PROCEEDINGS OF SCIENCE

# Probing the Higgs sector with gravitational waves



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We discuss the complementarity of collider experiments and gravitational wave detectors for studying particle physics at the electroweak scale, and for understanding the dynamics of the early Universe around the electroweak epoch. The bridge between particle physics and gravitational wave interferometry is established by the so-called electroweak phase transition, a process in the early Universe which could have given rise to a stochastic gravitational wave backgound, whose spectrum is strongly dependent on the particle content of the plasma and their high energy interactions. We give a brief introduction to this process, and then illustrate, in a concrete case of a two-Higgs-doublet model, how near-future interferometers such as LISA could be used to probe physics beyond Standard Model.

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## 1. Introduction

Modern cosmology teaches us that the Universe has a history consisting of different epochs, each characterised by the complexity of the structures inhabiting the primordial plasma, and their effective mutual interactions. The transition between these epochs can be "traumatic" to the cosmos, leaving scars that remain observable up to this day. An example is the gravitational wave (GW) spectrum typically produced when these phase transitions are first-order. The shape of this spectrum depends on the underlying dynamics of the high-temperature plasma at that early epoch, so a detection of cosmological gravitational waves could give us information on fundamental particle physics at energy scales comparable to or even larger than those we currently reach at colliders.

In the following we will briefly discuss how these cosmological GWs are produced in the so-called *electroweak phase transition* (EWPT), how we can detect them with the future space-based interferometer LISA [1, 2], and provide a concrete example of the afore-mentioned particle-cosmology complementarity in the context of a two-Higgs-doublet model.

## 2. Gravitational waves from the electroweak phase transition

In introductory books and courses on the subject, the Higgs mechanism is typically discussed under the assumption that the field inhabits a cold, nearly empty Universe. In this case the Higgs potential has the famous shape shown in figure 1 (left, $T = 0$ curve), where the true minimum breaks the electroweak symmetry, releasing a certain amount of free energy. But in the early Universe

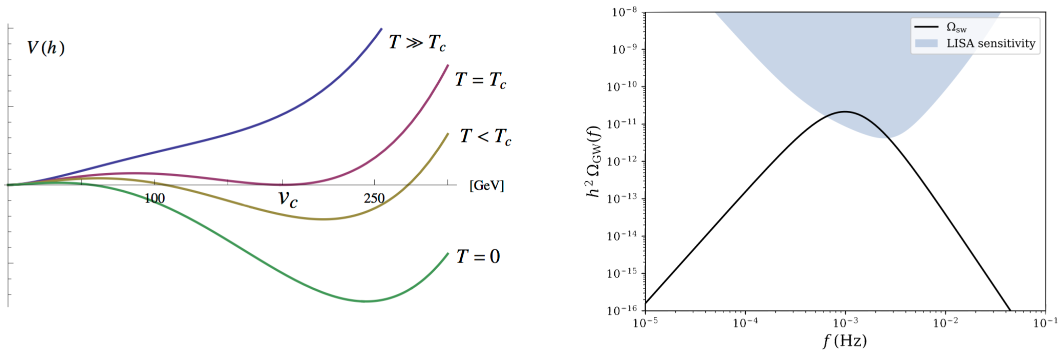


**Figure 1:** (Left) The Higgs potencial for various values of the plasma temperature. (Right) The broken power-law gravitational wave spectrum resulting from the electroweak phase transition. Figure from ref. [2], produced with the `PTPlot` tool [3].

the field is actually surrounded by a plasma of particles, and their interactions change the effective potential. At large enough temperatures, the plasma is so dense that the energy needed to give mass to all of its particles is never compensated by the energy released by the Higgs. At this point it is actually more favourable for the Higgs *not* to break the electroweak symmetry at all. Therefore there exists a critical temperature $T_c \sim O(100\text{ GeV})$, above which the electroweak symmetry is restored, i.e. the weak and electromagnetic interactions are phenomenologically indistinguishable.

In many particle physics models, the transition from the symmetric to the broken phase is a first-order phase transition. There is an energy barrier separating the two minima at $T = T_c$, as shown in figure 1, and the process takes place by bubble nucleation, like boiling water: there appear *bubbles* of broken vacuum (inside which particles are massive) in a plasma of massless particles. These bubbles then expand, eventually colliding with each other and filling the entire Universe.

Importantly, the collision of these bubbles induces a time-varying quadrupole moment of energy-momentum, which then leads to a production of gravitational waves [2]. This spectrum is stochastic, because it is produced by numerous uncorrelated sources, and has typically a broken power-law shape shown in figure 1 (right), with a peak at frequencies of order few milli-Hertz. This is within reach of future-generation interferometers such as LISA — the Laser Interferometer Space Antenna, a three-armed interferometer of $2.5 \times 10^9$ m each, which will be sent to space to reduce or eliminate the seismic, Newtonian and thermal noise (compared to Earth-based experiments), thus leading to a sensitivity to GWs in the $0.01 - 100$ mHz band of the spectrum [1, 5].

From a detection of a stochastic GW background at LISA, one could reconstruct certain thermodynamic parameters involved in the phase transition, such as the fractional amount of energy released to the plasma (relative to the total energy in radiation), $\alpha \equiv \rho_{\rm EWPT}/\rho_{\rm rad}$, the duration of the phase transition (in terms of the Hubble parameter), $\beta/H$, the temperature $T$ of the plasma at the GW production, and the velocity $v_w$ at which the bubbles expand and collide. But the value of these parameters depend crucially on the microphysics of the underlying effective theory at the electroweak scale. This means we can use GW detections to test physics beyond the Standard Model. We will illustrate this in a concrete example with a two-Higgs-doublet model (2HDM).

## 3. Testing the Higgs sector with gravitational waves: a 2HDM example

2HDMs are a minimal extension of the Standard Model (SM), with the scalar sector extended by the addition of an extra $SU(2)_L$ doublet [6]. This leads to a model with three neutral scalars — two CP-even states $h_0$ and $H_0$, and a CP-odd $A_0$ — and a pair of charged scalars $H^\pm$. The CP-conserving model can be generally described by 7 parameters: the masses of the four scalars, an overall mass scale for the second doublet, and two mixing angles. However, the measured properties of the 125 GeV scalar at the LHC, the searches for these new scalars, and the electroweak precision observables put several constraints on them [7, 8], leading to the following corner of the parameter space: (i) the mass of one of the scalars is fixed to $m_{h_0} = 125$ GeV; (ii) its properties are in good agreement with the SM predictions, so that $h_0 \approx h_{\rm SM}$, thus fixing the angle that mixes the two CP-even states; (iii) there must be a mass degeneracy of $m_{H^\pm} \approx m_{H_0}$ or $m_{H^\pm} \approx m_{A_0}$. When investigating the electroweak phase transition in this scenario, one finds that the other mixing angle (or, equivalently, the ratio $\tan\beta = v_2/v_1$ of the VEV of the two doublets) is essentially irrelevant for the electroweak phase transition [2, 9]. Moreover, for the phase transition to be first-order, there is a preference for a hierarchy in the scalar sector, with $m_{A_0} \gtrsim m_{H_0} \approx m_{H^\pm}$ [10, 11].

The latter fact is demonstrated in figure 2 (left): after scanning over the parameter space [9], the green contours show the density of points that pass all consistency checks (perturbativity and stability of the potential) and phenomenological (flavour and collider) constraints, whereas the brown and black curves show the percentage of points in the corresponding region that do have a first-order electroweak phase transition. One sees that most of the scanned points fall in the $m_{H_0} \approx m_{A_0}$ region, but only 5% of the points there have a first-order EWPT, whereas this percentage grows to 80% as we approach the $m_{A_0} \gtrsim m_{H_0} + m_Z$ corner. This has important phenomenological

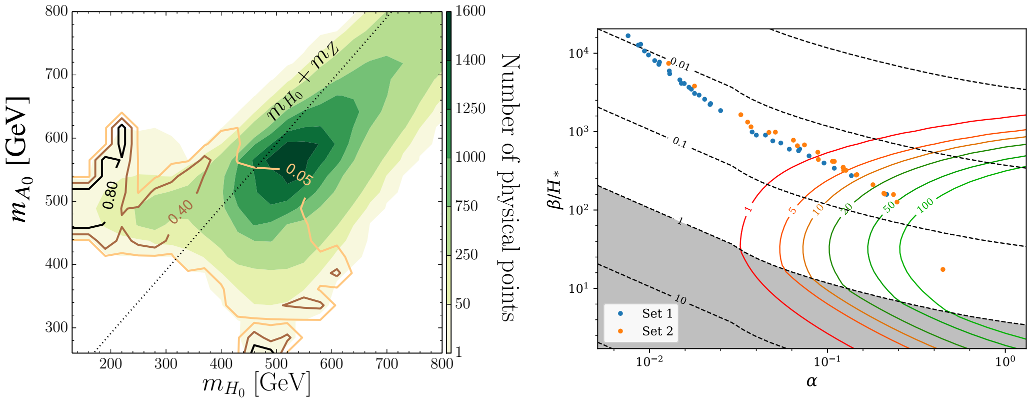


**Figure 2:** (Left) Distribution of points in 2HDM parameter space satisfying consistency checks and collider constraints, and fraction of these points that have a strong first-order electroweak phase transition. (Right) Orange points are excluded at the LHC for 2HDM Type-II, but not for Type-I, whereas blue points are not excluded at all. Green and red curves show LISA signal-to-noise ratio, thereby illustrating its potential for detecting some of the points that are not probed by the LHC. Figure from ref. [2].

applications, for it means that a detection of an $A_0 \to ZH_0$ would be a smoking-gun signature of a first-order phase transition in the early Universe [11]. Moreover, this decay is not open in many SM extensions (such as those motivated by SUSY), so this cosmological approach serves as a motivation to search for this otherwise neglected decay channel [12, 13]. This illustrates the dialogical aspect between GW detection and collider experiments in probing BSM physics.

In figure 2 (right) we show the complementary aspect of LISA relative to colliders. The colour coding is such that orange points are excluded by LHC for 2HDM Type-II (but not for Type-I), whereas blue points are not excluded for any model. The fact that many of these points fall within a LISA SNR $> 1$ (to the right of the red curve) shows that LISA could test models which are out of LHC reach.

## 4. Conclusions

We live in a golden age for cosmology, with the advent of precision measurements, the first GW detection, and many new experiments in sight. Because matter and radiation in the early Universe formed a plasma of highly energetic particles, one can use these cosmological observations to obtain information on particle physics and fundamental interactions. In this context, the study of the electroweak phase transition provides a rich particle-cosmology interface, because it involves processes at electroweak energies, which are accessible to current colliders and near-future GW interferometers such as LISA.

We have shown, in a concrete 2HDM example, that the relation between GW observations and collider experiments can be dialogical or complementary. In the first case, we can use collider constraints to corner the model into a parameter region, then predict the GW spectrum; or, reciprocally, we can predict the phenomenological behaviour of the model at colliders under the condition that an observable GW spectrum would ensue. On the other hand, GW detectors can also say something about models which are out of reach of current colliders.

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