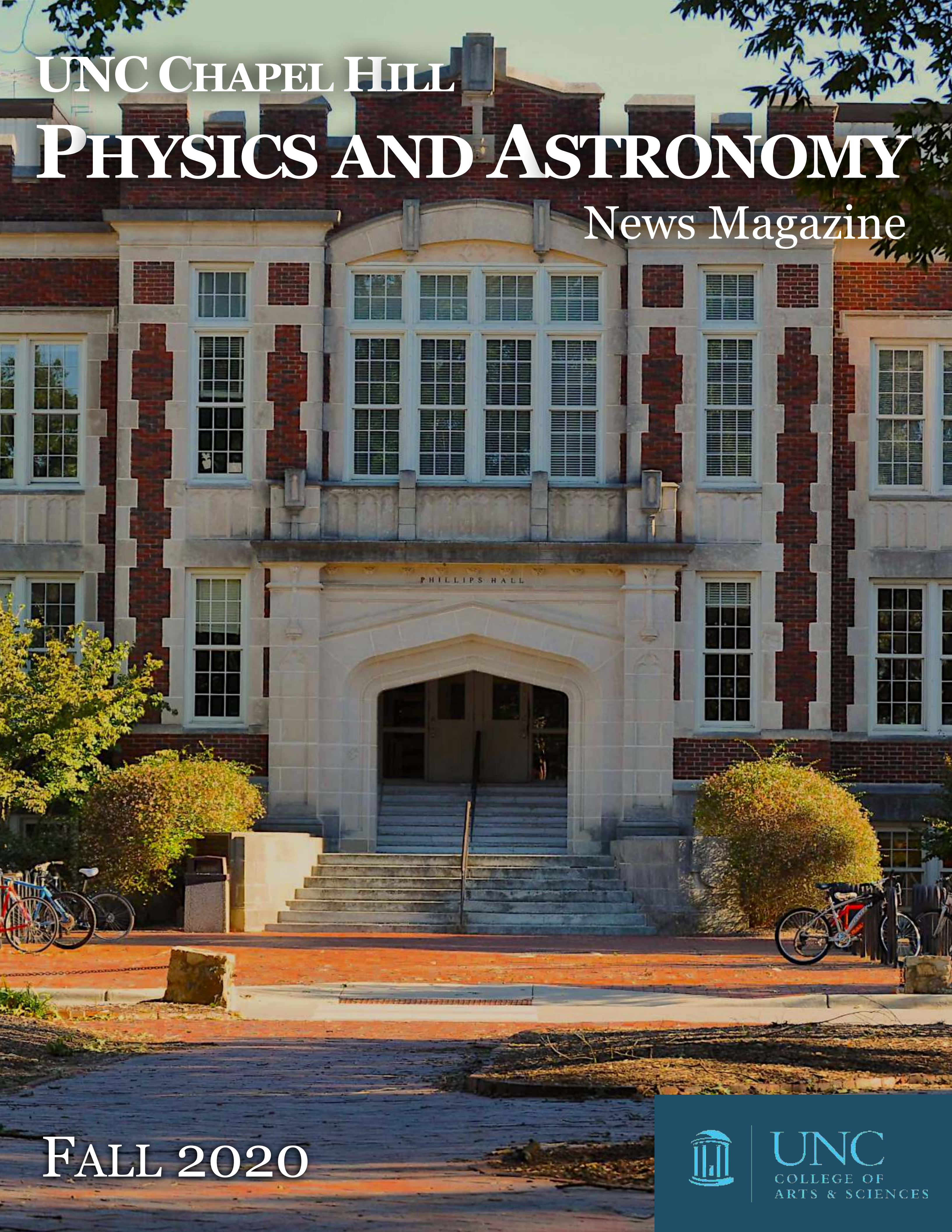
UNC Chapel Hill
Physics and Astronomy
News Magazine



Fall 2020

UNC
COLLEGE OF
ARTS & SCIENCES

Fall 2020

online
physics.unc.edu

Our Department in numbers:

34	Tenure-line faculty
6	Teaching faculty
4	Research faculty
11	Academic support staff
4	Instrument shop personnel
11	Elected Fellows of the APS, AAAS, SPIE, or AIMBE
85	Graduate students
7	Postdoctoral scholars
5800	Annual course enrollment
13269	Credit hours taught in 2019
200	Majors

UNC COLLEGE OF ARTS & SCIENCES

Physics and Astronomy
News Magazine

***On the cover**: the façade of Phillips Hall, home to our Department.*

Contents

Plus

Questions? Comments? Contact us: ambeck@email.unc.edu

From the **Chair**

The state of our department in the era of COVID19
By Christian Iliadis

You have heard it many times: life as we know it has changed. The pandemic continues to produce uncertainty and stress in our community. Despite the challenges we all face every day, this is also a time that is bringing out the best in our faculty, staff, and students. We are proud to play an important role in this fight, by demonstrating continued excellence in research, teaching, and service.

I hope that you will enjoy the new format of the newsletter. Our department's achievements over the past year look like small miracles to me. Despite significant budget constraints, we increased the size of our faculty to 44, which represents the highest number we have ever had in Physics & Astronomy. We also succeeded in hiring world-class faculty: Distinguished Professor Robert Janssens is the former director of the Physics Division at Argonne National Laboratory; Professors Gökçe Basar, Julieta Gruszko, and Akaa Daniel Ayangeakaa are outstanding junior faculty, who joined us from the University of Illinois at Chicago, the Massachusetts Institute of Technology, and the United States Naval Academy in Annapolis, respectively. A number of our faculty have received national recognition for their research. And to top it off, our entire department won this year's award for teaching innovations from the American Physical Society.

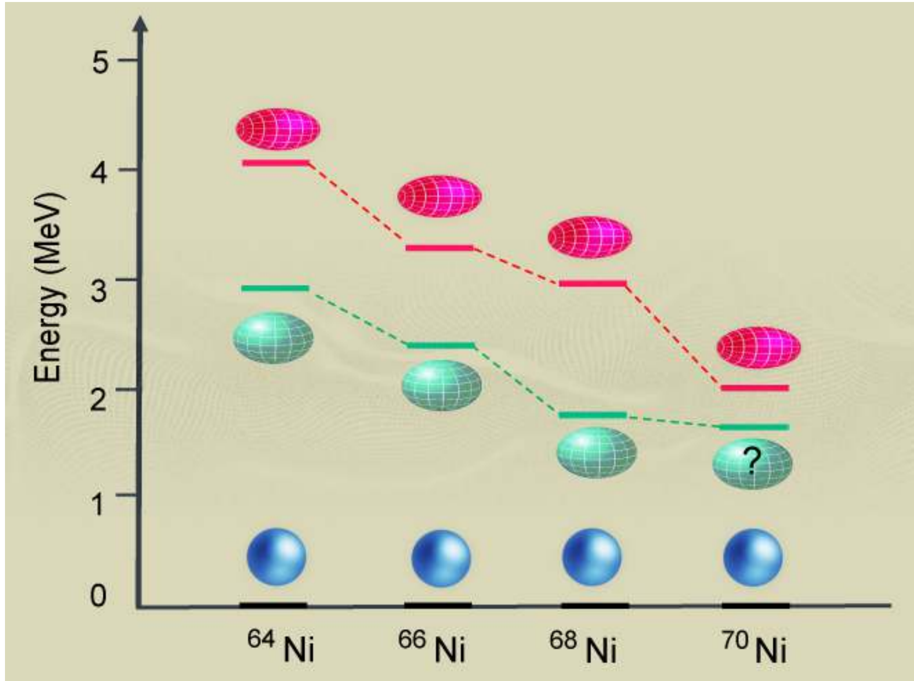
We do not know what the future holds. But we do know that we are all in this together and we encourage you to reach out to us at any time. Please stay safe and healthy. And thank you for your support.

Best wishes,
Christian Iliadis
Chair, UNC-CH Physics & Astronomy

Nuclear structure at the edge of stability

By Akaa D. Ayangeakaa and Robert V. F. Janssens

A major challenge for nuclear structure physics is to develop a comprehensive description of nuclei with particular emphasis on how they are assembled, why some are stable, and others are not, how they interact with each other and what is the nature of the driving force behind the rich diversity of nuclear phenomena. Internally, the atomic nucleus, made out of protons and neutrons, is a typical mesoscopic system. It is characterized by so few variables that a full statistical treatment is impossible, but also too many for an exact quantum mechanical description. The strong nuclear force that binds nuclei leads to a fascinating picture where the protons and neutrons manage to organize themselves and interesting phenomena emerge such as the appearance of nucleonic shells, of collective nuclear vibrations and rotations, superfluidity, and shape/ phase transitions.



Evolution of nuclear shapes in the nickel isotopic chain: the ground states are always spherical (blue), but oblate shapes (green) and prolate (red) are present as well and their location in energy varies with the number of neutrons. Note that the our earth is oblate, while the American football is prolate.

As with any quantum system, subjecting nuclei to extreme conditions in energy and angular momentum often results in exciting new features and insights. The research performed within the recently-established nuclear structure group at UNC/TUNL is focused on understanding how shell structure evolves with proton and or neutron number, quantifying the impact of this shell evolution on global nuclear properties such as nuclear shape, mass and binding energy. This research is organized under several subthemes, the most prominent being the establishment of a viable nuclear structure program at the local High Intensity Gamma Ray Source (HIγS) to complement the group's research activities at national and international user facilities. Other goals include (a) exploring the microscopic origin of the changes in shell structure found in exotic neutron-rich nuclei, and tracing the signatures of these interactions back to the stable systems; (b) addressing issues of relevance for UNC/TUNL-driven research programs in nuclear astrophysics and fundamental interactions; (c) expanding the scientific breath of the research portfolio through specific collaborations with other scientists using HIγS and other TUNL facilities for world-class research; and (d) developing new instrumentation for the research programs at TUNL, particularly at HIγS, while also contributing in the design and construction of equipment for use at other facilities such as the Facility for Rare Isotopes Beams (FRIB), which is located on the campus of Michigan State University and Argonne national laboratory's ATLAS/CARIBU facility.

The group's focus is on the low-excitation structure of medium- and heavy-mass nuclei, with emphasis on the evolution of nuclear shells as a function of proton and neutron number. For example, recent work has investigated the three distinct shapes nickel isotopes can adopt.

In stable nickel-64, three such shapes have now been identified in an extensive experimental effort. The lowest-energy state is spherical, but an elongated (prolate) and flattened (oblate) nuclear shape have been established at slightly higher excitation energies, as illustrated in the figure. Their presence indicates profound changes in the way protons and neutrons can arrange themselves and such observations constitute formidable benchmarks for nuclear theory in its quest for a predictive model of nuclei. From the figure, it is obvious that the energy associated with each shape changes as a function of neutron number. Combined with the exploration of different nuclear shapes in the germanium region, the group's work not only directly impacts the understanding of nucleosynthesis in heavy nuclei, but also provides nuclear data required for the description of neutrinoless double beta decay, a fundamental mode of decay studied by another group at UNC/TUNL (see article by Julieta Gruszko below). Additional efforts focus on studies of other properties such as the thickness of a neutron skin and its modes of oscillation with respect to the entire nucleus.

"…The strong nuclear force that binds nuclei leads to a fascinating picture where the protons and neutrons manage to organize themselves and interesting phenomena emerge…"

Research by the nuclear structure group combines measurements performed locally with others carried out at national and international user facilities. At TUNL's high intensity γ-ray source (HIγS), located on the Duke campus, nuclear resonance fluorescence (NRF) measurements exploit the world-unique availability of nearly monoenergetic, linearly polarized γ-ray beams. These enable researchers to scan nuclear excitations from the ground state to the particle emission threshold and beyond, and unambiguously determine with high precision the properties of the observed states. The original NRF experimental setup at HIγS has recently been significantly upgraded by the group. The new "Clover Array" setup provides enhanced capabilities to carry out high-statistics experiments as well as sub-nanosecond timing measurements. The array has been assembled by a collaboration between UNC/TUNL scientists, research groups from the Lawrence Livermore and Argonne National Laboratories as well as from the TU Darmstadt, Germany. Researchers from 32 institutions (11 US + 21 international) have expressed strong interest in using the device.

Akaa Daniel Ayangeakaa joined us in the summer of 2020 from the US Naval Academy (USNA), where he was an Assistant Professor. He obtained his Bachelor's degree in Physics at Benue State University in Nigeria and a Masters degree in radiation and environmental protection from the University of York in the United Kingdom. He obtained his PhD in nuclear structure at the University of Notre Dame, focusing on exotic modes of collective excitation such as rotations and vibrations. He was a postdoc at Argonne National Laboratory (ANL), and a visiting research fellow at the University of Maryland before joining USNA. Daniel works on understanding how nuclear shapes evolve in proton- and neutron-rich systems, and quantifying how this impacts nuclear properties.

Robert V. F. Janssens joined us in Fall 2018. He earned his PhD from the Catholic University of Louvain, Belgium, in 1978. After a few years as a research associate at the University of Groningen, The Netherlands, he moved to Argonne National Laboratory, where he pursued a steep career path. During 2000-2007, he had been the Scientific Director of the ATLAS facility, and during 2008-2017 he held the top-level position of Director of the Physics Division at Argonne National Laboratory. He is a world-renowned nuclear physicist, who has published more than 650 peer-reviewed papers in top journals.

Exoplanets across space and time

By Andrew Mann

We are used to a relatively constant Earth; to a distant observer our planet is a constant blue-green ball wrapped in white clouds. However, this apparent consistency is a consequence of our short lifetimes. Earth, like all planets in the Solar system, has changed dramatically over its lifetime. From its formation with a boiling-hot surface, with no Moon, and with a toxic atmosphere of hydrogen and helium, the atmosphere, surface, temperature, and appearance we recognize today are a byproduct of billions of years of gradual transformations.

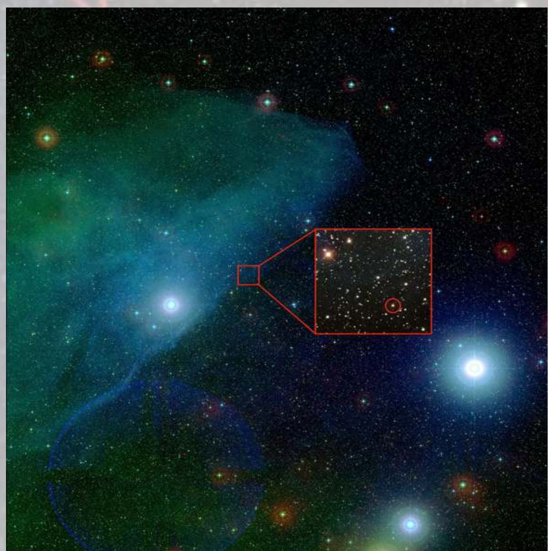
"The long-term goal is to learn what kind of early conditions gave rise to potentially habitable planets, put our own history in a Galactic context, and explore what makes Earth's history unique."

For planets around other stars, change is also the norm. In their young formative years, exoplanets can lose and re-form new atmospheres, migrate from a distant outer orbit to one right next to their host star, and undergo thousand-degree shifts in surface temperatures. These and similar evolutionary changes are driven largely by the planet's environment. Gravitational interactions and collisions with other nearby planets are common when planets are young, harsh stellar winds and flares common to young stars often strip planets of their tenuous atmospheres, and dust and debris left over from the planet-forming process can drag planetary bodies closer to their host star or eject it the from the system entirely.

These sculpting processes are most active when the planet is young (tens or hundreds of millions of years old) and take millions of years to noticeably alter a planetary system. We cannot observe the changes to exoplanets in real time. Instead, we compare the properties of planets with varying ages. Differences between the properties of ten-million-year-old planets and billion-year-old planets (and everything in between) are our most powerful tool for understanding the physical drivers and timescales for planetary evolution.

The challenge is finding planets around young stars with known ages. My team focuses on young associations of stars that formed together and have a common age. NASA's *K2* and *TESS* missions observe these associations for weeks or months measuring the brightness of each star every 2 minutes. We then mine through hundreds of thousands of the resulting light curves looking for the occasional drops in brightness that indicate the presence of a planet passing in front of its young stellar host (called a transit). This work requires careful removal of variations in brightness due to dark spots on the surface of the star, flares, and other variations that are ubiquitous in the light curves of young stars and mimic or mask transits.

There has been an explosion in the detection of young planets in recent years; the sample has helped explain how exoplanets lose atmosphere and migrate close to their host star at young ages. With the launch of the *James Webb Space Telescope*, we will soon get our first glimpse into the atmospheres of young Earth-sized planets (proto-Earths). The long-term goal is to learn what kind of early conditions gave rise to potentially habitable planets, put our own history in a Galactic context, and explore what makes Earth's history unique.



The young association Sco-Cen, a collection of 10-25 million-year-old stars surveyed by both K2 and TESS missions. The zoomed-in region shows the star K2-33, a 10 million-year-old star harboring a giant transiting planet.

Faculty Spotlight

Andrew Mann joined us in 2018 from a Hubble Fellowship at Columbia University before which he was the Harlan J. Smith Postdoctoral Fellow at the University of Texas at Austin. He received his Ph.D. from the University of Hawaii at Manoa. His research is focused on understanding how planets evolve over their lifetimes and the fundamental properties of low-mass and young stars. His group uses large surveys like the *K2* and *TESS* missions to identify young planets. Such systems offer a unique insight into the important early physical processes that sculpt and shape older planets and can tell us which early factors are important in the formation of Earth-like and potentially habitable planets. Mann's research uses a variety of ground-based facilities, including SOAR and the twin Keck telescopes, to follow targets identified from these missions and better characterize the properties of the planets and their stellar hosts. Mann's team also works on inferring properties of the bulk planet population (e.g., planet occurrence). Because of the size of the datasets involved, his team specializes in advanced computational and statistical methods to merge large collections of noisy and contaminated data. Recently, Mann's team has become involved in the design and launch of small satellites (Cubesats and Smallsats) for studying young stars and exoplanets with dedicated missions at lower cost compared to large-scale missions like *Kepler* and *TESS*. When not searching for planets, Mann is looking for the best hiking spots.

Mann's Lab: Student profile

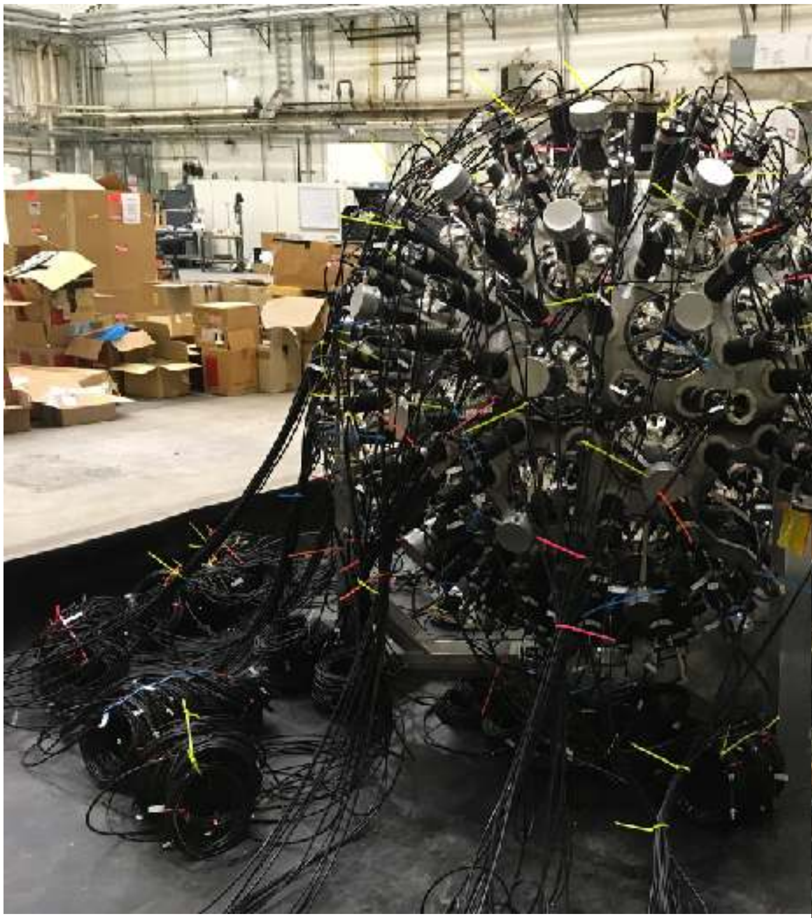
Pa Chia Thao is a National Science Foundation Graduate Research Fellowship recipient and a Jack Kent Cooke Graduate Scholar. She joined Dr. Mann's lab in 2018 before starting graduate school at UNC in 2019. Her research focuses on characterizing the atmosphere of young exoplanets through their transit depth as a function of wavelength (transmission spectroscopy). She uses ground-based facilities (SOAR and Keck) and space-based telescopes (K2, Spitzer, and HST) to understand how planetary atmospheres change with time. In the spring semester 2021, she will be joining the Flatiron Institute Center for Computational Astrophysics in New York as a PreDoctoral Fellow, where she will use artificial intelligence to mine TESS data for young planetary systems.

***Below**: Pa Chia during a visit to the Kitt Peak observatory in Arizona.*

Faculty Spotlight

Julieta Gruszko joined us in Spring 2020 from MIT where she was a Pappalardo Postdoctoral Fellow. Her research is focused on understanding the nature of the neutrino, a type of fundamental particle, using precision experiments that search for a rare type of nuclear decay called neutrinoless-double beta decay (NDBD). The detection of this as-yet unobserved process would prove that the neutrino is its own anti-particle and provide deep insights into the very origin of matter in the Universe. To this end, she is involved with the MAJORANA DEMONSTRATOR (MJD), LEGEND, and NuDot experiments. MJD and LEGEND use enriched germanium detectors fielded in ultra-low radioactive background experiments located deep underground in the Sanford Underground Research Facility in South Dakota and INFN Gran Sasso National Laboratory (LNGS) in Italy.

Julieta leads the **NuDot experiment**, which is a long-term effort to develop future generations of very large scintillator-based neutrino experiments that will continue the study of NDBD to even greater precision. NuDot will be located at the Triangle Universities Nuclear Laboratory (TUNL) before being moved underground for a proof-of-concept measurement of two-neutrino double-beta decay.



The NuDot experiment, led by Julieta Gruszko, currently at the Triangle Universities Nuclear Laboratory (TUNL)

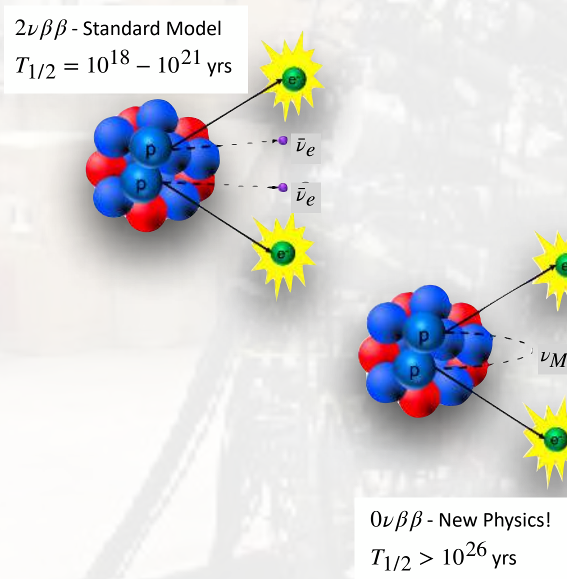
Matter, anti-matter, NuDot, and the future of neutrinoless double-beta decay detection

By Julieta Gruszko

Why is the universe dominated by matter, and not antimatter? Neutrinos, with their changing flavors and tiny masses, could provide an answer. If the neutrino is its own antiparticle, it would reveal the origin of the neutrino's mass, demonstrate that lepton number is not a conserved symmetry of nature, and provide a path to create the matter-filled universe we see. To discover whether this is the case, we must search for **neutrinoless** double-beta decay (0vββ).

Certain isotopes can undergo two-neutrino double-beta decay (2vββ), where two neutrons transform into two protons, emitting two electrons and two antineutrinos (see top of the diagram). This process is extremely rare; it took physicists 50 years to finally detect it! When 2vββ occurs, we only detect the electrons; the anti-neutrinos escape, carrying away some energy.

If the neutrino is a Majorana particle, meaning that it is its own antiparticle, an even rarer process could occur: the two anti-neutrinos could annihilate inside the nucleus instead of being emitted, leading to 0vββ (shown at the bottom of the diagram). In this case, all of the energy of the decay would go into the electrons, with none of the energy escaping our detectors. The signature would be a sharp peak in energy. 0vββ experiments search for this sharp peak, while trying to eliminate backgrounds from all other sources of radioactivity.



The Majorana nature of the neutrinos could explain their small but non-zero masses. Most excitingly, Majorana neutrinos could provide a pathway to making a matter-antimatter imbalance in the early universe that survives to this day, giving us a world full of "stuff."

"Large liquid scintillators represent a promising technology if we need to scale 0vββ experiments to masses larger than 1 ton."

To discover 0vββ, experiments must have large masses of the source isotope, low radioactive backgrounds, and high detection efficiency. Having a good energy resolution helps reduce backgrounds and maximize discovery potential.

Large liquid scintillators represent a promising technology if we need to scale 0vββ experiments to masses larger than 1 ton. As we move to these kiloton-scale experiments, however, we encounter a potentially higher radiation background, which scales with the volume of the detector, for example, scattering of solar neutrinos. One way to reject these background events is to count the number of charged particle tracks — 0vββ features two electrons, and these background events have just one outgoing electron. In a liquid scintillator, the electrons move faster than the speed of light, emitting directional "shockwaves" of Cherenkov light along their direction of travel. Using fast-timing photomultiplier tubes, we can distinguish this light from the far-more-abundant and isotropic scintillation light.

NuDot (see photos on previous page) is a half-ton proof-of-concept liquid scintillator experiment to test the techniques we'll need to build kiloton-scale detectors that aren't limited by backgrounds. Other work on NuDot focuses on the development of new fast-timing photodetectors and data acquisition systems, testing quantum dots as wavelength shifters and as a means to load the double-beta decay isotope, and on developing machine learning algorithms for event recognition.

Matter at the extremes of temperature and density

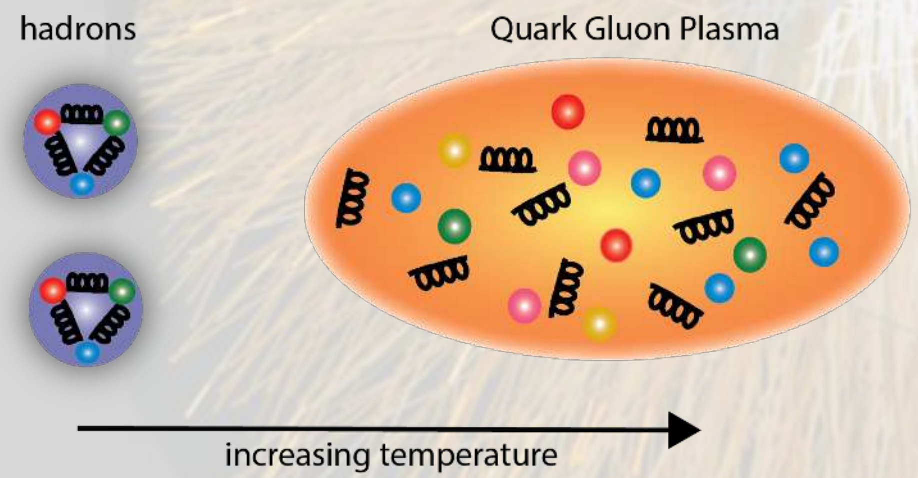
By Gökçe Basar

What are the properties of matter at extremely high temperatures and densities, namely: what happens to matter at temperatures around 10^{12} K? Since the early 1900s we have known that almost all the mass of an atom is concentrated in a small region called the nucleus, which is composed of nucleons (proton and neutrons). And since the mid-1970s, we have known that the nucleus also has constituents: quarks and gluons. These constituents are strongly bound, or "confined", within nucleons and are never observed free in nature.

At temperatures around 10^{12} K, the thermal energy is high enough to overcome the binding energy between quarks and liberate them. When the bonds that hold nucleons together are broken by the thermal energy, the nucleon melts and forms a new phase of matter known as **Quark Gluon Plasma** (QGP) where quarks and gluons roam freely. QGP filled the Universe microseconds after the Big Bang, and as the universe expanded and cooled down, it formed nuclei and eventually, ordinary matter as we know it. Even though we have the theory that governs the physics of quarks and gluons, **Quantum Chromo Dynamics** (QCD), the properties of different phases of quarks and gluons, including the phase transition between QGP and hadrons (particles composed of two or more quarks, such as protons and neutrons) remain largely unknown. My main goal is to shed light on the phase diagram of QCD (see sketch on next page).

First of all, how do we create QGP in a laboratory? Arguably, recreating the Big Bang in a laboratory is neither very practical nor safe. Instead, the idea is to create a "little bang" by accelerating heavy nuclei, such as lead or gold, up to approximately 0.99998% of the speed of light and collide them. These experiments are done at the Relativistic Heavy Ion Collider (RHIC) in Brookhaven National Laboratory and at the Large Hadron Collider at CERN. The collision creates an explosion where the temperature reaches 10^{12} K and forms QGP. The resulting fireball of QGP is approximately 10^{-45} Km^3 in size and exists for around 10^{-23} seconds. After the collision, the fireball expands in space. As it expands, it cools down and QGP eventually turns into hadrons–just like during the early universe. By measuring the trajectories and distributions of these final state hadrons, we obtain information about QGP. This is possible because unlike **the** Big Bang, billions of such little bangs are created in these experiments.

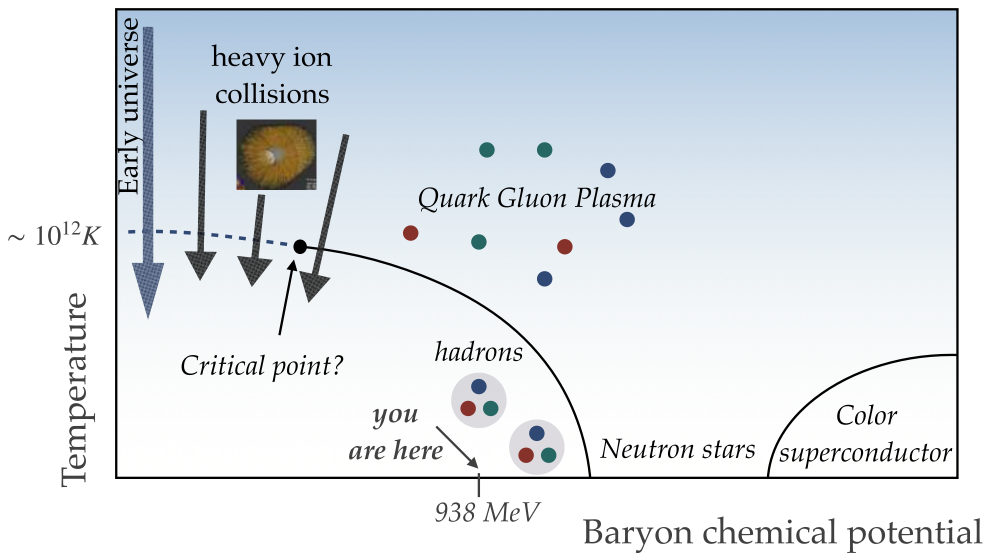
A major outstanding question at the moment is whether there is a singular point along the QGP/hadron phase transition curve where certain thermodynamic functions diverge, known as a critical point. Critical points are ubiquitous in nature, water being a textbook example. The boiling temperature of water increases with pressure, up to a particular value, above which boiling ceases to exist and vapor and liquid water cannot be separated from each other. The existence of a similar point in QCD which separates a smooth QGP/hadron transition from a first order transition (or " boiling") has been conjectured and is a major focus of the heavy ion program. I am currently working on developing theoretical tools to describe the physics of QGP near the critical point and come up with experimental observables that may signal the critical point in order to assist with the experimental efforts.



Matter behaves very differently near a critical point. The magnitude of thermal fluctuations grows and it takes longer for the system to reach equilibrium. Therefore, understanding the out-of-equilibrium properties of QGP is crucial for understanding the physics near the critical point, which constitutes an important part of my research.

With Xin An, a postdoctoral associate here at UNC, I have been developing a new framework where relativistic hydrodynamics are expanded to include out-of-equilibrium modes and critical fluctuations. With two other collaborators at the University of Illinois at Chicago, Misha Stephanov and Ho-Ung Yee, we have developed the most general hydrodynamic theory that incorporates quadratic out-of-equilibrium fluctuations. We are working on expanding it even further to account for higher order, non-gaussian fluctuations. Shuo Song, a UNC grad student, will be joining these research efforts next semester.

Given that the equations of QCD were discovered in the mid-1970s, why don't we just solve them and settle the question of the critical point? Unfortunately this is not possible. Due to the absence of a small parameter in these equations, it is not possible to solve them with paper and pencil. Instead, we run simulations on powerful supercomputers. However, these simulations cannot be used to study QCD at finite density due to a notorious computational obstacle known as the "sign problem." Yet this is the region which is believed to contain the critical point and is being explored by the heavy ion collisions. In the last five years, I have been developing a new framework to tackle the sign problem, which connects quantum field theory, various branches of mathematics such as topology, and various computational techniques. I have organized several workshops on this subject, bringing together nuclear physicists, mathematicians, and computational physicists – a rather unusual mix – which led to very fruitful collaborations. There remain many unanswered questions, however, which also means a lot of exciting work left to be done! Graduate students Joe Marincel and Kevin Knox are joining me in these research efforts.



Gökçe Basar joined us in 2019 from the University of Illinois at Chicago, where he was a Visiting Research Assistant Professor. Before that, he was a Postdoctoral Research Associate at the Maryland Center for Fundamental Physics and at Stony Brook University. Gökçe got his PhD at the University of Connecticut and his BS in Physics at the Middle East Technical University in Ankara, Turkey. His work focuses on understanding the dynamics of strongly interacting systems, with an emphasis in theoretical nuclear and particle physics. He explores non-perturbative aspects of quantum field theory by using and developing a variety of tools ranging from the more mathematical to the more computational and everything in between. Gökçe is especially interested in the critical phenomena around the QCD phase transition that separates the quark gluon plasma phase from ordinary matter, which is probed in heavy-ion collision experiments.

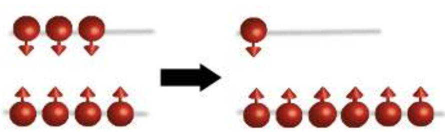
Branca Lab

Enhancing NMR sensitivity through nuclear hyperpolarization

By Tamara Branca

For the past 10 years, my work has focused on nuclear spin hyperpolarization techniques used to overcome the inherent sensitivity limitations of Nuclear Magnetic Resonance (NMR) and Magnetic Resonance Imaging (MRI). Almost 99% of MRI and NMR techniques are based on the detection of the nuclear spin of ^1H atoms, which are present at a very high concentration in tissues (tens of molar) in form of water.

When we **hyperpolarize** nuclear spins, we essentially increase the net magnetic field they produce by increasing their polarization, i.e. the difference in population between their energy levels.



With modern hyperpolarization techniques, the increase in nuclear spin polarization can be several orders of magnitude greater than what can be achieved at room temperature in clinical MR systems, enabling the detection of atoms and molecules other than ^1H that are present at a much lower concentration (milli-or micro-molar).

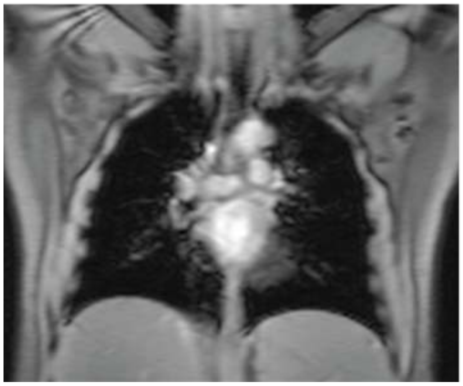
These techniques have greatly enhanced the potential of MRI over the past decade as a diagnostic tool, enabling new applications ranging from monitoring cancer metabolism to mapping lung function at the millimeter scale. In collaboration with the Center for Cystic fibrosis at UNC, our lab is currently using hyperpolarized Xe gas as a contrast agent for MRI to assess lung ventilation function in patients with cystic fibrosis (CF) (see images on next page). Considering that most CF patients are young and often need several x-ray scans over their lifetime, the lack of ionizing radiation of MRI coupled with the high sensitivity of hyperpolarization techniques is ideal to reduce radiation exposure.

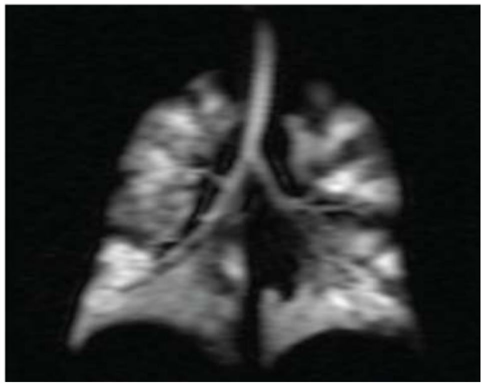
"Low-field NMR and MRI systems are becoming more and more popular as they are cheaper, portable, and often safer."

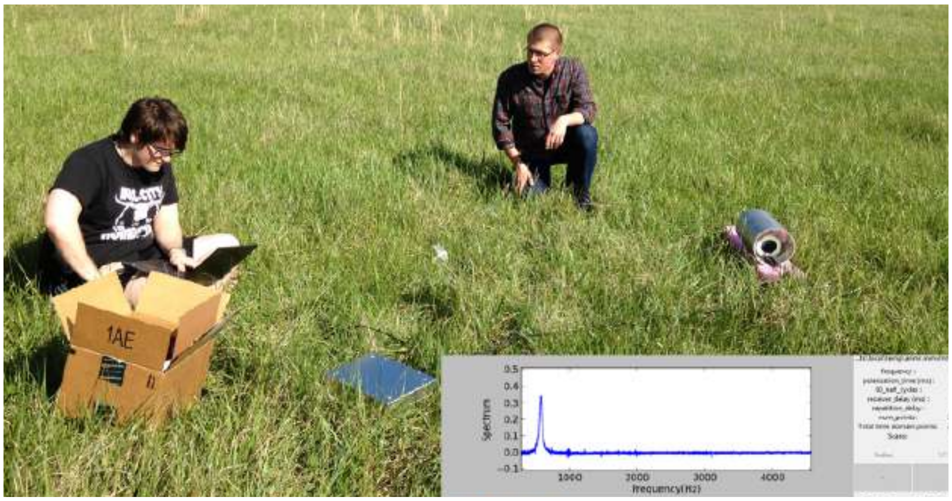
However, each hyperpolarization technique comes with its own unique challenges. For gas hyperpolarization, for example, one of the major challenges has been the low performance of currently available continuous-flow Spin Exchange Optical Pumping (SEOP) systems used to produce high quantities of highly polarized Xe gas needed for biomedical imaging applications. Experimental xenon polarization values have been notoriously much lower than what the standard theory predicts.

In the past, both our group and others have focused on depolarization mechanisms to understand the discrepancy between theoretical and experimental polarization values, but without much success. More recently, our group has taken a different approach. We have begun to question and evaluate the validity of the many assumptions made to adapt the general theory of SEOP (developed by UNC alumnus William Happer) to continuous flow SEOP setups. This work, led by Michele Kelley (see "student profiles" below), a fourth-year graduate student in my lab, is finally providing a better understanding of the discrepancy.
As in any other field, only when we have a good theoretical model, that is able to correctly reproduce experimental results, can we hope to make some progress.

My lab is also involved in studying the properties of hyperpolarized spin systems at low and ultra-low magnetic fields. Low-field NMR and MRI systems are becoming more and more popular as they are cheaper, portable, and often safer. For hyperpolarized nuclei, low field systems may even be more sensitive than high field systems,







Top left: *A standard* ¹H *MRI image of the chest of a young CF patient acquired at UNC-CH. The lungs cannot be seen because of their low water content and because of the many air tissues interfaces, which lead to the rapid decay of the small MR signal.* ***Top right***: *Hyperpolarized Xe gas MRI of the lungs of the same subject. Areas of the lungs that are poorly ventilated (dark regions) are clearly displayed. As opposed to standard pulmonary function tests that provide only a global measure of airflow obstruction and restriction, MRI with hyperpolarized xenon gas is more sensitive to early lung disease as it provides regional information about lung function and structure.* ***Bottom***: *Christian Browning (left), a former Physics undergraduate, with Michael Antonacci (right), a former graduate student in the Branca lab, and now a faculty member in the Physics Department at San Vincent College, testing the portable Earth field NMR spectrometer built by Christian in an open field just outside campus.*

but the opportunities of MRI with hyperpolarized nuclei at low field are largely unexplored.

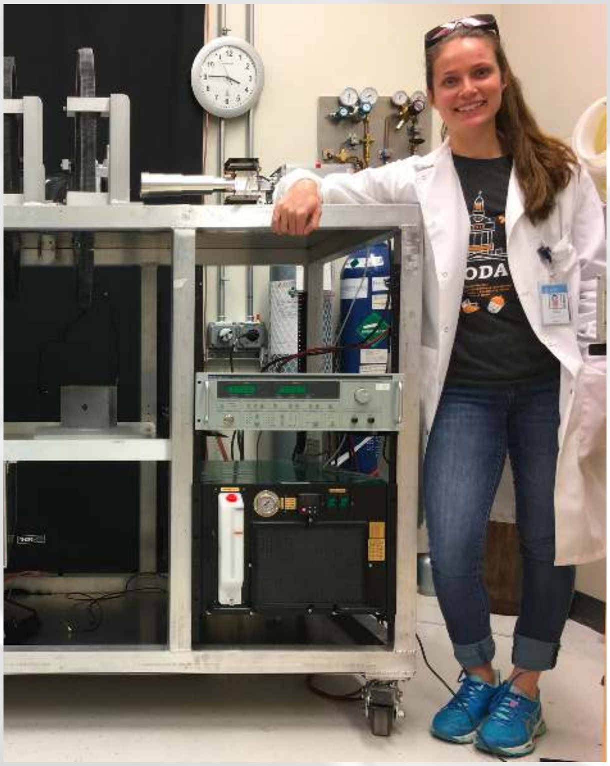
One of the research projects in my lab, led by Nick Bryden (see "student profiles" below) is focused on studying the magnetic properties of hyperpolarized Xe dissolved in biological tissues at low magnetic field strengths. Longer relaxation times of xenon at ultralow fields could open the doors to what we call "dissolved-phase" imaging, i.e. imaging of Xe atoms that, upon inhalation, dissolve in blood and tissues, changing their resonance frequency based on the chemical environment they probe. Nick took over the work started by Michael Antonacci, a former graduate student in my lab, and now a faculty member in the Physics Department at San Vincent College. Michael built, from scratch, an NMR spectrometer operating in the micro-Tesla to milli-Tesla range, a field that is several orders of magnitude smaller than that produced by superconducting magnets in typical clinical MRI systems. This is something that students working in an NMR lab rarely get to do, as these spectrometers are often treated as black boxes. It took a few months to build and debug a working spectrometer that could be used to detect the extremely small signal produced by the nuclear spins of hydrogen atoms at such low field. Anything from the power line in the nearby walls to a running laptop will produce noise that is orders of magnitude greater than the signal of interest.

"…there is something empowering for students to build their own detector from scratch and then use it to perform scientific experiments."

Along the same lines, several undergraduate students in my lab have worked on cheap (less than $100) spectrometers that could detect the nuclear spin signal at the very weak magnetic field of the Earth. Undergraduate students working for my lab have been building these spectrometers essentially from the ground up.

Despite the many setbacks that they faced along the way, there is something empowering for students to build their own detector from scratch and then use it to perform scientific experiments.

Branca Lab
Two student profiles

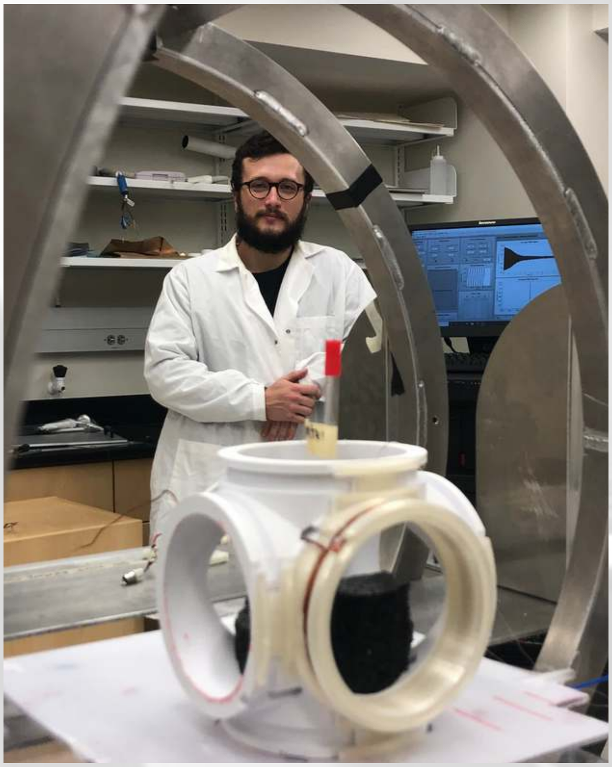


Michele Kelley

I am a fourth-year graduate student in the Branca Lab, a Royster Fellow, and the recipient of an NSF Fellowship. My work focuses on the hyperpolarization of ^{129}Xe nuclear spins for nuclear magnetic resonance spectroscopy (NMR) and imaging (MRI). Specifically, I am interested in understanding why theoretical models of ^{129}Xe hyperpolarization, which is done through a process called Spin-Exchange Optical Pumping (SEOP), have historically predicted much higher Xe polarization values than what we achieve experimentally. This has been an open question in my field for over 20 years. To answer this question, I have used a combination of experimental and computational techniques, as well as reevaluating some of the assumptions made in these models and I believe that finally we have an answer to why our theoretical models were so poor. The next step in my research is to use the computational tools I developed to optimize the design of a more efficient ^{129}Xe polarizer. In addition to my research, I also serve on the Graduate Studies and Affairs Committee, as a department media co-chair, and mentor in the new GRAM program.

Nick Bryden

I am a third-year graduate student and the recipient of an NSF Fellowship. My research is on the magnetic properties of hyperpolarized nuclei at ultra-low field (ULF) strengths. The insensitivity of NMR has necessitated the use of large magnetic fields to produce detectable signals from samples like the water in our bodies. Using hyperpolarized nuclei, like ^{129}Xe, this requirement is far less stringent, allowing the use of more space and cost-effective equipment. We have constructed an NMR spectrometer which operates at field strengths up to 100,000 times weaker than those used in conventional MR scanners. In this regime, many of the relaxation properties of ^{129}Xe are under-explored or unknown. Many of these are linked to its performance as an agent for MR imaging, which has been well characterized in high-field studies. We hope to further develop our spectrometer by adding imaging capabilities to extend this characterization into the ULF regime. The combined used of hyperpolarized nuclei and ULF MR is expected to drastically reduce the cost of medical imaging and introduce a level of portability otherwise unknown to the practice.



The Physics and Astronomy Education Research Group

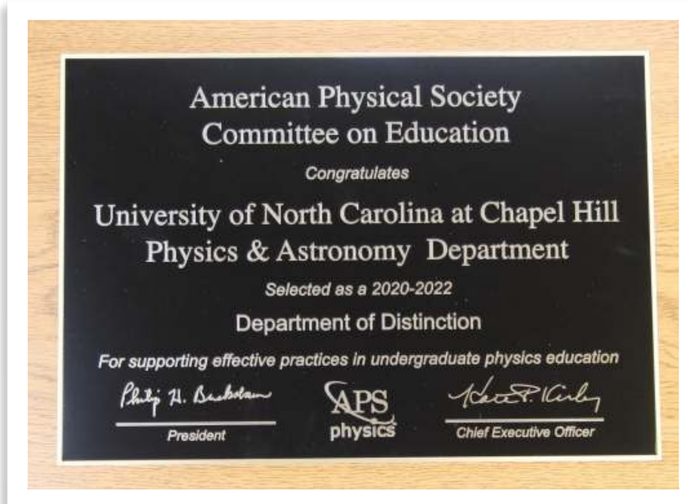
Multi-year effort recognized by APS

The work of the Physics and Astronomy Education Research (PAER) Group, in collaboration with numerous faculty from the Department of Physics and Astronomy, has been recognized by an Award for **Improving Undergraduate Education** from the American Physical Society. The award, which goes to no more than three of the 761 physics departments in the US each year, recognizes departments who use the best practices for teaching physics and achieve excellence in the education of undergraduates.

The department received this award because of its successful multi-year effort to boldly restructure its introductory physics courses. From 2004 to 2014, with funding from the National Science Foundation and the Association of American Universities, the department, led by the PAER Group, completely transformed all aspects of these courses, as well as how instructors are trained to teach them. In awarding this honor, the American Physical Society notes that the department "*provides high-quality learning environments for about 200 physics majors and minors and 4,000 students from other majors each year*." The comprehensive nature of this transformation makes it a model for institutional change, the society said.

Instructors in these courses now use the best teaching practices, as revealed by research into physics education. Students spend two-thirds of their class time each week in studio sessions in which they work in groups of three or four in a variety of active-learning exercises. These changes have led to dramatic increases in the students' understanding of physics. The department also modified the content of the introductory courses to include modern topics such as relativity and quantum mechanics or, in the courses intended for students of life sciences, physics directly relevant to authentic biological applications that is not traditionally included in introductory physics courses.

The transformation of the courses to emphasize active engagement and small-group work was aided by the renovation of four teaching lab rooms into spaces with round tables that facilitate collaborative learning. The university supported this renovation work through shared funding sources, including the College of Arts and



Sciences, the Center for Faculty Excellence, Information and Technology Services, and department funds. Inspired in part by the Physics and Astronomy Department's success in modernizing its pedagogy, up to 50 classrooms across campus will be renovated to facilitate similar modernization in other disciplines.

To help faculty members learn modern teaching techniques, the department adopted a mentor/apprentice model of professionalism in which a mentor (a faculty member who has experience in the course and might have a background in physics education research) is paired with an apprentice faculty member, who might be relatively new to teaching (an assistant professor) or might be a senior faculty member who has taught for many years but always in a traditional format. As a result, the cohort of faculty members capable of teaching in the reformed fashion now constitutes more than 60 percent of the members of the department with teaching responsibilities. The department also has established a program in partnership with the UNC-Chapel Hill School of Education to prepare physics majors to become high school physics teachers. Students in the program complete all requirements for a bachelor's degree in physics from the College of Arts & Sciences, as well as courses in education that qualify the graduates for licensure.

In its award letter, the American Physical Society stated that "*the department has contributed much to the education of future scientists and physicists*" and commended it for its continued efforts to improve physics education. Members of the PAER Group are continuing to study the learning that occurs in these courses and to develop research-informed curricula and assessments that are being used at UNC Chapel Hill and at other institutions across the country and around the world.

Astrophysical Fluid Dynamics Lab

By Fabian Heitsch

Interstellar gas — the gas filling the voids between the stars in our Galaxy — is the recycling bin of the Milky Way. In some locations, it condenses to clouds tens of lightyears across, eventually leading to new stars. Yet, stars do not hang on to all the gas out of which they formed. Stars not only radiate light, but also emit a constant stream of particles, or stellar winds. Older stars shed their outer layers, returning a large fraction of their mass to the ambient gas. In some stellar explosions, the star completely disintegrates, freeing all its material to form new stars.

Stars synthesize chemical elements, from helium to iron. Heavier elements, such as gold, silver, or lead, can only be synthesized in supernovae, or during the merger of two neutron stars. Given the chemical abundance patterns on Earth, the material making up the solar system and therefore us as we sit here, must have gone through approximately 50 supernovae.

My group explores several aspects of this cosmic recycling process, focusing on how the gas moves between the various stages of the process, from explaining chemical abundance patterns in the Solar system to star formation around black holes. The common theme for all the projects are the underlying physics, namely astrophysical fluid dynamics, including effects of radiation, magnetic fields, gravity, and chemistry. This requires extensive software development, both at the modeling level and at the data analysis/visualization level, providing a skill set useful beyond academia.

Former graduate student Matthew Goodson explored how certain trace elements present on Earth could have been injected from a supernova into the forming solar system. Goodson showed that time constraints imposed by previous models can be overcome by considering a different injection mechanism, reducing the need for a detailed choreography between explosion and solar system formation.

The center of the Milky Way contains a black hole of several millions times the mass of the Sun. The discovery was honored with the Nobel prize for Physics just this year. The black hole is surrounded by several extremely young stars, whose motions actually gave away the position and the mass of the black hole. Their presence so close to the black hole has puzzled astrophysicists because any gas cloud out of which these stars could have formed should have been torn apart by the gravitational pull of the black hole. Former graduate student Chris Frazer developed computer models of a gas cloud traveling toward and around the black hole, showing that the conditions within the cloud would be extreme enough to allow stars to form.

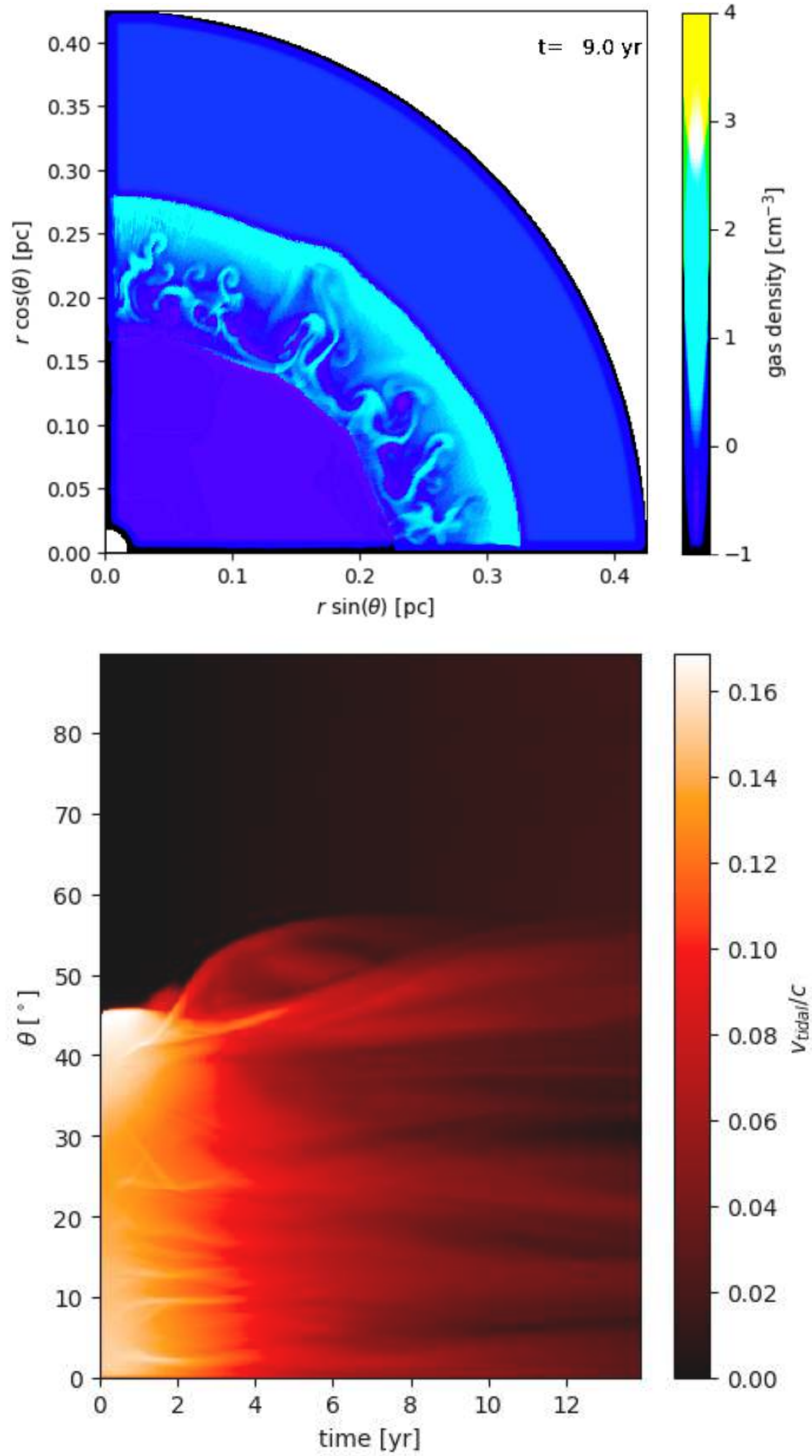
"My group explores several aspects of this cosmic recycling process, focusing on how the gas moves between the various stages of the process, from explaining chemical abundance patterns in the Solar system to star formation around black holes."

Former undergraduate student Roark Habegger and graduate student Taylor Stevenson have been working on modeling the evolution of the gas ejected during a merger of two neutron stars. Such events regained interest after the first detection of gravitational waves in 2017 and the subsequent identification of that event as a neutron star merger. Such mergers are believed to be one of the sources of certain heavy chemical elements, so-called r-process elements, in the Universe. Understanding the evolution of the ejected material, and how it is recycled into the next stellar generation, is relevant for understanding how stars and planets acquire their chemical composition.

Star formation has been one of my main interests over many years, and recently, graduate students Nicole Rider and Sophia Kressy, have started working on models of cloud formation in the Milky Way. Our Galaxy needs fresh fuel to keep its star formation running. Some of that gas may come from the outskirts of the Milky Way. How exactly that gas can make it to the star-forming disk is unclear - Nicole is exploring new ways. Once the gas has made it to the disk, it is pushed around and compressed (mostly) by stellar explosions, forming new clouds and eventually stars. How exactly this process works, is the topic of Sophia's research.

Numerical modeling has established itself as a third avenue of scientific inquiry, in addition to theory and experiment. Especially for astronomy and astrophysics, where the research objects are generally not directly accessible, numerical modeling has helped to understand the physical processes at the basis of observed phenomena.

Since my arrival at UNC Chapel Hill in 2009, I not only had the opportunity to develop my research program arranged around galactic matter cycles, but I also had the pleasure to regularly teach the numerical techniques courses offered to the physics majors, together with Professors Drut and Oldenburg. Introducing the students to some of the numerical techniques at the basis of my research is still one of my favorites.



Top: *Density map of kilonova ejecta, 9 years after launch. Finger-like structures arise in the shell of swept-up material due to hydrodynamical instabilities, eventually leading to mixing of ejecta. The kilonova is located in the bottom left corner.*
Bottom: *Color map of ejecta speed of a neutron star merger. The horizontal axis corresponds to time (increasing to the right), and the vertical to the polar angle (from equator to north pole). The ejecta shell fragments, leading to high-speed bullets indicated by the brighter strands.*

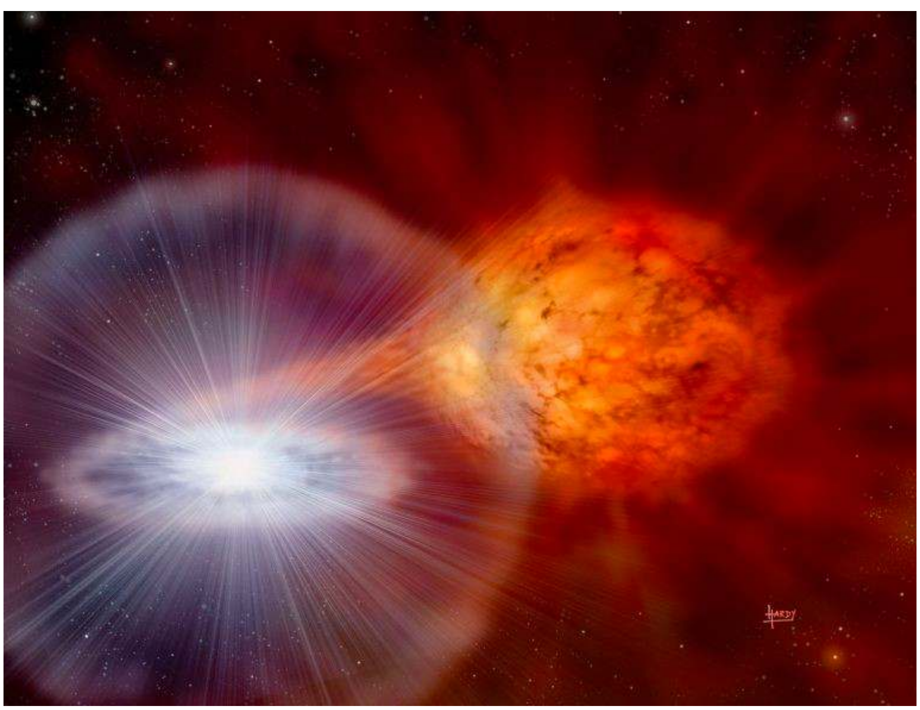
Recent Publications - Highlights

KATRIN cuts the mass estimate for the elusive neutrino in half; UNC is part of international collaboration

An international team of scientists announced a breakthrough in its quest to measure the mass of the neutrino, one of the most abundant, yet elusive, elementary particles in our universe. At the 2019 Topics in Astroparticle and Underground Physics conference in Toyama, Japan, leaders from the KATRIN experiment reported that the estimated range for the rest mass of the neutrino is no larger than 1 electron volt (eV), or 0.0002% of the electron mass. These inaugural results obtained by the Karlsruhe Tritium Neutrino experiment — or KATRIN — lowered the upper limit of the neutrino's mass from 2 eV to 1 eV. The lower limit for the neutrino mass, 0.02 eV, was determined in previous experiments by other groups.

The KATRIN experiment is based at the Karlsruhe Institute of Technology in Germany and involves researchers at 20 research institutions around the globe. At UNC, the team is led by John Wilkerson, the John R. and Louise S. Parker Professor of Physics.

The recent findings were published in **Physical Review Letters 123, 221802 (2019).**



*A nova explosion caused by a white dwarf (left) accreting matter from a Sun-like star (right). **Credit**: David A. Hardy.*

Class of stellar explosions found to be galactic producers of Lithium

A team of researchers from various universities across the country, that included the chair of our department, Dr. Christian Iliadis, has combined theory with both observations and laboratory studies and determined that a class of stellar explosions, called classical novae, are responsible for the synthesis of most of the lithium in our galaxy and solar system. Lithium is commonly used in things such as batteries, heat resistant ceramics. The results of their study have been recently published in **The Astrophysical Journal, Vol. 895, p. 70-94 (2020)**.

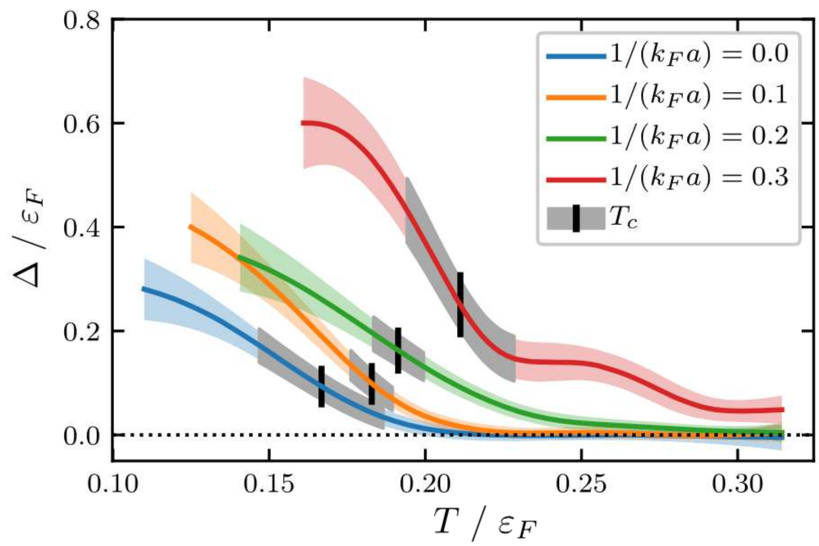
Co-author Dr. Iliadis from UNC provided the numerical rates of the nuclear reactions that are a crucial ingredient for the computer simulations of novae. Many of these nuclear fusion reactions have been directly measured over the past decade at the local Triangle Universities Nuclear Laboratory, which is a U.S. Department of Energy "Center of Excellence." This research has also recently been discussed in the June 30, 2020, Editor's Pick of Forbes Magazine.

Gold nucleus is wobbly

As the earth rotates along its axis, it wobbles a little bit. This wobbling comes, in part, from how mass is distributed across the planet. Nuclear physics researchers have now observed this same type of wobbling in Au187- a gold isotope that lives for just eight minutes. Fundamental science research like this can lead to major breakthroughs in a range of fields, including medical care.

Robert Janssens, Edward G. Bilpuch Professor of Physics, is a member of the research team that observed the wobble. The team published a paper on its findings in **Physical Review Letters 124, 052501 (2020).**

A gap above T_c? A long-standing question in strongly interacting superfluids



The gap Δ as a function of temperature T for a strongly interacting superfluid. Black bands show the location of the critical temperature T_c. The most strongly interacting case (red band) the gap survives above T_c.

The celebrated BCS theory of superconductivity (named after Bardeen, Cooper, and Schrieffer) explains the complete disappearance of electrical resistance in certain materials at low enough temperatures, which results in applications ranging from experimental particle physics to medical imaging. While BCS theory works when interactions between particles are weak, it fails when they are strong, posing a challenge to quantum many-particle theory that stands to this day.

Experimentalists use cold atoms to shed light on strongly interacting superfluids (the uncharged cousins of superconductors), but,these systems are also interesting for astrophysics. These superfluids are essentially of the same kind that appears in neutron stars, but at entirely different scales of temperature and density: inside such a star, where neutrons are compressed by gravity to densities beyond those of atomic nuclei, a strongly interacting neutron superfluid forms.

What distinguishes a strongly interacting superfluid (atoms, neutrons) from a conventional BCS type (electrons)? Part of the answer to that question is in a quantity called the energy "gap" Δ, which characterizes the strength of the inter-particle interaction. Loosely speaking, BCS theory works when Δ is small but breaks down when Δ is large (both considered in the zero-temperature limit). BCS predicts that, as the temperature is raised, Δ will vanish at the critical temperature T_c above which superfluidity disappears. A disappearing gap is thus usually associated with disappearing superfluidity. But… does the same thing happen in strongly coupled superfluids?

In a paper published in **Physical Review Letters 125 060403 (2020)**, Joaquín Drut (UNC-CH), in collaboration with Adam Richie-Halford and Aurel Bulgac (U. Washington), shed some light on this problem, using the quantum Monte Carlo method to tackle the strong interactions. As shown in the figure above, they found evidence for a so-called "pseudo-gap": Δ survives even for high temperatures where superfluidity is lost. Other properties of these intriguing systems are being explored.

The CoSMS Institute: Past, present, and future

By Christian Iliadis and John Wilkerson

After-lecture gathering at the famous 1957 "Conference on the Role of Gravitation in Physics," which put gravitational physics research on the map in the U.S. The conference took place in Chapel Hill in 1957 and was organized by the two directors of UNC's Institute of Field Physics, Dr. Cécile DeWitt-Morette and Dr. Bryce DeWitt, the (first) Agnew H. Bahnson, Jr. Professor of Physics. The image was taken at Danziger's Old World Restaurant on East Franklin Street.

In 1956, the enthusiasm of Agnew H. Bahnson, Jr., a member of the class of 1935, led to the establishment at the UNC Physics Department of the **Institute of Field Physics**, the first such institute in the Southeast. Bahnson famously wrote "*It will take the concerted efforts of many to pry forth one of the deepest and most obstinate, but one of the most important and potentially useful secrets of nature...In this quest we are reaching for the stars, and beyond*."

The main goal of the institute was to study the phenomenon of gravity and its relationship to other laws of nature. An important function of the institute was to fund extended visits by leading researchers and the organization of conferences. The inaugural conference took place in 1957 in Chapel Hill, hosted by distinguished UNC physicists Cécile DeWitt-Morette and Bryce DeWitt, which was of paramount importance for the development of gravitational physics. At the meeting, Felix Pirani and Richard Feynman gave compelling arguments for the reality of gravitational waves. Subsequently, gravitational waves were detected in 2015 by the LIGO and Virgo collaborations. To honor the Institute of Field Physics, the American Physical Society organized an entire session on **The Chapel Hill Conference and its Role in the Renaissance of General Relativity** at its April 2018 Meeting.

In 2015, UNC Physics & Astronomy launched the **Institute for Cosmology, Subatomic Matter, and Symmetries** (CoSMS Institute), with John Wilkerson, the John R. and Louise S. Parker Distinguished Professor, as the first institute director. The goal of CoSMS, which is partially supported by private gifts, is similar in design to the earlier Institute of Field Physics. It seeks to bring together a group of highly talented researchers from different subfields and let them work together on the most difficult problems in fundamental physics: Why is there more

COSMS INSTITUTE

COSMOLOGY & ASTROPHYSICS

SYMMETRIES

SUBATOMIC MATTER

Between-lecture gathering at the 20th Capra Meeting on "Radiation Reaction in General Relativity," which took place in 2017 in Chapel Hill. This event was among the first international conferences organized by the CoSMS Institute. The main organizer was Dr. Charles Evans, the (third) Agnew H. Bahnson, Jr. Distinguished Professor of Physics. He is seen on the far right, with his raised hand. Former department chair Chris Clemens is standing at the far left. Current department chair Christian Iliadis and CoSMS Director John Wilkerson appear in the center of the image.

matter than antimatter in the universe? What is the nature of neutrinos, black holes, neutron stars? Does life exist beyond Earth? How did the universe begin? CoSMS is the only such institute of fundamental physics in the Southeast.

Since its inauguration, CoSMS has sponsored visits and colloquia by eight internationally recognized researchers working on problems related to gravitational waves, accelerator technology, exploding stars, and black holes. We also organized six international workshops and conferences, on topics such as thermonuclear reactions, string theory, neutrino interactions, and general relativity.

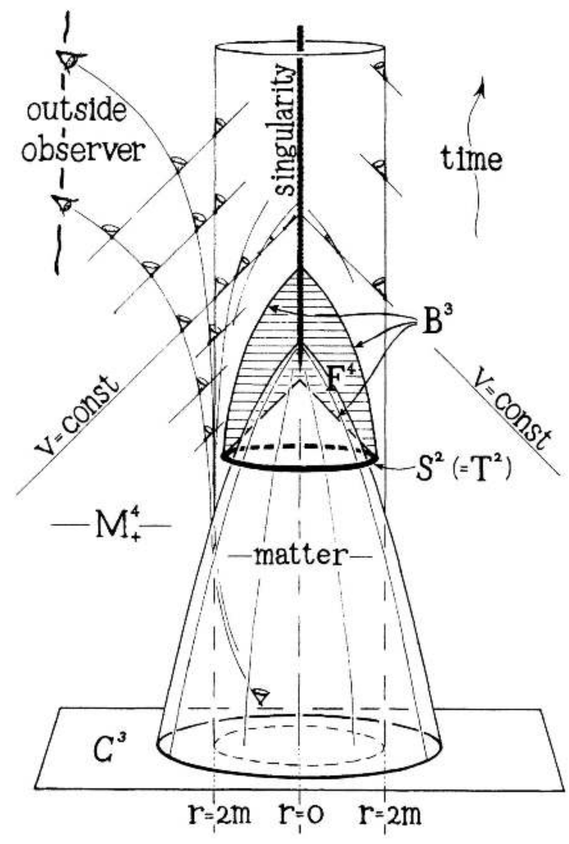
In early 2020, almost all CoSMS activities were put on hold because of the pandemic. We used this time wisely by focusing on renovating a physical home for CoSMS, on the second floor of an entire wing in Phillips Hall. A physical institute will not only provide the space for visitors and workshops but will also raise our international profile. We made significant progress so far. Three visitor offices, each large enough to accommodate three people, have been renovated and outfitted with modern furniture. The renovation of a large seminar room has also been achieved. At the moment, a new glass entrance to the institute is being installed. Once done, about 60% of the CoSMS Institute physical space will be finished. Completion of the institute will have to await further funding. We are looking forward to hosting distinguished visitors in this renovated space as part of our planned **New Horizons** speaker series. We plan to launch when the world returns to normal, hopefully in the fall of 2021.

2020 The Nobel Prize in Physics

By Charles R. Evans

The Nobel Prize in Physics for 2020 was recently awarded. This year the prize was divided, one half going to **Roger Penrose** (University of Oxford) "*for the discovery that black hole formation is a robust prediction of the general theory of relativity*" and the other half jointly awarded to **Reinhard Genzel** (Max Planck-Garching and University of California-Berkeley) and **Andrea Ghez** (University of California-Los Angeles) "*for the discovery of a supermassive compact object at the center of our galaxy*."

Einstein's gravitational field equations (i.e., general relativity) are notoriously difficult to solve exactly, unless one or more restrictive symmetry assumptions are made. Penrose's radical approach in the 1960s was to instead look at the global topological structure of spacetime by following the behavior of light rays. The behavior of light rays leads to the defining property of a black hole--its event horizon. An event horizon is a surface in space that marks the boundary between the region outside where an outward directed light ray can escape to infinity and the region inside where those same rays get trapped and dragged inward by gravity. It is what gives a black hole its name (originally coined by Wheeler), as nothing--not even light--can emerge from within the horizon and it appears completely black. By considering families of light rays, Penrose was able to show that once a star or other collection of matter collapses beyond a certain point, the gravitational field becomes so strong that a trapped surface and a singularity arise. He further argued that these singularities will be cloaked by the event horizon (the cosmic censorship conjecture), hiding the infinite curvature from external observers. Importantly, this approach showed that black hole formation is robust and does not require high degrees of symmetry during collapse. This theoretical and mathematical prediction has been borne out by decades of observations of black holes, including in recent years the observations by LIGO of multiple mergers of binary black holes to form new and larger single black holes.



Spacetime diagram depicting the gravitational collapse of a star, the motion of light rays, and the subsequent formation of a trapped surface and an event horizon.
Credit: *R. Penrose, Phys. Rev. Lett.* ***14****, 57 (1965).*

Roger Penrose
"for the discovery that black hole formation is a robust prediction of the general theory of relativity"

Reinhard Genzel and **Andrea Ghez**
"for the discovery of a supermassive compact object at the center of our galaxy"

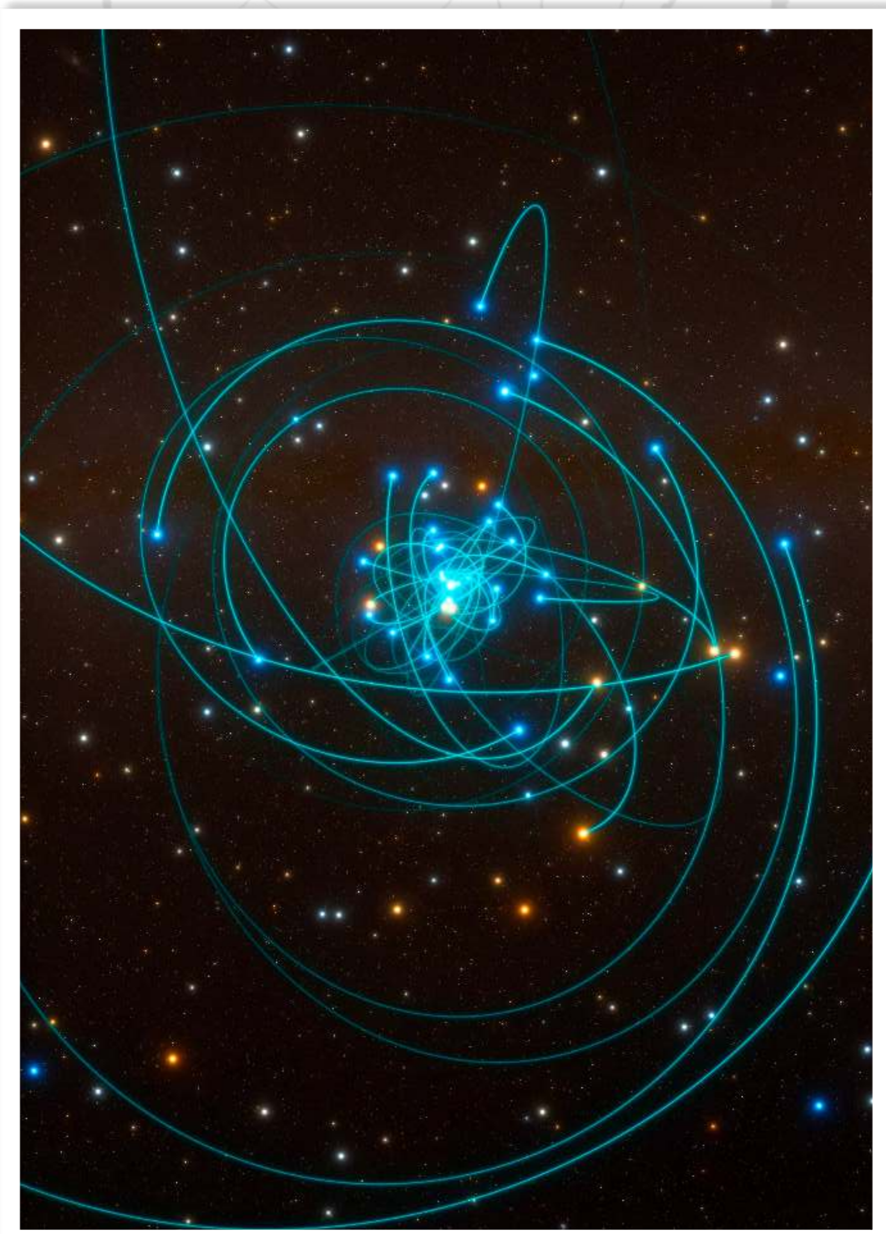


Illustration of the orbits of S stars about a 4 million solar mass (unseen) black hole at the center of the Milky Way.
Credit: *ESO/L. Calçada/spaceengine.org*

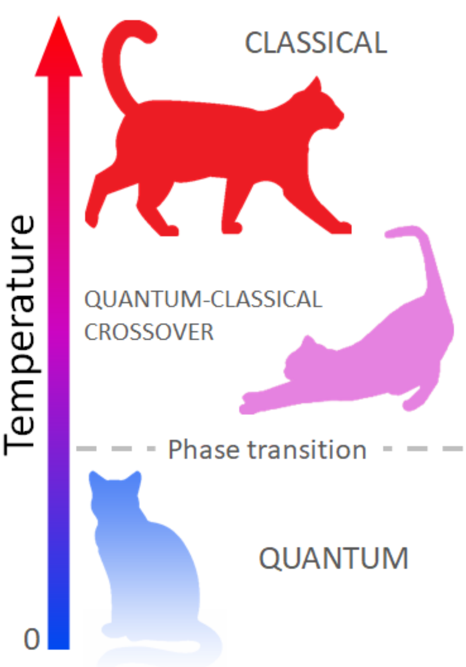
Reinhard Genzel and Andrea Ghez each led groups of astronomers who have monitored since the 1990s a region in our own Milky Way galaxy called Sagittarius A*. It is a bright, compact radio source located at the geometrical center of the Milky Way. While radio waves are able to reach us, this region is heavily shrouded in gas and dust, obscuring the view of many telescopic instruments. Genzel's and Ghez's teams used adaptive optics observations in near-infrared light to discover a set of stars, called S stars, that move on tight, fast orbits (as fast as 2.5% of the speed of light) about an invisible massive object at the center of the Milky Way. Some of these stars have made more than one orbit in the last twenty years. The inferred mass of this completely dark object is four million solar masses. These observations were the earliest and some of the most convincing evidence of the presence of a supermassive black hole at the center of our galaxy.

Focus on Grad Research

From Newton to Schrödinger, one particle at a time

By Yaqi Hou and Joaquín Drut

Systems made out of many quantum particles (atoms, neutrons, quarks, etc) are often referred to as **quantum matter.** Their true quantum mechanical nature usually appears at extremely low temperatures or extremely high densities (see the article above by G. Basar). These days, some of the most famous examples of quantum matter include ultracold atoms (clouds of a few million atoms cooled down to a few microKelvins) and the extremely dense core of neutron stars (where neutrons are compressed by gravity into a superfluid state, in which particles flow without resistance). In all of these systems, the quantum mechanical properties (such as superfluidity and superconductivity) start to disappear as the temperature is raised. This happens first abruptly as phase transitions are crossed, and then gradually as the so-called "classical limit" (where Newtonian mechanics dominates) is approached (see figure below).



This "**quantum-classical crossover**," interpolating between Schrödinger and Newton, is captured theoretically by the so-called "**virial expansion**" (VE). The VE encodes, at each order n, the contributions b_n coming from the n particle problem. The idea is that, by including the effect of b_n's of increasing n, one can approach the thermodynamic limit where $n \to \infty$ and thus understand what large realistic systems do. Calculating the b_n starts at $n = 1$, which is very easy to do because a single particle experiences no interactions. The two-body problem $n = 2$ is also relatively easy: a general formula for b_2 was obtained by Beth and Uhlenbeck in the 1930's. However, $n \geq 3$ has been historically very challenging. It is only in the last two decades that, combining analytic and numerical approaches, theorists began to tackle this difficult case up to $n = 4$.

Over the last couple of years, graduate students in the computational quantum matter group at UNC have worked to develop a new technique to calculate b_n efficiently for nonrelativistic matter, reaching the unexplored territory $n \geq 5$, to obtain a definitive description of the quantum-classical crossover mentioned above. The key element of the method is rewriting the problem so that it can be fully automated and handled by a computer. Crucially, this is not a numerical method: numerical approaches suffer from either massive memory requirements or huge statistical noise. Instead, the method implements a few mathematical tricks to expose an essential property of nonrelativistic matter: $E = p^2/2m$, i.e. the energy of a (nonrelativistic) particle goes like the square of the momentum. This simple property means that **all** the integrals involved in the method are Gaussians, which can be promptly calculated. The resulting approach is therefore computational yet entirely analytic and can be used to calculate b_n for different dimensions, interaction strengths, temperatures, and polarizations. Exploiting that analytic nature, calculations at varying parameter values become a walk in the park: just evaluate the resulting formula at the desired point. The new method thus yields smooth continuous results, which is a great advantage over numerical methods that yield discrete sample points.

Our method has achieved excellent agreement with experiment and theory, and also furnished predictions of thermodynamics (e.g. pressure, density, spin susceptibility) of ultracold atoms in two and three dimensions and for varying interaction strength. Generalizations to other observables and neutron matter are currently underway.

Focus on Undergrad Research

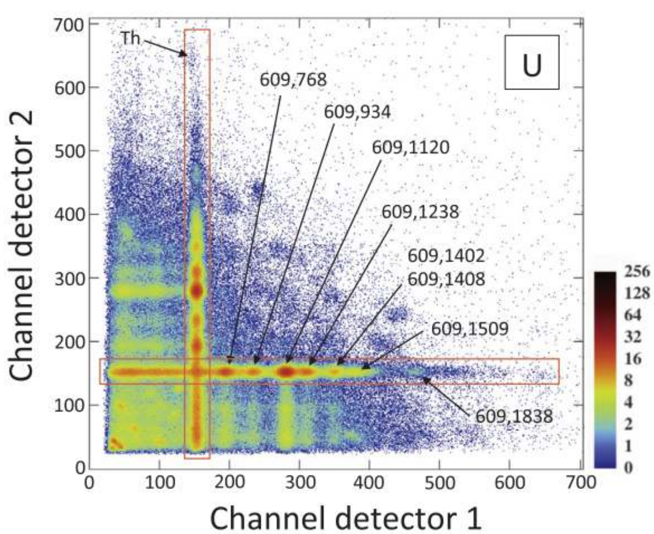
Measuring gamma radiation in North Carolina's soil

By Caroline Smith

Gamma radiation is ever-present at low levels in the food we eat, magazines we read, and soil we live on. In Dr. Iliadis' lab, a gamma spectrometer picks up on coincident gamma emissions from samples placed in between two sodium iodide (NaI) detectors. These detectors are placed facing each other, and emissions are picked up by photomultiplier tubes where the number of emissions and their energies are recorded. Since gamma radiation happens at low levels even in common household materials, there are background emissions that can be detected from the surrounding area. This background is eliminated by thick copper, lead, and aluminum shielding around the spectrometer.

When coincident gamma rays are picked up by the NaI detectors, their energies are recorded, sorted by energy gates, and graphed. Data are sorted into one-dimensional spectra (in which the number of counts picked up by one detector is graphed against the energy level of the emission) and two-dimensional spectra (in which one detector's data is graphed against the other). In between each sample run, spectra of ^{22}Na and ^{60}Co are each taken to ensure that the energy gates are accurate and reflect any shifts over time.

During the past year, Professor Larry Beninger, of UNC's geology department and I collected and prepared soil samples from Morgan Creek. The samples were then sorted into two groups to be placed into the spectrometer: one of particles 0.5-1.0 mm in size, and the other one less than 0.5 mm. The samples were counted in the spectrometer for three days each. The small particles were found to produce higher levels of radiation, producing activity that was an average of 13.15% higher than their larger size counterparts. One sample of soil taken on the side of NC Highway 150 was also tested and found to produce much higher activity by comparison, with levels over 28 times higher than the Morgan Creek samples.



Experimental two-dimensional spectrum of energy deposited by uranium powder in detector 2 (measured in channels) versus energy in detector 1. **From**: A. Tillett, L. Benninger, J. Dermigny, C. Iliadis, *Appl. Radiat. Isot.*, **141**, 24-32 (2018).

An important part of this research is simulating the experiment using Monte Carlo transport codes in order to correct for any self-absorption of the gamma rays by the sample material. To complete this procedure, the spectrometer, calibration materials, and environmental samples are being constructed within the simulation. This will then be used to recreate the experimental data. It is important to compare the experimental and simulated coincidence efficiencies of the different materials to determine the activity of volume sources, the self-absorption of which must be taken into account when determining a sample's activity. In similar previous experiments, the efficiency was found to be largely density-dependent, with higher-density samples experiencing greater rates of absorption.

When the COVID-19 pandemic began in March of 2020, the research pivoted to focus on simulation, since collecting samples and mapping gamma-ray activity throughout North Carolina as planned posed a greater health risk. This portion of the experiment is still in progress, with results to be expected in the upcoming months.

FROM THE SHOP

Our Department owns the only machine shop on campus. From Phillips Hall 115, Phil Thompson and his crew (William Harris, David Norris, and Cliff Tysor) offer complete professional instrument construction through a variety of services including CNC (programming, turning, milling), manual and electric-discharge machining, welding, sheet metal fabrication, and plastic fabrication.

Phil and his team are the people behind the construction of the sophisticated, high-precision instruments we use for world-class research. Among the most renowned instruments are the Evryscopes (the workhorses of Nick Law's time-domain astronomy research) and the LENA (Laboratory for Experimental Nuclear Astrophysics) accelerator, pictured behind this text, which produces the highest intensity proton beam in the world.

During the ongoing COVID19 pandemic, the shop is machining parts used in cell culture research at UNC's Department of Pharmacoengineering and Molecular Pharmaceutics.

William Harris (shop machinist) produces parts for cell culture research, supporting research on drug delivery options for COVID19 treatment.

STAFF NOTES

New staff members

Anne Beckman

Executive Assistant to the Chair

I was born and raised in Michigan but spent 4 years living in Alexandria, VA before settling in to Wake Forest with my partner Jeff and our German Shepherd Shane. I took an interesting path to get here by starting off as a preschool teacher, then an assistant director/principal, then got burnt out and worked as an EA for a government contracting firm. I enjoy getting to know all of the people in our department and seeing what new directions we are taking.

Artra Butler

Human Resources Manager

I am originally from Virginia, but now I live in Raleigh with my husband Corey and my two kids, Alaina & Ezra. I am a veteran Army Officer. I spent 7 years, stationed in many southern states and Afghanistan. Here, in the Physics & Astronomy department I am the HR Manager. I enjoy working in this department because it is completely different than the Army. I am able to learn a new skill every day.

Staff awards

Maggie Jensen

Graduate Affairs Coordinator

Donna Braxton Staff Excellence Award

This award recognizes outstanding overall performance by an SPA staff member during the previous year. The awards committee considered the employee's commitment to the department's mission along with examples of creativity, innovation, and leadership in performing duties.

Shane Brogan

Teaching Lab Manager

Personal Achievement Award

This award recognizes significant achievement and growth by an SPA staff member during the previous year. The awards committee looked for examples of job performance, creativity, innovation, commitment, and, in particular, actions beyond those required that constitute significant achievement and growth.

Patina Herring

Grant and Research Coordinator

Team Player of the Year

This award recognizes actions by an SPA staff member that boost morale, increase cooperation, demonstrate a positive attitude, and make the work environment more enjoyable.

The Awards

The **Paul E. Shearin Award** was established by W. E. Haisley, Professor Emeritus of Physics, to honor Paul E. Shearin, Professor of Physics, member of the faculty for 36 years, and for 12 years Chairman of our Department. This monetary award is given to the member of the senior class majoring in Physics who is judged most outstanding on criteria of scholarship, scientific insight and professional seriousness. The recipient is selected by the departmental faculty from candidates nominated by the undergraduate major advisors.

The **Daniel Calvin Johnson Memorial Award** in Physics. This award, established in 1960 by Mrs. Mildred Johnson in honor of her husband, Daniel C. Johnson, a former graduate of the department, is awarded annually to the physics major who is judged by the faculty to be the most outstanding student of the junior class.

The **Robert N. Shelton Award**, established in 2001, is given to one or more Physics and Astronomy undergraduate students for excellence in research. The award was first established by Provost Robert N. Shelton.

Outstanding Teaching Assistant Awards
Each year our department recognizes the most outstanding Teaching Assistants (TAs) for their exemplary work. Most TAs provide assistance teaching and grading for our introductory physics or astronomy courses, but some assist with more advanced or specialized courses. In a typical semester we employ approximately 40 graduate students and about 15 undergraduate students to serve as TAs, and we recognize the top 2 or 3 for the department TA award.

Paul E. Shearin Outstanding Senior Award

2019

Margaret Scott Hildebran
Yi Hu

2020

Thomas Ross Marshall

Daniel C. Johnson Memorial Award

2019

Thomas Ross Marshall

2020

Bowen Gu
Kate Richardson

Robert N. Shelton Outstanding Research Award

2019

Nick Clayton Konz
H. Patrick Taylor IV

2020

Kate Richardson

Outstanding Graduate Teaching Assistant Award

2019

Joseph B. Karlik
Qunqun Liu

2020

Ben Levy
Nikos Dokmetzoglou

Outstanding Undergraduate Teaching Assistant Award

2019

Thoai T. Vu

No undergraduate TA award was given in 2020.

Graduate program 2019

Ph. D.

M. A. Antonacci
C. L. Bartram
A. L. Cooper
P. Doyle
S. M. Hunt
Z. Li
A. C. Loheac
A. M. McCallister
S. J. Meijer
D. N. Morse
E. F. Nelsen
J. Rager
K. J. Redmond
C. R. Shill

M.S.

J. T. Brooks
N. Dokmetzoglou
C. M. Hobson

Graduate program 2020

Ph. D.

J. B. Barrick
C. E. Berger
M.D. Delos
L. N. Downen
R. E. Fowler
I. Rohan
Z. M. Jagoo
D. R. Little
J. R. McKenney
C. A. Miller
Z. Nasipack
J. K. Ratzloff

M.S.

S. G. Frye
M. Kelley
C. T. McHugh
C. Moakler
J. Redding
M. L. Wood

Undergraduate program 2019

B.S.

E. N. Armstrong
K. M. Barnes
G. D. Bradley
B. L. Canter
N. J. Cariello
N. T. Cleaves
N. F. Cohen
A. J. Czejdo
J. T. De Chant
P. Dontu
A. J. Ficker
A. Harrison
N. S. Hildebran
E. Horvath
Y. Hu
A. Jose
J. Low
D. J. Morrison
S. L. Pagan
T. W. Perry
R. Pierce
A. D. Pietraallo
L. A. S. Sanson
T. J. Schaaf
H. Patrick Taylor IV
M. A. Umantsev
E. P. Yelton

B.A.

K. S. Barnes
N. L. Barnett
S. J. Espinosa
M. B. Gordon
A. J. Gahrmann
C. L. Gsell
H. V. Hansel
N. A. Haragos
A. M. Houpt
B. C. Illies
F. H. Loendorf
A. Marsh
J. C. McNeill
J. B. Nitsos
C. F. Orr
S. C. Thompson

Undergraduate program 2020

B.S.

R. A. Armstrong
D. Bortolussi
D. R. Brown
M. A. Bruff
R. S. Habegger
D. C. Hirst
M. Hockenberry
M. Hunt
N. C. Konz
E. C. Leonard
R. Li
C. B. Mace
T. R. Marshall
D. Martin
J. K. Merchant
B. Mesits
J. Moore
M. S. Moss
R. A. Olson
J. A. G. Otterbein
C. Pahel-Short
N. J. Pierron
A. Pittella
L. A. Rabinowitz
T. Richards
Z. B. Rosen
C. H. Roycroft
A. Sethi
J. B. Sheely
Z. E. Walker
X. Boyu

B.A.

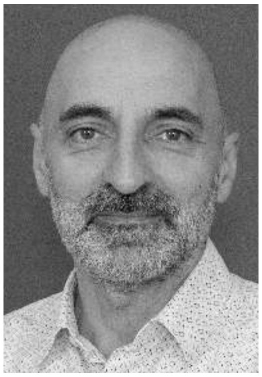
G. A. A. Deadwick
A. F. Martinez
J. McCormack
C. G. Snyder
G. L. Tatich
W. G. Tyler
J. S. Wixtrom
L. Xia
Y. A. Zefri

Jack Ng was one of the winners of the **2018 Buchalter Cosmology Prize** for his work entitled "Modified Dark Matter: Relating Dark Energy, Dark Matter and Baryonic Matter." It was recognized by the judging panel as "*an imaginative and courageous paper that proposes new ideas to address long unresolved fundamental questions in cosmology, proposing a form of modified dark matter that gives rise to a new MOND formulation accounting for observations at both galaxy and cluster scales.*" The prestigious judging panel for the prize was comprised of leading theoretical physicists noted for their work in cosmology, including Dr. Ruth Gregory of Durham University, Dr. Lee Smolin of the Perimeter Institute for Theoretical Physics, and Dr. Mark Trodden of the University of Pennsylvania.

Joaquín Drut received the **2018 Hettleman Prize for Artistic & Scholarly Achievement by Young Faculty**. The late Phillip Hettleman, a member of the Carolina class of 1921, and his wife Ruth, established the prestigious award in 1986 to recognize the achievements of outstanding junior faculty. The recipients of the $5,000 prize were recognized during the Faculty Council Meeting. Drut works on a wide range of topics within quantum many-body physics, including pairing, superfluidity, and quantum entanglement phenomena in ultracold atoms and neutron matter. Drut's group also works on developing new non-perturbative methods to tackle strongly coupled matter.

Adrienne Erickcek received a **National Science Foundation (NSF) CAREER award in 2018**. The Faculty Early Career Development (CAREER) Program aims to identify early-career faculty members who excel in both research and education, and these 5-year awards are among the most prestigious offered by the NSF. Erickcek's CAREER award supports her use of dark matter annihilation signals to close a troubling gap in the cosmological record. Observations of the cosmic microwave background indicate that the Universe experienced a period of accelerated expansion, called inflation, shortly after the Big Bang, but it is not known what drove inflation, why it ended, and how the Universe became hot enough for Big Bang nucleosynthesis to occur a few minutes after inflation.

Laurie McNeil was awarded the **2019 George B. Pegram Award** of the Southeastern Section of the American Physical Society. The prize recognizes physics educators who have demonstrated outstanding ability in undergraduate education. It has been 20 years since UNC-CH has last won this prize (1999, by Kian Dy). McNeil was also named **Sigma Xi Distinguished Lecturer for 2019-2021**. Sigma Xi is the international honor society of science and engineering. One of the oldest and largest scientific organizations in the world, Sigma Xi has a distinguished history of service to science and society for more than one hundred and twenty five years. Scientists and engineers, whose research spans the disciplines of science and technology, comprise the membership of the Society. Sigma Xi chapters can be found at colleges and universities, government laboratories, and industry research centers around the world. More than 200 Nobel Prize winners have been members.



Art Champagne and **Christian Iliadis** won the **2019 Jesse B. Beams Research Award** of the Southeastern Section of the American Physics Society for "*Their research leadership in experimental nuclear astrophysics, especially for the conception and development of their measurement program of thermonuclear reaction rates at TUNL's Laboratory for Experimental Nuclear Astrophysics.*" Only one other faculty from UNC-CH (Lawrence Slifkin, 1977) had won the prize before.

Amy Oldenburg became a **Fellow of the International Society for Optics and Photonics (SPIE)**. Each year, SPIE promotes members as new Fellows of the Society. SPIE honored 88 new Fellows of the Society in 2019. Fellows are members of distinction who have made significant scientific and technical contributions in the multidisciplinary fields of optics, photonics, and imaging. They are honored for their technical achievement and for their service to the general optics community and to SPIE in particular. More than 1,400 SPIE members have become Fellows since the Society's inception in 1955.

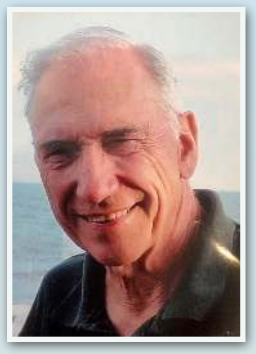
John Wilkerson received the **2019 Division of Nuclear Physics' Distinguished Service Award**, for *"His generous service to the Division of Nuclear Physics in numerous roles spanning more than three decades, including his role in the Division's Chair line, his thoughtful stewardship of numerous committees, and his continued service on the DNP Funding Issues Committee."*

Farewell

Contributed by Tom Clegg, Laurie McNeil, and Yue Wu

Our nuclear group has lost several of its earliest stalwarts, who were drivers of the great breadth, productivity, and international recognition that their programs at the Triangle Universities Nuclear Lab earned over several decades. Our eminent colleague, **Eugen Merzbacher,** whom we lost in 2013, worked with colleagues at Duke and UNC to attract to the new TUNL facility both Ed Ludwig in 1966 and Steve Shafroth in 1967.

Early in his TUNL career at UNC, **Steve Shafroth** helped develop TUNL's program in gamma-ray spectroscopy. But soon, stimulated by close association with Eugen, he was drawn to measurements at TUNL of X-rays from beam-induced atomic ionization and excitation processes. Steve had an easy-going personality that enabled productive collaborations, and he was always excited by finding new solutions to problems, rather than copying what others had done. We remember him as our inquisitive, social colleague who eagerly collected anyone willing to join him in a new experiment. Retiring didn't quench his enthusiasm for research. His learning at a conference in the early 1990s that pyroelectric crystals emit X-rays when heated stimulated 20+ years of post-retirement research, always with new students and with borrowed equipment. His many colleagues and students remember him as a close personal friend who was always enthusiastic about science. Steve passed away in August 2017.



For over three decades, **Ed Ludwig** oversaw the experimental training of both graduate and undergraduate students by developing essential hardware and making extensive charged-particle cross section and spin polarization measurements. Outside the lab, Ed was the instigator of memorable annual summer afternoon tennis and softball competitions between the "Protons" and "Neutrons," followed by a cookout with nuclear group student and faculty colleagues. At UNC, he was also a long-time undergraduate student science adviser in the College and developed enviable proficiency for attention grabbing demonstrations in his introductory physics classes for pre-med students. Ed passed away in September 2018. His widow, Helen, lives now in the local Carolina Meadows retirement community.

Larry Rowan died on 23 March 2019 at the age of 87. He earned his PhD in Physics from Berkeley in 1963 working with E. L. Hahn, the inventor of the spin echo technique in nuclear magnetic resonance. Larry's paper on electron spin echo modulation played an important role in the field and has been highly cited. He came to UNC the following year as a postdoc to work with Larry Slifkin building a resonance spectrometer. He joined the faculty in 1967 and had a 43-year career as a vital contributor to the educational mission of the department and the university. He directed the campus Center for Teaching and Learning for 15 years beginning in 1994. He was best known for his deep commitment to the upwards of 10,000 introductory physics students he taught during his career. His easy-going nature made students struggling with a hard subject willing to approach him for help, knowing he was on their side. In the classroom he kept hundreds of students alert and engaged by such unorthodox methods as having them stand and execute contradance moves in the middle of a class, prompted by his experience and skill as a contradance caller and (naturally) teacher.

Horst Kessemeier passed away on July 3, 2019, a month after his 88th birthday party with a group of his physics friends. He retired in 1997 but remained active till the very end, coming to the lab almost every day, working on electronic instruments, touching his beloved magnet, and engaging in pleasant conversations with everyone he encountered in the hallways of Phillips. In daily coffee-break conversations at the Campus Y, Horst told his intriguing stories to colleagues and friends, ranging from his encounter in Hamburg with Wolfgang Pauli to the lineage of Tai Chi moves he learned recently. He remembered vividly moving his young family to Chapel Hill in 1964, after completing his PhD thesis at Washington University in St Louis on the development of the magic-angle-spinning technique, the single most important technique in solid-state nuclear magnetic resonance. He shared with us his excitement of the discovery with his student Rhim in 1970 of the Loschmidt echo in many-spin systems, a seminal work on time reversal and the second law of thermodynamics, as well as his regret of not being able to continue this pursuit due to various circumstances. Horst was a beloved professor to generations of students. His graduate students went on to successful careers in diverse fields. To many of his friends, we miss his generosity and his enthusiasm for physics.

Larry Slifkin died on 2 December 2019 at the age of 94. (His wife of 71 years, Miriam Kresses Slifkin, followed him in death eight months later.) Larry joined the UNC Department of Physics (as it was called then) in 1955 after completing his PhD in Physical Chemistry at Princeton in 1950 and appointments at the University of Illinois at Urbana-Champaign and the University of Minnesota. Apart from sabbaticals, he remained here until his retirement in 1991, eventually being named Alumni Distinguished Professor. He was instrumental in establishing experimental solid-state physics (as it was called then) in the department, and was best known for his studies of diffusion and self-trapped holes in AgCl, a topic of great importance to the photographic film industry. He was a dedicated and award-winning educator, a passionate advocate for social justice, and an enthusiastic trumpet player.

Another faculty colleague, **Paul Hubbard**, died very recently in October 2020. Paul and his wife, Sylvia, came in 1958 to UNC from Harvard where Paul had studied nuclear magnetic resonance techniques under Nobel laureate Ed Purcell. Paul was a pioneer of the theory of spin-lattice-relaxation in NMR. His papers, seminal works, are filled with beautiful expositions of quantum mechanics and mathematics. Using the density operator theory of relaxation he helped to advance, Paul developed the theories of relaxations in liquids by spin-rotational interactions and quadrupole interactions in several papers that are still being frequently cited today after more than 50 years of their publication. In the department, he was known as a very effective, conscientious instructor in graduate courses, especially mathematical physics. After retiring in 1998, often accompanied by his golden retriever, Paul continued coming to his shared office with other retirees in Phillips Hall, the "bullpen." Paul's widow, Sylvia, lives in the Carol Woods retirement community in Chapel Hill.

In recent years, we have also lost talented spouses of these and other former faculty: **Ann Merzbacher**, **Helen Palmatier**, **Chantal Shafroth**, **Maryellen Bowers**, and **Miriam Slifkin**. Much more than being close friends for many of us, each also left behind a significant record of accomplishments.

Credits

Contributors

A. D. Ayangeakaa
G. Basar
A. M. Beckman
T. Branca
N. Bryden
A. Butler
A. Churukian
J. Cimmino
T. Clegg
J. E. Drut
C. R. Evans
J. Gruszko
F. Heitsch
Y. Hou
C. Iliadis
R. V. F. Janssens
M. Jensen
M. Kelley
N. Law
L. McNeil
A. Mann
C. Smith
P. C. Thao
F. Tsui
J. F. Wilkerson
Y. Wu

Design

J. E. Drut
A. M. Beckman

Q&A with Christian Iliadis

This Q&A section of the Magazine aims to provide an interview-style, one-on-one conversation with our faculty. For this Fall 2020 edition, we have invited our current Chair, Christian Iliadis, to reflect on his time at the helm of our Department and share some insights for the future. Christian is expected to complete his 5-year term as Chair on June 30, 2021.

Can you share any "behind-the-scenes" aspects of being Chair that students (and perhaps faculty) may not know about but which are essential to the Department?

Christian Iliadis: Transparency is essential for trust. That means the fewer "behind-the-scenes" situations the better. I cannot remember any information pertinent to the department that I did not share with at least a group of faculty or staff. Of course, information relevant to the entire department always needs to be shared with everyone involved. One of my main goals as chair was to promote transparency.

In the last few years, our Department has advanced considerably on several fronts. What would you say are the most important areas that moved forward during your time as Chair? In other words, what accomplishments are you most proud of?

CI: We hired outstanding new faculty. Our graduate curriculum was completely modernized. We became recognized national leaders in delivering introductory physics and astronomy courses. We initiated renovations, including for a physical home of the CoSMS Institute, despite very lean funds. I am proud of all these accomplishments, and many more. But none of these matter much if department morale is low. Our most important achievement is that overall the morale has improved compared to previous years.

What do you see as the challenges and opportunities for our Department looking forward?

CI: We do not know yet how the pandemic will affect the university budget and the implications for future funding of our teaching and research mission. Also, over the next few years it is likely that the university will hire fewer faculty than during normal times. This means that departments will shrink in size because of naturally occurring retirements. Fortunately, over the past few years we increased our faculty number to a record size. Therefore, we may be in a better position to absorb budget cuts compared to some other departments.

What is your advice for the next person taking on the job of Department Chair?

CI: Do's: Be transparent and approachable. Don'ts: Avoid telling everyone how busy you are and that you dislike the job. Support, and advocate for, all department members. Do not expect (m)any thanks. Oh, and don't take yourself too seriously.

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Thank you!

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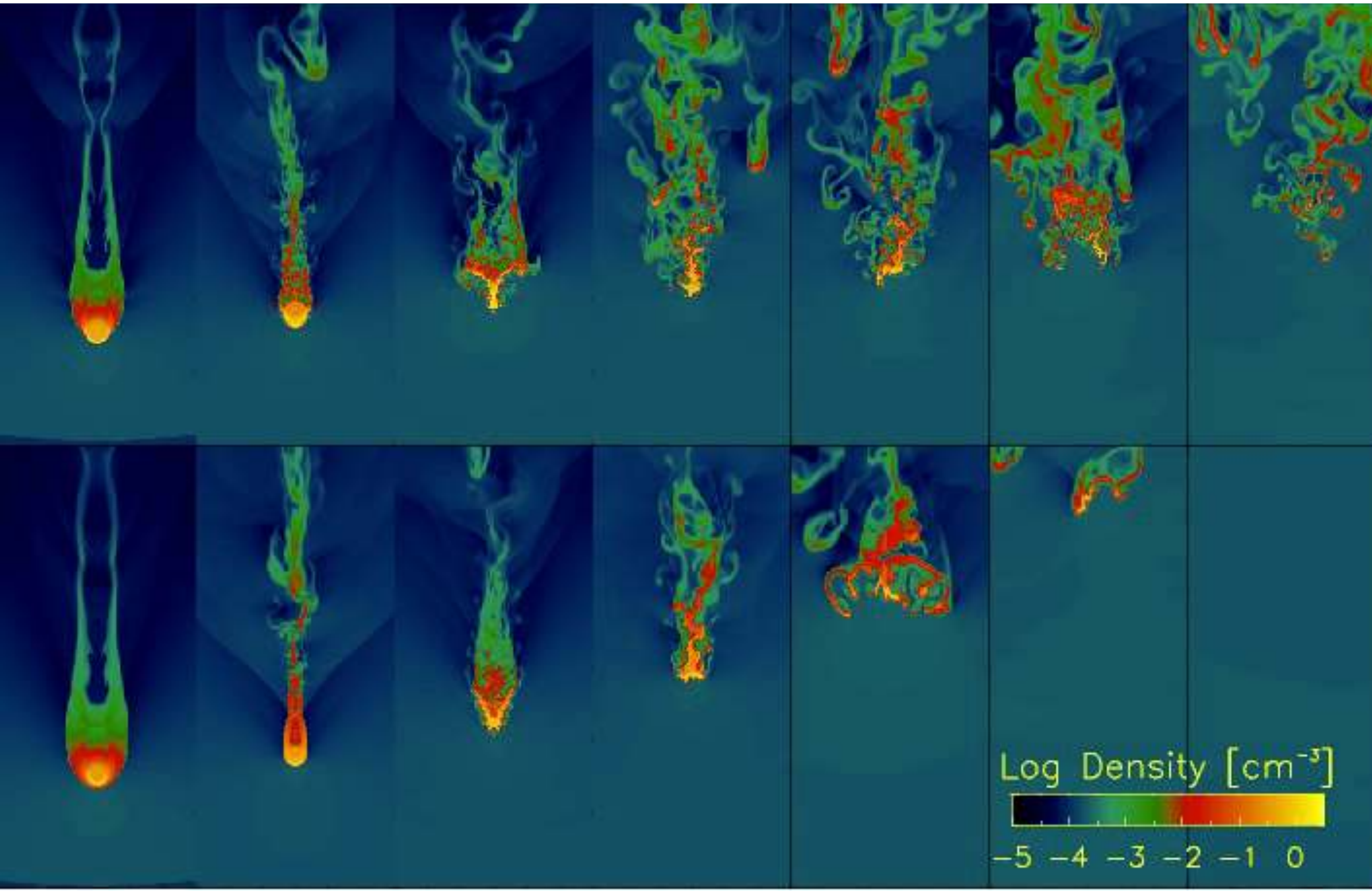

Disruption of a high-velocity cloud during its passage through the galactic halo [from Heitsch et al. MNRAS 462, L46–L50 (2016)]. See **Astrophysical Fluid Dynamics Lab** *article inside, by Fabian Heitsch.*

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