QCD Vacuum Structure and Confinement

Monday 26 August 2024 - Friday 30 August 2024

Book of Abstracts

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Were there any anomalies in the gluon jets in ALEPH?

Author: Inkyu Park[1]

[1] *University of Seoul, Department of Physics (KR)*

Corresponding Author: inkyu.park@cern.ch

According to the Abelian decomposition of QCD, there is a theoretical prediction that gluons can be classified into two types, each exhibiting distinct experimental signatures. The optimal setting for experimental verification of this theory is a clean environment such as the LEP, rather than the LHC. We have investigated whether there were any anomalies observed already in the gluon jets recorded in the ALEPH experiment and revisited the analyses with the archived ALEPH data. In this presentation, we will show our latest updates on our study on the gluon jet properties in ALEPH.

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Quantum Solution of Classical Turbulence

Author: Alexander Migdal[1]

[1] *Institute for Advanced Study, Princeton*

Corresponding Author: sasha.migdal@gmail.com

Abstract. I will present a recent advancement that transforms the problem of decaying turbulence in the Navier-Stokes equations in $3+1$ dimensions into a Number Theory challenge: finding the statistical limit of the Euler ensemble. We redefine this ensemble as a Markov chain, establishing its equivalence to the quantum statistical theory of N fermions on a ring, interacting with an external field associated with random fractions of π. Analyzing this theory in the turbulent limit, where $N \to \infty$ and $\nu \to 0$, we discover the solution as a complex trajectory (instanton) that acts as a saddle point in the path integral over these fermions' density.

By computing the contribution of this instanton to the vorticity correlation function, we derive an analytic formula for the observable energy spectrum—a complete solution of decaying turbulence derived entirely from first principles without the need for approximations or fitted dimensionless parameters. Our analysis reveals the full spectrum of critical indexes in the velocity correlation function in coordinate space, determined by the poles of the Mellin transform, which we prove to be a meromorphic function. Real and complex poles are identified, with the complex poles reflecting dissipation and uniquely determined by the famous complex zeros of the Riemann zeta function.

Significantly, the theoretical predictions for the energy spectrum, energy decay rate, and the velocity correlation in the inertial range closely match the results from grid turbulence experiments and recent DNS within data errors $\sim 2\%$.

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Landscape of Yang Mills vacuum fields and condensation of magnetic fluxes in QCD

Author: George Savvidy[1]

[1] *Nat. Cent. for Sci. Res. Demokritos (GR)*

Abstract. The moduli space of covariantly constant gauge fields is infinite-dimensional and describes non-perturbative solutions of the Yang-Mills equation of superposed chromomagnetic flux tubes (vortices) of opposite magnetic charges. These gauge field configurations are stretched along the potential valleys of a constant energy density and are separated by potential barriers between classically degenerate vacua that are forming a complicated potential landscape of the QCD vacuum. It is suggested that the solutions describe the condensate of dense chromomagnetic vortices representing a dual analog of the Cooper pairs condensate in a superconductor. The solutions represent exact non-perturbative solutions of the YM equation in the background chromomagnetic field.

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Lessons from Quantum Strings for Quantum Gravity

Author: Yuri Makeenko[1]

[1] *Niels Bohr Institute*

I consider a generalization of the Liouville action which corresponds to the Nambu-Goto string like the usual Liouville action corresponds to the Polyakov string. The two differ by higher-derivative terms which are negligible classically but revive quantumly. I exactly solve the four-derivative case and argue that conformal symmetry of the Nambu-Goto string in 4 dimensions is described by the (4,3) minimal model.

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Explorations in Metric-Affine Quadratic Gravity

Author: Kyriakos Tamvakis[1]

[1] *University of Ioannina*

Corresponding Author: tamvakis@uoi.gr

Abstract: It is a common assumption that well below the Planck scale gravity can be treated classically in the framework of General Relativity. Nevertheless, the quantum interactions of gravitating matter fields are expected to generate modifications in the Einstein-Hilbert action. Such modifications are non-minimal couplings of scalar fields to curvature or quadratic curvature terms. It has been known that in the framework of the Einstein- Hilbert action the standard (metric) formulation is entirely equivalent to the Palatini (or metric-affine) formulation in which the connection is an independent dynamical variable in addition to the metric. Nevertheless, in the presence of the above non-minimal terms the two formulations yield different theories, possibly with additional gravitational degrees of freedom. We consider metric-affine gravity coupled to scalar fields in the presence of the above non-minimal terms, derive the equivalent metric theory and its resulting particle content and discuss applications to inflation.

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Weyl-invariant Einstein-Cartan gravity: unifying the strong CP and hierarchy puzzles

Author: Mikhail Shaposhnikov[1]

[1] *École Spéciale de Lausanne*

Corresponding Author: mikhail.shaposhnikov@epfl.ch

Abstract. It is well-known since the works of Utiyama and Kibble that the gravitational force can be obtained by gauging the Lorentz group, which puts gravity on the same footing as the Standard Model fields. The resulting theory - Einstein-Cartan gravity - happens to be very interesting. I will overview the construction of this theory and discuss its applications in particle physics and cosmology. In particular, the minimal Weyl-invariant Einstein-Cartan gravity in combination with the Standard Model of particle physics contains just one extra scalar degree of freedom (in addition to the graviton and the Standard Model fields) with the properties of an axion-like particle which can solve the strong CP-problem. The smallness of this particle's mass as well as of the cosmological constant is ensured by tiny values of the gauge coupling constants of the local Lorentz group. The tree value of the Higgs boson mass and that of Majorana leptons (if added to the Standard Model to solve the neutrino mass, baryogenesis and dark matter problems) are very small or vanishing, opening the possibility of their computability in terms of the fundamental parameters of the theory due to nonperturbative effects.

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On calculating the mass-gap in Yang-Mills Theory

Author: Paul Romatschke[1]

[1] *University of Colorado, Boulder*

Abstract: The existence and mass-gap of Yang-Mills theory in 3+1 dimensions is an open Millennium Prize problem. In this lecture, I point out the curious similarities between the SU(2) mass gap and the superfluid gap in non-relativistic atomic systems when using an exact mathematical rewriting of the Yang-Mills Lagrangian. This may (or may not) constitute a new route towards calculating the mass-gap in Yang-Mills theory.

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Timecrystalline vortices, anyons and the Poincaré index formula

Author: Antti Niemi[1]

[1] *Nordic Institute for Theoretical Physics*

I start by an update of vortices, as described by the Gross-Pitaevskii (GP) equation, explaining why there is room for new phenomena. First I describe what a time crystal is in Hamiltonian context. Then, I show that minimal energy solutions of GP equation behave like a time crystal. Furthermore, I show that as a consequence vortices of GP equation have anyonic exchange. I conclude with a topological analysis of multi-vortex systems and their Kosterlitz-Thouless transition, using the Poincaré index formula. At the end, I comment on three dimensional extensions such as closed and possibly knotted vortex lines.

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Cosmological Constant and Renormalization

Author: Vincenzo Branchina[1]

[1] *University of Catania*

Corresponding Author: vincenzo.branchina@ct.infn.it

Abstract: According to the recently proposed dark dimension (DD) scenario, we might well live in a 5D universe with one compact extra dimension, whose mesoscopic (micrometer) size is dictated by the measured value of the cosmological constant. Considering the contributions to the vacuum energy from the Standard Model (that lives on a 4D-brane) and from the bulk, in the talk I discuss different aspects of this proposal, and investigate on the viability of the scenario .

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Cosmology of composite dynamics: dark matter, phase transitions and gravitational waves

Author: Roman Pasechnik[1]

[1] *Lund University*

Abstract:In this talk, I briefly overview recent progress in strong coupling dynamics at finite temperatures and its cosmological implications in SU(N) gauge theories, with and without fermions. In a confining pure Yang-Mills theory of dark sector, the scalar glueballs are considered as possible candidates for Dark Matter. To predict the relic abundance of glueballs for the various gauge groups and scenarios of thermalisation of the dark gluon gas, we employ a thermal effective theory that accounts for the strong-coupling dynamics in agreement with lattice simulations. In a QCD-like theory with N_f flavours, the Polyakov-loop Improved Linear Sigma Model in the Cornwall-Jackiw-Tomboulis formulation is employed to investigate the chiral phase transition in regimes that can mimic QCD-like theories incorporating in addition composite dynamics associated with the effects of confinement-deconfinement phase transition. We show that strong first-order phase transitions occur for weak effective couplings of the composite sector leading to gravitational-wave signals potentially detectable at future experimental facilities.

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Abelian Decomposition of QCD and Two Types of Gluons

Author: Yongmin Cho[1]

[1] *Seoul National University*

Corresponding Author: ymcho0416@gmail.com

We review the Abelian decomposition of QCD and discuss the physical implications of the decomposition. The Abelian decomposition decomposes the gluon potential to the restricted part which contains the non-topological Maxwellian Abelian potential which describes the color neutral neurons and the topological Diracian potential which describes the non-Abelian monopole, and the valence part which describes the colored chromons. It allows us to calculate the QCD effective potential gauge independently and demonstrate the monopole condensation as the physical vacuum of QCD. It allows us to decompose the QCD Feynman diagrams in such a way that the color conservation is explicit. It generalizes the quark and gluon model to the quark and chromon model in which the chromons become the constituent gluons of hadron, which clarifies the glueball picture of the hadron spectroscopy greatly.

Most importantly, the Abelian decomposition is not just a theoretical proposition. It can be verified by experiment. It tells that there are two types of gluons, the color neutral Abelian neurons which play the role of the binding gluon and the gauge covariant colored chromons which play the role of the constituent gluon. We show how to verify the existence of the two types of gluons, the neurons and chromons, experimentally by reanalyzing the old ALEPH and CMS gluon jet data.

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Flux Tubes and Confinement in Lattice Quantum Chromodynamics.

Author: Leonardo Cosmai[1]

[1] *Istituto Nazionale di Fisica Nucleare, Bari*

Corresponding Author: leonardo.cosmai@ba.infn.it

Abstract: Color confinement is a fundamental non-perturbative aspect of Quantum Chromodynamics (QCD). Despite decades of research and numerical lattice simulations, a complete understanding of this phenomenon has remained elusive. Although a rigorous mathematical proof is still lacking, efforts to understand confinement could hold significant value for comprehending broader aspects of QCD, such as the phase diagram. In this talk, following a brief general introduction, we will focus on the study of flux tube structures on the lattice, exploring them as a manifestation of color confinement.

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Proton Spin and twist particles

Author: Pengming Zhang[1]

[1] *Sun Yat-sen University, Zhuhai*

Abstract : Both electroweak monopole and electroweak string could exist in the standard model. In this talk we will argue that the existence of the electroweak Cho-Maison monopole indicates the existence of the electroweak string in the standard model made of monopole-antimonopole pair separated infinitely apart, which carry the quantized magnetic flux $4\pi n/e$. We show how to construct such quantized magnetic flux string solution. Our result strongly indicates that genuine fundamental electromagnetic string could exist in nature which could actually be detected.

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Non-Perturbative Yang-Mills Beyond One-Loop Order

Author: Seth Grable[1]

[1] *University of Colorado, Boulder*

Abstract: I present a novel analytic framework for SU(N) Yang-Mills theory in the four-dimensional continuum. Background and effective field theory techniques are used to include non-perturbative contributions from cubic and quartic interactions. This approach is inspired by Savvidy who claims that first-order contributions from quartic interactions stabilise IR divergence found at one-loop order, paving the way for IR finite Yang-Mills calculations. I assess the validity of this claim and discuss the implications of my findings.

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Round Table 3: Landscape of Yang Mills theory vacuum

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Duality, noncommutative space and quantum gravity

Author: Kostas Filippas[1]

[1] *INPP, NCSR Demokritos*

Corresponding Author: kfilippas21@gmail.com

Abstract: Recently, we proposed a new duality in flat space under Poincare symmetry, which exchanges between spin and orbital degrees of freedom. The 'spin-orbit duality' maps 4D bulk spacetime onto a 3D worldtube, a cylinder S2xR, which is noncommutative and for low energies reduces to the fuzzy sphere. Progress shows that, firstly, the duality is really the first Hopf map. As an illustration, we take the Landau levels of a uniform magnetic field in bulk space and show that the dual theory on the sphere has the same spectrum under a Dirac monopole, whose ground state (lowest Landau level) indeed implies a fuzzy sphere. In fact, this particular example yields that an oscillator in the bulk is dual to an Ising model on the sphere. Secondly, the duality transforms the bulk Poincare group ISO(1,3) into the conformal SO(2,3). Hence, the dual theory is really defined on the conformal class of the cylinder S2xR, which is the conformal boundary of AdS4. Therefore, set next to the AdS/CFT duality, spin-orbit duality could provide a bridge between (non-conformal) QFT and supergravity.

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Phase Transition and Gravitational Wave in Strongly Coupled Dark Matter

Author: Zhi-Wei Wang[1]

[1] *School of Physics, Chengdu University, Sichuan*

Abstract. 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 transition 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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Confinement and dimensional transmutation in classical lambda phi 4 theory

Author: Viatcheslav Mukhanov[1]

[1] *Ludwig Maximilian University, Munich*

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Caustics in self-gravitating N-body systems and large scale structure of universe

Author: George Savvidy[1]

[1] *INPP, NCSR Demokritos*

I will demonstrate the generation of gravitational caustics in a self-gravitating N-body system. The gravitational caustics are space regions where the density of particles is higher than the average density in the surrounding space. It is suggested that the intrinsic mechanism of caustics generation is responsible for the formation of the cosmological Large Scale Structure that consists of matter concentrations in the form of galaxies, galactic clusters, filaments, and vast regions devoid of galaxies.
In our approach the dynamics of a self-gravitating N-body system is formulated in terms of a geodesic flow on a curved Riemannian manifold of dimension 3N equipped by the Maupertuis's metric. We investigate the sign of the sectional curvatures that defines the stability of geodesic trajectories in different parts of the phase space. The regions of negative sectional curvatures are responsible for the exponential instability of geodesic trajectories, deterministic chaos and relaxation phenomena of globular clusters and galaxies, while the regions of positive sectional curvatures are responsible for the gravitational geodesic focusing and generation of caustics. By solving the Jacobi and the Raychaudhuri equations we estimated the characteristic time scale of generation of gravitational caustics, calculated the density contrast on the caustics and compared it with the density contrasts generated by the Jeans-Bonnor-Lifshitz-Khalatnikov gravitational instability and that of the spherical top-hat model of Gunn and Gott.

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A geometric-phase stochastic approach to topology change in quark confinement

Author: Antonino Marciano[1]

[1] *Department of Physics, Fudan University*

Corresponding Author: marciano@fudan.edu.cn

Abstract. We apply a stochastic version of the geometric Ricci flow in order to explain the area-low of large Wilson-loops in Yang-Mills fields confinement. Confinement is therefore interpreted, within this stochastic geometric flow approach, as a geometric-phase by-product of the dynamics of Yang-Mills fields, being provided by the Aharonov-Bohm effect induced by the concatenation of the chromo-electric and chromo-magnetic fluxes. This dynamical (in thermal time) stochastic geometric-phase approach naturally accomplishes a treatment of the emergence of the vortices and the generation of turbulence effects, due to intermittency. The linking among dual chromo-magnetic and chromo-electric fluxes introduces topological charges over which the path-integral formulation of the non-perturbative theory can be expanded. Braiding and knotting, resulting from topology changes, namely stochastic fluctuations of the Einstein-Yang-Mills system, stabilize the chromo-magnetic vortices and induce, as non-trivial topological features, chiral symmetry-breaking.

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Cosmological Implications of Electroweak (Cho-Maison) Monopole and Primordial Magnetic Blackhole

Author: Yongmin Cho[1]

[1] *Center for Quantum Spacetime, Sogang University*

Corresponding Author: ymcho0416@gmail.com

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Dual Theory of Decaying Turbulence

Author: Alexander Migdal[1]

[1] *Institute for Advanced Study, Princeton*

Corresponding Author: sasha.migdal@gmail.com

I will present a recent advancement that transforms the problem of decaying turbulence in the Navier-Stokes equations in 3 + 1 dimensions into a Number Theory challenge: finding the statistical limit of the Euler ensemble. We redefine this ensemble as a Markov chain, establishing its equivalence to the quantum statistical theory of N fermions on a ring, interacting with an external field associated with random fractions of π. Analyzing this theory in the turbulent limit, where $N \to \infty$ and $\nu \to 0$, we discover the solution as a complex trajectory (instanton) that acts as a saddle point in the path integral over these fermions'density.
By computing the contribution of this instanton to the vorticity correlation function, we derive an analytic formula for the observable energy spectrum—a complete solution of decaying turbulence derived entirely from first principles without the need for approximations or fitted dimensionless parameters. Our analysis reveals the full spectrum of critical indexes in the velocity correlation function in coordinate space, determined by the poles of the Mellin transform, which we prove to be a meromorphic function. Real and complex poles are identified, with the complex poles reflecting dissipation and uniquely determined by the famous complex zeros of the Riemann zeta function.
Significantly, the theoretical predictions for the energy spectrum, energy decay rate, and the velocity correlation in the inertial range closely match the results from grid turbulence experiments and recent DNS45 within data errors. These experiments invalidate the K41 scaling laws.

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A gauge-invariant measure for gauge fields on CPˆ2

Author: Antonina Maj[1]

[1] *The Graduate Center, CUNY*

Corresponding Author: amaj@gradcenter.cuny.edu

I discuss four-dimensional non-Abelian gauge theory parametrized on a complex pro- jective space CP2 as a way of gaining insights into (3+1)-dimensional QCD. The low- energy scale of non-Abelian gauge theories remains an elusive area of research even af- ter decades of work. Working on CP2 facilitates a manifestly gauge-invariant parametriza- tion of the gauge fields and a possibly non-perturbative way of analyzing the low-energy dynamics of QCD. In particular, we use this parametrization to find the gauge-invariant measure for the gauge orbit space, which is the space of all gauge potentials modulo the set of all gauge transformations. The terms appearing in the measure that are of particular interest are a four-dimensional Wess-Zumino-Witten (WZW) action for the longitudinal modes of the gauge potentials, and a mass-like term for the transverse components. I argue that the appearance of a WZW action indicates the existence of a kinematic regime where the Yang-Mills theory can be approximated by a 4d-WZW theory. This result can be used to draw similarities between the mechanism of confinement in four dimensions and two dimensions. On the other hand, the appearance of a mass term in the measure can provide dimensional transmutation in QCD through an explicit gauge-invariant mass term for the gauge fields. Finally, I briefly outline a trajectory for moving beyond CP2 and recovering 4d Euclidean geometry, thus, bringing this framework closer to QCD.

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Manifestations of high energy QCD asymptotic

Author: Victor Kim[1]

[1] *PNPI, Gatchina*

Corresponding Author: victor.kim@cern.ch

Abstract: Lipatov-Kuraev-Fadin-Balitsky (BFKL) evolution as the high-high-energy asymptotic of QCD is reviewed. Manifestations the BFKL evolution in high-energy data are discussed.

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Gravitational waves and their detection

Author: Marina Ioannou[1]

[1] *INPP, NCSR Demokritos*

Generation of gravitational waves. Review of the theoretical background, the gravitational detectors and experimental verification.

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Modified Villain formulation of axion-Maxwell theory and generalised symmetries.

Author: Mohammad Akhond[1]

[1] *Department of Physics, Kyoto University*

Abstract: Recently, there has been a dramatic shift in our understanding of the notion of symmetry in a quantum field theory. Lattice gauge theory provides one of the best non-perturbative approaches to understanding QCD. This motivates the need to understand the recent generalised symmetries in the context of lattice gauge theory. In this talk I will use the lattice description of axion-Maxwell theory as a toy model to explore these ideas. This model exhibits a rich symmetry structure, including higher group, as well as non invertible symmetries. I will comment on how such structures are manifested in the lattice regularisation and comment on application to non-abelian generalisations.

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Review of Lattice Gauge Field Theory

Author: Vaggelis Karydis[1]

[1] *National Technical University, Athens*

Lattice gauge theory provides a method for studying gauge theories in their non-perturbative regime and offers a formulation that can be simulated on powerful computers. I will present a review of gauge fields on a lattice and a Python implementation of lattice gauge theory simulations using

Metropolis Monte Carlo technique, following the pioneering work of M. Creutz and others, to measure important physical observables.

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Round Table 2: QFT and Turbulence. Loop transfer matrix and loop quantum mechanics

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Round Table 1: Standard Model and Cosmology

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Multimessenger studies of the physical basis of the modern Cosmology

Author: Maxim Khlopov[1]

[1] *Virtual Institute of Astroparticle Physics, France*

Abstract: BSM physics, on which the now standard inflationary cosmology with baryosynthesis and dark matter/energy is based, inevitably leads to cosmological scenarios beyond this standard model, involving specific model dependent choice of models and parameters of BSM physics. Such model dependent cosmological predictions may already found confirmation in the positive results of direct dark matter searches by DAMA/NaI and DAMA/LIBRA experiments, interpretation of the results of Gravitational Wave experiments in terms of Primordial Black Hole merging, observation of Stochastic Gravitational Wave background by Pulsar Timing Arrays, and searches for cosmic antihelium in the AMS02 experiment. We discuss these cosmological messengers of BSM physics as possible signatures of BSM cosmology,
specifying the choice of BSM models and determination of their parameters with 'astronomical accuracy'.

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Round Table 4: Landscape of Yang Mills theory vacuum

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Registration

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Summary and Future Directions