Snowmass2021 - Letter of Interest

Searching for Scalar Gravitational Waves in Neutron Star Binary Mergers

Thematic Areas:

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF01) String theory, quantum gravity, black holes

Contact Information:
Emil Mottola (Los Alamos National Laboratory & Perimeter Institute)[emil@lanl.gov]

Authors: Emil Mottola

Abstract: Any solution to the multiple fine tuning and hierarchy problems confronting the Standard Model of both High Energy physics and Cosmology must relate very disparate length scales. This is a natural feature of *conformal* theories, *i.e.* theories with no intrinsic length scale. Since conformal invariance is broken by the conformal anomaly, it plays a central role in any low energy theory based on these ideas. The effective action of the conformal anomaly implies the existence of a propagating long range effective scalar field with the striking prediction of *Scalar Gravitational Waves* that can be searched for in Neutron Star (NS) mergers with present and new GW detectors coming online in this decade.

With the first detection of GWs by LIGO in 2015, and the joint GW detection of the binary Neutron Star (NS) merger GW170817 in tandem with its EM counterparts, a new window on the Universe has been opened, and the era of GW multi-messenger astronomy and astrophysics has begun. The GW detection rate is expected to increase significantly with the current advanced LIGO upgrade, and already several more GW merger events have been observed by aLIGO. With the increased sensitivity and additional detectors coming online in this decade, the number and quality of GW detections is poised to increase further, with some of these events likely associated with EM and possibly neutrino signals. These multi-messenger observations present an unprecedented discovery potential for the fundamental physics governing both NSs and Black Holes (BHs), by directly probing the strong gravitational fields of nuclear matter in compact objects under extreme non-equilibrium conditions, that are difficult if not impossible to produce in terrestrial experiments.

A first principles Effective Field Theory (EFT) approach to including quantum effects in gravity has been developed, based on the conformal or trace anomaly of the energy-momentum tensor of massless quantum fields,[1,2] the one-loop local effective action corresponding to it, and the long range massless scalar degree of freedom this effective action implies.[3–7] This leads to a well-defined modification of classical GR, fully consistent with, and in fact *required* by quantum theory, the Standard Model (SM), and the Equivalence Principle, without any additional assumptions.

The conformal anomaly action[3,4,7] contains a new local massless scalar scalar of the EFT not present in classical GR, called a *conformalon* φ,

$$S_{\mathcal{A}}[\varphi] = \frac{b'}{2}\int d^4x\sqrt{-g}\left\{-\left(\Box\varphi\right)^2 + 2\left(R^{\alpha\beta}-\tfrac{1}{3}Rg^{\alpha\beta}\right)(\partial_\alpha\varphi)\,(\partial_\beta\varphi)\right\} + \frac{1}{2}\int d^4x\,\mathcal{A}\,\varphi \qquad (1)$$

where

$$\frac{\mathcal{A}}{\sqrt{-g}} = b\,C^2 + b'\left(E - \tfrac{2}{3}\Box R\right) + \sum_i \beta_i\,\mathcal{L}_i \qquad (2)$$

$E, C^2, \Box R$ in curved space, as well as matter invariants such as the gluonic contribution $\mathcal{L}_G = \mathrm{tr}\,\{G_{\alpha\beta}G^{\alpha\beta}\}$ of the strong nuclear interactions of QCD in the SM. The coefficients b, b', β_i are pure numbers multiplied by $\hbar$, depending upon the QFT,[1,2] so the conformal anomaly is a quantum effect with *no intrinsic length scale*, and in particular does not involve the ultrashort Planck scale $L_{Pl} = \sqrt{\hbar G/c^3} \simeq 1.6 \times 10^{-33}$ cm. The conformalon φ is the Goldstone-like scalar of conformal symmetry breaking, and an additional propagating massless scalar degree of freedom in the low energy EFT of gravity, not present in classical GR, that is induced by the quantum fluctuations of SM matter/radiation. When added to the usual Einstein-Hilbert term of classical GR, $S_{\mathcal{A}}$ amounts to a well-defined modification of Einstein's classical theory fully consistent with, and in fact *required* by first principles of QFT and general covariance, with no additional assumptions.[8]

Being massless, the Goldstone-like boson φ has an *a priori* infinite range and thus can affect even *macroscopic* phenomena in an otherwise classical Universe. Since the stress-energy tensor derived from (1) is the source of the gravitational metric field through Einstein's equations, the macroscopic effects of the conformal anomaly are transferred to the gravitational field. Qualitatively new phenomena are then predicted.[3–6,9] In particular, the coupling to the gluonic density of QCD, a striking prediction of the EFT including (1) is that collapsing or coalescing NS sources will radiate *Scalar Gravitational Waves* (SGWs) in amounts comparable to the transverse polarizations and thus be potentially detectable by the improved sensitivity GW detectors now coming online. This is a spin-0 'breather' polarization mode not present in Einstein's classical GR.

The amplitude of the SGW a distance r from its source has been computed,[7]

$$h_0(\mathbf{r},\omega) = -\frac{G}{3rc^4}\,e^{-i\omega(t-r)}\int d^3\mathbf{x}\,\exp(-i\,\omega\,\hat{\mathbf{r}}\cdot\mathbf{x})\,\mathcal{A}_\omega(\mathbf{x}) \simeq 0.5\times 10^{-21}\left(\frac{Mpc}{r}\right) \qquad (3)$$

in terms of the Fourier component $\mathcal{A}_\omega$ at frequency ω of the anomaly source $\mathcal{A}$. The preliminary estimate of (3) for the SGW amplitude comes from existing simulations and estimates of the QCD anomaly in the cores of

NSs, for a binary NS merger events where this core is excited to temperatures comparable to the QCD phase transition temperature (approximately 160 to 170 MeV, known from lattice simulations).[10] Determining the precise amplitude and waveforms requires knowing the EoS of nuclear matter through its temperature and density just after a merger event, and the excitation of the QCD condensate. For GW170817 at a distance of 40 Mpc, the amplitude estimate of (3) places the predicted SGW signal at 100 Hz at just about at the limit of detectability of aLIGO, had it been operating at its design sensitivity in 2017. As sensitivities improve, a significant SGW signal could be detected by aLIGO/VIRGO in future binary NS merger events, but likely requiring a dedicated data search, in tandem with more accurate NS modeling.

Antenna response to different GW polarizations depends upon the direction of the source with respect to the orientation of the arms of the GW detectors. The maximum sensitivity to the scalar breather mode polarization is attained if the direction is along one of the interferometer arms, as illustrated in Fig. 1 below. In general there is a geometric projection factor. LIGO's analysis found that the data so far favors a tensor-only model over vector-only and scalar-only models.[11] However, a search analysis incorporating *all three* tensor, and scalar modes as sum of terms within the same signal has not yet been attempted. Disentangling a scalar breather mode polarization h_0 from the two transverse polarizations h_+ and $h_\times$ requires a Bayesian statistical analysis depending upon astrophysical parameters such as masses, spins, and tidal deformability (the latter being particularly sensitive to the NS EoS). With three or more detectors in operation simultaneously and directional information from detection of possible concurrent γ-ray burst or kilonova events, such as provided by that associated with GW170817, it will be possible to disambiguate the three polarization components: Fig. 1.

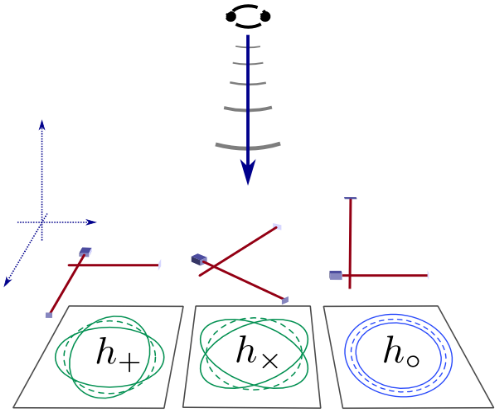

Figure 1: Two tensor polarization modes, h_+ and $h_\times$, and the scalar mode h_0. The optimal orientation of the GW detector arms for each mode is illustrated, for the case when the GW is propagating directly from above.

As a preliminary step, using existing solutions of the interior density profiles of NSs, one can solve the linear for $\varphi(r)$ resulting from $S_{\mathcal{A}}[\varphi]$ in the simplest case of a spherically symmetric static NS and evaluate its stress-energy tensor also derived from $S_{\mathcal{A}}[\varphi]$, making use of the nuclear EoS tables available online: DD2, SFHo and LS220.[12] If substantial, particularly in the central regions where QCD plays an increasingly important role, one should re-solve the full coupled GR + φ Tolman-Oppenheimer-Volkoff system for cold NSs, and find its effect on the NS Mass-Radius relation. These results can be compared to the NICER observational data,[13] to constrain the initial NS configuration and modify the equilibrium EoS tables, if necessary, prior to the merger event. Thus a by-product here may be an improved nuclear EoS for NSs.

Since details of nuclear or QCD EoS at the conditions encountered in the core of NSs, up to $7-10$ times normal nuclear densities, are currently not very well constrained, with different models giving varying predictions, the SGW analysis can be turned around so that detection or non-detection of SGWs will provide information and constraints on the nuclear/QCD EoS, as well as testing the anomaly EFT (1). This will allow us to determine what a LIGO non-detection of SGW component in GW170817 implies for the NS EoS.

In the early Universe at temperatures exceeding the QCD phase transition $T \sim 170$ MeV, the gluonic anomaly was fully unsuppressed. Thus these epochs in the early Universe are possible sources of a cosmological stochastic background of SGWs, albeit in lower frequency ranges, potentially detectable by the next generation of space-based GW detectors, such as LISA. The quantitative effect of primordial SGWs on the CMB polarization of E and B modes can be calculated by standard algorithms, such as CMBFAST, and compared to CMB polarization data the next generation of high precision CMB experiments, CMB-S4.

References

[1] M. Duff, Nucl. Phys. B **125**, 334 (1977).

[2] N. D. Birrell, N. D. Birrell, and P. Davies, *Quantum fields in curved space* (Cambridge Univ. Press, 1984).

[3] E. Mottola and R. Vaulin, Phys. Rev. D **74**, 064004 (2006).

[4] M. Giannotti and E. Mottola, Phys. Rev. D **79**, 045014 (2009).

[5] E. Mottola, Acta Phys. Pol. B **41**, 2031 (2010), `https://www.actaphys.uj.edu.pl/R/41/9/2031/pdf`.

[6] E. Mottola, arXiv:1103.1613 (2011), published in *Proc. XLV Rencontres de Moriond, 2010 Cosmology*, E. Auge, J. Dumarchez, J. Tran Tranh Van, eds. (Vietnam, Gioi).

[7] E. Mottola, Jour. High Ener. Phys. **2017**, 43 (2017).

[8] P. O. Mazur and E. Mottola, Phys. Rev. D **64**, 104022 (2001).

[9] E. Mottola, Jour. Phys. Conf. Ser. **314**, 012010 (2011).

[10] L. Baiotti and L. Rezzolla, Rep. Prog. Phys. **80**, 096901 (2017).

[11] B. P. Abbott and *al.*, Astrophys. Jour. **848**, L12 (2017).

[12] J. M. Lattimer and F. D. Swesty, Nucl. Phys. A **535**, 331 (1991), websites with various EoS compilations for astrophysical applications: http://www.astro.sunysb.edu/dswesty/lseos.html, https://stellarcollapse.org.

[13] G. Raaijmakers, T. E. Riley, A. L. Watts, S. K. Greif, S. M. Morsink, K. Hebeler, A. Schwenk, T. Hinderer, S. Nissanke, S. Guillot, Z. Arzoumanian, S. Bogdanov, D. Chakrabarty, K. C. Gendreau, W. C. G. Ho, J. M. Lattimer, R. M. Ludlam, and M. T. Wolff, Astrophys. Jour. **887**, L22 (2019).