MIT\_Department of Physics.\_267

The paramountcy of controlled transport for energy and informational transactions persists as a formidable challenge within the physical sciences, particularly emanating from complexities in modulating their physical vectors. While the governance of electrons and photons has entered a realm of procedural routine, the meticulous control of atomic vibrations—quantized as phonons—remains an intricate endeavor. The centrality of phonons, not only in the chaotic transport of energy manifest as heat but also within the domain of ordered sound waves, propounds persistent dilemmas. An inherent proclivity of phonons to engage in coupling—both amongst themselves and with alternate degrees of freedom—instigates a degradation of their encapsulated energy or informational content. The recent advent of mechanisms capable of reversing these couplings, and thereby regimenting atomic motion, illuminates a pathway toward enhanced control, diminishing parasitic losses, and concurrently, transfiguring phonons into viable informational carriers.

Dynamical influences emerge as a pivotal, albeit traditionally under-scrutinized, facet of this control, with static devices demonstrating palpable insufficiencies amidst fluctuating external conditions. The incorporation of dynamical control not only instills a requisite flexibility and versatility within phononic systems but also fundamentally predicates upon the employment of tunable materials. These materials, characterized by physical properties that yield to external signaling, underscore the essentiality of dynamical tuning, which inherently exhibits sensitivity to the relative frequencies of the tuning signal and the regulated phonons.

In this dissertation, an intuitive framework navigating through the temporal modulation regimes is meticulously developed. Within the domain of low-frequency tuning, phonons are enabled to adapt adiabatically to modifications within the material. A cornucopia of signals can be modulated—both temporally and spatially—to finely tune phonon transport within this regime. An adiabatic perspective is applied to assiduously analyze dynamical effects intrinsic to thermal cloaks. Conversely, tuning signals in proximal resonance with a particular phonon mode can incite resonant couplings, catalyzing a hybridization capable of inducing pronounced alterations in phonon properties. This hybridization concept is adroitly applied to the formulation of a rigorously nonreciprocal phononic computer, utilizing magneto-acoustic materials, and exhibiting the potential to eclipse conventional computers in designated tasks.

Navigating into the realm of high-frequency territories, phonons manifest a predisposition to respond perturbatively to modifications within the tuning signal. Although this regime predominantly circumscribes to optical control, it concurrently unveils innovative avenues for control. Pursuing an alternative modality to optical coupling, a model delineating inverse acousto-optics—construed as the modulation of the speed of sound with optical intensity—and dynamical phonon localization, is judiciously developed.

MIT\_Department of Physics.\_722

Lead sulfide colloidal quantum dots (PbS QDs) captivate scientific intrigue, emanating from their singularly tunable electronic properties, thereby steering a burgeoning interest towards their employment as active materials within lightweight, malleable, and solution-processed photovoltaics. The intrinsic ability of PbS QDs to modulate their bandgap across the entirety of the solar cell-relevant range through meticulous adjustment of the QD size, in conjunction with the alterable nature of additional QD electronic properties through precision control of the chemical ligands adjoined to the QD surface, presents a myriad of exploratory and applicative pathways.

The delineated thesis ventures to demonstrate the tangible applications of control over the energy level profile within PbS QD solar cells as a means to not merely understand but also to augment their operational efficacy. Initially, an enhancement in power conversion efficiency is substantiated for ZnO/PbS QD heterojunction photovoltaics, achieved through the integration of a MoO3 interlayer between the PbS QD film and the top-contact anode. The MoO3 layer, characterized by its profound work-function, acts as a mitigating agent against a Schottky junction that would conventionally formulate at the PbS/anode interface, thereby culminating in performance ameliorations for devices employing a diverse array of anode materials.

Subsequently, the thesis illuminates the utility of the adjustable bandgap of PbS QDs as a mechanism to elucidate charge and exciton-transfer processes, particularly within the realm of hybrid organic/QD photovoltaic devices that exemplify singlet exciton fission. Empirical findings demonstrate that PbS QDs can adeptly accept electrons from triplets, which are resultant from singlet fission in pentacene, and thus act as low-bandgap light absorbers, complementing the singlet fission material. Moreover, an exploration into the dependence of the triplet dissociation process on the energy levels of the QDs is undertaken.

In a concluding exploration, the thesis underscores that the energy levels of lead sulfide QDs, as ascertained by ultraviolet photoelectron spectroscopy, undergo a shift up to 0.9 eV amidst disparate chemical ligand treatments. The directionalities of these energy shifts, which not only are in concord with the results procured from density functional theory calculations but also scale with the ligand dipole moment, align with trends in the performance of photovoltaic devices that employ ligand-modified QD films. This investigation concurrently unearths energy level shifts, resulting from interface modifications, QD bandgap modifications via size control, and ligand-induced surface dipoles, as methods to predictably navigate the electronic properties of colloidal QD films, and subsequently, as adroitly adjustable parameters in the performance optimization of QD optoelectronic devices.

MIT\_Department of Physics.\_723

Friction, the fundamental and omnipresent mechanical interaction, engenders resistance to motion and consequential energy dissipation across two interfacing surfaces. In an endeavor to scrutinize long-established atomistic models pertinent to nanoscale frictional processes, this thesis introduces a synthetic nanofriction interface, innovatively juxtaposing a laser-cooled Coulomb crystal of singularly addressable ions—serving as the mobile entity—and a periodic light-field potential, acting as the substrate.

Embarking upon a manifold of experiments delineated herein, the thesis unfolds, with pronounced atom-by-atom specificity and remarkable spatial resolution, the compelling revelation that friction at the nanoscale can significantly deviate from the elementary phenomenological laws discernible at the macroscopic scale. Specifically, it is elucidated that atomic-scale stick-slip friction can be judiciously modulated from maximal to a state approaching frictionless, facilitated through meticulous arrangement of the ions in relation to the periodic potential. Concurrently, the associated transition in transport dynamics, as visually evinced through the propagation of kinks, is thoroughly examined.

The thesis further demonstrates that friction is concomitantly contingent upon velocity and temperature, exhibiting a harmonious accord with simplistic analytical models, and moreover, unveils that, within a suitable velocity regime, dynamics can be observed in a manner that effectively mimics zero-temperature conditions. A direct correlation between Aubry's structural transition for an infinite chain amidst an incommensurate periodic potential, and the dissipation of friction in nanocontacts, is also robustly established.

Conclusively, our model system bestows a microscopic and systematic exploratory avenue for friction, potentially extending into the enigmatic realm of quantum many-body regimes.

MIT\_Department of Physics.\_724

In the quest to unravel a more profound understanding of the Standard Model of particle physics and interrogate its constraints, the exigency to conduct precise calculations for juxtaposition with experimental results is paramount. Event shapes materialize as a strategically efficient methodology for condensing the multifaceted data derived from each collider event into a singular numerical entity. Employing effective theories and scrutinizing pertinent limits pave the way for delving into the underlying physics with sufficient precision to extract salient information from experimental findings.

In the incipient segments of this dissertation, the C-parameter, a distinct event shape, is utilized to execute a meticulous measurement of the strong coupling constant, \alpha\_sαs​. Initially, the e+e- C-parameter distribution is computed, leveraging the Soft-Collinear Effective Theory (SCET) with a resummation to N3LL' accuracy of the most singular partonic terms, valid for C across peak, tail, and far-tail regions. The treatment of hadronization effects employs a field-theoretic nonperturbative soft function, with moments \omega\_nωn​, and involves a renormalon subtraction concurrently integrating hadron mass effects.

A global fit for \alpha\_s(m\_Z)αs​(mZ​) is presented, analyzing extant C-parameter data in the resummation region, and encompassing center-of-mass energies between Q = 35 and 207 GeV, while also fitting for the dominant hadronic parameter, \omega\_1ω1​. The experimental data is counterposed with our theoretical prediction, proffering a perturbative uncertainty for the cross-section of \sim∼ 2.5% at Q = m\_Z in the pertinent t region for \alpha\_s(m\_Z)αs​(mZ​) and \omega\_1ω1​. The findings denote \alpha\_s(m\_Z) = 0.1123 \pm 0.0015αs​(mZ​)=0.1123±0.0015 and \omega\_1 = 0.421 \pm 0.063ω1​=0.421±0.063 GeV with \chi^2/\nuχ2/ν = 0.988 for 404 bins of data, and harmonize with the universality prediction for \omega\_?ω?​ between thrust and C-parameter within 1-\sigmaσ.

Subsequent portions of this study are devoted to elevating SCET beyond leading power, aiming to augment the potential precision of calculations. On-shell helicity methods emerge as potent tools for determining scattering amplitudes, which maintain a one-to-one correspondence with leading-power helicity operators in SCET, absent from singular regions of phase space. The dissertation elucidates that helicity-based operators also serve as instrumental for enumerating power-suppressed SCET operators, which encapsulate subleading amplitude information about singular limits. In particular, a comprehensive set of scalar helicity building blocks, applicable for constructing operators at any order in the SCET power expansion, is presented. Additionally, an intriguing angular momentum selection rule that governs the assembly of these building blocks is delineated.

MIT\_Department of Physics.\_733

While numerous astronomical sources give rise to transient phenomena at radio frequencies, the domain of the transient sky at low frequencies (sub-300 MHz) remains relatively uncharted. The undertaking of blind surveys, enabled by contemporary widefield radio instruments, is progressively illuminating this enigmatic realm. Despite the prevalent limitation imposed by classical confusion noise intrinsic to many of these instruments, the theoretical capability to discern transients beneath the classical confusion limit persists.

This dissertation delineates the development of a technique adept at detecting radio transients, rooted in the application of temporal matched filters directly to time series of images. Exhibiting well-defined statistical properties, this technique is universally applicable to variable and transient searches across any instrument. Through the exemplification of the Murchison Widefield Array, it is demonstrated that the technique maintains efficacy on authentic data notwithstanding the presence of classical confusion noise, sidelobe confusion noise, and additional systematic errors. A search for transients with durations spanning 2 minutes to 3 months was conducted, enhancing the upper limits on the transient surface density at 182 MHz for fluxes approximating 20-200 mJy.

Furthermore, this technique is employed to characterize the detectability of radio afterglows emanating from compact binary coalescence, which are theorized to be the electromagnetic counterparts of gravitational wave (GW) sources and the most propitious progenitors of short gamma-ray bursts. As the subsequent generation of GW detectors commences operations, detecting the inaugural GW event, their capacity for localizing these events is anticipated to be suboptimal during the initial phases of their operation. Numerous emergent widefield radio instruments, capable of covering expansive sky areas in a diminutive time frame, will be operational. Utilizing simulated afterglow light curves, rates of detection for various radio instruments under idealized conditions are estimated. The findings suggest that certain widefield radio instruments may possess the capability to detect radio afterglows and constrain their properties, thereby offering insightful parameters in the performance optimization of future transient search endeavors.

MIT\_Department of Physics.\_734

This dissertation elucidates advancements in comprehending the ensemble of 6D F-theory vacua, establishing a remarkably transparent correspondence between physics—specifically physical quantities—and mathematics, particularly geometrical quantities. Such a correspondence facilitates the articulation of precise mathematical declarations through well-established and comprehended methodologies.

Two interconnected results are presented herein, each contributing to a singular, principal objective: the exploration of the 6D F-theory vacua utilizing geometrical methodologies, subsequent to contrasting these with low-energy supergravities. Through this investigation, a nearly impeccable correspondence is discovered between low-energy supergravities derivable from F-theory and field theories satisfying acknowledged low-energy consistency conditions, such as anomaly cancellation. Nonetheless, several cases are isolated and proven to be unattainable within F-theory, despite exhibiting no apparent low-energy inconsistencies.

The exposition is articulated through two chapters. Initially, a comprehensive, systematic enumeration of all elliptically fibered Calabi-Yau threefolds (EF CY3s) with Hodge number h^{2,1} \geq 350h2,1≥350 is described. Physically, this classifies all F-theory models leading to low-energy supergravities with \geq 351≥351 neutral hypermultiplets, a result achieved through global geometric calculations in a finite set of specific geometries.

Subsequently, a classification of local geometrical structures—corresponding to amalgamations of gauge algebras and (potentially shared) matter achievable in F-theory—is undertaken via local geometric calculations. This exploration unveils a remarkably stringent correspondence between F-theory models and consistent low-energy supergravities. This near-perfect agreement casts discrepancies between F-theory and low-energy supergravities into stark relief. Detailed descriptions of these discrepancies, in which ostensibly consistent field theories find no description within F-theory, are provided.

The work rendered herein carries numerous implications. Primarily, it further refines the understanding of 6D supergravity models in F-theory, bearing implications for string universality in 6D. Additionally, it introduces a level of mathematical precision to the study of 6D superconformal field theories (SCFTs) initiated in [4, 3], representing a conjecturally complete classification of all 6D SCFTs. Our analysis not only corroborates numerous results from their studies but also unambiguously demonstrates that some of their posited models cannot be realized through their construction. Given that our findings can be articulated in geometrical terms, they also bear implications for the study of EF CY3s. Lastly, we explore the subset of our results that maintain validity in 4D F-theory, where they contribute additional structure in an as-yet challenging-to-constrain landscape.

MIT\_Department of Physics.\_735

This dissertation explores the applications of effective field theories, proffering insights into Quantum Chromodynamics (QCD) jets and their substructure within the context of the Large Hadron Collider. A pivotal introduction to an observable, designated D2, has been effectuated, constituting a tool adept for distinguishing boosted W/Z/H bosons from the QCD background, achieved through the meticulous examination of the radiation pattern internal to the jet, accompanied by the execution of a precision calculation of this observable. Concurrently, in order to streamline calculations in the soft collinear effective theory, the development of a helicity operator basis is undertaken. This facilitates congruent matching calculations to fixed order computations, implemented employing spinor-helicity techniques, and its utility is substantiated through the computation of an observable that is germane for examining the properties of the newly discovered Higgs boson. The dissertation endeavors to navigate through the complexities of the application of effective field theories in understanding QCD jets and, in doing so, contributes to the ongoing discourse and investigations within particle physics.

MIT\_Department of Physics.\_736

In the ensuing dissertation, an exhaustive exploration of the optical properties of the spin-1/2 kagome lattice antiferromagnetic Herbertsmithite, ZnCu3(OH)6Cl2, is undertaken, employing the methodology of Terahertz Time-Domain Spectroscopy. Herbertsmithite, reputed to exhibit Quantum Spin Liquid (QSL) behavior, presents a milieu wherein electron spins engage in potent antiferromagnetic interactions. However, it is quantum fluctuations that deter the establishment of magnetic order at 0 K, thereby yielding to a Resonating Valence Bond state instead. QSLs are renowned for hosting exotic fractionalized excitations, termed spinons, characterized by a spin 1/2 albeit devoid of charge. The low-energy dynamics of these excitations are conjectured to be steered by emergent gauge fields, which in turn are contingent upon the quantum order of the macroscopically entangled ground state wavefunction. A vigorous debate has permeated the past decade concerning the nature of the quantum order of the ground state in Herbertsmithite. While computational endeavors have proffered the notion that a gapped Z2 spin liquid is realized in Herbertsmithite, experimental endeavors have not discerned evidence of a spin gap, thereby positing that a U(1) Dirac spin liquid might instead be realized. Recent theoretical discourse has suggested that a signature of the quantum order of the ground state of Herbertsmithite is incarnated in its low-frequency optical conductivity, this resulting from the interplay of the charge and spin degrees of freedom through an emergent gauge field. Within the framework of this dissertation, Terahertz Time-Domain Spectroscopy measurements on Herbertsmithite single crystals are utilized to subject these theories to scrutiny and furnish evidence that substantiates the existence of a U(1) Dirac spin liquid state in Herbertsmithite.

MIT\_Department of Physics.\_942

Embarking upon a meticulous exploration within the realm of fluid dynamics—universally acknowledged as the definitive theory elucidating low-energy excitations proximate to equilibrium states and governing the physics embedded in the longevity of modes correlating with conserved charges—this thesis proffers a novel formulation of fluid dynamics, articulated through a path integral, which systematically interweaves both thermal and quantum fluctuations into its framework. Historically inscribed within the conventional formulations at the echelons of equations of motion and articulated via local fluid velocity intertwined with thermodynamic quantities, the present research espouses a departure, introducing dynamical degrees of freedom as Stuckelberg-type fields, inherently tethered to the conserved quantities and navigated by innate symmetry considerations. Moreover, this investigative journey is punctuated by the evolution of the path integral along a meticulously delineated closed-time contour. The established formulation, whilst enshrining the archetypal hydrodynamics, inclusively embraces constraints emanating from thermodynamics and the fluctuation-dissipation theorem, whilst simultaneously unveiling an additional non-linear generalization of the Onsager relations. A salient revelation within this scholarly endeavor is the manifestation of an emergent supersymmetry within the "classical statistical" demarcation of the propounded theory. Furthermore, when broaching the non-linear fluid, the formalism is encapsulated within a non-trivial differential geometric structure, necessitating a non-vanishing torsion tensor to meticulously recover the intricate physics intricately interwoven within the most generalized fluid. The dissertation proceeds to illuminate advancements achieved in procuring a holographic derivation of the action formulation at the ideal echelon, wherein the low-energy degrees of freedom naturally burgeon as the relative embedding of the boundary and horizon hypersurfaces.

MIT\_Department of Physics.\_2654

This dissertation endeavors to elucidate the intricate relationship intertwining black holes within the framework of holography, chaos manifest in strongly-coupled quantum systems, and the computational complexity inherent to holographic states. Through a methodical exploration of the temporal evolution of local operators, this research is shepherded towards a straightforward diagnostic tool for many-body chaos: a commutator of the aforementioned operators, judiciously separated within temporal and spatial parameters. Utilizing this diagnostic instrument, an examination into the growth of operators is undertaken, revealing a manifestation of the butterfly effect across an array of quantum systems. Upon engaging with the butterfly effect within a holographic context, evidence emerges, positing a detailed correspondence between the tensor network (or alternatively, the quantum circuit) constructing the holographic state, and the internal geometry of the black hole, exemplified by the Einstein-Rosen bridge. The ensuing investigation seeks to comprehend these connections through an exploration of entanglement distributed across time - namely, the entanglement juxtaposing an output system, consequent to time evolution, with a record or memory impeccably correlated with the initial system. This work strives to unravel, through meticulous analysis and exploration, the subtleties of these connected phenomena within the realm of quantum mechanics and holography, illuminating possible pathways for further research and understanding in the field.

MIT\_Department of Physics.\_3723

In the present dissertation, we embark on a meticulous exploration of microparticle flow through geometrically confined environments, constituting a fundamental aspect of myriad microfluidic technologies. While prevailing methodologies for ordering and manipulating flowing particles predominantly hinge on the application of external forces or employment of coflowing streams, these approaches occasionally exhibit constraints in terms of generality and scalability. Consequently, a burgeoning avenue of research has pivoted towards discerning conditions under which particles can autonomously organize through inherently prevalent interactions during the flow of suspensions within microchannels. Specifically, a particle navigating through a viscous medium induces a disturbance flow, thereby influencing the motion of other particles located distantly. The sensitivity of these hydrodynamic interactions (HI) to particle shape and confining boundaries unfurls a compelling opportunity: potentially, particle trajectories could be architecturally "encoded" into the particle morphology and channel design, such that many-body hydrodynamic interactions propitiously foster the self-organization of desired particle motions. The notion extends to the prospect that even an isolated particle could be conceived to “self-steer” to a prescribed position within the channel cross-section, mediated through its hydrodynamic self-interaction.

In this scholarly endeavour, a series of studies is proffered, probing into novel possibilities for actualizing self-organization, self-steering, and other collectively induced flow phenomena via astute design of particle shape and channel geometry. The spotlight of our analysis is cast on a specific condition: quasi-two-dimensional (q2D) confinement, wherein particles are assiduously “sandwiched” between parallel plates, thereby circumscribing their motion to a mere two dimensions. Within this confinement paradigm, hydrodynamic interactions adopt a unique, dipolar form, previously demonstrated to uphold novel collective phenomena with a substantially enhanced spatiotemporal coherence relative to that achievable in unconfined or weakly confined suspensions. Nevertheless, the self-organization of q2D suspensions remained unvalidated until our investigations.

Our analysis commences with a two-body problem, sequentially escalating towards accommodating larger particle numbers and increasingly complex particle shapes. Initially, we formulate model equations for the interlinked motion of two discs within a quasi-two-dimensional channel, identifying, through numerical exploration, that a pair can formulate a hydrodynamic bound state, encapsulating complex oscillatory motion. Notably, we establish that this “quasiparticle” can be manipulated via strategic patterning of confining boundaries. Subsequent studies encompass larger disc clusters, introducing symmetry principles for the a priori development of “flowing crystals”: particle configurations that maintain their relative positions whilst being transported by the flow. These crystalline states extend the two-body bound state into more intricate configurations and collective modes, whilst also unveiling metastable states characterized by newly coordinated particle motions.

In a quest for self-steering and self-organization, our attention veers towards particle shape, exploring the dynamics of a singular “dumbbell” comprising two interconnected discs. We discern that a fore-aft asymmetric dumbbell will align with the flow and gravitate towards the channel centreline, whilst a symmetric counterpart will perpetually oscillate between channel walls. Theoretical arguments isolate three viscous hydrodynamic mechanisms cumulatively inducing self-steering, mechanisms generically present for asymmetric particles in q2D confinement. Experimental validation, employing Continuous Flow Lithography (CFL), exhibits qualitative and semi-quantitative concordance with theoretical anticipations. Gathering statistics from numerous particle trajectories, we proffer a persuasive experimental substantiation of self-steering for device applications.

This logical progression finds its zenith in our concluding study, wherein a theoretical and numerical framework, inspired by the mobility formalism of polymer dynamics, is developed to retrieve the collective dynamics of numerous particles with intricate shapes. It is discovered that small clusters of dumbbells can self-organize from disorder into one-dimensional flowing crystals, though dumbbells can also pair as undesirable “defects”, an effect that disrupts self-organization in expansive dumbbell suspensions, instigating particle aggregate formation. In order to mitigate this aggregation, particle shape is rationally redesigned, calibrating hydrodynamic interactions to favour particle chaining in the flow direction. The redesigned “trumbbell” particles spontaneously organize into large, two-dimensional flowing crystals, revealing that crystal self-organization transpires via a multi-stage process, with one, two, several, and finally many-body interactions becoming engaged in successive stages. The present study pioneers in demonstrating that flowing lattices can be stabilized purely through viscous hydrodynamic interactions.

MIT\_Department of Physics.\_3724

In the research delineated herein, findings are elucidated, derived from the scrupulous analysis of 5.1 fb⁻¹ of proton-proton collision data at a center of mass energy of 7 TeV, complemented by an additional 19.7 fb⁻¹ at 8 TeV, underpinning a meticulous search for decays of the Standard Model (SM) Higgs boson into two Z bosons and, subsequently, to four charged leptons. An intriguing excess, incongruent with background expectations, is observably prominent, rendering a significance of 7.4 standard deviations, and is conspicuously centered at a mass of 125.6 ±0.4(stat) ±0.2(syst) GeV. Such an excess exhibits a signal strength parameter, which will be elaborated upon in subsequent sections. An assiduous examination of the transverse momentum spectrum of this novel particle reveals a consistency congruent with extant SM expectations. Furthermore, a pivotal determination has been made: the Standard Model J^P C = 0⁺⁺ is preferentially favored over plausible alternative hypotheses, underscoring a significant concurrence with established theoretical frameworks. This meticulously conducted investigation not only buttresses the empirical panorama of Higgs boson decay but also navigates through the subtle, complex facets of particle physics, offering an innovative lens through which to scrutinize the fundamental particles and forces of the universe.

MIT\_Department of Physics.\_3726

Extrapolated from astronomical and cosmological indicators, it is postulated that a substantial 27% of the universal energy content is constituted by non-baryonic matter, colloquially denominated "dark matter." The long-standing consideration of Weakly Interacting Massive Particles (WIMPs) emerges as a compelling candidate for this elusive dark matter, permeating a multitude of models which traverse the periphery of the Standard Model of particle physics. The Dark Matter Time Projection Chamber (DMTPC) experiment strategically employs low-pressure gas time projection chambers in the pursuit of detecting nuclear recoils, the aftermath of interactions transpiring between nuclei embedded within a detector and WIMPs constituting the dark matter halo of the Milky Way galaxy. Notably, these detectors possess the capability to reconstruct the vectors of the nuclear recoils, thereby enhancing the rejection of conceivable background events. This dissertation elucidates the conceptualization of a diminutive prototype detector and delineates the methodologies enacted by the DMTPC collaboration for event reconstruction, background rejection, and the discernment of nuclear recoil candidate events. The forthcoming sections will unveil the findings from a series of studies dedicated to deciphering background events within DMTPC detectors. Conclusively, this scholarly work will unveil inaugural results from a nuclear recoil search, executed utilizing this detector in a surface laboratory situated at the Massachusetts Institute of Technology (MIT).

MIT\_Department of Physics.\_3727

Embarked upon within this dissertation is a meticulous exploration for the Higgs boson, interrogating its decay through the conduit of a pair of tau leptons, wherein the tau-pair further decays to an electron, a muon, and neutrinos. This investigative pursuit is anchored in data harvested from proton-proton collisions as facilitated by the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider. The scrutiny encompasses 5.0 fb^-1 of integrated luminosity, recorded at a center-of-mass energy of 7 TeV, and an additional 19.7 fb^-1 at 8 TeV. The anticipated significance, correlated with a Standard Model Higgs boson bearing a mass of 125 GeV, aligns with a level of 1.2 standard deviations for the electron muon tau-pair decay mode. A subtle proliferation of events, transcending the Standard Model (SM) background expectation in this decay mode, aligns congruently with a SM Higgs boson of 125 GeV mass. When amalgamated with results derived from alternative tau-pair decay modes, an event excess surfaces above the background expectation, registering at a level of 3.4 standard deviations, thus marking the inaugural evidence supporting a Higgs boson decaying to leptons.

Moreover, this thesis extrapolates an analysis of the data within the broader spectrum of physics that extends beyond the Standard Model, with a particular lens focused upon its Minimal Supersymmetric extension, thereby offering an intricate exploration into new realms of particle physics and potential pathways to uncharted discoveries therein.

MIT\_Department of Physics.\_3728

This dissertation delves into the prolific domain of electronic transport within atomically thin layered materials, a field which has burgeoned significantly subsequent to the isolation of a single layer of graphene in 2004. Graphene, characterized as a semi-metal, manifests a singular, gapless, Dirac-like band structure at lower electronic energies, thereby inaugurating a pantheon of novel physical phenomena and consequent applications. Not only is graphene endowed with properties of lightness, strength, transparency, superior conductivity, and flexibility, rendering it a potent contender for forthcoming electronic advancements, but its triumph has also precipitated a swift proliferation in 2D electronics research. Researchers have been engrossed in the pursuit of analogous materials which too sustain stable, atomically thin, crystalline structures. The family of transition metal dichalcogenides (TMDs) emerges as a pivotal development in this endeavor, furnishing semi-conducting components to the 2D materials realm and thereby facilitating advancements in digital and optoelectronics. Notably, the single-layer variants of these materials can exhibit a direct band gap, significantly amplifying their optical properties.

This thesis encapsulates research executed on graphene and the dichalcogenides MoS2 and WSe2. Initially, it augments the array of compelling graphene devices, introducing innovative work in the fabrication and characterization of suspended graphene nanoelectromechanical resonators. It shall delineate novel techniques for graphene device suspension, ion beam etching of nanoscale patterns into suspended graphene systems, and characterization studies of high-frequency graphene nanoelectromechanical resonators encroaching upon the GHz regime. Subsequently, this document ventures into pioneering explorations pertaining to the characterization of atomically thin transition metal dichalcogenides, along with the development of electronics and optoelectronics underpinned by these materials. It elucidates the intrinsic electronic transport properties of high-quality monolayer and bilayer MoS2, executing Hall measurements and elucidating the temperature dependence of the material’s resistivity, mobility, and contact resistance. Furthermore, it presents data concerning optoelectronic devices grounded in electrically tunable p-n diodes in monolayer WSe2, showcasing a photodiode, solar cell, and light-emitting diode, thereby providing a comprehensive discourse on the expansive potentialities within the 2D materials space.

MIT\_Department of Physics.\_4294

This dissertation meticulously explores the phenomenon of charge exchange, a semi-resonant electron transfer from a neutral atom to an excited state within an energetic ion, prominently observed within contexts wherein energetic ions encounter a cold, partially neutral gas, such as in the immediate shock regions of supernova remnants. Such interactions, particularly within astronomical contexts like supernova remnants, offer environments propitious for charge exchange, whereby the emission emanating from ions—post charge-exchange—as the acquired electron spirals down to the ground state, unveils critical information regarding the physical conditions of the shock and the immediate post-shock material. This, consequently, emerges as an instrumental tool for delineating insights into supernova explosions and their subsequent material and energetic dispersions.

The initial segment of this thesis delves into an intricate study of charge exchange within the galactic supernova remnant G296.1-0.5, scrutinizing interactions across two distinct energy bands: the optical and the X-ray. The optical study, consummated through both imaging and high-resolution spectroscopy utilizing the IMACS instrument on the Magellan Baade Telescope at Las Campanas Observatory, aspires to discern 'Balmer-dominated shocks' within the remnant. Such shocks signal the occurrence of charge exchange interactions between hot, post-shock protons and the comparatively colder neutral hydrogen pervading the environment. Concurrently, the X-ray study meticulously examines line ratios within dispersed spectral data, obtained via XMM-Newton RGS from an X-ray lobe situated in the NW quadrant of the remnant, with the aim to unearth potential signatures of charge exchange. It warrants noting that the dispersed data undergo degradation owing to the source’s extended nature, thereby blurring emission lines and rendering precise measurements arduous.

In the latter half of the thesis, attention is accorded to Micro-X: a sounding rocket-borne X-ray telescope, designed to harness an array of microcalorimeters to achieve elevated energy resolution, even for extended sources. An exhaustive description of the design and commissioning of the payload is provided, in tandem with delineating the subsequent steps steering toward launch, which was projected for the spring of 2015.

MIT\_Department of Physics.\_4445

Encompassing a staggering 83% of the universe's mass, dark matter particles, about which our knowledge remains profoundly limited, dictate a compelling cosmic enigma. Direct detection of these elusive particles—via hypothesized weak-force-mediated recoils with nuclear targets on Earth—holds the potential to illuminate their intrinsic nature, their relationship with the standard model, and subsequently, how the standard model might be embedded within a more foundational understanding. This thesis delineates two pivotal experimental endeavors aimed at this profound astronomical and physical question: CDMS II (2007-2009) and the ongoing SuperCDMS Soudan.

The exposition herein meticulously articulates the general capabilities and sensitivities of both experiments, with an accentuated emphasis on the detector technology and its evolution from the initial to the subsequent experiment. While certain topics, particularly the minutiae of the CDMS II analysis, which has been comprehensively explicated in prior works, are treated here in an overview, others, notably those not detailed elsewhere, are afforded a more in-depth examination. Consequently, this thesis aspires to serve as a substantive reference for those engrossed in the annual modulation limits placed on the low-energy segment of the CDMS II exposure, the design intricacies of the detectors employed in SuperCDMS Soudan, and a panoramic overview of the incredibly informative data that these detectors elucidate.

The epoch is indeed exhilarating. The technology, with which I have had the privilege to engage over the previous years, yields a veritable trove of information pertaining to each event, surpassing any other direct detection experiment in its informative capacity. We continue to navigate the optimal utilization of this abundant information. Preliminary tests, both at the surface and subterranean levels, intimate that this technology possesses the requisite background rejection capabilities for a contemplated 200kg experiment and potentially, even a ton-scale experiment. Thus, we find ourselves perched on the brink of probing parameter spaces that extend orders of magnitude beyond the current frontiers of the field.

MIT\_Department of Physics.\_4446

In the endeavor presented herein, the deterministic lattice code, DRAGON, is scrupulously benchmarked against empirical data, subsequently being utilized to prognosticate the antineutrino flux emanating from the Chooz B1 and B2 reactors. A meticulous comparison is drawn utilizing data derived from the destructive assay of rods from the Takahama-3 reactor, as well as data procured from the SONGS antineutrino detector. The ensuing prediction, yielded from the finessed DRAGON code, is juxtaposed with the inaugural antineutrino event spectra emanating from Double Chooz. Additionally, this thesis ventures into a discourse concerning the application of this simulation in studies pertinent to nuclear nonproliferation, thereby delineating the multifaceted utility and potential future applications of the research and findings contained within. Consequently, this composition not only contributes substantively to the existing scientific dialogue but also extends a foundation upon which future investigative studies might invariably build.

MIT\_Department of Physics.\_4447

This dissertation proffers findings from the inaugural systematic survey scrutinizing Mg II absorption lines at z > 2.5z>2.5. Through the analysis of 46 infrared Quasi-Stellar Object (QSO) spectra, 111 Mg II systems are discovered, inclusive of five systems with z > 5z>5 — presently the most temporally distant systems identified. A scrutiny of the comoving line density for weaker systems reveals a statistical congruence with non-evolution from z = 0.4z=0.4 to z = 5.5z=5.5. Conversely, the density for more potent systems evidences a three-fold augmentation until z \approx 3z≈3 before regressing at elevated redshifts, hinting at a nexus with star formation. The lack of evolution in the weaker systems deviates from this interpretation but may be congruent with the extrapolation of low-redshift scaling relationships between host galaxy luminosity and absorbing halo radius into earlier epochs. Employing novel measurements derived from optical spectra of identical targets and low-redshift control samples, we probe evolutionary trajectories in the chemical composition of Mg II systems from z = 0z=0 to z = 5.33z=5.33. A palpable amplification in the characteristic N(H I)N(HI) for a given Mg II strength is observed as redshift ascends. Lower limits on the metallicity are established where H IHI can be measured, and it is discerned that systems with W\_{\lambda2796} = 0.3-1.0 \, \text{Å}Wλ2796​=0.3−1.0A˚ are substantially metal-rich at \approx 0.1≈0.1 Solar. Speculatively, if weaker Mg II systems epitomize accreting gas, their pronounced metal abundance proposes a re-accretion of recently expelled material rather than the initial infall from the metal-poor Intergalactic Medium (IGM), even in early cosmic times. Furthermore, a novel technique for the concomitant fitting of luminous point sources in ungridded visibility data — referred to as the side lobe matrix technique — is introduced. We also afford computational accelerations which facilitate real-time implementation. Analytic approximations for the error distributions of fit intensities, considering thermal noise, imperfect calibration, and ionospheric errors, are derived. It is found that the intensity errors of the brightest sources, given imperfect calibration and ionospheric errors, are predominantly dominated by 'self errors,' extant independent of side-lobe contamination. It is demonstrated that, to the lowest order, the dynamic range obtained with calibration/ionospheric errors parallels that when the source intensities are perfectly known. Consequently, this dissertation not only unveils critical insights into the nature and evolution of Mg II systems across cosmic time but also introduces methodological advancements in data analysis within the domain.

MIT\_Department of Physics.\_4448

In the vibrant arena of quantum information theory, the adept discrimination between quantum states emerges as a cardinal utility. The present thesis delves into the realm of state discrimination of continuous quantum variables, with a focused lens on bosonic communication channels and Gaussian states, exploring two particular state discrimination challenges: (a) quantum illumination and (b) optimal measurements for decoding bosonic channels.

Quantum illumination, a technique wherein entanglement between a probe and an ancilla fortifies sensitivity in detection and imaging, is meticulously explored. This discourse delineates how entanglement can enhance the discrimination between two noisy, lossy bosonic channels. Specifically, it navigates through scenarios in which a target partially reflects the probe light and those in which all probe light succumbs to loss, even when the channels in question are entanglement-breaking. Remarkably, the pinnacle findings of this exploration reveal that, under optimal detection and in the asymptotic limit of numerous detection trials, an enhancement of 6 dB in the error exponent is attainable by leveraging an entangled state over a classical state.

Transitioning to the study of optimal measurements for decoding bosonic channels, an alternative measurement to the pretty-good measurement is unveiled, aspiring to attain the classical capacity of the lossy bosonic channel, given product coherent-state inputs. This novel measurement necessitates only projective measurements at each measurement stage, exhibiting a sequential nature: the number of requisite steps burgeons exponentially with the code length, while the error rate of this measurement converges to zero in the large code length limit. Although not innately physically practical, this innovative measurement elucidates a straightforward physical interpretation via collective energy measurements, potentially spawning an implementation of an optimal measurement for lossy bosonic channels.

Conclusively, the two problems scrutinized within this thesis serve to illustrate the substantive utility of state discrimination in addressing challenges through the meticulous application of quintessential quantum mechanical properties, such as entanglement and entangling measurements, thereby weaving a tapestry that intertwines theoretical inquiry with tangible, applicative potentialities.

MIT\_Department of Physics.\_4449

Navigating through the intricate arena of particle physics, this thesis embarks upon an exploration of the proton’s structure, situated firmly within the realm of nonperturbative Quantum Chromodynamics (QCD). Proton structure models, continually sculpted and refined, invariably seek the informative and constraining touch of experimental data. The STAR experiment, ensconced within the Brookhaven National Lab, procured over 12 pb-1 of data emanating from polarized p+p collisions at a center-of-mass energy of 500 GeV, facilitated by the RHIC accelerator, in 2009. This data has bestowed a preliminary glimpse into the spin-dependent production of W+(-) bosons and, consequently, the spin-flavor architecture of the proton, where d+u (u+d) annihilation emerges as the predominant production modality.

Leveraging the expansive Time Projection Chamber of STAR, coupled with its wide-acceptance electromagnetic calorimeters, the identification of the e+ + v (e- + v) decay mode of produced W bosons is actualized. This scholarly work unveils the inaugural STAR measurement of charge-separated W production, elucidating both the pseudorapidity-dependent ratio and the longitudinal single-spin asymmetry. Astoundingly, these findings harmonize well with theoretical prognostications, thereby not only vindicating the methodologies employed but also embarking upon a path towards the analysis of more voluminous datasets, poised to be accessible imminently.

In an imminent epoch, the measurement spectrum of this study is slated for enhancement, courtesy of the Forward GEM Tracker. An in-depth discourse on the design and actualization of this augmentation is incorporated herein, complemented by foresights concerning its prospective impact, weaving a coherent narrative that seamlessly intertwines meticulous experimental data analysis with forward-looking technological advancements in the realm of particle physics. This thesis, therefore, not only contributes a granular analysis of proton structure but also foreshadows the forthcoming advancements in experimental methodologies and technologies.

MIT\_Department of Physics.\_4452

Delving into the profound biological intricacies posed by the conformation of DNA within cellular environments, this thesis navigates through both the fundamental and applicative aspects of DNA modeling, met with diverse challenges when enacted both theoretically and experimentally. Tracing in vivo conformations of DNA presently confronts an insurmountable barrier, thus emphasizing the importance and exigency of specialized techniques to model it effectively and illuminate its essential biological implications.

This scholarly contribution bifurcates into two pivotal computational projects, each addressing distinctive aspects of the aforementioned challenges. The inaugural project materializes in the form of both online and offline calculators, meticulously designed to compute conformational statistics. These calculators are forged through the amalgamation of a myriad of methods, both from previously published literature and novel, unpublished endeavors, adeptly addressing a prevailing void in user-accessible DNA model-building tools. Thus, this endeavor serves as an academically robust tool, poised to enhance the accessibility and feasibility of DNA modeling across varied research landscapes.

Concurrently, the secondary project immerses itself in a reconstructive analysis, aiming to pioneer a methodology capable of mapping DNA conformation in vivo with exemplary high resolution, harmonizing effectively with currently available experimental technology. This synthesis of theoretical and practical approaches offers a notable stride towards not only deciphering the complexities entwined with DNA conformation within a cellular context but also enabling its future exploration through enhanced computational and experimental avenues.

Therefore, through a seamless integration of computational prowess and biological knowledge, this thesis orchestrates a balanced narrative that navigates through the challenges and potentials residing within the study of DNA conformation, affirming its position within the wider discourse of cellular biology and computational modeling in contemporary scientific exploration.

MIT\_Department of Physics.\_4484

Navigating the nuanced complexities of the Standard Model (SM) of particle physics, a celebrated quantum field theory delineating the intricate relationships amongst the strong, weak, and electromagnetic interactions at microscopic scales, this dissertation seeks to explore the enigmatic domain of electroweak symmetry breaking (EWSB). Despite its remarkable success in elucidating a vast array of observed phenomena, the SM is yet to demystify the intricate mechanism underpinning EWSB. In the absence of EWSB within the theoretical framework, the gargantuan weak force mediators, specifically the W and Z bosons, necessitate a massless state to maintain gauge symmetry.

The quintessential approach to embedding EWSB into the SM is to invoke the Higgs mechanism. This proposition introduces a scalar field, the Higgs field, which engages in interactions with the W and Z bosons, thereby bestowing upon them their mass. Concurrently, the SM hypothesizes that fundamental fermions attain mass via interactions facilitated with the Higgs field. The identification of the field quantum, the Higgs boson, would invariably substantiate our conceptualizations regarding EWSB and consummate the tableau of fundamental particles anticipated by the SM. The Higgs boson, should it exist, has adeptly evaded detection for an extended temporal expanse.

The Large Hadron Collider (LHC), with its ambitious aspirations, seeks to articulate a definitive commentary on the existence of the elusive Higgs boson, establishing this objective as a primary aim. In its 2011 run, the LHC provisioned proton-proton collisions at \sqrt{s} = 7s​=7 TeV. The interrogation for the SM Higgs, utilizing the 2011 dataset, symbolized the LHC project’s inaugural substantial expedition into the search endeavour.

This dissertation unfolds a meticulous search for the SM Higgs boson in the ZZ \rightarrow 2\ell2\nuZZ→2ℓ2ν channel, guided by the analytical exploration of 4.9 fb^{-1}−1 of data amassed with the Compact Muon Solenoid (CMS) detector at the LHC. A thorough overview of electroweak theory and Higgs production at the LHC is proffered, succeeded by detailed descriptions of the CMS detector and the algorithms imperative for event reconstruction. To validate the measured efficiencies of electron and muon reconstruction and selection requirements, an inclusive cross-section measurement for Z boson production is elucidated. The treatise culminates with a detailed exposition of the Higgs search analysis and the resultant findings. Consequently, through a scrupulous intersection of theoretical understanding and experimental exploration, this thesis fortifies its position within the expansive discourse of electroweak symmetry breaking and the quest for the Higgs boson within the milieu of particle physics.

MIT\_Department of Physics.\_4486

Embarking upon an incisive exploration into the enigmatic realm of many-body physics, this dissertation delineates comprehensive experiments conducted on strongly-interacting gases composed of fermionic atoms, assiduously concentrating on non-equilibrium physics and the impactful role of dimensionality. The realm of two-component gases presents spin transport - engendered by relative motion between disparate spin components - as one of its intrinsic dissipative processes. Through the astute implementation of a spin dipole excitation, spin transport within strongly-interacting Fermi gases is generated, facilitating a meticulous measurement of the transport coefficients that articulate the dynamics of spin drag and diffusion. Remarkably, under the auspices of resonant interactions, a profound suppression of spin transport is observed, whereby the spin transport coefficients converge upon quantum-mechanical boundaries.

The pivotal role of dimensionality is elucidated within the formation of bound states amongst particle pairs. The dimensionality of a Fermi gas is artfully modulated from three dimensions (3D) to two (2D) employing an optical lattice potential, revealing a fascinating evolution of pair binding energy, as discerned through radio-frequency spectroscopy. An intriguing ascension of the binding energy is observed concomitant with increasing lattice depth, verging upon the 2D theoretical limit. Gases, which exhibit resonant interactions and, consequentially, lack a two-body bound state in a 3D context, manifest a substantial binding energy that is substantively determined by the confinement energy associated with the lattice wells.

The synergistic themes of non-equilibrium dynamics and dimensionality coalesce in a perspicacious study of soliton excitations within superfluid Fermi gases. A planar defect is meticulously crafted within the superfluid order parameter of an elongated Fermi gas, implemented via detuned laser light. The resultant defect, propagating through the gas as a non-dispersing solitary wave or soliton, evidences an oscillation period that remarkably exceeds mean-field theoretical predictions by an order of magnitude.

Conclusively, through a judicious fusion of experimental rigor and theoretical insight, this thesis augments our understanding of non-equilibrium dynamics and dimensionality within the context of strongly-interacting fermionic gases, offering a seminal contribution to the corpus of knowledge within many-body physics.

MIT\_Department of Physics.\_4487

In the intricate domain of biomechanics, this dissertation unfolds a data-delineated neuromuscular model of human ambulation and its adept application to prosthetic control, embodying a seminal approach by intertwining tendon elasticity to accurately prognosticate metabolic expenditure during locomotion, superseding conventional models in precision. The model, when amalgamated with a reflex-based neural drive, demonstrates pragmatic utility in controlling a robotic ankle-foot prosthesis, thereby engendering speed-adaptive behavior.

Prevailing neuromuscular models have evinced a propensity to substantially overstate the metabolic requisites of walking, a discrepancy posited herein to emanate from an insufficient consideration of elasticity. The parameters steering the force-length relationships of tendons in extant models predominantly derive from published values, ascertained through cadaver studies, and may not adequately mirror the dynamism intrinsic to living tissues. To dissect this predicament, kinematic, kinetic, electromyographic (EMG), and metabolic data were meticulously harvested from five subjects traversing at six distinct velocities. Utilizing kinematic and kinetic data to estimate muscle lengths, muscle moment arms, and joint moments, and EMG data to approximate muscle activations, a kinematically clamped optimization was executed for each subject. This involved modulating the parameters dictating the force-length curve of each tendon, concurrently minimizing metabolic cost and maximizing congruence with observed joint moments.

The findings elucidate a cadre of parameter sets that adeptly fulfill both objectives, harmonizing with the collated kinetic and metabolic data, and enabling the precise prediction of the metabolic expenditure of walking alongside the force and state of individual muscles. This divulges invaluable insights into the roles and control objectives of disparate muscles throughout the gait cycle. The optimized muscle-tendon morphology, when synchronized with an optimized linear reflex architecture, was proficiently employed in the control of a powered ankle-foot prosthesis. By feeding the robot's angle and state into the model to command output torque, clinical trials manifested speed-adaptive behavior, with commanded net work correspondingly escalating with walking speed. These results underpin both the efficacy and the prospective utility of the modeling approach in the domain of life-like prosthetic limb control, heralding a promising avenue for future research and development in biomechanical applications.

MIT\_Department of Physics.\_4488

Within the detailed framework of this dissertation, the jet fragmentation function of inclusive jets, characterized by a transverse momentum P\_T > 100 \, \text{GeV/c}PT​>100GeV/c, in PbPb collisions, is meticulously measured for reconstructed charged particles boasting P\_T > 1 \, \text{GeV/c}PT​>1GeV/c within the jet cone. A data sample, derived from PbPb collisions amassed in 2011 and possessing a center-of-mass energy of \sqrt{s\_{\text{NN}}} = 2.76 \, \text{TeV}sNN​​=2.76TeV, corresponding to an integrated luminosity of 150 \mu \text{b}^{-1}μb−1, serves as the empirical foundation for the analysis herein.

Results emanating from PbPb collisions, articulated as a function of collision centrality, are juxtaposed with reference distributions predicated upon pp data, procured at an equivalent collision energy. A palpable, centrality-dependent modification of the fragmentation function is unmasked through this comparative analysis. In the realm of the most central collisions, a notable enhancement becomes discernible in the PbPb/pp fragmentation function ratio for charged particles with P\_TPT​ less than 3 GeV/c, thereby unfolding novel insights into the intricate dynamics of high-energy particle collisions.

In navigating through the rich tapestry of data, this scholarly text endeavors not merely to delineate observed phenomena but also to cast light upon the underlying physical processes governing particle interactions in high-energy collisions. As such, it seeks to pave the way for subsequent explorations into the realm of quantum chromodynamics and the multifaceted world of particle physics.

MIT\_Department of Physics.\_4521

The present dissertation delves into the multifaceted implications of fluctuations in systems that deviate, potentially to a substantial degree, from equilibrium, as a consequence of their progression either towards or away from thermal equilibrium. The investigative scope envelops several pivotal topics within physics, which include, but are not limited to, the dynamical Casimir effect in scenarios involving mobile boundaries and non-contact friction amongst objects undergoing relative motion. In both instances, the origination of photons is observed, attributable to the interplay between motion and zero-point fluctuations in the vacuum, engendering phenomena of dissipation and radiative loss.

A comprehensive formalism is introduced, bearing equal applicability to objects characterized as either lossy or ideal, designated to compute quantum radiation and associated dissipation effects, exclusively in terms of the classical scattering matrices. The resultant trace formulas, agnostic to approximation schemes, exhibit generality, with an assortment of examples, several of which are unprecedented, being scrutinized in exquisite detail.

More particularly, an exact treatment of quantum fluctuations is afforded within the context of a neutrally rotating object, elucidating its propensity for spontaneous photon emission and its capability to exert a drag on proximate objects, in addition to computing affiliated photon statistics and entropy generation. Within the realm of non-contact friction, a quantum counterpart to the classical Cherenkov effect is identified for two neutral plates in relative motion, a phenomenon derived purely from quantum fluctuations. A plethora of arguments and exact proofs, inclusive of a methodology inaugurated within the context of quantum field theory in curved space, alongside the scattering approach, substantiate the manifestation of a frictional force between two plates, materializing at a threshold velocity dictated by the speed of light inherent to their medium.

The dissertation, in its intricate exploration and analysis, endeavors to furnish a profound understanding of the underlying processes and consequences of fluctuations in systems transitioning in and out of thermal equilibrium, aspiring to elucidate the subtle and complex behaviors of quantum phenomena in varied physical contexts. This scholarly text seeks not only to detail observed physical phenomena but also to unravel the concomitant physical processes that preside over particle interactions amidst high-energy collisions, thereby aspiring to illuminate future inquiries into the intricate domains of quantum chromodynamics and particle physics.

MIT\_Department of Physics.\_4522

Embarking upon a meticulous exploration of the interactions amidst charge and lattice degrees of freedom, this thesis meticulously scrutinizes their pivotal role in delineating the properties of canonical BCS superconductors. Within this domain, the integration out of the phonon subsystem culminates in an effective electron pairing interaction, derived from an intricate entwining of interactions. Conversely, within the realm of high-temperature superconductors, the phonons’ significance and charge ordering properties oscillate across different families of high-T\_cTc​ cuprates.

Although superconductivity in such materials is not ostensibly believed to be an offshoot of phonon excitations, manifestations of potent electron-phonon coupling are evidenced through pronounced electron dispersion renormalization and observed broadening in optical Cu-O bond modulating phonons. This dissertation elucidates measurements of acoustic phonons in both single and double-layer BSCCO, revealing multifarious effects such as the broadening of the longitudinal acoustic correspondent to approximately period-four ordering tendencies and discernible signatures indicative of time-reversal and inversion symmetry breaking.

The feasibility of measuring these anomalous properties can be attributed to the renormalization of the lattice propagator, an outcome of the intensive interactions with the foundational symmetry-breaking electronic states. Intriguingly, such symmetries, despite being disrupted at room temperature for all materials within the 'strange metal' state situated above the pseudogap, demonstrate an enhancement, especially proximal to the period four intercell ordering wavevector, as the system descends into the pseudogap state.

Employing in-plane acoustic phonons, which serve as a probe into the electron physics localized on the Cu-O plane due to the residual eigenvector components within this plane, a panorama of BSCCO is presented. Within this, charge correlations persistently remain dynamic, possessing a notable inclination towards ordering at a distinct wave-vector and subsisting within an underlying symmetry-breaking ground state.

Through its careful examination and analytic engagement, this dissertation does not merely enumerate the physical phenomena witnessed but seeks to unravel the convoluted physical processes overseeing interactions amidst such energetic particle collisions, thereby enlightening subsequent explorations into the enigmatic realms of quantum chromodynamics and advanced particle physics.

MIT\_Department of Physics.\_4604

Embarking upon the cutting-edge horizon where quantum mechanics gracefully intertwines with macroscale physical systems, this dissertation intricately explores the burgeoning epoch of interferometric gravitational wave detectors—technological marvels presently under meticulous construction, destined to adeptly skirt the enigmatic boundaries of fundamental quantum measurement limits. Concurrently, a burgeoning spectrum of experiments, strategically harnessing micro-mechanical oscillators, are incrementally pioneering into the hitherto elusive quantum domain, significantly aided by advanced optical cooling techniques.

This treatise delineates the navigational journey toward the quantum regime, perceptively articulated through the lens of a gram-scale opto-mechanical experiment, and subsequently juxtaposed with its monumental counterpart: large-scale gravitational wave detectors. The foray into the gram-scale experiment is architecturally crafted to ensure the unequivocal dominance of radiation pressure forces, comprehensively orchestrating the dynamic choreography of the mechanical mirror suspensions.

A panoramic review is presented, encompassing a diverse array of optical trapping and cooling techniques, which have been empirically manifested through the utilisation of this experimental apparatus. Adapting a variant of these seminal techniques to a gravitational wave interferometer unveils an effective temperature of a mere 1.4 microkelvin and a phonon occupation number of 234, elucidated within the confines of a kilogram-scale oscillator.

Upon meticulous analysis of the displacement noise spectrum, presently constrained by thermally-driven fluctuations of the mirror suspensions within the gram-scale system, this dissertation identifies innovative methodologies for enhancing the suspension. Such enhancements strategically unearth the inherently concealed quantum fluctuations, those quintessentially attributable to the back-action intricacies of a displacement measurement.

Conclusively, this thesis introduces a sagaciously conceived scheme, ingeniously exploiting the opto-mechanical coupling in this sophisticated system, thereby aiming to generate optical entanglement. Within the hallowed corridors of quantum mechanics and gravitational wave detection, this scholarly work stands as a sentinel, demarcating the intersection of theoretical quantum mechanics and applied physical reality, thereby nurturing the seeds for future academic and experimental exploration within this fascinating scientific frontier.

MIT\_Department of Physics.\_4605

Navigating through the vast, celestial tapestry, this thesis penetrates the enigmatic domain of high spectral resolution observations of X-ray phenomena, recognizing its latent capacity to unveil previously obscured physical laws. Presently, the scrutiny of high-resolution spectra is confined to point sources, meticulously facilitated by gratings, while the dissection of extended objects, such as supernova remnants, is hindered by an inability to be dispersed—rendering the rich tapestry of emission lines indistinguishably merged by the moderate resolution of contemporary instruments.

In the inaugural half of this discourse, two rigorous explorations are undertaken of the supernova remnant Cassiopeia A, employing the preeminent X-ray observatory, Chandra. The first investigation deftly marries the spatial resolution acumen of the ACIS instrument with the spectral discernment of the dispersive HETG, striving to scrutinize the evolutionary trajectory of ejecta knots. Subsequently, the second study enhances statistical boundaries of radioactive ejecta and projects simulations, seeking to mimic the observational capacities of forthcoming higher-resolution instruments.

Transitioning into the latter half, the focus meticulously shifts toward Micro-X, an innovative high-resolution X-ray telescope. The exposition delves into detailing the commissioning of this pioneering sounding rocket payload, which, by employing a focal plane of micro-calorimeters, attains lofty spectral resolution within each pixel. The flight hardware, as elucidated herein, exists in a terminal state of evaluation and integration, anticipatively poised for a launch envisaged in 2014.

Embarking upon a journey from the investigation of existing observational techniques to the intricate realms of forthcoming technologies, this thesis subtly bridges the observed phenomena of supernova remnants with the latent capabilities of spectral observation technologies. Thus, it stands not only as an exploration of celestial phenomena but also as a segue into the future of astrophysical observational capabilities, marking a subtle transition from the known to the anticipated, and skillfully elucidating a pathway toward uncovering the concealed astrophysical secrets nestled within the cosmos.

MIT\_Department of Physics.\_4606

Embarking upon a meticulous exploration within the realm of Lattice Quantum Chromodynamics (QCD), this thesis endeavors to illuminate the intricate structures and behaviors of quarks ensconced within hadrons through the lens of first-principles calculations of quantum chromodynamics. Two paramount calculations serve as the pillars of this scholarly discourse, each unveiling both qualitative and quantitative insights into the idiosyncratic behaviors of quarks nestled within hadronic confines.

The initial investigation delves into the enigmatic world of diquarks. By anchoring two quarks within a baryon to a static quark, the simultaneous two-quark density is computed, assiduously incorporating corrections pertinent to periodic boundary conditions. Defining an astute correlation function to meticulously isolate the intrinsic correlations intrinsic to the diquark, a compelling discovery emerges: beyond the proximate vicinity of the static quark, the diquark exhibits a remarkably consistent shape. A discernible disparity is observed in the correlation strength between scalar and axial-vector diquarks. This exploration furnishes results at pion masses of 293 and 940 MeV and provokes a contemplative discussion regarding the dependence upon the pion mass.

Segueing into the second ensemble of calculations, a decidedly quantitative analysis unfolds, encompassing a vast spectrum of primarily isovector nucleon observables. This spans the Dirac and Pauli radii, the magnetic moment, the axial charge, and the average quark momentum fraction, inter alia. This investigation heralds two salient advancements over preceding calculations: the incorporation of a near-physical pion mass, thereby significantly mitigating the uncertainty concomitant with extrapolation to the physical point, and an assiduous control over systematic errors induced by excited states, which constitutes a significant thematic focus of this thesis. Employing pion masses as diminutive as 149 MeV and spatial box sizes extending up to 5.6 fm, the criticality of rigorous control over excited states is underscored in order to realize successful postdictions, which are accomplished for numerous quantities. Furthermore, a residual source of systematic error is identified, plausibly accountable for discrepancies with experimental results within the axial sector.

This narrative thus fortifies a comprehensive understanding of the systematic underpinnings and employs this knowledge to proactively formulate predictions for observables as yet unmeasured in experimental frameworks. This thesis, therefore, not only presents a detailed exploration of the architecture of hadrons but also charts a navigable path toward future investigations within the domain of Lattice QCD, serving as a lighthouse guiding toward uncharted territories within quantum chromodynamics.

MIT\_Dept. of Physics.\_5

The pursuit of discerning the intricate electromagnetic structure of nucleons and nuclei compels a comprehensive understanding of nucleon elastic electromagnetic form factors, serving as fundamental quantities. Within this context, the evolution of the Sachs electric and magnetic form factors, as a function of Q^2Q2 (the square of the four-momentum transfer), proffers insightful correlations with the distribution of charge and magnetization inherent within the nucleon. High-fidelity measurements of these nucleon form factors emerge as imperative, presenting stringent tests to rigorously probe our extant theoretical understanding of confinement phenomena within the nucleon.

Particularly, measurements pertaining to the neutron form factors—and especially the neutron electric form factor—have perpetually presented a formidable challenge to experimental physicists. This complexity arises in part due to the absence of a free neutron target and the neutron’s integral charge, which vanishes. Despite the exacting measurement of the neutron electric form factor eluding experimentalists over numerous decades, the advent of high duty-factor polarized electron beam facilities has heralded a new era, facilitating experiments that harness polarization degrees of freedom and thus, enabling the acquisition of the inaugural precise measurements of this foundational quantity.

Subsequent to providing a comprehensive overview, elucidating both experimental and theoretical dimensions of nucleon form factors, this dissertation delineates a meticulous description of a meticulously devised experiment. This experiment, crafted to extract the neutron electric form factor, hinges upon measurements of the neutron's recoil polarization within the framework of quasielastic 2H(e, e')1H2H(e,e′)1H scattering. The experimental configuration deployed within this investigative context engaged the Thomas Jefferson National Accelerator Facility's longitudinally polarized electron beam, paired with a magnetic spectrometer to discern the scattered electron and a neutron polarimeter, uniquely designed and optimized for this experimental endeavor.

Measurements transpired at three distinct Q^2Q2 values: 0.45, 1.13, and 1.45 (GeV/c)^2(GeV/c)2. The ensuing dissertation proffers final results, extracted subsequent to an in-depth analysis of the amassed data, reporting and juxtaposing these findings with contemporaneous theoretical predictions intrinsically linked to the nucleon form factors. Thus, this research not only unveils novel insights into nucleon electromagnetic structure but also, more broadly, contributes substantively to our collective understanding within the arena of nuclear physics, interweaving sophisticated experimental methodologies with theoretical acumen.

MIT\_Dept. of Physics.\_14

The Relativistic Heavy Ion Collider (RHIC), furnishing the most energetically prodigious nucleus-nucleus collisions heretofore attained within a laboratory setting, affords a novel investigative lens through which to probe the properties of nuclear matter under conditions of extreme temperature and energy density. Such exploratory endeavors hold the potential to unearth novel states of matter engendered under such extremities. This dissertation proffers a meticulous examination of the elliptic flow amplitude, denoted as v\_2v2​, within Au+Au collisions at the zenith of RHIC’s center-of-mass energy—200 GeV per nucleon pair.

Elliptic flow, emerging as a compelling probe into the dynamical evolution of the system instantiated within the collision, evokes particular interest. The dependencies of the elliptic flow on transverse momentum, centrality, and pseudorapidity are scrutinized, utilizing data accrued by the PHOBOS detector amidst the 2001 RHIC operational run. The collision’s reaction plane was determined through the employment of the multiplicity detector, wherein the azimuthal angles of tracks, reconstructed in the spectrometer, were correlated with the discerned reaction plane.

Observationally, v\_2v2​ values augment almost linearly with transverse momentum, ascending up to P\_TPT​ of approximately 1.5 GeV, and saturating proximate to 14%. Centrality functionally informs v\_2v2​, minima for which are observable for central events—anticipatable from geometric considerations—and ascendances up to near 7% (for 0 < \eta < 10<η<1) at N\_{\text{part}} = 83Npart​=83. The v\_2v2​ dependency on pseudorapidity was measured over the range 0 < \eta < 1.80<η<1.8 for three centrality ranges: 3-15%, 15-25%, and 25-50%. For all but the most central of the three centrality ranges, v\_2v2​ is discerned to diminish with increasing \etaη, commencing already near mid-rapidity.

The results are systematically dissected, with comparative analyses vis-à-vis extant models and interpretative frameworks robustly discussed. Consequently, this research not only propounds novel empirical insights into the behaviological dynamics of nuclear matter under extreme conditions but also contributes sagaciously to the theoretical discourse permeating the field, providing a fertile ground for further research and exploration in the domain.

MIT\_Dept. of Physics.\_57

This dissertation delineates novel advancements in single-ion Penning trap mass spectrometry, with a particular emphasis on the meticulous measurements of the atomic mass of Cesium, achieving a remarkable relative uncertainty of 2 \times 10^{-10}2×10−10. This measurement ameliorates the uncertainty affixed to the mass of Cesium by an impressive factor of 100, thereby obviating this uncertainty as a constriction upon the precision of determining the fine-structure constant, \alphaα, through a Cesium photon recoil experiment. The abatement of this limitation prospectively facilitates a determination of \alphaα with a relative accuracy approaching ~1 1 ppb, potentially equating to or even surpassing the most precise measurement of \alphaα hitherto available. Such an accurate value of \alphaα is poised to illuminate the extant \sim 50∼50 ppb discrepancies between values of \alphaα discerned via disparate methodologies.

In a complementary vein, this thesis elucidates concomitant mass measurements of atomic Rubidium and Sodium, which mitigate the uncertainties on these masses by factors nearing 100, envisaging potential future applications in photon recoil measurements utilizing these atomic species. These measurements were executed utilizing a newly constructed Penning trap mass spectrometer, a collaborative creation of the author and colleagues. This innovative spectrometer adheres to the general design tenets of preceding MIT ICR Lab Penning trap mass spectrometers, while inaugural incorporation of a DC SQUID as an ion detector marks a pioneering departure in its design.

In conclusion, this thesis broaches a discourse on a passive two-coil system, specifically designed for the shielding of magnetic field gradients. This system may well materialize as a pivotal enabling technology for a prospective double Penning trap mass spectrometer, thereby facilitating further exploration and advancements in precision measurements within atomic physics. Consequently, the research proffered herein not only contributes empirical advancements but also enhances methodological approaches and technological apparatus within the realm of precision mass spectrometry and fundamental constant determination.

MIT\_Dept. of Physics.\_86

Part I of this dissertation fabricates a comprehensive physical framework delineating the kinetics of protein-DNA interactions, a phenomenon pivotal to cellular functionalities including transcription, replication, and recombination. The act of recognition, wherein a protein expeditiously searches and subsequently adheres to its specified site on a DNA molecule, has been a subject of profound scientific intrigue. The exploration herein implicates protein sliding, construed as one-dimensional diffusion within a sequence-dependent, topographically variegated energy landscape, as a crucial mechanism in rapid search phenomena. It is demonstrated that notwithstanding the corrugation of the landscape, efficacious search can be consummated when one-dimensional sliding is concomitant with three-dimensional diffusion. The investigation elucidates the spectrum of specific and nonspecific DNA-binding energies requisite for swift search, and propounds experimental frameworks that may substantiate the mechanism proffered.

A salient observation emergent from the investigation is that realistic energy functions ostensibly fail to concurrently facilitate rapid search and robust binding of a rigid protein. In the quest to reconcile these imperatives, a "search-and-fold" mechanism is posited, interlinking protein binding with concomitant partial protein folding, thereby introducing an effective energy landscape that embraces both longitudinal (sliding) and transversal (folding) dynamics. Additional exploration extends to evaluating the influence of a finite correlation length in the binding potential profile on one-dimensional diffusion. The implications of the mechanism proffered herein are myriad, with biological ramifications extending to searches amidst other proteins and nucleosomes, concurrent searches by multiple proteins, among other scenarios.

Part II segues into an analysis of random walk behavior in the vicinity of smooth manifolds. Initially, a random walk (or Gaussian polymer) confined to a half-space is explored through a field-theoretic lens. Utilizing path integrals, fundamental scaling relations and the probability distribution function for arbitrary coupling strength between the polymer and the manifold are derived. Subsequently, consideration is accorded to self-avoiding polymers affixed to the tip of an impenetrable probe. Scaling exponents \gamma \_1γ1​ and \gamma \_2γ2​, which characterize the number of configurations for the polymer attachment either by one end or at its midpoint respectively, are demonstrated to undergo continuous variation with the angle of the probe's tip. These apex exponents are analytically computed via \epsilonϵ-expansion and juxtaposed against numerical simulations in three dimensions. Notably, when the polymer possesses the liberty to traverse through the attachment point, it is typically inclined to slide to one extremity; the apex exponents quantify the entropic barrier to threading through the probe’s eye. This dissertation, therefore, provides not only a holistic analytical framework for protein-DNA interaction kinetics but also a profound inquiry into the behavior of random walks in proximity to manifolds, each with profound implications in their respective domains.

MIT\_Dept. of Physics.\_87

This thesis elucidates a parallel implementation of the Particle-Particle/Particle-Mesh (P3M) algorithm, articulated for distributed memory clusters, and introduces the "llp3m-hc" code, utilizing a hybrid method for both computation and domain decomposition. The long-range forces are computed through a Fourier transform gravity solver on a uniform mesh, distributed across parallel processes using a static one-dimensional slab domain decomposition. Conversely, short-range forces are computed by the direct summation of close pairs with particles being distributed through a dynamic domain decomposition rooted in a space-filling Hilbert curve. The research intricately devises a method nearing optimality to dynamically repartition particle distribution, thereby maintaining load balance, even amidst extremely inhomogeneous mass distributions.

Testing, through the utilization of 8003 simulations on a 40-processor Beowulf cluster, demonstrated commendable load balance and scalability, extending up to 80 processes. This document addresses the scalability limits imposed by communication and extreme clustering, and proffers potential solutions through an extension of our algorithm to include a novel adaptive P3M technique. This technique, introduced and presented as the "llap3m-hc" code, witnesses the optimization of adaptive P3M’s free parameters to minimize force errors and timing required to compute short-range forces.

Applied within the context of simulating the small-scale structure of the universe at redshift z > 50z>50, our codes enabled the observation and analysis of caustic formation within the structure, juxtaposing it with the predictions posited by semi-analytic models of structure formation. A notable inference drawn from this research is that the extant limits on neutralino detection experiments, which assume a Maxwell-Boltzmann velocity distribution and smooth spatial distribution of dark matter, are significantly impacted by an inhomogeneous distribution of dark matter on smaller scales, thereby altering the predicted event rates in direct detection dark matter experiments. Substantively, the spatial inhomogeneity attenuates the upper limits on neutralino cross section elicited from the Cryogenic Dark Matter Search Experiment, providing a nuanced perspective towards understanding dark matter distributions and their implications in the realm of experimental physics.

MIT\_Dept. of Physics.\_88

Intricacies and unparalleled physics emergent from nanoscale structures not only manifest unique theoretical challenges but also pave the way toward pioneering developments in the physical realm. This thesis meticulously navigates through such complexities, demonstrating four diverse applications that illuminate how first-principles calculations can adeptly navigate these challenges. Particularly, the exploration and identification of novel boron nanotube structures are elucidated, revealing their peculiar elastic properties. The identification of internal degrees of freedom facilitates the dissipation of longitudinal stress, sans altering the tube's diameter, culminating in a noteworthy lateral stiffness.

Investigations into self-trapped hole structures within amorphous silicon dioxide seek to forge a connection between the behavior of hole currents and atomic-scale structures, presenting a comprehensive study into the intricacies of electrical response and its manifestation at the atomic level. An examination of calculations on a paired-oxygen analogue to the elided center illustrates that such a configuration does not yield a metastable trapped-hole state, providing nuanced insights into the atomic interactions within these structures.

A novel methodology, enabling first-principles mobility calculations in ultrathin silicon-on-insulator (UTSOI) structures, is presented and employed to scrutinize interface roughness scattering within transistor channels. Through the utilization of self-consistent potentials, and the precision of wavefunctions and band structures, a direct nexus between measured electrical response and atomic structure is established. The investigation reveals atomic-scale interface roughness as a critical limitation on mobility at elevated carrier densities, while at reduced carrier densities, such short-wavelength roughness results in a qualitatively distinct mobility behavior as compared to the gradual fluctuations in UTSOI channel thickness.

Moreover, an effective Hamiltonian technique, designed to calculate short-time, non-equilibrium fluctuations in quantum devices, is developed and elucidated. Applications to quantum dots and resonant tunneling diodes underscore that temporal fluctuations are adroitly reproduced, weaving a complex tapestry that intertwines theoretical predictions with practical, observable phenomena at the nanoscale. This multifaceted exploration thus manifests as a pivotal step towards holistically understanding and innovating within the domain of nanoscale physics and its myriad applications.

MIT\_Dept. of Physics.\_89

Within the boundaries of this thesis, we delve into an incisive exploration of Sen’s conjectures pertaining to tachyon condensation upon a bosonic D-brane, employing as our primary analytical tool the level truncated open bosonic string field theory. Employing level truncation, we substantiate that the energy differential between the local zenith and nadir of the open bosonic tachyon effective potential aligns impeccably with the tension of a space-filling D-brane, thus affirming Sen’s first conjecture with a remarkable precision approximating 0.1%.

Concurrently, we architect lump solutions within the open bosonic string field theory, which, according to Sen's third conjecture, are theorized to manifest as D-branes within diminished dimensions. A meticulous examination ensures that the tensions of lumps, specifically those of codimension one and two, seamlessly correspond with the tensions of the respective D-branes, with a precision deviating by a scant few percent.

Moreover, the thesis lends empirical weight to Sen’s second conjecture, which propounds that in the nonperturbative tachyon vacuum, all open-string degrees of freedom are necessitated to vanish. This eventualization is ostensibly guaranteed, provided the identity string field, I, can be sculpted in the form I = QA, wherein A represents a particular string field, and Q symbolizes the BRST operator within the true vacuum. The evidence presented substantiates that the identity can indeed be moulded into this architecture.

Intriguingly, as we navigate through the dynamics of tachyon condensation, examining time-dependent solutions both within p-adic string theory and level truncated string field theory, the unfolding narrative reveals that while our rolling solutions maintain energy conservation, their pressure oscillates, with their amplitudes inexorably diverging. Thus, these findings, while illuminating, do not affirm Sen's proposition of a pressureless tachyon matter, introducing nuanced perspectives and beckoning further explorations within the enthralling domain of tachyon condensation.

MIT\_Dept. of Physics.\_98

This dissertation delineates the foundational architecture of a relativistic ray-tracing code, pivotal for elucidating accretion processes circumventing Kerr black holes. Chapter 1 inaugurates the discourse with a succinct historical encapsulation, highlighting seminal developments in black hole astrophysics that have transpired over preceding decades. Subsequently, Chapter 2 offers a meticulous articulation of the ray-tracing code, a tool adept at computing the transfer function interlinking the plane of the accretion disk and the detector plane, thereby becoming an indispensable asset for modeling relativistically broadened emission lines.

Observational data emanating from the Rossi X-Ray Timing Explorer, manifesting as high-frequency quasi-periodic oscillations (HFQPOs) in numerous black hole binary systems, forms the cornerstone of the discussions in Chapter 3. Herein, a simplified “hot spot” model is employed to decipher the locational and amplitude-oriented attributes of the aforementioned HFQPO peaks. It is elucidated that the power spectrum of the periodic X-ray light curve encompasses multiple peaks, strategically located at integral combinations of the black hole coordinate frequencies, whilst the relative amplitude of each peak is intricately influenced by orbital inclination, eccentricity, and hot spot arc length.

Progressing to Chapter 4, the model is augmented with additional features intended to elucidate the broadening of the QPO peaks and the attenuation of higher frequency harmonics within the power spectrum. This comprehensive model is judiciously applied to fit the power spectra observable in XTE J1550-564, subsequently providing confidence limits pertaining to each model parameter.

In Chapter 5, a descriptive analysis of the structure of a relativistic alpha-disk enveloping a Kerr black hole is presented. Utilizing the given surface temperature of the disk, the observed spectrum is calculated employing the aforementioned transfer function. The distinctive attributes of this modified thermal spectrum may be employed to deduce the physical properties not only of the accretion disk but also of the central black hole.

Finally, Chapter 6 develops a Monte Carlo code to meticulously calculate the nuanced propagation of photons from a hot spot emitter, scattering through a corona that envelops the black hole. This coronal scattering engenders two primary observable consequences: the inverse-Compton process modulates the photon spectrum, introducing a high-energy power-law tail, and the random scattering of each photon substantively dampens the highest frequency modulations in the X-ray light curve, thereby intertwining intricate physical processes and observational astronomy in a coherent analytical framework.

MIT\_Dept. of Physics.\_169

Situated at the Heavy Ion Fusion Virtual National Laboratory, the Neutralized Transport Experiment (NTX) materializes as an instrumental foray into the exploration of various physical phenomena and determining the definitive spot size of a high-intensity ion beam on a scaled rendition of a Heavy Ion Fusion driver, establishing itself as the inaugural successfully integrated beam system experiment of its kind. The determination of the final spot size is strategically governed by the conditions manifest in the beam produced within the injector, the ensuing beam dynamics extant in the focusing lattice, and the nuanced plasma neutralization dynamics occurring during the final transport.

In this intricate experiment, a high-brightness ion source, meticulously employing an aperturing technique, duly delivers a 25 mA single-charged potassium ion beam at an energy of 300 keV and a normalized edge emittance of 0.05 π-mm-mr. This ion beam is subsequently injected into a large bore magnetic quadrupole lattice, facilitating the production of a 20 mm radius beam, converging assiduously at 20 mr. The converging ion beam is then further introduced into a plasma neutralization drift section, wherein it is ballistically compressed to a diminutive 1 mm spot size.

NTX stands prominently as the harbinger of the first experimental proof of plasma-neutralized ballistic transport of a space-charge dominated ion beam, providing critical information regarding higher-order aberration effects on the spot size, while also validating numerous numerical tools—validation evidenced by the impeccable concordance between measurements and numerical simulations across a sweeping parameter regime. Additionally, it heralds the development of innovative diagnostics to meticulously scrutinize the dynamics of the ion beam.

The discourse herein unfurls theoretical and experimental outcomes, shedding light on the beam dynamics within the ion diode, the downstream quadrupole lattice, and the concluding neutralized transport, weaving a coherent narrative of groundbreaking discovery and meticulous experimental practice in the realm of ion beam physics.

MIT\_Dept. of Physics.\_170

In probing the intrinsic properties of the proton's first excited state, the Delta, both magnetic dipole spin flip (M1) of one of the constituent quarks and the engaging of electric and Coulomb quadrupole terms (E2 and C2)—indicative of a departure from spherical symmetry—are pathways to access. Quintessential quark models, employing the color hyperfine interaction, significantly underestimate quadrupole term magnitudes, often by more than an order of magnitude. In contrast, models invoking the pion cloud conspicuously align with extant data, a congruence anticipated due to the spontaneous chiral symmetry breaking, which precipitates a cloud of virtual p-wave pions thereby instigating non-spherical amplitudes.

The empirical data delineated herein adroitly bridge existing gaps in the low Q^2Q2, long-distance domain, a region wherein the pion cloud is theoretically foreseen to assert dominance and manifest discernible Q^2Q2 variation. Measurements of the p(e, e'p)\pi^0p(e,e′p)π0 reaction within the \DeltaΔ region, realized at a markedly low Q^2Q2 of 0.060 (GeV/c)^22—heretofore, the most diminutive for pion electroproduction—were executed utilizing out-of-plane magnetic spectrometers at the Mainz Microtron in Germany.

This discourse elucidates results for the prevailing transition magnetic dipole amplitude and the quadrupole to dipole ratios, derived from conjoining the newfound data with models, through a three-parameter, resonant multipole fit, yielding: M\_{3/2} = (40.33 \pm 0.63\_{\text{stat+syst}} \pm 0.61\_{\text{model}}) \times 10^{-3}/m\_{\pi^+}M3/2​=(40.33±0.63stat+syst​±0.61model​)×10−3/mπ+​, E2/M1 = \Re(E\_{3/2}/M\_{3/2}) = (-2.28 \pm 0.29\_{\text{stat+syst}} \pm 0.20\_{\text{model}})\%E2/M1=ℜ(E3/2​/M3/2​)=(−2.28±0.29stat+syst​±0.20model​)%, and C2/M1 = \Re(S\_{3/2}/M\_{3/2}) = (-4.81 \pm 0.27\_{\text{stat+syst}} \pm 0.26\_{\text{model}})\%C2/M1=ℜ(S3/2​/M3/2​)=(−4.81±0.27stat+syst​±0.26model​)%. These novel results for the transition multipoles contrast starkly with the prognostications of quark models, yet align, with reasonable accord, with a chiral extrapolation of lattice QCD, chiral effective field theory, and dynamic model outcomes—affirming both the dominance and general Q^2Q2 modulation of the extensive, pionic contribution. Notwithstanding the qualitative concord with the models, the absence of quantitative alignment underscores an imperative for further refinement therein.

MIT\_Dept. of Physics.\_187

This dissertation elucidates comprehensive investigations into high index-contrast (HIC) photonic crystals and corresponding microphotonic circuits, affording noteworthy insights into the realm of photonic structures and their inherent phenomena. The exposition commences with an exploration of macro-scale, two-dimensional photonic crystal meta-materials. Through a meticulous juxtaposition of experimental and theoretical beam evolutions in the vicinity of super-collimation frequencies, the nuanced effects of disorder on beam propagation are astutely discerned. Remarkably, super-collimation demonstrates robustness, evidenced by the manifestation of stationary beam-widths across an expansive trajectory of 600 isotropic diffraction-lengths, even in the context of extant disorder.

Subsequently, the narrative navigates toward an analysis of nano-scale photonic crystal defect modes across substantial optical bandwidths, enabled by the advent of pioneering supercontinuum-based methodologies. The deployment of innovative, all-fiber supercontinuum sources engenders the production of unpolarized supercontinuum light, spanning wavelengths from 1.2 to 2.0 microns, thereby affording broad-spectrum experimental modalities. These, in turn, facilitate the nuanced study of one- and three-dimensional photonic crystals featuring defect states.

The exposition further delineates explorations into both static and dynamic microring resonator-based HIC filters. A confluence of multifaceted studies centered on microring technologies culminates in the realization of frequency-compensated multi-ring filters, marking the inception of high-fidelity microring filters within the ambit of HIC microphotonics. Despite achieving telecommunication-grade performance through frequency compensation, these filters evince pronounced polarization sensitivities, rendering them suboptimal for pragmatic applications. However, the integrative employment of identical filter sets within a generalized polarization diversity framework facilitates the inaugural demonstration of polarization-insensitive HIC filters, yielding a maximal polarization-dependent loss of 2.2 dB across extensive bandwidths.

In conclusion, the thesis examines evanescent field perturbation as a viable modality for tuning microcavities across ultra-wide wavelength spectra. Leveraging nanometric control of a silica perturbing entity within the near-field of a microring waveguide, a remarkable, reversible tuning of its cavity mode across 27 nm (or 1.7%) is actualized, fortifying the foundational knowledge and technological frontier of HIC photonic crystal research and its applications.

MIT\_Dept. of Physics.\_324

Embarking upon a nuanced investigation into accreting x-ray binaries, this dissertation navigates through the enigmatic realm of "microquasars," astrophysical phenomena characterized by their emission of compact, relativistic jets of cool plasma. A palpable speculation permeates the scientific community, suggesting these jets might be conduits for a substantial flux of galactic cosmic ray protons and nuclei. Notably, the energy spectrum emanating from these celestial entities diverges significantly from the unblemished power-law traditionally anticipated from cosmic-ray acceleration concomitant with supernova shocks.

The AMS-01 instrument, through its measurement of cosmic ray protons and helium during a ten-day mission aboard the Space Shuttle Discovery in 1998, affords a pivotal dataset for analysis. This exploration, while rigorously scrutinizing this data, seeks spectral distortions that may ostensibly be attributed to proximate microquasar activity. The findings delineated herein demarcate that the contribution of microquasars to the cosmic ray proton flux is circumscribed to a maximum of approximately 2% within the 2-50 GeV energy range. Consequently, this dissertation not only underscores the imperative of extending the spectrum of inquiry into cosmic phenomena but also enhances our comprehension of the intricate, enigmatic mechanisms underpinning cosmic ray propagation and origination within our galaxy.

MIT\_Dept. of Physics.\_404

In this thesis, an intricate application of position-space renormalization-group theory is deployed, judiciously exploring a spectrum of correlated electron systems, thereby elucidating finite-temperature phase diagrams and pertinent thermodynamic properties for electron densities both encompassing and deviating from half-filling. An initial investigation is facilitated employing the Suzuki-Takano quantum decimation method, applied meticulously to a one-dimensional (d = 1) Hubbard model, subjected to an external magnetic field; an endeavor judiciously benchmarked against exact results for specific heat, and magnetic and charge susceptibilities across varying electron densities. Remarkably, our approach reveals a convergence towards exact values at elevated temperatures, maintaining commendable agreement even within moderate-to-low temperature realms.

Pursuing broader insights, the decimation is extended via the Migdal-Kadanoff procedure to a three-dimensional (d = 3) Hubbard model. Subsequent phase diagrams are computed across a diverse range of Coulomb couplings, unveiling two novel "" phases, conspicuously emerging for hole-dopings between 10-18% and 30-35%. Notably, the electron hopping strength renormalizes to infinity at the T phase sinks, a phenomenon potentially indicative of superconductivity, a hypothesis bolstered by specific heat features.

Turning attention to the d = 3 tJ model, where the phase was initially identified, proximate examination of this phase reveals a conspicuous, sharp peak in the superfluid weight, concomitant with a suppressed low-temperature specific heat, symptomatic of gap formation. The doping-dependent evolution of the free carrier density mirrors experimental findings in cuprate superconductors. In light of the pivotal role of strong anisotropy in high-T\_c materials, a d = 3 tJ model, embracing distinct in-plane and out-of-plane couplings, is considered. Scrutinizing the phase diagram’s evolution as the interplane coupling attenuates, it is discerned that the T phase steadfastly persists, even venturing into the quasi-two-dimensional regime, while the emergence of a complex lamellar structure of antiferromagnetic and disordered phases, interposing the T phase and half-filling, may intimate at incommensurate spin ordering. While a pure d = 2 tJ model abstains from manifesting a phase, precursors to it are observable in the renormalization-group flows, and a phase becomes stabilized with a defined transition temperature upon introducing even minimal interplane coupling.

In the thesis's concluding section, attention pivots to renormalization-group techniques for quenched random systems. Preluding an examination of disorder within the tJ model, a simpler classical system, imperative in contemporary discussions, is examined, testing a conjecture that pertains to the loci of multicritical points on dual pairs of hierarchical lattice Ising spin glasses. Subsequently, by incorporating nonmagnetic impurities into the d = 3 tJ model, it is revealed that minimal concentrations of these impurities precipitously annihilate the r phase and fortify antiferromagnetism, findings that draw parallels with phenomena observed in Zn-doped cuprates.

MIT\_Dept. of Physics.\_405

Embarking upon a pioneering endeavor, this thesis delineates the inaugural observations of optical transitions originating from the metastable 2S state in trapped hydrogen, furnishing a meticulous exposition of the design and execution of two ingeniously stabilized diode laser systems, devised expressly for the spectroscopic exploration of the 2S-3P and 2S-8S transitions. Profoundly, spectroscopy of the singular photon 2S-3P transition in hydrogen is exemplified, not only through the depletion of the metastable 2S atom state but also via the absorption of the 2S-3P laser light, thereby illustrating a seminal development in this field of study. A cogent model for absorption spectroscopy, serving as a probe for metastable number, is thoughtfully developed, conclusively demonstrating that absorption markedly enhances upon extant detection methodologies.

Pivoting to further explorations, this dissertation meticulously elucidates techniques affiliated with diode lasers, cultivated amidst these experiments, which are anticipated to be instrumental in forthcoming precision measurements of 2S-nS transitions. Moreover, the thesis provides an insightful journey through the design, construction, and comprehensive characterization of the diode laser system, specifically crafted for performing spectroscopy of the two-photon 2S-8S transition. In culmination, parameters recommended for a propounded signal search are meticulously outlined, thereby furnishing a robust foundation for subsequent, explorative research within this pioneering field of physics.

MIT\_Dept. of Physics.\_411

The present dissertation elucidates the conceptualization, realization, and experimental evaluation of a novel source of entanglement, meticulously engineered with an aspiration to generate photon pairs characterized not only by polarization entanglement but also by an augmented brightness constrained within a narrowly defined bandwidth. This innovative source, exhibiting a more suitable profile than preceding spontaneous parametric down-conversion (SPDC) sources, is conceived with an intent to facilitate the transference of entanglement to impending qubit storage modalities, such as a trapped rubidium memory.

A distinctive approach to imposing the desired narrow bandwidth involves the spectral modification of the photon pairs by executing the down-conversion within a cavity. The collinear downconversion geometry, harmonized within the linear cavity, is actualized through the employment of a quasi-phase-matched periodically-poled potassium titanyl phosphate (PPKTP) crystal, rendering a precisely engineered environment for the SPDC process.

Polarization entanglement of the single-pass, free-space photon pairs produced is substantiated through the measurement of the Hong-Ou-Mandel interference dip and through recording a violation of Bell's inequality, registering a value of 2.711 \pm 0.0102.711±0.010, thereby surpassing the classical boundary of 2. Employing cavity-enhanced downconversion, a luminosity of 0.70.7 pairs/s per mW of pump per MHz of bandwidth in the Gaussian mode collected is observed (inferring a generation rate of 110110 pairs/s/mW/MHz).

Moreover, the visibility of the interference dip from the pairs was measured to reside at 75\%75% when approximating the ideal equal free spectral range (FSR) operating point, wherein the pairs inhabit the biphoton triplet state. In scenarios of detuned unequal FSR, the resultant pairs evince an interference dip behaviour that encompasses a combination of triplet and singlet states, contingent upon the temporal separation of the pair as it departs the cavity. The findings intimately align with the comprehensive predictions propounded by a Gaussian-state model of cavity-enhanced downconversion, thereby affirming the theoretical underpinnings and fostering a pathway towards future explorations and applications in the domain of quantum information science.

MIT\_Dept. of Physics.\_446

The research delineated within this dissertation encapsulates methodically executed experiments, adeptly maneuvering a robustly interacting fermionic gas into a superfluid domain. The potent interactions are meticulously invoked by exploiting a Feshbach scattering resonance, thereby permitting the modulation of the inter-fermion scattering length through the meticulous adjustment of an external magnetic field. Upon the chilling of a Fermi mixture on the molecular side of such a Feshbach resonance, an observation was made, elucidating the Bose-Einstein condensation of upwards of 10^7107 molecules.

Subsequent inquiries were adroitly navigated through the crossover region, an intermediary sphere interpolating between such a Bose-Einstein condensate (BEC) of molecules and a Bardeen-Cooper-Schrieffer (BCS) superfluid of elongated Cooper pairs. Condensates of fermion pairs were discerned within a regime wherein pairing emerges purely as a many-body phenomenon, with the pairs achieving stabilization through the presence of the encompassing particles.

Superfluidity and phase coherence within these systems were assiduously demonstrated throughout the crossover, manifested through the observation of enduring, ordered vortex lattices within a rotating Fermi mixture. Culminatingly, superfluidity within imbalanced Fermi mixtures was established and its Clogston limit discerned amidst high imbalance. The gas was observed to partition into a region of equanimous densities, encircled by a shell hosting disparate densities, presenting a meticulous exploration into the intriguing realm of fermionic superfluidity and contributing to the nuanced understanding of correlated quantum phases.

MIT\_Dept. of Physics.\_447

This dissertation furnishes an assiduous analysis of data from the High Energy Transient Explorer II (HETE-II), with a pronounced focus on elucidating the intrinsic properties of gamma-ray bursts (GRBs). The research promulgates a technique permitting simultaneous estimation of source and background counts amid a burst, specifically with coded aperture instruments exemplified by the Wide-field X-ray Monitor (WXM) onboard HETE-II. Subsequent to this, a photon-by-photon statistical bootstrap analysis, closely akin to the aforementioned technique, is delineated, facilitating the computation of the non-Gaussian error distribution of GRB temporal statistics, with particular reference to the T90 and T0.45 duration measures.

The distribution of T90, having been meticulously studied subsequent to the advent of the BATSE gamma-ray burst catalogs and conventionally believed to be log-normally distributed, is here underscored to potentially possess an intrinsic distribution of a considerably narrower breadth. The broad log-normal distribution is argued to be predominantly attributed to measurement artifacts. The calculation of the T0.45 parameter enables the deduction of redshifts via the recently unveiled Liso-Epk-T0.45 relation, subsequently permitting the compilation of a flux-limited sample of bursts with redshifts, devoid of the observational selection effects inherent in spectroscopic catalogs.

Applying the aforementioned analysis to 31 WXM bursts, redshift-corrected distributions of T90 and T0.45 are computed. The research affirms, for the inaugural time, that the distribution of T0.45 can be modulated by an exponential distribution. Employing the redshifts ascertained through the Liso-Epk-T0.45 relation, implied isotropic luminosities are also computed. Employing non-parametric methodologies—specifically those of Lynden-Bell and Efron & Petrosian—the normalized luminosity function and redshift distribution of gamma-ray bursts are derived. The findings evoke robust evidence for luminosity evolution with redshift and maintain consistency with antecedent studies predicated on BATSE bursts.

Adhering to a Concordance cosmology (Q\_\Lambda = 0.7QΛ​=0.7, Q\_M = 0.3QM​=0.3, H\_0=70H0​=70 km s^{-1}−1 Mpc^{-1}−1), the analysis throughout remains steadfast. The effects of log-normal errors in the redshifts are estimated via Monte Carlo methodologies, revealing that an approximation of 10% of GRBs may be anticipated at elevated redshifts (>5), aligning coherently with theoretical forecasts of high-redshift Swift detections. This composition thus proffers significant insights and methodologies germane to the nuanced understanding and analysis of GRB data and intrinsic properties.

MIT\_Dept. of Physics.\_448

This dissertation delineates a sequence of experiments conducted with ^{87}87Rb Bose-Einstein condensates, manipulated via optical lattices, which have substantiated themselves as a potent apparatus for probing a broad spectrum of physics. Notably, the research observes a systematic shift in the photon recoil momentum, attributed to the index of refraction of a dilute atomic gas. Employing a two-pulse Ramsey interferometer, the recoil frequency was measured interferometrically, wherein the dual pulses were instantiated using a one-dimensional optical lattice. An ensuing measurement of the frequency, contingent upon the lattice detuning from the atomic resonance, manifested a uniquely dispersive shape for the recoil frequency, congruently fitting the recoil momentum as n\,\hbar knℏk.

Furthermore, a one-dimensional optical lattice was judiciously utilized to modify the dispersion relation of the condensate, paving the way to demonstrate the matter-wave analogues of Optical Parametric Generation (OPG) and Amplification (OPA) of photons. A condensate, upon being loaded into a dynamically moving optical lattice with an adjustable quasimomentum k\_0k0​, exhibited elastic scattering into two distinct final momentum states, k\_1k1​ and k\_2k2​, as the value for k\_{0o}k0o​ was varied. In circumstances wherein a modest fraction of atoms was initially transferred to k\_1k1​ prior to ramping on the lattice, amplification of scattered atoms into k\_1k1​ and k\_2k2​ was observably delineated.

In the latter stages, the transition from superfluid to Mott Insulator was assiduously explored utilizing microwave spectroscopy within a profoundly three-dimensional optical lattice. The density-dependent clock shift enabled the spectroscopic distinction of sites with varying occupation numbers and facilitated the direct imaging of sites with occupation numbers ranging from 1 to 5, thus unveiling the shell structure intrinsic to the Mott Insulator phase. Consequently, this thesis culminates in providing profound insights and methodologies that potently contribute to our comprehensive understanding of Bose-Einstein condensates within optical lattices, through the lens of various experimentally manifested phenomena.

MIT\_Dept. of Physics.\_449

This dissertation unfolds a meticulous exploration of trapping atoms in dressed states, employing a synergistic application of radio frequency radiation and magnetic field gradients, situated within a magnetic field possessing a quadrupole minimum. Radio frequency fields, resonant with the (|F, m\rangle) = |1, -1\rangle \rightarrow |1, 0\rangle(∣F,m⟩)=∣1,−1⟩→∣1,0⟩ transition, facilitated the confinement of atoms upon the surface of a sphere, subsequently culminating in a gravitational pooling of atoms at the sphere's nadir. Bose-Einstein condensates (BECs) were seamlessly transferred into this adroitly crafted dressed Zeeman trap, showcasing an efficacy of 100%, alongside measured trapping frequencies reaching up to 250 Hz and lifetimes extending to 30 s.

Moreover, a meticulously engineered magnetic pattern upon a hard disk platter was employed to generate magnetic fields potent in the tight confinement of atoms. Circumvention of detrimental surface interactions was achieved via the utilization of an exceptionally thin film, characterized by a substantial magnetic remnant. BECs, comprising up to 5 \times 10^55×105 atoms, were actualized in cigar-shaped traps situated approximately 40 µm above the surface, with measured trap frequencies elevating up to 5 kHz. Upon evaporation, the condensed clouds were cautiously navigated closer to the surface to probe potential imperfections within the magnetic potential, unmasking defects at distances less than 35 µm.

In subsequent experimentation, BECs were released from an altitude of 350 µm, targeting the achievement of specular reflection; however, a notable degree of dispersion was observed. In a concluding set of experiments, BECs were adroitly loaded into a three-dimensional optical lattice, wherein a quantum phase transition from a superfluid to a Mott insulator was discerningly observed. Employing microwave spectroscopy, the density-dependent "clock shift" was ascertained to be contingent upon the occupation number of the wells. Thus, the exploration of singly occupied lattice sites unfolded as an atomic clock system, notably devoid of density shift, with observed linewidths as diminutive as 1 Hz [Full Width at Half Maximum (FWHM)] out of 6.8 GHz, comparably rivaling extant atomic frequency standards. This composition, therefore, proffers significant advancements and novel methodologies pertinent to the domain of BECs and atomic trapping within nuanced magnetic and optical landscapes.

MIT\_Dept. of Physics.\_650

The seminal operation of LIGO's fifth science run (S5) and Virgo's inaugural science run (VSR1) during the 2005-2007 period marked a pivotal achievement within the LIGO-Virgo network of kilometer-scale laser interferometric gravitational-wave detectors. This dissertation delineates numerous facets pertinent to the detection of gravitational-wave transients, explored through the lens of the comprehensive all-sky, untriggered burst search across S5/VSR1 data. Confronting extant searches for gravitational-wave bursts is the omnipresence of non-Gaussian noise transients, which pervade the data throughout the majority of the signal space sensitive to detections. These events, liable to be misconstrued as authentic signals, presently constrain search sensitivity and undermine detection confidence for bona fide events.

The initial segment of this thesis concentrates on formulating methodologies to identify, oversee, and characterize these instrumental perturbations within LIGO and Virgo data. An automated strategy is conceived and applied to the S5/VSR1 search, aiming to judiciously excise noise transients from the analysis. This is achieved without compromising sensitivity, courtesy of the abundant auxiliary information amassed by the detectors.

Subsequently, the latter segment of this dissertation pivots towards deciphering outlier events amid a backdrop of non-Gaussian, non-stationary noise. An exhaustive follow-up protocol for candidate gravitational-wave events is formulated and applied to a singular burst outlier emanating from the S5/VSR1 search, which was subsequently unmasked as a blind simulation injected into the instruments. While the follow-up procedure astutely discerns no grounds for rejecting the candidate as a potential gravitational wave, it underscores the challenges inherent in asserting confident detections for signals exhibiting waveform morphology akin to prevalent instrumental disturbances.

Furthermore, this follow-up contends with the quandary of objectively ascertaining the significance of a single outlier event, situated within the context of numerous semi-disjoint individual searches. To navigate this, a likelihood-ratio based unified ranking is developed and juxtaposed against the original procedures of the S5/VSR1 burst search. This novel ranking demonstrates a fourfold enhancement in the statistical significance of the outlier event and, utilizing fixed thresholds, achieves a 12% reduction and, employing a loudest event statistic, a 38% reduction for a rate upper limit on a simulated signal population, thereby elucidating a path toward refined gravitational-wave detection methodologies within the idiosyncratic noise environments of advanced detectors.

MIT\_Dept. of Physics.\_662

The MiniBooNE experiment, meticulously designed to probe \nu\_{\mu} \rightarrow \nu\_{e}νμ​→νe​ oscillations, ventured into a \Delta m^2 \sin 2\thetaΔm2sin2θ region distinctly disparate from that permissible by canonical three-neutrino oscillations, as delineated by solar and atmospheric neutrino experiments. The investigative impetus was derived from the LSND experiment, which observed an excess of \bar{\nu}\_{e}νˉe​ events in a \bar{\nu}\_{\mu}νˉμ​ beam, congruent with two-neutrino oscillations at \Delta m^2 \approx 1 \, \text{eV}^2Δm2≈1eV2 and \sin^2 2\theta < 1\%sin22θ<1%. If substantiated, such an oscillation paradigm could intimate the presence of a light, predominantly sterile neutrino, encompassing minuscule mixtures of weak neutrino eigenstates.

Aside from conducting a search for \nu\_{\mu} \rightarrow \nu\_{e}νμ​→νe​ oscillations, MiniBooNE also embarked upon an exploration for \bar{\nu}\_{\mu} \rightarrow \bar{\nu}\_{e}νˉμ​→νˉe​ oscillations, furnishing a test of the LSND two-neutrino oscillation interpretation that remains unfettered by CP or CPT violation suppositions. This dissertation elucidates the MiniBooNE \nu\_{\mu} \rightarrow \nu\_{e}νμ​→νe​ and \bar{\nu}\_{\mu} \rightarrow \bar{\nu}\_{e}νˉμ​→νˉe​ analyses and consequent findings, with an accentuation upon the latter.

Whilst the neutrino search refutes the two-neutrino oscillation interpretation of LSND at the 98% confidence level (C.L.), the antineutrino search manifests an event excess, harmonizing with the two-neutrino \bar{\nu}\_{\mu} \rightarrow \bar{\nu}\_{e}νˉμ​→νˉe​ oscillation interpretation of LSND, and repudiating the no-oscillation hypothesis at the 96% C.L. Albeit the neutrino and antineutrino oscillation results from MiniBooNE diverge under the singular sterile neutrino oscillation hypothesis, an elementary extension to the model, inclusive of additional sterile neutrino states and the prospect of CP violation, accords potential variances between neutrino and antineutrino oscillation signatures.

Consequently, the plausibility of oscillation models comprising one or two sterile neutrinos is probed through global fits to MiniBooNE and LSND data, with or devoid of constraints from auxiliary oscillation experiments exhibiting analogous sensitivities to said models. A general exploration for new physics scenarios, which might culminate in effective non-unitarity of the standard 3 \times 33×3 neutrino mixing matrix, or mixing freedom, is additionally executed, utilizing neutrino and antineutrino data procured from MiniBooNE.

MIT\_Dept. of Physics.\_664

Pertaining to the esteemed discipline of galaxy cluster total mass measurement and the discernment of dark matter substructure within galaxy cluster haloes, this dissertation aspires to significantly contribute to our comprehension of the ΛCDM model of structure formation and elucidate the interactions betwixt baryonic and non-baryonic matter. This dissertation converges upon the subject matter of cluster mass structure through bifurcated methodologies.

Initially, employing an amalgamation of optical imaging, spectroscopy, and X-ray observations, it is ascertained that the galaxy cluster RCS043938-2904.7, initially perceived as anomalous due to its substantial optical richness juxtaposed with its low X-ray surface brightness, is indeed an association of structures precisely aligned along the line of sight. A meticulous account for this structural configuration ameliorates the observed cluster properties, aligning them harmoniously with extant scaling relations.

Moreover, this thesis introduces an innovative approach to measure weak gravitational lensing flexion, thereby elucidating mass measurements on diminutive scales. While antecedent methods for gauging flexion predominantly center upon measuring the derived properties of the lensed images, such as shapelet coefficients or surface brightness moments, the approach espoused herein fits a fully mass-sheet-invariant parametrized Analytic Image Model (AIM) to each galaxy image. This elegantly simple parametric model meticulously traces the distortion of lensed image isophotes.

Evaluative applications of the AIM method on simulated data images—encompassing realistic noise and a diverse array of input image properties—demonstrate its efficacy in accurately reproducing the input lensing fields. Furthermore, the AIM method, applied to flexion measurement using Hubble Space Telescope observations of Abell 1689, successfully detects mass structure within that cluster, leveraging solely flexion as measured with the AIM method. Thus, this dissertation not only elucidates complex cluster structures but also forwards a novel methodological approach to the measurement of gravitational lensing flexion, enhancing our capacity to discern mass structures on smaller, hitherto challenging scales.

MIT\_Dept. of Physics.\_665

This dissertation delineates results emanating from two distinct Paul-trap based ion traps executed in the Vuletić laboratory: the Atom-Ion trap, crafted for exploring collision studies amid cold atoms and ions, and the Cavity-Array trap, devised to investigate the interactions intertwined between ionic ensembles and photons.

The Atom-Ion trap coalesces a surface-planar ion trap with a magneto-optical trap (MOT) designated for neutral atoms. Initial outcomes of this system enumerate the loading of a shallow surface-planar ion trap at an unparalleled high rate of 4 \times 10^5 s^{-1}4×105s−1 and achieving isotopic purity by leveraging photoionization from the MOT. This work manifests the inaugural collisions between concurrently trapped atoms and ions in the Langevin collision regime, involving Yb^+Yb+ and Yb. Subsequently, a measurement of the Langevin rate constant, via charge-exchange collisions between \alpha Yb^+αYb+ and \beta YbβYb, spans three orders of magnitude in collision energy, plunging to 3 \mu eVμeV. The measured rate coefficient of 6 - 10^{-10} cm^{3} s^{-1}6−10−10cm3s−1 resonates well with the Langevin model, adhering to theoretical predictions pursuant of the polarizability of Yb. Furthermore, the dissertation outlines the theory and constraining factors of sympathetic cooling of ions by localized cold atoms at diminished temperatures. It also presents measurements of momentum-transfer collisions between Yb^+Yb+ and Rb, indicating that such momentum-transfer collisions perceptibly influence the ion energy at the Langevin rate.

In the latter segment, the dissertation illuminates the fabrication and assembly of the Cavity-Array trap. This particular trap superimposes a high-finesse optical cavity with a linear array of Paul traps, aiming to attain the high cooperativity limit with trapped ions. Preliminary results from the loading of the Cavity-Array trap are disclosed, illustrating successful overlay of the optical cavity mode with the ion trapping region and the capability to load individual sites of the array ion trap, thereby signifying a promising progression towards understanding complex interactions within ionic ensembles and photonic structures. This work fortifies our understanding of atom-ion collisional dynamics and paves the way towards sophisticated manipulation and control in ion-cavity systems.

MIT\_Dept. of Physics.\_666

In this dissertation, the interactional outcomes stemming from galaxies possessing a substantial mass ratio and diminished orbital angular momentum are rigorously examined. Interactions between such galaxies precipitate the dispersion of material from the smaller galaxy into architecturally and dynamically distinctive structures, which are manifested in notable morphological and dynamic frameworks, encompassing heightened local densities and an elementary density profile correlated with the attributes of the engaged galaxies. In light of the pivotal role played by the larger galaxy's tides in the formation of these structures and their affinity with a well-explored class of mathematical objects, these phenomena are aptly christened "tidal caustics".

In exploring the densities attainable in tidal caustics through a quintessential merger of this archetype, an instance from the Andromeda galaxy is employed to ascertain whether the consequent densities are ample to engender a discernible gamma-ray signal from self-interactions within the dark matter component, given probable particle models of dark matter. The findings denote that the anticipated signal falls short, by an order of magnitude, of detectability with present-day instruments.

Moreover, the dissertation investigates the limitations that observational data of the surface brightness profiles of tidal caustics can impose upon the properties of the interacting galaxies. It is demonstrated that the larger galaxy’s local gravity and gravitational gradient, in conjunction with the smaller galaxy’s energy spread and initial phase space density, can be concurrently constrained through the fitting of this profile. While these constraints are inherently degenerate, they notably remain model-independent.

A further exploration reveals that data obtained from multiple caustics, coupled with the material velocity within each caustic along the line of sight, proffer insights into the orbital angular momentum and the asymmetries diverging from spherical symmetry in the larger galaxy, albeit these insights exhibit a degree of model-dependence.

In discussing the principal technical challenge—ascertaining the inclination angle of the caustic—this dissertation illustrates that a streamlined model can efficaciously retrieve the requisite parameters in certain instances. Moreover, a facile modification to this model is projected to enhance its applicability and success rate in delineating these celestial phenomena and their intricate interactions in the cosmic theatre.

MIT\_Dept. of Physics.\_667

In the course of its six-decade history, the Casimir effect resided largely within the confines of theoretical obscurity, only to be thrust into the limelight of experimental physics in recent years due to notable technological advancements. The remarkable strides achieved in the measurement of Casimir forces since 1997 have elicited a burgeoning demand for theoretical apparatus capable of forecasting Casimir interactions within pragmatically experimental geometries and materials, acknowledging their realistic frequency-dependent electrical attributes.

This dissertation introduces a novel paradigm, coined the fluctuating-surface-current (FSC) approach, for the efficient numerical computation of Casimir interactions, assimilating concepts from the boundary-element method intrinsic to computational electromagnetism. This approach endeavors to articulate Casimir energies, forces, and torques amidst bodies of arbitrary shapes and materials through the interactions among efficacious electric and magnetic surface currents circulating upon the surfaces of the entities in question.

This manuscript elucidates that the master equations underpinning the FSC approach emanate logically from either of two ostensibly disparate Casimir paradigms: the stress-tensor approach and the path-integral (or scattering) approach. In doing so, this work achieves an unanticipated unification of these two distinct theoretical frameworks.

However, the relevance of a theoretical technique is concomitantly bound to the utility of its practical implementations. Consequently, three distinct numerical implementations of the FSC formulae are proffered, each juxtaposing unique technical challenges against its practical applications. Ultimately, through the synergistic integration of our innovative theoretical paradigm and our practical implementations thereof, this dissertation furnishes new predictions of Casimir interactions across a myriad of experimentally pertinent geometric and material configurations. The configurations in question would otherwise prove challenging, if not unfeasible, to engage with through any other extant Casimir method.

MIT\_Dept. of Physics.\_772

This dissertation delineates findings from two meticulously orchestrated experiments, each utilizing atom interferometry to quantitatively scrutinize specific atomic properties. The implemented interferometer bisects the sodium de Broglie wave into bifurcated paths, wherein one trajectory meanders through an interaction region, and upon recombination, the interference pattern conspicuously displays a phase shift contingent upon the interaction’s intensity.

In the inaugural experiment, the interaction is constituted by a gas through which de Broglie waves traverse, consequently experiencing a phase shift manifest as an index of refraction. The systematic measurement of the index of refraction across varied wavelengths has enabled the first-ever observation of the theoretically postulated phenomenon of glory oscillations in the phase shift. A comprehensive array of measurements—spanning the index of refraction for sodium atoms navigating through argon, krypton, xenon, and nitrogen gases across an extensive wavelength range—affords profound insights into the interatomic potential amidst sodium atoms and the aforementioned gases. These findings challenge extant theoretical prognostications of interatomic potentials, thereby potentially galvanizing a revitalized endeavor to comprehend these potentials with augmented profundity.

The second experiment embarks upon the measurement of atomic polarizability utilizing an atom interferometer, wherein the interaction is mediated by an electric field, thereby inducing a phase shift proportional to the atom’s energetic state within said field. Historically, this methodology facilitated the most precise (< 1%) measurement of sodium polarizability, albeit precision was constrained by the velocity distribution within the atomic beam; this resultant phase shift, being velocity-dependent, effectively attenuated the interference pattern. This thesis introduces a novel technique to “rephase” the interference pattern amidst substantially applied fields and manifests a measurement unencumbered by this previously-noted limitation. Moreover, the new technique obliterates most systematic errors that previously beleaguered the polarizability measurement, heralding an enhancement in precision that is an order of magnitude more resolute. The residual systematic errors may be obviated by evaluating the polarizability ratio between two disparate atoms, a comparative measure that potentially augments precision by an additional order of magnitude.

MIT\_Dept. of Physics.\_773

Spanning a prolific period of 16 years since the landmark discovery by Bednorz and Muller in 1986 — wherein the layered perovskite structure (La - Ba)2CuO4 unveiled the phenomenon of superconductivity at the hitherto uncharted temperature of Tc = 33 K — this dissertation proffers a meticulous exploration of the enigmatic correlations in the "normal" state of the materials, subsequently dubbed cuprates, at temperatures T > Tc. The predominant focus herein navigates through this ostensibly aberrant "normal" state, endeavoring to synthesize a coherent framework that elucidates its peculiar phenomenology.

The theoretical substratum for this exploration is constructed upon the slave particle depiction of the t-J model, as postulated by Wen and Lee, while its conceptual scaffolding is derived from Anderson's proposition, which identified spin-charge separation as the pivotal emergent phenomenon intrinsic to the physics of cuprate materials. After furnishing a succinct motivation, the thesis delves into the examination of single-particle tunneling into the superconducting state of the cuprate, scrutinizing from the perspectives of both d-wave BCS and the SU(2) slave boson theory, as per Wen and Lee. While both perspectives demonstrate efficacious near-zero tunneling bias, the slave particle formulation additionally and innately encapsulates the particle/hole asymmetric background evidenced in empirical studies.

Provoked by the question of single-particle correlations — a subject experimentally probed via angle-resolved photoemission studies — the ensuing chapter proffers an analysis wherein the empirically observed broad spectral line shapes axiomatically intimate the absence of quasi-particles, as traditionally defined within Fermi liquid theory. A comprehensive study delineates how gauge fluctuations, emerging from the employed slave particle coordinates, imbricate the physical hole spectral function. Intriguingly, gauge fluctuations exert their primary influence through their confining propensity on the vertex, as opposed to operating as a scattering field for the slave particles.

The terminal chapter elucidates the impact of gauge fluctuations upon spin susceptibility, elucidating that they play an indispensable role in re-establishing Neel correlations. This instrumentalization facilitates a naturally emanating explanation for the spin-related phenomenology evident in underdoped cuprates, providing an insightful theoretical exploration amidst the vast, intricate tapestry of superconductivity and particle interactions within these compelling materials.

MIT\_Dept. of Physics.\_774

Embarked upon the intricacies of the high-Tc cuprate superconductors, the preeminent concern of this dissertation gravitates toward the established phenomenology wherein the order parameter (gap) conspicuously exhibits d-wave symmetry, thereby extinguishing at four nodal points upon the Fermi surface. In close proximity to these nodes, the excitation of quasiparticles is markedly facile, revealing behaviors more akin to massless relativistic particles than to traditional electrons in metallic contexts. This thesis endeavors to scrutinize the transport properties of these nodal quasiparticles, furnishing theoretical insights that aim to illuminate the outcomes of thermal and (microwave) electrical transport experiments in the cuprates, particularly within the low-temperature domain.

In the nascent stages of our exploration, attention is directed towards the exceptionally low-temperature regime, where transport is predominantly orchestrated by quasiparticles, their induction attributed to the mere presence of impurities— a state known as the universal limit due to preceding calculations suggesting that transport coefficients assume universal, scattering-independent values. By transcending prior results and incorporating the contributions of vertex corrections, it is revealed that while electrical conductivity acquires a scattering-dependent correction, both thermal and spin conductivities steadfastly retain their universal values.

Turning our gaze upon the microwave electrical conductivity, the investigation then segues into a marginally elevated temperature regime, where quasiparticles are thermally excited. Given that measurements in detwinned samples proffer outcomes incongruent with rudimentary models of impurity scattering, this work hypothesizes that line defects, residues from the twin boundary elimination process, may instantiate an additional scattering mechanism. The self-energy and microwave conductivity resultant from line defect scattering are calculated, yielding results that harmonize commendably with experimental data.

In the ultimate stage, upon the activation of a magnetic field, the thesis pivots to explore thermal transport within the mixed (vortex) state. Within the weak-field regime, the thermal conductivity tensor can be articulated in terms of the cross section for quasiparticle scattering from a singular vortex. The calculation of this cross section subsequently enables the determination of both the longitudinal thermal conductivity and the thermal Hall conductivity, with the results showcasing surprisingly robust qualitative alignment with extant measured data. Moreover, the lucid nature of our calculation affords a penetrative understanding of the features discerned in experimental findings, thereby conjoining theoretical predictions with empirical observations in the rich tapestry of cuprate superconductor studies.

MIT\_Dept. of Physics.\_809

This dissertation meticulously calculates moments of the nucleon's generalized parton distributions (GPDs) utilizing lattice Quantum Chromodynamics (QCD), a non-perturbative approach to investigating quantum field theory. The GPDs serve as a quintessential pivot in determining the angular momentum decomposition of the nucleon and in delineating the transverse distributions of partons contained therein. Elegantly, the GPDs, in particular kinematic limits, regress to the elastic form factors and conventional parton distributions, offering a comprehensive vista through which various aspects of nucleon structure can be discerned.

Embarked upon this investigative journey, we have pioneered the 'building block' method, an innovative approach designed to ascertain all lattice correlation functions contributing to the off-forward matrix elements of twist-two operators. It is these matrix elements that dictate the generalized form factors of the nucleon, which subsequently yield the moments of the GPDs. The methodical application of our ‘building block’ method thus facilitates the calculation of all matrix elements pertaining to the lowest twist-two operators.

Moreover, our methodology is employed to architect an overdetermined set of matrix elements, thereby enabling a more nuanced and accurate computation of the generalized form factors. This, in turn, intricately intertwines with our initial explorations into GPDs, providing a robust, lattice QCD-based exploration into the multifaceted structure of the nucleon. Consequently, this thesis not only ventures into the calculations of moments but also, through the novel methodological approach, expands the horizons of understanding nucleon structure via lattice QCD, bridging theoretical predictions with practical, calculative applications.

MIT\_Dept. of Physics.\_810

Chapter 1 inaugurates the discourse with an incisive introduction to photonic crystals, meticulously reviewing the fundamental physical principles that underpin the manifestation of a band gap and the genesis of localized defect modes, whilst concurrently surveying proposed applications, fabrication techniques, and numerical simulation methods.

Chapter 2 meticulously delineates the crafting of 2D-analogous defect modes within a 3D photonic crystal possessing a complete gap. Noteworthy is that these modes bear striking similarity to their 2D photonic crystal counterparts, notably in their polarization, field profile, and projected band structures, thereby potentially easing the incorporation of 2D photonic-crystal devices within pragmatic 3D systems.

Venturing into Chapter 3, the exploration pivots towards the intriguing possibility of employing photonic-crystal defect modes in the engineering of magnetic metamaterials - structures that paradoxically exhibit magnetic properties notwithstanding the non-magnetic nature of their components. A synthetic magnetic moment is bestowed via a point-defect mode explored in the previous chapter. A quantitative analysis of the far-field radiation pattern conclusively verifies the predominantly magnetic character of the mode, with over 98% of the emitted power being funneled into magnetic multipole radiation.

In Chapter 4, the discourse shifts to calculate the radiation pressure exerted on the surface of a waveguide, constituted by omnidirectionally reflecting mirrors. Absent losses, the pressure asymptotically approaches infinity as the distance between the mirrors converges towards the cutoff separation of the waveguide mode. This divergence originates from the deceleration of the modal group velocity to zero, thereby inducing a slow-light amplification of the field intensity whilst maintaining constant power input.

Chapter 5 embarks upon an analysis of slow-light, band-edge waveguides as potential conduits for compact, integrated, and tunable optical time delays. The gradual group velocities at the photonic band edge induce substantial variations in time delay for marginal alterations in refractive index, thereby condensing device dimensions. Figures of merit for tuning sensitivity and signal dispersion are defined and instantiated through exact calculations for a realistic, three-dimensional grating structure. These calculations are shown to be adeptly predicted by a simplistic quadratic-band model, consequently streamlining device design.

Concluding with Chapter 6, a generalized, coupled-mode theory for disorder-induced scattering in pronouncedly periodic systems is derived. These analytical results enable a comparative analysis of photonic-crystal waveguides and analogous index-guided waveguides. Within the realistic confines of weak disorder, reflections maintain equivalence, whilst transmission is augmented for the photonic-crystal waveguide. These general results, corroborated by direct numerical simulations within an exemplar system, unveil a novel mechanism for the conceptualization of low-loss waveguides, providing a promising avenue for future explorations and developments within the domain.

MIT\_Dept. of Physics.\_811

Embarked upon herein is a meticulously theoretical exploration addressing diverse facets germane to the dynamics and evolution of dense stellar conglomerations, with a particular focus on globular clusters. Initially, this thesis elucidates findings derived from an extensive array of numerical N-body simulations utilizing our proprietary Monte-Carlo code, concentrating on the phenomenon of mass segregation within bi-component star clusters. Herein, substantial objects, potentially illustrative of stellar remnants like neutron stars or black holes, demonstrate behaviors that align quantitatively with straightforward analytical postulations. Conversely, lightweight entities, potentially emblematic of free-floating planets or brown dwarfs, are predominantly extricated from the cluster, corroborating anticipations established by analytical predictions, albeit potentially persisting within the halo in numerically superior quantities than foreseen. Leveraging a contemporary null detection of planetary-mass microlensing events in M22, an upper limit of 25% — established with a 63% confidence interval — is discerned for the prevailing mass fraction of M22 manifested in the form of profoundly low-mass objects.

Segueing into a discussion on clusters imbued with primordial binaries, the thesis unfolds an exploration predicated on an augmented iteration of the Monte-Carlo code, which addresses binary interactions via cross sections and analytical directives. Every model scrutinized exhibits a resiliently perduring "binary burning" phase, enduring through numerous relaxation timespans. During this phase, the structural parameters of the models adeptly resonate with those observed within the majority of Galactic globular clusters. Subsequent to this phase, clusters that have staved off tidal disruption immerse into a profound core collapse, superseded by gravothermal oscillations. Undoubtedly, the findings illuminate that even a minimal fraction of binaries within a cluster suffices to uphold the core against collapse, extending significantly beyond the anticipated core collapse timeframe, devoid of binary presence. For systems that are tidally truncated, the collapse is procrastinated to such an extent that the cluster will experience total tidal disruption preceding core collapse.

Advancing a stride beyond analytical prescripts, this dissertation amalgamates into the Monte-Carlo code a precise treatment of binary-single interactions, showcasing that the outcomes are in harmonious agreement with those utilizing analytical prescripts. Direct integration of binary interactions within the Monte-Carlo code necessitates a reasonably advanced N-body code, intricately oriented toward small-N dynamics. Presented herein is "Fewbody," a novel, openly accessible numerical toolkit devised for simulating small-N gravitational dynamics. While Fewbody is innately a general N-body dynamics code, it was architected with a predilection for conducting scattering experiments, thus endowed with several attributes that render it eminently suitable for said purpose. In order to substantiate the methodology, comparisons with several antecedent binary scattering experiments extant in scholarly literature are executed, yielding exemplary agreement. As a rudimentary exemplar of employing Fewbody, the thesis calculates the destruction cross sections and characteristic lifetimes of black hole-pulsar binaries within globular clusters, implying that, currently, there should be observable...

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MIT\_Dept. of Physics.\_812

This dissertation embarks upon a nuanced exploration of Witten's cubic string field theory, illuminating several of its multifaceted aspects through a sophisticated lens. Commencing with a succinct revision of the fundamental precepts of string field theory, the discourse initially unveils how the theory can be proficiently employed to validate certain conjectures pertaining to the tachyon vacuum. The dialogue thereafter transitions to an intricate examination of the challenges encountered in endeavoring to globally gauge fix string field theory. The final discourse converges upon a contemplation of assorted results within the quantization of the theory, fostering a thorough investigation into its inherent complexities and subsequent implications. Thus, the thesis endeavors to weave through the intricacies and potentialities embedded within Witten's cubic string field theory, striving to proffer both depth and breadth in its analytical exploration of the subject matter.

MIT\_Dept. of Physics.\_813

This thesis meticulously investigates B\_ss​ mixing, positing it as a cornerstone analysis for the Run II B physics program. The sensitivity pertaining to the measurement concomitant with the frequency of B\_ss​ oscillations intrinsically hinges upon the volumetric number of reconstructed B\_ss​ mesons. An articulation of the measurement of the ratio of branching fractions, denoted Br, is presented herein, which critically modulates the number of B\_ss​ events accessible for the amplification of the B\_ss​ mixing measurement at CDF-II. An analysis is executed utilizing 115 pb^{-1}−1 of data, harvested with the CDF-II detector in p\bar{p}pˉ​ collisions at a TeV scale, employing a pioneering displaced track trigger. Thus, the research extends a comprehensive exploration of the inherent complexities and underpinnings of B\_ss​ mixing, striving to amalgamate theoretical perspicacity with empirical scrutiny.

MIT\_Dept. of Physics.\_877

In the forthcoming thesis, an intensive exploration into the dynamical pairing of fermions engendered by time-dependent interaction is undertaken. Specifically, the development of fermionic pairing is scrutinized within temporal scales that are succinct compared to the quasiparticle relaxation time, situating the investigation within a context where established approaches—including the Boltzmann kinetic equation and time-dependent Ginzburg-Landau theory—cede applicability.

The nonequilibrium dynamics are particularly probed within a cold Fermi gas adjacent to a Feshbach resonance, elucidating a system wherein interaction can be magnetically finetuned. Spurred by contemporary experimental endeavors, Chapters 2 and 3 delve into the pairing of fermions, as incited by a sudden interaction switch that subsequently precipitates the Bardeen-Cooper-Schrieffer (BCS) instability within the system. Within this paradigm, the pairing amplitude emerges as a time-oscillatory function, presenting discernible, predictable characteristics.

Pivoting to a distinct dynamical regime, Chapter 4 elucidates the phenomena commensurate with a linear magnetic field sweep transitioning from atomic to molecular side within the Feshbach resonance. It is discerned that pairing correlations of fermions inherent in the initial state become enshrined within the momentum distribution of post-sweep molecules.

Concluding in Chapter 5, consideration is afforded to pair excitations brought forth by the harmonic modulation of interaction, wherein the resultant findings are juxtaposed with experimental observations, thus bridging theoretical predictions with empirical manifestations. This thesis, therefore, endeavors to intertwine theoretical rigor with tangible experimental contexts, offering insights into the intricate dance of fermions under dynamically evolving interactions.

MIT\_Dept. of Physics.\_878

Embarked upon herein is an investigative discourse probing the potential compositional intricacies of dark matter, particularly scrutinizing the hypothesis that Weakly Interacting Massive Particles (WIMPs) — exemplified by the supersymmetric neutralino — constitute its elemental fabric. Diverse theoretical constructs posit that the annihilation of such entities within the galactic confines might engender discernible anomalies amidst the otherwise homogenous spectra of charged cosmic rays.

Hitherto, quests for these spectral aberrations have predominantly centered upon antiparticles, namely antiprotons (p̅) and positrons (e⁺), attributed to their comparatively diminished astrophysical backgrounds. This thesis unfolds a meticulous inquiry into dark matter annihilation within the charge Z = -1 spectrum of AMS-01, essentially encapsulating electrons and antiprotons. To circumnavigate complications intrinsic to model dependency, it is postulated that the principal annihilation channel unfurls through W⁺W⁻ production.

Employing the galactic propagation software, GALPROP, the dissertation delineates the delineation of the dark matter spectra at Earth originating from a smooth isothermal source. Confrontations of theoretical predictions with empirical data did not unveil a discernible contribution emanating from dark matter. Consequently, constraints were imposed upon the rate of W⁺W⁻ production within the galaxy and, correlatively, upon the cross-section pertaining to WIMP annihilation via the W⁺W⁻ channel, under the presupposition of a smooth isothermal distribution.

This thesis, thereby, intertwines the theoretical predictions with empirical observations, providing not merely a reflection on the current understanding of dark matter’s ethereal nature but also a framework upon which future investigations might be scaffolded. This scholarly endeavor seeks to illuminate the elusive characteristics of dark matter, navigating through its spectral signatures, and providing foundational insights into our cosmic milieu.

MIT\_Dept. of Physics.\_996

This dissertation navigates through the intricate domain of gauge theories, meticulously explored within the contextual framework of D-branes probing toric singularities. An initial examination unveils the interconnections emergent in Toric Duality, wherein distinct dual gauge theory phases and the multiplicity of fields within the gauged linear sigma models, conjoined with the probed geometries, are scrutinized. A procedural introduction is proffered, elucidating a method for the determination of toric dual theories and partial resolutions, underpinned by the (p, q) web depiction of toric singularities.

In scenarios enveloping fractional branes, thereby engendering non-conformal theories, an in-depth exploration is undertaken. A structured approach is inaugurated, permitting an analytical perusal of the ensuing cascading Renormalization Group (RG) flows, incorporating the influence of anomalous dimensions upon beta functions. Subsequently, supergravity solutions, dual to logarithmic RG flows, are constructed, corroborating the field theory analysis intrinsic to the cascades.

In a further analytical trajectory, the Infrared (IR) dynamics of cascading gauge theories undergo a systematic examination, elucidating how the deformations in dual geometries are encoded via a quantum modification of the moduli space. An infinite family of superconformal quiver gauge theories is constructed, identified as the AdS/CFT dual to Sasaki-Einstein horizons, furnished with explicit metrics. Notably, the concordance between gauge theory and geometric computations of R-charges and central charges is demonstratively affirmed.

Additionally, novel Type IIB brane constructions—termed brane tilings—are introduced, epitomizing the dual aspect to D3-branes probing arbitrary toric singularities. Brane tilings encapsulate both the quiver and superpotential of the gauge theories operative on the D-brane probes, furthermore establishing a nexus with the statistical model of dimers. Remarkably, these tilings offer the most straightforward extant methodology for computing toric moduli spaces of gauge theories, essentially reducing to the computation of the determinant of a bipartite graph's Kasteleyn matrix.

In summation, this thesis weaves through the complex tapestry of gauge theories on D-branes, providing not only a panoramic view of the inherent dynamics and geometrical interplay but also pioneering methodologies and constructions that herald innovative avenues for future research within the realm of theoretical physics.

MIT\_Dept. of Physics.\_1011

This dissertation embarks upon a profound exploration of fermionic superfluidity, navigating through its complexities via a meticulously crafted mean-field approximation. This investigative framework, eminent for its comprehensive nature, seamlessly encapsulates both pairing and Hartree-Fock contributions, emerging rigorously from a foundational variational principle. The resultant analytical structure affords the examination of an extensive array of fermionic systems, thus providing a rich substrate for diverse investigations.

Within the purview of this thesis, consideration is accorded to two-species nonrelativistic atomic systems, subjected to varied interaction typologies, alongside relativistic Quantum Chromodynamics (QCD) systems, which are characterized by a multiplicity of 36 quark degrees of freedom (encompassing three colours, three flavours, and four relativistic degrees of freedom). A substantive discussion is proffered pertaining to the properties intrinsic to a novel state of matter: the gapless superfluidity, herein referred to as Breached Pair superfluidity. Furthermore, a succinct summary elucidating potential experimental realizations is encapsulated, providing a tangible bridge between theoretical constructs and empirical exploration.

Additionally, numerical results, pertaining to a self-consistent approximation to the Nambu–Jona-Lasinio (NJL) model within the realm of high-density QCD, are presented, with these findings further illuminating a microscopic realization of kaon condensation. The thesis delineates the methodology for adroitly matching the mean-field approximation to the low-energy chiral effective theory of pseudo-Goldstone bosons, culminating in the extraction of numerical coefficients correlated with the lowest order effective potential.

In summation, this thesis not only meticulously traverses the intricate landscapes of fermionic superfluidity, rendering insights into novel states of matter and facilitating a dialogue between theoretical and experimental realms, but also envisages and realises the integration of disparate physical systems under the unifying umbrella of a rigorously derived analytical framework, thus offering significant contributions to our understanding and future explorations within the domain of theoretical physics.

MIT\_Dept. of Physics.\_1084

This dissertation delineates an assiduous search for an annual fluctuation within a daily sidereal modulation of the frequency difference observed between concomitant ^{12}12Xe and ^{3}3He Zeeman masers, establishing a rigorous limit on boost-dependent Lorentz and CPT violation pertinent to the neutron, which harmonizes with an absence of effect at the meticulous level of 150 nHz. Grounded in the framework of the overarching Standard-Model Extension, our findings proffer the inaugural clean test for the fermion sector concerning the symmetry of spacetime under boost transformations, realized at a precision of 10^{-27}10−27 GeV [1].

Furthermore, progress pertaining to the optimization and operational dynamics of the Harvard-Smithsonian ^{12}12Xe/^{3}3He dual noble gas maser is articulated. Distinctively, the ^{12}12Xe/^{3}3He maser materializes as the premier apparatus to perpetuate simultaneous active maser oscillations on discrete transitions across two amalgamated atomic species, thereby facilitating a sensitive differential assessment of the ^{12}12Xe and ^{3}3He nuclear spin-\frac{1}{2}21​ Zeeman transition frequencies [2, 3, 4]. The optimized ^{12}12Xe/^{3}3He maser is poised to be instrumental for executing highly sensitive examinations of Lorentz and CPT symmetry, thus contributing nuanced insights and advancements within the field.

MIT\_Dept. of Physics.\_1138

This dissertation presents a comprehensive exploration of the transport properties of Bi (Bismuth) nanowires, meticulously prepared through the infusion of molten Bi into an alumina template. Sophisticated lithographic processes have been devised to intricately pattern 4-point electrodes on individual Bi nanowires post their extraction from the alumina template. The manifestation of high-resistance, non-ohmic contacts is ascribed to the formation of a substantial oxide layer enveloping the nanowires’ surface. An analytical understanding of the non-linear 2-point i(V) response of these contacts is formulated through the deployment of a tunneling model.

Concomitantly, innovative techniques have been developed to establish ohmic contacts to single bismuth nanowires, penetrating through the dense oxide coating. This was achieved by utilizing a focused ion beam (FIB) to meticulously sputter away the oxide, followed by the deposition of contacts. Through the amalgamation of FIB techniques and electron beam lithography, we secure contacts that exhibit stability from 300K to 2K for nanowires with diameters less than 100nm. Although annealing in H2 and NH3 environments is discerned to comprehensively reduce the oxide, the elevated temperatures requisite for this annealing prove incompatible with the lithographic techniques.

Moreover, a method to circumvent the burnout of nanowires due to electrostatic discharge has been developed and refined. A lithographic schema intended to facilitate the measurement of the Seebeck coefficient of a solitary Bi nanowire has been conceived and implemented. Additionally, methodologies have been developed for conducting measurements on a single Bi nanowire whilst situated within the template.

The electronic band structure of Bi nanowires is theoretically modeled, firmly anchored in the quantum confinement of electrons. Furthermore, 4-point resistivity data on singular Bi nanowires are reported and interpreted through the lens of the theoretical model of the quantized electronic band structure, whilst additionally considering the wire boundary and grain boundary scattering, phenomena absent in bulk bismuth. This investigative foray furnishes insightful advancements in the understanding and manipulation of Bi nanowires, providing a pivotal foundation for further research and potential applications in the realm of nanotechnology.

MIT\_Dept. of Physics.\_1159

The present dissertation delineates a refined methodology that enhances the capacity to compare the masses of singular ions, achieving an order of magnitude improvement to a fractional accuracy of approximately 7 \times 10^{-12}7×10−12. This enhancement is realized by simultaneously confining two ions within a Penning trap, and concurrently comparing their cyclotron frequencies, which bear an inverse proportionality to the ions' respective masses. The preceding technique, which employed alternate trapping of the two ions, encountered a precision ceiling imposed by magnetic field noise. The newly developed technique, herein detailed, attenuates the influences of both magnetic field and trap voltage noise by in excess of three orders of magnitude.

We introduce the capability to measure and regulate the relative motion of the two ions within the Penning trap, and a novel mode coupling technique has been developed to position the ions on a shared magnetron orbit, characterized by a diameter of 1 mm, yet positioned on antipodal sides of the trap. In conjunction with this magnetron motion, diminutive cyclotron orbits—each with a diameter of 150 μm—are superimposed to facilitate the concurrent comparison of cyclotron frequencies. The Coulomb interaction maintains a constancy in the separation of the cyclotron guiding centers, thus minimizing perturbations to the cyclotron frequencies induced by ion-ion interactions. Additionally, the ions spatially average magnetic field inhomogeneities and electrostatic imperfections at the magnetron frequency of 5 kHz.

Techniques have been crafted to both precisely measure and systematically modulate the ion-ion separation, with such control mechanisms proving critical for the exploration of systematic errors. A notable discovery within our investigation reveals our sensitivity to induced charge distributions within our molecular ions. An ion, in its course of cyclotron motion, experiences a motional electric field, which possesses the potential to polarize the ion. This induced charge distribution subsequently precipitates a systematic shift in the cyclotron frequency. Given the dependency of an ion’s polarizability on its quantum state, the quantum rotational state of a single CO^+CO+ molecule can be monitored by measuring its cyclotron frequency. Extracting data from the observed cyclotron frequency shifts between rotational states, we determine the electric dipole moment of the CO^+CO+ to be 1.025(15) e \cdot a\_01.025(15)e⋅a0​. This epitomizes a novel instantiation of a polarization force, a phenomenon hitherto unobserved. This exploration, in its profundity, not only introduces innovative methodologies in the realm of ion mass comparison but also unveils novel physical phenomena with potential implications for future research and technological applications in the field.

MIT\_Dept. of Physics.\_1161

In the intricate domain of transition metal oxides with low-dimensional geometries, a spectrum of novel phenomena such as high-temperature superconductivity and unconventional magnetism have emerged, establishing a fertile ground for exploratory research. The initial segment of this dissertation delves into this multifaceted subject, examining TiOCl as a representative instance of an S = \frac{1}{2}S=21​ layered Mott insulator. A critical review of preceding experiments—indicative of two-dimensional spin-liquid behavior—stands juxtaposed with new susceptibility data, propelling a reimagined perspective wherein band structure effects yield quasi-one-dimensional spin chains, engendered by t\_{2g}t2g​ orbitals. Under this lens, TiOCl is posited as a novel exemplar of Heisenberg chains undergoing a spin-Peierls transition. This perspective adequately elucidates the effects of doping with non-magnetic Sc impurities, aligning coherently with experimental observations. The magnetic energy scale of J = 660KJ=660K and the interchain geometry's frustration distinguish TiOCl amid materials experiencing a spin-Peierls transition. This atypical geometry is conceptualized as the principal catalyst for the incongruities between conventional mean-field theory descriptions and observed details of the transition, such as its first-order character. It is demonstrated that a rudimentary Ginzburg-Landau theory, aptly accounting for interchain frustration, is capable of elucidating this unorthodox behavior.

In the dissertation's subsequent part, the quandary of a doped dimerized spin chain is scrutinized within the one-dimensional tJJ'-model's ambit. The analysis particularly zooms into the regime where J'/J \approx .5J′/J≈.5, a spin gap manifests at minimal doping, and the undoped spin chain exhibits pronounced dimerization, focusing on the constraints of diminutive hole doping xx and small J/tJ/t, J'/tJ′/t. In this regime, earlier numerical calculations have wrestled with deriving definitive results. Utilizing a perturbative approach alongside Luttinger liquid considerations, this non-integrable class of models will be demonstrated to display charge degrees of freedom behaving as non-interacting spinless solitons in the diluted hole limit, a proposition substantiated up to the third order in perturbation theory. Employing the same methodology, the energy and mass renormalization of a single hole are evaluated, yielding non-analytic corrections in powers of \sqrt{J/t}J/t​. At J'/J = .5J′/J=.5, a variational spin-polaron wave function for the hole is formulated, showcasing a compelling alignment with perturbative results. Thus, this dissertation traverses from the exploration of the unconventional magnetic and superconductive properties of transition metal oxides to a rigorous theoretical examination of doped dimerized spin chains, offering new insights and methodologies in understanding the intricate behaviors of these low-dimensional systems.

MIT\_Dept. of Physics.\_1162

Operational since the 2nd of February, 2001, the HETE satellite has substantiated its utility within the realm of Gamma-ray burst (GRB) research, promulgating the localization and dissemination of 42 GRBs over the GRB Coordinates Network (GCN) in the initial 2.5 years of its mission, culminating on July 1, 2003. The inaugural segment of this dissertation is dedicated to elucidating the methodology underpinning the detection of GRBs in the data down-linked from the HETE satellite, achieved through a compendium of automated routines, colloquially termed "ground triggering." This mechanism was orchestrated to augment the HETE on-board triggering systems, and heretofore, has engendered the broadcast of six HETE GRBs to the GCN. A particularly novel trigger search routine, leveraging wavelets and incorporated within the suite, is delineated. Additionally, near-real-time explorations for GRBs of notably elongated duration (exceeding 300s), employing this methodology amongst others, are presented.

Subsequently, the dissertation pivots to concentrate on imaging observations via Chandra of two GRB X-ray afterglows, complemented by high-resolution spectroscopic observations of an additional five GRB X-ray afterglows. The imaging observations seek to unearth the intrinsic nature of the short/hard GRBs categorization and the "optically dark" GRBs classification, whereas the spectroscopic observations aim to scrutinize the affiliation between the long/soft GRB category and supernovae. The evidence marshaled herein intimates that no long/soft GRBs are categorically optically dark; rather, a multitude ostensibly align with an "optically faint" descriptor. In an isolated incident, a short/hard GRB may have epitomized optical darkness, conspicuously devoid of afterglow across optical, radio, and X-ray bands. Concluding, if the emission lines discerned in a Chandra spectrum of the X-ray afterglow of GRB 020813 bear authenticity, a supernova likely manifested approximately 2.2 months antecedent to the GRB. The statistical significance of the discrete spectral features thus far reported in high-resolution spectra, secured with Chandra, are examined in scrupulous detail, as the credibility of such features is paramount to forwarding the field with veracious insights and theories.

MIT\_Dept. of Physics.\_1163

This dissertation introduces a groundbreaking covariant formalism to address the transfer and Compton scattering of partially polarized light. In this innovative approach, the polarization state of a light beam is characterized by a tensor, formulated from the time-average of quadratic products of electric field components within a localized observer frame. This methodology seamlessly transitions into a covariant description, providing an optimal framework for computations related to the boosting of polarized light beams between Lorentz frames, presenting a more adaptable alternative than the traditional Stokes parameter methodology, which necessitates a distinct set of polarization basis vectors for each photon.

The covariant kinetic equation for Compton scattering of partially polarized light by relativistic electrons is deduced within the tensor formalism, following a heuristic semi-classical rationale. Initially derived in the electron rest frame in the Thomson limit, the kinetic equation is subsequently generalized to accommodate electron recoil and permit scattering from an arbitrary electron distribution. This formalism is judiciously applied to calculate the relativistic corrections to spectral distortions registered in the intensity and polarization of the cosmic microwave background radiation (CMB) through inverse Compton scattering in galactic clusters, a phenomenon known as the Sunyaev-Zeldovich effects.

A Monte Carlo method, predicated upon the tensor formalism and kinetic equation, is developed for simulating these effects. Furthermore, the utilization of the polarization signal, generated by the scattering of the CMB from distant clusters, as a probe of cosmological perturbations, is explored. Such observations facilitate an indirect assessment of the CMB quadrupole as perceived on the last scattering surfaces of observers positioned at a non-zero redshift. This study elucidates the statistical properties of this signal within a simplistic cosmological model, demonstrating that measurements of this signal could unveil more expansive information than that gleaned from observations of the CMB anisotropies on our own celestial sphere. Consequently, this might pave the way for a more accurate measurement of cosmological parameters and the primordial power spectrum of density fluctuations.

MIT\_Dept. of Physics.\_1183

This research diligently explores color superconducting phases of frigid quark matter, with a focus on densities pertinent to the internal constitution of compact stars. Within these density realms, electrically neutral and weak-equilibrated quark matter may manifest disparate numbers of up, down, and strange quarks. Intriguingly, the Quantum Chromodynamics (QCD) interaction exhibits a predilection for Cooper pairs that adhere to antisymmetry in both color and flavor, thereby enabling the potential emergence of a crystalline color superconducting phase. This phase accommodates pairing amidst flavors characterized by unequal number densities.

Within the realm of the crystalline color superconductor, quarks of distinct flavor engender Cooper pairs with a nonzero cumulative momentum, resulting in a spatially variant condensate that resembles the summation of plane waves. This state precipitates the spontaneous breaking of both rotational and translational symmetries. Utilizing a Ginzburg-Landau approach, this investigation evaluates prospective crystal structures, ultimately prognosticating a preferential manifestation of a face-centered-cubic structure. The research anticipates a sturdy crystalline phase, with gaps that are commensurate in magnitude to those within the color-flavor-locked phase, observable when flavor number densities achieve equilibrium.

Notably, crystalline color superconductivity emerges as a generic characteristic within the QCD phase diagram, materializing wherever quark matter, which is not color-flavor locked, prevails. In scenarios where substantial flavor asymmetry precludes the crystalline state, single-flavor pairing transpires; this, along with other spin-one color superconductors, is scrutinized within an exploration of generic color, flavor, and spin pairing channels.

The predictions articulated for the crystalline phase may be subjected to experimental verification within an ultracold gas of fermionic atoms, wherein a congruent crystalline superfluid state is plausible. Should a stratum of crystalline quark matter be present within a compact star, it possesses the potential to pin rotational vortices, thereby potentially engendering observable pulsar glitches, enhancing our astrophysical understanding and providing tangible applications to these theoretical explorations.

MIT\_Dept. of Physics.\_1245

This investigation meticulously delves into the kinetic properties of ions within the solar wind plasma. Utilizing the Faraday Cup instrument, a component of the Solar Wind Experiment on the Wind spacecraft, observations have been made of solar wind protons (+H) and helium ions (+2He). These ions exhibit magnetic field-aligned, convected, bi-Maxwellian velocity distribution functions. The resultant analysis elucidates best-fit values for the bulk velocity (U), number density (n), and parallel (T||) and perpendicular (T⊥) temperatures for each ion species.

A rigorous examination of the accuracy of these measurements was undertaken, and an absolute calibration of the Faraday Cup was executed, affirming the precision of the densities to within an equivalency/less than 2%. The range of the proton temperature anisotropy (Rp = Tp⊥/Tp||) was explored, revealing that thermodynamic concepts, such as the double adiabatic equations of state, serve as suboptimal approximations for a kinetic description of the solar wind plasma.

This research demonstrates that Rp is constrained on macroscopic timescales by Coulomb relaxation and solar wind expansion, and on kinetic timescales by mirror, cyclotron, and firehose plasma micro-instabilities. The solar wind reveals electromagnetic fluctuations, engendered by growing mirror and cyclotron modes. Moreover, the first detailed observations of the firehose instability are presented herein.

Limits to Rp imposed by these instabilities are meticulously measured and juxtaposed with theoretical predictions from fluid magnetohydrodynamics, linear kinetic Vlasov theory, and numerical simulations. Observations coalesce in agreement with the predictions of linear theory and simulations. Furthermore, a novel proton temperature anisotropy-driven instability in the regime Rp < 1, βP < 1 is discerned.

The kinetic properties of +H and +2He ions are scrupulously compared. For the first time, a cyclotron resonant instability, driven by proton temperature anisotropy, is demonstrated to limit the differential flow (U = Uα - Up) achievable in the solar wind, thereby validating recent theoretical predictions. The +2He temperature anisotropy (Rα = Tα⊥/Tα||) is similarly constrained by micro-instabilities, and the inaugural observations of the +2He cyclotron and firehose instabilities are presented. Finally, the parallel and perpendicular temperatures of +H and +2He are compared, providing evidence of cyclotron-resonant heating of +2He preferentially to +H in the interplanetary medium, thereby enriching our comprehension of kinetic ion behavior in solar wind plasma.

MIT\_Dept. of Physics.\_1321

This research meticulously explores the dynamics of magnetization and energy transport within high-temperature spin-1/2 lattice systems, inspired by recent experimental observations of "spin diffusion" among the dipolar-coupled nuclear spins in calcium fluoride, an insulator. The observed phenomena occur under conditions permitting the exclusion of coupling to any heat reservoir, thereby eliciting a coherent and reversible dynamic, yet paradoxically exhibiting signatures typically associated with irreversibility, such as diffusion. This ostensibly contradictory scenario poses a substantial conceptual enigma.

In addressing this challenge, this thesis introduces both phenomenological and microscopic models of spin diffusion, strategically retaining pivotal aspects of statistical transport approaches whilst integrating pertinent quantum effects. Such methodologies enable an efficient computation of energy diffusion pertinent to a long-range interaction, a problem which has predominantly remained intractable.

Intriguingly, the transport dynamics are studied within two distinct limits: firstly, where the XY term of the spin Hamiltonian exerts dominance, and secondly, where it is considered a perturbation relative to the Ising term. Remarkably, in the context of dipolar coupling, both limits reveal a slightly accelerated diffusion of inter-spin energy in comparison to magnetization, a phenomenon that harmonizes qualitatively with experimental results. This synthesis of statistical and quantum perspectives not only illuminates the underlying mechanisms of spin and energy transport in lattice systems but also casts light on the curious coexistence of coherent, reversible dynamics with ostensibly irreversible phenomena such as diffusion.

MIT\_Dept. of Physics.\_1322

This dissertation elucidates both theoretical and experimental aspects of a Smith-Purcell radiation experiment, facilitated by the electron beam derived from a 17 GHz high-gradient accelerator. Smith-Purcell radiation emanates when a charged particle traverses above a periodic grating structure. The investigated electron beam comprises a sequence of 15 MeV, 9 pC bunches, with bunch lengths oscillating between 600 fs and 1 ps.

An analytical resolution of the radiated energy for a single electron navigating above a periodic grating is furnished, subsequently extending considerations to the impacts of multiple electrons within a bunch and numerous bunches within a train. Illumination on the Smith-Purcell resonance condition, alongside the dependence of the radiated energy on variables such as beam current and beam height above the grating, is meticulously presented.

Experimental pursuits into the angular distribution of the Smith-Purcell radiation yielded bunch length measurements manifesting as 0.60 ± 0.1 ps and 1 ± 0.1 ps under distinct accelerator operational conditions. This underscores the efficacy of Smith-Purcell radiation as a non-destructive bunch length diagnostic tool, boasting a resolution of 100 fs.

It is emphasized that Smith-Purcell radiation parallels other radiation sources – such as transition radiation and synchrotron radiation – with the exception that it inherently affords an enhancement by a factor of Ng, representing the number of grating periods. Subsequent enhancement transpires when the electron bunch length is comparatively diminutive relative to the radiation wavelength, engendering coherent emission with an enhancement by a factor of Ne, indicative of the number of electrons in the bunch. Conclusively, considering the electron beam as comprising a regular train of Nb bunches, the energy density spectrum becomes confined in frequency space to harmonics of the bunch train frequency, amplifying the energy density at these frequencies by a factor of Nb.

Remarkably, this work reports the inaugural observation of Smith-Purcell radiation reflecting all three aforementioned enhancements, thereby, culminating in a total enhancement of Ng.Ne.Nb. This cumulative enhancement avails a straightforward methodology for generating potent THz radiation at specific frequencies, which can be perceptively detected with a robust signal-to-noise ratio by a heterodyne receiver, signifying a notable advancement in the field of experimental physics pertaining to Smith-Purcell radiation.

MIT\_Dept. of Physics.\_1323

This dissertation delves into the intricate domain of magnetic monopoles, notably characterized by their substantial ionizing capability and inherent curvature towards the magnetic field. A novel, dedicated magnetic monopole trigger at the Collider Detector at Fermilab (CDF) is introduced, necessitating pronounced light pulses in the scintillators of the time-of-flight system, while maintaining remarkable efficiency in monopole detection and utilizing a minuscule segment of the available trigger bandwidth.

An offline reconstruction, specialized in nature, scrutinizes the central drift chamber for tracks with sizable energy loss per unit distance (dE/dx) which refract from curving in the plane orthogonal to the magnetic field. A thorough exploration, spanning 35.7 pb⁻¹ of proton-antiproton collisions at a center-of-mass energy of 1.96 TeV, yielded no candidate events for monopoles. Consequently, these empirical findings impose a stringent upper limit on the monopole production cross section, denoted as [σ] < 0.2 pb, applicable to monopoles possessing a mass within the 100 and 700 GeV range. In the context of a Drell-Yan like pair production mechanism, these results further translate to a lower bound on the mass, stipulating m > 360 GeV.

This inquiry, underpinned by rigorous experimental methodology and astute theoretical discernment, contributes a pivotal framework to the exploration and understanding of magnetic monopoles, providing insights that fortify existing theoretical paradigms while navigating through the uncharted terrains of particle physics.

MIT\_Dept. of Physics.\_1451

Esteemed for its abundant availability and potential contributions toward a carbon-neutral cycle, hydrogen emerges as a pivotal energy carrier candidate, particularly within the realm of future automotive applications. The volumetric and gravimetric storage proficiencies of metal hydrides position them as optimal hydrogen carriers, contingent upon the resolution of inherent limitations, such as attenuated hydrogen release kinetics, elevated hydrogen release temperatures, and suboptimal thermal characteristics.

This thesis adeptly navigates through both the theoretical and experimental explorations concerning the thermodynamic and kinetic enhancements in the hydrogen release properties of nanostructured metal hydrides. Four seminal results are illuminated within this work. Primarily, the excess volume manifesting within deformed regions is distinguished as the principal element elucidating the experimentally-observed reduction in the enthalpy of formation within nanostructured materials. Employing three distinct equations of state, the impact of excess volume on the enthalpy of formation at 0K is quantitatively deciphered, revealing its importance as commensurate to the cumulative effect of surfaces, grain boundaries, and the incidence of metastable crystalline phases.

Subsequently, these insights into the properties of excess volume are extrapolated to elevated temperatures. It is substantiated that the temperature's impact will more propitiously facilitate a reduction of the enthalpy of formation if a substantial fraction of the metal hydride subsists in a state of minimal excess volume, juxtaposed with a smaller fraction in a state of high excess volume. Notably, the influence of a temperature augmentation on the enthalpy of formation of metal hydrides is discerned to counterbalance the effect of the excess volume as computed at 0K. The stability of regions harboring excess volume, across myriad hydriding/dehydriding cycles, is also meticulously calculated. Amidst high temperatures and significant excess volumes, the free energy barrier, engendered by the excess entropy, precipitously diminishes the recrystallization rate of the deformed regions, spanning several orders of magnitude. Consequently, a regime whereby the advantages of the excess volume on the enthalpy of formation can be sustained is identified.

In conclusion, an experiment to scrutinize the cycling properties of metal hydrides is meticulously designed utilizing Raman spectroscopy. This research conclusively demonstrates that Raman spectroscopy can accurately gauge the release temperature of hydrogen, thereby offering a novel methodology with notable implications for the future study and application of metal hydrides in energy storage and release. This doctoral inquiry thus navigates through the nuanced intersection of theory and praxis, propelling our understanding of metal hydrides within the broader hydrogen economy.

MIT\_Dept. of Physics.\_1452

In the elucidation of plasma confinement within the Levitated Dipole Experiment (LDX), this work illuminates significant advancements, employing a constructed 4-channel microwave interferometer with a central frequency of 60 GHz, to meticulously measure the density profiles of confined plasmas. The LDX, unprecedented in its design and singularity, is crafted to facilitate the study of plasmas confined by the magnetic field originating from a levitating dipole magnet. It utilizes a geometric approach that leverages plasma compressibility to realize stability, thereby embodying a pioneering endeavor in plasma confinement research.

Theoretical extrapolations—partially underpinned by observations discerned within planetary magnetospheres—propound that plasmas confined within a dipole will be propelled, via fluctuations, into pressure and density profiles that remain "stationary" with respect to Magnetohydrodynamic (MHD) interchange modes. A characterization of the stationary pressure profile reveals an equal distribution of entropy per flux-tube, whilst the stationary density profile exhibits an equal number of particles per flux-tube. These theoretical predictions beckon critical inquiry within the realm of nuclear fusion research, implying that the pressure and density profiles of dipole-confined plasmas can be concurrently peaked and stabilized.

Empirical measurements, facilitated by the interferometer, illuminate that the total density of LDX plasmas is profoundly influenced by several parameters, inclusive of: the mode of support for the central dipole coil, whether it be levitated or mechanically oriented; the input Electron Cyclotron Resonance Heating (ECRH) frequency and power; the background pressure exerted by neutral particles; and the plasma species. Contrariwise, the gradients of the density profiles largely retain their independence from experimental conditions, approximating the value prognosticated for the stationary profile. Non-linear analyses furnish the suggestion that dipole-confined plasmas are perpetuated in their stationary pressure and density profiles by a self-organized convection process.

The exposition of measurements herein, indicative of this self-organization process, emerges as discernible within LDX plasmas. Consequently, this doctoral dissertation not only traverses the intricate interplay of theoretical predictions and empirical observations within the ambit of dipole-confined plasmas but also enriches our understanding and capabilities regarding the manipulation and stabilization of such plasmas, with palpable reverberations for future endeavors in nuclear fusion research and related scientific inquiries.

MIT\_Dept. of Physics.\_1614

In this scholarly pursuit, the exploration commences with a meticulous examination of select axially symmetric supergravity geometries, which correspond to a distribution of Bogomol'nyi–Prasad–Sommerfield (BPS) D6-branes, conspicuously wrapped on K3, and conceived through extremal limits of a rotating solution. The ensuing geometry, afflicted by unphysical regions emergent from the wrapping, is subjected to restoration via the enhançon mechanism, yielding a dualistic shell configuration of two nested enhançon layers. A particular parameter subset enables these shells to coalesce into a singular toroidal surface, presenting an intricate geometric system conducive for the application and evaluation of previously employed techniques in contexts of spherical symmetry. The congruence of the construction is authenticated through the strategic employment of supergravity surgery methods and probe brane results, subsequently unraveling implications pertinent to the Coulomb branch of (2+1)-dimensional pure SU(N) gauge theory, gleaned from the geometric elucidations. Discussion also extends to encompass results relative to wrapped D4-- and D5-brane distributions.

The discourse seamlessly transitions to delve into the temporally complex subject matter of time travel, engaging with multiple solutions within General Relativity that ostensibly confer the potentiality for temporal voyaging. While the initial identification of such geometries spurred fascination, the ensuing causality violation – infringing upon foundational physical principles – instigates critical inquiry. Notwithstanding string theory’s revered position as a proposed fundamental theory of quantum gravity, geometries sporting closed timelike curves re-emerge as solutions within its low-energy equations of motion. The subsequent chapter embarks upon a detailed study of solutions within low-energy effective supergravity theories, with a particular focus on the BMPV black hole and the D1--D5-brane-SSW system. Within these geometries, the feasibility of time travel is explored and an endeavor to construct the causality-violating regions ensues. A proposition is advanced, suggesting that stringy effects impose prohibitions upon their construction. A demonstration unfolds, elucidating how the geometry is ameliorated, preserving causality upon correction, and tracing the chronology protection proposal within the dual conformal field theory. The abolition of closed timelike curves within the geometry concurs with the maintenance of unitarity in the conformal field theory, with our mechanism additionally serving as a safeguard for the second law of thermodynamics. The findings are subsequently generalized to envelop a more expansive class of geometries.

The final section delineates physics associated with horizons, formulating a de Sitter Space variant of Black Hole Complementarity, which asserts that an observer within de Sitter Space perceives the adjacent space as a sealed, finite temperature cavity, demarcated by a horizon which forestalls information loss. Subsequent discussions elucidate implications for the existence of boundary correlators within the posited dS/CFT correspondence, revealing that dS complementarity inhibits the manifestation of appropriate limits. These limits are discerned to exist exclusively within approximations where de Sitter Space entropy attains infinity. The existence of correlators within quantum field theory in the de Sitter Space background is attributed to the infinite nature of horizon entropy within Quantum Field Theory. Additionally, implications of a cosmological constant for universe evolution are contemplated, underpinning assumptions inspired by holographic and horizon complementarity principles. The "causal patch" description of spacetime, necessitated by this framework, is dissected, and simple examples of cosmologies are presented in a manner concomitantly coherent and elucidatory.

MIT\_Dept. of Physics.\_1696

The meticulous fitting of X-ray spectra, emanating from the thermal radiation of neutron stars, via the application of scrupulously developed atmospheric models, offers a conduit through which limitations upon their radii, surface gravities, and compositions may be exactingly imposed. Furthermore, such endeavors facilitate the probing of general relativity within the perimeters of a strong field limit and provide a platform to rigorously interrogate the equation of state pertaining to nuclear matter. In this dissertation, the exposition commences with the presentation of fits designed to circumscribe the radii and surface compositions of two neutron stars, specifically employing high-fidelity observations derived from the Chandra X-ray Observatory pertaining to the point source situated within the Cassiopeia A supernova remnant (Cas A XPS), as well as the isolated neutron star RX J1856.5-3754.

Models, conceptualized through advanced iterations of the ATM model atmosphere code—originally developed by Madej and Joss—are judiciously applied, serving to scrutinize neutron-star atmospheres constituted of various compositions, namely hydrogen, a hydrogen-helium amalgam, iron, or a silicon to iron composite. The resultant findings, predicated upon an assumed characteristic value of 1.4 solar masses, convey that X-ray emission emerges from localized hot spot regions, exhibiting a scale size in the vicinity of 3-4 km, situated upon stars possessing intrinsic radii of 9 and 12.5 km, respectively, thereby implying a discernably rigid equation of state.

With respect to the Cas A XPS, the fits are crafted from an unparalleled number of source photons, distilled from spectra extracted across three Chandra Advanced CCD Imaging Spectrometer observations (ObsIds 114, 1952, 1046), which cumulatively engender an effective exposure approximating 110,000 seconds. Employing this data, a substantiation is presented that attests to the enhanced fitting proficiency of atmospheric models over their blackbody counterparts, despite the concurrent permission of a broad spectrum of radii. Additionally, evidence is furnished delineating an absorption feature within the XPS spectrum, attributable to silicon residually present within the supernova remnant, alongside a discussion elucidating endeavors to fit the CCD pileup of the spectrum.

Concurrently, in relation to RX J1856.5-3754, a 450,000-second Chandra Low Energy Transmission Grating/High Resolution Camera observation is subjected to fitting. The ensuing findings harmonize with pre-existing results which advocate that a blackbody model proffers the optimal fit, thereby discrediting hydrogen and iron atmospheres. While antecedent attempts to align the spectrum with rotationally-blurred iron or solar abundance atmospheres have been rebuffed, the spectrum is proficiently fitted to a rotationally Doppler blurred silicon-ash model, a plausible surface composition in the aftermath of a supernova, which implies a rotational period proximate to 2 ms. Thus, through a lattice of meticulously executed fits and models, this dissertation threads a path that navigates through the intricacies of neutron star atmospheres and the profound implications contained therein.

MIT\_Dept. of Physics.\_1697

In the burgeoning realm of quaternary surfactant-phospholipid/fatty acid-sterol-water systems, helical ribbons, characterized by either 11° or 54° pitch angles, spontaneously congregate in a multitude of configurations. Despite the thermodynamic inclination of the sterol to crystallize into plate-like mono-hydrate formations, it frequently traverses a succession of metastable intermediates, metamorphosing from filaments to helical ribbons, and subsequently to tubules, prior to attaining the thermodynamically stable crystalline configuration. The focal point of the present investigation pivots on helical ribbons engendered within the Chemically Defined Lipid Concentrate (CDLC) system, characterized by radii and lengths, which typically span a few to several tens of microns and order of hundreds of microns respectively.

In an innovative approach, employing Devcon 5-Minute Epoxy® to achieve tethering to these mesoscopic helical ribbons, we navigated their elastic deformation, thereby scrutinizing their responsiveness to uniaxial tension. Within the domain of minimal deformations, the low-pitch helices mimic the behavior of linear elastic springs, with a representative spring constant measured to be (4.80 \pm 0.77) \times 10^{-6} \, \text{N/m}(4.80±0.77)×10−6N/m. Considering the observable variance in helix dimensions, our theoretical framework prognosticates a commensurate spectrum of spring constants for the structures, spanning 10^{-7}10−7 to 10^{-4} \, \text{N/m}10−4N/m, thereby offering a theoretically expansive range of forces for exploration.

Under the auspices of augmented tensions, both low and high-pitch helices have demonstrated a reversible bifurcation into a straight domain, exhibiting a pitch angle of 90°, and a helical domain, which encapsulates a pitch angle of (16.5 \pm 1.3)^{\circ}(16.5±1.3)∘ or (59.6 \pm 1.7)^{\circ}(59.6±1.7)∘ for the low and high pitches respectively. Leveraging a recently conceived continuum elastic free energy model, we elucidate this phenomenon as a mechanical phase transition of the first order. This analysis not only facilitates the determination of all pertinent parameters within our model but also underscores its capacity to self-consistently and quantitatively expound upon all observed properties of these spontaneously assembled helices. Consequently, through a lens of meticulous analysis and innovative methodology, this dissertation delves into the depths of helical ribbon behavior, shedding light on the mechanistic and thermodynamic properties inherent to their formation and deformation.

MIT\_Dept. of Physics.\_1698

The present dissertation delineates a thorough exploration, both theoretical and experimental, into electronic systems that capitalize on ballistic electron emission. Initially, the exposition meticulously unveils a Monte Carlo paradigm designed for simulating electron injection from a tunnel junction emitter into a semiconductor collector, furnishing a detailed narrative of its formulation along with a select exposition of its applicative realms.

Subsequently, attention is directed towards a methodological discourse on the treatment of ballistic electron transport through nano-scale heterostructures. This segment elucidates the contemplation of realistic, atomic-scale periodic potentials, providing an in-depth exploration of its pertinent mechanics and implications. The third facet of this thesis introduces experimental forays directed towards the developmental strides in innovating a novel scanning-probe microscopy, specifically tailored for the localized examination of obscured luminescent heterostructure layers.

In culmination, the dissertation juxtaposes the aforementioned results, weaving them into a tapestry that articulates several prospective trajectories for future research, thereby drawing upon the implications and findings that have emanated from the currents of the preceding analytical and experimental ventures. Consequently, this research not only enhances the contemporary understanding of electron dynamics within specified electronic systems but also sketches a pathway that may guide subsequent explorations within this intricate domain of physics.

MIT\_Dept. of Physics.\_1736

Within the previous decade, the trio of interferometers constituting the Laser Interferometer Gravitational Wave Observatory (LIGO) were meticulously constructed and commissioned. Achieving its design sensitivity in the autumn of 2005, characterized by a strain sensitivity of 2.5 \times 10^{-23} \, \text{Hz}^{-1/2}2.5×10−23Hz−1/2 at 150 Hz, LIGO’s three interferometers presently navigate through an extended scientific run. A pivotal stride towards this achievement was the amplification of power within the interferometer to over 200 Watt at the beam splitter, necessitating the commissioning of both a thermal compensation system and shot noise limited sensing electronics, aptly proficient in detecting the entirety of the light. Furthermore, a succession of unforeseen noise sources warranted mitigation, a process thoroughly delineated within the initial portion of this thesis.

Subsequently, the text introduces a radiometer analysis, endowed with the capacity to spatially resolve anisotropies within a stochastic gravitational wave background, and is optimized expressly for the identification of point sources of stochastic gravitational radiation. Conclusively, data extracted from LIGO’s fourth scientific run is employed to establish both isotropic and directional upper boundaries on the stochastic background of gravitational waves. The established bound on the normalized gravitational wave energy density is set at h^2 \Omega\_{\text{GW}}(f) < 6.25 \times 10^{-5}h2ΩGW​(f)<6.25×10−5, while the constraint set upon a broadband and flat strain power spectrum emanating from a point source fluctuates between 8.5 \times 10^{-49} \, \text{Hz}^{-1}8.5×10−49Hz−1 and 6.1 \times 10^{-48} \, \text{Hz}^{-1}6.1×10−48Hz−1, contingent upon the source position. In addition, a limitation is imposed on gravitational radiation originating from the direction of Sco-X1 — the most luminous X-ray source in the skies, surpassed only by the Sun — is set for each frequency bin, fortifying the dissertation’s contribution to the scientific dialogue concerning gravitational wave phenomena.

MIT\_Dept. of Physics.\_1737

Embarking upon an exploration into the construction of models encapsulating family symmetry, this thesis meticulously investigates the establishment of models that confer family structure upon the Higgs fields. The narrative initiates with the development of models engendering two generations, progressively extending the exploration towards models comprising three generations, and sequentially unfolds through Chapters 2 to 6. Remarkably, all models presented are embedded within a supersymmetric framework and introduce novel contributions not heretofore present in the existing literature.

In the detailed models, the masses and mixings of quarks (and leptons) are intrinsically determined by the vacuum expectation values (VEVs) emanating from the family sector. These VEVs potentially exhibit a hierarchical structure, attributable to their correspondence with the flat directions of a superpotential. At the domain of low energies, the models inherently contain merely a single light pair of Higgs fields.

The experimental facets of these models reveal their most compelling characteristics through the couplings bridging the low-energy Higgs and the moduli of the family sector. Importantly, these couplings manifest attributes that should be empirically discernible at the Large Hadron Collider, thereby providing a fertile ground for further experimental investigations and theoretical developments, enriching our understanding of the nuanced interplay between family symmetry and Higgs fields within the presented supersymmetric models.

MIT\_Dept. of Physics.\_1738

This dissertation delineates a meticulously conducted experiment, aimed at loading a shallow planar ion trap utilizing photoionization from a cold atom source of Ytterbium. The surface trap employed encompasses a three-rod radio frequency Paul trap, expertly fabricated through the utilization of standard printed circuit board techniques. Concurrently, the cold atom source is manifested as an isotope-selective magneto-optical trap, capturing naturally-occurring Ytterbium isotopes.

Profoundly, the confining beams are orchestrated by commercially-available ultra-violet diode lasers, meticulously locked to an atomic reference through the employment of the Dichroic Atomic Vapor Laser Lock technique. The experiment exploits photoionization emanating from the Ytterbium magneto-optical trap, strategically located within the potent region of the ion trapping potential. This work not only paves the way for further exploration into the realm of ion trapping and photoionization but also engenders a nuanced understanding of the underlying physics, thereby providing a fertile ground for subsequent research and technological advancements in the field.

MIT\_Dept. of Physics.\_1741

The encompassed thesis embarks upon a detailed exploration of the inclusive decays of the B meson, which facilitates the precise determination of CKM matrix elements and opens a window to unearth physics that transcends the Standard Model. Employing the scaffold of effective field theories, notably the Soft-Collinear Effective Theory (SCET), which emerges as a pertinent approach when the decay products incorporate a jet-like conglomerate of hadronic states, we derive factorization theorems and minutely engage with corrections up to [specified order], especially in the shape function region, elucidating [specified dynamics].

Furthermore, we unveil a comprehensive catalogue of [specified] contributions and highlight the emergence of new shape functions, a result of four-quark operators, thereby introducing an additional layer of uncertainty in certain inclusive determinations of [specified parameters]. Following, we meticulously derive the triply differential spectrum for [specified decay] in the aforementioned shape function region, which is mandated by experimentally imposed cuts. It is demonstrated that the same universal jet and shape functions emerge as witnessed in the decays [specified]. Additionally, it is showcased that one may independently treat the perturbative power counting above and below the scale [specified] through an approach we term "split matching". This method assuages the tension between what is deemed appropriate in each of these regions.

Concludingly, leveraging these results, we compute the fraction of the total rate discernible in the presence of a cut on the hadronic invariant mass, m\_xmx​. It is discerned that the impact of this cut robustly depends on the value of m\_tmt​ and approximately retains universality across all short-distance contributions. This characteristic can be adroitly exploited to minimize hadronic uncertainties, thereby preserving sensitivity to nascent physics. This dissertation, thereby, not only shines light on the intricate mechanics of B meson decays but also lays a robust foundation for future endeavors aiming to pierce the veil of physics beyond the established theoretical framework.

MIT\_Dept. of Physics.\_1742

The thesis propounds a profound exploration of quantum phases, extending beyond the traditional purview delineated by Landau's theory of symmetry breaking, which, for many years, was posited as a comprehensive descriptor for all phases and phase transitions. Over the recent two decades, a perceptible shift has been discerned at zero temperature, where quantum mechanics promulgates the existence of novel phases of matter, ostensibly extending beyond the well-trodden paths of the Landau paradigm.

Within the scope of this scholarly inquiry, we orchestrate a general theoretical framework, tailored to navigate through these so-dubbed "exotic phases," architecting an analogy to Landau's structural framework, which predominantly envelops symmetry-breaking phases. The spotlight is judiciously cast upon a distinctive subset of exotic phases, identified as "topological phases," with a special emphasis engaged upon a unique physical manifestation thereof—specifically, frustrated quantum magnets.

The embarked approach is scaffolded upon a nascent physical perspective for topological phases. A persuasive argument is put forth that, mirroring the origination of symmetry-breaking phases from the condensation of particles, topological phases take root from the condensation of dimensionally-extended entities, designated as "string-nets." Navigating through this conceptualization, we unveil that, paralleling the classification of symmetry-breaking phases via symmetry groups, topological phases may be systematically classified through entities recognized as "tensor categories." Moreover, akin to the manner in which symmetry-breaking order permeates through local correlations within a ground state wave function, topological order casts its signature through nonlocal correlations or quantum entanglement.

In this light, we introduce a nuanced quantity, denominated as the "topological entropy," which serves to precisely quantify this nonlocal entanglement. A noteworthy fraction of our findings find applicability to other exotic phases, even those that do not nestle under the topological categorization. Consequently, this dissertation not only illuminates the intricate mechanics and classifications of topological phases but also augments the theoretical infrastructure required to navigate through the rich tapestry of quantum phases that sprawl beyond the classical Landau paradigm.

MIT\_Dept. of Physics.\_1743

Embarked upon the intricate confluence of Cosmology and Particle Physics, this thesis elucidates a series of results emanating from meticulous research that probes the cosmic implications of numerous models that oscillate within the theoretical framework of Physics Beyond the Standard Model (BSM). The explorative journey traverses through diverse models, initiating from an inflationary exemplar predicated upon the condensation of a specter-like scalar field, gradually meandering through an array of models that are inspirited by the proposition that our theoretical understanding is underpinned by a landscape of vacua—a supposition potentially intimated by String Theory. These models, in turn, exude substantial influences upon the theorization of Baryogenesis, Dark Matter, and Big Bang Nucleosynthesis.

Moreover, the thesis proffers a thorough analysis of data emanating from the Wilkinson Microwave Anisotropy Probe (WMAP) experiment, particularly focusing upon the Cosmic Microwave Background (CMB), in a quest to discern a non-Gaussian signal. The results of the investigation culminate in establishing an upper boundary on the permissible non-Gaussianities, thereby presenting what is contemporarily the most precision-oriented and expansive limitation available.

Through a nuanced blend of theoretical exploration and empirical data analysis, this work not only sheds light upon the potentially rich and complex cosmological ramifications of multiple BSM models but also fortifies our understanding of the universe’s early thermal history, intricately interlinking it with the contemporaneous observational data, and hence, subtly nudging the boundaries of our understanding of the cosmos and its constituent particles.

MIT\_Dept. of Physics.\_1744

Navigating through the intricate web of string theory's foundational structure, this dissertation meticulously embarks upon a tripartite exploration of distinct approaches, each veering slightly from the canonical understanding furnished by perturbative string theory. Initially, the discourse propounds a concise review of the latter, subsequently transitioning into a detailed disquisition of three divergent topics, each constituting a substantive departure from the established theoretical baseline.

The inaugural investigation meticulously unravels the open string one-loop tadpole diagram within the framework of Witten cubic open string field theory. Through both analytical and numerical computation, divergences emerging from the collective dynamism of open string fields in the diagram’s short-distance region are astutely analyzed. The exploration reveals that this particular region harbors pivotal information pertaining to the linearized Einstein equation, thus chronicling the shift in the closed string fields in response to the D-brane, which substantiates the open strings. Furthermore, the singular modality through which this information is encoded is elucidated, coupled with a commentary on the potential ramifications this has for the quantum consistency of open bosonic string field theory.

The ensuing discourse delves into the calculation of closed string radiation emanating from a decaying D-brane within type II string theory, a calculation facilitated by recognizing that the integrals inherent in the pertinent disk one-point functions subsequently reduce to integrals over the group manifold, specifically, a product of unitary groups. A notable discovery denotes that the total number and energy of strings radiated throughout the decay process reaches a divergence for D-branes of sufficiently minimal dimension, mirroring the bosonic scenario with precise analogy.

Lastly, the dissertation explores a cogent class of type II string compactifications, encompassing nongeometric "fluxes" in conjunction with "geometric flux," and conventional H-field and R-R fluxes. Employing T-duality rules for NS-NS geometric and nongeometric fluxes, a superpotential for the dimensionally reduced four-dimensional theory is ingeniously constructed. Remarkably, the resultant structure persists invariant under T-duality, ensuring that the distribution of vacua in the IIA and IIB theories remains congruent when nongeometric fluxes are integrated into the analysis.

Collectively, this thesis not only offers nuanced insights into the foundational realms of string theory through a multifaceted investigative lens but also propels the current theoretical understanding towards novel horizons by elucidating the intricate correlations and implications each study fosters within the grander schematic of string theory.

MIT\_Dept. of Physics.\_1838

This dissertation elucidates and substantiates a novel physical mechanism pivotal for the accumulation of positrons, engaging profoundly with the formation and subsequent ionization of strongly magnetized Rydberg positronium, a process that capacitates the trapping of equal quantities of either positrons or electrons under a myriad of conditions. For the inaugural time, antiprotons are adeptly trapped, cooled, and stacked, utilizing the nascent Antiproton Decelerator facility, thereby launching a new epoch in antiproton manipulation and utilization.

The amalgamation of positrons and antiprotons unfolds a pioneering endeavor: the first instance of positron cooling of antiprotons. This cooling transpires within a 4.2 K, nested Penning trap, wherein conditions meticulously orchestrate an idyllic environment, propitious for steering towards the ultimate objective of forming antihydrogen. The findings and methodologies delineated within this work not only fortify our understanding of positron and antiproton manipulation but also carve out new pathways that can potentially cascade into further advancements within the domain of antimatter research.

MIT\_Dept. of Physics.\_1885

This dissertation delineates an explorative study into the design of quantum algorithms, exploiting continuous-time Hamiltonian dynamics and entwining with quantum computation via adiabatic evolution and quantum walks. Despite the recognition that quantum mechanical computers can solve certain problems with an asymptotic speed transcending that of any classical computing device, the intrinsic nature of quantum speedup remains enigmatic, rendering the invention of new quantum algorithms a formidable challenge.

In the realm of quantum computation by adiabatic evolution, the initial preparatory phase sees the computer entrenched in the known ground state of a simplistic Hamiltonian. This state is then languidly modified, ensuring its ground state gradually becomes an encoding of the solution to a particular problem. It is posited that this method innately exhibits robustness against low-temperature thermal noise and specified control errors, a claim substantiated through rigorous simulations within this work. Furthermore, the thesis demonstrates that any adiabatic algorithm can be executed alternatively, utilizing merely a sequence of measurements of the Hamiltonian. An illustration is proffered, showcasing how this methodology can achieve a quadratic speedup for the unstructured search problem.

Simultaneously, this work introduces instances of quantum speedup by quantum walk, the quantum mechanical counterpart of a classical random walk. Initially, the problem of spatially searching for a marked item is contemplated. In contrast to a classical algorithm, which demands time proportional to the number of items irrelative of geometry, it is demonstrated that a simplistic quantum walk algorithm can locate the marked item with a speed that is quadratically faster for a lattice of dimensionality surpassing four, and nearly quadratically faster for a four-dimensional lattice. Moreover, by infusing the walk with spin degrees of freedom, the critical dimension can be reduced to two. Secondly, the construction of an oracular problem is demonstrated, wherein a quantum walk can solve it exponentially faster than any classical algorithm, presenting a unique instance of exponential quantum speedup not reliant on the quantum Fourier transform.

In the final analysis, bipartite Hamiltonians, envisioned as a model of quantum channels, are explored to scrutinize their capability to process information amidst perfect local control. It is demonstrated that any interaction can simulate another at a non-zero rate and that tensor product Hamiltonians can simulate each other reversibly. Additionally, the optimal asymptotic rate at which specific Hamiltonians can generate entanglement is calculated, thereby intertwining theoretical insight with practical implications for quantum computing and information processing.

MIT\_Dept. of Physics.\_1889

This dissertation delineates the manifestation of a novel technique, enabling the comparison of masses with a fractional uncertainty at or beneath 1 x 10⁻¹¹, reflecting an order of magnitude enhancement over preceding outcomes. Through the confinement of two disparate ions in a Penning trap, we are now capacitated to measure the ratio of their respective cyclotron frequencies concomitantly, thereby rendering our mass comparisons impervious to numerous sources of fluctuations, such as those emanating from the magnetic field.

In an endeavor to attenuate the systematic error intrinsic to the Coulomb interaction betwixt the two ions, they are meticulously maintained approximately 1 mm distant from each other, placed on a communal magnetron orbit. This work elucidates novel methodologies developed to measure and govern all three normal modes of motion for each ion, which incorporates the two robustly coupled magnetron modes. Leveraging a newly devised computer control system, we have characterized the electric field anharmonicities and magnetic field inhomogeneities with a hitherto unparalleled level of precision, thereby optimizing the trap to ensure our measurement of the cyclotron frequency ratio is, to first order, insensitive to field imperfections.

Utilizing ¹³C₂H₂⁺ and ¹⁴N₂⁺ ions, numerous tests probing our comprehension of ion dynamics and various error sources inherent to this technique were executed. Subsequent analyses lead us to posit that there should exist no systematic error in our measurements at the level of 5 x 10⁻¹². Consequently, we confidently report a value for the mass ratio of these ions, subsuming an uncertainty of 10⁻¹¹. Moreover, this thesis furnishes measurements of the two mass ratios m[³³S⁺]/m[³²SH⁺] and m[²⁹Si⁺]/m[²⁸SiH⁺] with a relative uncertainty inferior to 10⁻¹¹, establishing them as the most precisely known mass ratios to this date.

These measurements, amalgamated with precise high-energy gamma-ray measurements, proffer a direct examination of the relation E = mc², offering a test of special relativity that judiciously circumvents the presumption of a preferred reference frame. Additionally, the uncertainty concerning the atomic mass of ²⁹Si has been mitigated by approximately an order of magnitude, substantiating the significance and the impact of the methodologies and findings expounded within this work.

MIT\_Dept. of Physics.\_1890

This dissertation ventures into the microscopic phenomena inherent in the shock compression of condensed matter, elucidating aspects that encompass electronic excitations at the shock front, a novel dynamical formulation of shock waves that facilitates a linkage from the microscopic to the macroscopic scale, and fundamental inquiries into the role of crystallinity in the propagation of electromagnetic radiation within a shocked material. Despite a century-long exploration into shock wave compression, the microscopic intricacies have largely remained enigmatic, thereby warranting the depth of exploration undertaken within this work.

Chapter 2 delves into the electronic excitations within crystalline solid nitromethane under shock compression conditions. Employing density functional theory calculations, this research probes the crystal bandgap under diverse stress conditions, such as hydrostatic stress, uniaxial strain, and shear strain, both in pure and defective materials. Remarkably, in all instances, the bandgap does not diminish sufficiently to yield a noteworthy population of excited states.

Chapter 3 unveils a newly formulated multi-scale simulation method tailored for the study of shocked materials. This innovative method facilitates the molecular dynamics simulation of the system under dynamical shock conditions for temporally expansive periods, vastly exceeding the capabilities offered by the widely-utilized non-equilibrium molecular dynamics (NEMD) approach. An exemplary calculation for a model potential for silicon is provided, wherein a computational acceleration of 10? is demonstrated, and the results from these simulations harmonize with some extant experimental observations.

Chapters 4 and 5 unfold unexpected physical phenomena emerging when light interacts with a shock wave propagating through a photonic crystal. These newfound phenomena include the capture of light at the shock wave front and its re-emission at a tunable pulse rate and carrier frequency across the bandgap, alongside bandwidth narrowing of an arbitrary signal, which starkly contrasts with the ubiquitous bandwidth broadening observed hitherto. Moreover, reversed and anomalous Doppler shifts are anticipated in the light reflected from the shock front.

This thesis, thus, serves to both broaden and deepen our comprehension of the underlying microscopic phenomena and electronic excitations occurring during the shock compression of condensed matter, thereby proffering substantial advancements in our understanding and characterization of shock wave dynamics.

MIT\_Dept. of Physics.\_1894

This dissertation elegantly interweaves the principles of statistical physics and non-equilibrium dynamics to explore matters of scale, randomness, and growth within plant communities through three methodologically related yet applicationally distinct projects.

The inaugural project astutely analyzes the interplay between resource availability and species richness at both community and regional levels within plant/tree communities. At localized scales, vegetation communities traditionally exhibit a unimodal relationship amidst resources and species richness. Contrastingly, larger scales, adhering to the species-energy theory, typically demonstrate a monotonically ascending relationship. A multi-species neutral contact process, paired with a heterogeneous resource landscape, is utilized to elucidate this scale-dependent transition. The resultant unimodal curve at the community scale is interpreted as a negotiation between colonization and competition for restricted resources. Subsequently, statistical aggregates of community-level ecosystems are constructed, unveiling two imperative conditions for a scale-dependent transition: (i) a notably correlated spatial distribution of resources and (ii) an escalation in the extent of species pools in regions abundant in overall resources.

In the second venture, the scrutiny of size-structured populations is integrated into the study of the contact process. Herein, the contact process with ontogeny is introduced to articulate the growth and dissemination of organisms with size-structured juvenile and adult phases. A mean field theory of the contact process with ontogeny is derived and solved, revealing an additional oscillatory phase. Despite the mean field phase diagram being delineated in terms of A, the dimensionless reproductive rate, and 0, the dimensionless growth rate, the oscillatory phase is not corroborated in explicitly spatial Monte Carlo simulations, contrary to the regular oscillations observed for well-stirred models of size-structured populations. Alternatively, a "corralled" phase emerges, wherein the growth of new seeds mutually infringe, constraining basal area and adult numbers, and culminating in a unimodal relationship between density p and reproductive rate A. The onset of the corralled phase is analyzed via spatial correlations, and it is revealed that this self-limiting phase is characterized by discrete peaks in the radial distribution function. Furthermore, the universality class of the transition between life and death is determined, and potential applications of generalizations of the model to plant/tree communities are highlighted.

The terminal project addresses the size distributions of systems where growth is constricted by geometric constraints. A model, termed packing limited growth (PLG), which delineates the interaction and growth of sessile organisms, is developed. It is demonstrated that a class of models, previously introduced in the context of growth and nucleation kinetics, may be mapped onto PLG. A scaling theory is formulated, bridging the fractal dimension of packings to the approach to the fully packed state. The equilibrium size distribution of PLG models is illustrated to be dependent on dimensionality, anisotropy, and geometric shape, with numerical estimates of fractal dimensions being calculated in d = 2, 3, and 4.

This thesis thereby not only propounds substantial advancements in our understanding of scale, randomness, and growth within plant communities, applying meticulously crafted methodologies, but also presents a myriad of possibilities for further exploration and application within the field.

MIT\_Dept. of Physics.\_1907

This dissertation delineates the implementation and findings of four innovative optical surveys, meticulously designed to identify gravitationally lensed quasars. The twofold objective of this scholarly endeavor aimed to: (1) scrutinize and refine strategies for executing optical surveys, with a particular focus on the southern hemisphere, thereby fine-tuning survey techniques to uncover systems of pronounced scientific significance, and (2) augment the quantity of optically-selected lenses, thereby enhancing the statistical analyses of future lens surveys through the amplification of the sample size of quasars scrutinized for lensing.

Optical surveys for potent lenses hold the potential to discern systems, surpassing by an order of magnitude the capabilities of radio surveys, to produce optically-luminous lenses, aptly suited for prolonged monitoring and subsequent observational studies, and to confer statistical constraints on the comprehensive geometry and dynamics of the Universe.

Three surveys embody traditional "targeted" searches, including: 1) a terrestrial survey of 173 radio-loud quasars utilizing the 2.4 m telescope at the Michigan-Dartmouth-MIT Observatory (MDM), yielding one confirmed lens and one binary quasar; 2) a terrestrial survey of 377 quasars in the southern hemisphere utilizing the 1.5 m telescope at the Cerro-Tololo Interamerican Observatory (CTIO), resulting in two confirmed lenses and one binary quasar; 3) a space-based snapshot survey targeting 320 quasars utilizing the Hubble Space Telescope (HST), unearthing three confirmed lenses and potentially a fourth.

The MDM survey was astutely crafted to amalgamate the high discovery efficiency inherent to optical surveys with the intricate image morphology often prevalent in radio-loud lenses. The CTIO survey leveraged two novel catalogs of luminous quasars to attain a high discovery efficiency of 0.7%. The HST snapshot survey endeavored to discover close separation lenses, specifically spirals, that prove challenging to resolve from terrestrial surveys.

Of the eight systems discerned from these surveys, quintuple are meticulously delineated herein. The inaugural object, FBQ 1633+3134, a 0"f7 double unearthed from the MDM survey, is most plausibly a physical binary quasar, attributed to the discrepant optical and radio flux ratios. The subsequent trio—CTQ 414, HE 0230-2130, and CTQ 839—were identified from the CTIO survey, with the initial two confirmed as gravitational lenses and the latter established as a binary quasar. Furthermore, CTQ 414 emerges as an exemplary candidate for future optical monitoring and potential time-delay measurement, while HE 0230-2130 presents as a complex four-image gravitational lens shaped by two lensing galaxies. The fifth system, the lensed quasar CTQ 327, was identified from the HST survey and is similarly apt for optical monitoring and potential time-delay measurement.

Additionally, the superior angular resolution proffered by the HST snapshot survey was employed to constrain the matter density of a hypothetical population of dark, compact objects at high redshift to less than 2.2% of the closure density for objects of mass 10^9 6M₀ and precludes a closure density of any compact object in the mass range 10^7.5 < M/M₀ < 10^11.5 at the 99.7% confidence level. This work not only substantively enhances the existing corpus of lensed quasars but also propels forward our methodological and analytical approaches in this illuminating domain of astrophysical research.

MIT\_Dept. of Physics.\_1908

Embarking upon an intricate exploration of varied condensed matter systems, this dissertation illuminates the properties therein, intricately interwoven with electronic behavior, as conveyed through coarse-grained interactions across three particular systems.

In the initial system scrutinized, the high-momentum, plane-wave states of the electronic wave function are subject to coarse-graining, whilst concurrently maintaining a meticulous resolution of the low-momentum states. Notably, the coarse-graining procedure seamlessly assimilates the response of the high-momentum states to environmental flux and its subsequent couplings to alterations within the low-momentum states. Employing density functional theory, this methodology facilitates the computationally viable representation of the electronic wave function—when deploying a plane-wave basis—negating the necessity for the pseudopotential approximation. This approach proves particularly efficacious in probing high-pressure systems, wherein the core region’s response emerges as pivotal. Utilizing this method, multiple solid phases of boron are explored, uncovering salient structural and electronic properties in its high-pressure and superconducting phases.

Shifting the lens to a marginally coarser scale, the second system draws focus towards developing a theory accentuating the elasticity of nanometer-sized entities. This theoretical framework adeptly translates understanding of nanoscale elasticity into terms of local group contributions, effectively establishing a conduit between atomic and continuum realms. The theory astutely delineates elastic fluctuations within length scales approximate to the decay length of the force constant matrix. Consequently, this facilitates the effortless development of innovative relationships between the bending and stretching attributes of nanomechanical resonators—demonstrating enhanced accuracy compared to presently utilized continuum-based relations within experimental analyses. Furthermore, the theory serves to correlate features of the underpinning electronic structure to the local elastic response in silicon nanoresonators, highlighting the electronic structure's pivotal influence on both local and overarching elastic responses.

Navigating towards the longest length scales—the continuum—the final system underscores the imperativeness of incorporating electronic structure within the study of dislocations' impact on the macroscopic property of slip. An exploration into the divergence between experimental data and theoretical calculations concerning the lattice resistance in bcc metals is undertaken within this thesis. Presented are findings pertaining to the temperature dependency of the Peierls stress and the inaugural ab initio calculation of the zero-temperature Peierls stress, which utilizes periodic boundary conditions. Notably, the ab initio value for the Peierls stress exceeds current extrapolations of experimental lattice resistance to zero-temperature by a factor exceeding five. While conventional techniques for such extrapolation are identified to typically underestimate the zero-temperature limit, this work demonstrates that mechanisms beyond the rudimentary Peierls mechanism are integral in governing the process of low-temperature slip. This dissertation, thus, not only elucidates multifaceted aspects of condensed matter systems but also accentuates the nuanced interplay between electronic structures and varied physical properties across disparate scales.

MIT\_Dept. of Physics.\_1909

In the imminent precipice of operational commencement for the initial generation of laser interferometric gravitational wave detectors, an intricate tapestry of research and development has been elegantly woven, embarking upon a journey toward enhancing the instrument's sensitivity within the confines of extant infrastructure. The Laser Interferometer Gravitational Wave Observatory (LIGO) finds itself enveloped in meticulous enhancements, slated for installation in the year 2007, with a keen ambition to augment its sensitivity toward test mass displacement and, concomitantly, gravitational wave strain, through the implementation of refined suspensions, test mass substrates, active seismic isolation, and the infusion of elevated input laser power.

Nonetheless, even when armed with the pinnacle of contemporary optical quality, the finite absorption of laser power within transmissive optics, seamlessly entwined with the formidable amount of optical power circulating in diverse sectors of the interferometer, culminates in pivotal wavefront deformations, thus threatening to severely debilitate the instrument’s performance. Herein, a methodology of active wavefront correction is broached, facilitated through direct thermal actuation upon the interferometer’s optical elements, or aptly coined as "thermally adaptive optics".

A judiciously simple nichrome heating element, elegantly suspended off the visage of an impacted optic, shall, through the mechanism of radiative heating, expunge the gross axisymmetric component of the original thermal distortion. Subsequently, a scanning heating laser shall be deployed to extirpate any residual non-axisymmetric wavefront distortion, borne from inhomogeneities within the substrate’s absorption, thermal conductivity, and beyond. This endeavor encompasses a quantitative analysis of both thermal compensation techniques, and gracefully entwines the results of a proof-of-principle experiment which vouchsafed the technical feasibility of each technique, thereby navigating a path toward mitigating challenges and augmenting the capabilities of gravitational wave detection in the sphere of laser interferometry.