The Ohio State University

High Energy Neutrino Astronomy through Radio Detection

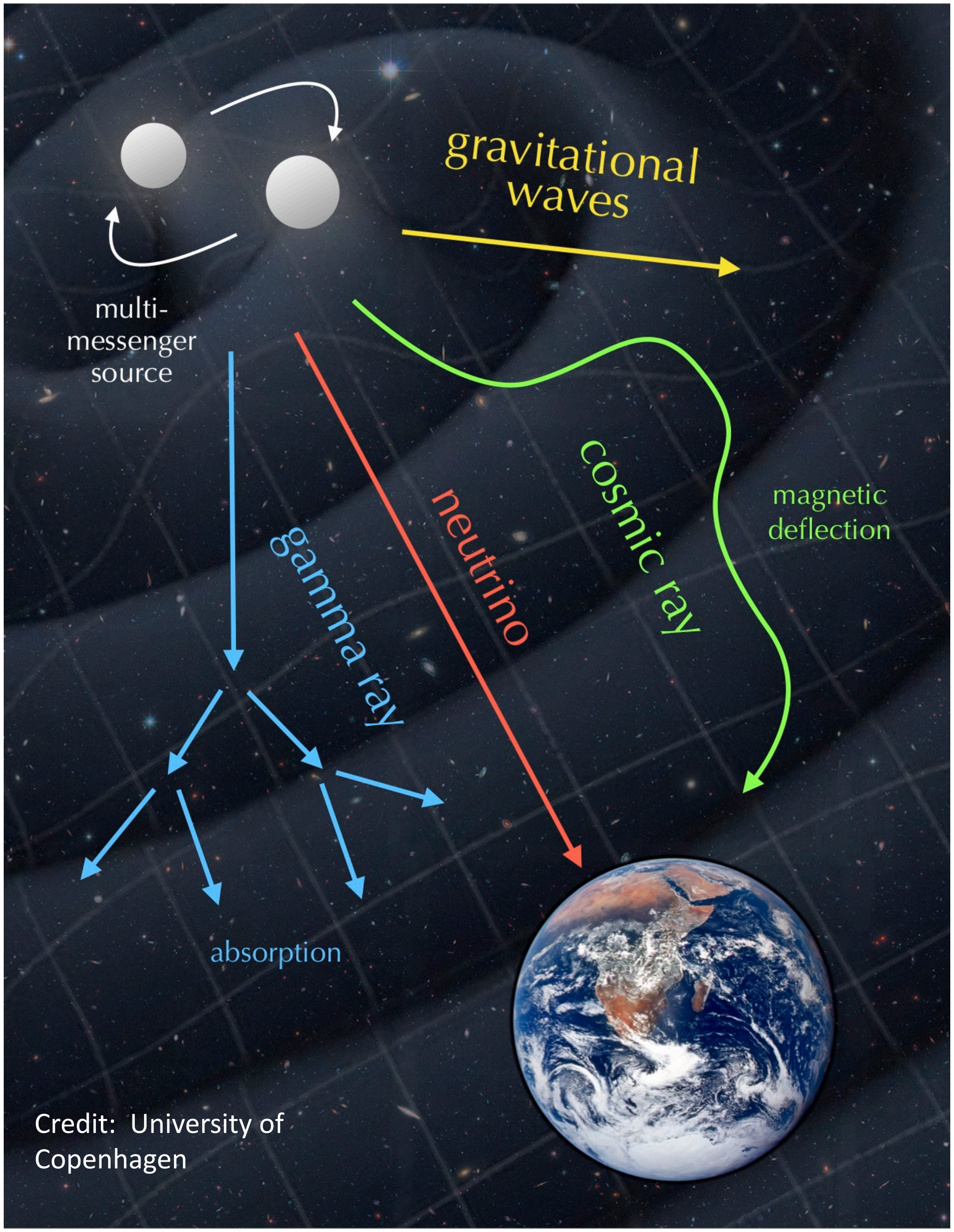
Prof. Amy Connolly

July 22, 2021

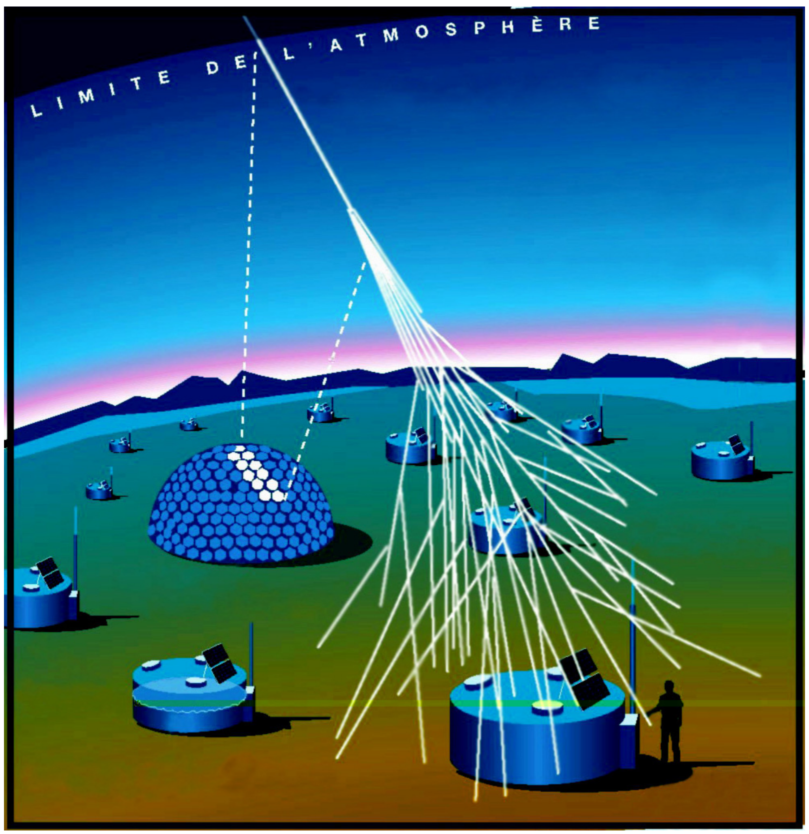
Outline

- Multi-messenger astronomy
- Motivation for observing UHE neutrinos
- Overview of radio technique
- Results and what's to come
- Developing new techniques for the strongest sensitivity

Multi-messenger astronomy


gravitational waves
multi-messenger source
gamma ray
neutrino
cosmic ray
magnetic deflection
absorption
Credit: University of Copenhagen

Pierre Auger Observatory - cosmic rays



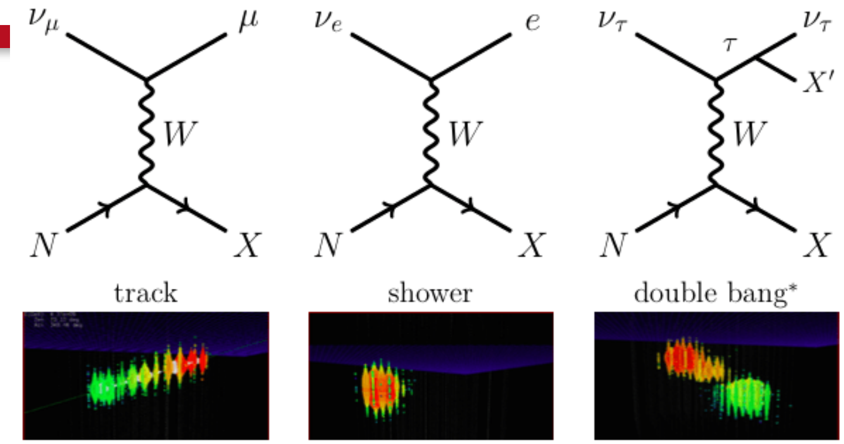
Credit: Pierre Auger - UCM group

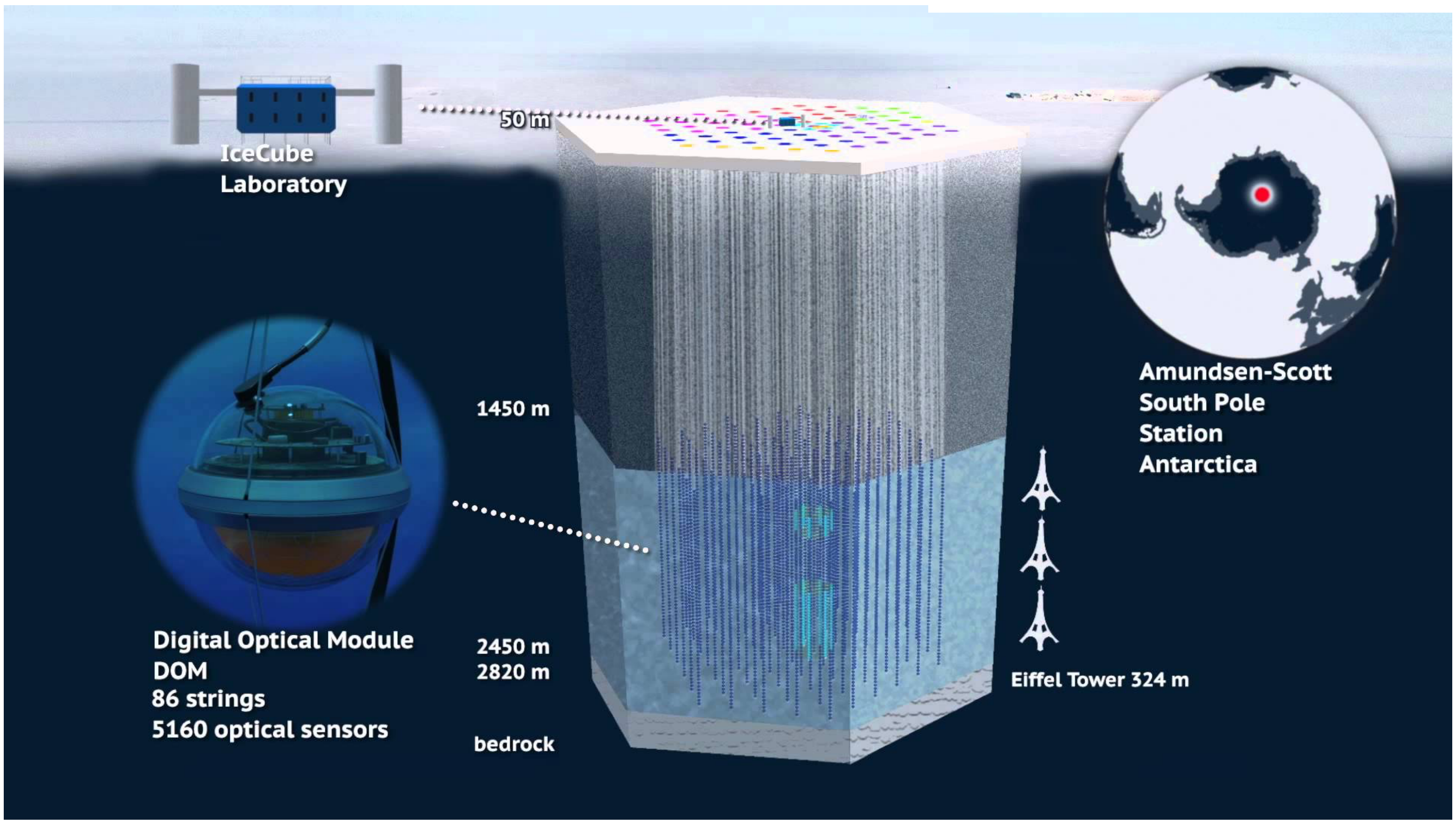
Fermi Gamma-ray Space Telescope

Credit: NASA

IceCube

- Detects optical Cerenkov light from particle tracks in cascades induced by neutrinos

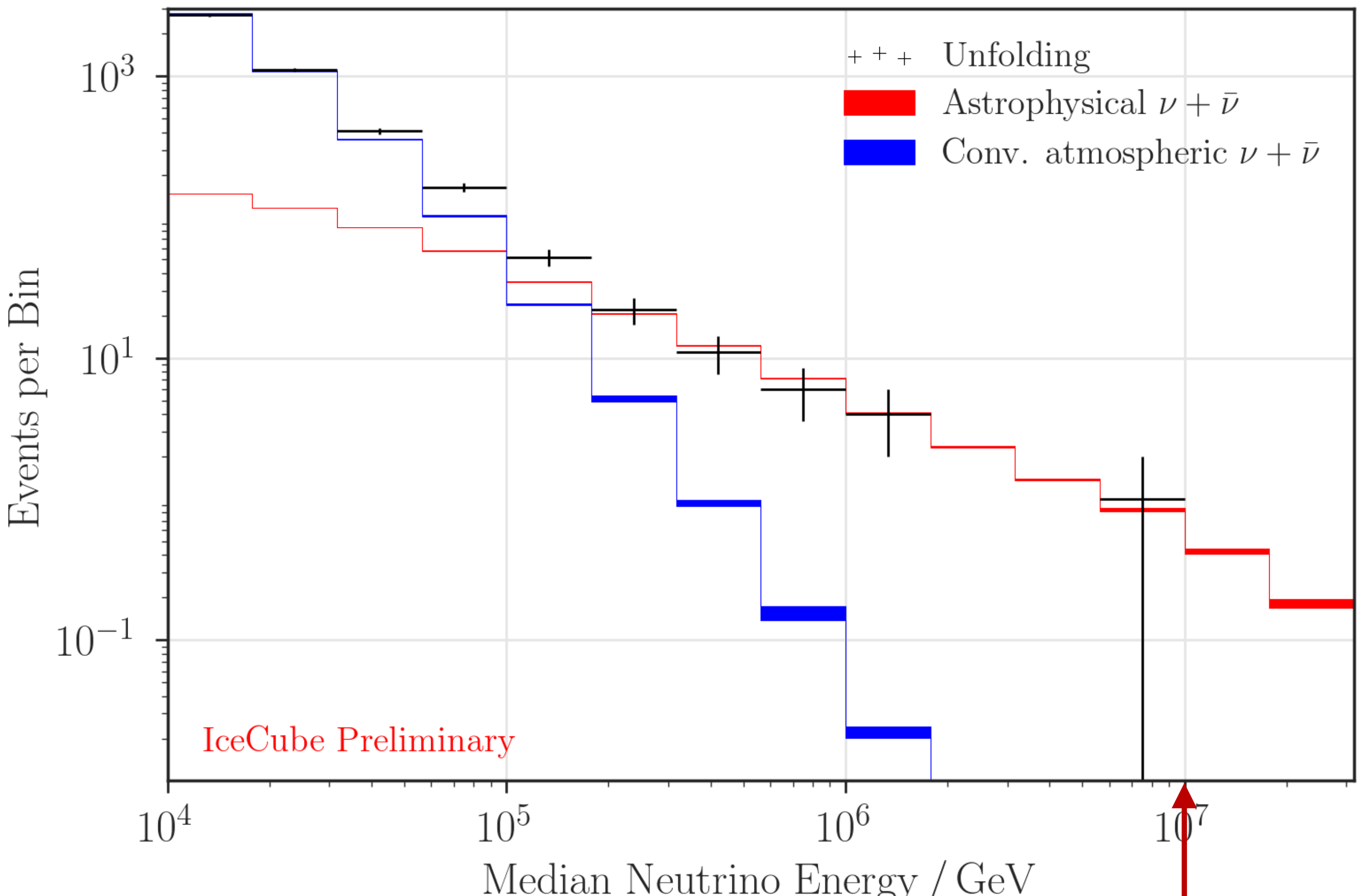




IceCube Neutrino Observatory

Optical signals absorbed/attenuated over ~tens of m

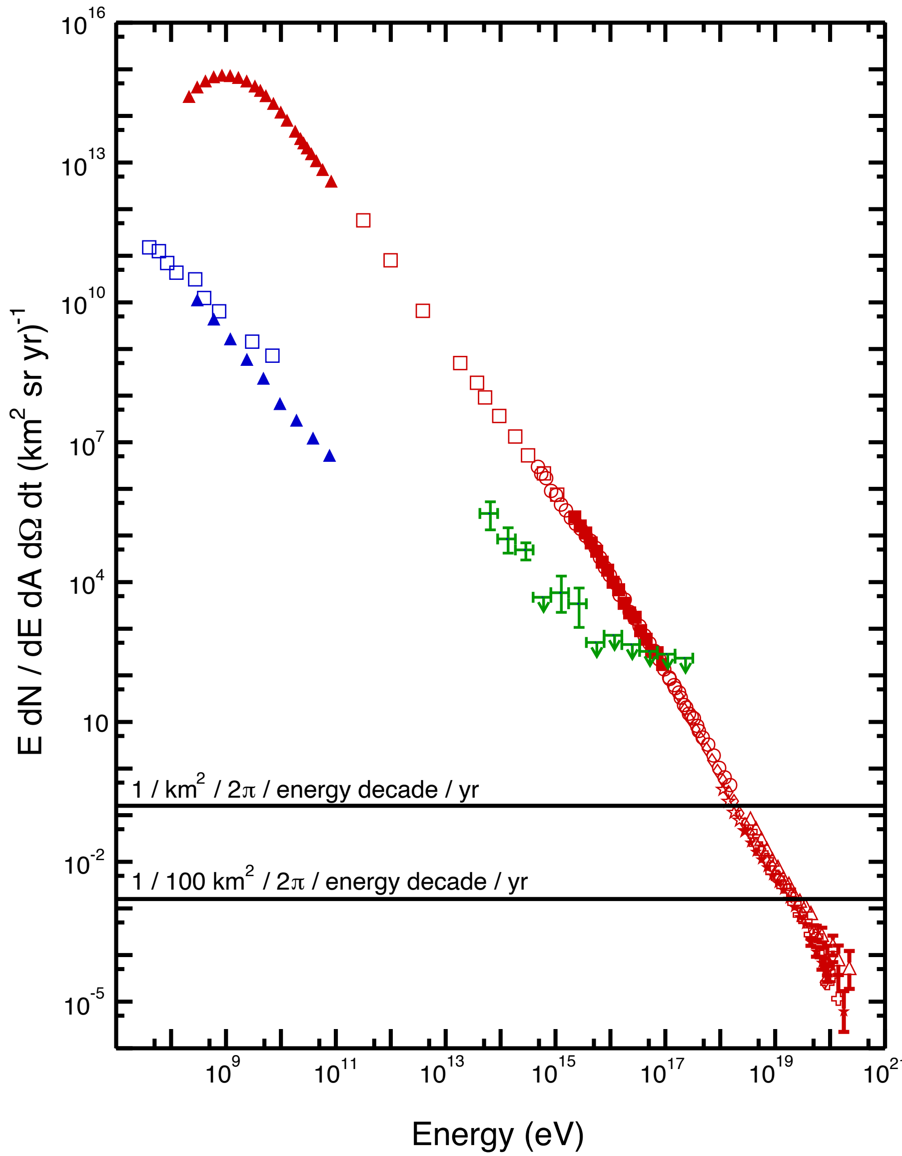
IceCube sees astrophysical neutrinos!



10 PeV = 10^{16} eV

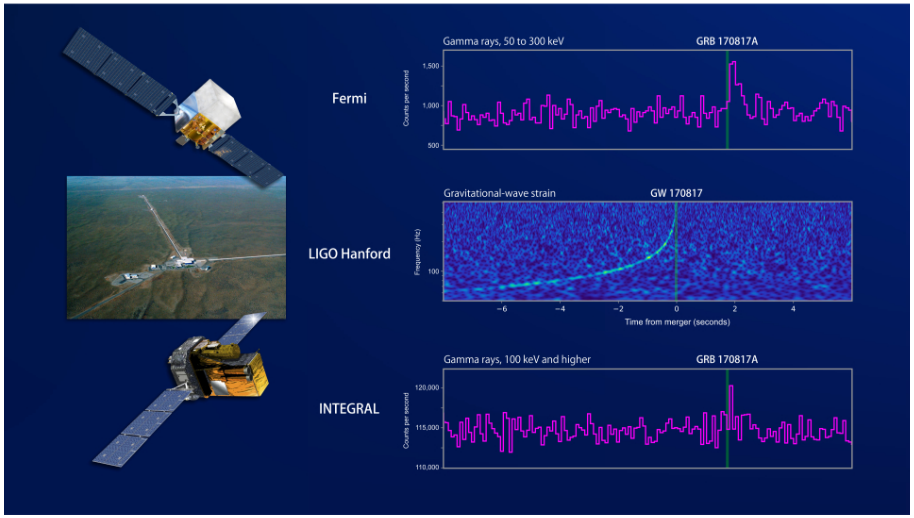
What it means

- Marked the beginning of an era of multi-messenger astronomy with all four!
  - cosmic rays
  - photons
  - neutrinos
  - gravitational waves!



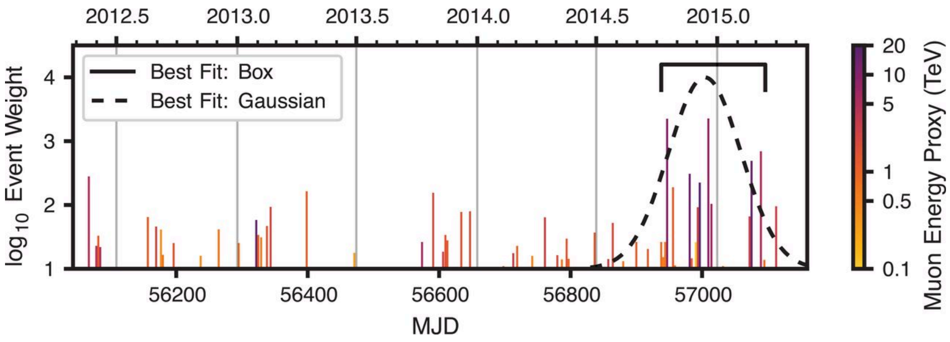
First energetic multi-messenger observations

August 17, 2017
Binary neutron star merger



Gamma rays, gravitational waves

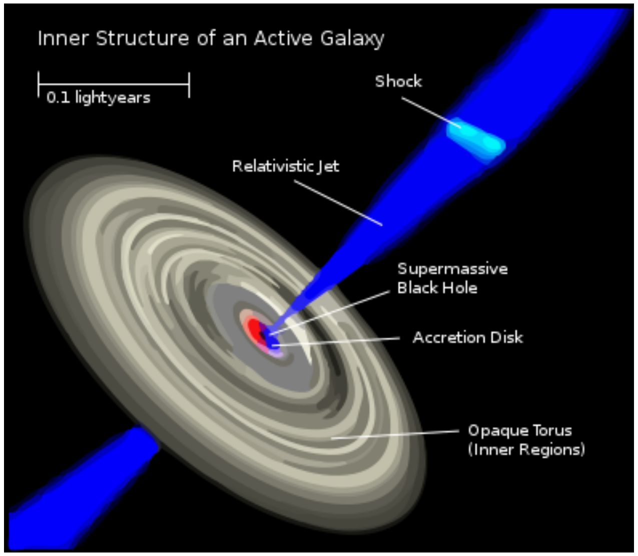
TXS 0506+056 Blazar
Possible Neutrino Flare seen by IceCube in same direction



No neutrinos beyond 10 PeV have been observed

Ultra high energy source candidates

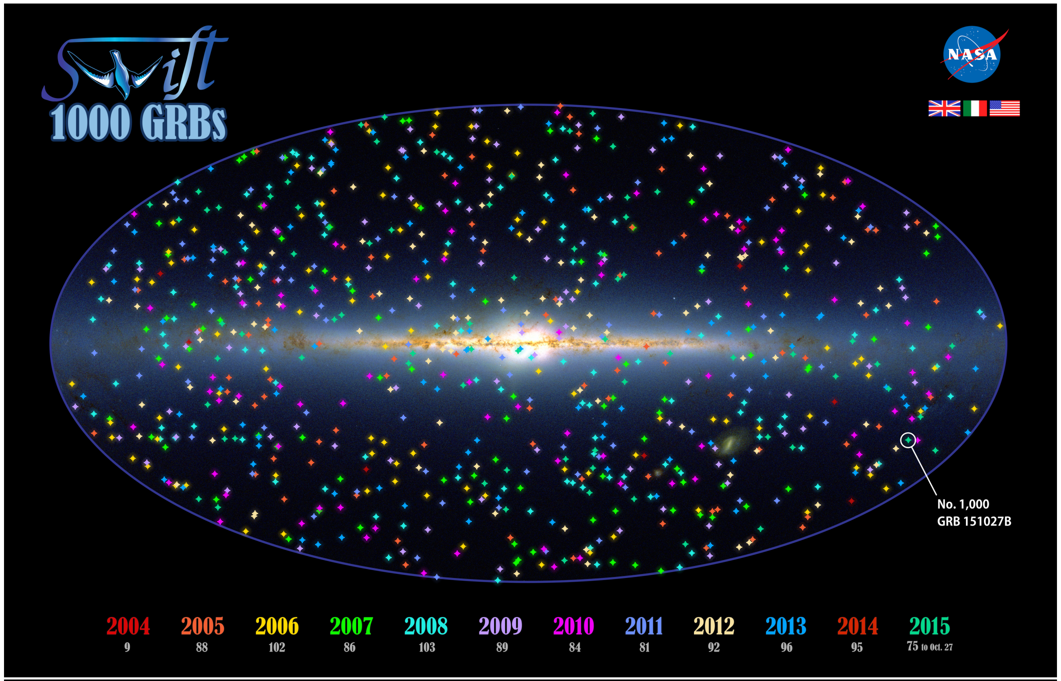
Active Galactic Nuclei (AGN)



https://en.wikipedia.org/wiki/Active_galactic_nucleus

- Black hole accreting mass

Gamma Ray Bursts (GRB)



- Star collapse, merger of neutron stars

Same sources that give cosmic rays also expected to produce neutrinos through photohadronic interactions

Overview of radio technique

Radio Cerenkov Technique

- Shower develops 20% charge asymmetry
- Cerenkov radiation
- *Coherent* for λ ≫ 10 cm

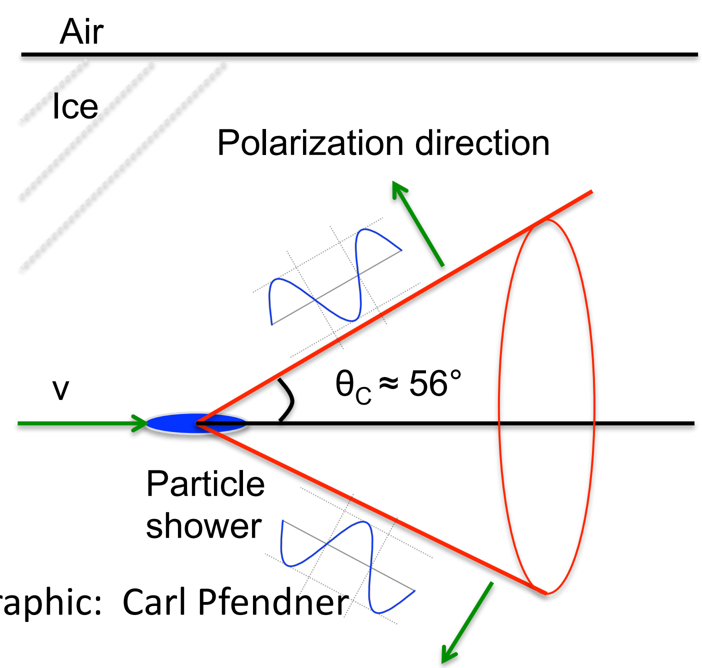
→ **RADIO**

Power ∝ E_{shower}^2

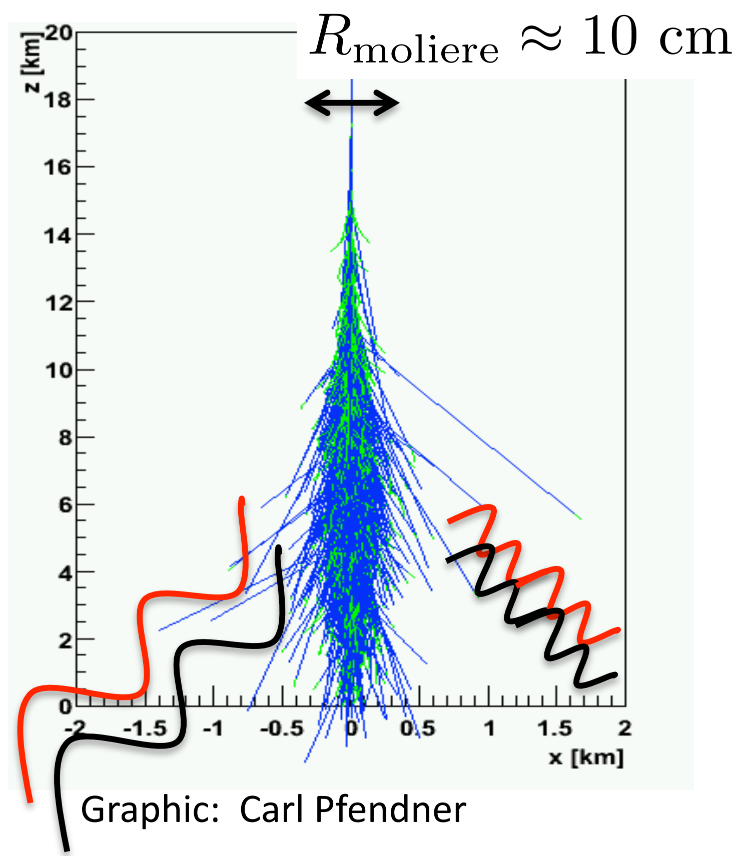
Gurgen Askaryan, 1962

Confirmed experimentally in sand, salt, ice:

PRL 86, 2802 (2002);
PRD 72, 023002 (2005);
PRD 74, 043002 (2006);
PRL 99, 171101 (2007)



Graphic: Carl Pfendner

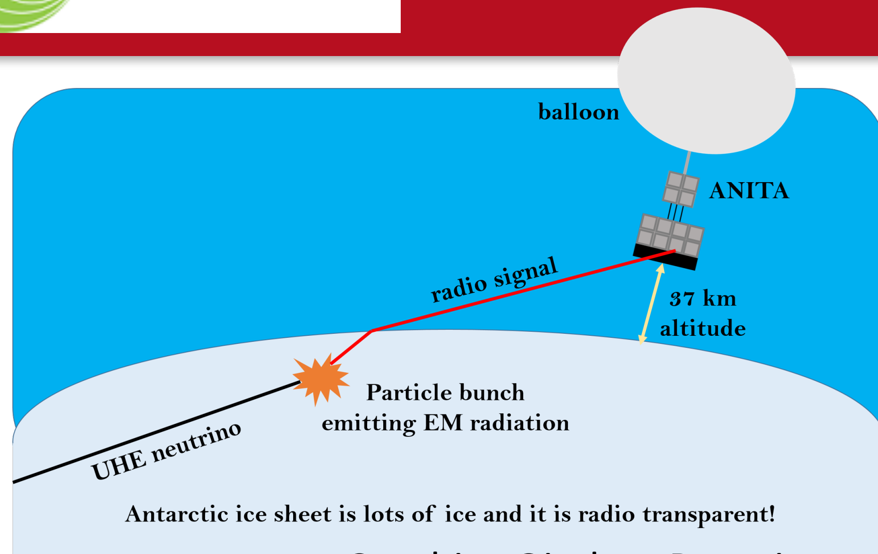


Graphic: Carl Pfendner

The Ohio State University

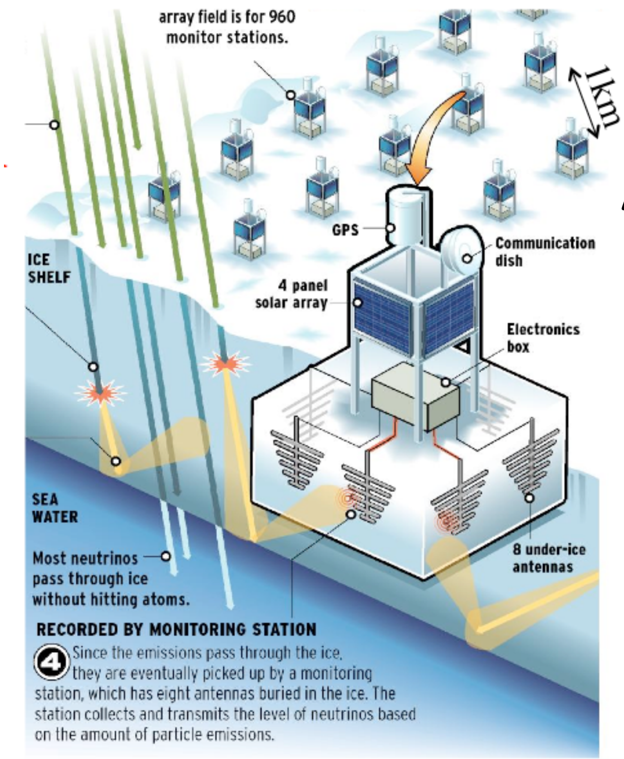
Current Radio Neutrino Projects

ANITA



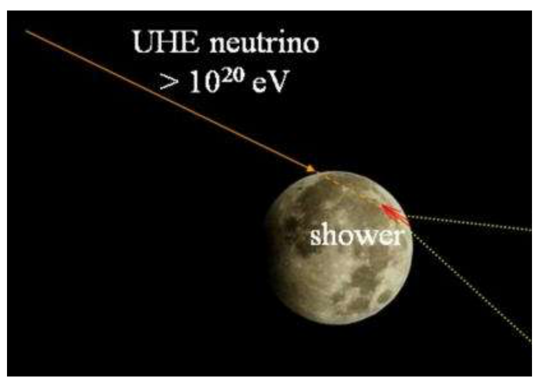
Graphic: Oindree Banerjee

ARIANNA

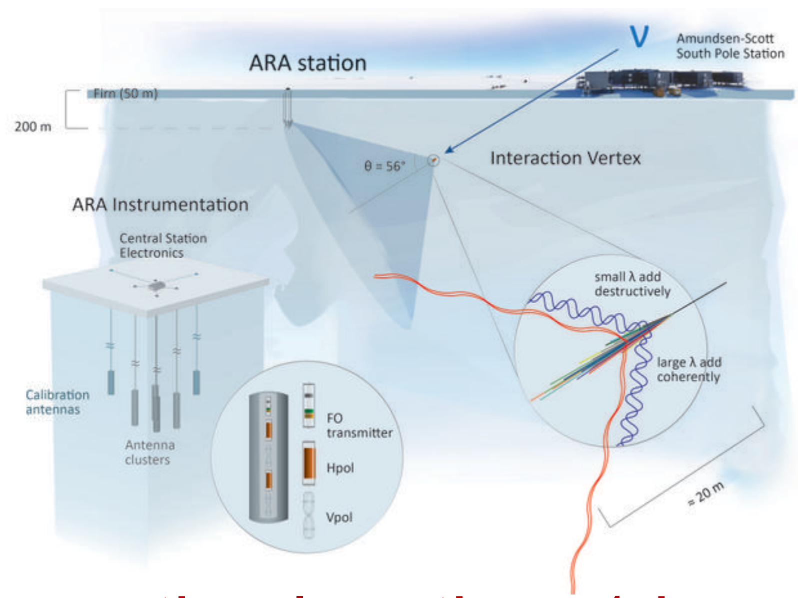


From OC Register 2012

Lunar projects: NuMoon



ARA



- Pure ice is low-loss for radio: field attenuation lengths ~1 km

Results and looking to the future

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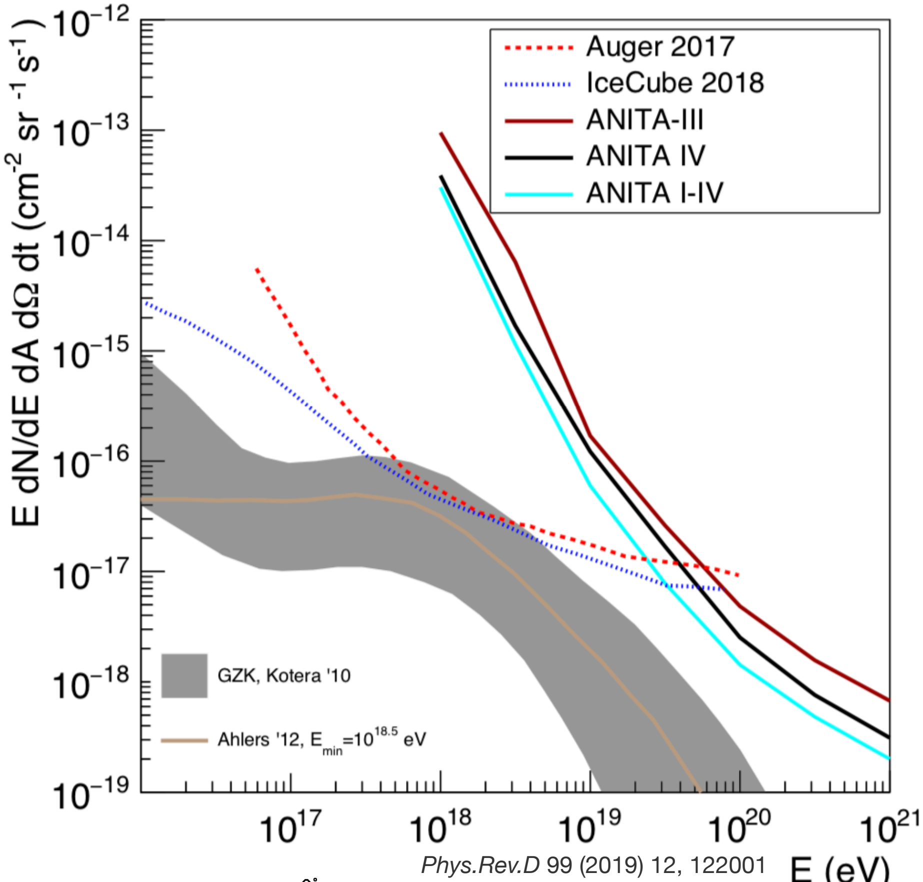
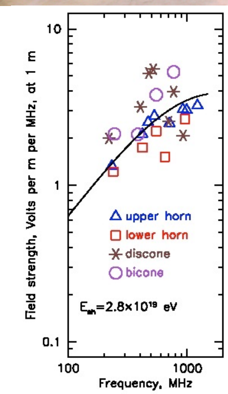
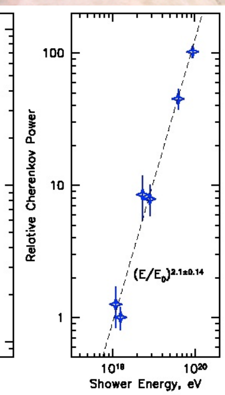
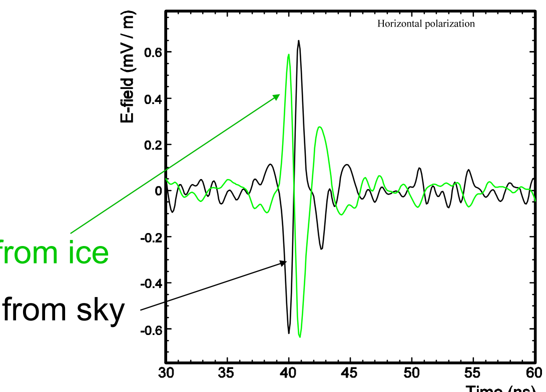
CCAPP

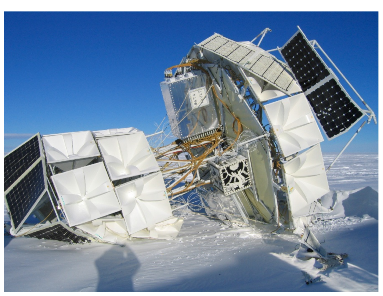
University of Hawaii, University of California, Los Angeles, University of Delaware, Jet Propulsion Laboratory, University of Kansas, National Taiwan University, The Ohio State University, Washington University in St. Louis, University College London











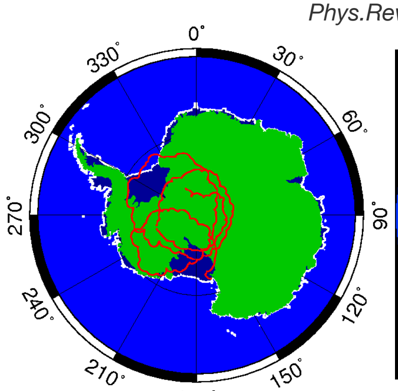
Four flights

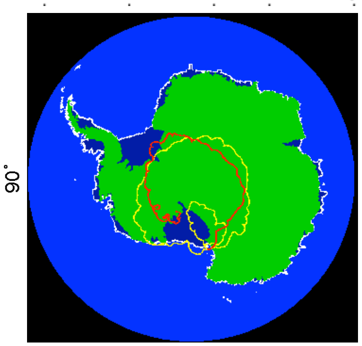
A1 2006

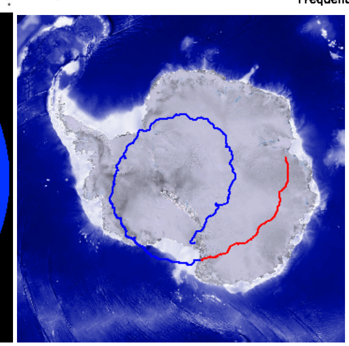
A2 2009

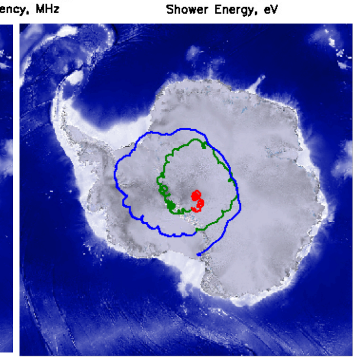
A3 2014

A4 2016









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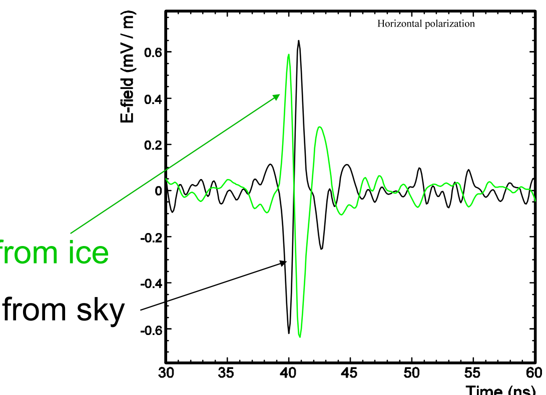
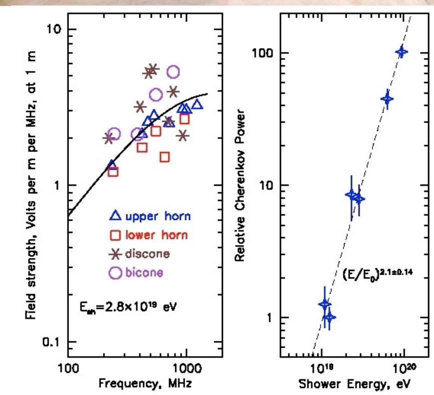
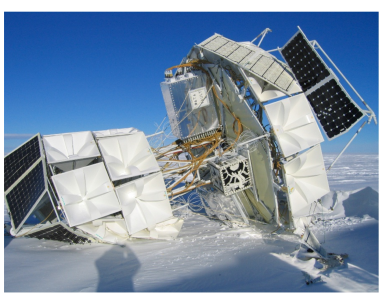
University of Hawaii, UCLA, University of Delaware, Jet Propulsion Laboratory, University of Kansas, National Taiwan University, The Ohio State University, Washington University in St. Louis, UCL







Four flights

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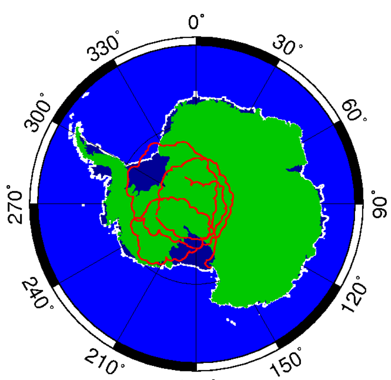
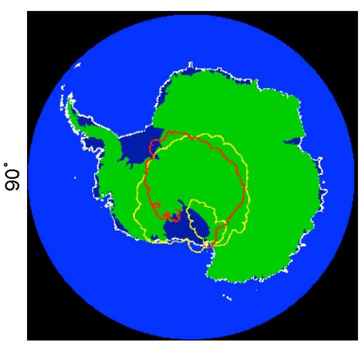
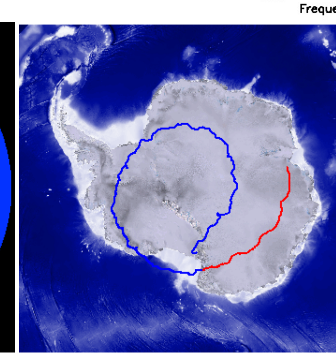
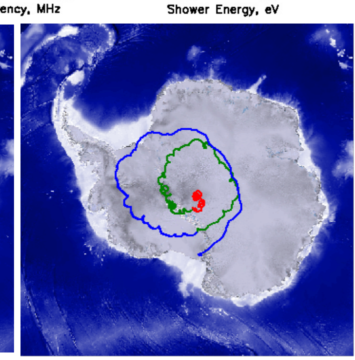
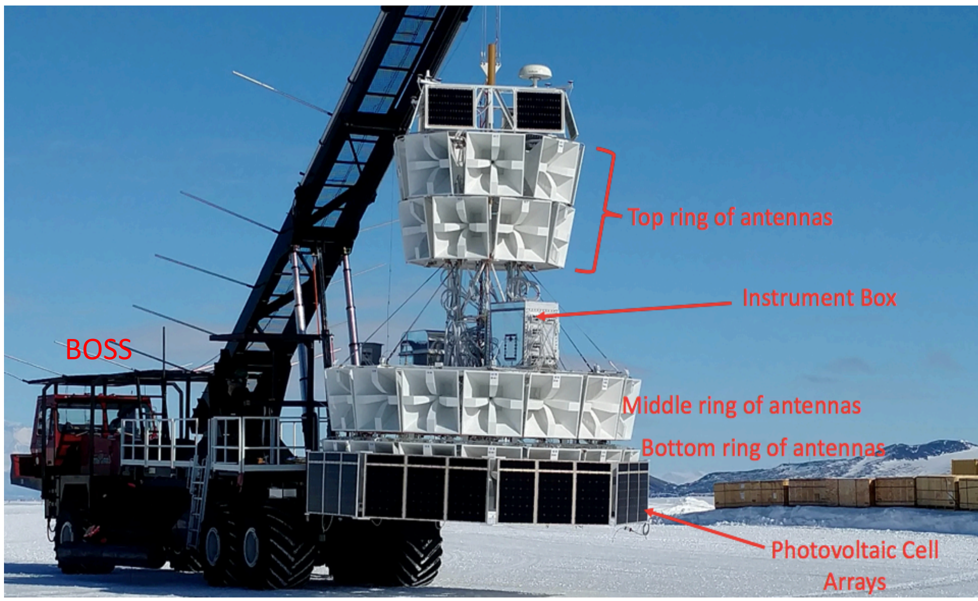




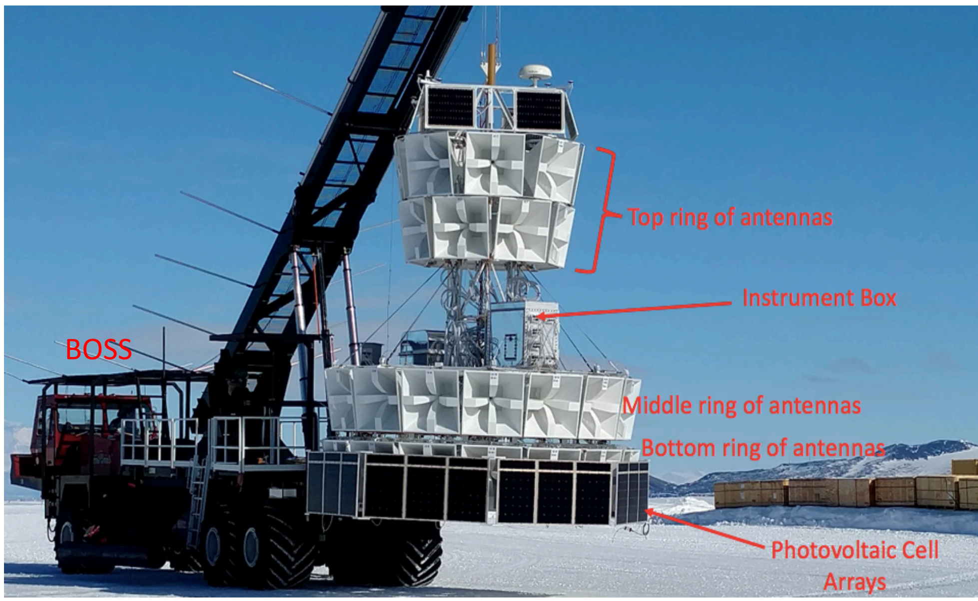




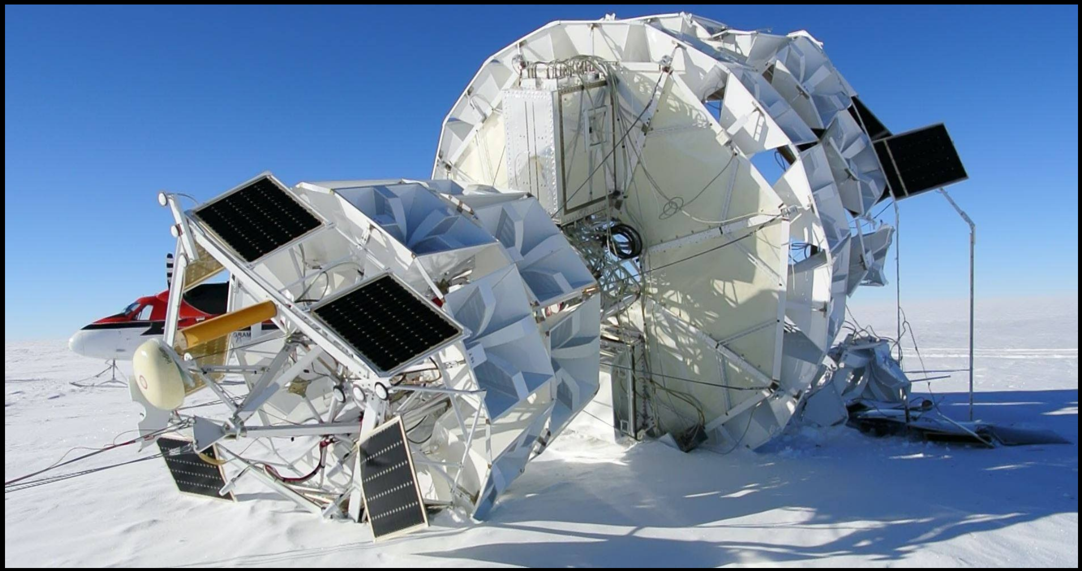
ANITA-4 Launch



ANITA-4 Launch



ANITA-4 Landing



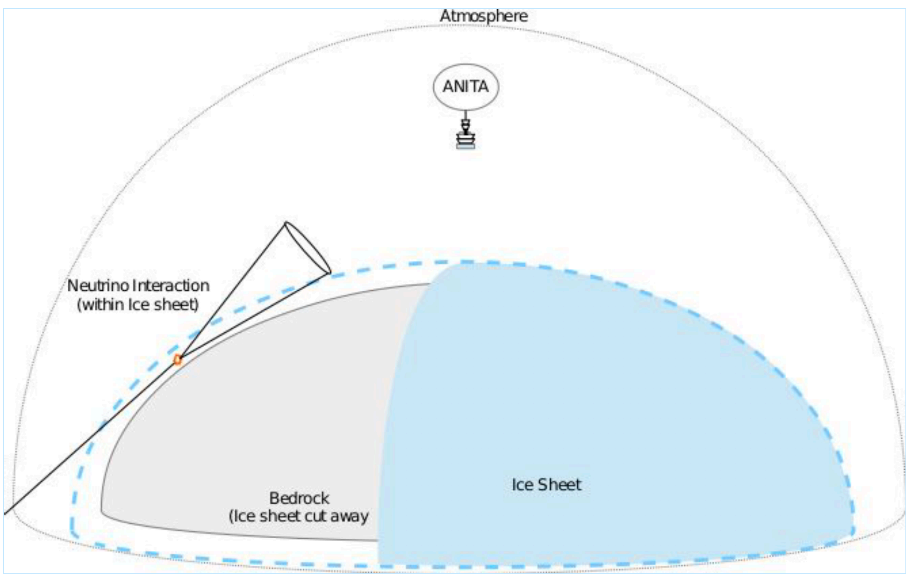
PC: Christian Miki

The Ohio State University

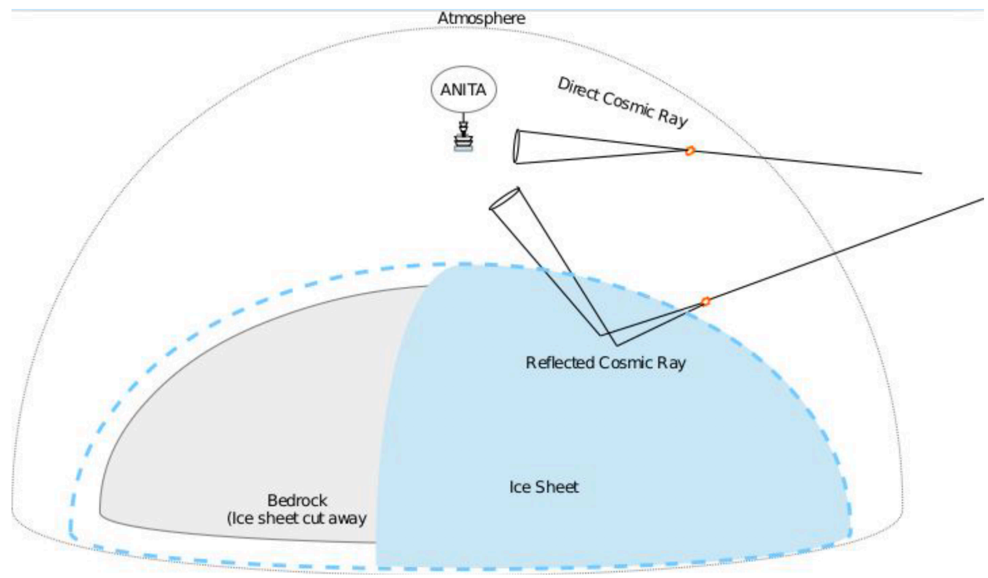
CCAPP

ANITA Detection Channels

Neutrinos



Cosmic Rays



Figures by Ben Rotter

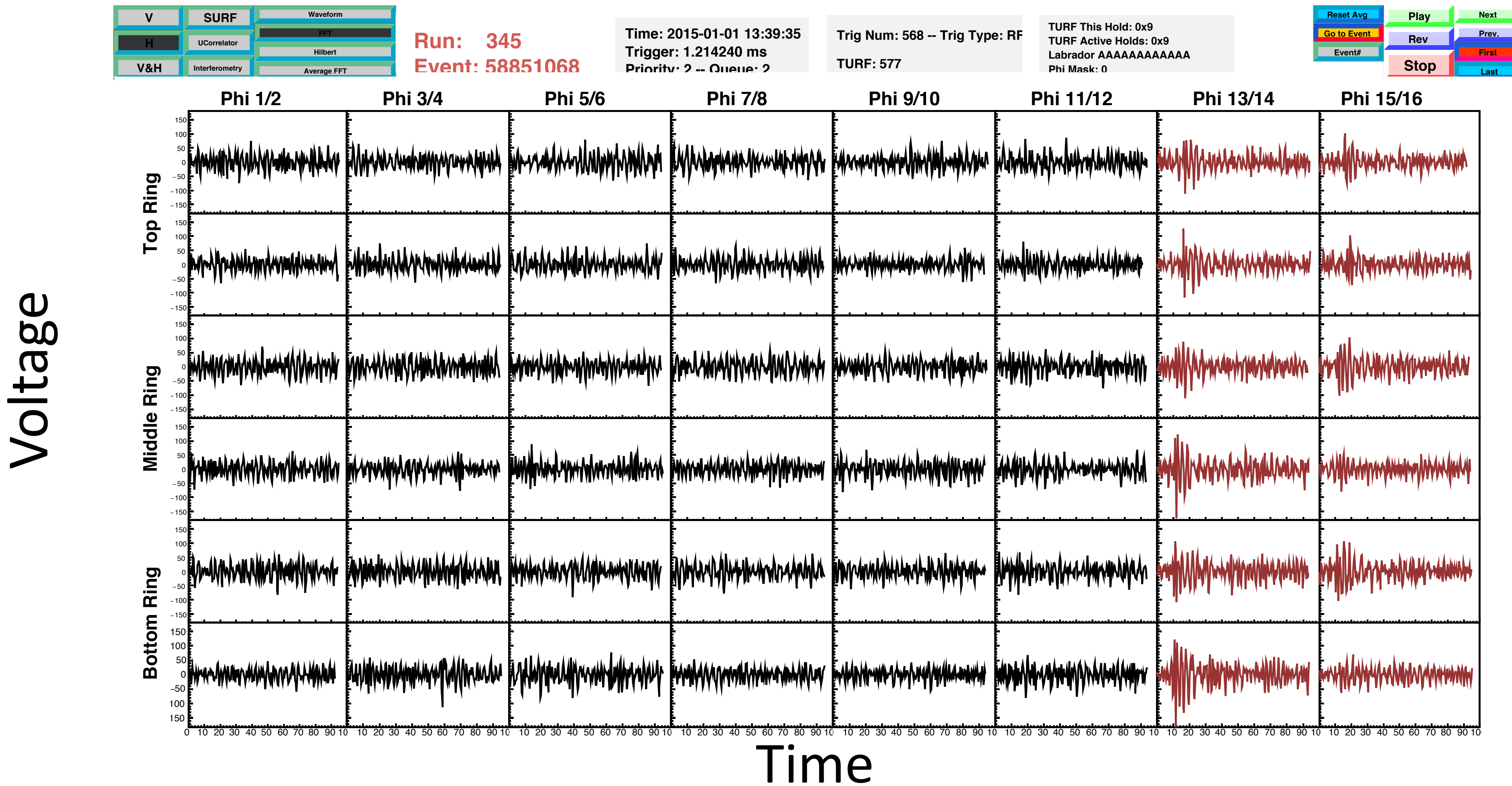
Vertical polarization (VPol)

HPol

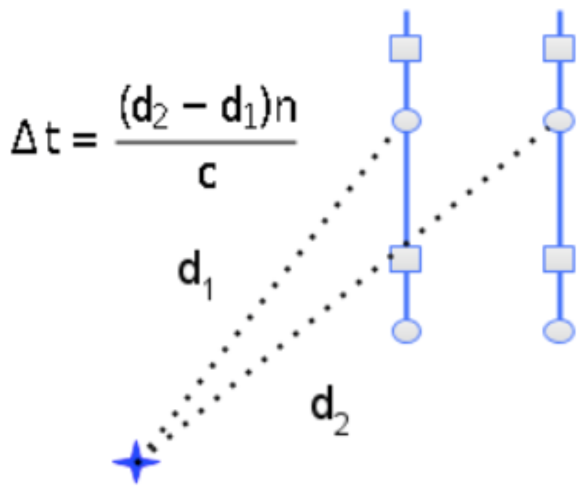
Four flights denoted A1-4

What data looks like

- ANITA-3 data in monitoring software



Interferometry

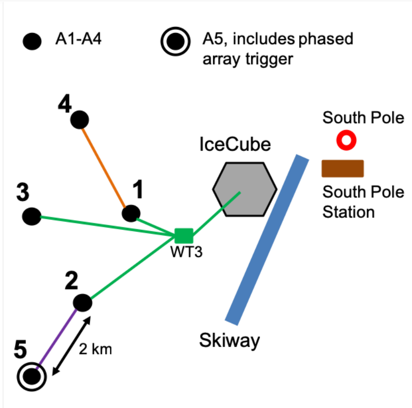


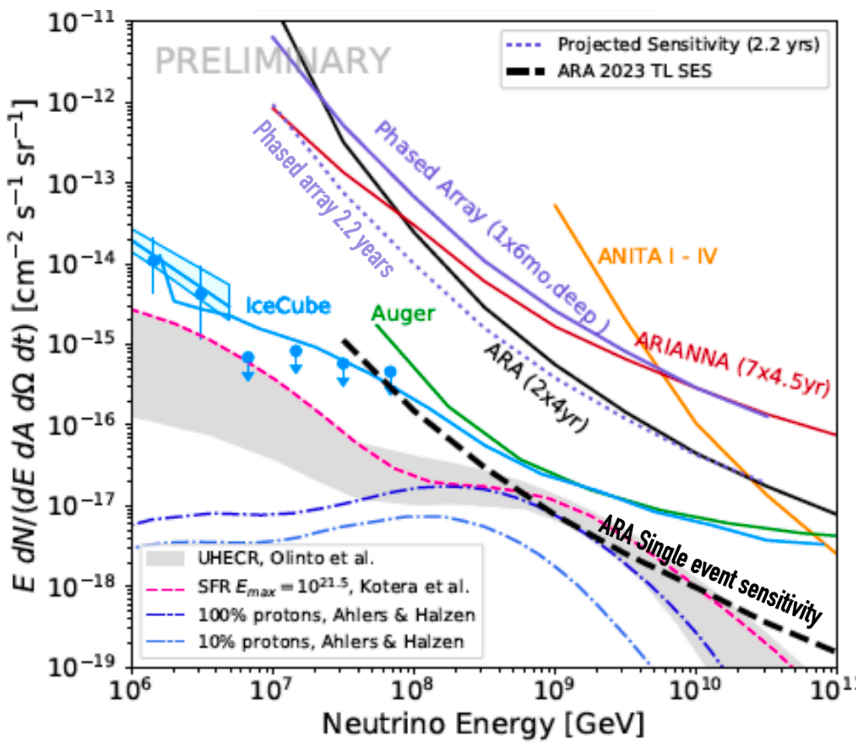
- For each pair of antennas in same polarization, signals arrive with relative delays depending on their incoming direction

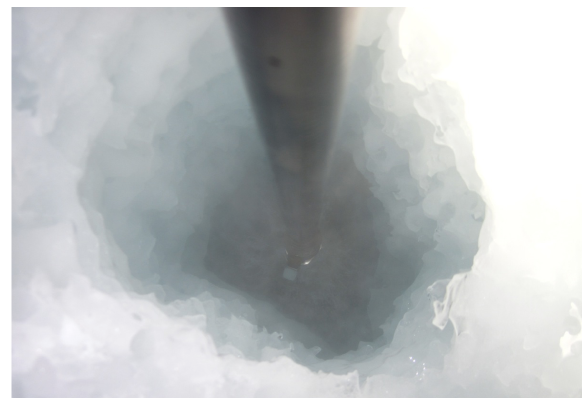
ANITA Results

- ~20 Cosmic Ray events/flight, all but a few reflected
- No excess in neutrino searches - *world's best limits >10^{19} eV*
- Two `anomalous' events in A1 and A3
  - Cosmic ray signature
  - Steeply upgoing: 27° and 35° below horizontal

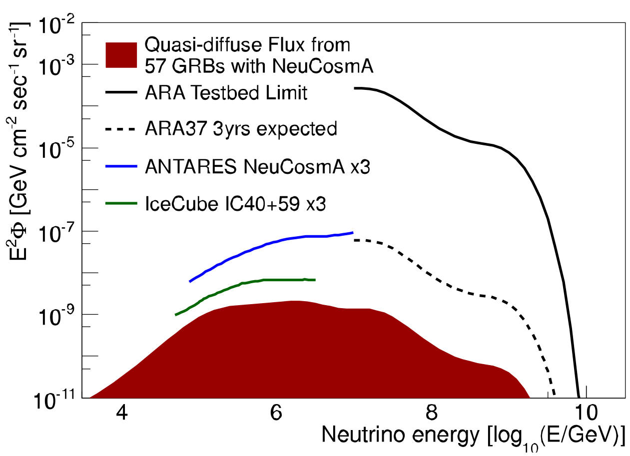
Askaryan Radio Array (ARA)

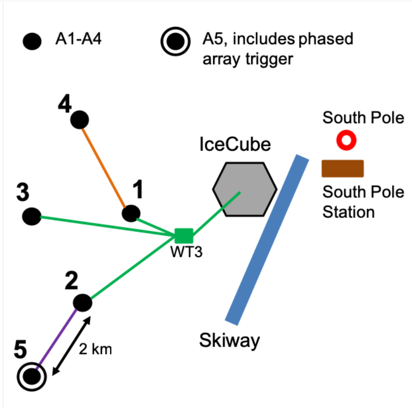






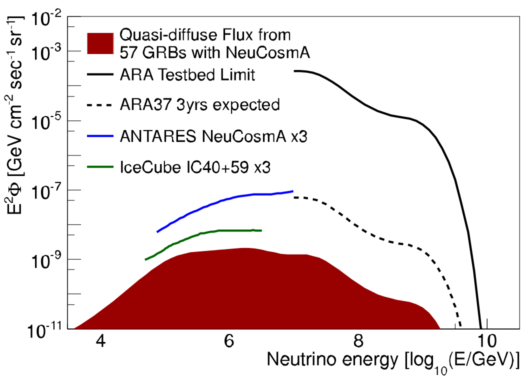
Credit: Mike Duvernois, ARA/NSF

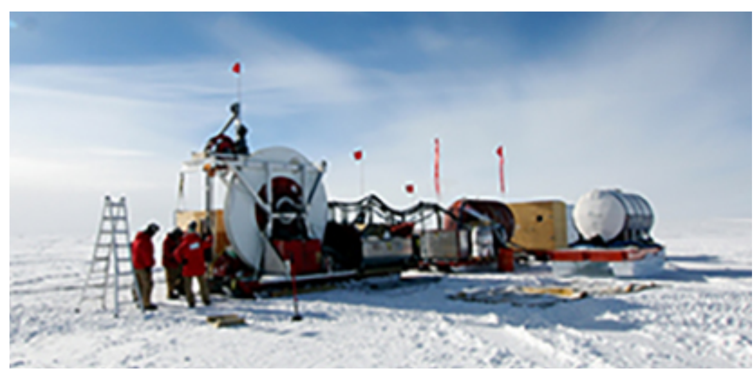




Credit: Mike Duvernois, ARA/NSF

Ohio State, University of Kansas, University of Wisconsin, University of Nebraska, University of Delaware, University of Maryland, National Taiwan University, Chiba University, UCL, University of Chicago, Penn State, Brussels, Denison





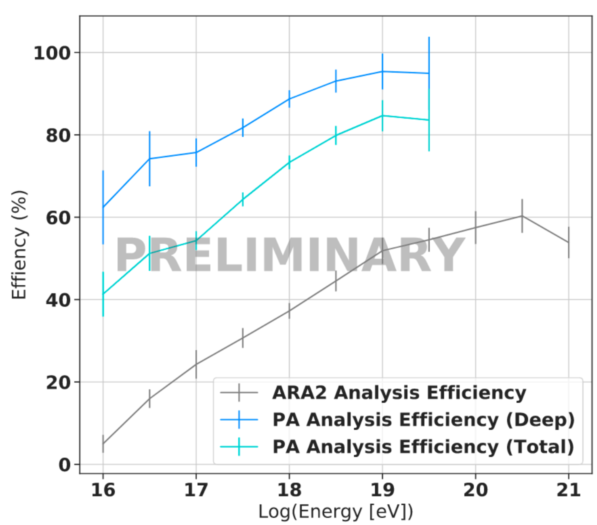
New ARA Results

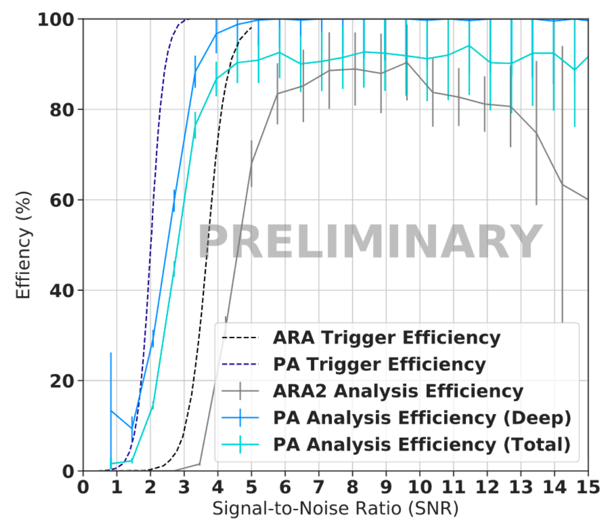
- Station 5: threshold-lowering phased array trigger
- Can analysis thresholds be reduced so that we can search in the new low-threshold region? YES

Analysis Efficiencies

➤ **Efficient in analysis on events that the traditional ARA trigger cannot see!**

➤ Better than previous ARA analyses at low energies by a factor of ~10





Kaeli Hughes 9

Kaeli Hughes (U Chicago) just shown at ICRC2021

Fundamental physics

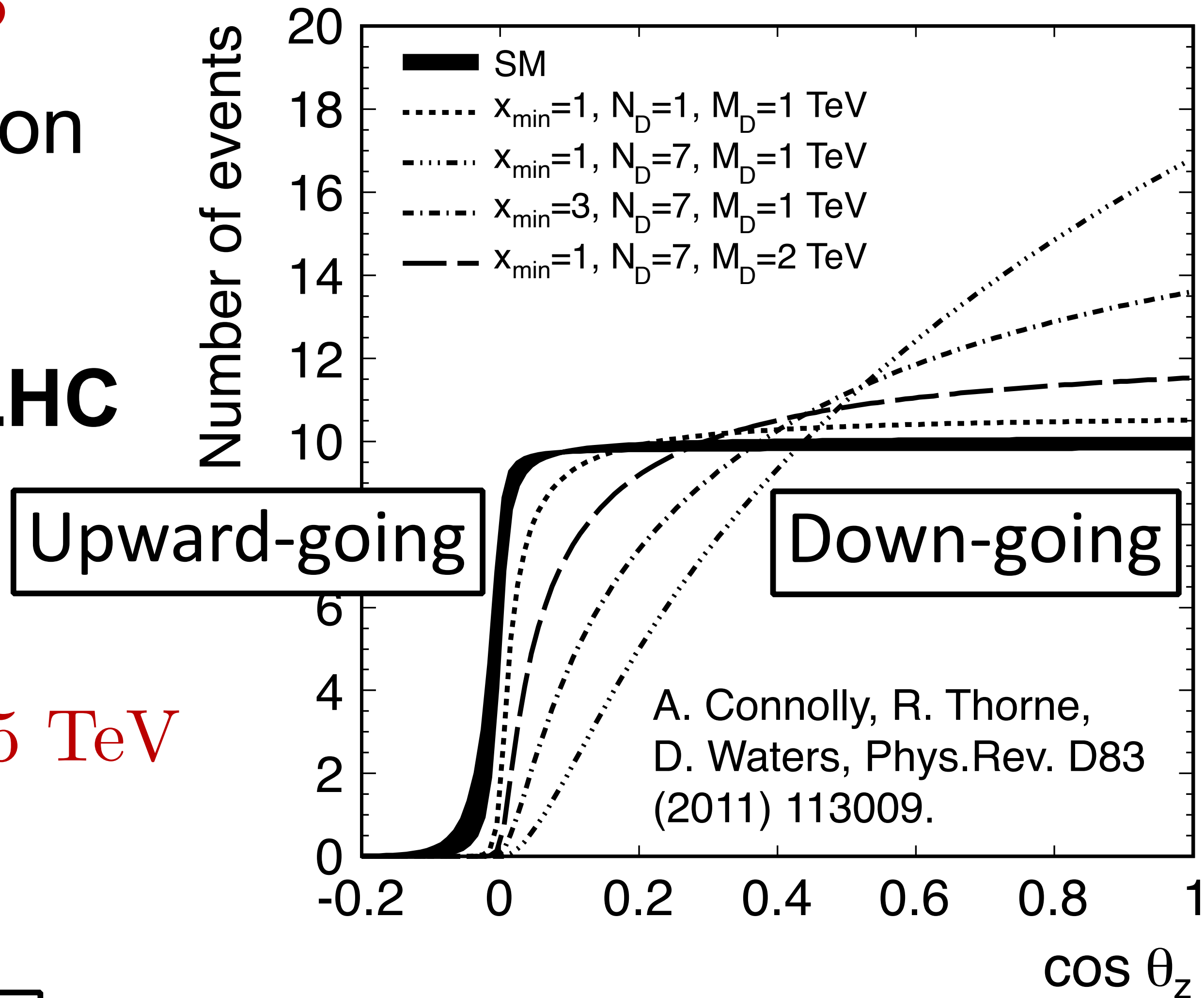
Cross Sections

- UHE neutrino-nucleon interactions probe **center-of-mass energies beyond LHC**

$E_\nu = 10^{18}$ eV:

$$E_{\rm CM} = \sqrt{2 m_N E_\nu} = 45\ {\rm TeV}$$

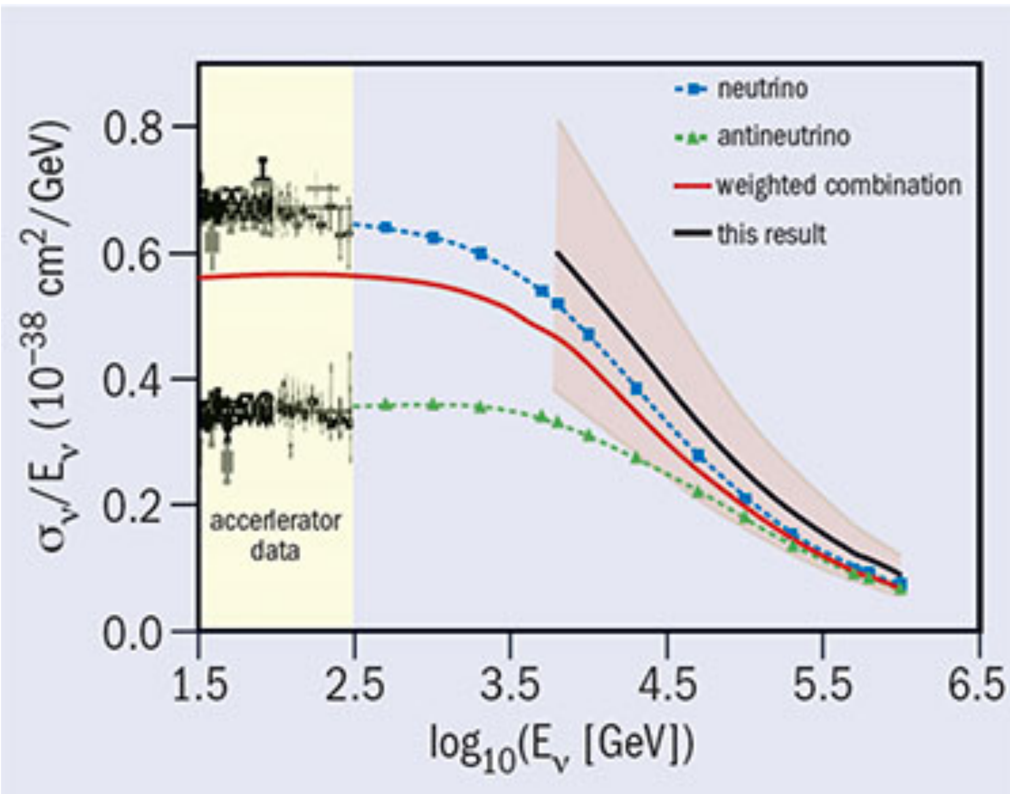
Assumes isotropic neutrino flux !



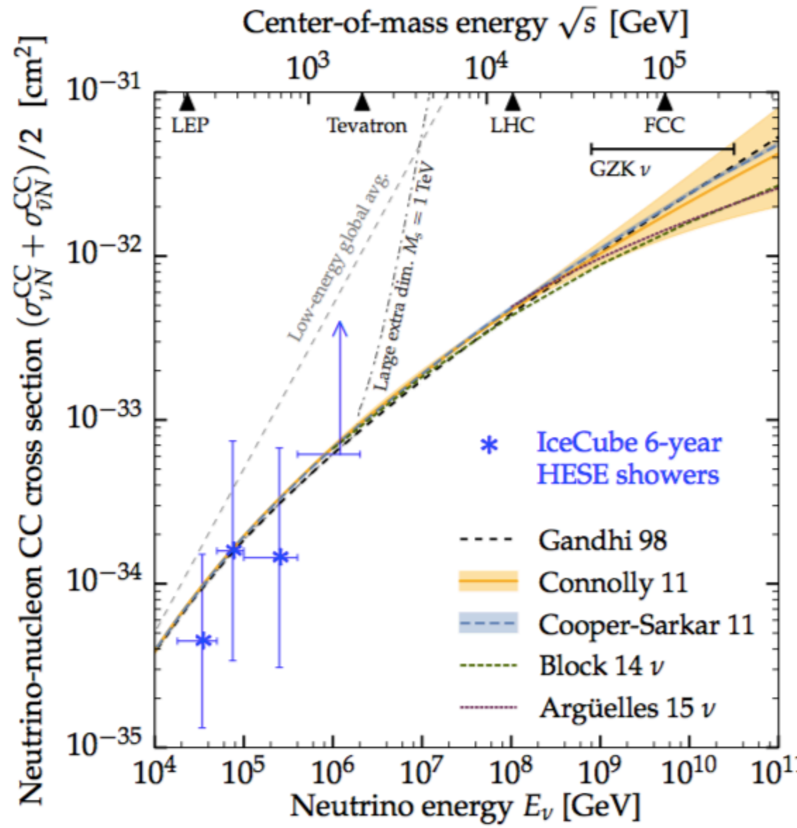
ED model predictions from J. Alvarez-Muniz and E. Zas, Phys. Lett. B411, 218 (1997).

Real measurements now!

IceCube Collaboration



IceCube Collaboration 2017 *Nature* **551** 596.



M Bustamante and A Connolly
Phys.Rev.Lett. 122 (2019) no.4, 041101

CERN COURIER

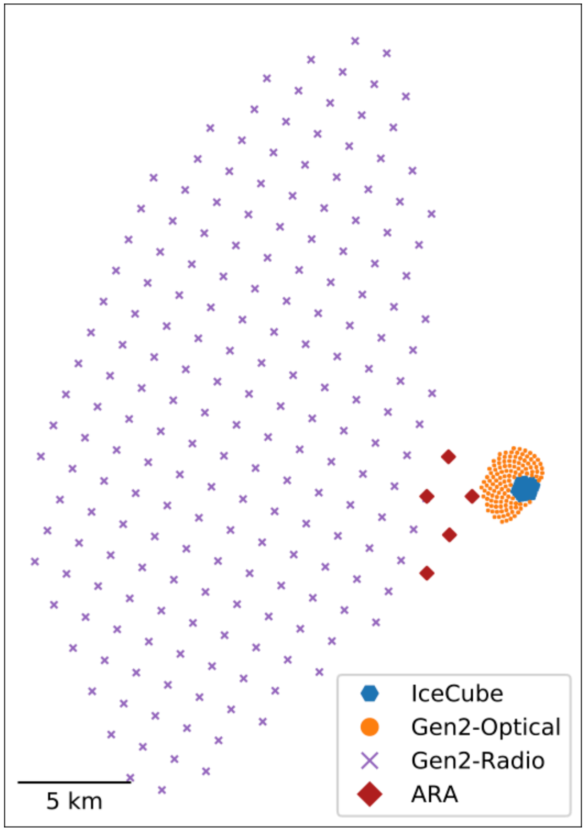
Jan 15, 2018

The case of the disappearing neutrinos

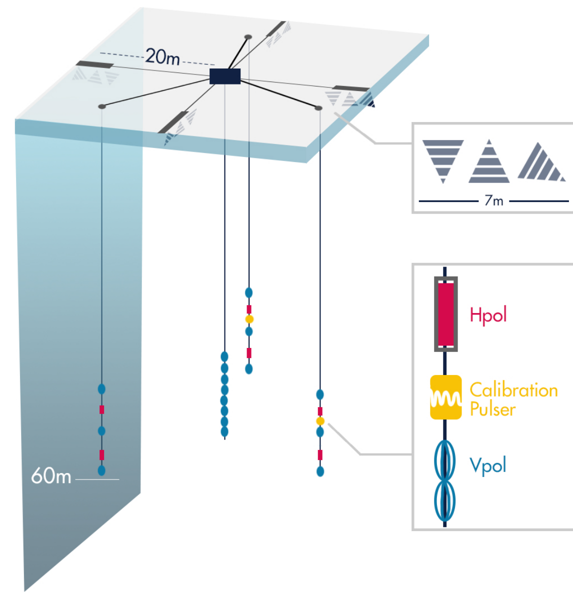
Future…

IceCube Gen2-Radio

- IceCube is proposing to expand to a next-generation array
  - Optical
  - Radio - to expand 3 orders of magnitude in energy
- Design of both components being finalized



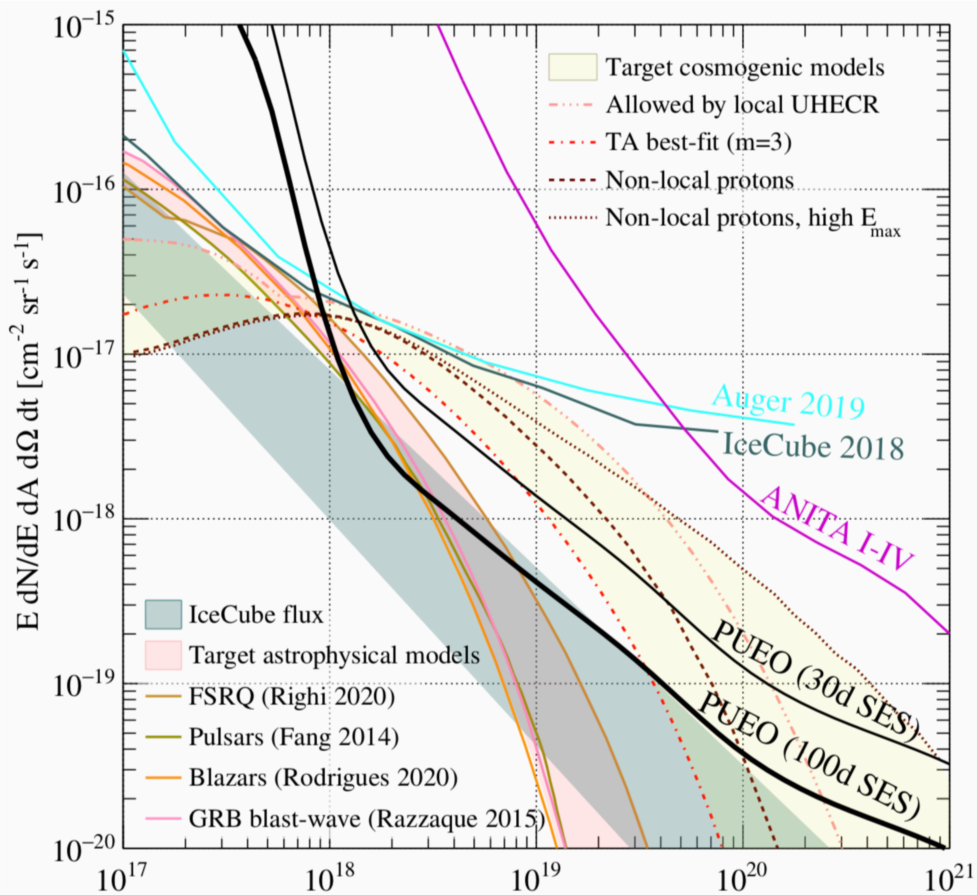
arXiv:2008.04323



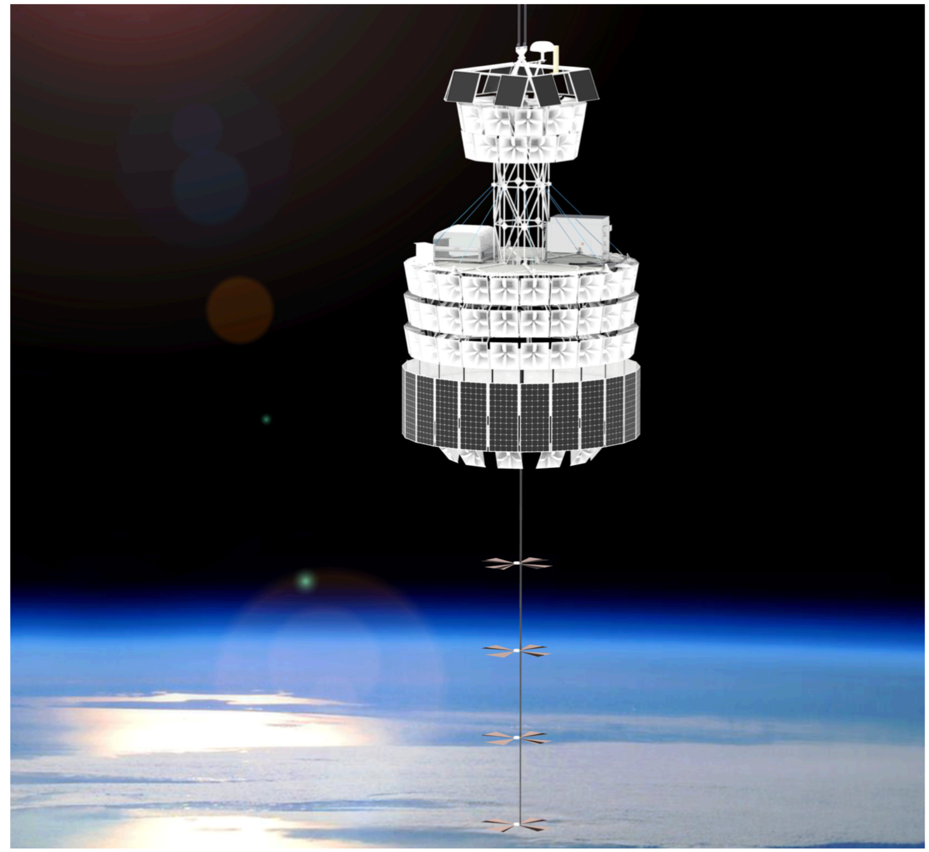
- Reference design - surface and deep
- RNO-G with stations of similar design being deployed in Greenland right now.

PUEO

Selected - Flight 2025-26



arXiv:2010.02892



- Interferometry at trigger level
- More antennas - without <300 MHz

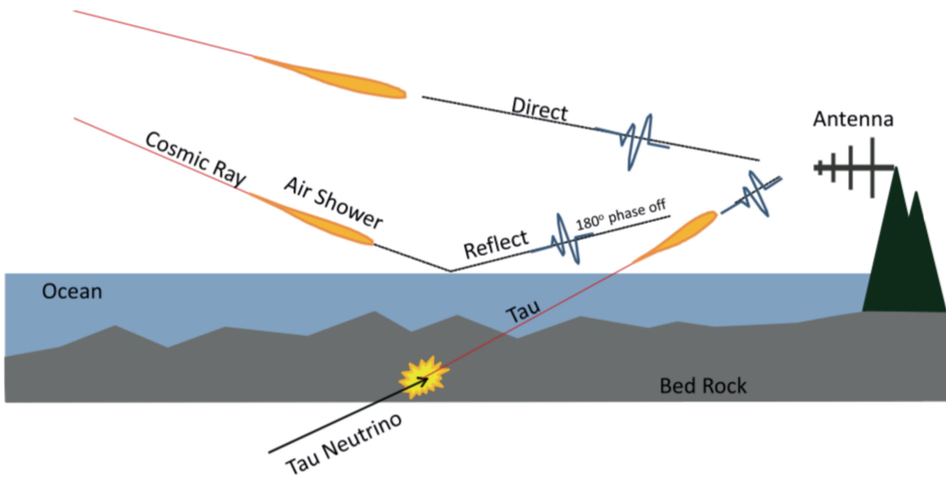
Other techniques…

…Tau-induced showers

Air showers induced by tau neutrinos

- Experiments being planned to exploit this technique

Particle and Nuclear Physics
93 (2017) 1-68



TAROGE-1

Other experiments -
POEMMA
arXiv:1708.07599
Trinity
See N. Otte, Apr. APS `18
TAROGE
ARIANNA
GRAND
arXiv:1508.01919
BEACON: Phased array atop a mountain - S. Wissel

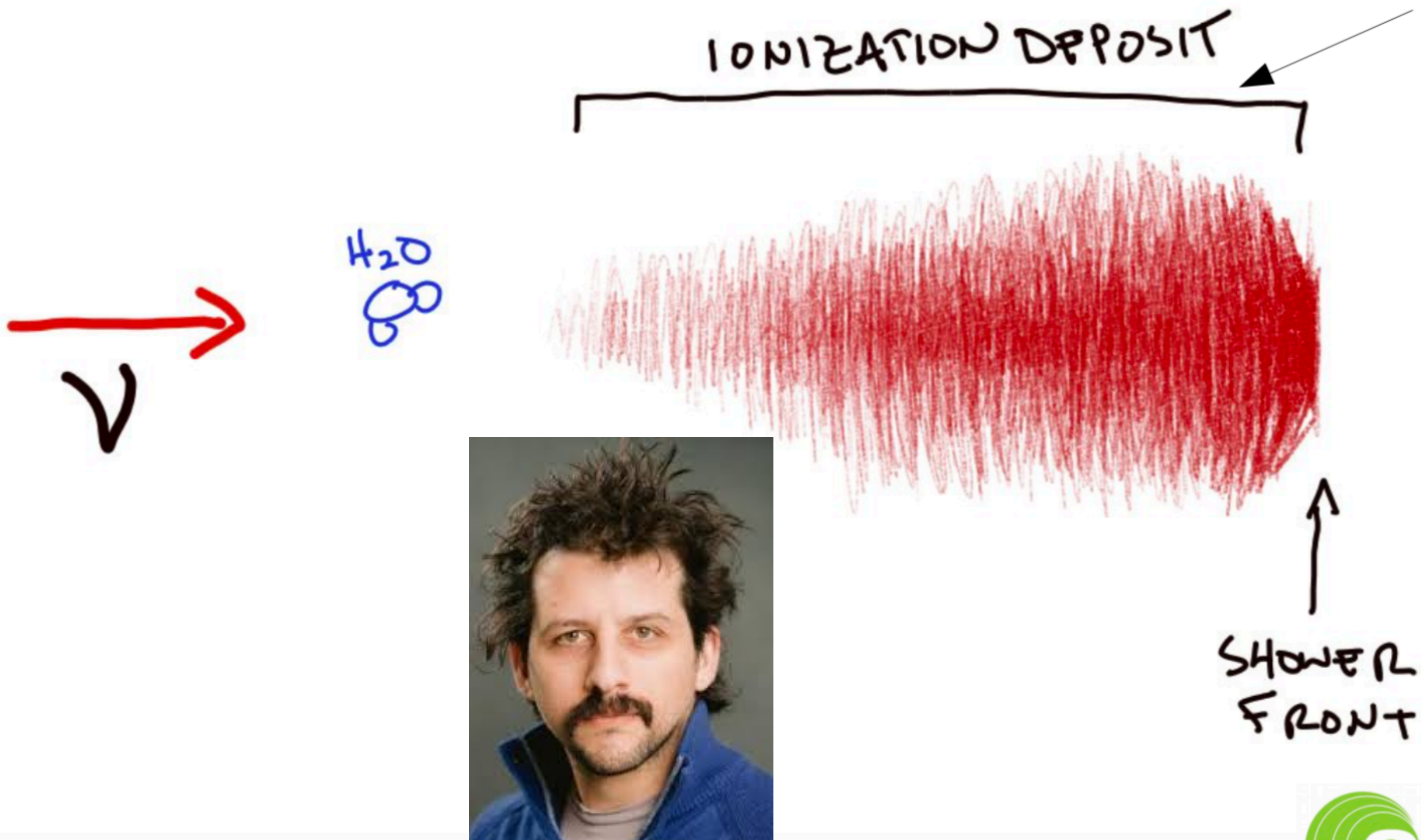
- Auger uses similar mechanism to set strong limits
- ANITA has reported two events that would fit this signature but their steep angle would require a lower cross section than SM expectations predict

arXiv:1803.05088

…Radar?

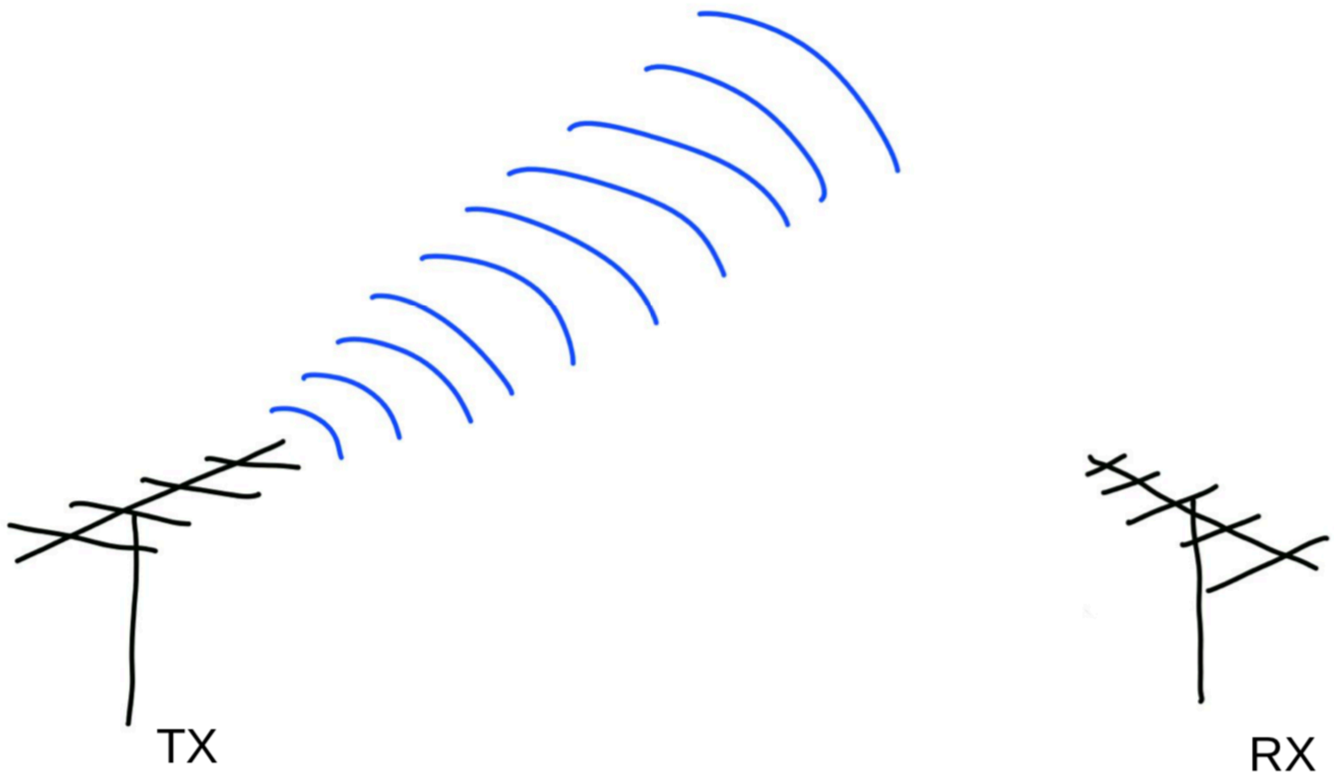
Concept #1: particle cascades

- high-energy primary interactions create cascades of relativistic particles
- cascade particles *ionize* the material, leaving behind a dense, short-lived cloud of charge



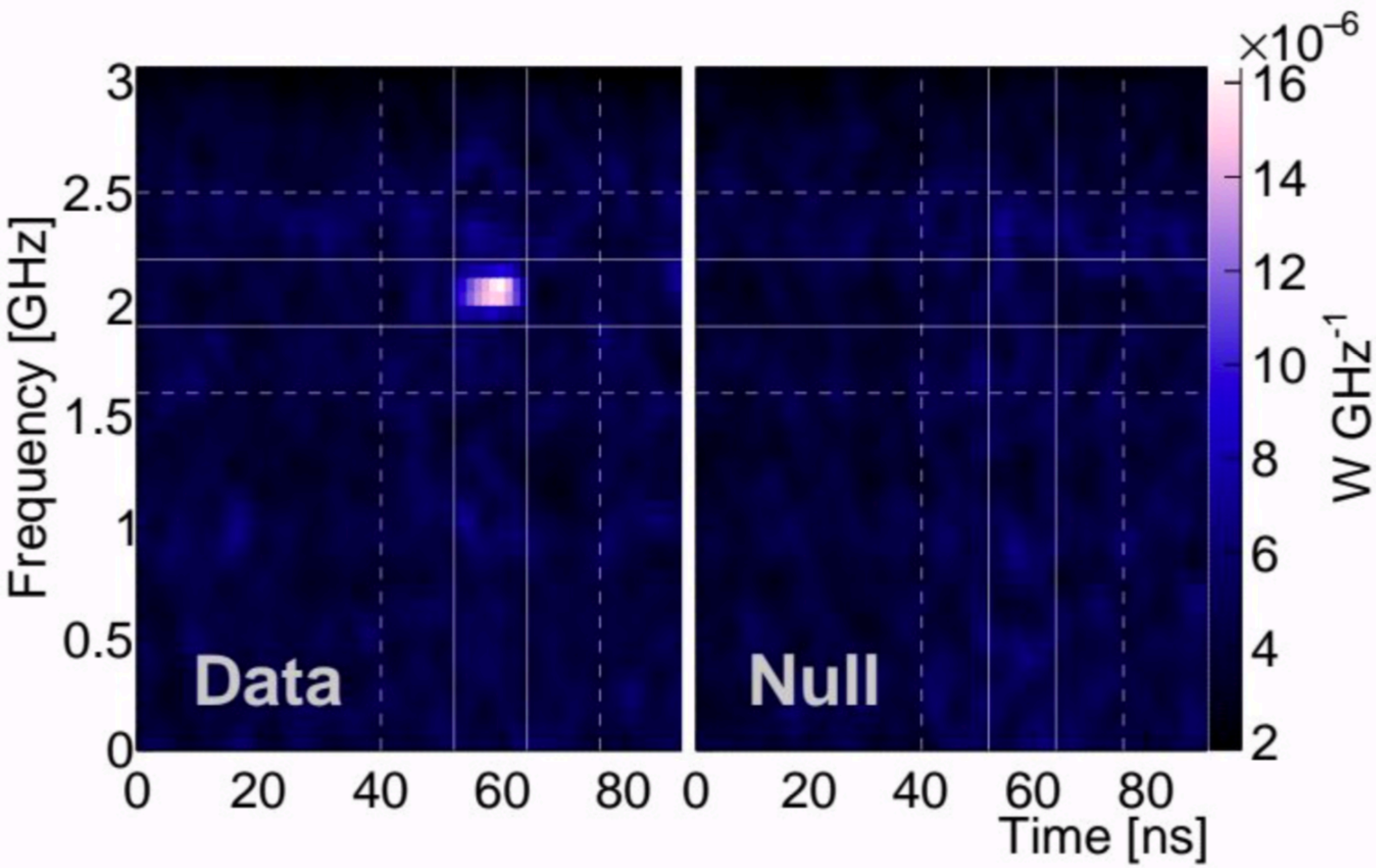
'length' of this deposit depends on the properties of the medium, the 'lifetime' of a free electron.

Concept #2: radar overview



- **Transmitter (TX) broadcasts a radio signal into a volume**
- **receiver(s)(RX) monitor this same volume**

Toward radar echo detection: T576



A signal was observed (here the bright blob at left) compared to a null hypothesis.

Observed at multiple transmit frequencies and in multiple receive antennas

details:

arXiv:1810.09914
arXiv:1910.11314
arXiv:1910.12830

PHYSICAL REVIEW LETTERS **124**, 091101 (2020)

Editors' Suggestion | Featured in Physics

Observation of Radar Echoes from High-Energy Particle Cascades

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GENETIS (Genetically Evolving NEutrIno TeleScopes

J. Rolla, *PoS* ICRC2019 (2021) 992.

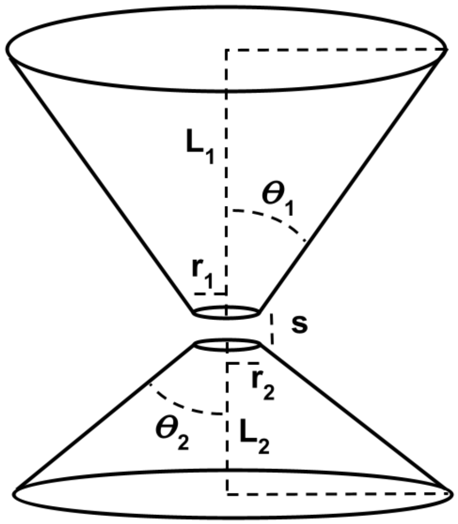
- Optimizing detector designs for neutrino telescopes in high dim. parameter space
- Evolve using genetic algorithms (type of machine learning)

GENETIS Mini-Collaboration Meeting April APS 2018

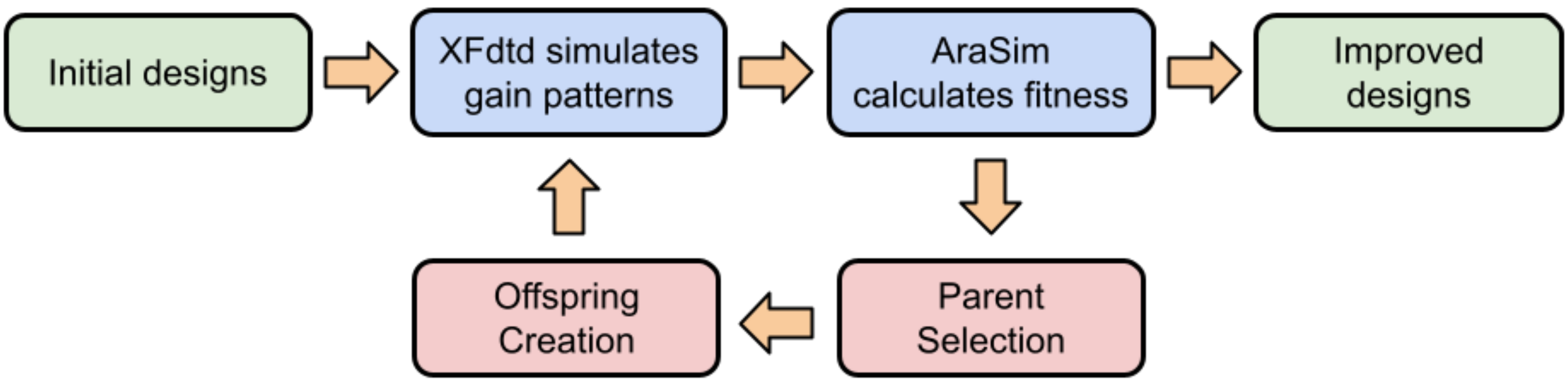
Prof. Amy Connolly (Physics), K. Staats (Univ. of Arizona), Prof. Edward Herderick (OSU CDME), Prof. Chi-Chih Chen (OSU Electrical & Computer Eng.), Prof. Pfendner (Denison), Wolfgang Banzhaf (Michigan State, ML)

Heavy involvement from undergraduates, interdisciplinary.

GENETIS

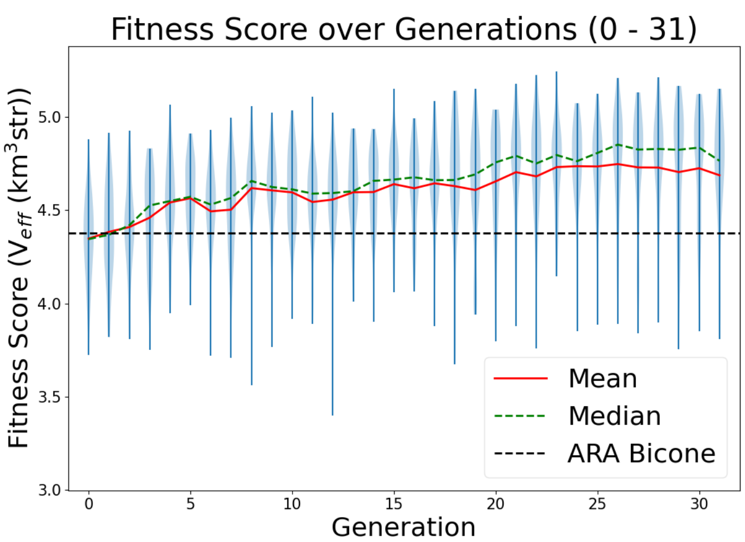


GENETIS loop (now in action):

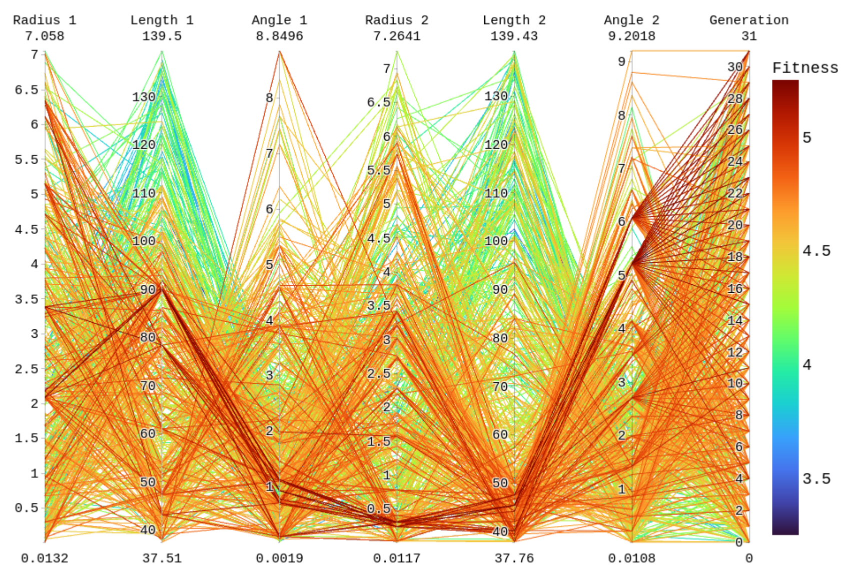


GENETIS

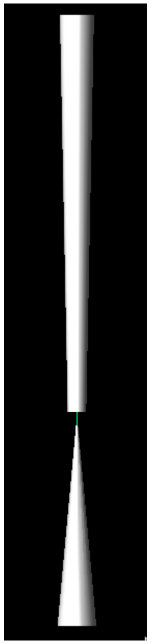
First results: Fitness scores improving over generations



Best fit antennas (red) have common design parameters



Best fit antenna, first run



Next: More complex designs, build at OSU's Center for Design and Manufacturing Excellence, test at ESL, deploy in ice, broaden scope

Summary

- Let's see what nature has in store above 10 PeV!
  - UHE astronomy at cosmic distances
  - Tests of fundamental physics
- Current experiments are expanding and reducing thresholds
- Watch for the development of many novel approaches

Thank you!