Workshop on Grand Unified Theories: Phenomenology and Cosmology (GUTPC)

Monday, 8 April 2024 - Friday, 12 April 2024

Book of Abstracts

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Testing fundamental theories with global fits

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We all want to build fundamental theories and test them against experimental data. Testing our theories is made challenging, however, by the fact that our theories often have many unknown Lagrangian parameters and that the constraints come from numerous sophisticated experiments in collider physics, astrophysics and cosmology. Thus, exploring the parameter spaces of our models and correctly combining experimental constraints requires careful application of statistical principles and computational methods. In this talk, I describe the GAMBIT community and software framework for achieving these goals, and showcase results from recent global fits of fundamental theories.

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Phase transition catalyzed by primordial black holes

Authors: Zhenmin Zeng[1]; Zongkuan Guo[1]

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We investigate the first-order phase transition catalyzed by primordial black holes˜(PBHs) in the early Universe. We find that super-horizon curvature perturbations generated in this scenario lead to the production of gravitational waves when the scalar modes re-enter the horizon. If PBHs with masses about $10^{-13}M_{\odot}$ constitute all dark matter, the first-order electroweak phase transition catalyzed by PBHs can explain the gravitational wave signal observed by pulsar timing array collaborations without the overproduction of PBHs.

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Minimal SU(5) theory on the edge: the importance of being effective

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It is well known that the minimal renormalizable SU(5) grand unified theory is ruled out: it predicts same masses of down quarks and charged leptons, the gauge couplings do not unify and neutrinos are massless. We show here that all this can be cured simultaneously by the addition of higher-dimensional effective operators. However, the theory lives on the edge since the unification scale turns out as low as roughly 10^{14} GeV, threatening proton longevity. If the lower bound on the proton lifetime was to be increased by an order of magnitude, the usual desert in energies between the weak and unification scales would be populated.

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On the Standard Model quark/lepton masses in an SU(8) theory

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We describe the orgins of Standard Model quark/lepton masses and the CKM mixing pattern in an SU(8) theory through a set of d=5 operators induced by the gravitational effect.

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Overview of Proton Decay Search Experiments

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Grand Unified Theories (GUTs) generically predict direct transition processes between quarks and leptons, and searching for proton decay is one of the unique ways to directly test GUTs. For most of the proton (and neutron) decay modes, the current lifetime limits are set by the Super-Kamiokande (Super-K) experiment, whose detector is the world ' s largest underground water Cherenkov detector. Besides the Super-K experiment, a few underground experiments are planned to start their data-taking in this decade, Hyper-K in Japan, DUNE in the U.S., and JUNO in China. Hyper-K is also an underground water Cherenkov detector with roughly 8 times larger water fiducial mass than Super-K, while the DUNE detector is equipped with liquid argon with a mass of about 40 kton and the JUNO detector consists of a 20-kton liquid scintillator. This talk will the basic proton decay search principles, current experimental status, and future expected sensitivities in those experiments.

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Unification and Composite Asymmetric Dark Matter

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Asymmetric dark matter is one of alternative framework of dark matter to the weakly interacting massive particle framework, where its relic abundance is determined by the particle-antiparticle asymmetry. Once the dark matter asymmetry is originated from the same mechanism as the baryon asymmetry, the dark matter mass is predicted to be of GeV. Compositeness of asymmetric dark matter plays significant roles in inducing strong depletion of symmetric component of particle and antiparticle. Dimensional transmutation would provide a natural explanation of the dark matter mass in GeV, but it still remains a question why the gauge dynamics in the dark sector has confined at the similar scale as QCD. Considering a unification structure and mirror parity between the SM sector and dark sector, we provide an ultraviolet completion for the composite asymmetric dark matter framework. The unification framework provides key ingredients for the composite asymmetric dark matter, such as confinement in the dark sector similar to the QCD scale, a portal interaction sharing the generated asymmetry, and a portal interaction releasing enormous entropy in the dark sector. I also discuss the phenomenological consequence of this framework.

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Axion dark matter and the cosmic dipole problem

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There is increasing evidence suggesting a discrepancy between the cosmic dipole observed in the number count of distant galaxies and the one derived from the cosmic microwave background (CMB). In this study, we investigate the possibility that the cosmic dipole problem can be addressed by considering the QCD axion, a hypothetical particle that arises from the spontaneous breaking of the Peccei-Quinn symmetry and is postulated to constitute the dark matter in our Universe.

Plenary / **8**

Modular Grand Unification Theories

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Flavor symmetry and grand unified symmetry are powerful tools to address the flavor structure of quarks and leptons. It is appealing to combine flavor symmetry with grand unification theories. In modular flavor symmetry, the flavons are replaced by modular forms and thus the resulting models are very economic and predictive. In this talk, I shall discuss the grand unification theories with modular flavor symmetry, the predictions for the fermion masses and flavor mixing and the correlation with the baryon asymmetry of the Universe will be presented.

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Investigating the BNV dinucleon to dilepton decays in the EFT

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Baryon number violation (BNV) is well-motivated by the BSM physics. Usually, the $\Delta B = 1$ nucleon decay is predicted with the NP scale being pushed around the GUT scale unaccessible directly for the current collider experiments. However, there exist TeV scale NP scenarios in which the $\Delta B = 1$ processes are suppressed but that of the $\Delta B = 2$ are dominant. In this latter case, I will take an effective field theory approach to discuss the $\Delta B = \Delta L = -2$ dinucleon to dilepton decays in nuclei ($pp \to l^+l'^+$, $pn \to l^+\bar{\nu}'$, $nn \to \bar{\nu}\bar{\nu}'$).

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Susy breaking in a UV finite GUT

Renormalisable supersymmetric grand unified theories typically
employ large representations which lead to a perturbative Landau pole at energies soon above the unification scale. The UV limit may still make sense if the theory approaches a nonperturbative fixed point there. Although the RG flow cannot be followed, one can check various constraints which a consistent fixed point must satisfy. In the talk I will show how supersymmetry breaking influences the existence of fixed points and how close to reality is an SO(10) candidate for a susy GUT with consistent UV limit.

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Modular Flavor Symmetry in Heterotic E_6 GUT

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We discuss a common origin of four-dimensional flavor and CP symmetries in the context of heterotic string theory with standard embedding. We find that the flavor symmetries of fundamental and anti-fundamental representations of E_6 gauge group are governed by geometric symmetries of Calabi-Yau threefolds, i.e., the symplectic modular symmetry. Furthermore, the CP symmetry is identified with an outer automorphism of the symplectic modular group of Calabi-Yau threefolds.

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Modular invariance and the QCD theta angle

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I will discuss a novel solution to the strong CP problem based on modular invariance. The latter is inherent to toroidal compactifications in string theory. We show that anomaly-free modular symmetry allows for simple effective theories of flavour and CP where (i) the QCD θ-angle vanishes, (ii) the CKM phase is large, (iii) quark and lepton masses and mixings can be reproduced up to order one coefficients. We implement such a general paradigm in supersymmetry or supergravity, with modular forms or functions, with or without heavy coloured states.

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Exploring GUT origins of SMEFT operators

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In the precision frontier, effective field theories have been widely used to describe the new physics effects in a model independent way. It is intriguing to find ultraviolate (UV) theories that generate certain effective operators in the low energy regime, but the traditional way of integrating out heavy fields requires individual studies of UV models, which can be at odds with the bottom-up philosophy of effective field theories. In this report, we provide a purely bottom-up approach based on the j-basis analysis to explore the possible tree-level UV origins of higher dimensional effective operators, especially the baryon/lepton number violating ones. In particular, for vector resonances, we study their potential identity as gauge bosons in a Grand Unified Theory (GUT).

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Revisiting Metastable Cosmic String Breaking

Author: Satoshi Shirai[1]

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In this talk, I will discuss the decay of metastable cosmic strings. By moving beyond the conventional thin string approximation, we explore the dynamics of cosmic strings with finite sizes, addressing a critical gap in previous estimates. This approach yields a more reliable lower limit on the tunneling rate, challenging earlier assumptions. The significance of these findings is underscored by their potential connection to gravitational wave signals detected in pulsar timing experiments, offering new perspectives in the study of cosmic strings within the framework of grand unified theories.

Plenary / **15**

Yukawa coupling unification in SO(10) GUTs and the origin of Yukawa hierarchy of third-generation fermions

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In the SO(10) GUTs with or without supersymmetry, the Yukawa couplings of the third-generation fermions can be unified by employing renormalization group (RG) analysis, similar to the gauge couplings. In the considered models, Yukawa unification implies that different Yukawa couplings are generated from a single coupling in the UV through the decomposition of scalar and fermion representations of the GUT group. Thus, the Yukawa hierarchy emerges from the CG coefficient of decomposition of the GUT group and vacuum expectation values (vevs) of different scalars. As earlier research has already examined the possibility of realizing Yukawa unification in the supersymmetric context, in this talk, we will focus on a non-supersymmetric SO(10) model with an intermediate Pati-Salam symmetry, where both gauge and Yukawa unification can be achieved simultaneously. As an

explicit example, we will justify Yukawa unification in SO(10) originate from a single Yukawa coupling between fermion bidoublet $\mathbf{27} \times \mathbf{27}$ with a scalar multiplet $\mathbf{351'}$ decomposed as $\mathbf{10} + \overline{\mathbf{126}} + \ldots$ in an E_6 model. Taking into account some phenomenological features such as the proton decay and the absence of flavor-changing neutral currents (FCNCs) at tree-level, we derive constraints on the parameters of the low energy model, in particular on the ratio of the two Higgs doublets vevs $\tan\beta$.

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Gravitational Waves from Early Universe Symmetry Breakings

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I will talk about the gravitational waves that can be produced from early universe symmetry breakings such as phase transitions and cosmic strings, which can help
reveal more information GUT and others. The focus is partially on theory development and partially on experimental status.

Plenary / **17**

A phenomenological study of SU(5) with Type-I+III seesaw

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We build a SU(5) model with type-I+III seesaw by introducing a fermion field $\mathbf{24}_F$. Under the condition of gauge coupling unification at two-loop level, we scan the parameter space of new particles. We find M_Σ should be light to increase the scale of $M_{\rm GUT}$. Three new particles satisfy the following mass hierarchy $M_\Sigma < M_{Q_8} < M_Q$. Taking into account current limits and future targets of proton decay experiments, we give a parameter space analysis by parameterizing the flavor mixing part in proton decay formula. In conclusion, there is hope te test this model in future proton decay experiments.

Plenary / **18**

Journey Towards Asymptotically Safe GUT

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Solving QFT is key to a more profound understanding of present and next generation of theories of Nature. The large number-of-flavour 1/Nf expansion has been a useful tool to go beyond Feynman diagrammatic computations. In this talk, I will discuss not only the theoretical perspectives of this method but, in particular, also its important applications in particle physics phenomenology. I will show that by using the large number-of-flavour 1/Nf summation techniques, the Standard Model can achieve an interacting ultraviolet fixed point to be asymptotically safe, addressing the famous

UV Landau Pole problem. We have also applied this method to Grand Unified Theory to explore the safety of Pati-Salam model and Trinification model.

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The Three-Family N=1 Supersymmetric Pati-Salam Models from Type IIA String Theory on Tˆ6/(Z_2 ×Z_2) Orientifold with Intersecting D6-Branes

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We provide a systematic construction of three-family N=1 supersymmetric Pati-Salam models from Type IIA orientifolds on Tˆ6/(Z_2 × Z_2) with intersecting D6-branes. All the gauge symmetries SU(4)*C × SU(2)_L × SU(2)_R arise from the stacks of D6-branes with U(n) gauge symmetries, while the hidden sector is specified by USp(n) D6-branes. The Pati-Salam gauge symmetry can be broken down to the SU(3)_C × SU(2)_L × U(1)*{B-L} × U(1)*{I*{3R}} via D6-brane splittings, and further down to the Standard Model (SM) via the D- and F-flatness preserving Higgs mechanism from massless open string states in a N=2 subsector. In addition, we propose a systematic method to construct all the possible three-family N=1 supersymmetric Pati-Salam models by solving all the common solutions for the RR tadpole cancellation conditions, N=1 supersymmetry conditions, and three generation conditions with deterministic algorithm. We show that there are only 33 independent models with different gauge coupling relations at string scale after modding out equivalent relations. In particular, there is one and only one independent model which has gauge coupling unification. Moreover, we can decouple the exotic particles in these models, realize the gauge coupling relation at string scale, and explain the SM fermion masses and mixings, etc.

Plenary / **20**

F-Theory GUTs: Prospects and Challenges

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This talk focuses on the construction of F-theory GUTs and their low energy implications. Alternative mechanisms of symmetry breaking will be described in prototype examples. Some phenomenological issues, including the computation of Yukawa couplings and the origin of discrete symmetries in this framework will be discussed.

Plenary / **21**

From first order phase transitions to Gravitational waves

Gravitational waves can be produced from first order cosmological phase transitions that occur early in the Universe. I will show exciting recent results showing that i) some scenarios with grand unification may already be constrained by LIGO data because they imply a first order phase transition that is too strong and ii) a possible signal of a stochastic gravitational wave background from pulsar timing array experiments. These results mean that we have now entered an era where robust predictions of the gravitational wave spectra from first order phase transitions are vital. Based on a recent invited review, Prog.Part.Nucl.Phys. 135 (2024) 104094, and several related works, I will discuss various subtle issues in the prediction of gravitational wave spectra from first order phase

transitions that can significantly impact the predictions and review the current status of predictions for gravitational waves from first order phase transitions. In particular I will discuss criteria for determining if a phase transition completes, and the dependence of gravitational wave predictions on the transition temperature and a variety of standard approximations.

Plenary / **22**

Dark matter from sterile-sterile neutrino mixing

I will discuss the possibility that a heavy, metastable, dark right-handed neutrino with mass in the TeV-PeV range can play the role of (cold) dark matter particle. The right abundance would be produced by the Higgs induced mixing with a seesaw right-handed neutrino (RHINO model), i.e., by sterile-sterile neutrino mixing. Such a mixing would necessarily require a further extension of the minimal seesaw mechanism and can be described, effectively, by a dimension-five operator. The same mixing would also necessarily induce dark neutrino instability with lifetimes that can be much longer than the age of the universe and can escape current constraints from neutrino telescopes. Alternatively, a contribution to very high energy neutrino flux produced by dark neutrino decays could explain an anomalous excess at 100 TeV energies recently confirmed by the IceCube collaboration. Finally, I will discuss a simple UV complete model where the mediator is given by a massive fermion. Intriguingly, it comes out that the favoured scale of new physics for RHINO to satisfy the dark matter requirements coincides with the grand-unified scale: an intriguing grand-unified RHINO miracle.

Plenary / **24**

Proton Decay and SU(5) Grand Unification

This talk will be an overview of the status of proton decay in SU(5) grand unification. After a brief history/review of grand unification and proton decay experiments, I will focus on the phenomenological impact of these coming proton decay experiments on a broad range of models. I will focus initially on several supersymmetric models such as minimal SU(5) (with various SUSY breaking scenarios), Missing Pattern Models, and Flipped SU(5) models. I will comment on how their proton decay signatures differ. Then, I will spend some time discussing what types of non-supersymmetric models are viable. I will finish by discussing a motivated grand unified theory which can explain the W-boson anomaly.

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Cosmic superstrings vs gauge strings: gravitational wave signals

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Theory and phenomenology of Flavoured Trinification

Given the tremendous phenomenological success of the Standard Model (SM) framework, it becomes increasingly important to understand to what extent its specific structure dynamically emerges from unification principles. In this talk, I will discuss an anomaly-free supersymmetric (SUSY) Grand Unification model based upon gauge trinification SU(3)ˆ3 symmetry and a local SU(2) x U(1) family symmetry, with particle spectra and gauge symmetries inspired by a possible reduction pattern E_8 -> E_6 x SU(2) x U(1), with subsequent E_6 -> SU(3)ˆ3 symmetry breaking step. In this framework, higher-dimensional operators of E_6 induce the threshold corrections in the gauge and Yukawa interactions leading, in particular, to only two distinct Yukawa couplings in the fundamental sector of the resulting SU(3)ˆ3 x SU(2) x U(1) Lagrangian. Among the appealing features emergent in this framework are the Higgs-matter unification and a unique minimal three Higgs doublet scalar sector at the electroweak scale as well as tree-level hierarchies in the light fermion spectra consistent with those observed in nature. In addition, I will overview interesting phenomenological prospects for New Physics searches at particle colliders and for neutrino physics.

Plenary / **28**

Proton Decay and Gravitational Waves as Complementary Tests of Grand Unification

I will discuss how proton decay, combined with gravitational waves, can be used to test Grand Unified Theories (GUTs). In particular, proton decay searches by large multipurpose neutrino experiments such as DUNE, Hyper-Kamiokande, and JUNO will either discover proton decay or further push the symmetry-breaking scale above 10ˆ16 GeV. Another possible observational consequence of GUTs is the formation of a cosmic string network produced during the breaking of the GUT to the Standard Model gauge group, which can produce a stochastic background of gravitational waves. Several gravitational wave detectors will be sensitive to this over a wide frequency range. I will demonstrate the non-trivial complementarity between the observation of proton decay and gravitational waves produced from cosmic strings in determining SO(10) GUT breaking chains and their compatibility with leptogenesis as a means of producing the observed matter-antimatter asymmetry.

Plenary / **29**

Hyperunified Theory

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Phenomenological tests of supersymmetric SO(10) grand unified theories

I will extend the discussion about SO(10) GUT phenomenology to the supersymmetric (SUSY) version. As the RG running is different in SUSY SO(10), the intermediate scale can be close to the GUT scale, providing a natural framework for metastable strings, which produce gravitational wave signal that is consistent with the new results from Pulsar Timing Arrays (PTAs). Moreover, the kaonic proton decay predicted by SUSY GUTs can be tested by the upcoming JUNO experiment. I will present how proton decay and gravitational wave can be used to constrain the parameters in a realistic SUSY SO(10), where the fermion mass and mixing are all considered.