THE OHIO STATE UNIVERSITY

Ultra High Energy Neutrinos with Radio

Prof. Amy Connolly

Sept. 7, 2018

CCAPP

NSF

NASA

Outline

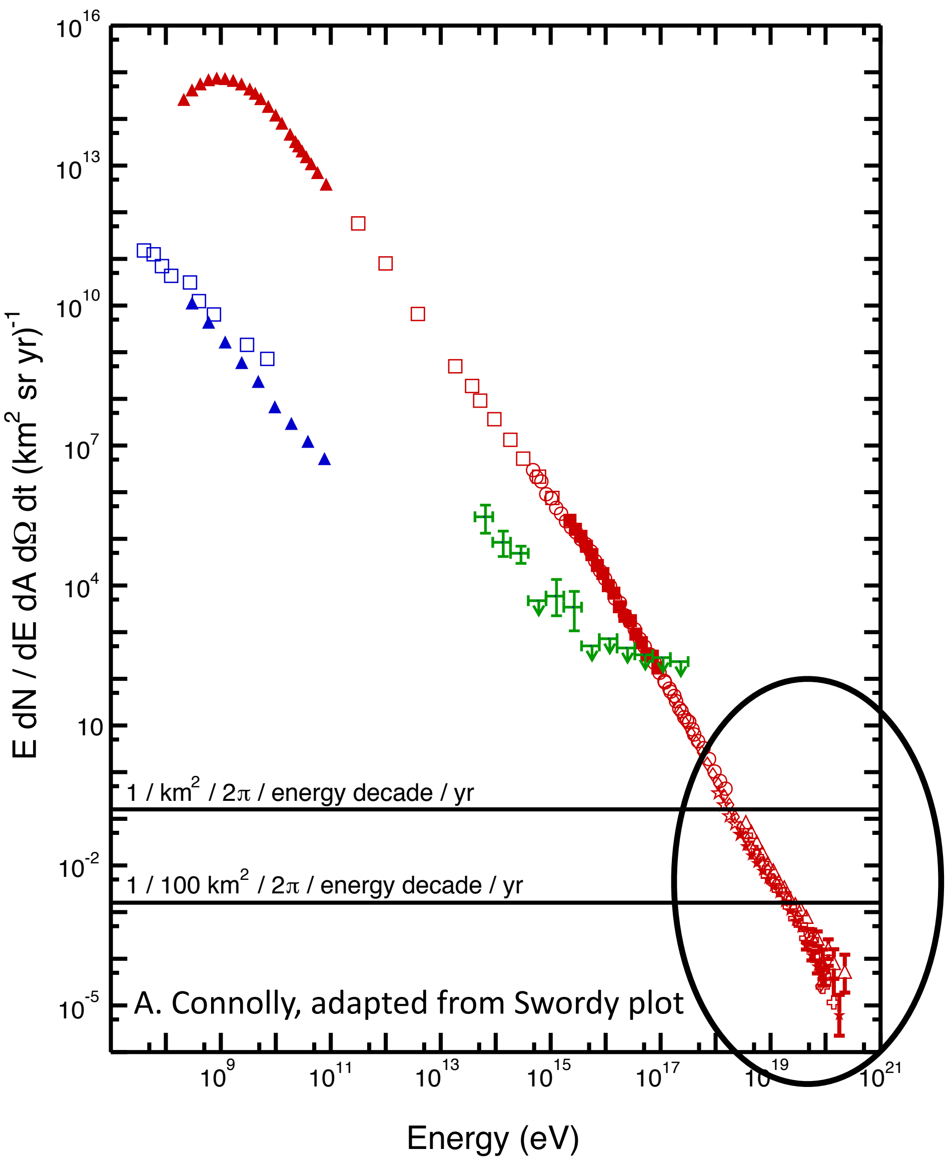
- Science motivation for going to higher energies
- Radio Cerenkov
- Other techniques
- Future

Science motivation

astronomy

The Ohio State University CCAPP

The High Energy Universe



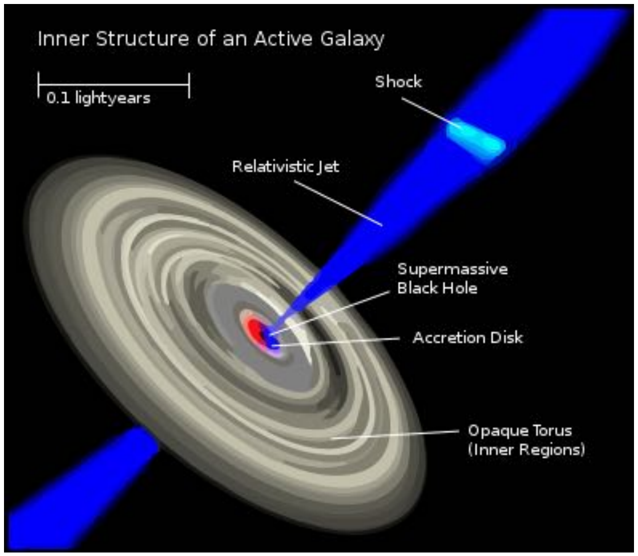
- Cosmic ray charged particles
- Gamma rays: Egret, Fermi
- Neutrinos! IceCube
- Gravitational waves! ~$1/r^2$

Ultra-high energy (UHE) regime

UHECRs

UHECR source candidates

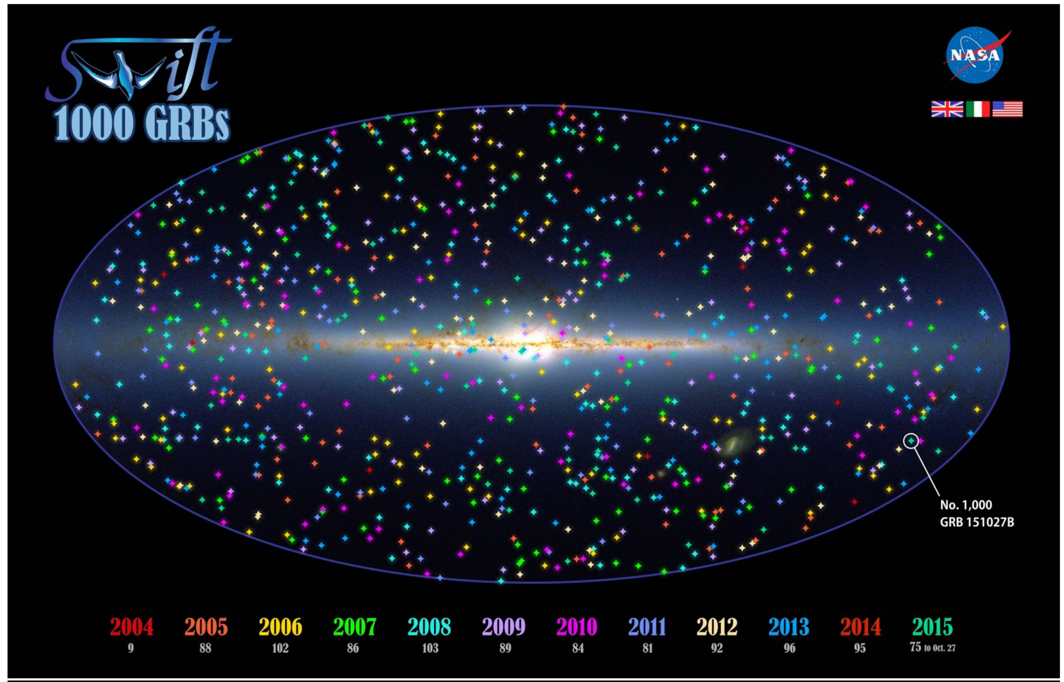
Active Galactic Nuclei (AGN)



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

- Black hole accreting mass

Gamma Ray Bursts (GRB)



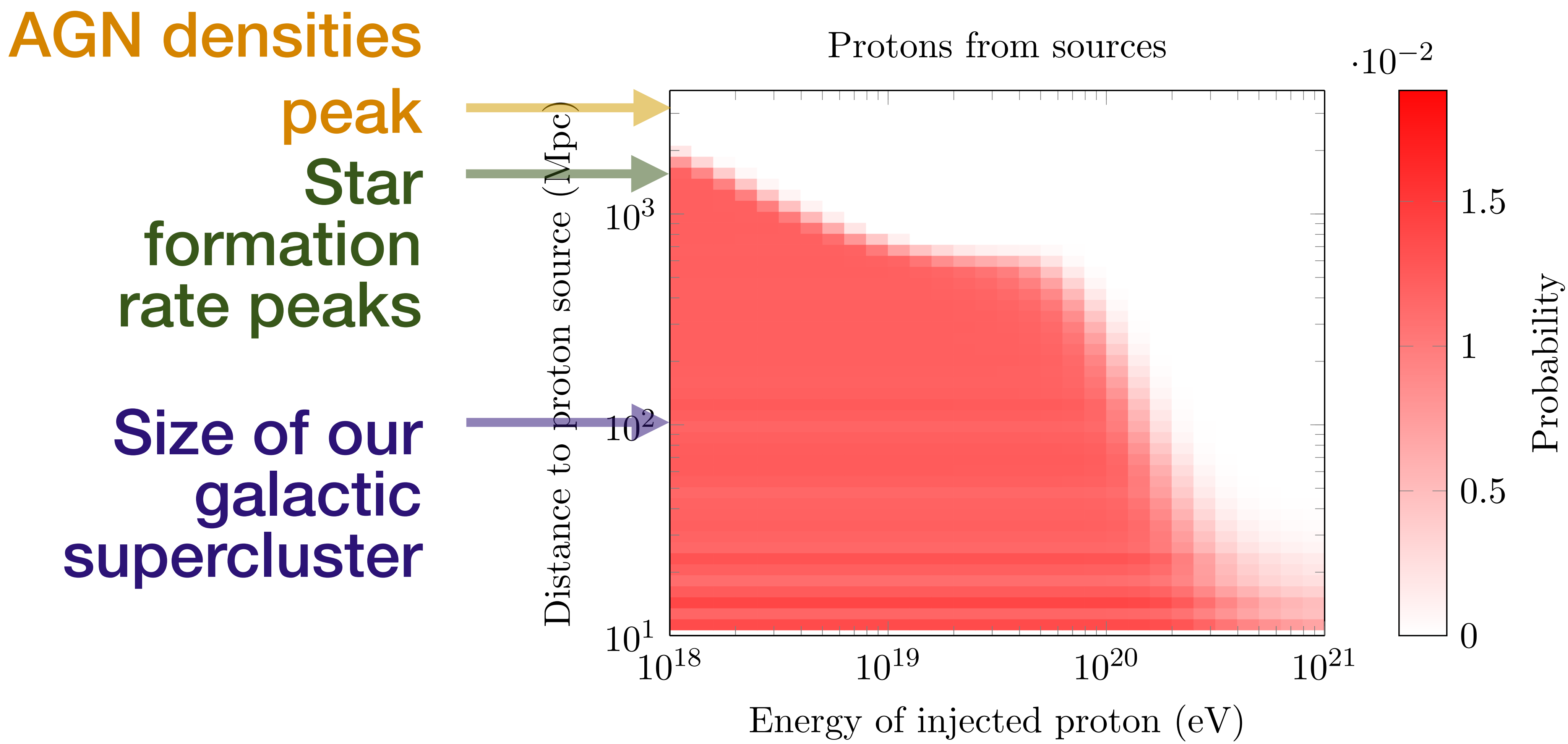
- Star collapse, merger of neutron stars

UHECR sources expected to produce neutrinos via photohadronic interactions

THE OHIO STATE UNIVERSITY

CCAPP

Which sources can cosmic rays see?



The Ohio State University

CCAPP

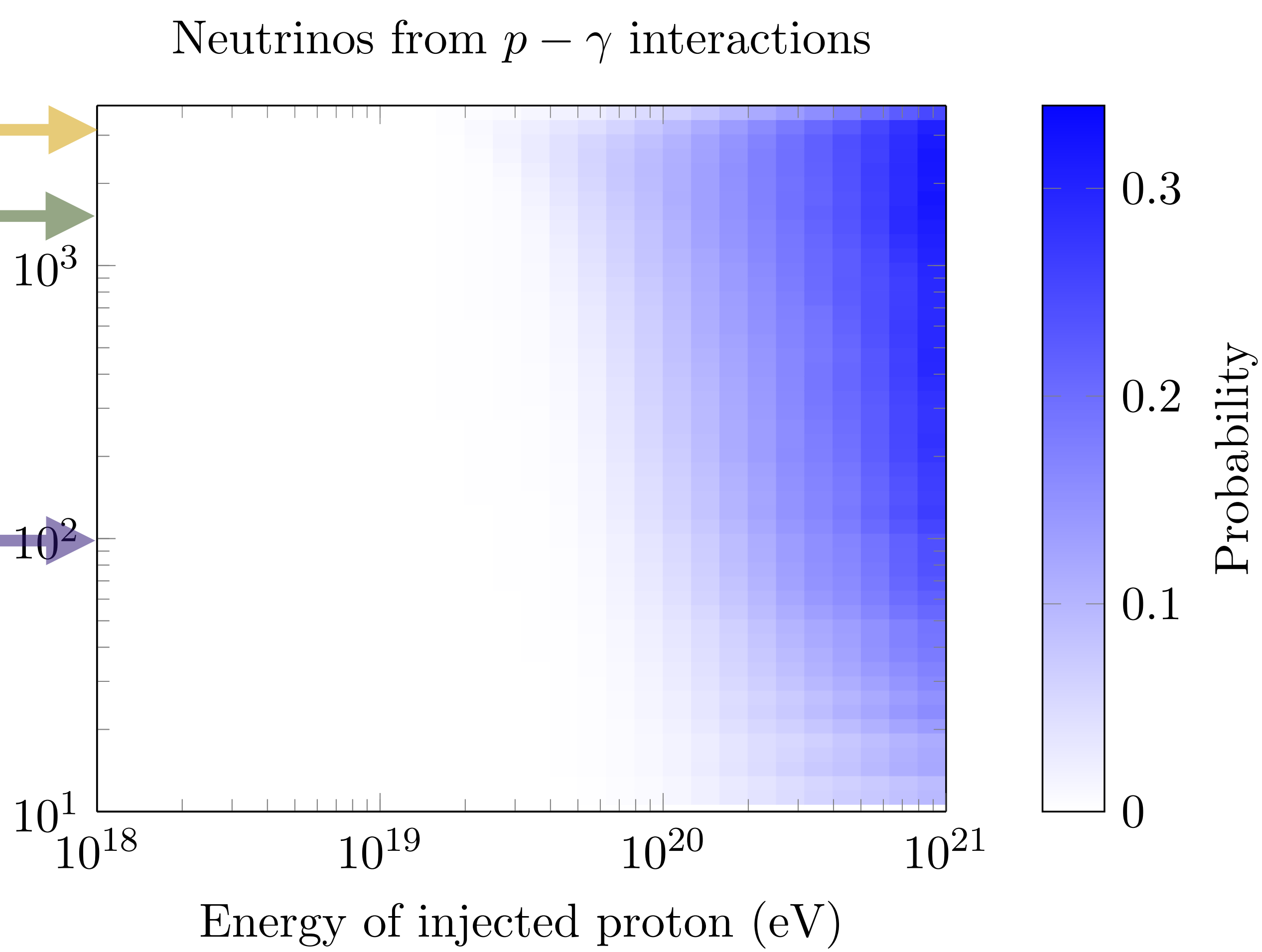
Which sources can neutrinos see?

UHECRs produce *neutrinos* when they interact with cosmic microwave background light

AGN densities peak

Star formation rate peaks

Size of our galactic supercluster



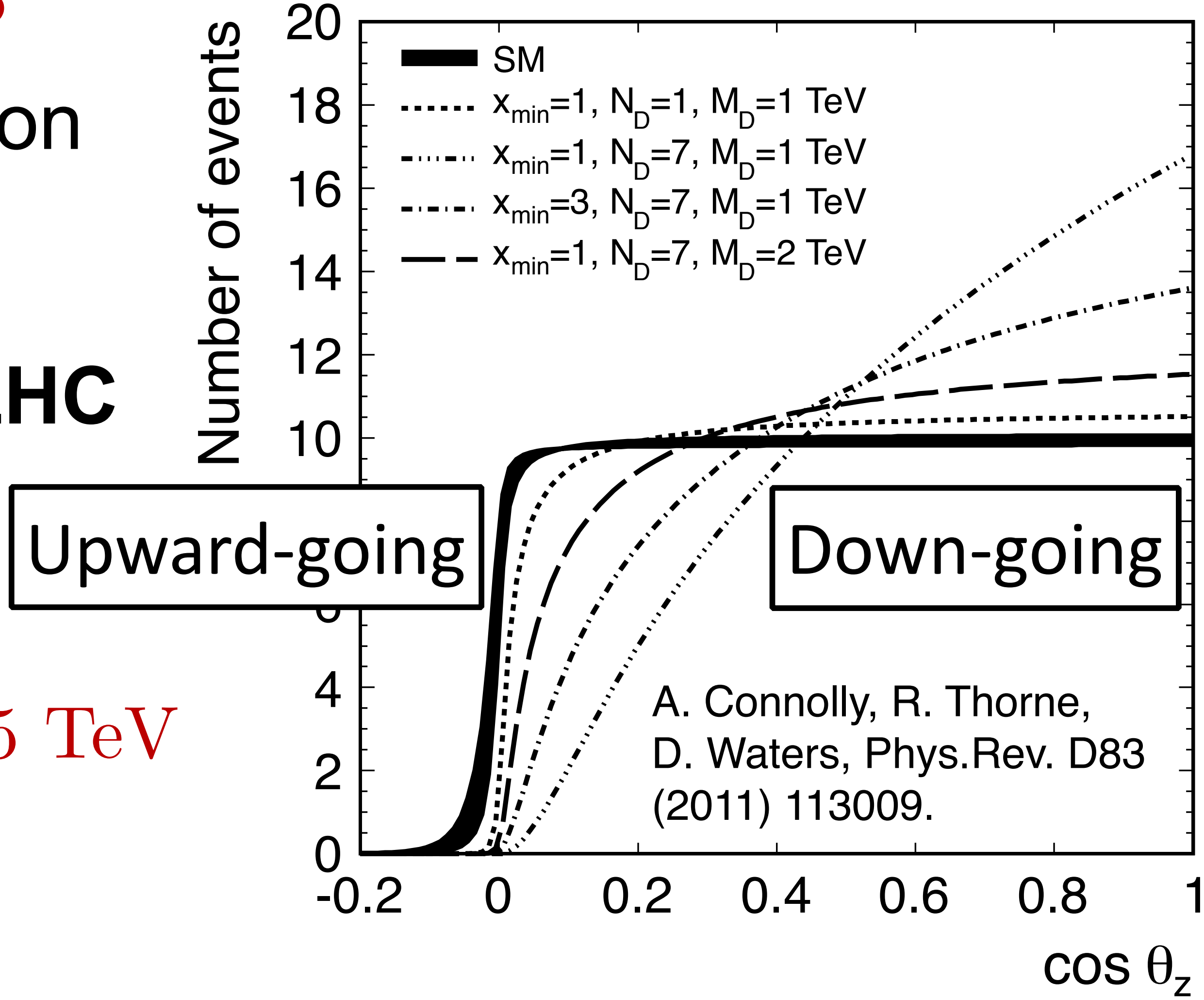
fundamental physics

Cross Sections

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

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

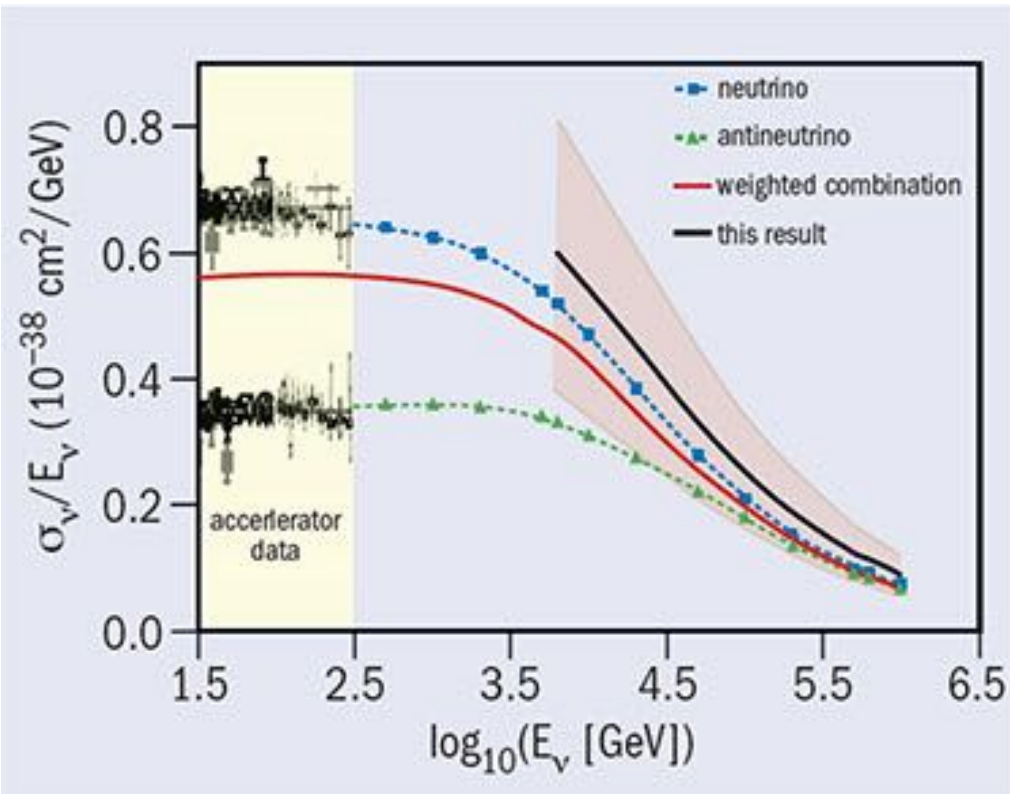
$$E_{\rm CM} = \sqrt{2 m_N E_\nu} = 45 \text{ TeV}$$



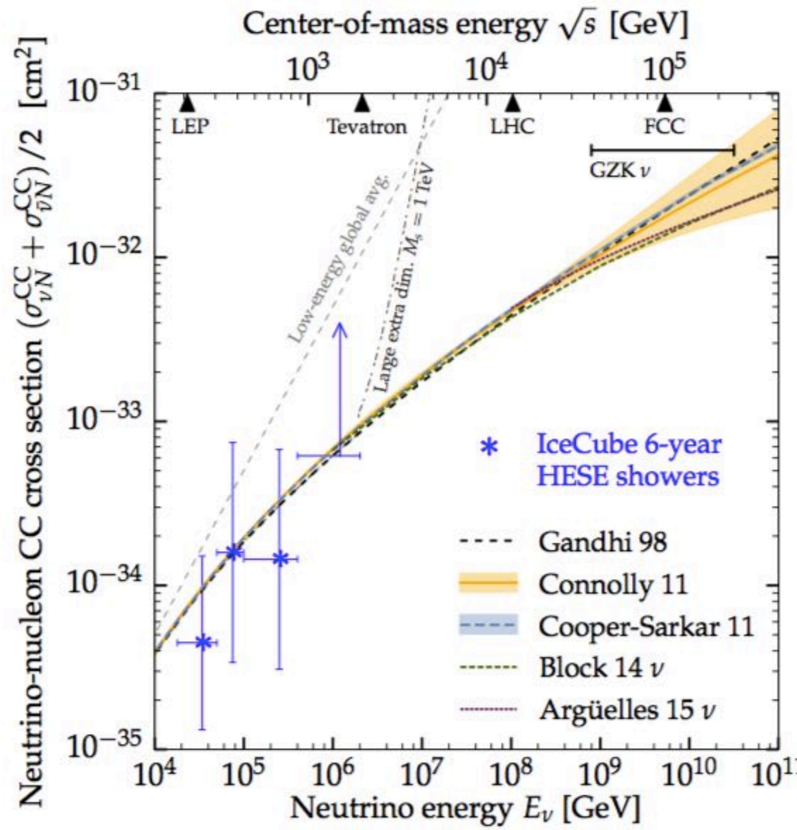
ED model predictions from J. Alvarez-Muniz and E. Zas, Phys. Lett. B411, 218 (1997).

Real measurements now!

IceCube Collaboration



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



M Bustamante and A Connolly 2017 arXiv:1711.11043

CERN COURIER

Jan 15, 2018

The case of the disappearing neutrinos

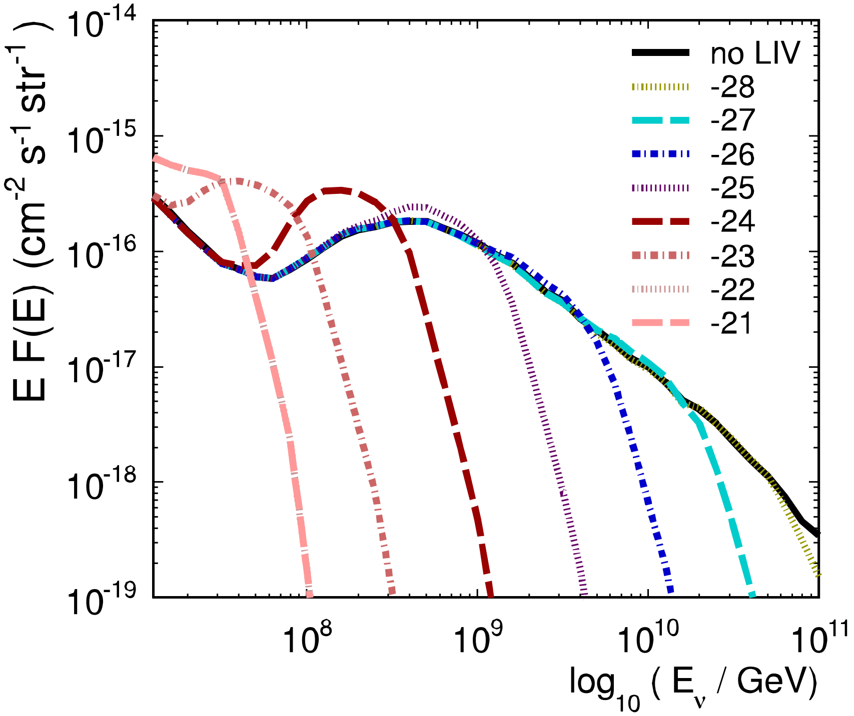
Lorentz Invariance Violation (LIV)

- Only particles we will be able to see at **1 Joule** after traveling **1 billion light years**

$$E_\nu = p_\nu c(1 + \alpha_\nu)$$

$$\nu_i = \nu_i' + e^- + e^+$$

$$\tau_\nu \propto E_\nu^{-5} \alpha_\nu^{-3}$$



P.W. Gorham, A. Connolly *et al.*, Phys.Rev. D86 (2012) 103006.

→Sensitive test of LIV

Radio

The case for going beyond optical

~ 10 cosmogenic neutrinos / km^2 / year

10^{18} eV: νN interaction length O(1000) km

→ 0.01 neutrinos / km^3 / year

At most, we see 1/2 the sky

→ 0.005 neutrinos / km^3 / year

Neutrinos from sources at a similar level

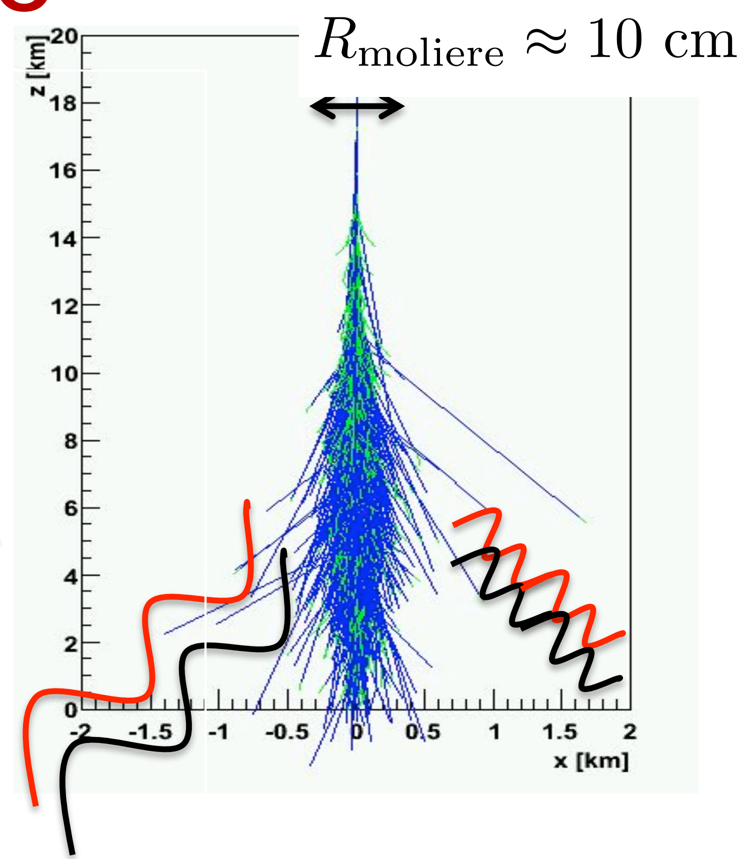
We need >100's of km^3 detection volumes

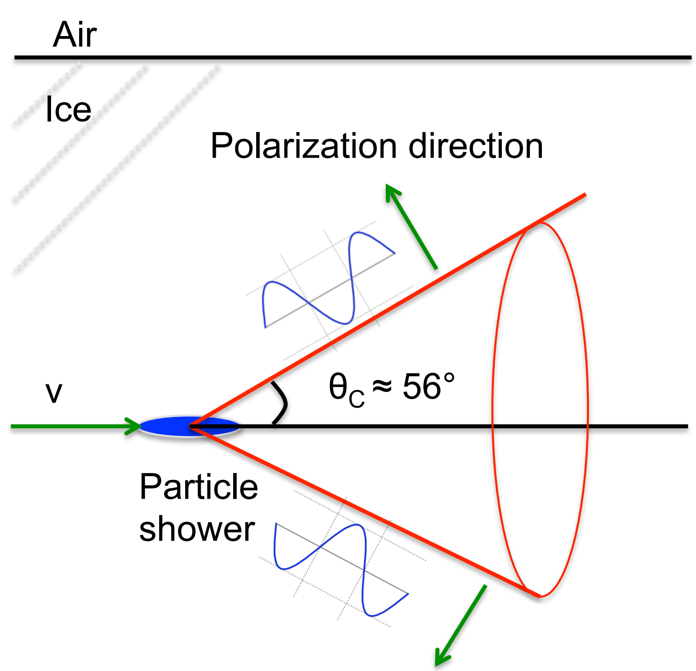
Radio Cerenkov Technique

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

→ RADIO

Power∝E_{shower}^2





Graphics: Carl Pfendner

Confirmed experimentally in sand, salt, ice:

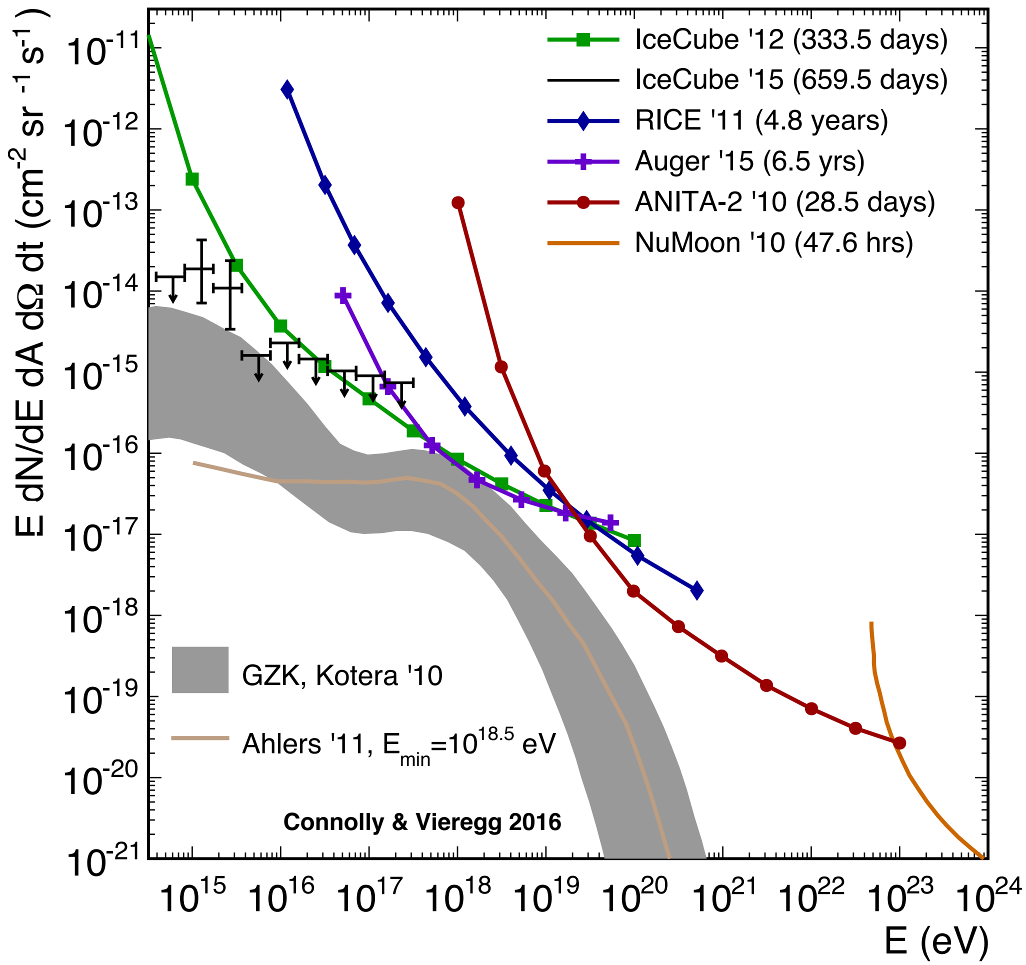
PRL 86, 2802 (2002);
PRD 72, 023002 (2005);
PRD 74, 043002 (2006);
PRL 99, 171101 (2007)

Gurgen Askaryan, 1962

High Energy Neutrino Astronomy

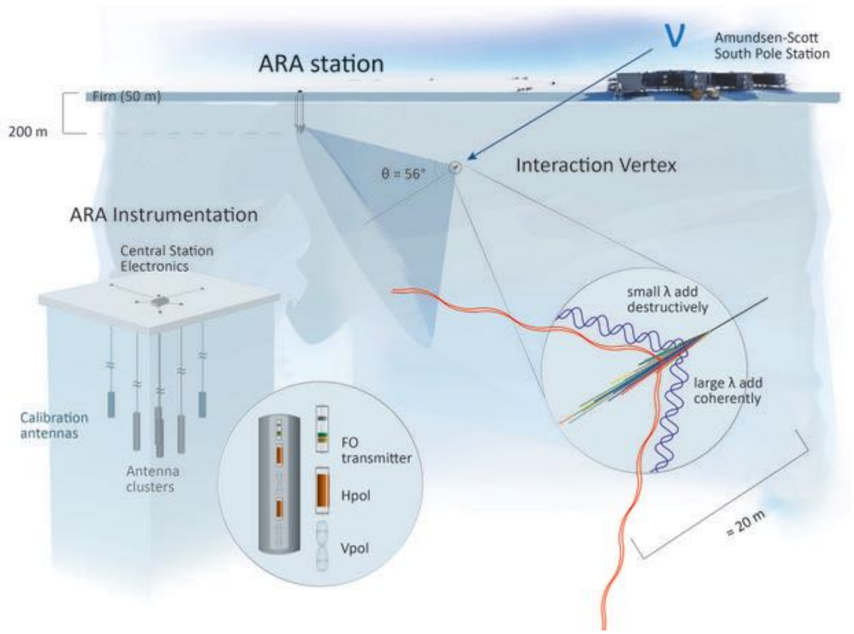
- <10^{19} eV: IceCube and Auger most competitive
- >10^{19} eV: radio dominates (ANITA)

- To improve sensitivity:
  - Move left (lower threshold)
  - Move down (increase area, livetime)

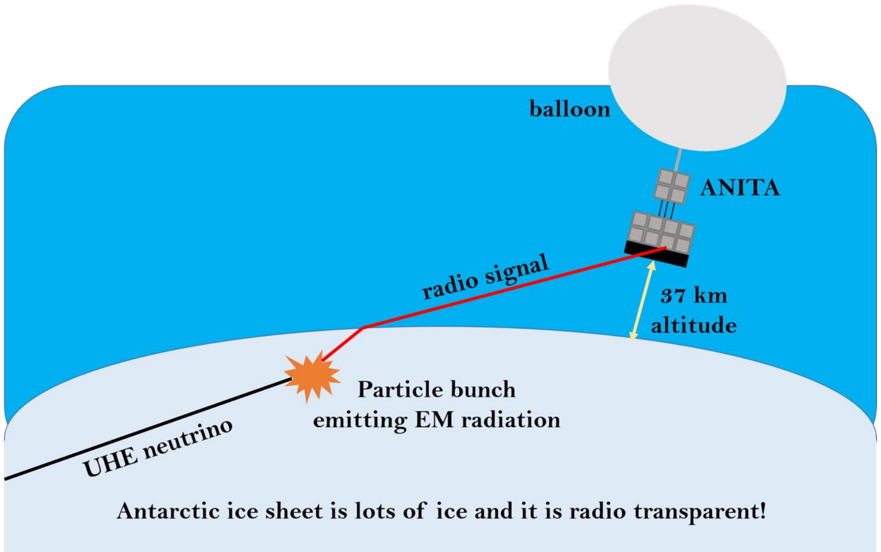


Two classic approaches

Instrument the ice



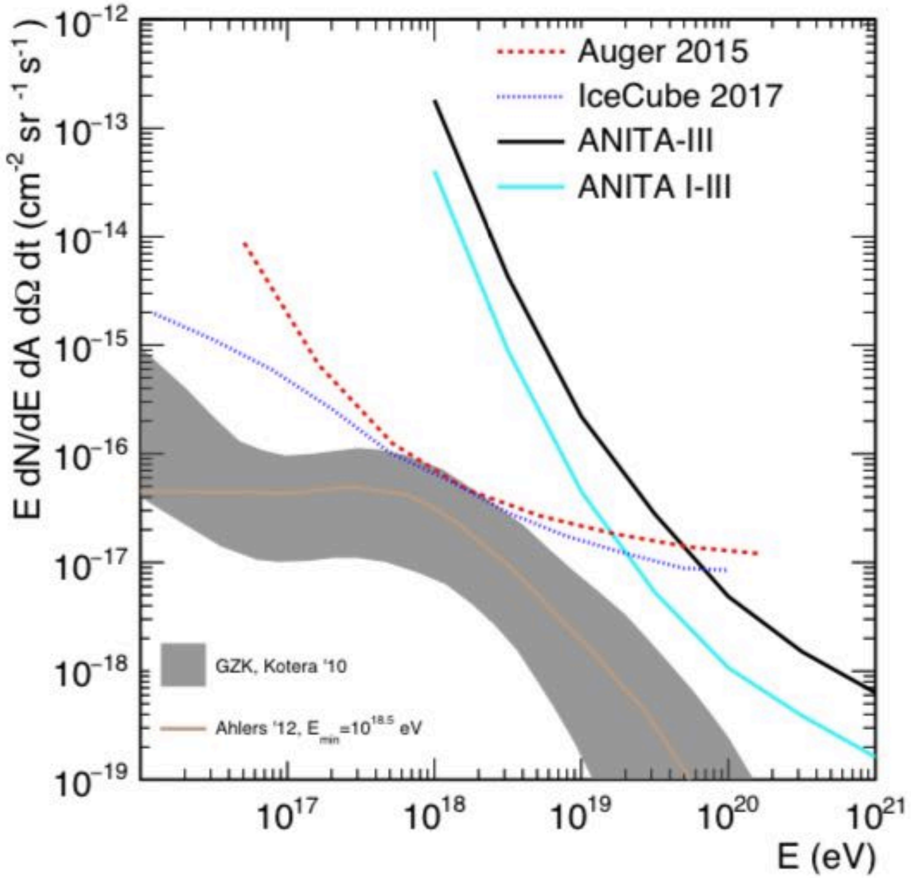
View from a distance

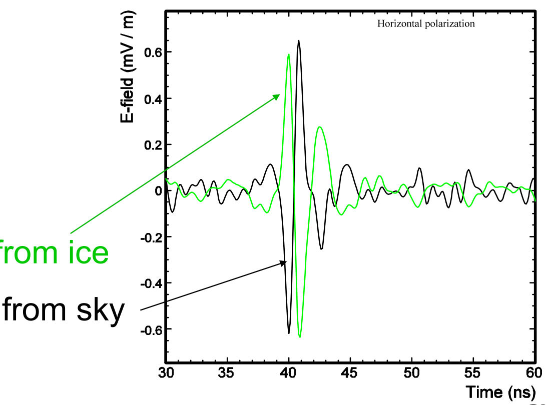


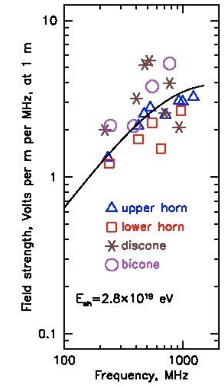
Graphic: Oindree Banerjee

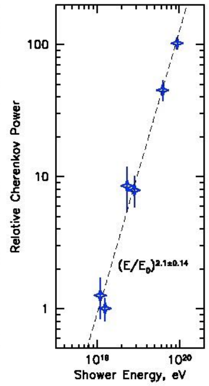
- Pure ice is low-loss for radio: field attenuation lengths ~1 km

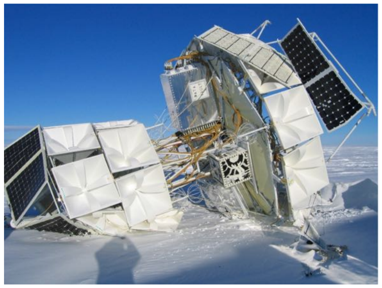
University of Hawaii, University of California, Los Angeles, University of Delaware, Jet Propulsion Laboratory, University of Kansas, National Taiwan University, The Ohio State University, Washington University in St. Louis, University College London











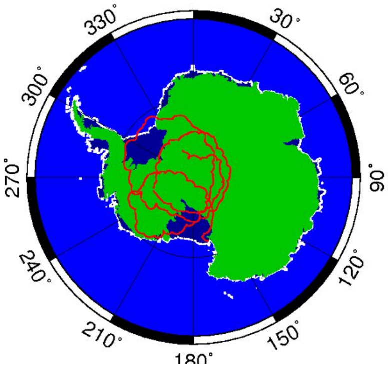
Four flights

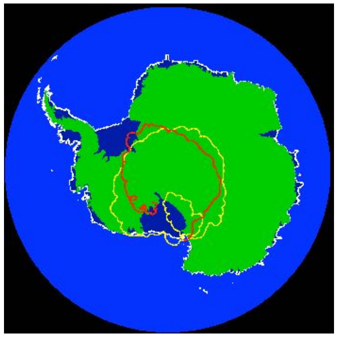
ANITA-1 2006

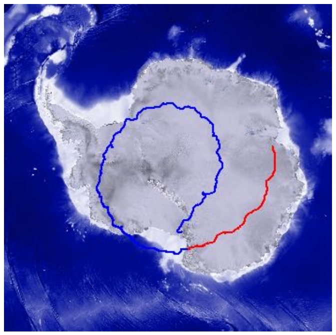
ANITA-2 2009

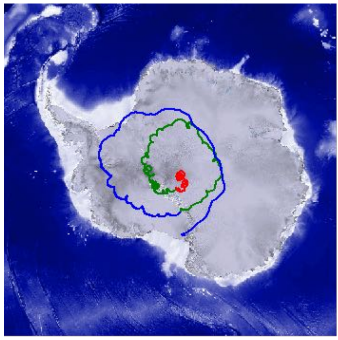
ANITA-3 2014

ANITA-4 2016

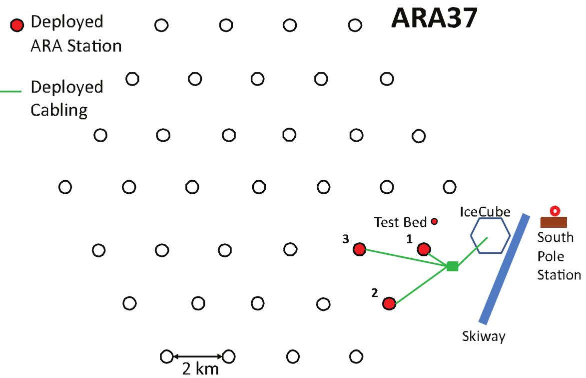


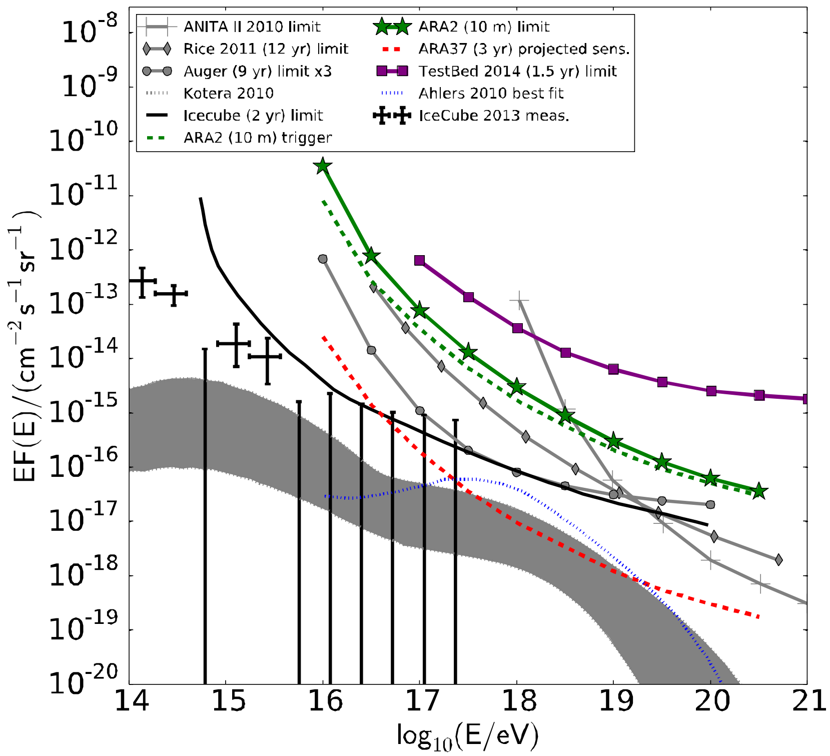


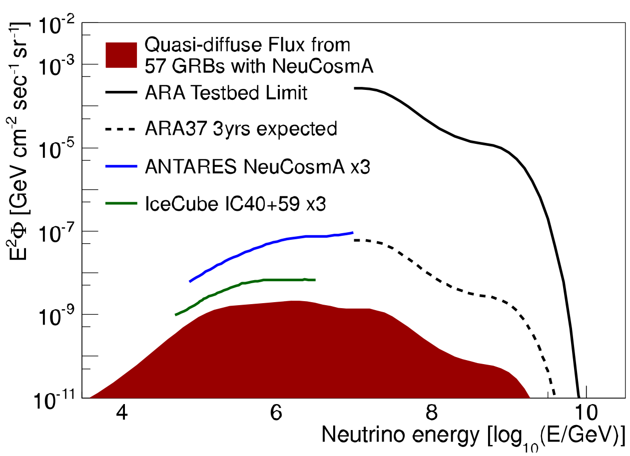


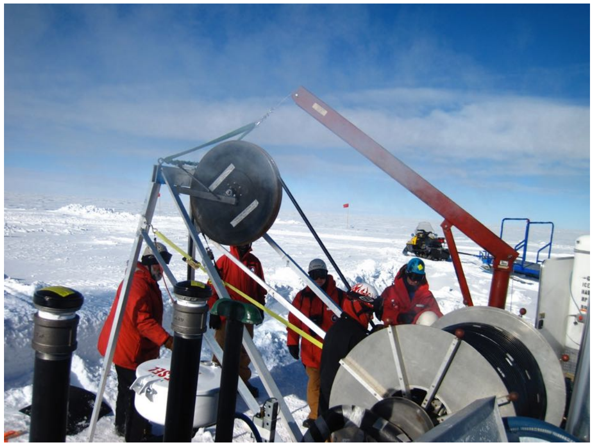


Askaryan Radio Array (ARA)



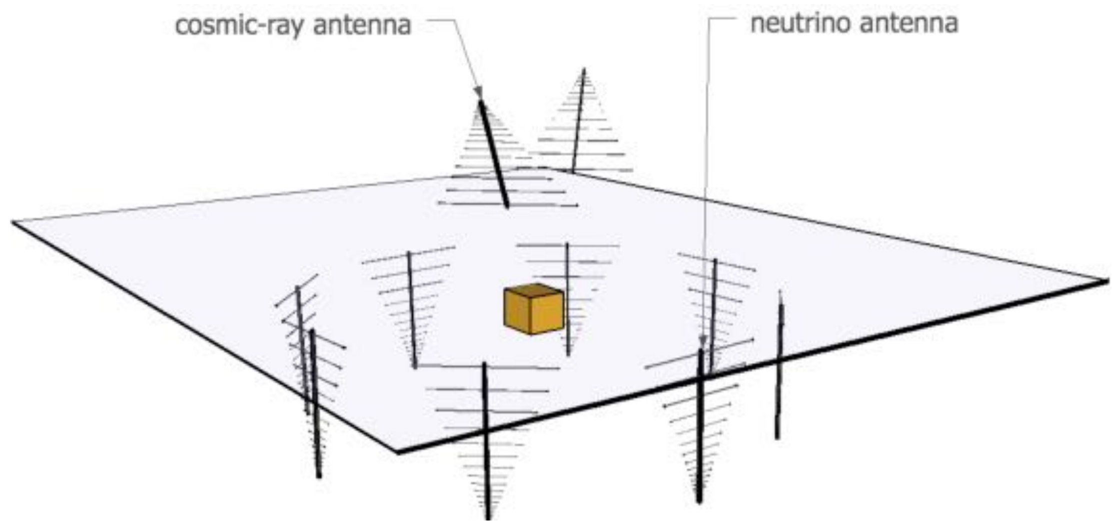






Credit: Mike Duvernois, ARA/NSF

ARIANNA - Moore's Bay



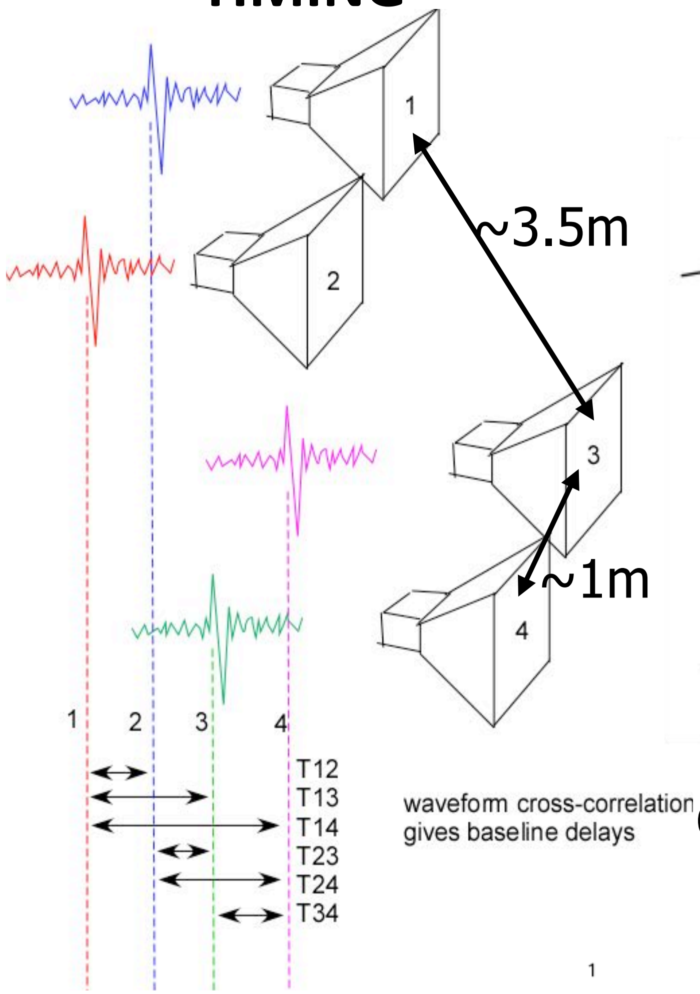
- ARIANNA designed for minimum power and remotely powered operation, surface design allows for access
- Observes cosmic rays

New developments

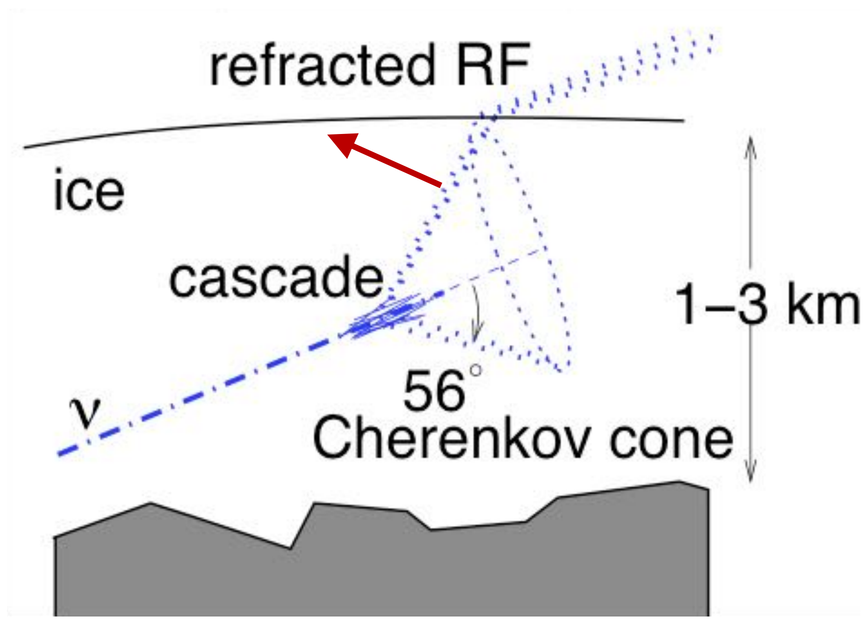
Reducing thresholds - *move left*

- Using complementary features to lower thresholds

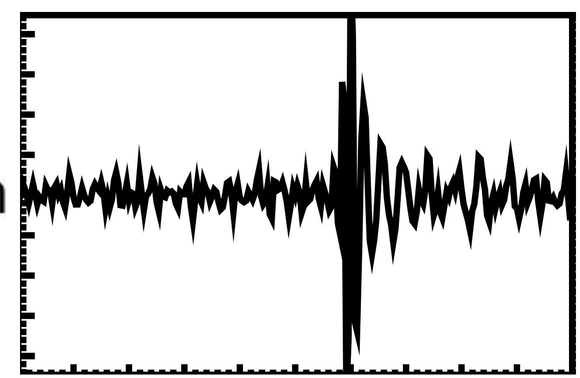
TIMING



POLARIZATION



PULSE SHAPE

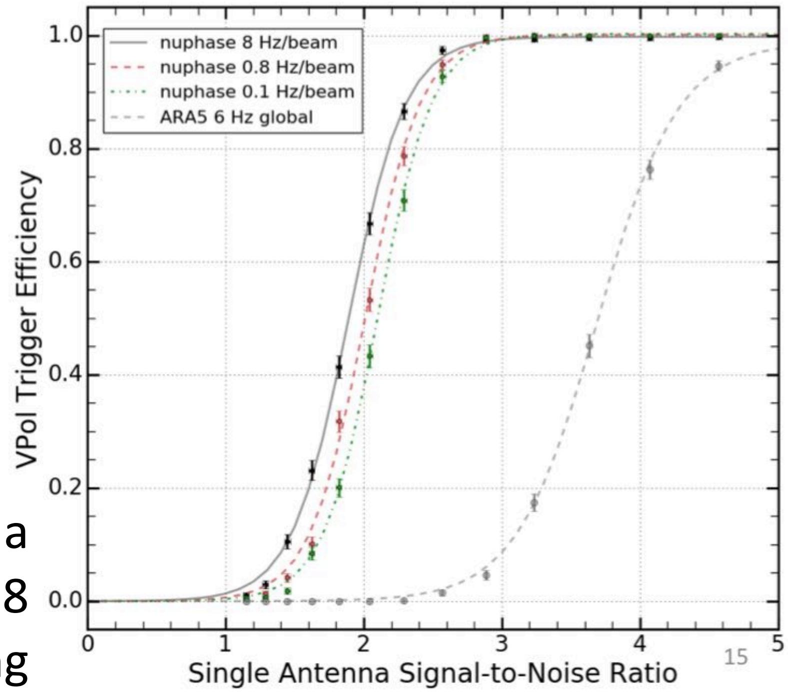


OTHER IDENTIFYING CHARACTERISTICS OF BACKGROUNDS

Phased array

A. G. Vieregg, et al., JCAP 1602 (2016) no.02, 005.

- Calculate *summed correlation* in electronics before trigger decision
- Newly deployed in ARA station 5 last season
  - SNR reduction as expected!



Shown by Eric Oberla
ARENA 2018
Paper draft circulating

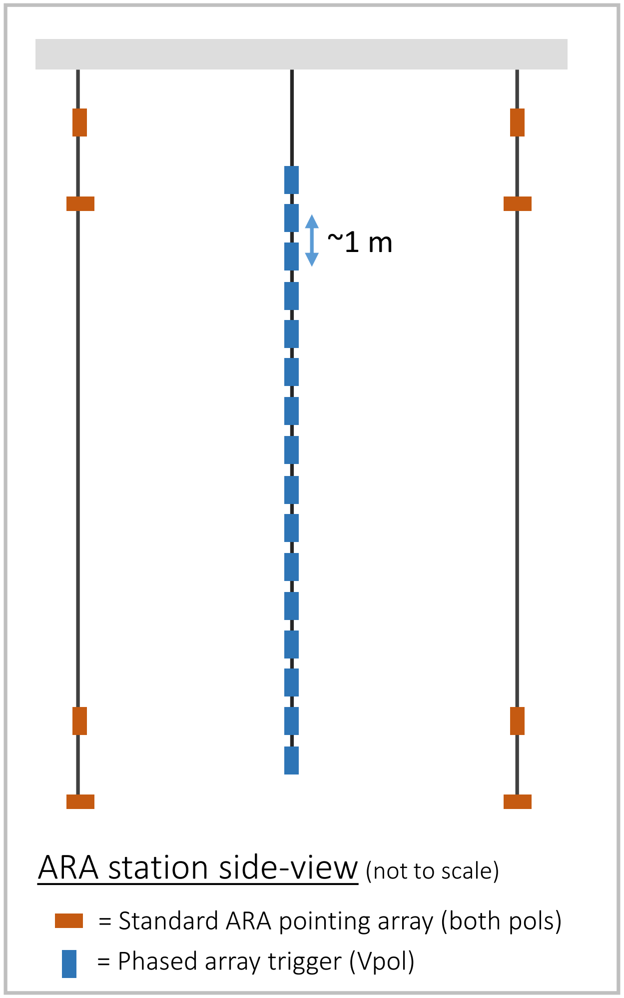
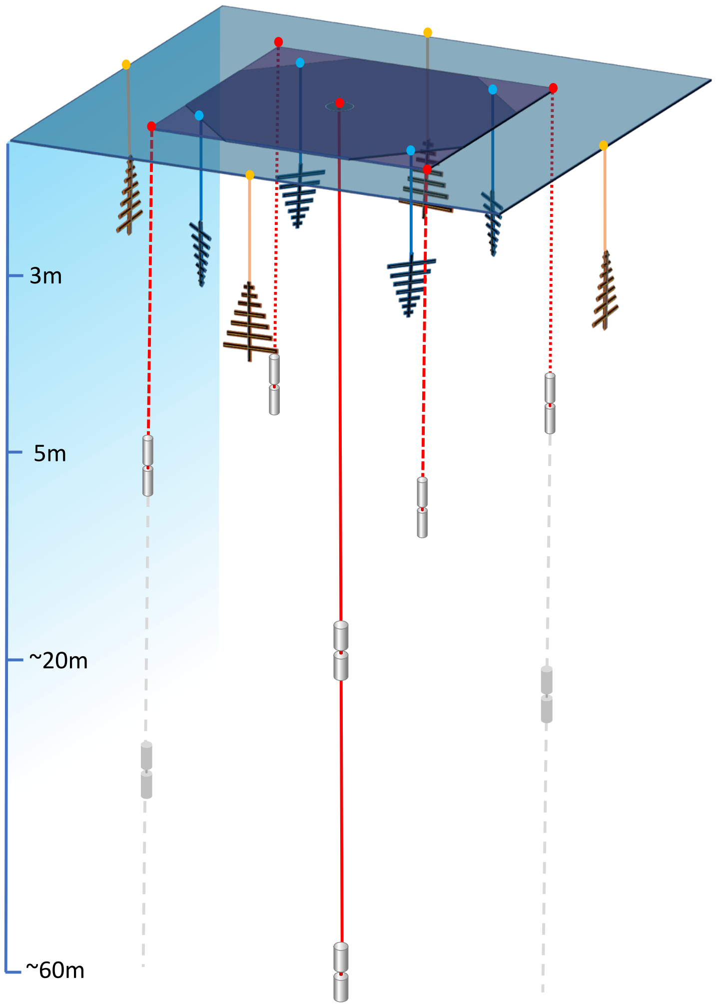


Figure credit: Eric Oberla
Univ. of Chicago

In-ice expansion - *move down and left*
Antarctic Radio In-Ice Array

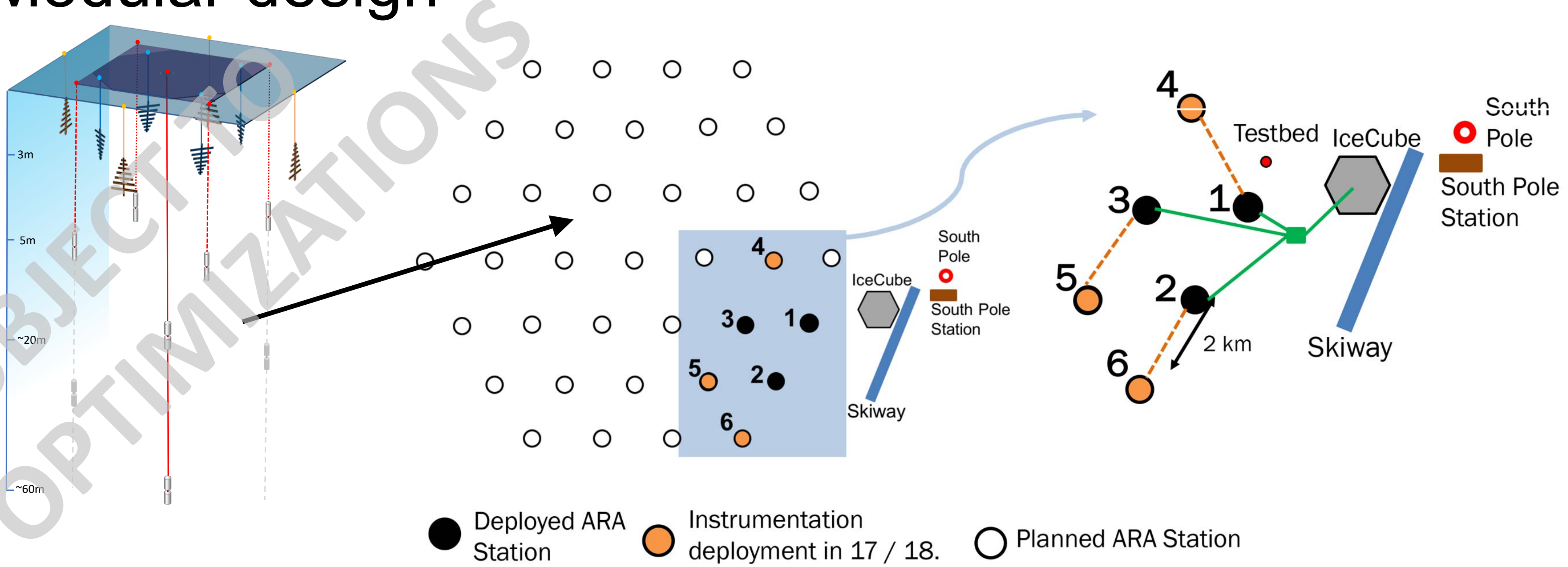


- Folks from existing in-ice arrays have been working together to design the next-generation array in the ice
- Discussions and optimizations ongoing
- Meeting next week

The Ohio State University CCAPP

In-ice expansion - *some recent thoughts*

- Make existing cabled region a *low-threshold zone*
  - phased array triggers, reduce analysis thresholds
- Further out deploy mostly *autonomous stations*, at first
- Modular design

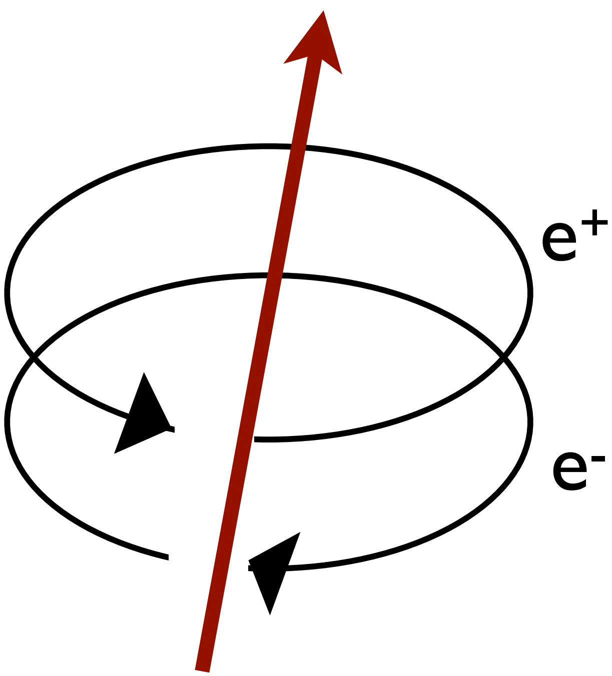


Science goals for Antarctic Radio In-Ice Array

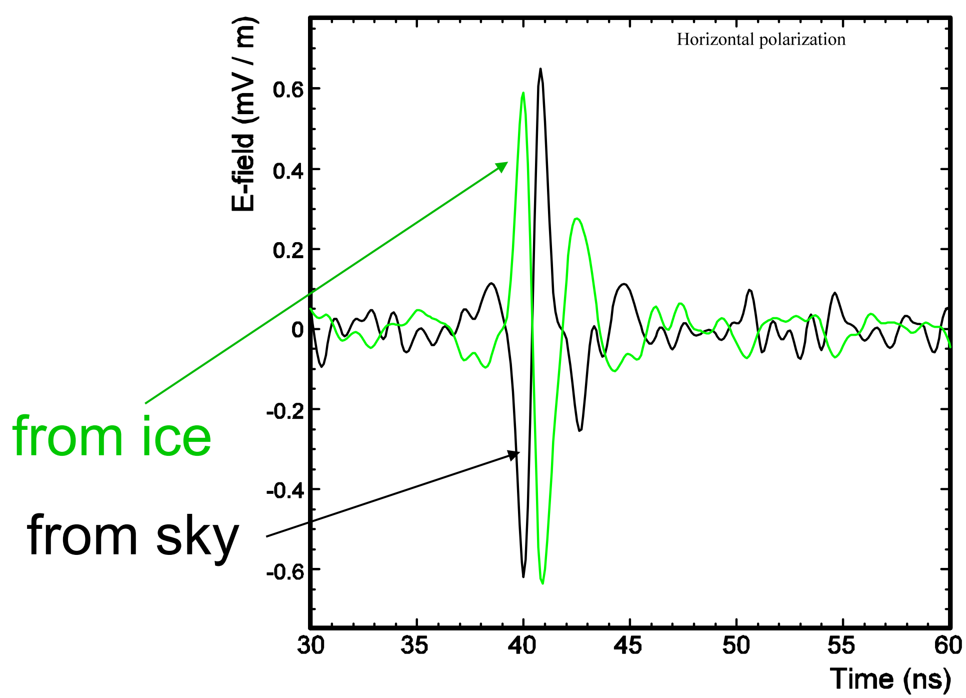
- Science goals two-fold
- Aim to overlap with IceCube's sensitivity near 10^{16} eV
- World's best sensitivity across broad energy range up to 10^{20} eV
- CRs: Don't aim for CR physics itself, measure CRs as a background on neutrino searches

Radio emission

- Air showers produce radio synchrotron emission due to earth's magnetic field (some Askaryan)
- Near South magnetic pole → field points "up"

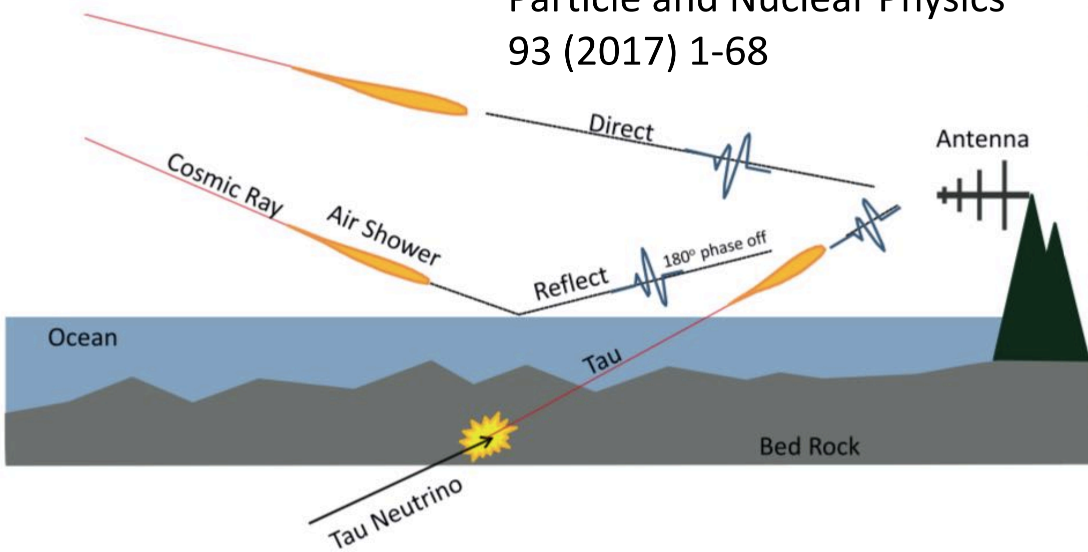


ANITA



Air showers induced by tau neutrinos

Particle and Nuclear Physics 93 (2017) 1-68



TAROGE-1

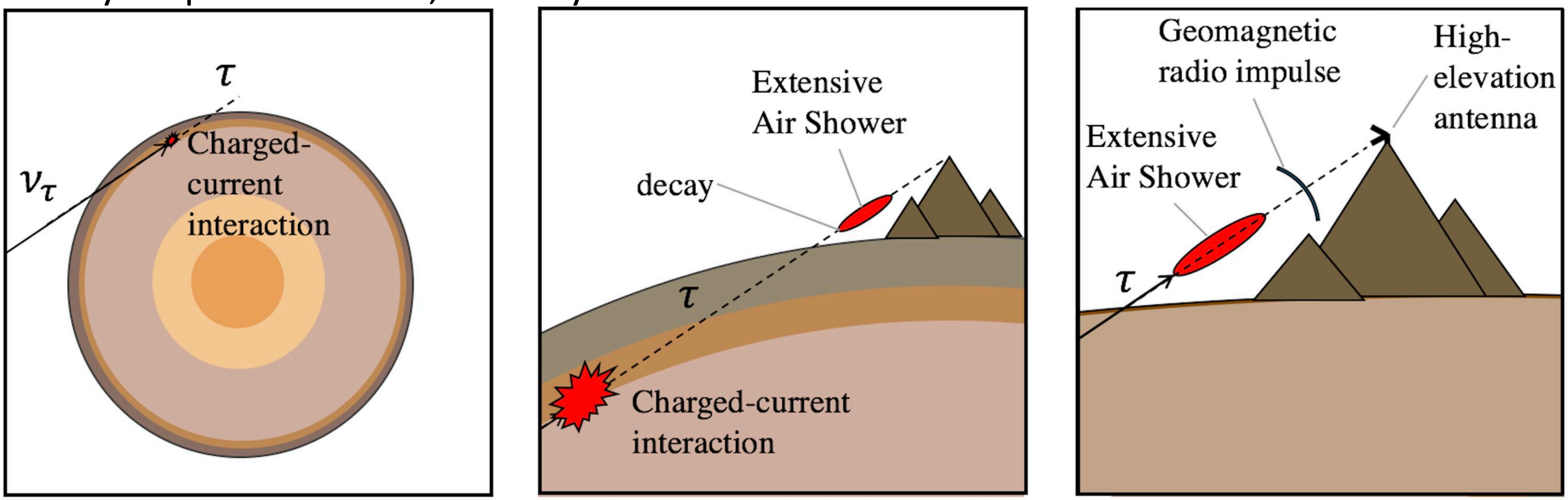
Other experiments -
POEMMA
arXiv:1708.07599
Trinity
See N. Otte, Apr. APS `18
GRAND
arXiv:1508.01919
Phased array atop a mountain - S. Wissel

- Experiments being planned to exploit this technique
- Mechanism used by Auger 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

BEACON: Beamforming Elevated Array for COsmic Neutrinos

Led by Stephanie Wissel, Cal Poly



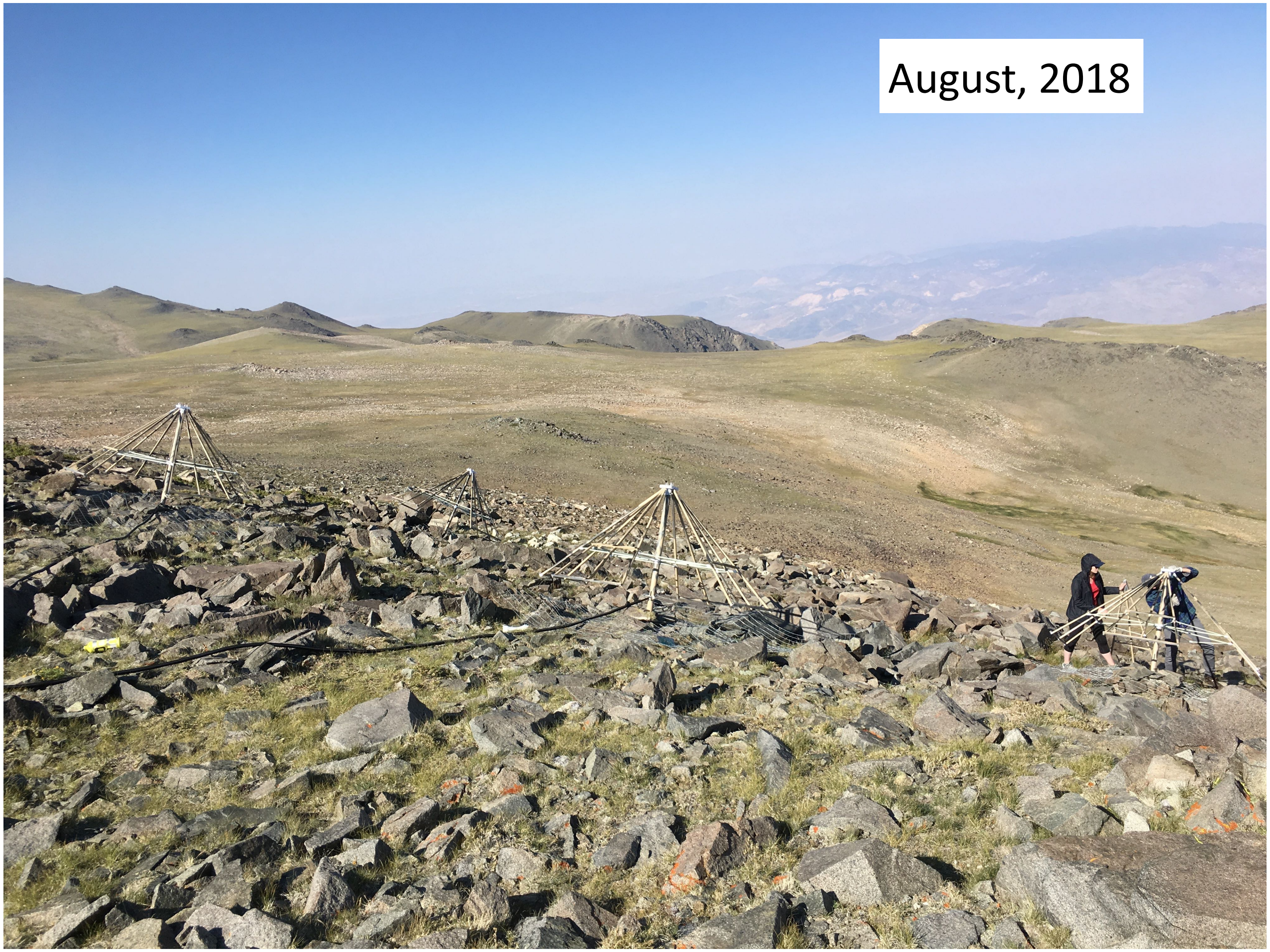
- **High Exposure :** High Elevation Mountain (>2 km) + Year-Round Duty Cycle
- **Scalable :** Inexpensive, low number of stations (~10) required for Kotera mix. models,
- Similar approach as TAROGE, ARIANNA, and GRAND, but optimizing for small-number of stations, high-elevation, & multiple sites

Challenges:

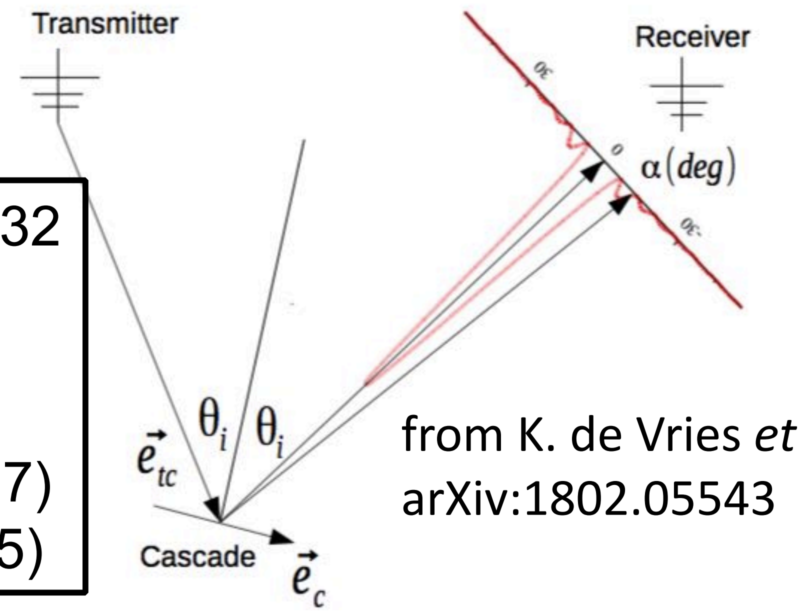
- Are the radio backgrounds manageable at high-elevation sites?
- Radio self-trigger on impulsive air showers?

SAW NSF CAREER #1752922
#1752922

BEACON: First deployment!



RADAR



from K. de Vries *et al.*, arXiv:1802.05543

S. Prohira *et al.*, Nucl.Instrum.Meth. A890 126-132 (2018)
K. de Vries et al., arXiv:1802.05543
S. Prohira arXiv:1710.02883
R.U. Abbasi *et al.*, Astropart. Phys. **87** 1-17 (2017)
K. de Vries *et al.*, Astropart. Phys.60:25-31 (2015)

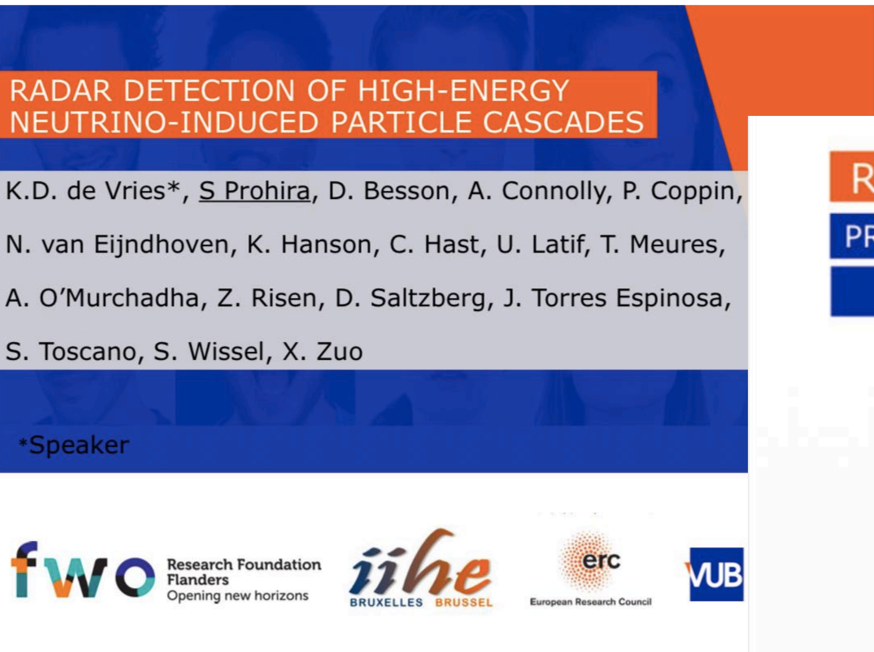
- K. de Vries *et al.* - low energy (40 MeV) beam test
- TARA experiment in Utah (PI's D. Besson & J. Belz) attempted with air showers
- Looks like dense media needed
- Steven Prohira KU, starting CCAPP Fellow Fall 2018. Led SLAC beam test under DOE Office of Science Grad Fellowship

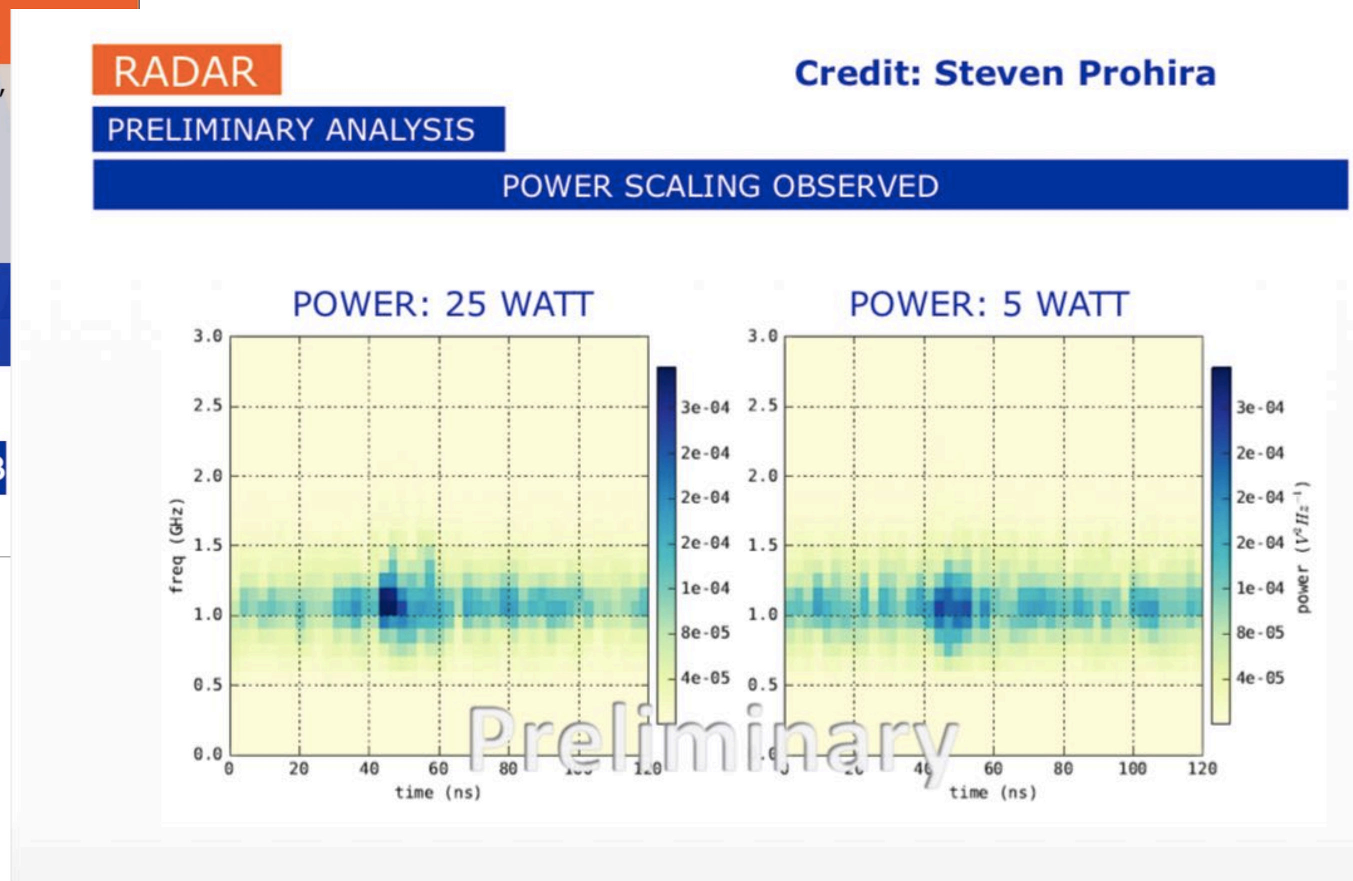
THE OHIO STATE UNIVERSITY CCAPP

RADAR

- Preliminary results shown at TeVPA

(left to right) Steven Prohira, Krijn de Vries, Jorge Torres Espinosa, Uzair Latif





Follow-up test scheduled for Oct. 2018

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!

Backup slides