Professional Evaluation and Growth Plan

Jordan C Hanson, PhD

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Contents

Chapter 1

Introduction

1.1 Beginning

Friends,

I have compiled a report on my progress as a liberal arts educator in the Department of Physics and Astronomy for the period of 2019 through 2021. The following is a reflection on the development of my educational and scholarly practices, and the service I have performed for the College as a mentor, advisor, and committee member. I strive to perfect my teaching abilities, and I am pleased to report that my students are learning and growing. In our last communication, after my supplemental PEGP from 2019, you concurred that my practices are serving the students well, and that meant a great deal to me. One note that stood out was a request to enrich my teaching philosphy by reflecting on how it serves the liberal arts. The given example was about the utility of physics to non-STEM students. I have put a lot of thought into this enrichment, I have progress to share with you.

I have included in my teaching philosphy (Sec. 2.1) my vision for the intersection of broader liberal arts education with physics, mathematics, computer science, and engineering, as I teach all of these. Further, I have created and taught new liberal arts courses in the *Connections 2* and *Culture 3* categories, as well as a College Writing Seminar on scientific and technical writing. I used these courses to show my students how physics, mathematics, and engineering intersect with the history of our ancestors and how we all use scientific modes of thought to thrive. In my College Writing Seminar, we sharpened the skills of conciseness, precision and clarity, and organization in writing. Though these skills apply to physics, they are useful in all writing in which abstract or difficult ideas are communicated.

At a PEGP workshop, a colleague emphasized weaving a narrative about who we are. I have shared my academic origins, and my vision for multi-disciplinary teaching and scholarship at Whittier College (Sec. 1.1.1). I have also written about my family and working during the pandemic (Sec. 1.1.2). I hope these sections provide you with helpful insight about our family and how we hope to serve Whittier College. We thank the FPC in advance for what is sure to be a difficult year of service. We also express our gratitude for allowing us to postpone the PEGP for one year. This helped my family avoid a difficult situation. My spouse is considered an essential worker, and was called back after a shortened maternity leave. I have been working as a full-time professor and a full-time parent *by myself* each day since that happened. Thankfully, my *suegra* (mother-in-law) has stepped in to help. I look forward to seeing you this Fall, and from our family to yours, we hope you are well.

Sincerely, Prof. Jordan C. Hanson

1.1.1 Academic Origins

We all share a common theme as professors, in that we encounter ideas that inspire us in college and graduate school. When I was an undergraduate at Yale University, my family was nudging me towards engineering. My curiousity, however, kept returning me to physics courses. In my heart, I knew that I wanted to offer fresh discoveries about the Universe to people, and I fell in love with enlightening others. I learned that the laws of physics morph and merge into one another as the energy of matter increases to relativistic scales where particles move near the speed of light. I also learned that deep from within the Universe originates a mysterious flux of sub-atomic particles ten thousand times more energetic than any human has ever created: *the cosmic rays*. The physics that explains their origin has remained unknown for a over a century, and it could reveal new fundamental laws of Nature. I applied for graduate school in the hopes of one day becoming a professor of physics.

The University of California at Irvine (UCI) is a pioneering institution in the field of cosmic-ray research. In particular, my colleagues at UCI began focusing on the study of cosmic ray *neutrinos*, also known as ultra-high energy neutrinos (UHE-ν), beginning with the Radio Ice Cherenkov Experiment (RICE) [1] and Antartic Impulsive Transient Antenna (ANITA) [2] collaborations. Neutrinos do not have electric charge, while cosmic rays do. Thus, neutrinos propagate in straight lines through the Universe, while any electromagnetic field would bend the trajectory of cosmic rays. Thus, UHE-ν could reveal the locations of the cosmic ray accelerators, thereby teaching us about fundamental physics unexplored on Earth [3] [4]. UHE-ν observations would, for example, provide insight into quantum mechanics at record-breaking energies [5].

Detection of UHE-ν has been a goal of the physics community for three decades. When UHE-ν have energies above a certain threshold, they create cascades of particles in matter that radiate in the radio-frequency (RF) bandwidth, a process known as the Askaryan effect [6] [7] [8] [9] [10]. The IceCube Collaboration published the observations of extra-solar neutrinos using optical techniques at record-breaking energies [11], and later showed that the flux is strikingly close to theoretical predictions [12] [13]. IceCube analyses have not found UHE-ν events, however, with energy greater than 10^{15} electron-volts [14]. It is above this energy that the UHE-ν could one day reveal the source of cosmic rays and new physics. The authors of [14] conclude that Askaryan-class detectors are the logical next step. My colleagues have decided to upgrade IceCube to include RF detectors in a project known as IceCube Generation 2, or IceCube Gen2 (`https://icecube.wisc.edu/`).

Askaryan-class detectors improve UHE-ν prospects because Askaryan radiation is in the RF bandwidth [15]. UHE-ν must strike some material in the Earth's crust that produces an observable radio pulse. It turns out that radio waves travel ≈ 1 km in *Antarctic ice* [16] [17] [18]. Thus, we can create stations comprised of RF antenna channels, supporting electronics, and solar panels [19], separated by 1 km to cover enormous volumes of ice. This is important because the expected UHE-ν flux is low. When a potential signal arrives, stations are triggered to read out the RF channel data [20]. The overall dataset is then comprised of RF waveforms representing signals from all the stations. The data will be used to reconstruct UHE-ν interactions [21] [22]. This type of detector is called an *in-situ* array. As a graduate student at UCI, I led two Antarctic expeditions to create a prototype *in-situ* array: the Antarctic Ross Ice Shelf Antenna Neutrino Array (ARIANNA).

We would leave Los Angeles International airport, and land in Auckland, New Zealand. After collecting our gear, we transferred to the local airline to fly to Christchurch, on the southern island of New Zealand. Usually there would be a week of down time in a bed and breakfast, while we waited for the weather in the Southern Ocean to clear. We would equip our cold weather gear, tinker with our equipment, and read. At the right moment, we filed on to an Army C-17 cargo plane that had both wheels and skiis for landing gear. After a five-hour flight, we would land on the frozen ocean near Ross Island, not far from the berth of the original Antarctic explorers. A truck brought us in to McMurdo Station, the home of the United States Antarctic Program (USAP). There we would receive safety training and logistics to prepare for our expedition into the field. A helicopter would transport us to ARIANNA. Our gear, which arrived by boat in New Zealand, and then by plane to McMurdo, followed us in a separate helicopter.

We began by measuring the ice shelf thickness and radio transparency in Moore's Bay, Ross Ice Shelf, Antactica [23]. We deployed prototype ARIANNA stations in two separate missions. I designed systems that managed station power consumption and recorded environmental data [19] [24]. We demonstrated with computer simulations that a 30 x 30 array would reach target UHE-ν sensitivity. Further, the sensitivity doubled in Moore's Bay through *reflected* events, in which signals reflect from the ocean beneath the ice shelf. We completed the seven-station prototype array, and published upper limits on the UHE-ν flux [25]. We also observed cosmic rays [26] (though we cannot determine their original direction), and completed a second UHE-ν search [27]. UHE-ν

interact more rarely in dense matter, and thus the visible flux is lower than that of cosmic rays. With much larger number of stations in IceCube Gen2, we hope to capture the precious UHE-ν signals.

As a post-doctoral fellow at the University of Kansas, I published the first complete analysis of the ice in Moore's Bay [16]. This research was an intersection of glaciology and physics, for we need to understand our detector and our detector is an ice shelf. I also published the first complete calibration of the ARIANNA RF chain [28]. Using the results, we showed simulations of our detector accurately modeled Askaryan signal strength. We created UHE-ν signal *template waveforms* that account for both the theoretical Askaryan signal and the aforementioned calibration. These templates now serve as the primary UHE-ν search criterion when cross-correlated with data collected in Antarctica [25] [27]. As a CCAPP Fellow at The Ohio State University[1], I improved upon the templates by developing a new analytic theory of Askaryan pulses [15].

Once I joined Whittier College, I turned my attention to the complex path taken by Askaryan pulses through Antarctic ice. The path is curved because the speed depends on the ice density, which changes with depth. An undergraduate student and I worked out solutions for the ray-path of the signals through ice given the density profile [29]. These calculations became a central component of our current software that we use to predict detector sensitivity to UHE-ν [30] [31]. Meanwhile, another student and I designed firmware upgrades to auto-calibrate the RF channel thresholds and presented the results at SCCUR, twice [32] [33]. These tools facilitate expansion and automation of our detector. The pandemic has prevented deployment of these upgrades in ARIANNA, but they will be incorporated in IceCube Gen2. For both projects, I included undergraduate students. The first was a young lady who went on to become a physics researcher for the LIGO project (gravity waves). The second was a student of color and Whittier native who majored in ICS/Math, and who is applying to graduate schools for engineering and machine learning.

I recently returned to the theory of Askaryan radiation, and have begun to study computational electromagnetism (CEM). For the first time, I have created an analytic time-domain model of Askaryan radiation [34]. We are happy to report that the work will be published in Physical Review D, and that it will be incorporated into IceCube Gen2 software. This achievement was made possible by a collaboration with a wonderful undergraduate student who has become a good friend over the past two years amid the pandemic. I describe the importance of this result in Sec. 3. Regarding CEM, I have won two Summer Faculty Research Fellowships with the Office of Naval Research (ONR), in which we apply CEM to radar design. This is an example of the liberal arts mindset in action: I was able to identify a connection between two seemingly unconnected fields, and form a mutually beneficial partnership.

Using CEM, my student and I have created a 3D printed radar design [35]. Knowing that Whittier College cannot afford to subscribe to every IEEE engineering journal, I selected an open-access journal named Electronics Journal so that our students have access to the research. I view choices like these as part of our mission to foster equity and inclusion. Our paper won Top 10 Most Notable Papers in the Electronics Journal for 2020-21 (see Sec. 3). Recently, my colleagues at the naval laboratory fabricated the 3D printed design, and they have provided powerful lab equipment to Whittier College for testing it. It is worth mentioning that this equipment is prohibitively expensive, and thus our partnership with my naval colleagues is opening new doors scientifically. If we succeed, this research has applications to UHE-ν physics (by creating new and better antennas), 5G communication, and radar applications. I describe in Sec. 3 my vision for a partnership with the Navy, and how this will benefit our students.

Finally, I would like to share with you my recent venture into the Whittier Scholars Program (WSP). A student heard of my scholarship regarding Antarctica, and sat down in my office one afternoon. He showed me photographs of glaciers he had taken while visiting family in Norway, and said that he'd like to perform a comparative photographic analysis with historical photos of glaciers all over the world, in order to assess the loss of ice due to global warming. We lept into a partnership that sent him to Norway, Iceland, Alaska, and the National Outdoor Leadership School (NOLS). He began by taking one of my new *Connections 2* courses about the history and current status of science in Antarctica. The research was at the intersection of glaciology, physics, climate science, and environmental social justice.

The work came together as my student gained experience living in the field. I did everything in my power to add him to one of my Antarctic expeditions. Alas, that particular mission was cancelled due to budget cuts and the pandemic. We had hoped to include photos of the glaciers near ARIANNA. These are the same glaciers passed by

[1] Center for Cosmology and Astro-Particle Physics

Robert Falcon Scott and Roald Amundsen as they raced for the discovery of the South Pole. I have been there twice and taken photos, but there were no similar photos to which we could compare. I helpd my student gain admission to the WSP, and our final project gave a holistic view of the environmental, agricultural, and cultural impact of glaciers around the world. My student, who graduated this Spring, told me that he is beginning a book with colleagues he met in Iceland, and that this book will feature our work. I enjoyed the project so much I have decided to help support WSP by serving on the WSP Advisory Board. My offer was accepted and I will begin this semester. Thus, I have come full circle regarding the FPC invitation to serve in the liberal arts. I will share more on this in Sec. 5.

1.1.2 My Family, East Los Angeles, and COVID-19

When I first came to Whittier, I lived down the street on Bright Avenue. I had met a wonderful young woman and we fell in love. In the summer of 2019 we married, and I moved to East Los Angeles to live with her family. My wife's family is quite extraordinary. Her family is originally from Jalisco, Mexico. The family immigrated to Los Angeles, and dealt with gangs and poverty where they originally lived. My wife and all six of her siblings worked hard in school and went to college. We strongly value higher education in our family. My wife and I share our Catholic faith, and we care about our children's education.

Even before I met my spouse, I knew that becoming fluent in Spanish would be helpful living in Whittier. I already spoke a little, and in my first year joining the Whittier community I decided to formalize my Spanish skill by taking Spanish 120. Prof. Doreen O'Conner-Gómez was kind enough to let me audit her course that Fall. She remarked that this was the first time she had seen a STEM professor audit a language course. It turned out to be wonderfully necessary in my family, because our older generation usually does not speak English at home. Our family as a whole is highly diverse, with Mexican, Romanian, American, and Filipino roots. Given the dark and divisive trends that have arisen within our broader culture, and as a Christian and someone who considers himself a loving person, I felt a genuine desire to share this with you.

In my first years as part of the Whittier community, I recognized the same diversity in the families of my students. Many of our students speak Spanish at home with their parents, but English at school. There have been times when I have helped the mother or guardian of a student navigate campus by speaking Spanish, and it has made them more comfortable. As part of a statistics course I taught for the Whittier Summer Session II (2020), I was gathering data from the Whittier College Factbook. It reveals two important numbers about our students. About seventy percent of our students are students of color, and about forty percent are first-generation. My spouse and every single one of her siblings are all first-generation students. Back when we were teaching in person, sometimes colleagues would explain to me over lunch about "the first-generation experience," assuming that the white male physicist was new to the concept. I would always smile inwardly, since my entire family has shared this experience with me.

Given these experiences, I am keenly aware of the importance of our curricular theme of *belonging.* Despite the challenges brought upon Whittier by the pandemic, I have put effort into making that theme a reality. I socialize on Zoom with my first-year advisees and research students in order to make them all feel that they belong. I ensure that I account for equity and inclusion in each decision I make. One stark example was when a student in my section of INTD100 connected to class via Zoom *while at work in CostCo.* I learned to arrange my schedule to account for students' jobs, knowing that many were supporting themselves and loved ones. Being inflexible would have made class accessible only for the wealthy students. Regarding belonging, I am often reminded of a basic fact: *even though my heritage is different from my family and my community, they have accepted me as one of their own.* In the Gospels, we find the Golden Rule to treat others as we would like to be treated. I am called therefore to ensure the students feel that they belong.

Inspiration for New Courses

Inspired by my family, and the theme of belonging, I have created two new courses that serve our current liberal arts curriculum. One is entitled *A History of Science in Latin America,* which was assigned a *Culture 3* and *Connections 2* designation. I could tell there was a hunger for this course. Our students needed to see that *all* of our ancestors performed science. One aspect of that course was the ideas of *central* and *peripheral* scientific communities. Taking STEM courses alone might lead a student to believe that European and American cities have been central to scientific progress, and that Latin American communities have been *peripheral.* Peripheral, in this sense, refers to a community that merely adopts discoveries from the central ones and rarely produces progress. By honestly covering the colonial period in Latin America, we found examples in which Latin American communities were *central* and their European counterparts were *peripheral.* A more accurate description of scientific progress for Latin America and Europe would be a full two-way exchange of knowledge (Sec. 2). I invited colleagues from the Wardman Library to introduce my students to digital storytelling. The students used this skill to create final projects that wove together their cultural heritage, history, mathematics, and scientific discovery.

The second liberal arts course I have created was inspired by the theme of belonging, and my research. It is called *Safe Return Doubtful: History and Current Status of Modern Science in Antarctica.* At first glance, the connection between themes like inclusion and belonging and Antarctica is not obvious. This course is a metaphor for self-exploration. We address three main areas, interwoven throughout the semester. First, we address the history of the race to discover the South Pole in the early 20th century. Second, we cover current scientific endeavors in Antarctica. Third, we perform weekly journal activities that invite the students to look inside themselves and to discover their potential for exploration. The connection to inclusion and belonging emerges as we learn that the winner of the race for the South Pole was a person who took indigenous science seriously. This was the same captain who completed the Northwest Passage, before trying the South Pole. In Northern Canada, the explorers encountered the *Netsilik* people. The European explorers observed how the Netsilik *used physics and engineering strategies* to travel through the harsh environment, rather than assuming their technology was better. These strategies were adapted to the Ross Ice Shelf, and *that group won the race for the South Pole.* Thus the course connects inclusion and belonging to survival and exploration. The students learn through history, science, and self-reflection that their survival in new areas of life will be enhanced if they are able to include knowledge earned by those *indigenous* to that area.

Keeping a Sense of Humor under Quarantine

My fellow tenure-track colleagues and I sometimes discuss if it's appropriate to add a "COVID-19 Impact Statement" to our PEGP. At first I thought, no, just stick to the important, serious stuff. But I also thought it would be a laugh. So here goes. For those with a sense of humor, this next section is for you.

For those without a sense of humor, I have to ask, like, how are you still here? After we duct-taped together a way to teach our students online in spring 2020, we watched the world lose its freaking mind that summer[2]. Then, the module system, for *a year.* But hooray! The vaccines arrived. Funny thing about vaccines, though, is that you have to go *get them.* Ugh, who has time, right? Seriously, a few people in my family flatly refuse. Here's a fun exercise: try teaching a science course on Zoom and hearing your phone buzzing from an argument about how *the scientists are wrong* in Spanish. Focus, focus ... *just get the blasted shot already* ... "Ok students, let's talk about ... friction! Am I right?" Ay yay yay.

Teaching students remotely was like watching those YouTube channels where people crash into stuff. What I mean is, students would log in to class while driving. Had to make a rule against that. Everyone survived, but ... wow. I thought one of my students was driving on the wrong side of the road while Zooming, but it's ok, he was in India. Another rule I had to make for class: wear clothes. I don't wanna see that. This is a family establishment. After 2.1 seconds of research, I found the Zoom button to have the camera off by default.

My spouse always says that she has the worst luck. I always reassure her: "Have faith honey. We'll be alright." After years of searching, we find each other, marry, and then BAM. Pandemic. Whoops. Our daughter was born right in the exact middle (like, literally within the error of the mean) of the first wave of COVID-19. Whyyyy. The nurses weren't going to let me in the hospital. For the birth of my child. What. Actually they weren't really that keen on letting my wife in either. *Just hang out in the parking garage*, they told my wife, *who was in labor.* After the required amount of suffering took place, they let us come inside to give birth.

Sometimes I had to fight for my students. We made sure to purchase enough bandwidth from Spectrum, but sometimes it still felt choppy. After running some checks, I realized a need to call Spectrum. They told me, "What do you expect? It's slow all over the city." I got all idealistic: "This is about access to education! For first-generation students no less! Let's get it fixed." They finally sent a techician, who came to our door holding small metal piece. "Did you know there was a 3 dB attenuator in your coaxial line?" I half-choked on my coffee. I knew that the ONLY JOB of this component is to cut signal power by a factor of two. Whyyyyy. So the man removed the Education Blocking Device, and the signal was greatly improved.

[2]After watching *I Am Not Your Negro*, directed by Raoul Peck, and reading *Notes of a Native Son* by James Baldwin, maybe it's more apt to say that we should have lost our minds sooner. I ended up making a chapter of Notes of A Native Son the summer reading assignment for my College Writing Seminar.

Working from home during summer 2020 did make it easier to care for our daughter. We were quarantined, but I managed to convince the ONR that we could perform the research project remotely. My spouse is a dentist, and the state provided maternity leave. For added spice, they took it away, though, after 12 weeks. Right at the beginning of Fall semester. No vaccines were available yet, so I had to just teach and parent alone. The upside is that I got to spend more time with the baby. My spouse bravely went back to work to help pay her student loans. She treats patients who are supposed to test negative for COVID-19, but the positives sneak past the guard. So basically The Hunger Games for dentists, who tend to be around a lot of, you know, mouths and throats.

Here's another fun exercise: try teaching college-level physics with a six-month-old pooping in your lap. Keep composure. Another one: the baby is napping in her seat, and all is quiet and ready for class. My chihuahua looks at me like he wants to bark at the dogs outside. *Don't you do it, Lobo! I swear...* Does it anyways. So I trained him not to bark, but my neighbors responded by buying a rooster. They. Bought. A. Rooster. In the city. Not chickens! Chickens I would understand for the eggs. We love eggs. Fun fact about cities: they sell alarm clocks. Quirky thing about roosters: they don't have a snooze. This particular rooster sucked though because he made the dog bark which woke the baby during class, and not you know, when the sun came up. Bad rooster.

Joking aside, my students were wonderfully accepting of my child being there. The same is true for my colleagues in committee meetings. I like to think she brightened people's day a little. A female research colleague from another institution who gave birth recently lamented to me that it has been *so hard* lately, for she and her husband (both physicists working from home) hadn't had child care in *six whole weeks!* I died a little inside. It had been almost a year for me flying solo. Once we all got vaccinated, my *suegra* (mother-in-law) who lives next door, started to come each day to help. Que santa, no? (What a saint, no?). My family has supported us, and we are so grateful. My parents, who live in Oklahoma, are sore that they haven't been able to see the baby more, but airports are full of La Rona.

I hope you are all safe and sound. It turns out that some people in my extended family in the Midwest were not so lucky. My cousin's husband, who was a well-loved football coach and mentor to many junior college students, already needed a lung transplant before COVID-19 arrived. He finally got the lung transplant three years ago and recovered beautifully. And then someone gave him the virus, and he's gone now, along with his father. We pray for them each night now. If any of you have lost loved ones, we will pray for them as well. I've had students miss class to go to funerals. Even though we have all suffered, and perhaps lost loved ones, I still believe it's important to keep a smile on. We are still here, and Whittier College needs us. Soon the students will return, and Whittier College will grow and thrive.

Chapter 2

Teaching

2.1 Teaching Philosophy: A Philosophy of Growth

A

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B

2.2 Addressing Equity and Inclusion

A

2.2.1 Open Educational Resources (OER)

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C (10to8) (Take-home tests) (Flexibility) (Arranging assessment schedule) (Take-home final projects)

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2.3.2 Traditional Teaching Modules

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A

Elec

B

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A

Elec

B

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A

Elec

B

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A

Elec

B

2.12 Outlook

A

Elec

B

Chapter 3

Scholarship

Whittier College faculty classify scholarship using the *Boyer* model [36]. My scholarship primarily falls within two categories: the scholarship of discovery, and the scholarship of application. I utilize physics education research (PER) in my teaching practices. When I tried my hand at advising a Whittier Scholars Program major, I found myself performing the scholarship of integration (see Sec. 4). In the following sections I reflect upon my scholarly work, and share my vision for the future. In Sec. 3.1, I describe my research field, giving it proper historical context. In Sec. 3.2, I share exciting news regarding my research and Whittier College. In Sec. 3.3, I organize my scholarship of discovery into five categories and list progress made by my students and I. I also draw a connection to my teaching and advising practices in each category, since they are interconnected. In Sec. 3.4, I describe my new venture into the scholarship of application. This has been a fruitful partnership with the Office of Naval Research (ONR). Finally, in Sec. 3.5, I propose an idea that for a partnership program has been shared with me by my colleagues at the ONR.

3.1 IceCube, Cosmic Rays, and Neutrinos from Deep Space

Cosmic rays are high-energy protons, electrons, and nuclei propagating through space near the speed of light. They carry information from other regions in the galaxy, and in some case, other galaxies. Since the discovery of extremely energetic cosmic rays more than a half century ago, the elusive quest to uncover the sources of these enigmatic particles has provided many challenges. Despite progress in experimental capabilities and theoretical insight, we do not yet know the acceleration mechanism for those particles with energies that have been measured in excess of 10^{20} electron-volts [37]. Being electrically charged, the paths of cosmic rays are curved by galactic and intergalactic magnetic fields. By the time the cosmic ray arrives at Earth, the arrival direction no longer points back to their origin. In addition, interactions with cosmic microwave background photons prevent ultra-high energy cosmic rays from propagating to the Earth, unless the sources are in our local galactic cluster [38] [39].

Neutrino astronomy offers a new and powerful tool to provide insight into the physics associated with the acceleration process, and complements and extends measurements not accessible through the observation of other *messengers*: cosmic-rays, gamma-rays, and optical photons. Charged cosmic rays which interact with gas, dust, or radiation near an accelerating object produce gamma-rays and high-energy neutrinos. These neutrinos are called *astrophysical* neutrinos. Whereas gamma-rays can be absorbed in dense environments, astrophysical neutrinos can escape and travel unimpeded to a detector ([3] and references therein). Neutrinos travel at the speed of light in straight lines, undeflected by magnetic fields. This allows for identification of sources, as well as the potential for finding sources that emit both neutrinos and gravitational waves, which also travel in straight lines [40].

The most energetic cosmic rays which do escape their source can interact with the cosmic microwave background en route to the Earth, generating cosmogenic neutrinos with a characteristic energy distribution peaking at 10^{18} electron-volts [41] [42]. The distance over which these neutrinos could physically propagate given the distribution of cosmic microwave background photons is larger than the known Universe. So despite the distance limitations of cosmic rays, neutrinos offer a window into regions of the Universe *far beyond anything possible* with other messengers.

The flux of neutrinos originating from outside the solar system with energies between 10^{13} and 10^{15} electron-volts has been measured by the IceCube collaboration [11]. Previous analyses have shown that the discovery of

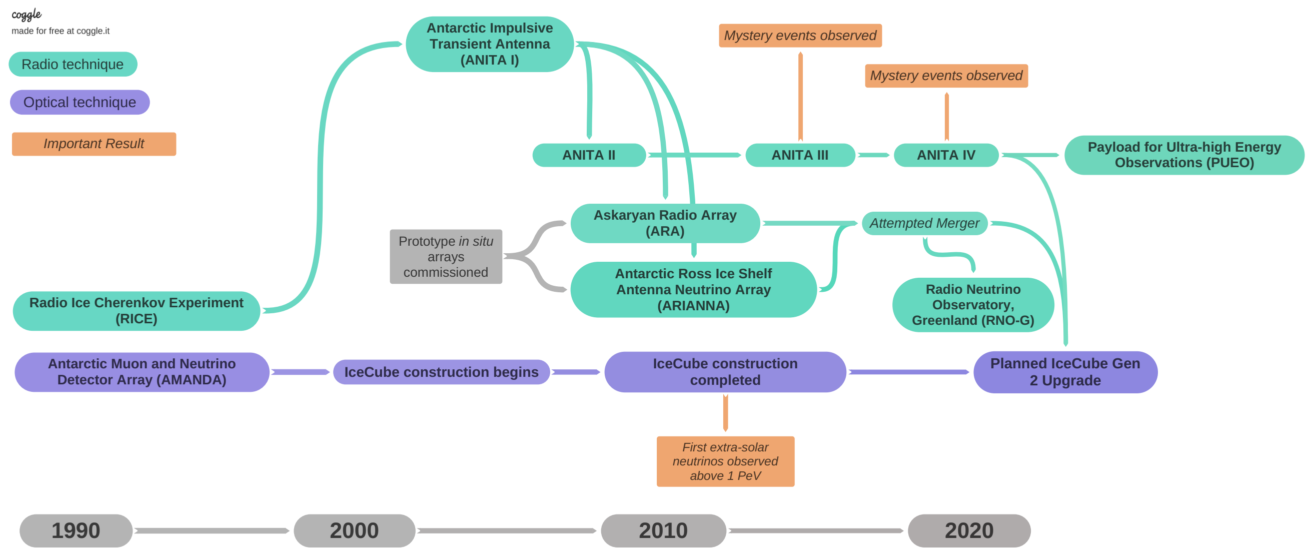

Figure 3.1: A general timeline of the UHE-ν sub-field of physics.

ultra-high energy neutrinos (UHE-ν, energy greater than 10^{15} electron-volts) will require an upgraded detector design with a larger effective volume because the flux is expected to decrease with energy [14]. Neutrinos with energies above 10^{15} are the ones that could potentially explain the origin of cosmic rays, and provide the chance to study quantum mechanical interactions at record-breaking energies when the UHE-ν interact in our detector [3] [4].

3.1.1 Why Antarctica?

Utilizing the *Askaryan effect*, in which UHE-ν creates a radio-frequency pulse, greatly expands the effective volume of UHE-ν detector designs. This effect is important for UHE-ν detection, because radio pulses travel more than 1 kilometer in Antarctic and Greenlandic ice [16] [17] [43] [44]. That means stations can be placed 1 km apart, and the volume of the overall array of stations is large enough to capture UHE-ν. The large volume is necessary for two reasons. First, cosmic rays and neutrinos at these energies are rare enough that a 10×10 km^2 target is necessary. Second, neutrinos do not always interact in dense matter quantum mechanically, unlike protons or heavy ions that always smash into some nucleus. To ensure that we catch the signals from the UHE-ν that do interact, we must construct a large detector. A third reason that attracted my field to Antarctica is that Antarctica is a well-organized open playground for cutting-edge science. This is a topic that I cover in one of my new *Connections 2* courses: *Safe Return Doubtful: History and Current Status of Modern Science in Antarctica.*

3.1.2 Radio Expansions: IceCube Generation 2

In Sec. 1.1.1, I reflected on my academic origin story and the contributions I have made to the field. The plot of that story has taken an interesting and favorable turn for Whittier College. Not only has the IceCube Collaboration finally recognized the necessity of radio-based detectors [14], but IceCube Gen2 designs now include specific designs inspired by ARIANNA. Further, Whittier College has been invited to become a member institution of The IceCube Collaboration through my scholarship. This will give us a seat at the table for cutting edge physics research. I provide a complete list of advantages in Sec. 3.2 below.

The diagram in Fig. 3.1 illustrates the progress my field has made in the last decade. IceCube is the largest neutrino detector in the world, and one of the more expensive physics projects in US history ($0.28 billion). In perspective, the Mars rover Curiosity cost $2.5 billion, and the Advanced LIGO gravity-wave detector cost $1.1 billion. IceCube was built from a predecessor called AMANDA, constructed at the South Pole for the ice quality and several-kilometer depth[1]. AMANDA and IceCube have relied on the *optical technique*, observing tracks of

[1] Being at the South Pole is like being atop a 2.8 km ice mountain. The ice thickness is needed to form the largest block of ice possible for the detector.

optical photons left by passing neutrinos. The optical technique requires *digital optical modules* (DOMs) to be deployed 1 kilometer below the surface, separated by 100 meters. Practically, this limits the detector volume to 1 km^3. After 20 years of detecting neutrinos that originate from cosmic rays striking the atmosphere, IceCube announced the observation of *extra-solar*[2] neutrinos with energies of 10^{15} electron-volts in 2013 [11].

This result broke the world record for highest-energy neutrino ever observed by humans. There is also nothing in our solar system capable of accelerating particles to those energies, so the neutrinos at least had to come from outside the solar system. Currently, IceCube has established a flux of neutrinos below 10^{15} electron-volts, and the arrival directions indicate they might have *extra-galactic* origin. Meanwhile, with the deployment of AMANDA came RICE, the earliest *in situ* Askaryan-class detector. Deployed before IceCube construction began, RICE operated for just over a decade.

In many ways, RICE was ahead of its time. Gurgen Askaryan predicted what we call the Askaryan effect in the 1960s. The radio pulses from neutrinos and other high-energy particles would be conveniently observable as radio pulses, but physicists did not take advantage of this until the 1990s. In the interim, the Askaryan effect was observed in the lab [8] [9]. RICE eliminated many of the earlier optimistic models for UHE-ν sources, and concluded in 2012 with its last publication [1]. The time came to build a UHE-ν detector capable of listening for signals from more ice. A brilliant idea was hatched: the detector could fly above Antarctica, observing all the ice at once. Thus, ANITA was born.

ANITA was a UHE-ν version of the long tradition of cosmic ray balloon flights. In fact, cosmic rays were originally discovered by Victor Hess and Domenico Pacini in 1911, and Hess used a high-altitude balloon to make observations. ANITA eventually did observe cosmic rays (which create radio pulses in the atmosphere), along with *the mystery events.* These mystery events are so-named because they look like cosmic ray signals, but coming up from the ice. Normally, they would be ideal UHE-ν signals, but neutrinos with energies above 10^{16} electron-volts do not penetrate through the Earth at the observed angles. Either fundamental physics is wrong, or the interpretation of the signals is. ANITA has flown four times, and the planned upgrade is called PUEO.

The main drawback with ANITA is that the balloon has to fly 20 km in the air (like a weather balloon). That means the radio pulse from the UHE-ν has to travel that much farther to the detector, and the amplitude diminishes. If the UHE-ν is extra-energetic, it makes an extra-large radio pulse which can be detected by ANITA. However, the higher the energy, the rarer the UHE-ν. Thus, ANITA has not observed the flux observed by IceCube, because the average neutrino in the flux has less than 1% of the energy necessary to trigger ANITA. The physics community decided to install two versions of ANITA *in situ* (in the ice), in order to be closer to potential UHE-ν signals: ARA and ARIANNA.

ARA and ARIANNA had to overcome a number of technical challenges. While a weather balloon is a standard piece of technology operated by NASA, deploying a physics experiment in the middle of Antarctica is as complex as deploying a satellite orbiting the planet. Power, communications, data collection, and deployment missions are all technically challenging. ARIANNA was deployed at Moore's Bay on the Ross Ice Shelf to take advantage of the ocean beneath the ice. The ocean reflects radio pulses, and thus gives detectors multiple chances to detect them. ARA was deployed at the South Pole to take advantage of the colder ice. Colder ice is more radio transparent. The competition to successfully develop a prototype array lead to seven ARIANNA stations in Moore's Bay, and later two at the South Pole. ARA deployed three stations at the South Pole, and data from two of them was published. Later, a fifth[3] ARA station was deployed at the South Pole with a *phased array antenna* (see Sec. 3.3).

ARA and ARIANNA can detect UHE-ν with energies of 10^{16} electron-volts, *just above* the most energetic portion of the IceCube data. We are tantalizingly close to breaking the world record for the highest energy neutrino observed, and opening a new window into physics and astrophysics. The National Science Foundation (NSF) will no longer fund ARA and ARIANNA separately. In 2018, the two collaborations were tasked with merging and to produce a final detector design at Ohio State University. The primary issue was the deployment strategy: the ARIANNA design utilizes solar power, RF antennas in the surface snow (called the *firn*), and satellite communications. The approach is simple and conservative, and hardened for deployment in a harsh environment. The ARA design calls for drilling boreholes in the ice, similar to IceCube, so that the antennas can be lowered to depths below the *firn*. The ARA design also involved fiber optics, line-of-sight WiFi, and more antenna channels. The added complexity leads to a more sensitive experiment, but comes with higher risk.

[2] Originating from outside the solar system.

[3] I never learned from my ARA colleagues what happened to the fourth ARA station.

The merger would have lead to approximately $250k in funding to Whittier College to work on antenna testing and fabrication. Unfortunately, the merger also required baby-boomers to compromise. Since that is impossible, the merger failed. Meanwhile, European physics foundations decided to fund RNO-G, a hybrid of mostly ARA and some ARIANNA designs to be deployed in Greenland. Thus, many from ARA floated over to RNO-G. Greenland can be accessed in the summer of the northern hemisphere, whereas access to Antarctica in general takes place during the northern winter (when the sun is up in Antarctica). Despite the pandemic, there is an ongoing mission to build the first RNO-G stations. Meanwhile, the IceCube Collaboration has adopted radio *in situ* arrays as a key design component into the next major upgrade, IceCube Gen2. Many in our field consider IceCube Gen2 inevitable once the pandemic lifts. *Whittier College has been invited to become a member institution (see Sec. 3.2).* Although this comes with no cost to Whittier College, it provides invaluable access to one of the most dynamic physics collaborations in history. Once complete, IceCube Gen2 will begin to detect the most powerful neutrino events in human history.

3.2 Invitation to Become a Member Institution of IceCube

Recently, I was invited to become an official member of the IceCube Collaboration. The IceCube Collaboration (`https://icecube.wisc.edu`) includes more than 300 physicists from 53 institutions in 12 countries. It began in 1999 with the submission of the first IceCube grant proposal, and many of the original members are still active on the project. Senior scientists, graduate students, technicians, software specialists, ice drillers, and engineers came together from around the world to build what is now the worlds largest neutrino detector. To be granted a membership in the group at the forefront of neutrino physics is an honor, and it represents a great opportunity for Whittier College.

My successful bid for IceCube Membership brings several advantages for Whittier College. Whittier College will be added to the *list of member institutions* (included in the supporting materials). This means that our students and professors would gain access to archived IceCube data and be able to use it for research. Whittier College will also gain visibility, and we would be the only Title V HSI on the list. Whittier College will be added to IceCube publications, and my students and I may submit papers on behalf of the IceCube Collaboration. Whittier students and professors could attend the annual IceCube Collaboration Meeting, which is like a physics conference specializing in neutrino physics and astrophysics. Finally, I could use my IceCube membership status to help with grant proposals for items like my CEM cluster idea (see Sec. 3.3.1).

3.3 Five Areas of Research Focus

In the following five sections, I highlight five key areas of impact into which my UHE-ν research activities can be classified. I explain how they relate to the goal of UHE-ν research, and how they are interconnected. In each section, I highlight how the activity connects back to my teaching and mentorship practices.

3.3.1 Computational Electromagnetism

Observable Askaryan signals originate in ice and propagate to *in situ* RF channels. The path they follow is called a ray-tracing solution, and it depends on the speed of light in ice versus depth. The ray-tracing solution is a curved path because the speed of light changes according to the *index of refraction*, n, which depends on ice and snow density. The density depends on depth because the surface is snow ($\rho \approx 0.4$ g cm^{-3}) that is compressed to solid ice ($\rho \approx 0.917$ g cm^{-3}) over millenia [16]. A classical physics approach called the Lagrangian method can produce the ray-tracing solution. Combining the Lagrangian approach with a smooth function that describes the oberved n results in a formula for the ray-tracing solution. The formula produces special cases: (1) straight-line paths in deep ice (where the speed is constant), (2) quadratic paths near the surface (where the speed changes), and (3) a general form stitching the two together.

The official simulation software used by IceCube Gen2 is named NuRadioMC [30]. NuRadioMC is built on four pillars: (1) UHE-ν generation, (2) Askaryan emission, (3) ray tracing, and (4) RF channel simulation. My analytic ray-tracing solution is pillar (3). We assume a functional fit for n that is motivated by glaciology. Snow accumulates at the top of the ice sheet at a rate that depends on the yearly conditions. Compressed over millenia, the snow steadily increases in density, which in turn decreases the speed of light within it. The function is constrained by density and radio measurements [29]. The key finding of [29], however, was RF *horizontal* *propagation* not predicted by ray-tracing. I can correct my ray-tracing framework with a *perturbed* Lagrangian to produce horizontal solutions. I showed in my PhD dissertation that the effect depends on frequency [45], and therefore cannot be explained with ray-tracing alone. Horizontal propagation has been noted as an interesting detection scheme for UHE-ν [46].

The inaccuracy of ray-tracing solutions is compounded by the selection of phased arrays as triggers of *in situ* stations. In this context, phased-arrays are vertical arrangements of identical antennas that work together. One can think of received signal in terms of relative timing between antennas. For example, in transmitting mode, the each element of a phased array radiates the same signal, but shifted in time such that the time shift increases across the array. The result is a plane wave emitted at the desired direction. Conversely, the arrival direction of plane waves from the Askaryan effect can be deduced from the relative timing of the signals in each antenna. However, this all assumes a constant index n, and we know it is not constant. Knowing that sensitivity of IceCube Gen2 *in situ* designs depends on the phased array precision, I have created a solution that leaves behind ray-tracing all together.

Beyond Ray-Tracing: Open-Source Parallel FDTD Methods

I have received two **Summer Faculty Research Internship grants** from the Naval Surface Warfare Center (NSWC) Corona Division, in Corona, CA. My group focuses on phased-array radar development. My colleagues at other institutions that do not have the liberal arts tradition sometimes ask how radar development is related to IceCube Gen2. I identified a connnection between the two fields: phased-arrays are useful for testing other radar systems because they can mimic a radar reflection that moves. I adapted a Python3 software packaged called MEEP, originally designed for μm wavelengths, to work for radio wavelengths [35]. From there, I developed phase-array models in which I could control things like the speed of light versus depth (i.e. the problem we face in IceCube Gen2). I performed design studies for single-frequency and broadband arrays, and the computed properties matched phased-array antenna theory beautifully. Intriguingly, the work represents the first time MEEP, originally designed for μm-wavelength applications, had been applied to phased array design. The results have been published in Electronics Journal [47], where the work has been named among the Top 10 most notable articles of 2020-21[4].

I can envision a wide range of CEM applications for IceCube Gen2. The phased array trigger for IceCube Gen2 must be designed accounting for the changing index of refraction. *I plan to combine a Python3 machine learning package with MEEP to optimize and study phased array trigger output given the index of refraction profile and Askaryan emission proerties.* These computations could be performed in parallel on a small dedicated cluster we would assemble. I'm currently searching for the right NSF grant to do this, however I do have some startup grant funding remaining that can be used for computer hardware. If successful, the *in situ* trigger would thus be trained to detect the smallest hint of a UHE-ν signal. Theoretically, we expect a higher UHE-ν flux with smaller amplitudes, so in this way we would be maximizing the scientific output.

My proposed CEM computation cluster would also serve the PUEO collaboration for another reason [48]. PUEO will seek UHE-ν signals with arrays of RF elements flown in the atmosphere. PUEO antennas are the same type as the ones I designed for the Navy, and would be flown on a weather balloon gondola. PUEO is therefore dubbed an *in air* version of Askaryan-class detector. PUEO faces a computational requirement that *in situ* detectors do not: the signal must refract through the rough snow surface and into the air. The Antarctic snow surface roughness has been measured [49], and ta can degrade the signal. With the measured roughness as initial conditions, I can calculate the predicted signal in PUEO arrays with near-to-far-field projection. In my work published recently in Electronics Journal [47], I produced this type of refraction, but with a smooth surface. It would not be difficult to add the effect of the rough snow surface.

Connection to Teaching and Academic Mentorship

We always attempt to form connections between our research and teaching, and my work for the Navy has required me to teach. My contacts are Dr. Christopher Clark, Dr. Eisa Osman, and Dr. Gary Yeakley, who work on active seeking radar. Dr. Clark relayed a compliment I received from Dr. Yeakley, who had this to say about my 1-2 hour lectures given once per week in Summer 2020.

"One of the most stunning compliments Prof. Hanson received was from my Senior RF Engineer, Mr.

[4]The notice of these awards is included in the supplemental material.

Gary Yeakley (who has been working developing, designing, and testing radar since the 1970s), where Gary stated "every week I learn new RF Physics from Jordan [Prof. Hanson]."

I have included a letter of advocacy in the supplemental materials from Dr. Clark. Researching a new subject, mastering it, and teaching it to colleagues in the Navy was a rewarding experience, and I was grateful to serve. My Navy contacts invited me back for Summer 2021 to teach an RF Field Engineering Course. In practice, this amounted to creating tutorial videos my colleagues can download. This content will also be useful for digital signal processing (DSP), my upcoming January term course.

This past summer (2021), I included in this work a student named Adam Wildanger through a Fletcher-Jones Fellowship. Adam is a great help, because he has taught me computer assisted design (CAD). The process begins with me creating an antenna design using CEM tools. Next, Adam ports my work as a machine-readable design using his favorite CAD programs. Third, Adam sends the machine-readable design to our Navy colleagues, who fabricate it using a 3D printer. Finally, they have sent the fabricated components to me. Adam and I have begun to test them in the Science and Learning Center using equipment provided by ONR. The key is to use 3D printer material that conducts some amount of electric current at high frequencies. If successful, this collaborative effort has applications as diverse as UHE-ν research, radar development, 5G mobile communications, and remote sensing for climate science (`https://cresis.ku.edu/`). The key lesson here is that sometimes the mentor can learn new things from the student. I am working on securing Adam an position at the national lab where my ONR colleagues are based. That has been Adam's dream job throughout college.

3.3.2 Mathematical Physics

In 2015, I became a CCAPP Fellow at The Ohio State University, where I began to work on an analytic Askaryan radiation model. At the time, the simulation package for IceCube Gen2 (NuRadioMC) was under development. The two *in situ* groups, ARIANNA and the Askaryan Radio Array (ARA), relied on the MC codes ShelfMC and AraSim, respectively. Both ShelfMC and AraSim were derived from the same legacy code. We learned, however, that ShelfMC and AraSim did not always produce the same results, and were cumbersome to compare. Further, the Askaryan models in both were 5-10 years old, and derived from *semi-analytic* parameterizations.

The results of foundational work in Askaryan effect simulated every single sub-atomic particle in the cascade initiated by the UHE-ν, and the corresponding radiation [50]. Overall radio pulse amplitude was found to be proportional to the energy of the neutrino. A distribution of radiated power was observed to radiate in a special direction: the Cherenkov angle. Such models were called *full-MC* models. By tradition, physics simulations are sometimes called *Monte Carlo* simulations (MC). Semi-analytic parameterization models provide part of the electric field at the Cherenkov angle, and simulate the cascade development along the UHE-ν direction. Mixing these two results produces the electric field (radio wave) at a variety of angles [10].

Frequency-Domain Model

Missing from the 2018 ShelfMC/AraSim integrations was a common analytic understanding of Askaryan radiation. I responded by developing a fully analytic model[5] that accounted for several important effects [15]. The independent variable in the equations is the frequency of the radio wave, so the model is classified as a *frequency-domain* model. I was inspired by work by Prof. John Ralston and Roman Buniy [51]. Using simulations on the Ohio Supercomputing Cluster (OSC), we determined the shape of the electric charge distribution in the UHE-ν induced cascades with total energies of 10^{17} electron-volts.

We then wrote a function that followed this shape, and finished the ensuing electromagnetic calculations to obtain the radio wave. My model produces template waveforms for UHE-ν searches with IceCube Gen2 [15]. The community began to use the model after I presented it at workshops at KICP (Univ. of Chicago), and TeVPA conferences. Colleagues shared with me that a time-domain model at all angles relative to the Cherenkov angle would be highly useful. In the final section of [15], we did provide an example, but only if the viewing angle equals the Cherenkov angle.

Time-Domain Model

There are four main advantages of analytic time-domain models. First, when they are matched to observed radio waveforms, UHE-ν cascade properties like total energy may be derived directly from waveform shapes. Second,

[5] In this sense, analytic means a set of equations, not a simulation.

evaluating a fully analytic model technically provides a speed advantage in software compared to other approaches. Third, when analytic models are combined with RF antenna properties (derived using CEM), the resulting template can be embedded in detector firmare to form a filter that enhances the probability that a passing UHE-ν signal is detected, rather than be mistaken for radio noise. Fourth, parameters in analytic models may be scaled to account for snow density in addition to ice density. This application is useful for understanding potential signals in the Antarctic firn, or the upper 100-meter layer of snow that rests on top of the ice. My student, Raymond Hartig, and I are proud to announce that our work will be published in Physical Review D [34]. My vision for the future of this work involves three tracks.

The first track involves UHE-ν template analysis. Our simulation for IceCube Gen2, NuRadioMC, is broken into four pillars (steps). Currently, UHE-ν are simulated first as *events* (NuRadioMC pillar (1)) and the *RF emissions* (Askaryan signals) are generated next (NuRadioMC pillar (2)). Our ability to match simulated waveforms to potential UHE-ν waveforms from the detector is limited because we cannot scan through properties of the simulated *cascades*, only UHE-ν with a single RF emissions model. For example, two UHE-ν with the same energy could generate different cascades with different shapes of electric charge. The effect of the cascade shape is important for the interpretation of future IceCube Gen2 data. Conversely, if the effect of the cascade shape is well-understood, it becomes possible to measure the UHE-ν energy by templates to observed data [34].

The second track involves embedding the model itself in detector firmware. Potential UHE-ν signals are recorded alongside noise, but all data has to be shipped with limited bandwidth. Embedding the model on the detector would allow us to flag priority events. The physics community expects IceCube Gen2 to provide a real-time alert system so that other physics and astronomy collaborations could search for any UHE-ν or cosmic-ray sources we identify. This is not possible if the data has to be shipped back to the United States and then be searched with powerful algorithms, because this takes too much time. Sending events that correlate with analytic predictions is a strategy that solves the problem, because the UHE-ν alert is generated *on board the detector* and is transmitted to the USA.

The third track involves the connection between CEM and our Askaryan model. In NuRadioMC the simulated signal is created by code in pillars (1)-(4) sequentially. That is, the basic Askaryan model is mixed with detector response *after* ray-tracing. In reality, the radiation flows immediately from the cascade according to the details of the index of refraction of the ice. It is a wave that *generally* follows ray-tracing, but that reflects from internal ice layers, propagates horizontally, and can change shape. In other words, all the effects *not captured* by the original index of refraction function, n. In this regard, fully-analytic Askaryan models have a unique advantage: analytic equations can be implemented as MEEP sources, and MEEP *can* account for all those effects, while ray-tracing cannot. The analytic model is in a unique position to provide advanced insight into the effect of 3D propagation previously unexplored.

Connection to Teaching and Academic Mentorship

Researching mathematical physics and radio waves has sharpened my teaching of electromagnetism for obvious reasons. I taught our version of upper-division electromagnetism this past semester: Electromagnetic Theory (PHYS330). I included detail about this experience, which was wonderful, in Sec. 2.

I have been mentoring an undergraduate double-major in physics and mathematics named Raymond Hartig who plans to attend graduate school. Our partnership began in Spring 2020, when Raymond approached me for training in complex analysis. These are the mathematical tools necessary to perform some electromagnetic calculations. We then won the Fletcher-Jones Undergraduate Research Fellowship for that summer. The experience of coaching him in his development as a theoretical physicist has been rewarding, and I have taken note of a key skill project leaders must have.

Similar to teaching courses, one has to think pedagogically when explaining projects to young researchers. If they understand the direction at least as well as the syllabus of a course, they are more likely to succeed. *From the perspective of equity and inclusion*, my experience mentoring students pedagogically is useful. By structuring the students' time, and explaining goals and productivity expectations in advance, students from diverse backgrounds feel called to participate in the same sense that they feel invited to participate in the classroom. Sometimes research can make first-generation students, for example, feel that the work is not for them because it is too unfamiliar. Providing structure pedagogically can eliminate that stress and increase productivity.

3.3.3 Firmware, Software, and Hardware Development

Askaryan-class detectors must operate autonomously due to the limited Antarctic infrastructure. Stations must be powered sustainably with solar panels and wind turbines, and communications bandwidth is restricted to satellite modems and LTE networks [19] [52]. Every sub-system that can operate autonomously is another sub-system that does not use bandwidth. The ARIANNA stations, for example, send text messages via satellite modem to the server in the USA. Configuration files are sent by the server to the stations with operational instructions. This includes channel thresholds, which control the RF thermal trigger rate. All radio and radar systems trigger inevitably on *thermal noise*. A lower threshold increases the chance of hearing signal at the cost of recording more thermal noise. To adjust thresholds in response to fluctuating thermal noise (which can fill up detector memory with useless data), we have to analyze the data between satellite messages, optimize thresholds, and send the stations new instructions. The stations can therefore run autonomously without power-hungry, high-bandwidth ethernet. This process, however, should be automated for hundreds of stations in IceCube Gen2.

The Multi-Mode Frequency Counter (MMFC) and ARIANNA

My student, John Paul Gómez-Reed and I developed firmware for the ARIANNA boards that would perform this automation. This was a two-year process that began when we won the Keck Fellowship in the summer of 2018. First, we learned to design and load firmware into circuits. John Paul named the system the Multi-Mode Frequency Counter (MMFC), because it is a digital counter that measured the rate at which particular ARIANNA channel was triggered by thermal noise. We demonstrated it could measure channel trigger rates from from 10 hits per second to 10 million hits per second. (When a channel is triggered millions of times per second, that is the effect of just noise and no interesting RF signal). The digital input was provided by RF lab equipment I purchased for Whittier College using my startup grant. John Paul presented the results at the Southern California Conference for Undergraduate Research (SCCUR) [32]. We then received ARIANNA systems from UC Irvine for systems integration. *In summer 2019, we won the Ondrasik-Groce Fellowsip.* Throughout 2019 and early 2020, we used that fellowship to integrate the MMFC into the ARIANNA circuitry. The circuit boards began to auto-adjust station thresholds. We were in the process of final testing when the pandemic forced us to pause. We did, however, present at SCCUR a second time [33].

Future Plans and Applications

To continue this research, I have submitted a grant proposal to the Cottrell Scholars Program[6]. The proposal outlines in detail the next three phases of this research, broken into concrete steps within each phase. The overall goal is to enhance the trigger capability of our detectors with my analytic Askaryan models (Sec. 3.3.2).

Phase 1 includes two main steps: (1) completing the integrated threshold automation firmware and software, and (2) completing the analytic Askaryan model. As of this summer, both (1) and (2) are complete. The integration of (1) into ARIANNA systems had to be put on hold due to the pandemic, but both the software and firmware are written. The latest version of the Askaryan model is complete, and will be published in Physical Review D [34]. **Thus, phase 1 is already complete.**

Phase 2 includes two main steps: (1) learning to match templates to data in firmware, and (2) demonstrating the system in an anechoic chamber[7]. The reliability of this process must be proven before the firmware is deployed in Antarctica. The key to step (2) is to calibrate the whole planned RF chain: a signal generator programmed with my analytic Askaryan model, transmitting and receiving antennas, amplifiers, filters, and digitization circuits. I have performed similar processes as a post-doctoral fellow at KU [28].

Phase 3 includes three steps: (1) publication of threshold automation and Askaryan model, (2) installation of the Askaryan-trigger firmware in detectors, and (3) field deployment. It is wise to have the components of this project peer-reviewed and published before installing them in many detectors. As of this summer, the Askaryan has passed peer review. Once the IceCube Gen2 collaboration has a chance to review the firmware, we could move forward with deployment.

[6] This is included in the supplemental material.
[7] An anechoic chamber is a space that blocks all radio noise and reflections for the testing of sensitive RF equipment.

Connection to Teaching and Academic Mentorship

There are important connections to mentorship and teaching within this work. First, John Paul Gómez-Reed is a Whittier local, and from a background under-represented in physics and engineering. I was able to coach him through courses, application processes, and two SCCUR conferences. We are currently working on graduate school and job applications. Working with him has honed my mentorship skills, including when to hammer out details in the lab with my students, and when to leave them to figure it out on their own. Working with a self-motivated student like John Paul required me to become attuned to that dynamic.

I have taught two courses connected to this research: Computer Logic and Digital Circuit Design (PHYS306/COSC330), and Digital Signal Processing (COSC390), which introduced an interesting synergy. When I selected the Xilinx pynq-z1 board (`www.pynq.io`) for PHYS306, the system allowed students to operate a Unix-based processing system (PS) integrated with a programmable logic (PL) firmware layer using Jupyter notebooks (Python3). Learning how to use Jupyter notebooks boosted my CEM research, because MEEP work is often done in Jupyter. Because this resarch is a DSP project, it can serve as an important unit in my DSP course.

3.3.4 Open-source Antenna Design

The MEEP-based phased array design technique has generated enthusiastic feedback. Currently, my phased array design paper is ranked top 10 most notable works in Electronics Journal for 2020-2021 [47][8]. Using my second ONR grant, we are exploring the possibility of 3D printing phased arrays with conductive filament. Additionally, UHE-ν collaborators are interested in validating antenna designs created with expensive, proprietary software against MEEP designs. Cross-checks help us to assess systematic errors. If we find similar results from both packages, we eliminate the need for the proprietary software, which reduces costs. Comparisons of antenna modeling software are also found in Electronics Journal [53], which insipired the selection of that journal in addition to it being open-access for our students. Using the aforementioned CEM cluster in Sec. 3.3.1, I could perform calculations that compare and optimize the antennas *themselves*, in addition to refining our UHE-ν signal predictions.

Connection to Teaching and Academic Mentorship

Creating RF antennas requires laboratory skill. I have been teaching several courses with significant laboratory components: Computer Logic and Digital Circuit Design (PHYS306/COSC330), and each year-long sequence of algebra-based and calculus-based introductory physics (PHYS135A/B, and PHYS150/PHYS180). These courses have laboratory components taught in an integrated online/lecture/laboratory format. I have also mentored students on occasion to work with our machine shop to build antennas, and to use the 3D printer. Although it would be a stretch, I could envision including student-led RF antenna design projects in DSP, PHYS180, or PHYS135B. The two latter courses are our introductory courses for electromagnetism.

3.3.5 Drone Development and The Whittier Scholars Program

A gap exists in Askaryan-based UHE-ν science. Although we have made detailed measurements of the ice properties necessary to create our detectors [16] [17] [18], we do not scan these same properties for kilometers of distance across the arrays. IceCube Gen2 radio will require a glaciological understanding of the ice across a 10×10 km^2 area. Though CReSIS[9] measurements have been used to constrain these properties across Greenland [43], there is little CReSIS data at the South Pole.

The Open Polar Server Data Gaps, and Drones

The Open Polar Server (OPS) is a service provided by CReSIS. Researchers may download radio sounding data from Greenland and Antarctica. The radio sounding data are recorded from plane flights over the ice. Radio sounding is like sonar in water, but the echo is a radio wave and the medium is ice. There are three disadvantages to the flight data. First, there may not be a flight near the detector. Second, flights only give a snapshot of the ice at the time. Third, the bandwidth of CReSIS radar does not always overlap with the proposed IceCube Gen2 bandwidths.

[8] See supplemental material.
[9] Center for Remote Sensing of Ice Sheets.

There is a trade-off between spatial and temporal data in radio sounding. A plane flight covers hundreds of kilometers, but a plane might not return for years. Conversely, a fixed station records data over time, but only at one location. A dedicated drone could constrain the ice properties in both regimes. In the machine shop and my RF design lab in the Science and Learning Center, a student and I constructed a 3D printed drone with ≈ 1 kg payload. Before the pandemic hit, we had plans to equip it with solar charging and cold-temperature components. A similar effort is underway at CReSIS: Prof. Emily Arnold of the KU Dept. of Aerospace Engineering has begun an NSF CAREER grant to utilize RC military drones to study the Jakobshavn glacier in Greenland. Unlike the off-the-shelf drones, our drone design can be 3D printed and assembled from commercial parts for $<$ $1k, but we need valuable insights from the CReSIS group on retro-fitting for cold temperatures.

Connection to Academic Mentorship and the Whittier Scholars Program

This project required me to mentor a driven engineering student named Nick Clarizio. We worked well together, and the work reminded me of designing ARIANNA. The student became my first physics double major (business, physics) to graduate as my advisee. Once we completed the drone, Nick was able to demonstrate it for my PHYS150 class, as an example of balancing forces. The drone has four motors, each with controllable thrust. Thus, if the thrust is lowered in two motors and raised in two others, the drone will move in a certain direction. Thus, my students received a hands-on demonstration of an important leture topic. This year I will have another student graduate in this area, who chose to focus on glaciology as part of the Whittier Scholars Program.

I described my Whittier Scholars Program project with Nicolas Bakken-French earlier in this report (Sec. 1.1.1). The basic idea was to perform research in climate science as part of my connections to Antarctic expeditions and other polar research programs. One facet of the project not yet mentioned was that Nicolas was able to learn some programming and help me with glaciological analysis of CReSIS data from Moore's Bay Antarctica. I also helped him earn a research internship at UC Irvine with my colleagues there. He helped them to develop a device that can melt a slot into a snowbank so that an RF antenna can be installed inside it. This enables more rapid deployment of both glaciology and physics experiments involving RF sensors in snow. I had such a great experience working with Dr. Andrea Rehn and the WSP team that I have offered to serve on the Whittier Scholars Advisory Board. My offer has been accepted and I will begin in Fall 2021.

3.4 CEM and Engineering with the ONR

During 2019-2020, it became clear that not only were missions to Antarctica postponed, but that progress in my field will only resume once the IceCube Gen2 design is finalized. This is expected to happen in Fall 2021. I have been participating in the IceCube Gen2 radio task-force, which meets weekly to share results and plans for the design. In the mean time, I decided to widen my research profile so I could make meaningful progress during quarantine.

In the Fall of 2019, three separate individuals sent me emails, inquiring if I would be interested in something called the Summer Faculty Research Program, administered by the Office of Naval Research (ONR). An old friend from graduate school who works at the Naval Surface Warfare Center (NSWC) in Corona, CA, sent me a note. A contractor working for the Navy contacted me. Finally, my department chair, Prof. Seamus Lagan, forwarded me a message similar to that of the contractor. There is a long tradition of cross-over and cooperation between academics in physics, math, computer science, and the military. Because three separate people suggested I consider this program, I decided to apply.

I was contacted by Dr. Christopher Clark, who explained to me that there is a division at NSWC that focuses on radar applications. The Navy relies on radar for defending ships and aircraft, and defending our nation from missle attacks. Scientifically, though, the Navy has always been at the forefront of *computational electromagnetics* (CEM) [54]. For example, CEM provides engineers a way to design and manage systems that manipulate microwaves for 5G telecommunications. CEM can be used for modelling electromagnetic effects in weather. In my sub-field of physics, CEM will be useful for understanding the propagation of radio waves through ice in precise detail. The Navy has created research programs much like those in civilian national labs (e.g. LANL, LBL) that provide the public with technological research (`https://www.onr.navy.mil/`).

I have been awarded this fellowship in Summer 2020, and Summer 2021. The connections to my physics research have been fruitful. In Sec. 3.3.1, I described the connection between my physics research and the CEM skill I gained from my Navy collaboration. In Sec. 3.4.1, I discuss the applications to radar and how they are useful for the ONR. My students and I use CEM to design radar antennas with useful properties like high bandwidth, low amounts of energy loss, and the ability to steer a radar beam in the right direction. In Sec. 3.4.2, I discuss the efforts of my Navy collaboration to use 3D printers to fabricate our radar designs. We are currently collecting data in our lab in the Science and Learning Center, and hope to have results to report soon. In Sec. 3.4.3, I review the potential applications for ONR, UHE-ν physics, and RF antenna design in general.

3.4.1 CEM Phased Array Design for Radar

In Sec. 3.3, I described how *phased arrays* will be useful for UHE-ν physics. Imagine a radio antenna radiating power at some frequency. The direction corresponding to the maximum power is called the *boresight.* The antenna always radiates some power away from boresight. The *radiation pattern* is a graph of this relative power versus angle from boresight. The radiation pattern of a single radio antenna is just a function of the fixed shape of the antenna. The field of RF antenna design is concerned with clever ways to find shapes that have efficient radiation patterns for a given frequency range. To track moving targets, the radar antenna must be *steered* so that the target falls within the strong part of the radiation pattern. There are disadvantages, however, to mechanical steering.

A phased array is simply an arrangement of identical radio antennas that vary in phase or timing. By cleverly arranging the phases or relative timing of signals radiated by each array element, the overall radiation pattern *steers* without any moving parts. Imagine a line of pebbles dropped in a pond. If they are each dropped at the same time, the water wave of each pebble helps to form one large wave proceeding in a direction perpendicular to the line. Now imagine that the first pebble is dropped, then a fraction of a second later the second, and then a fraction of a second later the third, and so on. The ensuing wave will proceed in a different direction. Phased array radar is this principle but applied to electromagnetic waves instead of water waves.

I summarized our CEM development in a recent publication [47]. I selected the open-source Python3 package MEEP[10], and used it to produce single-frequency and broad bandwidth phased array designs. I explored Yagi-Uda antennas (lines of dipoles much like a TV antenna), and horn antennas (shaped like a lily). The radiation patterns match theoretical predictions beautifully. I experimented with *one-dimensional* and *two-dimensional* phased arrays. The term one-dimensional refers to the line of identical RF elements mentioned above in the water analogy. A two-dimensional phased array is the same idea, but a grid of antennas. A grid allows for beem-steering in two angles (azimuth and zenith angle). This work was remarkable for at least three reasons.

First, after a simple literature review, I believe my work represents the first time anyone has shown MEEP can produce phased array designs. RF antennas are usually designed with expensive, proprietary software[11] MEEP is open-source, so my students and I have installed it and create designs for free. MEEP was originally designed for applications with micrometer wavelengths (optical photonics). However, Maxwell's equations that govern electromagnetism demonstrate *scale independence*. For example, if an object is a few micrometers across, then it probably emits radiation with micrometer wavelengths when energized. But if I scale its size to a few centimeters across, the radiation is the same pattern, but with centimeter wavelengths. We adapted MEEP to describe phased arrays where antennas are centimeters long. The authors of [53] contacted to congratulate me and excitedly request code examples so they could utilize these tools. They are professors in northern Italy, and their publication was a review of open-source results for simple antennas in Electronics Journal[12].

Second, IceCube Gen2 will utilize phased arrays to detect UHE-ν in an environment with non-constant index of refraction (see Sec. 3.3.1). The index of refraction is usually called n, and the speed of light is c. In a medium with an index of refraction, electromagnetic waves travel at speed $v = c/n$. If n changes with ice depth, the path of radiation through the ice is curved and complicated. Normally the software used by the IceCube Gen2 and RNO-G collaborations (xFDTD) to design phased arrays does not account for depth-dependent index of refraction. In our recent work [47], I explored the effect of the depth-dependence of n on our phased array designs. In future work, I will incorporate our knowledge of the internal ice layers frozen into the *firn* (upper portion of the ice sheet made of snow and ice). These layers act like hidden mirrors and can alter the results of IceCube Gen2. A similar work by a colleague uses a slightly different method [55].

Third, the results show that our design forms the proper wave ≈ 10 cm in front of the antennas. The system would be compact enough to install in an *anechoic chamber*, acting as a model radar echo to test other radars. A

[10] MIT Electromagnetics Equation Propagation: `https://meep.readthedocs.io/en/latest/`.

[11] For example, xFDTD by RemCom costs between $5k and $10k, depending on the desired features.

[12] I have included their communication in the supplemental material.

large anechoic chamber is a room where there are no RF reflections. Normally, RF pulses bounce off of flat surfaces (hence, radar). Anechoic chambers have shapes built into the walls that cancel RF reflections, making testing a radar system possible without the confusion of reflections. Anechoic chambers large enough for radar are rare[13]. Smaller ones designed for smartphones are more common. Our design is so compact and forms the wave in such a short distance that it could potentially fit in the small variety. Our design enables the following type of experiment. Imagine bringing in a radar system that has been deployed in the field for years. It has not been recalibrated, and has been banged around at sea. When placed in front of our system, it would see a variety of signals changing direction and we could identify any systematic error in the radar output to recalibrate it. This is one of a variety of applications we envision for the Navy.

3.4.2 3D Printing of RF Antennas

This summer, my ONR colleagues and my student, Adam Wildanger, and I have explored the idea of fabricating the RF antennas with 3D printing. Adam and I were awarded the Fletcher Jones Fellowship to do this work. Adam has shown me a variety of computer assisted design (CAD) programs useful for creating 3D models of our antennas. I have identified one CAD program that can render a design into a format that can be imported to MEEP. This was a huge leap forward over last year. Last year, I constructed my antennas like children's blocks. I would write Python3 code that would define a small piece of metal, and then in a loop, I would assemble the antenna from thousands of pieces. Now, any shape we can imagine we can simply draw in the CAD program and load into MEEP. Thus, I can model the radiation of the design with CEM *and* manufacture the same design with a 3D printer capable of using the CAD file. Using a 3D printer has a number of unique advantages. The main one is that strangely shaped antennas designed with machine learning can have highly useful radiation patterns and bandwidth [56] [57]. Manufacturing such antennas with standard shop tools is time-consuming. With a 3D printer, CAD file appropriate print material, the process is automated. We are now experimenting with different printing materials and have already begun lab testing of printed horn antennas.

3.4.3 Applications to Mobile Broadband

This work could have an impact in a number of broader applications. Progress in high-gain ultra-wideband radar development, is hindered because desireable parameters compete with each other. The authors of [56] created a highly intriguing system that appears to have beaten some of these limitations, but have to manufacture it by welding and printing circuits using standard methods. One intriguing application for the private sector is applying 3D printing to such antennas for 5G mobile broadband. The mid-band designation for 5G is [2.5-3.7] GHz, right where our design and others radiate efficiently. If we can show that 3D printing may be used to create phased arrays of complex antennas in this range, it represents the potential for reducing the cost of 5G antenna system production.

3.5 My Vision for Collaboration between ONR and Whittier College

3.5.1 Building Student Success after Whittier College

C

3.5.2 Equipping Whittier College Laboratories

D

3.5.3 Financial Support

E

[13]For example, the CReSIS anechoic chamber: `http://chamber.ku.edu`.

Chapter 4

Advising and Mentoring

4.1 Connections to Teaching and Service

4.1.1 Inclusion, Community, and a Sense of Belonging

4.2 Advising and Mentoring First Year Students

A

4.2.1 First Year Advising, by the Numbers

B

4.2.2 Navigating the First Year

C

4.2.3 Discernment of Major

D

4.2.4 Equity of Access

E

4.2.5 Inclusion and Belonging: Activities with First Year Advisees

4.3 Advising and Mentoring Majors in Physics, ICS, and 3-2 Engineering

A

4.3.1 Discernment within STEM: Major Selection, and Diverse Pathways to Graduation

B

4.3.2 Graduate School

C

4.3.3 Private Sector

D

Reverse Engineering Social Media

E

4.3.4 Letters of Recommendation

F

4.4 Advising and Mentoring Whittier Scholars Program Majors

A

4.4.1 Interdisciplinary Connections and Recruiting Students

B

4.4.2 Organization of Field Deployments

C

United States Antarctic Program

Describe the attempt to deploy Nicolas to Antarctica

4.4.3 Organizing the Program of Study and Executing

E

4.4.4 Polishing the Finished Product

F

Chapter 5

Service

5.1 Committee Service

Admissions sub-committee, data analysis, maybe a graph

5.1.1 Enrollment and Student Affairs Committee, Years 1 and 2

Write about how I learned about orientation issues from these meetings
Interactions with Falone Serna

5.1.2 Educational Resources and Digital Liberal Arts Committee

Creation of senior thesis archival program

5.1.3 Whittier Scholars Program Advisory Board

I was invited! Sort of.

5.2 Departmental Service

This one can be stronger, maybe

5.2.1 Departmental Self-Study

5.2.2 Departmental Annual Assessment

5.3 First Year Orientation

A

5.3.1 Connection to Teaching and Advising

B

5.3.2 Inclusion and Belonging

C

5.4 Open Educational Resources (OER) Workshops

openstax, oercommons, and openstax tutor, dspguide.com

5.4.1 Open Educational Resources (OER) and Equity

5.4.2 The Tradition of Open Access/Open Source in STEM

The OpenStax Platform

Integrations with Machine Learning

Open Access in Digital Signal Processing

5.4.3 Lectures at Wardman Library Collaboratory

5.5 Center for Engagement with Communities: The Artemis Program

A

5.5.1 Equity and Inclusion in STEM

B

5.5.2 Connections to Teaching at Whittier College

5.6 Summer Working Group Contribution

A

Elec

B

Chapter 6

Conclusion

Jordan C. Hanson, PhD
Assistant Professor, Department of Physics and Astronomy
Science and Learning Center, 212
Whittier College
562.907.5130
jhanson2@whittier.edu

Chapter 7

Supporting Materials

Bibliography

[1] I. Kravchenko, S. Hussain, D. Seckel, D. Besson, E. Fensholt, J. Ralston, J. Taylor, K. Ratzlaff, and R. Young, "Updated results from the RICE experiment and future prospects for ultra-high energy neutrino detection at the south pole," *Phys. Rev. D*, vol. 85, p. 062004, Mar 2012.

[2] P. W. Gorham et al, "Constraints on the ultrahigh-energy cosmic neutrino flux from the fourth flight of ANITA," *Phys. Rev. D*, vol. 99, p. 122001, Jun 2019.

[3] Ahlers, M, et al, "Astro2020 science white paper: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos," *Bull. Am. Astron. Soc.*, vol. 51, no. 185, 2019.

[4] Ahlers, M, et al, "Astro2020 science white paper: Fundamental physics with high-energy cosmic neutrinos," *Bull. Am. Astron. Soc.*, vol. 51, no. 185, 2019.

[5] A. Connolly, R. S. Thorne, and D. Waters, "Calculation of high energy neutrino-nucleon cross sections and uncertainties using the Martin-Stirling-Thorne-Watt parton distribution functions and implications for future experiments," *Phys. Rev. D*, vol. 83, p. 113009, Jun 2011.

[6] G. Askaryan, "Excess negative charge of an electron-photon shower and its coherent radio emission," *Soviet Physics JETP*, vol. 14, no. 441, 1962.

[7] G. Askaryan, "Coherent radioemission from cosmic showers in the air and dense media," *Soviet Physics JETP*, vol. 21, no. 658, 1965.

[8] D. Saltzberg, P. Gorham, D. Walz, C. Field, R. Iverson, A. Odian, G. Resch, P. Schoessow, and D. Williams, "Observation of the Askaryan Effect: Coherent Microwave Cherenkov Emission from Charge Asymmetry in High-Energy Particle Cascades," *Phys. Rev. Lett.*, vol. 86, pp. 2802–2805, Mar 2001.

[9] P. W. Gorham, S. W. Barwick, J. J. Beatty, D. Z. Besson, W. R. Binns, C. Chen, P. Chen, J. M. Clem, A. Connolly, P. F. Dowkontt, M. A. DuVernois, R. C. Field, D. Goldstein, A. Goodhue, C. Hast, C. L. Hebert, S. Hoover, M. H. Israel, J. Kowalski, J. G. Learned, K. M. Liewer, J. T. Link, E. Lusczek, S. Matsuno, B. Mercurio, C. Miki, P. Miočinović, J. Nam, C. J. Naudet, J. Ng, R. Nichol, K. Palladino, K. Reil, A. Romero-Wolf, M. Rosen, L. Ruckman, D. Saltzberg, D. Seckel, G. S. Varner, D. Walz, and F. Wu, "Observations of the Askaryan Effect in Ice," *Phys. Rev. Lett.*, vol. 99, p. 171101, Oct 2007.

[10] J. Alvarez-Muñiz, P. M. Hansen, A. Romero-Wolf, and E. Zas, "Askaryan radiation from neutrino-induced showers in ice," *Phys. Rev. D*, vol. 101, p. 083005, Apr 2020.

[11] M. G. Aartsen et al, "First Observation of PeV-Energy Neutrinos with IceCube," *Phys. Rev. Lett.*, vol. 111, p. 021103, Jul 2013.

[12] M. G. Aartsen et al, "A Combined Maximum-Likelihood Analysis of the High-Energy Astrophysical Neutrino Flux Measured with IceCube," *The Astrophysical Journal*, vol. 809, p. 98, aug 2015.

[13] E. Waxman and J. Bahcall, "High energy neutrinos from astrophysical sources: An upper bound," *Phys. Rev. D*, vol. 59, p. 023002, Dec 1998.

[14] M. G. Aartsen et al, "Differential limit on the extremely-high-energy cosmic neutrino flux in the presence of astrophysical background from nine years of IceCube data," *Phys. Rev. D*, vol. 98, p. 062003, Sep 2018.

[15] J. C. Hanson and A. L. Connolly, "Complex analysis of Askaryan radiation: A fully analytic treatment including the LPM effect and Cascade Form Factor," *Astroparticle Physics*, vol. 91, pp. 75–89, 2017.

[16] J. C. Hanson, S. W. Barwick, E. C. Berg, D. Z. Besson, T. J. Duffin, S. R. Klein, S. A. Kleinfelder, C. Reed, M. Roumi, T. Stezelberger, J. Tatar, J. A. Walker, and L. Zou, "Radar absorption, basal reflection, thickness and polarization measurements from the Ross Ice Shelf, Antarctica," *Journal of Glaciology*, vol. 61, no. 227, pp. 438–446, 2015.

[17] J. Avva, J. Kovac, C. Miki, D. Saltzberg, and A. Vieregg, "An in situ measurement of the radio-frequency attenuation in ice at Summit Station, Greenland," *Journal of Glaciology*, 2014.

[18] S. Barwick, D. Besson, P. Gorham, and D. Saltzberg, "South polar in situ radio-frequency ice attenuation," *Journal of Glaciology*, vol. 51, no. 173, p. 231238, 2005.

[19] S. Barwick, E. Berg, D. Besson, T. Duffin, J. Hanson, S. Klein, S. Kleinfelder, K. Ratzlaff, C. Reed, M. Roumi, T. Stezelberger, J. Tatar, J. Walker, R. Young, and L. Zou, "Design and Performance of the ARIANNA HRA-3 Neutrino Detector Systems," *IEEE Transactions on Nuclear Science*, vol. 62, no. 5, pp. 2202–2215, 2015.

[20] S. A. Kleinfelder, E. Chiem, and T. Prakash, "The SST Multi-G-Sample/s Switched Capacitor Array Waveform Recorder with Flexible Trigger and Picosecond-Level Timing Accuracy," *arXiv*, 2015.

[21] A. Anker, S. W. Barwick, H. Bernhoff, D. Z. Besson, N. Bingefors, D. Garca-Fernndez, G. Gaswint, C. Glaser, A. Hallgren, J. C. Hanson, S. R. Klein, S. A. Kleinfelder, R. Lahmann, U. Latif, J. Nam, A. Novikov, A. Nelles, M. P. Paul, C. Persichilli, I. Plaisier, T. Prakash, S. R. Shively, J. Tatar, E. Unger, S. H. Wang, C. Welling, and S. Zierke, "Neutrino vertex reconstruction with in-ice radio detectors using surface reflections and implications for the neutrino energy resolution," *arXiv*, vol. 2019, no. 11, pp. 030–030, 2019.

[22] Anker, A, et al, "Probing the angular and polarization reconstruction of the ARIANNA detector at the South Pole," *Journal of Instrumentation*, vol. 15, no. 09, pp. P09039–P09039, 2020.

[23] J. C. Hanson, "Ross Ice Shelf Thickness, Radio-frequency Attenuation and Reflectivity: Implications for the ARIANNA UHE Neutrino Detector," *32nd International Cosmic Ray Conference*, 2011.

[24] L. Gerhardt, S. Klein, T. Stezelberger, S. Barwick, K. Dookayka, J. Hanson, and R. Nichol, "A prototype station for ARIANNA: A detector for cosmic neutrinos," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 624, no. 1, pp. 85–91, 2010.

[25] S. Barwick, E. Berg, D. Besson, G. Binder, W. Binns, D. Boersma, R. Bose, D. Braun, J. Buckley, V. Bugaev, S. Buitink, K. Dookayka, P. Dowkontt, T. Duffin, S. Euler, L. Gerhardt, L. Gustafsson, A. Hallgren, J. Hanson, M. Israel, J. Kiryluk, S. Klein, S. Kleinfelder, H. Niederhausen, M. Olevitch, C. Persichelli, K. Ratzlaff, B. Rauch, C. Reed, M. Roumi, A. Samanta, G. Simburger, T. Stezelberger, J. Tatar, U. Uggerhoj, J. Walker, G. Yodh, and R. Young, "A first search for cosmogenic neutrinos with the ARIANNA Hexagonal Radio Array," *Astroparticle Physics*, vol. 70, pp. 12–26, 2015.

[26] S. Barwick, D. Besson, A. Burgman, E. Chiem, A. Hallgren, J. Hanson, S. Klein, S. Kleinfelder, A. Nelles, C. Persichilli, S. Phillips, T. Prakash, C. Reed, S. Shively, J. Tatar, E. Unger, J. Walker, and G. Yodh, "Radio detection of air showers with the ARIANNA experiment on the Ross Ice Shelf," *Astroparticle Physics*, vol. 90, pp. 50–68, 2017.

[27] A. Anker, S. W. Barwick, H. Bernhoff, D. Z. Besson, N. Bingefors, D. Garca-Fernndez, G. Gaswint, C. Glaser, A. Hallgren, J. C. Hanson, S. R. Klein, S. A. Kleinfelder, R. Lahmann, U. Latif, J. Nam, A. Novikov, A. Nelles, M. P. Paul, C. Persichilli, I. Plaisier, T. Prakash, S. R. Shively, J. Tatar, E. Unger, S. H. Wang, and C. Welling, "A search for cosmogenic neutrinos with the ARIANNA test bed using 4.5 years of data," *Journal of Cosmology and Astroparticle Physics*, 2019.

[28] S. Barwick, E. Berg, D. Besson, T. Duffin, J. Hanson, S. Klein, S. Kleinfelder, M. Piasecki, K. Ratzlaff, C. Reed, M. Roumi, T. Stezelberger, J. Tatar, J. Walker, R. Young, and L. Zou, "Time-domain response of the ARIANNA detector," *Astroparticle Physics*, vol. 62, pp. 139–151, 2015.

[29] S. W. Barwick, E. C. Berg, D. Z. Besson, G. Gaswint, C. Glaser, A. Hallgren, J. C. Hanson, S. R. Klein, S. Kleinfelder, L. Kpke, I. Kravchenko, R. Lahmann, U. Latif, J. Nam, A. Nelles, C. Persichilli, P. Sandstrom, J. Tatar, and E. Unger, "Observation of classically 'forbidden' electromagnetic wave propagation and implications for neutrino detection.," *Journal of Cosmology and Astroparticle Physics*, vol. 2018, no. 07, pp. 055–055, 2018.

[30] C. Glaser, D. Garca-Fernndez, A. Nelles, J. Alvarez-Muiz, S. W. Barwick, D. Z. Besson, B. A. Clark, A. Connolly, C. Deaconu, K. D. d. Vries, J. C. Hanson, B. Hokanson-Fasig, R. Lahmann, U. Latif, S. A. Kleinfelder, C. Persichilli, Y. Pan, C. Pfendner, I. Plaisier, D. Seckel, J. Torres, S. Toscano, N. v. Eijndhoven, A. Vieregg, C. Welling, T. Winchen, and S. A. Wissel, "NuRadioMC: simulating the radio emission of neutrinos from interaction to detector," *The European Physical Journal C*, vol. 80, no. 2, p. 77, 2020.

[31] C. Glaser, A. Nelles, I. Plaisier, C. Welling, S. W. Barwick, D. Garca-Fernndez, G. Gaswint, R. Lahmann, and C. Persichilli, "NuRadioReco: a reconstruction framework for radio neutrino detectors," *The European Physical Journal C*, vol. 79, no. 6, p. 464, 2019.

[32] J. C. Hanson and J. P. Gómez-Reed, "A 100 MHz Frequency-Counter Deployed in FPGA for RF Neutrino Research in Antarctica," in *Proceedings of the Southern California Conference for Undergraduate Research*, sccur.org, 2018.

[33] J. C. Hanson and J. P. Gómez-Reed, "Communications between an onboard fpga and microcontroller system for antarctic neutrino research," in *Proceedings of the Southern California Conference for Undergraduate Research*, sccur.org, 2019.

[34] J. C. Hanson and R. Hartig, "Complex Analysis of Askaryan Radiation: A Fully Analytic Model in the Time-Domain," *arXiv*, 2021.

[35] A. F. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. Joannopoulos, and S. G. Johnson, "Meep: A flexible free-software package for electromagnetic simulations by the FDTD method," *Computer Physics Communications*, vol. 181, no. 3, pp. 687–702, 2010.

[36] E. Boyer, D. Moser, T. Ream, J. Braxton, *Scholarship Reconsidered: Priorities of the Professoriate.* Jossey-Bass (Expanded Edition), 2015.

[37] L. Miramonti, "Latest results and future prospects of the pierre auger observatory," *Journal of Physics: Conference Series*, vol. 1766, no. 1, p. 012002, 2021.

[38] K. Greisen, "End to the cosmic-ray spectrum?," *Phys. Rev. Lett.*, vol. 16, pp. 748–750, Apr 1966.

[39] G. T. Zatsepin and V. A. Kuz'min, "Upper Limit of the Spectrum of Cosmic Rays," *Soviet Journal of Experimental and Theoretical Physics Letters*, vol. 4, p. 78, Aug. 1966.

[40] M. G. Aartsen, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, C. Alispach, K. Andeen, T. Anderson, I. Ansseau, G. Anton, C. Argelles, J. Auffenberg, S. Axani, H. Bagherpour, X. Bai, A. B. V, A. Barbano, I. Bartos, S. W. Barwick, B. Bastian, V. Baum, S. Baur, R. Bay, J. J. Beatty, K. H. Becker, J. B. Tjus, S. BenZvi, D. Berley, E. Bernardini, D. Z. Besson, G. Binder, D. Bindig, E. Blaufuss, S. Blot, C. Bohm, S. Bser, O. Botner, J. Bttcher, E. Bourbeau, J. Bourbeau, F. Bradascio, J. Braun, S. Bron, J. Brostean-Kaiser, A. Burgman, J. Buscher, R. S. Busse, T. Carver, C. Chen, E. Cheung, D. Chirkin, S. Choi, B. A. Clark, K. Clark, L. Classen, A. Coleman, G. H. Collin, J. M. Conrad, P. Coppin, K. R. Corley, P. Correa, S. Countryman, D. F. Cowen, R. Cross, P. Dave, C. D. Clercq, J. J. DeLaunay, H. Dembinski, K. Deoskar, S. D. Ridder, P. Desiati, K. D. d. Vries, G. d. Wasseige, M. d. With, T. DeYoung, S. Dharani, A. Diaz, J. C. Daz-Vlez, H. Dujmovic, M. Dunkman, E. Dvorak, B. Eberhardt, T. Ehrhardt, P. Eller, R. Engel, P. A. Evenson, S. Fahey, A. R. Fazely, J. Felde, K. Filimonov, C. Finley, D. Fox, A. Franckowiak, E. Friedman, A. Fritz, T. K. Gaisser, J. Gallagher, E. Ganster, S. Garrappa, L. Gerhardt, K. Ghorbani, T. Glauch, T. Glsenkamp, A. Goldschmidt, J. G. Gonzalez, D. Grant, T. Grgoire, Z. Griffith, S. Griswold, M. Gnder, M. Gndz, C. Haack, A. Hallgren, R. Halliday, L. Halve, F. Halzen, K. Hanson, A. Haungs, S. Hauser, D. Hebecker, D. Heereman, P. Heix, K. Helbing, R. Hellauer, F. Henningsen, S. Hickford, J. Hignight, G. C. Hill, K. D. Hoffman, R. Hoffmann, T. Hoinka, B. Hokanson-Fasig, K. Hoshina, F. Huang, M. Huber, T. Huber, K. Hultqvist, M. Hnnefeld, R. Hussain, S. In, N. Iovine, A. Ishihara, M. Jansson, G. S. Japaridze, M. Jeong, K. Jero, B. J. P. Jones, F. Jonske, R. Joppe, D. Kang, W. Kang, A. Kappes, D. Kappesser, T. Karg, M. Karl, A. Karle, U. Katz, M. Kauer, A. Keivani, M. Kellermann, J. L. Kelley, A. Kheirandish, J. Kim, T. Kintscher, J. Kiryluk, T. Kittler, S. R. Klein, R. Koirala, H. Kolanoski, L. Kpke, C. Kopper, S. Kopper, D. J. Koskinen, P. Koundal, M. Kowalski, K. Krings, G. Krckl, N. Kulacz, N. Kurahashi, A. Kyriacou, J. L. Lanfranchi, M. J. Larson, F. Lauber, J. P. Lazar, K. Leonard, A. Leszczynska, Y. Li, Q. R. Liu, E. Lohfink, C. J. L. Mariscal, L. Lu, F. Lucarelli, A. Ludwig, J. Lnemann, W. Luszczak, Y. Lyu, W. Y. Ma, J. Madsen, G. Maggi, K. B. M. Mahn, Y. Makino, P. Mallik, K. Mallot, S. Mancina, I. C. Mari, S. Marka, Z. Marka, R. Maruyama, K. Mase, R. Maunu,

F. McNally, K. Meagher, M. Medici, A. Medina, M. Meier, S. Meighen-Berger, G. Merino, J. Merz, T. Meures, J. Micallef, D. Mockler, G. Moment, T. Montaruli, R. W. Moore, R. Morse, M. Moulai, P. Muth, R. Nagai, U. Naumann, G. Neer, L. V. Nguyen, H. Niederhausen, M. U. Nisa, S. C. Nowicki, D. R. Nygren, A. O. Pollmann, M. Oehler, A. Olivas, A. O'Murchadha, E. O'Sullivan, T. Palczewski, H. Pandya, D. V. Pankova, N. Park, P. Peiffer, C. P. d. l. Heros, S. Philippen, D. Pieloth, S. Pieper, E. Pinat, A. Pizzuto, M. Plum, Y. Popovych, A. Porcelli, P. B. Price, G. T. Przybylski, C. Raab, A. Raissi, M. Rameez, L. Rauch, K. Rawlins, I. C. Rea, A. Rehman, R. Reimann, B. Relethford, M. Renschler, G. Renzi, E. Resconi, W. Rhode, M. Richman, S. Robertson, M. Rongen, C. Rott, T. Ruhe, D. Ryckbosch, D. R. Cantu, I. Safa, S. E. S. Herrera, A. Sandrock, J. Sandroos, M. Santander, S. Sarkar, S. Sarkar, K. Satalecka, M. Scharf, M. Schaufel, H. Schieler, P. Schlunder, T. Schmidt, A. Schneider, J. Schneider, F. G. Schrder, L. Schumacher, S. Sclafani, D. Seckel, S. Seunarine, S. Shefali, M. Silva, R. Snihur, J. Soedingrekso, D. Soldin, M. Song, G. M. Spiczak, C. Spiering, J. Stachurska, M. Stamatikos, T. Stanev, R. Stein, J. Stettner, A. Steuer, T. Stezelberger, R. G. Stokstad, A. Stssl, N. L. Strotjohann, T. Strwald, T. Stuttard, G. W. Sullivan, I. Taboada, F. Tenholt, S. Ter-Antonyan, A. Terliuk, S. Tilav, K. Tollefson, L. Tomankova, C. Tnnis, S. Toscano, D. Tosi, A. Trettin, M. Tselengidou, C. F. Tung, A. Turcati, R. Turcotte, C. F. Turley, B. Ty, E. Unger, M. A. U. Elorrieta, M. Usner, J. Vandenbroucke, W. V. Driessche, D. v. Eijk, N. v. Eijndhoven, J. v. Santen, S. Verpoest, D. Veske, M. Vraeghe, C. Walck, A. Wallace, M. Wallraff, N. Wandkowsky, T. B. Watson, C. Weaver, A. Weindl, M. J. Weiss, J. Weldert, C. Wendt, J. Werthebach, B. J. Whelan, N. Whitehorn, K. Wiebe, C. H. Wiebusch, L. Wille, D. R. Williams, L. Wills, M. Wolf, J. Wood, T. R. Wood, K. Woschnagg, G. Wrede, J. Wulff, D. L. Xu, X. W. Xu, Y. Xu, J. P. Yanez, G. Yodh, S. Yoshida, T. Yuan, and M. Zcklein, "IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgos First Gravitational-wave Transient Catalog," *The Astrophysical Journal*, vol. 898, no. 1, p. L10, 2020.

[41] F. W. Stecker, "Ultrahigh energy photons, electrons, and neutrinos, the microwave background, and the universal cosmic-ray hypothesis," *Astrophysics and Space Science*, vol. 20, no. 1, pp. 47–57, 1973.

[42] V. Beresinsky and G. Zatsepin, "Cosmic rays at ultra high energies (neutrino?)," *Physics Letters B*, vol. 28, no. 6, pp. 423–424, 1969.

[43] M. Stockham, J. Macy, and D. Besson, "Radio frequency ice dielectric permittivity measurements using CReSIS data," *Radio Science*, vol. 51, no. 3, pp. 194–212, 2016.

[44] P. Allison, J. Auffenberg, R. Bard, J. Beatty, D. Besson, S. Bser, C. Chen, P. Chen, A. Connolly, and J. Davies, "Design and initial performance of the Askaryan Radio Array prototype EeV neutrino detector at the South Pole," *Astroparticle Physics*, vol. 35, no. 7, pp. 457–477, 2012.

[45] J. Hanson, *The Performance and Initial Results of the ARIANNA Prototype*. PhD thesis, University of California at Irvine, 2013.

[46] J. Ralston, "Radio surf in polar ice: A new method of ultrahigh energy neutrino detection," *Physical Review D*, vol. 71, no. 1, 2005.

[47] J. C. Hanson, "Broadband rf phased array design with meep: Comparisons to array theory in two and three dimensions," *Electronics*, vol. 10, no. 4, 2021.

[48] P. Allison, J. Alvarez-Muñiz, J. J. Beatty, D. Z. Besson, P. Chen, Y. Chen, J. M. Clem, A. Connolly, L. Cremonesi, C. Deaconu, P. W. Gorham, K. Hughes, M. Israel, T. C. Liu, C. Miki, J. Nam, R. J. Nichol, K. Nishimura, A. Novikov, A. Nozdrina, E. Oberla, S. Prohira, R. Prechelt, B. F. Rauch, Q. Abarr, J. M. Roberts, A. Romero-Wolf, J. W. Russell, D. Seckel, J. Shiao, D. Smith, D. Southall, G. S. Varner, A. G. Vieregg, S. A. Wissel, E. Zas, and A. Zeolla, "The Payload for Ultrahigh Energy Observations (PUEO): A White Paper," *arXiv*, 2020.

[49] P. W. Gorham et al, "Antarctic surface reflectivity measurements from the anita-3 and hical-1 experiments," *Journal of Astronomical Instrumentation*, vol. 06, no. 02, p. 1740002, 2017.

[50] E. Zas, F. Halzen, and T. Stanev, "Electromagnetic pulses from high-energy showers: Implications for neutrino detection," *Physical Review D*, vol. 45, no. 1, p. 362, 1992.

[51] R. V. Buniy and J. P. Ralston, "Radio detection of high energy particles: Coherence versus multiple scales," *Physical Review D*, vol. 65, no. 1, 2001.

[52] J. Aguilar, P. Allison, J. Beatty, H. Bernhoff, D. Besson, N. Bingefors, O. Botner, S. Buitink, K. Carter, B. Clark, A. Connolly, P. Dasgupta, S. de Kockere, K. de Vries, C. Deaconu, M. DuVernois, N. Feigl, D. García-Fernández, C. Glaser, A. Hallgren, S. Hallmann, J. Hanson, B. Hendricks, B. Hokanson-Fasig, C. Hornhuber, K. Hughes, A. Karle, J. Kelley, S. Klein, R. Krebs, R. Lahmann, M. Magnuson, T. Meures, Z. Meyers, A. Nelles, A. Novikov, E. Oberla, B. Oeyen, H. Pandya, I. Plaisier, L. Pyras, D. Ryckbosch, O. Scholten, D. Seckel, D. Smith, D. Southall, J. Torres, S. Toscano, D. V. D. Broeck, N. van Eijndhoven, A. Vieregg, C. Welling, S. Wissel, R. Young, and A. Zink, "Design and sensitivity of the radio neutrino observatory in greenland (RNO-g)," *Journal of Instrumentation*, vol. 16, p. P03025, mar 2021.

[53] A. Fedeli, C. Montecucco, and G. L. Gragnani, "Open-Source Software for Electromagnetic Scattering Simulation: The Case of Antenna Design," *Electronics*, vol. 8, no. 12, p. 1506, 2019.

[54] Allen Taflove and Susan C. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method, 3rd ed.* Boston: Artech House, 2005.

[55] S. Prohira, C. Sbrocco, P. Allison, J. Beatty, D. Besson, A. Connolly, P. Dasgupta, C. Deaconu, K. D. d. Vries, S. D. Kockere, D. Frikken, C. Hast, E. H. Santiago, C. Y. Kuo, U. A. Latif, V. Lukic, T. Meures, K. Mulrey, J. Nam, A. Novikov, A. Nozdrina, J. P. Ralston, R. S. Stanley, J. Torres, S. Toscano, D. V. d. Broeck, N. v. Eijndhoven, and S. Wissel, "Modeling in-ice radio propagation with parabolic equation methods," *arXiv*, 2020.

[56] G. Yang, S. Ye, F. Zhang, Y. Ji, X. Zhang, and G. Fang, "Dual-Polarized Dual-Loop Double-Slot Antipodal Tapered Slot Antenna for Ultra-Wideband Radar Applications," *Electronics*, vol. 10, no. 12, p. 1377, 2021.

[57] F. Pizarro, R. Salazar, E. Rajo-Iglesias, M. Rodriguez, S. Fingerhuth, and G. Hermosilla, "Parametric Study of 3D Additive Printing Parameters Using Conductive Filaments on Microwave Topologies," *IEEE Access*, vol. 7, pp. 106814–106823, 2019.