Generation, evolution, and observations of cosmological magnetic fields

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Bernoulli Center

Book of Abstracts

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1

Lattice Simulations of Axion-U(1) Inflation

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I will present the first nonlinear lattice simulation of an axion field coupled to a U(1) gauge field during inflation. The Chern-Simons coupling induces a tachyonic growth of one of the two helicities of this electromagnetic inflationary field, often invalidating the standard perturbation theory approach. We use the simulation to study the production of the gauge field on the lattice and its effect on scalar perturbation. We find that the evolution of the gauge field is highly sensitive to the choice of the spatial discretization scheme. After identifying a suitable discretisation scheme, I will present results on the statistics of the primordial curvature perturbation. We find high-order statistics to be essential in describing non-Gaussianity in the linear regime of the theory. On the contrary, non-Gaussianity is suppressed when the dynamics becomes nonlinear. This relaxes bounds from overproduction of primordial black holes, allowing for an observable gravitational waves signal at pulsar timing array and interferometers scales.

2

Cosmological-scale magnetic fields from galactic outflows

Author: Kyrylo Bondarenko[1]

[1] *Cosmological-scale magnetic fields from galactic outflows*

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We study the effects of galaxy formation physics on the magnetization of the intergalactic medium (IGM) using the IllustrisTNG simulations. We demonstrate that large-scale regions affected by the outflows from galaxies and clusters contain magnetic fields that are several orders of magnitude stronger than in unaffected regions with the same electron density. Moreover, like magnetic fields amplified inside galaxies, these magnetic fields do not depend on the primordial seed, i.e. the adopted initial conditions for magnetic field strength. We study the volume filling fraction of these strong field regions and their occurrence in random lines of sight. We discuss the effects of these strong magnetic fields on Faraday Rotation Measure, ultra-high energy cosmic rays, gamma-ray propagation, and put bounds on the photon-axion conversion from spectral distortion of the CMB.

3

Vacuum Energy of the Universe, Large scale magnetic field and nontrivial topology in QCD.

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We discuss a new scenario for early cosmology when the de Sitter phase emerges dynamically.
This genuine quantum effect occurs as a result of dynamics of the topologically nontrivial sectors in a strongly coupled QCD in an expanding universe.
We argue that the key element for this idea to work is the presence of nontrivial holonomy in strongly coupled gauge theories. The effect is global in nature and cannot be formulated in terms of a gradient expansion in an effective

local field theory. We discuss some profound phenomenological consequences of this scenario as the dynamical generation of the Dark Energy (DE).
The corresponding estimates lead to the dark energy magnitude which is expressed in terms of the dimensional QCD parameter and is amazingly close to the observed value, $\rho_{\rm DE} \sim H\Lambda^3_{QCD} \sim (10^{-3}eV)^4$. We argue that anomalous coupling of the dark energy emergent field with Maxwell electrodynamics generates the large cosmological magnetic field as a result of the helical instability. The generated magnetic field must be correlated on the scale of the visible Universe.

The talk is based on recent paper:
Ariel Zhitnitsky, "Cosmological Magnetic Field and Dark Energy", Phys.Rev.D 99 (2019) 10, 103518
e-Print: 1902.07737

4

Magnetogenesis from axion-SU(2) inflation

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The origin and maintenance of magnetic fields is an outstanding question of modern cosmology and astrophysics. Dynamo and compression mechanisms during gravitational collapse accompanying the structure formation can only amplify existing magnetic fields, but cannot explain their genesis. The need for a "seed"field motivates the investigation of primordial origin of magnetic fields. The search for primordial magnetic fields is further inspired by recent γ-ray observations of distant blazars, which set lower limits on the magnetic field strength and suggest the existence of magnetic fields in intergalactic voids. In this talk I will discuss the magnetogenesis scenario during the axion-SU(2) inflation –inflation with the axion field coupled to the weak sector of the Standard Model. I will investigate the viability of such a scenario together with its observational predictions.

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Dark matter minihalos from primordial magnetic fields

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Primordial magnetic fields (PMF) can enhance baryon perturbations on scales below the photon mean free path. However, a magnetically driven baryon fluid becomes turbulent near recombination, thereby damping out baryon perturbations below the magnetic Jeans length. In this Letter, we show that the initial growth in baryon perturbations gravitationally induces growth in the dark matter perturbations, which are unaffected by turbulence and eventually collapse to form 10^{-11}–10^{3} $M_\odot$ dark matter minihalos. If the magnetic fields purportedly detected in the blazar observations are causally generated PMFs with a Batchelor spectrum, then such PMFs could potentially produce dark matter minihalos.

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Structure Formation with Primordial Magnetic Fields: enhancing baryon fraction in halos

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Primordial magnetic fields (PMFs) can enhance matter power spectrum on small scales ($lesssim$ Mpc) and still agree with bounds from cosmic microwave background (CMB) and Faraday rotation measurements. As modes on scales smaller than Mpc have already become non-linear today, constraints on PMFs from the impact on small-scale structures require dedicated cosmological simulations. Here, for the first time, we perform a suite of hydrodynamical simulations that take into account the dissimilar impact of PMFs on baryons and dark matter. The form of initial conditions and their role is emphasized. We also highlight the large theoretical uncertainty in the peak enhancement of the matter power spectrum due to PMFs, which was not considered in previous studies. We show that PMFs can generate galaxies with baryon fraction several times larger than the cosmic average at high redshifts. This is simply a consequence of the fact that PMFs enhance baryon perturbations, causing them to be larger than dark matter perturbations. We argue that this scenario could help reconcile the large efficiency of gas conversion suggested by the first JWST observations and deserves further investigation.

9

Evolution of Cosmological Magnetic Fields from Early to Late Times

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The physics of primordial magnetic fields can be broken down into three main motifs that are addressed: the generation of a magnetic field in the early universe, the evolution of this magnetic fields subject to
magnetohydrodynamic (MHD) effects through the various cosmological epochs, and the detection and/or probing of this magnetic field with a comprehensive array of astrophysical and cosmological observations. After the seed magnetic field is formed at the magnetogenesis epoch, its subsequent evolution is governed by a coupling to plasma turbulence, decay due to adiabatic expansion and Alfvenic unfolding, and resistive dissipation. After the recombination epoch the seed field stays frozen-in and starts to interact with cosmic again during first structure formation and reionization. In this talk I will review the evolution of the magnetic fields from the moment of its generation till today.

10

Imprints of primordial curvature perturbations on inflationary magnetic fields

Author: Rajeev Kumar Jain[None]

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We examine the imprints of sharp departures from slow-roll inflation which lead to strong features in the scalar power spectra, on the spectra of the primordial electromagnetic fields generated during inflation. In particular, we find that an epoch of ultra-slow roll inflation leads to a severe suppression of the magnetic field spectrum over large scales. We also make use of the code magcamb to calculate the effects of the magnetic fields on the anisotropies in the cosmic microwave background and investigate if the magnetic field spectra with features are broadly consistent with the current observational constraints.

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Constraining inflationary magnetogenesis and reheating via GWs in light of PTA data

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Recent advancements in our observation of the cosmos have led to significant progress. However, we still lack a complete understanding of the dynamics involved in the reheating process after cosmic inflation. Gaining a deep understanding of reheating dynamics is crucial for deciphering the unfolding story of our universe. It is essential for reheating to conclude before the Big Bang Nucleosynthesis (BBN) temperature, denoted as $T_{\rm re} > T_{\rm BBN} \simeq 10^{-2}$ GeV.
Detecting reheating dynamics through observations of the Cosmic Microwave Background (CMB) faces challenges due to their shorter wavelengths. Fortunately, the recent detection of Gravitational Waves (GWs) by collaborations like LIGO-Virgo and Pulsar Timing Arrays (PTAs) has opened up a new avenue in observational cosmology. Our research, detailed in the paper (arXiv:2401.01864v1 [astro-ph.CO]), utilizes constraints on the epoch of reheating and inflationary magnetogenesis, employing limits on primordial magnetic fields (PMFs) and their contributions to secondary GWs.
Our analysis reveals that the combined spectral density of primary and secondary GWs from PMFs can generally be described as a broken power law with five distinct indices. We demonstrate that PMFs with blue tilt spectra, while adhering to other observational constraints, can generate significant GWs detectable by PTAs and upcoming observatories such as LISA, DECIGO, and BBO.
Importantly, our study identifies a specific spectral type whose slope depends on both the magnetic spectra index and the equation of state of the universe during the reheating period. Additionally, we determine that for $w_{\rm re} > 1/3$, the high frequency of GWs may impact the extra relativistic degree of freedom known as $\Delta N_{\rm eff}$.

13

Gravitational Waves from Chiral Plasma Instability in Standard Cosmology

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In the primordial plasma, at temperatures above the scale of electroweak symmetry breaking, the presence of chiral asymmetries is expected to induce the development of helical hypermagnetic fields through the phenomenon of chiral plasma instability. It results in magnetohydrodynamic turbulence due to the high conductivity and low viscosity and sources gravitational waves that survive in the universe today as a stochastic polarized gravitational wave background. In this article, we show that this scenario only relies on Standard Model physics, and therefore the observable signatures, namely

the relic magnetic field and gravitational background, are linked to a single parameter controlling the initial chiral asymmetry. We estimate the magnetic field and gravitational wave spectra, and validate these estimates with 3D numerical simulations.

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Magnetic field seeds from black holes accretion disks

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The origin and evolution of cosmological magnetic fields not only remains a subject that is still unresolved, it also has the potential to serve as a test for current cosmological models. This talk focuses on investigating different magnetic field seeds and explores potential origins involving black holes with charge, amplification processes, and distribution mechanisms on large scales.

The presentation delves into the possibility of primordial or stellar black holes as sources of these seeds, examining their potential to generate the required magnetic field amplitude trough (i) their accretion disks acting as Biermann batteries that generate the magnetic field, and (ii) through black holes carrying an intrinsic electric charge. We employ numerical simulations, specifically using Illustris TNG-300 simulation, to investigate the sources of magnetic field seeds. We estimate the magnetic field in halos and the intergalactic power spectrum of magnetic amplitude.

Finally, we compare the observational estimates obtained on various scales, providing insights into the validity of the proposed mechanisms.

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Magnetogenesis and baryogenesis in pseudoscalar inflation

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Pseudoscalar inflation with Chern-Simons coupling to U(1) gauge fields generates helical magnetic field during inflation. If this U(1) gauge field is the Standard Model U(1) hypergauge interaction, the baryon (or B+L) asymmetry is generated at the same time through the chiral anomaly in a way that the total chirality vanishes. We could expect that it explains the present Baryon Asymmetry of the Universe (BAU). However, it is not trivial if the BAU remains until today since the sphaleron washout and/or the annihilation of magnetic helicity and baryon (chiral) asymmetry through the chiral magnetic effect may erase the baryon asymmetry. On the other hand, the baryogneesis from the hypermagnetic helicity decay at the electroweak symmetry break would also take place in this scenario. In this talk, I will explain all these ingredients and clarify how the present BAU can be explained in the pseudoscalar inflation. Implication on the intergalactic magnetic fields are also discussed.

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Exploring the PMF imprints through rotation measure in the rarified cosmic regions

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Faraday rotation of linearly polarized emission as light passes through the foreground magnetised medium is one of the powerful indirect probes of the large-scale magnetic fields (LSMFs). Rotation measure (RM) which quantifies the amount of the rotation of the polarisation plane has been used for reconstructing the magnetic field properties in the intracluster medium. In the recent years, constraining the value of the RM in the intergalactic medium (IGM), referred to as the residual RM (RRM), as well as studying its dependence on redshift has also become a promising approach in the search of the LSMF imprints. In my talk, I will present results of our ongoing research on constraining the primordial magnetic field (PMF) models, candidates for the seeds of the observed large-scale magnetisation of the Universe, through observations of the RM in the rarified regions of the cosmic web. We use deep light cones, constructed by stacking the simulated boxes until redshift 2 to compare the evolution of the simulated RRM with the observational data. We study different PMF models having different coherence scales to understand how the observational RRM evolution translates into constraints on the PMF strengths. For the first time, we use original (non-replicated) data from cosmological magnetohydrodynamical (MHD) simulations to study the evolution of the RRM statistics for different PMF models. Apart from our results on the RRM statistics, I will also review some of the unxeplored questions that can help us in constraining the Universe's magnetism and the open questions related to the PMF evolution during structure formation.

17

Magnetic dynamo in SWIFT simulations

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Dynamos and astrophysical magnetic field (MF) evolution can be studied with numerical simulations.
There is an ongoing effort to implement cosmological MFs evolution in SWIFT code using smoothed particle hydrodynamics (SPH) for the first time. The code contains several implementations: solve direct induction equations or evolve vector potential. Having different implementations might help to estimate numerical uncertainty in MF evolution.
To check the capabilities of the schemes we simulate a well-studied Roberts Flow dynamo.
We demonstrate the ability of all schemes to converge with the resolution, as well as reproduce critical magnetic Reynolds number that is within the 10% range from Pencil code results, and recover correct growth rate behaviour vs physical resistivity when the latter is large.
However, we find direct induction schemes produce incorrect growth rates, chaotic field configuration and unphysical growth in planar flow where we don't expect dynamos to happen.
We explore how adding artificial resistivity helps to fix the ideal MHD limit.
Next, we consider a system with MFs with two separate physical scales to see how the inverse cascade of magnetic fields happens in SWIFT and compare the results with analytical estimates from mean-field theory.
Dynamo action happens in galaxies, and created MFs are expelled by outflows. To test the code in the astrophysical setting we study a conducting gas disc with MFs and move on to low-resolution cosmological MHD runs.

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Connecting the observed and simulated cosmic web to primordial magnetism

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I will show how the development of new simulations, jointly with the latest extragalactic radio surveys are giving us a deep and new view of cosmic magnetism on scales never probed so far. Jointly with other probes from different wavelengths, they have started producing seemingly consistent constraints on the presence of very diffuse magnetic fields on the largest scales in the Universe, which favours a primordial origin of extragalactic magnetic fields.
I will discuss the (many) still pending numerical and theoretical open issues in this challenge, and discuss how the future is likely to bring us closer to a definitive answer to this fascinating cosmic puzzle, with deep consequences on cosmology, galaxy formation and cosmic rays physics.

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Charge transfer induced by chiral plasma instability

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It is well known that the weak sphaleron exchanges chemical potentials of left-handed fermions and plays important roles in baryogenesis. In this talk, we will focus on another source of $B + L$ violation, i.e., $U(1)_Y$ Chern-Pontryagin density. We discuss several examples where the charge transfer induced by this term plays a central role in the early Universe.

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Constraints on extragalactic magnetic fields from ultra-high-energy cosmic rays

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Ultra-high-energy cosmic rays (UHECRs) get deflected by extragalactic magnetic fields (EGMFs) when they propagate from their sources to Earth. The spread of UHECRs around their original source position provides a measure for the strength of the EGMFs in between the UHECR sources and Earth. Furthermore, the density of UHECR sources plays an essential role in determining the relative contribution from nearby sources compared with the isotropic background. In Ref. [1], we investigated which combinations of magnetic-field strengths and source densities can explain the correlations between star-forming galaxies and UHECR directions observed by the Pierre Auger Collaboration. We found that, if UHECRs are predominantly produced by star-forming galaxies, relatively strong EGMFs ($B > 0.2$ nG for a coherence length of 1 Mpc at the 5σ confidence level) between the UHECR sources and the Milky Way are necessary to explain the observed correlations. Weaker EGMFs are allowed if UHECRs are predominantly produced in sources with an even larger

source density than star-forming galaxies. These findings will be improved and extended upon in Ref. [2], which will include a more direct comparison with publicly-available UHECR arrival-direction data of the Pierre Auger Collaboration.

[1] Van Vliet A., Palladino A., Taylor A. M. and Winter W., 2021, MNRAS, 510, 1289.
[2] AL-Zetoun A., Taylor A. M., Winter W. and Van Vliet A., 2024, in preparation.

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Magnetisation of radio relic and implication for dark matter searches

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In galaxy clusters, the seed magnetic field of primordial or astrophysical origin is thought to be amplified through Biermann battery mechanism or small-scale dynamo action to μG-strength magnetic fields as estimated through Faraday Rotation measurements. Shock waves driven by merger events can continuously source self-generated magnetic fields. Diffuse non-thermal emission and polarization measurements from radio relics indicate a magnetisation of the intracluster medium due to merger shocks in addition to particle acceleration at the shock site. In this talk, I will outline the growth and saturation of such magnetic fields, and touch upon its implication on the astrophysical searches of dark matter.

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Cosmological simulations including magnetic fields and realistic feedback from galaxies

Author: Matthieu Schaller[None]

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We use the FLAMINGO model of galaxy formation to study the cosmological evolution of primordial magnetic fields. This model was calibrated, using machine-learning techniques, to reproduce key observables of the galaxy and cluster population. This gives strong constraints on the feedback mechanisms around haloes and, as a consequence, on the spatial regions where magnetic field sourced in galaxies is present.
We can thus analyze the level of void pollution by strong fields and put interesting limits on what primordial fields information can be recovered from observational campaigns targeting void regions.

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Very large magnetohydrodynamical simulations of structure formation with the cosmological code SWIFT

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Numerical simulations can substantially support the study of the origin and evolution of cosmic magnetic fields. Leveraging on algorithmic advances at the heart of the novel cosmological code SWIFT, and developing a suite of Modern Lagrangian Magnetohydrodynamical (MHD) Solvers - each with a different formulation of Ideal and Resistive MHD - we seek to make predictions for the large-scale structure (LSS) of magnetic fields in the late-time universe. Such a plural approach seeks to identify systematic biases introduced by the solver, so as to account for them when making forecasts.

I will discuss how we incorporated a state of the art, 'Direct Induction' formulation of Smoothed Particle MHD in SWIFT, how it yields competitive results on benchmark test cases (at a fraction of the computational cost when compared to other commonly used methods) and how it performs on a set of cosmological problems. I will compare and contrast this with a 'Vector Potential' implementation of magnetic field physics, also present in SWIFT, emphasising where the two solvers converge or diverge and commenting on what can be learned from comparing their predictions. I will finally elaborate on the coupling of our MHD prescriptions to a full galaxy formation model, which has been shown to successfully reproduce several galaxy, cluster and LSS observations in the very large cosmological hydrodynamical simulation suite FLAMINGO.

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Magnetogenesis from vorticity in the primordial universe

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I explore the speculation that a physical mechanism underlying primordial magnetogenesis could arise from the vorticity field in the quark-gluon plasma (QGP) phase of the early universe. This possibility is motivated by the recent discovery of giant rotating filaments connecting the cosmic web in the large scale structure (P. Wang et al., Possible observational evidence for cosmic filament spin, Nature Astronomy). The process of generation of angular momentum at such cosmic scales is unknown as is the seeding mechanism of the intergalactic magnetic field. Could both share a common or related origin (s) in the microsecond old universe when the QGP phase filled it? I address this question using relativistic hydrodynamics. The rich interplay of mechanical rotation and magnetic field in the extreme arena present in the primordial universe is the main subject of enquiry in the context of magnetogenesis and a critical comparison with observations is the goal.

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Baryon inhomogeneities by causal primordial magnetic fields

Author: Fabio Finelli[None]

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We compute the enhancement of baryon density fluctuations sourced by a stochastic background of primordial magnetic fields by means of an Einstein-Boltzmann code which evolves the full system for cosmological perturbations and computes the cosmic microwave background anisotropy temperature and polarization power spectra.

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Stochastic effects and Primordial magnetogenesis

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In this talk, I delve into the intricacies of primordial magnetogenesis during inflation, incorporating a thorough consideration of the dynamics of stochastic noises associated with electromagnetic perturbations. By deriving the Langevin and Fokker-Planck equations governing the evolution of electromagnetic fields, I achieve analytical solutions. Our investigation reveals that, although the backreactions of the electric field energy density have the potential to prematurely disrupt inflation, certain regions of parameter space exhibit an unconventional mean-reverting process in the stochastic dynamics, altering the typical decaying behavior of magnetic fields. Consequently, magnetic fields can reach an equilibrium state with amplitudes significantly larger than those obtained without accounting for stochastic noises. I will demonstrate that, under controlled backreactions of electric field perturbations, magnetic fields with a present amplitude of ~10ˆ(-13) Gauss and a correlation length of Mpc can be generated.

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Probing high-frequency gravitational waves in cosmic magnetic fields

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High-frequency gravitational waves (HFGWs), loosely defined as above kHz, could stem from new physics, e.g., light primordial black holes, beyond-Standard Model mechanisms. One approach to detect such HFGWs is via the inverse Gertsenshtein effect, where gravitons convert to photons in an external magnetic field. Since magnetic fields are ubiquitous in the universe, such graviton-photon conversions are expected to take place and the induced photons could, in principle, distort the otherwise blackbody CMB temperature spectrum. I will present the conservatively estimated upper limits of HFGWs using existing measurements from telescopes such as MWA, LOFAR, and EDGES, as well as improved forecast constraints with the upcoming radio telescope SKA and future CMB surveys.

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Primordial Magnetic Fields in Galaxy Clusters

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Galaxy clusters host Mpc-scale diffuse radio emission giving us evidence of large-scale magnetic fields in the Universe. Among the potential explanations for the observed magnetic fields in these

clusters are primordial magnetic fields (PMFs). There are two main theories for primordial magnetogenesis: those formed during inflation and those created during phase transitions. In my talk, I will discuss the dynamics of initially large- and small-scale correlated magnetic fields corresponding to inflation- and phase-transition-generated PMFs in simulated galaxy clusters. I will additionally touch upon a hybrid numerical framework to study continuum and polarised emission in MHD simulations of galaxy clusters.

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Sterile Neutrino Dark Matter and Magnetic Fields

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I will discuss how the Abelian part of the electroweak anomaly can influence the generation of lepton asymmetry of the Universe and its impact on dark matter sterile neutrino.

32

Backreaction from magnetic fields generated during inflation

Author: Ruth Durrer[1]

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In this talk I shall discuss how magnetic fields generated during inflation can back-react on the inflaton perturbation spectrum. I shall first outline the problem and present the generic form of the equations which have to be solved. I shall then discuss the effects which have been neglected in previous work. I can also outline an example which will be discussed in detail by another speaker (Deepen Garg).

33

Symmetry breaking and magnetic fields

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TBA

34

Cosmological Seed Magnetic Field from Inflation

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A cosmological magnetic field of nG strength on Mpc length scales could be the seed magnetic field needed to explain observed few microG large-scale galactic magnetic fields. I first briefly review the observational and theoretical motivations for such a seed field, two galactic magnetic field amplification models, and some non-inflationary seed field generation scenarios. I then discuss an inflation magnetic field generation model. I conclude by mentioning possible extensions of this model as well as potentially observable consequences.

36

Magnetic fields effects on particle interactions strength in the early universe

Author: Gabriella Piccinelli[1]

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Motivated by our work on inflationary scenarios in presence of magnetic fields, we have focused on one of the puzzling features with which we have faced: the effect of magnetic fields on the particles' interaction processes, which may be a relevant issue during inflation or in the subsequent stages of the Universe evolution. The importance of magnetic fields'contribution comes from the fact that they are widespread in the Universe , at all scales.

There is a vast literature on this topic, but the problem is that the results, in different situations, do not match.

A vast assortment of physical situations and of analytical and numerical approaches can be found in the literature, making the comparison between them not straightforward. Our aim is to focus attention on differences and similarities between the different situations and approaches, looking for a systematization scheme that could be predictive, once the role played by each physical ingredient could be understood.

The literature in this subject is so vast that the present work is far from being exhaustive. We mainly focus here on some seminal papers and on recent literature, both from our working group and from other research teams.

37

Simulating the Early Universe

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One approach to exploring the dynamical properties of systems is to use computer simulations, and these can take many different forms depending on the energy scales and length scales of interest. In this talk I shall give an overview of some techniques for real-time simulations of the underlying fields. This allows one to examine some of the microscopic processes underlying the development of physical phenomena.

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Particle production by axion-like particles

Author: Valerie Domcke[1]

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Axion-like particles may play a key role in early universe cosmology. In this talk I discuss the dual production of gauge fields and fermions induced by axion-like particles, and its implications for magnetogenesis from axion inflation.

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TBA

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TBA

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Scenarios of inflationary magnetogenesis

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In this talk I will review the motivation behind the idea that the cosmic magnetic fields observed today were originated in some dynamics that occurred during inflation. I will then discuss the pros and cons of some of the most popular among these scenarios of inflationary magnetogenesis, with a particular focus on the role that might be played, in this context, by axionic degrees of freedom

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Statistical Mechanics of the Universe

Author: Jürg Fröhlich[1]

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To start with I summarize some key puzzles of cosmology to be clarified in the future. I then briefly sketch how to describe the geometry and the state of matter in the Universe after its inflationary

era. The main part of my talk is devoted to describing possible mechanisms for the generation of primordial magnetic fields in the Universe. These mechanisms are based on the chiral magnetic effect and a generalization thereof involving an axion. Time permitting I sketch ideas of how to explain the accelerated expansion of the Universe and the Matter-Antimatter Asymmetry.

Literature:

Papers with A. Alekseev and V. Cheianov (chiral magentic effect, 1D quantum wires, particle jets from rotating stars) (90's)
Paper with B. Pedrini (1999) (anomalies, chiral magnetic effect, axions, generation of magnetic fields)
Papers with A. Boyarsky and O. Ruchayskii (anomalies, chiral magnetic effect, axions, generation of magnetic fields)
(Papers with R. Brandenberger et al., Dark Matter & Dark Energy)

42

The Non-linear early Universe

Author: Daniel Figueroa[1]

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We review "Lattice Cosmology" techniques as a method to solve non-linear dynamics of interactive fields in an expanding Universe. As a demonstration we apply these ideas to solve two different problems of early Universe cosmology: i) the non-linear dynamics of axion inflation when backreaction of the produced gauge field becomes relevant, and ii) gravitational wave emission from (global and local) cosmic string loop dynamics

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Primordial Magnetic Fields from Preheating at the Electroweak Scale

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TBA

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How's Schwinger effect affect primordial Magnetogenesis?

Author: Tomohiro Fujita[1]

[1] *Waseda University*

The Schwinger effect is a non-perturbative phenomenon in QED in which an electric field stronger than a certain strength decays into charged particle pairs. In primordial magnetogenesis, especially

in inflationary magnetogenesis, the Schwinger effect can drastically change the dynamics of the electromagnetic fields and significantly alter theoretical predictions. However, until recently this effect has been often neglected. Even now that its importance has been recognized, reliable computational methods for it is yet to be established. In this talk, I will introduce several prescriptions proposed so far, including my own work, and discuss what we can do to elucidate a realistic mechanism of magnetogenesis that incorporates the Schwinger effect.

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Numerical simulations from reheating to turbulent MHD

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TBA

46

Production of chiral anomaly, dynamo instabilities and generation of turbulence

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The standard model of particles predicts the occurrence of a macroscopic quantum phenomenon named the chiral magnetic effect (CME) in plasmas with chiral, electrically charged particles. The CME implies an electric current along a magnetic field, which arises if there is an asymmetry in the chemical potentials of left- and right-handed fermions related to a chiral anomaly. This effect can be incorporated in the framework of magnetohydrodynamics, and leads to chiral dynamo instabilities, which can amplify magnetic energy by many orders of magnitude. The CME and the chiral dynamo instabilities have relevance for the early universe, neutron stars, quark-gluon plasmas, heavy ion collisions, and for quasi-particles in new materials such as graphene and Dirac semi-metals. In this talk, we discuss various effects related to production of a chiral anomaly, the excitation of a chiral dynamo instability, the production of magnetically driven turbulence, and the generation of a large-scale magnetic field via the magnetic alpha effect related to fluctuations of current helicity.

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Primordial Magnetic Fields, CMB and the Hubble tension

Author: Levon Pogosian[1]

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A stochastic primordial magnetic field (PMF), if present in the plasma prior to last scattering, would induce baryon inhomogeneities and speed up cosmic recombination. The consequently smaller sound horizon at last scattering, along with more subtle changes in recombination history, have a significant impact on the observed cosmic microwave background (CMB) temperature and polarization, and may help relieve the Hubble tension. Intriguingly, the strength of the magnetic field required to alleviate the Hubble tension happens to be of the right order of magnitude to also explain the observed magnetic fields in galaxies, clusters of galaxies and the intergalactic space. I will review this proposal and provide an update on its current status.

48

Modeling the galactic dynamo in the cosmological context

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TBA

49

Cosmic Recombination in the Presence of Primordial Magnetic Fields

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Primordial magnetic fields (PMFs) may explain observations of magnetic fields on extragalactic scales. They are most cleanly constrained by observations of details of the cosmic microwave background radiation (CMB). Their effects on cosmic recombination may even be at the heart of the resolution of the Hubble tension. Employing detailed MHD- and Monte-Carlo- simulations we present an analysis of the effects of PMFs on cosmic recombination taking into account of all so far known relevant physical processes. The simulations are compared to current CMB data showing that the existence of PMFs at recombination is consistent with the CMB data, while relieving the Hubble tension.

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Magnetism footprints in cosmological envirnments

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TBA

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Simulation CRs and Magnetic Filed evoluton in Cosmological Structures

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TBA

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Challenges in understanding primordial magnetic fields and its evolution (remote)

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TBA

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PMFs and their density perturbations through recombination

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TBA

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Magnetic reconnection in the early Universe

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TBA

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Probing primordial magnetic fields with 21 cm line observations

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TBA

57

New Models of the Coherent Galactic Magnetic Field

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Galaxies are known to be permeated by large-scale magnetic fields with energy densities comparable to the turbulent and thermal energy densities of the interstellar medium. A good knowledge of the global structure of these fields is important to understand their origin and to infer their effect on galactic dynamics and the propagation of charged particles in galaxies. In this talk I will present new studies of the global structure of the magnetic field of our Galaxy based on the analysis of recent new full-sky data of extragalactic rotation measures and the final polarized intensity maps from WMAP and Planck. The analysis employs the latest models for the thermal electron density tuned to the dispersion measures of Galactic pulsars and state-of-the-art cosmic-ray electrons models, needed to predict the rotation measures and synchrotron emission from the Galaxy, respectively. As a result, I will present a major revision of the widely-used Jannson-Farrar 2012 model of the magnetic field of the Galaxy. In addition to a fiducial magnetic field model, a suite of alternative models was studied that fit the data with similar quality, but use different model assumption. This suite of models is then used to place a lower limit on the model uncertainties. As an application, I will discuss the uncertainties of the predicted deflection of ultrahigh-energy cosmic rays in the Galaxy, in particular the origin of the extremely energetic "Amaterasu particle" recently reported by the Telescope Array Collaboration.

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Multimessenger constraints on intergalactic magnetic fields: quo vadis?

Author: Rafael Alves Batista[1]

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Recently, there has been a burgeoning interest in the exploration of intergalactic magnetic fields (IGMFs) through the use of multiple astrophysical messengers. In fact, this has prominently featured as a primary science case of gamma-ray and (ultra-high-energy) cosmic-ray observatories. While numerous studies have derived bounds on IGMFs, many of these results have been obtained under assumptions that do not reflect the true nature and distribution of these fields. Moreover, other potentially relevant effects have been neglected. In this presentation, I will discuss how certain limitations in the construction of models can impact the results, and explore strategies to mitigate modelling uncertainties when constraining IGMFs.

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Cosmic magnetic field probes with electromagnetic cascades and cosmic rays

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Weak relic magnetic fields produced in the early Universe can be probed through their influence on electromagnetic cascades in the relatively pristine environment of cosmic voids. Such electromagnetic cascades are initiated by powerful blazars and lead to gamma-ray spectra from GeV to TeV energies whose spectrum at Earth that are sensitive to cosmic magnetic fields, but also to pair beam plasma instabilities. We plan to present simulations based on the public code CRPropa that aim to disentangle these two effects on observed gamma-ray spectra.

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CR propagation in intermittent magnetic fields

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TBA

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Searching for Primordial Magnetism in the Cosmic Microwave Background with LiteBIRD

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LiteBIRD will map the Cosmic Microwave Background polarization on the whole sky with unprecedented accuracy, opening a whole new world of opportunities in cosmology. One of these is the study of primordial magnetism. In particular, the combination of the many signatures in CMB polarization of primordial magnetic fields and the sensitivity and cleanness of LiteBIRD data will enable the study of primordial magnetism from several points of view by using complementary effects and different data products. I will present how these different effects of primordial magnetic fields on the CMB can be used to provide constraints on their characteristics with LiteBIRD future data.

62

Observations of Magnetic Fields in the Large Scale Structure of the Universe (remote)

Author: Valentina Vacca[1]

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Precious information about the history of cosmological magnetic fields comes from their observation in the large scale structure of the Universe. Diffuse synchrotron emission represents a powerful tool to constrain the strength and geometry of the magnetic fields in clusters and in filaments of the cosmic web. A complementary probe is the Faraday effect on the signal of background radio sources, caused by clusters and filaments in front of the radio sources themselves. During this talk, I will present recent results on the study of magnetic fields in galaxy clusters and filaments, obtained with new generation instruments and advanced techniques of analysis and interpretation. I will present as well future perspectives with the SKA telescope.

64

CRPropa 3.2 - a public framework for high-energy astroparticle simulations

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In this contribution, we introduce CRPropa 3.2, a Monte Carlo framework revolutionizing the simulation of (ultra-)high-energy particle propagation in the Universe. Encompassing cosmic rays, gamma rays, electrons, and neutrinos across a vast energy spectrum, from ZeV to GeV for gamma rays and electrons, and TeV for cosmic rays and neutrinos, CRPropa 3.2 represents a significant leap towards a universal multi-messenger platform. Noteworthy enhancements include extensions for simulating cosmic-ray acceleration and particle interactions within astrophysical source environments, a comprehensive Monte Carlo treatment of electromagnetic cascades, refined ensemble-averaged Galactic propagation, and substantial performance improvements in cosmic-ray tracking through magnetic fields. The framework's versatility is showcased through applications in diverse astrophysical environments, such as the surroundings of astrophysical sources, galactic, and extragalactic landscapes. With a user-friendly implementation of custom photon fields, CRPropa 3.2 opens up possibilities for tailored simulations. This contribution offers an overview of the framework's new features and presents applications focusing on cosmic-ray and gamma-ray propagation, with a specific emphasis on aspects crucial for researching Intergalactic and Galactic Magnetic Fields.

65

CMB spectral distortions meet PMFs

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CMB spectral distortions provide a new window to early-universe and particle physics. This opens new ways to constrain the amplitude of fluctuations at small scales and also during the cosmological recombination era. In my talk, I will highlight some of the exciting opportunities for constraining the effects of PMFs on the CMB spectrum and how this might allow us to shed new light on the Hubble tension and the origin of primordial black holes and magnetic fields.

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IceCube/CTAO

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TBA

67

Probing the intergalactic magnetic field through gamma-ray observations

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Magnetic fields in galaxies and galaxy clusters are believed to be the result of the amplification of seed fields during structure formation. However, the origin of this intergalactic magnetic field (IGMF) remains unknown. Observations of high-energy gamma rays from distant sources offer an indirect probe of the IGMF. Gamma-rays interact with the extragalactic background light to produce electron-positron pairs, which can subsequently initiate electromagnetic cascades whose gamma-ray signature depends on the IGMF. The absence of the cascade signal has been used to place lower bounds on the IGMF. In this overview, I will introduce the method of how to search for this cascade emission using spectral, spatial, and timing information of the signal, and review recent results and highlights. I will also discuss sources of uncertainties regarding predictions of the cascade and provide an outlook for the potential of future gamma-ray observations, in particular with the upcoming Cherenkov Telescope Array.

68

Primordial magnetogenesis from electroweak dumbbells

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The "electroweak dumbbell"consists of a magnetic monopole and an antimonopole of the standard electroweak model connected by a string made of Z−magnetic field. We have scrutinized the structure of static electroweak dumbbells using "constrained relaxation"for a range of separations and twists, and find that dumbbells with a twist have a novel magnetic field structure. Using the relaxed field configurations, we simulated the annihilation of dumbbells, studying their lifetimes and relics. In particular, we find that the relic magnetic field in the twisted case is helical. The topology of electroweak theory gives rise to monopole pairs that are confined by strings, whose distribution we have determined by an extension of the Kibble mechanism. These monopole-antimonopole pairs would undergo annihilation and leave behind cosmological relic magnetic fields during the epoch of electroweak symmetry breaking (EWSB) in the early Universe. For a general pair of monopole and antimonopole, the twist angle will be non-zero and the magnetic field lines emanating from a monopole will terminate on an antimonopole of some other dumbbell. This is likely to have consequences for the correlation length of magnetic fields leftover from the electroweak epoch. We conduct EWSB simulations to examine the generated primordial magnetic field. This could carry important implications for the cosmological magnetic field properties in the present Universe and provide a new avenue to constraint electroweak phenomena.

69

Rethinking Recombination: Primordial Magnetic Fields and the Hubble tension

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Perhaps the most significant challenge to the widely successful Lambda-CDM theory is the disagreement between late and early Universe measurements of the present day Hubble expansion rate (H0), referred to as the Hubble tension. One of the ways to resolve the Hubble tension is to modify the recombination history of the early universe. An intriguing proposal to realize this invokes primordial magnetic fields (PMFs) to stir up the plasma on small scales and speed up recombination. An earlier recombination shrinks the sound horizon at the surface of last scattering and consequently increases the early Universe inference of H0. On the small scales at which PMFs introduce baryon clumping, the nonlocal transport of photons in the Lyman-alpha resonance and Lyman-continuum, which mediate the recombination process, becomes important. Utilizing a linearized scheme for magnetohydrodynamics in the early Universe, our work provides a self-consistent and computationally inexpensive treatment of the evolution of PMF-induced small-scale inhomogeneities from magnetogensis to and through Recombination incorporating nonlocal radiative transport.

70

Efficient subsonic turbulent dynamo during cosmic RD era

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TBA

71

Scalar perturbations from inflationary magnetogenesis

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Primordial non-Gaussianities, though yet unobserved, remain an important observable since they can help differentiate various models of inflation. This necessitates a deep understanding of the various processes that could contribute to these non-Gaussianities, with inflationary magnetogenesis being one of them. Often, the spectrum and the bispectrum of the perturbations produced during inflation are studied under the assumption that the metric perturbations can be neglected and that all the relevant physics resides in the coupling of the inflaton and the gauge fields. Here, we present a full set of equations self-consistently accounting for the perturbations of the inflaton and the gauge field along with the scalar perturbations of the metric. In this talk, I will specifically consider the case of axion inflation with purely axial coupling of the inflation to the gauge fields. I will compare the scalar power spectrum and bispectrum derived from our equations to those reported in earlier literature. In particular, by comparing the amplitude of the scalar bispectrum with modern observational constraints for primordial non-Gaussianity, I will reconcile the existing constraints for the axion-vector coupling during inflation.

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Stochastic effects in Helical Magnetic Fields from Inflation

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Using the stochastic formalism, we study the helical magnetic fields during an inflationary period, which is the result of the tachyonic growth of the gauge field. By considering the stochastic effects to the field's perturbations, we obtain the corresponding Langevin equations as well as the Fokker-Planck partial differential equation in the presence of the electric conductivity and then, study the evolution of the model. We analyze how these stochastic effects will modify the amplitude of the electric and magnetic fields at the end of inflation. We also discuss the observational constraints on the magnetic fields at the present time and search the parameter space of the model where the constraints are satisfied.

73

Multi-messenger signatures of cosmological magnetic fields

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In this talk I'll review recent developments in the measurements of intergalactic magnetic fields in the voids of large scale structure with gamma-ray telescopes and by ultra-high energy cosmic ray detectors.

74

Fluid and Magnetic Spectra in First-Order Phase Transitions

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First-Order Phase Transitions in the early universe can be an important source for a Stochastic Gravitational Wave Background (SGWB). All particle sectors can contribute to it: the scalar sector through quantum fluctuations and collision of true vacuum bubbles, the fermionic sector, usually considered within a fluid description, through fluid longitudinal perturbations leading, after bubble collision, to sound waves and the gauge sector (magnetic fields) through the coupling with the fluid and the development of (magnetohydrodynamic) turbulence. In the present talk I will focus on the fluid and magnetic contributions to a SGWB showing the important role that two- and four-point correlators of fluid velocity and magnetic fields cover in the analytical determination of the final GW spectrum.

75

Magnetogenesis form axion-U(1) preheating

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I will review the numerical results that demonstrate efficient preheating of an axion-inflaton to photons and the prospects for magnetogenesis. I will also discuss possible correlated observables and possible connections to SM and BSM physics.

Course "Simulations of Early Universe Magnetohydrodynamics" day 1 / 76

Theory lecture 1a. Fluid dynamics

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Theory lecture 1b. Fluid dynamics

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Practice session 1. Sound waves

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Course "Simulations of Early Universe Magnetohydrodynamics" day 2 / 79

Theory lecture 2. MHD

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Course "Simulations of Early Universe Magnetohydrodynamics" day 2 / 80

Theory lecture 3. Turbulence

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Introduction

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Practice session 2a. MHD waves

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Practice session 3. Driven turbulence

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Course "Simulations of Early Universe Magnetohydrodynamics" day 3 / 84

Lecture 5. Cosmology

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Lecture 6a. MHD in an expanding universe

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Lecture 6b. MHD in an expanding universe

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Practice session 4. MHD decaying turbulence

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Course ”Simulations of Early Universe Magnetohydrodynamics” day 4 / 88

Lecture 7. Magnetic chiral dynamo

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Lecture 8. Gravitational waves

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Course ”Simulations of Early Universe Magnetohydrodynamics” day 4 / 90

Practice session 5. Chiral dynamo

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Practice session 6. Gravitational waves

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Lunch break

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Coffee break

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Practice session 2b. MHD waves

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Course ”Simulations of Early Universe Magnetohydrodynamics” day 4 / 95

Practice session 5. Chiral dynamo

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Welcome and registration

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Welcome

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Welcome

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Welcome reception

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On adiabatic renormalization and Gauge invariant backreaction in U(1)-axion inflation

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I describe a new approach to renormalize physical quantities in curved space-time introducing a comoving infrared cut-off in defining the adiabatic counterpart of the physical quantity under consideration. This infrared cut-off is fundamental to avoid unphysical divergences that can be generated by a pathological behavior of the adiabatic subtraction extended to the infrared domain. Applying such formalism to symptomatic case of U(1)-axion inflation model, we evaluate properly the expectation value of gauge contribution setting the cut-off by the conformal anomaly. We then evaluate the quantum backreaction due to gauge field. The backreaction is evaluated using a gauge invariant approach, taking in consideration inflaton fluctuations as well as scalar perturbations of the metric.