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Editorial

Modern Approaches to Non-Perturbative QCD and Other Confining Gauge Theories

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Citation: Antonov, D. Modern Approaches to Non-Perturbative QCD and Other Confining Gauge Theories. *Universe* **2022**, *8*, 49. https://doi.org/10.3390/universe8010049

Received: 10 January 2022
Accepted: 10 January 2022
Published: 13 January 2022

The primary goal of this Special Issue was to create a collection of reviews on the modern approaches to the problem of quark confinement in QCD. Such approaches include both the microscopic models of the confining Yang–Mills vacuum and the models of the quark–antiquark string. Over the course of this project, the Special Issue also benefited from contributions on other related subjects, such as the topology of baryon-rich matter or a model of the axionic dark matter.

In their broad review [1], Roman Pasechnik and Michal Šumbera provided an outlook on some currently popular scenarios of the confinement phenomenon. The key topics covered by this review include the order parameters for confinement, magnetic order/disorder phase transition, the center-vortex and the monopole models of the Yang–Mills vacuum, as well as realizations of confinement in the gauge-Higgs and Yang–Mills theories, and the phases of QCD matter.

The review [2] by Maria Paola Lombardo is devoted to the subject of topology in dense matter. After a short overview of the status of the corresponding studies at zero density, lattice results for baryon-rich matter were presented. This subject was mostly studied in the two-color QCD and for matter with isospin and chiral imbalances. At high temperatures, some coherent pattern was shown to emerge. Namely, above the critical temperature for superfluidity/superconductivity, the topological susceptibility, as a function of either the isospin or the baryonic chemical potential, turned out to be clearly correlated with the chiral condensate and the confinement-related quantities. This finding holds true also for the chiral chemical potential. In that case, a striking effect, called chiral enhancement, has been found, which is the growth of the chiral condensate with the chemical potential. The same growth turns out to take place also for the topological susceptibility and the string tension.

The review [3] by Michele Caselle starts with a general introduction to the Effective-String-Theory (EST) approach to the description of confinement in the Yang–Mills theory. It further shows that, close to the deconfinement critical temperature, several universal features of confining gauge theories can be accurately described by the EST. Such features include the ratio of the deconfinement critical temperature to the square root of the zero-temperature string tension, the linear increase of the square of the flux-tube width with the interquark distance, and the temperature dependence of the interquark potential. Moreover, close to the deconfinement critical temperature, the behavior of the confining string turns out to be well described by the general principles of conformal invariance and by the Svetitsky–Yaffe dimensional-reduction conjecture. This finding provides further support for the description of confinement by means of the EST.

As mentioned above, this Special Issue contains several reviews and research articles devoted to specific models of the confining Yang–Mills vacuum. In particular, the review [4] by Maria Cristina Diamantini and Carlo Andrea Trugenberger as well as the article [5] by Hideo Suganuma and Hiroki Ohata are devoted to the monopole-based scenario of confinement.

The review by Maria Cristina Diamantini and Carlo Andrea Trugenberger discusses superinsulators (SI), which represent a new topological state of matter that can exist in the vicinity of the superconductor/insulator phase transition. Being dual to superconductors, SI provide a realization of the electric/magnetic duality. The effective field theory that describes SI is governed by the compact Chern–Simons term in (2 + 1)D and the compact BF term in (3 + 1)D. Unlike the superconductor, where the condensate of Cooper pairs leads to the Meissner effect, Cooper pairs in SI form bound states owing to the *dual* Meissner effect, i.e., the monopole-condensate-triggered squeezing of electric fields into the flux tubes. In fact, magnetic monopoles, while elusive as elementary particles, can be realized in certain materials in the form of emergent quasiparticle excitations. The monopole Bose condensate can exist at low temperatures and can manifest itself as a superinsulating state of infinite resistance. The related monopole supercurrents can thus result in the electric counterpart of the Meissner effect, which leads to the linear confinement of Cooper pairs. This way, SI realize one of the mechanisms proposed to explain confinement in the Yang–Mills theory. Furthermore, for SI samples smaller than the width of the confining string, a metallic-like low-temperature behavior of SI has been predicted and experimentally confirmed. It is also predicted that an oblique version of SI can be realized as a pseudogap state of high-temperature superconductors.

In the article by Hideo Suganuma and Hiroki Ohata, the interrelation between the chiral condensate, monopoles, and color-magnetic fields in QCD was studied on the lattice. First, idealized Abelian systems, consisting of a static monopole–antimonopole pair and a magnetic flux without monopoles, were explored. Lattice simulations of the chiral condensate of quasi-massless fermions, coupled to the Abelian gauge field in the mentioned systems, show that this condensate is localized in the vicinity of the magnetic field. Furthermore, by using SU(3) lattice-QCD Monte-Carlo simulations, the Abelian-projected QCD in the Maximal Abelian gauge was studied. The results of these studies show a clear correlation between the chiral condensate, the distribution of monopoles, and the color-magnetic fields of the Abelianized gauge-field configurations. As a statistical indicator, the coefficient measuring the correlation between the chiral condensate and the square of the color-magnetic field in the Abelian-projected QCD, was calculated and found to be approximately equal to 0.8. The same correlation was found to become weaker in the deconfinement phase. Thus, the obtained results show that, similar to what happens in the case of magnetic catalysis, the chiral condensate is locally enhanced by the strong color-magnetic field, which exists in the vicinity of monopoles in the Abelian-projected QCD.

The results of other studies of the interrelation between the dynamics of quarks and the confining dynamics of the Yang–Mills fields were reported in the review [6] by Matteo Giordano and Tamás Kovács, as well as in the articles [7,8] by Manfried Faber, Rudolf Golubich, and their collaborators.

The review by Matteo Giordano and Tamás Kovács is devoted to the Anderson-type localization transition, which affects eigenmodes of the lower part of the Dirac spectrum. Several aspects of this transition were reviewed, mostly by making use of the tools of lattice gauge theory. In particular, the connection of the localization transition with the finite-temperature phase transitions was illustrated. This connection makes the localization transition related to the deconfinement of quarks as well as to the restoration of chiral symmetry, which is spontaneously broken at low temperatures. The review also discusses the universality of the localization transition as well as its connection to the topological excitations of the gauge field, i.e., instantons, and the associated fermionic zero modes. While the review is mostly focused on QCD, it also discusses how the localization transition appears in other gauge models, with different fermionic contents and gauge groups, and in the various space-time dimensions.

The article [7] by Manfried Faber, Rudolf Golubich, and their collaborators, which is devoted to the center-vortex model of the confining Yang–Mills vacuum, discusses back-reaction of quarks on the gauge fields of the model. In particular, it shows that the model reproduces the phenomenological QCD string tension (at interquark distances smaller than the string-breaking distance) also in the presence of dynamical quarks. Their other article [8] suggests a possible resolution for the problems of vortex detection in smooth lattice configurations and discusses recent improvements in the detection of center vortices.

The related review [9] by Luis Esteban Oxman and his collaborators provides an overview of the recent progress achieved by the authors in an analytic derivation of the center-vortex model of the Yang–Mills vacuum. This research program starts with modeling, in the continuum limit, of some of the properties of center vortices that were found in the lattice simulations, and proceeds toward the derivation of the corresponding effective field representations. In particular, when modeling the measure of the center-vortex ensemble, the authors emphasized the importance of the inclusion of the non-oriented center-vortex component and the non-Abelian degrees of freedom. The so-constructed model of percolating center vortices turns out to be capable of reproducing several known important features of confining flux tubes in the SU(N) Yang–Mills theory.

In their review [10], Ibrahim Burak Ilhan and Alex Kovner discuss the approach aimed at constructing an effective 4D theory that could provide a simple classical picture of the main qualitatively important features of both the Abelian and the non-Abelian gauge theories. This approach starts with ensuring the presence of massless photons, i.e., the Goldstone bosons, in the Abelian theory, and their disappearance in the non-Abelian case, which is happening together with the formation of confining strings between charged states. The suggested formulation avoids the use of vector fields, operating instead with the basic degrees of freedom, which are the scalar fields of a certain non-linear sigma model. The Mark 1 model, discussed in the review, turns out to have a large global symmetry group, with the 2D diffeomorphism invariance in the Abelian limit, which is isomorphic to the group of all canonical transformations in the classical 2D phase space. This symmetry is not present in QED, and it is thus further eliminated by “gauging” this infinite-dimensional global group. By introducing additional modifications to the model (Mark 2), the authors have first proved that the “Abelian” version of such a modified model is equivalent to the theory of a free photon. Achieving the desired properties in the “non-Abelian” regime turns out to be tricky. To this end, the authors introduced a perturbation that led to the formation of confining strings in the Mark 1 model. These strings have somewhat unusual properties, as their profile does not fall off exponentially, away from the center of the string. In addition, the perturbation explicitly breaks the diffeomorphism invariance. The questions of how to preserve this invariance in the gauged model as well as how to obtain realistic confining strings in the Mark 2 model currently remain open.

Last but not least, the article [11] by Janning Meinert and Ralf Hofmann, motivated by the SU(2)$_{\text{CMB}}$-modification of the cosmological model ΛCDM (where “CMB” stands for Cosmic Microwave Background), considers isolated fuzzy-dark-matter lumps, made of ultralight axion particles with the masses arising due to distinct SU(2) Yang–Mills scales and the Planck mass M_P. Unlike the SU(2)$_{\text{CMB}}$-model, the corresponding Yang–Mills theories, which are associated with the three lepton flavors of the Standard Model of particle physics, stay in the confining (zero temperature) phase throughout most of the universe’s history. As the universe expands, axionic fuzzy dark matter comprising a three-component fluid undergoes certain depercolation transitions when dark energy (represented by the global axion condensate) is converted into dark matter. The authors extracted the lightest axion mass $m_{a,e} = 0.675 \cdot 10^{-23}$ eV from the well-motivated model fits to observed rotation curves in the low-surface-brightness galaxies (SPARC catalogue). Since the virial mass of an isolated lump solely depends on M_P and the associated Yang–Mills scale, the properties of an e-lump predict those of μ- and τ-lumps. As a result, a typical e-lump virial mass $\sim 6.3 \cdot 10^{10} M_\odot$ suggests that massive compact objects in galactic centers, such as Sagittarius A* in the Milky Way, are (merged) μ- and τ-lumps. In addition, τ-lumps may constitute global clusters. If the axial anomaly indeed links leptons with dark matter and the CMB with dark energy, that would demystify the dark universe through a firmly established feature of particle physics.

Funding: This Guest Editor's activity received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

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