Exploring the gravitational wave power spectrum from first-order phase transitions

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Why is this important?

Gravitational waves from cosmological first-order phase transitions could give us direct information from the earliest moments of the universe and put new constraints on its physics.

Introduction

- Many beyond the Standard Model theories predict an electroweak first-order phase transition (PT) in the early universe.
- Gravitational waves (GWs) are tensor perturbations of spacetime that propagate at the speed of light.
- First-order PTs at the electroweak scale are a cosmological source of GWs, potentially detectable with the future space-based GW detector LISA[1].

From PTs to GWs

- In a first-order PT the universe transitions from a symmetric to a broken phase via bubble nucleation.
- The expanding bubbles can cause GWs in three stages: bubble collisions, sound waves, and turbulence.
- The GW signal depends on the thermal properties of the PT, which connect it to the underlying particle physics model.
  - phase transition strength α
  - bubble wall velocity v_w
  - (inverse) phase transition duration β/H_* or mean bubble separation $H_* R_*$
  - transition temperature T_* and effective degrees of freedom g_*

The PTPlot tool

- We compute the GW signal and estimate how likely it is to be detected with the `Python`-based PTPlot[2] tool.
- PTPlot uses a broken power-law ansatz[3,4] fitted to simulations of the shape of the sound wave power spectrum.
- Using the power spectrum and the sensitivity of LISA, PTPlot calculates the signal-to-noise ratio (SNR).

PT parameters

↓

PTPlot

↓

GW power spectrum

+

SNR of LISA

What are we doing?

- We are adding an alternative method of computation to PTPlot using PTtools[5], a `Python` library for PTs.
- PTtools uses the Sound Shell Model[6] (SSM) to directly calculate the sound wave power spectrum from the fluid velocity.
- This allows for comparison between a simulation-motivated fit and a full derivation of the power spectrum.

The Sound Shell Model

- The GW power spectrum can be computed from the velocity power spectrum of the cosmological fluid surrounding the bubbles.
- In the model the velocity power spectrum is determined from a superposition of fluid shells similar to those around the expanding bubbles.
- The shapes of these sound shells can be solved computationally with relativistic hydrodynamics.

What should you take away?

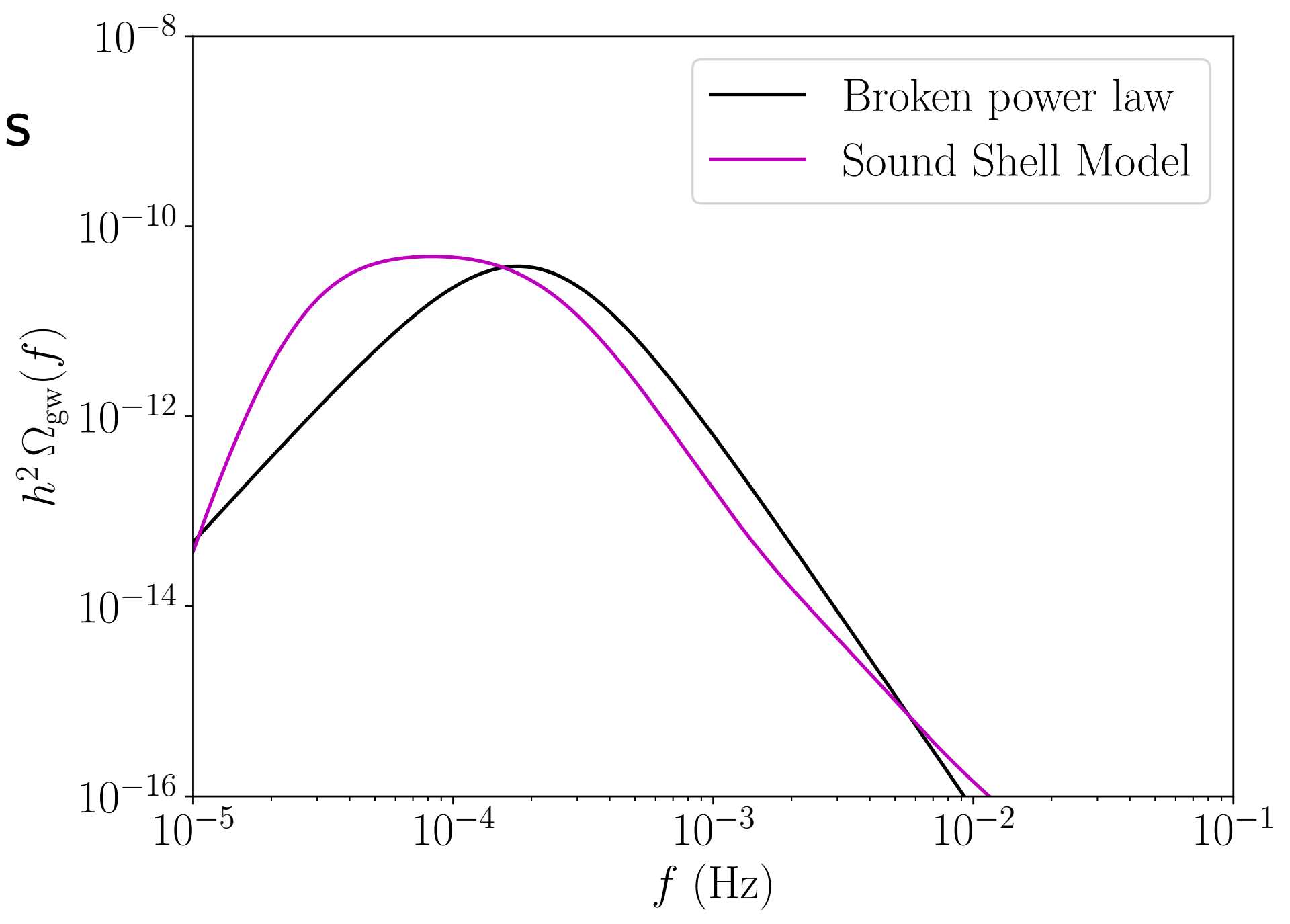
Comparing different models of the gravitational wave power spectrum is necessary to accurately estimate the detectability of the resulting signal from cosmological phase transitions.

The GW power spectrum

- The power spectrum describes how the GW energy density ρ_gw is distributed over frequencies f.

$$\Omega_\mathrm{gw}(f) \equiv \frac{1}{\rho_\mathrm{crit}} \frac{\mathrm{d}\rho_\mathrm{gw}}{\mathrm{d}\ln(f)}$$

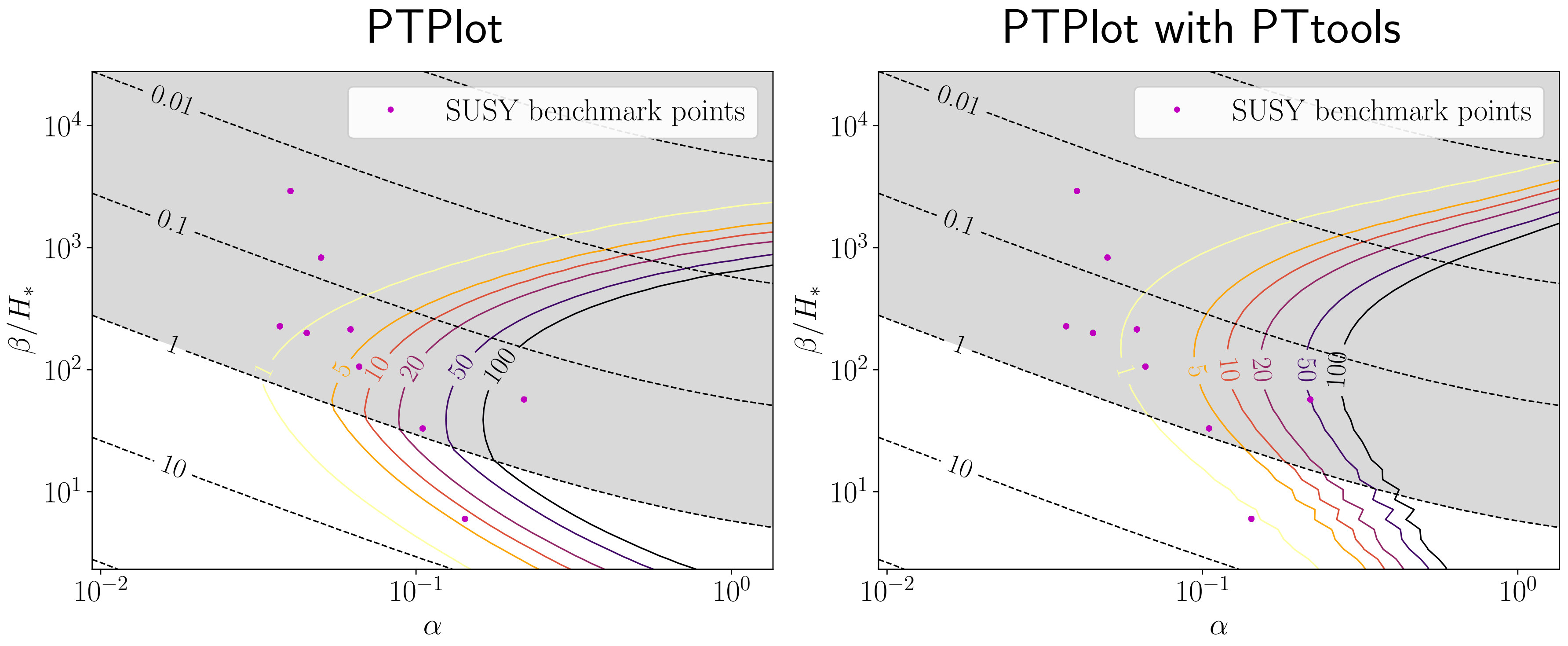
- The SSM power spectrum has a double broken power-law shape.



$v_\mathrm{w} = 0.5, \alpha = 0.1, \beta/H_* = 10, T_* = 100\ \mathrm{GeV}, g_* = 100$

The SNR curves

- The SNR measures the strength of the GW signal relative to noise from the detector or foregrounds.
- The larger the SNR, the more likely the signal is to be detected.
- We compare a benchmark case for supersymmetry (SUSY) using the two alternative methods.



$v_\mathrm{w} = 0.95, T_* = 100\ \mathrm{GeV}, g_* = 100$

Conclusions

- The change from a broken power-law fit to the double broken power-law shape of the SSM power spectrum affects the peak amplitude and frequency of the GW signal.
- This has a direct impact on the SNR curves, which can already be seen with our preliminary results.
- For the benchmark points we used, the SNR is generally lower for the SSM than for the current fit, tightening the constraints on the PT parameters.

References and more information

You can find more information, full bibliographic details, and a link to try out PTPlot yourself by scanning the QR code.

1. LISA, lisamission.org
2. PTPlot, ptplot.org
3. arXiv:1910.13125
4. arXiv:1704.05871
5. PTtools (soon public), github.com/CFT-HY
6. arXiv:1909.10040

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