The 2023 Shanghai Symposium on Particle Physics and Cosmology: Phase Transitions, Gravitational Waves, and Colliders (SPCS 2023)

Friday, 22 September 2023 - Sunday, 24 September 2023

Tsung-Dao Lee Institute

Book of Abstracts

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Gravitational waves from Dark Phase Transitions at Strong Coupling

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In this talk, we demonstrate how to predict the gravitational wave spectra of Strongly coupled QFTs using holography and lattice data input for a pure SU(N) Yang-Mills theory with small uncertainties. We will elaborate on how we obtain an effective potential using holography with the free energy landscape approach and formulate an effective action. Once the effective action is in our grasp, we will use this to study bubble nucleation to predict the gravitational wave spectra. Furthermore, we will discuss how the bubble wall velocity computations can be made in steady-state configurations using holographic techniques by computations of the plasma friction force.

Parallel 2 / **2**

Cosmic Stasis from Primordial-Black-Hole Evaporation and Its Phenomenological Implications

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Cosmic stasis is a phenomenon in which the abundances of multiple cosmological energy components —components such as matter, radiation, or vacuum energy —remain effectively constant despite the expansion of the universe. One mechanism which can give rise to an extended period of cosmic stasis is the evaporation of a population of primordial black holes (PBHs). In this talk, I review how PBH evaporation can lead to a stasis epoch and examine the observational consequences of such a modification to the cosmic expansion history. These include implications for inflationary observables, for the stochastic gravitational-wave background, and for the production of dark matter and dark radiation.

Saturday 3 / **3**

Perturbative EFT expansions for cosmological phase transitions

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Gravitational waves (GW) from cosmological phase transitions bear huge discovery potential and can be probed by planned future space-based experiments. Complementary to current and future collider experiments, such GW signatures can offer a powerful probe for beyond the Standard Model physics. Predictions for stochastic GW spectrum of a cosmological origin are often plagued by large theoretical uncertaintities related to poor understanding of phase transition thermodynamics. In this talk, I present novel reformulation to the perturbative analysis of equilibrium thermodynamics for generic cosmological phase transitions in terms of effective field theory (EFT) expansions. These EFT expansions resolve all theoretical inconsistencies that have plagued previous studies (spurious infrared divergences, imaginary parts, gauge dependence and renormalisation scale dependence). Moreover, EFT expansions provide a numerically inexpensive method to determine thermodynamics, and significantly improve agreement with the non-perturbative lattice simulations.

Saturday 3 / 4

From first order phase transitions to gravitational waves

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Gravitational waves have now emerged as an important experimental test of first-order phase transitions in the early Universe and we have entered an era in which predictions from particle physics models can be compared to existing gravitational wave data. In this two-part talk, we review the path from a particle physics model that can admit first-order cosmological phase transitions to predictions of the gravitational wave spectra. We discuss in particular the subtleties and challenges that can affect the robustness of the predictions and emphasise effects that lead to significant uncertainties in the predictions.

Parallel 2 / 5

Stochastic gravitational wave background: birth from axionic string-wall death

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This talk is based on the paper arXiv: 2307.08185. I will introduce a new source of stochastic gravitational wave background (SGWB) from the final collapse of a string-wall network. In the context of $N_{\rm DW} = 1$ axionic string-wall network, the final collapse of walls bounded by strings can release gravitational waves (GWs). This source is typically considered negligible due to its subdominance compared to GW emissions throughout the longterm evolution in the scaling regime. However, in some cases, a network can be driven outside of horizon by inflation and later re-enter horizon. Then, the network’s final collapse after re-entering horzion becomes the dominant GW source and therefore cannot be neglected. The caculation of the corresponding GW spectrum suggests it could potentially explain the nano-Hertz SGWB signal that has been possibly detected by various Pulsar Timing Array experiments. In addition, with different parameter choices, the resultant GWs could be probed by various GW interferometry experiments.

Friday 3 / 6

Gravitational waves from phase transitions during inflation

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The large excursion of the inflaton may trigger phase transitions in the spectator sector that couples to the inflaton field. Such phase transitions can produce gravitational waves. In this talk, I will discuss the properties of the gravitational waves produced in this way. I will discuss both first- and second-order phase transitions. The phase transitions during inflation can also produce large curvature perturbations, which will lead to secondary gravitational waves after inflation. I will show that it is possible to use the secondary gravitational waves produced in this way to explain the gravitational wave signals observed recently by pulsar timing array collaborations.

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Collider tests of nanohertz gravitational waves from minimal dark phase transition

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Recently, compelling evidence of nanohertz gravitational waves is indicated by the pulsar timing array collaborations. In this talk, I will present an MeV-scale first-order phase transition from a minimal dark sector to explain the gravitation waves, with a focus on the collider tests via a minimal Higgs portal. I will demonstrate that to explain the observed gravitational waves, the Higgs portal coupling should be so sizable that it can be probed through Higgs invisible decay at the LHC and future lepton colliders such as CEPC, ILC, and FCC-ee. It opens up a promising avenue to uncover the physical origin of the nanohertz GWs via colliders and to hear and see the minimal dark.

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Solitons and Primordial black holes from a boiling Universe

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Higgsless simulations of first-order phase transitions and gravitational wave production

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Gravitational waves offer a unique probe to the early Universe. A particularly interesting scenario is that of a first-order phase transition, in which bubbles of true vacuum nucleate, expand, and collide, involving the dynamics of surrounding plasma particles. In this talk, we introduce the Higgsless scheme for numerical simulations of sound waves and the resulting gravitational wave production in first-order phase transitions proposed in 2010.00971 and 2209.04369. This scheme integrates out the dynamics of the Higgs field, and thus avoids contamination from the thickness of the scalar walls.

Saturday 4 / 10

Hydrodynamic perspectives on cosmological first-order phase transitions

Authors: Jun-Chen Wang[1]; Rong-Gen Cai[2]; Shao-Jiang Wang[3]; Zi-Yan Yuwen[2]; Li Li[2]

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The detection of stochastic gravitational wave backgrounds from cosmological first-order phase transitions (FOPT) is a promising probe for new physics beyond the standard model of particle physics. However, the terminal wall velocity as one of the key parameters has been largely left undetermined thanks to its intimate relation to the non-equilibrium nature of FOPT near the bubble wall. In this talk, I will first introduce the general effective equation of motion of bubble wall expansion during both accelerating expansion and asymptotic expansion stages, then I will introduce the general back-reaction from plasma against expansion followed by a particular focus on the strong-coupling limit, and next, I will introduce a new method to identify the terminal wall velocity from hydrodynamics. In the end, I will introduce a new analytic estimation of the sound-wave spectrum before bubble percolations as well as recent developments on sound waves.

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Hydrodynamic sound shell model and bubble wall velocity

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For a cosmological first-order phase transition in the early Universe, the associated stochastic gravitational wave background is usually dominated by sound waves from plasma fluid motions, which have been analytically modeled as a random superposition of freely propagating sound shells but with the force by the scalar field that produces the self-similar profile removed. Recently, we proposed a new analytic sound shell model by focusing on the forced propagating contribution from the initial collision stage of sound shells while the moving bubble walls still maintain their self-similar profiles. We reproduce the causal k^3 scaling in the infrared consistent with numerical simulations, and also recover the broad dome in the power spectrum first observed in numerical simulations. We also provided a new method to estimate the bubble wall velocity from the junction condition given by the conservation of particle number density flow.

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First Order Phase Transitions: How, When and Why?

Author: Andrea Addazi[1]

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We discuss several possible scenarios for first order phase transitions (FOPTs) in early Universe which can be tested from gravitational waves interferometers and pulsar timing radio-astronomy. Many FOPTs are inspired by Dark Matter, Neutrino mass, baryon/lepton violations, baryogengesis and Grand Unification Theories.

We will not only discuss first electroweak phase transitions but also FOPTs at higher and lower energies.

Concerning low energy phase transitions, recent NANOGrav 15yrs results may provide a hint of FOPTs in the Dark Matter sector.

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Detecting gravitational waves in the space: The Taiji project

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LIGO's detection of gravitational wave events has entered a "new normal", and the era of gravitational wave astronomy has arrived. Constructing a gravitational wave detector with a longer arm length in space can detect low-frequency gravitational waves in the millihertz band. In this talk, I will introduce the Taiji project —- the space-borne gravitational wave detector by China. Its targets are mainly supermassive black holes and primordial gravitational waves in the early universe. The report will give an overview of the Taiji project, and then discuss in detail the scientific issues concerned by low-frequency gravitational wave observations. It mainly focuses on discussing the standard whistle of cosmology, the physical properties of black holes, and the testing of gravitational theories.

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Higgs physics highlights from the CMS experiment

Author: Chen Zhou[1]

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This talk will highlight some recent Higgs physics results from the CMS experiment.

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Confinement Phase Transition with Quasi-paticle model and its Gravitational wave signal

Author: Jiang Zhu[1]

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It is challenging to build a model that can correctly and unifiedly account for the deconfinement phase transition and thermodynamics of the hot $SU(N)$ pure Yang-Mills (PYM) system, for any N. In this article, we slightly generalize the massive PYM model to the situation with a quasigluon mass $M_g(T)$ varying with temperature, inspired by the quasigluon model. In such a framework, we can acquire an effective potential for the temporal gauge field background by perturbative calculation, rather than adding by hand. The resulting potential works well to describe the behavior of the hot PYM system for all N, via the single parameter $M_g(T)$. Moreover, under the assumption of unified eigenvalue distribution, the $M_g(T)$ fitted by machine learning is found to follow N-universality. We will also use this model to discuss the gravitational wave from the confinement phase transition which is generated by possible pure- Yang-Mills dark sector.

Sunday 2 / 19

DiHiggs combination at the ATLAS experiment

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This talk will present the latest diHiggs combination results (including both resonant and non-resonant) based on the full Run 2 dataset at the at the ATLAS experiment.

Saturday 4 / 20

First principles determination of bubble wall velocity and local thermal equilibrium approximation

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I will briefly review the fluid equations needed to compute the wall velocity from first principles. As a concrete example, I will apply these equations to the singlet scalar extension of the Standard Model. The solutions obtained can naturally be classified as deflagration/hybrid walls ($v_w \sim c_s$) or ultrarelativistic detonations. In the second part, I will explain how this calculation can be significantly simplified when local thermal equilibrium (LTE) is maintained in the plasma. Using this LTE assumption, the fluid equations can be reexpressed in terms of only four parameters that completely characterize a particle physics model. Finally, I will discuss the properties of their solutions and compute the kinetic energy fraction which is essential for predicting the gravitational wave spectrum produced during the phase transition.

Parallel 1 / **21**

Electroweak sphalerons, scalar multiplets, and symmetry breaking patterns

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In this study, we present a comprehensive analysis of the electroweak sphaleron formalism and its application to electroweak phase transition (EWPT) patterns in extensions of the Standard Model scalar sector with electroweak multiplets. We offer an equivalence proof for different choices for the form of sphaleron configurations; construct the previously unestablished high-dimensional SU(2) sphaleron transformation matrix; investigate the scalar multiplet topology map and baryon number charge relation;
and revisit the required boundary conditions needed for solving the sphaleron field equations. We then scrutinize the leading order sphaleron dynamics in the context of a multi-step EWPT. We showcase two distinct analytical approaches for extending the SU(2) scalar multiplet to the standard model (SM) under differing EWPT scenarios, and perform an explicit calculation of the sphaleron energy using a septuplet example. In the context of a single-step EWPT leading to a mixed phase, we find that the additional multiplet's contribution to the sphaleron energy is negligible, primarily due to the prevailing constraint imposed by the ρ parameter. Conversely, in a two-step EWPT scenario, the sphaleron energy can achieve significantly high values during the initial phase, thereby markedly preserving baryon asymmetry if the universe undergoes a first-order EWPT. In both cases, we delineate the relationship between the sphaleron energy and the parameters relevant to dark matter phenomenology.

Sunday 4 / **22**

Phase Transition and Gravitational Wave in Strongly Coupled Dark Sectors

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We go beyond the state-of-the-art by combining first principal lattice results and effective field theory approaches as Polyakov Loop model to explore the non-perturbative dark deconfinement-confinement phase transition and the generation of gravitational-waves in a dark Yang-Mills theory. We further include fermions with different representations in the dark sector. Employing the Polyakov-Nambu-Jona-Lasinio (PNJL) model, we discover that the relevant gravitational wave signatures are highly dependent on the various representations. We also find a remarkable interplay

between the deconfinement-confinement and chiral phase transitions. In both scenarios, the future Big Bang Observer and DECIGO experiment have a higher chance to detect the gravitational wave signals. Most recently, via Quark-Meson model, we find the phase transitions and thus gravitational wave signals will be significantly enhanced when the system is near conformal. In addition, we find that this effective field theory approach can be implemented to study the glueball dark matter production mechanism and for the first time provide a solid prediction of glueball dark matter abundance. Our prediction is an order of magnitude smaller than the existing glueball abundance results in the literature.

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Have pulsar timing array methods detected a cosmological phase transition?

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We show [1] that the recent detection of a gravitational wave (GW) background reported by various pulsar timing array (PTA) collaborations including NANOGrav-15yr, PPTA, EPTA, and CPTA can be explained in terms of first order phase transitions (FOPTs) from dark sector models (DSM). Specifically, we explore a model for first order phase transitions that involves the majoron, a Nambu-Goldstone boson that is emerging from the spontaneous symmetry breaking of a U(1)L or U(1)B−L symmetry. We show how the predicted GW power spectrum, with a realistic choice of the FOPT parameters, is consistent with 1-σ deviations from the estimated parameters of the background detected by the PTA collaborations.

[1] A. Addazi, Y.F. Cai, A. Marciano and L. Visinelli, [arXiv:2306.17205 [astro-ph.CO]].

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Detecting High-Frequency Gravitational Waves with Astronomical Tools

Author: Tao Liu[1]

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TBD

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Extended Scalar Sectors and Baryogenesis: The CP story

Author: Jose Miguel No[1]

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I will give a personal perspective on the possibility of achieving EW baryogenesis in extensions of the SM, based on enhancing the CP violating sources in the early Universe as compared to the ones constrained by EDMs at present times.

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Collider probes of the Electroweak phase transition for scalar extended models

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The detection of the gravitational wave provides new opportunities to probe the evolution of the early Universe. On the other hand, the current and future collider experiments will also play important roles in probe new physics. One of the connections ties on the Electroweak phase transition associated with the scalar sector. The modification from the extended scalar sector will be important to achieve strong 1st order phase transition which can hence be probed through its gravitational wave signal. However, such modification will also be reflected in collider searches. In this talk, I will briefly talk, based on my previous works, about the collider coverage of the EWPT and its complementarity to GW probes.

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Triple Higgs coupling, GWs and PBH as probes of 1st order EW Phase Transition

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In this talk, I would like to discuss various phenomenological consequences of first order EW phase transition, which is required for successful EW baryogenesis scenarios. Using the NaHEFT which can describe non-decoupling property of new physics beyond the SM, we evaluate parameter regions in which conditions of strongly 1st order EW Phase Transition and completion of the phase transition are satisfied. Then, we discuss its prediction on the triple Higgs coupling, GW and PBH observations. We show that, in addition to the triple Higgs coupling and gravitational waves, PBH produced at the EW phase transition can also constrain some parameter region of the EFT.

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Bubble Expansion at Strong Coupling & General Backreaction Force

Authors: Jun-Chen Wang[1]; Shao-Jiang Wang[2]; Zi-Yan Yuwen[3]

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In this report, we show our recent two works. In one of the works, we focus on the backreaction force and point out that besides the friction force, the thermal force should also be taken into consideration. Besides the plasma near the wall, the sound shell and the shock front will also contribute to the backreaction force. In the other work, we derive the test formula for the holographic simulations and get the simulation results analytically. For both of our works, we focus on the system beyond the bag equation of state.

Parallel 1 / **30**

A new approach to rescue the trapped vacuum

Author: Dongdong Wei[1]

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The first-order phase transition is one of the promising scenarios as it can explain the observed matter-antimatter asymmetry of the early universe. In most cases, the transition proceeds through the nucleation of bubbles of the true vacuum. If the nucleation rate is highly suppressed, then vacuum trapping may occur so that the transition ceases. In this work, we will discuss a new approach where the trapped vacuum can rescued to realize the EW symmetry breaking and also produce the gravitational wave signals.

Parallel 2 / **31**

Instability of the Electroweak Vacuum in Starobinsky Inflation

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We study the stability of the electroweak vacuum during and after the Starobinsky inflation, assuming the existence of the non-minimal Higgs coupling to the Ricci scalar. In the Starobinsky inflation, there exists R2 term (with R being the Ricci scalar), which modifies the evolution equation of the Higgs field. We consider the case that the non-minimal coupling is sizable so that the quantum fluctuation of the Higgs field is suppressed and that the Higgs amplitude is settled near the origin during the inflation. In such a case, the Higgs amplitude may be amplified in the preheating epoch after inflation because of the parametric resonance due to the non-minimal coupling. We perform a detailed analysis of the evolution of the Higgs field in the preheating epoch by a numerical lattice simulation and derive an upper bound on the non-minimal coupling constant ξ in order to realize the electroweak vacuum in the present universe. We find that the upper bound on ξ in the Starobinsky inflation model is more stringent than that in conventional inflation models without the R2 term.

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First Order Phase Transitions: How, When and Why?

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Constraining the Cosmological Phase Transition by Real Data

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Taiji and milli-Hz Gravitational Wave Astronomy

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Ali CMB Polarization Telescope

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Search for Di-Higgs resonances in the ATLAS experiment

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HH searches with VBF and VHH at the CMS experiment

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Probing Electroweak Phase Transition in the Singlet Standard Model at the LHC

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New approaches to false vacuum decay and produced gravitational waves

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Electroweak phase transition patterns: an effective perspective

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cxSM Collider/EWPT

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From first order phase transitions to gravitational waves

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Anatomy of the electroweak phase transition for dark sector induced baryogenesis

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Non-resonant di-Higgs at ATLAS

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H combination at the CMS experiment

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Collider probes of the Electroweak phase transition for scalar extended models

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Topological Defects and GWs

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Dark photon/EWPT

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EWPT/GW/2HDM

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Conference Close Out

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Addressing the Gravitational Wave - Collider Inverse Problem

Authors: Leon S.˜Friedrich[1]; Michael Ramsey-MusolfN[one]; Tuomas Tenkanen[2]; Van Que Tran[1]

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This talk is based on arXiv:2203.05889. Next generations of gravitational wave and future collider detectors can probe beyond the Standard Model theories that predict a strong first order electroweak phase transition. A combination of these two signals could be used to determine BSM scenarios and to measure relevant model parameters. In this talk, I will show a roadmap for addressing this gravitational wave –collider inverse problem. Our study relies on a combination of state-of-the-art perturbative treatments for thermodynamics and results from non-perturbative simulations. For illustration, we apply our methods to a real scalar triplet extension of the Standard Model.

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Status and Experiments of the CEPC

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Summary of the LHC Anomaly Workshop

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Welcome

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Parallel 1 / **58**

Lattice study of singlet-assisted electroweak phase transition

In this study, we use lattice to reveal nonperturbative information of the electroweak phase transition in the real-singlet extension of the Standard Model, based on the 2-loop 3D EFT framework.
Importantly, the new information is that the lattice determines the true nature of the electroweak phase transition, capable to identify it as the first order type or not, an important qualitative behavior to which perturbation theory is blind. In scenarios where perturbation theory implies a weakly first order phase transition, lattice is more reliable than the perturbation theory. In this regime, the symmetry-breaking transition may be crossover rather than a true phase transition. On the other hand, for strong transitions, both methods yield quantitatively close results, particularly when 2-loop perturbation theory is used.
This nonperturbative framework holds potential for other Higgs-sector extensions of the SM. Besides, by holding two powerful tools, 2-loop perturbation scanning and lattice, we will explore associated phenomenology in the future.

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Gravitational Waves Produced by Domain Walls During Inflation