Gravitational phase transitions with Cosmic Explorer

SUMMARY

General relativity (GR) has stood the test of time. Nevertheless, it is undoubtedly incomplete; for example, it predicts its own unpredictability when it comes to black holes (BHs) because of the singularity theorems. Although unlikely to neutralize the singularity problem, scalar-tensor theories (STTs) provide a natural arena to study extensions of GR. In some STTs, there exists two branches of neutron stars – ones with zero scalar 'hair' coinciding with GR, and scalarized ones. As we validated with numerical simulations, a star can jump between the two branches, realizing a phenomenon dubbed a "gravitational phase transition" (GPT). These events would release copious scalar radiation as the star sheds its hair, producing a signal that is detectable with next-generation (XG) detectors, notably the Cosmic Explorer (CE), out to $\lesssim$Mpc. The predicted number of detections scales strongly with the observability horizon.

Key question(s) and scientific context in brief

In some STTs, representing well-motivated 'low-energy' limits of certain string theories (Brans 2005), neutron stars *scalarize*. In general, there then exists two disconnected but stable branches of stars in these theories, namely those with zero scalar field and scalarized ones. If a star could *transition* between the two branches however, producing an event that bears close similarities with first-order matter phase transitions, a burst of scalar radiation would be released as the star promptly balds (Kuan et al. 2022). Interestingly, this phenomenon reaches beyond classical STTs and is not unique to neutron stars. For example, a similar phenomenon is present also for BHs in the quantum-gravity motivated Gauss-Bonnet theory (Doneva and Yazadjiev 2022).

In both material and gravitational PT, the star reaches a critical energy density and rapidly transitions toward a new state (see, e.g., Schaffner-Bielich et al. 2002). The key difference, however, is that with a GPT one expects a burst of scalar radiation, thereby providing an avenue to differentiate these two types of events via GWs. For BHs as well a clear imprint in the observed GW signal during a merger may be visible (Doneva, Vañó-Viñuales, and Yazadjiev 2022). In theories where the scalar field is endowed with mass[1], radiation propagates dispersively (higher frequency waves travel faster), and thus the signal behaves more like that of a continuous-wave source. The question we asked in Kuan et al. 2022 is: can XG detectors measure GPT events? This is important to answer because a detection would provide a smoking gun for the modification of GR at high energies.

Potential scientific impact of XG detectors on the key questions

How might such a GPT be realised in Nature? One possibility is through accretion, either of fallback material in the case of a newborn object or from a companion star. Kuan et al. 2022 investigated this phenomenon numerically by injecting matter into a *scalarized* neutron star of near-critical density and dynamically tracking the transition to a non-scalarized state. A pulse of scalar gravitational radiation follows the GPT, the amplitude of which would be very challenging for current detectors even for Galactic sources ($\lesssim$10kpc). However, XG detectors should be powerful enough to capture even extragalactic events! This is summarised in Figure 1.

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[1] Massless STTs are practically ruled out by binary pulsar experiments (Zhao et al. 2022). Massive theories avoid these constraints because scalar effects are exponentially suppressed outside of the relevant Compton length-scale. A mass as light as $\gtrsim 10^{-16}$ eV already ensures that scalar dynamics are negligible on orbits with periapses $\lesssim 10^{10}$ m, thus circumventing binary pulsar constraints. Interestingly, the scalarized stars for such small masses are virtually indistinguishable from those obtained in the massless STTs.

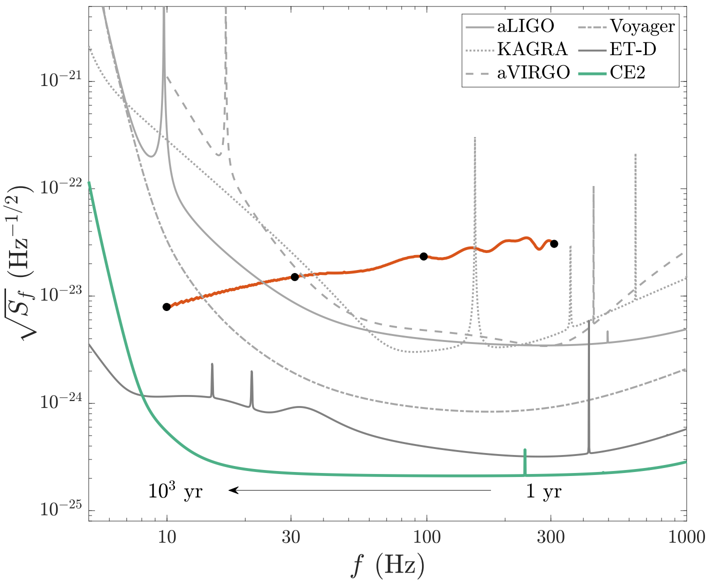

Figure 1: The effective strain (solid red curve) for a GPT at 10 kpc, associated with a particular theory and NS equation of state, assuming a phase-coherent search period of 2 months. The black dots represent the signal predicted at $10^{0,1,2,3}$ years after the outburst. The green curve shows the CE noise curve – well below the anticipated signal. (Figure reproduced from Kuan et al. 2022, where more details can be found).

Benchmarks for XG detectors to enable the scientific impact

The proposed sensitivity curve for CE would be sufficient to detect GPTs for reasonable STT parameters (permitted within current experimental bounds) to ∼ Mpc distances, as shown in Fig. 1. Benchmark points are:

- We predict that the signal is strongest in the ∼ 10 to ∼ 300 Hz band: sensitivity here is critical.
- The signal is dispersively stretched because of the scalar field mass, implying it may be visible for some ∼ years via a phase-coherent strategy; narrow-band searches are important.
- Prime targets for GPTs are over-accretion events, thus continual monitoring of recent type II supernovae, merger remnants, and extremely massive neutron stars in active binaries (e.g., black widows) is imperative.

SCIENTIFIC IMPACT OF XG DETECTORS

Key impacts: probing modified gravity (GPTs are ‘smoking guns’ for non-GR physics) and effects found when dense matter and strong gravitational fields coexist (e.g., material vs gravitational transitions).

Dependencies on other multi-messenger capabilities

Acretion flows onto neutron star remnants from binary mergers show a wealth of multi-wavelength emissions. After a GPT, the star is expected to compactify on a dynamical ($\gtrsim$ ms) timescale, influencing the electromagnetic outputs that depend on its mass-radius relationship. As described in Kuan et al. 2022, gamma-ray burst X-ray afterglows are a key target. One event, GRB 170714A, is already a promising candidate for a GPT.

XG DETECTOR AND NETWORK REQUIREMENTS

If the sensitivty curve of CE outlined in Figure 1 can be realised, powerful constraints on modified theories of gravity can be made; or, perhaps, smoking guns will be found!

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