Instabilities of Scalar Fields around Oscillating Stars

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The behavior of fundamental fields in strong gravity or nontrivial environments is important for our understanding of nature. This problem has interesting applications in the context of dark matter, of dark energy physics, or of quantum field theory. The dynamics of fundamental fields has been studied mainly in static or stationary backgrounds, whereas most of our Universe is dynamic. In this Letter we investigate "blueshift" and parametric instabilities of scalar fields in dynamical backgrounds, which can be triggered (for instance) by oscillating stars in scalar-tensor theories of gravity. We discuss possible implications of our results, which include constraints on an otherwise hard-to-access parameter space of scalar-tensor theories.

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Introduction.—General relativity (GR) is currently the best description of the gravitational interaction, and has been successfully tested on different scales [1]. The recent direct detection of gravitational waves (GWs) [2–4] indicates that even dynamical, strong-field regions are adequately described by GR (up to the precision probed by current detectors). In spite of its brilliant status, there are a number of conceptual issues with GR, ranging from the large-scale description of the cosmos to the fate of classical singularities in gravitational collapse or the incorporation of quantum effects; see, e.g., Refs. [5–7] and references therein. The resolution of some of these challenges most likely requires that GR be superseded by a more sophisticated description.

There is currently no single compelling alternative to GR that solves the above issues without introducing new problems of their own. However, a variety of modified theories have been proposed, mostly with the view to exploring the mathematical and physics content of possible contenders to GR. These frequently include additional degrees of freedom, which might lead to unique observational signatures. The simplest modifications of GR are scalar-tensor theories, where a new scalar degree of freedom couples to curvature or matter. Some of these theories arise naturally as possible alternatives, since they have a well-posed initial value problem and simultaneously evade all known constraints. Scalars are also a generic prediction of string theory or of extensions of the standard model of particle physics, and are also natural candidates for dark energy and dark matter [5–9].

Depending on the coupling to matter, to curvature and on the self-interactions, such theories and new fundamental fields may give rise to a wide array of new effects, such as the spontaneous "scalarization" of objects [10–17], screening mechanisms on astrophysical scales [18–20], etc. Potential astrophysical consequences of these theories were mostly based on analysis in stationary settings [10–14,18,19,21,22]. Time-dependent setups include spontaneous scalarization during the inspiral and merger of neutron stars [23–27], black holes [28,29], cosmological evolutions [30,31], or situations aimed at understanding well posedness or other fundamental issues [32–34].

Here, we wish to understand possible new phenomena induced by time-periodic motion, in particular by vibrating stars such as the ones summarized in Table I. Theories for which a constant scalar is a ground state typically have the same stationary solutions as GR, making it challenging to tell the two apart. However, when such stars are disturbed (stochastically, like our Sun, or via mergers or accretion for a neutron star), they provide a time-periodic background on which a scalar fluctuation propagates. Indeed, we show that oscillating stars trigger various instabilities of fundamental fields. Such instabilities may facilitate constraints on otherwise hard-to-access parameter space of the theory.

A toy model had been studied in a Minkowski spacetime [41,42]. Our results confirm and extend the general picture, but in a nontrivial way, by dealing also with general relativistic backgrounds and fluctuations and providing realistic timescales for the mechanism (details on the general relativistic case are discussed in the Supplemental Material [43]).

We use geometrized units $c = G = 1$ and parametrize stars by their mass M, radius L_0, and compactness

$$\mathcal{C} \equiv \frac{2M}{L_0}. \tag{1}$$

TABLE I. List of some stellar objects which can be prone to the processes described here. We take the radial mode of a neutron star (NS) of mass 1.3 $M_\odot$ and radius $L_0 = 9.7$ km described by equation of state A in Ref. [35]. For white dwarfs (WD) we take a degeneracy parameter $1/y_0^2 = 0.05$ as quoted in Refs. [36–38]. The Sun's description was taken from Refs. [39,40]. The compactness $\mathcal{C}$ is defined in Eq. (1).

	$\mathcal{C}$	L_0 (km)	$\omega L_0/c$	Radial frequency
NS	0.3	10	0.6	3 kHz
WD	10^{-3}	10^3	0.004	0.2 Hz
Sun	10^{-6}	7×10^5	0.029	2 mHz

Setup.—Our main purpose is to show that oscillating backgrounds can trigger instabilities of fundamental fields nonminimally coupled to matter. We will show this explicitly for the simplest example of a scalar-tensor theory, but our results are valid for more general setups.

We focus on theories in which a scalar field Φ is coupled to matter, described by the Lagrangian density

$$\mathcal{L} = \frac{R[g]}{16\pi} - \frac{1}{2} g^{\mu\nu}\nabla_\mu\Phi\nabla_\nu\Phi - V(\Phi) + \mathcal{L}_m[\Psi_m, \tilde{g}], \quad (2)$$

where $\tilde{g}_{\mu\nu} = A(\Phi)^2 g_{\mu\nu}$ is the physical metric and $\mathcal{L}_m$ the Lagrangian describing matter fields Ψ_m (these could be the microscopic, fundamental description leading to notions of density and pressure, for example). The equations of motion for the system are

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi T_{\mu\nu}, \quad (3a)$$

$$T_{\mu\nu} = \nabla_\mu\Phi\nabla_\nu\Phi - g_{\mu\nu}\left(\frac{1}{2}(\nabla\Phi)^2 + V(\Phi)\right) + T^{(m)}_{\mu\nu},$$

$$\Box\Phi - V'(\Phi) = -A(\Phi)^3\partial_\Phi A(\Phi)\tilde{T}^{(m)}. \quad (3b)$$

Here, $\tilde{T}^{(m)} = \tilde{g}^{\mu\nu}\tilde{T}^{(m)}_{\mu\nu}$ while $T^{(m)}_{\mu\nu}$ and $\tilde{T}^{(m)}_{\mu\nu}$ are the energy-momentum tensors of the matter fields with respect to metric $g_{\mu\nu}$ and $\tilde{g}_{\mu\nu}$.

The phenomena we wish to describe are also part of more generic theories: the fundamental ingredient is a position-dependent effective mass function for the scalar Φ. Once linearized around a specific background, the right-hand side of Eq. (3b) is proportional to $\tilde{T}^{(m)}\Phi$. In other words, the coupling of the scalar to matter gives rise to an effective scalar mass which depends on the matter content $\tilde{T}^{(m)}\Phi$. This is one key ingredient of our study. Thus, direct couplings to curvature would also produce similar effects [15–17,48].

For concreteness, we focus exclusively on the following scalar potential and coupling function:

$$V(\Phi) = \frac{\mu_0^2}{2}\Phi^2, \qquad A(\Phi) = e^{\frac{\beta}{2}\Phi^2}, \quad (4)$$

but our results and methods can be applied to other models. Scalar self-interactions can play an important role in the *nonlinear* development of the instability; here we focus exclusively on the physics at small Φ. Hence, our results describe the early-time dynamics of more general self-interacting theories. Here, μ_0 is the (bare) mass parameter of the scalar field (note that the mass m_s of the field is related to the mass parameter via $m_s = \mu_0\hbar$ in these units). With this choice of scalar potential and coupling function, a vanishing scalar field is a solution to the theory and fluctuations around this solution endow the scalar with an effective, time and position-dependent mass. Our analysis can also be generalized to theories with nontrivial, stable scalar profiles, including popular examples such as spontaneous scalarization [10–12,15–17,49] and screening mechanisms [18–20,50,51].

Let us consider matter fields Ψ_m describing a perfect fluid. Focus on a geometry with vanishing scalar, $\Phi = 0$, describing a static star of (constant, for simplicity) density $\tilde{\rho}_0$ and radius L_0 [52]. The total mass of this solution can be written as $M = (4\pi/3)\tilde{\rho}_0 L_0^3$.

We ignore the effect of the scalar field on the profile of the fluid. In other words, we deal only with the Klein-Gordon equation (3b) on this fixed geometry. Perturbing around a background solution $\Phi_0(r)$, one finds that the stability of such solutions depend dramatically on the value of the coupling β [10–13]. For concreteness, here we take $\beta < 0$ with $\mu_0^2 - \beta\tilde{T}^{(m)} \gg -L_0^{-2}$ and such that $\Phi_0 = 0$ is a stable solution. The assumption of zero background scalar is a conservative assumption, made to highlight the nontrivial effects of the mechanism we discuss below, which provides a unique tool to constrain the theory. When the background scalar is not zero other effects become important. For example, an oscillating body with a nontrivial background scalar will radiate monopolar radiation, a topic explored in the past [33,53,54].

Instabilities of oscillating astrophysical objects.—Let us then consider the dynamical behavior of a (nonminimally coupled) scalar field in a geometry describing a radially oscillating star. For simplicity, the results shown below assume a Minkowski background and are thus valid only for Newtonian stars. General relativity effects change the quantitative but not the qualitative behavior, and are discussed in the Supplemental Material [43], including an analysis of general-relativistic fluctuations of compact stars [35,55,56]. Fluctuations around a background value of the scalar field are described by the Klein-Gordon equation

$$\Box\Phi = \mu^2\Phi, \quad (5)$$

with an effective mass

$$\mu^2 = \mu_0^2 - \beta\tilde{T}^{(m)},$$

which acts as a position-dependent mass term that depends on the energy density of the star. If the star oscillates [with a time-dependent radius $L(t)$], so does the effective mass of the scalar field. For simplicity we here assume the simple model

$$L(t) = L_0 + \delta L \sin \omega t, \tag{6}$$

$$\mu^2(t,r) = \mu_0^2 + \beta[\tilde{\rho}_0 + \delta\tilde{\rho}(t,r)\sin(\omega t)], \tag{7}$$

where $\delta\tilde{\rho}(t,r)$ is the amplitude of the density oscillation, and $\tilde{\rho}_0$ is the average of the energy density. We assume $\beta < 0$, in such a way that $\mu_0^2 + \beta\tilde{\rho}_0 \gtrsim 0$ to avoid tachyonic instabilities. The competition between different mechanisms is discussed in detail below and in the Supplemental Material [43].

Here, we assumed $\delta L \ll L_0$ and $\delta\tilde{\rho} \ll \tilde{\rho}_0$. This dependency has two important aspects: (i) Because the effective mass inside the star is smaller than the exterior bare mass μ_0, cf. Eq. (7), long wavelength modes are trapped inside the star. The oscillating star surface therefore provides reflecting boundary conditions at the periodically varying location $L(t)$. For setups where there is a continuous mass profile, a radially oscillating star corresponds, nevertheless, to periodically varying field profiles at the surface, possibly changing on scales smaller than a wavelength. (ii) The local density oscillations cause a time-varying effective mass for the scalar, which lends itself to parametric instabilities as we show below.

In astrophysically realistic stars, the time dependence of the radius and density of the star is quite involved. Normal modes of oscillation of a star will cause a density profile with a sinusoidal-like radial profile as well. We studied other profiles for the perturbation (in particular $\delta\tilde{\rho} \propto \sin \omega r$) and fully general-relativistic settings and find that they lead to similar results as described below and in the Supplemental Material [43].

We decompose the scalar field into spherical harmonics and evolve each mode, $\Phi_{lm}(t,r)$, using a fourth-order accurate Runge-Kutta scheme for the time integration where spatial derivatives are approximated by fourth-order accurate finite difference stencils. Radiative boundary conditions are imposed at the boundary of the computational domain, which is not in causal contact with the star during our numerical evolutions.

We use time-symmetric initial data with a profile parametrized by

$$\Phi_{lm} = e^{-(\frac{r-r_0}{\sigma})^2}, \qquad \dot{\Phi}_{lm} = 0, \tag{8}$$

where σ and r_0 denoting the width and initial position of the scalar field pulse. Since the equation to be solved is linear we set the initial amplitude of the pulse to unity. We focus our discussion on $l = 0$ modes and we fix $r_0 = 0.5L_0$ and $\delta L = 0.1L_0$. We studied higher-l modes, and found no qualitative difference. The results discussed below all show fourth-order convergence.

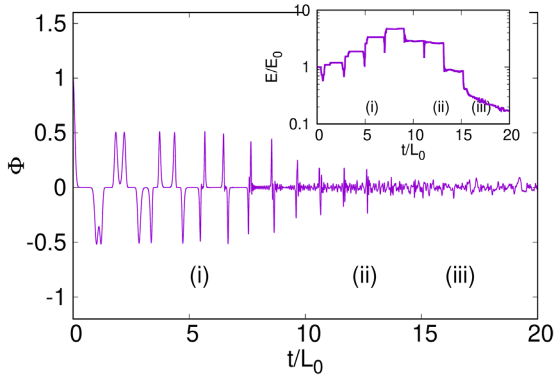

FIG. 1. Time evolution of a massive scalar field nonminimally coupled to geometry, such that it is effectively massless inside the star ($\mu_{\rm in} = 0$) but with bare mass $\mu_0 L_0 = 100$ and $\delta\tilde{\rho} = 0$. The field "sees" only an oscillating boundary with $\omega L_0 = 3.1$; we froze density variations inside the star. The field is extracted at $r = 0.5L_0$ and the corresponding integrated energy inside the star is shown in the inset. Here, the initial data is characterized by $\sigma = 0.1L_0$.

Results.—Consider setups where the effective mass inside [cf. Eq. (7)] the star satisfies $\mu_{\rm in}^2 < \mu_0^2$. Low-energy fluctuations of the scalar are trapped inside the star and subject to conditions at the surface which might be prone to *blueshift* instabilities—the growth of energy in the field can be understood from a simple particle picture as a cumulative Doppler effect [57], which is discussed in greater depth in the Supplemental Material [43]. Such an analysis indicates the dominant instability window to be [57],

$$\frac{\pi}{L_0 + \delta L} < \omega < \frac{\pi}{L_0 - \delta L}. \tag{9}$$

In such cases, we see a transfer of energy from the oscillating star to the scalar field, increasing the scalar frequency. We can see this behavior in Figs. 1–2. Upon each reflection at the surface the scalar drifts to higher frequencies, and after a sufficient amount of reflections it is no longer confined: the field is finally able to leak to outside the star (and has frequency $\omega \sim \mu(1+\epsilon)$, $\epsilon \ll 1$). This mechanism causes the energy to grow as $E \sim E_0 e^{\lambda_B t} = E_0 e^{2n_{\rm ref} L_0 \lambda_B}$, with $n_{\rm ref}$ the number of reflections and λ_B the instability growth rate. Here, $E_0 \sim \sigma^{-1}$ is the initial dominant spectral content at low energies, the ones that linger long enough to be amplified. Thus, the field is able to leak away from the star and out to spatial infinity when $e^{2n_{\rm ref} L_0 \lambda_B} \sigma^{-1} > \mu_0$. This occurs after a number of reflections

$$n_{\rm ref} > n_* \sim \frac{\ln|\mu_0 \sigma|}{2\lambda_B L_0}. \tag{10}$$

At the critical number of reflections, the total energy confined inside the star as scalar field is

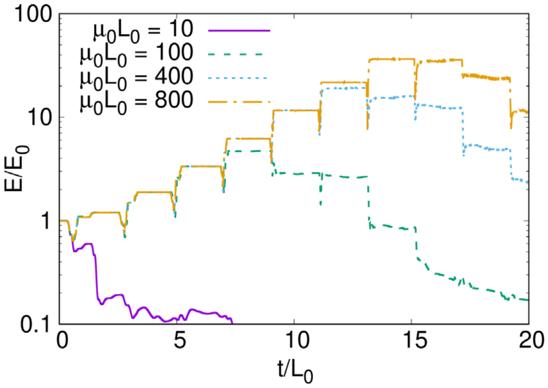

FIG. 2. Evolution of the integrated energy of a scalar inside an oscillating star, for different bare mass parameters μ_0. The coupling to matter is such that the field is massless inside the star ($\mu_{\rm in} = 0$). The field sees only an oscillating boundary with $\omega L_0 = 3.1$; we froze density variations inside the star. The initial data is characterized by $\sigma = 0.1 L_0$.

$$\frac{E}{E_0}\bigg|_{\rm max} = \sigma\mu_0, \qquad (11)$$

this being also the total amount of energy extracted from the star.

We have thus far focused only on the effect of oscillating boundaries, while the interior is nondynamical. However, real objects will also have an oscillating density. Thus, the effective mass inside the star will have a periodic time variability, potentially giving rise to "parametric" instabilities [58–61]. Figure 3 summarizes our results for nonvanishing $\beta\delta\tilde{\rho}$. Two mechanisms now compete, a blueshift and a parametric mechanism. For small $L_0^2\delta\tilde{\rho}$, the evolution of the scalar field is almost identical to that with a vanishing $\delta\tilde{\rho}L_0^2$, and the blueshift mechanism dominates. For large $\delta\tilde{\rho}L_0^2$, we observe instead that the amplitude of the scalar field grows while its frequency is barely changing, a clear sign that we are dealing with a different process. This is in fact a parametric instability. Contrast this with the blueshift instability cases, where the scalar field pulse becomes narrower (due to the oscillating boundary) as time passes, but its amplitude remains constant. Here, the width of the scalar pulse is roughly constant and the instability is driven by a growth in the amplitude of the field (due to the oscillating effective density).

Application to astrophysical systems.—We have shown that pulsating stars or other objects may excite important instabilities of nonminimally coupled fields. Compact stars, such as neutron stars, have radial pulsations with frequencies satisfying $\omega L_0 \sim 1$ for the lowest overtones [35], and are ideal systems where such instabilities might be relevant. These change the local density and distribution of the scalar (which could be one dark matter component) and may even backreact on the star. A precise description of the evolution of the instability requires a precise knowledge of stellar oscillations and careful modeling of the evolution of the scalar in such backgrounds. This is a challenging program that requires further study.

Notice first that one can apply our results for stars as long as other dissipation mechanisms are subdominant. Of particular importance are shear viscosity effects, which in neutron stars have a timescale [62,63]

$$\tau_\eta \approx 100\rho_{17}^{-5/4}T_5^2\left(\frac{L_0}{10\ \rm km}\right)^2\ \rm s, \qquad (12)$$

where $\rho_{17} = \rho/(10^{17}\ \rm kg/m^3)$, $T_5 = T/(10^5\ \rm K)$ and T is the neutron star temperature.

The blueshift instability is quenched after

$$t_B \sim 2L_0 n_* = 3\times 10^{-2}\ \rm s\left(\frac{10^{-3}}{\lambda_B(\omega)L_0}\right)\left(\frac{L_0}{10\ \rm km}\right) \times \ln\left|10\frac{\mu}{10^{-10}\ \rm eV}\frac{\sigma}{10\ \rm km}\right|, \qquad (13)$$

and on this timescale an energy $E \sim E_0\sigma\mu_0$ is removed from the star. This result is not very sensitive to the initial conditions. It is, in principle, only weakly affected by backreaction, unless $\sigma\mu_0$ is an extremely large number. Our numerical results indicate that $\lambda_B L_0 \sim 10^{-3}$ is a reasonable estimate for $\delta L > 0.01 L_0$. The instability window for the blueshift mechanism to work is tight, however [cf. Eq. (9)]. Only large overtones are affected by it, unless the star is oscillating nonlinearly with $\delta L \gtrsim 0.1 L_0$.

Consider now the parametric instability. When $\beta \sim -(\mu^2/\tilde{\rho}_0)$, with $\tilde{\rho}_0$ the temporal average of the density of the star, the relevant dynamics is governed by the Mathieu equation [64,65]. This particular case provides a test on our results, and allows us to estimate analytically the timescales involved. For small $\delta\mu^2$, the instability condition amounts to $L_0\omega = 4\pi/j$ ($j \in \mathbb{Z}$). The instability rate timescale for $j = 1$, for example, is roughly $t_A \sim 2\omega/\delta\mu^2$, or

$$t_A \sim \frac{2\omega}{\delta\mu^2} \sim 1\ \rm s\left(\frac{10\ \rm km}{L_0}\right)\left(\frac{\omega L_0}{4\pi}\right)\left(\frac{10^{-2}\rho_{17}}{\delta\tilde{\rho}}\right)\left(\frac{-10}{\beta}\right),$$

for small $\delta\mu^2/\omega^2$. These estimates assume that the field is effectively very light inside the star, which amounts to requiring that

$$|\beta| \sim 7\left(\frac{0.3}{\mathcal{C}}\right)\left(\frac{\mu}{10^{-10}\ \rm eV}\right)^2\left(\frac{L_0}{10\ \rm km}\right)^2, \qquad (14)$$

but the instabilities discussed here are expected to set in even at small nonzero effective masses. The star oscillations can be induced by accretion, tidal effects or even mergers [66–68]. Note that numerical relativity simulations show that the amplitude of density perturbations during

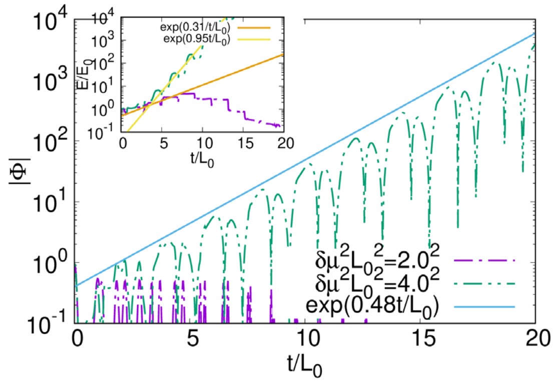

FIG. 3. Evolution of the energy and scalar field for setups that probe both an oscillating boundary and a time-varying effective mass inside the star. The initial data has width $\sigma = 0.1L_0$, and the star is oscillating with frequency $\omega L_0 = 3.1$. The (background) effective mass inside the star is zero, $\mu_{\rm in}^2 = \mu_0^2 + \beta\tilde{\rho}_0 \approx 0$, while the bare mass is $\mu_0 L_0 = 100$. The time-varying component of the density is proportional to $\delta\mu^2 \equiv \beta\delta\tilde{\rho}$. Even though both the blueshift and parametric instabilities are present, the parametric mechanism dominates at large $\delta\mu^2$.

coalescence, for example, can be significant and of the order of the central density itself [69,70]. Thus, both mechanisms may act on timescales short enough to be relevant. In fact, at large couplings β—not yet ruled out for large bare masses—parametric instabilities will be dominant.

Final remarks.—Nonminimally coupled, massive scalar fields can evade all observational constraints from the observation of nearly stationary configurations, yet produce distinct signatures when evolving around oscillating backgrounds. We have shown that there are at least two possible instability mechanisms: one blueshifts light scalars inside oscillating stars [71]; the second mechanism is of parametric origin, triggered by a periodic oscillation of the star material. Possible excitation mechanisms for the scalar field could include, for instance, coherently or stochastically oscillating dark matter.

Both instabilities act on short timescales when compared to viscous timescales [62], and are expected to play a role in neutron star oscillations. They can backreact on the star—perhaps leading to gravitational collapse, or (in the blueshift mechanism) simply result in a leakage of high frequency, high amplitude scalar. If a fraction, or all of dark matter is made of a scalar component, then these mechanisms can act to produce overdensities close to neutron stars, providing one more route to constraining dark matter. Details on observational signatures of these instabilities require further studies, beyond the scope of this work.

Similar instabilities are expected not only in scalar-tensor theories, but also in other theories with vectors or spinors [78–80]. Scalarized background solutions are not prone to the type of instabilities discussed here, but star oscillations will lead to radiation emission [33]. We expect that the instabilities discussed here could describe and affect other systems where a light degree of freedom is confined to an oscillating background, potentially observable in condensed matter systems.

Finally, other periodic systems include compact binaries; it can be expected that similar blueshift mechanisms act on such binaries. Their high degree of asymmetry makes it more challenging to model, but their immense gravitational potential energy certainly makes them important candidates.

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[1] C. M. Will, The confrontation between general relativity and experiment, Living Rev. Relativity **17**, 4 (2014).
[2] B. P. Abbott *et al.* (LIGO Scientific, Virgo Collaborations), GW150914: The Advanced LIGO Detectors in the Era of First Discoveries, Phys. Rev. Lett. **116**, 131103 (2016).
[3] B. P. Abbott *et al.* (LIGO Scientific, Virgo Collaborations), Tests of General Relativity with GW150914, Phys. Rev. Lett. **116**, 221101 (2016); **121**, 129902(E) (2018).
[4] R. Abbott *et al.* (LIGO Scientific, Virgo Collaborations), Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog, Phys. Rev. D **103**, 122002 (2021).
[5] T. Clifton, P. G. Ferreira, A. Padilla, and C. Skordis, Modified gravity and cosmology, Phys. Rep. **513**, 1 (2012).
[6] E. Berti *et al.*, Testing general relativity with present and future astrophysical observations, Classical Quantum Gravity **32**, 243001 (2015).
[7] V. Cardoso and P. Pani, Testing the nature of dark compact objects: A status report, Living Rev. Relativity **22**, 4 (2019).
[8] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, String axiverse, Phys. Rev. D **81**, 123530 (2010).

[9] L. Barack *et al.*, Black holes, gravitational waves and fundamental physics: A roadmap, Classical Quantum Gravity **36**, 143001 (2019).

[10] T. Damour and G. Esposito-Farese, Nonperturbative Strong Field Effects in Tensor-Scalar Theories of Gravitation, Phys. Rev. Lett. **70**, 2220 (1993).

[11] T. Damour and G. Esposito-Farese, Tensor-scalar gravity and binary pulsar experiments, Phys. Rev. D **54**, 1474 (1996).

[12] T. Harada, Neutron stars in scalar tensor theories of gravity and catastrophe theory, Phys. Rev. D **57**, 4802 (1998).

[13] P. Pani, V. Cardoso, E. Berti, J. Read, and M. Salgado, The vacuum revealed: The final state of vacuum instabilities in compact stars, Phys. Rev. D **83**, 081501(R) (2011).

[14] F. M. Ramazanoğlu and F. Pretorius, Spontaneous scalarization with massive fields, Phys. Rev. D **93**, 064005 (2016).

[15] G. Antoniou, A. Bakopoulos, and P. Kanti, Evasion of No-Hair Theorems and Novel Black-Hole Solutions in Gauss-Bonnet Theories, Phys. Rev. Lett. **120**, 131102 (2018).

[16] D. D. Doneva and S. S. Yazadjiev, New Gauss-Bonnet Black Holes with Curvature-Induced Scalarization in Extended Scalar-Tensor Theories, Phys. Rev. Lett. **120**, 131103 (2018).

[17] H. O. Silva, J. Sakstein, L. Gualtieri, T. P. Sotiriou, and E. Berti, Spontaneous Scalarization of Black Holes and Compact Stars from a Gauss-Bonnet Coupling, Phys. Rev. Lett. **120**, 131104 (2018).

[18] J. Khoury and A. Weltman, Chameleon Fields: Awaiting Surprises for Tests of Gravity in Space, Phys. Rev. Lett. **93**, 171104 (2004).

[19] J. Khoury and A. Weltman, Chameleon cosmology, Phys. Rev. D **69**, 044026 (2004).

[20] A. Joyce, B. Jain, J. Khoury, and M. Trodden, Beyond the cosmological standard model, Phys. Rep. **568**, 1 (2015).

[21] V. Cardoso, A. Foschi, and M. Zilhao, Collective Scalarization or Tachyonization: When Averaging Fails, Phys. Rev. Lett. **124**, 221104 (2020).

[22] S. Tsujikawa, T. Tamaki, and R. Tavakol, Chameleon scalar fields in relativistic gravitational backgrounds, J. Cosmol. Astropart. Phys. 05 (2009) 020.

[23] E. Barausse, C. Palenzuela, M. Ponce, and L. Lehner, Neutron-star mergers in scalar-tensor theories of gravity, Phys. Rev. D **87**, 081506(R) (2013).

[24] C. Palenzuela, E. Barausse, M. Ponce, and L. Lehner, Dynamical scalarization of neutron stars in scalar-tensor gravity theories, Phys. Rev. D **89**, 044024 (2014).

[25] M. Shibata, K. Taniguchi, H. Okawa, and A. Buonanno, Coalescence of binary neutron stars in a scalar-tensor theory of gravity, Phys. Rev. D **89**, 084005 (2014).

[26] M. Khalil, N. Sennett, J. Steinhoff, and A. Buonanno, Theory-agnostic framework for dynamical scalarization of compact binaries, Phys. Rev. D **100**, 124013 (2019).

[27] L. Annulli, CLAP for modified gravity: scalar instabilities in binary black hole spacetimes, arXiv:2105.08728.

[28] H. O. Silva, H. Witek, M. Elley, and N. Yunes, Dynamical Descalarization in Binary Black Hole Mergers, Phys. Rev. Lett. **127**, 031101 (2021).

[29] W. E. East and J. L. Ripley, Dynamics of Spontaneous Black Hole Scalarization and Mergers in Einstein-Scalar-Gauss-Bonnet Gravity, Phys. Rev. Lett. **127**, 101102 (2021).

[30] C. Llinares and D. Mota, Releasing Scalar Fields: Cosmological Simulations of Scalar-Tensor Theories for Gravity Beyond the Static Approximation, Phys. Rev. Lett. **110**, 161101 (2013).

[31] R. Hagala, C. Llinares, and D. F. Mota, Cosmic Tsunamis in Modified Gravity: Disruption of Screening Mechanisms from Scalar Waves, Phys. Rev. Lett. **118**, 101301 (2017).

[32] R. Brito, A. Terrana, M. Johnson, and V. Cardoso, Nonlinear dynamical stability of infrared modifications of gravity, Phys. Rev. D **90**, 124035 (2014).

[33] A. Silvestri, Scalar Radiation from Chameleon-Shielded Regions, Phys. Rev. Lett. **106**, 251101 (2011).

[34] T. Nakamura, T. Ikeda, R. Saito, N. Tanahashi, and C.-M. Yoo, Dynamical analysis of screening in scalar-tensor theory, Phys. Rev. D **103**, 024009 (2021).

[35] K. D. Kokkotas and J. Ruoff, Radial oscillations of relativistic stars, Astron. Astrophys. **366**, 565 (2001).

[36] E. Schatzman, Sur la période de pulsation radiale des naines blanches, Ann. Astrophys. **24**, 237 (1961).

[37] H. P. Singh and M. K. Das, Radial oscillations of finite temperature white dwarfs, Astrophys. Space Sci. **186**, 117 (1991).

[38] D. E. Winget and S. O. Kepler, Pulsating white dwarf stars and precision asteroseismology, Annu. Rev. Astron. Astrophys. **46**, 157 (2008).

[39] S. Turck-Chieze and I. Lopes, Toward a unified classical model of the sun: On the sensitivity of neutrinos and helioseismology to the microscopic physics, Astrophys. J. **408**, 347 (1993).

[40] S. Turck-Chièze and I. Lopes, Solar-stellar astrophysics and dark matter, Res. Astron. Astrophys. **12**, 1107 (2012).

[41] C. H. T. Wang, P. M. Bonifacio, R. Bingham, and J. T. Mendonca, Parametric instability induced scalar gravitational waves from a model pulsating neutron star, Phys. Lett. B **705**, 148 (2011).

[42] C. H. T. Wang, A. O. Hodson, A. S. J. Murphy, T. B. Davies, R. Bingham, and J. T. Mendonça, Dynamical trapping and relaxation of scalar gravitational fields, Phys. Lett. B **726**, 791 (2013).

[43] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.127.191101, which includes Refs. [44–47] for more details regarding the blueshift instability and we show that parametric instabilities occur also in the context of full General Relativity.

[44] J. Antoniadis *et al.*, A massive pulsar in a compact relativistic binary, Science **340**, 6131 (2013).

[45] C. K. Law, Resonance Response of the Quantum Vacuum to an Oscillating Boundary, Phys. Rev. Lett. **73**, 1931 (1994).

[46] C. Posada and C. Chirenti, On the radial stability of ultra compact Schwarzschild stars beyond the Buchdahl limit, Classical Quantum Gravity **36**, 065004 (2019).

[47] J. M. Lattimer and M. Prakash, Neutron star structure and the equation of state, Astrophys. J. **550**, 426 (2001).

[48] G. Ventagli, A. Lehébel, and T. P. Sotiriou, Onset of spontaneous scalarization in generalized scalar-tensor theories, Phys. Rev. D **102**, 024050 (2020).

[49] R. F. P. Mendes, Possibility of setting a new constraint to scalar-tensor theories, Phys. Rev. D **91**, 064024 (2015).

[50] K. Hinterbichler, J. Khoury, A. Levy, and A. Matas, Symmetron cosmology, Phys. Rev. D **84**, 103521 (2011).

[51] K. Hinterbichler and J. Khoury, Symmetron Fields: Screening Long-Range Forces Through Local Symmetry Restoration, Phys. Rev. Lett. **104**, 231301 (2010).

[52] S. L. Shapiro and S. A. Teukolsky, *Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects* (Wiley, New York, 1983).

[53] H. Sotani, Scalar gravitational waves from relativistic stars in scalar-tensor gravity, Phys. Rev. D **89**, 064031 (2014).

[54] R. F. P. Mendes and N. Ortiz, New Class of Quasinormal Modes of Neutron Stars in Scalar-Tensor Gravity, Phys. Rev. Lett. **120**, 201104 (2018).

[55] S. Chandrasekhar, The dynamical instability of gaseous masses approaching the Schwarzschild limit in general relativity, Astrophys. J. **140**, 417 (1964).

[56] J. M. Bardeen, K. S. Thorne, and D. W. Meltzer, A catalogue of methods for studying the normal modes of radial pulsation of general-relativistic stellar models, Astrophys. J. **145**, 505 (1966).

[57] J. Dittrich, P. Duclos, and P. Šeba, Instability in a classical periodically driven string, Phys. Rev. E **49**, 3535 (1994).

[58] M. Boskovic, R. Brito, V. Cardoso, T. Ikeda, and H. Witek, Axionic instabilities and new black hole solutions, Phys. Rev. D **99**, 035006 (2019).

[59] L.-Y. Chen, N. Goldenfeld, and Y. Oono, The Renormalization group and singular perturbations: Multiple scales, boundary layers and reductive perturbation theory, Phys. Rev. E **54**, 376 (1996).

[60] S. S. Dave and S. Digal, Effects of oscillating spacetime metric background on a complex scalar field and formation of topological vortices, Phys. Rev. D **103**, 116007 (2021).

[61] S. S. Dave and S. Digal, Field excitation in fuzzy dark matter near a strong gravitational wave source, arXiv:2106.05812.

[62] C. Cutler and L. Lindblom, The effect of viscosity on neutron star oscillations, Astrophys. J. **314**, 234 (1987).

[63] D. Barta, Effect of viscosity and thermal conductivity on the radial oscillation and relaxation of relativistic stars, Classical Quantum Gravity **36**, 215012 (2019).

[64] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables* (Dover, New York, 1972).

[65] C. M. Bender and S. A. Orszag, *Advanced Mathematical Methods for Scientists and Engineers* (McGraw-Hill, New York, 1978).

[66] A. Reisenegger and P. Goldreich, Excitation of neutron star normal modes during binary inspiral, Astrophys. J. **426**, 688 (1994).

[67] C. Chirenti, R. Gold, and M. C. Miller, Gravitational waves from f-modes excited by the inspiral of highly eccentric neutron star binaries, Astrophys. J. **837**, 67 (2017).

[68] S. Ma, H. Yu, and Y. Chen, Excitation of f-modes during mergers of spinning binary neutron star, Phys. Rev. D **101**, 123020 (2020).

[69] A. Perego, S. Bernuzzi, and D. Radice, Thermodynamics conditions of matter in neutron star mergers, Eur. Phys. J. A **55**, 124 (2019).

[70] S. Bernuzzi *et al.*, Accretion-induced prompt black hole formation in asymmetric neutron star mergers, dynamical ejecta and kilonova signals, Mon. Not. R. Astron. Soc. **497**, 1488 (2020).

[71] There were important hints that such an effect could occur. The classical Fermi acceleration process is one example of energy extraction from a zero-average motion [72]. Similar processes exist for fields trapped inside cavities with periodically moving boundaries [73–77]. We showed that oscillating stars are also prone to such instabilities.

[72] E. Fermi, On the origin of the cosmic radiation, Phys. Rev. **75**, 1169 (1949).

[73] J. Cooper, Long-time behavior and energy growth for electromagnetic waves reflected by a moving boundary, IEEE Trans. Antennas Propag. **41**, 1365 (1993).

[74] J. Dittrich, P. Duclos, and P. Šeba, Instability in a classical periodically driven string, Phys. Rev. E **49**, 3535 (1994).

[75] G. T. Moore, Quantum theory of the electromagnetic field in a variable-length one-dimensional cavity, J. Math. Phys. (N.Y.) **11**, 2679 (1970).

[76] M. A. Andreata and V. V. Dodonov, Energy density and packet formation in a vibrating cavity, J. Phys. A **33**, 3209 (2000).

[77] V. V. Dodonov, Nonstationary Casimir effect and analytical solutions for quantum fields in cavities with moving boundaries, Adv. Chem. Phys. **119**, 309 (2001).

[78] L. Annulli, V. Cardoso, and L. Gualtieri, Electromagnetism and hidden vector fields in modified gravity theories: Spontaneous and induced vectorization, Phys. Rev. D **99**, 044038 (2019).

[79] M. Minamitsuji, Stealth spontaneous spinorization of relativistic stars, Phys. Rev. D **102**, 044048 (2020).

[80] M. Minamitsuji, Spontaneous vectorization in the presence of vector field coupling to matter, Phys. Rev. D **101**, 104044 (2020).