The Ohio State University

Ultra high energy neutrino detection in Antarctic ice: an evolving story

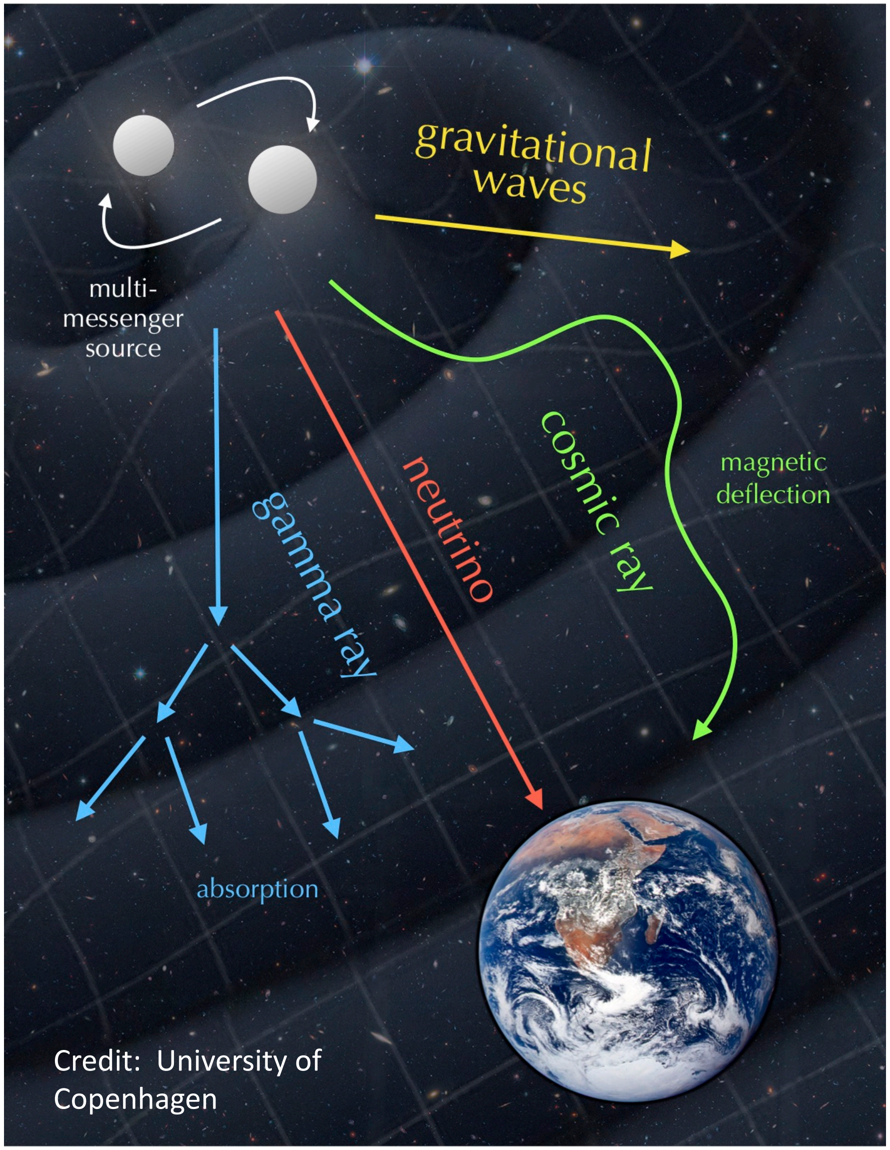
Prof. Amy Connolly, The Ohio State University

May 18, 2023

Plan for this talk

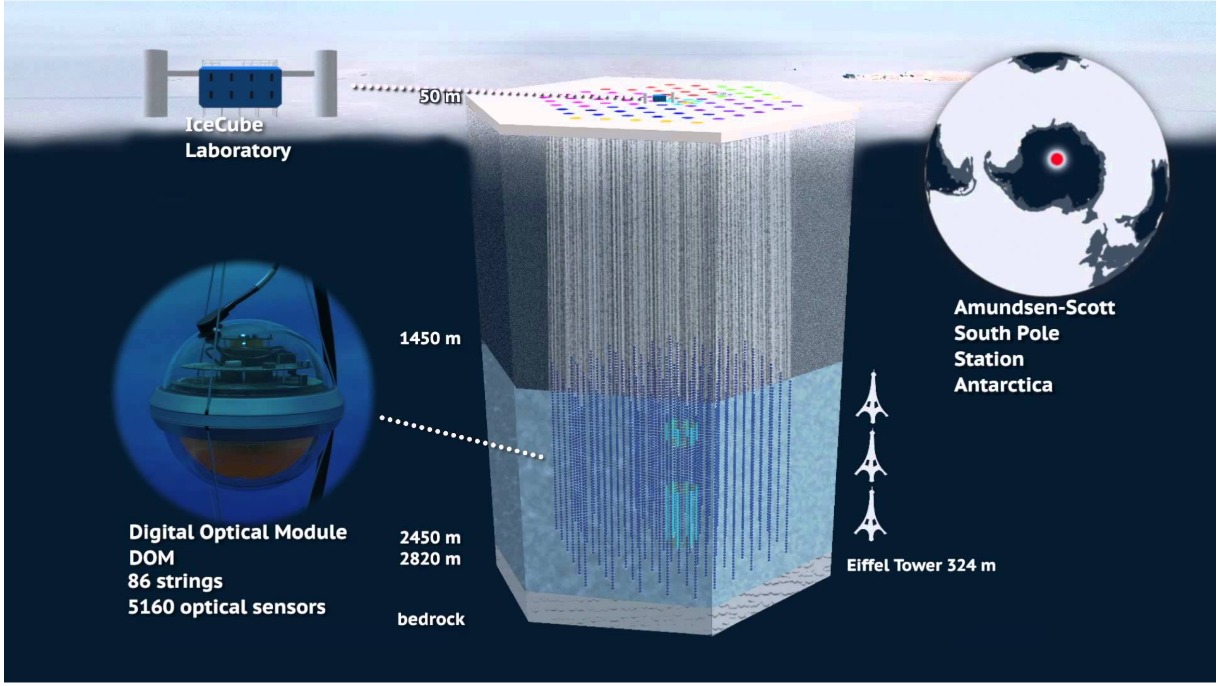
- Overview of UHE neutrinos
  - Motivation
  - Experiments
- The complexity of Antarctic ice
- Evolving design solutions in complex environments

Multi-messenger astrophysics



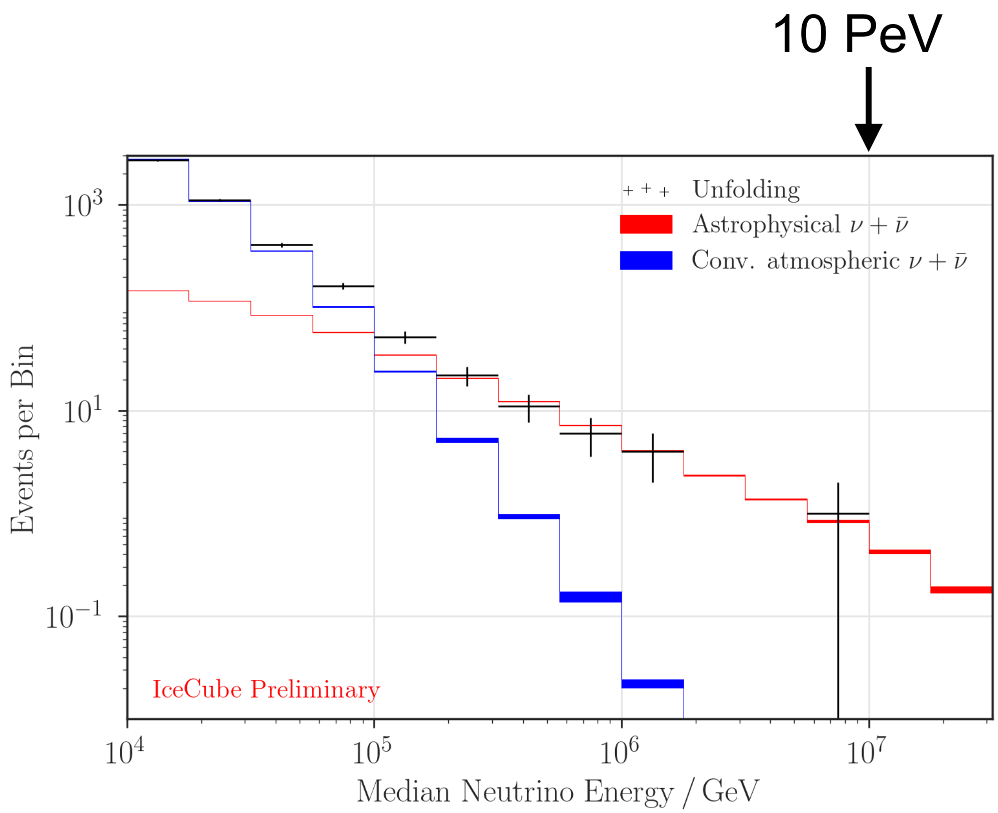
Astrophysical neutrinos

- IceCube observes astrophysical neutrino flux up to O(10 PeV=10^{16} eV)
- Two sources identified, both active galaxies
  - TXS 0506+056
  - NGC 1068



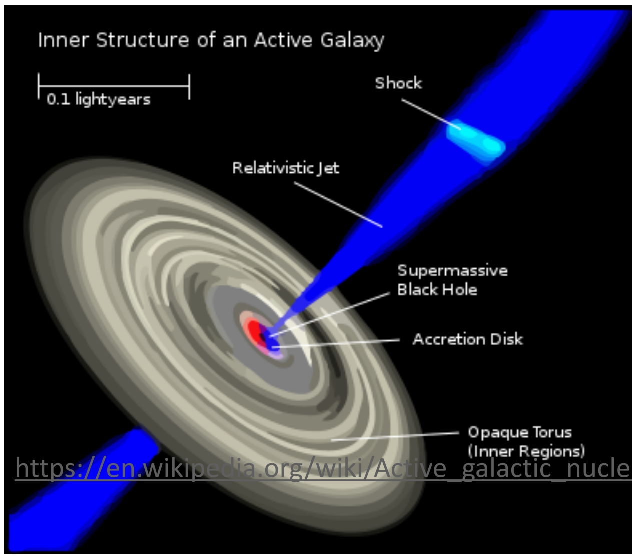
Astrophysical neutrinos

- No neutrinos above ~10 PeV have yet been observed
- Optical technique limits detector scale to O(1 km^3)



Ultra high energy (>10^{17} eV) neutrinos: candidate sources

Active Galactic Nuclei (AGN)

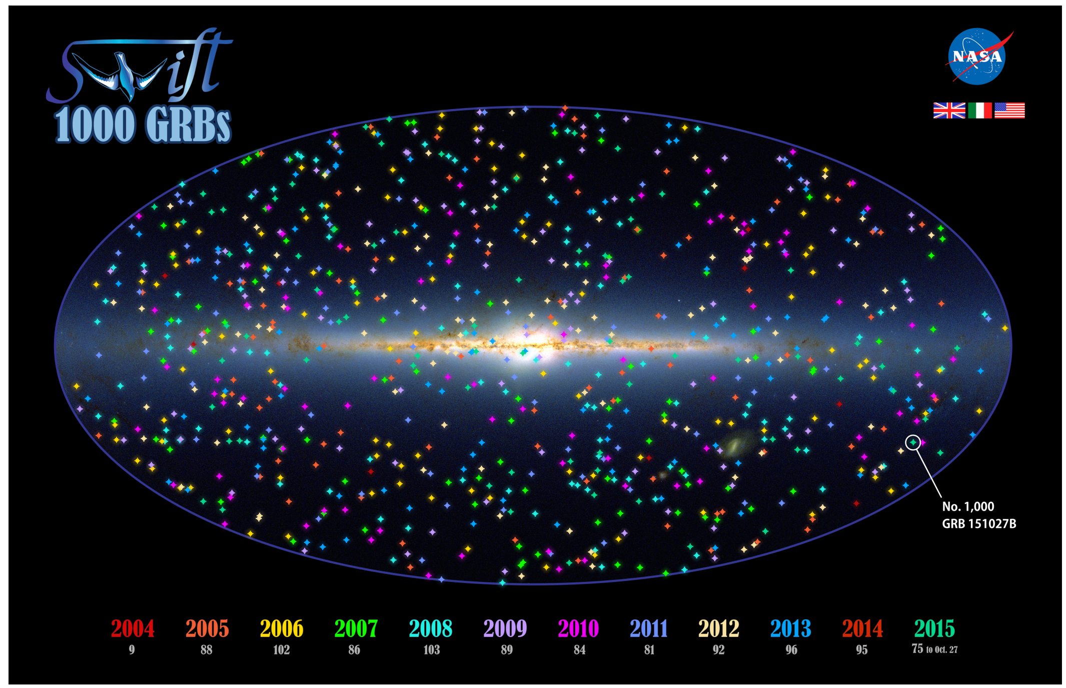


https://en.wikipedia.org/wiki/Active_galactic_nucleus

- Black hole accreting mass

CRs themselves produce neutrinos en route

Gamma Ray Bursts (GRB)



- Star collapse, merger of neutron stars

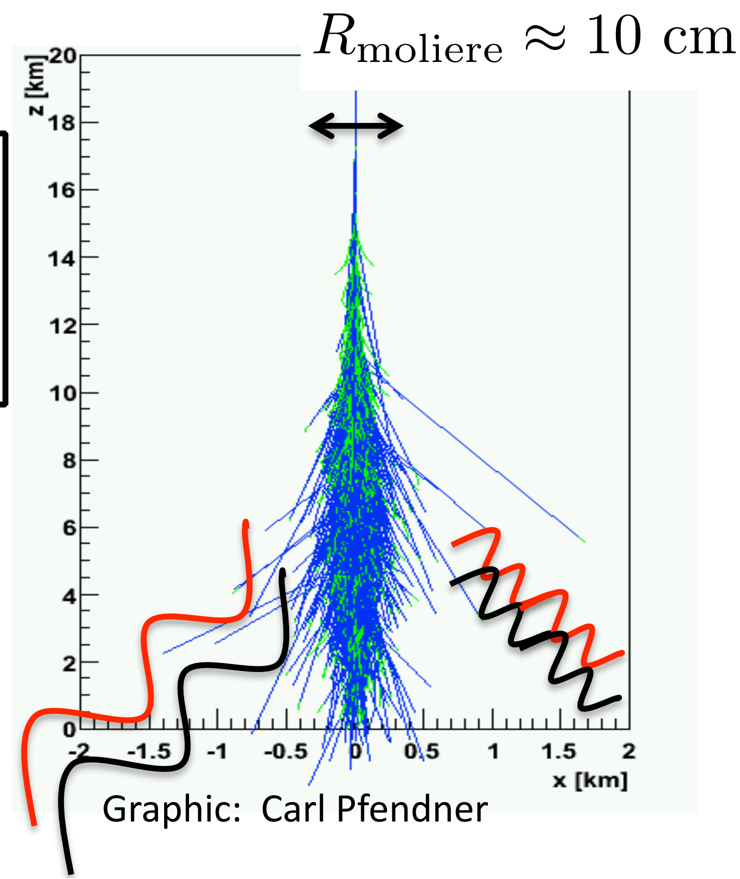
What can we learn from UHE neutrinos

- UHE neutrinos are the only particles that can reach us with such high energies from cosmic distances
  - What produces them
  - What are the acceleration mechanisms
  - What is the ultimate energy of particles in the universe
- UHE neutrinos probe fundamental physics
  - Test Einstein's equations
  - New physics? ~100 TeV νN interactions

Radio Askaryan emission

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

Gurgen Askaryan, 1962



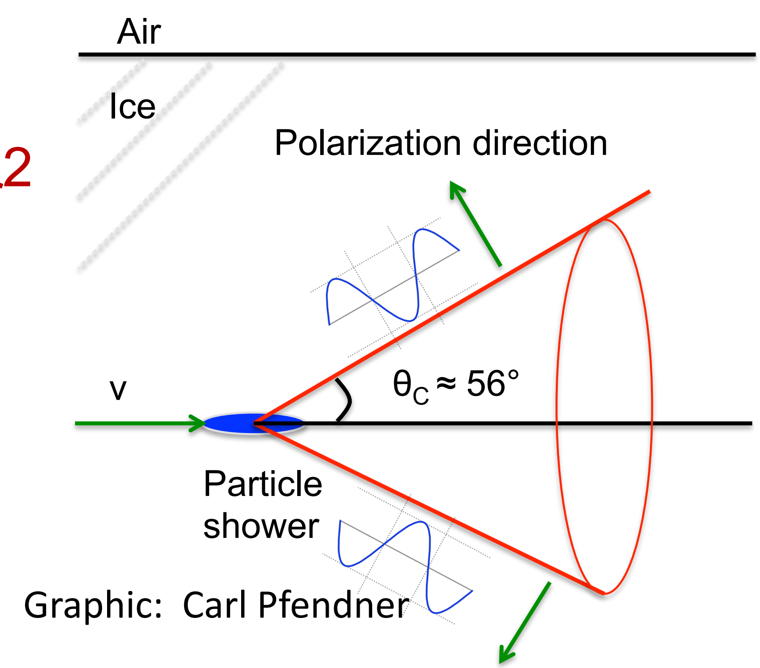
Graphic: Carl Pfendner

→ RADIO

Power∝E_{shower}^2

Confirmed experimentally in sand, salt, ice:

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



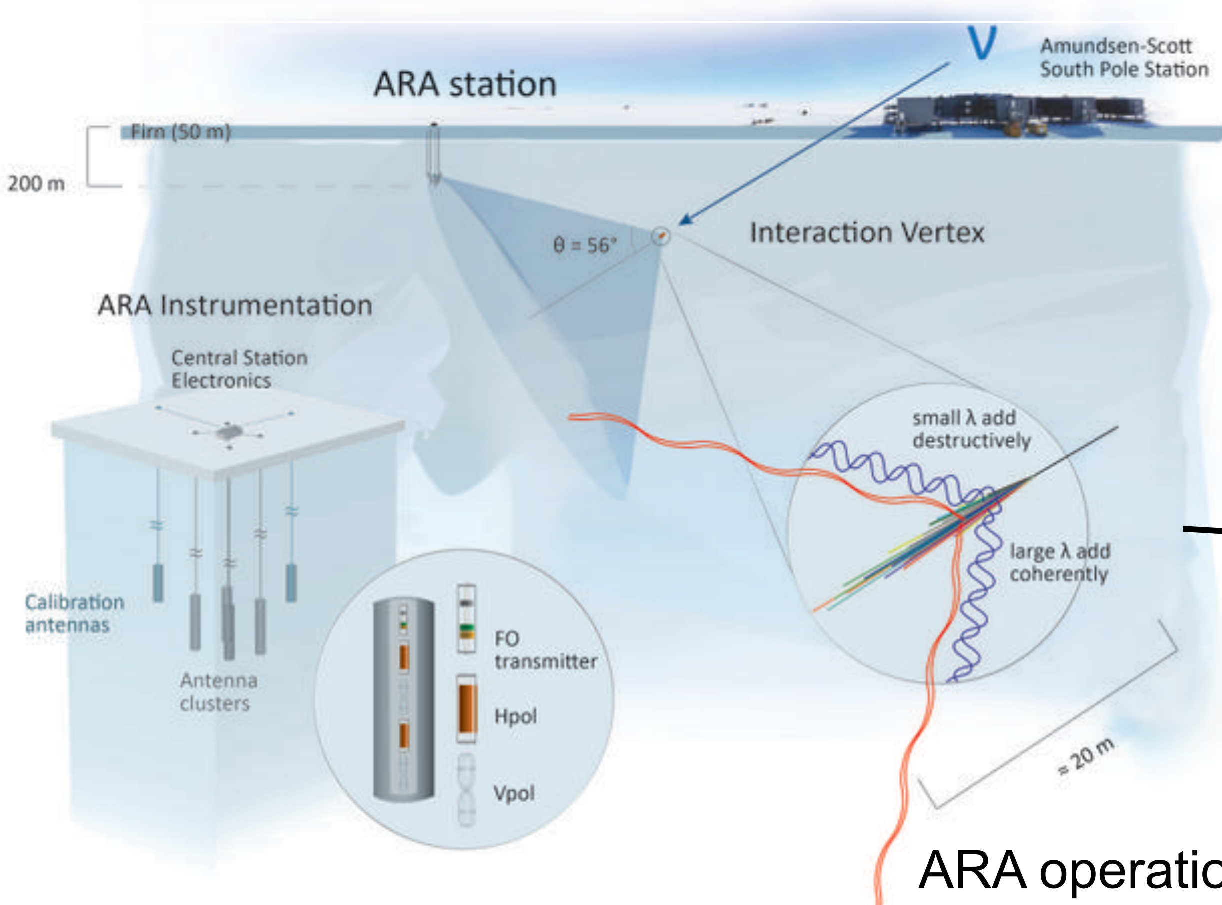
Graphic: Carl Pfendner

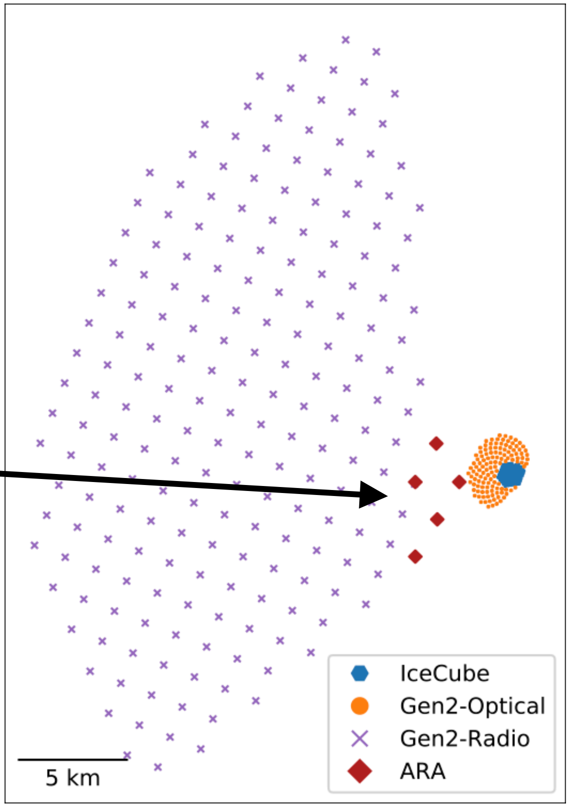
- Pure ice is low-loss for radio: field attenuation lengths ~1 km

Experiments searching for UHE neutrinos

In-Ice Detection Technique: ARA

- Close to interactions → low-ish thresholds





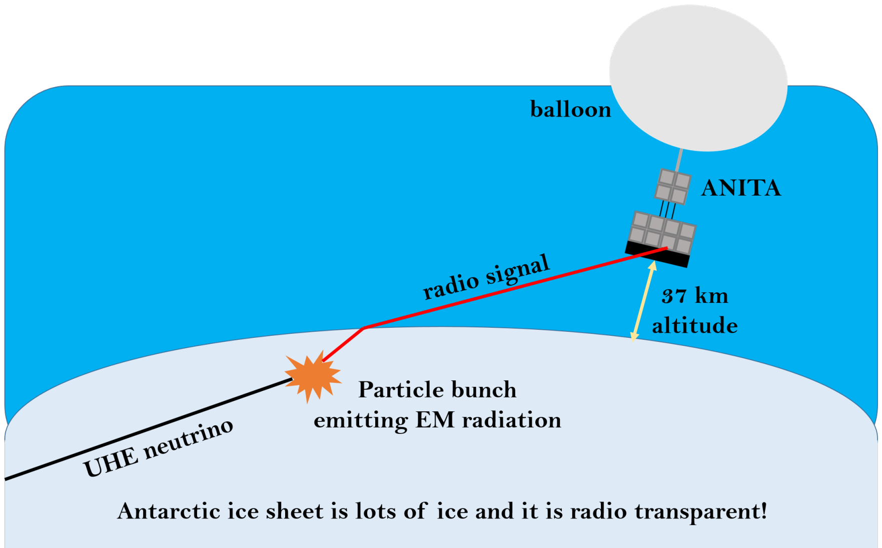
Credit: Brian Clark

ARA operations under NSF award #2013134

Also ARIANNA, RNO-G

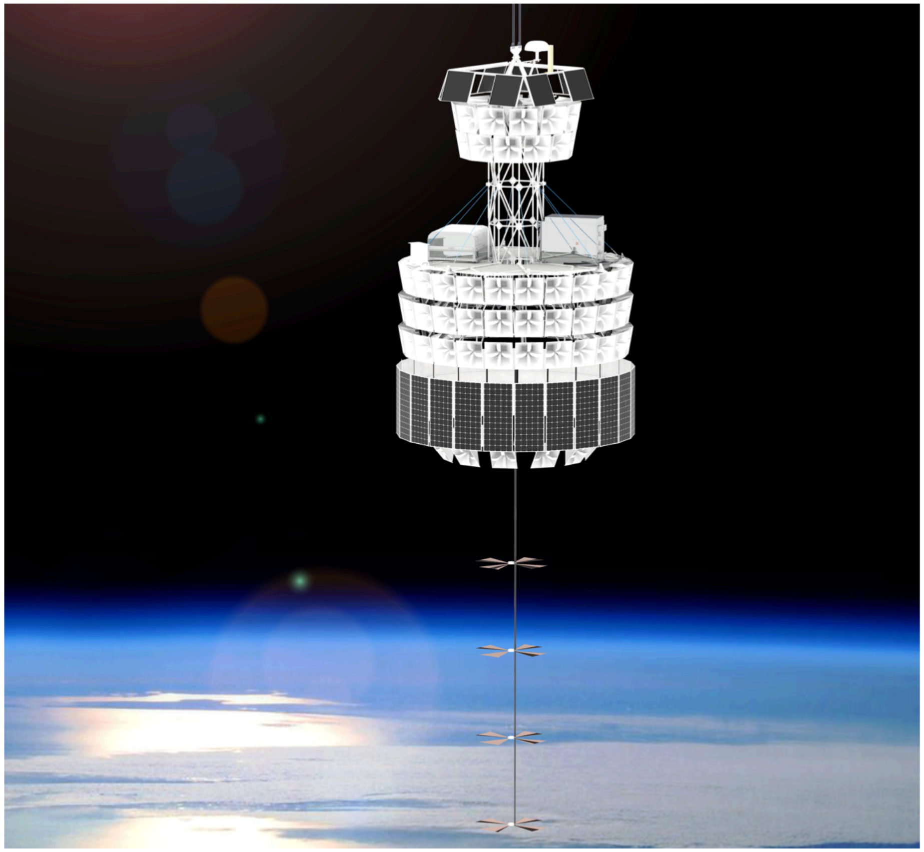
From above: ANITA / PUEO

- Higher energy threshold, enormous ice volume



Graphic: Oindree Banerjee

- NASA long-duration balloons launch from McMurdo station
- ~30 day flights in stratosphere

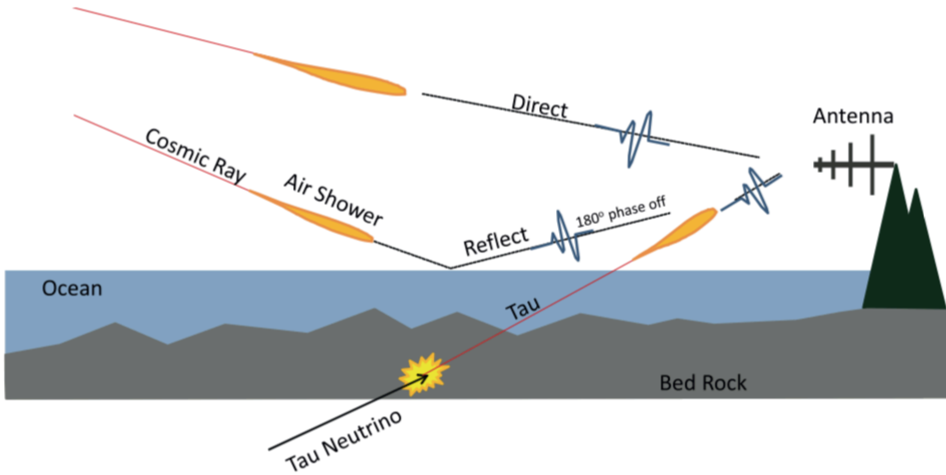


PUEO: flight 2024-25

Air showers induced by tau neutrinos

- Identifies νs of one flavor

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

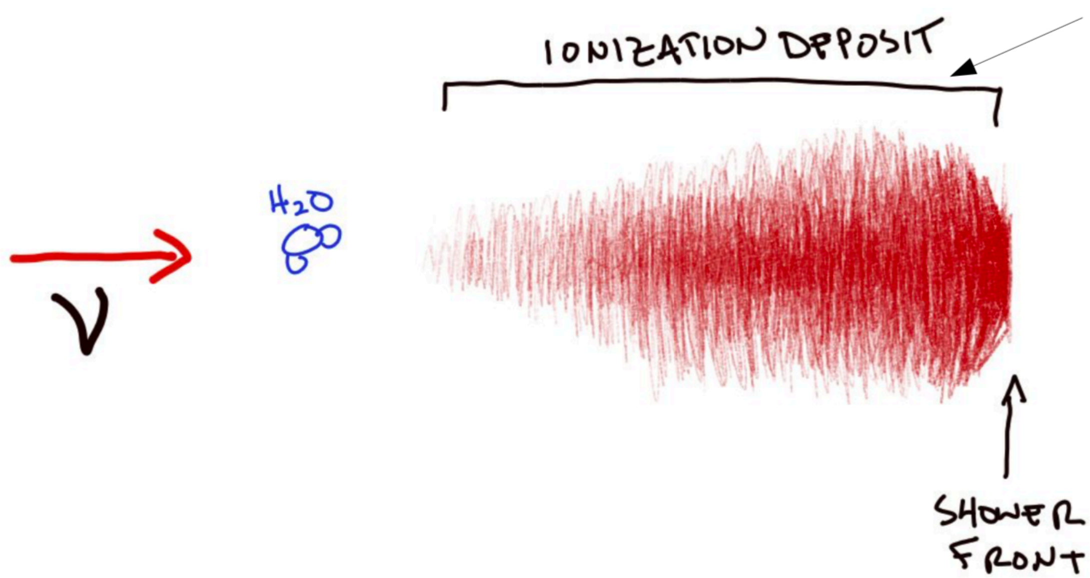
- Auger uses similar mechanism to set strong limits
- ANITA/PUEO also sensitive to this channel

RADAR Technique: RET

- Active rather than passive approach

Led by Prof. Steven Prohira, KU
2022 MacArthur Fellow

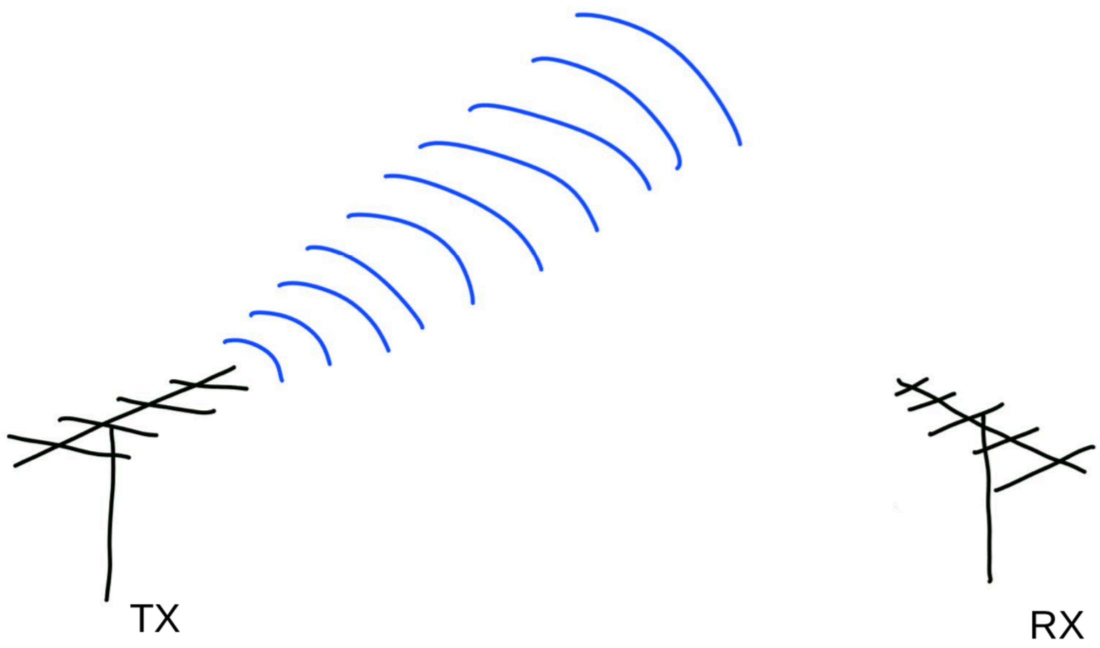
- **high-energy primary interactions create cascades of relativistic particles**
- **cascade particles *ionize* the material, leaving behind a dense, short-lived cloud of charge**



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

RADAR Technique: RET

Prototype currently being deployed in Greenland



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

UHE neutrino experiments: summary

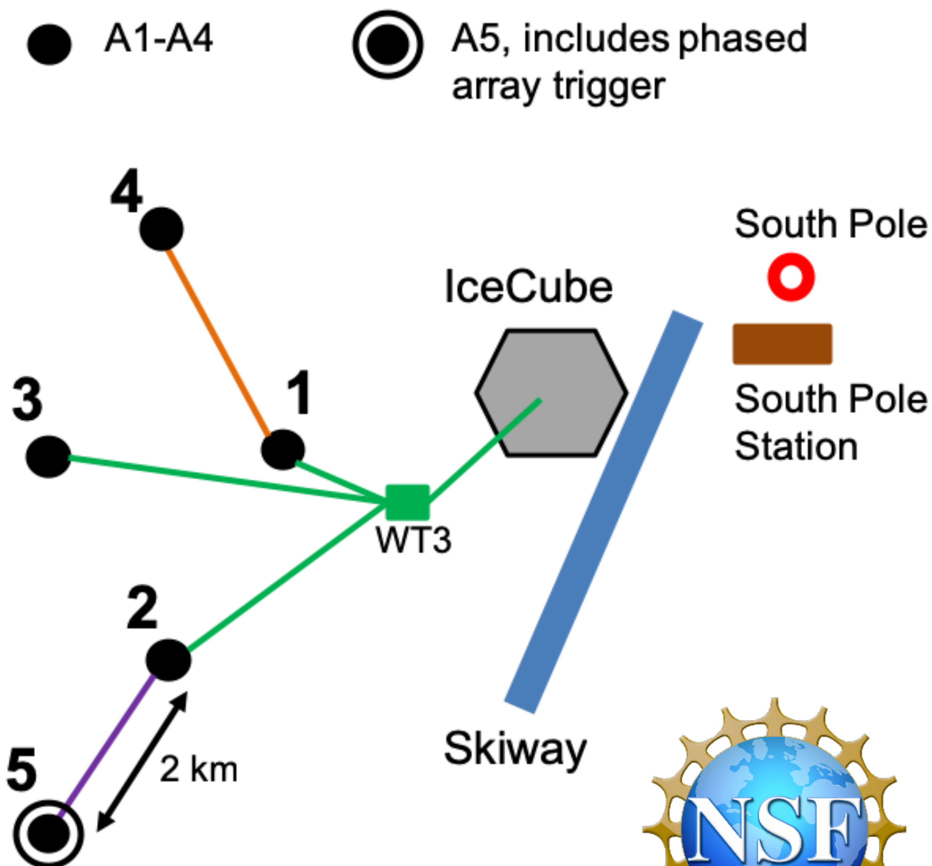
- There are many complementary approaches in play for reaching UHE neutrinos
- This approach is important because
  - UHE neutrinos have not yet been observed
  - Once first UHE neutrino measured, cross-checks and different ways to characterize their properties

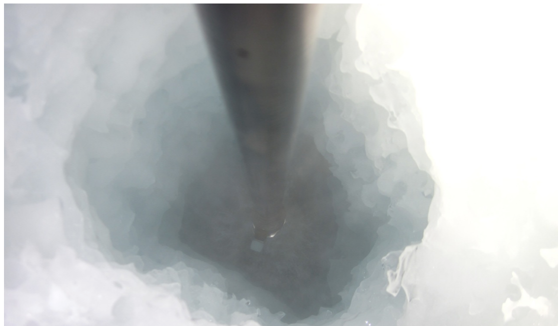
Ice: Clear at radio frequencies and occurring naturally in large volumes

THE OHIO STATE UNIVERSITY

Askaryan Radio Array (ARA)

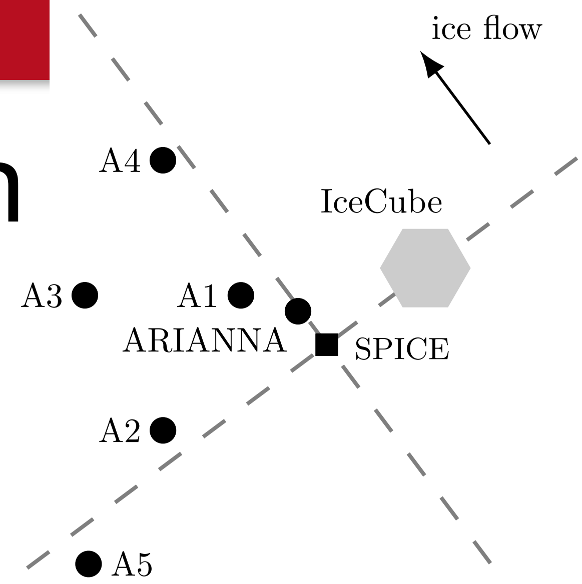
Ohio State University, University of Kansas, University of Wisconsin, University of Nebraska, University of Delaware, Michigan State University, University of Maryland, National Taiwan University, Chiba University, University College London, University of Chicago, Penn State, Vrije Universiteit Brussel, Université Libre de Bruxelles, UCL



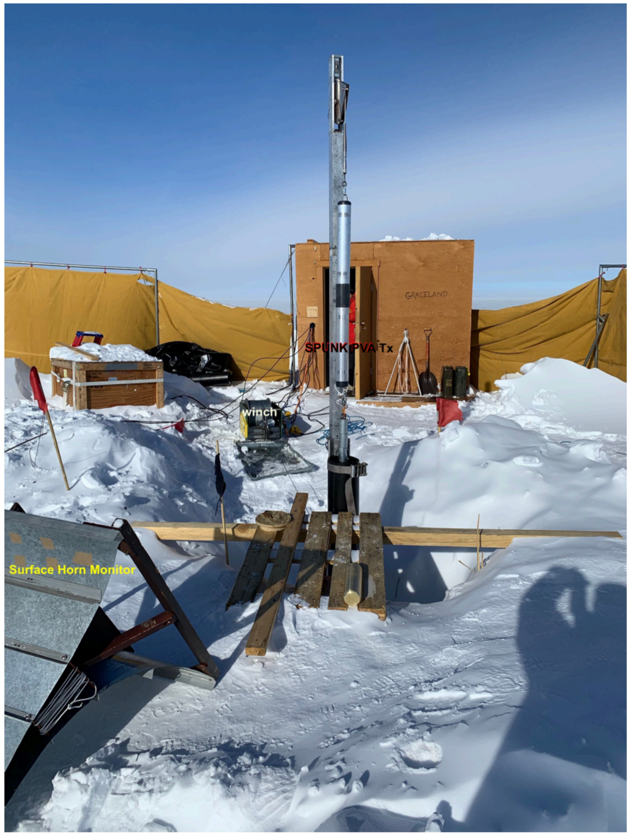


Credit: Mike Duvernois, ARA/NSF

SPICEcore pulsing campaign

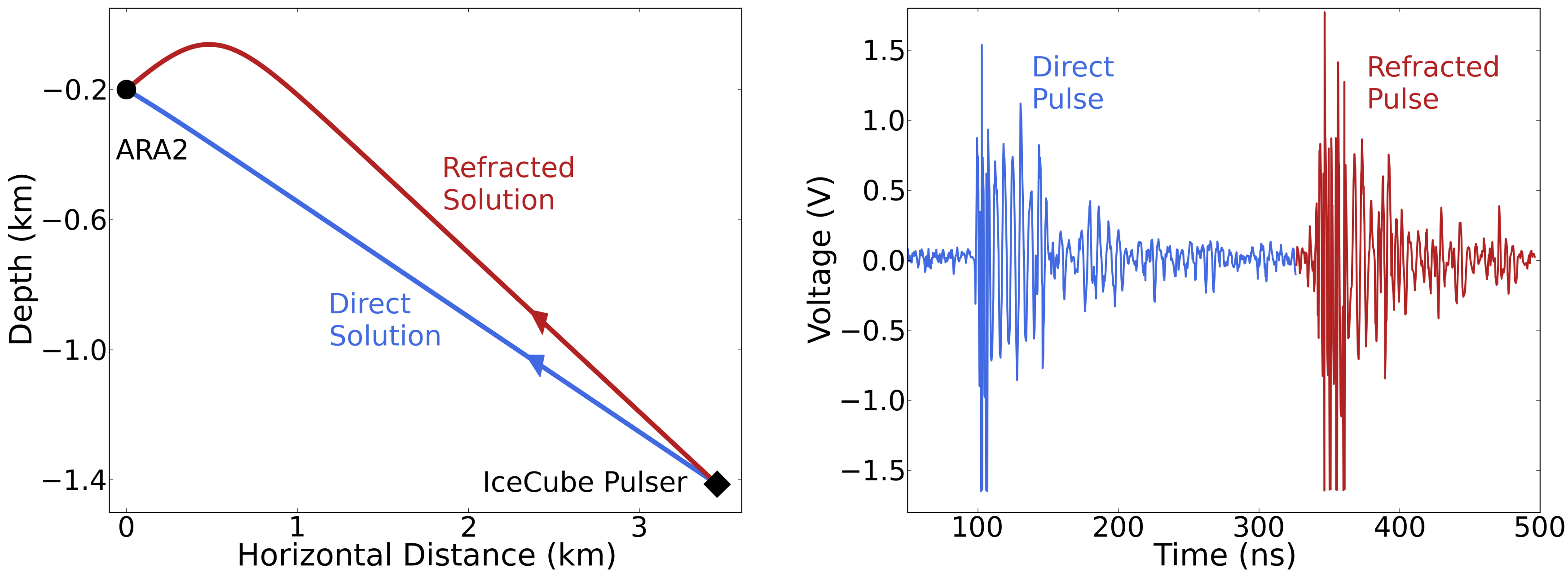


- 2016: core drilled to 1751m and recovered
- Dec. 2018: broadband pulser lowered in the hole and pulses received by ARA (A1-A5), ARIANNA
- Transmitted in nominally *vertical* polarization
- Important calibrations, ice properties measurements



Depth-dependent index of refraction

- Direct and Refracted signals due to depth-dependent index of refraction



[ARA Collaboration] Astropart.Phys. 108 (2019) 63-73

THE OHIO STATE UNIVERSITY

CCAPP

Funny behavior observed in polarizations

- Sometimes the variations look oscillatory
- Sometimes the behavior is more erratic

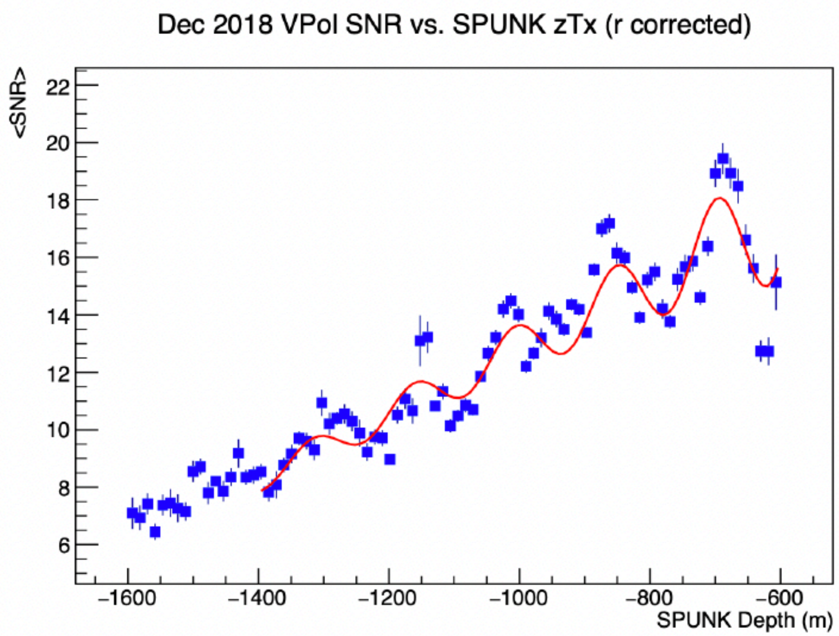


Figure 13. VPol Station A5 measured Signal-to-Noise ratio have been fit to a functional form $A(z) = A_0 \cos(kz + \phi_0)$.

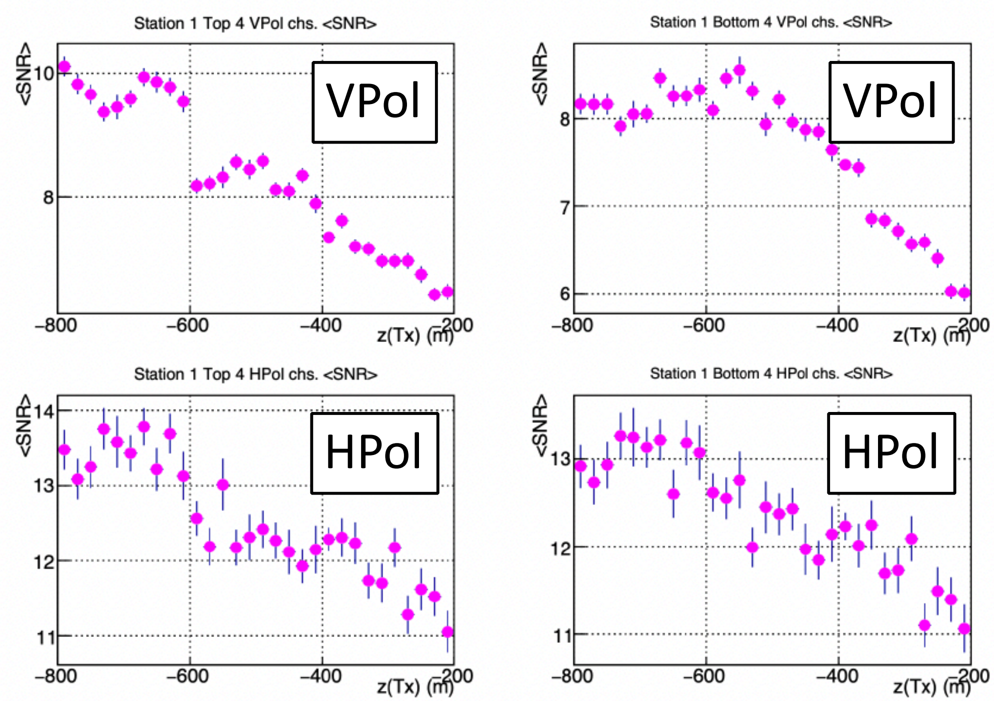
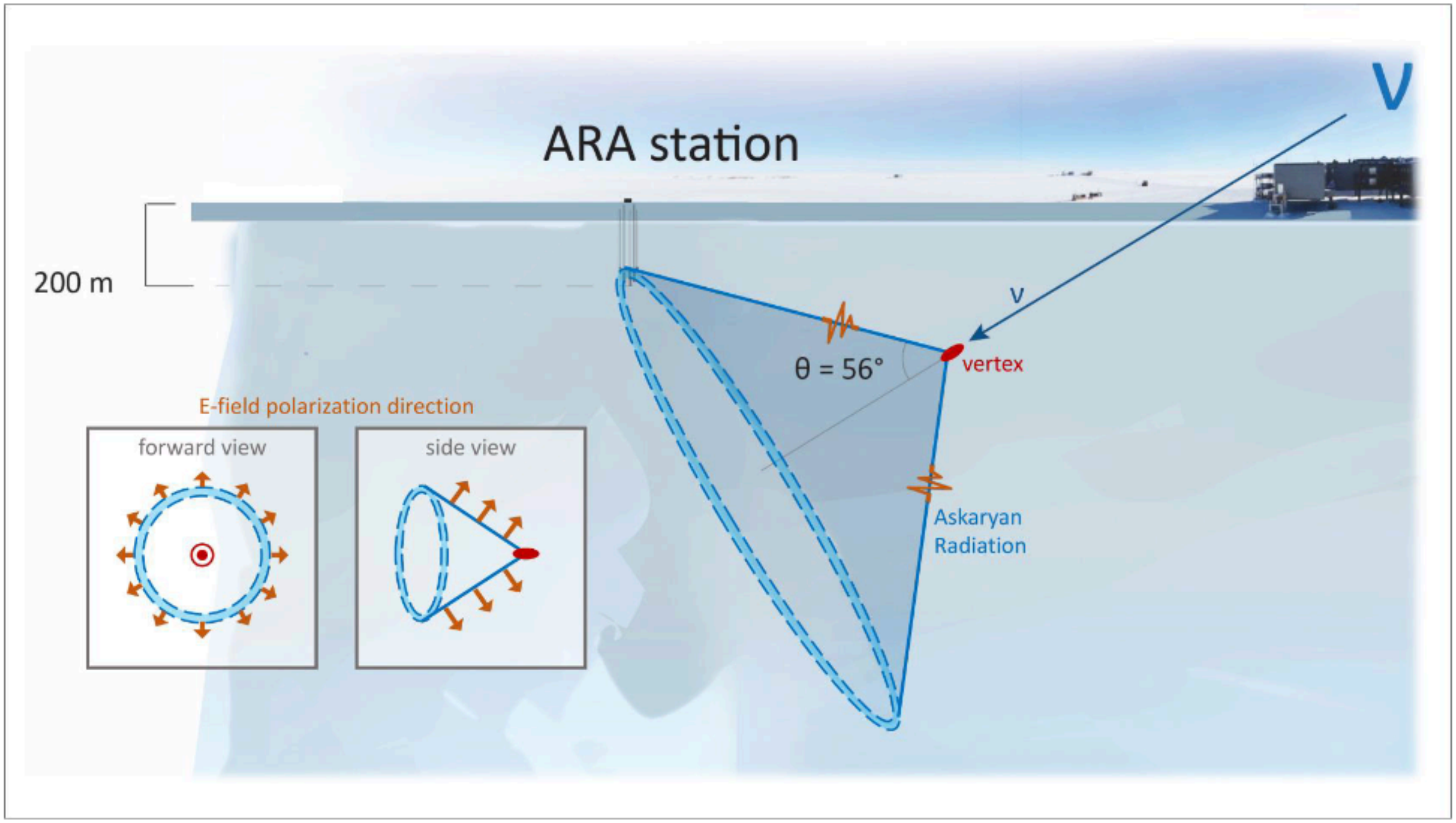


Figure 10. A1 Signal-to-Noise ratio, as function of transmitter depth. Note the enhancement in VPol SNR as the transmitter crosses the shadow zone boundary at approximately z=-600 m.

[ARA Collaboration] Astropart.Phys. 108 (2019) 63-73

Polarization and neutrino pointing

- Polarization is essential for reconstructing the direction of neutrinos

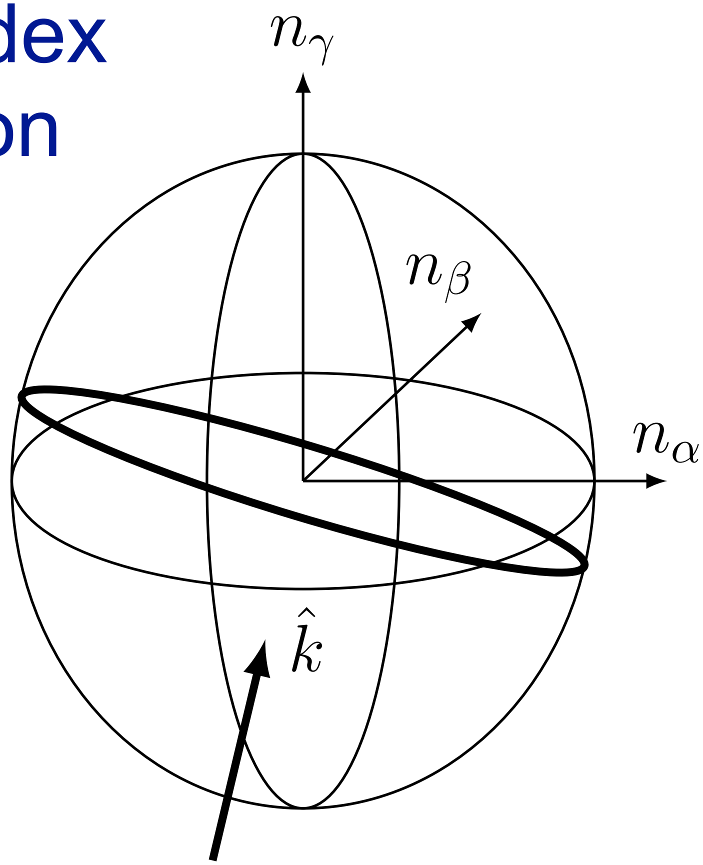


Birefringence

- In a birefringent medium, the index of refraction depends on direction

  → anisotropic

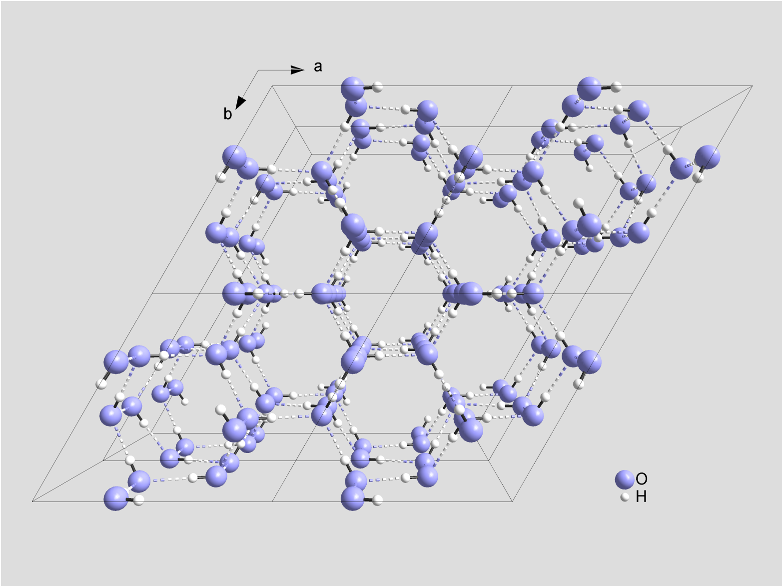
- Described by 2 parameters: Uniaxial ($n_\alpha = n_\beta$)
- Described by 3 parameters: Biaxial ($n_\alpha \neq n_\beta \neq n_\gamma$)
- Polarization can't just take any direction ⊥ to k
  - Two eigenstates



Ice is birefringent

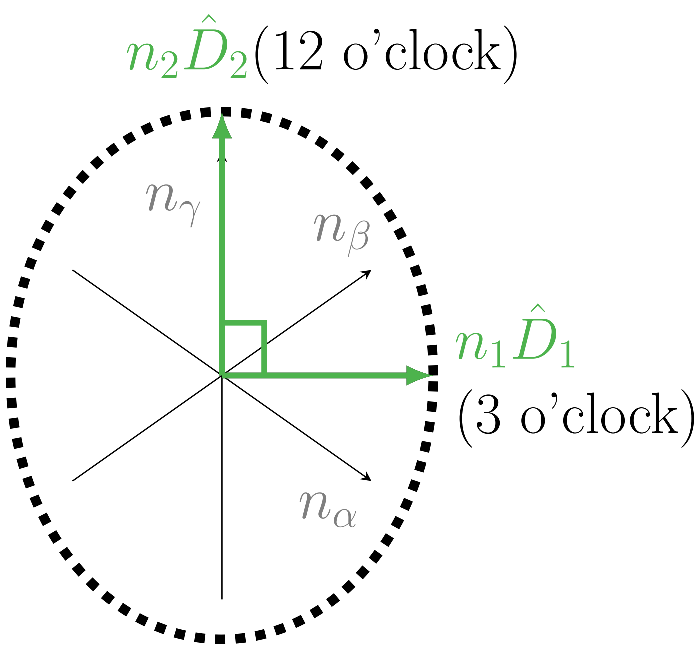
- Hexagonal crystal structure → near-cylindrical crystal symmetry → uniaxial
- Ice sheet is made of crystals (~cms³-size) with some pattern in their alignments (crystal-orientation fabric, COF)
  - COF influenced by ice flow, compression

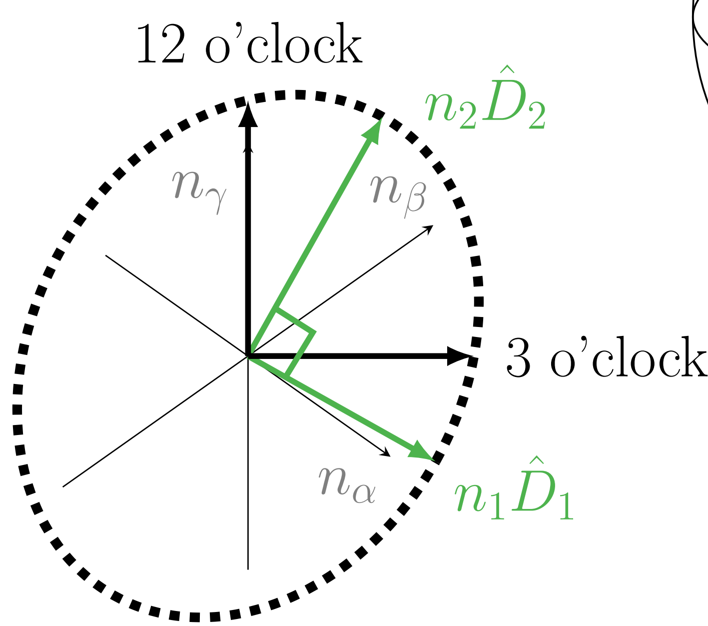
Ice 1h crystal "normal" ice

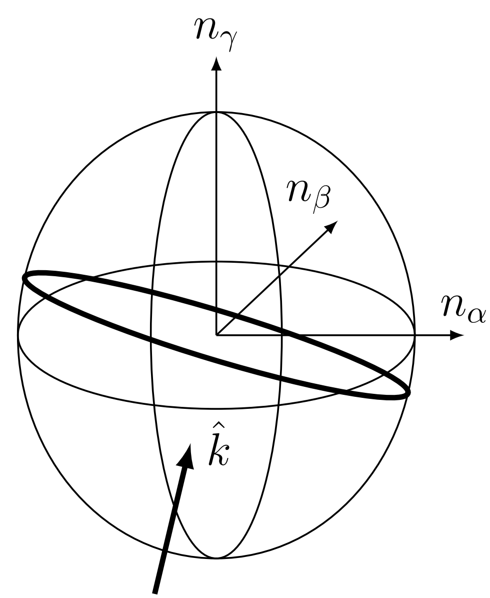


- At radio frequencies, ice can be treated as *biaxially* birefringent with depth-dependent properties (Matsuoka 2009)

Polarization eigenstates



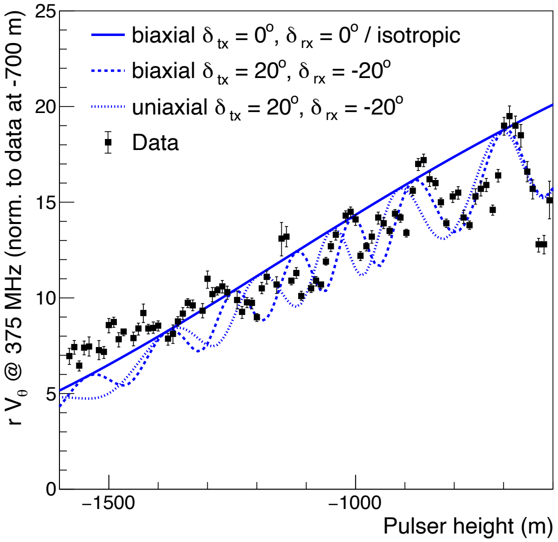




- As signals propagate
  - They hit this ellipsoid from different directions
  - n_α, n_β, n_γ are depth-dependent

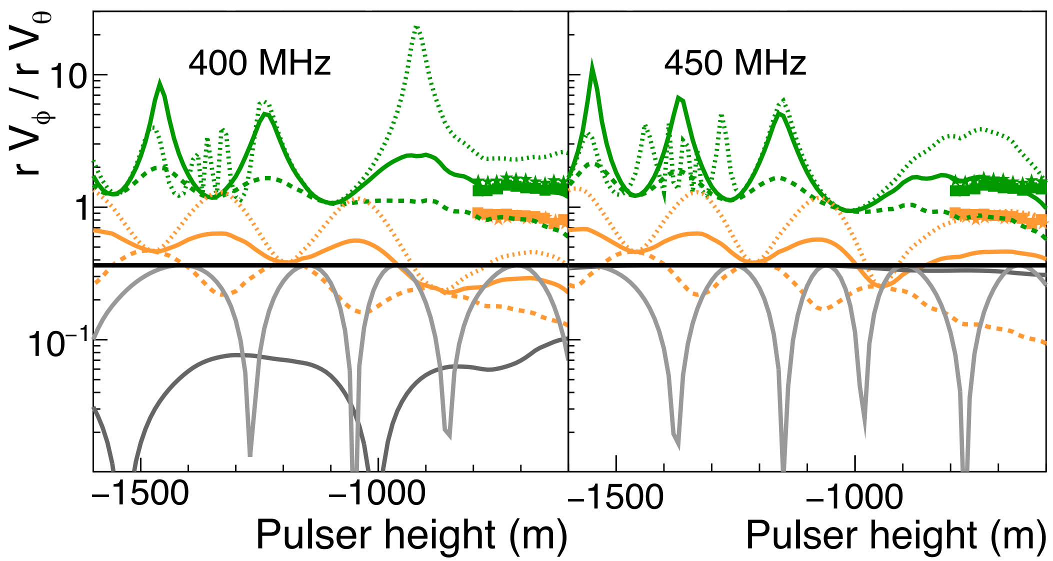
Back to the funny behavior

- Sometimes the variations look oscillatory



- This could be interference between two eigensolutions arriving with slight (~few ns) delay

- Sometimes the behavior is more erratic



- This could be rotations of the eigenstates

A. Connolly, Phys. Rev. D 105 (2022) 12, 123012

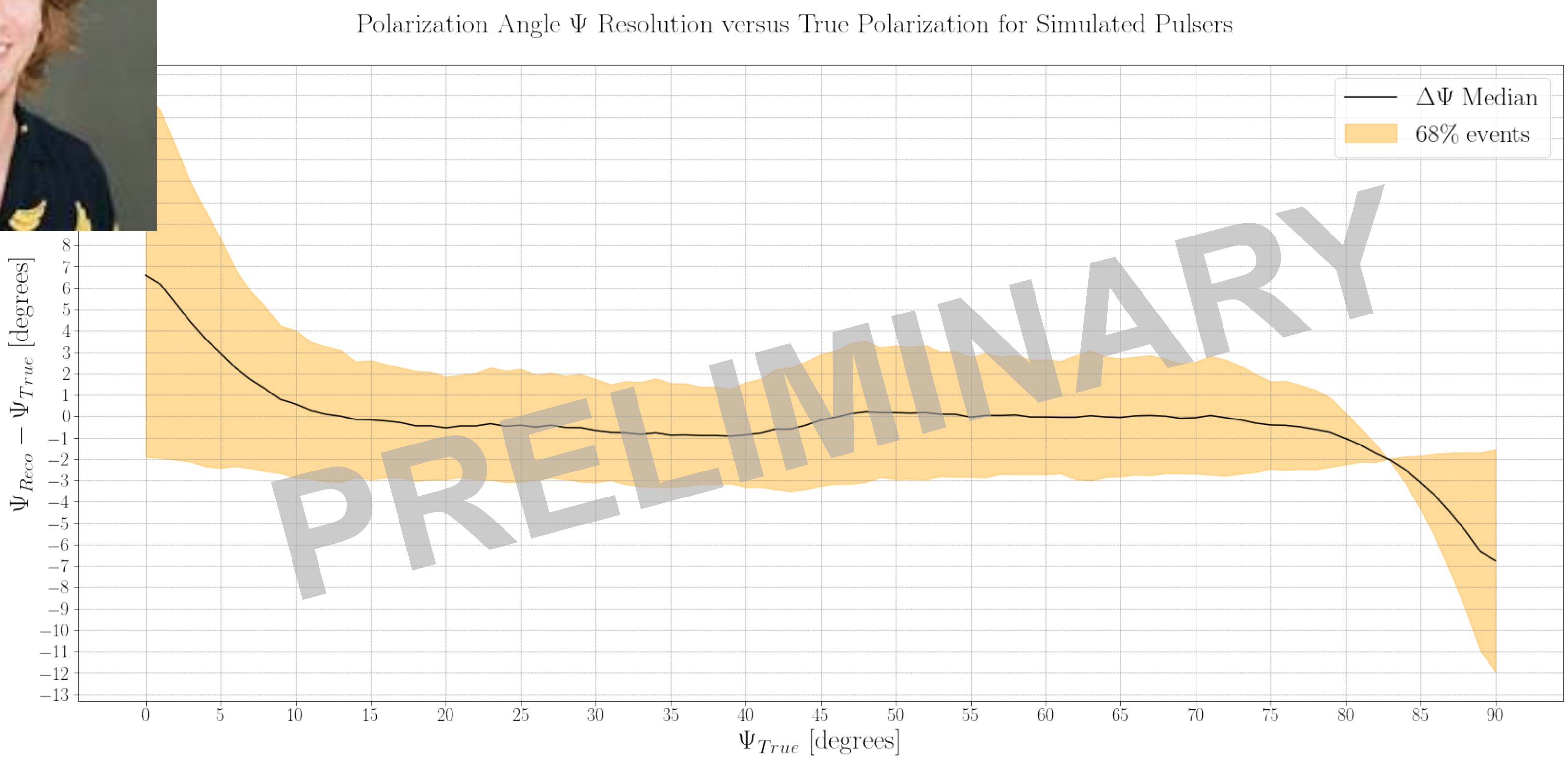
THE OHIO STATE UNIVERSITY

CCAPP

ARA polarization measurements

- Polarization measurements from SPICE pulses will be able to confirm or reject this model

OSU graduate student
Justin Flaherty



Genetic algorithms: optimization in high-dimensional parameter space

GENETIS (Genetically Evolving NEuTrIno teleScopes

- The GENETIS project was started in 2017 after an OSU workshop on genetic algorithms (GAs)
  - Inspired by *previous* NASA GA-designed antenna:

Antenna designed in 2006 for NASA ST5 spacecraft using evolutionary algorithms

GENETIS Mini-Collaboration Meeting April APS 2018

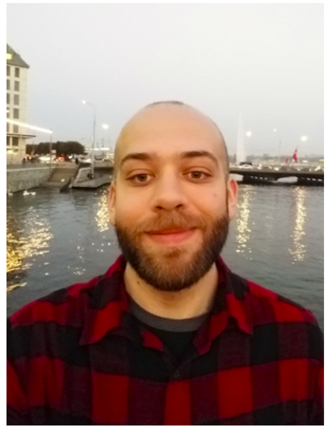
GENETIS:

- Student (largely undergraduate) -driven
- Fitness measure: *science outcome*

Student-driven


Julie Rolla
JPL Scientist

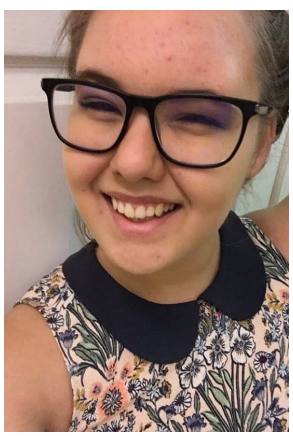

Alex Machtay
grad student


Bryan Reynolds
OSU PhD


Dennis Calderon-Madera
Bridge student


Ben Sipe
gap


Ryan Debolt
gap


Audrey Zinn
undergrad


Autumn Stephens
undergrad


Dylan Wells
undergrad


Ethan Fahimi
undergrad

Jack Tillman,
undergrad

Lydon Bindall
undergrad

Jacob Weiler,
undergrad

Interdisciplinary

Kai Staats
Univ. of Arizona
Biosphere 2
(GENETIS co-founder)

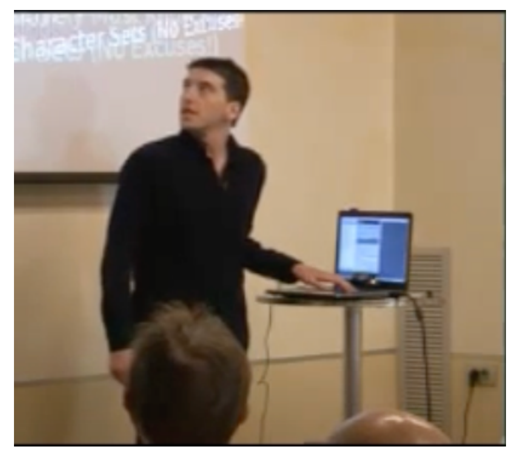
Edward Herderick
Director, Additive
Manufacturing at OSU's
Center for Design and
Manufacturing Excellence

Prof. Wolfgang
Banzhaf, Endowed
Chair in Genetic
Programming at
Michigan State
University

Prof. Chi-Chih Chen
Electrical and Computer
Engineering
ElectroScience Lab

Prof. Stephanie
Wissel, neutrino
astrophysics,
Penn State University
(GENETIS co-founder)

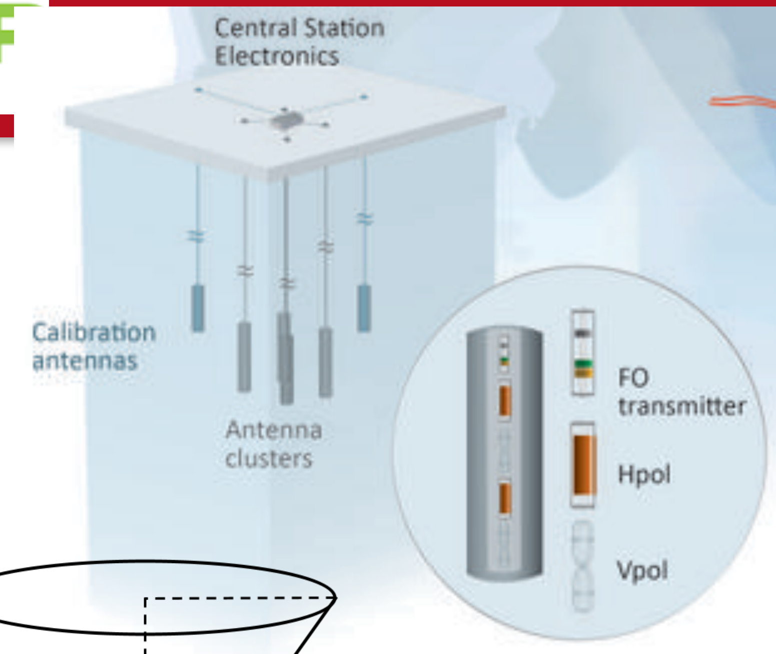
Ezio Melotti
Software
Engineer

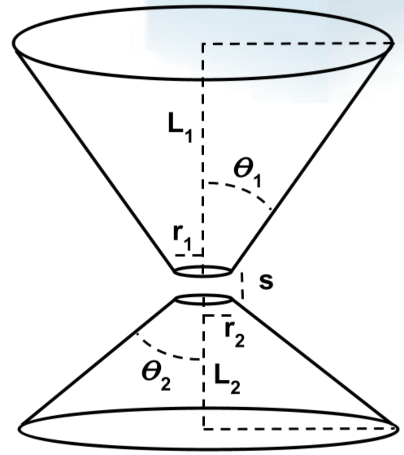


GENETIS

- First major project: design antennas optimized for detection of UHE neutrinos in the ice
- Begin with a bicone-like design
- Fitness score: number of neutrinos detected by ARA when using the evolved "individual"

This project is not limited to antenna design though

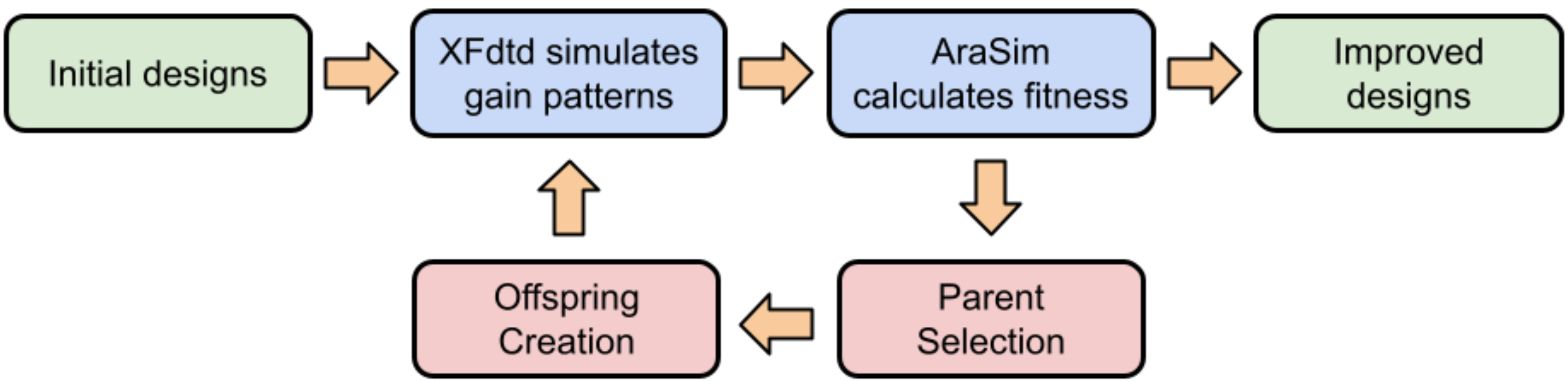




- Lengths, inner radii, opening angles are "genes"

GENETIS

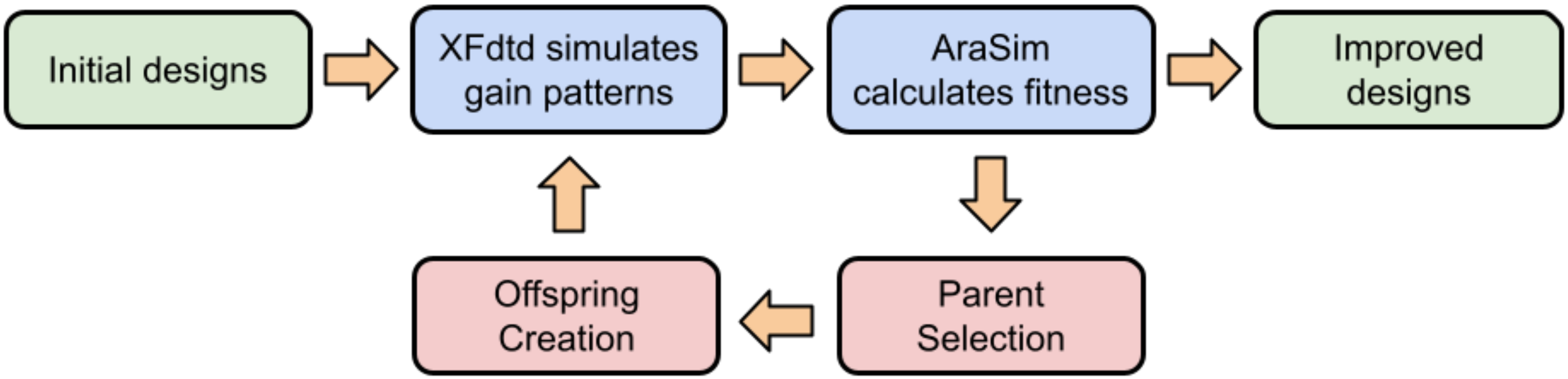
The Loop:



- 50 individuals/generation
- Computing time: 14 hours / generation
- ~35 generations to plateau

GENETIS ARA loop

The Loop:



- Completely automated - no human intervention needed in the loop itself
- Interfaces between programs running many different types of code including GUIs

Parameters of the GA itself

- Parent selection
  - Roulette
  - Tournament
- Genetic operators
  - Mutation
  - Crossover
  - Reproduction
  - Injection

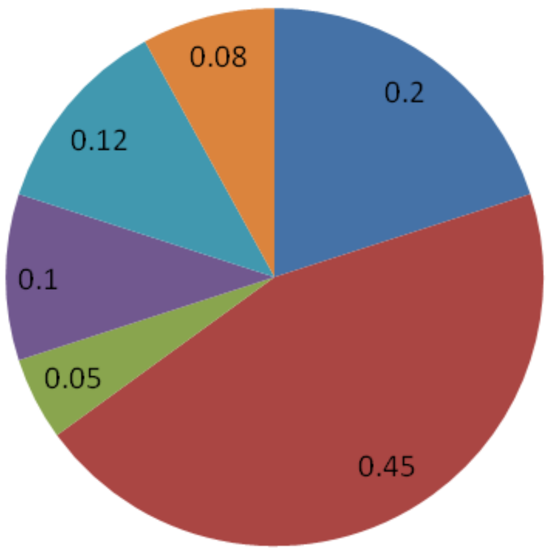
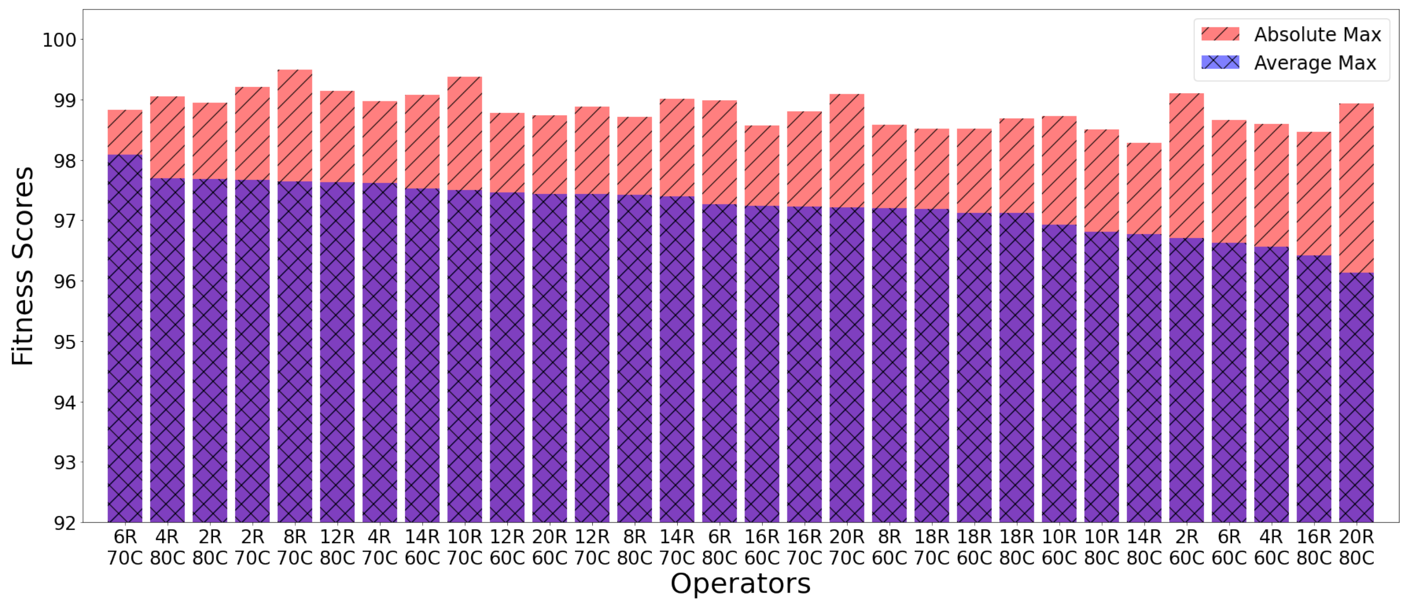


Illustration of roulette selection
towardsdatascience.com

Optimizing the GA (not the antenna yet)

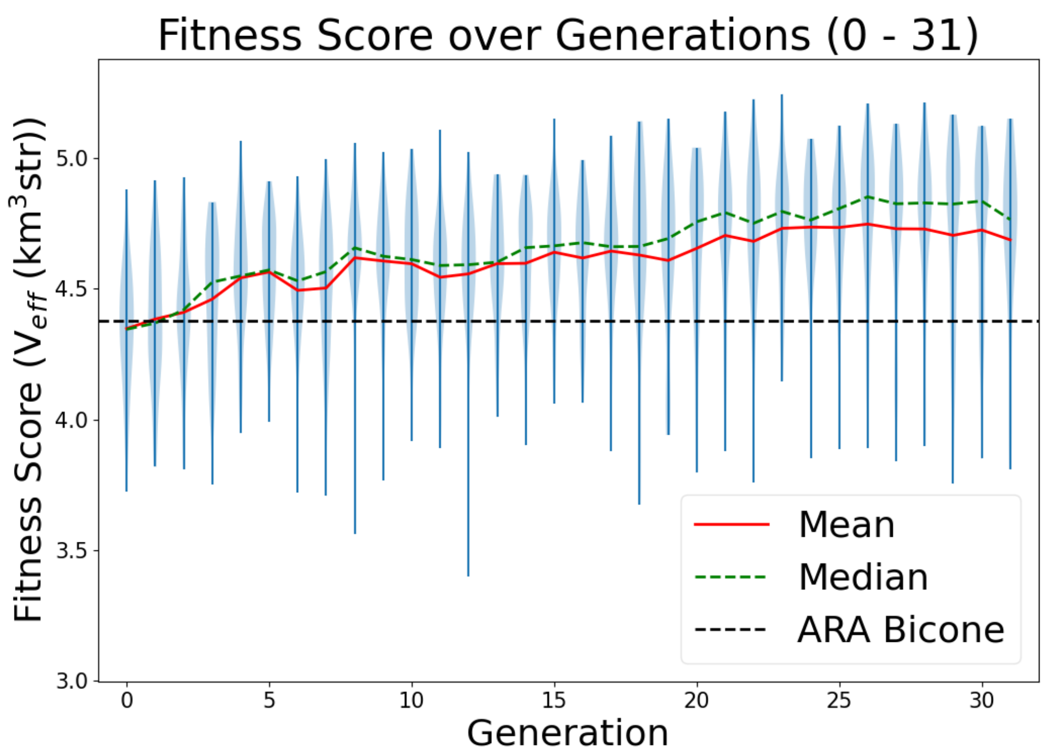
- Use a toy problem that runs faster
  - Fitness is measure of likeness to predetermined antenna shape
  - Try different ratios of selection methods, genetic operators

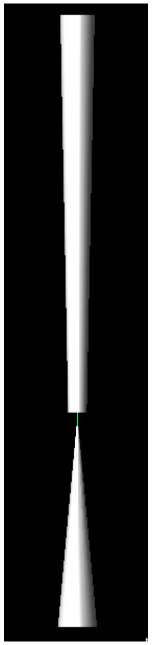


Ryan Debolt, OSU

GENETIS antenna optimization

- First results



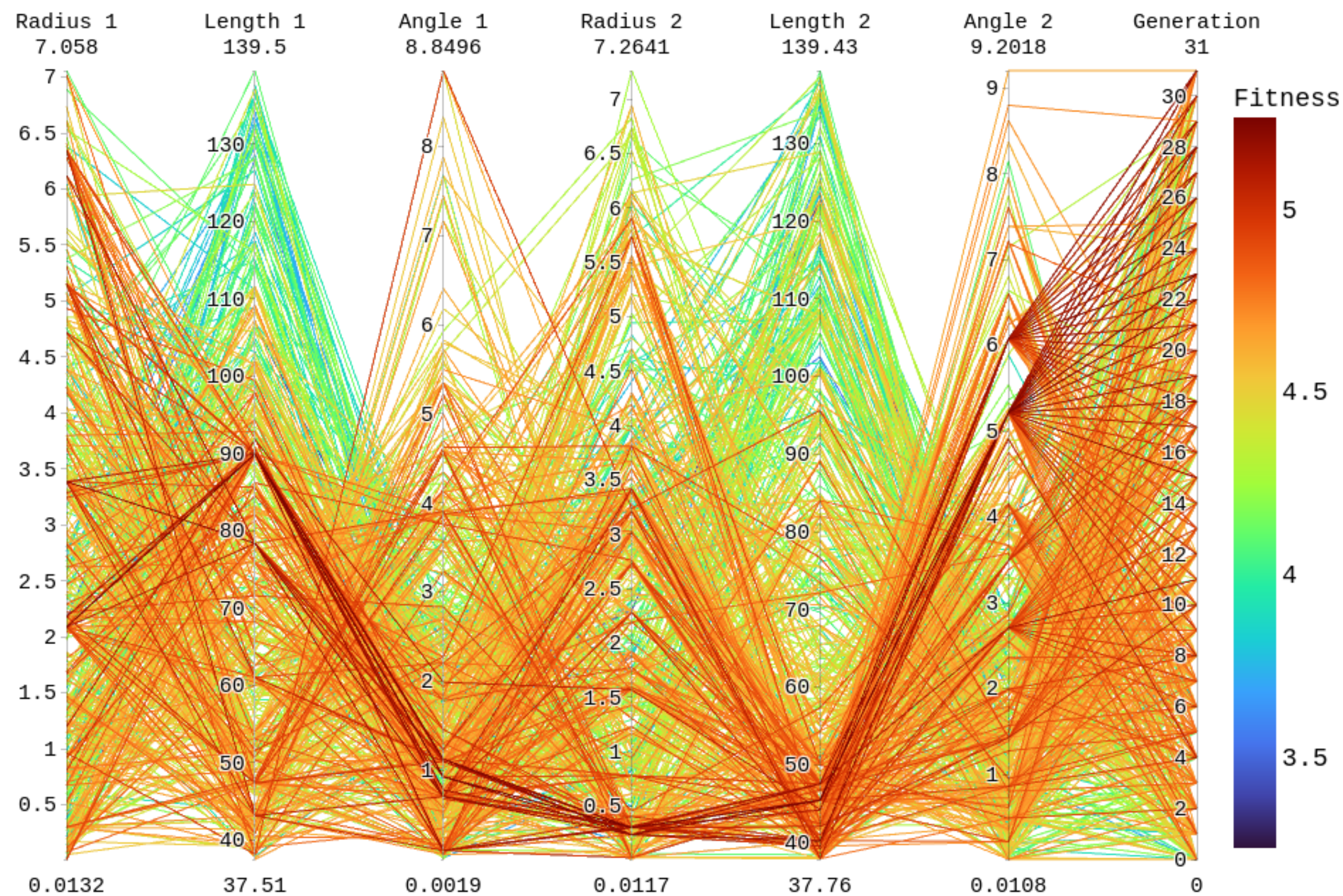


Most fit antenna, first run

GENETIS team, OSU students Julie Rolla and Alex Machtay playing lead role

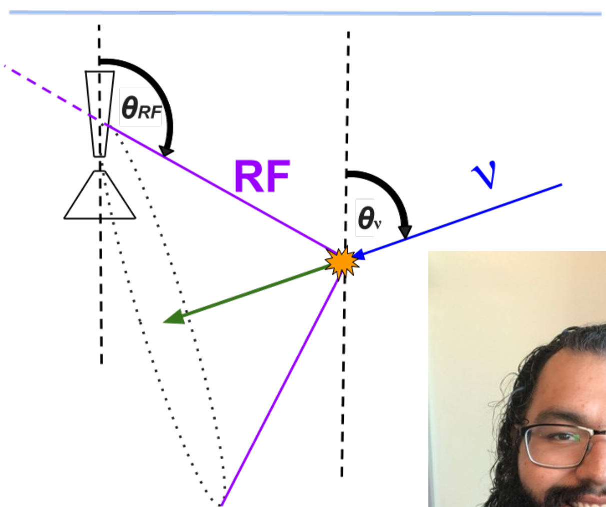
Rainbow plot

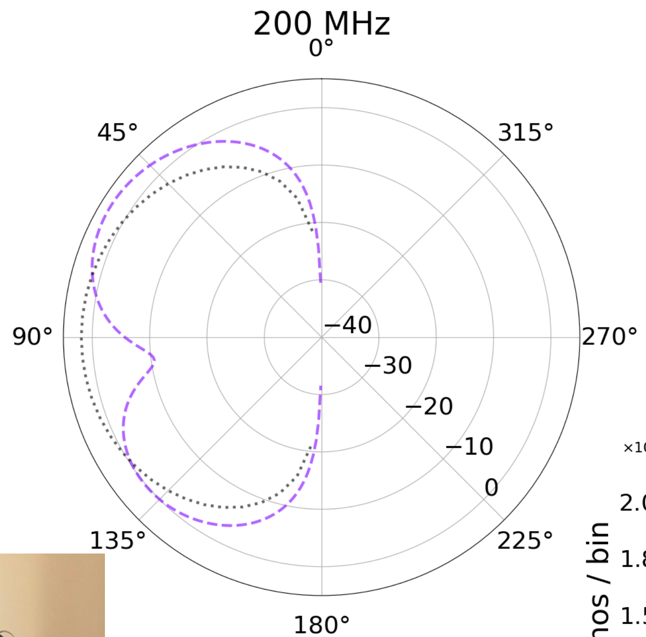
- Most fit antennas have common design parameters



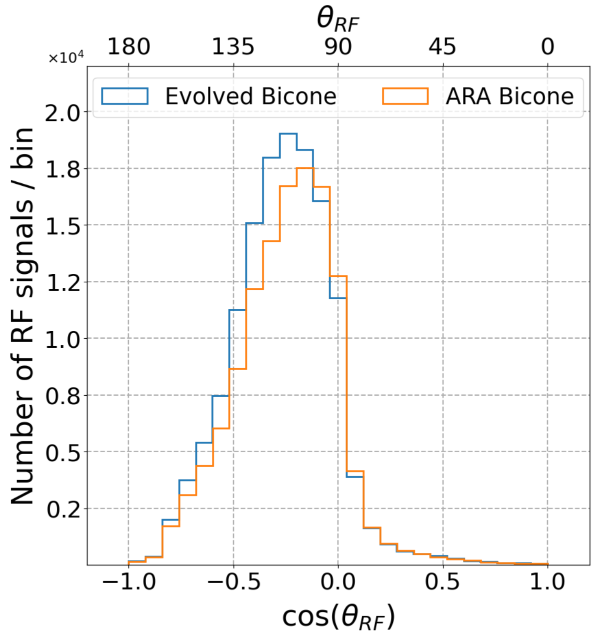
OSU student Ben Sipe

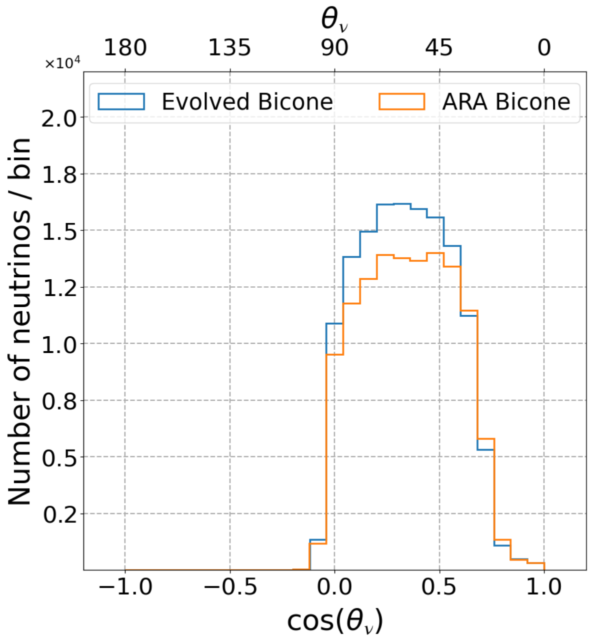
How they can better detect neutrinos





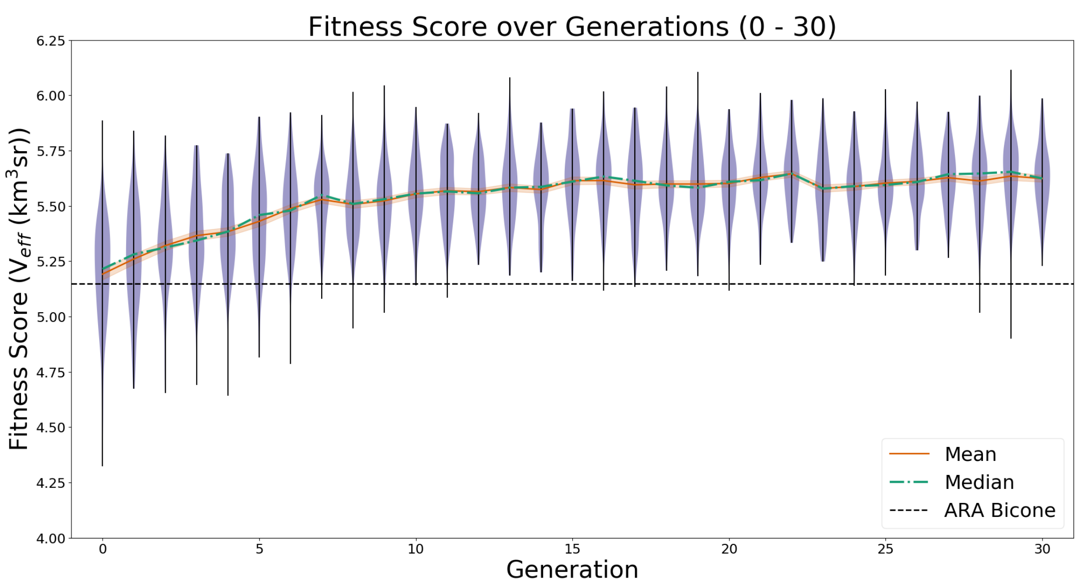
Dennis Calderon-Madera

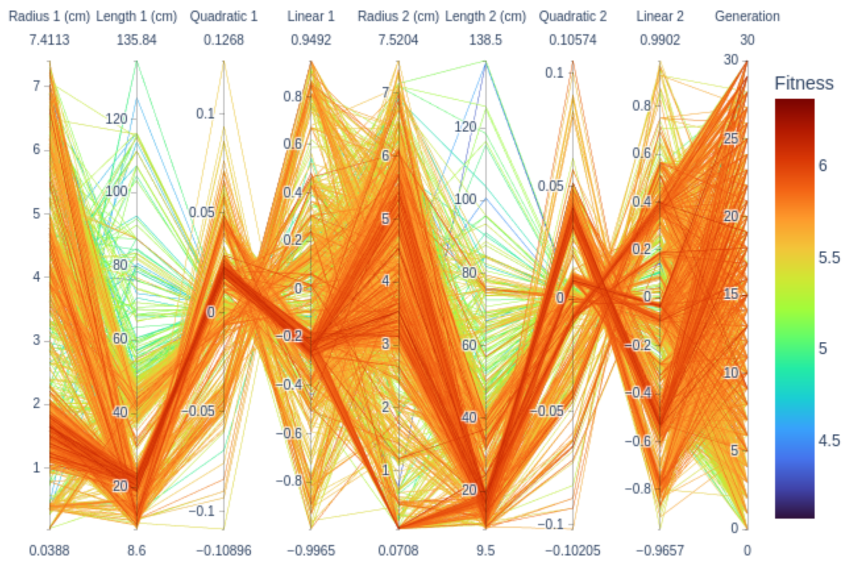




Bicone evolution - “Crazy sides”

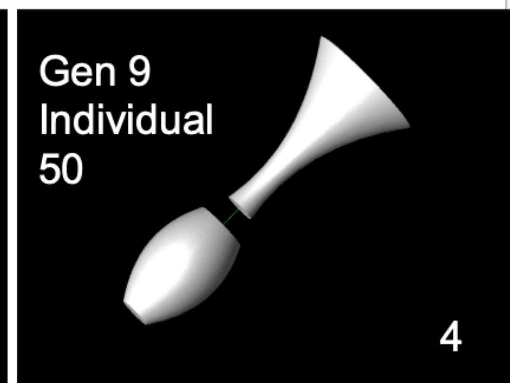
- Same as before but now sides allowed to be curved
- Each side described by linear and quadratic term

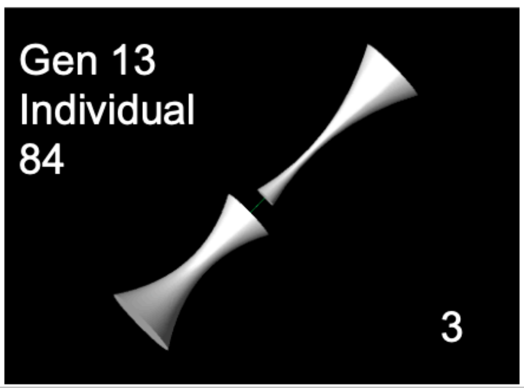


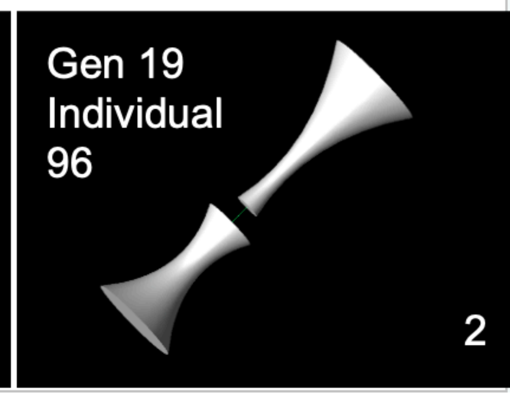


Bicone evolution - crazy sides: Best individuals

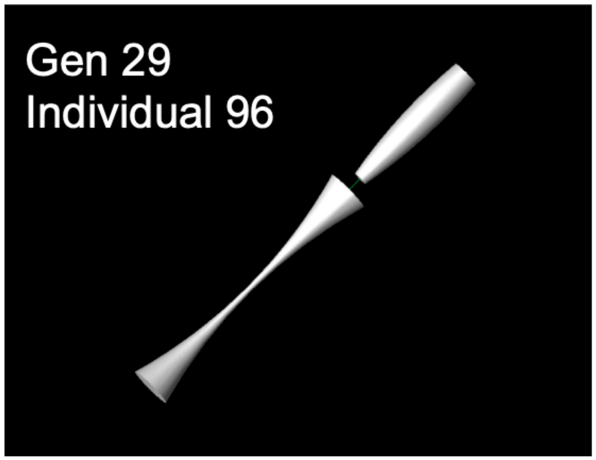
r_0	L	A	B
1.15986	18.7904 cm	0.0233761	-0.204119
0.0806527	15.0253 cm	-0.00721627	0.428999

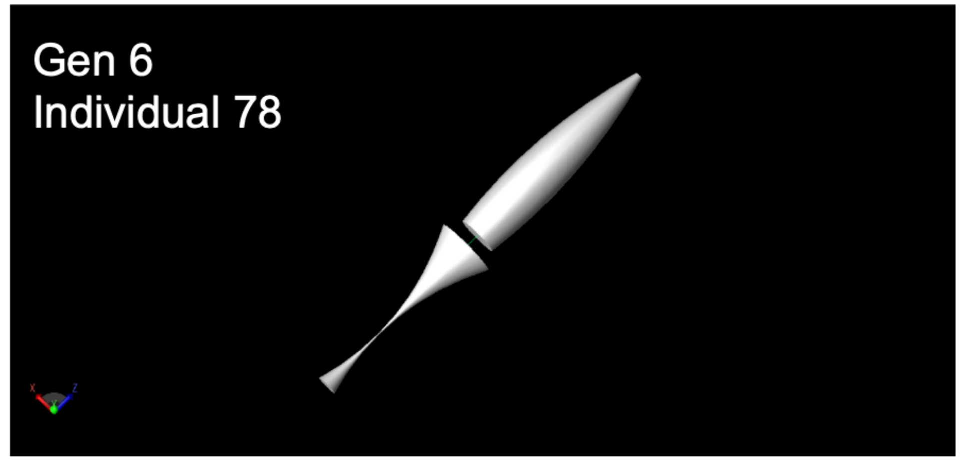


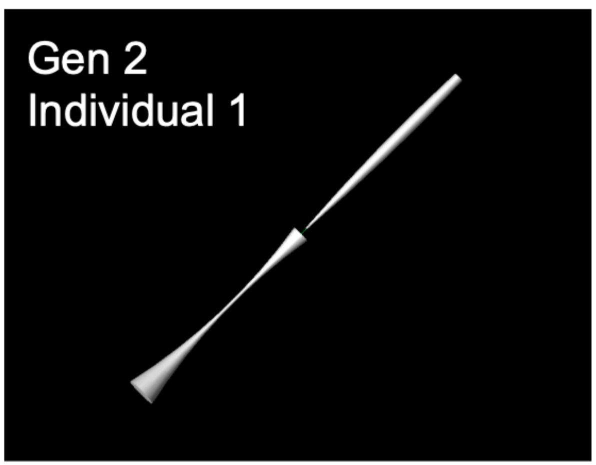


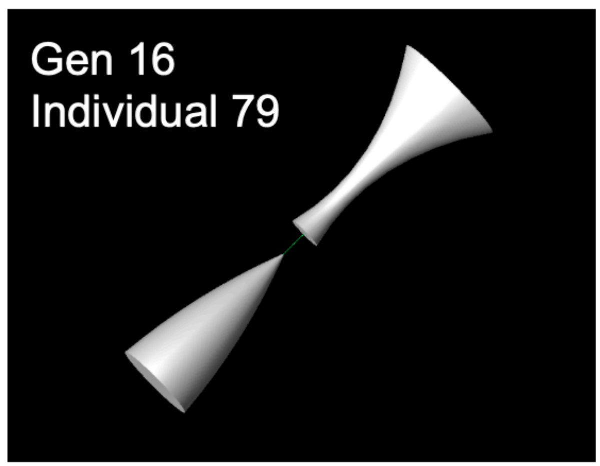


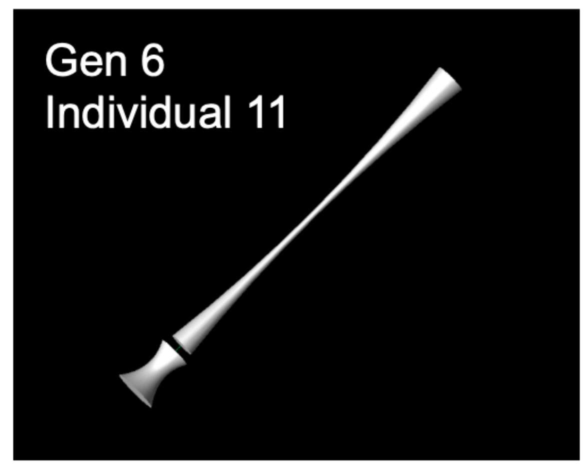
Bicone evolution - crazy sides: Some mid-range, worst







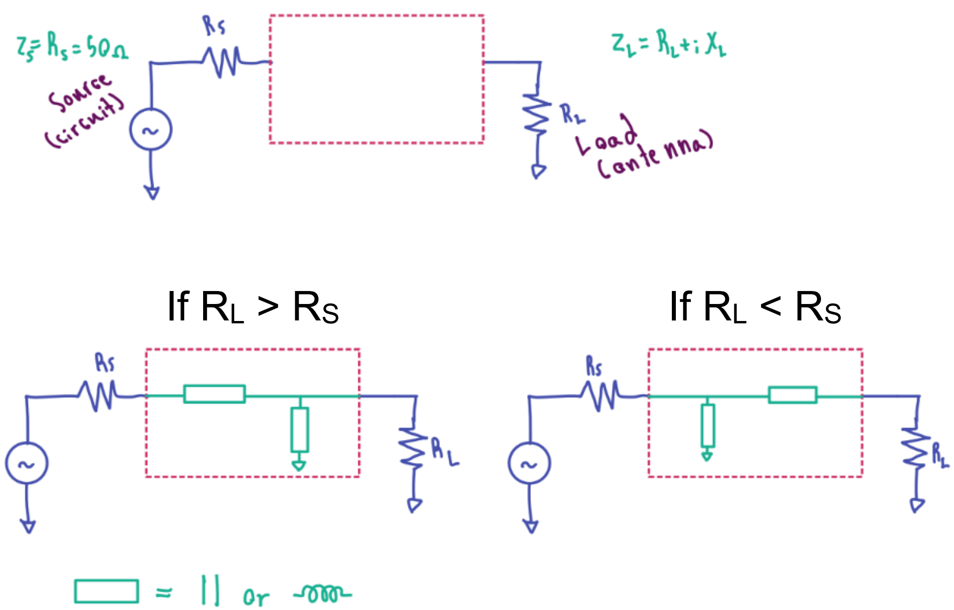




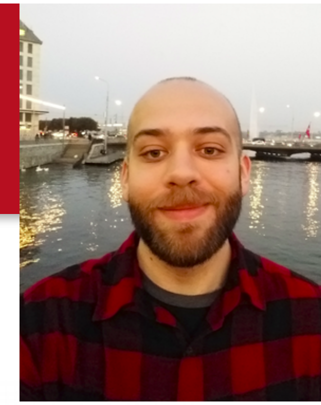
Dylan Wells
undergrad

Next steps for GENETIS in-ice antennas

- Working with director of Additive Manufacturing at OSU's Center for Design and Manufacturing Excellence (CDME) to build GENETIS evolved antenna
- Matching circuit designed for transition from 50 Ω cable to antenna



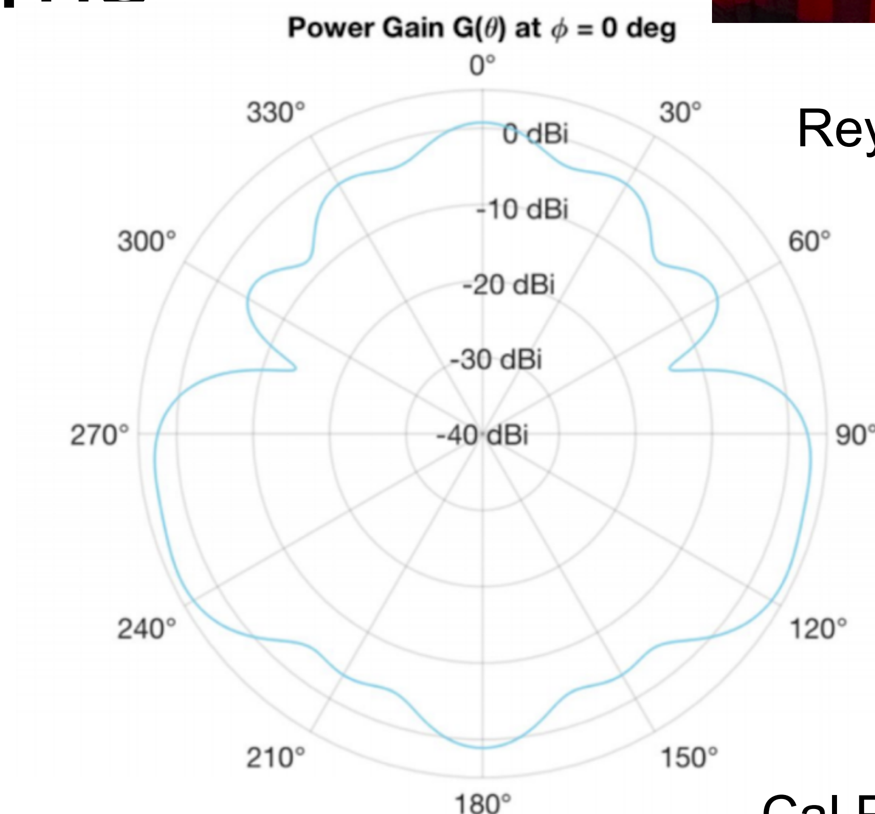
OSU student Dylan Wells



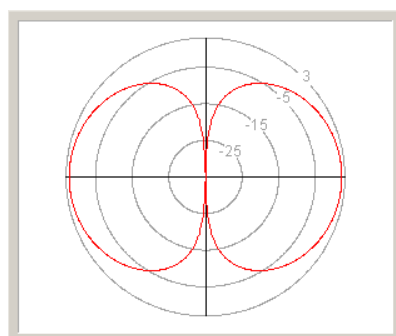
Bryan Reynolds

Evolving beam patterns

- We can evolve just antenna beam pattern (gains vs. direction) for improved sensitivity to neutrinos
  - (nevermind how we'd build the antenna)
- This allows us to test
  - Is there room for improvement



Cal Poly undergraduate thesis



Typical bicone pattern (up-down symmetric)

GENETIS PUEO loop

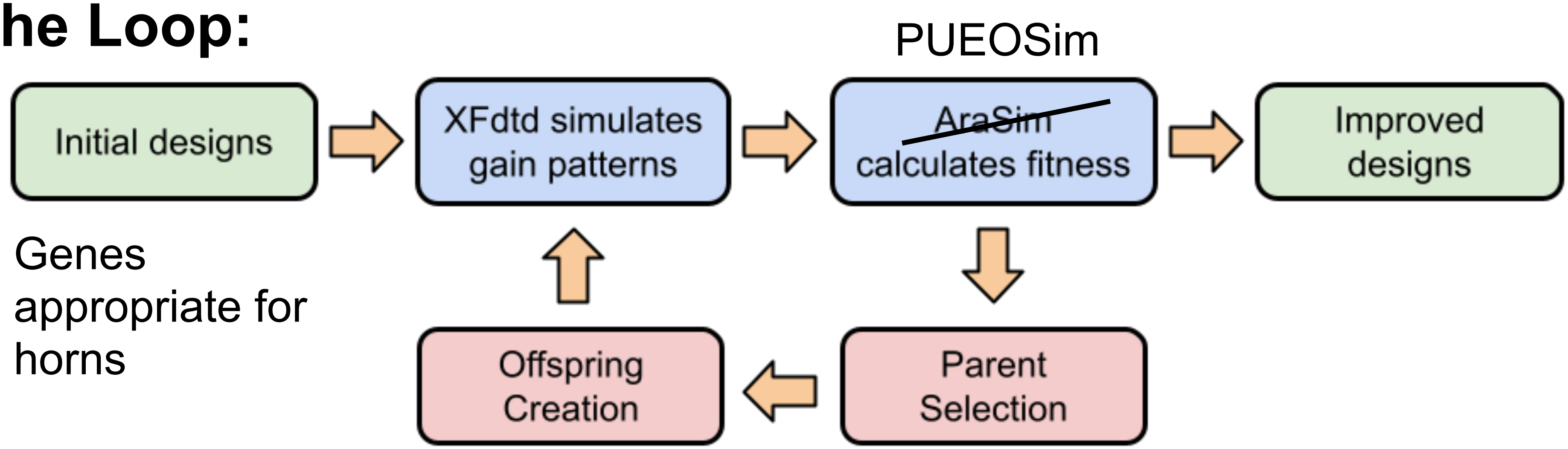
Julie Rolla

Alex Machtay

Dylan Wells

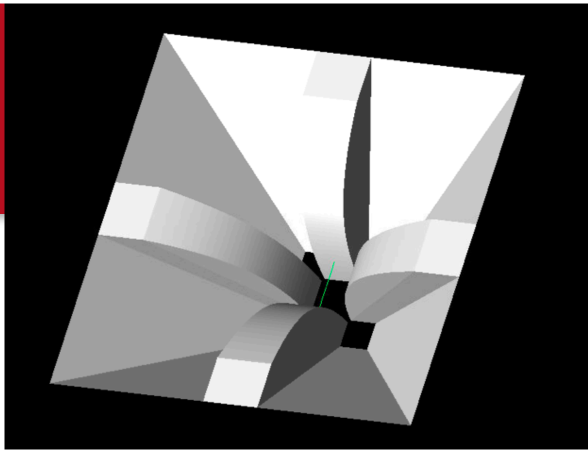
Ryan Debolt

The Loop:



Genes appropriate for horns

- Running now!



GENETIS PUEO loop genes

- **Antenna Walls**
  - S is half the side length of the bottom of wall
    m is the slope of the outer wall
    H is the max height of the outer wall
- Current Constraints:
  - S < 50cm
    H < 50cm
    m = 1
- **Antenna Ridges**
  - x_0, y_0, z_0 are the initial points of the inner most part of the ridge
    x_f, y_f, z_f are the final points of the inner most part of the ridge
    β determines curvature of the ridge

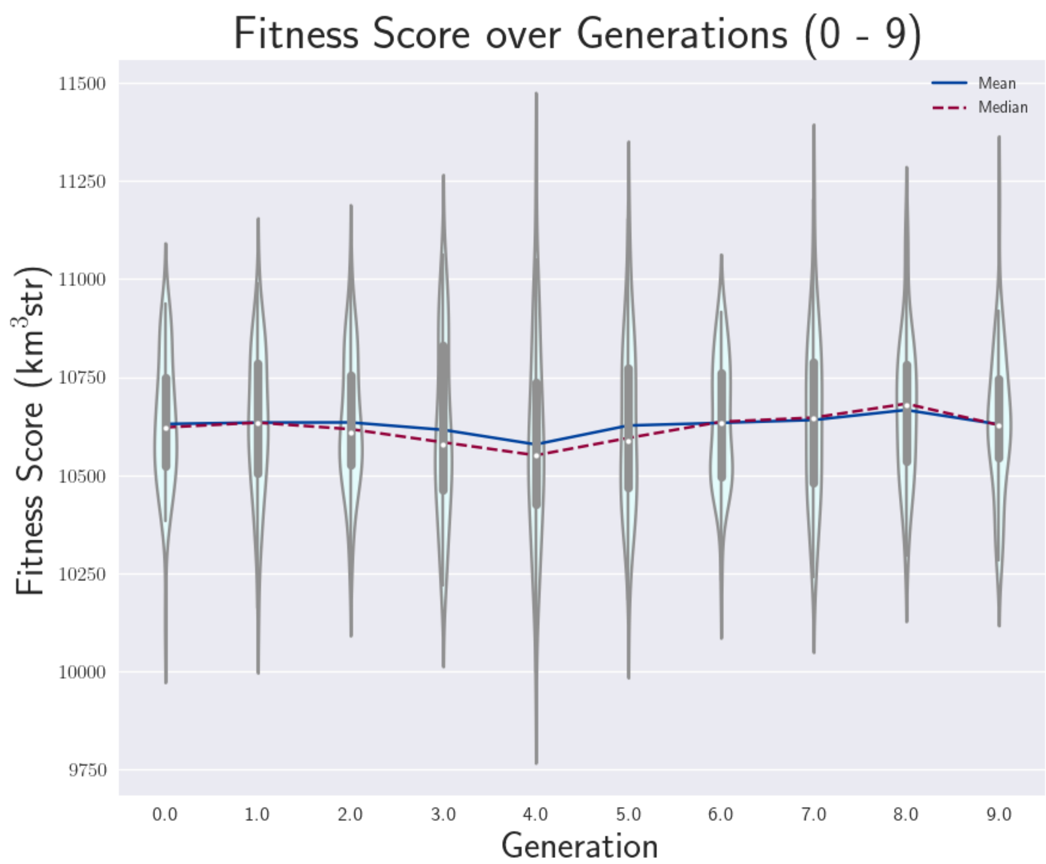
Will add a binary gene for whether or not there are walls

The Ohio State University | CCAPP

GENETIS PUEO first ten generations

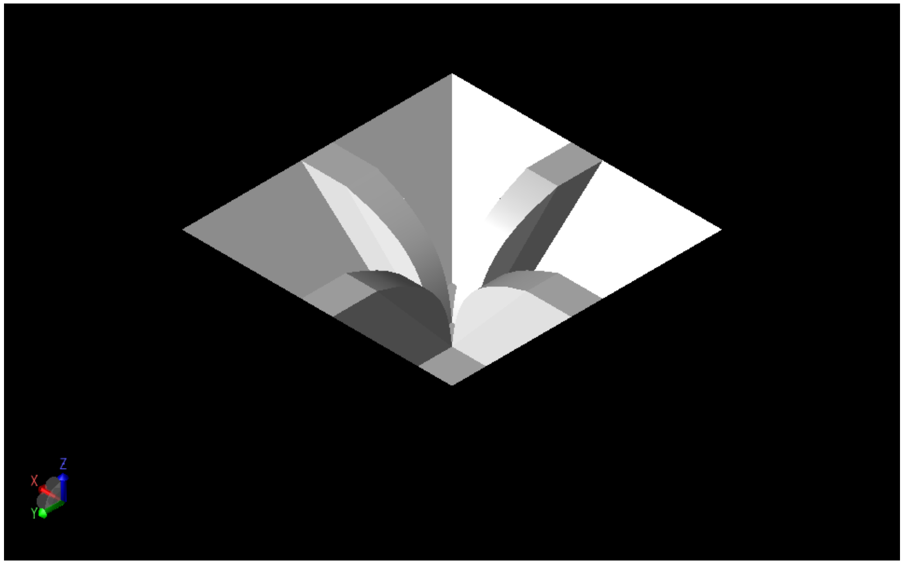
Neutrinos at 10^{19} eV

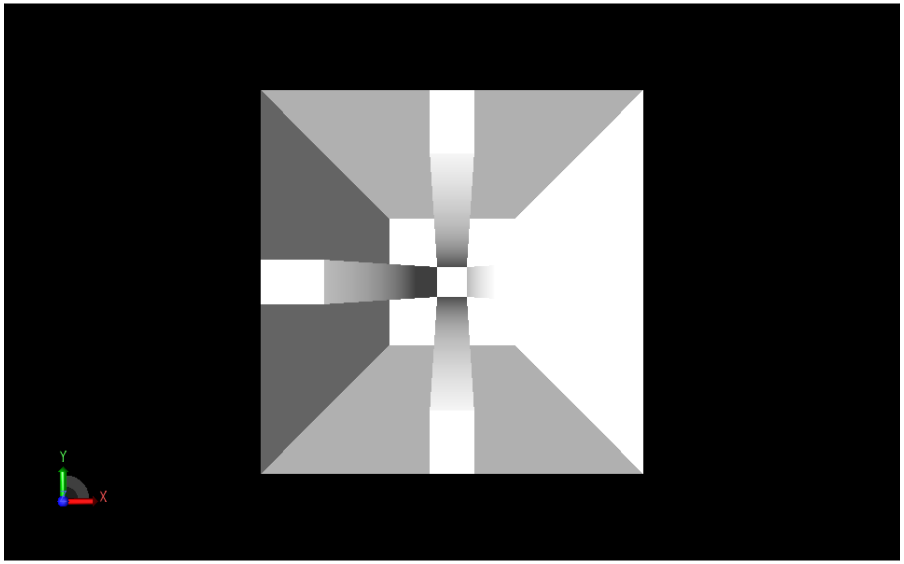
- Only two parameters being evolved at first so improvement is subtle
- Loop is working!
- First time we switched out a new experiment in the loop
  - Lays groundwork for more!



Current PUEO design: 11700 km^{3}str at 10^{19} eV

GENETIS PUEO good individual



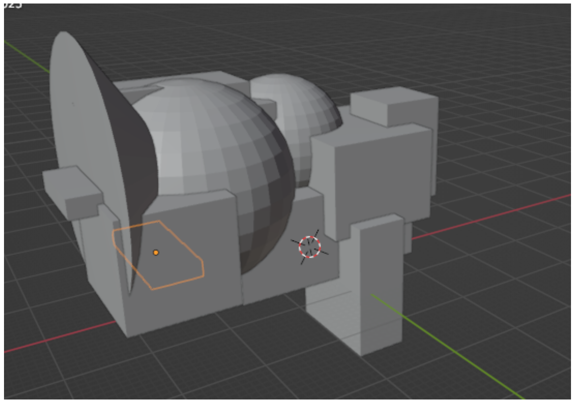


Generation 4, Individual 46

"Nebulous" (star wars legos) project

- Small trl0 funding from JPL Division 33 (communications, tracking, and radar)
- Instead of having a preconceived idea for the type of antenna (bicone, horn), start from scratch and build something from legos
- As first step, evolving to a target shape
- Group is working out complicated math
- This initial work complete in June

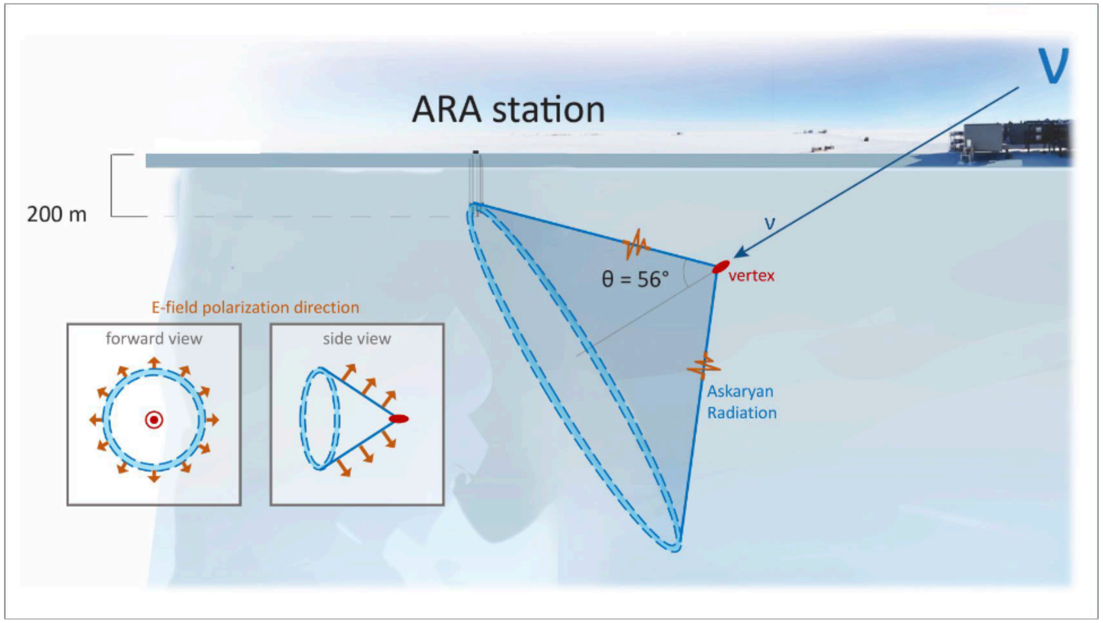
Julie Rolla
JPL Scientist



Other GENETIS spin-off projects

- We are expanding!
- Evolving beam patterns and antennas for PUEO
- Alex Kyriacou (grad student Wuppertal) finding depth-dependent index refraction in glacial ice
- Suren Gourapura (now Princeton grad student) calibrated sample times on digitizing chip
- Various research groups have recently approached us with interest in applying this to design of detectors - next slide
- Lots of possibilities

Bringing together birefringence, GENETIS



- ARA simulations being developed to include biaxial birefringence
- GENETIS to evolve
  - VPol and HPol antennas
  - Array geometry

- NSF Award #2209588: further investigate ice birefringence and neutrino detection, evolve
- First federal funding for GENETIS!

Summary

- UHE neutrinos are an important missing piece of the exciting, expanding field of multi-messenger astrophysics
- Antarctic ice is rich in its challenges and opportunities
- GENETIS is a maturing project designed for tackling complex problems for science outcomes