Constraining primordial magnetic fields from gravitational wave observations

SPS Annual Meeting 2026

EPFL, Lausanne (Aug. 26, 2026)





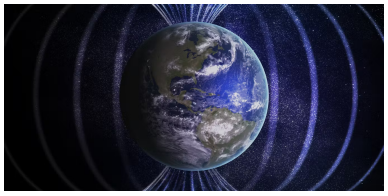
Alberto Roper Pol

University of Geneva

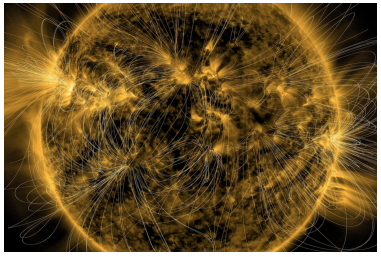


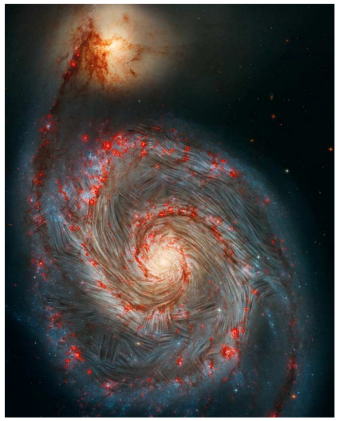
SNSF Ambizione grant (2023–2027): "*Exploring the early universe with gravitational waves and primordial magnetic fields.*"

Our magnetized Universe



$\sim 1\,\mathrm{G}$





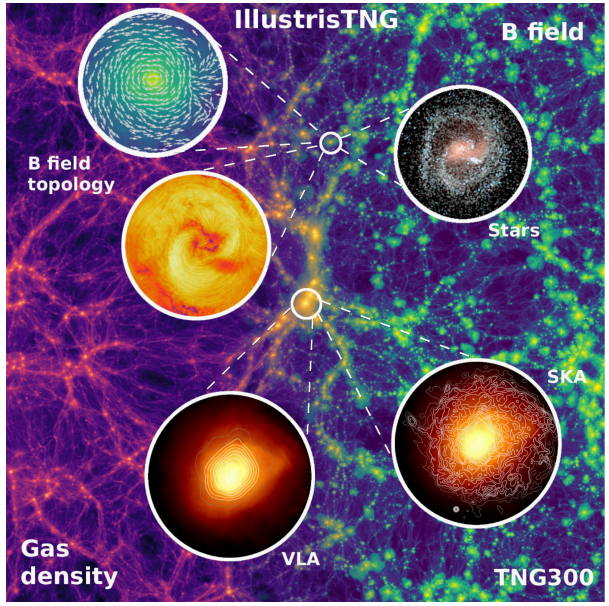
(FIR 145 μm)



(Radio 6 cm Fletcher et. al)

$\sim 10^{-5}\,\mathrm{G}$

Borlaff et al. (2021), SOFIA, M51

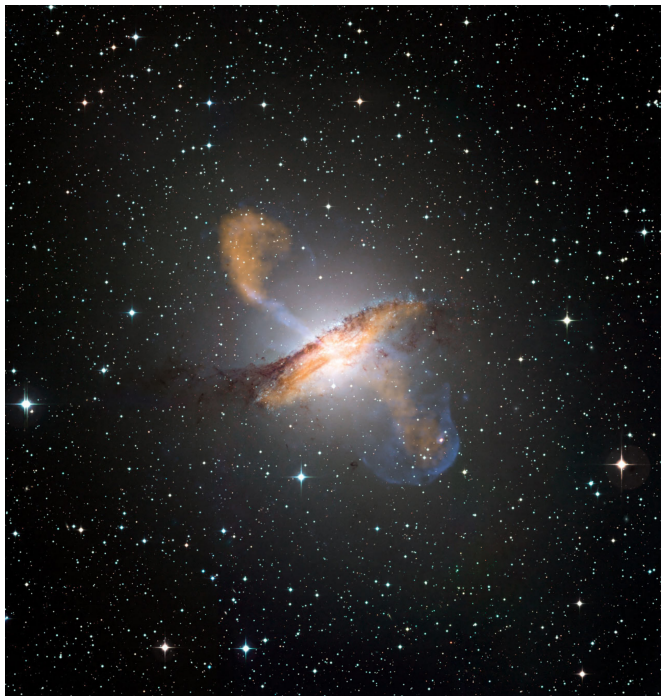


Marinacci et al. (2017), Illustris TNG

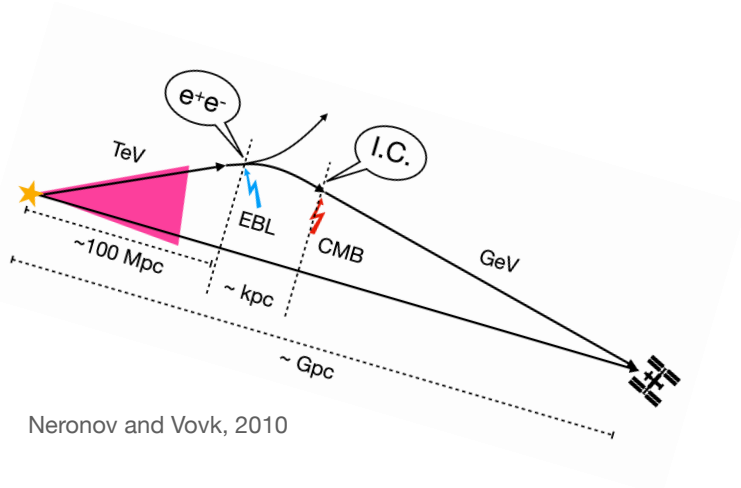
$\sim 10^{-9} - 10^{-6}\,\mathrm{G}$

- Dense regions in our Universe are strongly magnetized with $B \sim 10\mu$G in galaxies and clusters ($\sim$10 kpc). Radio and far-infrared (FIR) observations.
- Filaments also contain magnetic fields with $B \sim$10 nG (LOFAR observations of Faraday rotation measurements).

Intergalactic magnetic fields in voids of the LSS



- γ-ray observations from distant blazars by Fermi/MAGIC collaboration show a removal of power at GeV, providing evidence for an intergalactic magnetic field.
- Lower bound of $B \sim 10^{-16}$ G at Mpc scales.



Neronov and Vovk, 2010

Relics from the early Universe?

- The observed intergalactic magnetic fields could have a **primordial** (from inflation or from a phase transition) or an **astrophysical** origin.
- Observations indicate a large volume filling factor in the voids and large correlation length scales (Mpc), favoring a primordial origin.
- Alternative possibilities to explain the blazar observations are:
  - *Beam-plasma instabilities* (suppressing the GeV emission) proposed[1], but seems to not be significant at the intergalactic scales.
  - *Magnetized galactic outflows.* Studied using cosmological simulations. However, it is difficult to reach large volume filling factors.[2]
- Primordial magnetic field present at recombination could alleviate the Hubble tension by reducing the sound horizon.[3]

[1] Broderick et al. (2018).

[2] Ni et al. (2024), Tjemsland et al. (2024).

[3] Jedamzik & Pogosian (2020).

Generation of primordial magnetic fields during inflation

- Magnetic fields could be amplified from quantum fluctuations during inflation.
- For inflationary magnetogenesis to be viable, conformal invariance needs to be broken,[4] with $\mathcal{L} \sim f(\phi) F_{\mu\nu} F^{\mu\nu}$ or $g(\phi) F_{\mu\nu} \tilde{F}^{\mu\nu}$. Otherwise, magnetic field perturbations would decay with the Universe expansion.
- After reheating, magnetic fields are strongly coupled to the primordial plasma and effectively produce vortical motion, inevitably leading to the development of MHD turbulence.[5]
- Alternatively, small seed magnetic fields can be amplified by primordial turbulence induced by phase transitions, e.g., via dynamo.[6]

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[4] Turner & Widrow (1988), Ratra (1992), Gasperini *et al.* (1995).

[5] J. Ahonen and K. Enqvist, *Phys. Lett. B* **382**, 40 (1996).

[6] A. Brandenburg *et al.* (incl. ARP), *Phys. Rev. Fluids* **4**, 024608 (2019).

Generation of primordial magnetic fields during phase transitions

- Parity-violating processes during the electroweak phase transition ($T \sim 100$ GeV) are predicted by SM extensions that account for baryogenesis and can produce helical magnetic fields through sphaleron decay or B+L anomalies.[7]

$$\boldsymbol{B} = \boldsymbol{\nabla} \times \boldsymbol{A} - i\frac{2\sin\theta_w}{gv^2}\boldsymbol{\nabla}\Phi^\dagger \times \boldsymbol{\nabla}\Phi$$

- Also after inflation, axion fields can amplify and produce magnetic fields.[8] For example, the QCD axion could oscillate and produce magnetic fields around the QCD scale ($T \sim 100$ MeV).[9]

$$\mathcal{L} \supset \frac{\phi}{f} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

[7] T. Vachaspati, *Phys. Rev. B* **265**, 258 (1991), T. Vachaspati, *Phys. Rev. Lett.* **87**, 251302 (2001), J. M. Cornwall, *Phys. Rev. D* **56**, 6146 (1997).

[8] M. M. Forbes and A. R. Zhitnitsky, *Phys. Rev. Lett.* **85**, 5268 (2000).

[9] Miniati, Gregori, Reville & Sarkar (2018).

Generation of primordial magnetic fields from chiral anomalies

- Chiral magnetic effect in the early Universe at large temperatures $T > 80$ TeV can lead to the production of hypermagnetic fields.[10]
- Proposed chiral magnetic effect relevant at smaller scales[11] leading to a chiral plasma instability and development of magnetic fields that undergo inverse cascading.[12]
- Chiral magnetic effect also present for zero chiral chemical potential from local inhomogeneities.[13]
- Chiral magnetic effect can be activated from an active source of chiral chemical potential (e.g. associated to baryogenesis as the electroweak scale)[14]

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[10] M. Joyce and M. E. Shaposhnikov, *PRL* **79**, 1193 (1997)

[11] A. Boyarsky *et al. PRL* **108**, 031301 (2012).

[12] I. Rogachevskii *et al. Astrophys. J. Lett* **845** (2017) L21, J. Schober *et al. Astrophy. J.* **858**, 124 (2018).

[13] J. Schober *et al. PRL* **132**, 6 (2024)

[14] M. Gurgenidze *et al.* (incl. ARP), *Phys. Rev. D*, arXiv:2512.09177 (2025).

Cosmological Gravitational Waves

- Gravity is the *weakest fundamental force*. Hence, GWs are difficult to detect but they propagate freely carrying *clean information of the source.*

- Cosmological GWs from the early Universe have the potential to provide us with *direct information on early universe physics* that is *not accessible via electromagnetic observations, complementary to collider experiments*.

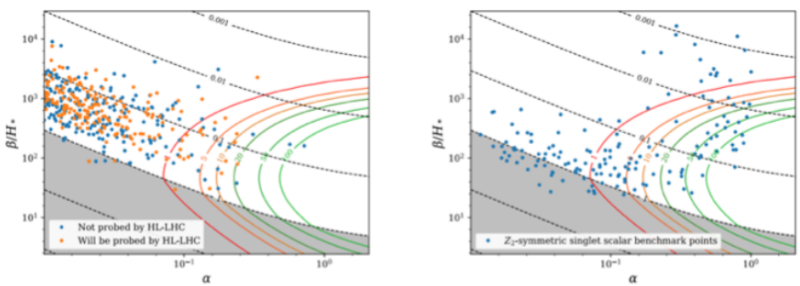


Figure 4: LEFT: Predicted values of α and β/H for $m_2 = 170$ GeV and 240 GeV (combined in one plot) in the general singlet model obtained by linearly varying the free parameters of the model and imposing requirements as described in the text. The mixing angles considered were $\sin\theta = 0.01$ (blue points) and 0.1 (orange points). The models in blue (orange) are unlikely (likely) to be probed by the high-luminosity LHC. The expected LISA sensitivities correspond to $T_* = 50$ GeV. RIGHT: Sensitivity curve for the Z_2 symmetric singlet extension. In both the left and right panels we have taken $v_w = 1$.

From [LISA CosWG], Caprini et al., *Detecting gravitational waves from cosmological phase transitions with LISA: an update* (2019)

Probing the early Universe with GWs

Cosmological (pre-recombination) GW background

- Why background? Individual sources are not resoluble, superposition of single events occurring in the whole Universe.

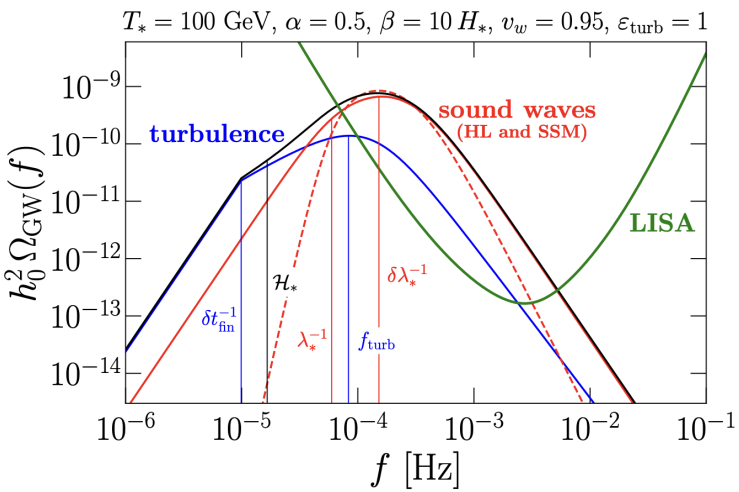
$$f_* \simeq 1.64 \times 10^{-3} \frac{100}{R_* \mathcal{H}_*} \frac{T_*}{100\,\mathrm{GeV}}\,\mathrm{Hz}$$

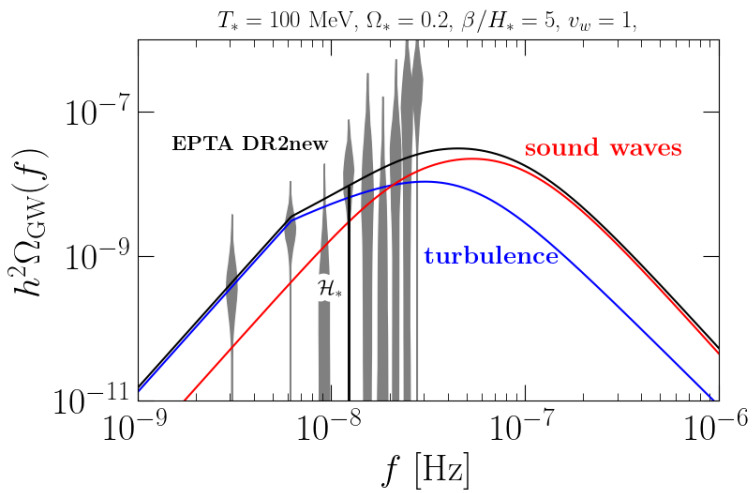
- Phase transitions
  - Ground-based detectors (LVK, ET, CE) frequencies are 10–1000 Hz
    Peccei-Quinn, B-L, left-right symmetries $\sim 10^7, 10^8$ GeV.
  - Space-based detectors **(LISA)** frequencies are 10^{-5}–10^{-2} Hz
    Electroweak phase transition $\sim$ 100 GeV
  - Pulsar Timing Array **(PTA)** frequencies are 10^{-9}–10^{-7} Hz
    Quark confinement (QCD) phase transition $\sim$ 100 MeV

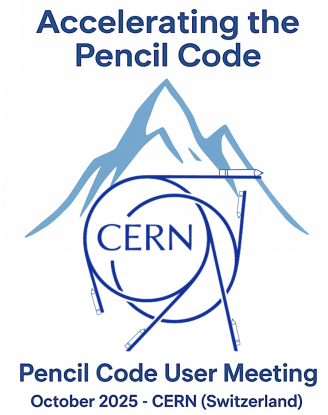
GW sources in the early Universe

- Magnetohydrodynamic (MHD) sources of GWs:
  - Sound waves generated from first-order phase transitions.
  - (M)HD turbulence from first-order phase transitions.
  - Primordial magnetic fields.

ARP *et al.*, 2307.10744, 2308.12943; [EPTA/InPTA] (incl. ARP), 2306.16227







Primordial magnetic fields and GWs from MHD turbulence

- During the radiation-dominated era, after they are produced, magnetic fields will decay following MHD turbulence.
- Direct numerical simulations using the Pencil Code[15] to solve:
  1. Relativistic MHD equations adapted for radiation-dominated era (after electroweak symmetry is broken).
  2. Gravitational waves equation.
- In general, large-scale simulations are necessary to solve the MHD nonlinearities (e.g., unequal-time correlators UETC and non-Gaussianities, which require simplifying assumptions in analytical studies).

[15] Pencil Code Collaboration, JOSS **6**, 2807 (2020), https://github.com/pencil-code/

Conservation laws for MHD turbulence

$$\nabla_\nu T^{\mu\nu} = 0, \quad \nabla_\nu F^{\mu\nu} = -J^\mu, \quad \nabla_\nu \mathcal{F}^{\mu\nu} = 0$$

In the limit of subrelativistic bulk flow:

$$\gamma^2 \sim 1 + (v/c)^2 + \mathcal{O}(v/c)^4$$

Relativistic MHD equations are reduced to[16]

$$\begin{aligned}
\frac{\partial \ln \rho}{\partial t} &= -\frac{4}{3}\left(\boldsymbol{\nabla}\cdot\boldsymbol{u} + \frac{1}{2}\boldsymbol{u}\cdot\boldsymbol{\nabla}\ln\rho\right) + \frac{1}{\rho}\left[\eta \boldsymbol{J}^2 - \boldsymbol{u}\cdot(\boldsymbol{J}\times\boldsymbol{B})\right], \\
\frac{D\boldsymbol{u}}{Dt} &= \frac{\mathbf{u}}{3}\left(\boldsymbol{\nabla}\cdot\boldsymbol{u} + \frac{1}{2}\boldsymbol{u}\cdot\boldsymbol{\nabla}\ln\rho\right) - \frac{\boldsymbol{u}}{\rho}\left[\eta J^2 + \frac{1}{2}\boldsymbol{u}\cdot(\boldsymbol{J}\times\boldsymbol{B})\right] \\
&\quad - \frac{1}{4}\boldsymbol{\nabla}\ln\rho + \frac{3}{4\rho}\boldsymbol{J}\times\boldsymbol{B} + \frac{2}{\rho}\boldsymbol{\nabla}\cdot(\rho\nu\boldsymbol{S}), \\
\frac{\partial \boldsymbol{B}}{\partial t} &= \boldsymbol{\nabla}\times(\boldsymbol{u}\times\boldsymbol{B} - \eta\boldsymbol{J}), \quad \boldsymbol{J} = \boldsymbol{\nabla}\times\boldsymbol{B},
\end{aligned}$$

for a flat expanding universe with comoving and normalized $p = a^4 p_{\rm phys}, \rho = a^4 \rho_{\rm phys}, B_i = a^2 B_{i,{\rm phys}}, u_i$, and conformal time t ($\mathrm{d}t = a\mathrm{d}t_c$).

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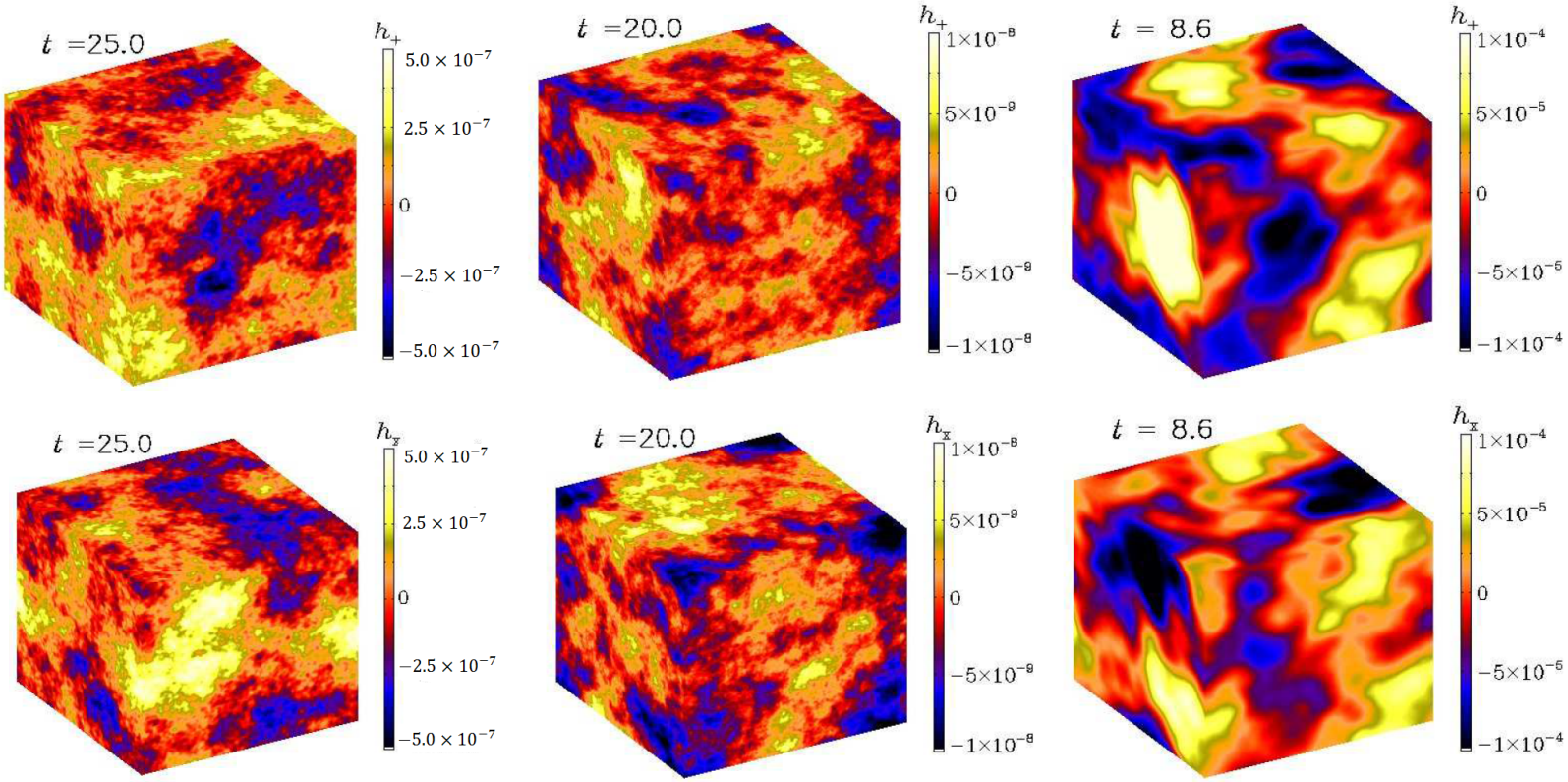
[16] A. Brandenburg, *et al., Phys. Rev. D* **54**, 1291 (1996).
ARP, Midiri, *Relativistic Magnetohydrodynamics in the early Universe*, *JCAP* **06** (2026) 070, arXiv:2501.05732 (2025).

Numerical results for decaying MHD turbulence[17]

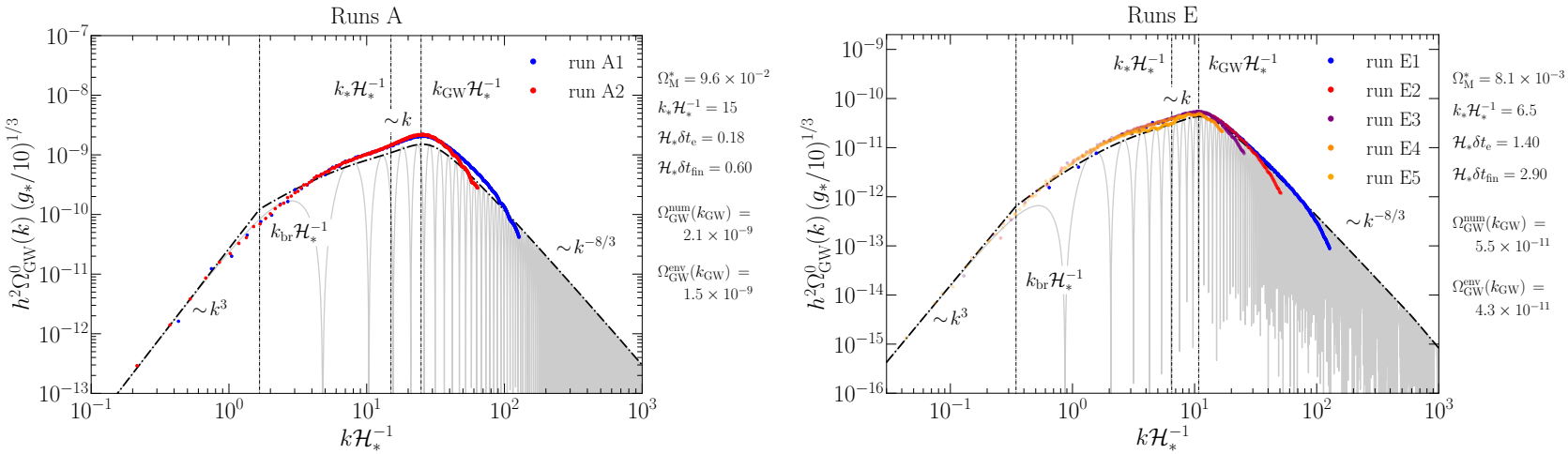
$1152^3, \Omega_{\rm M} \sim 10^{-2}$



$k_{\rm M}/k_H = 300$ $k_{\rm M}/k_H = 60$ $k_{\rm M}/k_H = 2$

[17] ARP *et al.*, *Phys. Rev. D* **102**, 083512 (2020).

Numerical results for decaying MHD turbulence[18]



run	$\Omega^*_{\rm M}$	$k_*\mathcal{H}_*^{-1}$	$\mathcal{H}_*\delta t_e$	$\mathcal{H}_*\delta t_{\rm fin}$	$\Omega^{\rm num}_{\rm GW}(k_{\rm GW})$	$[\Omega^{\rm env}_{\rm GW}/\Omega^{\rm num}_{\rm GW}](k_{\rm GW})$	n	$\mathcal{H}_*L$	$\mathcal{H}_*t_{\rm end}$	$\mathcal{H}_*\eta$
A1	9.6×10^{-2}	15	0.176	0.60	2.1×10^{-9}	1.357	768	6π	9	10^{-7}
A2	–	–	–	–	–	–	768	12π	9	10^{-6}
E1	8.1×10^{-3}	6.5	1.398	2.90	5.5×10^{-11}	1.184	512	4π	8	10^{-7}
E2	–	–	–	–	–	–	512	10π	18	10^{-7}
E3	–	–	–	–	–	–	512	20π	61	10^{-7}
E4	–	–	–	–	–	–	512	30π	114	10^{-7}
E5	–	–	–	–	–	–	512	60π	234	10^{-7}

[18] ARP *et al.*, *Phys. Rev. D* **105**, 123502 (2022).

Analytical CiT model for GWs from decaying turbulence

- Assumption: magnetic or velocity field evolution $\delta t_{\rm e} \sim 1/(u_* k_*)$ is slow compared to the GW dynamics ($\delta t_{\rm GW} \sim 1/k$) at all $k \gtrsim u_* k_*$.
- We can derive an analytical expression for nonhelical fields of the envelope of the oscillations[19] of $\Omega_{\rm GW}(k)$.

$$\Omega_{\rm GW}(k,t_{\rm fin}) \approx 3 \left(\frac{k}{k_*}\right)^3 {\Omega_{\rm M}^*}^2 \frac{\mathcal{C}(\alpha)}{\mathcal{A}^2(\alpha)} \, p_\Pi\left(\frac{k}{k_*}\right) \times \begin{cases} \ln^2[1+\mathcal{H}_* \delta t_{\rm fin}] & \text{if } k\,\delta t_{\rm fin} < 1, \\ \ln^2[1+(k/\mathcal{H}_*)^{-1}] & \text{if } k\,\delta t_{\rm fin} \geq 1. \end{cases}$$

- p_Π is the anisotropic stress spectrum and depends on spectral shape, can be approximated for a von Kárman spectrum as[20]

$$p_\Pi(k/k_*) \simeq \left[1+\left(\frac{k}{2.2k_*}\right)^{2.15}\right]^{-11/(3\times 2.15)}$$

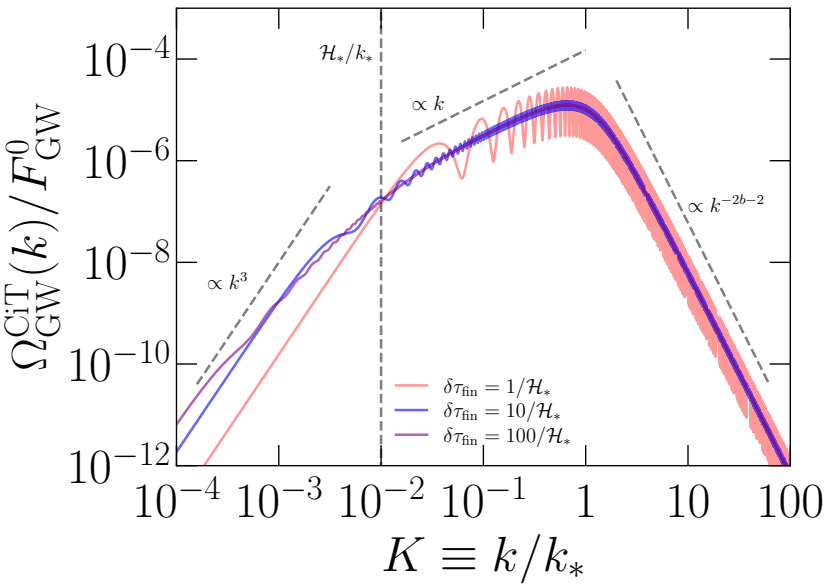
[19] ARP *et al.*, *Phys. Rev. D* **105**, 123502 (2022); ARP, Midiri, Salomé, Caprini, in preparation.

[20] ARP *et al.*, arXiv:2307.10744 (2023).

Constant-in-Time (CiT) model (arXiv:2609.xxzz)

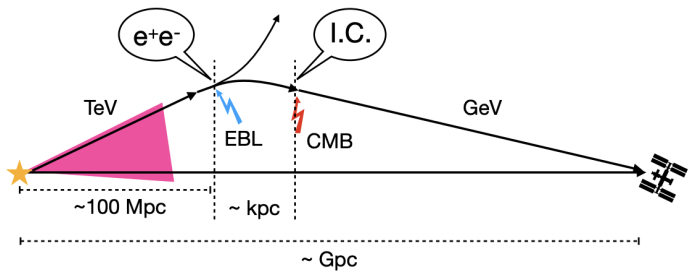
[PRELIMINARY work with A. Midiri, M. Salomé, C. Caprini]

- Applicable to generic slowly-decaying sources
- Extension to include decay of the source impacts IR part of the spectrum
- Used to compute circular polarization, compatible with numerical results.
- Applicable to generic vector and scalar fields sourcing GWs.
- Application to sound waves when $c_s \ll 1$ and to turbulence when $u_{dc} \ll 1$.

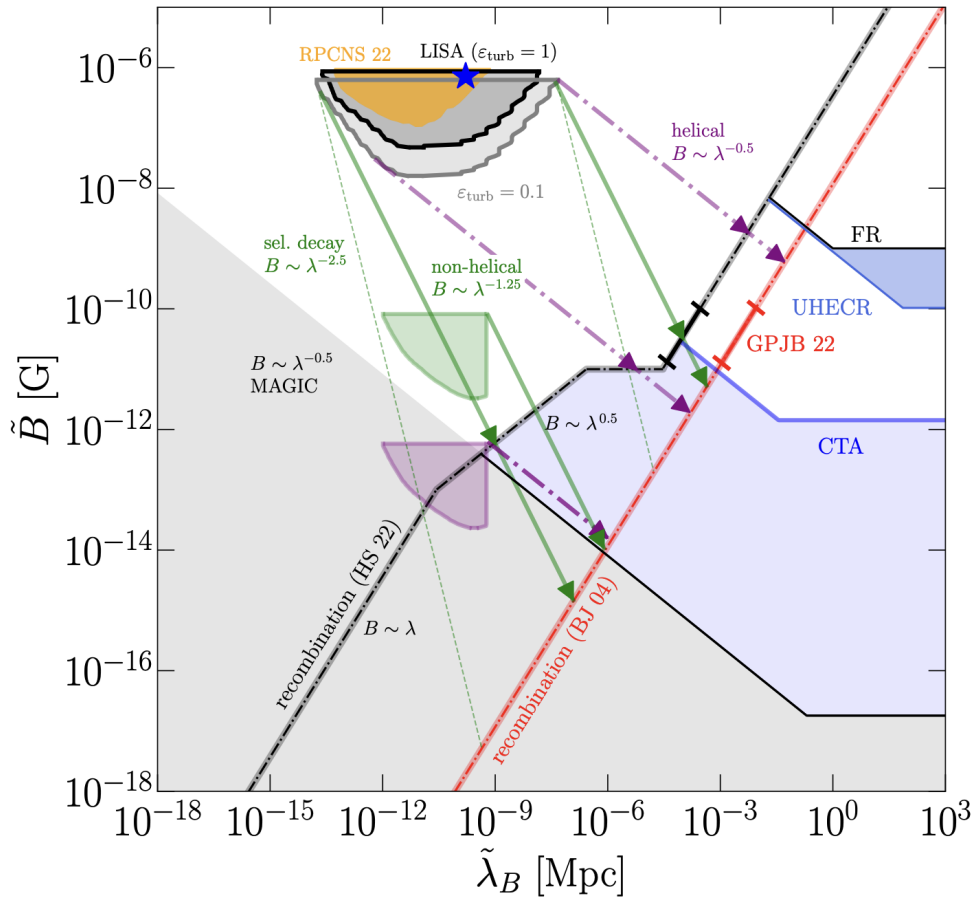


Multi-messenger studies of primordial magnetic fields (LISA)[30]

- Primordial magnetic fields would evolve through the history of the universe up to the present time and could explain the lower bounds in cosmic voids derived by the Fermi collaboration.[31]



- Maximum amplitude of primordial magnetic fields is constrained by the big bang nucleosynthesis.[32]
- Additional constraints from CMB, Faraday Rotation, ultra-high energy cosmic rays (UHECR).

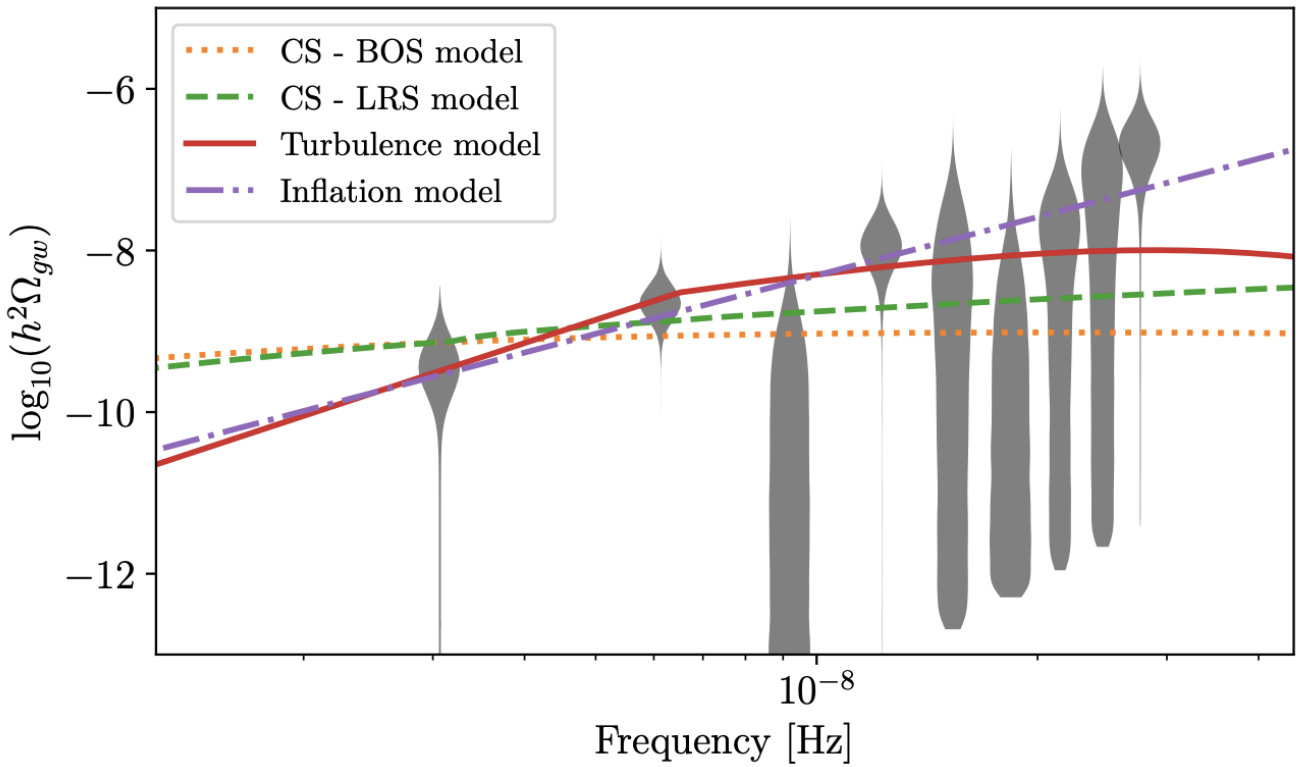


[30] ARP *et al.*, *Astron. Astrophys.* **708** (2026) A337, arXiv:2307.10744.

[31] A. Neronov and I. Vovk, *Science* **328**, 73 (2010).

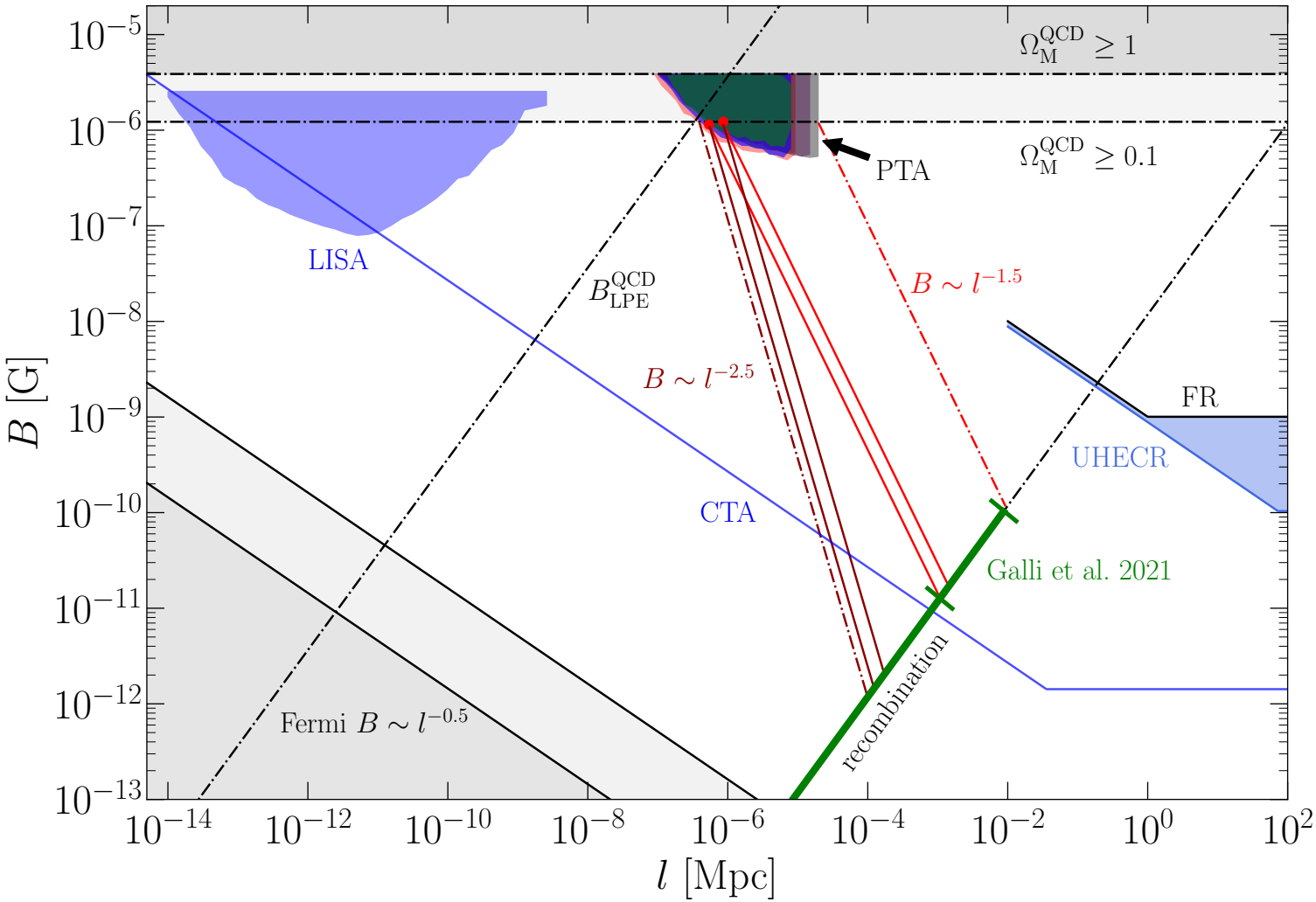
[32] V. F. Shvartsman, *Pisma Zh. Eksp. Teor. Fiz.* **9**, 315 (1969).

EPTA 24.7 yr data observation (DR 2)[21]



[21] [EPTA Collaboration] (incl. ARP), arXiv:2306.16227.

Primordial magnetic field constraints with PTA[22]



[22] ARP *et al.*, *Phys. Rev. D* **105**, 123502 (2022).

Conclusions

- Magnetic fields are ubiquitous in nature at all scales, from the smallest structures up to galaxies, cluster of galaxies, filaments, and potentially in cosmic voids of the LSS.
- Observations from γ-rays indicate the presence of intergalactic magnetic fields that could have their origin in the early Universe and potentially alleviate the Hubble tension.
- Magnetic fields can be produced in the early Universe during the period of inflation or during a cosmological phase transition (EW or QCD), leaving at the same time an imprint on the gravitational wave background (GWB).
- The large conductivity during the radiation-dominated era implies the development of MHD turbulence and therefore, the primordial plasma is non-linearly stirred by the magnetic field.
- LISA, PTA, and next-generation ground-based detectors can be used to probe the origin of magnetic fields in the largest scales of our Universe, which is still an open question in cosmology.
- In summary, magnetic fields can be used as multi-messenger probes for early Universe physics combining astrophysical and cosmological observations, and can help us understanding high-energy physics, at scales inaccessible by other means.



















Thank You!

alberto.roperpol@unige.ch

github.com/cosmoGW/cosmoGW

https://albertoroper.github.io/