Activity report based on CPU time and storage used on PDC and NSC of 2022/2023

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In this activity report, we describe and list some highlights of the 29 papers that all acknowledge SNAC. Out of those, 3 are submitted, 1 is in press, 19 were from 2023, and another 10 were already published in 2022. For the calculations, we use the code Runko and the Pencil Code, both of which are hosted on github (`https://github.com/natj/runko` and `https://github.com/pencil-code`). The Pencil Code Collaboration consists of currently 38 developers who have published their effort in JOSS, the Journal of Open Source Software **6**, 2807 (2021).

Here and below, the 3-digit numbering of the papers coincides with that of Brandenburg's full list of publications on `http://www.nordita.org/~brandenb/pub`. Those preceded by the letter B are also in that list, but under invited conference proceedings. All the papers quoted below acknowledge SNIC, PDC, and/or NSC.

1 Shocks and turbulence in collisionless astrophysical plasmas

Many astrophysical plasmas are extremely diluted and, hence, appear almost collisionless. In order to investigate such plasmas that are beyond the validity regime of MHD, we in Nordita have developed a new open-source particle-in-cell (PIC) simulation code Runko [1]. The main focus of the code is to perform self-consistent fully-kinetic studies of non-thermal particle acceleration in collisionless plasmas.

Under a strong radiation field (such as close to black holes) the turbulence dynamics is altered due to strong radiative cooling. In order to understand the non-linear behavior of turbulent plasma in such a strong radiation environment, we have performed pioneering radiative kinetic turbulence simulations [2]. This in turn, will help us understand, for example, particle acceleration and heating of diluted plasmas near black holes and neutron stars.

In realistic astrophysical environments, one can expect the upstream plasma not to be homogeneous as assumed in these studies but, to present perturbations or even to be turbulent. How upstream turbulence affects the shock properties and particle acceleration is to date an open question. Using the Runko code, we have studied how a relativistic magnetized shock responds to upstream density perturbations and found, unlike previous works, evidence of particle acceleration [3].

We have also investigated the conversion from electric to magnetic energies, which is relevant to the epoch of reheating in the early Universe [446].

The following papers presenting our results have appeared:

[1] Nättilä, J.: 2022, "Runko: Modern multiphysics toolbox for plasma simulations," *Astron. & Astrophys.*, **664**, A68.

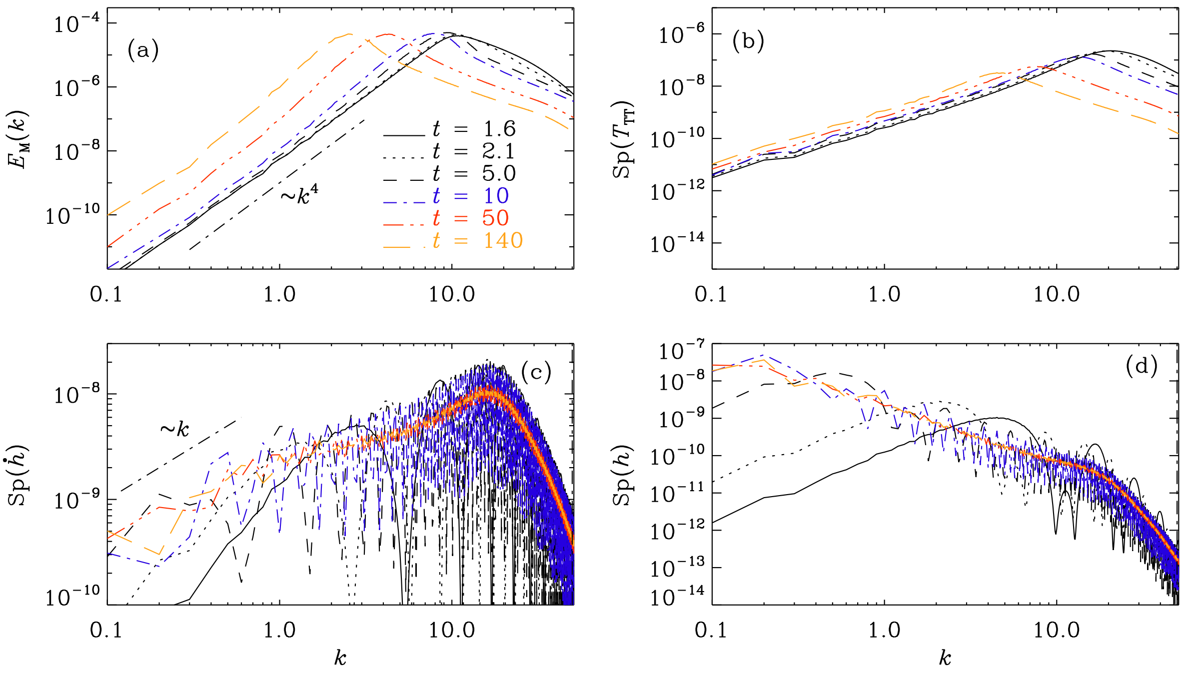

Figure 1: Spectra of the magnetic field, the TT-projected stress, the strain derivative, and the strain for suddenly initiated turbulence with magnetic helicity.

[2] Pjanka, P., Demidem, C., Veledina, A.: 2023, "Shock Corrugation to the Rescue of the Internal Shock Model in Microquasars: The Single-scale Magnetohydrodynamic View," *Astrophys. J.* **947**, 57

[3] Demidem, C., Nättilä, J., & Veledina, A.: 2023, "Relativistic Collisionless Shocks in Inhomogeneous Magnetized Plasmas," *Astrophys. J. Lett.* **947**, L10

446. Brandenburg, A., & Protiti, N. N.: 2023, "Electromagnetic conversion into kinetic and thermal energies," *Entropy* **25**, 1270

2 Gravitational waves and early universe magnetic fields

An important activity involves the computation of the stochastic gravitational wave background from the Big Bang. Those can be measured in future with LISA and the pulsar timing array. We have continued studying the chiral magnetic effect and have now calculated the resulting GW production [451]. We have also studied in more detail the circular polarization of gravitational waves from early-universe helical turbulence [426]. In [442], we computed the effects of departures from general relativity on the spectrum of turbulence-sourced gravitational waves. We have now also studied in more detail the low frequency tail of gravitational wave spectra from hydromagnetic turbulence [434]; see also Figure 1, where we show spectra of the magnetic field, the traceless-transverse-projected stress, the strain derivative, and the strain for suddenly initiated turbulence with magnetic helicity. The accuracy of the so-called sound-shell model of gravitational wave production is examined in [453], where we also find a new source of departures.

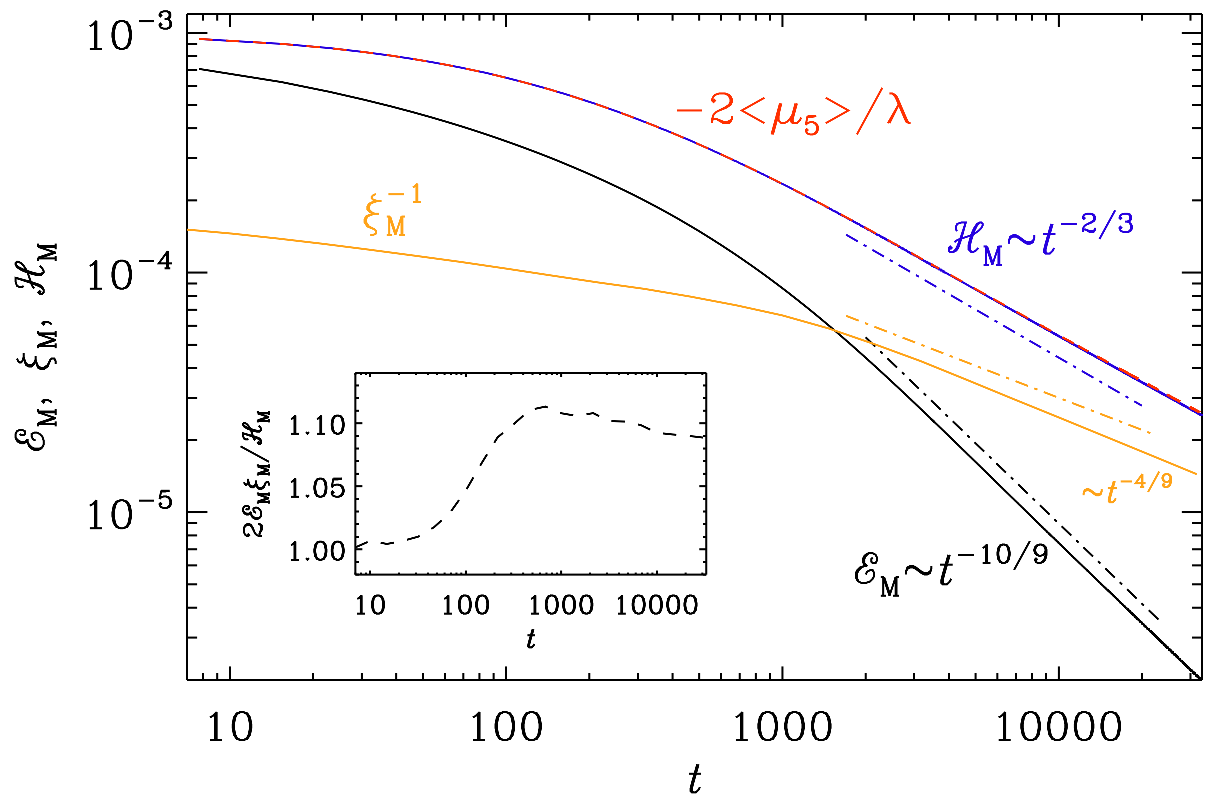

Figure 2: Time dependence of $\mathcal{E}_\mathrm{M}$ (black), ξ_M (orange), $\mathcal{H}_\mathrm{M}$ (blue), and $-2\langle\mu_5\rangle/\lambda$ (red). The inset confirms that $2\mathcal{E}_\mathrm{M}\xi_\mathrm{M}/\mathcal{H}_\mathrm{M} \approx 1$ during the whole time.

453. Sharma, R., Dahl, J., Brandenburg, A.,i & Hindmarsh, M.: 2023, "Shallow relic gravitational wave spectrum with acoustic peak," *J. Cosmol. Astropart. Phys.*, submitted (arXiv:2308.12916)

451. Brandenburg, A., Clarke, E., Kahniashvili, T., Long, A. J., & Sun, G.: 2023, "Relic gravitational waves from the chiral plasma instability in the standard cosmological model," *Phys. Rev. D*, submitted (arXiv:2307.09385)

442. He, Y., Roper Pol, A., & Brandenburg, A.: 2023, "Modified propagation of gravitational waves from the early radiation era," *J. Cosmol. Astropart. Phys.* **06**, 025

434. Sharma, R., & Brandenburg, A.: 2022, "Low frequency tail of gravitational wave spectra from hydromagnetic turbulence," *Phys. Rev. D* **106**, 103536

429. Kahniashvili, T., Clarke, E., Stepp, J., & Brandenburg, A.: 2022, "Big bang nucleosynthesis limits and relic gravitational wave detection prospects," *Phys. Rev. Lett.* **128**, 221301

426. Roper Pol, A., Mandal, A., Brandenburg, A., & Kahniashvili, T.: 2022, "Polarization of gravitational waves from helical MHD turbulent sources," *J. Cosmol. Astropart. Phys.* **04**, 019

3 Turbulent decay and Hosking integral

A major development of the last year concerns the Hosking integral. It is the correlation integral of the magnetic helicity density. It is conserved and gauge-invariant [433]. In MHD, its dimensions are $\mathrm{cm}^9\,\mathrm{s}^{-4}$, but for the Hall cascade, the dimensions are $\mathrm{cm}^{13}\,\mathrm{s}^{-4}$, which has consequences on the decay [439]. Yet another remarkable situation occurs in chiral MHD [440.450]. To understand the resulting decay, it is important to remember that the real space realizability condition of magnetic helicity $\mathcal{H}_\mathrm{M}$ is always valid and implies $|\mathcal{H}_\mathrm{M}| \leq 2\mathcal{E}_\mathrm{M}\xi_\mathrm{M}$, where $\mathcal{E}_\mathrm{M}$ is the magnetic energy density and ξ_M the correlation length. Assuming the inequality to be saturated, we find the scaling $|\mathcal{H}_\mathrm{M}| \propto |\langle\mu_5\rangle| \propto t^{-r}$ with $r = p - q = 2/3$, where μ_5 is the chiral chemical potential. This is indeed well obeyed, as is shown in Figure 2. In the inset, we show that $2\mathcal{E}_\mathrm{M}\xi_\mathrm{M}/\mathcal{H}_\mathrm{M} \approx 1$ at early times and about 1.1 at late times. It is thus fairly constant, therefore confirming the validity of our underlying assumption. On top of this evolution of the chiral asymmetry, the growth rate of the CPI, $\gamma_5 \propto \langle\mu_5\rangle^2 \propto t^{-4/3}$, decays more rapidly than t^{-1}, which causes it to grow less efficiently so as not to spoil the scaling properties of the system.

The conservation of the Hosking integral is not restricted to an initial k^4 spectrum [441], but can also occur for shallower spectra [448].

450. Brandenburg, A., Sharma, R., & Vachaspati, T.: 2023, "Inverse cascading for initial MHD turbulence spectra between Saffman and Batchelor," *J. Plasma Phys.*, submitted (arXiv:2307.04602)

448. Brandenburg, A., Kamada, K., Mukaida, K., Schmitz, K., & Schober, J.: 2023, "Chiral magnetohydrodynamics with zero total chirality," *Phys. Rev. D* **108**, 063529

441. Brandenburg, A., & Larsson, G.: 2023, "Turbulence with magnetic helicity that is absent on average," *Atmosphere* **14**, 932

440. Brandenburg, A., Kamada, K., & Schober, J.: 2023, "Decay law of magnetic turbulence with helicity balanced by chiral fermions," *Phys. Rev. Res.* **5**, L022028

439. Brandenburg, A.: 2023, "Hosking integral in nonhelical Hall cascade," *J. Plasma Phys.* **89**, 175890101

433. Zhou, H., Sharma, R., & Brandenburg, A.: 2022, "Scaling of the Hosking integral in decaying magnetically-dominated turbulence," *J. Plasma Phys.* **88**, 905880602

4 Dynamo action in the Sun and Galaxies

To connect our early Universe simulations discussed above with the later cosmological evolution, we have now performed simulations of large-scale structure formation with realistic magnetic fields [427,438]. We have also studied the dynamo effect in self-gravitating turbulence [428], and found that most of the amplification comes from the vortical contribution that is amplified during the gravitational collapse. In [445], we studied α-type dynamo in non-equilibrium turbulence. A major reviews of galactic dynamos has appeared in [443], and one on the Sun in [447].

447. Brandenburg, A., Elstner, D., Masada, Y., & Pipin, V.: 2023, "Turbulent processes and mean-field dynamo," *Spa. Sci. Rev.* **219**, 55

445. Mizerski, K. A., Yokoi, N., & Brandenburg, A.: 2023, "Cross-helicity effect on α-type dynamo in non-equilibrium turbulence," *J. Plasma Phys.* **89**, 905890412

443. Brandenburg, A., & Ntormousi, E.: 2023, "Galactic Dynamos," *Annu. Rev. Astron. Astrophys.* **61**, 561–606

438. Mtchedlidze, S., Domínguez-Fernández, P., Du, X., Schmidt, W., Brandenburg, A., Niemeyer, J., & Kahniashvili, T.: 2023, "Inflationary and phase-transitional primordial magnetic fields in galaxy clusters," *Astrophys. J.* **944**, 100

428. Brandenburg, A., & Ntormousi, E.: 2022, "Dynamo effect in unstirred self-gravitating turbulence," *Mon. Not. Roy. Astron. Soc.* **513**, 2136–2151

427. Mtchedlidze, S., Domínguez-Fernández, P., Du, X., Brandenburg, A., Kahniashvili, T., O'Sullivan, S., Schmidt, W., & Brüggen, M.: 2022, "Evolution of primordial magnetic fields during large-scale structure formation," *Astrophys. J.* **929**, 127

5 Axionlike particle–photon conversion in MHD simulations

The conversion of axionlike particles (ALPs) and photons in magnetized astrophysical environments such as galaxy clusters provides a promising route to search for ALPs. We have presented the first systematic study of ALP–photon conversion in more realistic, turbulent fields from dedicated magnetohydrodynamic (MHD) simulations [449], which we compare with Gaussian random field (GRF) models. We find that the MHD models agree with the exponential law for typical, small-amplitude mixings but exhibit distinctly heavy tails for rare and large mixings. We explain how non-Gaussian, local spikes in the MHD magnetic field are mainly responsible for the heavy tail. The results indicate that limits placed on ALPs using GRFs are conservative but that MHD models are necessary to reach the full potential of these searches.

449. Carenza, P., Sharma, R., Marsh, M. C. D., Brandenburg, A., Müller, E.: 2023, "Magnetohydrodynamics predicts heavy-tailed distributions of axion-photon conversion," *Phys. Rev. D*, in press (arXiv:2208.04333)

6 Small-scale dynamo turbulence

We have continued to study small scale dynamos both in forced and decaying non-helical turbulence and have shown that the Hosking integral, describing the correlation of magnetic helicity fluctuations, this gauge-invariant and conserved in non-helical turbulence [439]. In driven turbulence, the small-scale dynamo develops a $k^{3/2}$ Kazantsev spectrum, which is well known. We have now shown that in the kinematic regime of the dynamo, it connects to a very steep k^4 Batchelor spectrum, which turns to a shallower k^2 Saffman spectrum as the dynamos saturates. The turning point is the integral of scale of turbulence. We have studied its diagnostics properties in terms of the rotational invariant E and B polarizations [435]. To our surprise, the two are very different from each other, especially at large magnetic Prandtl numbers Pr_M, which is 30 in Figure 3. In [441], we also show that the ratio of wavenumber of dissipative to viscous structures is $k_\eta/k_\nu = (\mathrm{Pr}_M/\mathrm{Pr}_M^{\mathrm{crit}})^{1/2}$, where $\mathrm{Pr}_M^{\mathrm{crit}} \approx 0.27$.

436. Brandenburg, A., Rogachevskii, I., & Schober, J.: 2023, "Dissipative magnetic structures and scales in small-scale dynamos," *Mon. Not. Roy. Astron. Soc.* **518**, 6367–6375

435. Brandenburg, A., Zhou, H., & Sharma, R.: 2023, "Batchelor, Saffman, and Kazantsev spectra in galactic small-scale dynamos," *Mon. Not. Roy. Astron. Soc.* **518**, 3312–3325

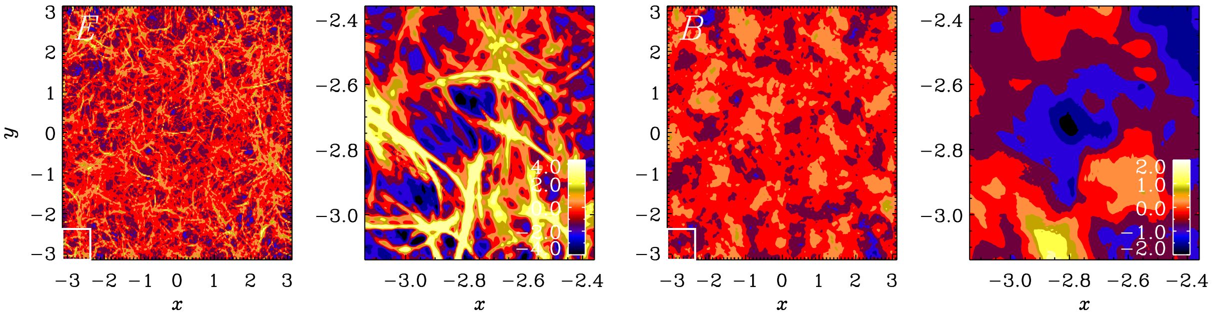

Figure 3: Diagnostic slices of E (left 2 panels), and B (right two panels), for a run with $\mathrm{Pr}_M = 30$ during the kinematic stage. The small white squares on the left column mark the part that is shown enlarged on the right column. All quantities are normalized by their rms value and the color bars for the enlarged frames are clipped at ±2 times the rms value, while those for the full frames are clipped at ±4 times the rms value.

7 Particles in Turbulence

We have started a new project on the spectral characterization of inertial particle clustering in turbulence. We have found spectra to be an excellent tool to identify *different* and *new* mechanisms of particle clustering in supersonic turbulence [423]. We have also now completed several papers on the subject of multi-dimensional condensation and coagulation. Finally, we have characterized the importance of fluctuations in dilute systems [431].

431. Li, X.-Y., Mehlig, B., Svensson, G., Brandenburg, A., & Haugen, N. E. L.: 2022, "Collision fluctuations of lucky droplets with superdroplets," *J. Atmos. Sci.* **79**, 1821–1835

423. Haugen, N. E. L., Brandenburg, A., Sandin, C., & Mattsson, L.: 2022, "Spectral characterisation of inertial particle clustering in turbulence," *J. Fluid Mech.* **934**, A37

8 Astrobiology and chemical reactions

With the Pencil Code, we can perform simulations of chemical reactions. The spreading of COVID-19 is in principle one such example. This led us to understand why the spreading of COVID-19 follows a piecewise quadratic growth [409]. In [B.42], we have studied the effect of fluctuations in accomplishing reactions that drive the system toward a homochiral state without the explicit effects of autocatalysis or enantiomeric cross-inhibition.

437. Brandenburg, A.: 2023, "Quadratic growth during the COVID-19 pandemic: merging hotspots and reinfections," *J. Phys. A: Math. Theor.* **56**, 044002

B.42 Brandenburg, A.: 2022, "Chirality in Astrophysics" in *Proceedings to Nobel Symposium 167: Chiral Matter*, ed. E. Babaev, D. Kharzeev, M. Larsson, A. Molochkov, & V. Zhaunerchyk, World Scientific, pp. 15–35

In [B.42], we have reviewed chirality in various fields of astrophysics, but biological homochirality is one aspect. The spatial spreading of COVID, which was already discussed in previous PDC and NSC reports, is also covered there and in a new paper [438], where we investigate the effects of reinfections on the spreading in a spatially extended two-dimensional model.

Academic achievements

PhD student Yutong He has now reached the last stage, he has defended his Licentiate thesis on 16 December 2022, and will defend his PhD thesis in the fall of 2024. During 2023, Gustav Larsson has defended his Batchelor thesis in June 2023, while Nousaba N. Protiti has defended her Master's thesis in October 2023.