Snowmass2021 - Letter of Interest

Peering inside Black Holes with Gravitational Waves

Thematic Areas:

■ (TF01) String theory, quantum gravity, black holes
☐ (TF2) Effective field theory techniques
☐ (TF3) CFT and formal QFT
☐ (TF4) Scattering amplitudes
☐ (TF5) Lattice gauge theory
☐ (TF6) Theory techniques for precision physics
☐ (TF7) Collider phenomenology
☐ (TF8) BSM model building
☐ (TF9) Astro-particle physics & cosmology
☐ (TF10) Quantum Information Science
☐ (TF11) Theory of neutrino physics
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics

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Abstract: In classical General Relativity (GR) the interiors of Black Holes (BHs) are not only singular but, if rotating, also admit closed timelike curves, violating causality.[1] This feature occurs at *macroscopic* distance scales, far larger than the microscopic Planck scale L_{Pl}. When quantum effects are considered, severe conflicts with statistical thermodynamics, conservation of probability and an enormous BH entropy arise also at the macroscopic horizon scale.[2,3] This suggests that a low energy semi-classical Effective Field Theory (EFT) approach should be applicable. In this LOI such an approach based the conformal anomaly is proposed, which leads to a non-singular horizonless, but ultra-compact object called a gravitational condensate star. The gravastar hypothesis can be tested by searching for *discrete* surface modes and GW *echoes* emitted after binary merger events. In this new era of GW and multi-messenger astronomy with additional GW detectors coming online in this decade, the time is now ripe for a full-fledged effort to confront these theoretical ideas with the observational data that hold the promise of resolving the conundrum that BHs pose, and potentially point to a new path to ultimate synthesis of gravitation and quantum theory.

The presumption that gravitational collapse of stars above a certain mass leads inevitably to an event horizon and a BH singularity is based upon an essentially classical view of the collapsing matter as a collection of uncorrelated pointlike particles, with pressure $p \geq 0$ and Equation of State (EoS) obeying classical energy conditions, neglecting quantum coherence. These assumptions remain widely held, despite the experimental evidence of the wavelike properties of matter, quantum violation of classical energy conditions and macroscopic quantum coherence in a wide variety of sufficiently cold, condensed systems, as well as the quantum degeneracy pressure responsible for highly compact stars such as White Dwarfs and Neutron Stars.

The fact that BHs and the problems they pose arise at *macroscopic* scales strongly suggests that there is a missing element in the low energy content of classical gravity. 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,[7,8] and the one-loop local effective action corresponding to it. This identifies the missing element in GR to be the long range massless scalar degree of freedom this effective action implies.[9–13] The conformal anomaly action[9,10,13] expressed in local form is

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

where $\mathcal{A}$ is the conformal trace anomaly, made up of curvature invariants as well as matter invariants such as the gluonic contribution of QCD in the SM.[7,8] The conformal anomaly is a quantum effect with *no intrinsic length scale*, and in particular does not involve the ultrashort Planck scale L_{Pl}. The new scalar field φ is the Goldstone-like boson 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, the Wess-Zumino action $S_{\mathcal{A}}$ 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.[14]

Since the stress-energy tensor $T^{\alpha\beta}_{\mathcal{A}}[\varphi]$ 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.[9–12,15] In particular, $T^{\alpha\beta}_{\mathcal{A}}[\varphi]$ can *dominate* the classical terms in the vicinity of the apparent horizon of a forming BH. Indeed the linear eq. for φ resulting from variation of (1) may be solved in static spherical backgrounds that possess a time translation symmetry and Killing vector $K = \partial/\partial t$, with scalar invariant norm $K^\alpha K_\alpha = g_{tt} = -f(r)$. The result is that

$$\varphi(r) = c_{_H}\ln\left(-K^\alpha K_\alpha\right) + \dots = c_{_H}\ln\left[f(r)\right] + \dots \tag{2}$$

generically *diverges* as $f(r) \to 0$, where $c_{_H}$ is a dimensionless state-dependent integration constant.[9,11] The condition $f(r) = -K^\alpha K_\alpha = 0$ of the Killing vector becoming null is the condition for the location of the Schwarzschild BH horizon at $r = r_S = 2GM$. Because of the logarithmically divergent behavior (2) at the horizon the stress tensor derived from (1) also generically grows *arbitrarily large* $\propto c^2_{_H}/f^2$ as r approaches the horizon, in *any state* for which $c_{_H} \neq 0$.[9,11] This shows that it is possible for coherent quantum effects to become large enough to affect the classical geometry of BHs *no matter how small the local curvature* is. That quantum effects arise at BH horizons is supported by a variety of other considerations, arising from QFT, string theory, AdS/CFT, gauge/gravity duality, supergravity, and loop quantum gravity[4,19–23]. Thus $T^{\alpha\beta}_{\mathcal{A}}$ affects the classical geometry and also causes a *change in the vacuum energy* in the interior, so that the final endpoint of collapse may not be that of a classical BH at all, but a *gravitational condensate star*, free of singularities and all BH paradoxes.[6,15–17]. By taking a positive value in the interior of a fully collapsed star, the effective cosmological term with $p = -\rho$ EoS removes any singularity, replacing it with a smooth dark energy de Sitter interior. The quantum boundary layer where the effective value of the gravitational vacuum energy changes rapidly is determined by the anomaly stress tensor, and gives rise to a finite surface tension.[18]

With a definite EFT Lagrangian this LOI is to find the self-consistent spherically symmetric condensate star solution and derive its linear perturbations and normal modes of free oscillation.[24]. With no BH singularity to which perturbations can be lost, the spectrum is expected to be *real*, and *discrete*, classified by its angular momentum eigenvalue. The discrete frequency spectrum of normal modes of the surface oscillations will provide a clear basis for distinguishing gravitational condensate stars from BH ringdown modes in GW signatures. Predicting these characteristic frequencies of the surface prior to possible detection in present and planned GW antennas, such as aLIGO II will be a clean and powerful test of the theory.

Another striking observational signature of a non-singular horizonless ‘BH’ are ‘echoes’ after a merger event.[25] a characteristic time[25–27] $\Delta t \simeq r_S \ln(1/\epsilon)$ after the coalescence and main burst of GWs. The echo signal delay isthe result of (possibly multiple) reflection(s) from the interior centrifugal barrier: Fig. 1.

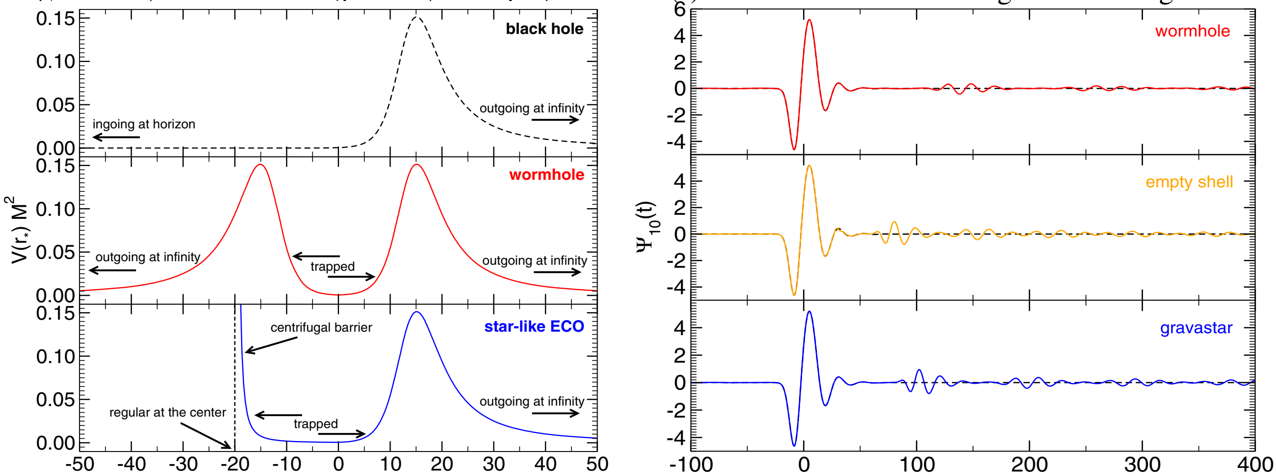

Figure 1: LeftPanel: Effective potentials experienced by GW perturbations for a Schwarzschild BH, wormhole, and star-like Extreme Compact Object (ECO) such as a gravastar respectively, showing the inner centrifugal barrier in the last two cases. Right Panel: The characteristic GW echoes produced in the latter ECO cases, emerging characteristic times $\Delta t, 2\Delta t, \dots$ later after multiple refelections from the centrigugal barrier.[26]

Since Δt is logarithmic in ϵ, an echo signal should emerge within 90 to $100\, r_S$ or a few to tens of msec after the coalescence and formation of a gravastar. The form of the reflecting barrier in the non-rotating condensate star final state is completely determined by the interior de Sitter geometry. With the surface layer also determined we can compute both the time delay and amplitude of the GW echo signal, allowing also for a general frequency dependent scattering loss and attenuation due to non-linear SM interactions at the surface. This will provide a detailed signature template for GW detectors and GW data analysis.

Any detection of an echo signal would be clear observational evidence of a non-singular interior to a ‘BH’ and physics beyond Einstein’s GR in fully collapsed stars. The startling possibility thus presents itself of testing quantum effects in gravitational physics, peering into the interior of BH-like objects for the first time. Even more strikingly, if EM waves are produced in the collision and coalescence event, they will also be trapped by the same gravitational potential, and also emerge after the same characteristic echo delay time, in sharp contrast to the behavior expected of a BH. Either or both of these multi-messenger signals would be smoking guns for new physics at and beyond the ‘BH’ horizon, and confirmation of the effective theory.

An in-depth analysis of the gravitational condensate star alternative to BHs is particularly timely now, as the possibility of gravitational echo signals being emitted from a ‘BH’ merger is being actively considered, and claims of their detection have been made,[27],while a subsequent analysis found just a 1.5 σ significance for the echo signal[28]. This situation is poised to change with more GW data. The limitations of low S/N should be gradually ameliorated by improved sensitivity of an expanded GW detector network, multiple detections, making stacked analysis with improved statistics possible, and the potential for EM counterpart observations. In order to take full advantage of these improved observations, they must be matched by more accurate predictive theory based on the well-motivated EFT of (1). Any positive detection of a GW echo signal would *revolutionize* BH physics and reverberate to the foundations of GR *vis-á-vis* quantum theory.

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