LISA, PTA and γ-ray telescopes as multi-messenger probes of a cosmological first-order phase transition and intergalactic magnetic fields

Cosmology in the Alps 2024
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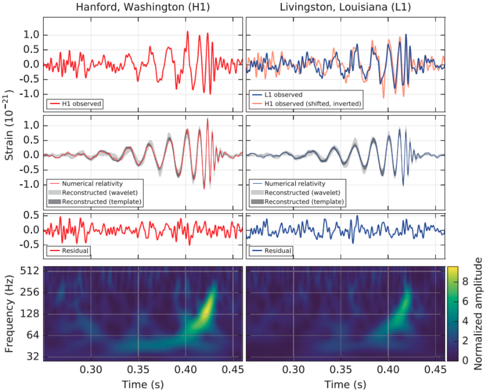
arXiv: 1903.08585, 2009.14174, 2201.05630, 2307.10744, 2403.03723

`https://github.com/AlbertoRoper/cosmoGW` [CosmoGW]

Introduction and Motivation

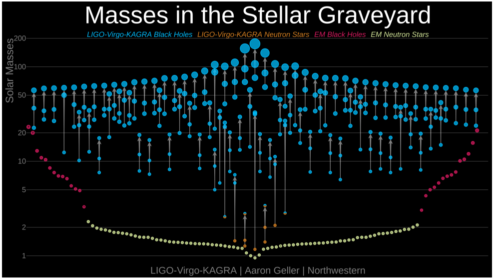
- Gravitational waves are opening a new window into our understanding of the Universe
  - First event GW150914 detected[1]

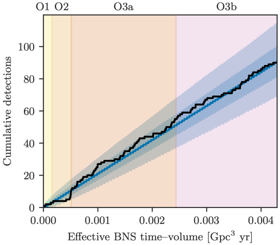


[1] [LIGO-Virgo Collaboration], *Phys. Rev. Lett.* **116**, 061102 (2016)

Introduction and Motivation

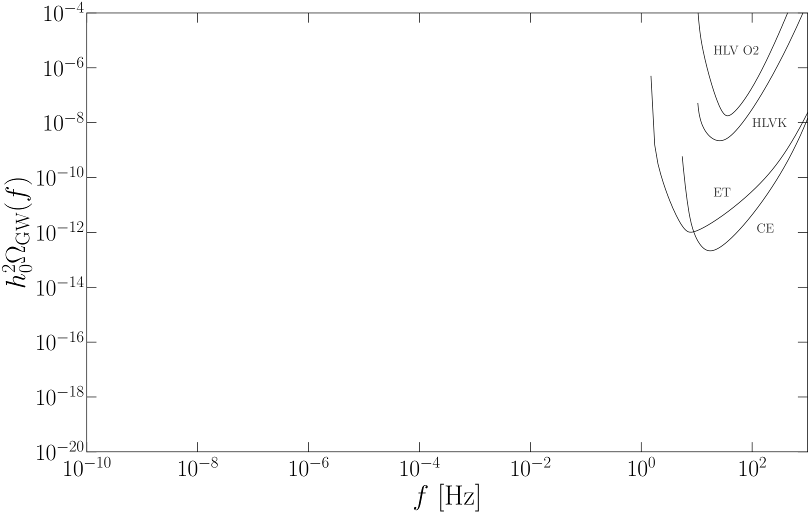
- GW170817 NS binary merger: first detection of GW and EM counterpart (constraint on the GW speed, measure of the Hubble rate)
- Several following events: LIGO-Virgo-KAGRA started the fourth observing run (O4) in May 2023 → 90 events up to O3b[2]





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

Gravitational spectrum (ground-based detectors)



LISA

- Laser Interferometer Space Antenna (LISA) is a space–based interferometer
- Approved in 2017 as one of the main research missions of ESA (L3) with NASA collaboration
- Mission adoption phase in January 2024
- Launch planned for 2034
- Composed by three spacecrafts in a distance of 2.5M km

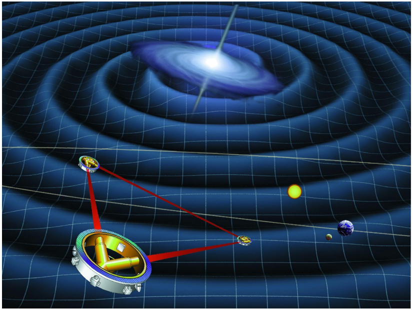
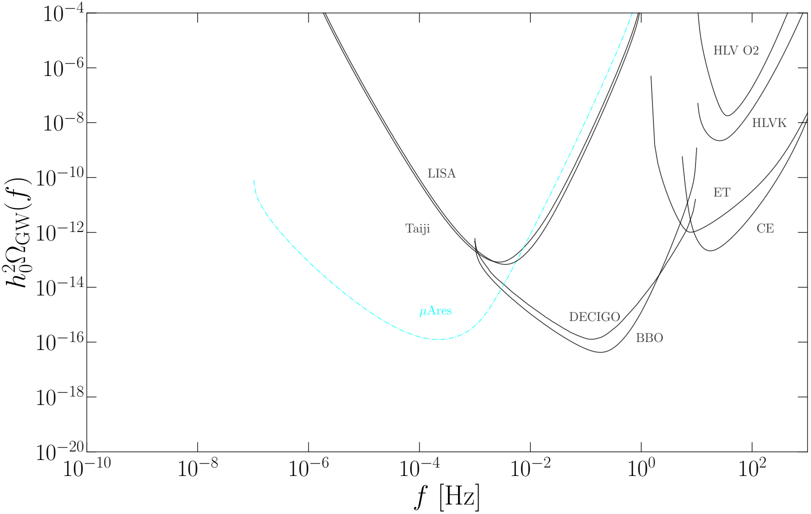


Figure: Artist's impression of LISA from Wikipedia

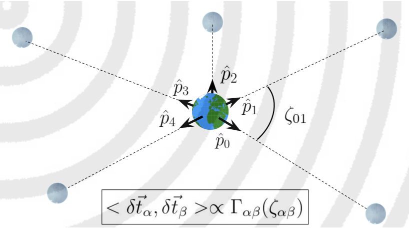
Gravitational spectrum (space-based detectors)



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:

$$\delta t^i = t^i_{\rm obs} - t^i_{\rm TM}$$



Credit: Mikel Falxa

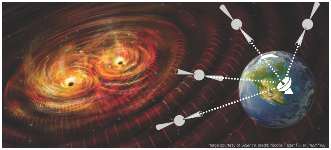
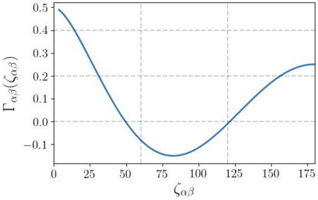


Figure: Image courtesy of Science, credit: Nicolle Rager Fuller

The correlation $\Gamma_{\alpha\beta}$ follows in GR the Hellings-Downs curve[3]



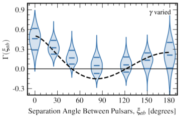
[3] R. W. Hellings and G. S. Downs, *Astrophys. J. Lett.* **265** (1983) L39-L42.

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).

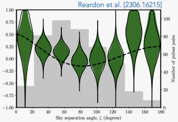
NANOGrav:
68 pulsars, 16yr of data
~3-4σ significance

Agazie et al. [2306.16213]



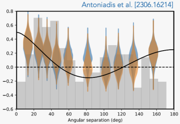
PPTA:
32 pulsars, 18yr of data
~2σ significance

Reardon et al. [2306.16215]



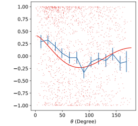
EPTA + InPTA:
25 pulsars, 24yr of data
~3σ significance

Antoniadis et al. [2306.16214]



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

Xu et al. [2306.16216]



Credit: Andrea Mitridate

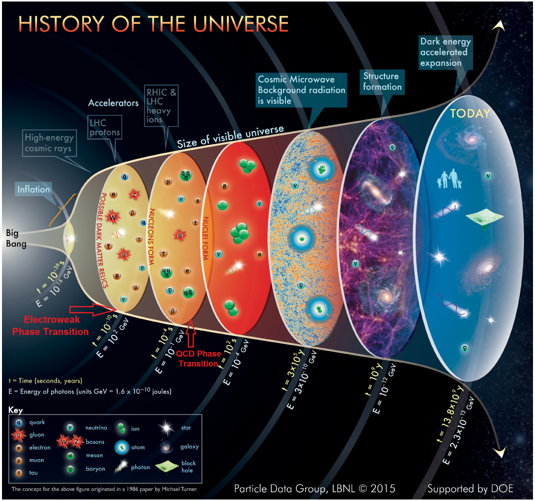
Cosmological GWs

Main considered source of the signal is from the superposition of supermassive black hole binaries (SMBHB), but other sources are also possible: individual sources[4] or early universe sources[5] (cosmological GW background).

Cosmological GWs have the potential to provide us with *direct information on early universe physics* that is *not directly accessible via electromagnetic observations, possibly complementary to collider experiments*:
nature of first-order phase transitions (baryogenesis, BSM physics, high-energy physics),
primordial origin of intergalactic magnetic fields.

[4] [EPTA Collaboration], *The second data release from the European Pulsar Timing Array IV. Search for continuous gravitational wave signals*, arXiv:2306.16226

[5] [EPTA Collaboration] (incl. ARP), *The second data release from the European Pulsar Timing Array: V. Implications for massive black holes, dark matter and the early Universe*, arXiv:2306.16227.
[NANOGrav Collaboration], *The NANOGrav 15 yr Data Set: Search for Signals from New Physics*, arXiv:2306.16219.



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
Electroweak Phase Transition
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
QCD Phase Transition
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

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

- From inflation
  - B-modes of CMB anisotropies ($f_c \sim 10^{-18}$ Hz).
  - Can cover all f spectrum, depending on end-of-reheating T, and blue-tilted (beyond slow-roll inflation).

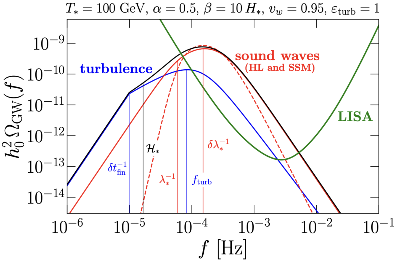
GW sources in the early universe

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

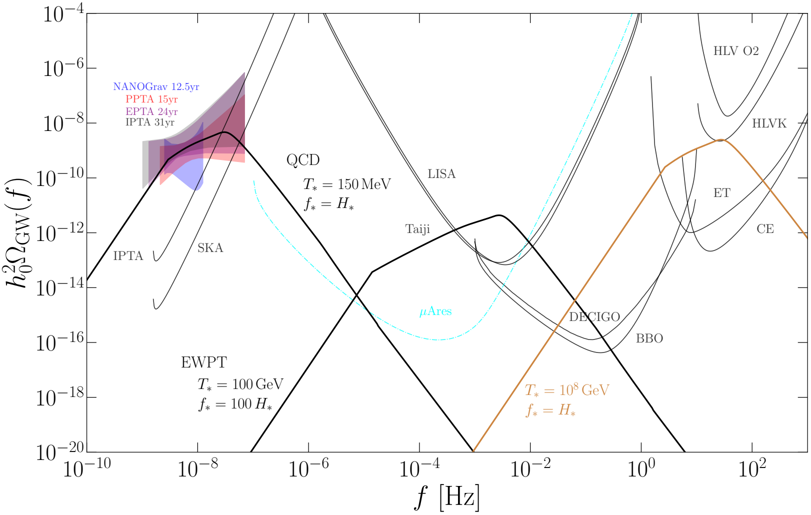
- High-conductivity of the early universe leads to a high-coupling between magnetic and velocity fields.

- Other sources of GWs include
  - Bubble collisions.
  - Cosmic strings.
  - Primordial black holes.
  - Inflation.

ARP *et al.*, 2307.10744, 2308.12943



Gravitational spectrum (turbulence from PTs)[6]



[6] 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).

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 inevitably lead to MHD turbulence.[7]
- Present magnetic fields can be amplified by primordial turbulence via dynamo.[8]
- Primordial magnetic fields are assumed to reach equipartition after the phase transition, modelled as a fraction $\varepsilon/2$ of the total energy.[9]

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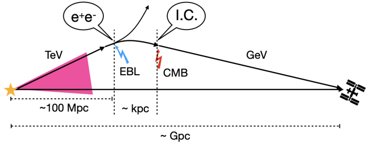
[7] J. Ahonen and K. Enqvist, *Phys. Lett. B* **382**, 40 (1996).

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

[9] ARP *et al.*, arXiv:2307.10744 (2023)
[LISA Cosmology Working Group] (incl. ARP), arXiv:2403.03723 (2024)

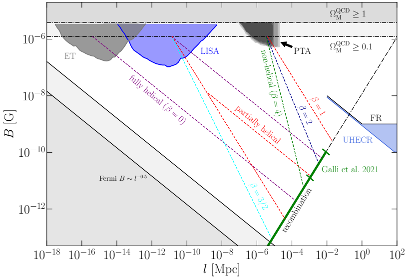
Multi-messenger constraints on primordial magnetic fields[3]

- 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 found by the Fermi collaboration.[4]



- Maximum amplitude of primordial magnetic fields is constrained by the big bang nucleosynthesis.[5]

- Additional constraints from CMB, Faraday Rotation, ultra-high energy cosmic rays (UHECR).



- CTA telescopes will allow to explore a broader range of parameters of the intergalactic magnetic field with strengths 1–10 pG, estimated[6] using deep exposure of the nearest hard spectrum blazar Mrk 501

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

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

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

[6] Korochkin, Kalashev, Neronov, Semikoz, *PoS ICRC2021* (2021) 919

Conclusions

- Primordial magnetic fields in the early universe can significantly contribute to the stochastic GW background (SGWB) and lead to the production of MHD turbulence.
- The SGWB produced by MHD turbulence requires, in general, performing high-resolution numerical simulations, which can be done using the Pencil Code.
- LISA, PTA (SKA), 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.
- γ-ray observations (Fermi LAT, CTA) can constrain intergalactic magnetic fields.
- Primordial magnetic fields can be studied in a multi-messenger approach, combining GW (interferometers and radio telescopes), CMB, and γ-ray observations.

Thank You!

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github.com/AlbertoRoper/cosmoGW
cosmology.unige.ch/users/alberto-roper-pol

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APC, CNRS, FRANCE

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Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

NORDITA
The Nordic Institute for Theoretical Physics

Extra slides

Generation of primordial magnetic fields

- Bubble collisions and velocity fields induced by first-order phase transitions can amplify seed magnetic fields.
- Parity-violating processes during the EWPT are predicted by SM extensions that account for baryogenesis and can produce helical magnetic fields through sphaleron decay or B+L anomalies.[10]

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

- Axion fields can amplify and produce magnetic field helicity.[11]

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

[10] 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).

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

Generation of primordial magnetic fields

- Inhomogeneities in the Higgs field in low-scale electroweak hybrid inflation.[12]
- Magnetic fields from inflation can be present during phase transitions (non-helical[13] and helical[14]).
- Low-scale (QCD and EWPT) magnetogenesis during reheating.[15]
- Chiral magnetic effect.[16]

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[12] M. Joyce and M. E. Shaposhnikov, *Phys. Rev. Lett.* **79**, 1193 (1997), J. García-Bellido *et al.*, *Phys. Rev. D* **60**, 123504 (1999).

[13] M. S. Turner and L. M. Widrow, *Phys. Rev. D* **37**, 2743 (1988).

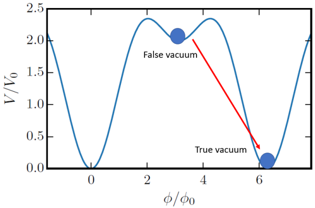
[14] M. Giovannini, *Phys. Rev. D* **58**, 124027 (1998).

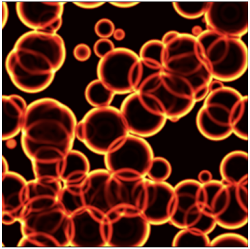
[15] R. Sharma, *Phys. Rev. D* **97**, 083503 (2018).

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

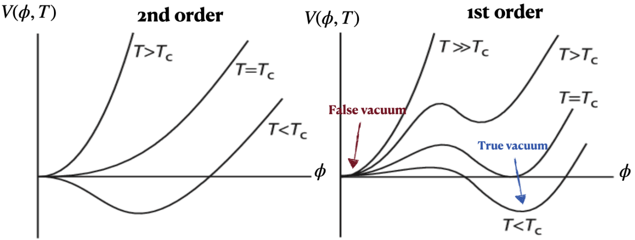
First-order phase transition

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

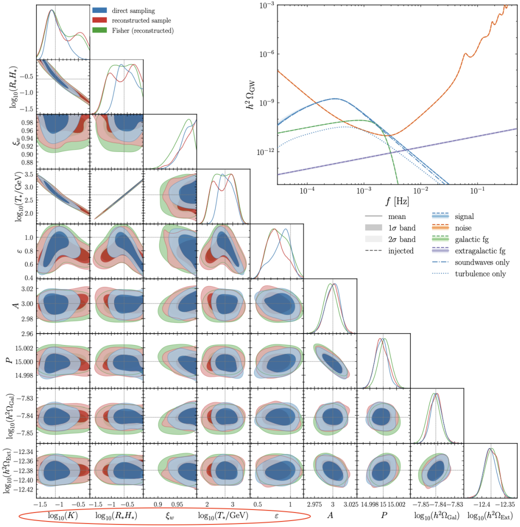




Credits: I. Stomberg



Parameter reconstruction of phase transitions with LISA[17]



K: fraction of kinetic energy density

R_*: mean size of bubbles

ξ_w: velocity of bubbles

T_*: temperature at the end of the PT

ε: fraction of turbulence energy density

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[17] [LISA Cosmology Working Group] (incl. ARP), arXiv:2403.03723 (2024)

GWs from (M)HD turbulence

- Direct numerical simulations using the Pencil Code[18] to solve:
  1. Relativistic MHD equations adapted for radiation-dominated era (after electroweak symmetry is broken).
  2. Gravitational waves equation.

- In general, large-resolution simulations are necessary to solve the MHD nonlinearities (e.g., unequal-time correlators UETC and non-Gaussianities, which require simplifying assumptions in analytical studies).

[18] Pencil Code Collaboration, JOSS **6**, 2807 (2020), `https://github.com/pencil-code/`
ARP *et al., Geophys. Astrophys. Fluid Dyn.* **114**, 130 (2020).

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[19]

$$\frac{\partial \ln \rho}{\partial t} = -\frac{4}{3}\left(\boldsymbol{\nabla} \cdot \boldsymbol{u} + \boldsymbol{u} \cdot \boldsymbol{\nabla} \ln \rho\right) + \frac{1}{\rho}\left[\boldsymbol{u} \cdot (\boldsymbol{J} \times \boldsymbol{B}) + \eta \boldsymbol{J}^2\right],$$

$$\frac{D\boldsymbol{u}}{Dt} = \frac{1}{3}\mathbf{u}\left(\boldsymbol{\nabla} \cdot \boldsymbol{u} + \boldsymbol{u} \cdot \boldsymbol{\nabla} \ln \rho\right) - \frac{\boldsymbol{u}}{\rho}\left[\boldsymbol{u} \cdot (\boldsymbol{J} \times \boldsymbol{B}) + \eta J^2\right]$$

$$-\frac{1}{4}\boldsymbol{\nabla} \ln \rho + \frac{3}{4\rho}\boldsymbol{J} \times \boldsymbol{B} + \frac{2}{\rho}\boldsymbol{\nabla} \cdot (\rho \nu \boldsymbol{S}),$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times (\boldsymbol{u} \times \boldsymbol{B} - \eta \boldsymbol{J}), \quad \boldsymbol{J} = \boldsymbol{\nabla} \times \boldsymbol{B},$$

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 ($\mathrm{d}t = a \mathrm{d}t_c$).

[19] A. Brandenburg, *et al.*, *Phys. Rev. D* **54**, 1291 (1996).

GW equation for a flat expanding Universe

- Assumptions: isotropic and homogeneous Universe.
- Friedmann–Lemaître–Robertson–Walker (FLRW) metric $\gamma_{ij} = a^2\delta_{ij}$.
- Tensor-mode perturbations above the FLRW model:

$$g_{ij} = a^2\left(\delta_{ij} + h_{ij}^{\mathrm{phys}}\right), \quad |h_{ij}^{\mathrm{phys}}| \ll |g_{ij}|$$

- GW equation is[20]

$$\left(\partial_t^2 - \frac{a''}{a} - c^2\nabla^2\right) h_{ij} = \frac{16\pi G}{\mathbf{a}c^2} T_{ij}^{\mathrm{TT}}$$

  - h_{ij} are rescaled $h_{ij} = a h_{ij}^{\mathrm{phys}}$.
  - Comoving spatial coordinates $\nabla = a\nabla^{\mathrm{phys}}$.
  - Conformal time $\mathrm{d}t = a\,\mathrm{d}t_c$.
  - Comoving stress-energy tensor components $T_{ij} = a^4 T_{ij}^{\mathrm{phys}}$.
  - Radiation-dominated epoch such that $a'' = 0$.

[20] L. P. Grishchuk, *Sov. Phys. JETP* **40**, 409 (1974).

Numerical results for decaying MHD turbulence[21]

Initial conditions

- Initial stochastic magnetic (or velocity) field with fractional helicity $\sigma_{\rm M}$.

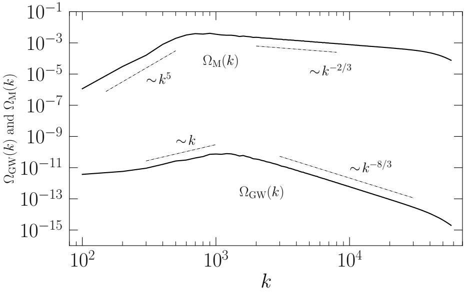
$$kB_i(\boldsymbol{k}) = \left(\delta_{ij} - \hat{k}_i \hat{k}_j - i\sigma_{\rm M}\varepsilon_{ijl}\hat{k}_l\right) g_j \sqrt{2\Omega_{\rm M}(k)/k}$$

- Batchelor spectrum for magnetic (or vortical velocity) fields, i.e., $\Omega_{\rm M} \propto k^5$ for small $k < k_* \sim \mathcal{O}(\xi_{\rm M}^{-1})$.
- Kolmogorov spectrum in the inertial range, i.e., $\Omega_{\rm M} \propto k^{-2/3}$.

[21] A. Brandenburg *et al.* (incl. ARP), *Phys. Rev. D* **96**, 123528 (2017).
ARP *et al.*, *Phys. Rev. D* **102**, 083512 (2020).
ARP *et al.*, *JCAP* **04** (2022), 019.
ARP *et al.*, *Phys. Rev. D* **105**, 123502 (2022).

Numerical results for decaying MHD turbulence[22]

$1152^3, k_* = 2\pi \times 100, \Omega_{\rm M} \sim 10^{-2}, \sigma_{\rm M} = 1$



- **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).

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

Analytical 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[23] of $\Omega_{\rm GW}(k)$.

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

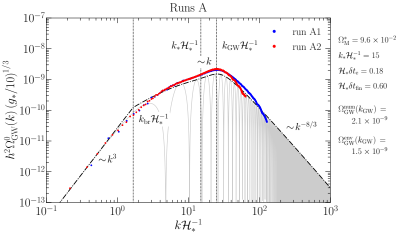
- p_Π is the anisotropic stress spectrum and depends on spectral shape, can be approximated for a von Kárman spectrum as[24]

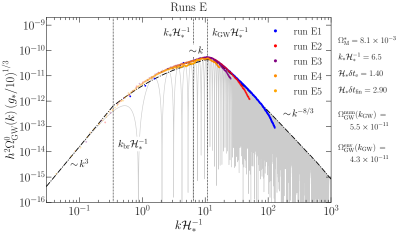
$$p_\Pi(k/k_*) \simeq \left[1 + \left(\frac{k}{2.2 k_*}\right)^{2.15}\right]^{-11/(3\times 2.15)}$$

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

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

Numerical results for nonhelical decaying MHD turbulence[25]





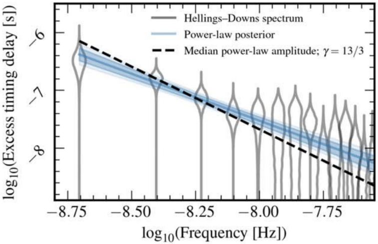
run	$\Omega_{\rm M}^*$	$k_*\mathcal{H}_*^{-1}$	$\mathcal{H}_*\delta t_{\rm e}$	$\mathcal{H}_*\delta t_{\rm fin}$	$\Omega_{\rm GW}^{\rm num}(k_{\rm GW})$	$[\Omega_{\rm GW}^{\rm env}/\Omega_{\rm GW}^{\rm num}](k_{\rm GW})$	n	$\mathcal{H}_*L$	$\mathcal{H}_*t_{\rm end}$	$\mathcal{H}_*\eta$
A1	9.6×10^{-2}	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}

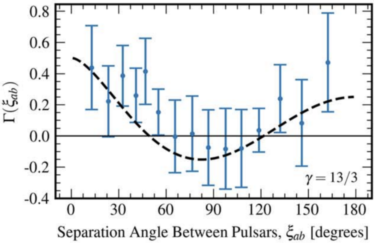
[25] ARP *et al.*, *Phys. Rev. D* **105**, 123502 (2022).

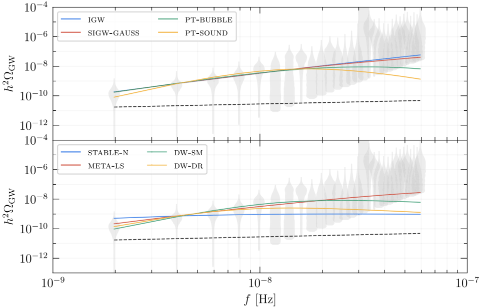
Pulsar Timing Array (PTA) collaborations

- International PTA collaborations combine their data in the IPTA collaboration.
- European Pulsar Timing Array (EPTA): *Effelsberg, Lovell, Nancay Radio Telescope, Sardinia Radio Telescope, Westerbork Synthesis Radio Telescope.*
- North American Nano-Hertz Observatory for Gravitational Waves (NANOGrav): *Green Bank Telescope (GBT), Arecibo (until 2020), Very Large Array (VLA), Canadian Hydrogen Intensity Mapping Experiment (CHIME).*
- Parkes PTA (PPTA): *Murriyang radio telescope.*
- Indian PTA (InPTA): *GMRT.*
- Chinese Pulsar Timing Array (CPTA): *Five-hundred-meter Aperture Spherical Telescope (FAST).*
- MeerKAT PTA (MPTA).

NANOGrav 15 yr data observation[26]

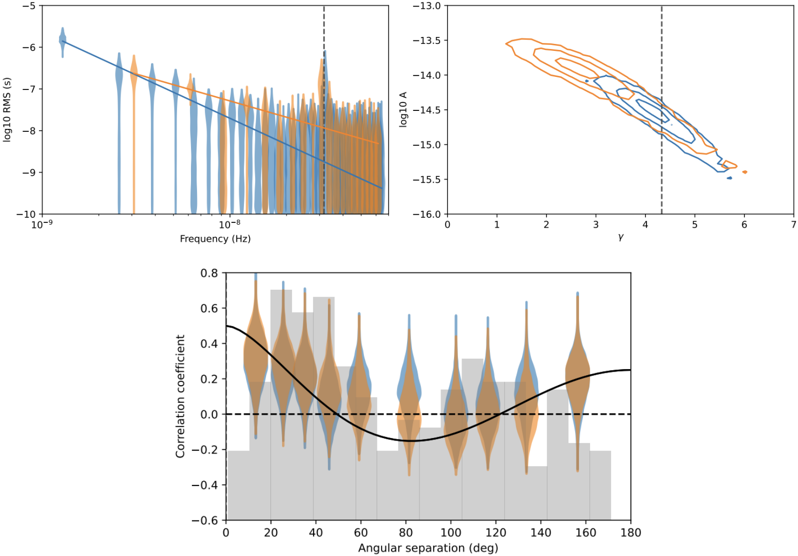






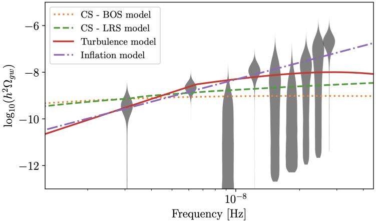
[26] [NANOGrav collaboration], *ApJ Lett.* **951**, 8 & 11 (2023).

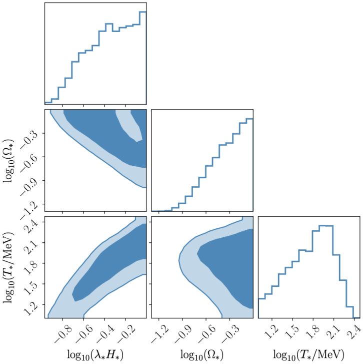
EPTA 24.7 yr data observation (DR 2)[27]



[27] [EPTA Collaboration], arXiv:2306.16224.

Primordial magnetic fields constraints with EPTA DR 2[28]





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