Gravitational waves from phase transitions in the early Universe: sound waves and MHD turbulence

Gravitational Wave Probes of Physics Beyond Standard Model
University of Warsaw, Jun. 26

Alberto Roper Pol
University of Geneva

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GW background from the early 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, possibly complementary to collider experiments*:

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

Probing the early Universe with GWs

Cosmological (pre-recombination) GW background

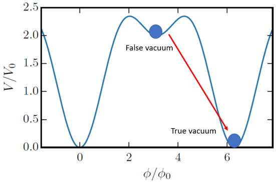
- Why background? Individual sources are not resoluble, superposition of single events occurring in the whole Universe.

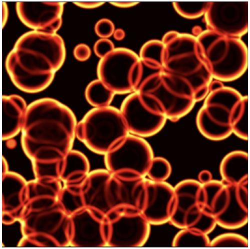
$$f_* \simeq 1.64 \times 10^{-3} \frac{100}{R_* \mathcal{H}_*} \frac{T_*}{100\,\mathrm{GeV}}\,\mathrm{Hz}$$

- 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

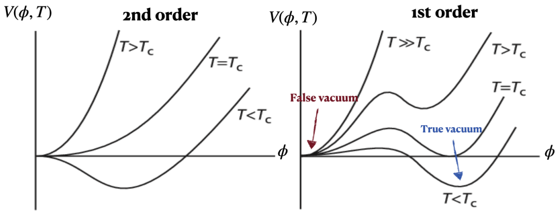
First–order phase transition

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



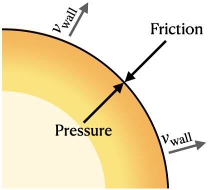


Credits: I. Stomberg



Hydrodynamics of first-order phase transitions[1]

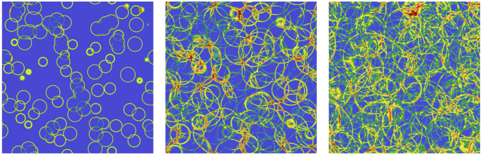
- Broken-phase bubbles are nucleated and expand
- Friction from particles yield a terminal velocity ξ_w of the bubbles
- The bubble can run away when the friction is not enough to stop the bubble's acceleration
- A fraction κ of the vacuum energy will be transferred into kinetic energy of the primordial fluid



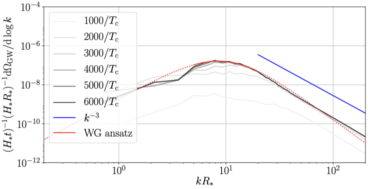
$$\nabla_\mu T^{\mu\nu}_{\rm field} = \frac{\partial V}{\partial \phi}\partial^\nu \phi + \eta u^\mu \partial_\mu \phi \partial^\nu \phi\,,$$
$$\nabla_\mu T^{\mu\nu}_{\rm fluid} = -\frac{\partial V}{\partial \phi}\partial^\nu \phi - \eta u^\mu \partial_\mu \phi \partial^\nu \phi\,,$$

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

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



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



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

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

$$S(s) = \mathcal{N} s^3 \left(\frac{7}{4+3s^2}\right)^{\frac{7}{2}},$$ [LISA CosWG] 2020

$$S(s, s_2) = \mathcal{N} s^3 (1+s^3)^{-2/3}(3+s_2^2)^{-2}, \quad s_2 = f\Delta R_*$$

ARP *et al.* 2023, [LISA CosWG] 2024.

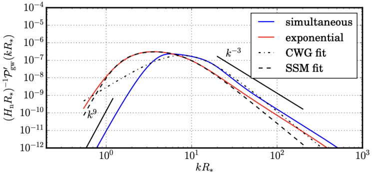
[2] Hindmarsh *et al.*, 2013, 2015, 2017, Cutting *et al.*, 2019, Correia *et al.*, 2025

GWs from sound waves: Sound Shell Model[3]

- The sound shell model assumes linear superposition of velocity fields from each of the single bubbles and averages over nucleation locations and bubble lifetimes (semi-analytical model), and the development of sound waves at the time of collisions. It assumes stationary UETC $P_\Pi = P_\Pi(k, t_2 - t_1)$.

$$\Omega_{\rm GW}(f) = 3\,\tilde\Omega_{\rm GW}\, K^2\,(H_*\tau_{\rm sw})\,(H_* R_*)\,S(f\,R_*)$$

- HH19 predicts a steep k^9 spectrum and linear growth with time and k^{-3} at large frequencies, with an intermediate k between $1/R_*$ and $1/\Delta R_*$.
- GW predictions usually assume $\tau_{\rm sw} = \min(\tau_{\rm sh}, H_*^{-1})$, with $\tau_{\rm sh} \sim R_*/\sqrt{K}$ being the expected time to develop non-linearities. This is an interval in conformal time $\tau_{\rm sw} = \tau_{\rm fin} - \tau_*$ due to the conformal invariance of the fluid equations (ARP & Midiri 2025).

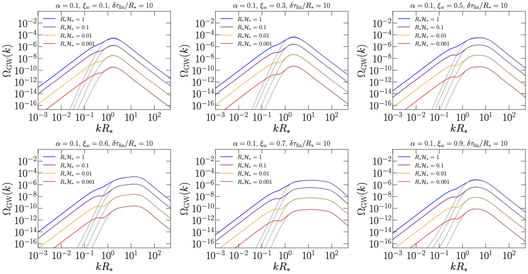


(b) Intermediate, $v_{\rm w} = 0.92$

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

GWs from sound waves: Sound Shell Model revisited[4]

- Extended Sound Shell model to an expanding Universe and omitted assumptions that were not holding at small k, finding a new contribution previously omitted.
- HH19 model is shown to hold at $k\tau_{\rm sw} \sim kR_*/\sqrt{K} \gg 1$, so it holds around the spectral peak when $\sqrt{K} \ll 1$.
- Recovered causal branch at small frequencies, proportional to $k^3 \ln^2(1 + \tau_{\rm sw} H_*)$.
- Linear growth becomes $\Upsilon = \frac{\tau_{\rm sw} H_*}{1+\tau_{\rm sw} H_*} < 1$ when expansion is included (Guo *et al.*, 2021)



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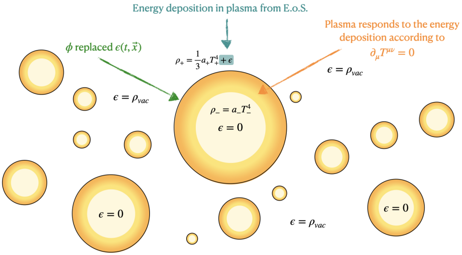
[4] ARP, Procacci, Caprini, Phys. Rev. D, arXiv:2308.12943

Sharma *et al.*, JCAP 12 (2023) 042.

GWs from sound waves: Higgsless simulations[5]

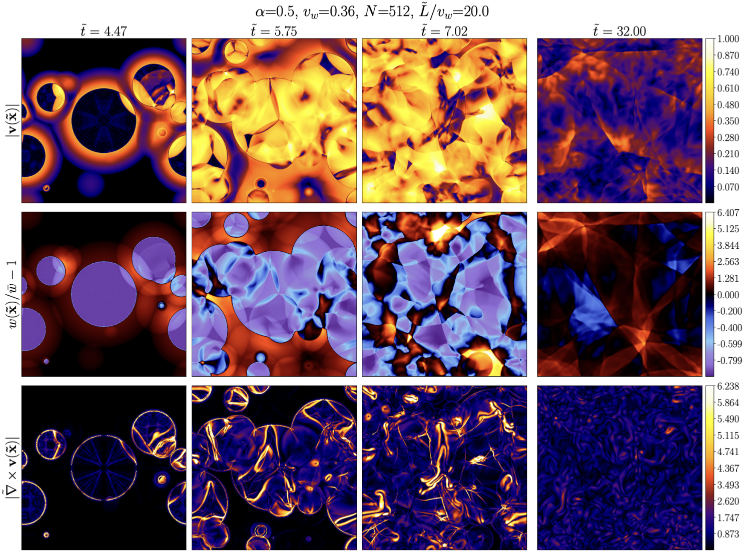
- Difficulty on simulations is due to the different scales of the scalar field ϕ and the fluid shell, so one can consider a nucleation history and set the pressure and energy density by knowing the value of ϵ and setting it during the simulation.
- Effect of bubble collisions on GWs is subdominant when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



Credit: I. Stomberg

[5] Jinno *et al.* JCAP 02 (2023) 011, 2209.04369,
ARP, Stomberg *et al.*, JHEP, arXiv:2409.03651 (2024).

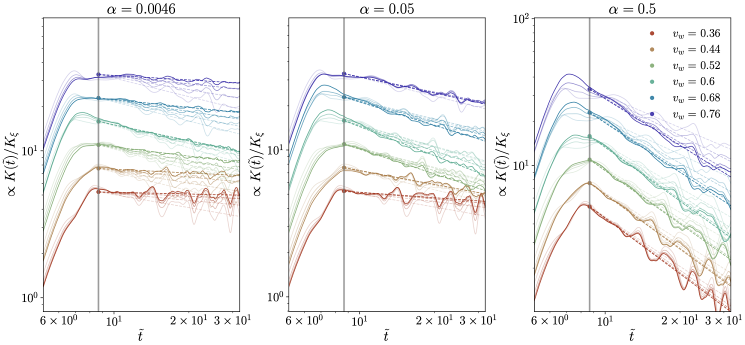
Higgsless simulations of strong PTs[6]



[6] ARP, Stomberg *et al.*, JHEP, arXiv:2409.03651.

Higgsless simulations (results)[7]

- Kinetic energy decay is observed in the simulations
- For weak and strong PTs, increasing resolution enhances the decay.
- Potential indication of the development of non-linearities (turbulence), around 30% of vortical motion at the end of the simulations for strong deflagrations.



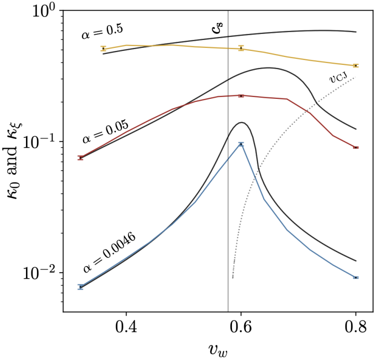
[7] ARP, Stomberg *et al.*, JHEP, arXiv:2409.03651 (2024).

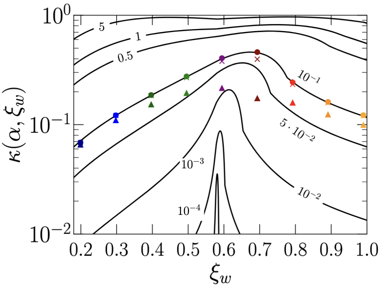
Higgsless simulations (results)[8]

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

$$\Omega_{\rm GW}(f) = 3\,\tilde{\Omega}_{\rm GW}\, {\color{red}K^2}\,(H_* \tau_{\rm sw})\,(H_* R_*)\,S(f\,R_*)$$

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





ARP, Procacci, Midiri, Caprini, in preparation

[8] ARP, Stomberg *et al.*, JHEP, arXiv:2409.03651 (2024).

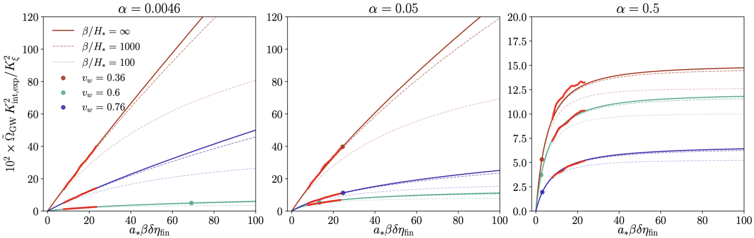
Higgsless simulations (results)[9]

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

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

- 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)

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



[9] ARP, Stomberg *et al.*, JHEP, arXiv:2409.03651 (2024).

Higgsless simulations (results)[10]

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

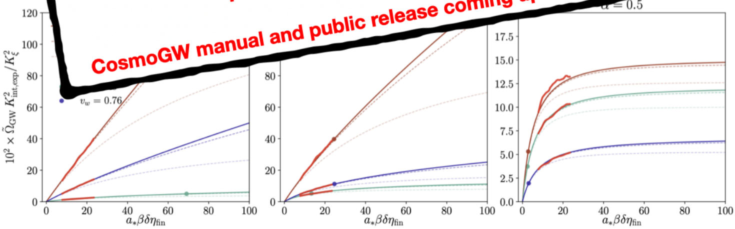
- The linear growth, which ... is modified when the d... ...ment of
- ... Dahl *et*

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)

Next week proceedings on arXiv with a tutorial notebook

For use: pip install cosmoGW

CosmoGW manual and public release coming up soon! (July)

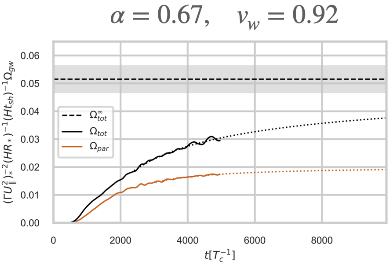


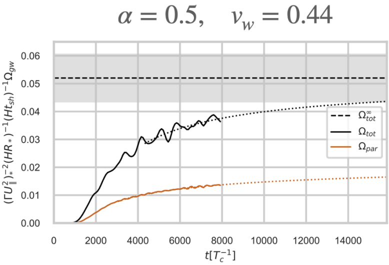
[10] ARP, Stomberg *et al.*, JHEP, arXiv:2409.03651 (2024).

Strong PTs in fluid+scalar simulations[10]

- Extended model to proposed locally stationary UETC (also assumed in Dahl *et al.*, 2024 and found in Correia *et al.*, 2025)

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

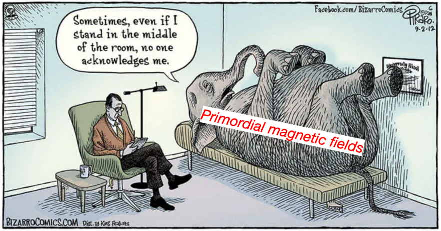




[10] Correia *et al.*, arXiv:2505.17824 (2025).

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.[11]
- Present magnetic fields can be amplified by primordial turbulence via dynamo.[12]



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

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

Generation of primordial magnetic fields in phase transitions

- Charge separation around bubble walls produce seed magnetic fields.[13]
- The Higgs field Φ is naturally charged under the weak SU(2) and the hypercharge $U(1)_Y$ gauge fields. After the symmetry breaking the resulting gauge field strength is[14]

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - i\frac{2\sin\theta_w}{g\eta^2}(\partial_\mu\Phi^\dagger\partial_\nu\Phi - \partial_\nu\Phi^\dagger\partial_\mu\Phi)$$

- Monopole-antimonopole pairs are produced during the electroweak phase transition and will produce a magnetic dipole field that will survive after the pair annihilates[15]
- 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.[16]
- Axion fields can amplify and produce magnetic field helicity.[17]

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

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13 Quashnock, Loeb, and Spergel, *Astrophys. J. 344*, L49 (1989).

14 T. Vachaspati, *Phys. Rev. B* **265**, 258 (1991)

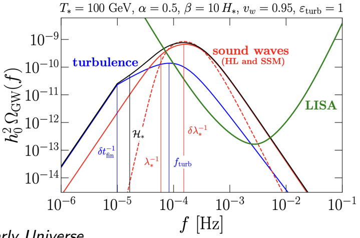
15 Y. Nambu, *Nucl.Phys.B* 130 (1977) 505, Patel & Vachaspati, JHEP 01 (2022) 059

16 T. Vachaspati, *Phys. Rev. Lett.* **87**, 251302 (2001), J. M. Cornwall, *Phys. Rev. D* **56**, 6146 (1997).

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

MHD sources of GWs in the early Universe

- Magnetohydrodynamic (MHD) sources of GWs:
  - Compressional motion (e.g. 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.
- Plasma dominated by radiation-like particles can be described by a traceless stress-energy tensor and the fluid equations become conformal invariant.[18]
- Other sources of cosmological GWs:
  - Bubble collisions.
  - Cosmic strings.
  - Scalar-induced GWs
  - Inflation.



[18] A. Brandenburg, *et al.*, *Phys. Rev. D* **54**, 1291 (1996).
ARP, Midiri, *Relativistic magnetohydrodynamics in the early Universe*, arXiv:2501.05732 (2025).

GWs from (M)HD turbulence

- Direct numerical simulations using the PENCIL CODE[19] 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).

- Current efforts to develop $\mathcal{C}$osmo$\mathcal{L}$attice-MHD are under development (work with D. Figueroa, K. Marschall, A. Midiri).

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

Contributions to the stress-energy tensor

$$T^{\mu\nu} = (p + \rho) U^\mu U^\nu + p g^{\mu\nu} + \pi^{\mu\nu} + F^{\mu\gamma} F^\nu{}_\gamma - \frac{1}{4} g^{\mu\nu} F_{\lambda\gamma} F^{\lambda\gamma}$$

- From fluid motion:

  $$T_{ij} = (p + \rho)\gamma^2 u_i u_j + p\delta_{ij}$$

  - Ultrarelativistic EoS: $p = \rho/3$
  - Viscous stresses: $\pi_{ij} = \nu(p + \rho)(u_{i,j} + u_{j,i})$

- From magnetic fields:

  $$T_{ij} = -B_i B_j + \delta_{ij} B^2/2$$

- 4–velocity $U^\mu = \gamma(1, u^i)$
- 4–potential $A^\mu = (\phi, A^i)$
- 4–current $J^\mu = (\rho_{\mathrm{e}}, J^i)$
- Faraday tensor $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

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:

$$\gamma^2 \sim 1 + u^2 + \mathcal{O}(u^4)$$

Relativistic MHD equations are reduced to[20]

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

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

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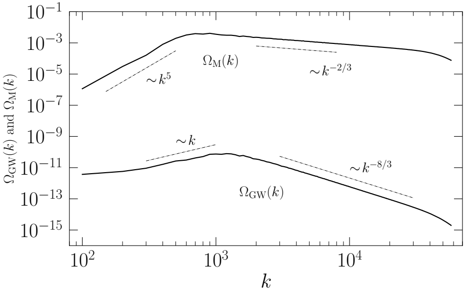
[20] A. Brandenburg, *et al.*, *Phys. Rev. D* **54**, 1291 (1996).
ARP, Midiri, *Relativistic magnetohydrodynamics in the early Universe*, arXiv:2501.05732 (2025).

Numerical results for decaying MHD turbulence[21]

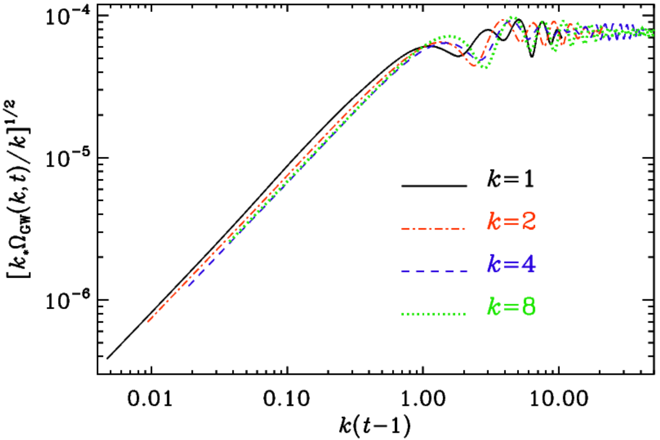
1152^3, $k_* = 2\pi \times 100, \Omega_{\rm M} \sim 10^{-2}, \sigma_{\rm M} = 1$



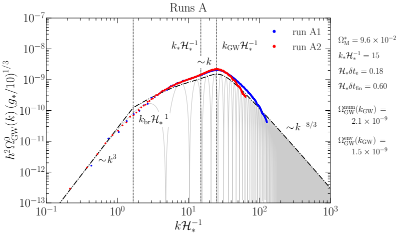
- **Characteristic k scaling in the subinertial range for the GW spectrum.**
- k^2 expected at scales $k < k_*$ and k^3 at $k < H_*$ according to the "top-hat" model (Caprini *et al.*, 2020).

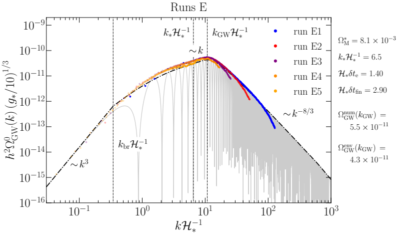
[21] ARP *et al.*, *Phys. Rev. D* **102**, 083512 (2020).

Early time evolution of the GW spectrum



Numerical results for nonhelical decaying MHD turbulence[22]





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}

[22] 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[23] of $\Omega_{\rm GW}(k)$.

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

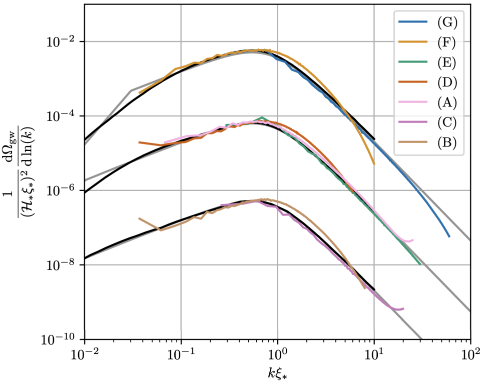
- p_Π is the anisotropic stress spectrum and depends on spectral shape, can be approximated for a von Kárman spectrum as[24]

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

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

[24] ARP *et al.*, arXiv:2307.10744 (2023), [LISA CosWG] 2024

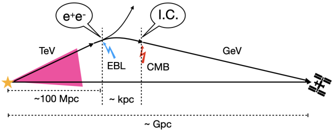
Numerical results for decaying HD vortical turbulence[25]



[25] P. Auclair *et al.*, *JCAP* **09** (2022), 029.

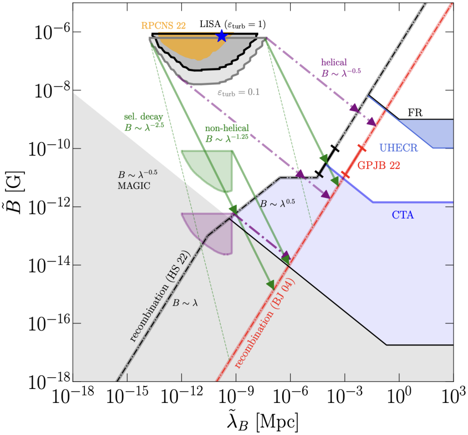
Primordial magnetic fields[30]

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



- Maximum amplitude of primordial magnetic fields is constrained by the big bang nucleosynthesis.[32]

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



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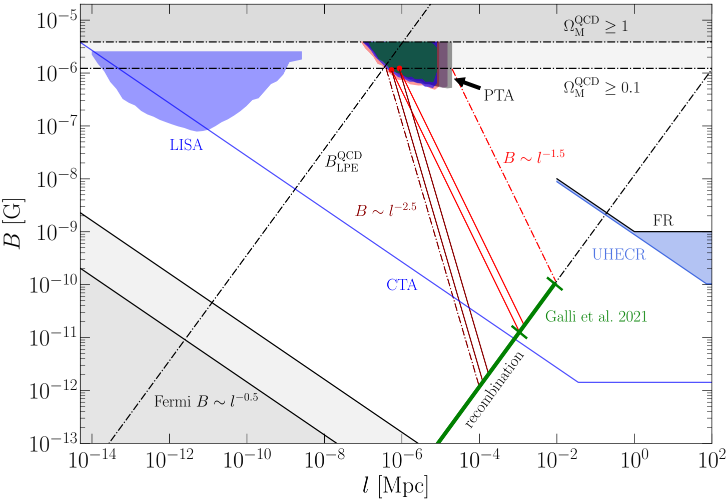
[30] ARP *et al.*, arXiv:2307.10744 (2023).

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

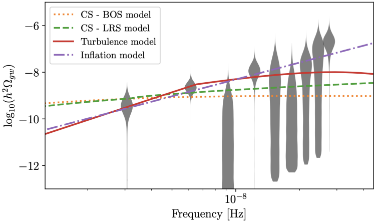
[32] V. F. Shvartsman, *Pisma Zh. Eksp. Teor. Fiz.* **9**, 315 (1969).

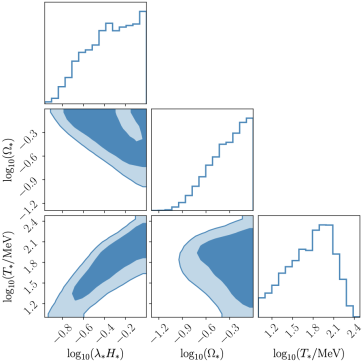
Primordial magnetic field constraints with PTA[26]



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

Primordial magnetic fields constraints with PTA[27]





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

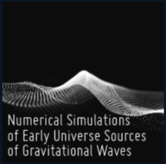
Conclusions

- Velocity and magnetic fields in the early universe can significantly contribute to the stochastic GW background (SGWB) via sound waves and (M)HD turbulence.
- The SGWB produced by non-linear motion 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 (acoustic motion) and the development of turbulence is not well understood. It plays an important role on the relative amplitude of both sources of GWs. On-going studies of phase transitions are required to understand this issue.
- 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.
- γ-ray observations (Fermi LAT, CTA) can constrain intergalactic magnetic fields, providing a potential multi-messenger approach to study primordial magnetic fields.

Thank You!

alberto.roperpol@unige.ch

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



Numerical Simulations of Early Universe Sources of Gravitational Waves

If interested, online registration available, email one of the organizers

July 28, 2025 to August 15, 2025 — Albano Building 3

Enter your search term

Scope

We are happy to announce the three-week program on numerical simulations of early Universe sources of gravitational waves at Nordita, Stockholm, that will take place from July 28 to August 15 of 2025.

The main objectives of the program are to review the different possible sources contributing to a cosmological background of gravitational waves, the state-of-the-art numerical codes that are available and used by the community, to discuss numerical techniques for these studies, and to discuss what are the priorities that we should address as a community in the coming years.

For this purpose, the program is divided into three weeks, covering the following potential sources of GWs in the early Universe:

Week 1 (Jul 28-Aug 1): Inflation, (p)reheating, and primordial black holes

Week 2 (Aug 4-8): First order phase transitions and primordial turbulence

Week 3 (Aug 11-15): Topological defects: cosmic strings, domain walls, and others

Organizers

Chiara Caprini (CERN and University of Geneva)

Amelia Drew (University of Cambridge)

Daniel Figueroa (IFIC, Valencia)

Alberto Roper Pol (University of Geneva)

David Weir (University of Helsinki)

Confirmed Invited speakers

- *Pierre Auclair* (Louvain University)
- *Jorge Baeza-Ballesteros* (DESY)
- *Jose Juan Blanco-Pillado* (University of the Basque Country)
- *Axel Brandenburg* (Nordita)
- *Malte Buschmann* (University of Amsterdam)
- *Angelo Caravano* (IAP, Paris)
- *Jose Ricardo Correia* (University of Helsinki)
- *Emanuela Dimastrogiovanni* (University of Groningen)
- *Matteo Fasiello* (IFT)
- *Marco Gorghetto* (DESY)
- *Mark Hindmarsh* (University of Helsinki)
- *Oksana Iarygina* (Nordita)
- *Ryusuke Jinno* (Kobe University)
- *Tina Kahniashvili* (Carnegie Mellon University)
- *Marek Lewicki* (University of Warsaw)
- *Joanes Lizarraga* (University of the Basque Country)
- *Swagat Mishra* (University of Nottingham)
- *Ilia Musco* (University of Nova Gorica)
- *Gerasimos Rigopoulos* (Newcastle University)
- *Henrique Rubira* (LMU/Cambridge)
- *Kari Rummukainen* (University of Helsinki)
- *Philipp Schicho* (University of Geneva)
- *Lara Sousa* (University of Porto)
- *Francisco Torrenti* (University of Barcelona)
- *Tanmay Vachaspati* (Arizona State University)
- *Jorinde van de Vis* (CERN)
- *Masahide Yamaguchi* (Institute for Basic Science, Daejeon)

Advancing gravitational wave predictions from cosmological first-order phase transitions

Aug 25 – 29, 2025
CERN

As the detection of a stochastic gravitational wave background from the early universe becomes increasingly promising, signals from hypothetical first-order phase transitions are attracting growing interest. Predicting these signals often requires the solution of plasma dynamics at macroscopic scales, which, in turn, depends on the phenomena that characterize the phase transition at microscopic scales. Therefore, various assumptions on distinctive scales and their separation are usually employed to enable concrete evaluations.
This workshop aims to bring together researchers from both the microscopic and macroscopic communities to collaboratively address theoretical shortcomings and refine current gravitational wave spectral templates across different regimes.

1. Microscopic scales – Quantitative uncertainties affect the fundamental phase transition parameters within minimal scenarios beyond the Standard Model, where a scalar field drives the symmetry-breaking mechanism.

2. Intermediate scales – Different approaches have been employed to describe the interactions between the scalar field and the plasma, including bubble wall dynamics and plasma viscosity. A key question is, e.g., whether the bubble wall runs away or reaches a terminal velocity.

3. Macroscopic scales – Several approximations are used to connect to large-scale phenomena during and after the phase transition, such as collisions between the bubbles, the development of turbulence, and the evolution of sound shells.

Confirmed speakers:

1.	2.	3.
Bogumila Swiezewska, *U. Warsaw*	Wen-Yuan Ai, *U. Vienna*	Jani Dahl, *U. Helsinki*
Anna Kormu, *U. Helsinki*	Ryusuke Jinno, *U. Kobe*	Lorenzo Giombi, *U. Helsinki*
Joonas Hirvonen, *U. Nottingham*	Benoit Laurent, *U. McGill*	Mark Hindmarsh, *U. Helsinki*
Mikko Laine, *U. Bern*	Andrew J. Long, *Rice U.*	Tina Kahniashvili, *U. Carnegie Mellon*
Kari Rummukainen, *U. Helsinki*	Andrii Dashko, *DESY*	Thomas Konstandin, *DESY*
	Carlo Branchina, *U. Calabria*	Antonino S. Midiri, *U. Geneva*
	Marek Lewicki, *U. Warsaw*	Tae Hyun Jung, *IBS*
	Csaba Balazs, *Monash U.*	

If interested, online registration available, email one of the organizers

This event is sponsored by the Department of Theoretical Physics at CERN as well as the CERN-Korea collaboration program.

CERN

Organizing committee:

Chiara Caprini (CERN & University of Geneva)
Hyun Min Lee (Chung-Ang University)
Seong Chan Park (Yonsei University)
Simona Procacci (University of Geneva)
Alberto Roper Pol (University of Geneva)
Philipp Schicho (University of Geneva)
Jorinde van de Vis (CERN)

CosmoLattice — School 2025 —

CosmoLattice School 2025 (IBS, Korea), Sept 22-26

This school offers a pedagogical introduction to lattice field theory techniques and their application to the simulation of interacting fields in an expanding Universe. Participants will also be introduced to CosmoLattice, an open-access code designed for such simulations. The school will provide a comprehensive guide to using CosmoLattice for modeling the non-linear dynamics of scalar and gauge fields in cosmological contexts.

The school is aimed to anyone who would like to learn (or simply improve their knowledge on) how to simulate in a lattice the dynamics of early Universe field theory scenarios. Topics covered include:

- **Lattice field theory techniques**: discretization schemes, lattice gauge techniques, and more
- **Numerical algorithms for differential equations**: Leapfrog, Verlet, Runge-Kutta, etc
- **Overview of CosmoLattice**: libraries, modularity, parallelization, ...
- **Lattice simulations of interacting fields in an expanding background**:
  - Scalar field dynamics with arbitrary potentials
  - U(1) gauge theories coupled to complex charged scalars
  - SU(2) gauge theories coupled to doublet charged scalars
- **Modern applications to early Universe scenarios**:
  - Preheating scenarios and onset of radiation domination
  - Production and evolution of gravitational waves
  - Dynamics of derivatively coupled Axion-like fields
  - Dynamics of non-minimally coupled scalar fields
  - Fluid dynamics and gravitational waves from turbulence
  - Evolution and experimental signatures of topological defects

Lecturers:

J. Baeza-Ballesteros .... DESY, Zeuthen, Germany
D. G. Figueroa .... IFIC, Valencia, Spain
N. Loayza .... IFIC, Valencia, Spain
K. Marschall .... IFIC, Valencia, Spain
A. S. Midiri .... University of Geneva, Switzerland
T. Opferkuch .... SISSA, Trieste, Italy
A. Roper Pol .... University of Geneva, Switzerland
B. A. Stefanek .... IFIC, Valencia, Spain
F. Torrenti .... University of Barcelona, Barcelona, Spain
A. Urio .... UPV/EHU, Bilbao, Spain

Pencil Code school and user meeting

Oct 20 – 31, 2025
CERN

Pencil Code (http://pencil-code.nordita.org/) is a modular MPI public code to efficiently solve coupled systems of partial differential equations in high-performance computing architectures using high-order finite-difference schemes. Started in 2001 by A. Brandenburg and W. Dobler, its core application initially focused on magnetohydrodynamics (MHD) for solar physics. Since then, it has been continuously under development by a total of 90 contributors covering a broad range of applications.

In particular, it has been used for studies of early universe physics including the evolution and formation of primordial magnetic fields and chiral MHD; the production of gravitational waves and propagation of gravitational waves in modified gravity, and inflation.

1st Pencil Code school on early Universe physics and gravitational waves (Oct 20-24)

The Pencil Code school on early Universe physics and gravitational waves will take place on October 20-24 as part of a two-week CERN TH institute.

The school targets early-career and senior researchers that are interested in learning and developing numerical skills applied to early Universe physics using Pencil Code.

The lectures will cover numerical aspects:

- *Introduction to Pencil Code*
- *Finite-difference schemes for partial differential equations*
- *Post-processing of data with IDL and Python*
- *GPU acceleration of Pencil Code*

as well as applications to particular physics cases with hands-on exercises on:

- *Magnetohydrodynamics of the early Universe*
- *Generation and evolution of primordial magnetic fields*
- *Chiral magnetohydrodynamics*
- *First-order phase transitions*
- *Gravitational wave production*
- *Axion inflation*

Registration is open and will close on ***July 31st***. The school is limited to a maximum of 30 participants.

Participants of the school are encouraged to also participate in the user meeting (Oct 27-31) and need to register separately.

Lecturers:

- Axel Brandenburg (Nordita)
- Philippe Bourdin (University of Graz)
- Simon Candelaresi (University of Augsburg)
- Deepen Garg (University of Bonn)
- Frederick Gent (Aalto University & Nordita)
- Matthias Rheinhardt (Aalto University)
- Alberto Roper Pol (University of Geneva)
- Isak Stomberg (IFIC, Valencia)

21st Pencil Code user meeting PCUM2025 (Oct 27-31)

The Pencil Code user meeting will take place on October 27-31 as part of a two-week CERN TH institute.

Registration for the Pencil Code user meeting is open and will close on ***September 28th***.