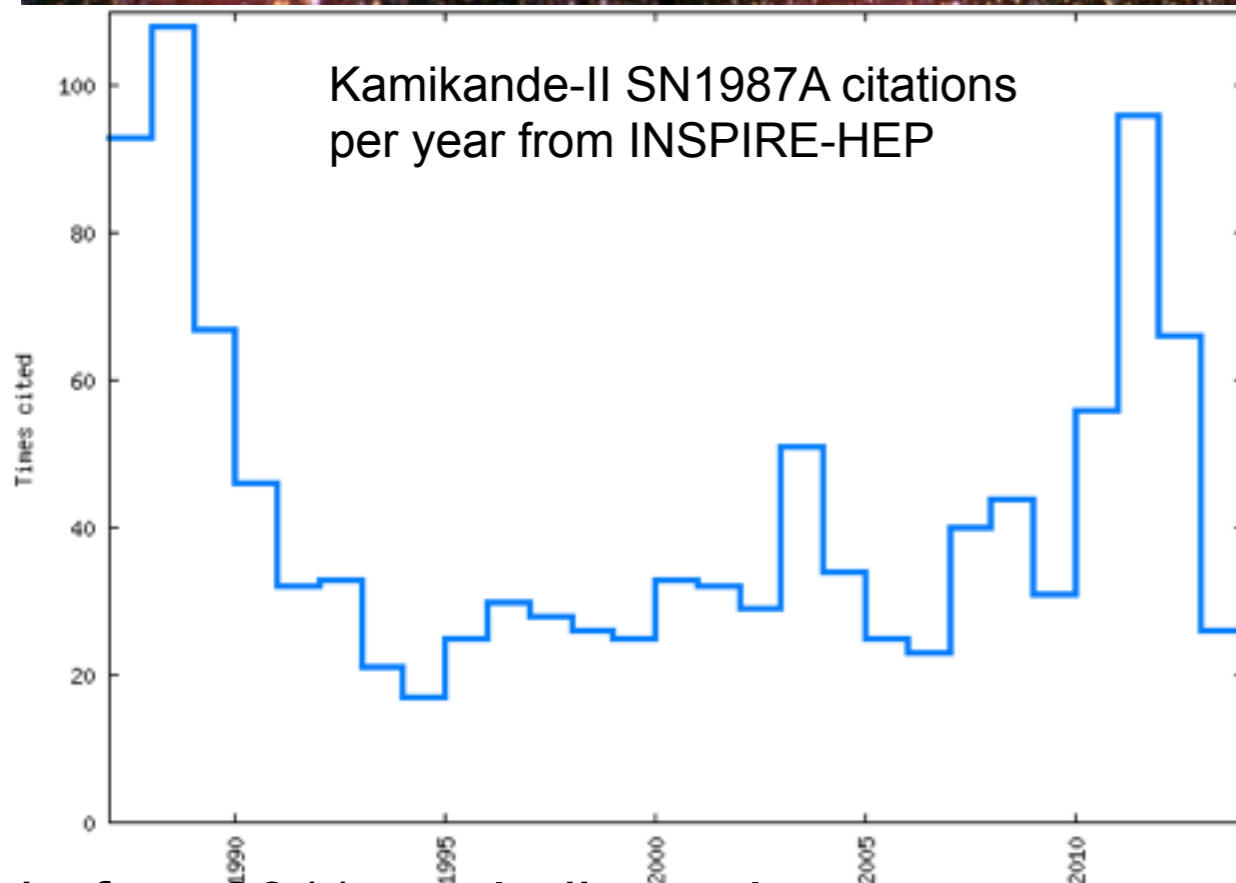


• SN1987A

–24 neutrino events detected by Kamikande-II, IMB and Baksan

–Learned about

- Supernova collapse mechanisms
- Neutrinos feel gravity (similarly to photons)
- Neutrino mass $< 23\text{eV}$ from time of flight dispersion
- Neutrinos are not charged
- Limits on non-neutrino weakly interacting particles
- Axion bounds
- Neutrino mixing and oscillations
- Exotic neutrino disappearance²

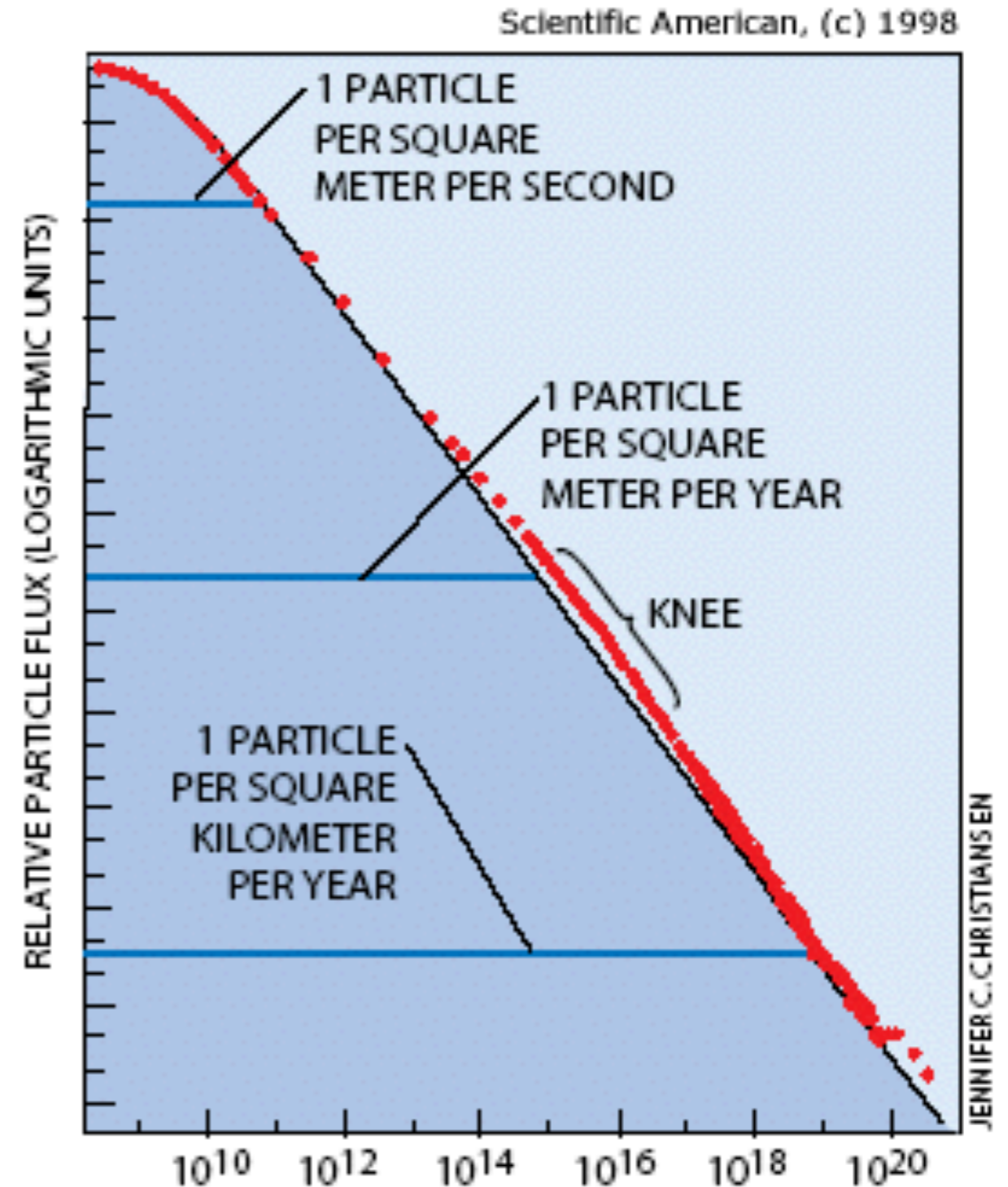


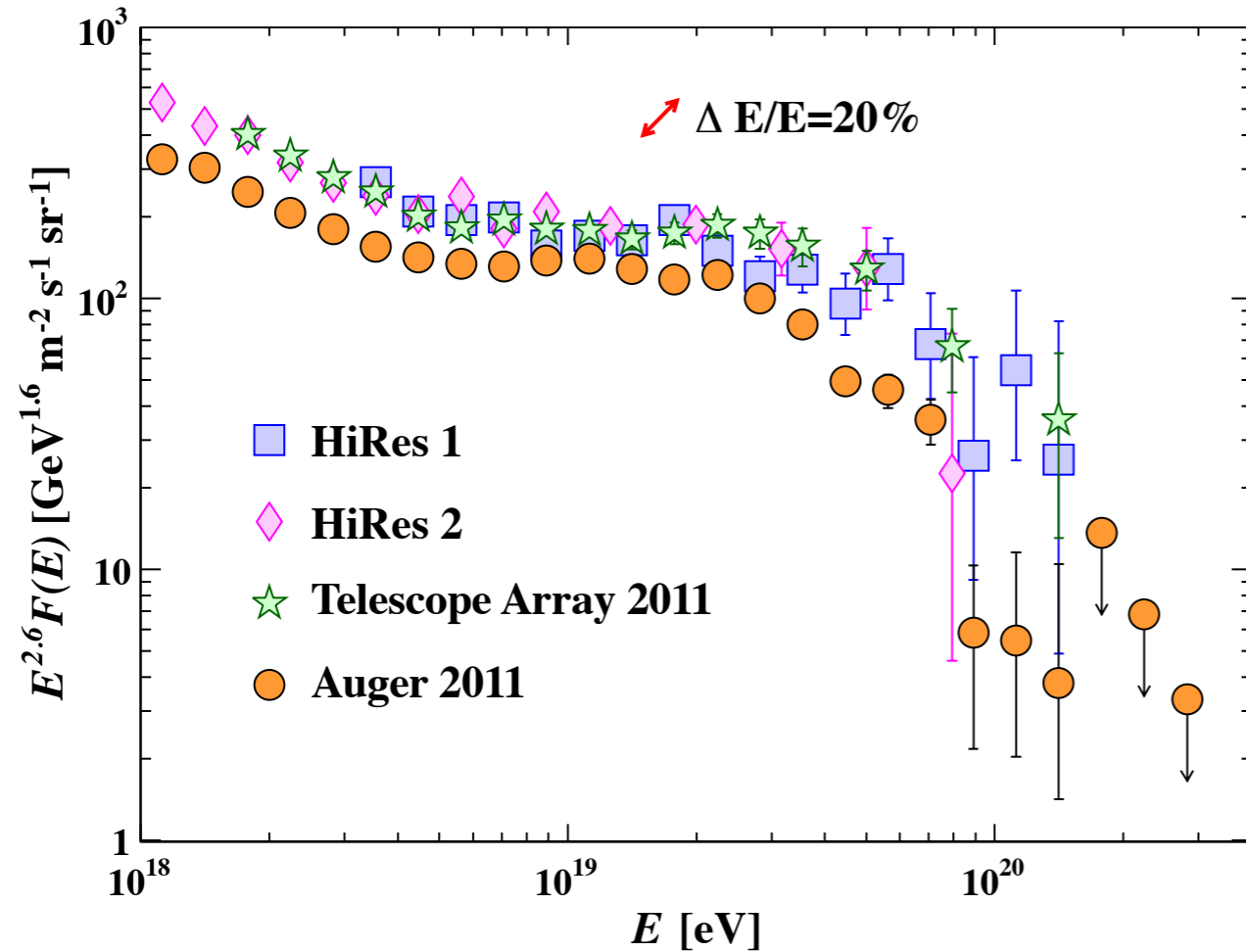
* before 2011, excluding solar



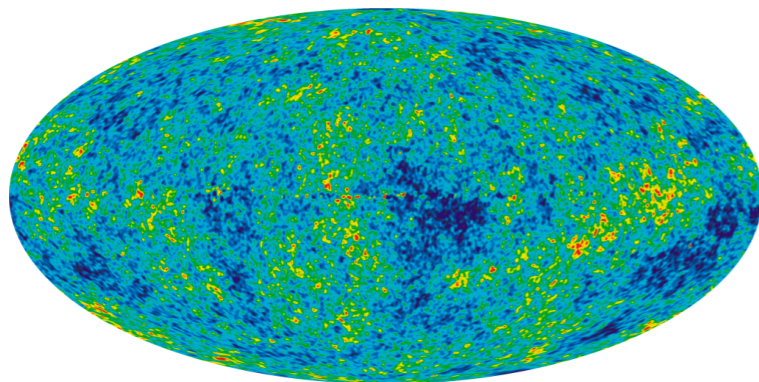
Symmetry Magazine, Sandbox Studio

- Where do the highest energy cosmic rays come from?
- Nearby sources should point
- Faraway sources should be attenuated by the cosmic microwave background
- Could neutrinos solve the problem?

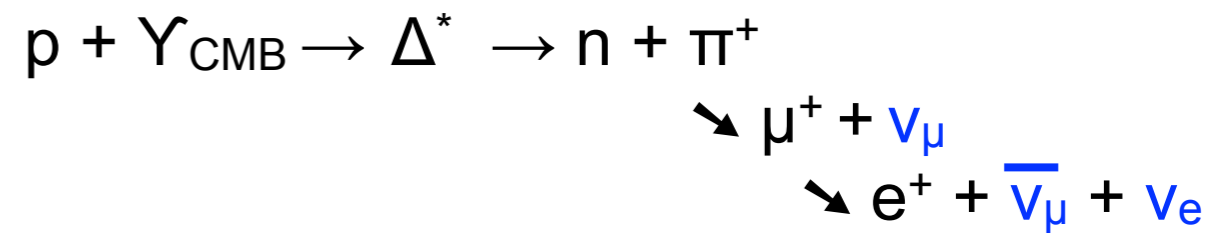




+

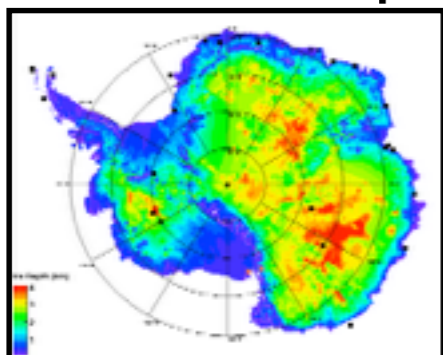


- Greisen-Zatsepin-Kuzmin (GZK) calculated cosmic rays above $10^{19.5}$ eV should be slowed by CMB within 50 Mpc.
- Berezhinsky and Zatsepin realised this would produce a flux of cosmogenic neutrinos



= “Guaranteed” Neutrino “Beam”!

- Antarctica
 - It is the coldest, driest, windiest place on Earth
- But...
 - Lots of Ice
 - Despite our best efforts
 - Over 4km thick in places
 - Also:
 - The only continent exclusively dedicated to scientific research
 - A rich history of particle physics and cosmology experiments



- Mediterranean Sea
 - It is not the coldest, driest, windiest place on Earth
- And...
 - Lots of Water
 - Also:
 - Much better food and culture than Antarctica
 - The sea is literally swimming with potential signals
 - A range of oceanographic measurements unavailable in Antarctica
 - Not a rich history of particle physics and cosmology experiments

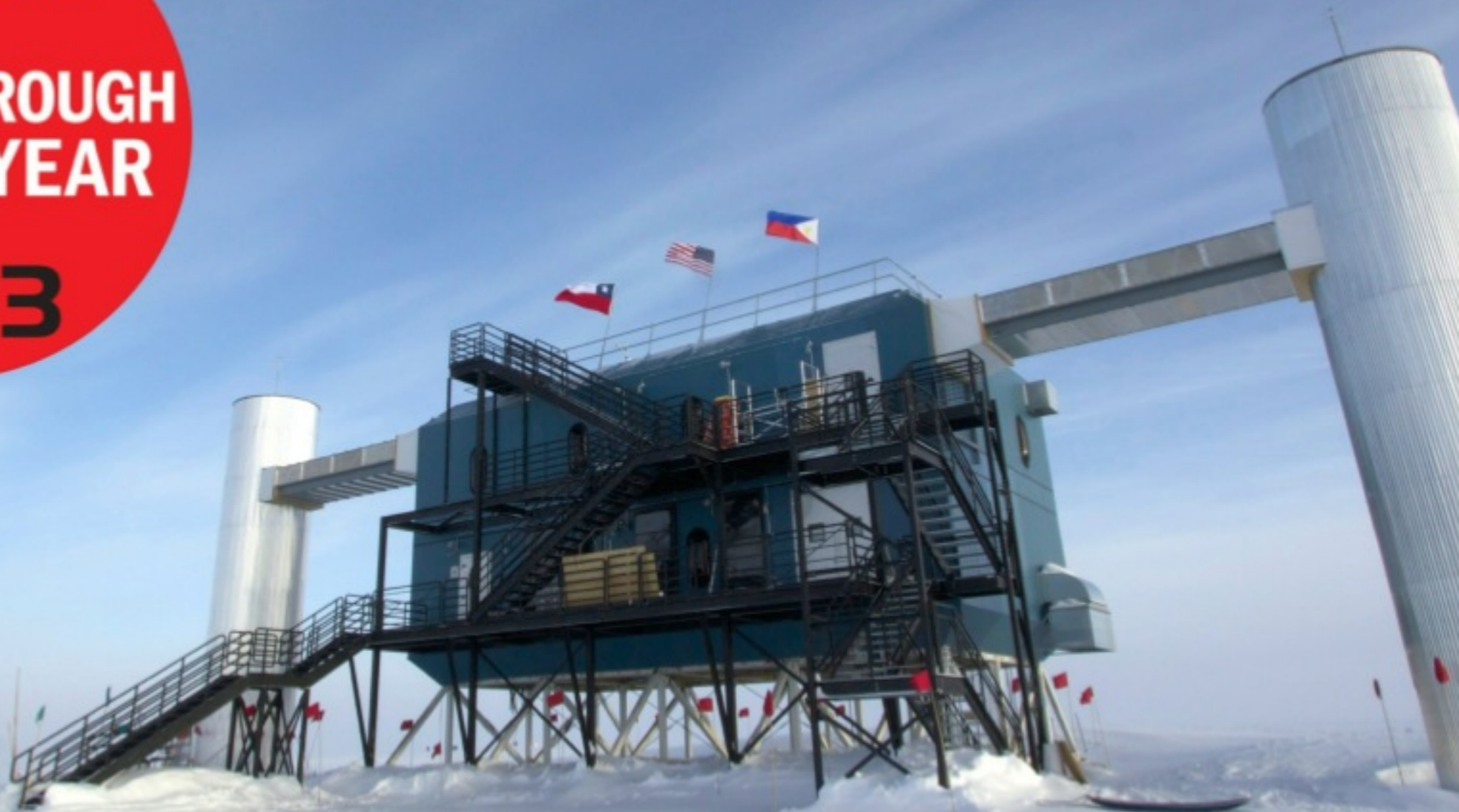


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physicsworld

**BREAKTHROUGH
OF THE YEAR**

2013



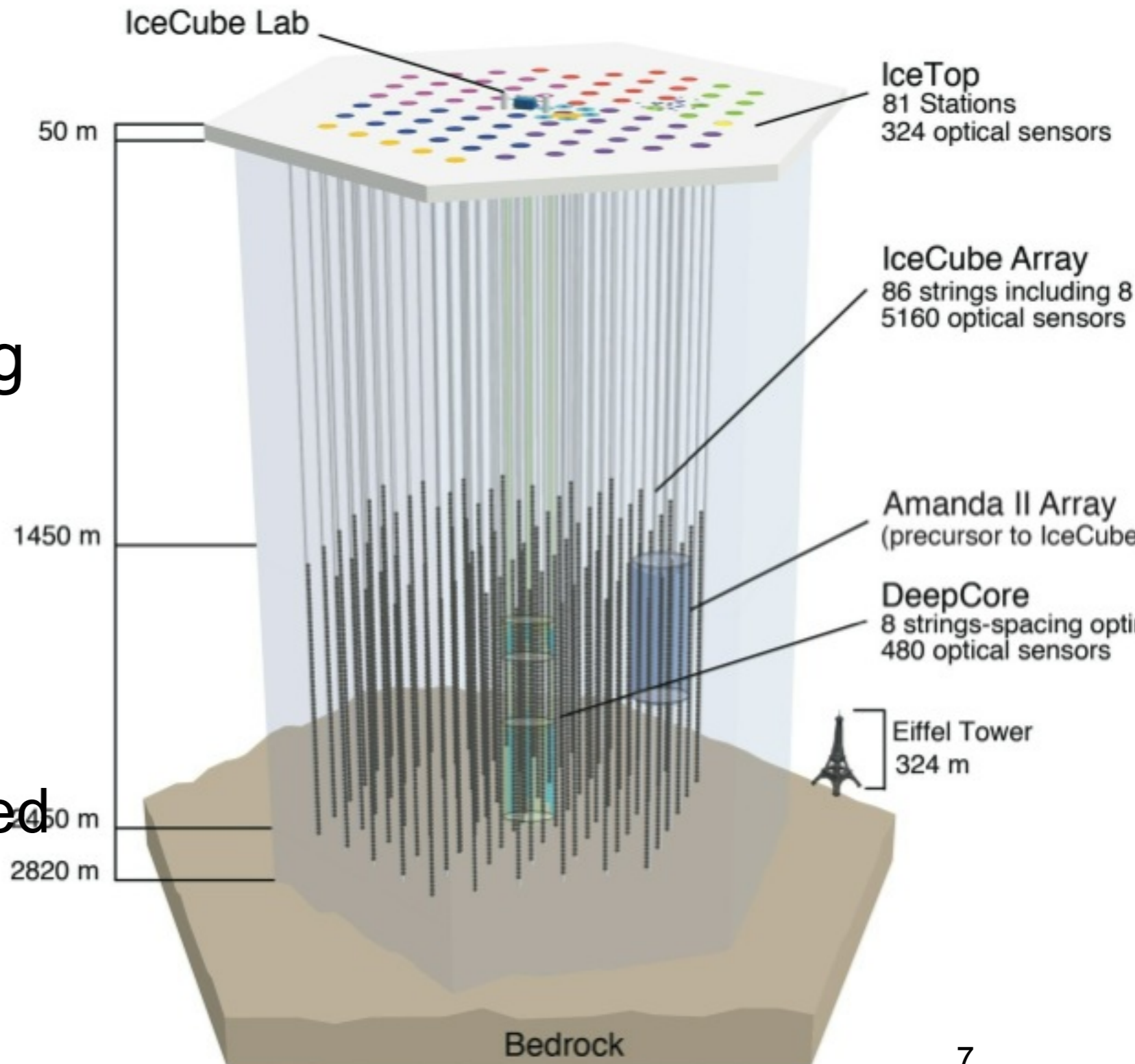
ICECUBE



IceCube

Some slides from C. Kooper, Moriond 2014

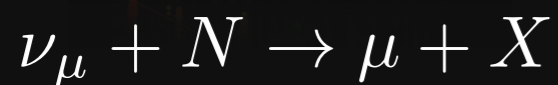
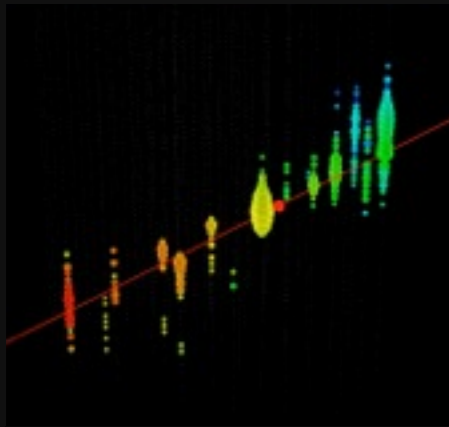
- Completed in 2010
- 1km^3 of ice at the South Pole
- 5160 PMTs
- 86 strings
- 17m vertical spacing
- 125m horizontal spacing
- DeepCore
 - Densely instrumented array of 8 strings in deep good ice



Neutrino Event Signatures

Signatures of signal events

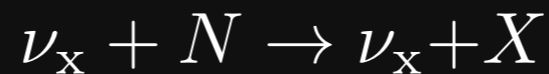
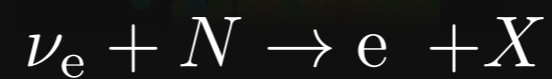
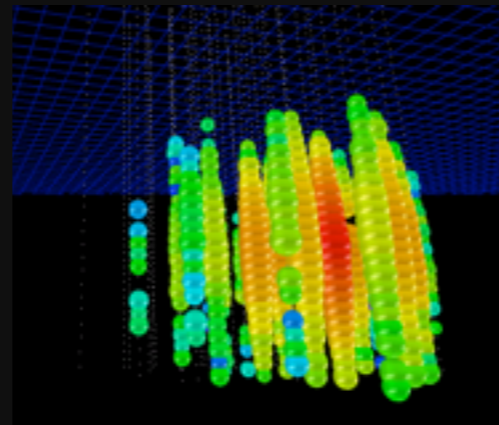
CC Muon Neutrino



track (data)

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

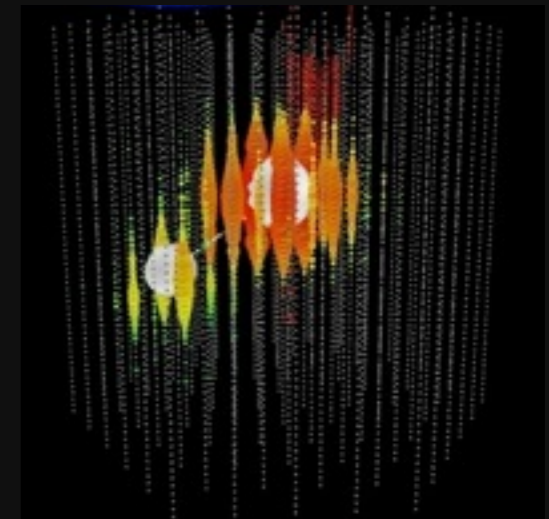
Neutral Current / Electron Neutrino



cascade (data)

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

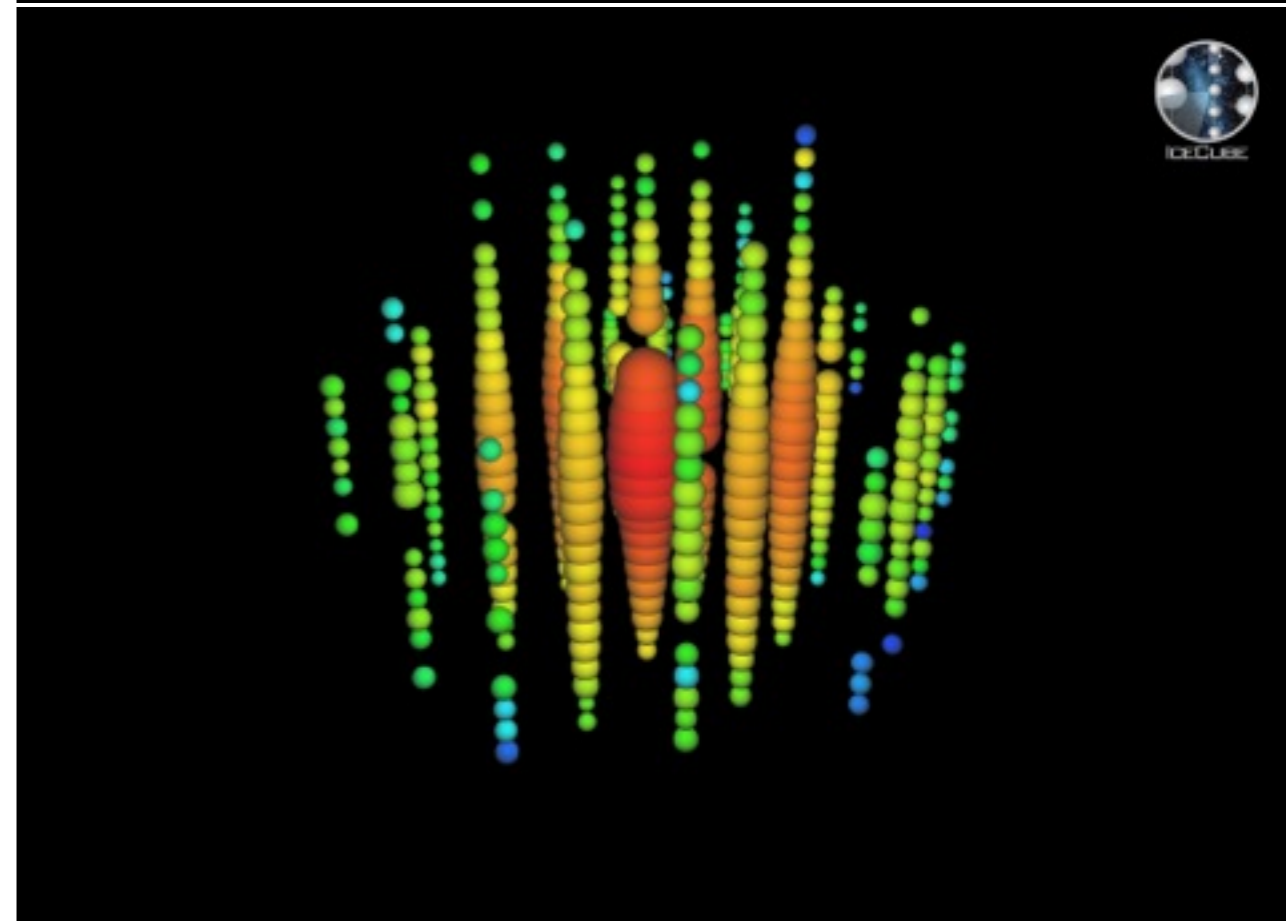
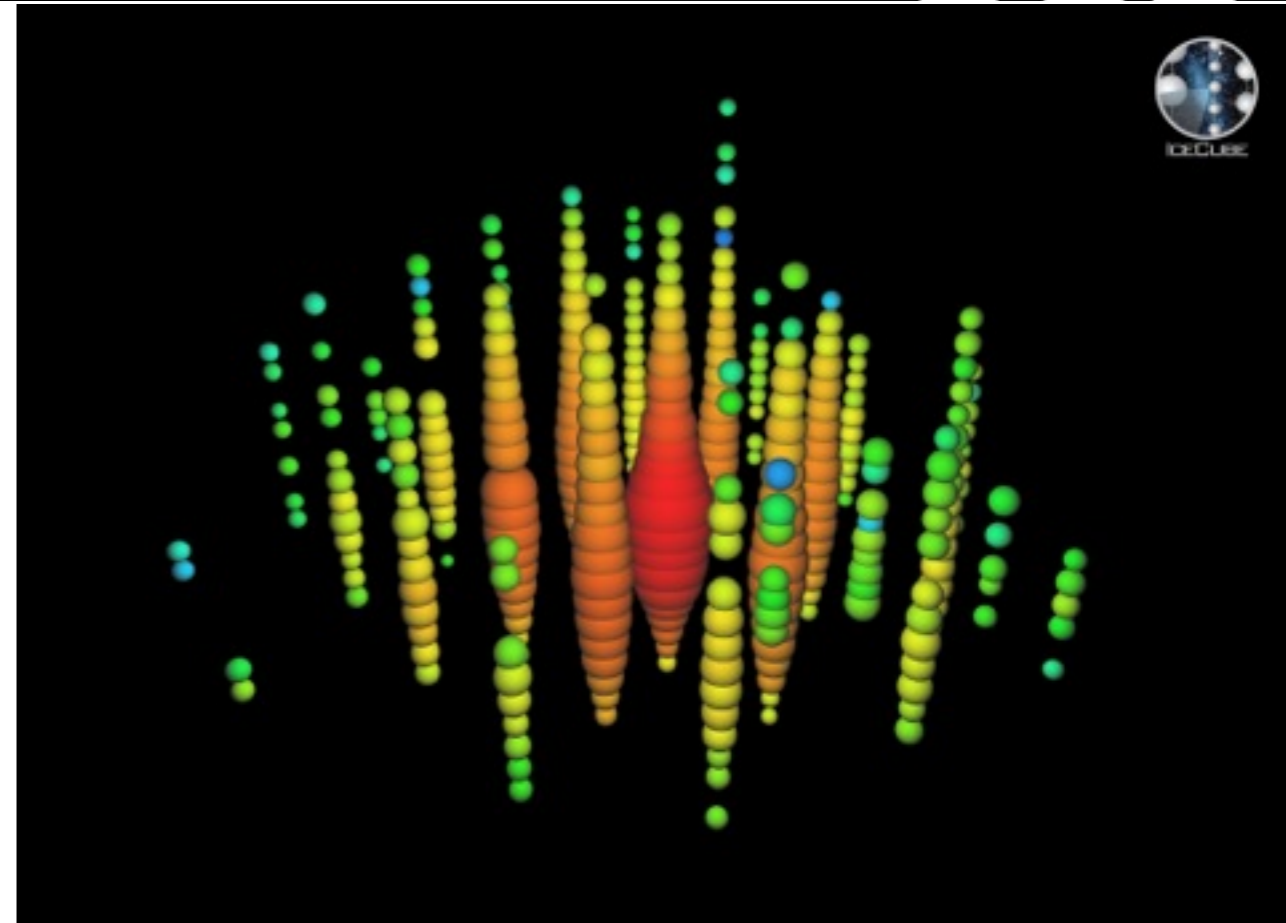
CC Tau Neutrino



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

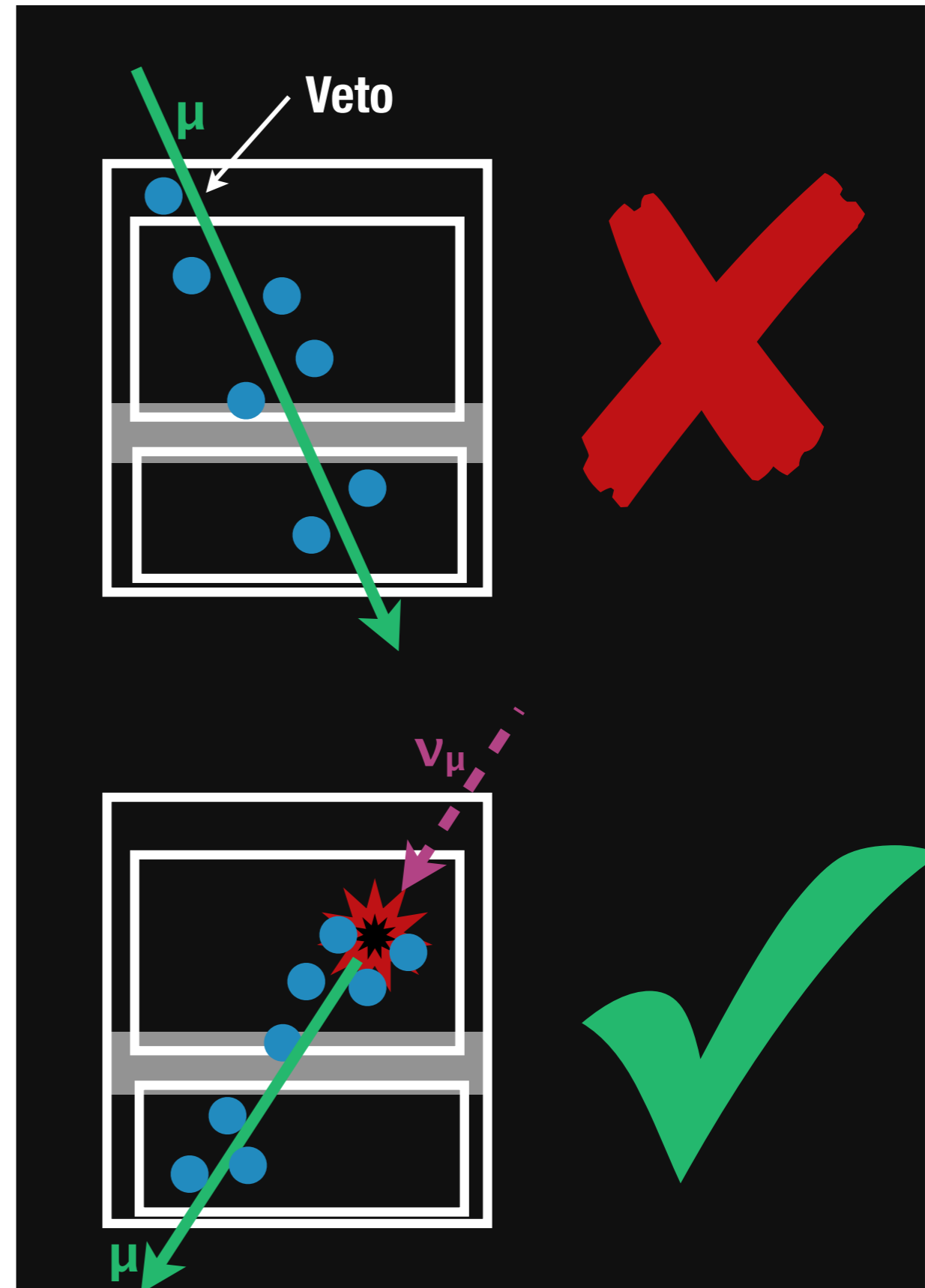
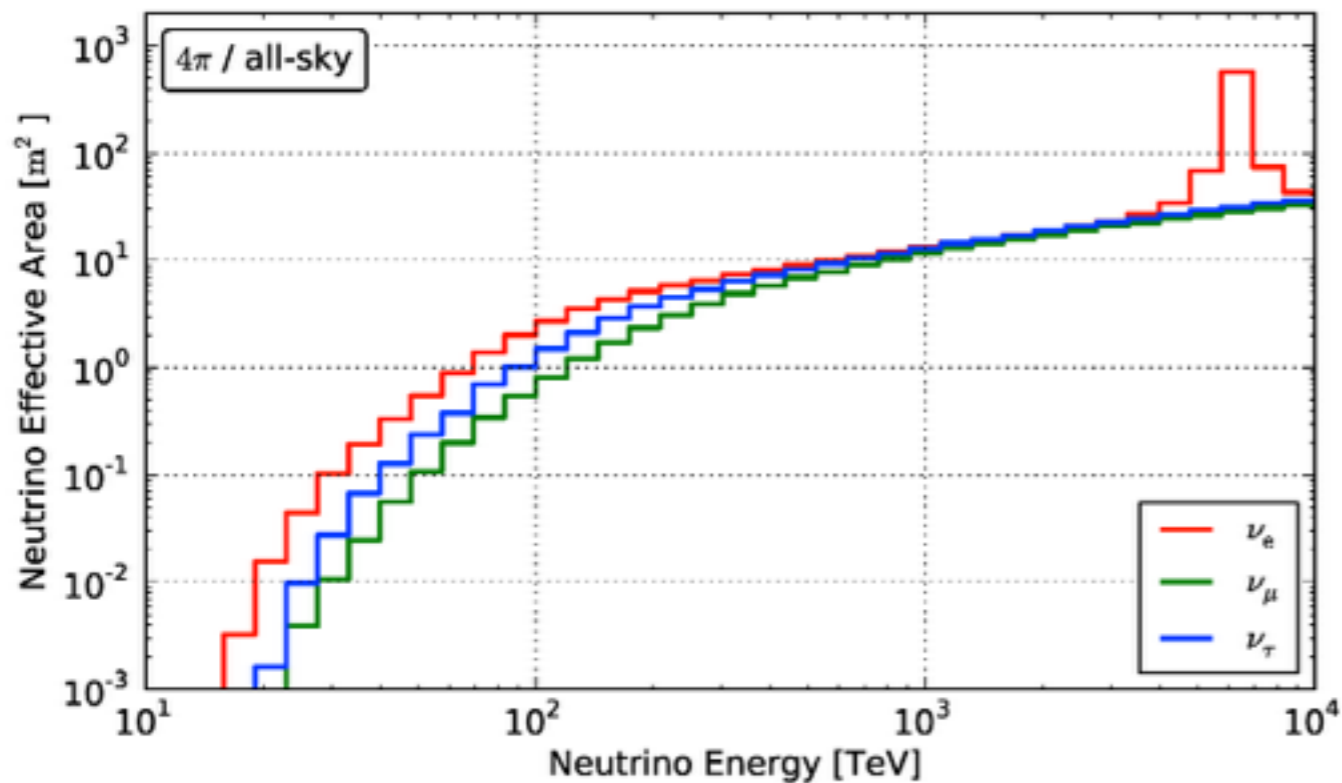
(not observed yet)

- A high energy search found two at threshold \sim PeV neutrino events
- Down-going events
- 2.8σ above background
- Too low in energy to be cosmogenic
- Too high in energy/flux to be atmospheric
- PRL 111, 021103 (2013)
- Clearly needed more statistics

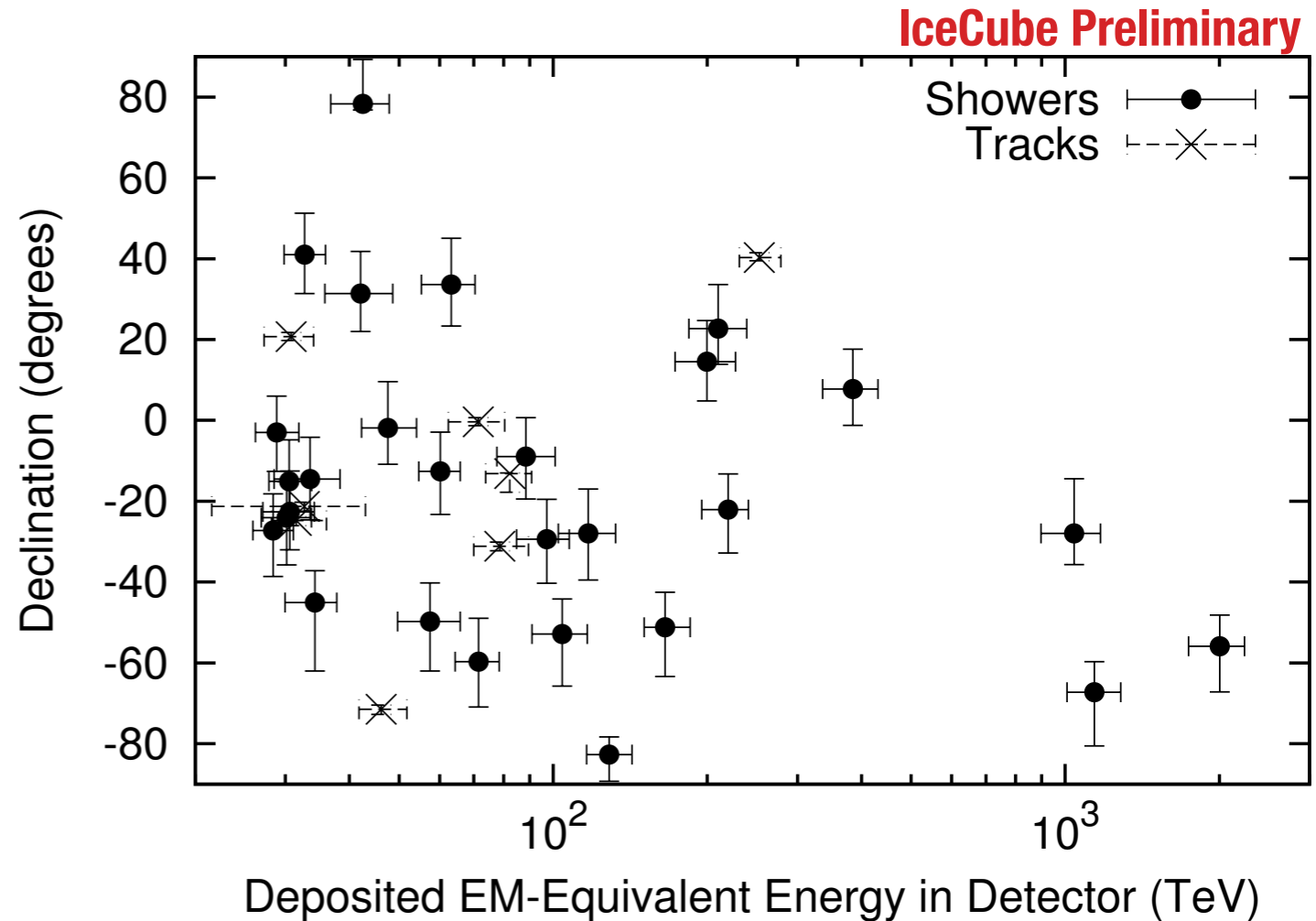


Contained Vertex Search

- Contained vertex search at high energies ($Q > 6000 \text{ P.E.}$)
- Veto atmospheric muons and muons associated with atmospheric neutrinos

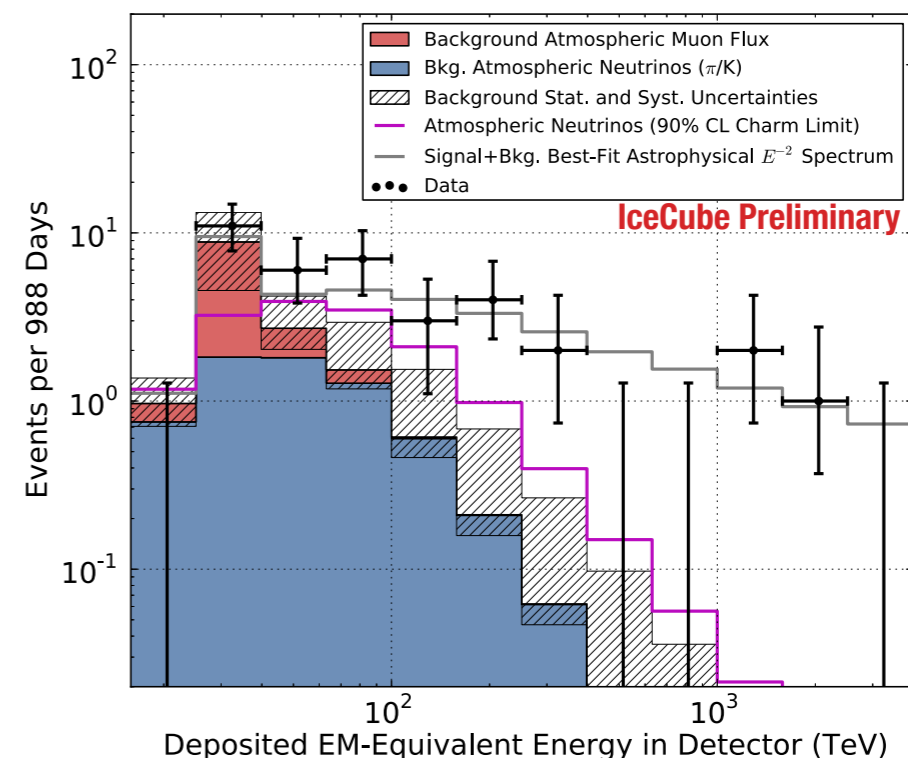
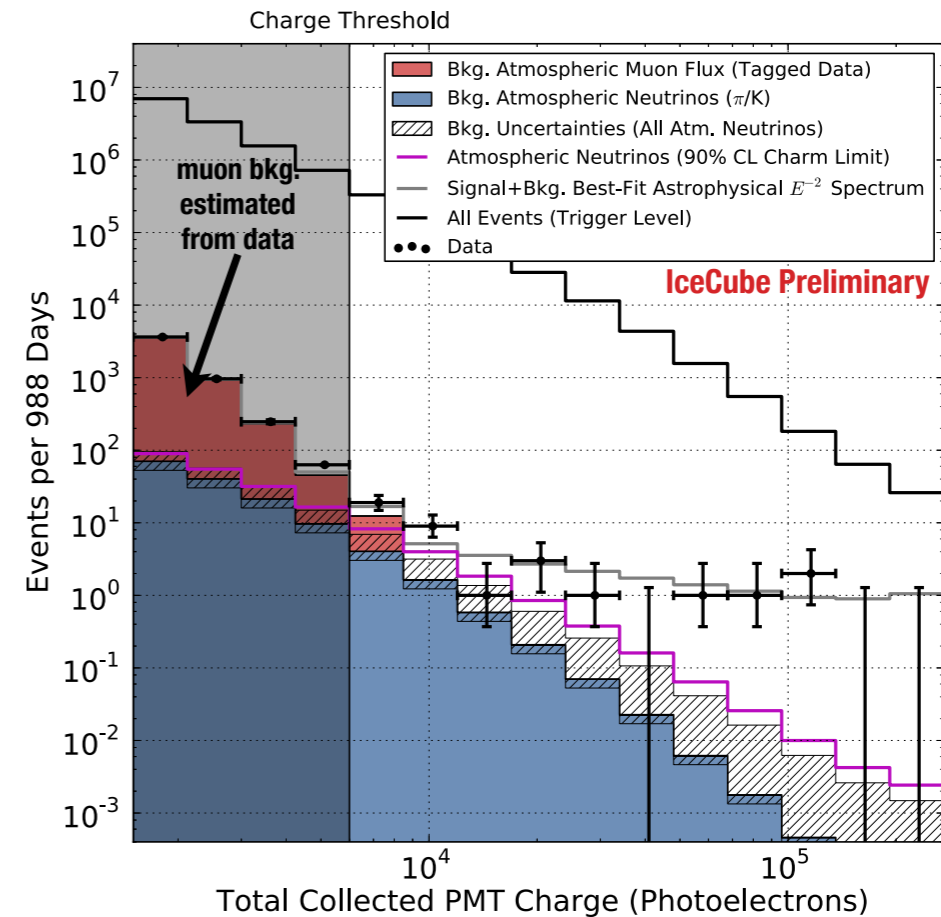


- Three years of data
 - 37 events observed
 - 35 new plus 2 PeV events
- Estimated backgrounds
 - Atm. neutrinos 6.6 (+5.9/-1.6)
 - Atm. muons 8.4 (± 4.2)
- One of the 37 events is a background from coincident muons from air showers



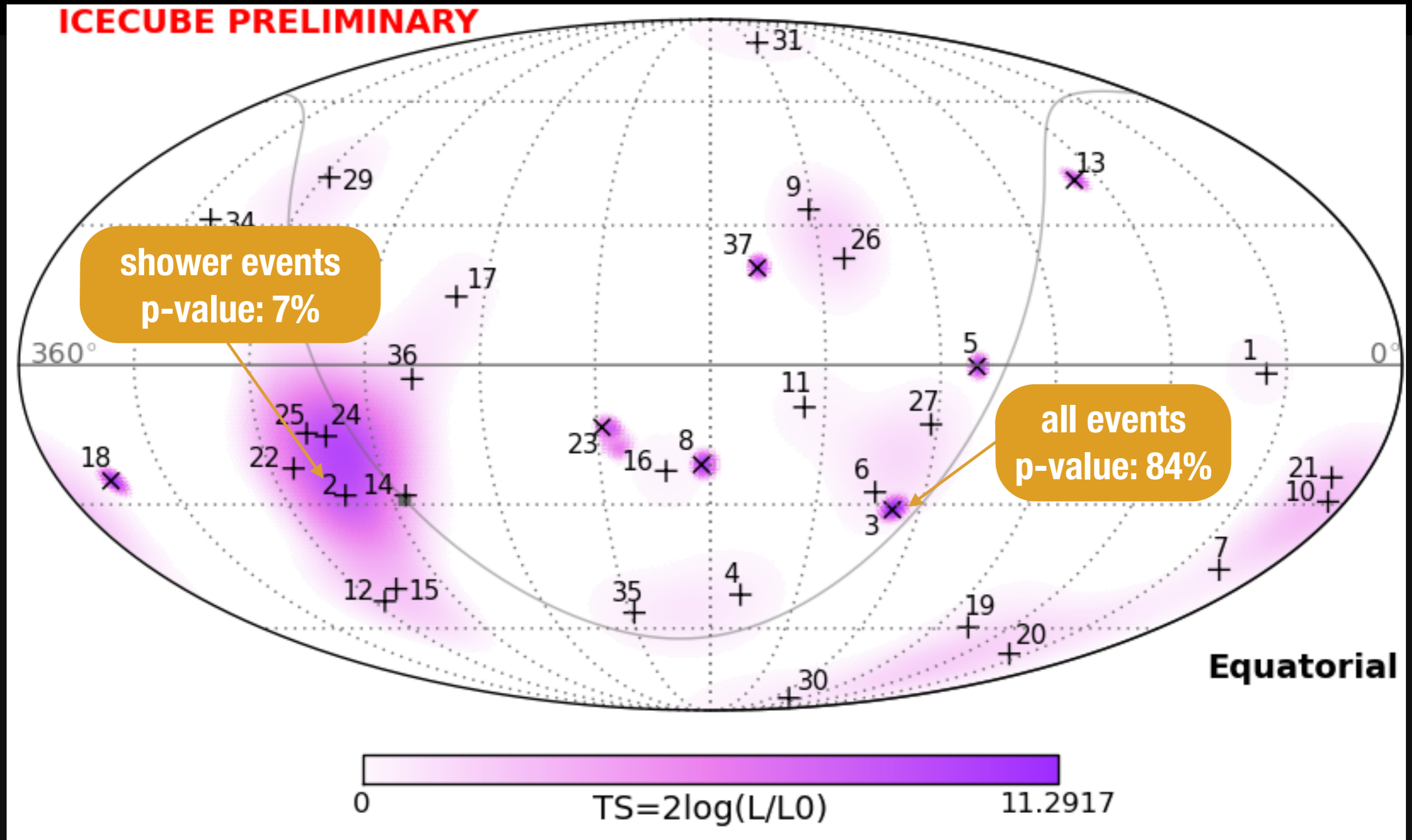
- Likelihood from background
 - 4.8σ for 35+2 events
 - 5.7σ for 36(+1) events from “full likelihood”

- The data fits well to the tagged atmospheric muon data (red) below threshold
- Hatched region indicates uncertainties in conventional and charm atmospheric neutrinos
- Clear excess of events at high energy that merges into the atmospheric background
- Best-fit per-flavour flux
 $- 0.95 \pm 0.3 \times 10^{-8} E^{-2} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$



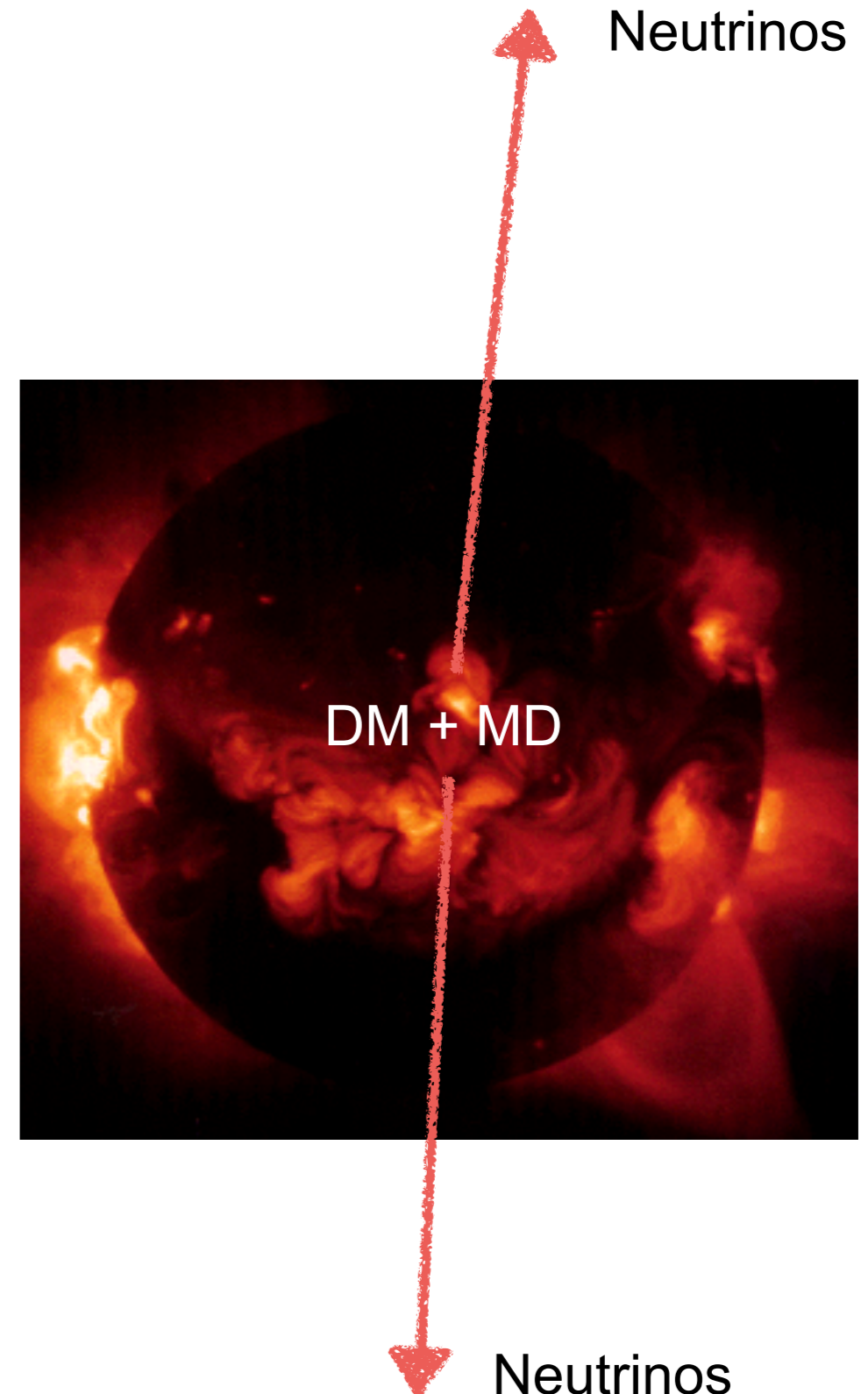
Skymap / Clustering

No significant clustering observed (three years)



(all p-values are post-trial)

- Searches for point sources and anisotropy
- Various WIMP searches
 - Solar
 - Galactic centre
 - Galactic Halo
 - Dwarf spheroids
 - Galaxy Clusters
 - See C. Kooper Moriond 2014 and references therein
- Neutrinos from gamma ray bursts
- Monopole searches
- First neutrino oscillation measurements

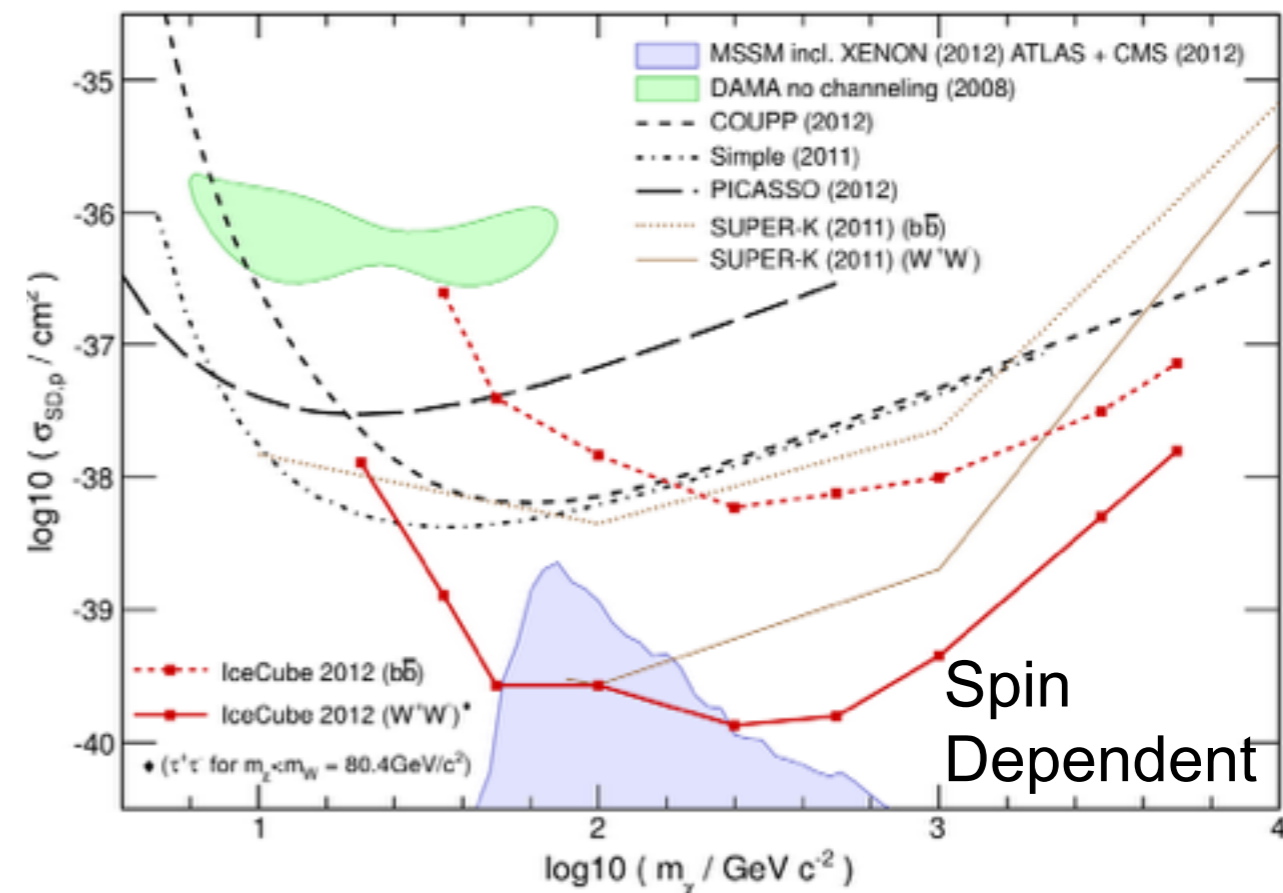
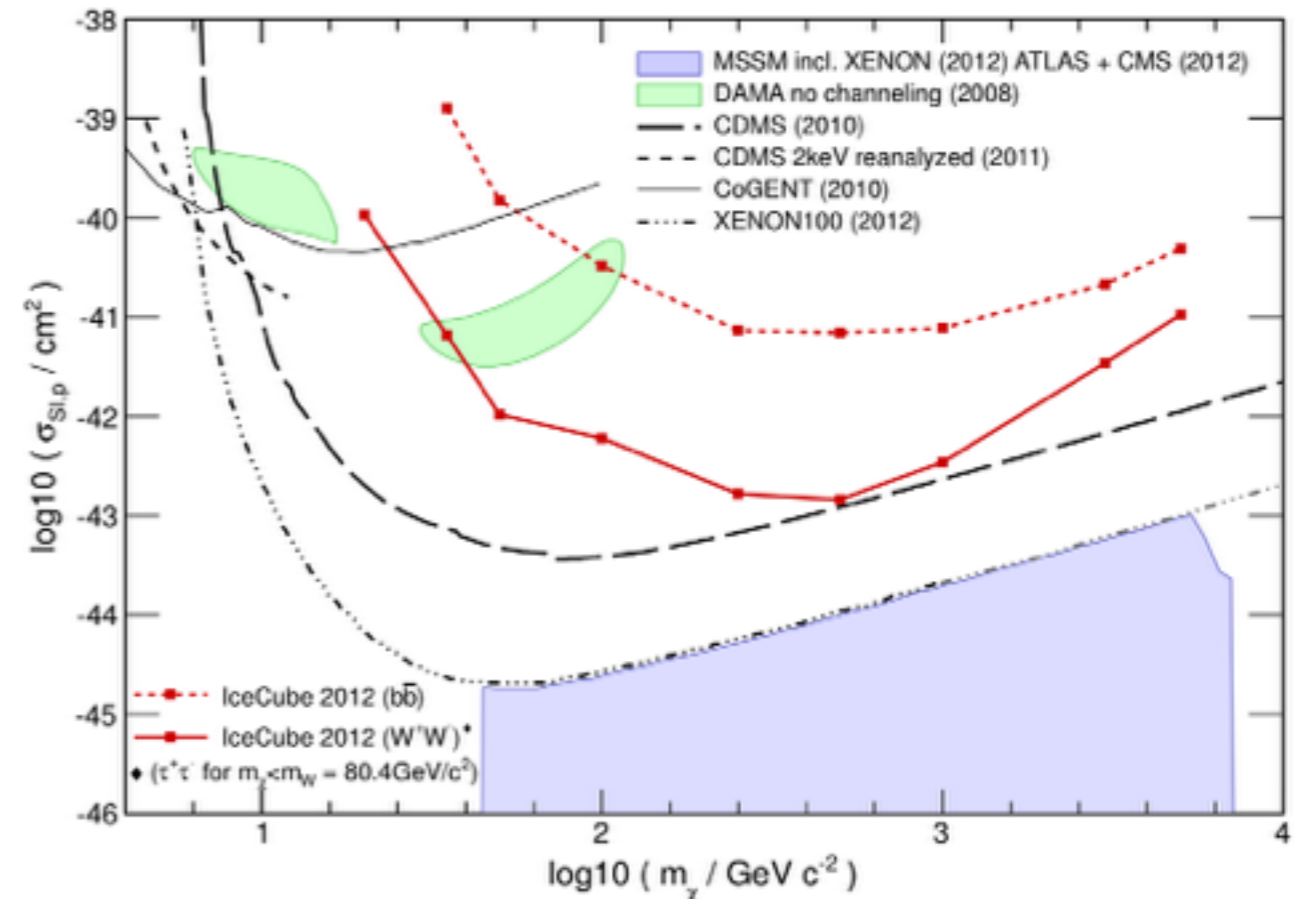


Other IceCube Highlights

- Searches for point sources and anisotropy
- Various WIMP searches
 - Solar
 - Galactic centre
 - Galactic Halo
 - Dwarf spheroids
 - Galaxy Clusters

• See C. Kooper Moriond 2014 and references therein

- Neutrinos from gamma ray bursts
- Monopole searches
- First neutrino oscillation measurements



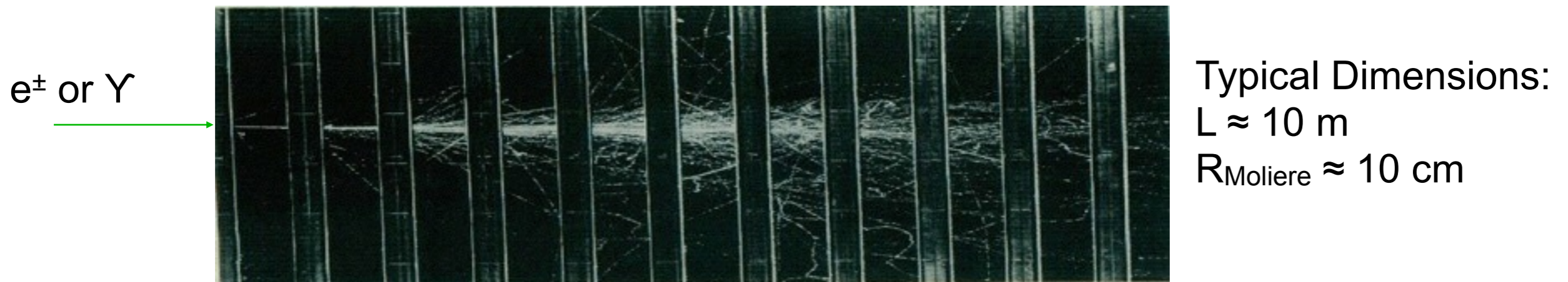


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ANITA & ARA



- In 1962 Gurgun Askaryan hypothesised coherent radio transmission from EM cascades in a dielectric:



–20% Negative charge excess:

- Compton Scattering: $\gamma + e^-_{(\text{rest})} \Rightarrow \gamma + e^-$

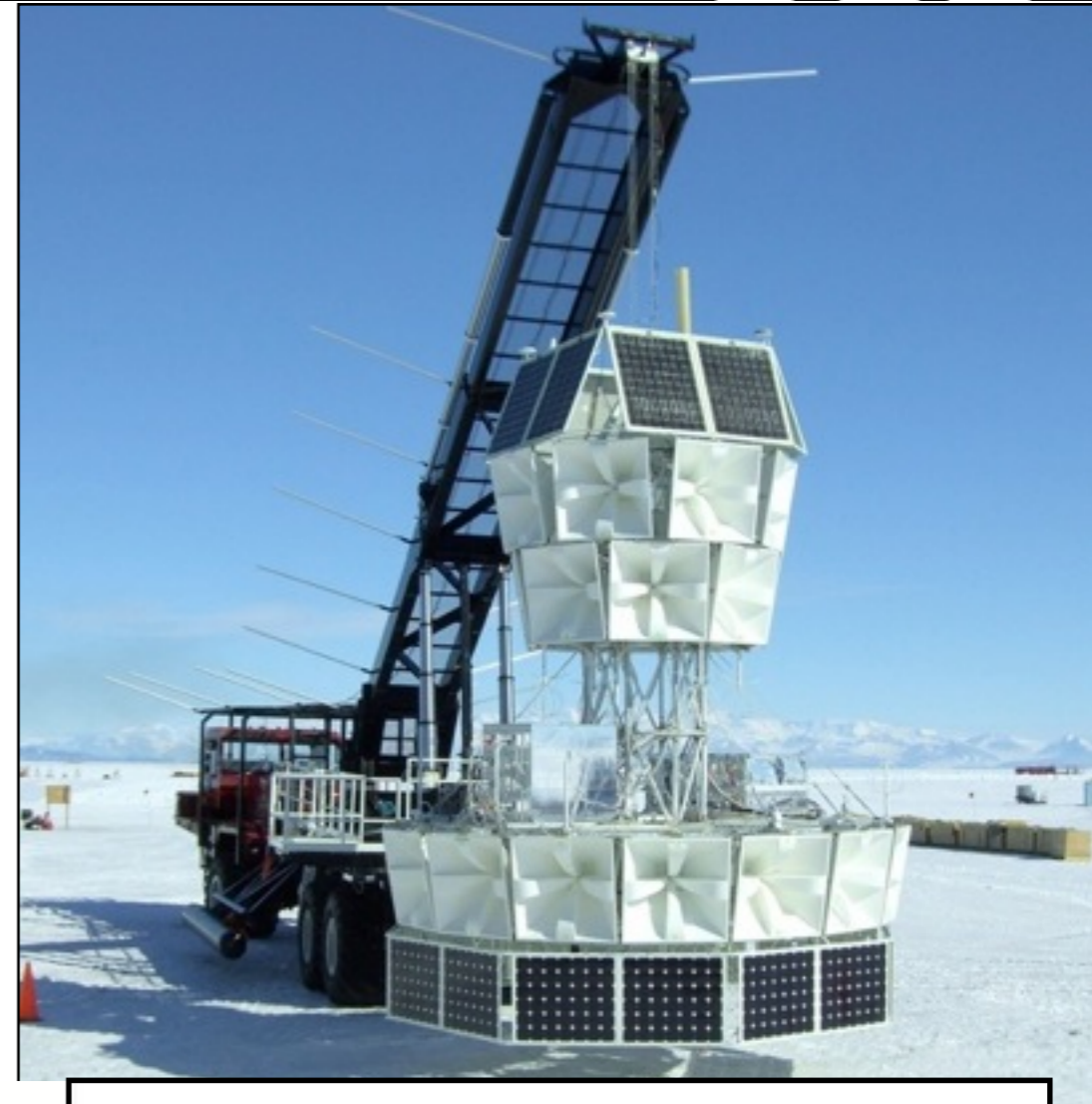
- Positron Annihilation: $e^+ + e^-_{(\text{rest})} \Rightarrow \gamma$

–Excess travelling with, $v > c/n$

- Cherenkov Radiation: $dP \propto \nu d\nu$

–For $\lambda > R$ emission is coherent, so $P \propto E^2_{\text{shower}}$

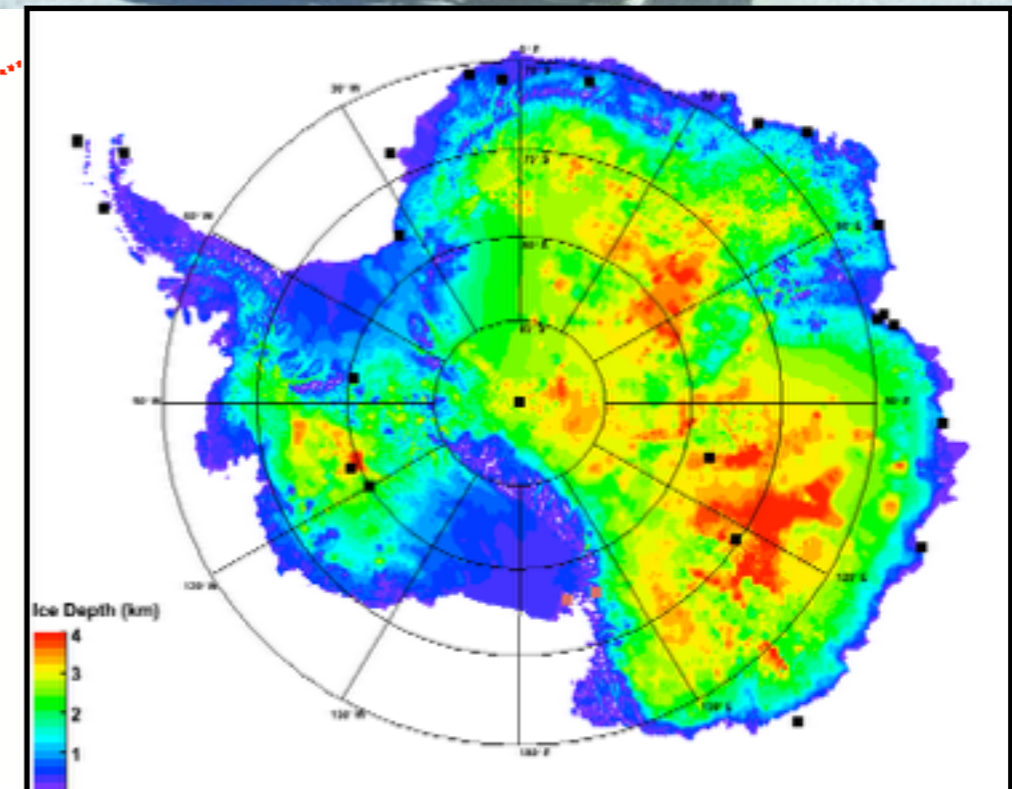
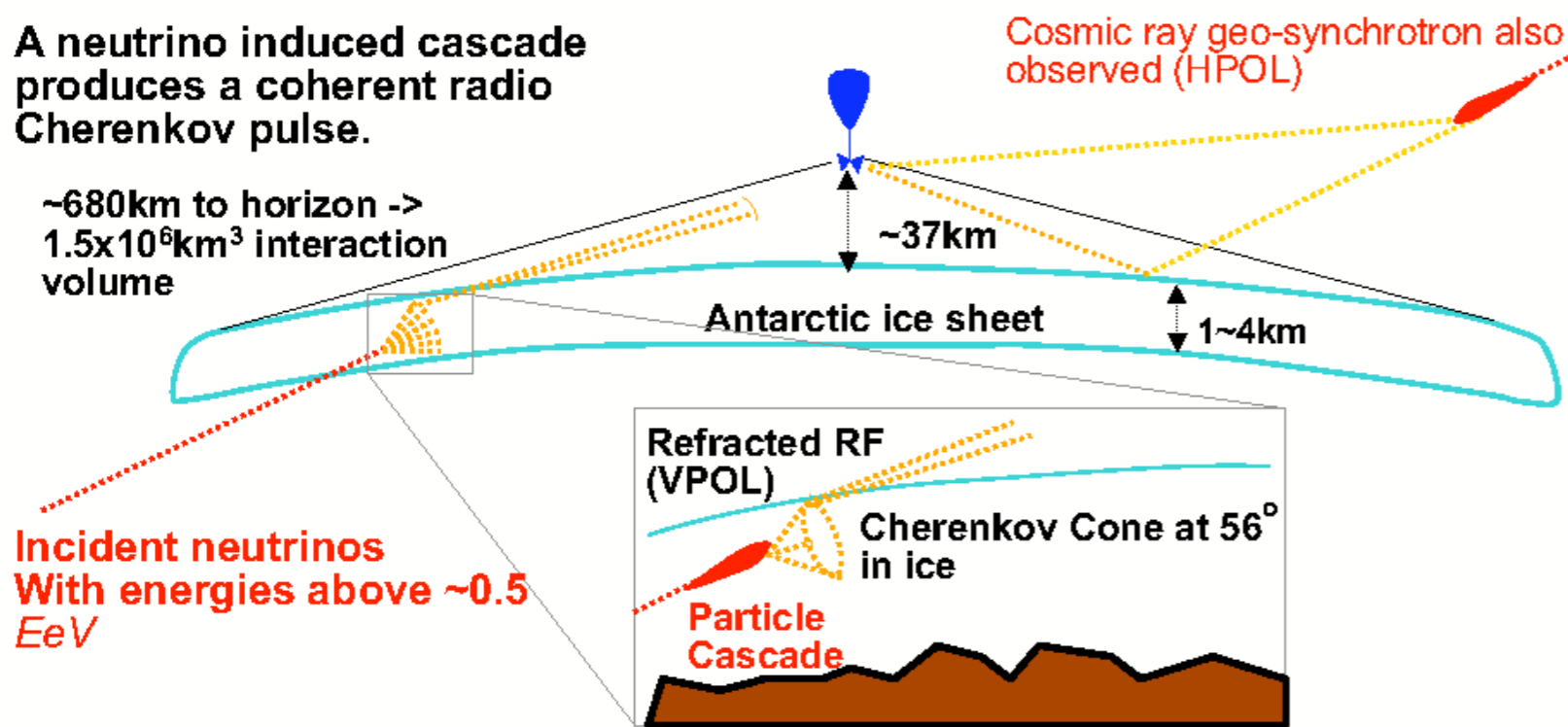
- A balloon borne experiment
 - 40 dual polarisation antennas
 - Altitude of 37km (120,000 ft)
 - Horizon at 700km
 - Over 1 million km³ of ice visible
- Sensitive to ultra-high energy neutrinos interacting in the ice and cosmic ray air showers
- Third flight schedule for December 2014



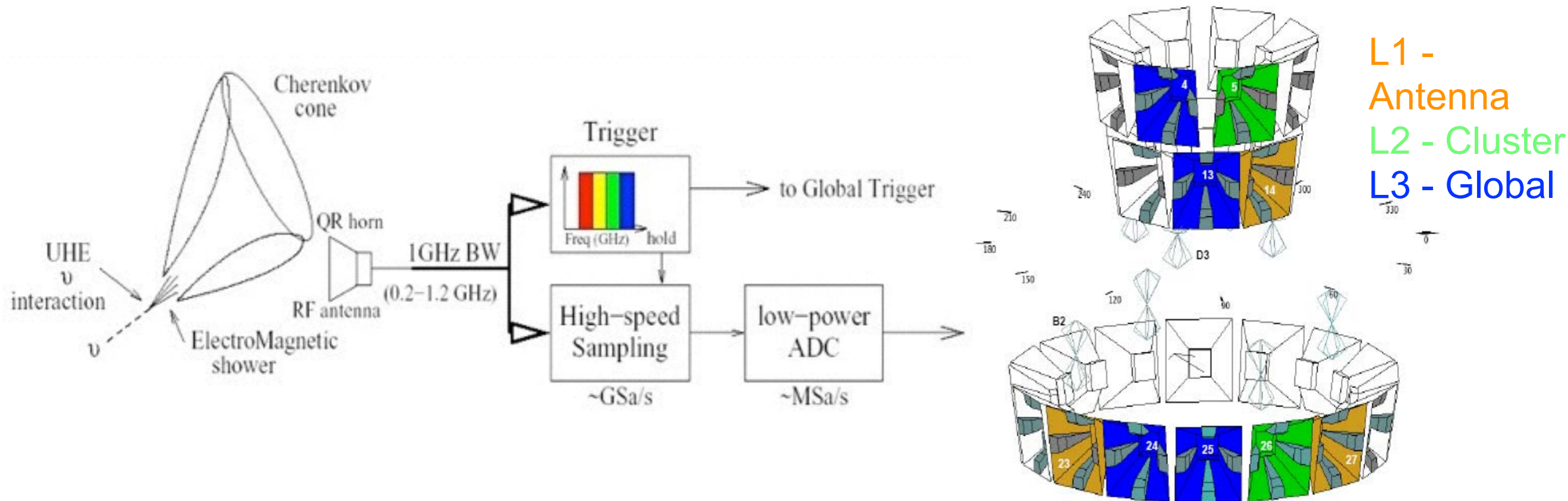
A neutrino induced cascade produces a coherent radio Cherenkov pulse.

~680km to horizon -> 1.5x10⁶km³ interaction volume

Cosmic ray geo-synchrotron also observed (HPOL)

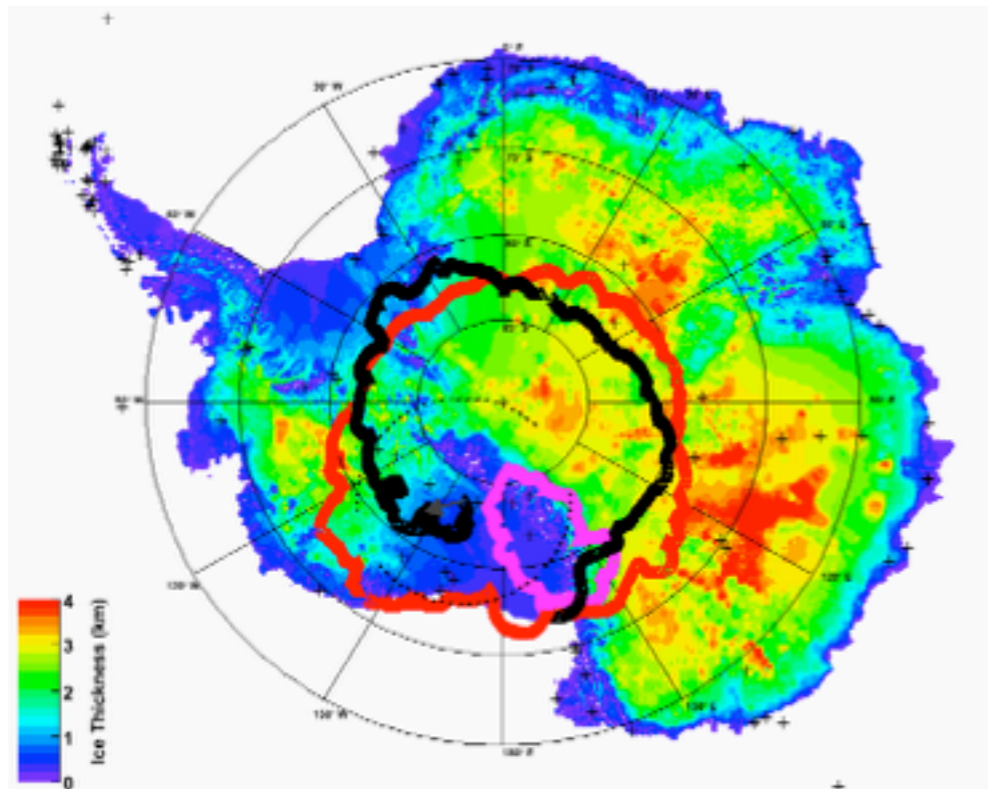
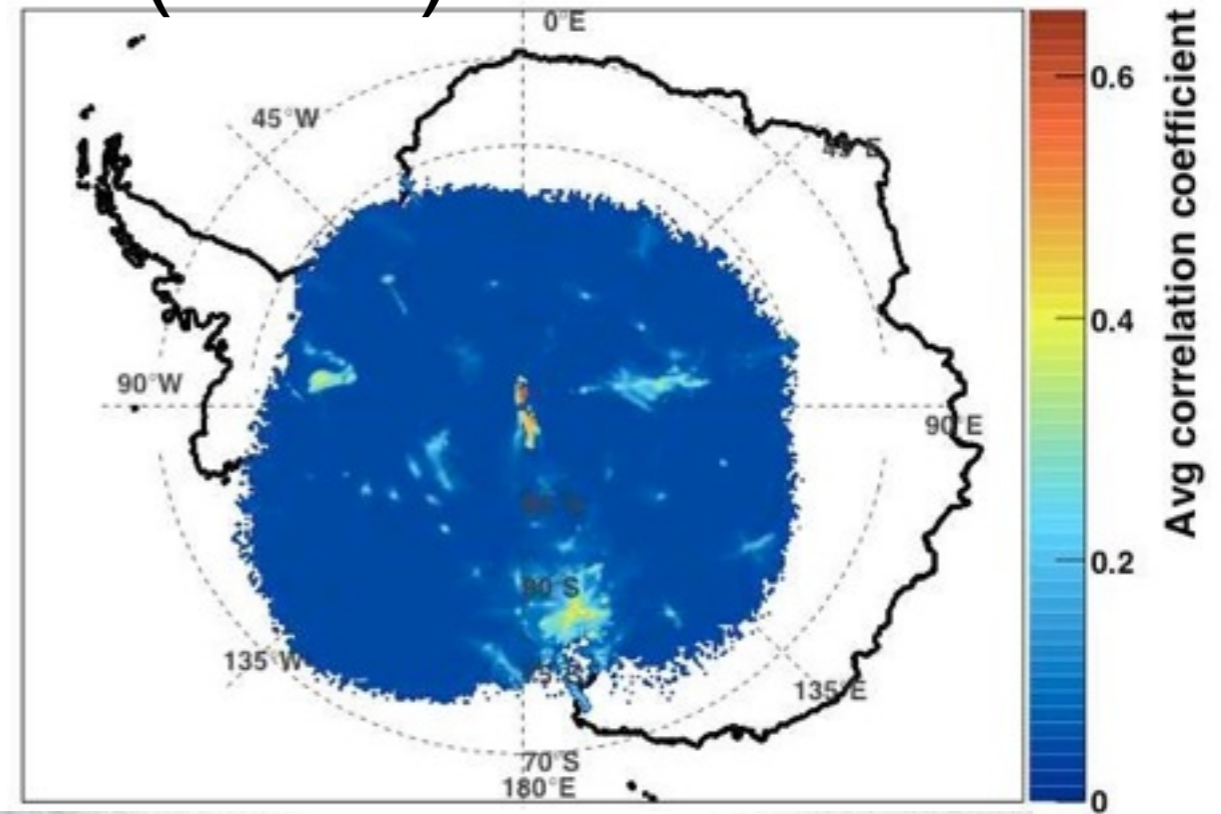
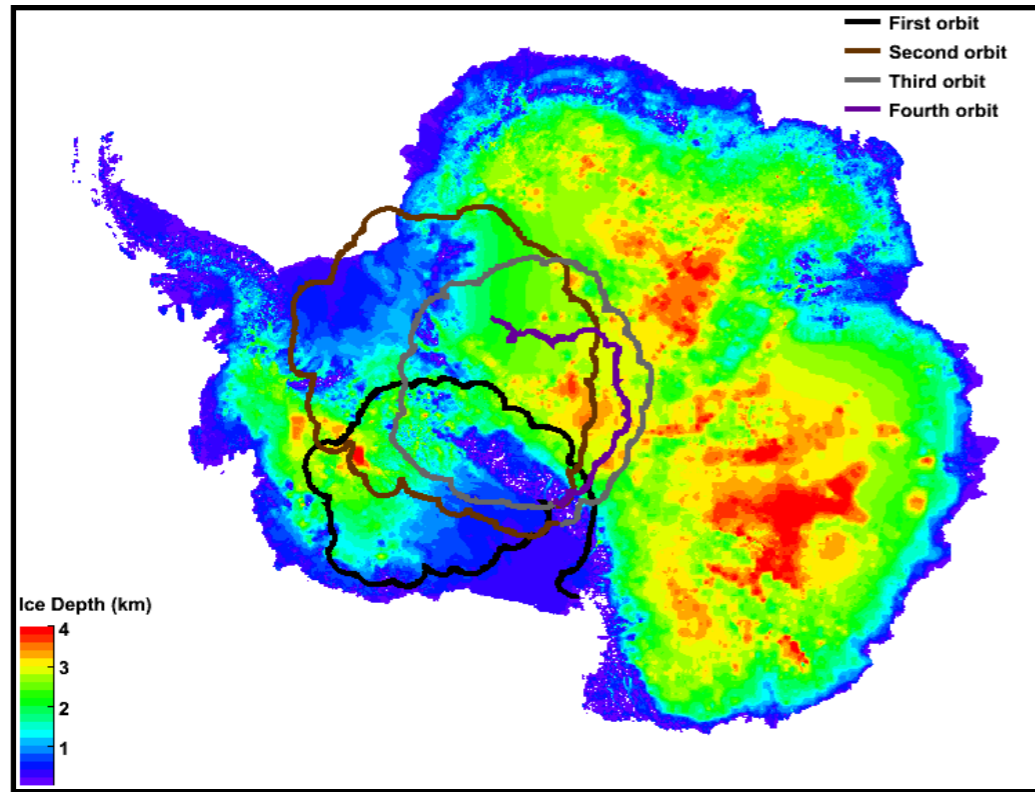


- Need a low power (only solar energy), 90 channel, GHz bandwidth oscilloscope.

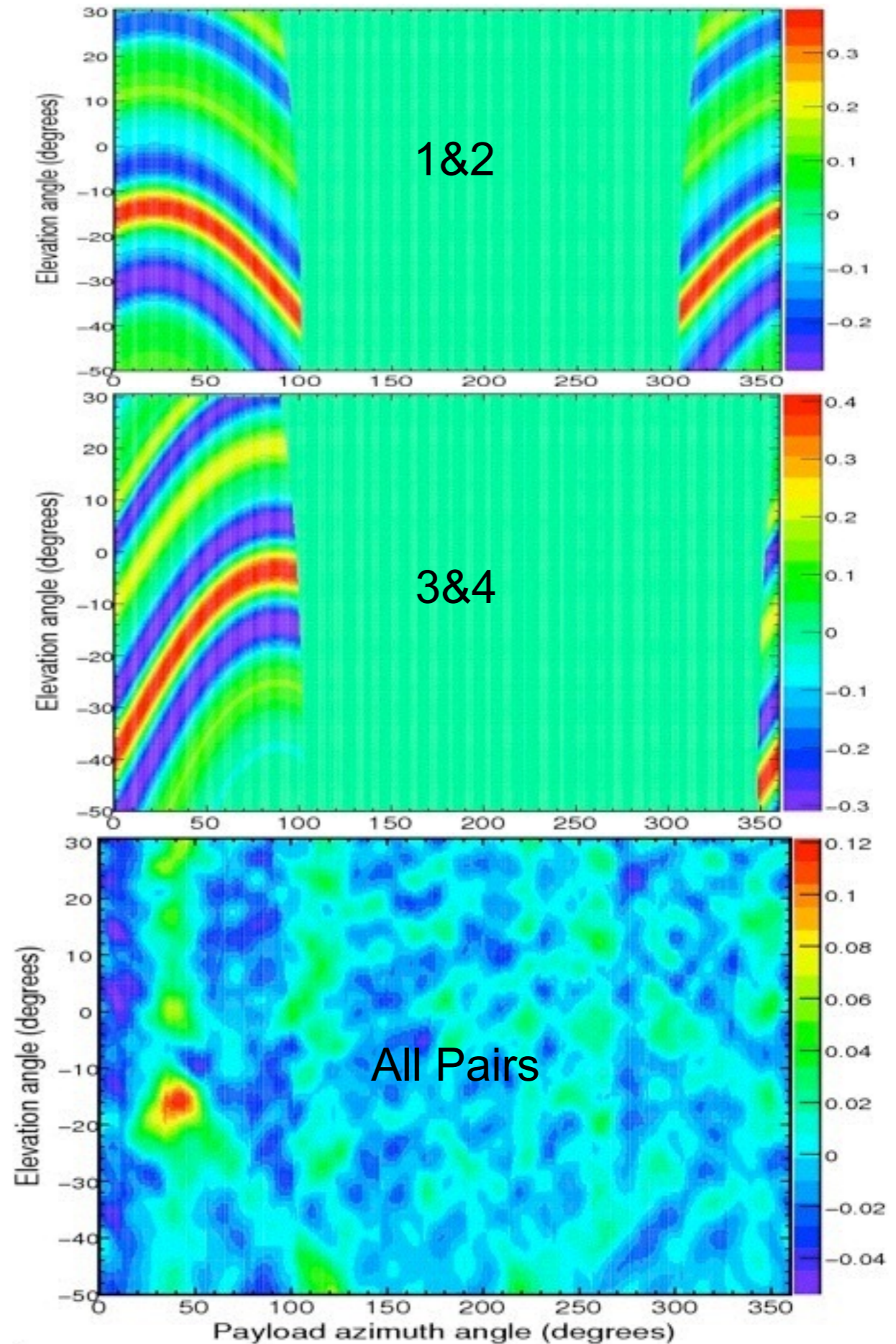
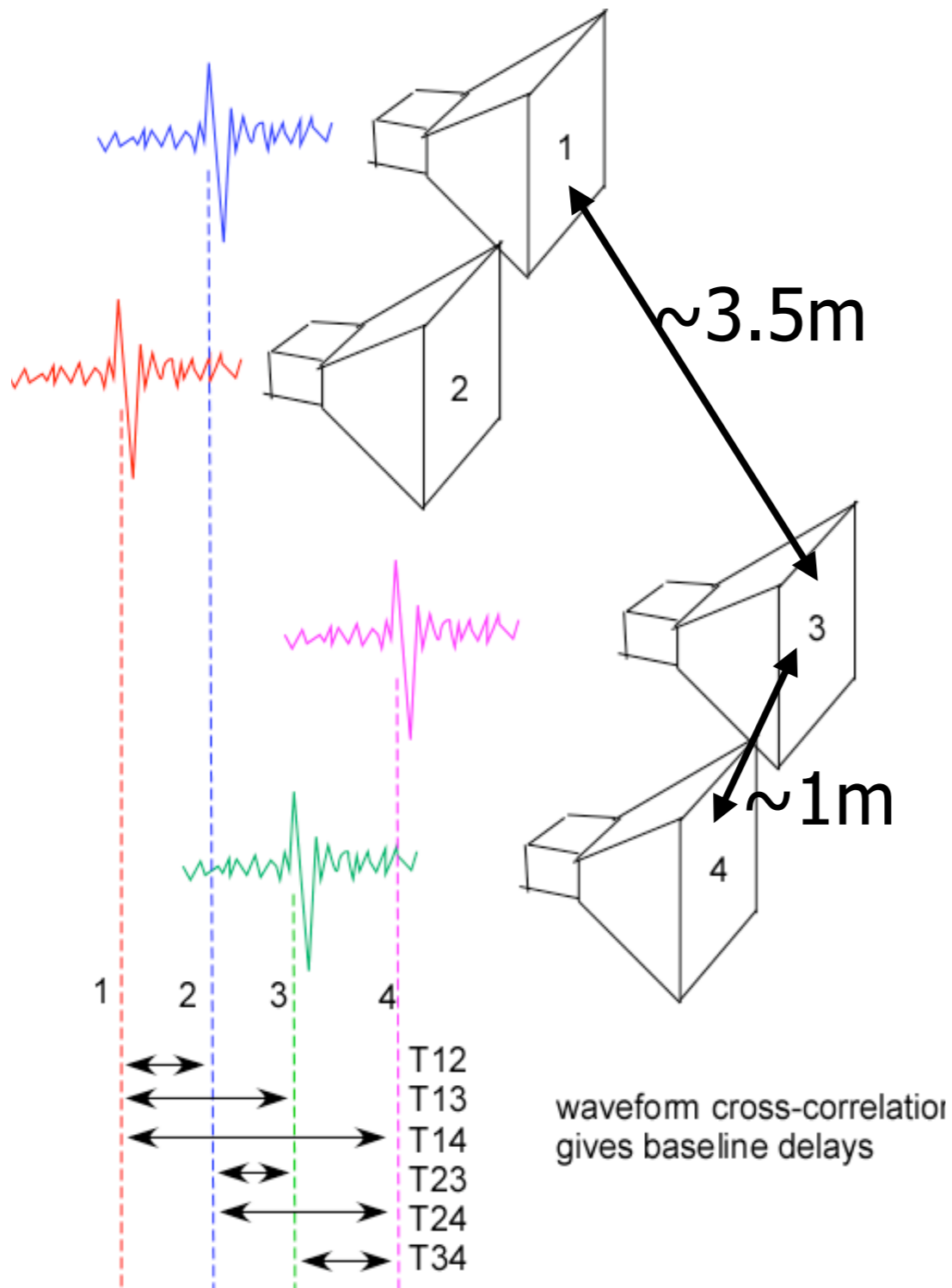


- Split trigger and waveform paths
- Trigger based on 3-bit digitisation and correlation
- Buffer waveform data in switched capacitor array
- Only digitise when we have a trigger
- A GPU-based high-level software trigger

- Over 65 days of flight over Antarctica
- Over 35 million triggered (noise) events



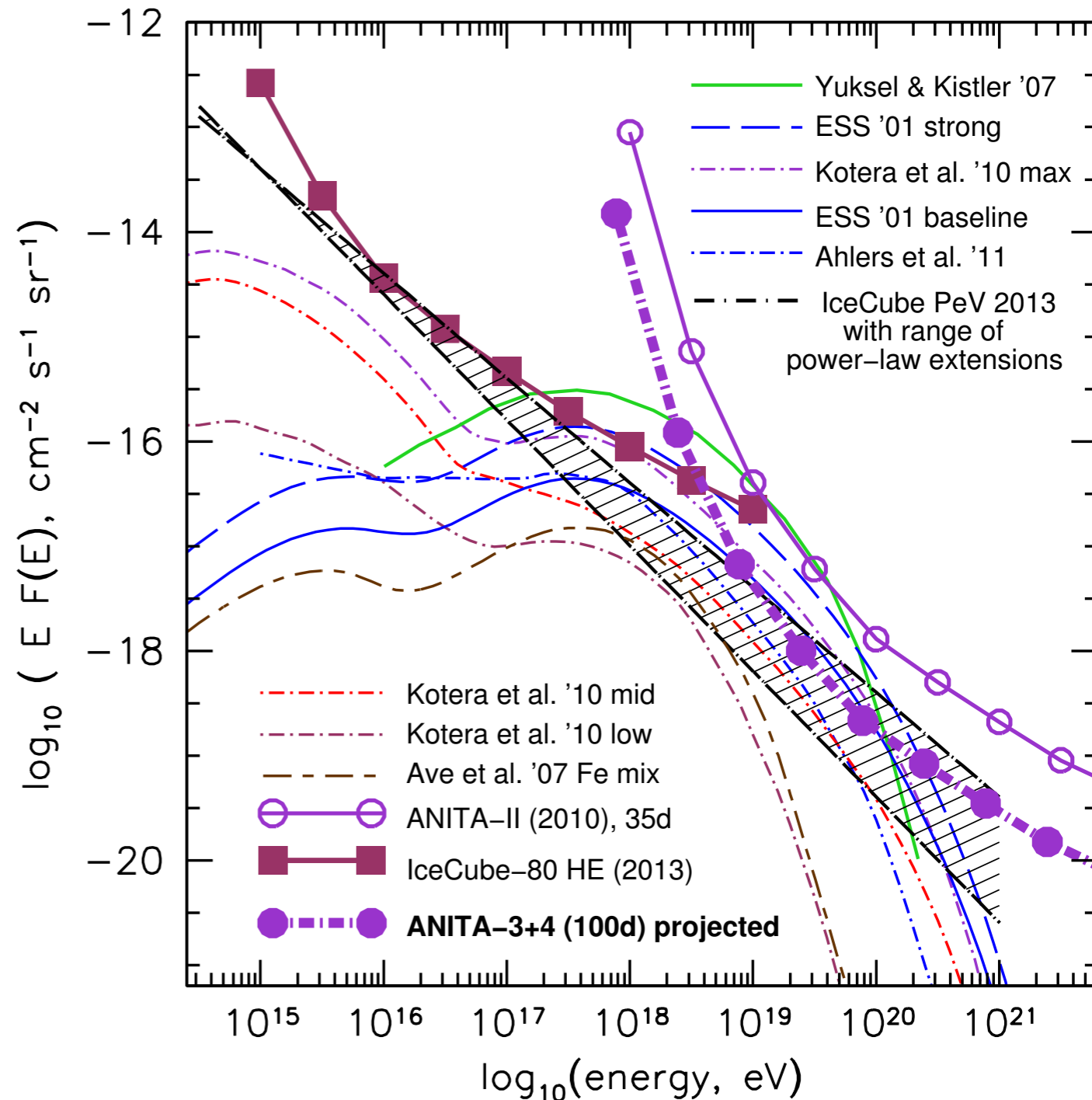
Analysis -- Cross Correlation



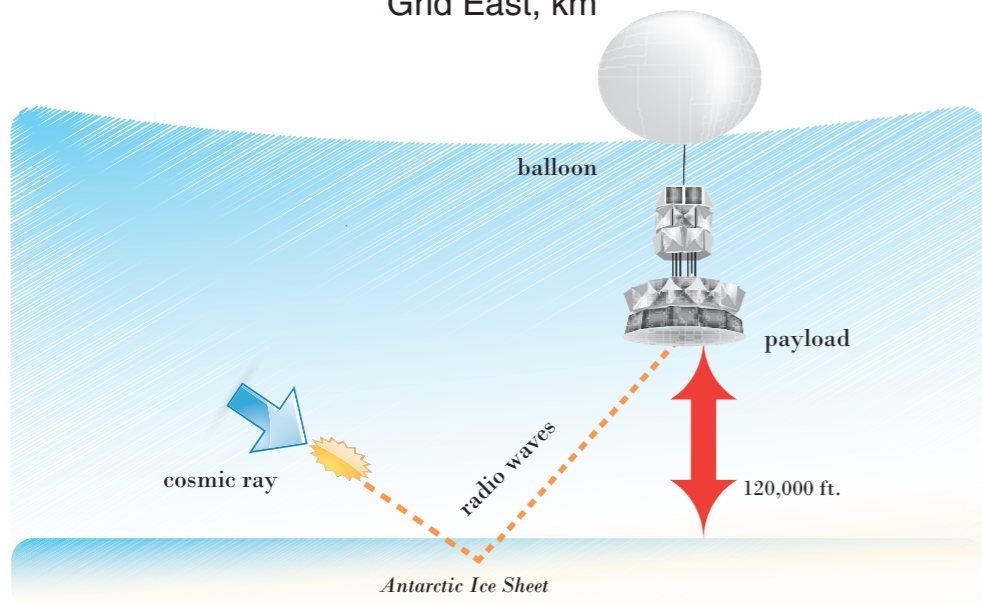
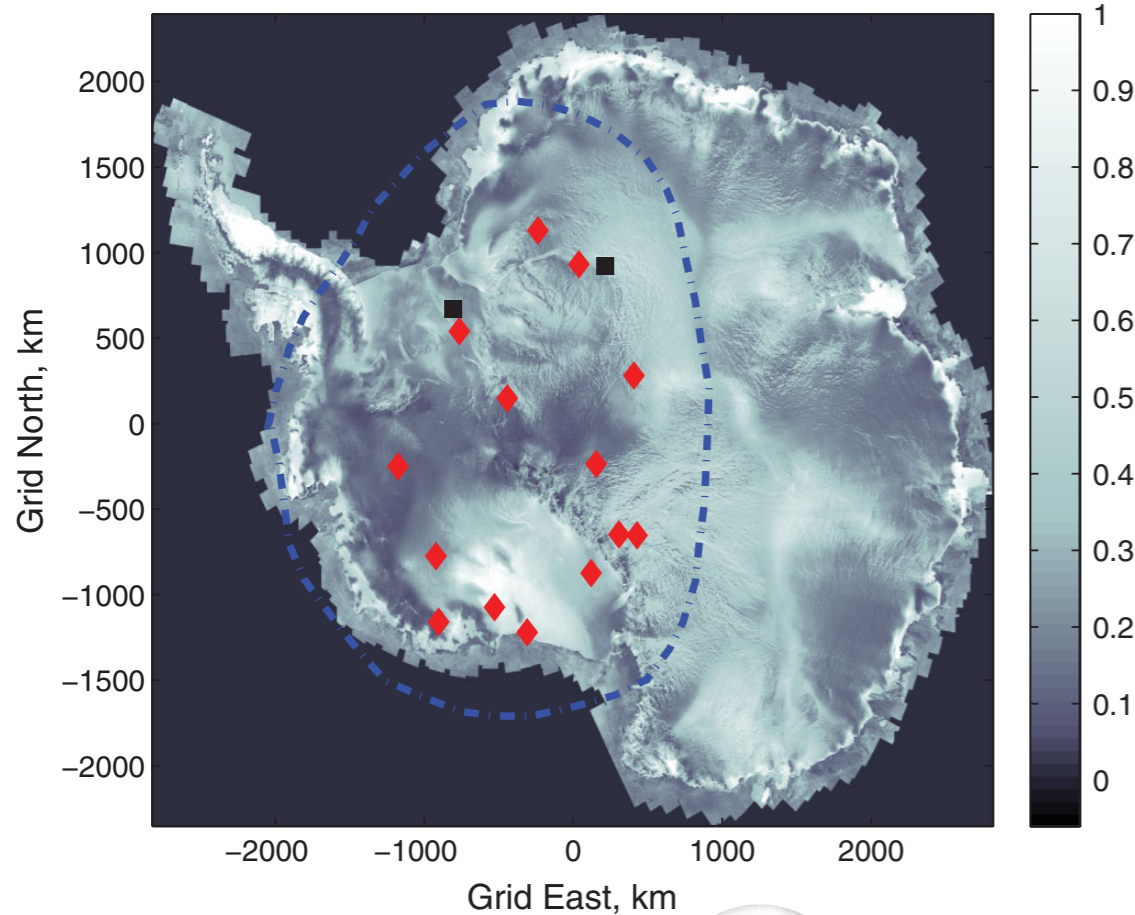
• ANITA-2 Results

Isolated ν -pol events	1
Expected background events	0.97 ± 0.42

- Combine with efficiency to extract world's best limit on UHE neutrino flux above 10^{19} eV
- Many improvements for ANITA-3, including new GPU high level trigger
 - UK responsibility



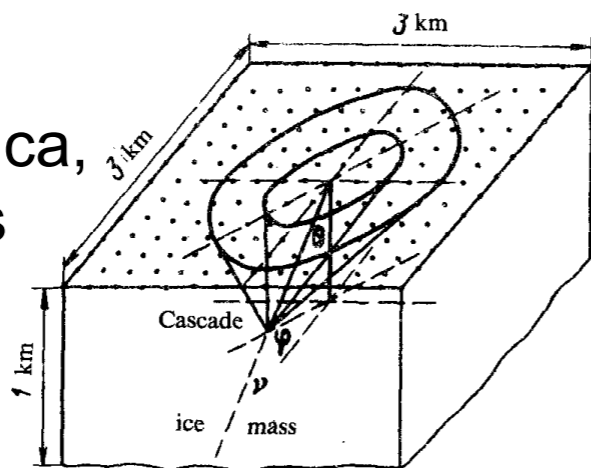
PRL 105, 151101 (2010)



- A combination of $v \times B$ and Fresnel coefficients result in air shower emission being horizontally polarised at the payload
- ANITA-I detected 16 isolated H-pol candidate UHECR events
- ANITA-II did not trigger on the H-pol channels
–Doh!!
- Still detected 5 UHECR candidate events

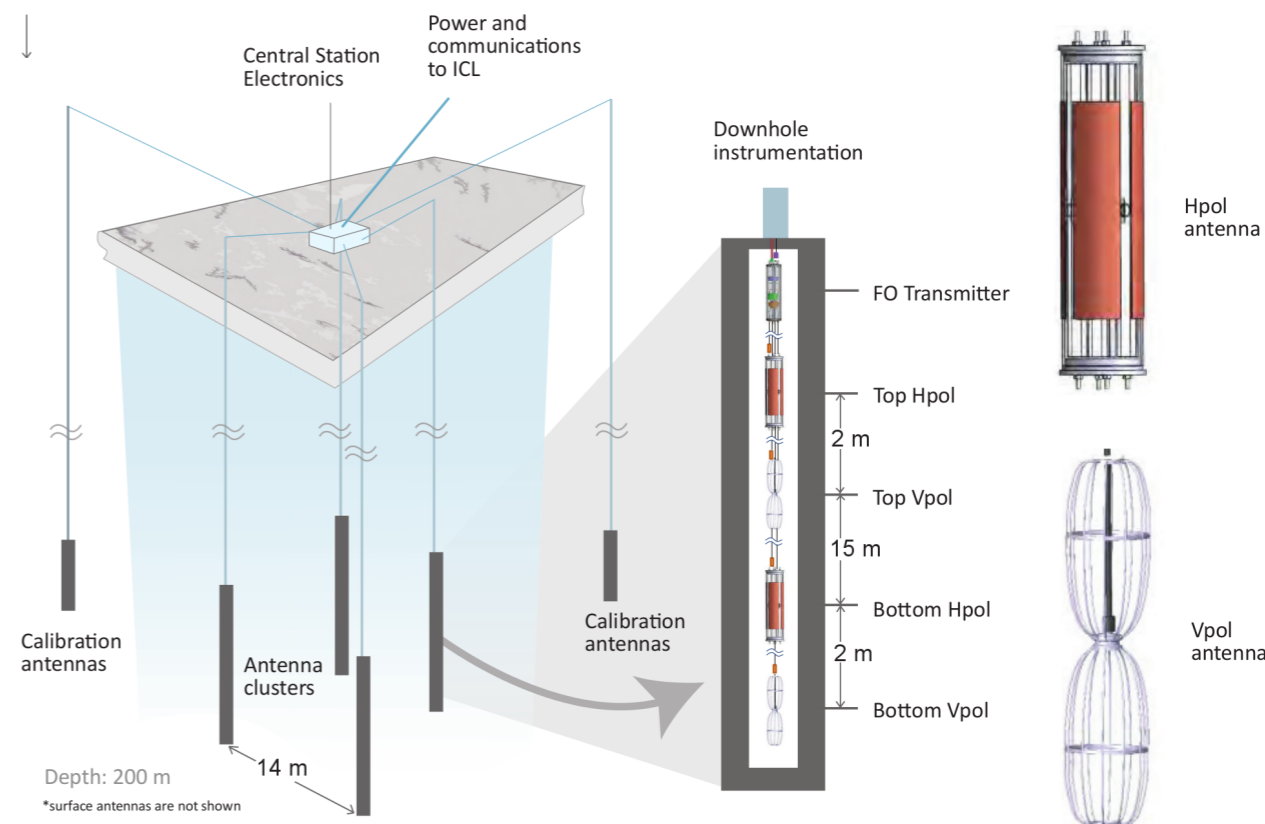
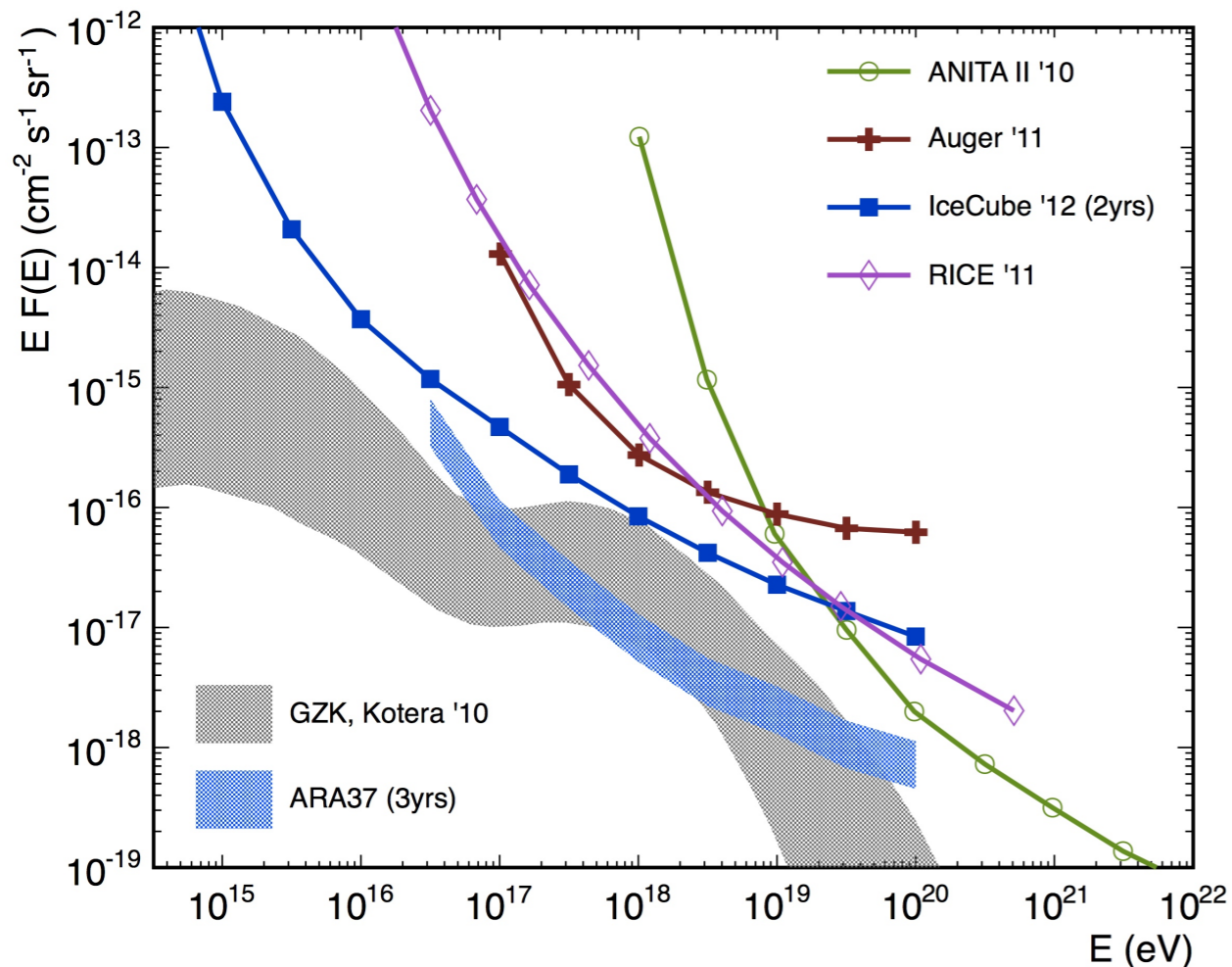
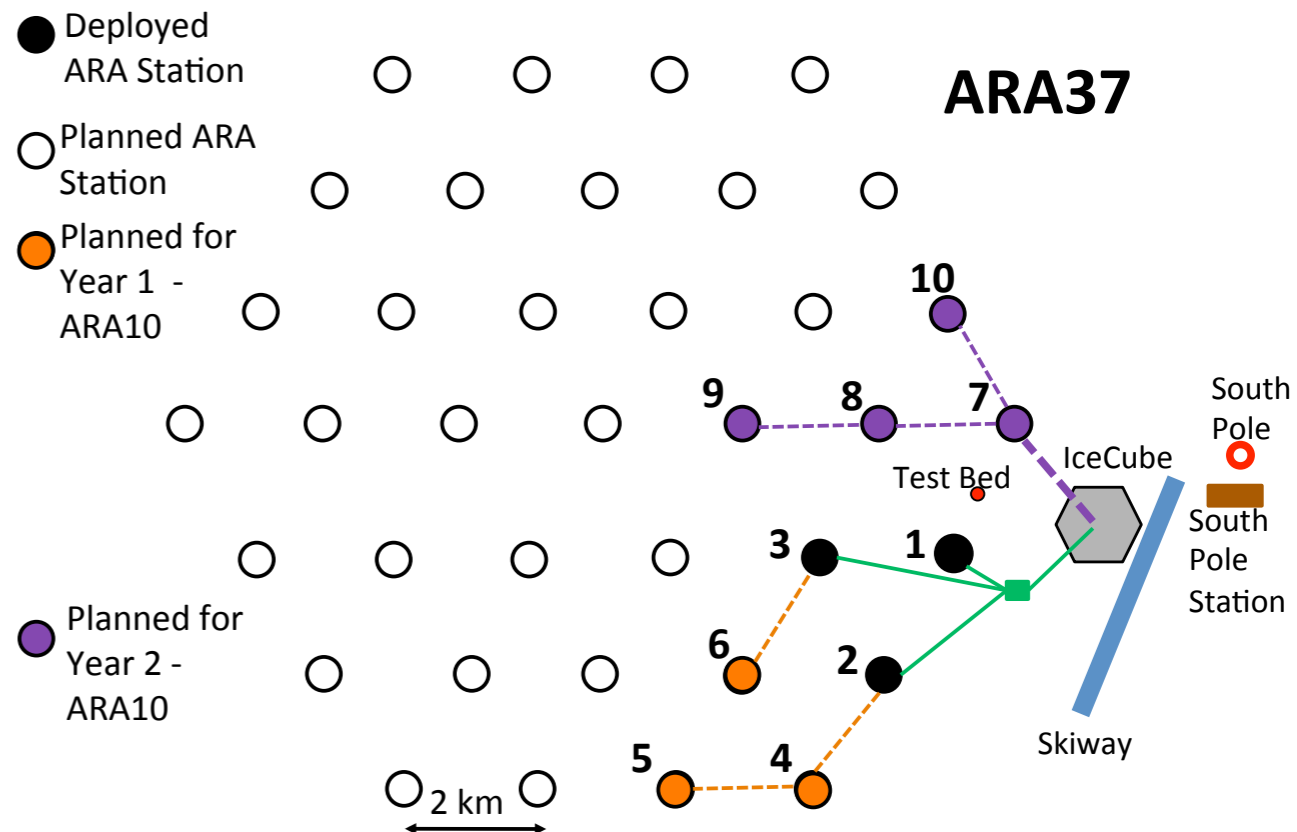
Askaryan Radio Array

Radio array in Antarctica, proposed in the 1980s



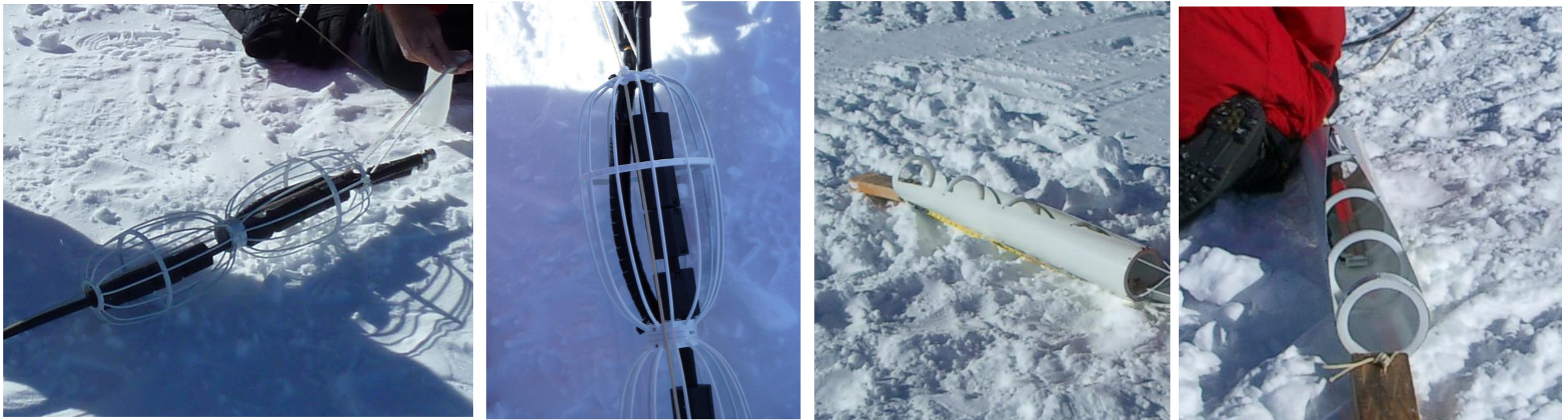
Neutrino and muon detection from the radio-emission of cascades created by them in natural dielectric media

G. A. Gusev and I. M. Zheleznykh
 Institute of Nuclear Research, Academy of Sciences of the USSR
 (Submitted 27 September 1983)
 Pis'ma Zh. Eksp. Teor. Fiz. **38**, No. 10, 505–507 (25 November 1983)

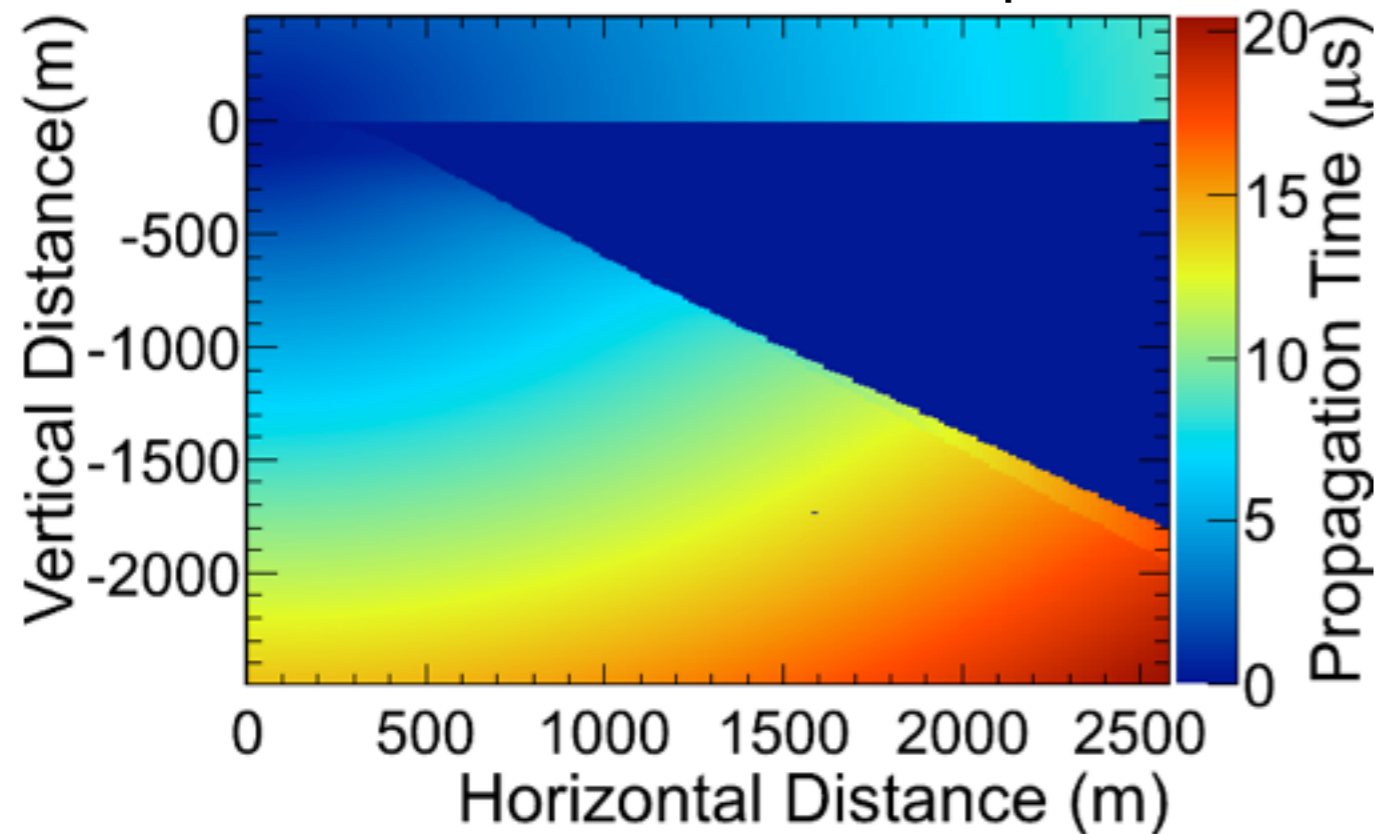


Askaryan Radio Array

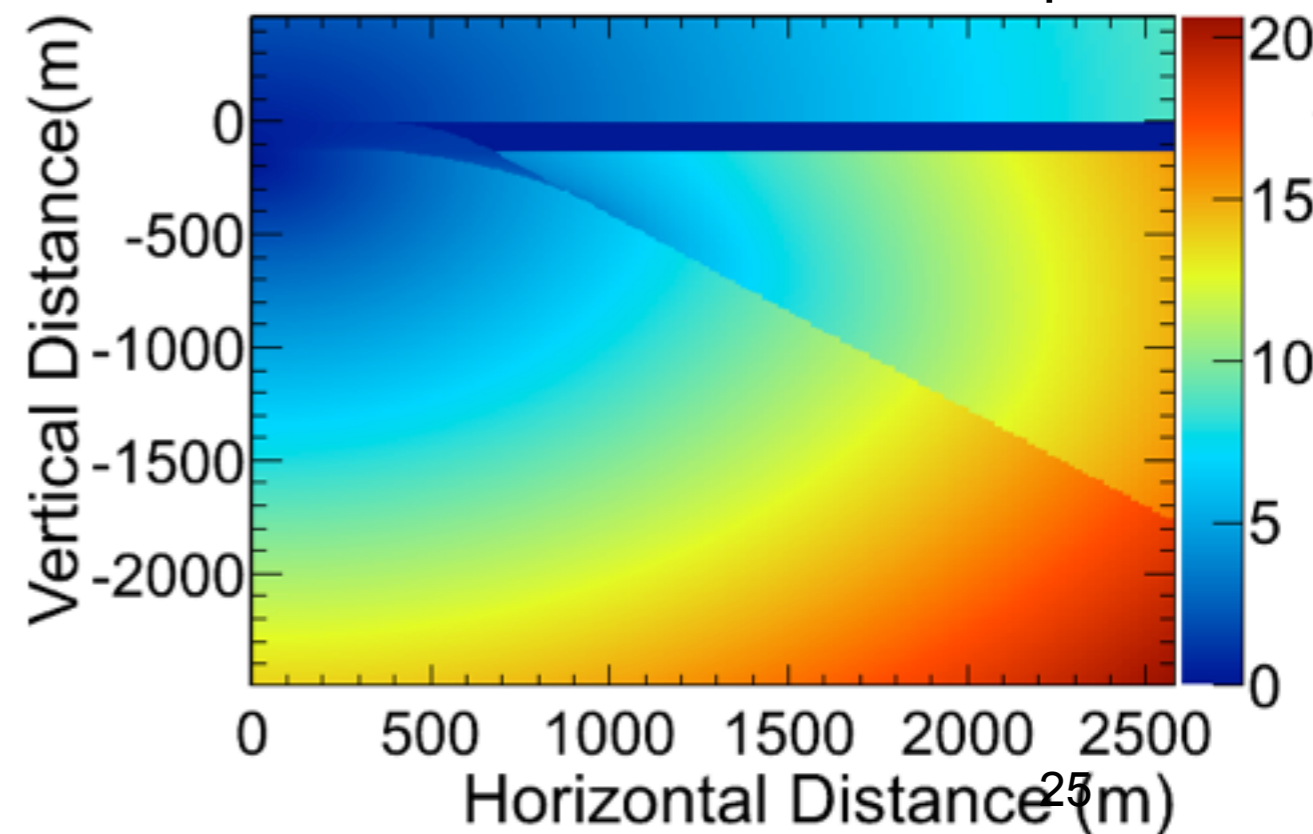
- Three deep stations deployed



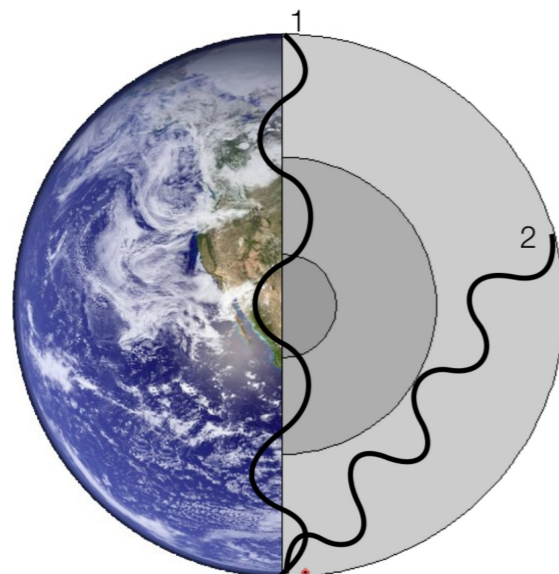
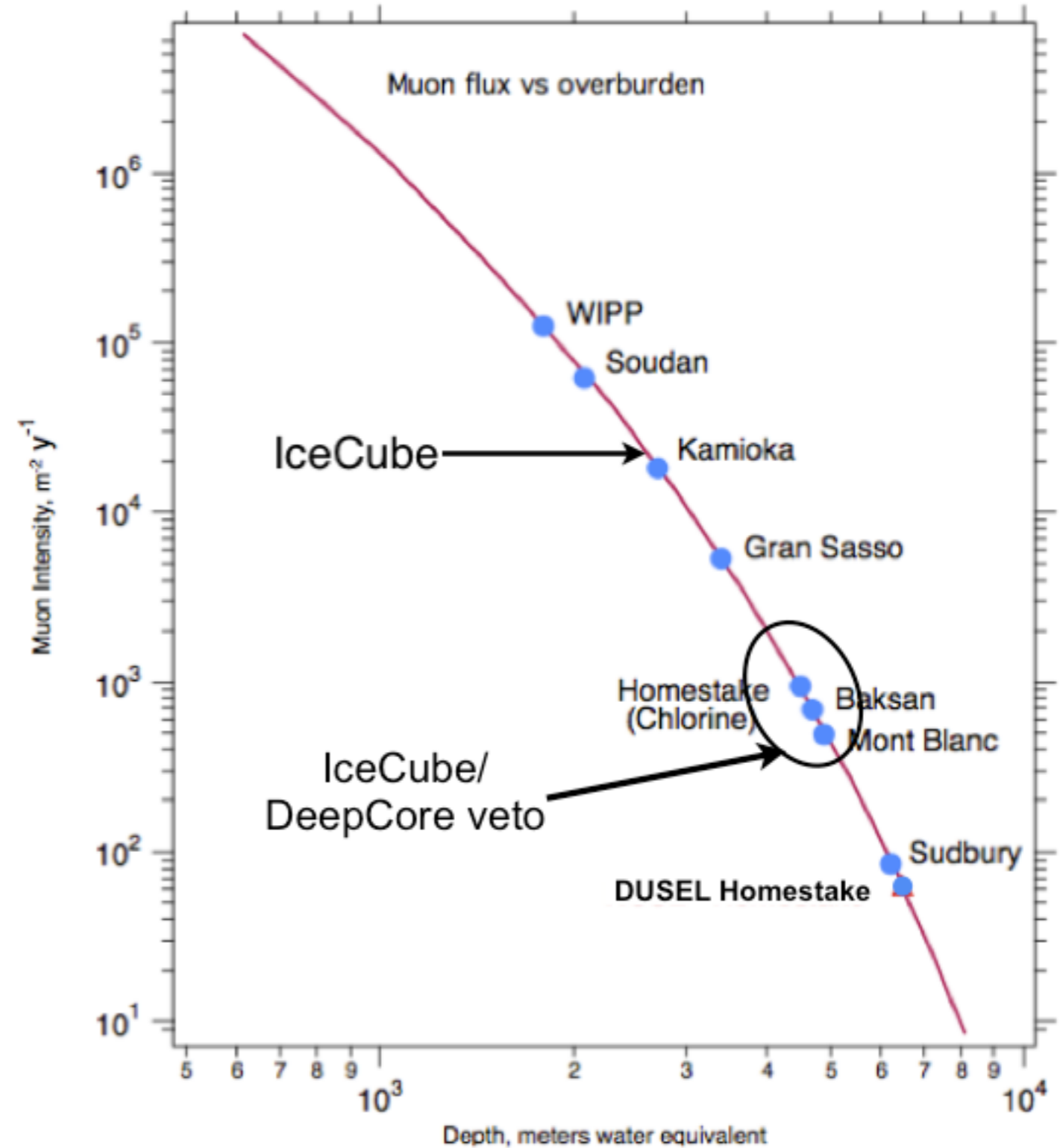
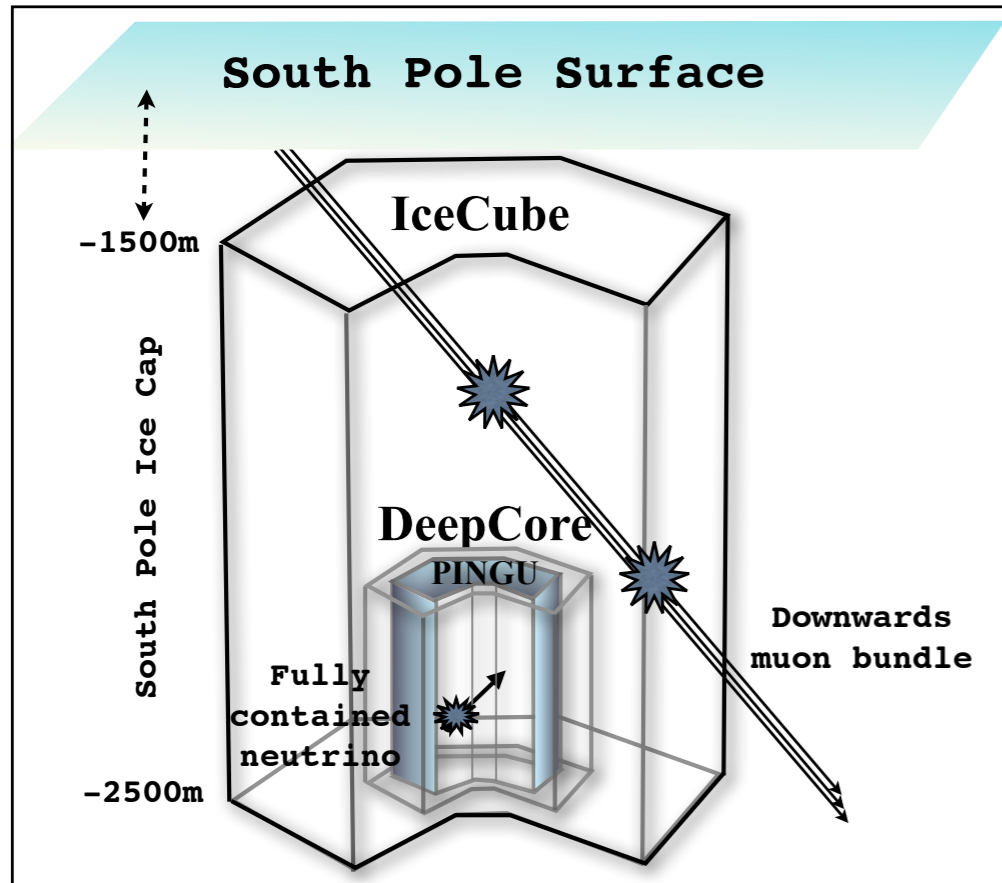
Test Station ~25m deep



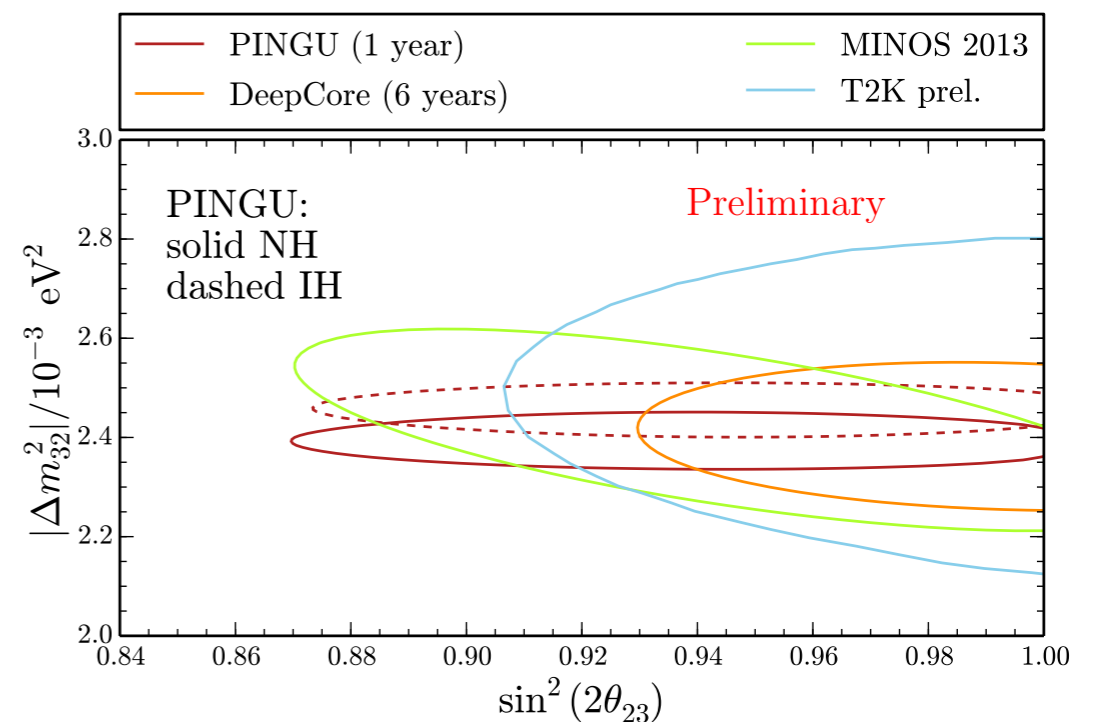
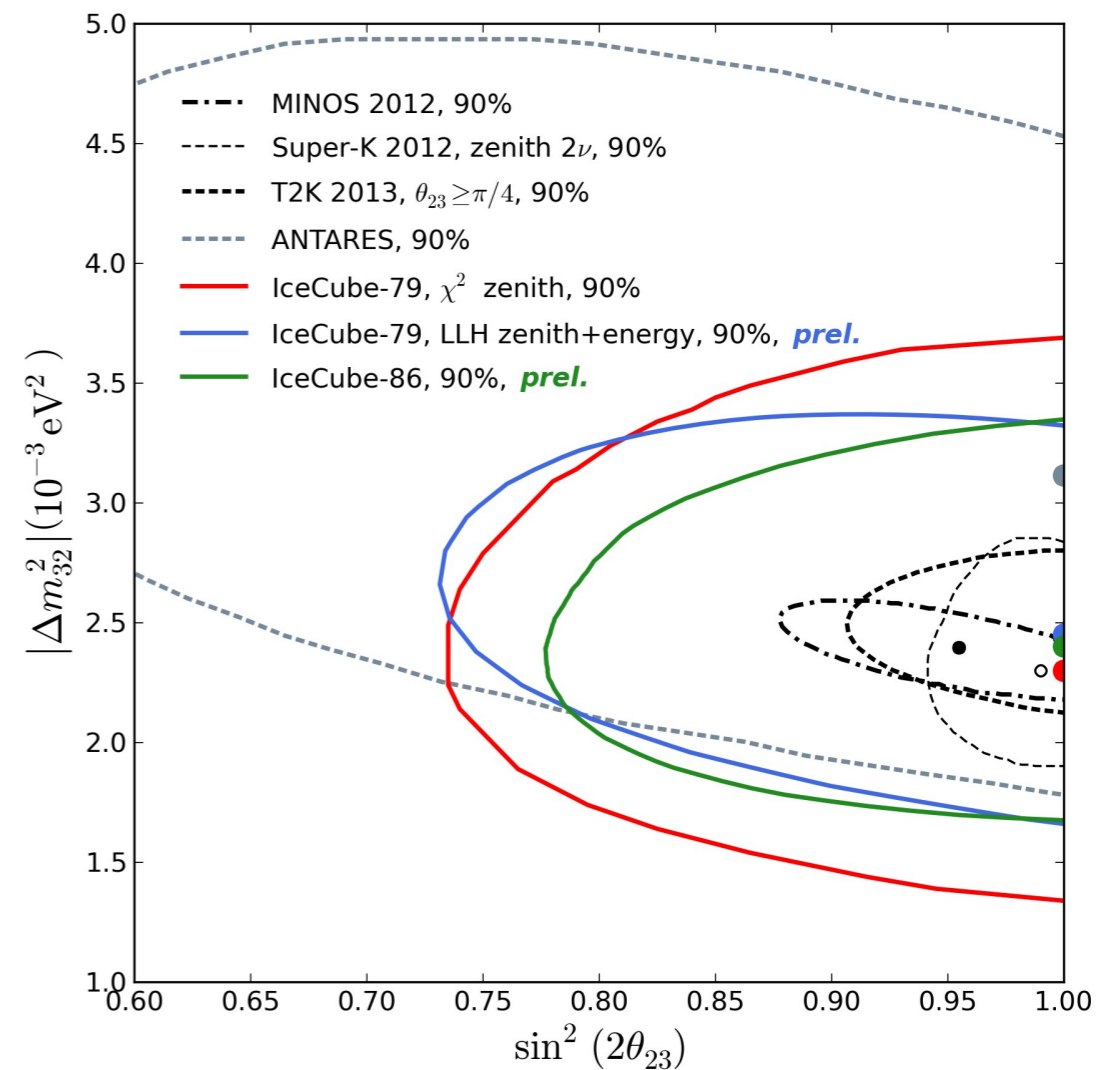
Full Station ~175m deep



Neutrino Oscillations

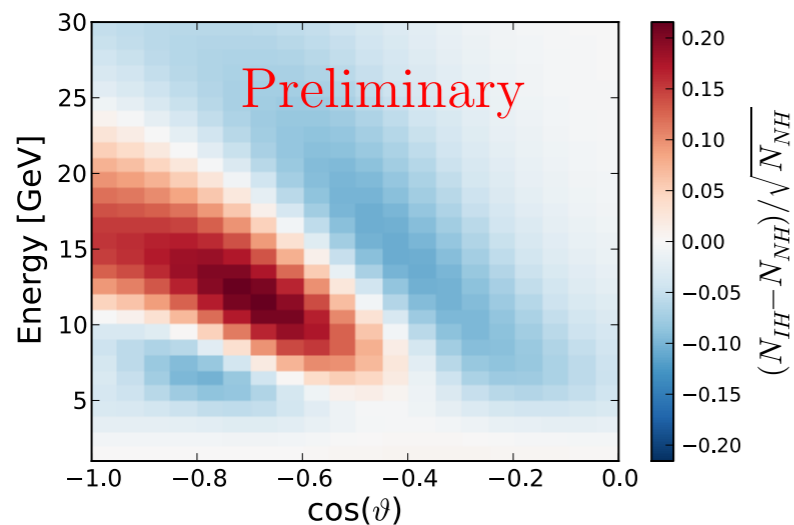
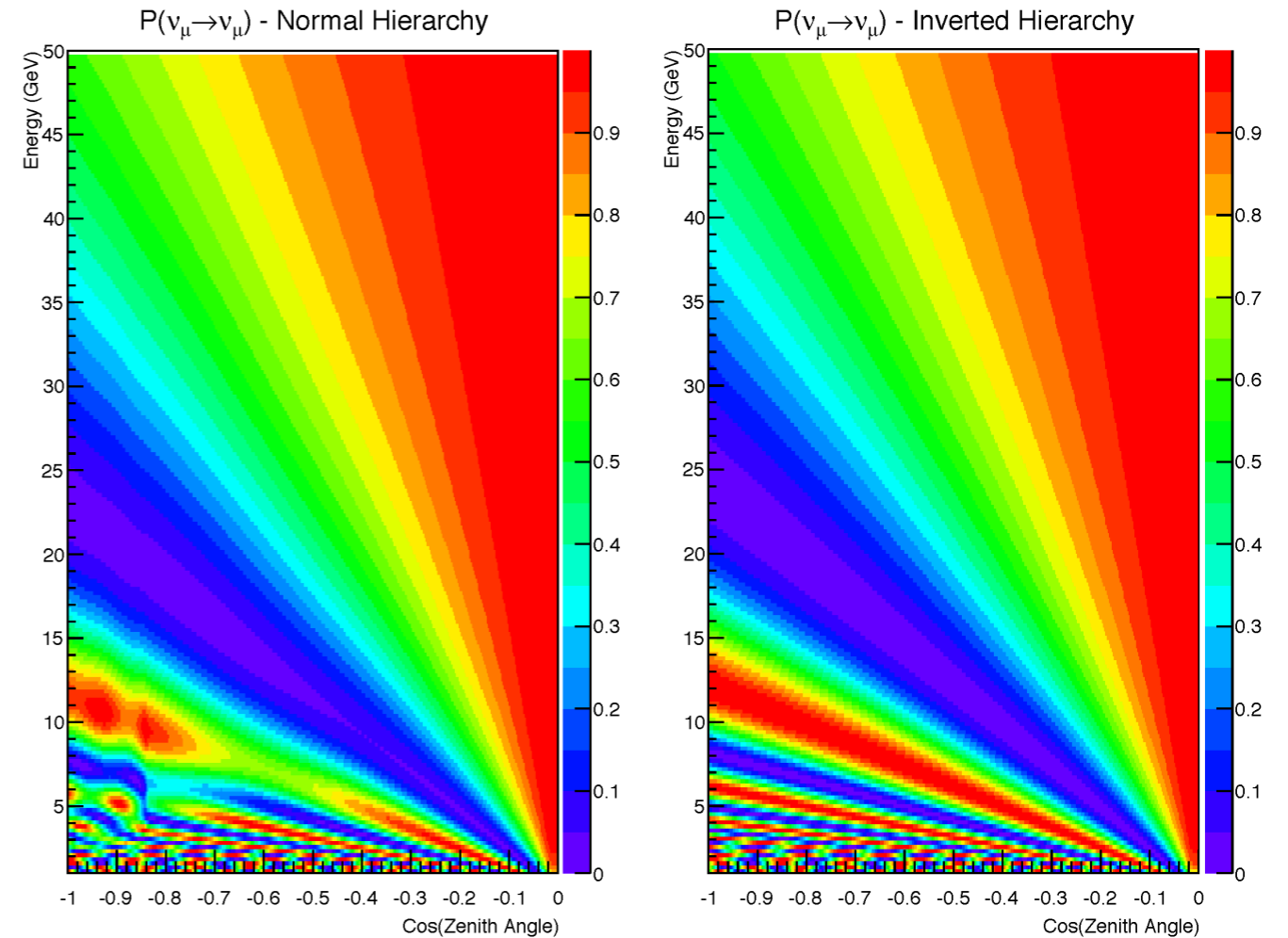


- IceCube and Antares have both measured atmospheric muon neutrino disappearance
- Current limits are not competitive with Super-K, T2K and MINOS
- More statistics and analysis improvements to come
- One year of PINGU data would have comparable sensitivity to current results

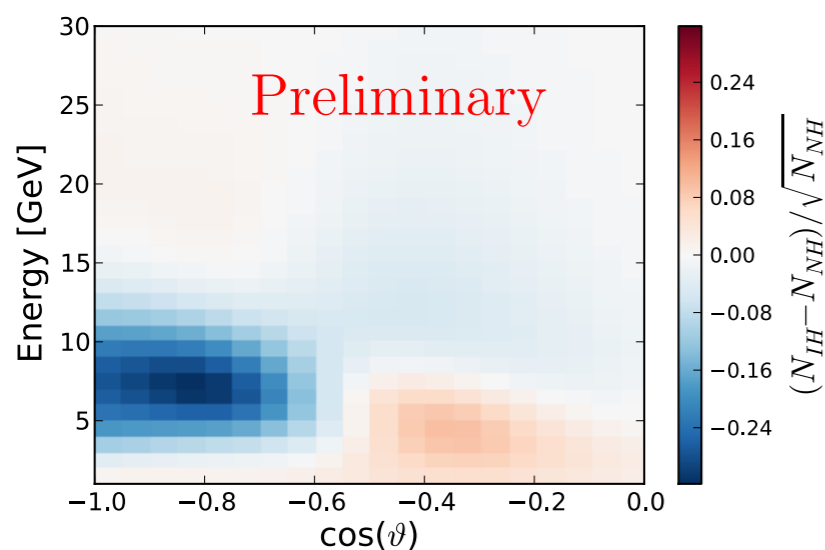


Mass Hierarchy Sensitivity

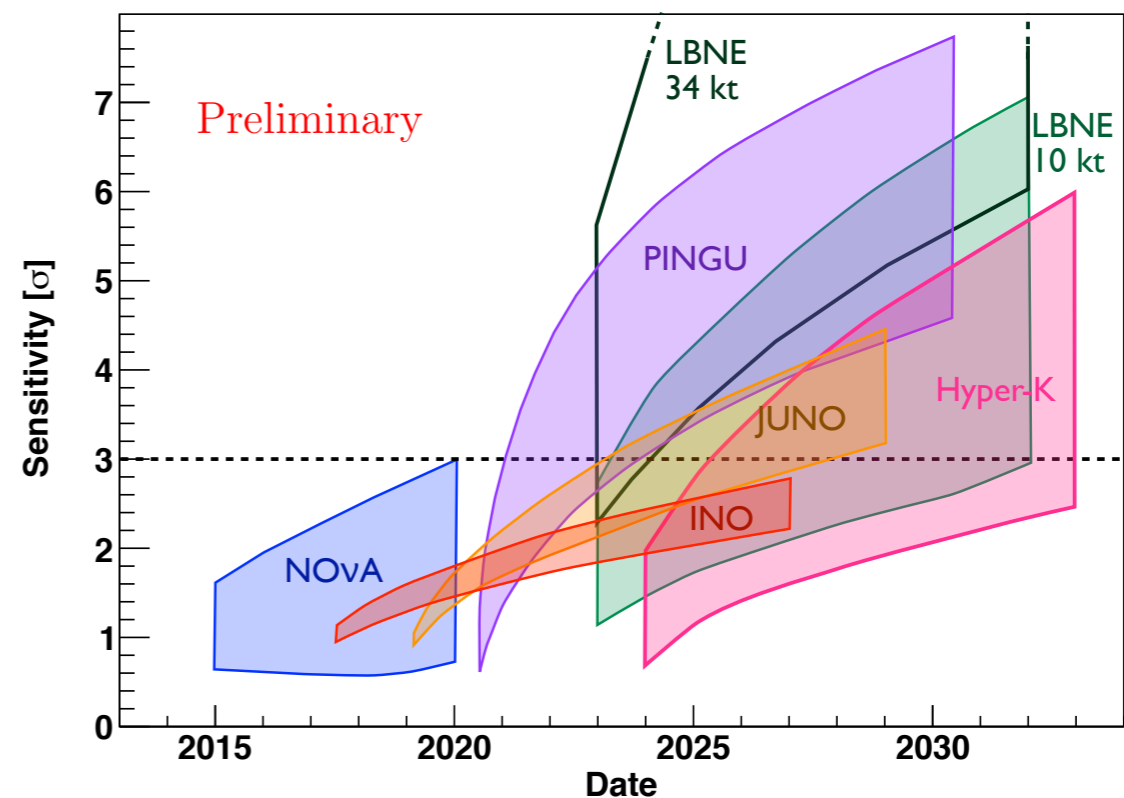
- Matter effects introduce differences in the muon neutrino survival probability between the two hierarchies



(a) Track-like events.

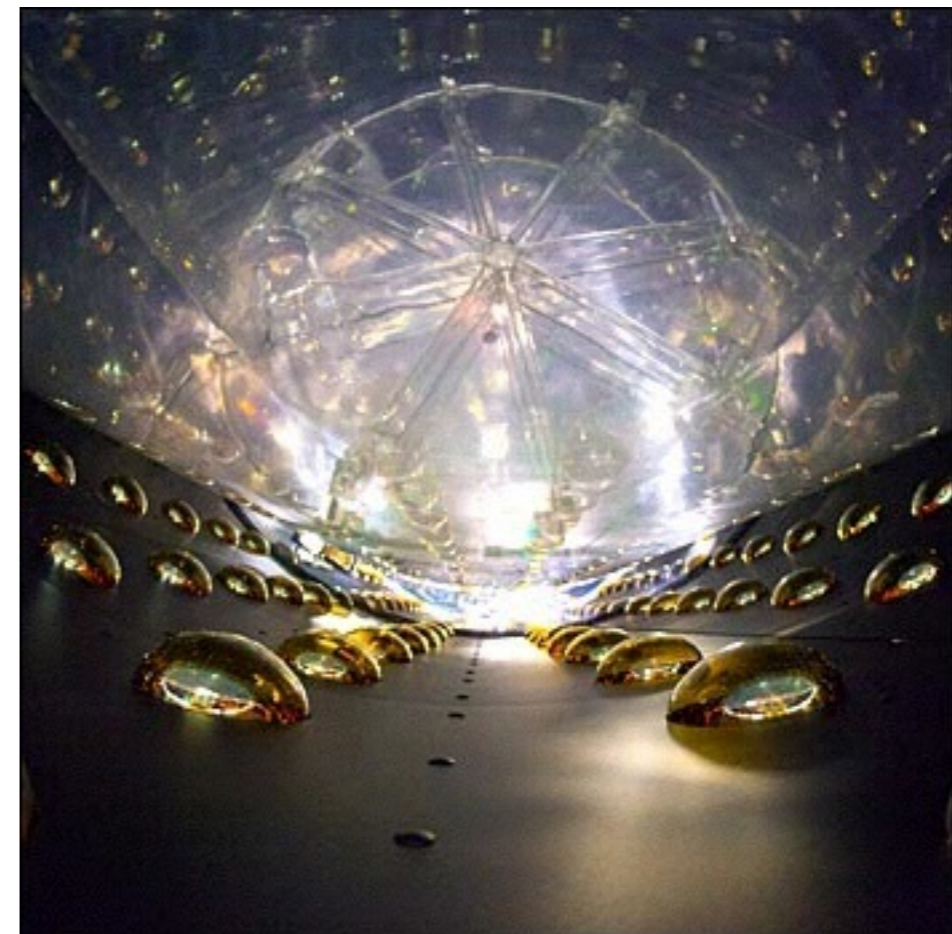
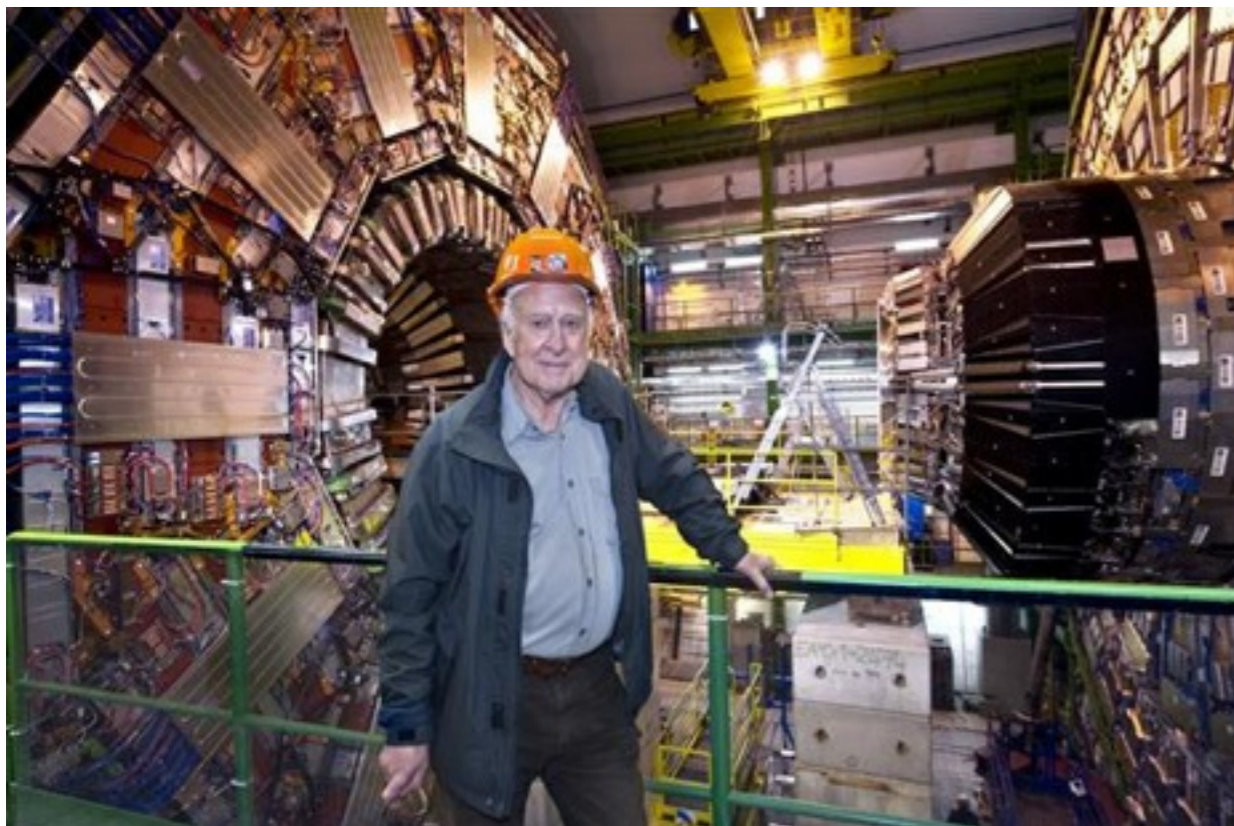
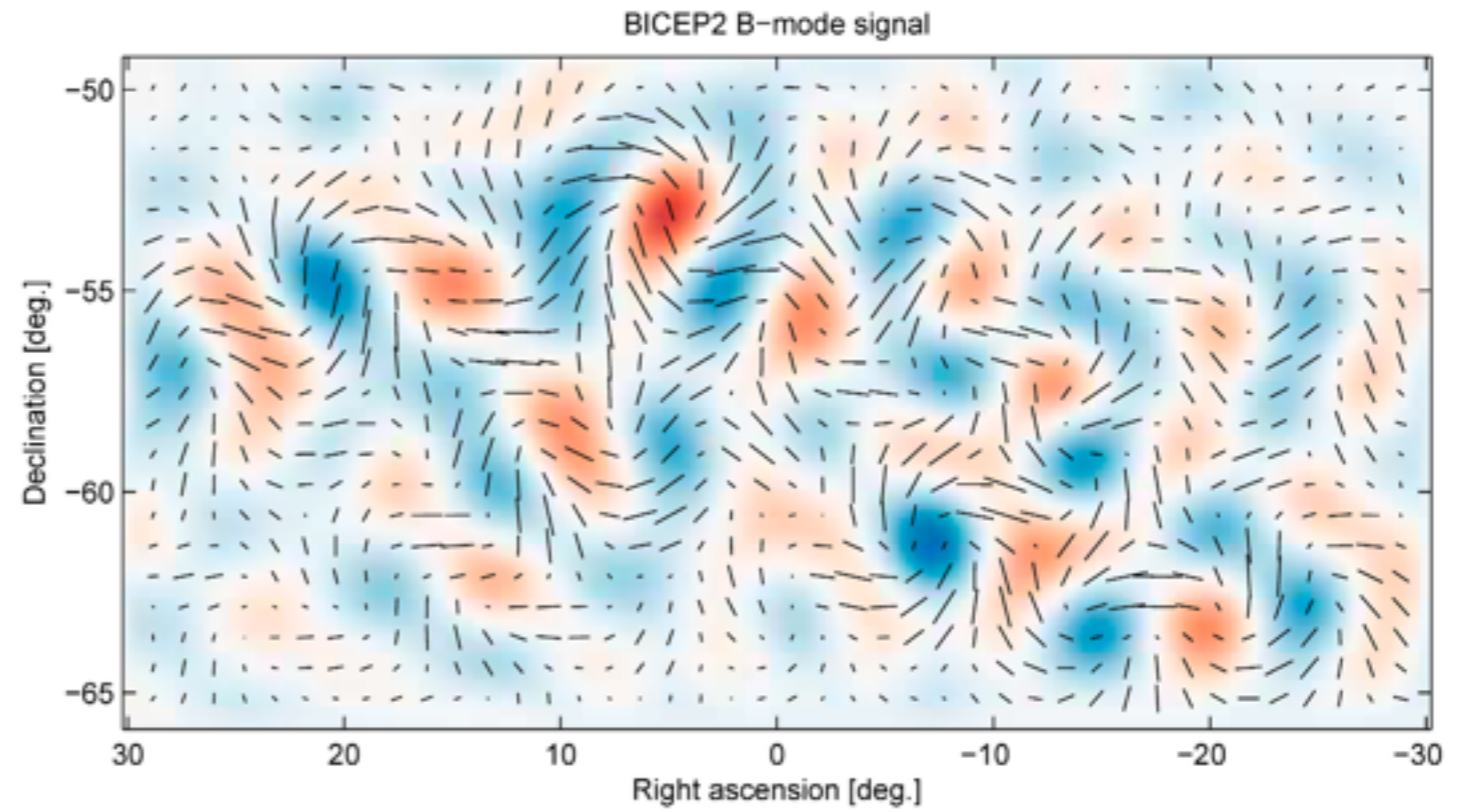
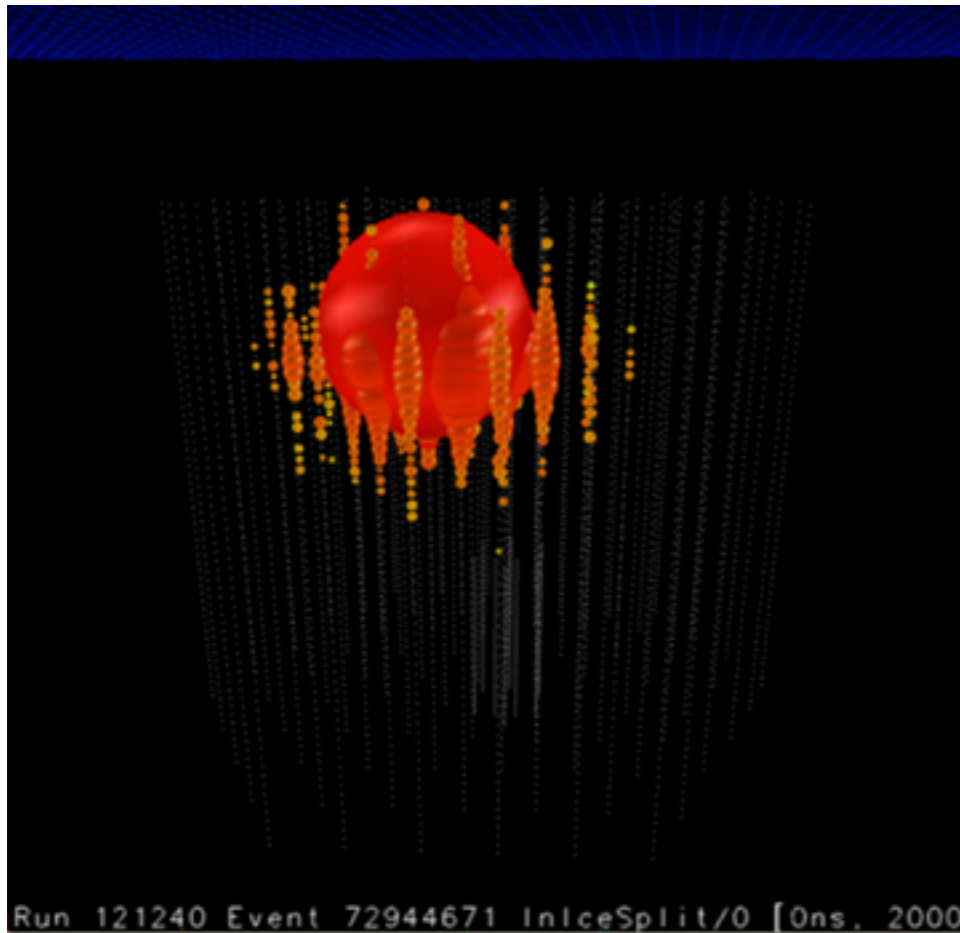


(b) Cascade-like events.



- In 2013, IceCube announced evidence for the first detection of high energy extraterrestrial neutrinos
 - These may be the first neutrinos from outside our solar system since SN1987A
 - It is not yet clear where these neutrinos come from
 - The adolescence of neutrino astronomy?
- ANITA & ARA are utilising the Askaryan effect to search for the cosmogenic neutrinos from the GZK effect
- PINGU, a low energy IceCube infill, could help disentangle the mass hierarchy before the next generation of long-baseline oscillation experiments are up and running

Recent Discoveries



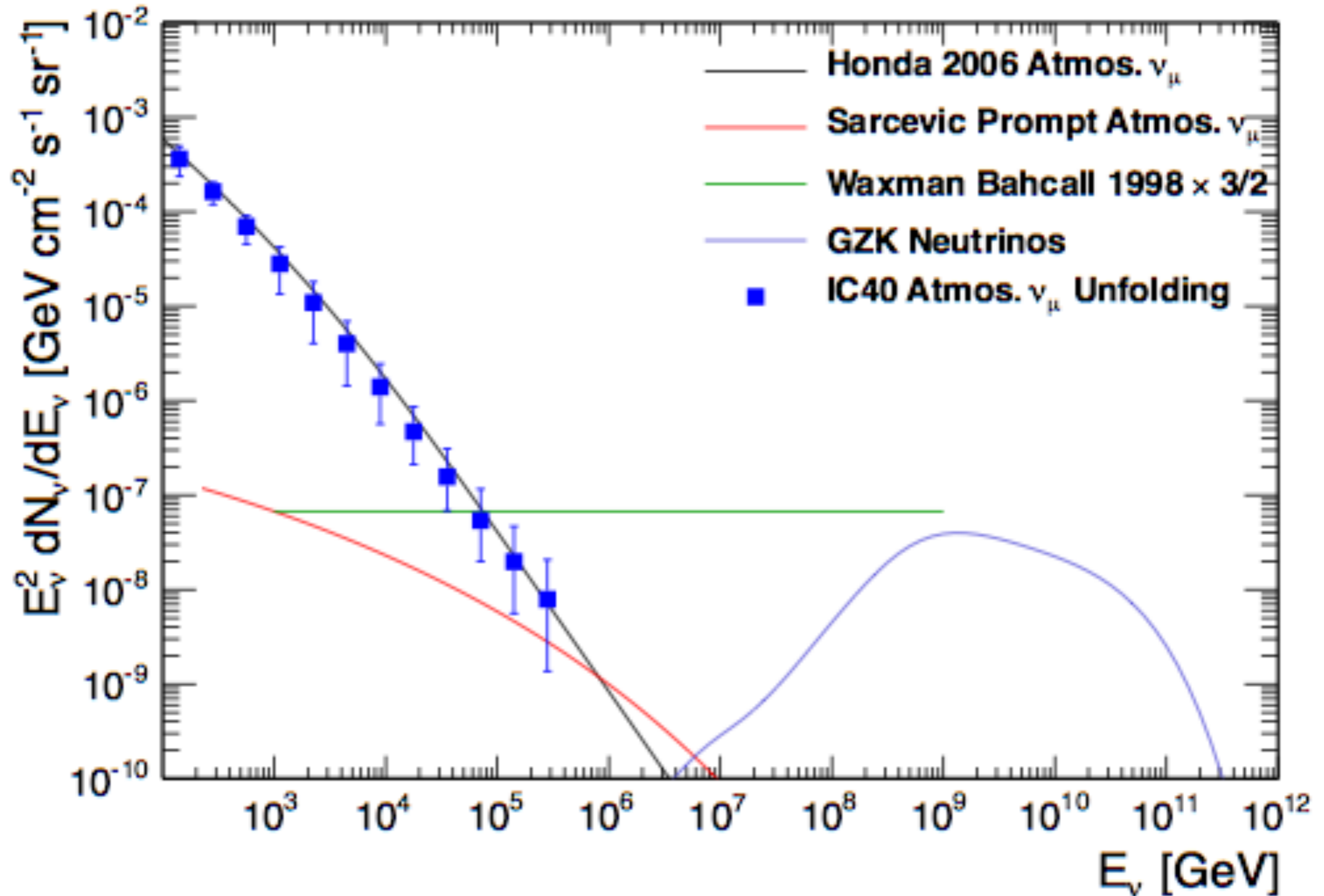


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Backup

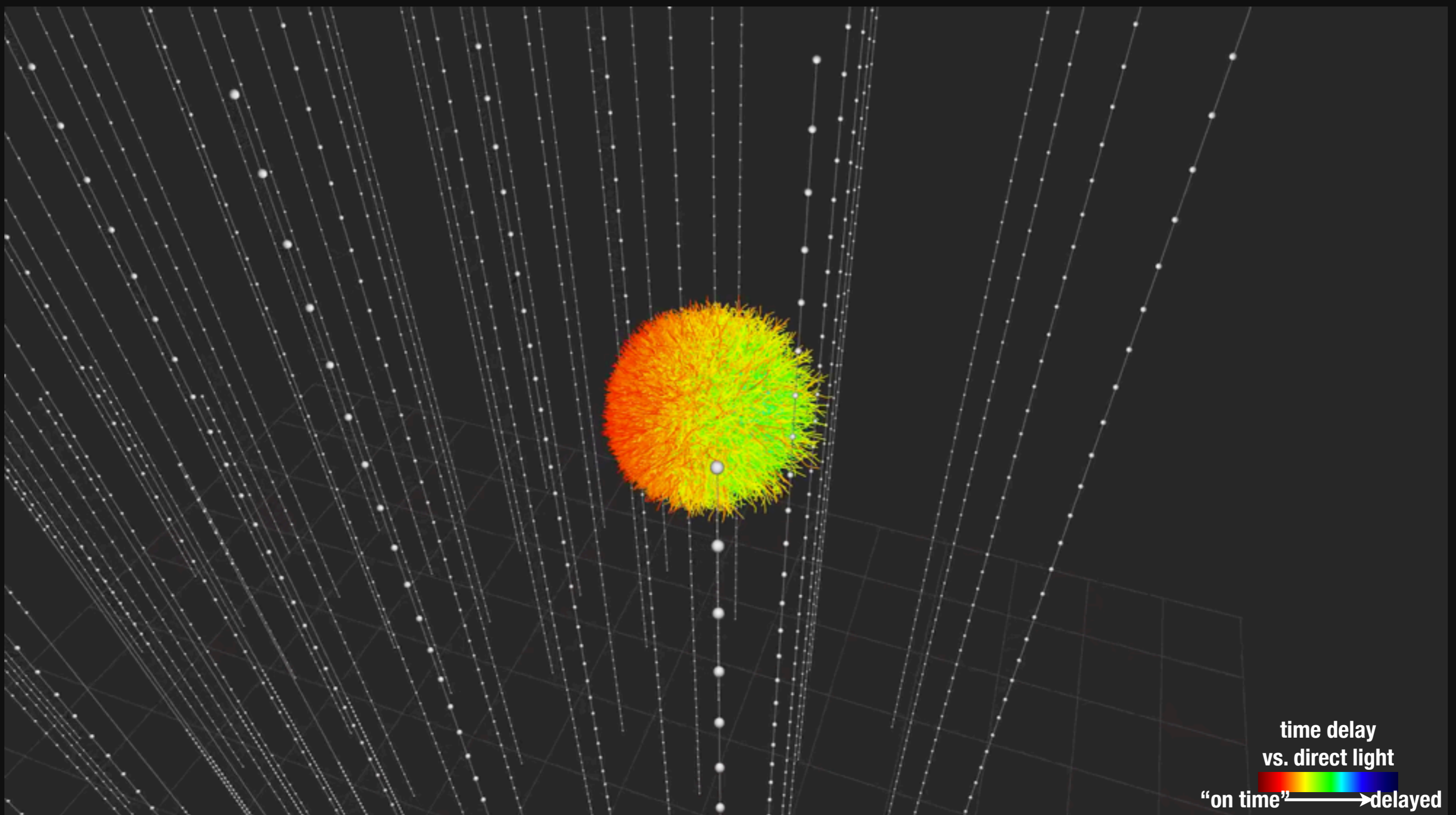


- All neutrinos above 1 TeV are interesting neutrinos



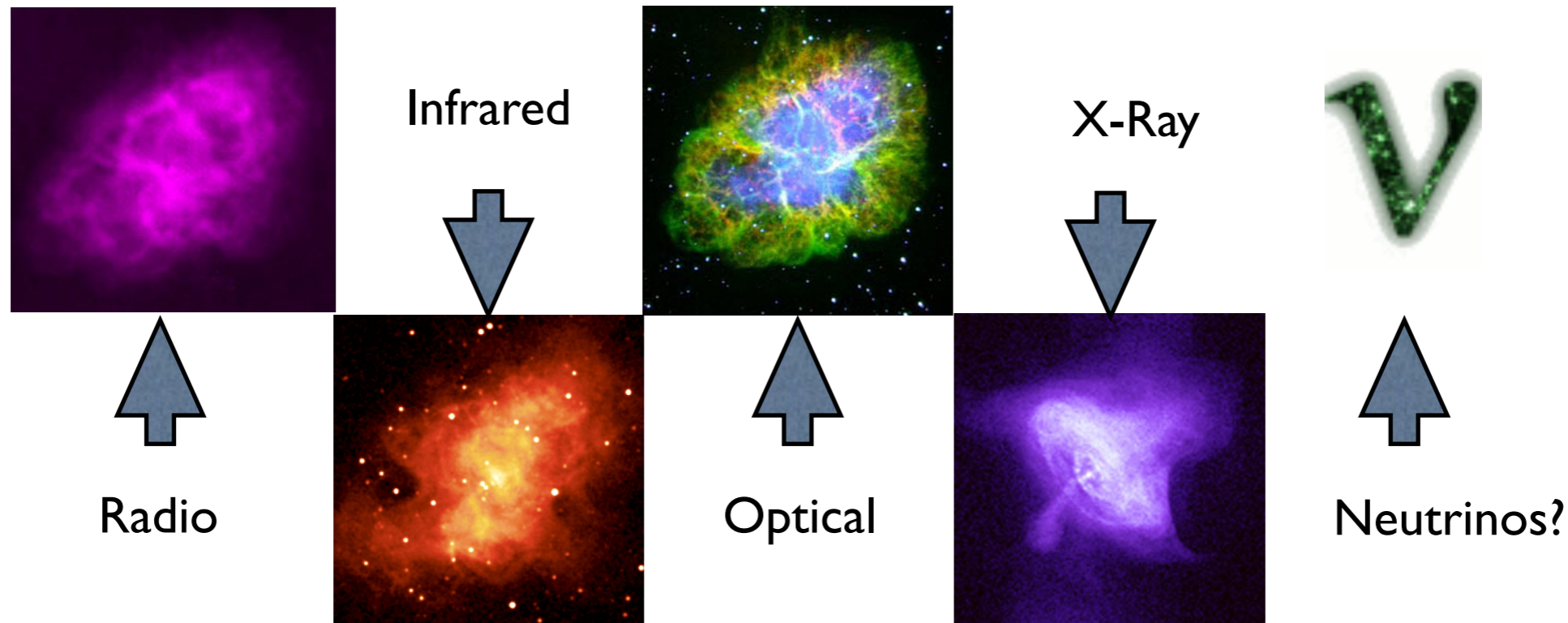
Directional Resolution for Showers

Showers directions reconstructed from timing profile



Why High Energy Neutrinos?

For Astronomers:
The Pretty Pictures Argument

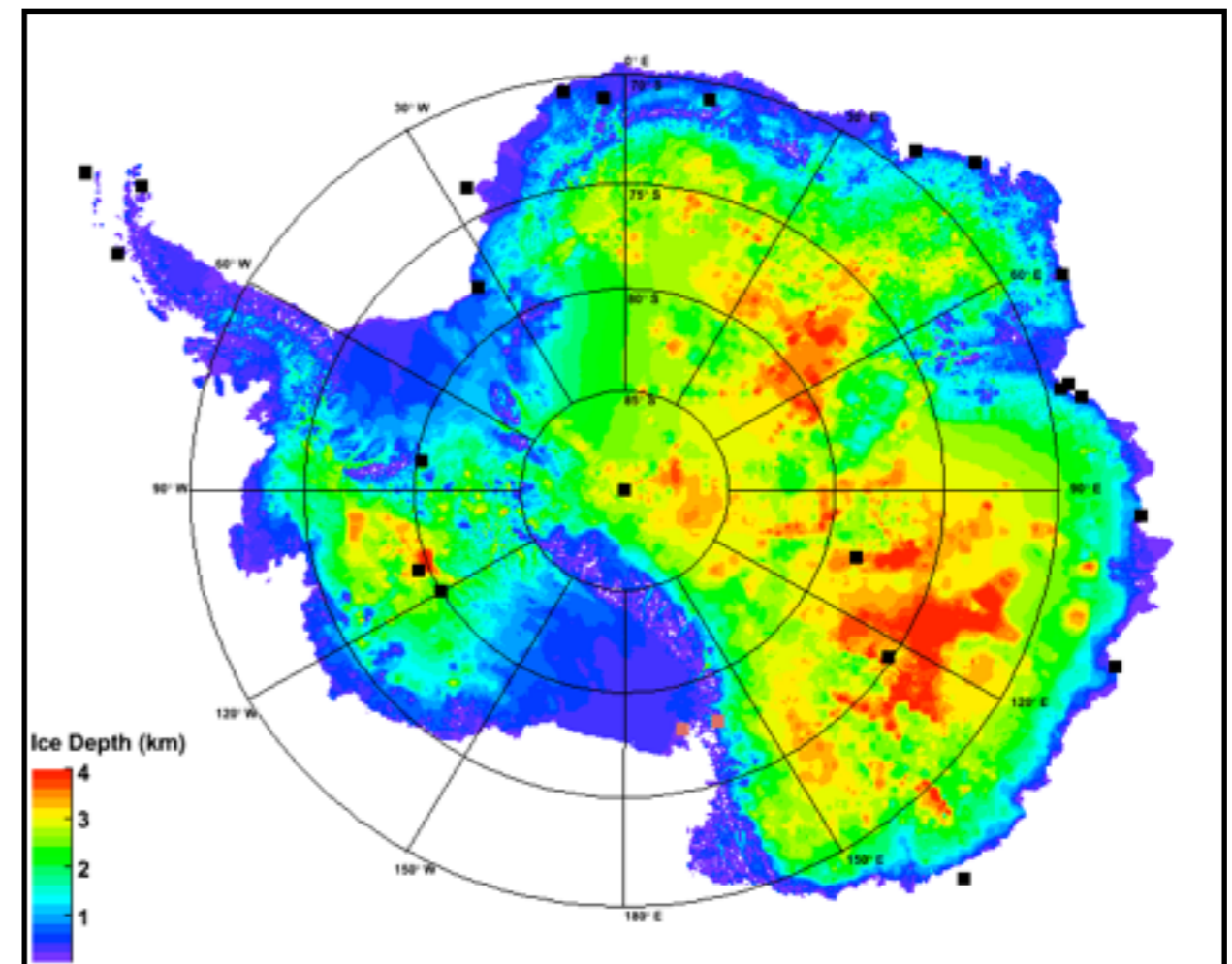
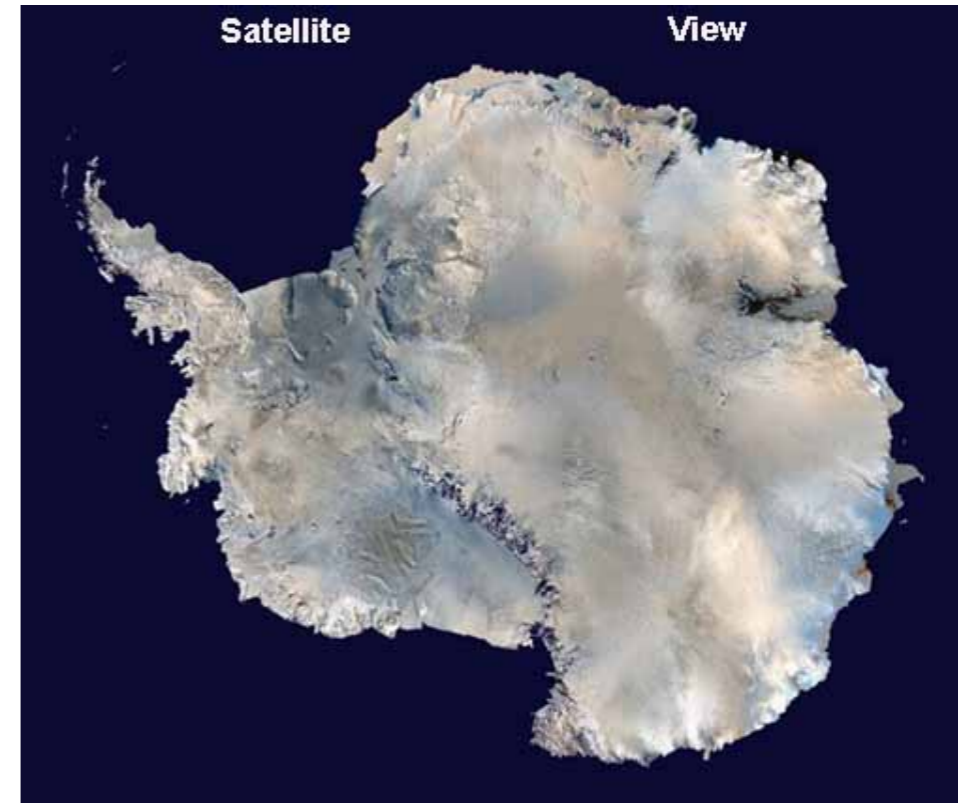


For Particle Physicists:
The 300 TeV (CoM) Neutrino Beam Argument

type	L/E	$t_{proper} \sim (L/c)(m_\nu/E)$
CERN SpS/WANF	500 m/25 GeV	3 attoseconds
Stopped μ (LAMPF)	30 m/ 40 MeV	130 attoseconds
NUMI	735 km/ 4 GeV	30 femtoseconds
Reactor (KamLAND)	150 km/5 MeV	800 femtoseconds
Atmospheric	10,000 km/1 GeV	2 picoseconds
Sun	150,000,000 km/5 MeV	800 nanoseconds
GZK	1 Gpc/100 PeV	50 milliseconds
SN-1987a	50 kpc/15 MeV	1 hour

Why Antarctica?

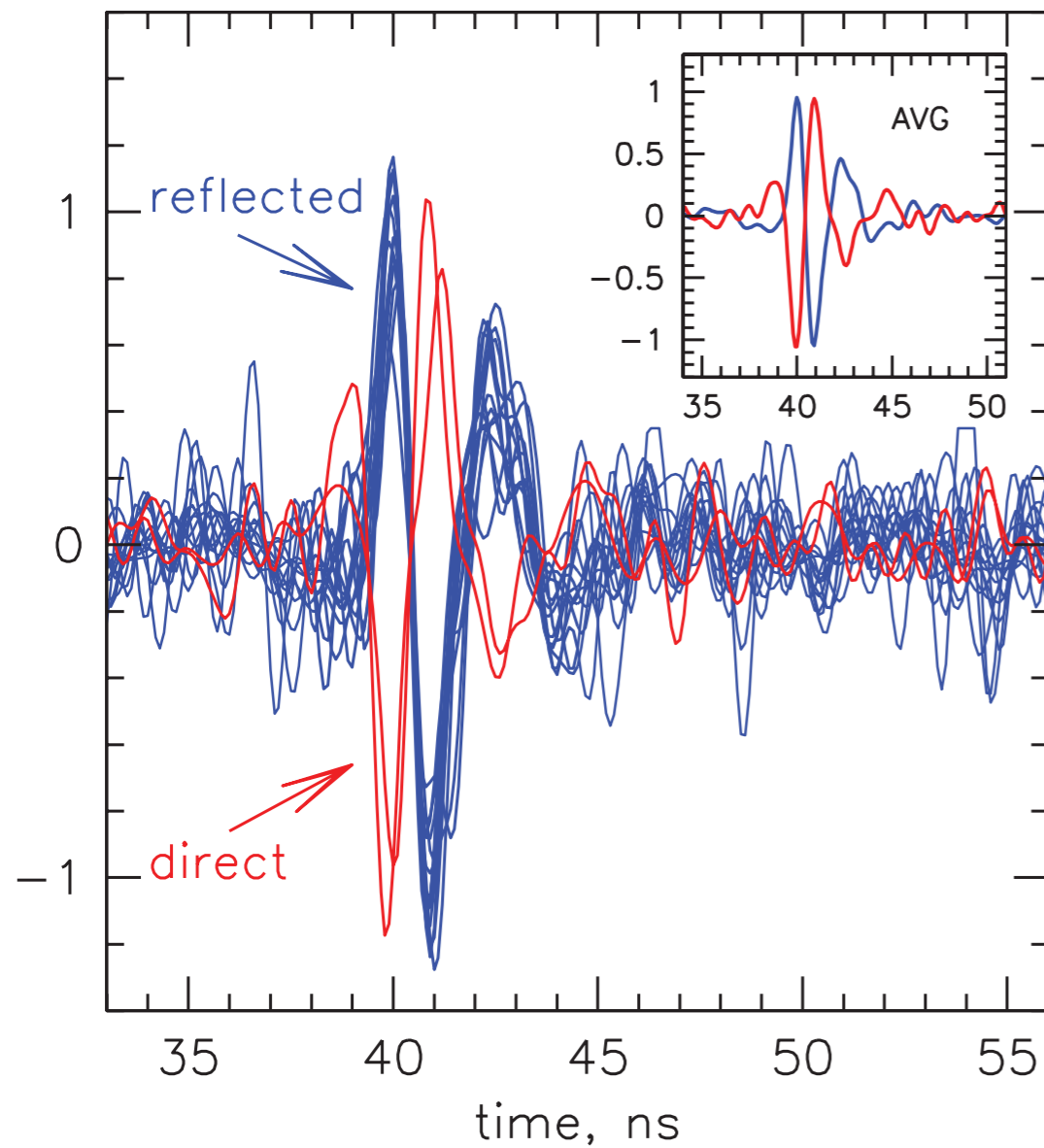
- It is the coldest, driest, windiest place on Earth
- But...
 - Lots of Ice
 - Despite our best efforts
 - Over 4km thick in places
 - Also:
 - The only continent exclusively dedicated to scientific research
 - No indigenous (human) population
 - So relatively free of manmade noise



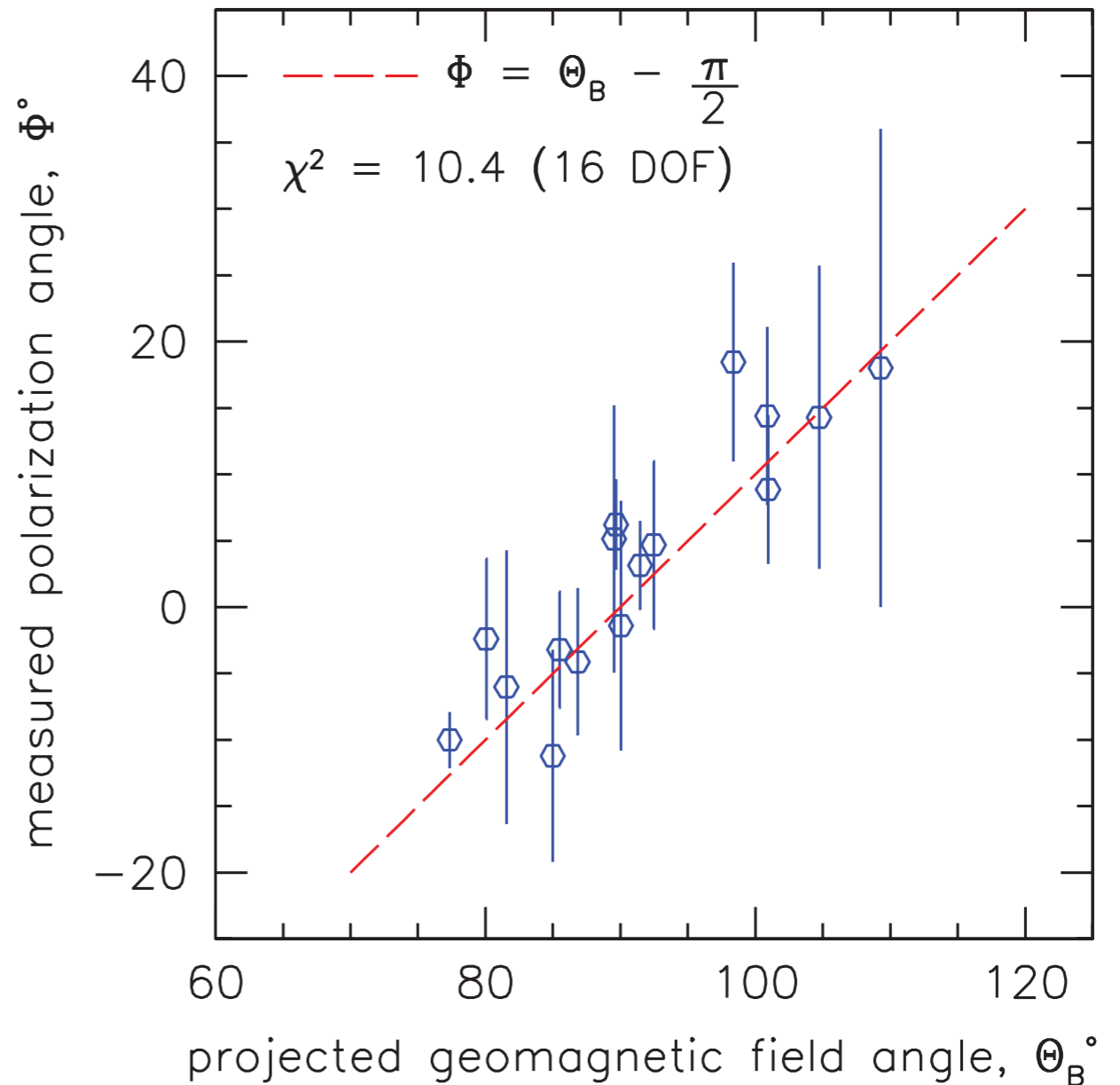
Ice depth data from BEDMAP consortium

- Some Numbers:
 - ~1 GZK neutrinos/km²/year
 - @ 10¹⁸ eV the ν -N interaction length ~ 300km
 - \therefore 0.003 neutrino interactions/km³/year
- Need a huge detector volume ($\gg 100$ km³) to ensure detection
- Use naturally occurring medium
 - Transparent (to some signal)
 - Possibilities
 - Air, Ice, Salt, Water, The Moon

Direct vs Reflected flip polarity



Correlation of measured polarisation with local geomagnetic field angle



More data needed to fully understand energy scale. ANITA III will fly in 2014 and should collect 500-1000 UHECR air shower events during its flight.

IC86 oscillation results

- Focus: new reconstruction techniques using unscattered photons
- Good angular resolution at lowest energies
- Highest event rates at ~ 10 GeV

33rd ICRC conference,
contribution 0450
included in arxiv:1309.7008

