Production of baryon asymmetry and relic gravitational waves by random hypermagnetic fields

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References

- M. Dvornikov, Impact of hypermagnetic fields on relic gravitational waves, neutrino oscillations and baryon asymmetry, to be published in Int.J.Mod.Phys.D, arXiv:2203.00530
- M. Dvornikov, Gravitational waves generation in turbulent hypermagnetic fields before the electroweak phase transition, JCAP 01 (2022) 021, arXiv:2110.04214
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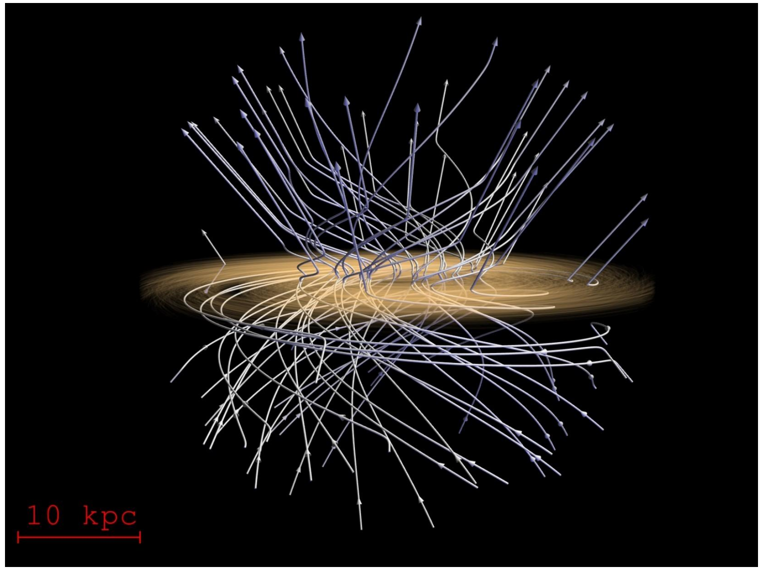
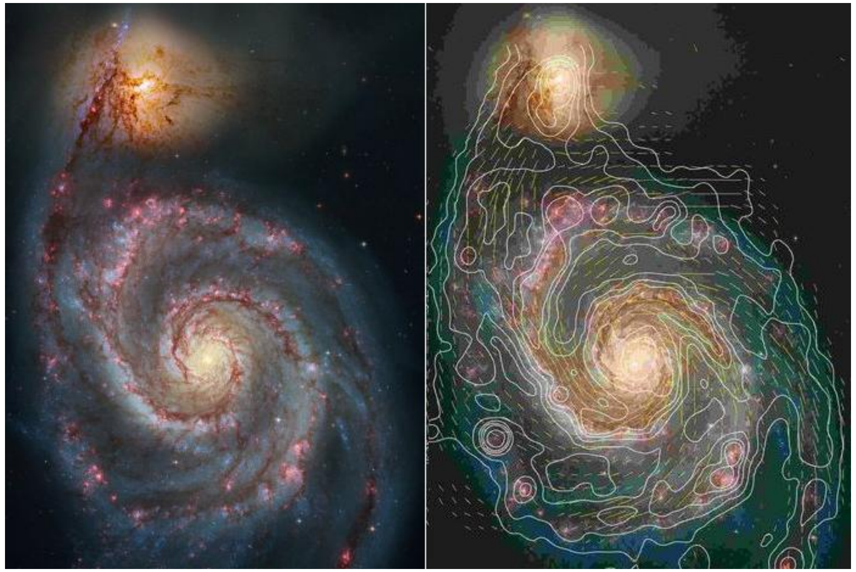
Plan of talk

- Introduction
- Properties of hypercharge field
- Anomalies
- Formulation of the problem: spectra, hypermagnetic field (HMF) dynamics, initial condition
- Relic gravitational waves (GWs) produced by random HMFs
- Generation of baryon asymmetry of the universe (BAU) by stochastic HMFs
- Summary

Origin of cosmic magnetic fields

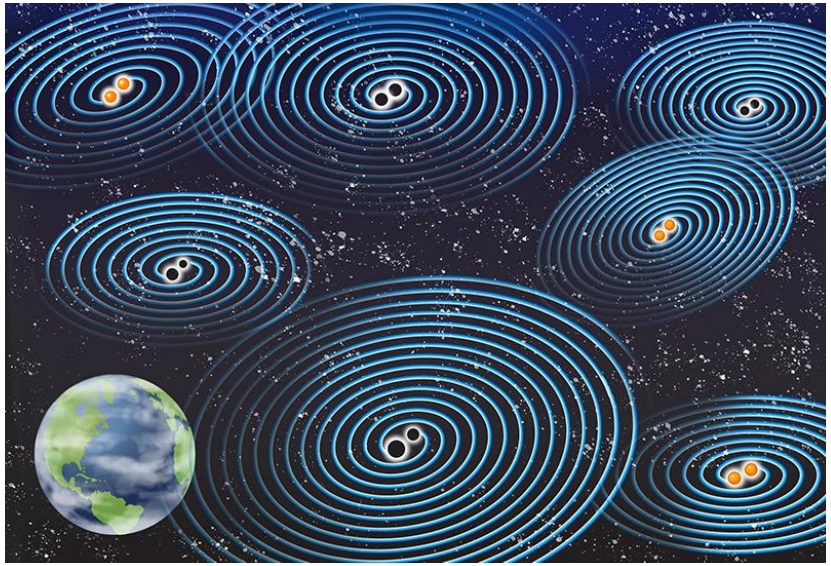
- Neronov & Vovk (2010) suggested that there are large scale magnetic fields with $B \sim 10^{-16} G$ in intergalactic space
- Standard electrodynamics cannot explain the generation of such magnetic fields after the structure formation
- These magnetic fields can originate from the early universe





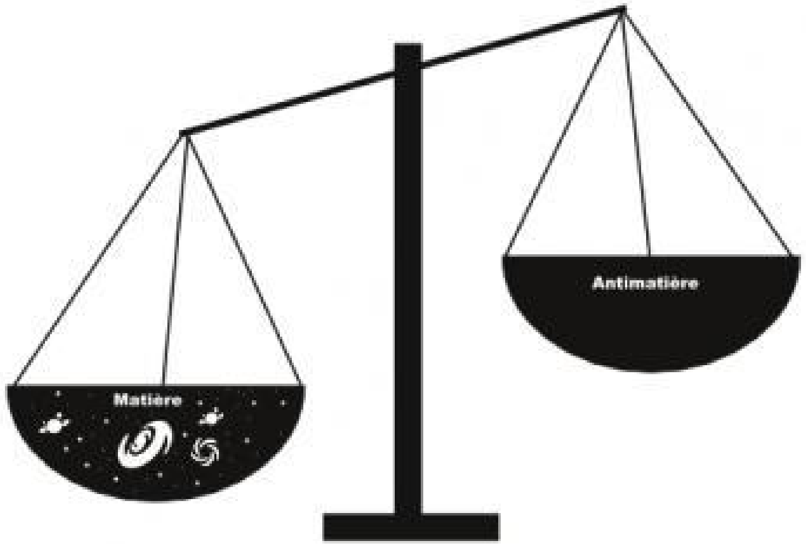
- Various mechanisms for the generation of cosmological magnetic fields were reviewed by Durrer & Neronov (2013); Subramanian (2016)
- Present days Maxwell magnetic fields can originate from HMFs existing before electroweak phase transition

Relic GWs and BAU



- LIGO-Virgo collaborations (2016) directly detected GWs from merging binary black holes
- NANOGrav collaboration (2020) claimed the observation of stochastic GW background
- Various physics processes in the early universe (see, e.g., Caprini & Figueroa, 2018) can be sources of stochastic GWs
- Kosowsky et al. (2002) studied the production of relic GWs in the relic primordial magnetized plasma

- We have more matter than antimatter in our universe: BAU is nonzero
- The generation of BAU is a long standing issue of cosmology and particle physics
- Numerous models of lepto- and baryogenesis are reviewed by Buchmüller et al. (2005)
- Joyce & Shaposhnikov (1997) proposed the model of lepto- and baryogenesis in primordial HMFs



Hypermagnetic fields

Before EWPT (T = 100 GeV)

Particles are massless, including Z-boson

Hypercharge field is a long range (massless) analogue of the Maxwell field

$$Y^{\mu} = \sin\theta_W Z^{\mu} + \cos\theta_W A^{\mu}$$

Field tensor has hyperelectric and hypermagnetic strengths

$$F_{\mu\nu} = (\mathbf{E}_Y, \mathbf{B}_Y) \quad \mathbf{B}_Y = (\nabla \times \mathbf{Y})$$

After EWPT (T = 100 GeV)

EWPT (crossover) happens at T = 100 GeV. Particles become massive

Hypercharge field is a source of Maxwell field

$$Y^{\mu}(T = 100\ \mathrm{GeV}) = A^{\mu}$$

Usual Maxwell equations are valid

Anomalies of hypercharge fields

Divergence of axial current of massless fermions is nonzero in the presence of hypercharge field (analogue of the Adler-Bell-Jackiw anomaly)

$$\partial_\mu j_5^\mu = \partial_\mu j_R^\mu - \partial_\mu j_L^\mu = \frac{g^2}{2\pi^2}(\mathbf{E}_Y \mathbf{B}_Y)$$

A nonzero current is generated in the presence of the hypermagnetic field and the chiral imbalance (analogue of the chiral magnetic effect; Vilenkin, 1980)

$$\mathbf{J} = \frac{g^2}{2\pi^2}\mu_5 \mathbf{B}_Y = \Pi_{CME}\mathbf{B}_Y,\ \Pi_{CME} = \frac{g^2}{4\pi^2}(\mu_R - \mu_L)$$

Hypermagnetic field becomes unstable (dynano amplified) in this case

Spectra of stochastic HMFs

HMFs are affected by stochastic motion of primordial plasma

Using the mean field approximation, the hypermagnetic energy is

$$E_Y = {B_Y^2}/_2 = \int dk \rho_Y(k, t)$$

Topology of HMFs is described by the hypermagnetic helicity

$$H_Y = \int d^3x (\mathbf{YB}_Y) = \int dk h_Y(k, t)$$

The evolution of HMFs is expressed in terms of the spectra $\rho_Y(k, t)$ and $h_Y(k, t)$

Factors affecting the HMFs dynamics

- Abelian anomalies for the assymetries of right electrons (main contribution; Giovannini & Shaposhnikov, 1997), left leptons (electrons and neutrinos), and of Higgs bosons
- Analog of the CME
- Sphaleron effects
- Analog of the MHD turbulence (Sigl, 2002; Campanelli, 2007) to take into account the random nature of HMFs

Eventually, Dvornikov & Semikoz (2021); Dvornikov (2022) derived the closed system of kinetic equations for the spectra of HMFs and the asymmetries of all leptons and bosons

Initial condition

The evolution of HMFs starts at T = 10 TeV. Below this temperature, the production of left fermions becomes possible (Campbell et al., 1992)

At T = 10 TeV, the IR part (small k) of the seed spectrum is of Batchelor type $\propto k^4$. The UV part (great k) is of Kolmogorov type $\propto k^{-5/3}$

The maximal (conformal) mometum (inversed minimal length scale) is $k_{max} = (10^{-3} - 10^{-2})$. Such momenta are still below the Debye one

The IR and UV parts are glued at $k_* = (10^{-3} - 10^{-2})k_{max}$

The strength of the conformal seed HMF is $B_Y^{(0)} = (10^{-6} - 10^{-1})$. It is below the constraint of BBN nycleosynthesis

The seed asymmetry of right electrons is $(10^{-9} - 10^{-10})$

Interaction between gravitational and hypermagnetic fields

Einstein equaton in an expanding Universe in presence of HMF

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu} \quad T_{ij} =- \frac{1}{a^2}\left(B_{Yi}^{(c)} B_{Yj}^{(c)} - \frac{1}{2}\delta_{ij} B_Y^{(c)2}\right)$$

We study the Friedmann-Robertson-Walker metric perturbation under the influence of HMF

$$g_{\mu\nu} = \overline{g}_{\mu\nu} + h_{\mu\nu} \quad \overline{g}_{\mu\nu} = diag(1, -a^2, -a^2, -a^2)$$

Thus, evolving HMFs can produce, e.g., gravitational waves (GWs)

We track the production of GWs from $T_{RL} = 10\ TeV$ down to $T_{EWPT} = 100\ GeV$

Detailes of the derivation

The metric perturbation is $h_{ij} = a^2 D_{ij}$

Using transverse-traceless gauge, we get

$$D_{ij}'' + 2HD_{ij}' + k^2 D_{ij} = f_{ij},$$

where f_{ij} is the properly projected energy-momentum tensor

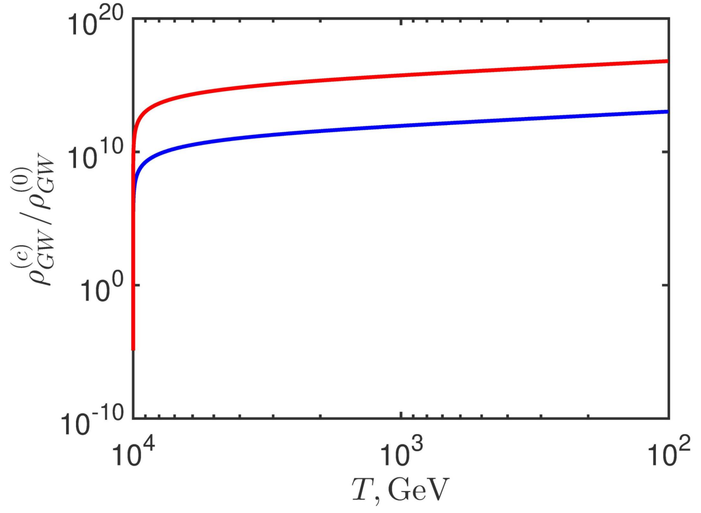
The effective energy-momentum tensor of GW is $t_{\mu\nu} = \frac{1}{32G}\langle \partial_\mu h_{\alpha\beta} \partial_\nu h^{\alpha\beta} \rangle$

After the propper averaging over the source (HMFs), we get the conformal energy density of GWs as $\rho_{GW}^{(c)}(\eta) \propto t_{00}$

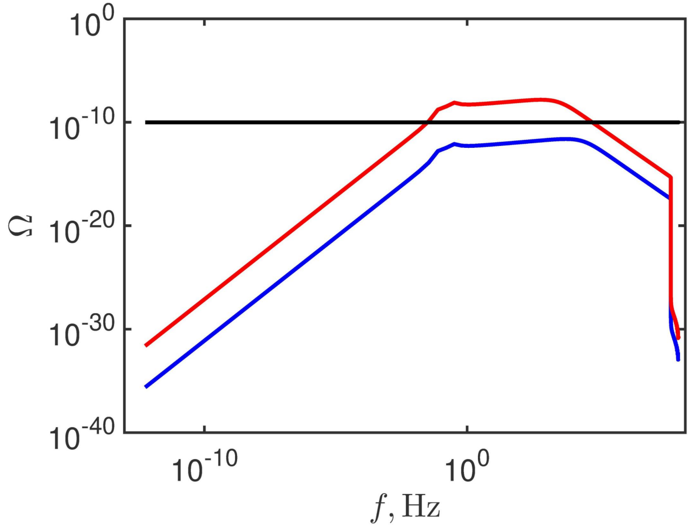
We also get the spectrum of the energy density $\rho_{GW}^{(c)}(\eta, k)$. It can be expressed in terms of the spectra of HMFs: $\rho_Y(k, t)$ and $h_Y(k, t)$

Production of relic GWs by random HMFs

Using the transverse-traceless gauge and properly averaging over the source, Dvornikov (2022) obtained the conformal spectrum and the energy density of relic GWs



The measurable quantity is $\Omega = \frac{1}{\rho_{crit}} \frac{d\rho_{GW}}{d\ln f}$



Using the results of LIGO-Virgo-KAGRA Collaborations (2021), $\Omega_{obs} < 10^{-10}$, we get the constrant on $B_Y^{(0)} < 10^{-1}$

Baryon asymmetry

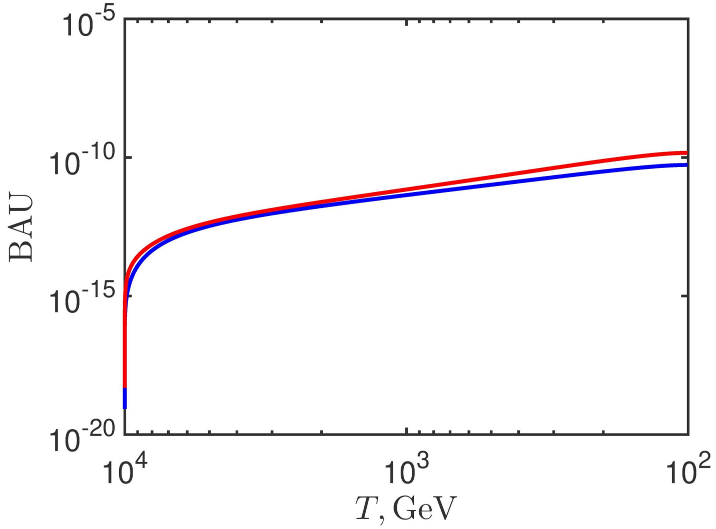
Evolution of HMFs is driven by lepton asymetries. They contribute to the analogue of the CME

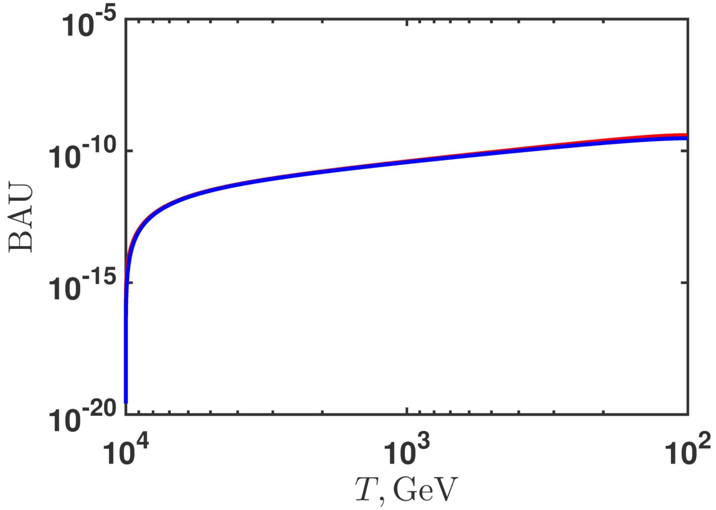
HMFs influence the asymmetries through the abelian anomaly, i.e. lepton number changes

Using 't Hooft conservation law, B - L = const, we get that $BAU = \frac{n_B - n_{\overline{B}}}{s}$ will change under the influence of HMFs

We study the generation of BAU from $T_{RL} = 10\ TeV$ down to $T_{EWPT} = 100\ GeV$

Using value of the observed   BAU = 10^{-10}, we establish the stronger constraint on $B_Y^{(0)} < 10^{-6}$





Summary

We studied HMFs having the Batchelor (IR) and Kolmogorov (UV) seed spectra

Abelian anomaly and the analogue of the CME, as well as the (H)MHD turbulence were accounted for

We track the evolution of such HMFs from $T_{RL} = 10\ TeV$ down to EWPT

Using the obtained behavior of random HMFs and the lepton asymmetries, we studied the production of relic GWs and BAU

These results allowed us to establish the constraints on the strength of seed HMFs