1 Introduction

Building upon three years experience in machine learning applied to the development of advanced designs in antennas for neutrino detection, we propose developing the groundwork for applied artificial intelligence tools to confront the unique challenges faced by high energy astroparticle physics instruments, from design to operation to the preparation of data for analysis. This will lead to substantial improvements in the science capabilities of these experiments, and at the same lower the cost of construction and operation.

2 Intellectual Merit

2.1 Overview

This proposed planning phase builds on the undergraduate-led collaborative effort called GENETIS (Genetically Evolving NEuTrIno TeleScopes), which planted the seeds for this bold project in early 2017. GENETIS will build prototypes of the first antennas designed through evolutionary computation (EC), a subset of artificial intelligence (AI), for an improved physics outcome. GENETIS will expand the project to benefit experiments spanning astroparticle physics. The advances from multi-parameter optimizations in this work will lead to a) greater sensitivity for astroparticle physics experiments; b) a streamlined pipeline for more timely data processing; and c) fewer deployed units which in turn reduces logistics, cost of construction, commissioning, and maintenance.

2.1.1 AI and Astroparticle Physics

In the past decade astroparticle physics has entered an exciting new "multimessenger" era. This opens unprecedented capabilities for uncovering the astrophysical processes in catastrophic events while providing unique probes into fundamental physics. IceCube has for the first time observed neutrinos of astrophysical origin and measured the spectrum from now-dozens of events, including the highest energy neutrinos ever measured, at $\mathcal{O}(10)$ PeV [1]. Meanwhile, in 2015, the Laser Interferometer Gravitational-Wave Observatory (LIGO) Scientific Collaboration made a stunning announcement of the discovery of gravitational waves, opening a new window to extreme events at cosmic distances, and has since reported more than 50 such observations.

Cosmic ray observatories Auger [2] and Telescope Array (TA) [3] are breaking new ground in measuring the composition of the highest energy cosmic rays and possible sources [4]. Productive gamma ray programs such as those at observatories HAWC [5] and Veritas [6] continue to broaden our understanding of energetic, cosmic sources. Many new experiments, and new phases of existing experiments are going after these multimessenger events with unprecedented sensitivity to extract the rich astroparticle physics and fundamental physics now made available [7–9].

Excitingly, the first possible coincident observations from the same source are being reported, including gamma ray-neutrino [10] and gravitational wave-gamma ray [11]. Such coincident detections enable unprecedented opportunities to leverage information obtained through each medium, and form a more complete picture of these extreme processes [12]. There remains an important missing piece of the multimessenger picture–ultra-high energy (UHE) neutrinos. Their interactions are so rare they are the only particles observable from cosmic distances in their energy regime, producing collisions at center-of-mass energies that exceed those probed by accelerators.

To capture these events, neutrino detectors must cover enormous areas, with stations of instruments dispersed over hundreds of km^2 in area [13]. The "Askaryan" radio emission produced by neutrino-induced particle cascades in dense media, coupled with the radio transparency of clear ice, enables individual stations of antennas to be deployed sparsely ($\sim$ 1 km separation).

These experiments are faced with the additional challenge of needing to detect signals of both horizontal and vertical polarizations (HPol and VPol) with antennas under tight geometric constraints of a narrow, deep, vertical hole (approximately 15 cm diameter), embedded in naturally occurring ice.

Following a ten-year prototyping phase in the field of radio neutrino detection, including ARA [14] and ARIANNA [15], the field of UHE neutrino astrophysics envisions an expansive (500 km^2) radio component to the proposed, expanded South Pole observatory IceCube-Gen2 in 2025 [16]. An intermediate-size array called the Radio Neutrino Observatory (RNO) [17] is being deployed in Greenland beginning this summer 2020, with a unique view of the northern sky. It will offer the extremely valuable experience of scaling-up radio arrays, and associated data processing and analysis in advance of IceCube-Gen2.

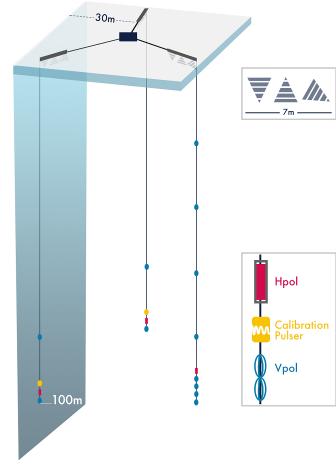

Figure 1: A single RNO-G station consists of three strings of antennas and surface antennas.

RNO is an exceptional, timely opportunity to deploy evolved antennas that will improve the capabilities of next generation neutrino detection arrays. GENETIS co-founders Connolly and Wissel are co-investigators for RNO and integral to the field of UHE neutrino detection. They have tasked the GENETIS group with its first challenge to design antennas for in-ice arrays optimized for sensitivity to UHE neutrinos. GENETIS plans to expand its applications to areas across the field of astroparticle physics.

2.2 Research Theme Areas and Team Selection

This proposed work on the Planning Track lays the groundwork for an Institute for machine learning applied to the design of experiments in astroparticle physics. Such an Institute would contribute to three of the themes currently identified as high-priority areas by NSF: Foundations of Machine Learning, Trustworthy AI, and AI for Discovery in Physics.

2.2.1 Foundations of machine learning

Evolutionary computation (EC) is a type of machine learning, the functional foundation for modern artificial intelligence, and is inspired by real-world biology. [18] A subset of EC, supervised genetic algorithms (GA) employ key principals found in biological evolution to guide the multi-generational improvement of a program's ability to solve a problem, [19] as developed by Prof. John Holland in 1960 and his student David E. Goldberg. [20]

The hypotheses, or potential solutions, are represented as individual parameter sets. In the case of GENETIS, the parameters represent antennas. In each generation, a random set of individuals are selected from the current population and tested for their ability to solve a *known* problem. A fitness function guides the process of comparing the output of each selected individual versus the known result. With each generation, their code is modified by one of the evolutionary operators: reproduction (copy without change), mutation, recombination (sexual reproduction). Termination of any given evolutionary run is defined by the total number of generations, an elapsed period of time, and/or having achieved a desired quality of performance against the given test. [21]

2.2.2 Trustworthy AI

While advanced machine learning algorithms are readily available, and Deep Learning algorithms for GPUs dominate the AI landscape, we selected a GA as the ideal tool for this challenge as they are a transparent, “white box” algorithm. This provides both confidence in the evolved solution and a powerful platform from which students new to AI can “see” the internal processes unfolding. The student code developers on the GENETIS team have written a body of code of their own design, following the principals of EC. In addition, GAs offer the following benefits for the problems engaged by the GENETIS team:

- Are compact, portable, and a relatively simple code base.
- Can be written in Python or C++, and function on a personal computer or cluster.
- Can be optimized for parallel CPU and GPU computation.
- Do not readily over-fit even when the number of input parameters is low.
- Are inherently designed to work with an external validation tool suite (fitness function)

The parameter space for the current GENETIS problem is low, with just three parameters to evolve. The GENETIS team will in the Summer of 2020 increase the parameter space to describe an antenna. The next stage involves the application of more complex machine learning algorithms and to the design of broader aspects of the entire array, including the spacing of antennas and the non-uniform deployment of heterogeneous antenna designs. Ultimately, these techniques will be carried into the domain of complex astropartical physics experiments outside of neutrino detection, building on each subsequent success of the GENETIS suite of tools and applications.

As machine learning algorithms become more complex, the ability to monitor and understand the internal functions becomes more difficult. GENETIS will always refer to first-order principals of physics, trusted models, and field-test prototypes to validate the outcome of the evolved designs.

Application of a Genetic Algorithm

In the GENETIS application, the GA conducts a random walk through the parameter landscape of the genotype. The external, third party, radio frequency response evaluation tool XFdtd combines with a detector response tool (AraSim) to conduct the evaluation of the phenotype, the real-world expression of the parameters that define any given antenna design. The results of the fitness function evaluations are used to guide the evolution of the next generation.

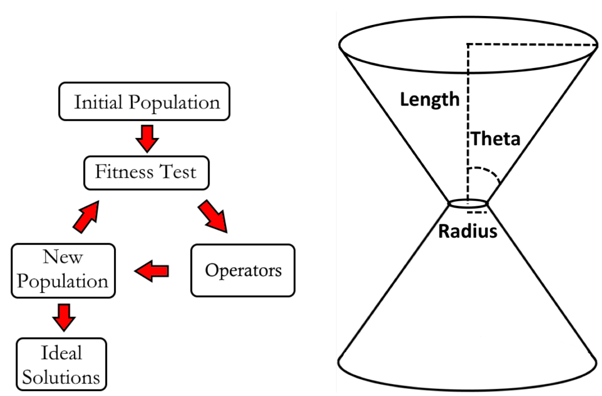

Figure 2: (Left) General GA evolution procedure, (Right) Geometry of bicone antenna evolved by GENETIS showing the genes of length, opening angle theta and minor radius.

Fig. 2 shows the bicone design that GENETIS has begun to evolve. The bicone antennas' form and function are defined by *genes* that correspond to values of three parameters. The parameters are the length of the cone, the radius of the small center of the bicone, and opening angle from the small radius. The ARA experiment deployed “birdcage dipoles,” [22] but here a bicone design was chosen for first tests because it is suitable for broadband signals like the Askaryan emission.

The evolution of the parameters to generate novel antenna designs, and as such navigate the solutions space of the problem is conducted through a hybrid GA that draws from the existing body of work in GAs [23,24]. We employ *roulette selection* to choose the parent programs to produce offspring for the subsequent generation. Roulette selection randomly chooses individuals from the parent population, with each individual's probability of being selected related to their fitness score. This selection method was chosen over tournament selection because giving all individuals a chance to reproduce allows the algorithm to explore the full parameter space, in a relatively small population of individuals.

The probability of an individual being selected to become a parent and pass on its genes is defined as: $P_i = F_i / \sum_i F_i$ where P_i is the probability of an individual being selected and F_i is the individual's fitness score. As in the real-world, cross-over mutation (sexual reproduction) generates children with some characteristics of each parent antenna. In addition, some randomly selected individuals in the new population undergo a mutation of randomly selected genes in order to introduce a greater diversity in the gene pool. The selection of parents, crossover mutation, and random point mutation are repeated until the population of the next generation is formed.

2.2.3 AI for Discovery in Physics

Given the current literature on the application of EC to astroparticle physics, we found that GENETIS is unique in its simulation of the measurement of an antenna's machine learning fitness score against the real-world physics outcome. This illustrates the potential of GENETIS to both impact neutrino detection experiments and bring GAs into the field of particle physics and applied physics as a whole. While antennas have been evolved to produce improved or specified responses, the physics community has yet to realize the promise of GAs on applied experiments.

Antennas designed by evolutionary computation

Over the past three decades, there has been significant growth in the GA research, including for antenna design [25]. These GA are often able to produce human-competitive results [26]. The most famous example is NASA's successful use of GAs to evolve a wire antenna that was developed for the Space Technology 5 (ST5) mission [27]. Additional wire antennas have been evolved in [28] and [29], among others. Yagi-Uda Antennas [30], patch antennas [31–33], printed optical antennas [34], horn antennas [35] and antenna arrays [36]. Besides antennas, GAs have been used for numerous applications including optimization of truss structures [37], wind-turbine support structures [38], and metamaterials [39]. Significant opportunity for GAs in the optimization of topology design remains, especially when there are accurate simulators to measure performance [26].

The software package XFdtd was used for the electromagnetism simulation to produce the gain and phase patterns for physically realistic evolution of antennas. XFdtd is based on the Finite Difference Time Domain (FDTD) method of electromagnetic calculations and can be used to simulate the response of a wide variety of antennas types This flexibility is well suited for a evolutionary system to obtain arbitrary antenna shapes. For the physical evolution of a bicone the antenna receives a simulated neutrino signal as a broadband impulse in the band 83 MHz - 1.066 GHz. XFdtd calculates the gain in dBi in all directions.

Evolving antennas for a physics outcome

The GENETIS group has recently developed a GA that evolves the geometry of a bicone antenna to improve sensitivity for detecting UHE neutrino signatures in ice. Antenna simulation software XFdtd and neutrino simulation software AraSim are utilized in conjunction to calculate the fitness score for each individual used in the GA. The procedure of the GA is illustrated in Figure 3. The process and outcomes are presented in the following paragraphs.

Bicone antennas were chosen as the first antenna to evolve because they are defined by only a few geometric parameters and bicone antennas are currently used in the ARA experiment, which provides a practical baseline for measuring the success of the GA. As demonstrated in Figure 2, bicone antenna geometry can be described by the inner radius, length, and the angle of the cone. For each starting individual, these parameters are randomly generated from a Gaussian distribution (and act as the genes that are evolved in future generation. For this algorithm, the separation distance is currently a fixed value, but could be evolved in future algorithms.

In order to determine the fitness scores of each individual, the geometric parameters are input into XFdtd, which builds a model of the antenna and then calculates the antenna's gain (ratio of signal to noise). The gain is found for electric fields with 60 different frequencies over the full range of theta and phi in 15 degree increments. These gain patterns are then input into the AraSim software which determines the response of the individual to Askaryan radiation from thousands of simulated neutrinos interacting with ice in the proximity of the antenna [40,41]. AraSim outputs the effective volume of the antenna – the volume of ice that the detector is sensitive to. This effective volume becomes the fitness score of the individual after passing through a function that reduces the score if the outer diameter of the antenna is greater than the diameter of the ARA borehole used to place antenna in the ice.

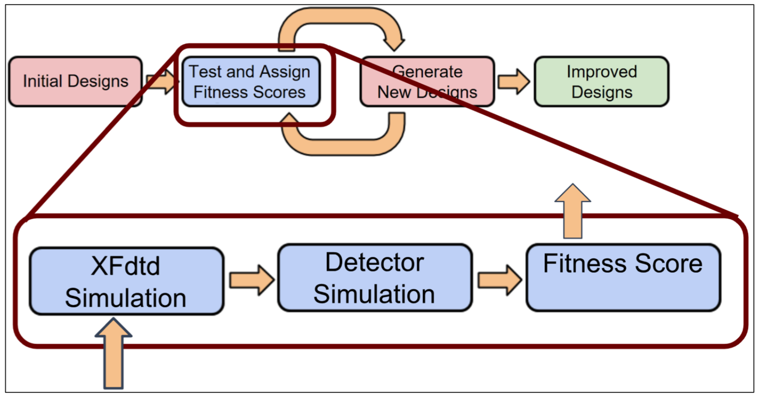

Figure 3: The antenna-evolving procedure with a detailed inset of the fitness score procedure.

Achieving a GA that uses XFdtd and AraSim is a significant programming accomplishmeraThere are over 15 independent programs need to properly run the loop using multiple different languages. A Bash script dictates the control and the order of the loop. XFdtd is designed for graphical user interactions and substantial work was required to create input files and run XFdtd from the Bash script. The XFdtd output files must then be interpreted to generate separate inputs to be read by AraSim. Finally, the AraSim outputs must be parsed for the calculation of the fitness scores. This all must be performed using a supercomputer cluster, which requires additional interfacing.

GENETIS First Light

Preliminary results demonstrating the promise of our GA for the physical evolution of bicone antennas are presented in Figures 4 and 5. Figure 4 shows the change in length, radius, and theta for each individual in each generation. The initialized values are shown in Generation 0. The effective volume and corresponding error found through the AraSim simulations is given in Figure 5. The fitness scores are shown in Figure 5, which have been adjusted from the effective volumes based on the constraint of the outer radius of the antenna. Due to the limited computational power in this exploratory phase, a limited number of individuals and generations were required. With additional funding, additional computational power could be utilized and the GA could be optimized to reduce computational load, which will provide significant improvements over the current functioning loop.

The success of this multifaceted, exploratory investigation has paved the way for expanded AI involvement in other a variety of other applications both for in-ice antenna arrays and broader

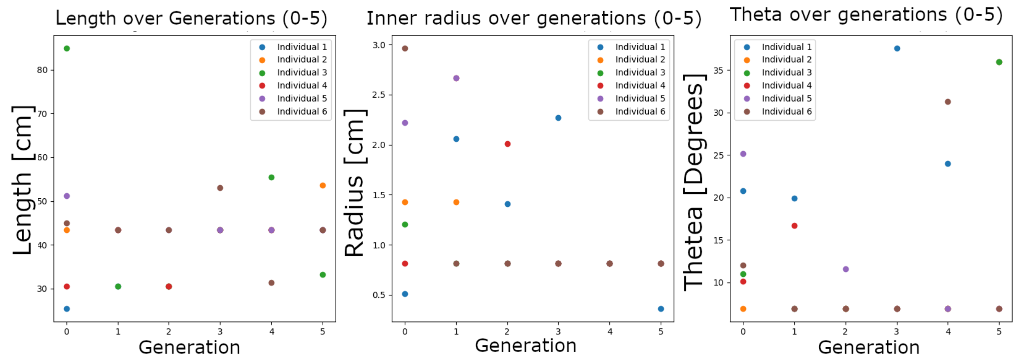

Figure 4: Plots of the length, inner radius, and opening angle of six individuals in generations 0–5.

areas of research. In the short term, we hope to expand the analysis to include a variety of antenna types and sizes that have the potential to significantly improve sensitivity of in-ice experiments.

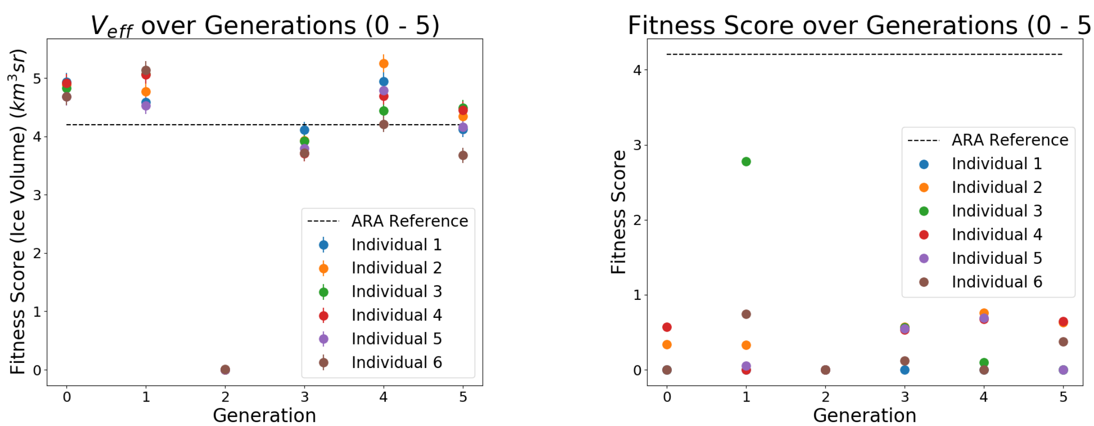

Figure 5: Effective volume and Fitness scores of six individuals in generations 0–5.

Expanding the GENETIS Genetic Algorithm

The foundation and expertise expanded by GENETIS could be utilized in other applications that benefit experiments. As one example, members of the GENETIS team developed a GA to calibrate an analog-to-digital converter used in the ANITA [42] experiment and as a secondary DAQ for experiment T576 [43], which made the first detection of radar echoes from particle cascades. The Sampling Unit for Radio Frequencies version 5 (SURFv5) is a 12-channel radio-frequency analog-to-digital converter and data acquisition system employing the LAB4D [42] digitizer.

During the experiment, the SURFv5 was inadvertently operated in an uncalibrated mode, where the sample-to-sample timing had not been calibrated to the optimal level of stablility ($\Delta t_0 \sim$5 ps), and instead drifted over the 128 sample (40 ns) window by up to 100 ps. When observing signals near the Nyquist limit (1.6 GHz) such timing errors make analysis difficult, if not impossible.

A GA was devised to calibrate the SURFv5 from T576. This algorithm, written by Suren Gourapura (then- undergraduate, now a Princeton graduate student) solves for all 128 sample-timing offsets simultaneously using 2 different fitness functions. On a single core of a modern processor, the algorithm can calibrate one channel in about 5 minutes, using a subset of background data from T576, while traditional calibration techniques can take weeks.

An example of an evolved solution is shown in Figure 6, where the raw data and calibrated data (shifted x-axis time values as found by the GA) are shown in comparison to a continuous-wave (CW) signal. The timing error drifts over the 128-sample (40 ns) interval, then resets and repeats every 40 ns, as can be seen in the 'raw' trace. The 'corrected' trace agrees equally well with the 'CW' trace before or after the red line that indicates a new cycle. This example demonstrates the potential for GENETIS to develop algorithms in a wide range of areas, including device calibration and in the case of T576, help to recover an entire dataset on which further analysis can be performed.

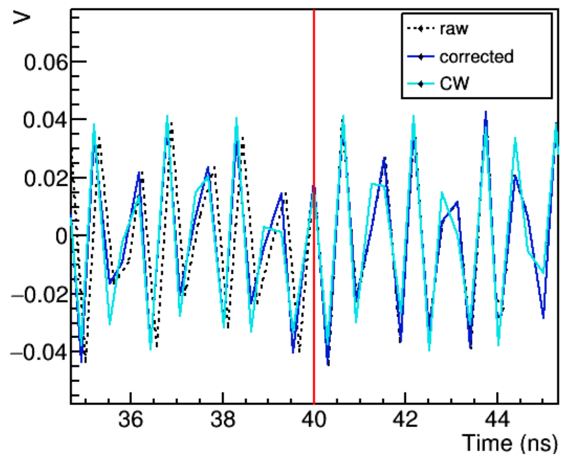

Figure 6: Digitized waveforms with time offsets calibrated with a GA designed by GENETIS.

Producing evolved antennas

Having achieved the goal of completing the GENETIS loop and obtaining initial results, we will explore the parameter space of the GA (number of generations, number of individuals per generation, and parameters of the Tournament and Crossover selections, and also expand the parameters of the antenna design itself, such allowing a curved side of the bicone, and exploring parameters in other design types, like the slotted cylinder designs for horizontally-polarized signals in ARA. These evolutions will take place throughout the Summer of 2020.

In September 2020 we will select three antenna designs that we would like to build and test. We will utilize the Center for Design and Manufacturing Excellence (CDME) at Ohio State University (OSU) to produce three of each of the three designs. CDME has an additive manufacturing laboratory capable of processing a range of materials, specializing in prototyping and medium-size production. Based on a discussion with the CDME Director of Additive Manufacturing, the antenna prototypes would be metal-plated plastic. The postdoctoral researcher would be trained in 3D printing of polymers for the base, and then we would have the antennas commercially plated

In Spring 2021, the postdoctoral researcher and a graduate and undergraduate student will perform "S11 measurements" of the reflected power for the impedence of each antenna using the anechoic chamber in Connolly's lab, and temperature cycled in our $\sim$m^2 thermal chamber. Both are part of the NSF- and CCAPP-funded CART (CCAPP Antarctic RF Test) Facility in Connolly's lab designed for prototyping and testing of RF instrumentation for (Ant)arctic experiments.

Then we will measure the beam patterns of each antenna type in the Electrosciences Laboratory (ESL) at OSU. The OSU group has utilized the same facility for similar measurements before for the EVA (ExaVolt Antenna) project [44]. Using a pair of antennas of the same type, we will transmit a broadband pulse from one antenna, from different directions, and receive by the other, measuring the received spectrum with a vector network analyzer. From these we derive the complex gains.

The one or two designs that test the most favorably will be chosen for deployment as part of

RNO-G in summer 2021. Collaborator Prof. Wissel is responsible for building and testing the HPol antennas for RNO-G. Connolly is an RNO-G Co-I and will work with Wissel to ensure that the GENETIS antennas are tested and characterized to the same degree as RNO-G antennas.

2.2.4 The GENETIS team

The GENETIS project came out of a workshop titled Computing in High-Energy AstroParticle Research (CHEAPR) on data analysis and computing in astroparticle physics.The workshop was hosted by OSU's Center for Cosmology and Astroparticle Physics (CCAPP) and co-organized by Kai Staats, a collaborator on this proposal. Researchers were connected by a dynamic range of expertise across areas of particle astrophysics and machine learning. A presentation showed the now-well-known GA-designed antenna for NASA, [27] and right then, the idea of GENETIS was born. The dynamic GENETIS team is uniquely qualified to carry out this proposed work. The collaboration was co-founded by Co-Is Amy Connolly and Carl Pfendner, and consultant Kai Staats and Stephanie Wissel, who are excited to lay the groundwork for an Institute that will make important impacts in astroparticle physics outcomes.

Prof. Amy Connolly is a Professor at OSU. Connolly has contributed to UHE neutrino experiments since 2003, and played a key role in the development of the balloon-borne ANITA experiment [45], the proposed, next generation PUEO [46], and ARA [47]. Connolly developed first-generation, detailed simulations of the experiments and currently oversees science output for both PUEO and ARA. Connolly came to the field of astroparticle physics after a PhD in particle physics that led to production of electronics for the silicon detector for CDF at Fermilab. Her dissertation was a search for Higgs decaying to tau leptons [48]. She is a member of Neutrino Physics Working Group of the DOE Office of High Energy Physics (HEP) Basic Research Needs (BRN) Study on HEP Detector Research and Development (R&D), 2019.

Connolly organized and led the discussions between members of the ARA and ARIANNA neutrino arrays to form the RNO collaboration, decide its science goals, and design the stations. Connolly has hosted four CCAPP workshops since arriving in 2010: simulations of neutrino experiments, radio data analysis across disciplines, GA, and RNO design. She initiated the formation of a simulation working group with students across the field of UHE neutrinos that has worked together now for years to develop simulation tools and deepen understanding of ice properties. Connolly regularly collaborates with theorists to to connect experimental results to scientific interpretation, as with Connolly's work in predicting and extracting neutrino-nucleon cross sections from in-ice arrays and probing new physics through those measurements.

Prof. Carl Pfendner is a Visiting Assistant Professor at Denison University, having recently transferred from a similar position at Otterbein University after completing a postdoctoral position at the OSU. Pfendner concentrates his research goals on the detection of UHE particles, in particular, UHE neutrinos. As a postdoctoral researcher working with Connolly, Pfendner's primary research topics were Askaryan-based detection of UHE neutrinos using and improvements to analysis methods and simulation of the Askaryan Radio Array. The pursuit of these projects provided him a robust working knowledge of cluster computing, analysis, and simulation design.

Pfendner worked on the proposed balloon experiment ExaVolt Antenna [44] where he used the XFdtd simulation package to model the response of a 1:20 scale prototype reflector with accuracy to within 2 dB of the measured results. He extended this experience in both XFdtd and antenna measurements into the GENETIS evolutionary antenna design program developed at OSU. With Prof. Connolly he supervised graduate and undergraduate students in its development. He is the primary developer of the AraSim package used to assess the sensitivity of detector configurations to neutrino flux models. Since leaving his postdoctoral position, he has remained involved in this project and continues to contribute his expertise in XFdtd, antennas, and AraSim.

Kai Staats, MSc is an entrepreneur and independent researcher with three decades experience in software and hardware product development, project management, and science communication. He holds a BSc in Industrial Design from Arizona State University, an MSc in Applied Mathematics from the University of Cape Town, and is a graduate of the ISU, Space Studies Program. His MSc thesis work was the first to apply EC to noise mitigation in radio astronomy, at the Square Kilometer Array, South Africa [49]. Staats was founder and CEO of the leading operating system Yellow Dog Linux, and architect of three Top500 supercomputers. His team satisfied contracts for NASA, DoD, DoE, and top-tier universities world-wide. Today, Linux users world-wide use the package manager *yum* originally developed by Staats' team.

In 2016, Staats co-hosted the CHEAPR workshop, leading discussions and hands-on exploration of EC for first-time users. He is a visiting Researcher at Northwestern University's CIERA astrophysics group for LIGO, where he has co-published research in the application of EC to the discovery of mechanical couplings [50] and a novel method for isolating supernova in LIGO data [51]. From 2017-19 Staats led a team at Arizona State University's School of Earth & Space Exploration to develop a computer model of a Moon/Mars habitat [52]. The National Geographic Society, Biosphere 2, and Arizona Science Center are slated to host the educational interface in early 2020, granting students world-wide a deeper understanding of the challenges in long-term, off-world, human habitation.

Prof. Stephanie Wissel is an Assistant Professor at the Pennsylvania State University (PSU), having recently moved from the California Polytechnic State University (Cal Poly) in San Luis Obispo. Her PhD work on the VERITAS gamma ray experiment developed a novel method for measuring the cosmic ray iron spectrum using imaging Cherenkov detectors. Now her work focuses on the radio detection of UHE neutrinos, which she started contributing to in 2012 with the ANITA experiment. Since then she has played pivotal roles in the design and deployment of several instruments relevant for the GENETIS project. Wissel has developed custom antennas for the ANITA, BEACON, GNO experiments through models developed with XFdtd and through antenna test measurements in anechoic chambers and antenna ranging. Her group at PSU is responsible for improving the horizontally polarized antennas for the RNO-G experiment as well as instrument testing. As a part of her NSF CAREER award, she oversees the full detector design for the BEACON experiment [8].

2.3 Education and Workforce Development

2.3.1 GENETIS is built by students

From its very beginning, the GENETIS project has supported and benefited from the work of undergraduate researchers and some graduate student support. This emphasis on student involvement has allowed the students to develop skills in machine learning, electrical engineering, computation and physics that make them well-placed for the workplace and academia. Student have also participated in talks on GENETIS at the American Physical Society annual meetings. The GENETIS team also presented preliminary results at the 2019 International Cosmic Ray Conference [53].

The first major steps in this antenna evolution project were performed by Jordan Potter, then-undergraduate from Kenyon College who worked at OSU in the summer of 2017, now a data scientist at Accenture. Potter developed the core of the XFdtd and bash scripts that eventually produced an optimized dipole antenna length at a given frequency as an first test. Important changes to the structure of the evolutionary loop were also developed by OSU undergraduates Hannah Hasan and David Liu, who are currently applying to top graduate programs in related fields.

Next, then-OSU undergraduate Gourapura, developed a GA to construct gain patterns with user-defined characteristics by evolving coefficients of spherical harmonic functions. This has been used as a testbed for GAs and could be used to design a fitness score to design an antennas with desired beam patterns. Gourapura and then-OSU undergraduate Thomas Sinha (now an OSU graduate student) also developed an evolution algorithm to evolve wire designs based on extensions of linear elements, what we call a “paperclip” model using a user-defined fitness score.

Evolving beam patterns

Professor Wissel supported a number of undergraduate researchers during her time at Cal Poly, a primarily undergraduate institution. Under Wissel’s supervision, undergraduate students Luke Letwin, Corey Harris, and Jacob Trevithick developed a technique for gain pattern evolution, using spherical harmonics as the basis functions for a total antenna gain pattern. These students won CalPoly’s College of Engineering Outstanding Senior Project for this work, and each has continued with success in this field: Letwin and Trevithick have obtained industry positions in RF engineering; and Harris is pursuing a graduate degree in electrical engineering. This Beam-Evolving GA evolves

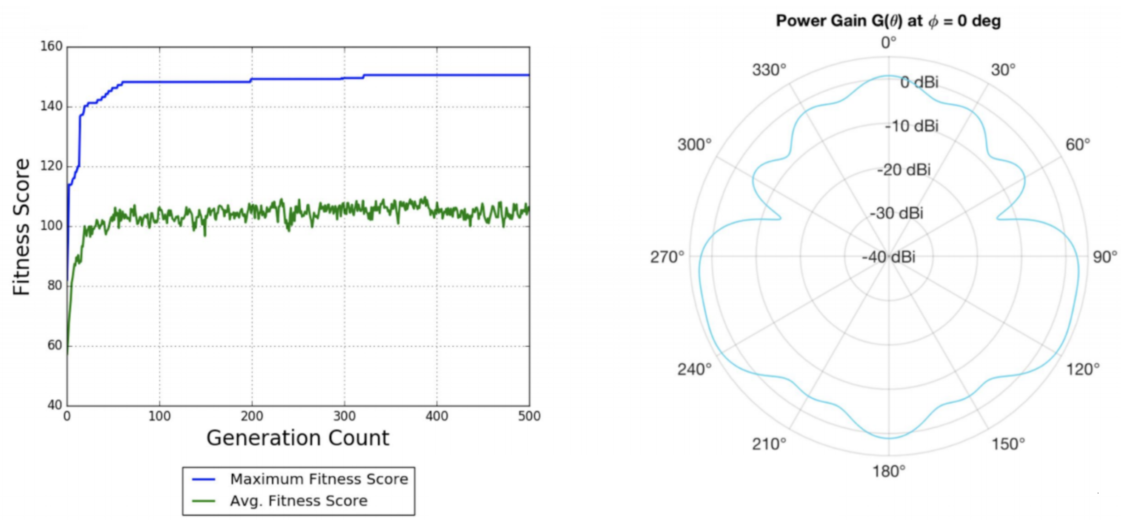

Figure 7: Results of an example beam-evolving procedure for energy 10^{18} eV over 500 generations: (Left) The change in maximum and average fitness score; note a convergence in less than 100 generations (Right) The radiation pattern with the best fitness score

RF antenna responses (or beam patterns) themselves, regardless of whether a physical antenna in a narrow hole can produce such a response. The goal of this endeavour is two-fold: 1) to identify characteristics of antenna beam patterns that would improve the sensitivity of in-ice arrays for neutrino detection and 2) to quantify potential improvements to neutrino sensitivities that are possible through improved antenna designs.

This beam-evolving algorithm represents the gain patterns as a linear sum of 13 azimuthally symmetric, spherical harmonic functions. After the initial generation is randomly generated, the next generation is created through four different selection method and operator combinations. The fitness score of each individual is evaluated using a library of AraSim radio signal outputs, known as AraSimLite, rather than the full simulation, in order to reduce run-time [40]. The process is repeated until a specified number of generations is reached. The results of an initial beam-evolving algorithm test are presented in Fig. 7. This procedure demonstrated the ability to evolve radiation patterns that matched the expected geometry of an antenna designed to detect neutrinos from a particular arrival direction. Over the two-year term of this award, undergrads, graduate students and postdoctoral researchers will be at the forefront of every step of the project:

1. Produce and deploy a new evolved antenna design in the ice as part of RNO;
2. Expand GENETIS to include other types of machine learning algorithms and to be adaptable enough to improve the scientific reach of other projects;
3. Produce an initial release of public software that will enable experiments in astroparticle physics to efficiently and effectively adapt their designs for desired physics outcomes;
4. Build and strengthen interdisciplinary connections among evolutionary biologists, antenna and electronics engineers, developers of electromagnetic simulation software, machine learning specialists, and astroparticle physics experimentalists through yearly workshops.

2.4 Management and Integration Plan

2.4.1 The Foundation of GENETIS

GENETIS is currently composed of professors and students from three universities: OSU, Denison University, and PSU. Dr. Connolly, Dr. Pfendner, and Dr. Wissel have provided the structure for the weekly engagement and mentoring of students for three years. Independent researcher Kai Staats, MSc attends weekly calls and guides the efforts of the team. He has also played an important role in guiding the regular application of meeting minutes, archiving of processes and outcomes, and documentation of code. This multi-institution, interdisciplinary and student-driven working group structure is the foundation of the current GENETIS project, which we intend to expand through this award.

Since the beginning, through the rotation of two generations of students, the project itself has evolved from one of exploration and investigation to the current effort that is producing a high-performance, pipe-line environment in which solutions can be evolved more rapidly. Through their current research and practical coding, students investigate approaches to machine learning that lead to improved performance of the simulated instrument, solutions to parallel processing of the GA itself, and documentation to guide the next generation of researchers.

This effort has been conducted with the support of Remcom, provider of XFdtd 3D electromagnetic simulation software, through regular communications. Recent updates to the XF product line has enabled support of GPUs for greatly improved performance and reduced time with each generation of evolved, candidate solutions. Further collaboration is anticipated, with the potential of further improvements to the performance of XF and the total GA pipeline.

2.4.2 Proposed Structure and Management

This award will lay the groundwork for a future GENETIS institute via the proof-of-principle demonstration of the technique and through broad-reaching workshops. The former is necessary to establish a pipeline through which other astroparticle experiments can tap into for ease of the design of instrumentation. The latter is necessary to ensure that the techniques developed reach a broad, multi-disciplinary audience. Table 1 provides a timeline for how through this award we will use the GENETIS project to 1) develop the first set of instruments designed via EC for an astroparticle physics experiment and 2) expand the pipeline to evolve instruments for use in other astroparticle physics experiments. Table 2 describes how the two lead institutions, OSU and Denison, will oversee and manage the work.

Year	Product/Outcome
1	Complete in-ice array antenna evolution with GENETIS
	Host first multi-disciplinary workshop on GAs for astroparticle instruments
	Develop evolved prototype antennas for RNO-G.
	Expand GENETIS loop to evolve antenna designs with array geometries
	Publish results of antenna evolution for in-ice arrays
2	Host second multi-disciplinary workshop
	Make public generalized GA for improving detector designs
	Publish results of expanded GENETIS loop.

Table 1: Timeline of products

This award will be jointly managed by existing GENETIS team members Connolly and Pfendner, through their respective institutions OSU and Denison University, anticipating the planned governance for the future GENETIS Institute. The plans for the Institute will be developed as a part of this award. The organizational structure both of this award and the planned Institute will reflect the form and function of the governing universities, with an advisory board composed of existing members Connolly, Pfendner, Wissel, and Staats, and two students from each represented university. The student advisors will rotate once each two years, as selected by the merit of projects under the guidance of their advisors. With full funding, a GENETIS Institute will award post-doctoral fellowships and invite an external review once per year.

Outside advisement will be welcome by researchers and professionals in the fields astroparticle physics and machine learning. These key influences will work to guide the function of the GENETIS Institute toward a) areas of greatest needs; b) projects of highest potential impact; and c) applications of machine learning tools most unique to the respective fields of study. The primary method for external review for this award will be through the Workshops described in Section 2.4.4 which will bring together a broad range of collaborators (Sec. 2.4.3) to provide guidance not only for the project goals but also for the goals of the GENETIS Institute.

Table 2: **Summary of Institutional Roles**

Activity	Sub-division	OSU	DU
Machine learning	GAs	■	
	Other types		■
Modeling	XFdtd	■	■
	Detector Sims	■	■
Antennas	Construction	■	
	Testing	■	
Evolutionary computation	Evolving	■	■
	Validating	■	
	Expanding	■	
Workshops		■	■

2.4.3 Collaborations and Interdisciplinary Connections

Through this award we will strengthen our connections with leaders in EC and build new ones. Of immediate interest are collaborations with Michigan State University's BEACON Center, the premier research center for EC in the United States. Dr. Wolfgang Banzhaf, John R. Koza chair in Genetic Programming there, is the lead author of the first textbook in genetic programming [54] and the host of the annual Genetic Programming Theory and Practice, invite-only workshops that Staats contributes to each year.

With evolution for neutrino detection as the cornerstone of GENETIS, the proposed institute will amplify our impact on instruments and techniques for astroparticle physics experiments. While the current GENETIS team has relied upon literature review, in-house experiments and trial and error, the Institute will have the capacity to leverage a far greater network of individuals and the full knowledge of other institutes. For example, Gustavo Olague from the Ensenada Center for Scientific Research and Higher Education, Mexico will bring his institute's unique approach to web interfaces and control systems for complex EC to GENETIS, helping to move the interface from the barrier of command line to a more practical, and user-friendly web interface for remote management of complex, dynamic evolutionary design runs on advanced cloud computing systems.

GENETIS brings multiple disciplines together at institutions where scientists will benefit from applying EC to astroparticle physics experiments. OSU is the home of the Center for Cosmological and AstroParticle Physics (CCAPP) and Penn State is home to the Institute for Gravitation and the Cosmos (IGC). At these places, theoretical and experimental astroparticle physicists use cosmic rays, neutrinos, photons and gravitational waves to expand our understanding of the non-thermal and transient universe. Connolly's colleagues at CCAPP work on the NSF Facilities IceCube and Auger. At PSU, Wissel's colleagues work on LIGO, Auger, IceCube, HAWC, and Helix. Staats works in close collaboration with Professor Vicky Kalogera at Northwestern where they together have been at the forefront of applying evolutionary computation to gravitational wave science. It is the intent of this proposed work to expand its reach in the funded two years to plan for the an institute that will encompass a dozen universities in North America such that the full potential of EC is realized across a wide spectrum of astroparticle physics experiments.

2.4.4 Workshops

Dr. Banzhaf of the MSU BEACON Center first introduced GENETIS co-founder Staats to the annual Genetic Programming Theory and Practice, invite-only workshops in 2016. In this intimate, hands-on learning environment, advanced practitioners in EC share research, techniques, and challenges. This direct engagement among professors and students alike is foundational to the proposed GENETIS Institute, and lead to the CHEAPR workshop in 2016.

Through two new workshops GENETIS will build collaborations among an interdisciplinary group of scientists – physicists, engineers, computational scientists, biologists, among others – interested in using and developing GA to enhance detector design. Each day will begin with a plenary talk given by an expert in either astroparticle physics or EC, followed by a discussion and a hands-on working session, building on the success of the original CHEAPR workshop. The workshops will last three days, ample for discussion of the challenges facing astroparticle physics detectors, the promise of new computational techniques, and how to implement solutions. The workshops will be organized by the project postdoctoral researcher as an important opportunity to make multidisciplinary connections.

The first workshop will be held at OSU and will bring together astroparticle physicists from CCAPP and computational scientists, evolutionary biologists, geophysicists, and engineers from OSU and other institutions around the country. OSU is equipped with a variety of institutions and laboratories to support these workshops. The Center for Design and Manufacturing Excellence (CDME) is a premier facility for additive manufacturing. CDME's Additive Director, Ed Herderick is excited about GENETIS, calling it "a unique application to additive manufacturing" and offered to speak at a workshop. Connolly's group stays connected with the Byrd Polar and Climate Research Center, a prominent center focused on polar experiments and climate change, as a natural contributor. The Ohio Supercomputing Center has often supported CCAPP workshops, responding to questions on efficient use of available resources.

The second workshop will be held at PSU as a way to engage not only scientists from more astroparticle experiments like Auger, HAWC, and IceCube, but to bring in experts in antenna design and RF engineering from PSU, the Advanced Research Lab, and Remcom, the manufacturer of XFdtd. For example, as an expert in antenna engineering, radio network design, and remote sensing, Gregory Huff at PSU can contribute to the workshops by discussing how best to test the designs produced through the GENETIS pipeline. PSU also hosts the CyberLamp facility, a compute cluster funded through the NSF-MRI program emphasizing the use of GPUs for scientific applications, in particular astroparticle searches and gravitational wave searches. OSU and PSU are in the heart of the Midwest and Mid-Atlantic, making them ideal locations for these workshops.

2.4.5 Public release of software

The GENETIS collaboration will prepare and maintain a public release of the full suite of machine learning tools under an open source license such that any educational institution may download, use, modify, and benefit from the experience. The code, example data, and documentation will be made available from GitHub or an equivalent delivery platform.

3 Results from Prior NSF Support

Connolly at OSU is currently the PI of an NSF grant titled "Leveraging Novel Complementary Variables to Boost the Sensitivity of Ultra-High Energy Neutrino Experiments," a $503,686, award from 07/01/2018 - 06/30/2021, award number 1806923.

Intellectual Merit: Under this award, Connolly's group is developing new techniques in analysis, simulations and instrumentation to lower thresholds for UHE neutrino experiments, including ARA. Under this grant an algorithm for filtering continuous-wave interference developed for a different experiment has been incorporated into the ARA two-station diffuse search just completed [55].

Broader Impacts: Connolly's group is strengthened by contributions from high school and undergraduate researchers. Connolly's group initiated and runs an biannual workshop called ASPIRE for high school women, served on the DAP Executive Committee for APS, and serves on the DOE Basic Research Needs Neutrino Working Group.

4 Broader Impacts

Undergraduate research, including female students and underrepresented groups, has been and continue to be the foundation of the GENETIS project. This award will also allow us to augment an existing outreach project led by the Connolly group with an exciting new AI-based project.

4.1 Improving the Gender Imbalance in Physics

In 2013, Connolly initiated an NSF-funded workshop "Achieving in Science through Physics Instrumentation, Research and Exploration" (ASPIRE) (u.osu.edu/aspire) aimed at giving high school women hands-on experience with instrumentation and analysis used in physics research. This grant award will augment ASPIRE with new AI-based projects that give the participants experience in designing and running GAs, and the ability to construct and take home their own designs. This workshop has been extremely successful, with five-day workshops with up to 30 students participating for little to no cost. Graduate students in Connolly's group have developed projects related to their research that teach the participants important hands-on research skills. Students have learned how to perform interferometric calculations in Mathematica, program microcontrollers, operate oscilloscopes, and give scientific talks. Students are exposed to a variety of physics topics, touring OSU research labs, the Byrd Polar Research Center, and the OSU planetarium. ASPIRE hosts outside speakers, including a regular speaker from Evolutionary Biology on OSU's campus.

This new ASPIRE project will be one day of the week-long workshop, led by an OSU graduate student and post-doctoral researcher. The students will develop a wire antenna, much like the first GA antenna design designed by NASA [27]. For example, this program led to the curled shape illustrated in Fig. 8. The students will learn about GAs, experiment with selection methods, operators, the number of individuals and generations, and print their design using additive manufacturing. On the last day, students are given the opportunity to return to a favorite project, present to their parents, and tour OSU's Center for Design and Manufacturing Excellence and its additive manufacturing laboratory.

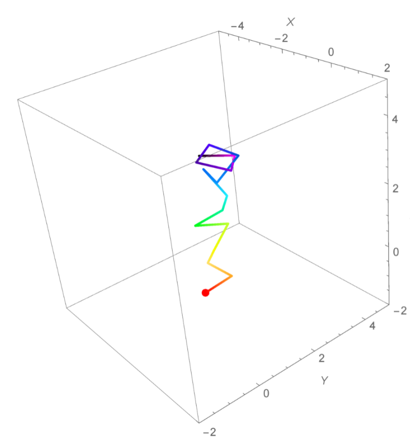

Figure 8: Example of a partially evolved segmented wire antenna. Note the general counterclockwise spiral.

The participants are surveyed at the conclusion of each workshop to evaluate how to improve the projects. The feedback is overwhelmingly positive, with many saying they did not expect to enjoy science. ASPIRE builds upon the earliest GENETIS work at OSU where undergraduate students successfully developed an algorithm for evolving wire antennas to a variety of shapes.

4.2 Empowering High School and Undergraduate Students to be Key Contributors to UHE Neutrino Research

A significant portion of the current GENETIS achievements have been as result of the work of undergraduate students as described in Section 2.3.1. Connolly is dedicated to educating and working with a diverse range of students at all levels. This commitment is evident in the wide range of high school and undergraduate students that have contributed to GENETIS. The ASPIRE workshops have led to involvement in GENETIS from high school female students. Through a high school mentorship program, two students worked with the GENETIS team developing a deeper understanding of GAs and programming. One of these students, Evelyn Shank received the 4-year Valentino Scholarship from OSU and is now a Physics undergraduate student that has continued to contribute to this project. As ASPIRE continues to grow, Connolly is working to develop a program that connects ASPIRE students with research advisors to continue their involvement with physics research.