LISA (and PTA) and γ-ray telescopes as multi-messenger probes of a first-order cosmological phase transition

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arXiv:2009.14174, 2201.05630, 2307.10744, 2308.12943

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

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).

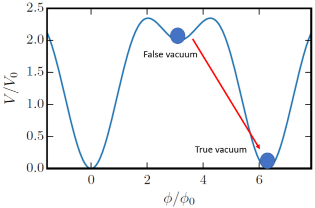
Cosmological GWs

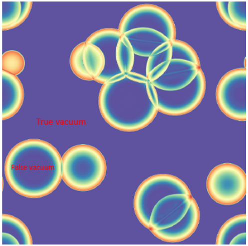
Cosmological GWs have the potential to provide us with *direct information on early universe physics* that is *not accessible via electromagnetic observations, possibly complementary to collider experiments*:

nature of first-order phase transitions (baryogenesis, BSM physics, high-energy physics),
primordial origin of intergalactic magnetic fields.

First–order phase transition

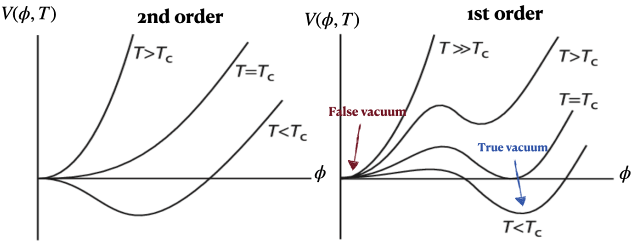
$$V(\phi, T) = \frac{1}{2}M^2(T)\phi^2 - \frac{1}{3}\delta(T)\phi^3 + \frac{1}{4}\lambda\phi^4$$





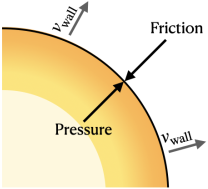
Credits: D. Weir (above),

I. Stomberg (below)



Hydrodynamics of first-order phase transitions[1]

- 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



$$\nabla_\mu T^{\mu\nu}_{\rm field} = \frac{\partial V}{\partial \phi}\partial^\nu \phi + \eta u^\mu \partial_\mu \phi \partial^\nu \phi\,,$$

$$\nabla_\mu T^{\mu\nu}_{\rm fluid} = -\frac{\partial V}{\partial \phi}\partial^\nu \phi - \eta u^\mu \partial_\mu \phi \partial^\nu \phi\,,$$

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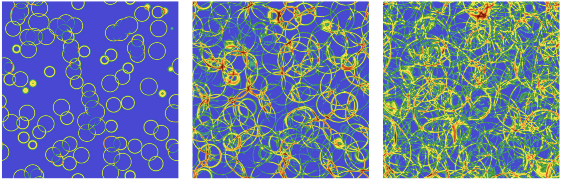
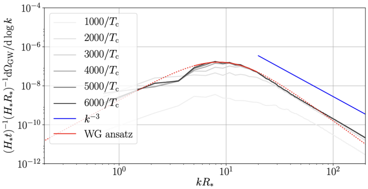
[1] Espinosa, Konstandin, No, Servant, *JCAP* **06** (2010) 028.

GWs from sound waves[2]

- Numerical simulations of the scalar + fluid system can be performed including an effective friction term



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



(b) Intermediate, $v_w = 0.92$

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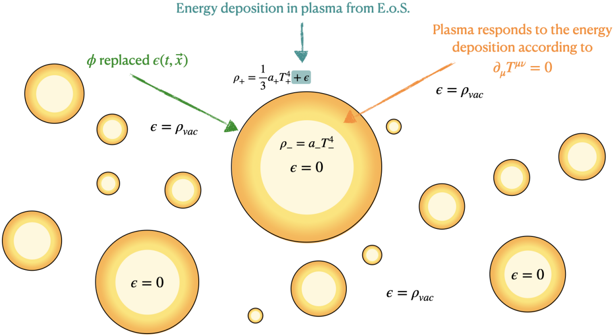
[2] Hindmarsh *et al.*, 2013, 2015, 2017.

GWs from sound waves: Higgsless simulations[3]

- 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.



Credit: I. Stomberg

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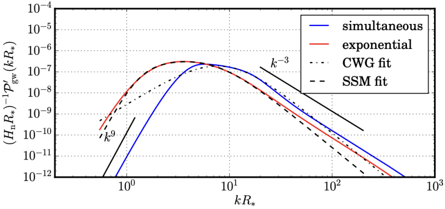
[3] Jinno *et al.*, 2020, 2022.

GWs from sound waves: Sound-shell model[4]

- The sound-shell model assumes linear superposition of velocity fields from each of the single bubbles and averages over nucleation locations and bubbles lifetimes (semi-analytical model), and the development of sound waves at the time of collisions.
- It predicts a steep k^9 spectrum and linear growth with time, according to HH19, and k^{-3} at large frequencies, with an intermediate k between $1/R_*$ and $1/\Delta R_*$.



(b) Intermediate, $v_{\rm w} = 0.92$

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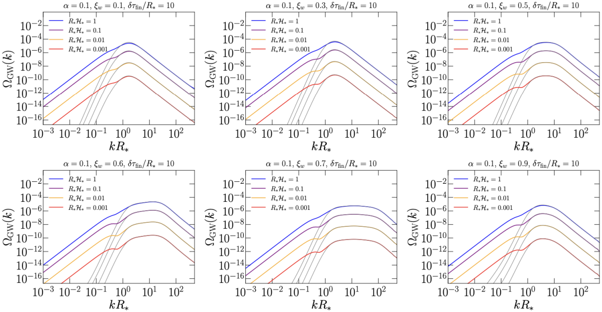
[4] Hindmarsh, 2016; Hindmarsh & Hijazi, 2019.

GWs from sound waves: Sound-shell model revisited[5]

- Extended sound-shell model to an expanding Universe and omitted assumptions that were not holding at small k.
- Recovered k^3 at small frequencies and found a $\ln^2$ time evolution of the causal branch and the linear-in-time evolution around the peak, as well as a sharp bump.



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[5] ARP *et al.*, arXiv:2308.12943.

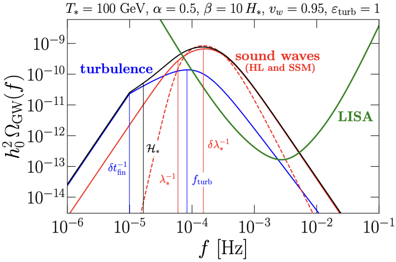
GW sources in the early universe

- 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

- 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.[6]
- Present magnetic fields can be amplified by primordial turbulence via dynamo.[7]

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

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

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.[8]

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

- Axion fields can amplify and produce magnetic field helicity.[9]

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

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[8] 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).

[9] 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.[10]
- Magnetic fields from inflation can be present during phase transitions (non-helical[11] and helical[12]).
- Low-scale (QCD and EWPT) magnetogenesis during reheating.[13]
- Chiral magnetic effect.[14]

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

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

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

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

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

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[15]

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

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

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

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

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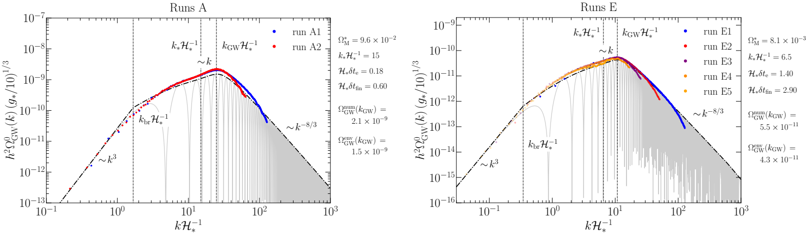
[15] A. Brandenburg, *et al.*, *Phys. Rev. D* **54**, 1291 (1996).

Numerical results for nonhelical decaying MHD turbulence[16]



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}

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

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[17] 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[18]

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

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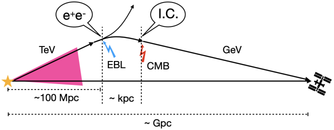
[17] ARP *et al.*, *Phys. Rev. D* **105**, 123502 (2022).

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

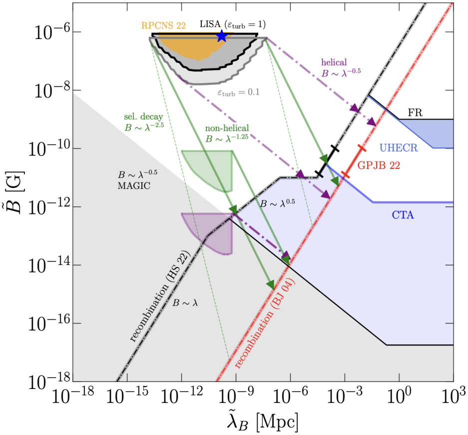
Primordial magnetic fields[3]

- 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 derived 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).



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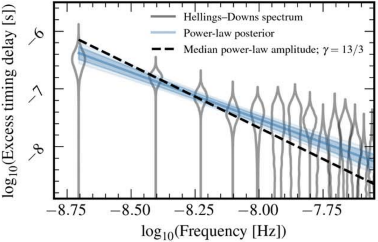
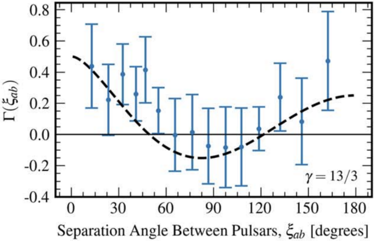
[3] ARP *et al.*, arXiv:2307.10744 (2023).

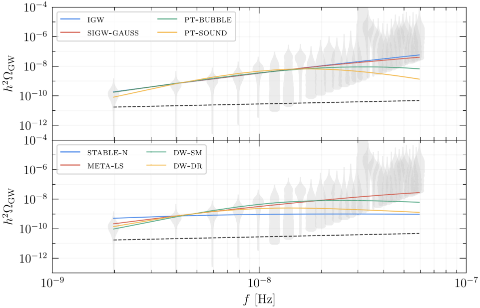
[4] A. Neronov and I. Vovk, *Science* **328**, 73 (2010).

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

NANOGrav 15 yr data observation[19]







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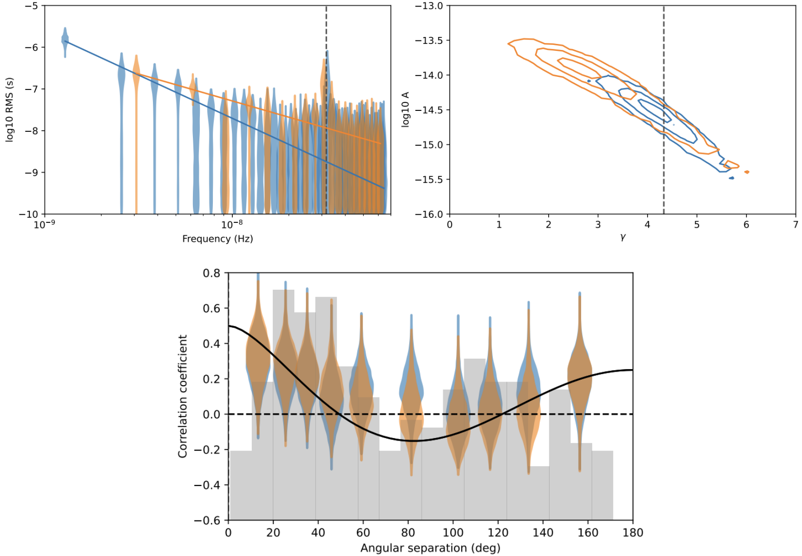
[19] [NANOGrav collaboration], *ApJ Lett.* **951**, 8 & 11 (2023).

EPTA 24.7 yr data observation (DR 2)[20]



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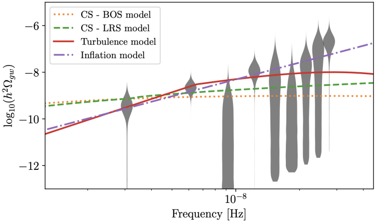
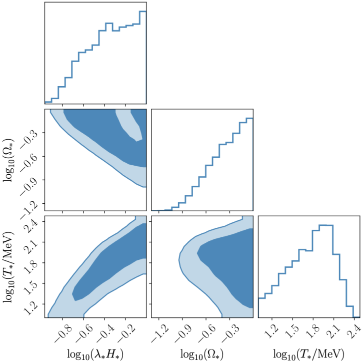
[20] [EPTA Collaboration], arXiv:2306.16224.

Primordial magnetic fields constraints with EPTA DR 2[21]





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

Conclusions

- Velocity and magnetic fields in the early universe can significantly contribute to the stochastic GW background (SGWB) via sound waves and (M)HD turbulence.
- MHD requires, in general, performing high-resolution numerical simulations, which can be done using the Pencil Code.
- Since the SGWB is a superposition of different sources, it is extremely important to characterize the different sources, to be able to extract clean information from the early universe physics.
- The interplay between sound waves and the development of turbulence is not well understood. It plays an important role on the relative amplitude of both sources of GWs.
- LISA, PTA, and next-generation ground-based detectors can potentially be used to probe the origin of magnetic fields in the largest scales of our Universe, which is still an open question in cosmology.
- Bubble nuccleation, sound wave production, and magnetogenesis physics can be coupled to our equations for more realistic production analysis (future work).

The End

Thank You!

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