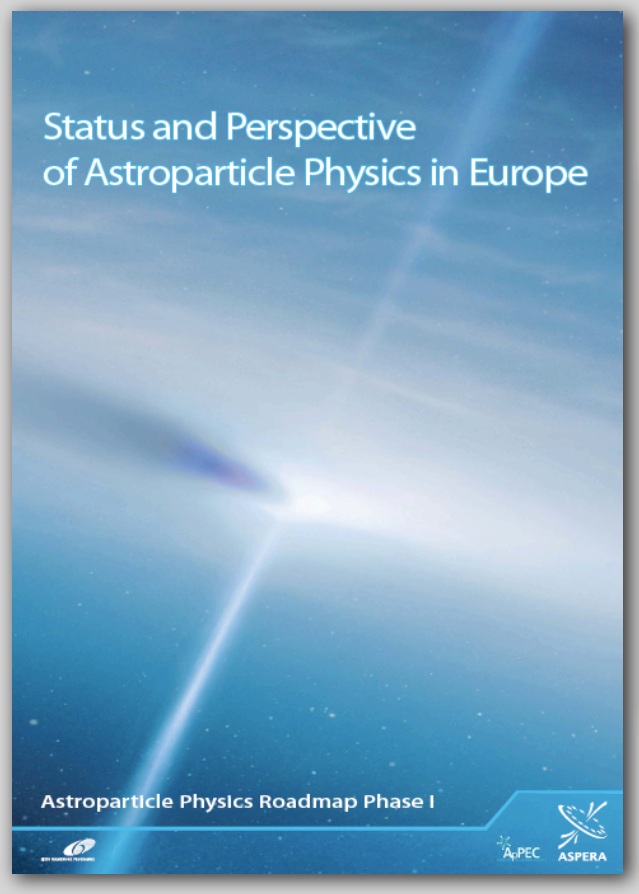
Radio Detection of UltraHigh Energy Cosmic Neutrinos at the South Pole

RWTH – Aachen June 16, 2009

Kael Hanson
Université Libre de Bruxelles

ASPERA roadmap recommendation



Link

"Several promising techniques to detect cosmic neutrinos of highest energy – like radio Cherenkov detection in ice, in the atmosphere or in the moon crust – will be tested with existing detectors; others, like acoustic detection, or radio detection in salt domes, are still in an R&D phase. In order to cover the full range of all possible energies of cosmic neutrinos, exploitation of these techniques is mandatory. **The ongoing coordinated R&D work should be supported**."

Part I

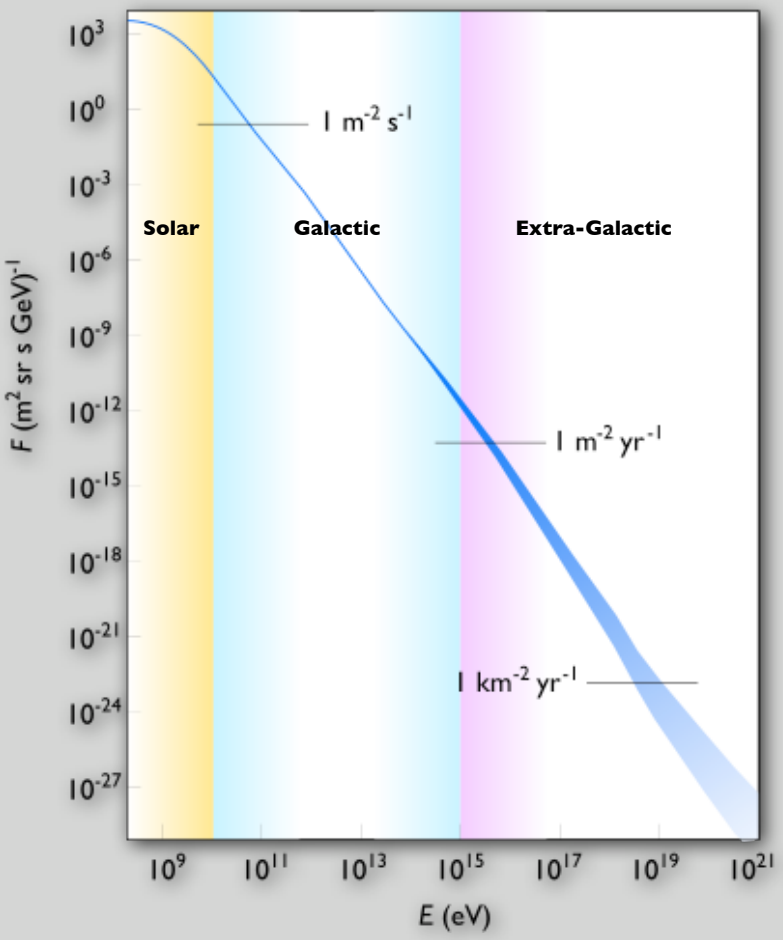
Motivating the hunt for ultrahigh energy neutrinos

The Science

- Understanding of ultrahigh-energy cosmic ray composition and fluxes
  - Origin of cosmic rays - identification of point emitters of UHE neutrinos.
  - Source physics / cosmic propagation [Seckel & Stanev PRL **95** (2005) 141101]
- UHE neutrino cross-section measurement
- Probe physics beyond the Standard Model [Sarcevic J. Phys. Conf. Ser. **60** (2007) 175]

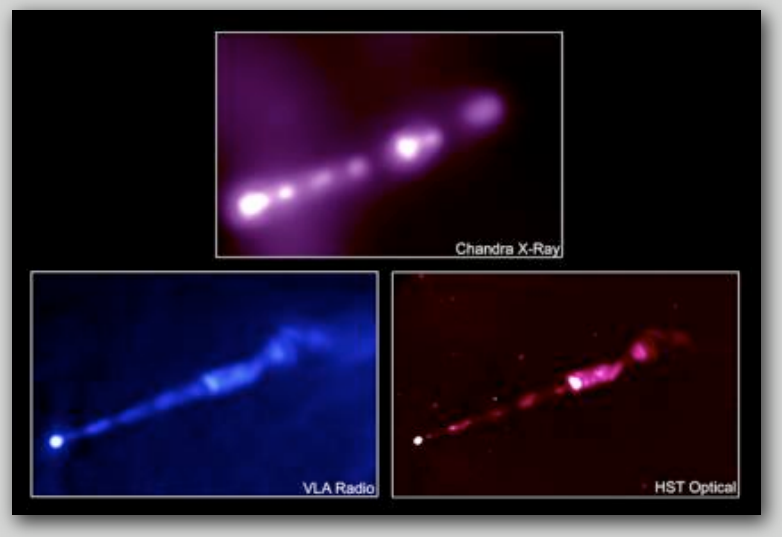
The cosmic ray all-particle spectrum

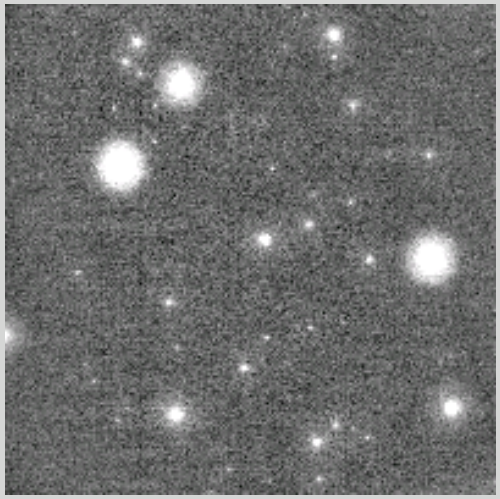
- For GeV and above dominated by protons, heavier nuclei.
- Composition at upper end of spectrum largely unknown.
- Observations by giant air-shower arrays (Auger, AGASA, HiRes) all the way up to 10^{20} eV.



The origin of cosmic rays

- Shock acceleration in supernova remnants is a plausible, but unconfirmed, theory of CR origin
- However these sources do not seem sufficient to accelerate CR above PeV, so we speculate production in
  - Jets of active galaxies
  - Gamma ray bursts
- Because of absorption - horizon for potential sources is limited to near 10's of Mpc - UHECR from small number of nearby sources?





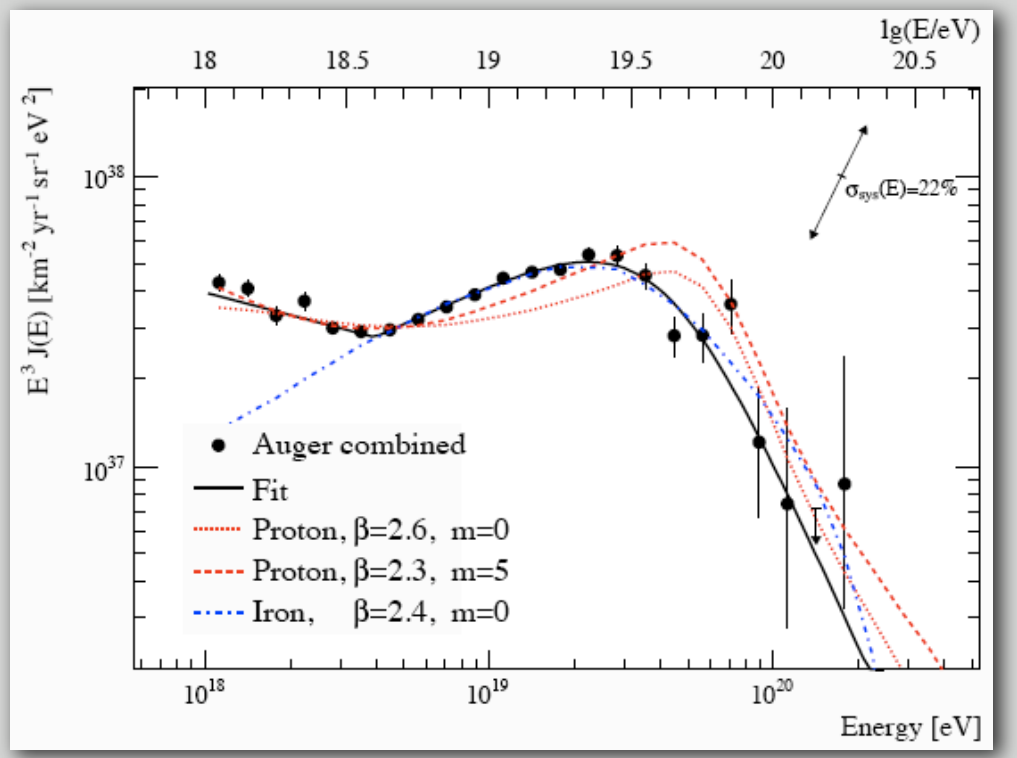
The Greisen-Zatsepin-Kuzmin cutoff

- Density of 2.7 K CMBR field is 400 photons / cm3. At very high energies the protons will hit resonance

$$p + \gamma \rightarrow \Delta^+ \quad \rightarrow \quad p + \pi^0$$
$$\rightarrow \quad n + \pi^+$$

- This effectively limits the propagation distance of protons above CMS energy sufficient to produce π (about 30 EeV) to 10's of Mpc [cf, for example, Stanev et. al. PRD **62** (2000) 093005 for recent discussion and modeling]
- The charged pions will decay after seconds to neutrinos - "guaranteed" flux of neutrinos
- Thus - protons bent in magnetic fields or absorbed. The neutrinos however, point straight back to the source(s).

Auger sees a cutoff



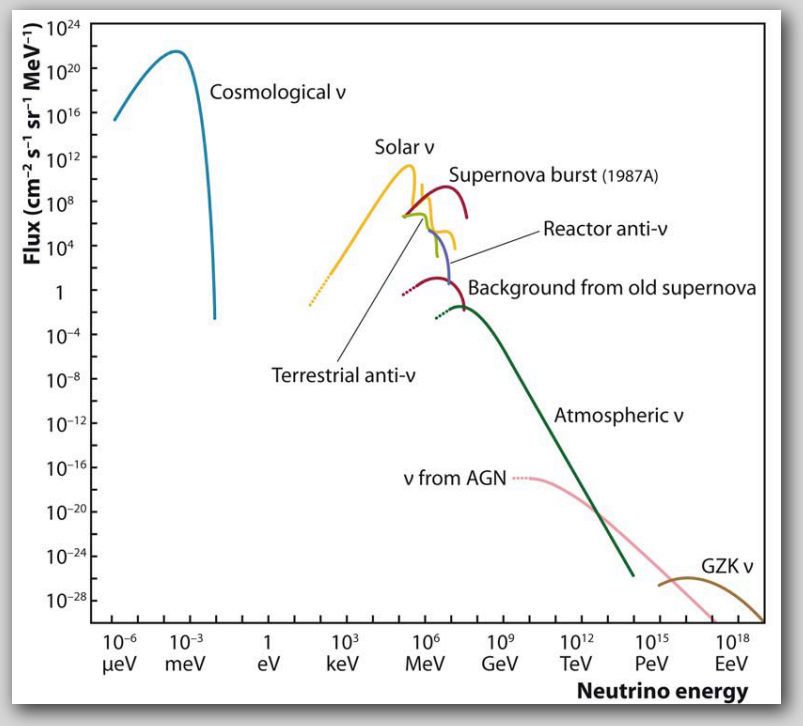
Abraham et. al. (Pierre Auger Collaboration) ICRC 2009

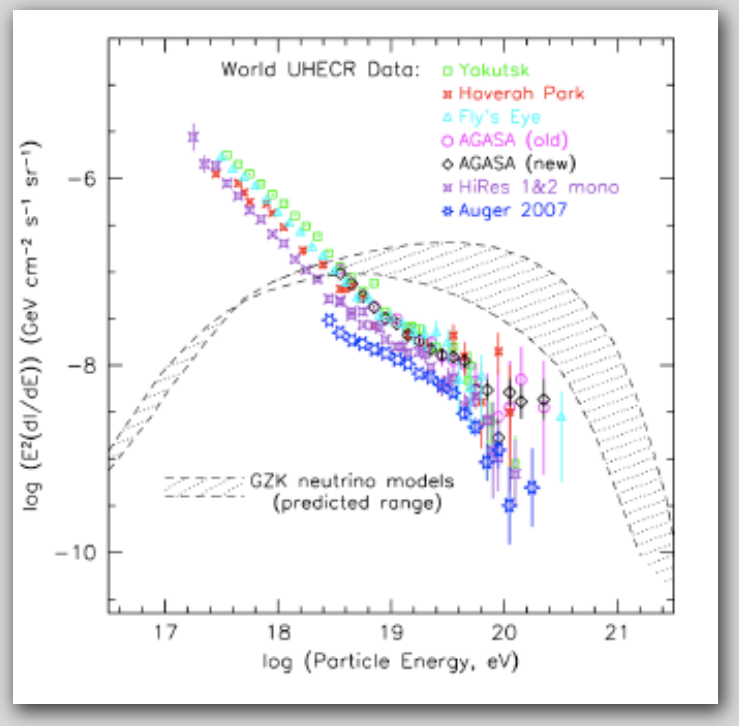
Part II
Radio detection of neutrinos

Cosmic neutrino detection

- Fluxes are a problem - typically falling off faster than E^{-2}
  - Neutrino cross-sections increase approx as $E^{0.4}$ at high energy, gain a little here
  - For muons, one picks up another power at low energy falling off exponentially eventually due to muon range
  - For radio pulses - the field strength increases linearly with energy, however, eventually attenuation limits range
- Whether optical or radio detection - sensors pick up Cherenkov radiation from neutrino-induced lepton or resulting EM cascade.
- The earth is opaque to neutrinos of > 100 TeV. This limits UHE neutrino searches to upper hemisphere.
- Optical detection technique well-established, but, IceCube expects O(0.1) or less GZK ν per year: it is difficult to envision scaling optical technology to size sufficient to detect large statistical sample of GZK ν. Recall: optical atten len ~ 100 m in ice.

Neutrino fluxes

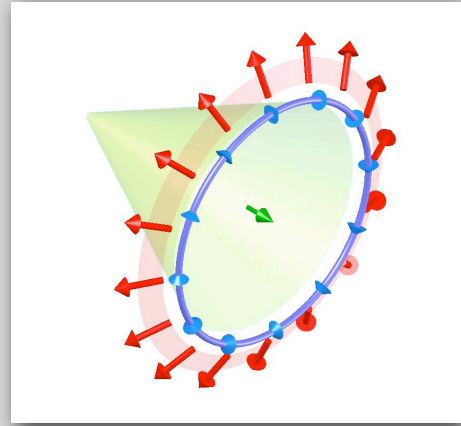




The Askaryan Effect

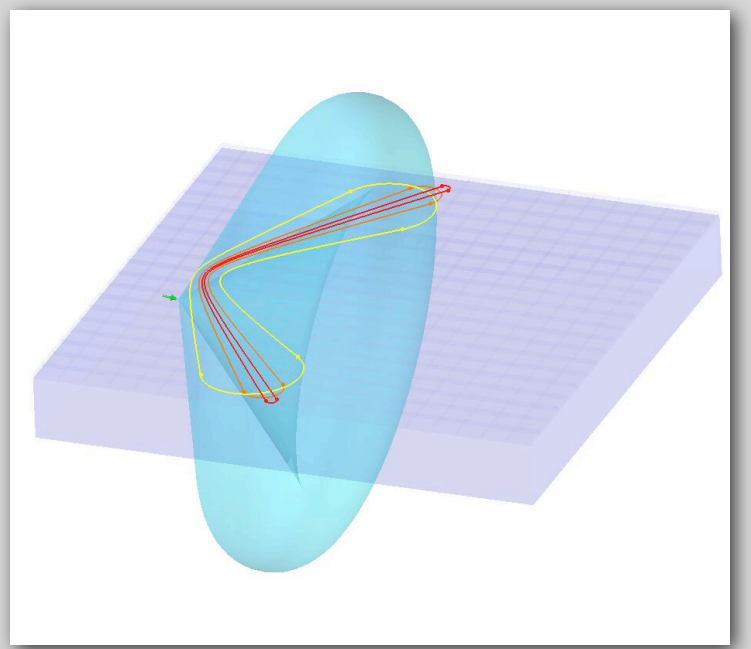
- Gurgen Askaryan proposed almost 50 years ago [Sov. Phys. JETP **14** (1962) 441] that high energy EM cascade will develop excess negative charge which coherently radiates energy to infinity.
- Real models of this pulse emerged with Zas, Halzen, Stanev (ZHS) [PRD **45** (1992) 362] and AVZ (Alvarez, Vázquez, Zas) [PRD **62** (2000) 063001]
- It is essentially a radio Cherenkov pulse emitted at the Cherenkov angle corresponding to the index of refraction of ice at MHz - GHz $n \approx 1.8$.

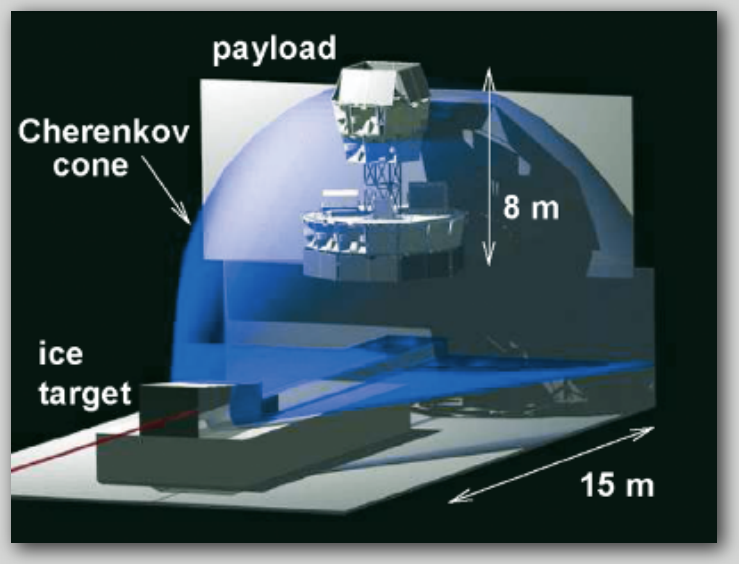
Radio Cherenkov



Cherenkov radiation from conical wavefront polarized as shown - provides possible background discrimination from HPOL + VPOL antennas

Illustration of idea of large-scale radio detector - note that scale of detected radio pulse exaggerated.





Validity of Askaryan pulse and ZHS / AVZ approximation tested in SLAC beam with ANITA payload [PRL **99** (2007) 171101

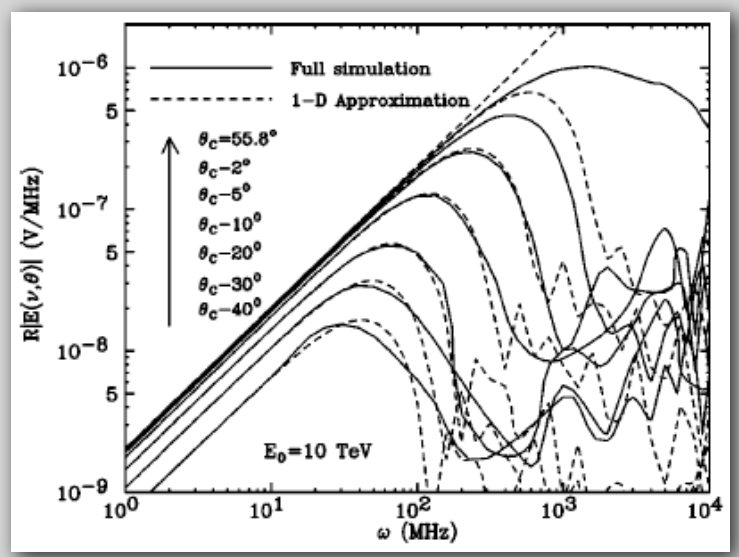
Modeling Askaryan pulses

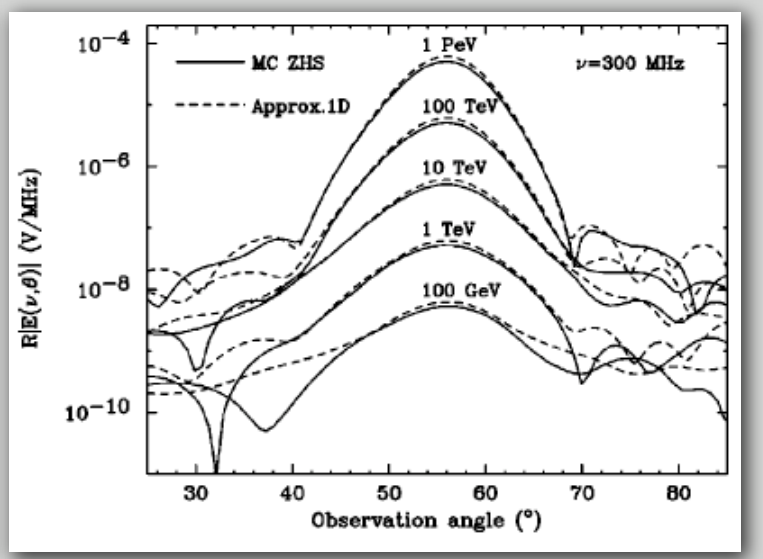
$$R|\vec{E}(\theta_c)| = 2.53 \times 10^{-7} \left[\frac{E}{\mathrm{TeV}}\right] \left(\frac{\nu}{\nu_0}\right) \left[\frac{1}{1+(\frac{\nu}{\nu_0})^{1.44}}\right] \mathrm{V \cdot MHz^{-1}}$$

$$R\left|\vec{E}(\theta)\right| = R\left|\vec{E}(\theta_c)\right| \times \exp\left(-\frac{1}{2}\left[\frac{\theta-\theta_c}{\sigma_\theta}\right]^2\right)$$

$$\sigma_\theta = 2.2^\circ \left(\frac{1\,\mathrm{GHz}}{\nu}\right)$$

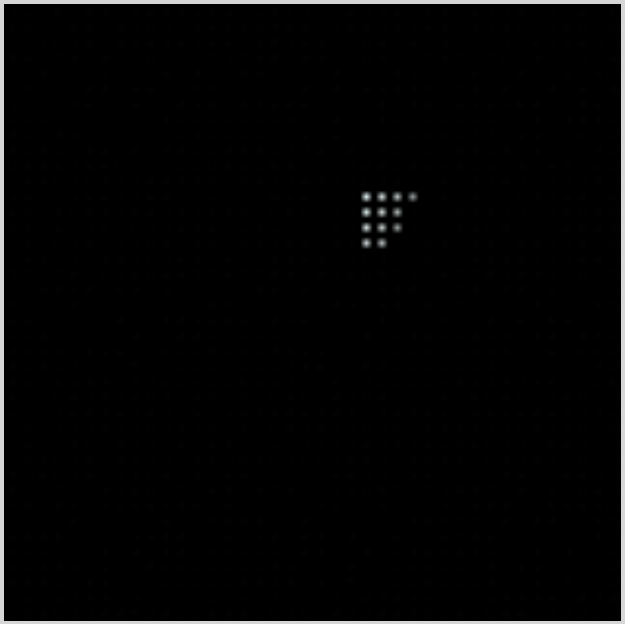
$$\nu_0 = 1.15\,\mathrm{GHz}$$



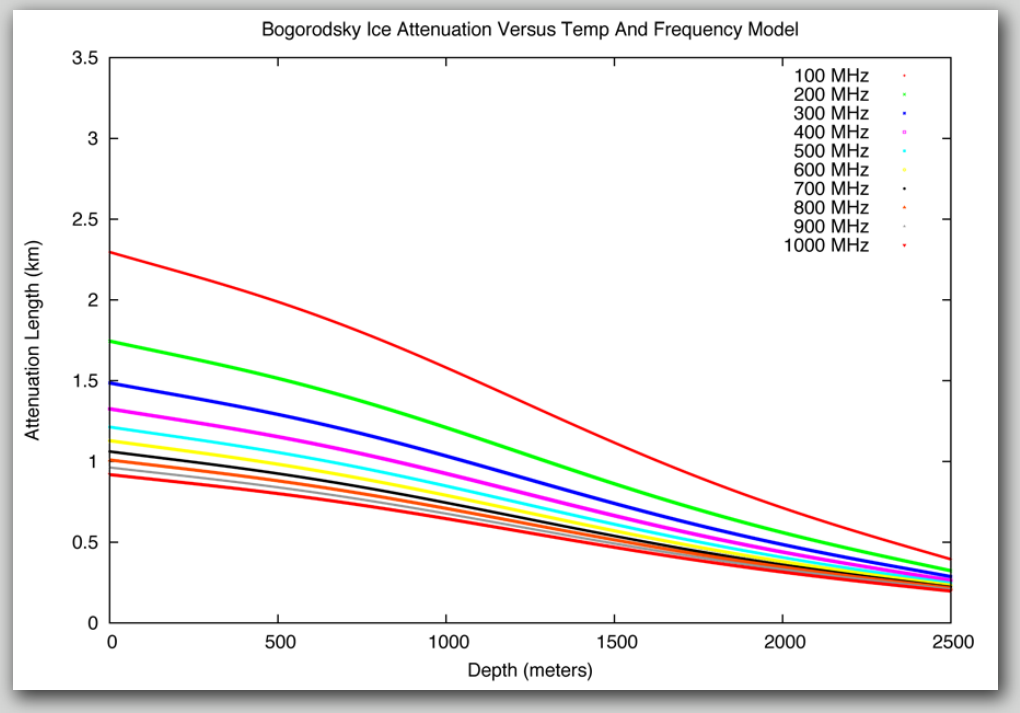


See Alvarez, Vázquez, Zas

Simple MC



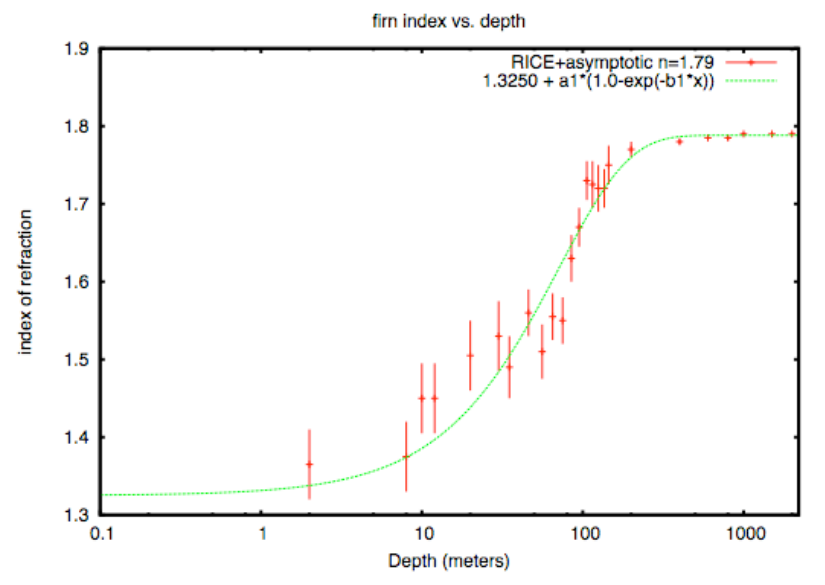
Radio transparency of glacial ice

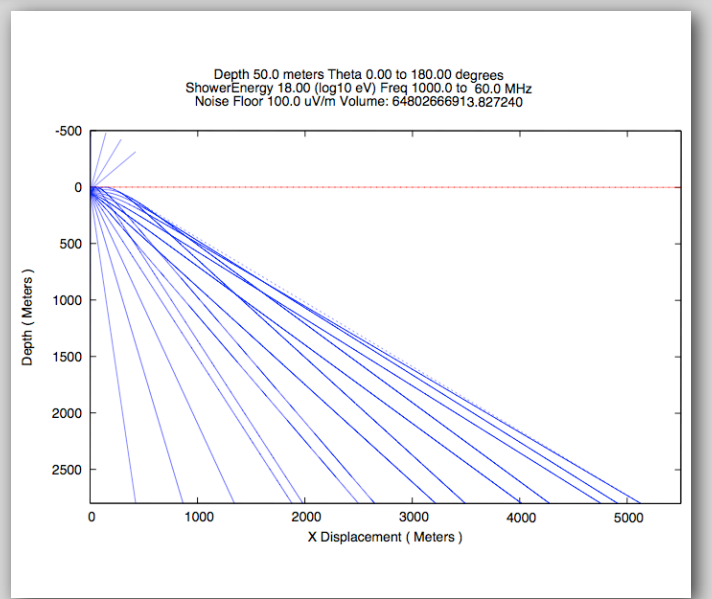


Measurements of radio pulse reflections off of the bedrock have been performed at South Pole by S. Barwick and D. Besson [S. Barwick APS04 presentation]. Data has been analyzed and supplemented with theoretical models and other ice temperature measurements to obtain detailed frequency and depth behavior.

Firn effects

- **Firn** the layer of compacted snow at the surface of the South Pole that has not yet been compressed into ice. The index of refraction varies as the density and in the firn it continuously changes from ~ 1.8 for the bulk ice to ~ 1.3 at the snow surface.
- You surely know what happens when light rays pass through graded indices …
- This has two undesirable effects for radio detectors near the surface:
  - The rays bend which means that the reconstruction must include non-trivial raytracing algorithms; there is also possibly more than one solution
  - Neutrino vertices can lie outside the ray horizon and therefore, even a loud nearby vertex could fail to be detected by an antenna.

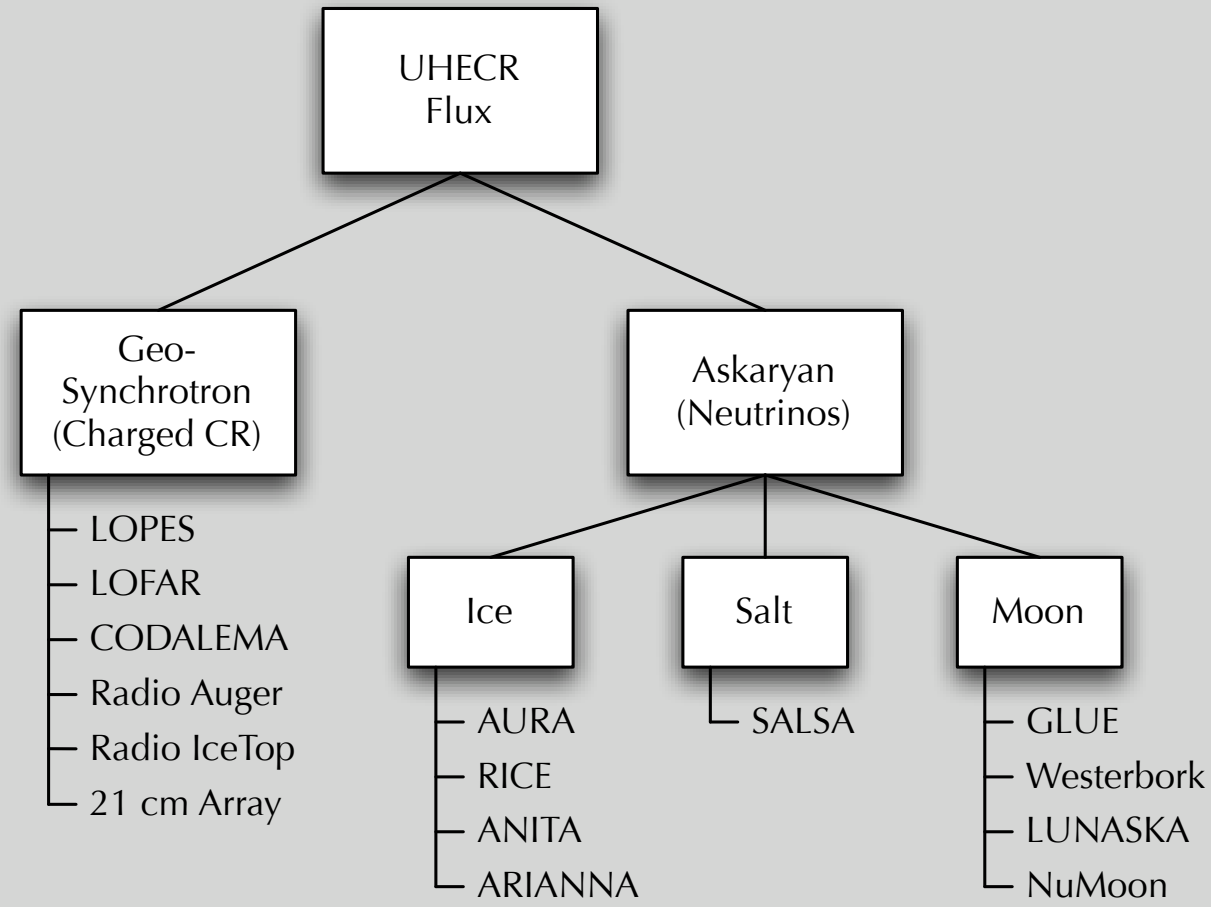




Part III

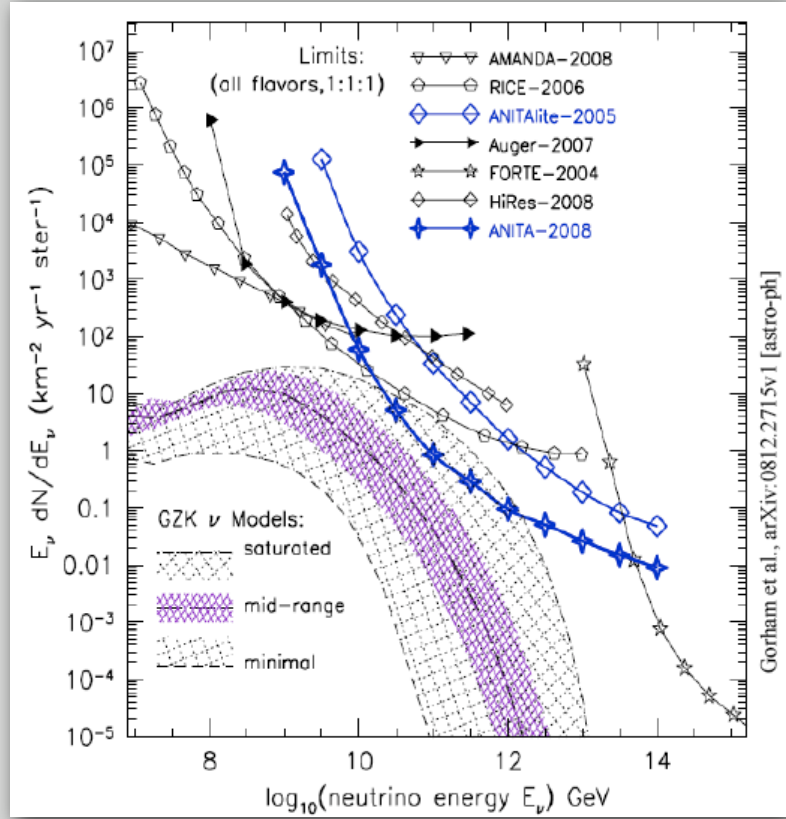
Review of existing Antarctic radio experiments

Radio detection of UHECR : the experiments

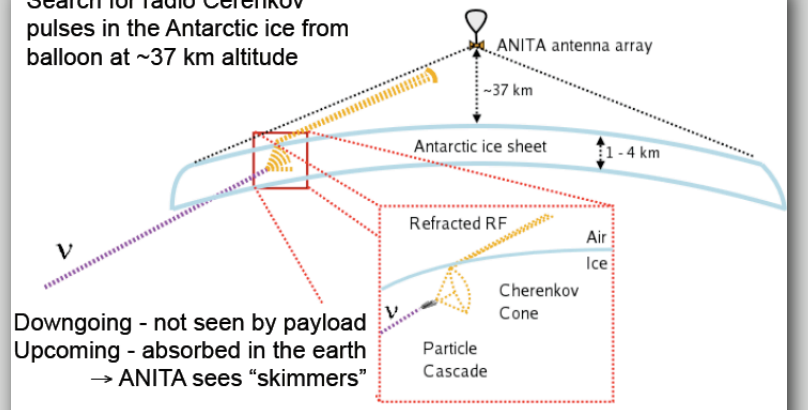


ANITA

ANITA balloon borne expt samples Antarctic ice sheet with array of H/V pol horn antennas feeding GHz WF capture devices.
Two runs: ANITA-I and ANITA-II (plus ANITA-"lite" earlier) - ANITA-II results pending.



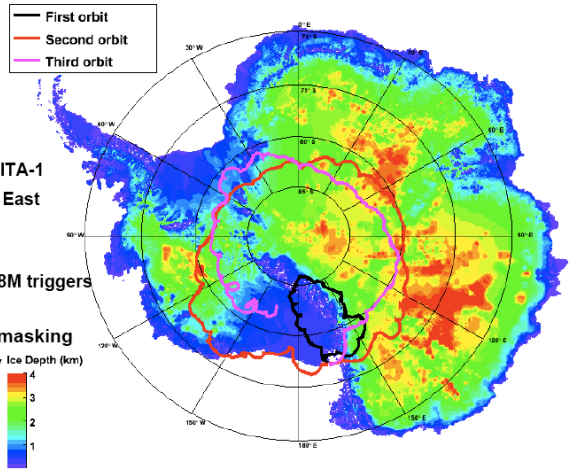
Search for radio Cerenkov pulses in the Antarctic ice from balloon at ~37 km altitude



Downgoing - not seen by payload
Upcoming - absorbed in the earth
→ ANITA sees "skimmers"

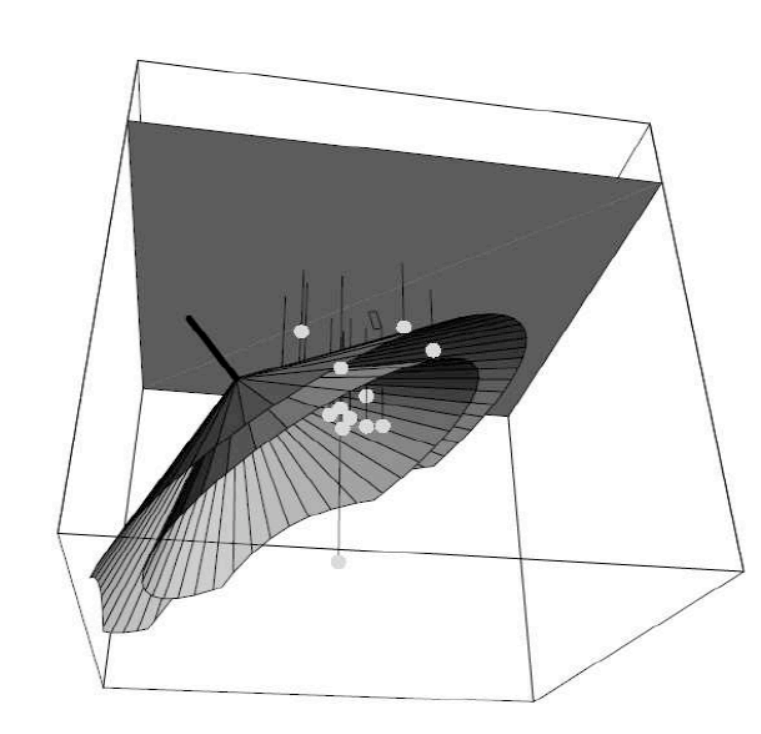
ANITA observes ~1.5 x 10^6 km^2 of ice at once!

ANITA-2: Beautiful Flight Path



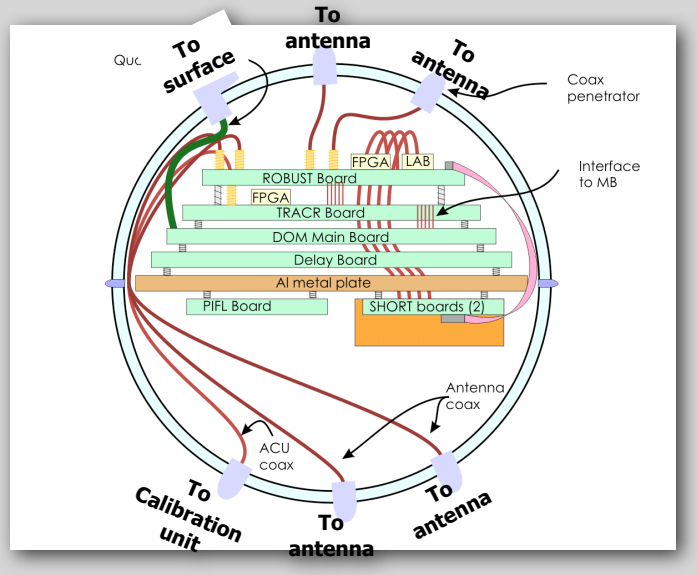
- 2+ Orbits
- Time aloft: 30d
- Compared with ANITA-1
  - More time over East Antarctica
  - Avoided S.P.
  - 27M triggers > 8M triggers
    - (and better!)
- Dynamic azimuth masking worked beautifully

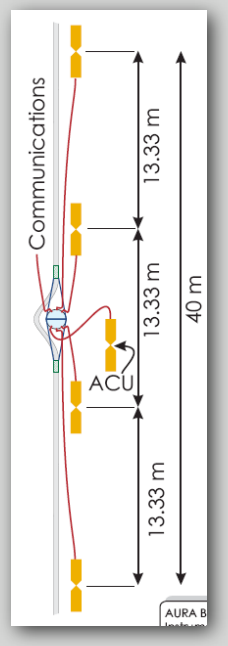
RICE



- 16 fat-dipole antennas (200 MHz - 1 GHz) deployed at shallow depths in AMANDA holes
- Analog signals sent to surface and digitized by triggered DSOs.
- From approx. 13000 hours live time limits on flux of neutrinos 10 x WB.
- Energy threshold of 100 PeV

AURA

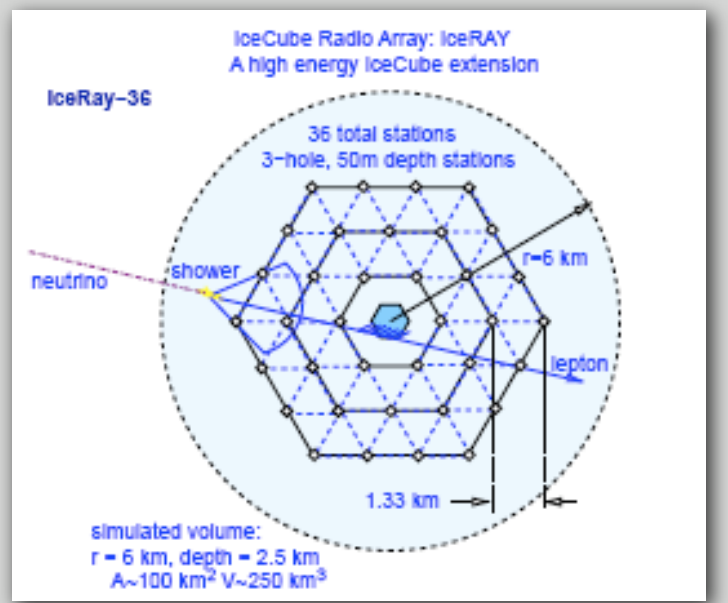


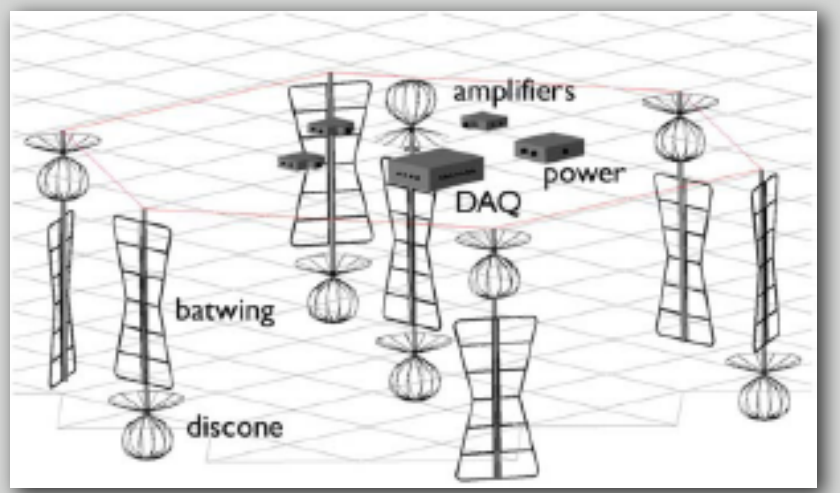




- AURA is marriage of IceCube DOM technology to support electronics in deep ice, comms, timing with ANITA front end (trigger system and waveform capture unit) and RICE “fat dipole” antennas.
- 2 AURA DRMs (digital radio module) deployed 2006-2007 year (1 shallow, 1 deep), 3 deployed last year (2 shallow, 1 deep) in IceCube holes
- Data collection and analysis by small team of dedicated individuals - finally this year we are beginning to see good measurements of ice attenuation and identification of background signals.

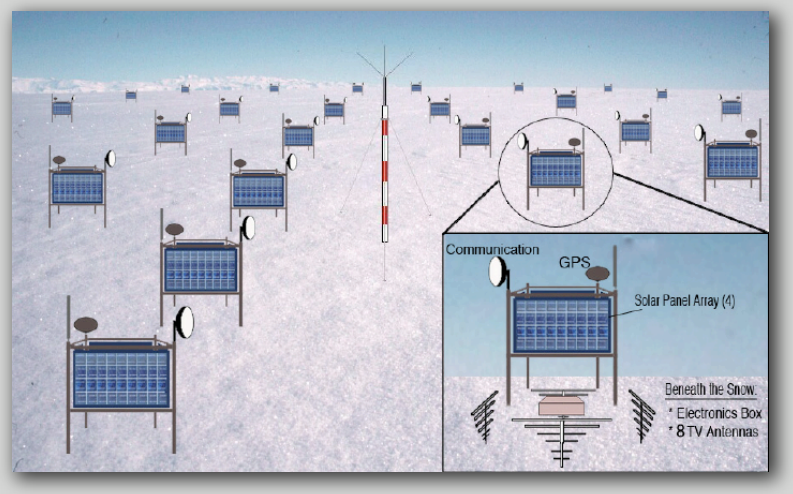
IceRay

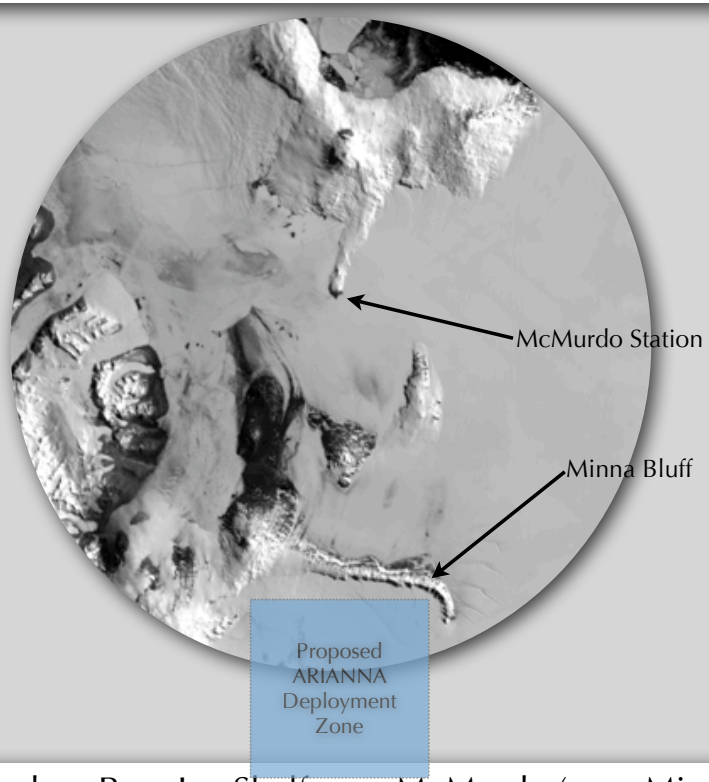




- IceRay is the name of one of the initial large-scale proposals from group composed of ANITA and South Pole radio physicists to construct 100 km^2 detector based on ANITA technology
- The group had prepared a testbed which was a surface prototype station outfitted with a multitude of antennas buried at shallow depths (meters) in order to study backgrounds at South Pole
- Developed and waiting, the testbed was turned down for deployment support by NSF.

ARIANNA





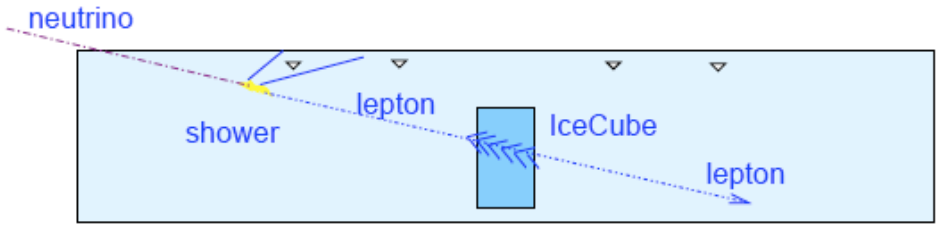
- ARIANNA is array of radio detectors to be deployed on Ross Ice Shelf near McMurdo (over Minna Bluff to obscure noise from busy McMurdo station)
- Full detector array would be 100x100 array covering 900 km^2 from 2015-2020 (2000 stations per year assumed)
- In 2006 test station was deployed to prove concept and assessment of properties of site
- Solar powered stations only operation 50% of year but array is large enough to compensate for limited duty cycle.
- MRI is in preparation for later this summer.

Part IV

Designing a GZK neutrino array at the South Pole (merger of IceRay, AURA, surface airshower groups)

Why South Pole?

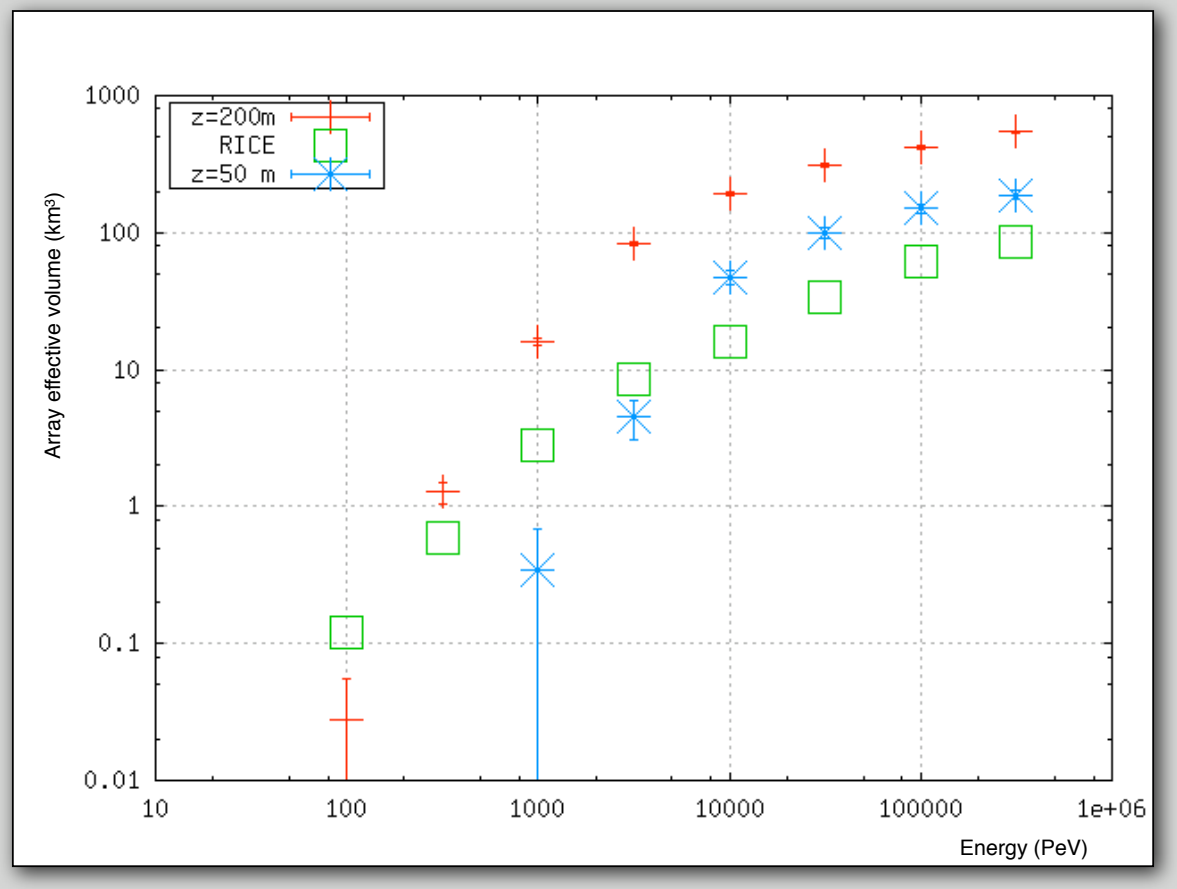
- Profit from favorable conditions presented by South Pole site
  - 3 km thick glacier of cold, radio-transparent ice
  - SPS infrastructure - power, comms, logistics
- Leverage existing IceCube facility
  - Hybrid detection of multi-PeV events
  - Radio air-shower array enhances IceCube physics



Design Considerations

- Array density: grid of 500 m spacing
- Depth: get beneath firn if possible (200 m); at least > 50 m
- Power and communications: undefined at this point, it's obviously advantageous to remain low power. Currently favor wired system to deliver power and data transmission - for 100 km^2 array but this is likely unfeasible for larger array. I personally feel this hurdle should be solved in the short term.
- Sensitivity: target effective volume of O(1 km^3) for each sensor at 100 PeV - this gives full coverage for 500 m array spacing

Effective volume versus depth



Noise

- Overcoming noise is not surprisingly a central theme … for this application important sources are
  - **kT noise** thermal noise from the antenna. Being in the ice at 250 K helps this - a typical system of 100 MHz BW will have -125 dBW noise (equivalent to about 5 μV into 50 ohms)
  - **anthropogenic noise** things like radios, snowmobiles emit EM pulses that could fake a signal. Good vertex reconstruction important - this background localized to ice surface
- kT noise sets lower limit on signal detectability - LNA at front end needed to boost signal

Signal capture : two approaches

- Waveform digitization
  - Maximal capture of information content from signal: frequency, phase
  - Comes at price of additional cost, complexity, power, data volume and data processing overhead
  - This is the gold standard: ANITA, AURA, RICE, ARIANNA
  - These devices actually use envelope detectors (tunnel diodes) for triggering
- Envelope detection
  - Explosion cellular and other commercial: cheap, low-power, simple ICs now available
  - Information is lost at digitization but value of this information is unclear in large-scale array
  - Lower frequency envelope (10 - 100 MHz) can be detected local to antenna and sent to surface easily.
  - The basic principle - replace the redundancy of waveform capture with higher density array for background rejection - lower threshold.
- The chosen technology must be capable of
  - Measuring the weak Askaryan pulse - the target energy thresholds in region of 10's - 100's of PeV.
  - Separating background (anthropogenic noise) from signal with high confidence

Example of envelope detection in lab

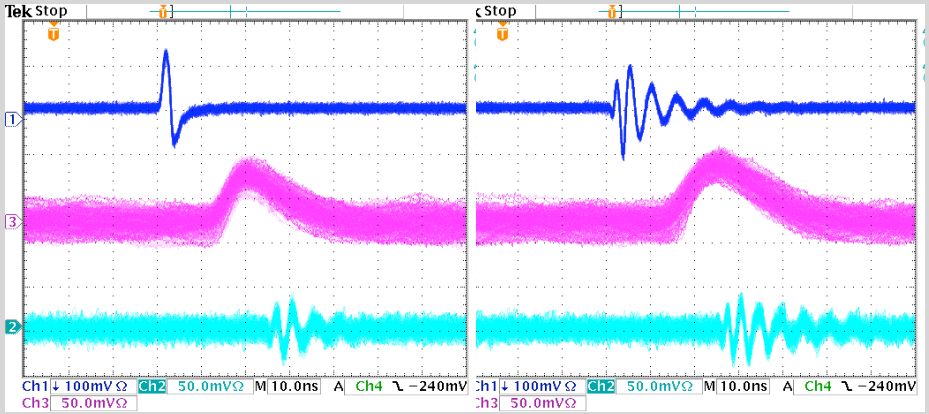
TDA vs. AURA / IceRay
Low-level Sensitivity

With long persistence to show electronics noise

200uV$_{p-p}$ Stimulus

TDA Output

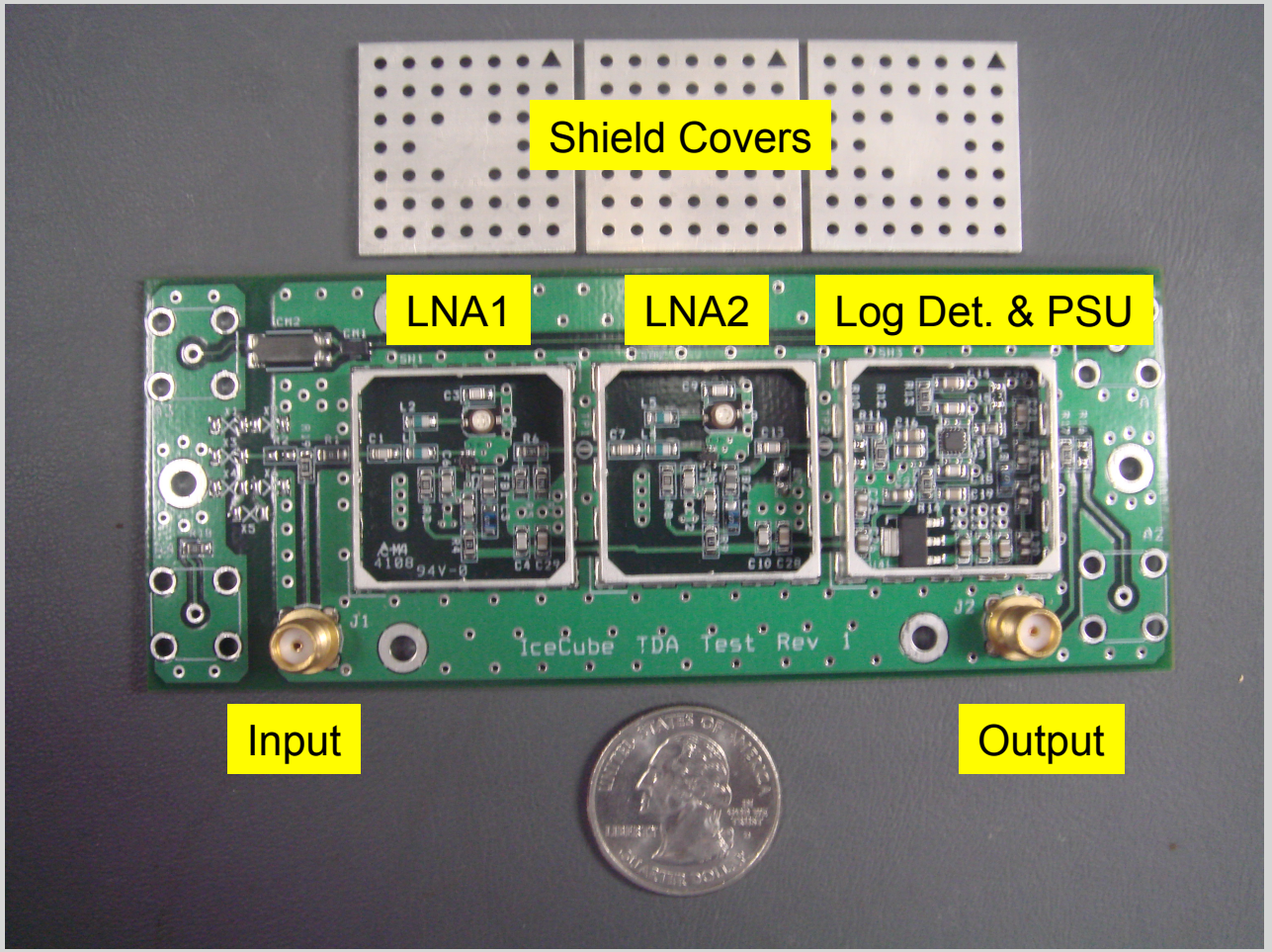
AURA Front End Output



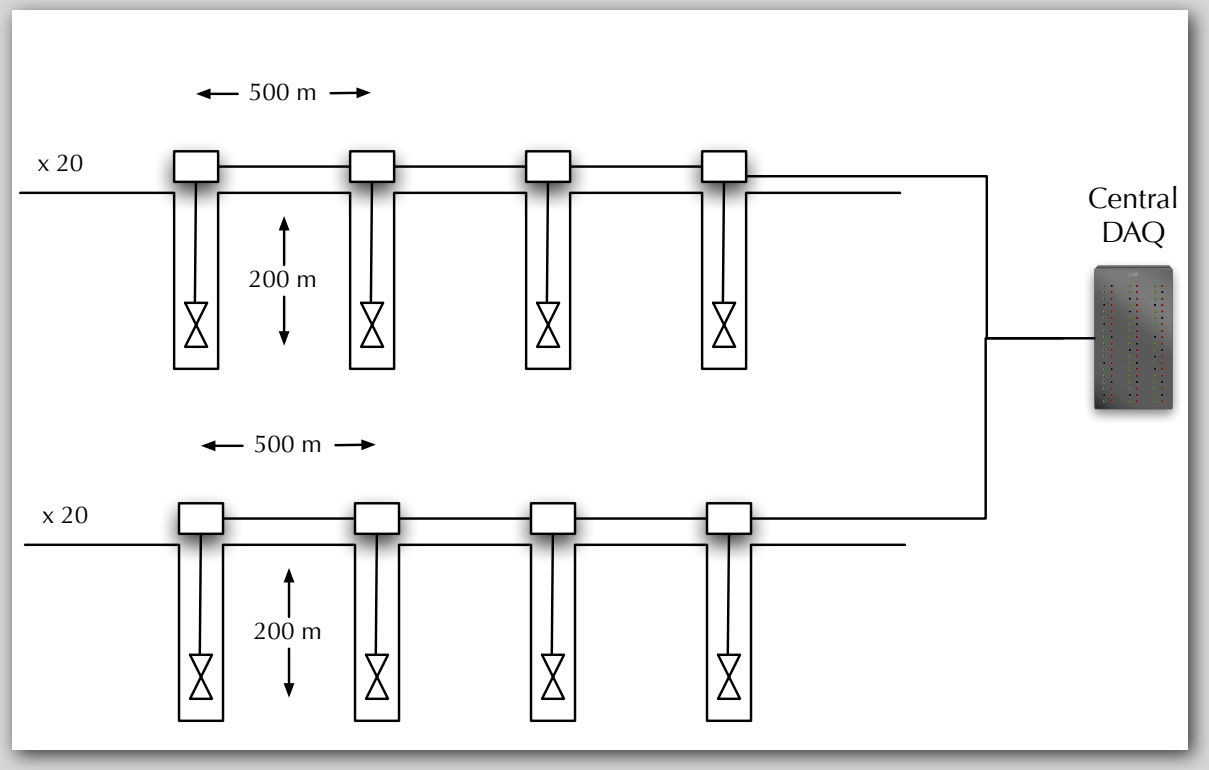
Short Bipolar Pulse
2.5ns pulse through 22pF capacitor

“Antenna-like” Transient
2.5ns pulse through SHP-200 (185MHz-800MHz)

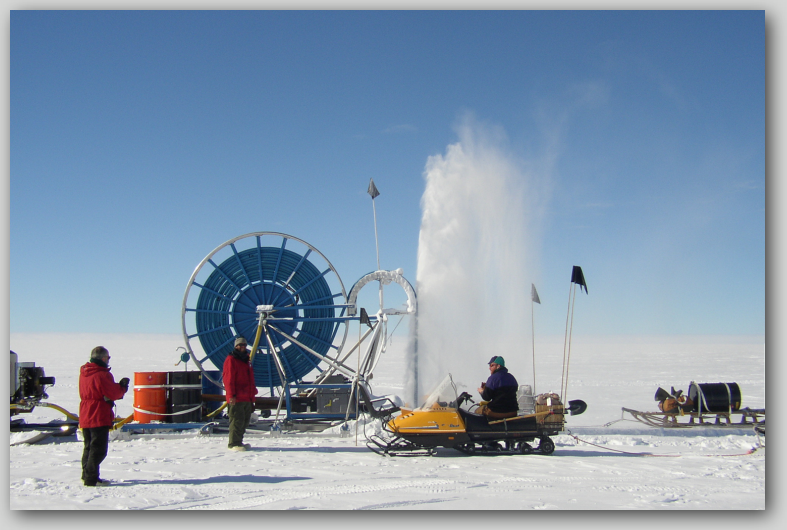
Prototype front-end



Strawman design for Phase II array



Drilling and deployment



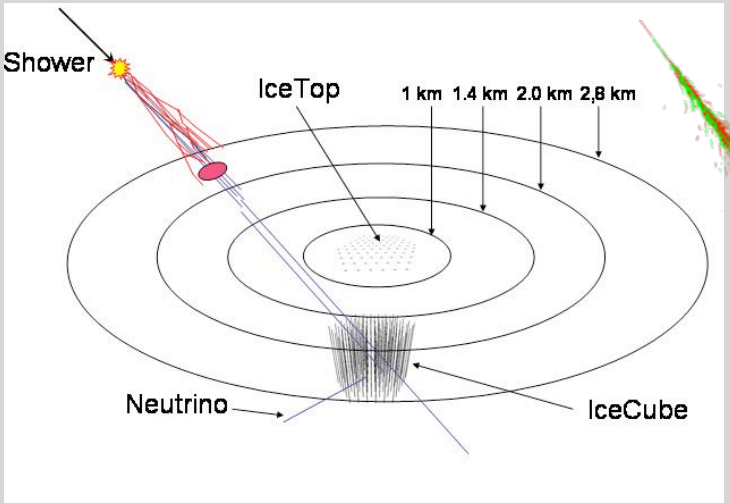


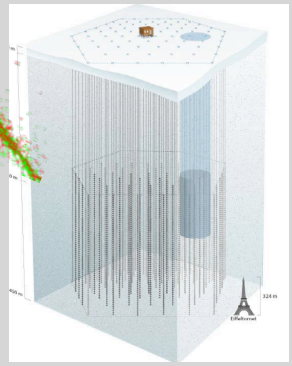
- Drilling needs quite different from IceCube
  - Shallow (200 m) hole to get beneath firn layer
  - Small diameter OK
  - Dry holes OK
  - Need many holes fast
- RAM drill uses compressed air to drive mechanical cutter
  - 4″ holes
  - 6 gal per 60 m hole
  - 20 min per hole

Timeline - 3 phase approach

- US groups submitting MRI O(4 M$) 2009 …
- Phase I (2010-2012): small R&D deployment
  - Deploy sensors up to 1.5 km outside of IceCube
  - Development of envelope detector technology, compare with waveform capture and finally make decision
  - Drilling development
  - DAQ infrastructure development
- Phase II (2012-2015): 100 km^2 array
  - Expected event rate - 2 to 5 GZK neutrinos / year
  - Decide on feasibility of future array
- Phase III (2015-?): 1000 km^2 array (???)

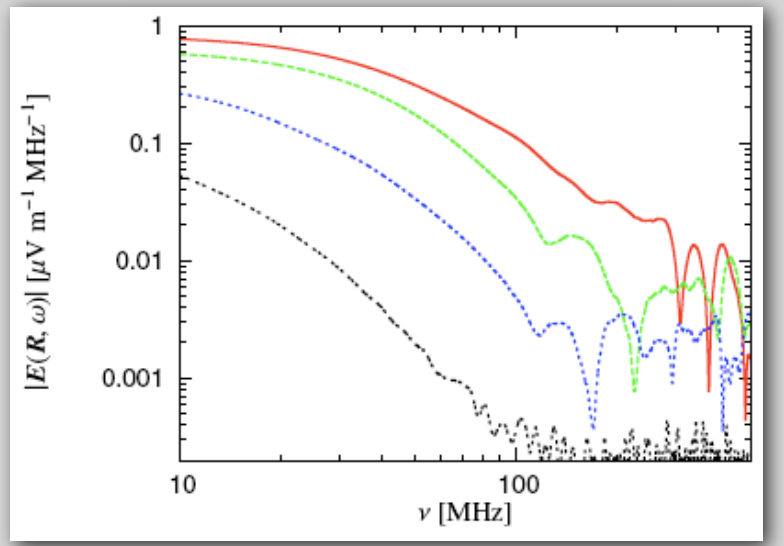
Surface radio airshower array





Huege and Falcke, A&A **430**, 779-798 (2005)

- MRI proposal contains surface array option to profit from infrastructure and deploy instrumentation at surface to detect 10-100 MHz radio waves from UHECR (geosynchrotron)
- Also has been proposed to use CR shower cores as Askaryan sources for verification of deep array (current AURA task).



Conclusions

- Auger well-measured UHECR fluxes and confirmed GZK cutoff - the fluxes of GZK neutrinos should now be solidly grounded .
- After several years of R&D a new large-scale radio initiative seems poised to launch at South Pole.
- Simultaneously (in fact perhaps a bit ahead) ARIANNA is planning to gear up the Ross Ice Shelf with an array of 100 km^2 by 2013.
- ANITA-II results this year will either find GZK neutrinos or cut into the current flux estimates and restrict fluxes to lower end of range.