Cosmological Background Interpretation of Pulsar Timing Arrays data

IPTA Science Meeting 2026 (Jun. 23, 2026)
Alpine Heath, Drakensberg, South Africa

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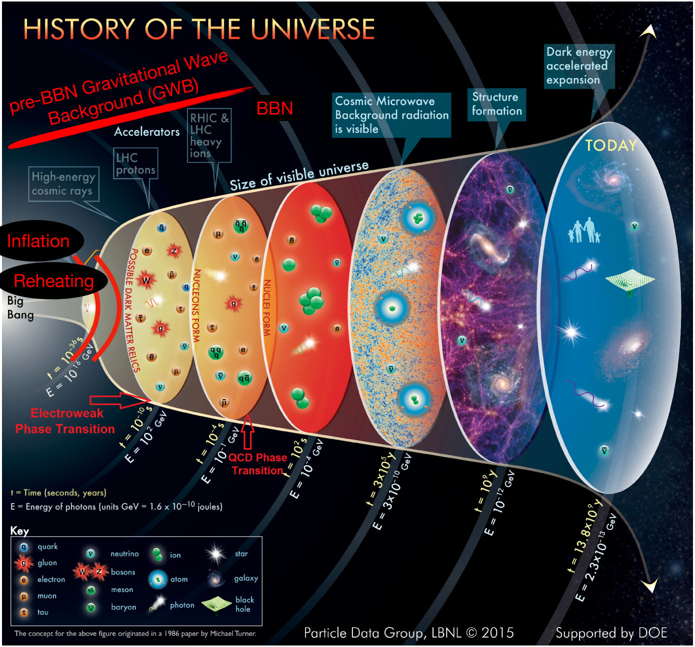
GWs from the *Early Universe*

Gravity is the *weakest fundamental force*. Hence, GWs are difficult to detect but they propagate freely carrying *clean information of the source.*

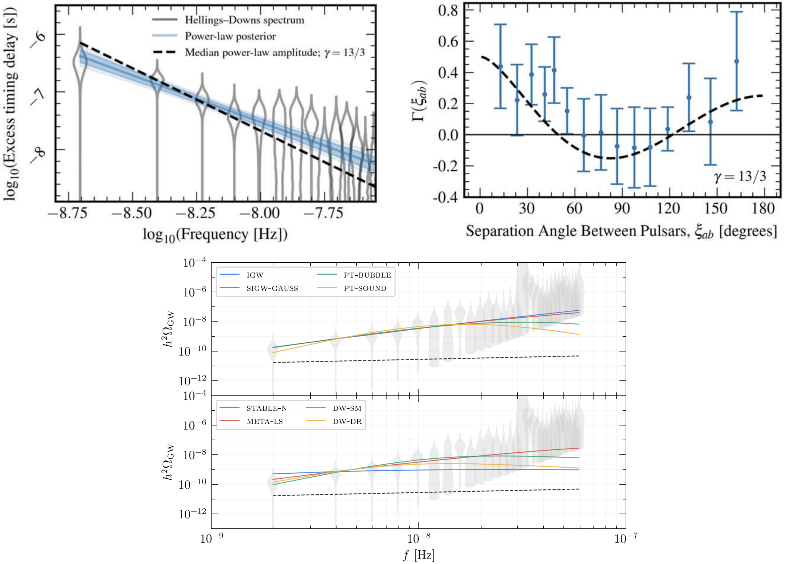
GWs from the early Universe have the potential to provide us with *direct information on early universe physics* that is *not accessible via electromagnetic observations, complementary to collider experiments*.

- 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 (QCD, dark sector), topological defects (e.g., cosmic strings, domain walls).
- Primordial origin of intergalactic magnetic fields.



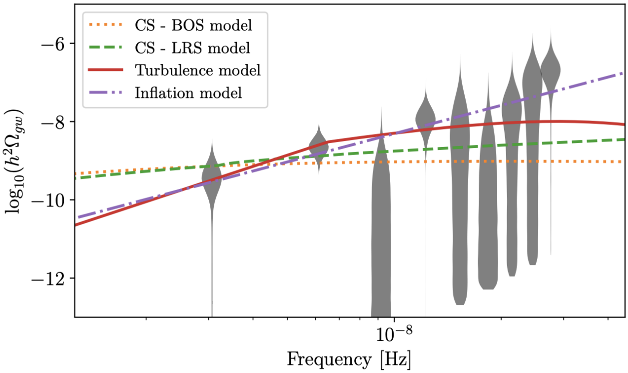
HISTORY OF THE UNIVERSE
pre-BBN Gravitational Wave Background (GWB)
BBN
Accelerators
RHIC & LHC heavy ions
LHC protons
High-energy cosmic rays
Cosmic Microwave Background radiation is visible
Structure formation
Dark energy accelerated expansion
TODAY
Size of visible universe
Inflation
Reheating
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
Electroweak Phase Transition
QCD Phase Transition
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
$E = 10^{-1}$ GeV
$t = 10^{2}$ s
$E = 10^{-4}$ GeV
$t = 3\text{x}10^{5}$ y
$E = 3\text{x}10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\text{x}10^{9}$ y
$E = 2.3\text{x}10^{-13}$ 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

NANOGrav 15 yr data observation[1]



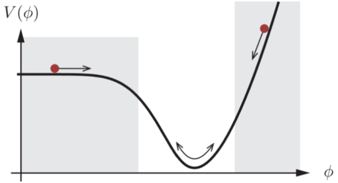
[1] [NANOGrav collaboration], *ApJ Lett.* **951**, 8 & 11 (2023).

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



[2] [EPTA-InPTA Collaborations], *Astron. Astrophys.* **685** (2024) A94.

GW background from inflation



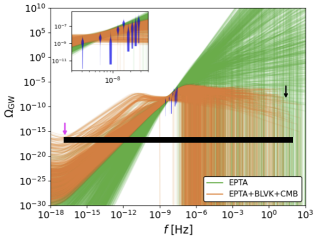
Slow-roll model

$$w = \frac{p}{\epsilon} \simeq \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} = -1$$

$$\Omega_{\rm GW}(f) = \frac{3}{128}\,\Omega_{\rm rad}\, r\, \mathcal{P}^*_{\mathcal{R}} \left(\frac{f}{f_*}\right)^{n_T} \left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{16}{9}\right]$$

$n_T \simeq -2\epsilon$ is the tilt, controlled by slow-roll parameter

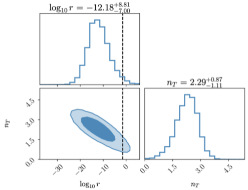
$r < 0.07$ is the scalar-to-tensor ratio constrained from B-mode polarisation in CMB



From P. Turgeon, C. Caprini, A. Chudaykin, M. Kunz, D. Perrodin, I. Cognard, L. Guillemot, G. Theureau, arXiv:2606.09810

Slow-roll model would predict almost flat spectrum $f^{-2\epsilon}$ with a red tilt, so we need to enhance it.

Only constrained at CMB scales, many models predict blue tilt (e.g. coupling to gauge fields, multi-field inflation).



[EPTA-InPTA Collaborations], arXiv:2306.16227

GW background from phase transitions

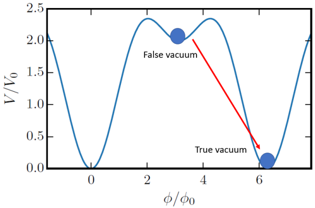
- The Hubble scale at the time of production determines the characteristic frequency of the GW background.

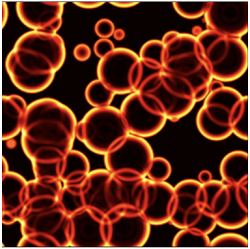
$$f_* \simeq 1.64 \times 10^{-3} \frac{100}{R_* \mathcal{H}_*} \frac{T_*}{100\,\mathrm{GeV}}\,\mathrm{Hz}$$

- 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

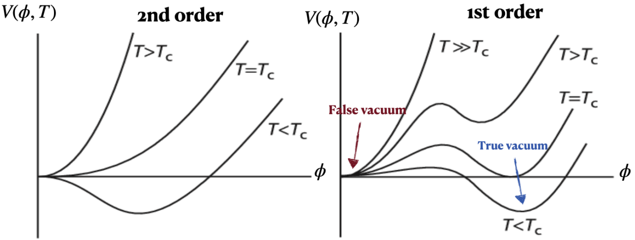
First-order phase transition

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



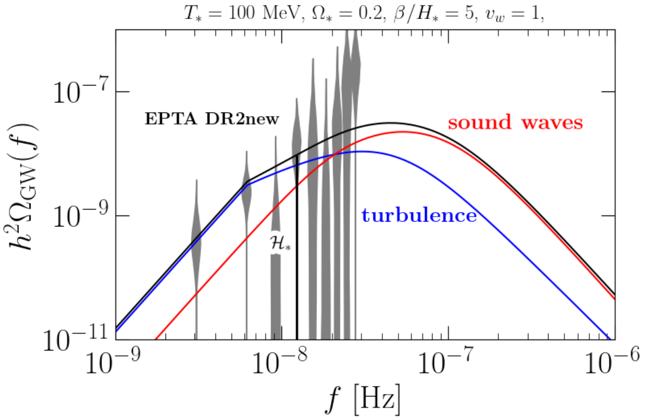


Credits: I. Stomberg



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.



Topological defects (e.g., cosmic strings)

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

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

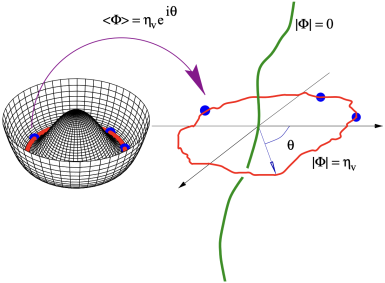


Figure from C. Ringeval, 2010.

GW background from cosmic strings

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

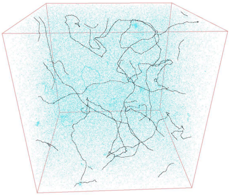
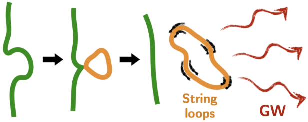


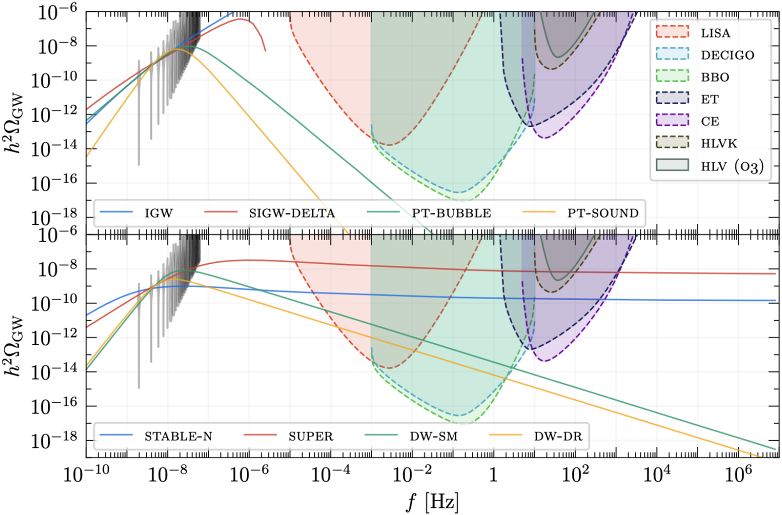
Figure from C. Ringeval, 2010.

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



Credit: Peera Simakachorn

GW background from cosmic strings



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

GW signals from the early Universe

Accurate predictions of the cosmological GW background

- Many of the theoretical developments to predict these signals are on-going with significant effort by the community to produce accurate and reliable GW predictions (spectral shape, polarization, non-Gaussianities).
- Many of these GW signals are inherently *non-linear*, as large perturbations are required to produce observable GW backgrounds. Hence, accurate modeling usually implies high-performance computation of cosmological lattice-field theory and magnetohydrodynamics for relativistic plasmas.
- Realistic and accurate predictions for GW backgrounds from each source are crucial to extract *clean information* from the signal but might not be enough to fully disentangle sources.

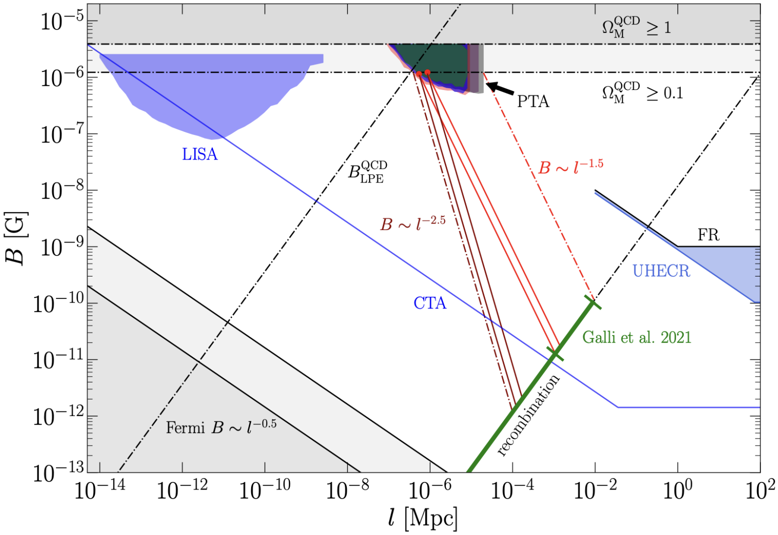
GW signals from the early Universe

How else can we distinguish them?

- **Multi-band observations/constraints**: combining observations with LISA/LVK, correlating data with astrometry.
- **Non-Gaussianities**: Non-Gaussianities are predicted in many models of GW production in early Universe but stochastic superposition of sources Gaussianize the signal.
- **Polarization**: CP-violating signals (e.g., axion inflation, helical magnetic fields) can lead to fully polarized backgrounds, but can only be observed via anisotropies. Additional polarization modes can indicate modified GR.
- **Anisotropies**: Cosmological backgrounds are expected to be highly isotropic, so characterization of anisotropies can be a key aspect to distinuish astro vs cosmo.
- **Multi-messenger observations:** Explore additional observational consequences related to the source of the GW signal.

Multi-messenger observations

(e.g., primordial magnetic fields)



Thank You!

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