Experimental Particle Astrophysics in Antarctica

New Vistas in Astronomy Lecture Series

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CCAPP @ OSU

Outline

I. **Cosmic Ray Origins** ... *A 100 year journey*
II. **Antarctic Science** ... *Beautiful and Dangerous*
III. **Detectors and Discoveries** ... *Culmination*
IV. **Future Designs** ... *Expanding the Horizon*

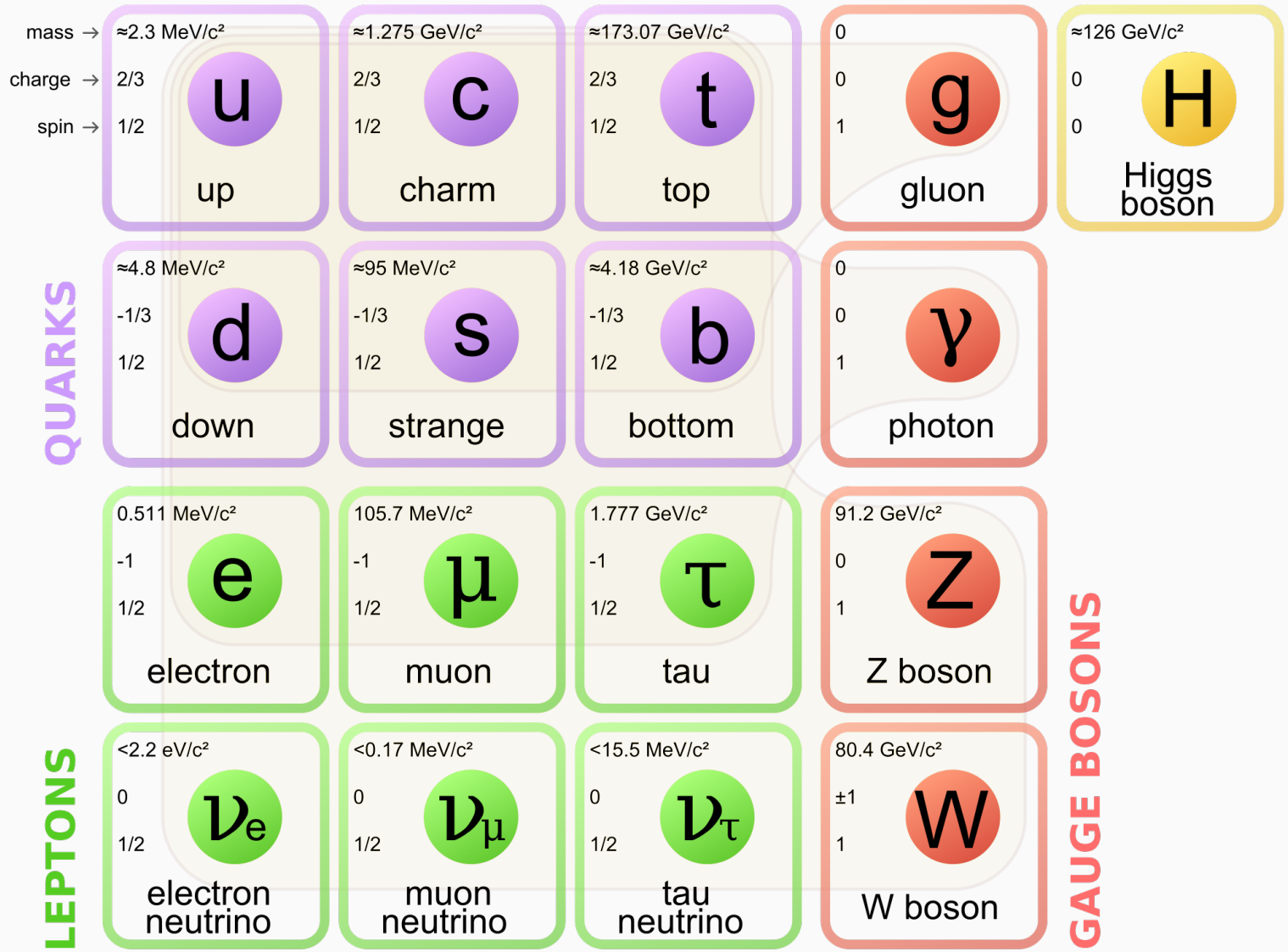
Cosmic Ray Origins

Cosmic Ray Origins … *Definition of a Cosmic Ray*

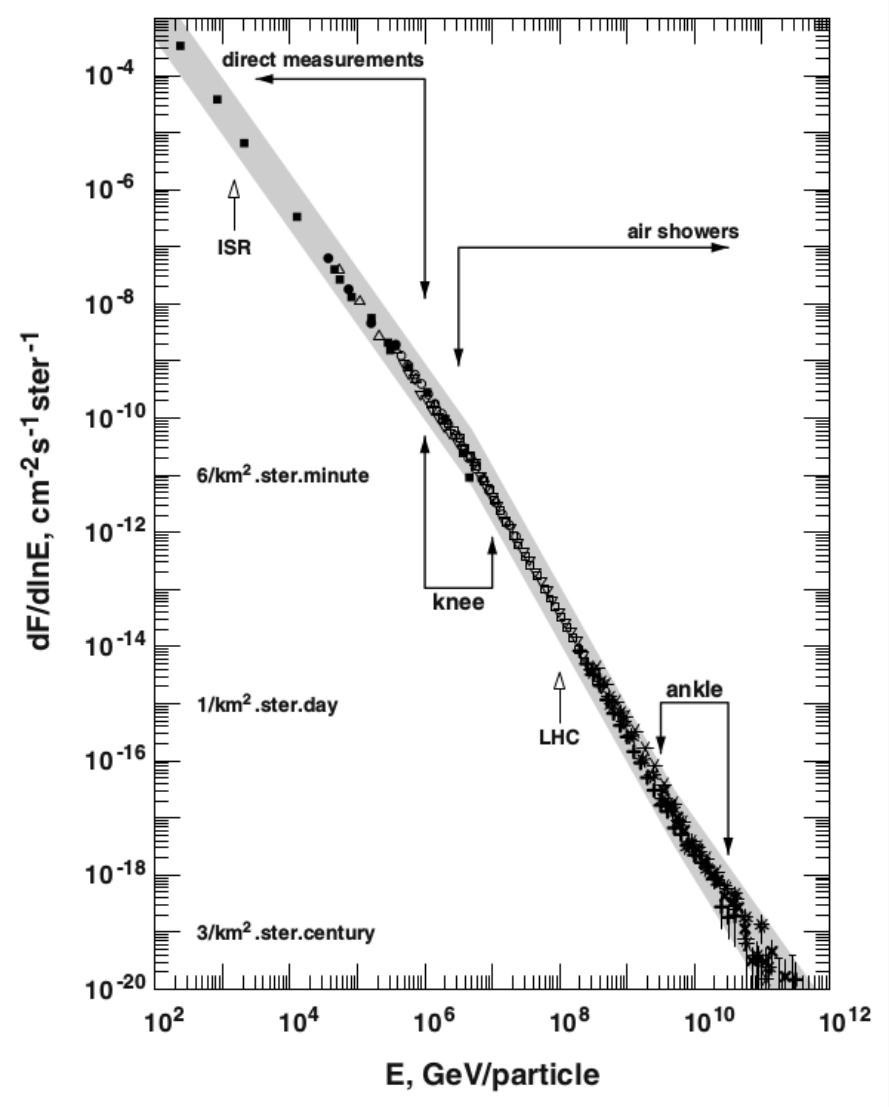
Definition of a Cosmic Ray *A cosmic ray is a relativistic particle in deep space.* Often in science, decades of work can be encapsulated in a single statement. Cosmic rays, like all other particles, have the following properties:

- Total Energy and Rest Mass
- N/Z, the number of nucleons, the number of protons
- Momentum, in a certain direction
- Flux, in units of particles per area per solid angle per time

Particles and Astro-physics



Cosmic Ray Origins … *The Energy Spectra*



Definitions

Flux in $km^{-2}str^{-1}min^{-1}$

Direct Measurement

Air Shower

Energy in GeV

LHC

Knee, Ankle

Cosmic Ray Origins … *Discoveries that led to this picture*

From Earth or from Space?

Fr. Theodor Wulf (Jesuit priest), electroscope discharge vs. height, Eiffel Tower, 1909

Domenico Pacini, Prof. Physics, Bari, Italy. Electroscope discharge vs. depth underwater, Livorno, Italy, 1911

Victor Hess, Prof. Physics, Vienna, Austria. Electroscope discharge vs. balloon height, Austria, 1911-12

Robert Millikan and Arthur Compton. Research confirmed that particles were from space, and charged. 1930s Chicago, California

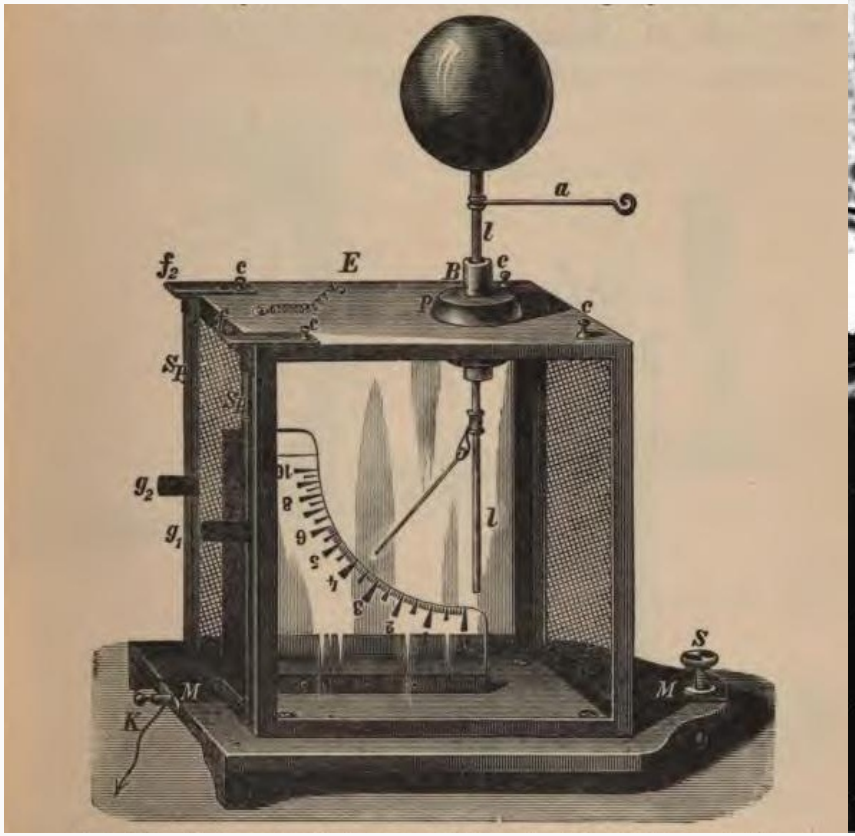
Cosmic Ray Origins ... *Discoveries that led to this picture*

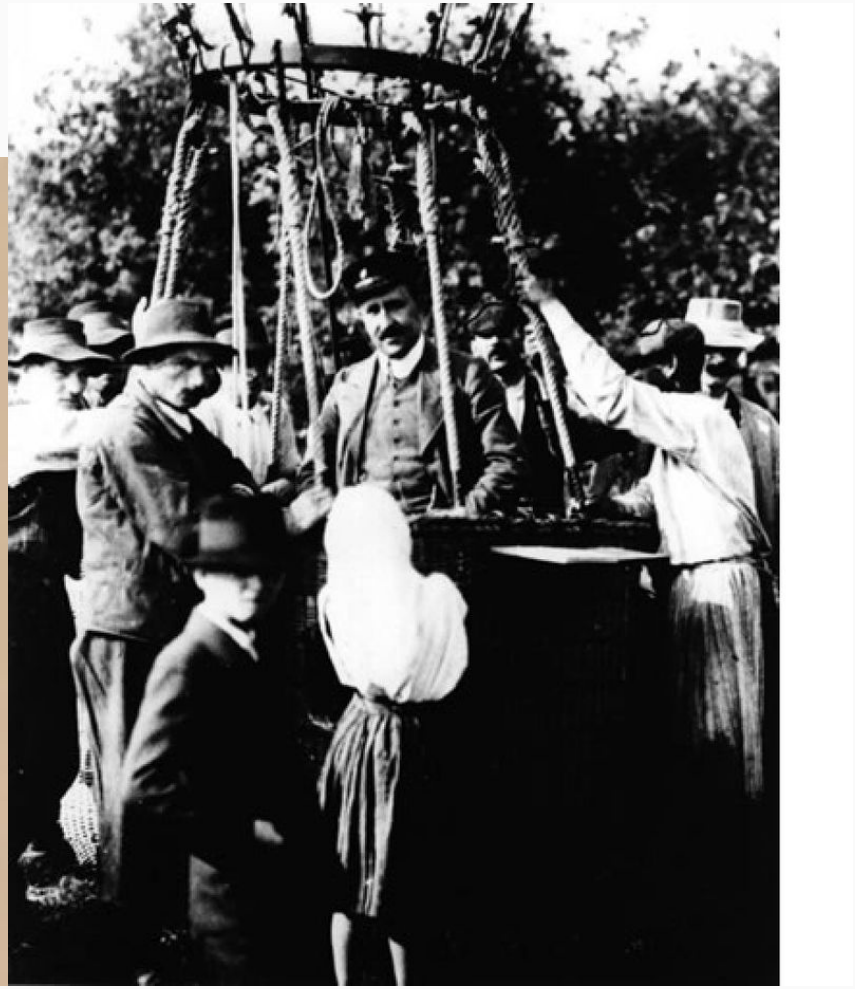
But what's in there?

Charles Wilson wins Nobel Prize for invention of cloud chamber, 1927. Allows photography of sub-atomic tracks

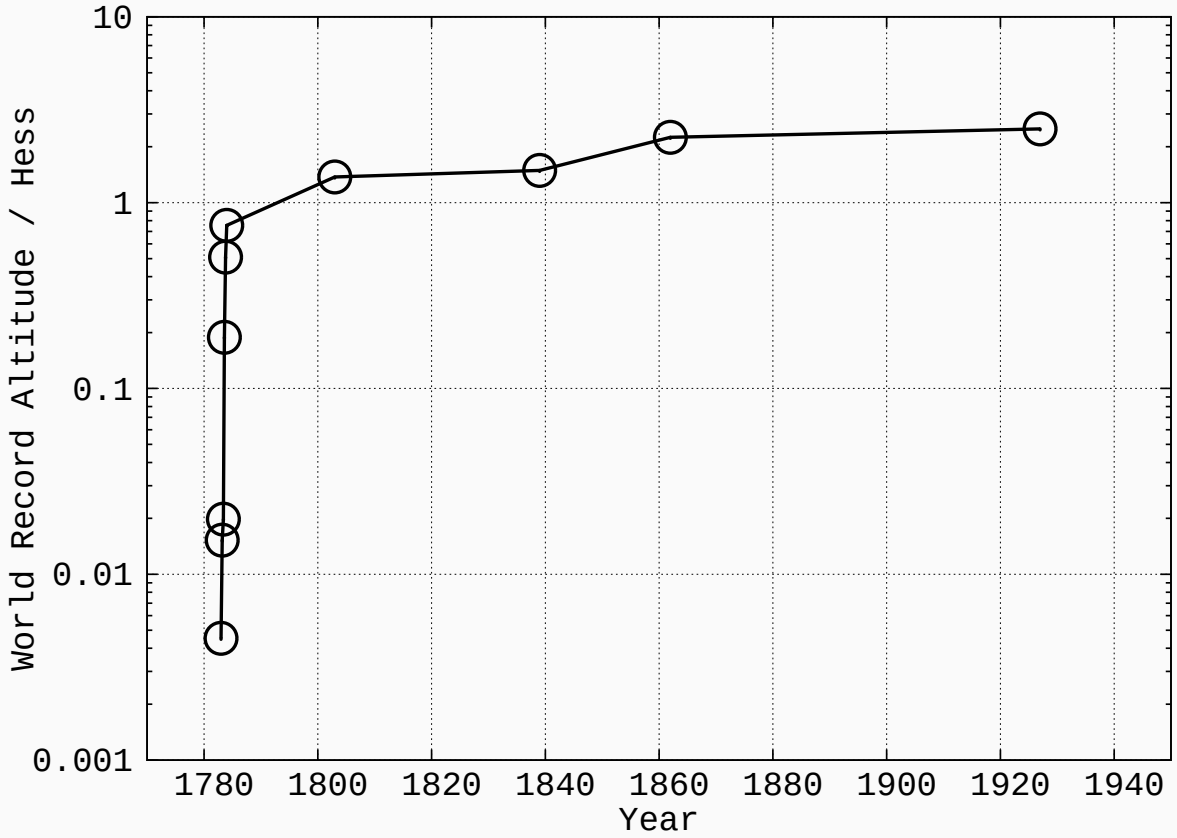
Carl Anderson discovers muon and positron, shares 1936 Nobel Prize with Victor Hess. Anti-matter (positron) discovered in cosmic rays

Cosmic Ray Origins … *1936 Nobel Prize, Culmination*





Cosmic Ray Origins … *1936 Nobel Prize, Culmination*



Cosmic Ray Origins … *1936 Nobel Prize, Culmination*

Table 2.1 Summary of Hess' results

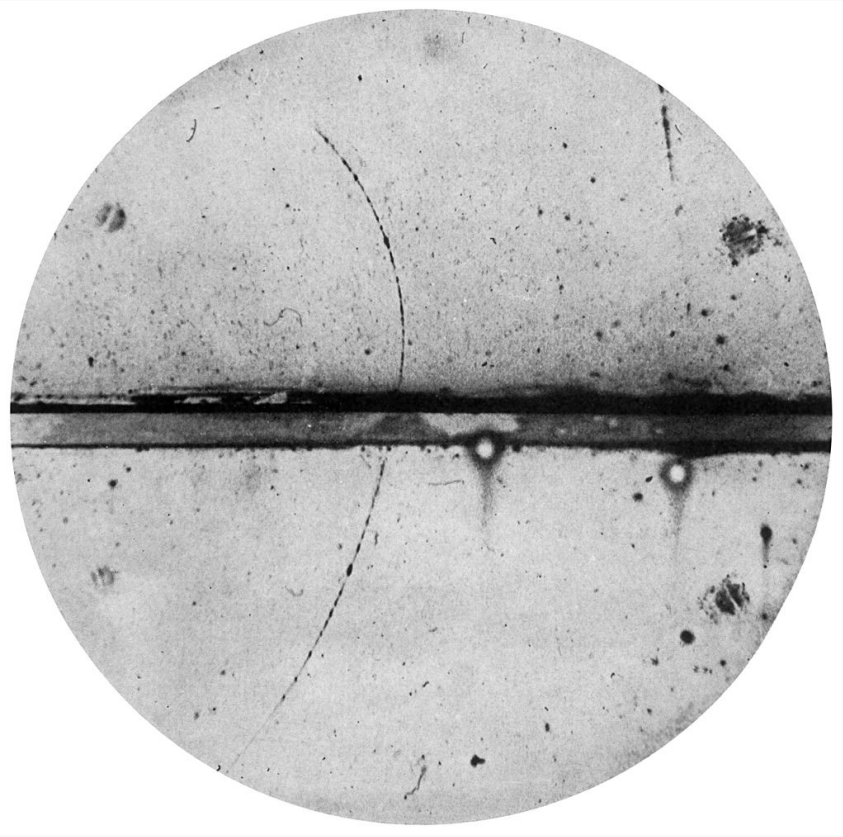
	Measured radiation (ions per cc per second)		
Mean height from ground (m)	Electrosc. 1	Electrosc. 2	Electrosc. 3
0	16.3	11.8	19.6
Up to 200	15.4	11.1	19.1
300–500	15.5	10.4	18.8
500–1,000	15.6	10.3	20.8
1,000–2,000	15.9	12.1	22.2
2,000–3,000	17.3	13.3	31.2
3,000–4,000	19.8	16.5	35.2
4,000–5,200	34.4	27.2	–

Table 2.2 Differences between altitude and ground measurements

	Variation between altitude and ground (ions per cc per second)			
Mean height from ground (m)	Electrosc. 1	Electrosc. 2	Electrosc. 3	Mean
300–500	−0.8	−1.4	−0.8	−1
500–1,000	−0.7	−1.5	1.2	−0.3
1,000–2,000	−0.4	0.3	2.6	0.8
2,000–3,000	1	1.5	11.6	4.7
3,000–4,000	3.5	4.7	15.6	7.9
4,000–5,200	18.1	15.4	–	11.2

Cosmic Ray Origins … *1936 Nobel Prize, Culmination*

Cosmic Ray Origins … *1936 Nobel Prize, Culmination*



All the best discoveries are simple and clear. The lead plate decreases energy of the positron, increasing curvature. The magnetic field goes into the page.

What is the GZK effect?

One version:

$$p^+ + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+ \tag{1}$$

$$n + \pi^+ \rightarrow e^+ + \nu_\mu + \bar{\nu}_\mu + \nu_e \tag{2}$$

The initial cosmic ray (the proton) cannot propagate across the universe forever. It interacts with ambient photons and decays into electrons, positrons, neutrinos, and *lower energy cosmic rays*.

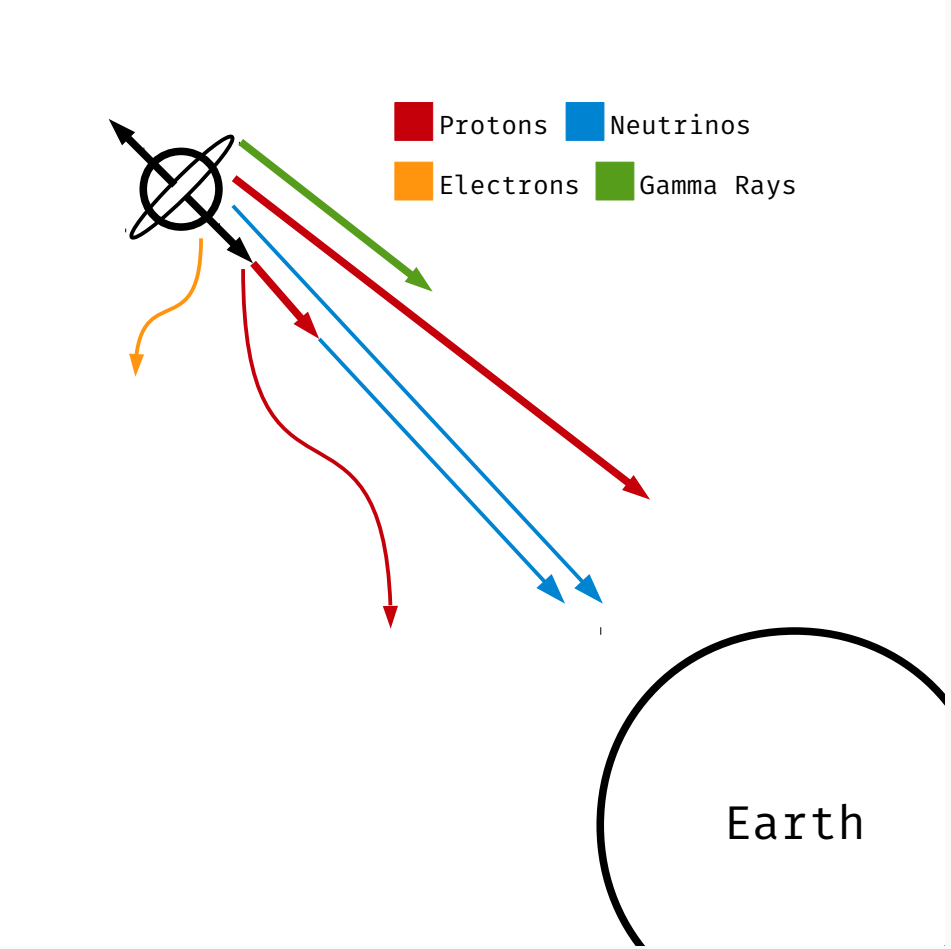
Cosmic Ray Origins … From the 1960s to Today

Multi-messenger astrophysics and particle physics = astro-particle physics

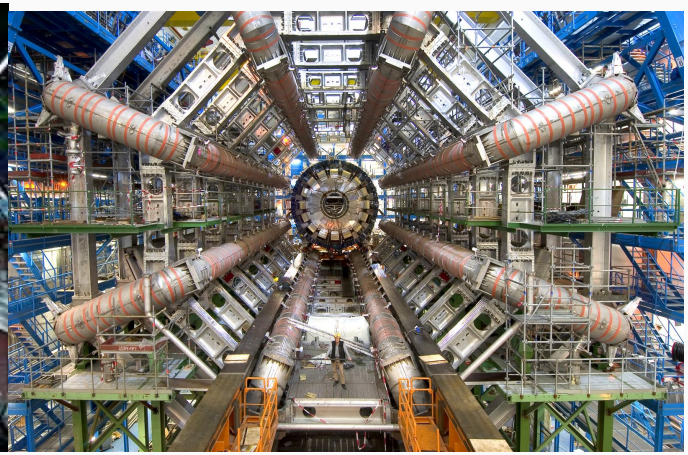
The GZK-cutoff

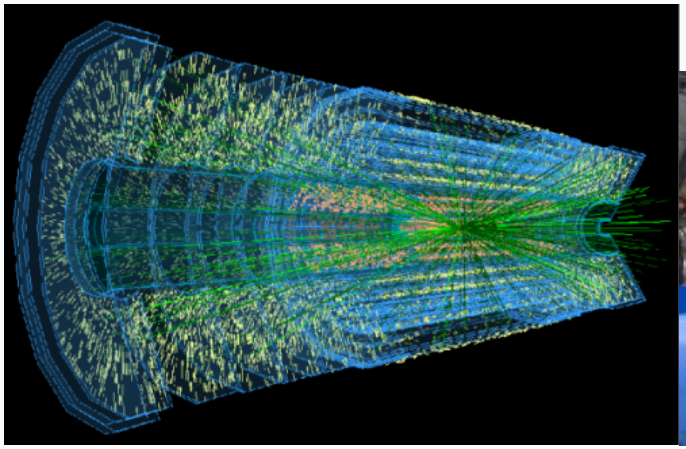
Double-edged sword

Unimaginable distances



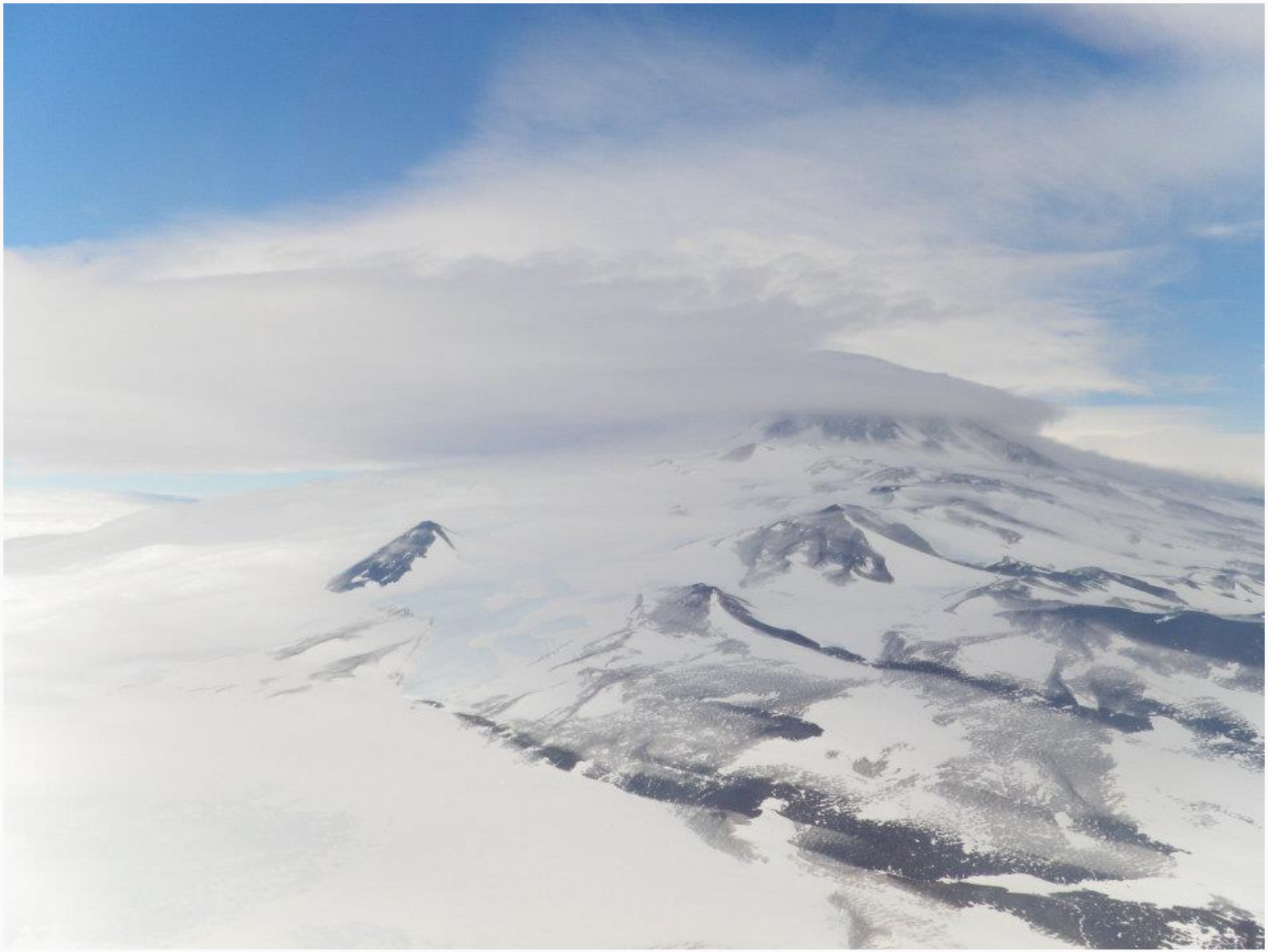
And then came the machines … (10 TeV)





Antarctic Science

Antarctic Science … A Beautiful, Scientific Wonderland



Antarctic Science … 25 years ago, someone had a bright idea

Gurgen Askaryan had published on the "Askaryan effect" in the 1960s

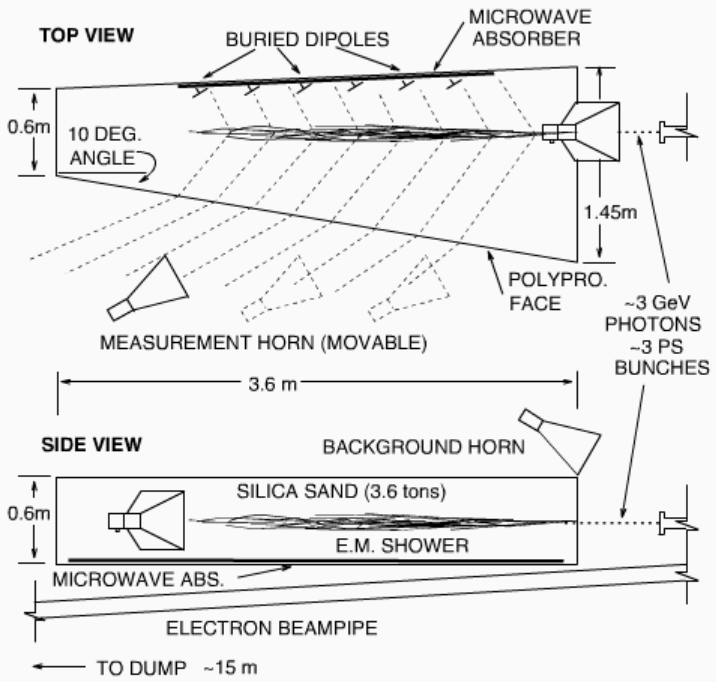


FIG. 1. Sectional views of the target geometry.

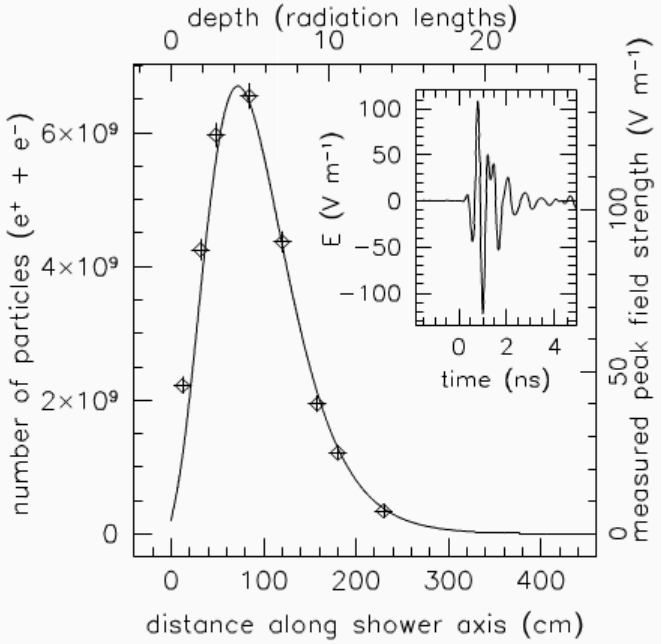
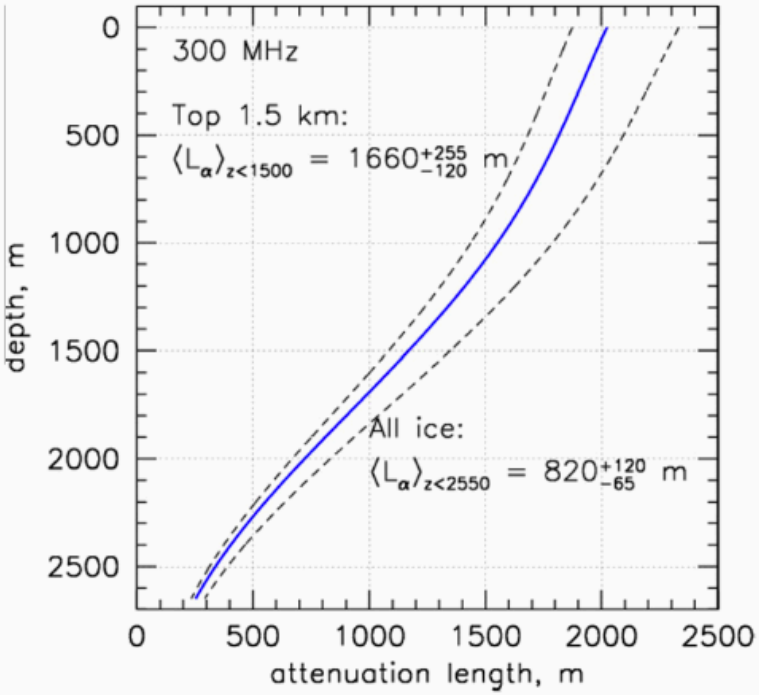


FIG. 2. Expected shower profile (solid line), with measured peak field strengths (diamonds) plotted normalized to the peak. Inset: typical pulse time profile.

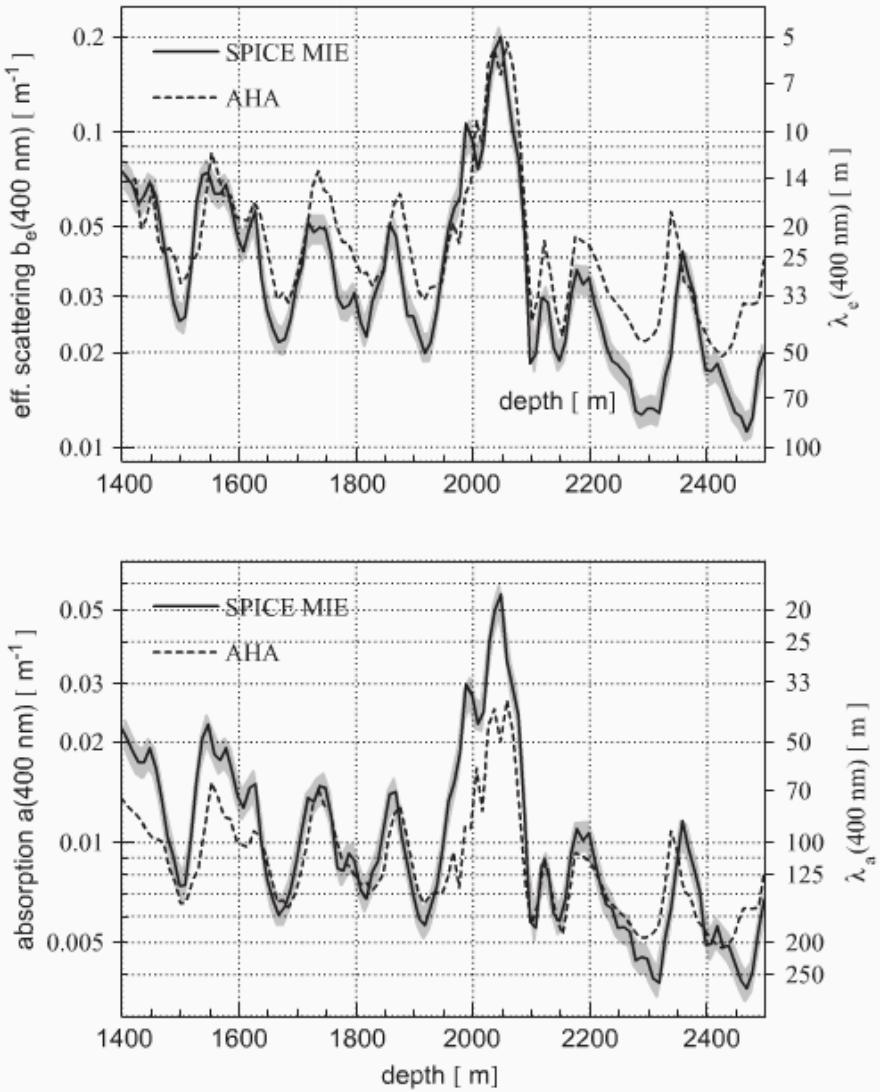
Antarctic Science … Antarctic Ice is Radio Clear

Table 3. Summary of dielectric parameters. The first column is the frequency, ν, followed by the attenuation lengths, which are uncorrected ($\langle L_0 \rangle$) and corrected ($\langle L \rangle$) for $\sqrt{R} = 0.82 \pm 0.07$. The fourth column is $\langle L \rangle$ expressed in dB km^{-1}. The imaginary part of the dielectric constant, ϵ'', is shown in the fifth column. The final column shows $\nu \tan\delta$ (GHz). The typical error on the quantity $\nu \tan\delta$ is 0.2×10^{-4}

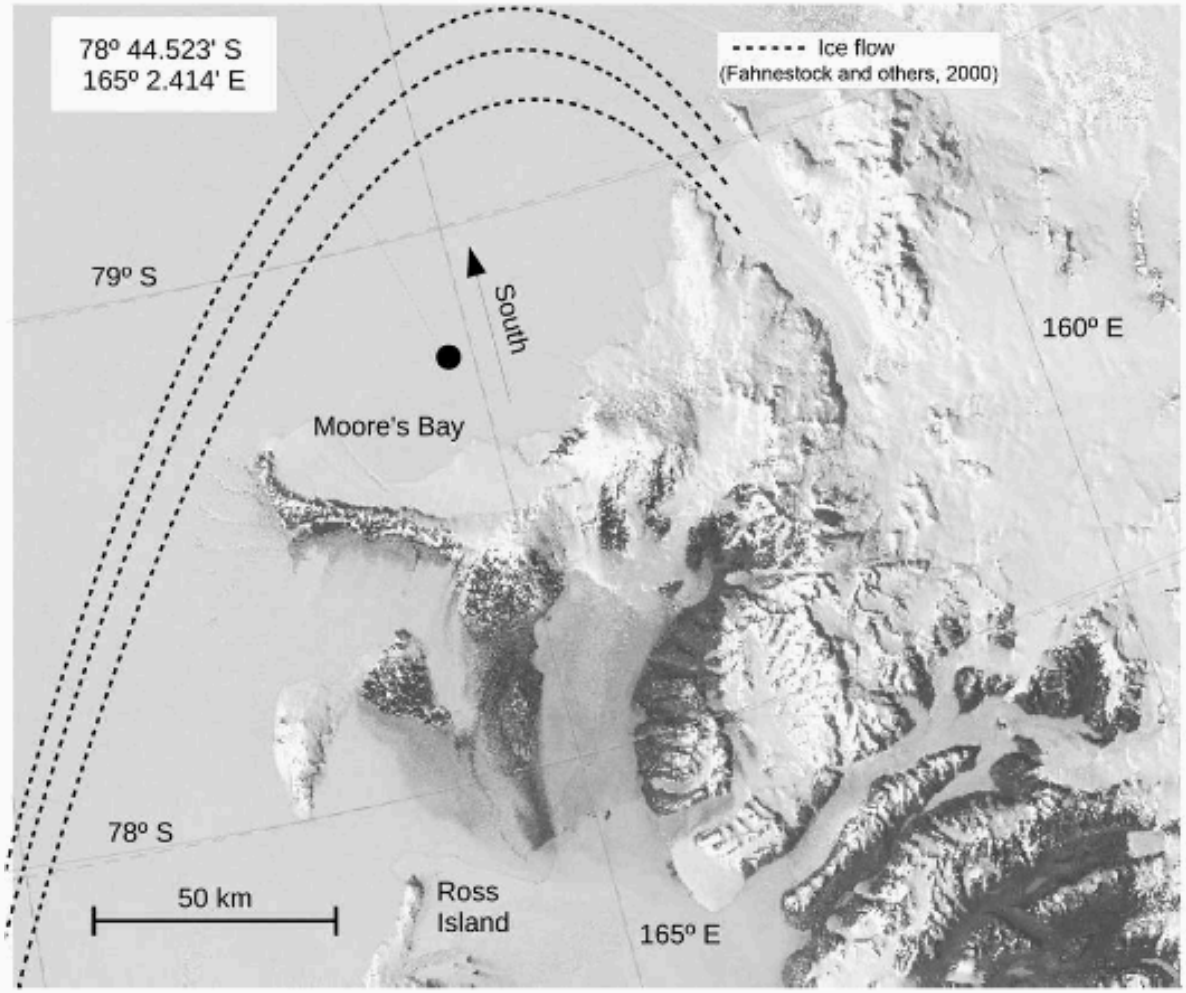
ν	$\langle L_0 \rangle$	$\langle L \rangle$	$\langle L \rangle$	$\epsilon'' \times 10^3$	$\nu \tan\delta \times 10^4$
GHz	m	m	dB km^{-1}		GHz
0.100	432	449	19.3	3.8	1.2
0.175	467	487	17.8	2.0	1.1
0.250	457	476	18.2	1.4	1.1
0.325	422	438	19.8	1.2	1.2
0.400	408	423	20.5	1.0	1.3
0.475	366	378	23.0	0.95	1.4
0.550	349	360	24.1	0.86	1.5
0.625	363	375	23.2	0.72	1.4
0.700	331	341	25.5	0.71	1.6
0.775	310	319	27.2	0.69	1.7
0.850	320	329	26.4	0.61	1.6
Ave.	380 ± 16	400 ± 18	22 ± 1	1.3 ± 0.3	1.37 ± 0.06



Antarctic Science … Antarctic Ice is Optically Clear



Antarctic Science … In the Name of Science: McMurdo Base



Antarctic Science … McMurdo Base. Nice vacation spot.

Antarctic Science … McMurdo Base: Training

Formal name: Snow School 1. Actual name: **Happy Camp.**

Menu: Beef noodles, tears (before they freeze).

Antarctic Science … Amundsen-Scott Base, South Pole

Antarctic Science … Amundsen-Scott Base, South Pole

Antarctic Science … Amundsen-Scott Base, South Pole

Antarctic Science … Live Webcams

For more information, go to

http://usap.gov - United States Antarctic Program

https://arianna.ps.uci.edu

http://ara.wipac.wisc.edu/home

http://icecube.wisc.edu

http://www.phys.hawaii.edu (ANITA)

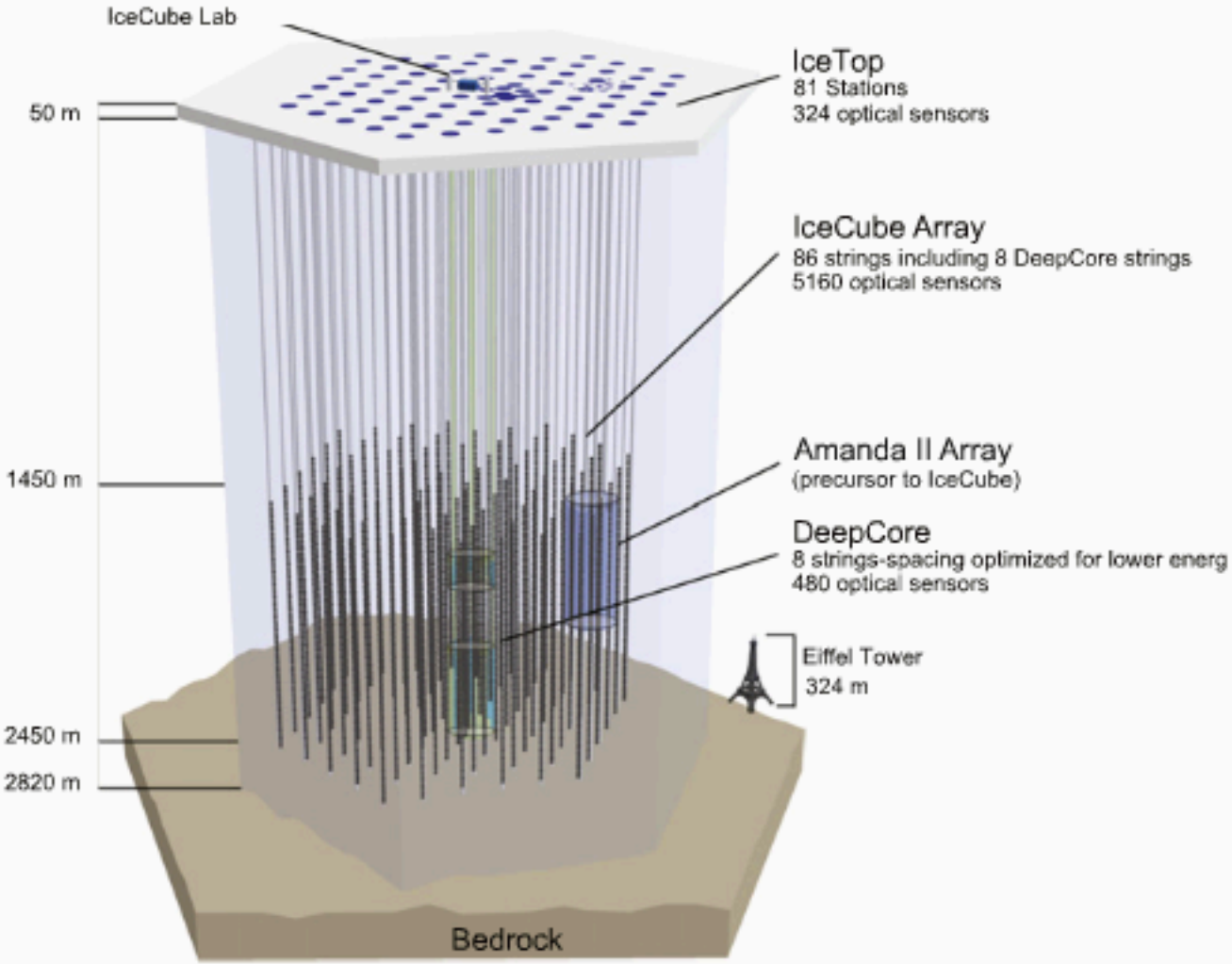
Detectors and Discoveries

Detectors and Discoveries

List of Neutrino Detectors in Antarctica with Active Campaigns

- IceCube - km^3 volume, optical photon detector at the South Pole.
- HRA-7 (ARIANNA) - Askaryan-based cosmogenic neutrino detector in Moore's Bay.
- ARA2/ARA3 - Askaryan-based *in-situ* cosmogenic neutrino detector at the South Pole.
- ANITA-1, ANITA-2, ANITA-3 - Balloon-borne cosmogenic neutrino and cosmic ray detector launched from McMurdo

Detectors and Discoveries … IceCube (AMANDA, DeepCore, DMIce, IceTop, RICE)



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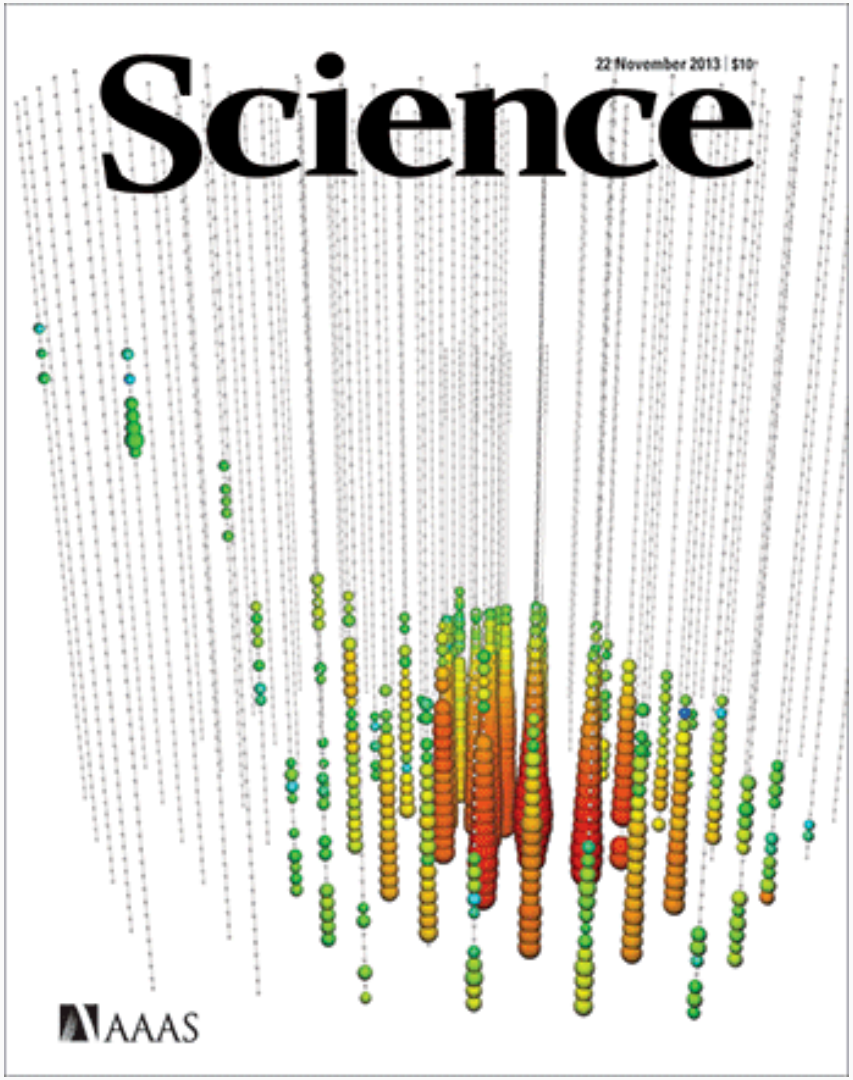

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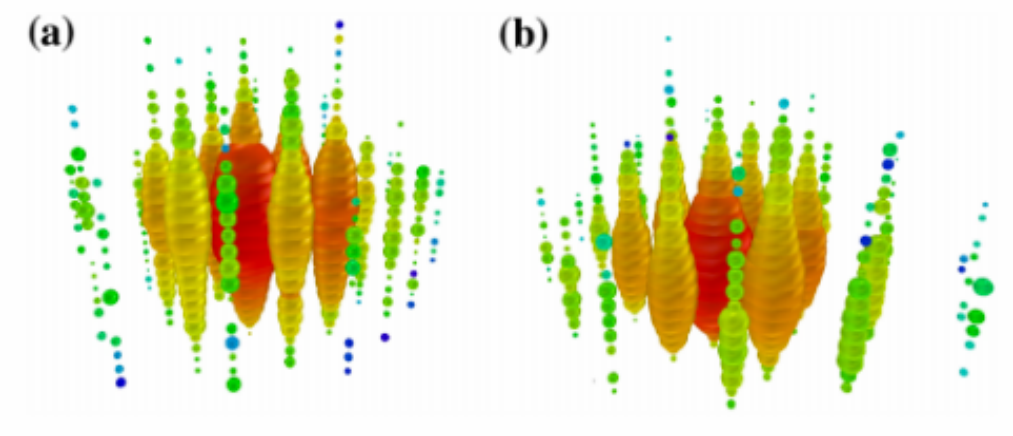
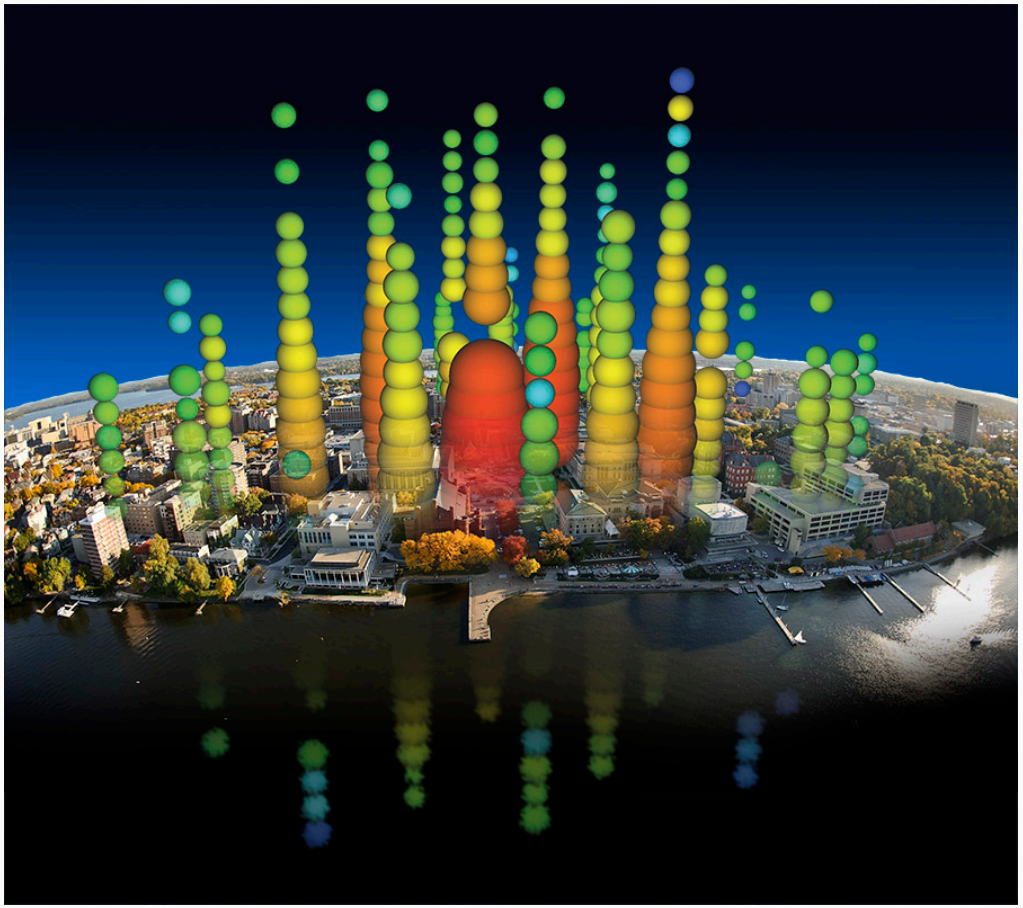


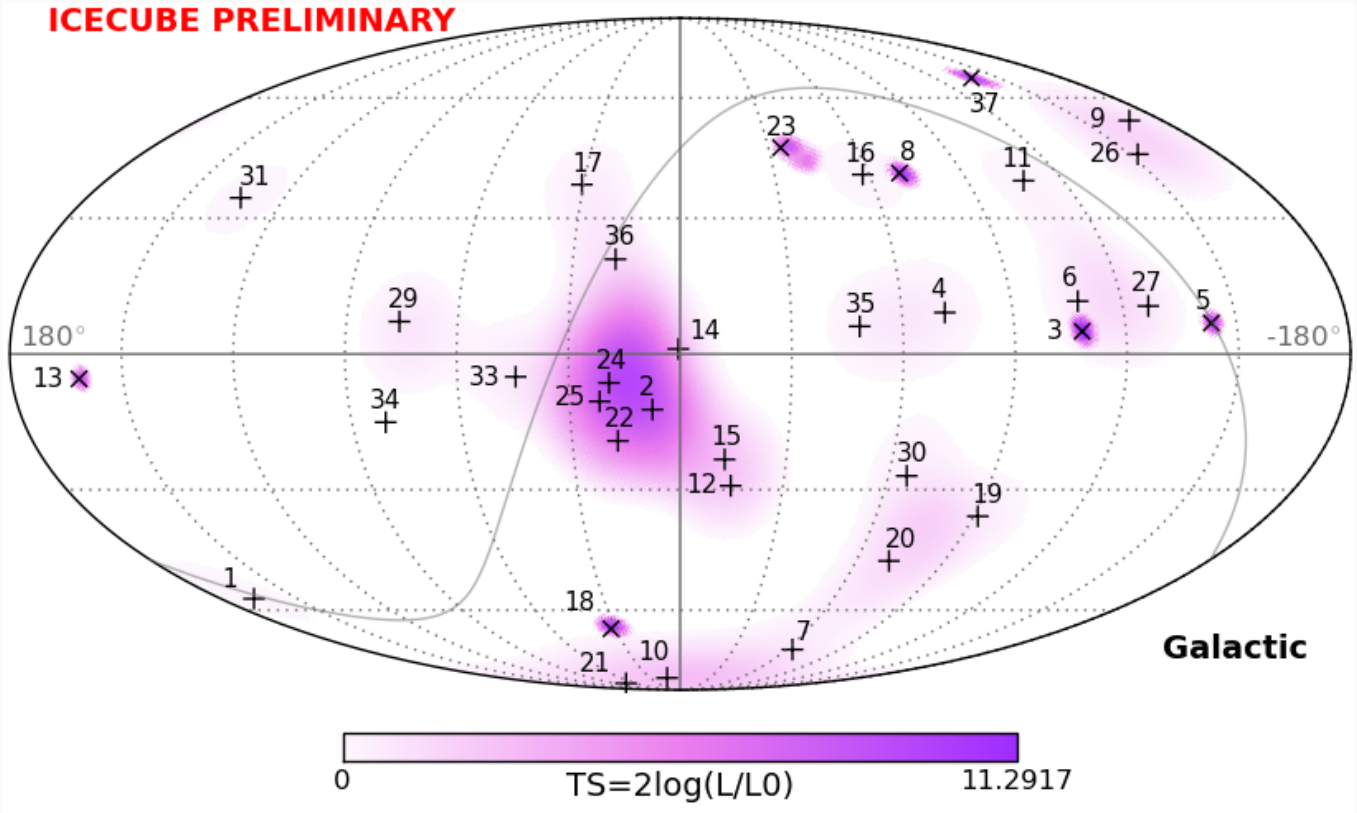
First observation, 2013. Reconstructed energies of 1.04 ± 0.16 and 1.14 ± 0.17 PeV, from the number of photo-electrons that hit DOMs. These are two "cascade" type events.

Detectors and Discoveries ... IceCube (AMANDA, DeepCore, DMIce, IceTop, RICE)

To scale, at higher energies. That's the University of Wisconsin.

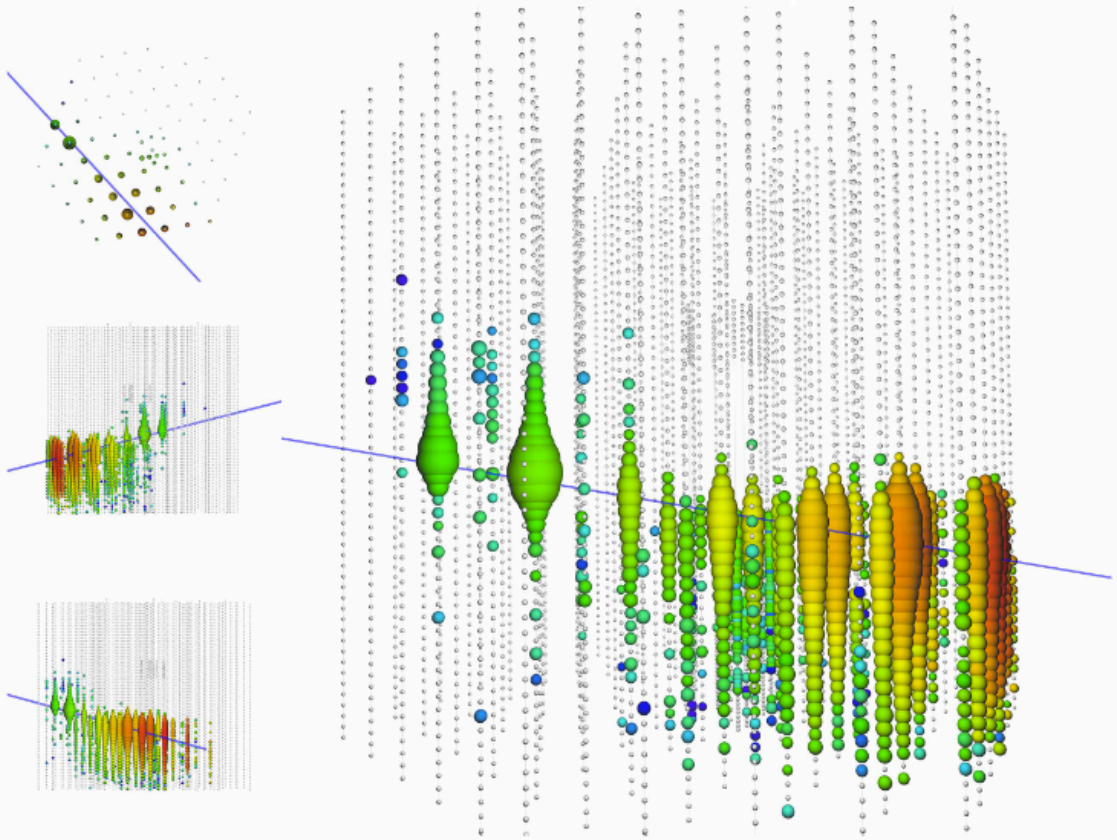


Detectors and Discoveries … IceCube (AMANDA, DeepCore, DMIce, IceTop, RICE)

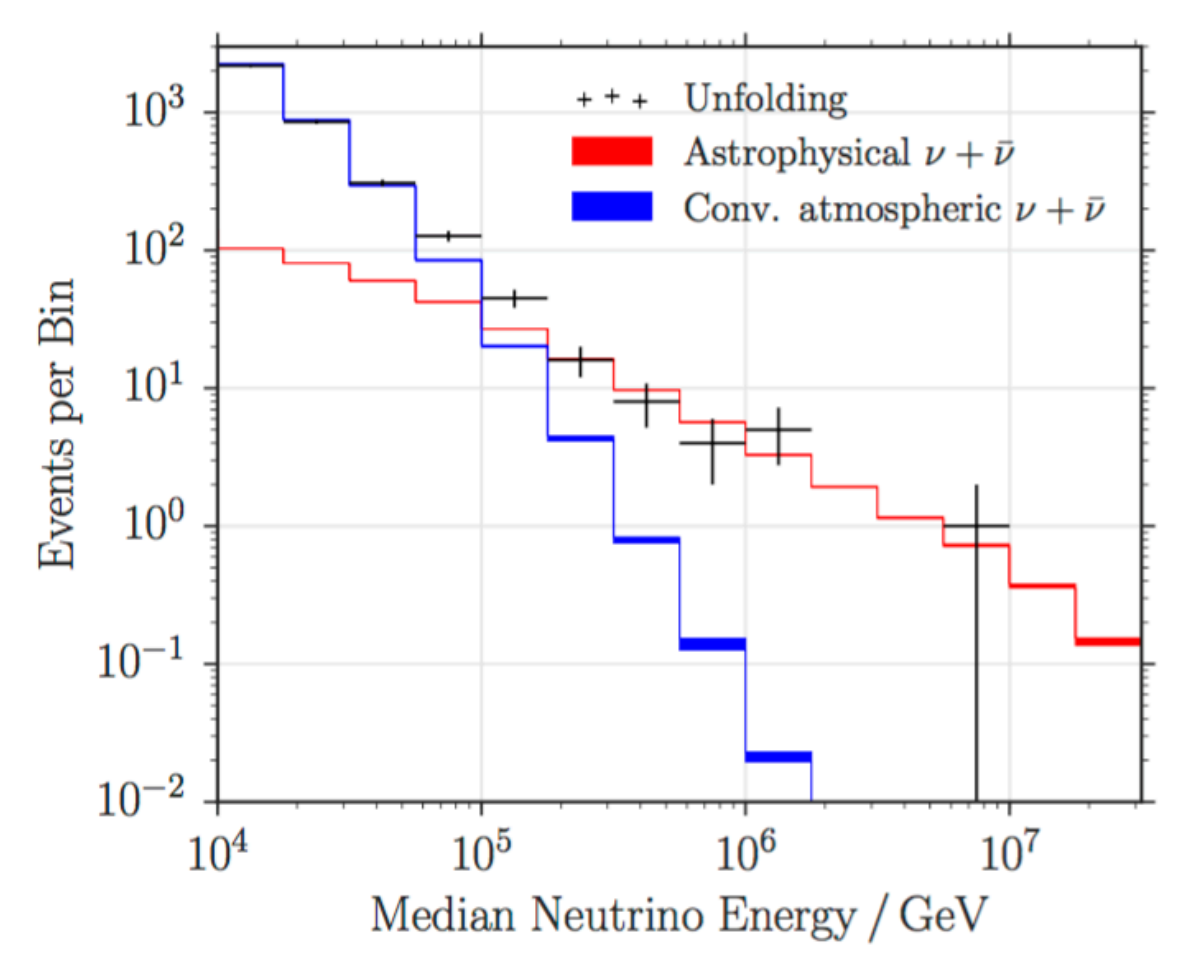


Detectors and Discoveries ... IceCube (AMANDA, DeepCore, DMIce, IceTop, RICE)

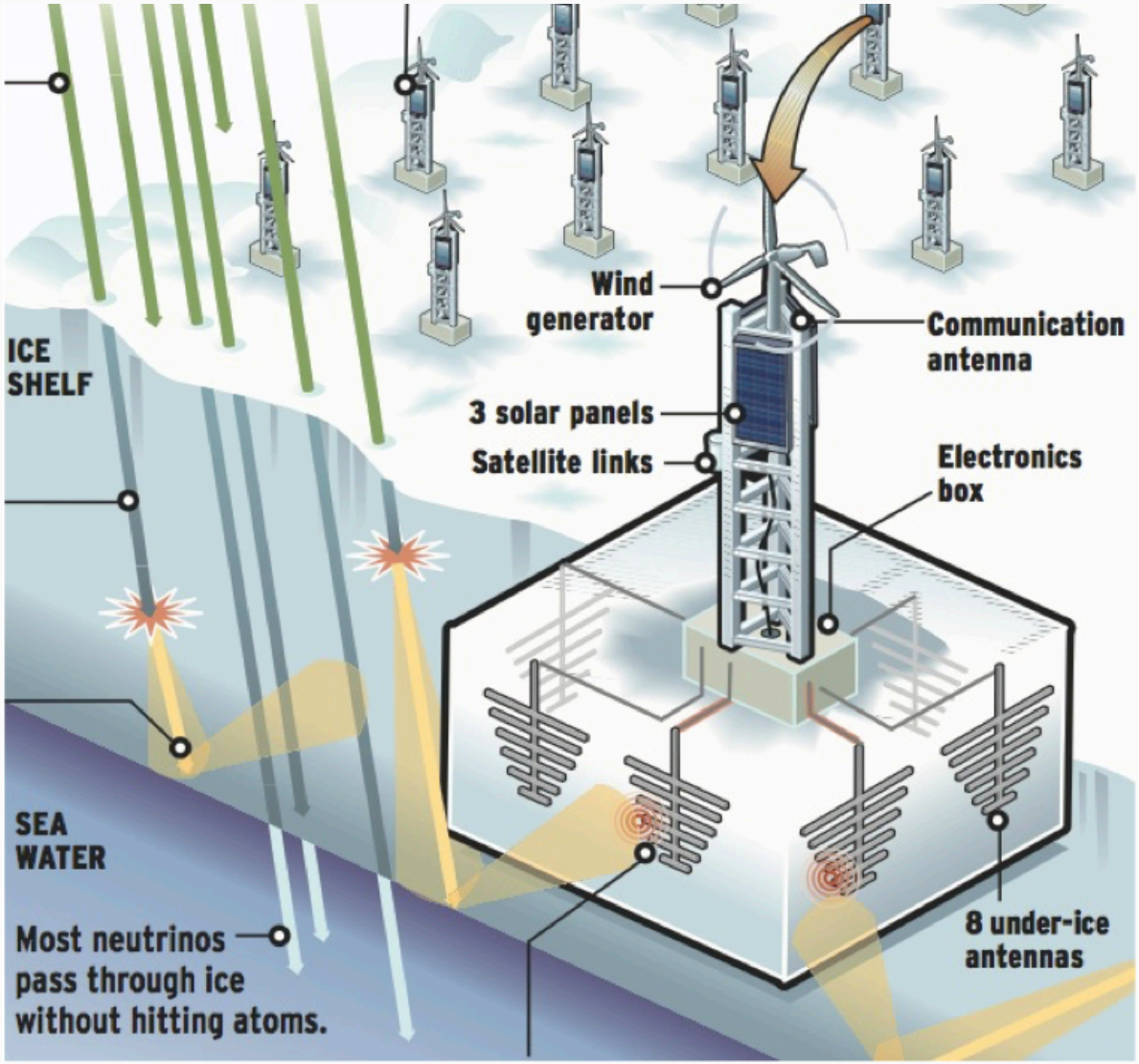
Deposited energy: (2.6 ± 0.3) PeV. Muon energy: (4.5 ± 1.2) PeV.
Neutrino energy: 8.7 PeV



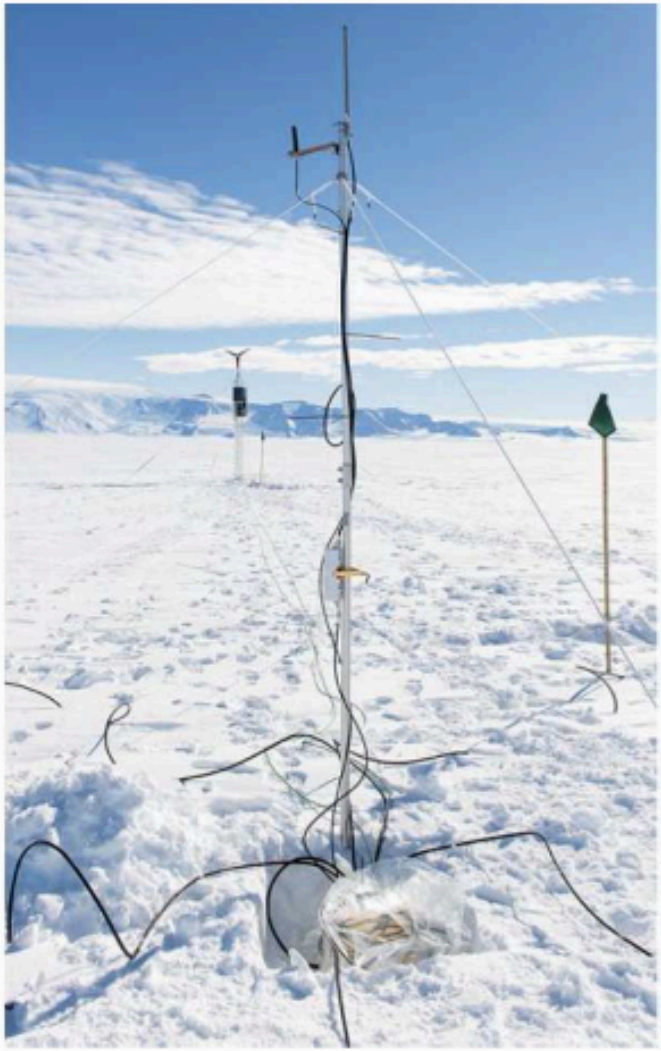
Detectors and Discoveries … IceCube (AMANDA, DeepCore, DMIce, IceTop, RICE)



Detectors and Discoveries … ARIANNA



Detectors and Discoveries … ARIANNA



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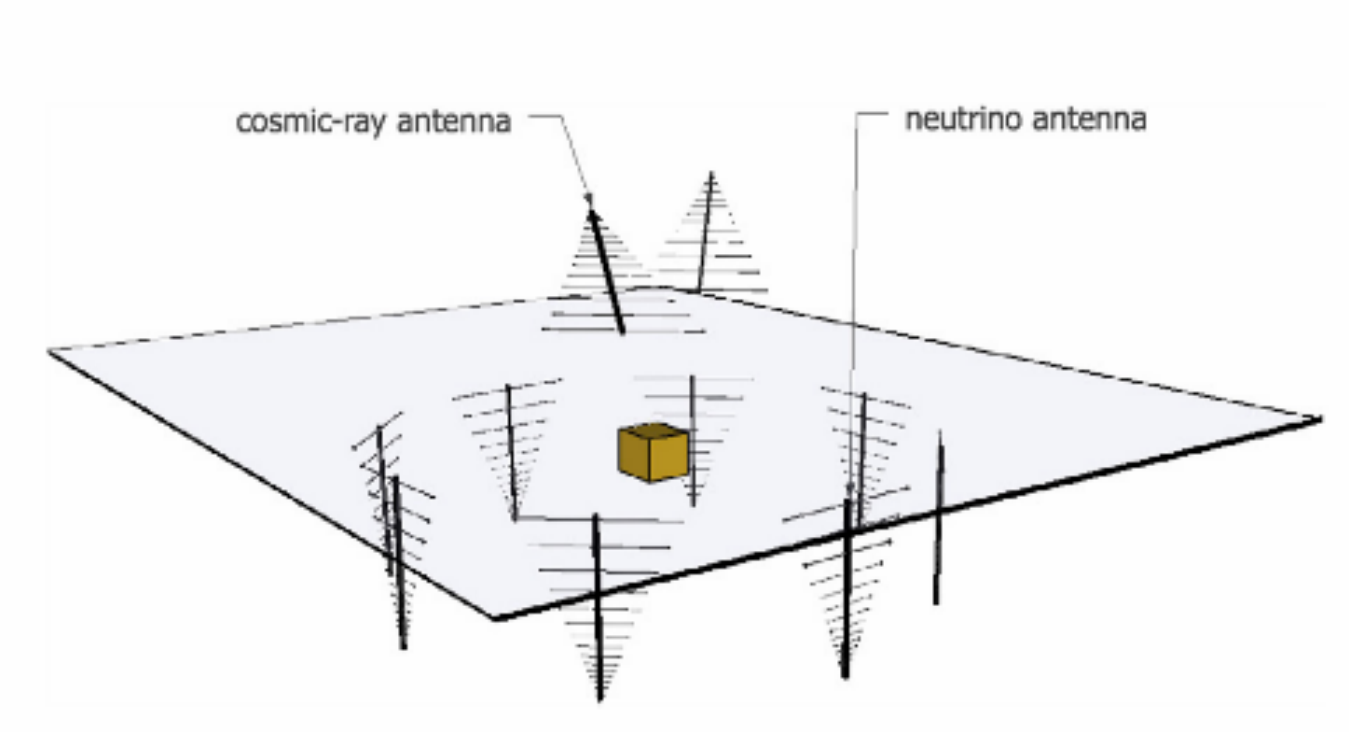
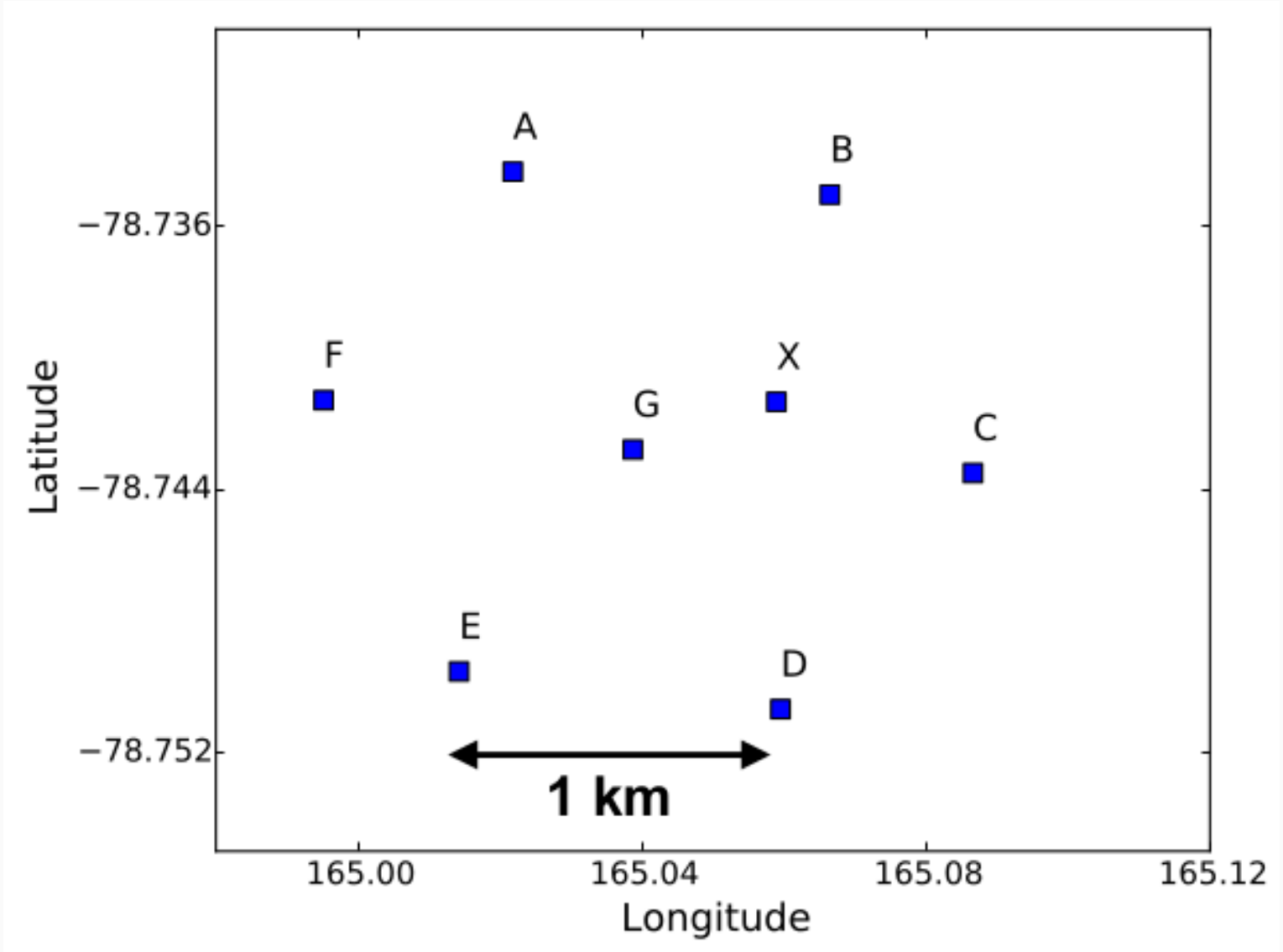
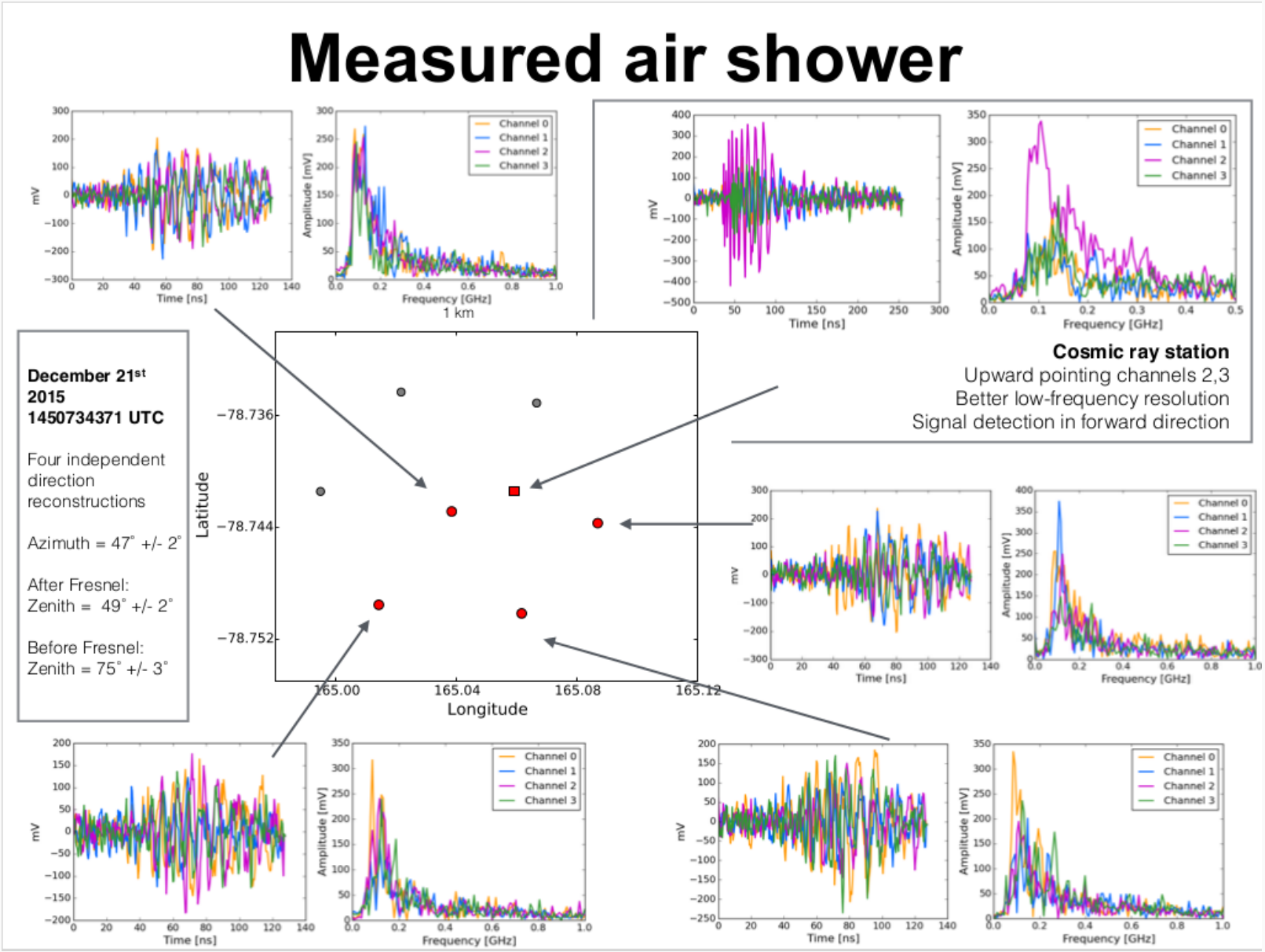


Detectors and Discoveries … ARIANNA



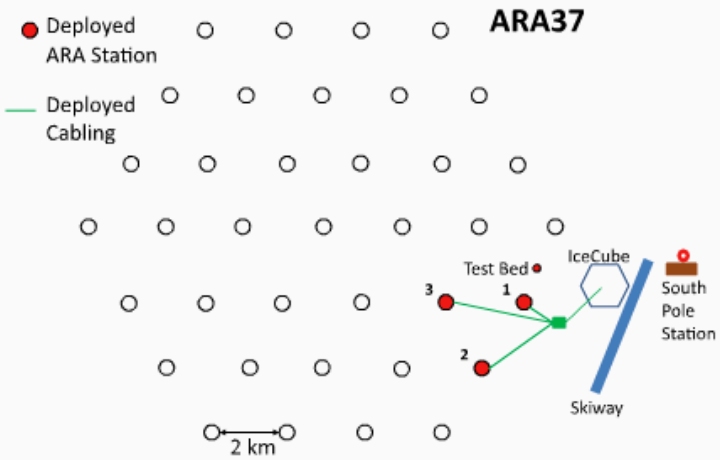
Interlude: ARIANNA deployment

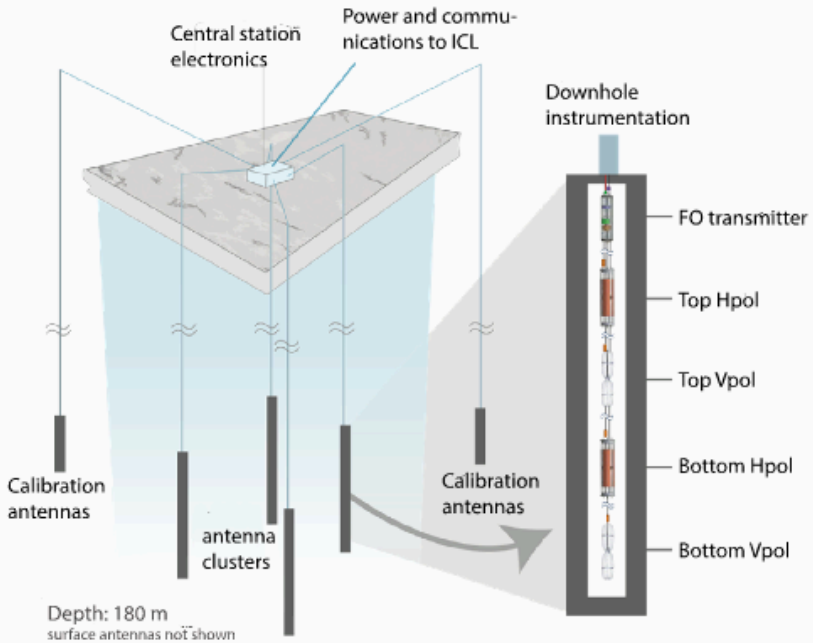
Detectors and Discoveries … ARIANNA: Detection of UHECRs



Detectors and Discoveries … ARA

ARA is currently the most competitive of the *in situ* detectors.





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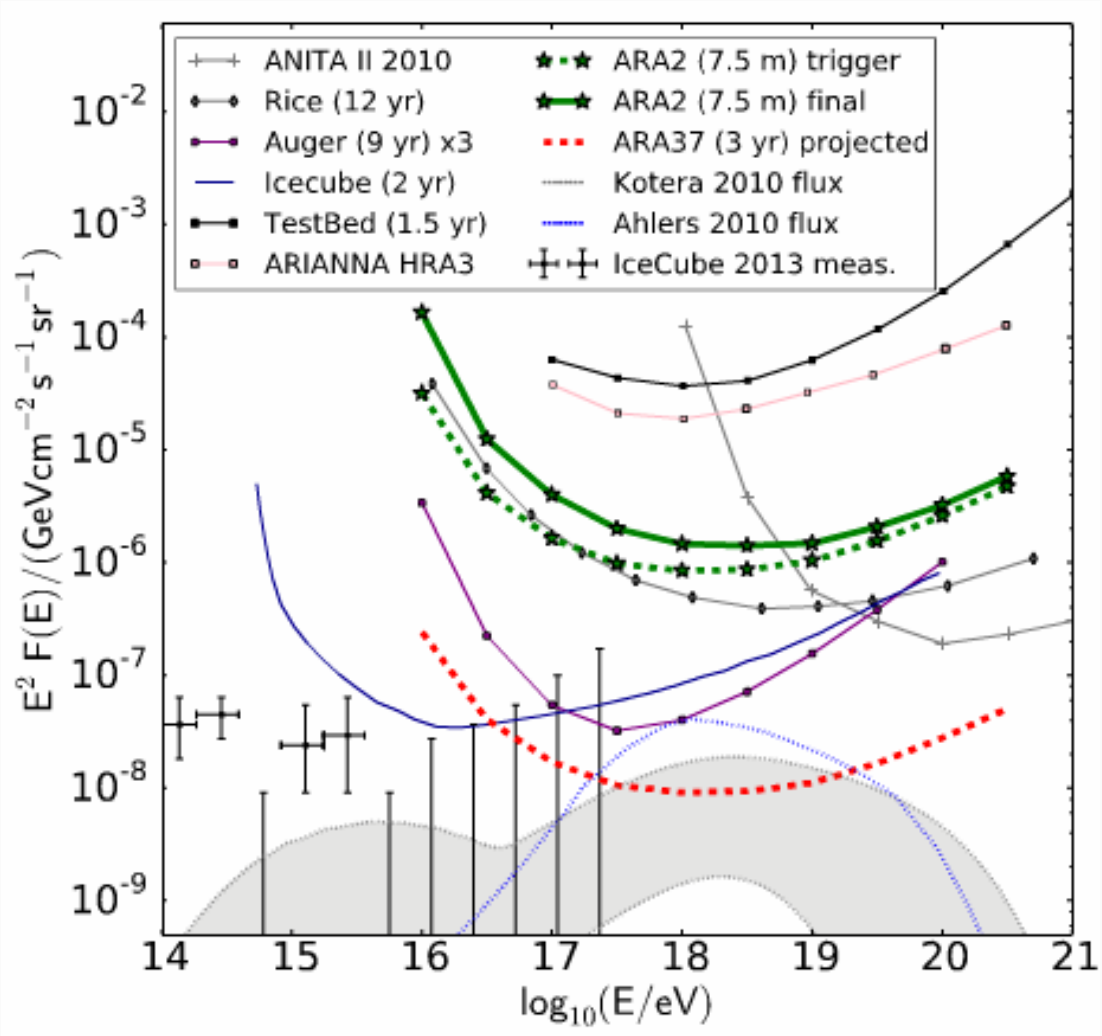


Future Designs

Future Designs

List of Neutrino Detectors in Antarctica with Active Campaigns

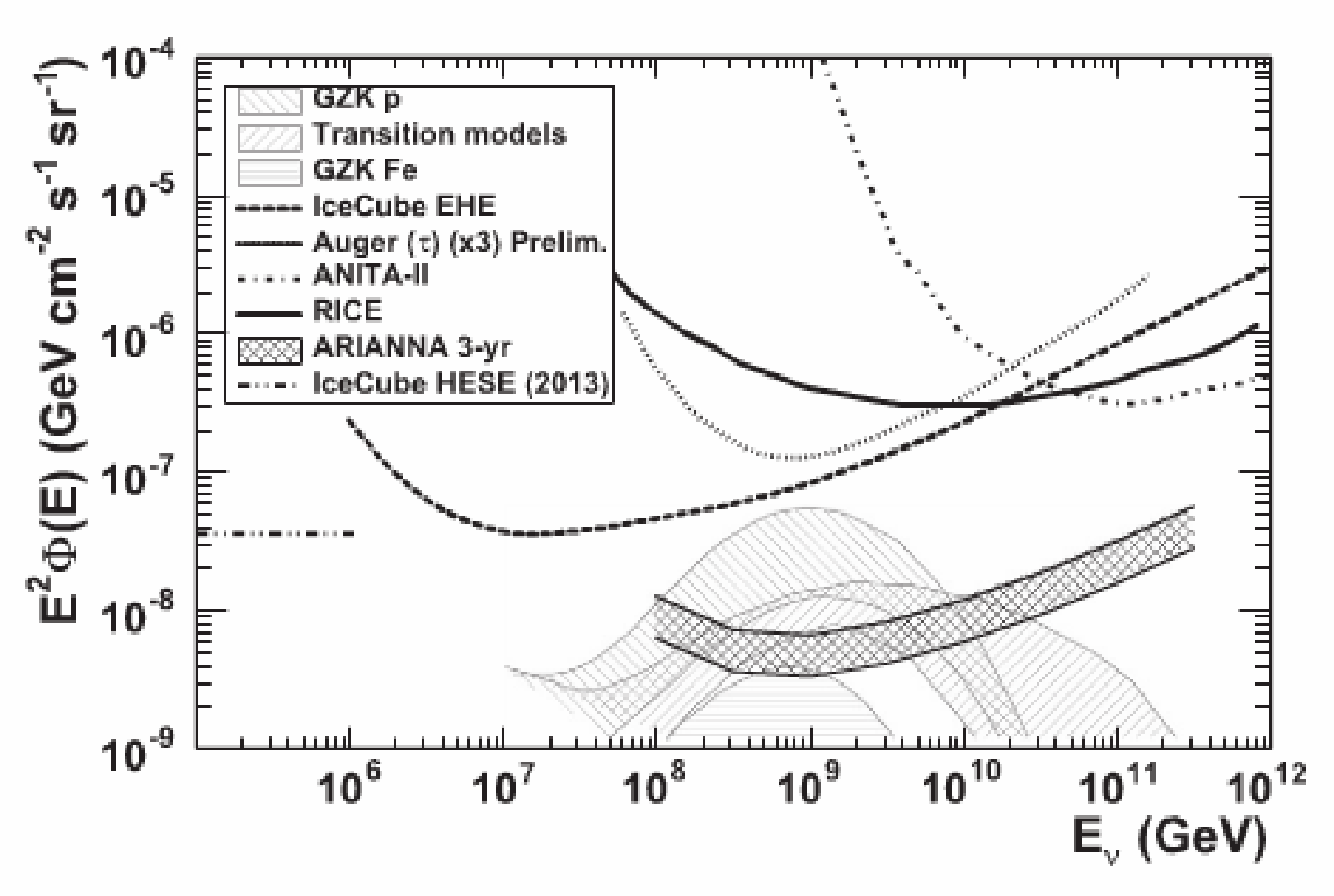
EVA - km^3 volume, optical photon detector at the South Pole.

ARIANNA - Askaryan-based cosmogenic neutrino detector in Moore's Bay.

ARA-37 - Askaryan-based *in-situ* cosmogenic neutrino detector at the South Pole.

ANITA-4 - Balloon-borne cosmogenic neutrino and cosmic ray detector launched from McMurdo

The Future … ARIANNA-1296



The Future … ARIANNA-1296

Neutrino model	Model type	N_ν triggers ($E_\nu > 10^8$ GeV)	
		ARIANNA	IceCube [12]
ESS [38]	$m = 4,\ \Omega_M = 1$	55	
WB [62]	E_ν^{-2} QSO source evolution	65	
Yuksel et al. [63]	E_ν^{-2} GRB source evolution	100	
Kotera et al. [64]	Protons, SFR1 evolution	7.3	0.46 (0.64)
Kotera et al. [64]	Protons, GRB2 evolution	9.0	0.48 (0.67)
Kotera et al. [64]	Protons, FRII evolution	48	2.9 (4.0)
Yoshida et al. [65]	$m = 4,\ z_{max} = 4$	34	2.0 (2.8)
Ahlers et al. [66]	$E_{min} = 10^{10}$ GeV (best fit)	26	1.5 (2.1)
Ahlers et al. [66]	$E_{min} = 10^{10}$ GeV (maximal)	58	3.1 (4.3)
Kotera et al. [64]	Mixed composition	7.4	
Kotera et al. [64]	Pure iron	2.5	
Ave et al. [67]	Pure iron, $m = 4,\ z_{max} = 1.9$	18	
Olinto et al. [43]	Pure iron, $E_{max}/Z = 10^{11}$ GeV	0.097	
Aartsen et al. [23]	$E_\nu^{-2.3}$ IceCube best fit	2.8	
Fang et al. [68]	Young pulsar sources	43	

The Future … ARA-37

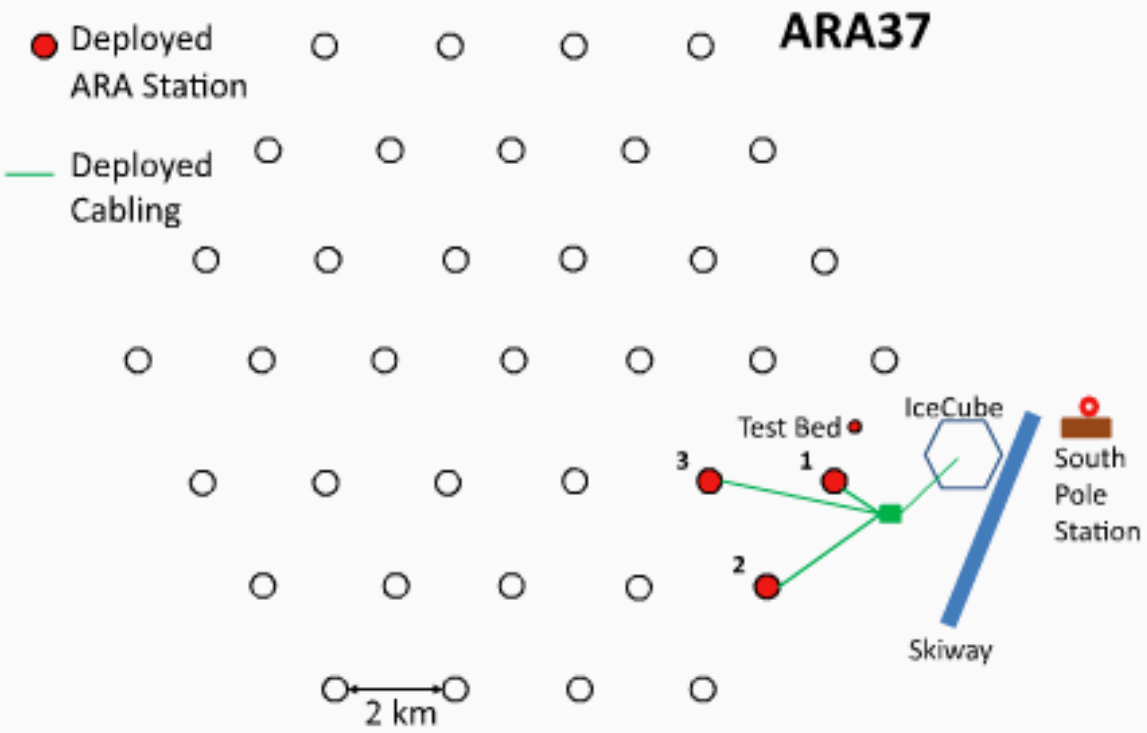
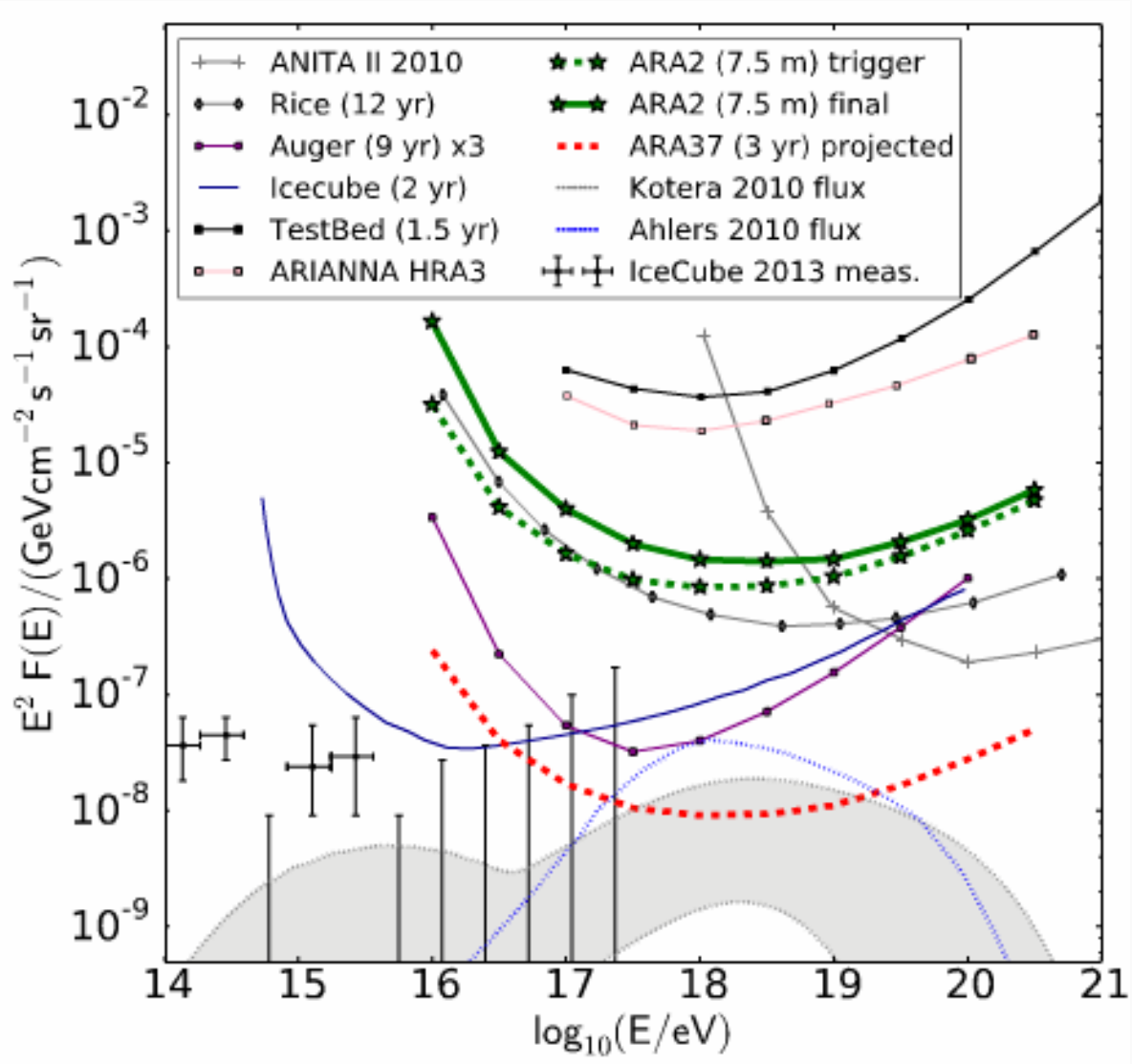
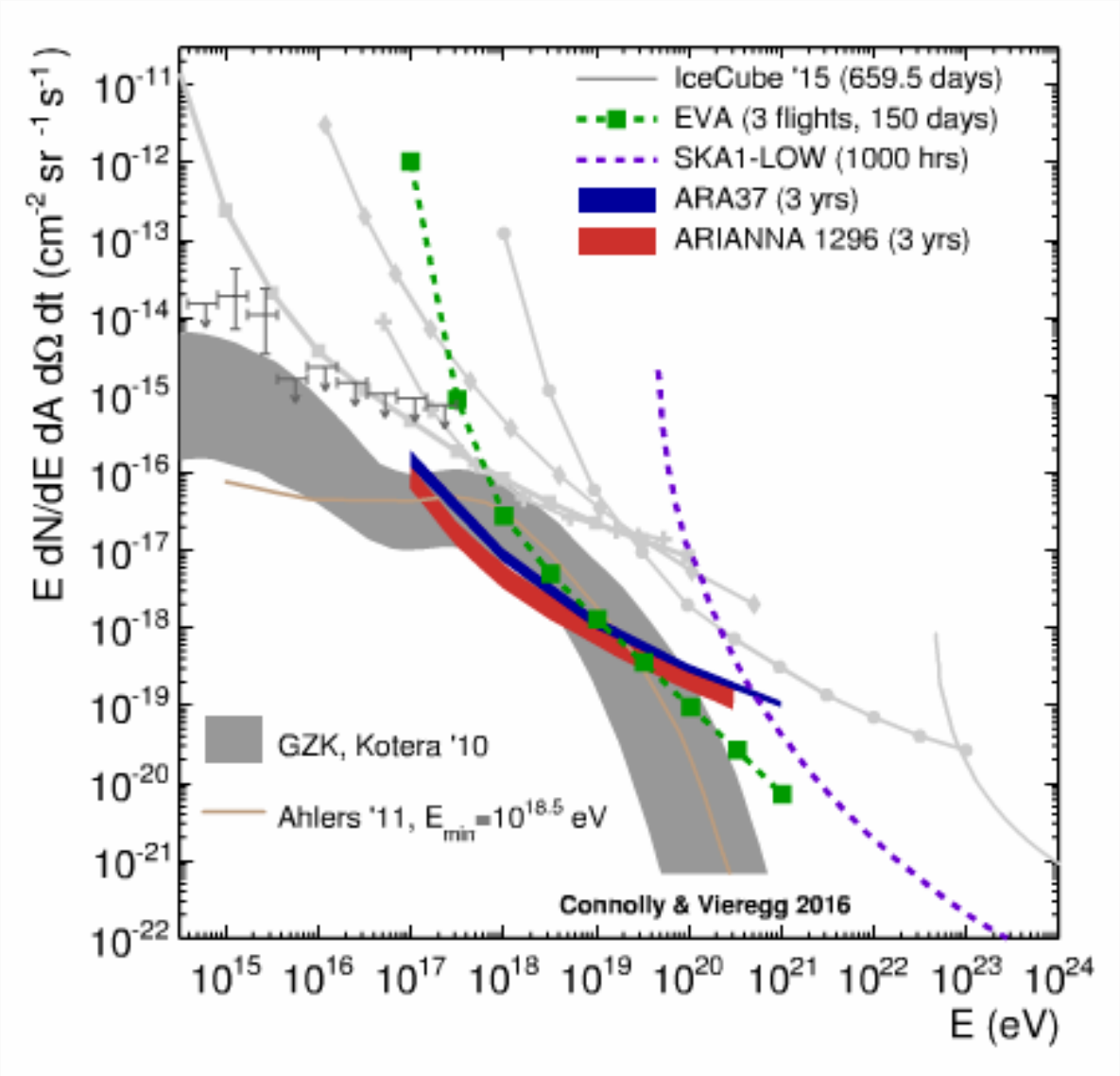


FIG. 1. An area map of the planned ARA detector at the South Pole. The stations are indicated by the black circles. Red filled circles denote the currently deployed stations.

The Future … ARA-37

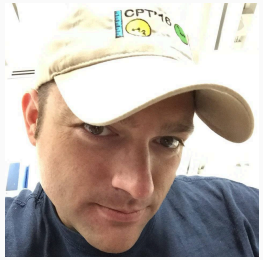


The Future … Sensitivities



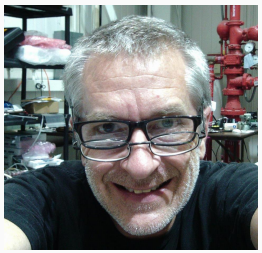
The Future is People

Dr. Amy Connolly, Prof. of Physics (CCAPP @ OSU), and her group (ARA, ANITA, ARIANNA, EVA)








Dr. Jordan Hanson, Dr. Carl Pfendner, Dr. Patrick Allison, Ms. Oindree Banerjee, Mr. Brian Clark, Mr. Brian Dailey, Mr. Samuel Stafford, Mr. Jorge Espinosa

Conclusion

I. **Cosmic Ray Origins** ... *A 100 year journey, about to be solved*

II. **Antarctic Science** ... *Useful for science and worthy of continued preservation*

III. **Detectors and Discoveries** ... *Major breakthroughs have taken place in recent years*

IV. **Future Designs** ... *Soon, there will be a new form of astro-particle physics*