

Multi-messenger studies of primordial magnetic fields and gravitational waves

Ilia State University (Dec. 18, 2025. Tbilisi, Georgia)



Alberto Roper Pol
University of Geneva



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

Cosmological gravitational wave background from phase transitions in the early Universe

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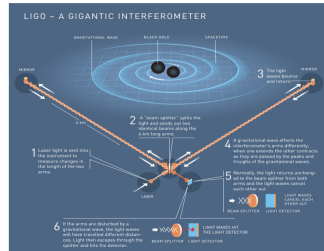
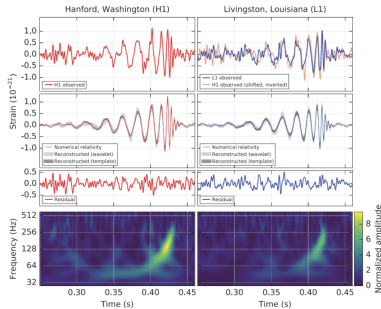
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First detections of gravitational waves

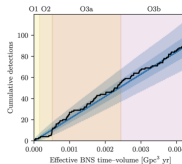
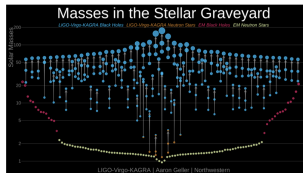
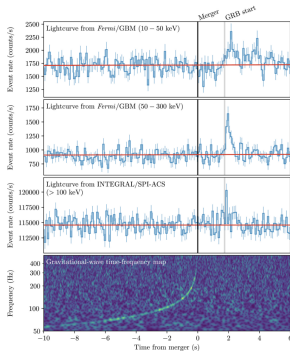
- Gravitational waves are opening a new window into our understanding of the Universe
 - First event GW150914 detected by LIGO-Virgo collaboration¹



¹[LIGO-Virgo Collaboration], *Phys. Rev. Lett.* **116**, 061102 (2016)

Introduction and Motivation

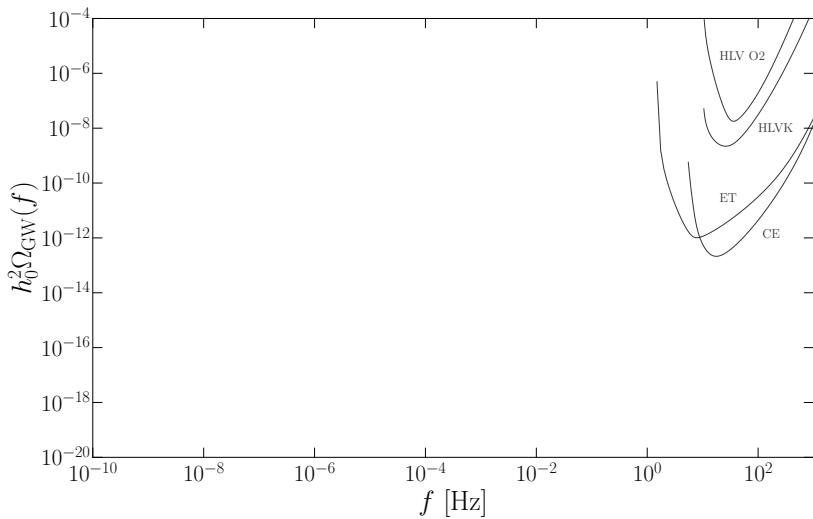
- GW170817 NS binary merger² first detection of GW and EM counterpart (constraint on the GW speed, measure of the Hubble rate, neutron star equation of state, ...)
- Several following events: LIGO-Virgo-KAGRA started the fourth observing run (O4) in May 2023 → 90 events up to O3b³ with O4 running until June 2025.



²[LIGO-Virgo-Fermi GBM-Integral collaborations], Astrophys.J.Lett. 848 (2017) 2, L13

³[LIGO-Virgo Collaboration], GWTC-3, arXiv:2111.03606 (2021).

Gravitational spectrum (ground-based detectors)



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, ~ 230 members)

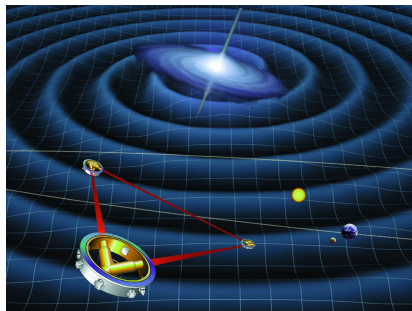
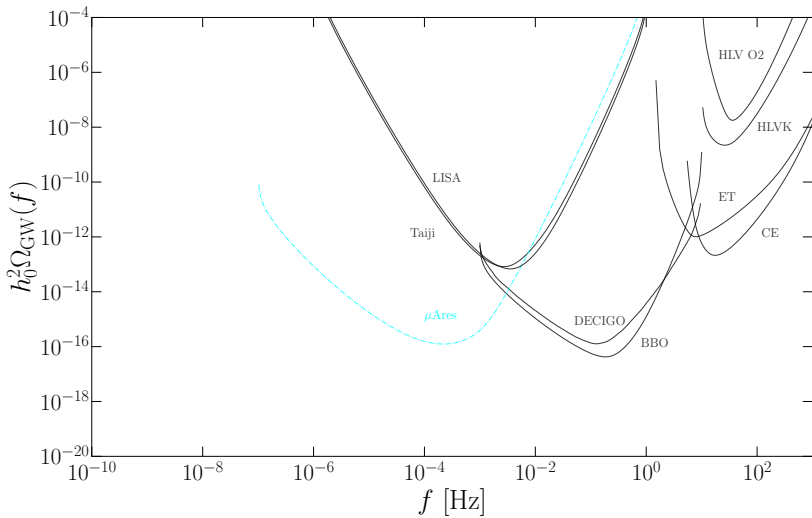


Figure: Artist's impression of LISA from Wikipedia

White paper:

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

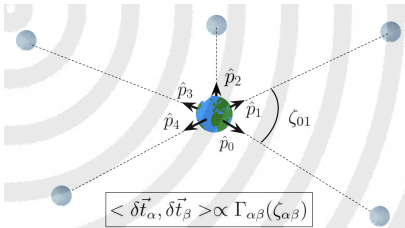
Gravitational spectrum (space-based detectors)



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

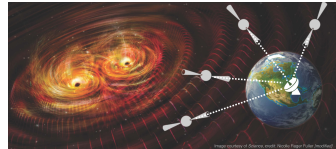
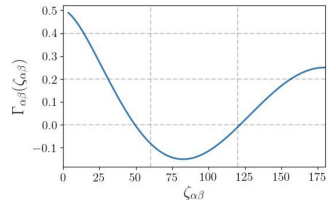


Figure: Image courtesy of Science, credit: Nicole Rager Fuller

The correlation $\Gamma_{\alpha\beta}$ follows in GR the Hellings-Downs curve⁴

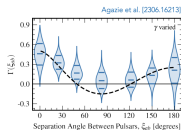


⁴R. W. Hellings and G. S. Downs, *Astrophys. J. Lett.* **265** (1983) L39-L42

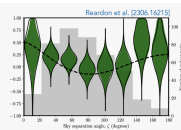
PTA detection

- 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).

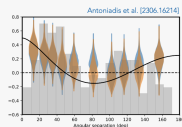
NANOGrav:
68 pulsars, 16yr of data
~3-4 σ significance



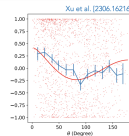
PPTA:
32 pulsars, 18yr of data
~2 σ significance



EPTA + InPTA:
25 pulsars, 24yr of data
~3 σ significance



CPTA:
57 pulsars, 3yr of data
~4.6 σ significance

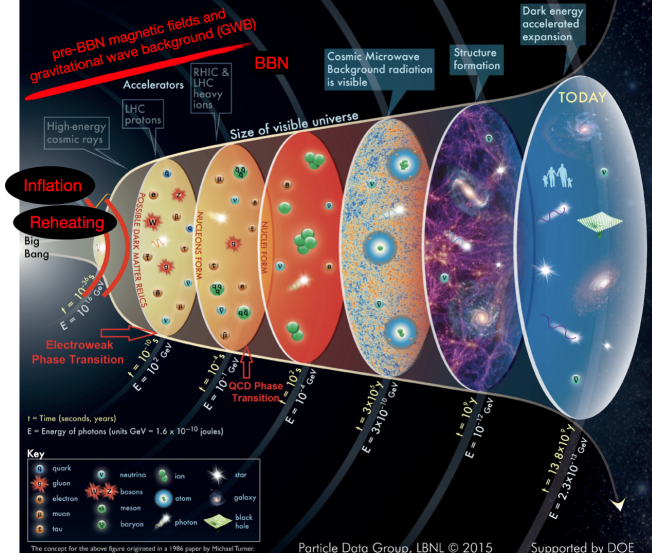


Credit: Andrea Mitridate

GWs from the early Universe

- Gravity is the *weakest fundamental force*. Hence, GWs are difficult to detect but they propagate freely carrying *clean information of the source*.
- Primordial magnetic fields and MHD turbulence in the primordial plasma can produce *a gravitational wave background* potentially observable with *LISA, PTA, or other GW experiments*.
- Observations of gravitational wave backgrounds and primordial magnetic fields can be combined for *multi-messenger studies of the primordial Universe*.
- 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*.

HISTORY OF THE UNIVERSE



The concept for the above figure originated in a 1986 paper by Michael Turner.

Probing the early Universe with GWs

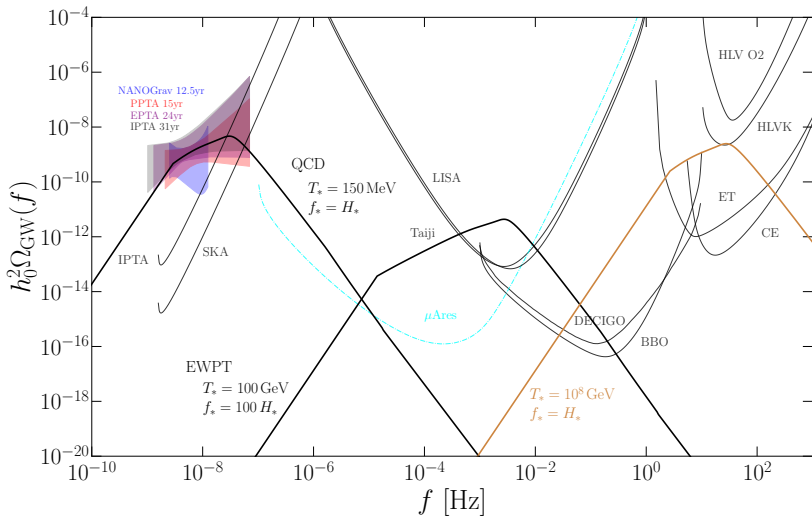
Cosmological (pre-recombination) GW background

- 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 ~ 100 GeV
 - Pulsar Timing Array (**PTA**) frequencies are 10^{-9} – 10^{-7} Hz
Quark confinement (QCD) phase transition ~ 100 MeV

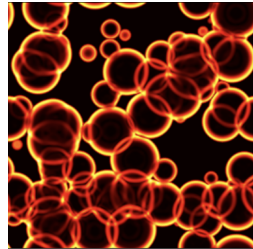
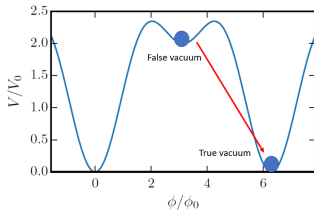
Gravitational spectrum from PTs⁵



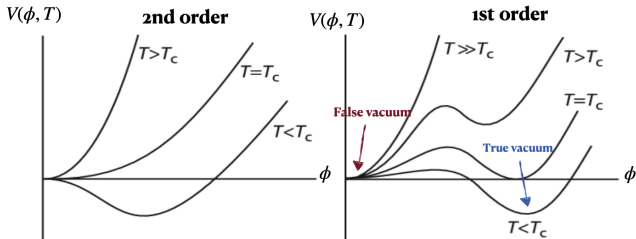
⁵ ARP, C. Caprini, A. Neronov, D. Semikoz, *PRD* **105**, 123502 (2022)
 A. Neronov, ARP, C. Caprini, D. Semikoz, *PRD* **103**, L041302 (2021)
 ARP *et al.*, arXiv:2307.10744 (2023).

First-order phase transition

$$V(\phi, T) = \frac{1}{2}M^2(T)\phi^2 - \frac{1}{3}\delta(T)\phi^3 + \frac{1}{4}\lambda\phi^4$$

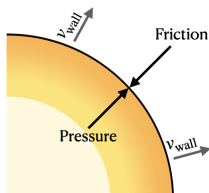


Credits: I. Stomberg



Hydrodynamics of first-order phase transitions⁶

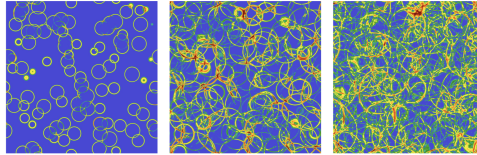
- Broken-phase bubbles are nucleated and expand
- Friction from particles yield a terminal velocity ξ_w of the bubbles
- The bubble can run away when the friction is not enough to stop the bubble's acceleration



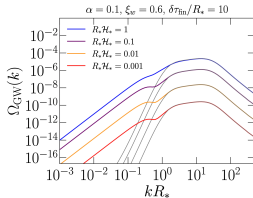
$$\nabla_{\mu} T_{\text{field}}^{\mu\nu} = \frac{\partial V}{\partial \phi} \partial^{\nu} \phi + \eta u^{\mu} \partial_{\mu} \phi \partial^{\nu} \phi,$$
$$\nabla_{\mu} T_{\text{fluid}}^{\mu\nu} = -\frac{\partial V}{\partial \phi} \partial^{\nu} \phi - \eta u^{\mu} \partial_{\mu} \phi \partial^{\nu} \phi,$$

GWs from sound waves⁷

- Numerical simulations of the scalar + fluid system performed by the Sussex/Helsinki group via an effective friction term indicate sound-wave regime to dominate for weak/intermediate phase transitions.



- Sound-shell model. Two scales are found that determine the GW spectrum: R_* and ΔR_* (sound-shell thickness).



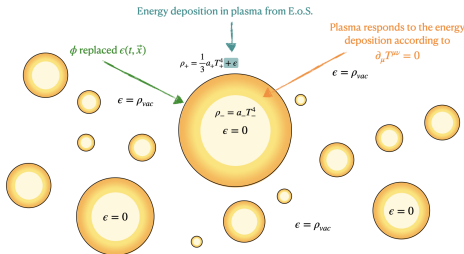
$$\Omega_{\text{GW}}(f) = 3 \tilde{\Omega}_{\text{GW}} K^2 \Upsilon(\tau_{\text{sw}})(H_* R_*) S(f R_*)$$

$$\Upsilon(\tau_{\text{sw}}) = \frac{H_* \tau_{\text{sw}}}{1 + H_* \tau_{\text{sw}}}$$

⁷ Hindmarsh *et al.*, 2013, 2015, 2017, Cutting *et al.*, 2019, Correia *et al.*, 2025

GWs from sound waves: Higgsless simulations⁸

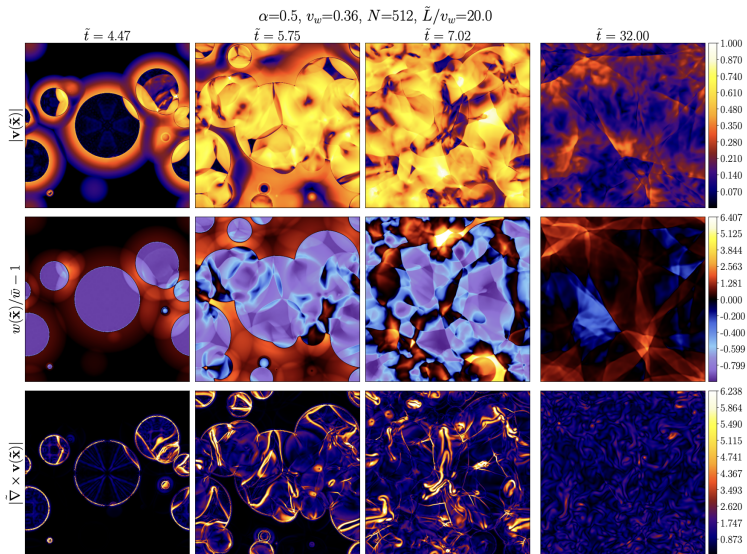
- Difficulty on simulations is due to the different scales of the scalar field ϕ and the fluid shell, so one can consider a nucleation history and set the pressure and energy density by knowing the value of ϵ and setting it during the simulation.
- Effect of bubble collisions on GWs is subdominant when sound waves are produced, so one can ignore the scalar field.
- Nucleation history is produced from an exponential probability distribution $P(t) \propto \exp[\beta(t - t_*)]$.



Credit: I. Stomberg

⁸Jinno *et al.* JCAP 02 (2023) 011, 2209.04369, ARP, Stomberg *et al.*, arXiv:2409.03651 (2024).

Higgsless simulations of strong PTs⁹

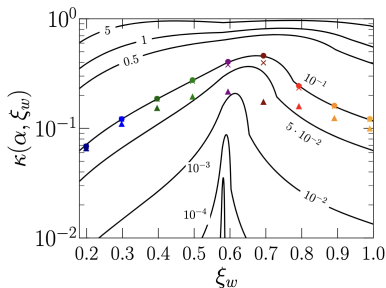
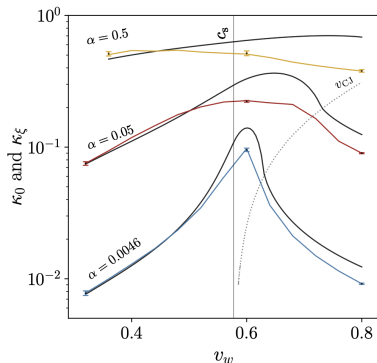


Higgsless simulations (results)¹⁰

- In the literature, the GW spectrum from sound waves is usually assumed to be

$$\Omega_{\text{GW}}(f) = 3 \tilde{\Omega}_{\text{GW}} \kappa^2 (H_* \tau_{\text{sw}}) (H_* R_*) S(f R_*)$$

- $K \equiv \kappa \alpha / (1 + \alpha)$ is the fraction of kinetic (in the sound-wave regime!) to radiation energy density

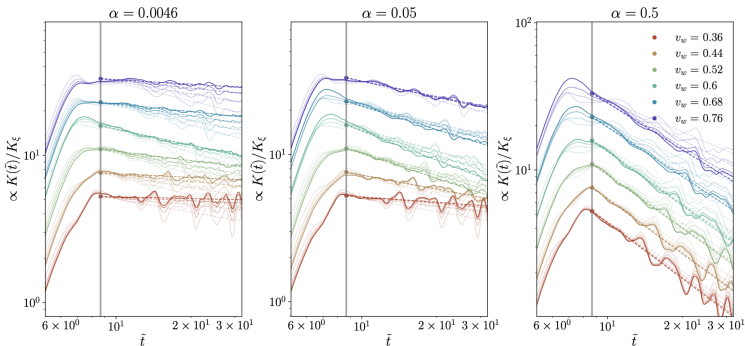


ARP, Procacci, Midiri, Caprini, in preparation

¹⁰ ARP, Stomberg *et al.*, JHEP, arXiv:2409.03651 (2024).

Higgsless simulations (results)¹¹

- Kinetic energy decay is observed in the simulations.
- For weak and strong PTs, increasing discretization enhances the decay.
- Potential indication of the development of non-linearities (turbulence).



¹¹ ARP, Stomberg et al., arXiv:2409.03651 (2024).

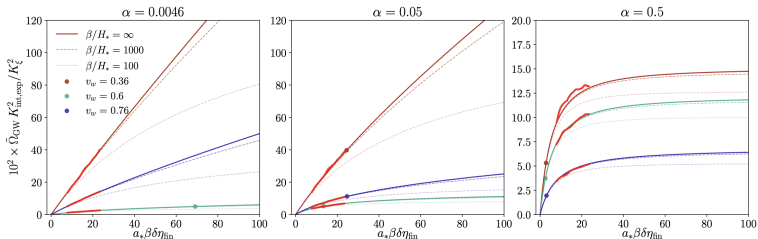
Higgsless simulations (results)¹²

- In the literature, the GW spectrum from sound waves is usually assumed to be

$$\Omega_{\text{GW}}(f) = 3 \tilde{\Omega}_{\text{GW}} K^2 \mathfrak{T}(\tau_{\text{sw}}) (H_* R_*) S(f R_*)$$

- The linear growth, which only appears when expansion is neglected, is modified when the decay of the source is significant (e.g., due to the development of non-linearities).
- Extended model to proposed locally stationary UETC

$$\Omega_{\text{GW}}(f) = 3 \tilde{\Omega}_{\text{GW}} \mathbf{K}_{\text{int,exp}}^2 (H_* R_*) S(f R_*)$$



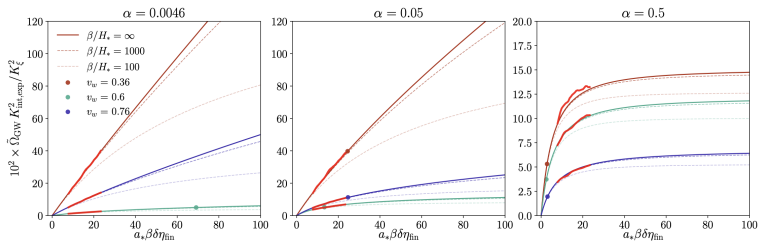
Higgsless simulations (results)¹³

- In the literature, the GW spectrum from sound waves is usually assumed to be

$$\Omega_{\text{GW}}(f) = 3 \tilde{\Omega}_{\text{GW}} K^2 \mathfrak{T}(\tau_{\text{sw}}) (H_* R_*) S(f R_*)$$

- The linear growth, which only appears when expansion is neglected, is modified when the decay of the source is significant (e.g., due to the development of non-linearities).
- Extended model to proposed locally stationary UETC (also assumed in Dahl *et al.*, 2024 and found in Correia *et al.*, 2025)

$$\Omega_{\text{GW}}(f) = 3 \tilde{\Omega}_{\text{GW}} \mathbf{K}_{\text{int,exp}}^2 (H_* R_*) S(f R_*)$$



Higgsless simulations (results)¹⁰

- In the literature, the GW spectrum from sound waves is usually assumed to be

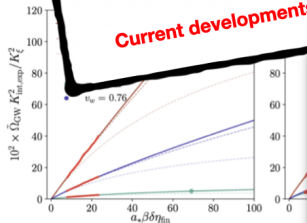
$$\Omega_{\text{GW}}(f) = 3 \tilde{\Omega}_{\text{GW}} K^2 \mathcal{T}(\tau_{\text{sw}}) (H_* R_*) S(\epsilon, \beta)$$

- The linear growth, which ends when the decay of the fluid motion is modified

- sources based on Higgsless simulations available using public code CosmoGW

Template for sound-shell model and template for non-linear
sources based on Higgsless simulations available using public
code CosmoGW
(<https://github.com/cosmoGW/cosmoGW>)
proceedings on arXiv with I. Stomberg (2508.04263) and tutorial
available on CosmoGW documentation

For use: pip install cosmoGW
Current developments undergoing to extend CosmoGW to
other sources



Gravitational wave spectra for cosmological phase transitions with non-linear decay of the fluid motion

Isak Stomberg^a and Alberto Roper Pol^b

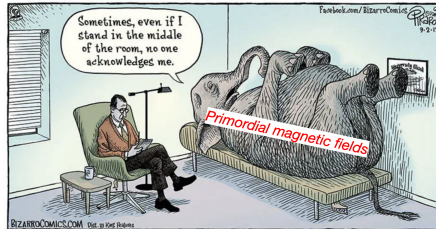
^a IFIC, Universitat de València-CSIC, C/ Catedrático José Beltrán 2, E-46980, Paterna, Spain

^b Département de Physique Théorique, Université de Genève, CH-1211 Genève, Switzerland



Primordial magnetic fields

- Magnetic fields can either be produced at or present during cosmological phase transitions.
- The magnetic fields are strongly coupled to the primordial plasma and effectively produce vortical motion, inevitably leading to the development of MHD turbulence.¹⁴
- Present magnetic fields can be amplified by primordial turbulence via dynamo.¹⁵



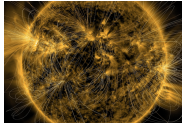
¹⁴ J. Ahonen and K. Enqvist, *Phys. Lett. B* **382**, 40 (1996).

¹⁵ A. Brandenburg *et al.* (incl. ARP), *Phys. Rev. Fluids* **4**, 024608 (2019).

Our magnetic Universe



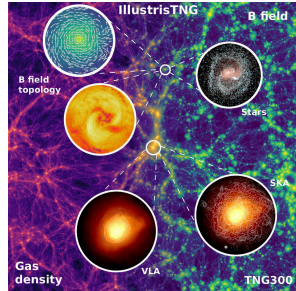
$\sim 1\text{ G}$



(FIR 145 μm)



(Radio 6 cm Fletcher et. al)



Marinacci et al. (2017), Illustris TNG

$\sim 10^{-5}\text{ G}$

Borlaff et al. (2021), SOFIA, M51

$\sim 10^{-9} - 10^{-6}\text{ G}$

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

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,¹⁶ 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.¹⁷
- Alternatively, small seed magnetic fields can be amplified by primordial turbulence induced by phase transitions, e.g., via dynamo.¹⁸

¹⁶Turner & Widrow (1988), Ratra (1992), Gasperini *et al.* (1995).

¹⁷J. Ahonen and K. Enqvist, *Phys. Lett. B* **382**, 40 (1996).

¹⁸A. 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.¹⁹

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

- Also after inflation, axion fields can amplify and produce magnetic fields.²⁰ For example, the QCD axion could oscillate and produce magnetic fields around the QCD scale ($T \sim 100$ MeV).²¹

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

¹⁹ 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).

²⁰ M. M. Forbes and A. R. Zhitnitsky, *Phys. Rev. Lett.* **85**, 5268 (2000).

²¹ 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.²²
- Proposed chiral magnetic effect relevant at smaller scales²³ leading to a chiral plasma instability and development of magnetic fields that undergo inverse cascading.²⁴
- Chiral magnetic effect also present for zero chiral chemical potential from local inhomogeneities.²⁵
- Chiral magnetic effect can be activated from an active source of chiral chemical potential (e.g. associated to baryogenesis at the electroweak scale)²⁶

²² M. Joyce and M. E. Shaposhnikov, *PRL* **79**, 1193 (1997)

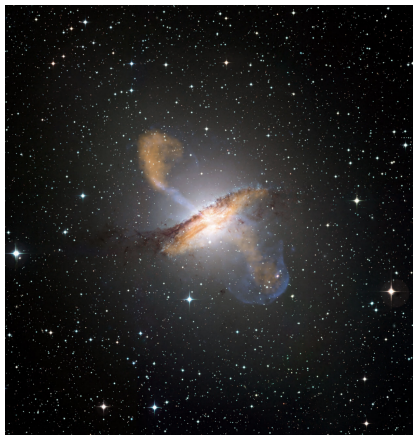
²³ A. Boyarsky *et al.* *PRL* **108**, 031301 (2012).

²⁴ I. Rogachevskii *et al.* *Astrophys. J. Lett* **845** (2017) L21, J. Schober *et al.* *Astrophys. J.* **858**, 124 (2018).

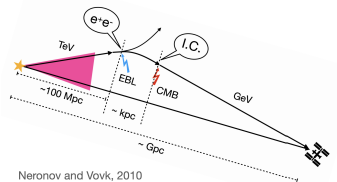
²⁵ J. Schober *et al.* *PRL* **132**, 6 (2024)

²⁶ M. Gurgunidze *et al.* (incl. ARP), arXiv:2512.09177 (2025).

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.



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) proposed²⁷, but seems to not be significant at the intergalactic scales, *recently shown to be suppressed experimentally with the Super Proton Synchrotron at CERN*.²⁸
 - *Magnetized galactic outflows*. Studied using cosmological simulations. However, it is difficult to reach large volume filling factors.²⁹
- Primordial magnetic field present at recombination could alleviate the Hubble tension by reducing the sound horizon.³⁰

²⁷ Broderick et al. (2018).

²⁸ Arrosmith et al. (2025).

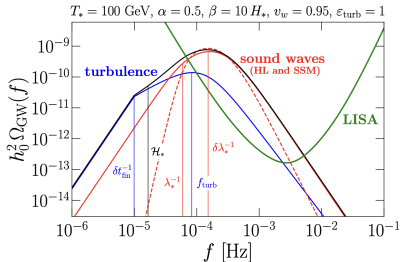
²⁹ Ni et al. (2024), Tjemsland et al. (2024).

³⁰ Jedamzik & Pogosian (2020).

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 CODE³¹ 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).

³¹Pencil Code Collaboration, JOSS **6**, 2807 (2020),
<https://github.com/pencil-code/>

MHD description

Right after the electroweak phase transition we can model the plasma using continuum MHD.

- Charge-neutral, electrically conducting fluid.
- Relativistic magnetohydrodynamic (MHD) equations.
- Radiation-dominated fluid

$$p = \rho c^2/3,$$

i.e., $c_s^2 = 1/3$ (ultrarelativistic EoS).

- Friedmann–Lemaître–Robertson–Walker metric

$$g_{\mu\nu} = \text{diag}\{-1, a^2, a^2, a^2\}$$

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 to³²

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

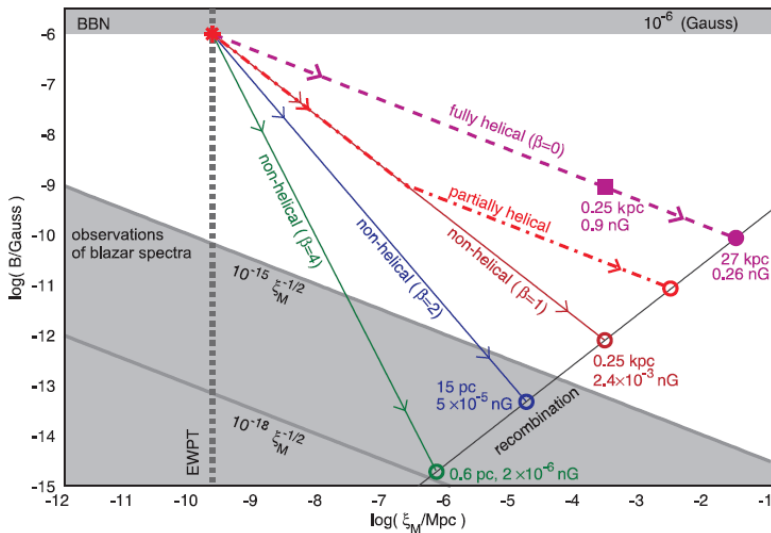
for a flat expanding universe with comoving and normalized

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

³²A. Brandenburg, *et al.*, *Phys. Rev. D* **54**, 1291 (1996).

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

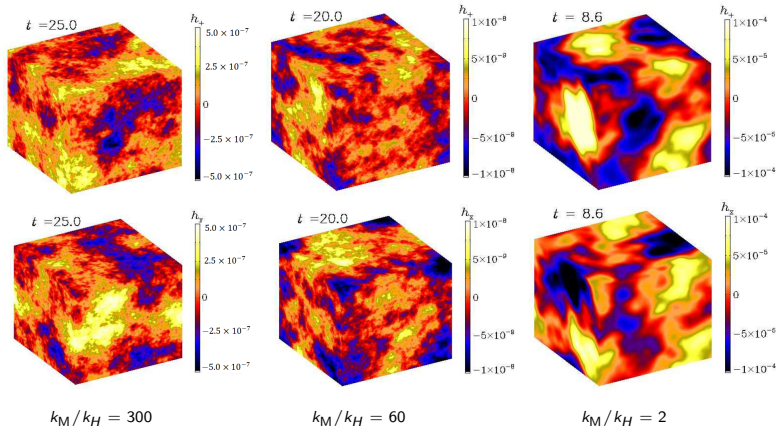
Evolution of magnetic strength and correlation length³³



³³ A. Brandenburg *et al.* (incl. ARP),
Phys. Rev. D **96**, 123528 (2017).

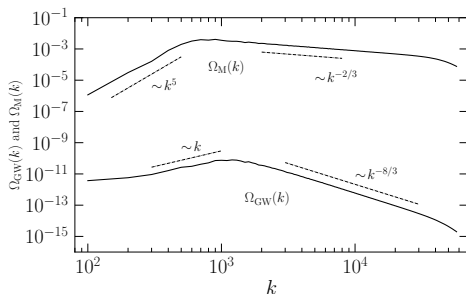
Numerical results for decaying MHD turbulence³⁴

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



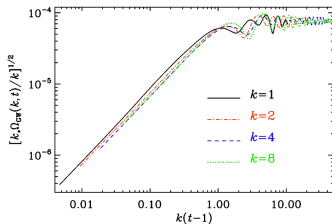
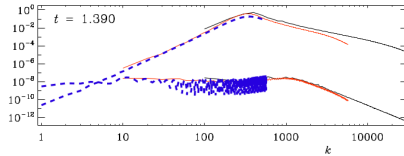
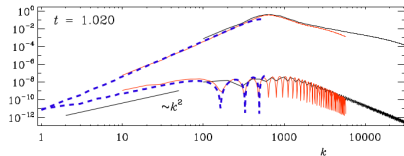
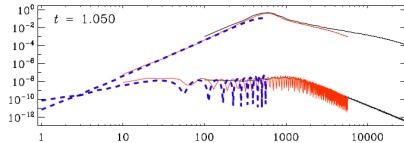
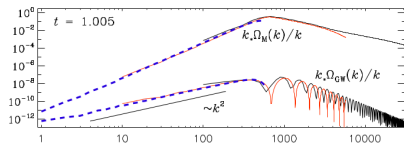
Numerical results for decaying MHD turbulence³⁵

$$1152^3, k_* = 2\pi \times 100, \Omega_M \sim 10^{-2}, \sigma_M = 1$$

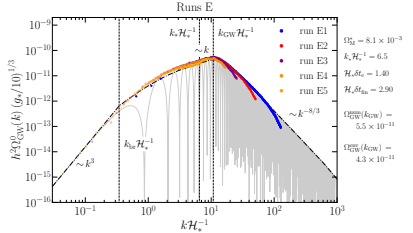
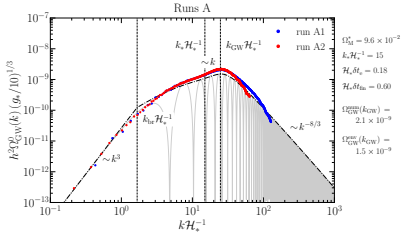


- **Characteristic k scaling in the subinertial range for the GW spectrum.**
- k^2 expected at scales $k < k_*$ and k^3 at $k < H_*$ according to the “top-hat” model (Caprini *et al.*, 2020).

Early time evolution of the GW spectrum



Numerical results for decaying MHD turbulence³⁶



run	Ω_{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	9.6×10^{-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}

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 oscillations³⁷ of $\Omega_{\text{GW}}(k)$.

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

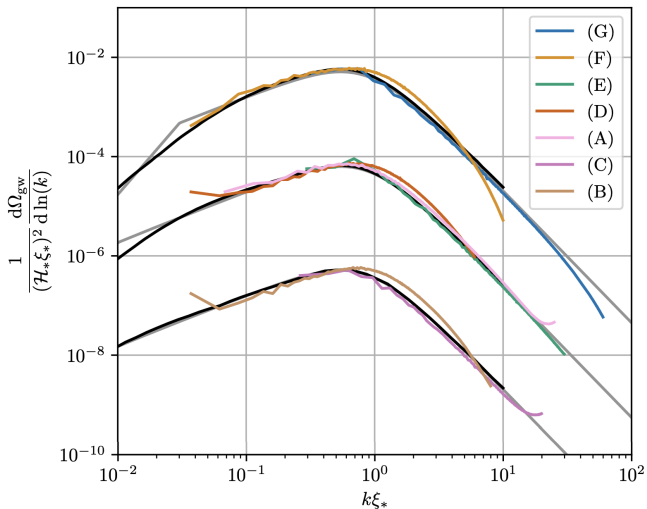
- p_{Π} is the anisotropic stress spectrum and depends on spectral shape, can be approximated for a von Kármán spectrum as³⁸

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

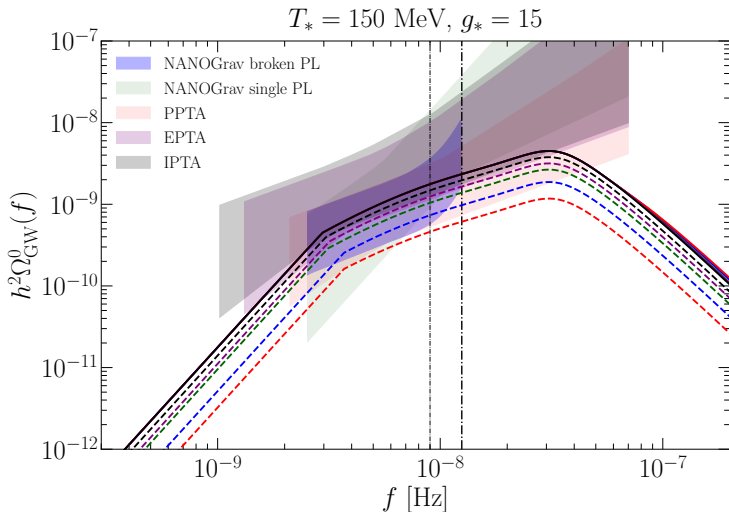
³⁷ ARP et al., *Phys. Rev. D* **105**, 123502 (2022).

³⁸ ARP et al., arXiv:2307.10744 (2023).

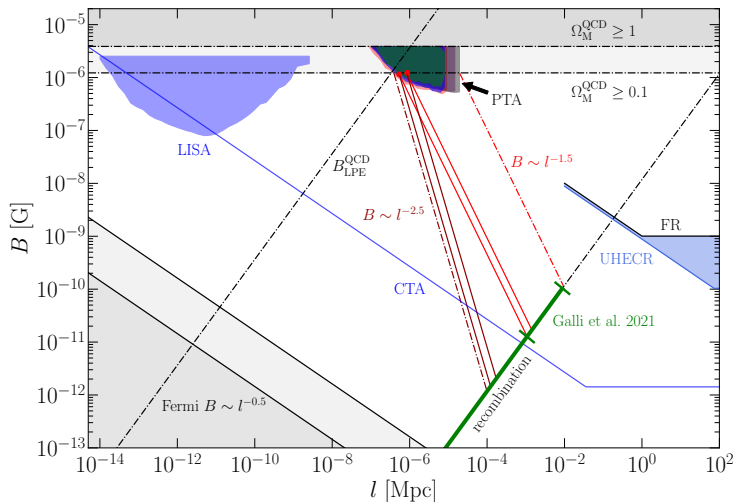
Numerical results for decaying HD vortical turbulence³⁹



Using PTA to constrain primordial magnetic fields at the QCD scale⁴⁰

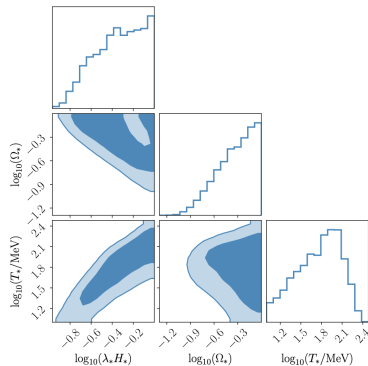
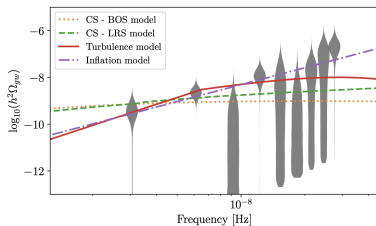


Primordial magnetic field constraints with PTA⁴¹



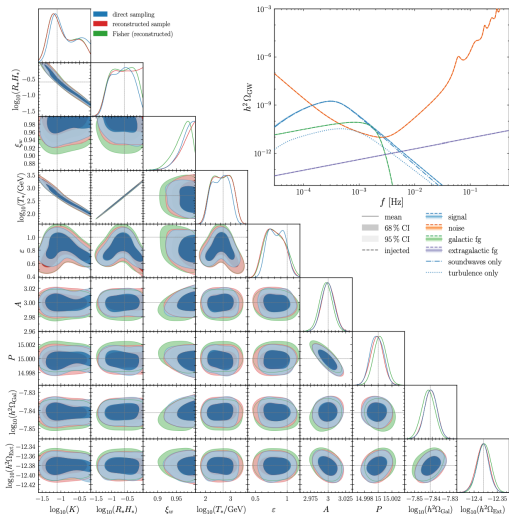
⁴¹ ARP et al., *Phys. Rev. D* **105**, 123502 (2022).

Primordial magnetic fields constraints with PTA⁴²



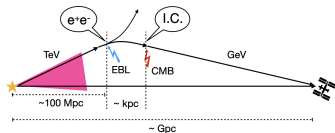
⁴²[EPTA collab.] (incl. ARP), arXiv:2306.16227 (2023).

Parameter reconstruction of GW signal for sound waves and turbulence from a PT with LISA⁴³

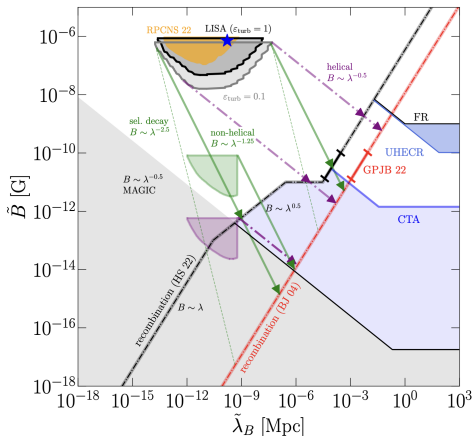


Multi-messenger studies of primordial magnetic fields³⁰

- 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.*, arXiv:2307.10744 (2023).

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

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

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
- The existence of primordial magnetic fields at the epoch of recombination could 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, modifying the dynamics with respect to a fluid dominated by acoustic motion.
- 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!

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github.com/AlbertoRoper/cosmoGW
albertoroper.github.io

