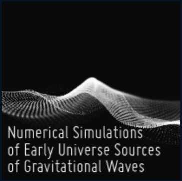
Numerical Simulations of Early Universe Sources of Gravitational Waves

Nordita Niels Bohr Colloquium (Jul. 28, 2025)

Alberto Roper Pol
University of Geneva

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



Numerical Simulations of Early Universe Sources of Gravitational Waves

NORDITA
The Nordic Institute for Theoretical Physics

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

https://indico.fysik.su.se/e/NumericalCosmoGW

Organizers

Chiara Caprini (CERN and University of Geneva)

Amelia Drew (ICTP, Trieste)

Daniel Figueroa (IFIC, Valencia)

Alberto Roper Pol (University of Geneva)

David Weir (University of Helsinki)

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

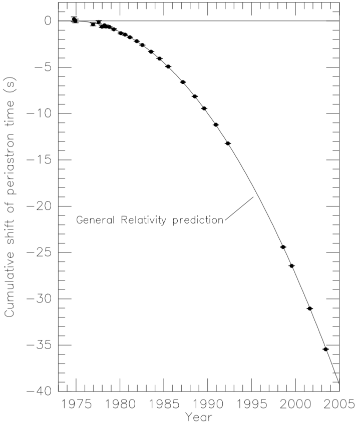
Week 3 (Aug 11-15): Topological defects: cosmic strings, domain walls, and others

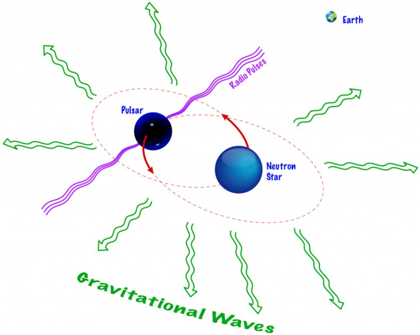
Confirmed Invited speakers

- ***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)
- ***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)

Astrophysical GWs from binary pulsars: first indirect detection

PSR B1913+16 by Hulse & Taylor (1974) → 1993 Nobel Prize

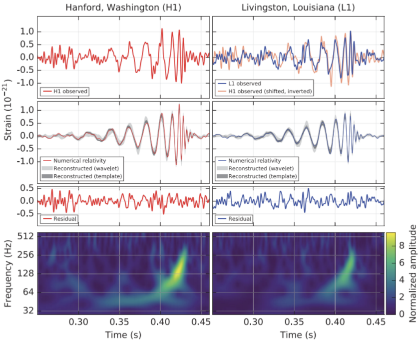


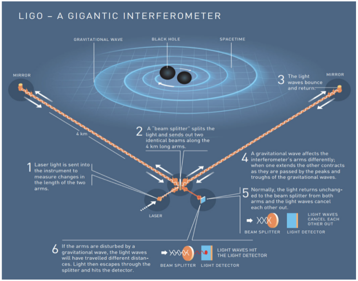


[1] Left figure: Weisberg & Taylor (2005). Right figure: Shane L. Larson

2015: first direct GW detection

- First event GW150914 detected by LIGO-Virgo collaboration[1]
- Birth of GW astronomy, opening a new window into our understanding of the Universe

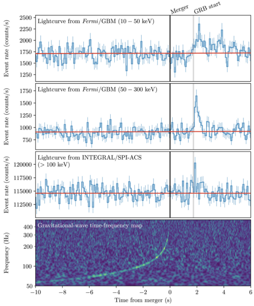


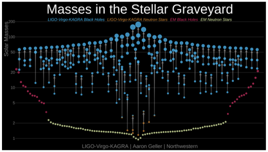


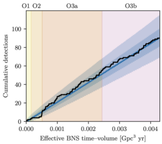
[1] [LIGO-Virgo Collaboration], *Phys. Rev. Lett.* **116**, 061102 (2016)

Astrophysics, cosmology, fundamental physics

- GW170817 NS binary merger[2] 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 $\rightarrow$ 90 events up to O3b[3] with O4 running until November 2025. Currently, around $\gtrsim 200$ events publicly reported[4]







---

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

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

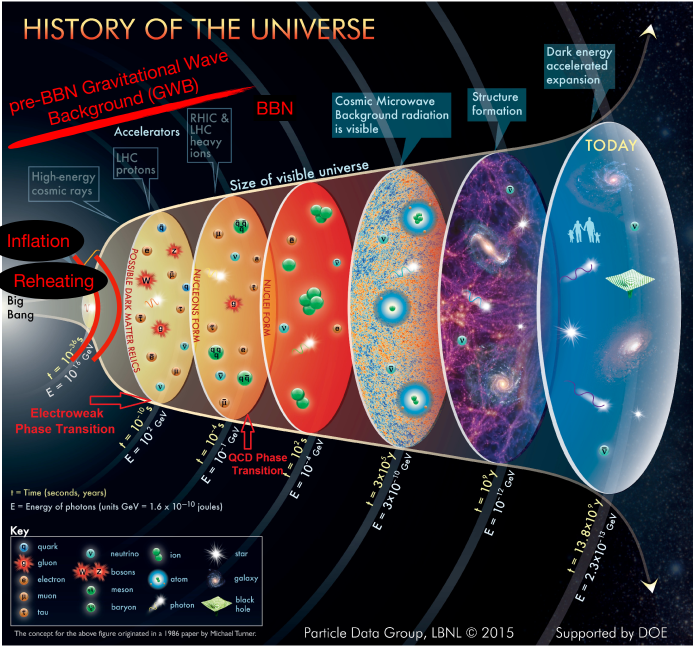
[4] https://gracedb.ligo.org/superevents/public/O4/

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.*

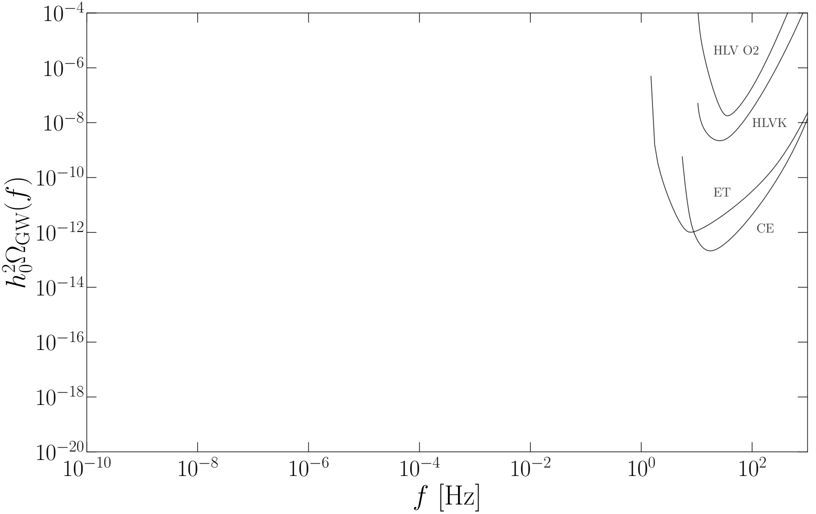
GWs from the early Universe have the potential to provide us with *direct information on early universe physics* that is *not accessible via electromagnetic observations, complementary to collider experiments*.

- Nature of inflation and transfer of energy to thermal particles (reheating), particle production (preheating),
- Primordial perturbations at all scales, primordial black holes, origin of dark matter,
- Nature of first-order phase transitions (baryogenesis), topological defects (e.g., cosmic strings),
- Primordial origin of intergalactic magnetic fields.



HISTORY OF THE UNIVERSE
pre-BBN Gravitational Wave Background (GWB)
BBN
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
Size of visible universe
TODAY
Inflation
Reheating
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

Gravitational spectrum (ground-based detectors)



Laser Interferometer Space Antenna (LISA)

- LISA is a space–based GW detector
- Approved in 2017 as one of the main research missions of ESA (L3) with NASA collaboration
- Mission adoption by ESA in Jan. 2024. Launch planned for 2035
- Composed by three spacecrafts in a distance of 2.5M km
- LISA cosmology working group (since 2015, ~ 230 members)

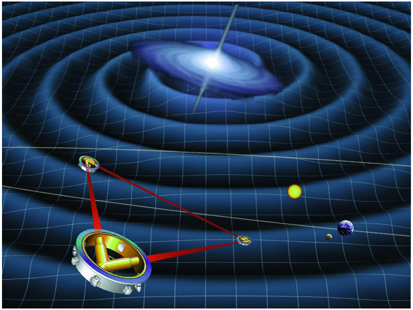
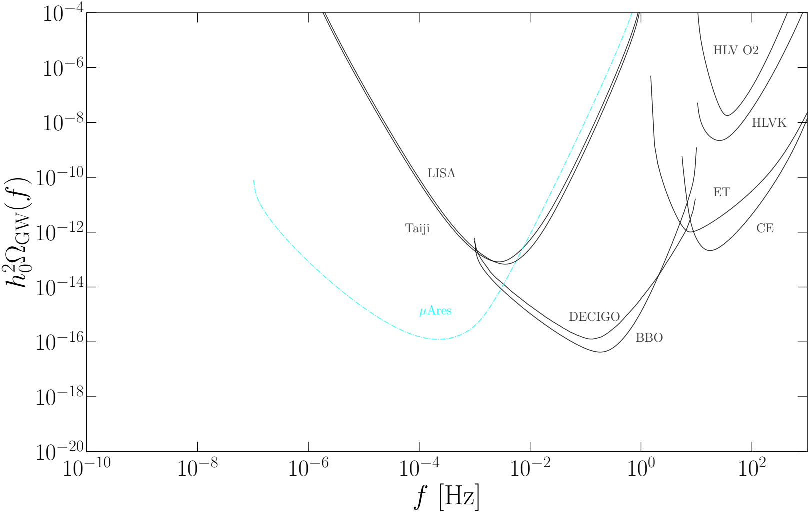


Figure: Artist's impression of LISA from Wikipedia

White paper:

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

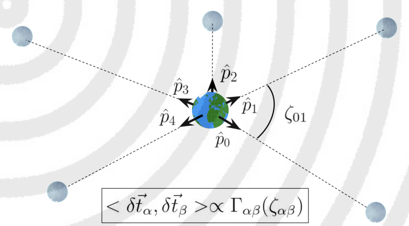
Gravitational spectrum (space-based detectors)



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:

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



Credit: Mikel Falxa

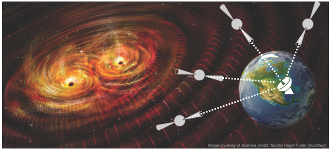
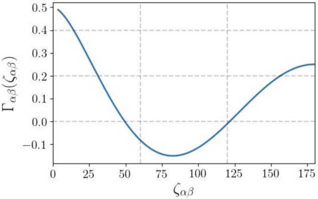


Figure: Image courtesy of Science, credit: Nicolle Rager Fuller

The correlation $\Gamma_{\alpha\beta}$ follows in GR the Hellings-Downs curve[5]



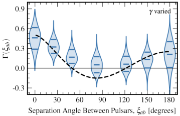
[5] R. W. Hellings and G. S. Downs, *Astrophys. J. Lett.* **265** (1983) L39-L42.

PTA reporting strong evidence of a GW background

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

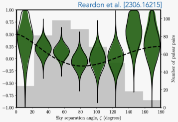
NANOGrav:
68 pulsars, 16yr of data
~3-4σ significance

Agazie et al. [2306.16213]



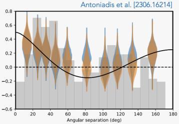
PPTA:
32 pulsars, 18yr of data
~2σ significance

Reardon et al. [2306.16215]



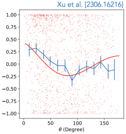
EPTA + InPTA:
25 pulsars, 24yr of data
~3σ significance

Antoniadis et al. [2306.16214]



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

Xu et al. [2306.16216]



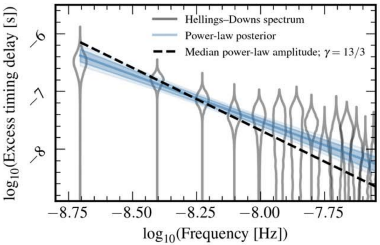
Credit: Andrea Mitridate

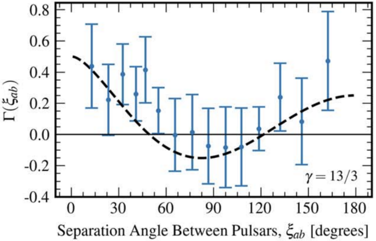
Pulsar Timing Array (PTA)

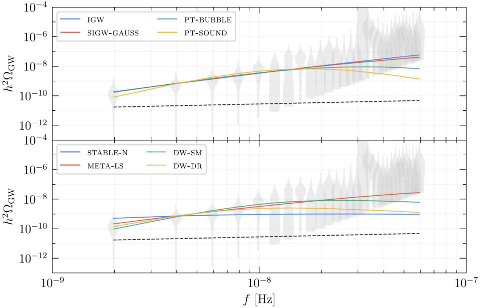
- The PTA collaborations reported for the first time strong evidence of a stochastic gravitational wave background on a press release on June 28, 2023 (plus a series of papers by each collaboration).
- A plausible source of the signal corresponds to the superposition of supermassive black hole binaries.
- However, the reported evidence also allows us to search for new physics and is compatible with *more exciting* sources of cosmological origin contributing to the background: cosmic strings, first-order phase transitions, primordial turbulence, primordial black holes, inflation.[6]

[6] [EPTA and InPTA Collaborations] (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

NANOGrav 15 yr data observation[7]

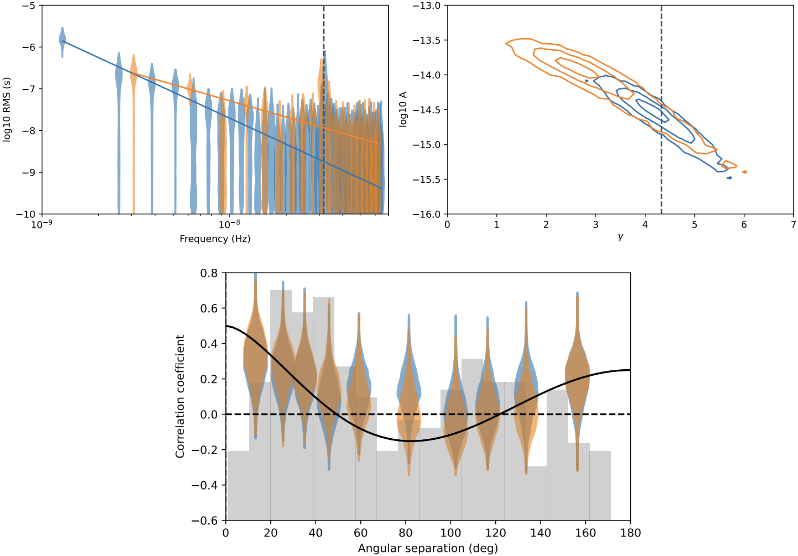






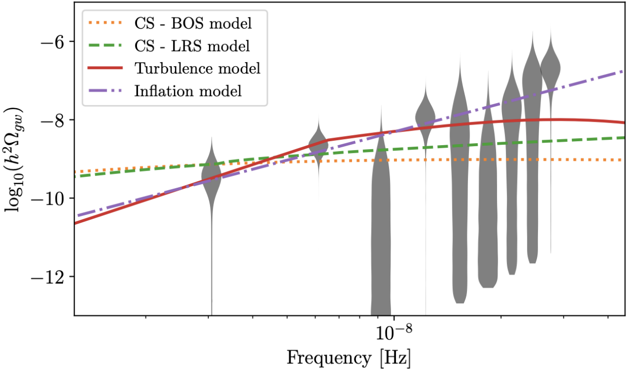
7 [NANOGrav collaboration], *ApJ Lett.* **951**, 8 & 11 (2023).

EPTA 24.7 yr data observation (DR 2)[8]



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

EPTA 24.7 yr data observation (DR 2)[9]



[9] [EPTA Collaboration] (incl. ARP), arXiv:2306.16227.

GW signals from the early Universe

Predicting the cosmological GW background

- Inflation[10] (*week 1 of the program*)
  - Quantum fluctuations: constrained by CMB at large scales.
  - Particle production from coupling of inflaton to other fields (e.g., multi-field inflation, axion inflation).
  - Scalar-induced GWs[11] and primordial black holes (PBH).[12]
  - Non-standard cosmology, modifications of gravity.
- (P)reheating (*week 1 of the program*)
  - Production of Standard Model particles during the process of reheating.
  - Parametric resonance during preheating due to production of bosons.

---

[10] [LISA CosWG], 2407.04356
[11] [LISA CosWG], 2501.11320
[12] [LISA CosWG], 2310.19857

GW signals from the early Universe

Predicting the cosmological GW background

- Phase transitions[13] (*week 2 of the program*)
  - Bubble collisions (production by the gradients of a scalar field).
  - Bulk motion induced in the primordial plasma (sound waves and turbulence).
- Primordial turbulence (*week 2 of the program*)
  - Coupling of primordial magnetic fields to the primordial plasma: Magnetohydrodynamic (MHD) turbulence
- Topological defects[14] (*week 3 of the program*):
  - Cosmic strings and domain walls produced during first-order phase transitions

[13] [LISA CosWG], 2403.03723
[14] [LISA CosWG], 2405.03740

GW signals from the early Universe

Predicting the cosmological GW background

Most of these GW signals are inherently *non-linear*, as large perturbations are required to produce observable GW backgrounds.

Therefore, *numerical simulations* to accurately describe the GW backgrounds resulting from the different non-linear processes are, in general, necessary.

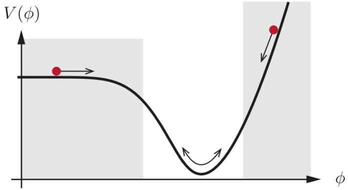
Work in the last decades has led to publicly available numerical codes that target some of the GW signals in the early Universe.

Some examples of public codes widely used by the community (there are many more):

- $\mathcal{C}$osmo-$\mathcal{L}$attice: Lattice-field theory for classical evolution of fields,
- GRChombo: Numerical relativity code,
- Pencil Code: Generic MHD code with applications to early universe, axion inflation, GW production.

GW from inflation. Example: axion inflation[18]

- Axion coupling of inflaton field to a gauge field (Abelian or non-Abelian), $\mathcal{L} \propto \phi F\tilde{F}$,
- Leads to a chiral instability, exponentially increasing one chiral mode of the gauge field A_+,
- Rich phenomenology: inflaton perturbations highly non-Gaussian,[15] PBH formation,[16] chiral magnetic fields and GW background.[17]



$$\ddot{\phi} + 3H\dot{\phi} - \cancel{\nabla^2\phi} = V_{,\phi} + \cancel{\frac{\alpha\Lambda}{a^3 m_p} \boldsymbol{E}\cdot\boldsymbol{B}},$$

$$\ddot{A}''_\pm + \left(k^2 \pm \frac{k\dot{\phi}}{\Lambda H\tau}\right) A_\pm = 0,$$

Anber-Sorbo solution

---

[15] Barnaby & Peloso, 2010

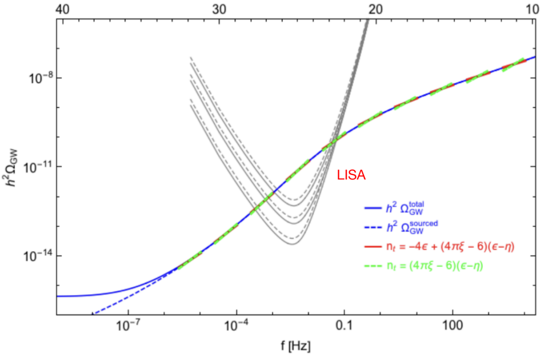
[16] Linde, Mooij & Pajer, 2013

[17] Kahniashvili, Gogoberidze & Ratra, 2005, Cook & Sorbo, 2011

[18] Anber & Sorbo, 2006

GW background from axion inflation

- Based on homogeneous inflaton, assuming non-linear backreaction of gauge fields on the inflaton evolution is negligible, signal is detectable by LISA.[19]

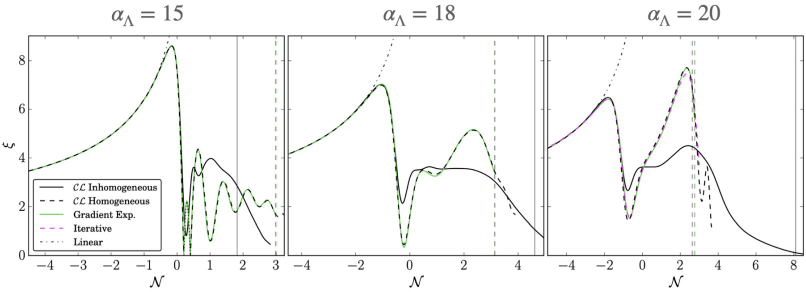


[19] Bartolo *et al.*, 2016

GW background from axion inflation

- However, when including non-linear effects, high-performance lattice simulations are required to describe the inflaton/gauge field dynamics, leading to different results for the couplings required for a detectable signal,[20]

$$\ddot{\phi} + 3H\dot{\phi} - \nabla^2\phi = V_{,\phi} + \frac{\alpha_\Lambda}{a^3 m_p}\boldsymbol{E}\cdot\boldsymbol{B}\,.$$



[20] Figueroa, Lizarraga, Urio & Urrestilla, 2023 & 2024, Sharma *et al.*, 2025.

GW background from phase transitions

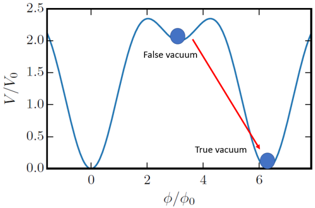
- The Hubble scale at the time of production determines the characteristic frequency of the GW background.

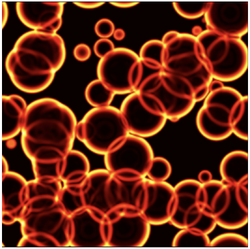
$$f_* \simeq 1.64 \times 10^{-3} \frac{100}{R_* \mathcal{H}_*} \frac{T_*}{100\,\mathrm{GeV}}\ \mathrm{Hz}$$

- 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

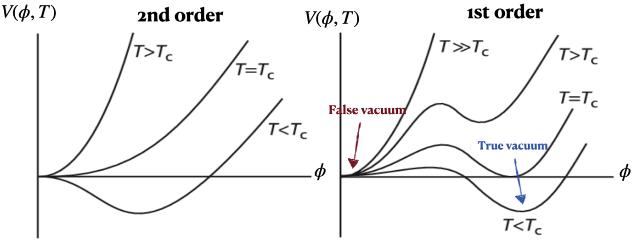
First-order phase transition

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



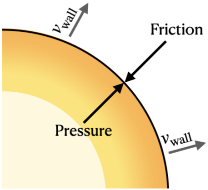


Credits: I. Stomberg



Hydrodynamics of first-order phase transitions[21]

- 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

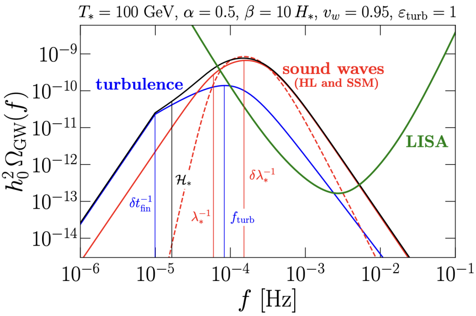


$$\nabla_\mu T^{\mu\nu}_{\rm field} = \frac{\partial V}{\partial \phi}\partial^\nu \phi + \eta u^\mu \partial_\mu \phi \partial^\nu \phi\,,$$
$$\nabla_\mu T^{\mu\nu}_{\rm fluid} = -\frac{\partial V}{\partial \phi}\partial^\nu \phi - \eta u^\mu \partial_\mu \phi \partial^\nu \phi\,,$$

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

GW sources from first-order phase transitions

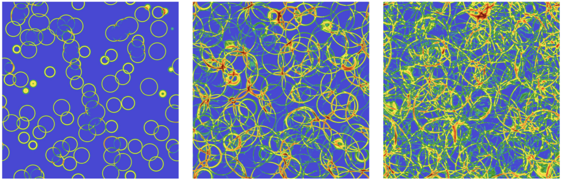
- Sound waves induced by the broken-phase bubbles (linear regime).
- (M)HD turbulence from first-order phase transitions.
- Primordial magnetic fields. High-conductivity of the early universe leads to a high-coupling between magnetic and velocity fields.



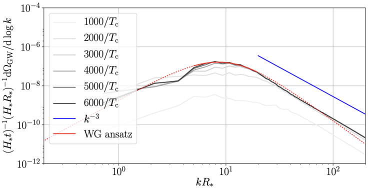
ARP *et al.*, 2307.10744, 2308.12943

GWs from sound waves[22]

- Numerical simulations of the scalar + fluid system performed by the Sussex/Helsinki group via an effective friction term.



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



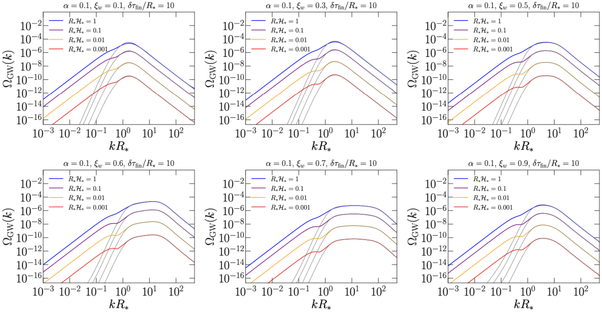
(b) Intermediate, $v_w = 0.92$

[22] Hindmarsh *et al.*, 2013, 2015, 2017, Cutting *et al.*, 2019.

GWs from sound waves: Sound Shell Model[23]

- 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 $P_\Pi = P_\Pi(k, t_2 - t_1)$.

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

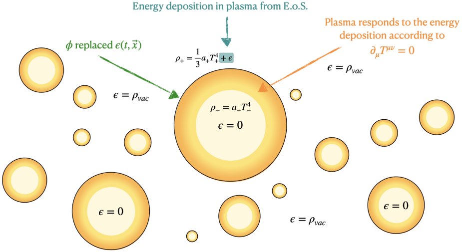


[23] Hindmarsh, 2016; Hindmarsh & Hijazi, 2019.

ARP, Procacci & Caprini, 2024; Sharma *et al.*, 2024.

GWs from sound waves: Higgsless simulations[24]

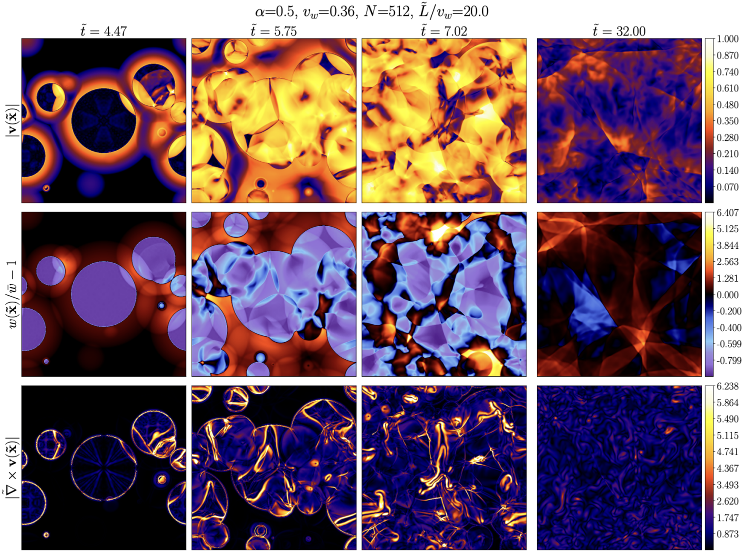
- Difficulty on simulations is due to the different scales of the scalar field ϕ and the fluid shell, so one can consider a nucleation history and set the pressure and energy density by knowing the value of ϵ and setting it during the simulation.
- Effect of bubble collisions on GWs is subdominant when 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

[24] Jinno *et al.* JCAP 02 (2023) 011, 2209.04369, ARP, Stomberg *et al.*, 2409.03651.

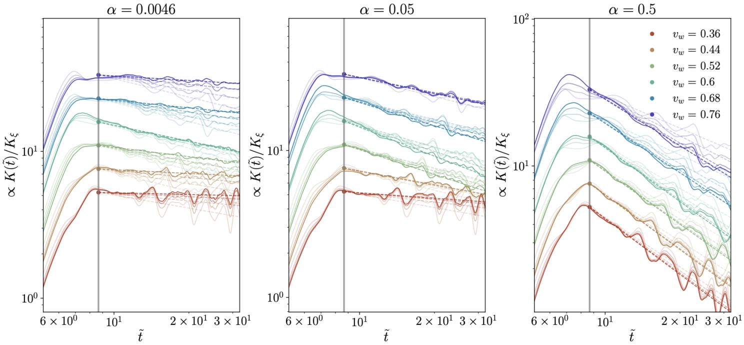
Higgsless simulations of strong PTs[25]



[25] ARP, Stomberg *et al.*, 2409.03651.

Higgsless simulations (results)[26]

- 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).



[26] ARP, Stomberg *et al.*, 2409.03651 (2024).

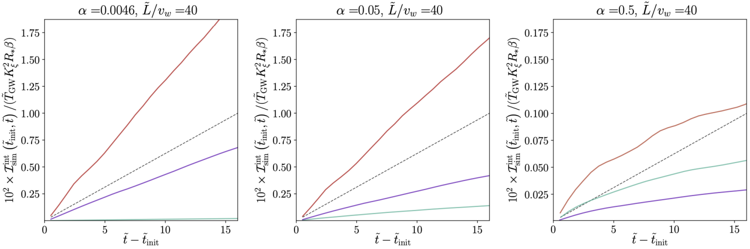
Higgsless simulations (results)[27]

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

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

- 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

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



[27] ARP, Stomberg *et al.*, 2409.03651.

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.[28]
- Present magnetic fields can be amplified by primordial turbulence via dynamo.[29]
- Axion fields can amplify and produce magnetic field helicity in the early Universe.[30]

---

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

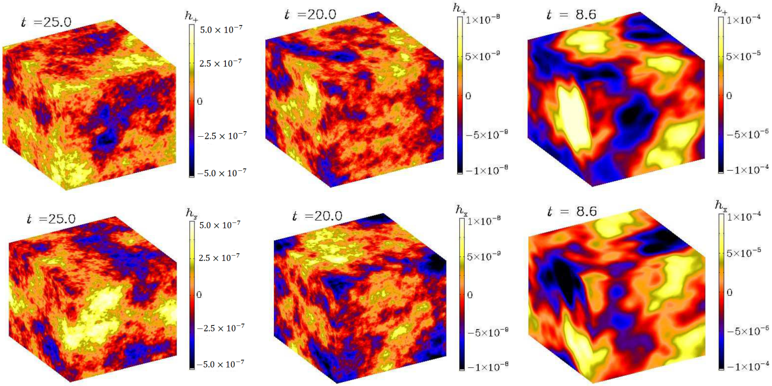
[29] A. Brandenburg *et al.* (incl. ARP), *Phys. Rev. Fluids* **4**, 024608 (2019).

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

Numerical results for decaying MHD turbulence[31]

$1152^3, \Omega_{\rm M} \sim 10^{-2}, \sigma_{\rm M} = 1$

Box results for positive initial helicity:

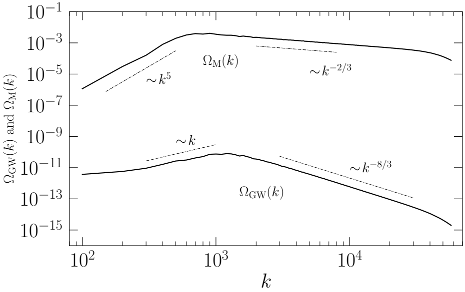


$k_{\rm M}/k_H = 300$ $k_{\rm M}/k_H = 60$ $k_{\rm M}/k_H = 2$

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

Numerical results for decaying MHD turbulence[32]

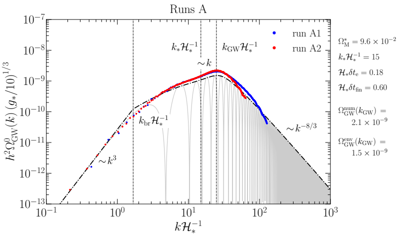
$1152^3, k_* = 2\pi \times 100, \Omega_{\rm M} \sim 10^{-2}, \sigma_{\rm M} = 1$

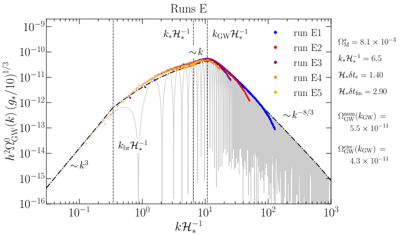


- **Characteristic k scaling in the subinertial range for the GW spectrum.**
- k^2 expected at scales $k < k_*$ and k^3 at $k < H_*$ according to the “top-hat” model ([LISA CosWG], 1910.13125).

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

Numerical results for decaying MHD turbulence[33]

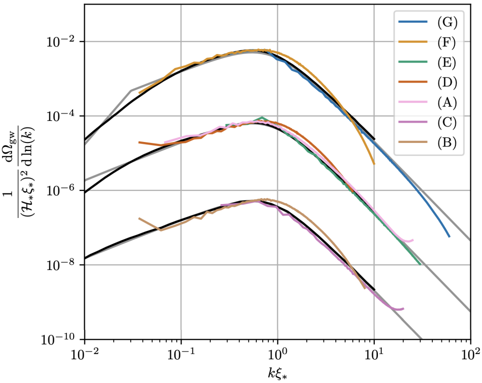




run	$\Omega_{\rm M}^*$	$k_*\mathcal{H}_*^{-1}$	$\mathcal{H}_*\delta t_{\rm e}$	$\mathcal{H}_*\delta t_{\rm fin}$	$\Omega_{\rm GW}^{\rm num}(k_{\rm GW})$	$[\Omega_{\rm GW}^{\rm env}/\Omega_{\rm GW}^{\rm num}](k_{\rm GW})$	n	$\mathcal{H}_*L$	$\mathcal{H}_*t_{\rm end}$	$\mathcal{H}_*\eta$
A1	9.6×10^{-2}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

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

Numerical results for decaying HD vortical turbulence[34]



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

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[35] 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[36]

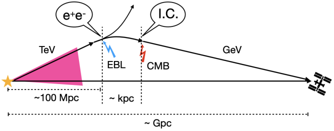
$$p_\Pi(k/k_*) \simeq \left[1 + \left(\frac{k}{2.2 k_*}\right)^{2.15}\right]^{-11/(3\times 2.15)}$$

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

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

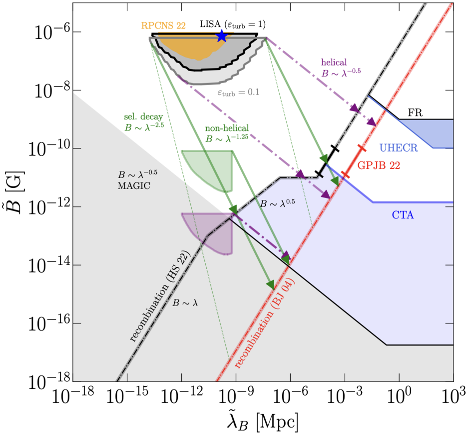
Primordial magnetic fields[30]

- 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).



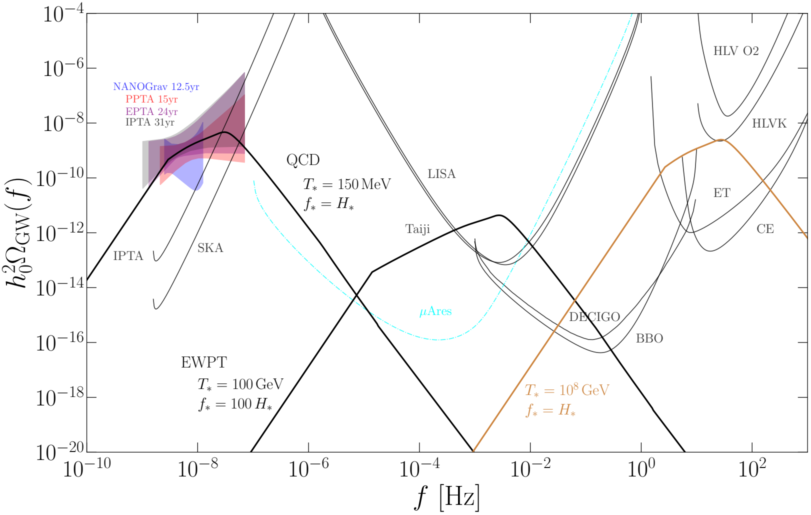
---

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).

Gravitational spectrum (turbulence from PTs)[37]



[37] 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).

Cosmic strings

- Cosmic strings are formed from a spontaneous symmetry breaking phase transition at an energy scale η, with a tension,

$$G\mu \simeq 6.7 \times 10^{-11} \left(\frac{\eta}{10^{14}\ \mathrm{GeV}} \right)^2$$

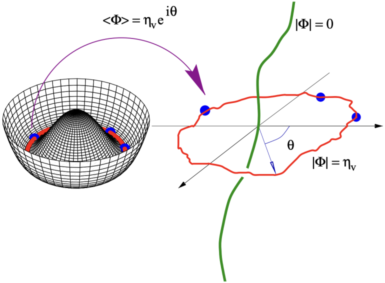


Figure from C. Ringeval, 2010.

GW background from cosmic strings

- A phase transition then can produce a network of strings if the vacuum manifold is non-trivial.

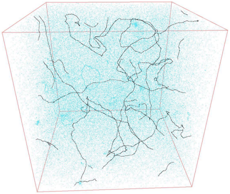
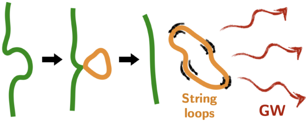


Figure from C. Ringeval, 2010.

- As the strings form loops, they will emit GWs (also cusps produce GW bursts)



Credit: Peera Simakachorn

GW background from cosmic strings

The GW production from loops of cosmic strings is a long-lasting source,

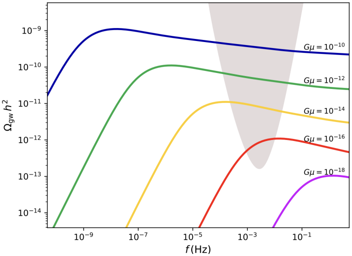
$$\Omega_{\rm GW}(f) = \frac{\Gamma G\mu^2}{3H_0^2 M_{\rm Pl}^2} \int_{t_*}^{t} {\rm d}t \left(\frac{a(t)}{a_0}\right)^3 \int {\rm d}l \, n(l,t) \, \mathcal{P}_{\rm GW}(l),$$

- $a(t)$ determines the expansion history,
- $n(l,t)$ is the number density of loops with length l,
- $\mathcal{P}_{\rm GW}(l)$ is the GW power emision per length l.

Determining each of these functions relies on the complicated dynamics of the strings in the network and their nature and requires, in general, high-performance numerical simulations.

GW background from cosmic strings (Nambu-Goto approach)

- Under the Nambu-Goto approach (infinite length to width ratio of the cosmic strings), the GW background is[38]



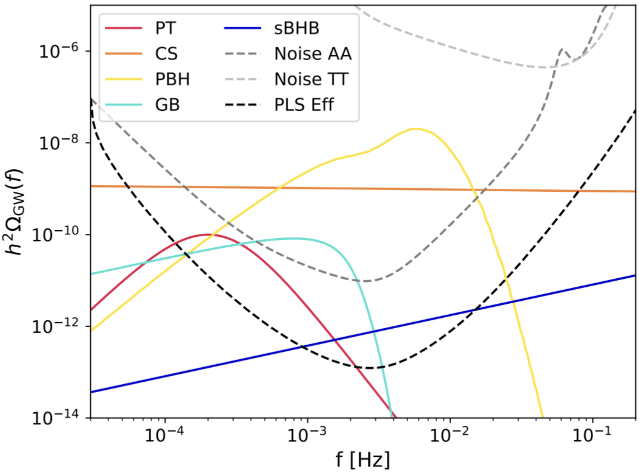
- GW spectrum is very sensitive to the modeling and it is an active area of research, highly depending on non-linear dynamics.

- Field-theory simulations have shown for $L/w \sim 200 - 6000$ that particle production from finite-size local strings can suppress the GW production.[39]

[38] [LISA CosWG], 2405.03740

[39] Baeza-Ballesteros *et al.*, 2024.

GW backgrounds: cosmological and astrophysical[40]



[40] LISA Red Book, Colpi *et al.*, 2402.07571.

Conclusions

- Detection of a gravitational wave background of cosmological origin could provide us with *direct and clean* information of the early Universe physics:
  - BSM, high-energy physics, baryogenesis,
  - origin of dark matter, existence of primordial black holes,
  - nature of phase transitions, existence of and cosmic strings,

  and many more.
- Since detectable sources of GWs require to have large amplitudes, their dynamics is, in general, *non linear*. Hence, accurate predictions of the GW background require performing high-resolution numerical simulations. This is an active are of research in progress and the objective of our program.
- Detecting a cosmological background is a *very challenging task*, as it requires:
  - accurate understanding of the noise (especially challenging for LISA),
  - a correct resolution of individual sources (there could be, for example, residuals from LISA Global fit),
  - extraction of the astrophysical background, which depend on the population statistics,
  - accurate charaterization of the GW backgrounds.

  An effort in the community is under-going to combine data analysis, accurate predictions of the GW backgrounds, and theoretical modeling of the different sources, which needs to be validated with efficient and optimized numerical simulations.

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

Registration is open until August 31st

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*

Lecturers: *Registration is open until September 10th*

- 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***.

Thank You!

alberto.roperpol@unige.ch

github.com/AlbertoRoper/cosmoGW

cosmology.unige.ch/users/alberto-roper-pol