First result on cosmological first-order phase transitions with LIGO-Virgo's three observing run data

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subgroup of the LIGO scientific collaboration
Most primordial gravitational waves are stochastic (SGB).
For stochastic GWs that is Gaussian, stationary, isotropic and unpolarized,

\[
\langle \tilde{h}_A^*(f, \hat{n}) \tilde{h}_{A'}(f', \hat{n}') \rangle = \delta(f - f') \frac{\delta^2(\hat{n}, \hat{n}')}{4\pi} \frac{1}{2} S_h(f) \]

\[
\Omega_{gw}(f) = \frac{4\pi^2}{3H_0^2} f^3 S_h(f)
\]

Cosmological First Order Phase Transition (FOPT)

Bubble Collisions -> Sound Waves -> MagnetoHydrodynamic Turbulence


https://home.mpcdf.mpg.de/~wcm/projects/homog-mhd/mhd.html
Envelope Approximation

**Simulations:**
Kosowsky, Turner, Watkins, Kamionkowski
Huber, Konstandin, JCAP09(2008)022

**Analytical Modelling:**
Jinno, Takimoto, PRD95,024009(2017)

Beyond the Envelope Approximation

**Bulk flow model:** Konstandin, JCAP03(2018)047, Jinno, Takimoto, JCAP01(2019)060
**Direct large scalar lattice simulations:** Cutting, Escartin, Hindmarsh, Weir, PRD97,123513(2018), arXiv:2005.13537:

\[
\Omega_{\text{coll}}(f) h^2 = 1.67 \times 10^{-5} \Delta \left( \frac{H_{\text{pt}}}{\beta} \right)^2 \left( \frac{\kappa_\phi \alpha}{1 + \alpha} \right)^2 \\
\times \left( \frac{100}{g_*} \right)^{1/3} S_{\text{env}}(f),
\]

Consider a scenario when BC is dominant
Sound Waves

Numerical Simulations:
Hindmarsh, Huber, Rummukainen, Weir,

Analytical Modelling (sound shell model)
Minkowski: Hindmarsh, 120, 071301 (2018)
Hindmarsh, Hijazi, JCAP 12(2019)062
FLRW: HG, Sinha, Vagie, White, JCAP 01 (2021) 001

The dominant source for a FOPT in a thermal plasma.
Consider a scenario with this dominant (SW).

\[ \Omega_{sw}(f) h^2 = 2.65 \times 10^{-6} \left( \frac{H_{pt}}{\beta} \right) \left( \frac{K_{sw} \alpha}{1 + \alpha} \right)^2 \left( \frac{100}{g_*} \right)^{1/3} \]
\[ \times v_w \left( \frac{f}{f_{sw}} \right)^3 \left( \frac{7}{4 + 3 \left( f/f_{sw} \right)^2} \right)^{7/2} \]

\[ \Upsilon = 1 - \left( 1 + 2 \tau_{sw} H_{pt} \right)^{-1/2} \]

Previous formula mistakenly enforces an infinite lifetime.
Both can be approximated by a broken power law.

Peak frequency is determined by the mean bubble separation, and redshifting (Temperature).

Temperature LIGO is sensitive to $10^6 \sim 10^9 \text{GeV}$

We thus also consider a generic broken power law model.

\[ \Omega_{\text{BPL}}(f) = \Omega_\ast \left( \frac{f}{f_\ast} \right)^{n_1} \left[ 1 + \left( \frac{f}{f_\ast} \right) \Delta \right]^{(n_2-n_1)/\Delta} \]

- n1: low f power, fixed to be 3, (causality)
- n2: high f power, -4(SW), -1(BC), not entirely determined, will vary in the range (-8,0)
- \(\Omega_\ast\), \(f_\ast\), reference amplitude and frequency.
- \(\Delta=2\) (SW), 4(BC), fixed to be 2 which gives a more conservative result

In all models (BPL, SW, BC), we also consider the non-negligible CBC contribution.

\[ \Omega_{\text{CBC}} = \Omega_{\text{ref}} \left( \frac{f}{f_{\text{ref}}} \right)^{2/3} \]

\(f_{\text{ref}} = 25\) Hz
The Cross-Correlation Method

- The standard method of searching for SGB
- Remove majority of noises specific to a single interferometer

\[
\hat{\mathcal{C}}^{IJ}(f) = \frac{2}{T} \text{Re}[\hat{s}_I^*(f)\hat{s}_J(f)]
\]

\[
\langle \hat{\mathcal{C}}^{IJ}(f) \rangle = \Omega_{GW}(f)
\]

O1, O2 and O3 data from interferometer I(J): (H, L, V)

Cross-correlation estimator
Overlap reduction function

For more details on the cross-correlation analysis, see the LIGO, Virgo and KAGRA collaboration paper arxiv:gr-qc/2101.12130

https://www.ligo.org
Likelihood

$$\log p(\hat{C}_{I,J}(f)|\theta_{gw}, \lambda) \propto \frac{1}{2} \sum_f \left[ \frac{\hat{C}_{I,J}(f) - \lambda \Omega_{gw}(f, \theta_{gw})}{\sigma_{ij}^2(f)} \right]^2$$

Priors for two analysis strategies:

- **broken power law**

  $$\Omega_{\text{bpl}}(f) = \Omega_{*} \left( \frac{f}{f_{*}} \right)^{n_1} \left[ 1 + \left( \frac{f}{f_{*}} \right)^{\Delta} \right]^{(n_2 - n_1)/\Delta}$$

  - $\Omega_{\text{ref}}$ (Prior: LogUniform($10^{-10}$, $10^{-7}$))
  - $\Omega_{*}$ (Prior: LogUniform($10^{-9}$, $10^{-4}$))
  - $f_{*}$ (Prior: Uniform(20, 256 Hz))
  - $n_1$ (Prior: 3)
  - $n_2$ (Prior: Uniform(-8,0))
  - $\Delta$ (Prior: 2)

- **sound waves, or bubble collision**

  - $\alpha$ (Prior: LogUniform($10^{-3}$, 10))
  - $\beta/H_{\text{pt}}$ (Prior: LogUniform($10^{-1}$, $10^{3}$))
  - $T_{\text{pt}}$ (Prior: LogUniform($10^{5}$, $10^{9}$ GeV))
  - $\nu_{w}$ (Prior: 1)
  - $\kappa_{\phi}$ (Prior: 1)
  - $\kappa_{\text{sw}}$ (Prior: $f(\alpha, \nu_{w}) \in [0.1 - 0.9]$)
Broken Power Law Searches

95% CL UL (CBC+BPL)

\[ \Omega_{\text{ref}} = 6.1 \times 10^{-9} \]
\[ \Omega_* = 5.6 \times 10^{-7} \]
\[ \Omega_{\text{BPL}}(25 \text{ Hz}) = 4.4 \times 10^{-9} \]

CBC + BPL

No Evidence for BPL Signal

\[ \log B^{\text{CBC+BPL}}_{\text{noise}} = -1.4 \]
\[ \log B^{\text{BPL}}_{\text{noise}} = -0.78 \]
\[ \log B^{\text{CBC+BPL}}_{\text{CBC}} = -0.81 \]

Posterior distributions for 2 variables (correlations)
**Bubble Collision + CBC**

No Evidence for Bubble Collision Signal

95% CL UL with fixed Tpt and beta/Hpt

<table>
<thead>
<tr>
<th>Phenomenological model (bubble collisions)</th>
<th>$\Omega_{coll}^{95%}$ (25 Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta/H_{pt}$</td>
<td>$T_{pt}$</td>
</tr>
<tr>
<td>0.1</td>
<td>$9.2 \times 10^{-9}$</td>
</tr>
<tr>
<td>1</td>
<td>$1.0 \times 10^{-8}$</td>
</tr>
<tr>
<td>10</td>
<td>$4.0 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

excluded at 95% CL

no sensitivity
Sound Waves + CBC

No Evidence for Sound Waves Signal

Signal is generically weak, no preference for most parameters

$\log B_{\text{noise}}^{\text{CBC+sw}} = -0.66$

$v_w = 1$

95% CL UL with fixed $T_{pt}$ and $\beta/H_{pt}$

$\Omega_{sw}(25 \text{ Hz}) = 5.9 \times 10^{-9}$

$\beta/H_{pt} < 1$ and $T_{pt} > 10^8 \text{ GeV}$
Summary

The first search for GW from cosmological FOPT with LIGO data was performed.

- (Bayesian) analysis with combined O1, O2 and O3 data.
- Searches done for 3 models: broken power law, bubble collisions, sound waves
  In all cases, CBC background are included.
- No evidence for such stochastic GWs
- Upper limits set

We would like to thank Pat Meyers for allowing us to use his code and Alberto Mariotti for his useful comments.
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Thanks!