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Education and Academic Appointments

University of Notre Dame Postdoctoral Researcher 2023-Present

University of Chicago Oehme Postdoctoral Fellow, Enrico Fermi Institute 2020-2023

University of California, Santa Barbara MA, PhD in Physics Aug 2020
Dissertation: New Approaches to the Hierarchy Problem and their Signatures from Microscopic to Cosmic Scales advised by Prof. Nathaniel Craig

University of Pennsylvania May 2015
BA in Physics (w/ honors, astro concentration) and Math, MS in Physics

Montgomery County Community College, PA gap year after high school due to illness 2010-2011

Honors and Awards

UChicago EFI 91st Arthur H. Compton Lecturer, 2023

American Physical Society's 2022 Sakurai Dissertation Award

UCSB Graduate Student Association's 2019 Excellence in Teaching Award

UPenn William E. Stephens Memorial Prize for a graduating physics major

UPenn Roy and Diana Vagelos Science Challenge Award, full tuition scholarship

Teaching and Mentorship

Particles, the Cosmos, and You: An Origin Story from the Edges of Space and Time is a series of lectures for the general public on fundamental particle physics and cosmology

The Hierarchy Problem: From the Fundamentals to the Frontiers is a pedagogical guide to renormalization and the hierarchy problem

UChicago Introduction to Particle Physics Seminar – Spring 2021

I volunteered to lead an undergraduate reading seminar on introductory particle physics as I was concerned students weren't getting time with professors during the pandemic. I lectured on important concepts, emphasized the role of quantum mechanics, and wrote mastery questions for students to work on to firm their understanding. I also introduced particle simulation software and wrote a final project to reinterpret an ATLAS search and `discover' the Higgs.

UCSB Worster Fellowship for summer mentorship (awarded 2017 and 2019)

Introduction to Quantum Mechanics 1 – Fall 2016, Fall 2017, Fall 2018
Complex Variables – Winter 2020

With Nathaniel Craig in Fall 2017, I worked to overhaul the Introductory Quantum Mechanics course using active learning methods and placing increased effort on pedagogy and on instructor accessibility. This worked marvelously and students both had better learning outcomes and reported feeling more comfortable in the classroom and with the material. Since then, our model has been implemented throughout the physics classes at UCSB.

Invited Talks († = zoom talk)

UV/IR Mixing and the Hierarchy Problem
- **Yale** Mossman Seminar, November 2019
- **SoCal Grads Fields and Strings** at UC Los Angeles, February 2020
- **Cornell/UMaryland** Particle Phenomenology Seminar, October 2020†
- **UC Berkeley** Particle Seminar, October 2020†
- **Caltech** High Energy Physics Seminar, October 2020†
- **UMichigan** Particle Theory Seminar, November 2020†

The Hydrogen Mixing Portal, Its Origins, and Its Cosmological Effects
- **UToronto** Theoretical High Energy Physics Seminar, November 2020†
- **Fermilab** Theoretical Physics Seminar, November 2020†

Discrete Gauged B-L and the Cosmological Lithium Problem
- **Stony Brook University** Theoretical Physics Seminar, December 2021
- **UW Madison** High Energy/Cosmology Theory Seminar, April 2022
- **American Physical Society** Sakurai Dissertation Award Talk, New York, April 2022
- **Harvard CMSA** Quantum Matter Seminar, May 2022†
- **UC Irvine** Particle Physics Seminar, June 2022†
- **UNAM Instituto de Fisica** Seminario Sandoval Vallarta, June 2022
- **Brookhaven National Lab** High Energy Theory Seminar, August 2022
- **UI Urbana-Champaign** High Energy Phenomenology Seminar, September 2022
- **Notre Dame** Particle Physics Seminar, October 2022
- **MIT** Nuclear and Particle Theory Seminar, October 2022
- **UMaryland** Particle Theory Seminar, December 2022

Naturalness In Your Face
- **Aspen Center for Physics** Prospecting for New Physics, March 2023

Putting Generalized Symmetries to Work for Particle Physics
- **Cornell** Particle Theory Seminar, February 2023
- **McGill** Theory HEP Seminar, February 2023†
- **UMinnesota** HEP Theory Seminar, February 2023
- **UC Berkeley** Particle Seminar, March 2023
- **UVictoria** Theory Seminar, March 2023†
- **Caltech** High Energy Physics Seminar, April 2023
- **Rutgers** NHETC Seminar, May 2023
- **UOregon** IFS Seminar, May 2023
- **Aspen Center for Physics** Pheno to Formal, August 2023
- **Sydney-CPPC** Seminar, August 2023†

Non-Invertible Symmetries, Leptons, Quarks, and Why Multiple Generations
- **Harvard CMSA** Quantum Matter Seminar, October 2023
- **Boston University** High Energy Seminar, October 2023
- **Pitt** High Energy Physics Seminar, November 2023
- **UToronto** High-Energy Physics Seminar, November 2023
- **UKentucky** Theory Seminar, December 2023
- **KAIST** HET Seminar, Daejeon, South Korea, December 2023
- **SLAC** EPP Theory Seminar, March 2024
- **UC Irvine** Informal Seminar, March 2024
- **Nankai University** Special Seminar, March 2024†

Fractionally-Charged Particles, The SM Gauge Group, and One-Form Symmetries
- **CERN** EFT Coffee, June 2024
- **Glasgow** PPT Seminar, August 2024

Generalized Global Symmetries and Nonperturbative Quantum Flavodynamics
- **Simons Center** Symmetric Mass Generation, May 2024
- **CERN** Crossroads Between Theory and Phenomenology, Geneva, June 2024
- **Durham IPPP** Seminar, August 2024
- **Symmetries 2024** at Oxford, August 2024
- **Texas A&M** High Energy Seminar, August 2024
- **UMichigan** HET Seminar, September 2024
- **UMinnesota** HEP Theory Seminar, September 2024
- **Brown** BCTP IDEA Seminar, October 2024

TRIUMF Theory Seminar, Vancouver, Canada, November 2024
Tata Institute of Fundamental Research Free Meson Seminar, Mumbai, India, December 2024
Institute for Basic Science Seminar, January 2025
University of Oklahoma HEP Seminar, February 2025
Northwestern HEP Seminar, March 2025
IU-Bloomington, May 2025

Model Building in Fundamental Physics: Naturalness, New Symmetries, and the Generation Puzzle
Pitt Colloquium, January 2025

Naturalness and Generalized Symmetries
KITP What is Particle Theory?, Santa Barbara, April 2025
CNRS New Approaches to Naturalness in Lyon, France, May 2025
PLANCK 25 in Padova, Italy, May 2025

The Standard Model Plus
KAIST Symmetries in Quantum Field Theory and Particle Physics, July 2025

Conferences and Workshops (*=contributed talk)

*__IHEP__ Workshop on the High Energy Circular Electron-Positron Collider, Beijing, November 2018
*__CERN__ Fifth Workshop of the LHC Long-Lived Particle Community, Geneva, May 2019
*__Galileo Galilei Institute__ New Physics From The Sky Workshop, October 2021
*__Aspen Center for Physics__ Frontiers of Particle Physics Workshop, March 2022
*__Pheno 2022__ at University of Pittsburgh, May 2022
*__Cambridge High Energy Workshop__ at Harvard CMSA, August 2022
*__Aspen Center for Physics__ Effective Field Theories Workshop, August 2022
*__ICTP-SAIFR__ New Directions in Particle Physics, São Paulo, Brazil, September 2022
CERN Exotic Approaches to Naturalness, Geneva, January 2023
*__Simons Center__ Lighting New Lampposts for DM and BSM, February 2023
*__Amherst Center for Fundamental Interactions__ Theoretical Tests of the Landscape, April 2023
*__Pheno 2023__ at University of Pittsburgh, May 2023
*__Mainz Institute for Theoretical Physics__ New Proposals for Baryogenesis, June 2023
Chicagoland Pheno at UIUC, October 2023
PIKIMO Fall 2023 at IU Bloomington, November 2023
*__DCPIHEP__ Workshop, University of Colima, Mexico, January 2024
Amherst Center for Fundamental Interactions Surveying the Landscape, April 2024
*__PIKIMO Spring 2024__ at UIUC, May 2024
*__Pheno 2024__ at University of Pittsburgh, May 2024
*__Mainz Institute for Theoretical Physics__ Dark Matter and Flavor Puzzles, Capri, June 2024
*__Chicagoland Pheno__ at UIUC, November 2024
*__PIKIMO Fall 2024__ at UMichigan, November 2024
*__BCVSPIN 2024__ in Kathmandu, Nepal, December 2024
*__HKUST IAS__ Program on Fundamental Physics, Hong Kong, January 2025
*__KITP__ Generalized Symmetries, March 2025
MIAPbP Navigating New Horizons, Munich, Germany, June 2025

My aim is to bring new perspectives to physics beyond the Standard Model by employing a broad range of ideas from field theory, particle physics, and cosmology, and engaging with a diverse set of experimental observables. I search for any possible insight we can gain in order to learn more about the universe, so my research is necessarily interdisciplinary and—like myself—defies strict labeling, but in the following I will share some highlights of recent directions. By understanding developments in both real world data and abstract field theory, I have uniquely been able to see connections across fields to find insights into deep problems of particle phenomenology.

Generalized Symmetries in Particle Physics

Symmetries are at the core of particle physics, and usually we think about symmetries by examining the Lagrangian data of a theory and analyzing transformations of local operators. However theories of particle physics often contain *extended operators* such as cosmic strings or domain walls which often appear in the early universe, or just the Wilson lines of a gauge theory. And it turns out there are Generalized Global Symmetries (GGS) under which these extended operators can transform. Learning there are new types of symmetries in theories of particle physics is obviously exciting, and I have been at the forefront of understanding what GGS can teach us about the physics of the SM and what may lie beyond.

Clarifying the Standard Model Structure Starting with the SM itself, the familiar flavor symmetries are actually intertwined in a structure known as a 'two-group' with the magnetic symmetry of 't Hooft lines of hypercharge. Understanding this structure teaches us from the IR that there are tight constraints on how the SM fermions appear in theories of unification [1]. Furthermore, understanding SM yukawas as 'spurions' of this enlarged structure gives us further insight into theories which introduce vector-like fermions.

Examining the symmetries of line operators more closely, there is an ambiguity in the symmetry of SM Wilson lines related to the 'global structure' of the SM gauge group, and understanding this structure provides strong motivation for searching for fractionally-charged particles at the LHC [2]. This is a very high-stakes search, since their presence would provide nonperturbative information about the SM and would falsify some or all of the minimal models of unification, different models of which demand different line operators be present in the SM. In fact there are further ambiguities about the gauge group of the SM fermions corresponding to discrete gauge factors, or certain global symmetries possessed by cosmic strings that the SM fermions may interact with. I explored novel phenomenologies allowed by these possibilities in [3], and am currently fully classifying the various possibilities in [4]. These include theories where proton stability is guaranteed nonperturbatively, which is intriguing in relation to surprisingly long lower bounds on its lifetime.

BSM Model Building Insight Furthermore I have understood how a certain type of GGS known as a 'noninvertible symmetry' offers a refinement to the familiar EFT tool of spurion analysis which reveals from the IR which operators might be generated by nonperturbative gauge theory effects in the UV. This is information which an effective field theorist who only knows about symmetries of local operators should not expect would be available to us from an IR analysis, and shows concretely how these GGS can provide novel model building tools. My pioneering usage of this was in examining the theory of gauged muon minus tau number $U(1)_{L_\mu - L_\tau}$, which has been studied intensely for three decades, and finding a noninvertible symmetry protecting neutrino masses [5]. This then guided me to a non-Abelian lepton flavor gauge theory $SU(3)_{\text{leptons}}$ which naturally produces Dirac neutrinos whose masses are generated by instantons and so exponentially suppressed from those of charged leptons. By providing essentially the first four-dimensional theory of naturally small Dirac masses, this gives us new insight into whether it is sensible for neutrinos to be Dirac rather than Majorana.

Finding such a noninvertible symmetry in the quark sector led me to a novel approach to the strong CP problem. This is the puzzle of why, of the two CP-violating phases in the theory of quarks, the 'CKM angle' is $\sim \pi/3$, but the strong CP angle is observationally constrained to $\bar{\theta} \lesssim 10^{-10}$. Here I understood symmetries that *discrete* magnetic monopoles from the quark sector can possess, which led me to a beautiful UV theory of color-flavor unification [6], which has remarkably not been studied before. While the 'massless up quark solution' fails in the SM, the structure of color-flavor unification provides a massless *down-type* quark solution with nonperturbative UV gauge theory effects. Together with the lepton sector, these ideas point to novel theories of family unification which have been overlooked.

Overall, the new perspective gained by studying GGS in theories of particle physics is an exciting development, and we have much more to learn from such explorations. These theories of flavor unification have much interesting phenomenology to be studied, and various aspects of model building and early universe cosmology are underway [7, 8]. More broadly, there are many more interesting GGS structures to be uncovered in various theories of particle physics [9, 10].

The Standard Model Generation Puzzle

One exciting aspect of this subtler understanding of symmetries is that it might shed some new light on one of the deepest mysteries of particle physics: why we have multiple generations of fundamental particles $N_g = 3$. Remarkably, our understanding thereof has essentially not advanced since Rabi's "Who ordered that?" after the discovery of the muon in 1936. One possible sort of answer I have been exploring is to understand some physics possibilities which are only possible with multiple generations.

Earlier I explained that the proton is stable in the SM as the result of a discrete global symmetry $\mathbb{Z}_{N_g}$ that exists only with multiple generations [11]. I further proposed a novel BSM theory where this symmetry leads to cosmic strings which can naturally resolve the cosmological lithium problem [3], which has plagued our otherwise-precise understanding of Big Bang Nucleosynthesis for decades. This solution makes use of the special fact that our predictions work for isotopes of hydrogen ($Z = 1$) and helium ($Z = 2$), but fail for lithium with $Z = N_g$ protons, and recognizing this discrete SM symmetry led me to the first such new physics solution which automatically affects only lithium. With related reasoning, there is a novel theory of flavored Higgses which can be constructed specifically because $N_g = 3$ matches the number of fields in a Yukawa interaction, and allows the special structure $y_t \epsilon_{ijk} H^i Q^j \bar{u}^k$ [12].

The noninvertible symmetries I found in flavorful Z' theories in fact show a special role for $N_g = 3$. In the lepton sector, the symmetry protecting neutrino masses is roughly a Z_{N_g} subgroup of lepton number, so only for $N_g \geq 3$ are both Majorana and Dirac neutrino masses protected. While people had previously studied horizontal unification, these ideas have not received much attention because it was not clear what was gained. But these novel nonperturbative effects provide a compelling reason for the SM with multiple generations to have more-interesting fundamental physics. Even more strikingly, the GGS structure I discovered in the quark flavor Z' model is present specifically because we have the same number of colors as generations $N_c = 3 = N_g$. This is a fascinating, novel connection, and is responsible for the possibility of these strong UV instanton effects which can resolve the strong CP problem in color-flavor unification.

The Hierarchy Problem at Colliders and in Cosmology

An important target for particle physicists is the hierarchy problem, which is interesting as a guide toward new physics since it is intrinsically associated with an experimentally accessible energy scale: the Higgs mass. This issue is sorely in need of bold, novel ideas [13, 14, 15], and I continue to think in a variety of exotic directions, including the application of GGS. I took the opportunity of my thesis to write a pedagogical resource on the problem [16], which received the APS' 2022 Sakurai

Dissertation Award. A related important program is to explore models which explain why the conventional signatures of solutions to the hierarchy problem have not appeared. A prototypical such framework is the 'Twin Higgs', which introduces a dark copy of the SM. These models point to new experimental probes of the hierarchy problem, which has been the focus of my work in this area.

On the front of collider physics, I have been involved in exploring an exotic, striking signature of such models: long-lived particles. The LHC [17] or future lepton colliders [18] might produce dark particles which propagate some distance into the detector before decaying into visible states. In addition to appearing in many well-motivated BSM scenarios, searches for such particles have very low SM backgrounds. They are thus a good way to make the most out of our collider capabilities, for example in rare top decays, which are a remarkably sensitive probe [19]. Long-lived particle searches also provide a valuable probe of fractionally-charged particles, since the lightest of these is necessarily stable [2].

Signatures of the hierarchy problem might also appear in the sky, and I have worked to develop the rich phenomenlogical possibilities in the cosmology of such models, which intimately involves the symmetry between the SM sector and the twin sector and its possible breaking. As a grad student I suggested the first sensible 'asymmetric reheating' cosmological history for such models which involved only minimal symmetry-breaking [20]. Such 'mirror twin Higgs' models thereafter received increased attention, including my explanation that there is a surprising interplay between the two possible renormalizable interactions between the SM and mirror sectors, with kinetic mixing generated from the Higgs portal at no less than five loops. Intriguingly, such a naturally small kinetic mixing leads to a beautiful model of freeze-in dark matter [21]. An extension of the twin Higgs symmetry to six clone sectors can provide a natural reason why there is five times as much dark matter as SM matter in the framework of asymmetric dark matter [22].

If the symmetry is instead unbroken at late times, there are interesting late-time cosmological effects that can occur, such as the oscillations of entire hydrogen atoms into their twin counterparts. Such an effect provides a first BSM alternative hypothesis for the longstanding 'missing baryon problem' around $z \sim 0$ [23, 24]. The early cosmology of these models had seemed untenable, but I recently explained how they may work using 'inverse symmetry breaking' where a broken symmetry is restored at low temperatures [25]. These nontrivial cosmological histories appear in simple theories, and can lead to interesting dynamics for the SM fermions during the phase transitions [26].

Zooming out again, particle physics is in dire need of novel ideas and diverse perspectives to make further progress toward insight into nature at its smallest scales. To me, this motivates a broad approach to searching for further understanding of new physics, and thinking about all the deep puzzles with which we are faced. It is possible that the next breakthrough in particle physics may come from cosmology [20, 21, 23, 24, 3] or a collider [17, 18, 27, 28, 29, 19, 2] or astrophysics [30, 31, 32, 33, 24]. Or the next fruitful direction may be inspired by developments in gravity [13, 14, 15] or formal field theory [1, 2, 5, 34, 35, 6]. The next years I am excited to learn more from LHC searches for rare processes and exotic new physics signatures; from the universe in the form of gravitational waves and 21cm cosmology and high energy astrophysics; and from any number of smaller-scale experiments looking for new, feebly-interacting particles or subtle deviations from SM predictions. And in the absence of something new appearing, I am confident that there is yet more to learn about the possibilities for BSM physics by better-understanding field theory and thinking creatively about model-building. My track record, informed by my background, positions me uniquely to recognize interdisciplinary connections and to make progress on what undiscovered new physics lies Beyond the Standard Model.

References

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