Preface

The General Theory of Relativity is an extremely successful theory, with a well-established experimental footing, at least for weak gravitational fields. Its predictions range from the existence of black holes, gravitational radiation (now confirmed) to the cosmological models, predicting a primordial beginning, namely the big-bang. All these solutions have been obtained by first considering a plausible distribution of matter, and through the Einstein field equation, the spacetime metric of the geometry is determined. However, one may solve the Einstein field equation in the reverse direction, namely one first considers an interesting and exotic spacetime metric and then finds the matter source responsible for the respective geometry. In this manner, it was found that some of these solutions possess a peculiar property, namely "exotic matter," involving a stress-energy tensor that violates the null energy condition. These geometries also allow closed timelike curves, with the respective causality violations. It is thus perhaps important to emphasize that these solutions are primarily useful as "gedanken-experiments" and as a theoretician's probe of the foundations of general relativity, and include traversable wormholes and superluminal "warp drive" spacetimes. This book, in addition to extensively exploring interesting features, in particular, the physical properties and characteristics of these "exotic spacetimes," is meant to present a state of the art of wormhole physics, warp drive spacetimes and recent research on the energy conditions. The ideal audience is intended for undergraduate and postgraduate students, with a knowledge of general relativity, and researchers in the field, who are interested in exploring new avenues of research in these topics.

More specifically, in this book, general relativistic rotating wormhole solutions, supported by a phantom scalar field, are presented. The properites of these rotating wormhole solutions including their mass, angular momentum, quadrupole moment, and ergosphere are discussed, and the stability issues are explored. Concerning the astrophysical signatures, physical properties and characteristics of matter forming thin accretion disks in wormhole geometries are analyzed. It is shown that specific signatures appear in the electromagnetic spectrum of thin disks around wormhole spacetimes, thus leading to the possibility of distinguishing these geometries by using astrophysical observations of the emission spectra from accretion disks.

Explicit examples of globally regular static, spherically symmetric solutions in general relativity are also constructed with scalar and electromagnetic fields, describing traversable wormholes with flat and AdS asymptotics and regular black holes, in particular, black universes. (A black universe is a regular black hole with an expanding, asymptotically isotropic spacetime beyond the horizon.) Such objects exist in the presence of scalar fields with negative kinetic energy ("phantoms," or "ghosts"), which are not observed under usual physical conditions. To account for that, "trapped ghosts" (scalars whose kinetic energy is only negative in a strong-field region of spacetime) are considered, as well as "invisible ghosts," i.e., phantom scalar fields sufficiently rapidly decaying in the weak-field region. Self-sustained traversable wormholes, which are configurations sustained by their own gravitational quantum fluctuations, are also considered. The investigation is evaluated by means of a variational approach with Gaussian trial wave functionals to one loop, and the graviton quantum fluctuations are interpreted as a kind of *exotic energy*. It is shown that for every framework, the self-sustained equation will produce a Wheeler wormhole of Planckian size. Some consequences on topology change are discussed together with the possibility of obtaining an enlarged wormhole radius.

In the context of modified theories of gravity, it is shown that the higher-order curvature terms, interpreted as a gravitational fluid, can effectively sustain wormhole geometries, while the matter threading the wormhole can be imposed to satisfy the energy conditions. In this context, a systematic analysis of static spherically symmetric solutions describing a wormhole geometry in a Horndeski model with Galileon shift symmetry is presented. In addition to this, working in a metric-affine framework, explicit models are explored in four and higher dimensions. It is shown that these solutions represent explicit realizations of the concept of geon introduced by Wheeler, interpreted as topologically nontrivial self-consistent bodies generated by an electromagnetic field without sources. Several of their properties are discussed. Furthermore, using exactly solvable models, it is shown that black hole singularities in different electrically charged configurations can be cured. These solutions describe black hole spacetimes with a wormhole giving structure to the otherwise point-like singularity. It is shown that geodesic completeness is satisfied despite the existence of curvature divergences at the wormhole throat. In some cases, physical observers can go through the wormhole, and in other cases, the throat lies at an infinite affine distance. The removal of singularities occurs in a nonperturbative way.

Quantum field theory violates all the classical energy conditions of general relativity. Nonetheless, it turns out that quantum field theories satisfy remnants of the classical energy conditions, known as quantum energy inequalities (QEIs), that have been developed by various authors since the original pioneering work of Ford in 1978. Here, an introduction to QEIs is introduced, as well as to some of the techniques of quantum field theory in curved spacetime (particularly, the use of microlocal analysis together with the algebraic formulation of QFT) that enable rigorous and general QEIs to be derived. Specific examples are computed for the free scalar field, and their consequences are discussed. QEIs are also derived for the class of unitary, positive energy conformal field theories in two spacetime dimensions. In that setting, it is also possible to determine the probability distribution for individual measurements of certain smearings of the stress-energy tensor in the vacuum state. Semiclassical quantum effects also typically violate the energy conditions. The characteristics of a nonlinear energy condition and the flux energy condition (FEC) are also studied, and a quantum version of this energy condition (QFEC) is presented, which is satisfied even in more situations of physical interest. Other possible nonlinear energy conditions are introduced, namely the "trace-of-square" (TOSEC) and "determinant" (DETEC) energy conditions.

While General Relativity (GR) ranks undoubtedly among the best physical theories ever developed, it is also among those with the most striking implications. In particular, GR admits solutions that allow faster-than-light motion and consequently allow closed timelike curves, with the respective causality violations, such as warp drive spacetimes. The basic definition and interesting aspects of these spacetimes are extensively discussed, such as the violation of the energy conditions associated with these spacetimes, the appearance of horizons for the superluminal case, and the possibility of using a warp drive to create closed timelike curves. Applying linearized gravity to the weak-field warp drive, it is found that the energy condition violations in this class of spacetimes are generic to these geometries and are not simply a side effect of the superluminal properties. Furthermore, a "pre-emptive" chronology protection mechanism is considered that destabilizes superluminal warp drives via quantum matter back-reaction and hence forbids even the conceptual possibility to use these solutions for building a time machine. This result will be considered both in standard quantum field theory in curved spacetime and in the case of a quantum field theory with Lorentz invariance breakdown at high energies. Some lessons and future perspectives will be finally discussed.

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