Statistical Analysis of FOPT over an Extended Bandwidth as a probe of New Physics

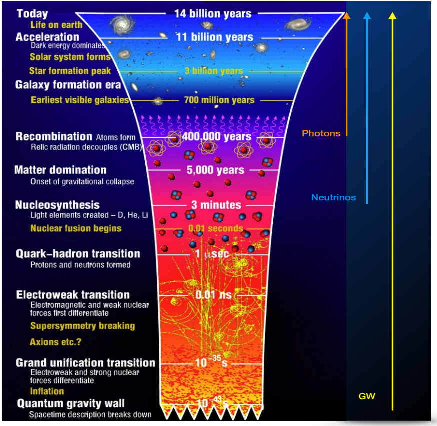
L. Velasco Sevilla CQUeST, Sogang University (S. AbdusSalam, J. Kersten)

Focus Workshop on Cosmological Phase Transitions, IBS, Daejon, Nov. 2025

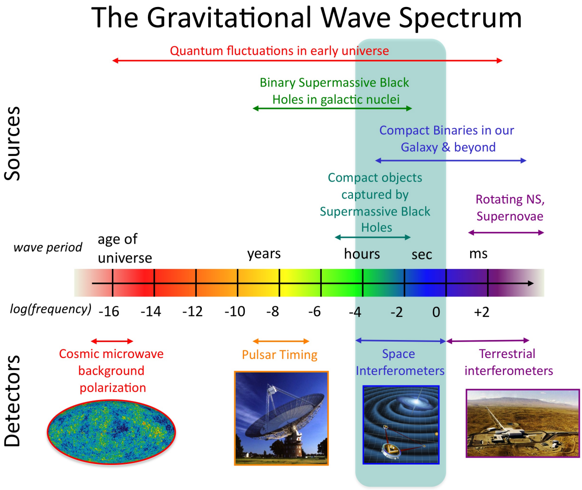
Motivation

- Gravitational waves (GWs) offer a new window into early Universe physics.
- First-order phase transitions (FOPTs) can generate a stochastic GW background.
- Supercooled FOPTs enhance GW production, making them detectable by LVK.
- Goal: general constraints to particle physics models using LVK O1–O4 data (O4 data will be released soon).
- Extend the analysis to use data from other detectors.
- Distinguish cosmological SGWB from Astrophysical foreground

- Gravitational Waves offer us a unique opportunity to test theory well beyond the way photons and neutrinos can do.
- In particular, uncovering fundamental scales,

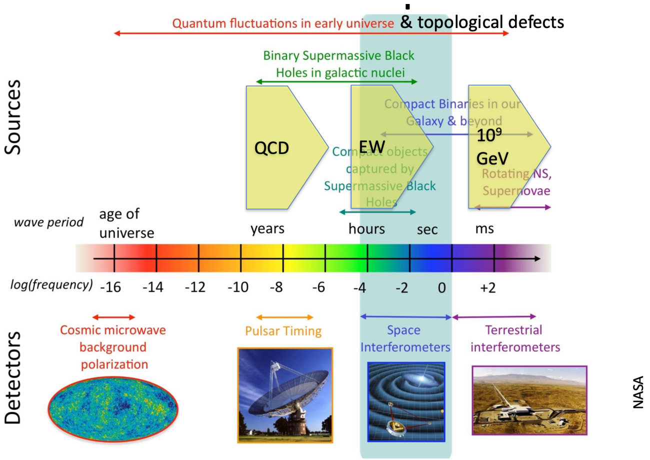


- Decades of effort in planning experiments has given fruits: the 2015 GW detection of a binary-merger has changed the focus of the particle physics community



[Credit: NASA]

- Decades of effort in planning experiments has given fruits: the 2015 GW detection of a binary-merger has changed the focus of the particle physics community, because we see the opportunities in terms of a fundamental scale:



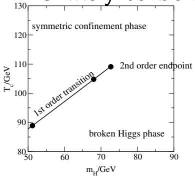
- ⊛ Stochastic backgrounds of cosmological origin are signals that comes from all over the directions of the sky dome, as opposed to signals of astrophysical origin. The characterization and detection of physical processes giving rise to them will be a milestone of the human civilization. Among them we have:
  - Phase transitions of the early universe (e.g. triggered by the breaking of groups of models of particle physics)
  - Also these kind of breakings can produce topological defects with very important GW signatures
  - The plasma itself particle physics gauge groups can produce GW
  - Inflation models can be associated to a particular particle physics theory and many parameters there can relate reheating temperature and GW
  - Leptogenesis and baryogenesis models
  - All of which point out to a fundamental scale!

- Instead of testing a specific model, with specific predictions, look for general predictions.
- These predictions can be given in terms of the reach of the amplitude GW density and the peak frequency, and the peak frequency OR
- In terms of the nucleation parameters: T_n, α, β, etc.
- In this way, we can constrain a meaningful fundamental quantity: a new fundamental scale. This is the spirit of the analysis.
- Of course, for a well-motivated model, we can constrain in terms of fundamental couplings and masses.

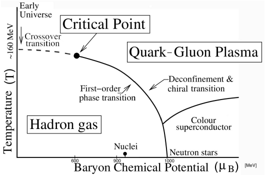
First-Order Phase Transition

- Characterization of the complete signal it is very difficult: simulations, assumptions, etc.
- Maybe the only robust prediction is the peak frequency
- Key parameters:
  - Bubble wall velocity v_w
  - Nucleation temperature T_n
  - Inverse transition duration β/H_n
  - Transition strength α
- Supercooling: $T_n \ll$ symmetry-breaking scale, leading to $\alpha \gg 1$.
- Enhanced GW production from bubble collisions and sound waves.

- We are here because we would like to explore modifications/extensions of:
- Electroweak phase transition ($T \sim 160$ GeV)
  - A transition happens as a result of the breaking of $SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}$ (The order parameter is the vev of the Higgs)
  - With the measured value of the Higgs mass, $m_H = 125$ GeV, the phase transition is a cross-over
- QCD transition:
  - The global chiral symmetry is broken, triggering the transition
  - The quark-gluon plasma becomes confined in hadrons: the order parameter is the quark condensate $\overline{\psi}\psi$
  - Is likely to be a cross over phase transition



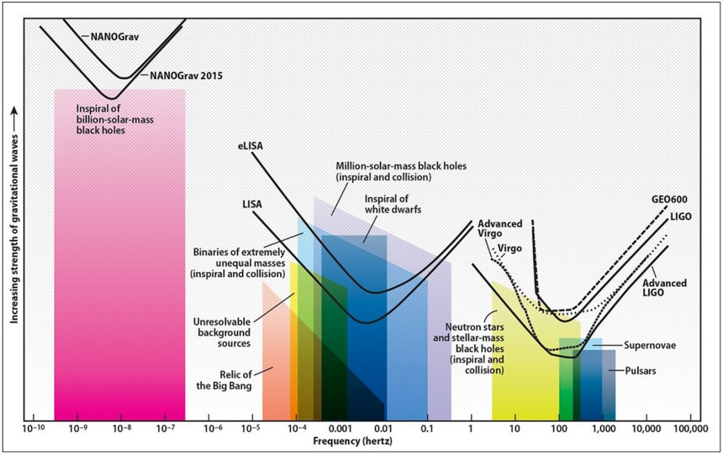
Laine, Rummukainen, arXiv: 9809045



Gauss_centre.eu

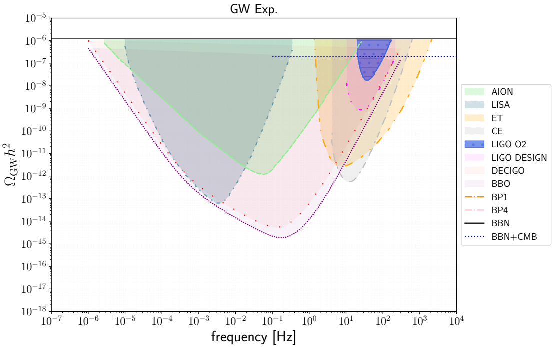
Methodology

- ⊛ Identify an actual experiment with data (IPTA, LVK)
- ⊛ Select a model [template] for a source of GW waves
- ⊛ Substract the astrophysical forewground



- ⊛ Apply Bayesian statistics

Identify and actual experiment with data: LVK



One motivation is to extend the analysis once data from experiments becomes available

Select a model for a source of GW

- Bubble collisions [naïve]:

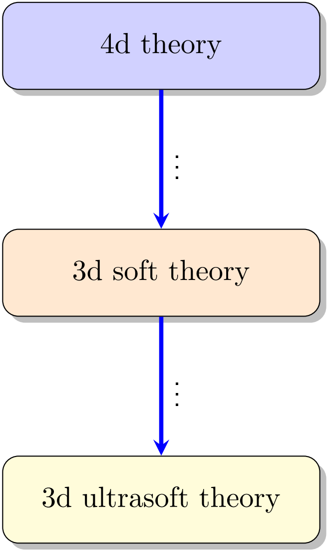
$$h^2\Omega_{bc}(f) \propto \left(\frac{H}{\beta}\right)^2 f^{2.8}(1+2.8f^{3.8})^{-1}$$

- Sound waves [naïve]:

$$h^2\Omega_{sw}(f) \propto \left(\frac{H}{\beta}\right) f^{3}(1+0.75f^{2})^{-7/2}$$

  - Peak frequencies depend on β/H and reheating temperature T_{RH}.
- Specific model ($U(1)$, etc.)

Disclaimer: Results here have been obtained in 4d theory [however, for the general results, the 4d theory is all what is needed]



We are currently constructing a pipeline to use the 3d theory for the analysis of specific models.

Methodology

- LVK O1–O3 stochastic background data used.
- Bayesian likelihood:

  $$p(C_{IJ}(f)|\theta) \propto \exp\left[-(C_{IJ} - \Omega_{GW})^2/2\sigma^2\right].$$

  Here, C_{IJ} are the cross-correlation estimator for the GW background using data from detectors I and J and σ, the variance [Used actual LVK data].
- Includes astrophysical foreground (CBCs, etc.) [Expanding to more foreground].

Goal: Separating Astrophysical and Cosmological SGWB

Cosmological sources with LIGO-band signatures:

- First-order phase transitions (FOPTs)
- Topological defects: cosmic strings, domain walls
- Primordial black holes (PBHs)
- Exotic inflationary relics: preheating, spectator fields
- Axion-like scalars

Astrophysical SGWB:

Compact Binary Coalescences (CBCs):

$$\Omega_{\rm GW}(f) = A\left(\frac{f}{f_{\rm ref}}\right)^{2/3}, \qquad \Omega_{\rm GW}(f) = \frac{f}{\rho_c H_0}\int dz\, \frac{R(z)\,\frac{dE_{GW}}{df}}{(1+z)\,E_z(z)}.$$

Rotating Neutron Stars:

$$\Omega_{\rm GW}(f) = \frac{f}{c\rho_c}\int dz\, \frac{1}{4\pi d_L(z)^2}\,\frac{dE_{GW}}{df}\,\frac{df_{\rm source}}{df}\,\frac{dR(z)}{dz}.$$

Magnetars:

$\Omega_{\rm GW}(f)$ same form as rotating NSs, but with $\dfrac{dE_{GW}}{df} = \dfrac{32\pi^6 G}{5c^5}\, I^2 \epsilon(B)^2 f_{\rm source}^6.$

NS Phase Transitions:

$$\Omega_{\rm GW}(f) = \frac{\pi f}{2\rho_c G}\int dz\, h_{NS}^2\, \dot{\rho}_*(z)\,\frac{dV}{dz}\, f_{pt}\int dm\,\phi(m).$$

First Stars (Pop III):

$$\Omega_{\mathrm{GW}}(f) = \frac{16\pi D^2}{15 G \rho_c} \int dz \, \frac{R(z)\, f_{\mathrm{source}}^3 \, f |\tilde{h}(f_{\mathrm{source}})|^2}{(1+z) H_0 \sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}}.$$

Results

- Generic supercooled FOPT framework
- Ingredients:
  - Scalar potential with two minima separated by a barrier.
  - Bubble nucleation governed by Euclidean action $S(T)$.
  - Supercooled transitions: $\alpha \gg 1$, $T_{RH} \ll T_n$.
- GW sources: bubble collisions and sound waves.

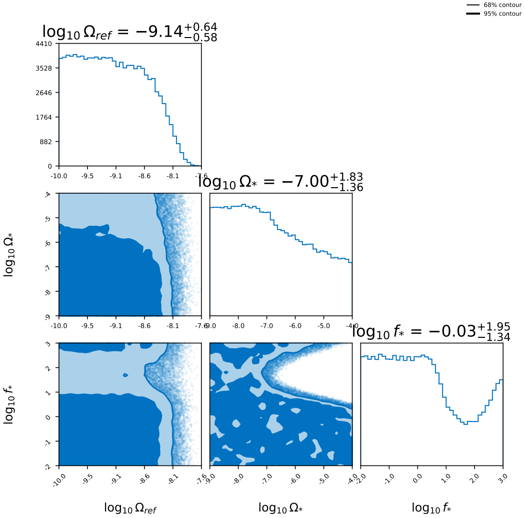
- Large supercooling $\Rightarrow$ enhanced amplitude.
- GW detectability depends on:
  - β/H (duration)
  - T_{RH} (energy scale)
  - Dominant mechanism (collisions or sound waves)
- Suitable for interpreting LVK constraints, up to the assumptions of
  - GW spectrum approximated by broken power law.
  - Parameters constrained: Ω_*, f_*, spectral slopes.
  - No evidence for FOPT signal; upper limits established.

Priors for Parameter Estimation

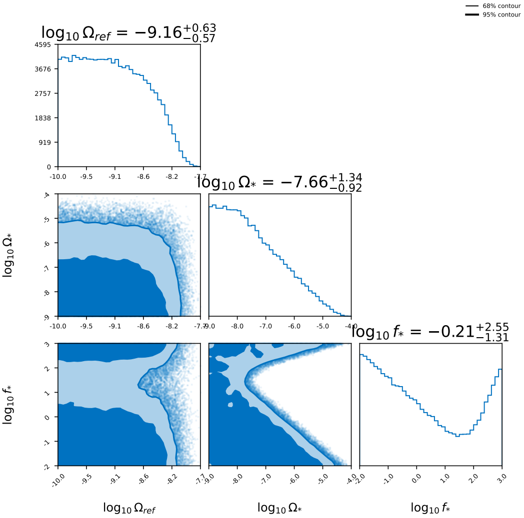
	Broken power-law	**Templates (from simulations)**
Ω_{ref}	$\mathrm{Log}[10^{-10}, 10^{-7}]$	$\mathrm{Log}[10^{-10}, 10^{-7}]$
Ω_*	$\mathrm{Log}[10^{-9}, 10^{-4}]$	–
f_*	$\mathrm{Log}[10^{-2}, 10^{3}]$	–
$\beta/H_{\rm RH}$	–	$\mathrm{Log}[1, 10^{3}]$
$T_{\rm RH}$	–	$\mathrm{Log}[10^{5}, 10^{10}]$

Here Ω_{ref} means the priors of the astrophysical foreground and Ω_*, f_* relate to the cosmological GW parameters that need to be constrained.

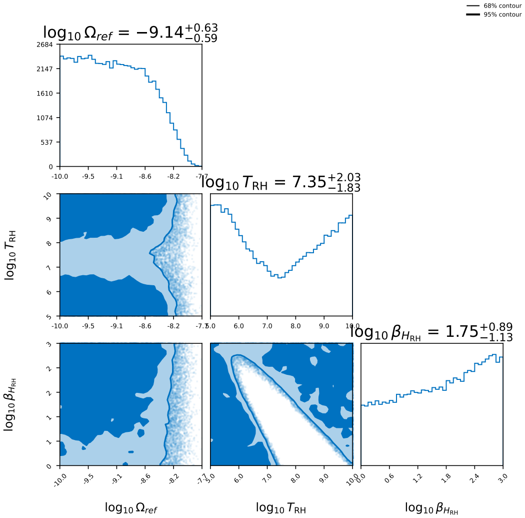
♠ Fit to a simple power broken law assuming an unbiased range of $\Omega_{\rm GW}$ withing the LIGO range and the source of GW production coming from sound waves



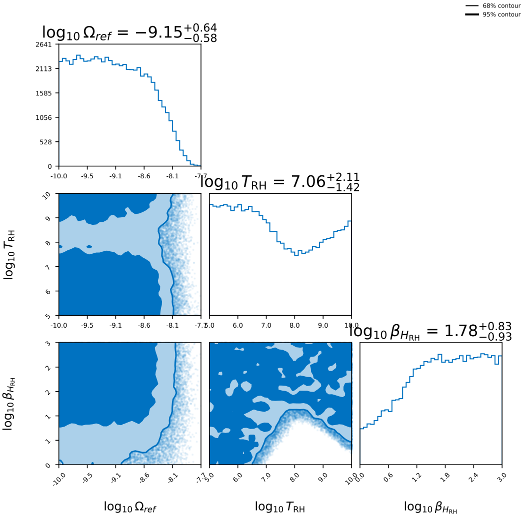
♠ Fit to a simple power broken law assuming an unbiased range of Ω_{GW} within the LIGO range and the source of GW production coming from bubble collisions



♣ Simple power broken law, assuming sound waves as the dominant source of GW production



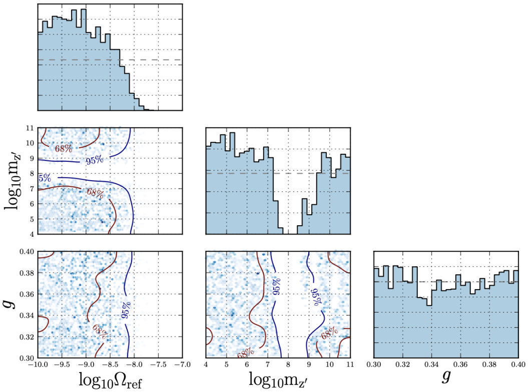
♣ Simple power broken law, assuming bubble collisions as the dominant source of GW production



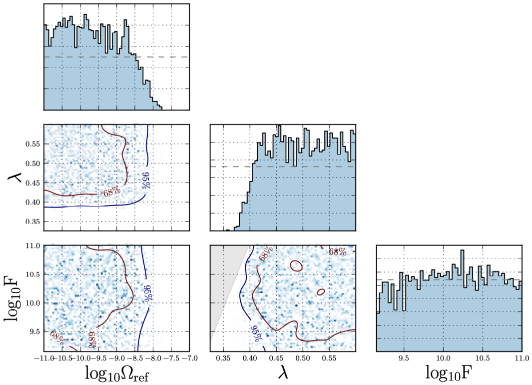
Application to specific models ($U(1)_{B-L}$)

- Minimal extension with new scalar and Z' gauge boson.
- Supercooling arises naturally.
- LVK constraints exclude region around $m_{Z'} \sim 10^8$ GeV.

Example from 2209.14707, Badger, Sakellariadou



Example from 2209.14707, Badger, Sakellariadou



Final remarks

- LVK data already constrains early-Universe models: waiting for O4 results
- Supercooled FOPTs provide promising targets for GW searches: refined templates needed
- Application to specific particle physics specific models: refined constraints
- Future detectors [LISA, ET, CE] will probe PeV-scale particle physics.
- Just as the IPTA example: robust statistical analysis, both from the experimental side and the theoretical side are needed.