Letter of Interest: Gravitational Waves From Low Energy Supersymmetry Breaking

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Abstract: Supersymmetry-breaking hidden sectors can lead to observable gravitational wave signals. As a first case, we study hidden sectors where a first order phase transition occurs along the flat complex scalar direction generically associated with supersymmetry breaking, leading to a stochastic gravitational wave background. On the more phenomenological side, we point out that the detection of a gravitational wave signal from a supersymmetry-breaking phase transition likely indicates superpartners within the reach of the high-luminosity LHC or future high energy colliders.

1 Introduction

The detection of gravitational waves (GW) by the LIGO-Virgo collaboration [1] has opened a new era in the exploration of the early Universe. In particular, the detection of a stochastic gravitational wave background (SGWB) would provide unique information about the cosmological history of our Universe. Interpreting these signatures motivates exploring beyond the Standard Model (BSM) scenarios capable of generating stochastic gravitational waves and assessing the near- and far-future reach of GW interferometers,[1] in comparison with other probes of new physics such as present and future colliders.

The absence (thus far) of new physics at the LHC and in dark matter experiments suggests the existence of a mass gap between BSM particles and the electroweak scale. This challenges many scenarios of BSM physics, including minimal realizations of low energy supersymmetry breaking (LESB). However, compelling theoretical motivations for the existence of supersymmetry (SUSY) such as gauge coupling unification, WIMP dark matter, mininimal flavor violation, and a possible string theory embedding suggest that the per-mille fine tuning of the electroweak scale may be a reasonable price to pay from the top-down perspective [4–6]. In this letter we highlight the role of SBGW signatures in probing SUSY theories with superpartners beyond the reach of current LHC exclusions.

A first order phase transition associated with the breaking of a global or gauge symmetry in the early universe is among the extreme events capable of producing a SGWB. As we will see, LESB is a natural candidate for such a phase transition because at least one pseudo-flat complex scalar direction generically exists in hidden sectors where SUSY is broken. The phase of this complex scalar direction is associated to the R-symmetry, which is in turn tied to the SUSY-breaking dynamics by many known theorems about SUSY quantum field theories [7–9]. This complex scalar direction is lifted by quantum corrections and the resulting potential is likely to possess a metastable minimum at the origin (where R-symmetry is preserved), which will then decay to the true minimum through a first order phase transition in the early Universe. At the true minimum the R-symmetry is broken, consistent with a realistic SUSY spectrum featuring Majorana gaugino masses. In this framework, the SUSY-breaking scale in the hidden sector correlates directly with the frequency range of the SGWB and indirectly to the soft spectrum (once a mediation mechanism is specified) allowing the possibility of cross-correlating GW and collider signals.

Our first study will explore novel mechanisms for generating large GW signals from first order phase transitions in calculable SUSY-breaking hidden sectors [10]. Such SUSY-breaking phase transitions possess distinctive features which distinguish them from their non-SUSY counterparts. These features ultimately stem from the fact that the vacuum energy is small compared to the typical mass scales in SUSY hidden sectors, due to SUSY cancellations. The same cancellations ensure that the SUSY-breaking operators destabilizing the vacuum at the origin are irrelevant at large field values where the potential automatically flattens out.

[1]Note that the LIGO-Virgo collaboration already places direct constraints on SGWB [2, 3] beyond existing indirect limits.

In general, the scalar potential along the pseudo-flat direction associated with SUSY breaking will have a metastable vacuum at the origin and another one far away in field space.[2] Phase transitions between these vacua possess the following qualitative features:

- *Vacuum energy and GW frequency range:* The vacuum energy is controlled by the SUSY-breaking scale $\sqrt{F}$ so that the typical nucleation temperature is $T_n \sim \sqrt{F}$.

- *Low temperature vs. high temperature expansion:* The scale of the hidden sector states is $m_*^2 \pm \lambda F$, generically much higher than T_n. For this reason, the low temperature expansion typically gives a good description of these transitions, as opposed to most non-SUSY theories where the high temperature expansion is always assumed as a good description for sufficiently strong phase transitions.

- *Relation between GW frequency and soft spectrum:* The peak frequency of the SGWB signal is controlled by $\sqrt{F}$ while the superpartner masses scale as $m_{\rm soft} \sim (g/g_*)^{n+1}\lambda F/m_*$ where n distinguishes different mediation schemes (e.g. $n = 1$ corresponds to the standard gauge mediation scheme [12]), g_* is the typical size of the coupling in the hidden sector ($g_* = 4\pi/N_{\rm mess}$), and g is a Standard Model coupling. Setting $m_{\rm soft} \gtrsim 10$ TeV implies [13]

$$f^{\rm GW}_{\rm peak} \sim 10^{-1}\ {\rm mHz} \left(\frac{\sqrt{F}}{\rm TeV}\right)\left(\frac{g_*}{g}\right)^{n+1} . \tag{1.1}$$

  This highlights the sense in which the absence of superpartners at the LHC leaves open the possibility of observing SGWB at high frequency interferometers. Moreover, for observable SGWB, perturbativity of the mediation scheme forces the superpartners to lie within the reach of future high-energy colliders. This provides a unique opportunity to test the origin of a high frequency SGWB signal.

There are a number of interesting directions in which the observations in Ref. [10] can be extended, with the ultimate goal of pinpointing the SUSY theories that generate detectable GW signals. These include

- classifying the possible SUSY-breaking phase transitions depending on how the metastable vacuum is generated. This would provide the SUSY analog of the classifications already performed for the Higgs potential [14].

- extending the study of phase transitions to SUSY theories with multiple flat directions [15].

- exploring SUSY scenarios featuring phase transitions with supercooling which would drastically modify the relation between GW frequency and superpartner masses.

- studying the dynamics of the R-strings and domain walls associated to the SUSY R-symmetry. The dynamics of these extended object could be substantially different from their non supersymmetric counterparts.

[2] Notice that latter vacuum would preserve SUSY unless new soft terms are added along the lines of stimulated SUSY-breaking [11].

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