

# Multi-messenger searches of primordial magnetic fields and gravitational waves

NPACT meeting, University of Stavanger (Jun. 10, 2026)

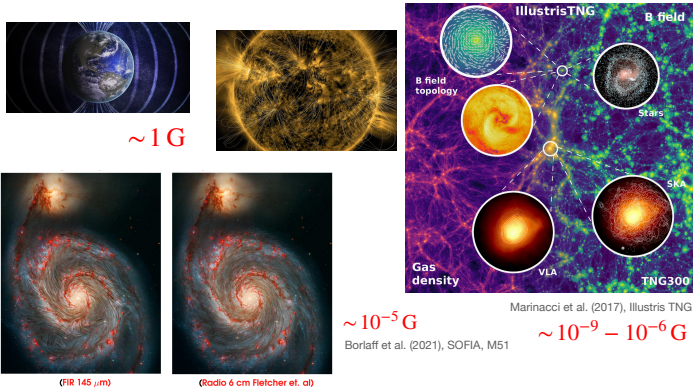


Alberto Roper Pol  
*University of Geneva*



SNSF Ambizione grant (2023–2026): “*Exploring the early universe with gravitational waves and primordial magnetic fields.*”

# Our magnetized Universe



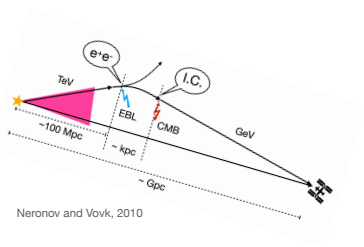
- Dense regions in our Universe are strongly magnetized with  $B \sim 10 \mu\text{G}$  in galaxies and clusters ( $\sim 10$  kpc). Radio and far-infrared (FIR) observations.
- Filaments also contain magnetic fields with  $B \sim 10$  nG (LOFAR observations of Faraday rotation measurements).



## Intergalactic magnetic fields in voids of the LSS



- $\gamma$ -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.



# 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<sup>1</sup>, 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.<sup>2</sup>
- Primordial magnetic field present at recombination could alleviate the Hubble tension by reducing the sound horizon.<sup>3</sup>

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<sup>1</sup>Broderick et al. (2018).

<sup>2</sup>Ni et al. (2024), Tjemsland et al. (2024).

<sup>3</sup>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,<sup>4</sup> 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.<sup>5</sup>
- Alternatively, small seed magnetic fields can be amplified by primordial turbulence induced by phase transitions, e.g., via dynamo.<sup>6</sup>

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<sup>4</sup>Turner & Widrow (1988), Ratra (1992), Gasperini *et al.* (1995).

<sup>5</sup>J. Ahonen and K. Enqvist, *Phys. Lett. B* **382**, 40 (1996).

<sup>6</sup>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.<sup>7</sup>

$$\mathbf{B} = \nabla \times \mathbf{A} - i \frac{2 \sin \theta_w}{g v^2} \nabla \Phi^\dagger \times \nabla \Phi$$

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

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

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<sup>7</sup> 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).

<sup>8</sup> M. M. Forbes and A. R. Zhitnitsky, *Phys. Rev. Lett.* **85**, 5268 (2000).

<sup>9</sup> 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.<sup>10</sup>
- Proposed chiral magnetic effect relevant at smaller scales<sup>11</sup> leading to a chiral plasma instability and development of magnetic fields that undergo inverse cascading.<sup>12</sup>
- Chiral magnetic effect also present for zero chiral chemical potential from local inhomogeneities.<sup>13</sup>
- Chiral magnetic effect can be activated from an active source of chiral chemical potential (e.g. associated to baryogenesis at the electroweak scale)<sup>14</sup>

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<sup>10</sup> M. Joyce and M. E. Shaposhnikov, *PRL* **79**, 1193 (1997)

<sup>11</sup> A. Boyarsky *et al.* *PRL* **108**, 031301 (2012).

<sup>12</sup> I. Rogachevskii *et al.* *Astrophys. J. Lett* **845** (2017) L21, J. Schober *et al.* *Astrophys. J.* **858**, 124 (2018).

<sup>13</sup> J. Schober *et al.* *PRL* **132**, 6 (2024)

<sup>14</sup> M. Gurgunidze *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*.

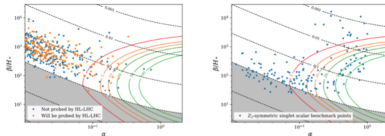


Figure 4: LEFT: Predicted values of  $\alpha$  and  $\beta/H$  for  $m_2 = 170$  GeV and 240 GeV (combined in one plot) in the general singlet model obtained by linearly varying the free parameters of the model and imposing requirements as described in the text. The mixing angles considered were  $\sin \theta = 0.01$  (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)*

# LISA

- Laser Interferometer Space Antenna (LISA) is a space-based GW detector
- Approved in 2017 as one of the main research missions of ESA (L3) with NASA collaboration
- Launch planned for 2035
- Composed by three spacecrafts in a distance of 2.5M km
- LISA cosmology working group (since 2015,  $\sim 230$  members)

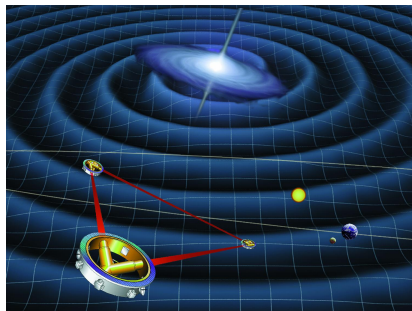


Figure: Artist's impression of LISA from Wikipedia

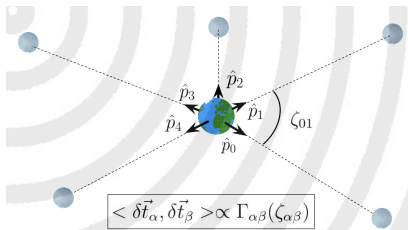
White paper:

[LISA Cosmology Working Group] (incl. ARP),  
*Living Rev. Rel.* **26** (2023), arXiv:2204.05434.

## Pulsar Timing Array (PTA)

- An array of millisecond pulsars (MSP) is observed in the radio band to compute the delays on the time of arrival due to the presence of GWs.
- Collected data is the time series of residuals for each pulsar:

$$\delta t^i = t_{\text{obs}}^i - t_{\text{TM}}^i$$



Credit: Mikel Falxa

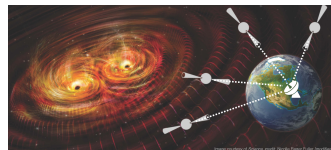
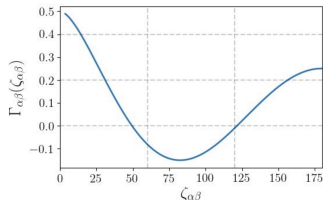


Figure: Image courtesy of Science, credit: Nicolle Rager Fuller

The correlation  $\Gamma_{\alpha\beta}$  follows in GR the Hellings-Downs curve<sup>15</sup>



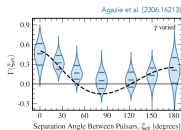
<sup>15</sup>R. W. Hellings and G. S. Downs, *Astrophys. J. Lett.* **265** (1983) L39-L42



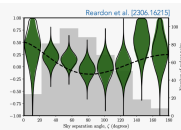
# PTA detection

- The PTA collaborations reported for the first-time evidence of a stochastic gravitational wave background on a press release on June 28, 2023 (plus a series of papers by each collaboration).

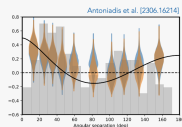
**NANOGrav:**  
68 pulsars, 16yr of data  
~3-4 $\sigma$  significance



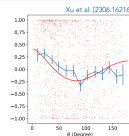
**PPTA:**  
32 pulsars, 18yr of data  
~2 $\sigma$  significance



**EPTA + InPTA:**  
25 pulsars, 24yr of data  
~3 $\sigma$  significance



**CPTA:**  
57 pulsars, 3yr of data  
~4.6 $\sigma$  significance



Credit: Andrea Mitridate

# Probing the early Universe with GWs

## Cosmological (pre-recombination) GW background

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

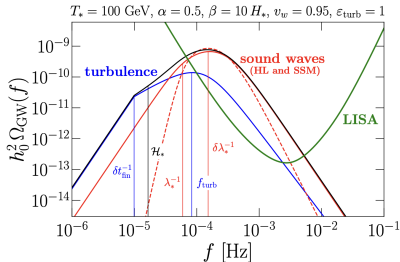
$$f_* \simeq 1.64 \times 10^{-3} \frac{100}{R_* \mathcal{H}_*} \frac{T_*}{100 \text{ GeV}} \text{ Hz}$$

- 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.
- High-conductivity of the early universe leads to a high-coupling between magnetic and velocity fields.
- Other sources of GWs include
  - Bubble collisions.
  - Cosmic strings.
  - Primordial black holes.
  - Inflation.

ARP *et al.*, 2307.10744, 2308.12943



## 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`<sup>16</sup> 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).
- Currently, *CosmoLattice*-MHD module is under-development (work with D. Figueroa, K. Marschall, A. Midiri).

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<sup>16</sup>Pencil Code Collaboration, JOSS **6**, 2807 (2020),  
<https://github.com/pencil-code/>

## Conservation laws for MHD turbulence

$$T^{\mu\nu}_{;\nu} = 0, \quad F^{\mu\nu}_{;\nu} = -J^\mu, \quad \tilde{F}^{\mu\nu}_{;\nu} = 0$$

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<sup>17</sup>

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

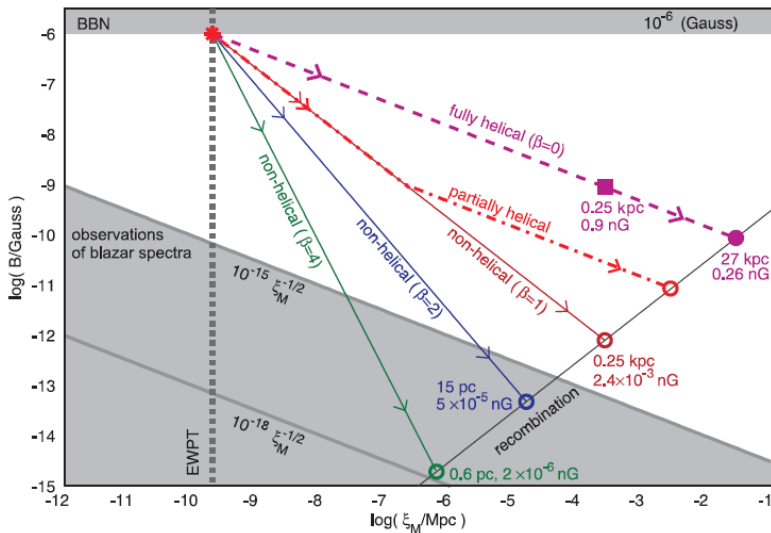
for a flat expanding universe with comoving and normalized

$\rho = a^4 \rho_{\text{phys}}$ ,  $\rho = a^4 \rho_{\text{phys}}$ ,  $B_i = a^2 B_{i,\text{phys}}$ ,  $u_i$ , and conformal time  $t$  ( $dt = a dt_c$ ).

<sup>17</sup> A. Brandenburg, *et al.*, *Phys. Rev. D* **54**, 1291 (1996).

ARP, Midiri, *Relativistic Magnetohydrodynamics in the early Universe*, *JCAP*, arXiv:2501.05732 (2025).

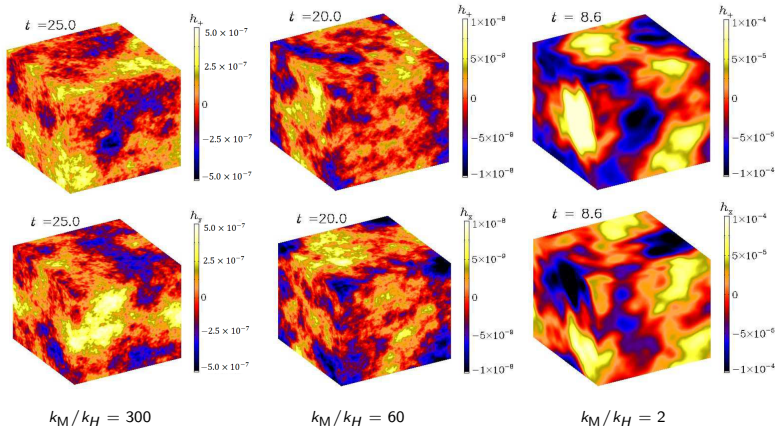
## Evolution of magnetic strength and correlation length<sup>18</sup>



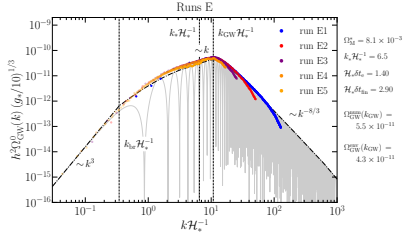
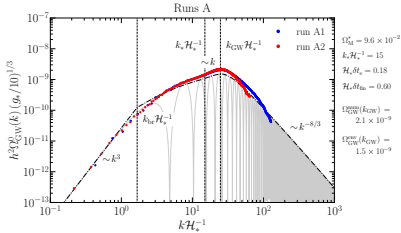
<sup>18</sup> A. Brandenburg *et al.* (incl. ARP),  
*Phys. Rev. D* **96**, 123528 (2017).

# Numerical results for decaying MHD turbulence<sup>19</sup>

$1152^3, \Omega_M \sim 10^{-2}$



# Numerical results for decaying MHD turbulence<sup>20</sup>



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



## Analytical model for GWs from decaying turbulence

- Assumption: magnetic or velocity field evolution  $\delta t_e \sim 1/(u_* k_*)$  is slow compared to the GW dynamics ( $\delta t_{\text{GW}} \sim 1/k$ ) at all  $k \gtrsim u_* k_*$ .
- We can derive an analytical expression for nonhelical fields of the envelope of the oscillations<sup>21</sup> of  $\Omega_{\text{GW}}(k)$ .

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

- $p_{\Pi}$  is the anisotropic stress spectrum and depends on spectral shape, can be approximated for a von Kármán spectrum as<sup>22</sup>

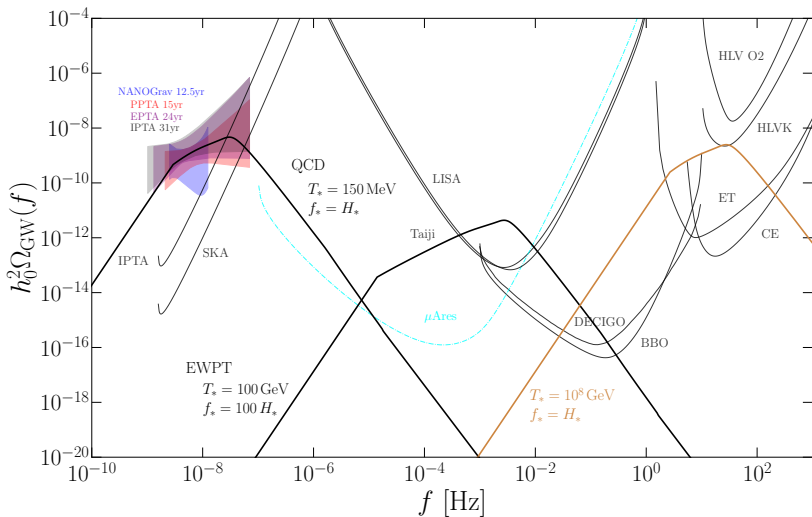
$$p_{\Pi}(k/k_*) \simeq \left[ 1 + \left( \frac{k}{2.2k_*} \right)^{2.15} \right]^{-11/(3 \times 2.15)}$$

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<sup>21</sup>ARP et al., *Phys. Rev. D* **105**, 123502 (2022).

<sup>22</sup>ARP et al., arXiv:2307.10744 (2023).

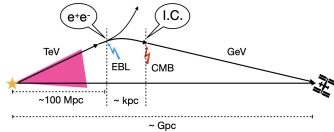
## Gravitational spectrum (turbulence from PTs)<sup>23</sup>



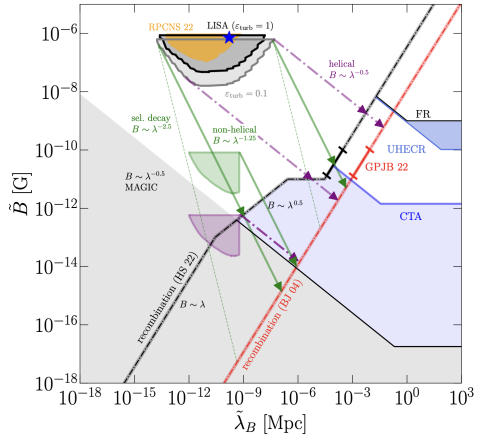
<sup>23</sup> ARP, C. Caprini, A. Neronov, D. Semikoz, *PRD* **105**, 123502 (2022)  
 A. Neronov, ARP, C. Caprini, D. Semikoz, *PRD* **103**, L041302 (2021)  
 ARP *et al.*, arXiv:2307.10744 (2023).

## Multi-messenger studies of primordial magnetic fields (LISA)<sup>30</sup>

- 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.<sup>31</sup>



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

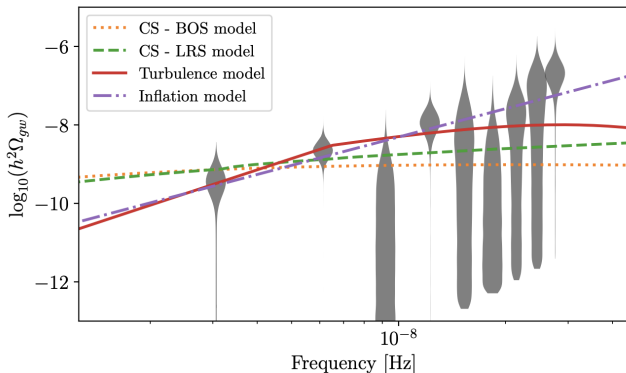


<sup>30</sup> ARP et al., *Astron. Astrophys.* **708** (2026) A337, arXiv:2307.10744.

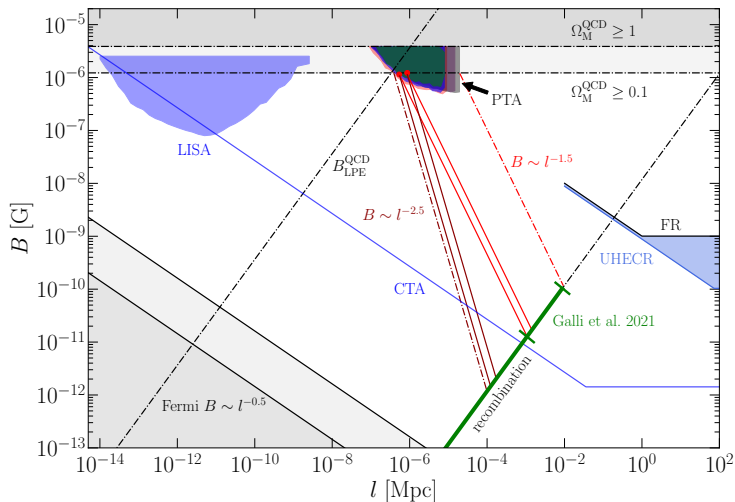
<sup>31</sup> A. Neronov and I. Vovk, *Science* **328**, 73 (2010).

<sup>32</sup> V. F. Shvartsman, *Pisma Zh. Eksp. Teor. Fiz.* **9**, 315 (1969).

## EPTA 24.7 yr data observation (DR 2)<sup>24</sup>



# Primordial magnetic field constraints with PTA<sup>25</sup>



# 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  $\gamma$ -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.



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TATA INSTITUTE OF FUNDAMENTAL RESEARCH

# Magnetic fields in the primordial universe

The main objective of the meeting is to provide a comprehensive description of cosmological magnetic fields, covering different mechanisms of magnetic field production in the early Universe, the recent developments focusing on the evolution of primordial magnetic fields (PMFs) in terms of both their strength and coherence length scale, and the different observational probes connected to PMFs, including the Big Bang Nucleosynthesis, gamma rays, the cosmic microwave background, the large-scale structure, and gravitational waves.

**30 Nov - 04 Dec 2026**

Madhava Lecture Hall,  
ICTS Bengaluru

## Organizers |

Pallavi Bhat (ICTS-TIFR Bengaluru, India)  
Alberto Roger Pol (University of Geneva, Switzerland)  
Kandaswamy Subramanian (Ashoka University & IUCAA, India)  
Tanmay Vachaspati (Arizona State University, USA)

ICTS is committed to building an environment that is inclusive, non-discriminatory and welcoming of diverse individuals. We especially encourage the participation of women and other under-represented groups.

## Speakers |

|                      |                        |
|----------------------|------------------------|
| Andi Brandenburg     | Levon Pogosian         |
| Gennya Farrar        | T.R. Sathadri          |
| Fabio Finelli        | Ranjithar Sharma       |
| Balraj Kumar Jain    | Qinxi Siqi             |
| Kuntan Jedamzik      | Lakshmanan Sriramkumar |
| Tina Kahniashvili    | Pranjal Trivedi        |
| Salome Mchedlishvili | Tejashri Venumadhav    |
| Andrei Neronov       |                        |
| Shane O'Sullivan     |                        |

**Eligibility Criteria:** We welcome applications from researchers at all career stages (PhD students, postdocs/senior) working on different aspects of primordial magnetic fields, from generation mechanisms in the early Universe to observational signatures of intergalactic magnetic fields. Note that in-person participation will be restricted to 45 participants.

**Application Deadline:**  
15 July 2026

📧 <https://www.icts.res.in/discussion-meeting/mfp2026>  
✉ [mfp@icts.res.in](mailto:mfp@icts.res.in)



# Thank You!

[alberto.roperpol@unige.ch](mailto:alberto.roperpol@unige.ch)

[github.com/cosmoGW/cosmoGW](https://github.com/cosmoGW/cosmoGW)  
<https://albertoroper.github.io/>

