

Maximal Tests in Minimal Gravity

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Recent tests have generated impressive reach in the gravity sector of the Standard-Model Extension. This contribution to the CPT'19 proceedings summarizes this progress and maps the structure of work in the gravity sector.

1. Lorentz violation in gravity

As demonstrated by the breadth of contributions to these proceedings and the ongoing growth of the *Data Tables for Lorentz and CPT Violation*,¹ the search for Lorentz violation as a signal of new physics, such as that originating at the Planck Scale,² is an active research area. The gravitational Standard-Model Extension (SME)^{3–5} provides a field-theory-based framework for performing the search systematically. The structure of the SME can be thought of as a series expansion about known physics, with additional terms of increasing mass dimension constructed from conventional fields coupled to coefficients for Lorentz violation.⁶ The leading terms, associated with operators of mass dimension $d = 3, 4$, are known as the minimal SME. In the gravity sector, phenomenology has been developed and tests have been performed based on a variety of complementary limits of the full SME. Relations among these efforts are summarized graphically in Fig. 1.

The framework for phenomenology in the gravity sector of the SME began in 2004 with Ref. 4, which developed the Lagrange density and associated theory to be used in searches for minimal Lorentz violation in gravity. Lorentz-violating effects in gravity can be understood as coming from the pure-gravity sector through Lorentz-violating modifications to the dynamics of the gravitational field,⁷ or through gravitational couplings in Lorentz-violating terms in the other sectors of the theory.⁸ In the latter case, Lorentz-violating effects are dependent on the species of matter contained in the test and source bodies, while in the former case they are not. References 7, 8 address theory and phenomenology associated with minimal

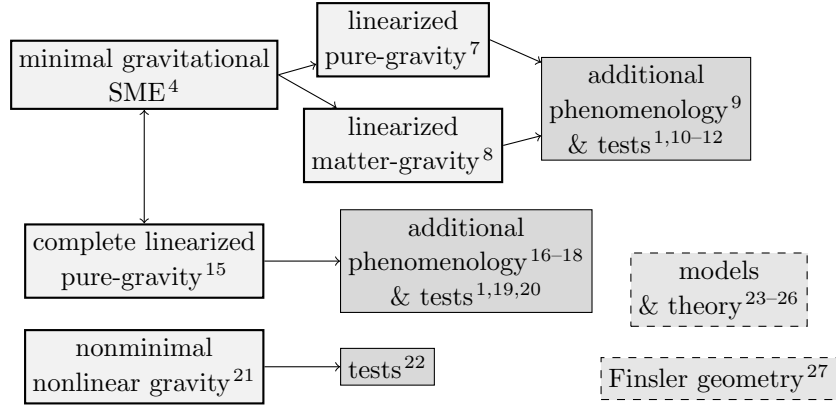


Fig. 1. Progress in SME gravity as of CPT'19. Light gray boxes show the various limits of the gravity sector that have been explored. Dark gray boxes show work that builds out the search in the respective limits. Dashed boxes show theoretical contributions.

terms in pure gravity and matter-gravity couplings, respectively. A large amount of additional phenomenology⁹ and experimental and observational searches¹ have been done based on these works, some of which are discussed in Sec. 2 and elsewhere in these proceedings.^{10–12}

Some nonminimal gravity-sector terms were analyzed for short-range gravity experiments¹³ and for gravitational Čerenkov radiation,¹⁴ and the complete linearized theory of pure gravity was developed in Ref. 15, with initial applications to gravitational waves (GWs). Since then, additional phenomenology^{16–18} as well as experimental and observational work¹ has been done in nonminimal gravity. Examples of searches in nonminimal gravity are contained in these proceedings.^{12,19,20} We note in passing the expected overlap between the linearized limit of the minimal work of Refs. 4, 7 and the minimal limit of the complete linearized theory in Ref. 15. Study of the nonminimal gravity sector beyond the linearized limit has also begun.^{21,22}

In addition to work aimed directly at seeking signals of Lorentz violation in experiments, several theory-oriented results deserve discussion in this context. While it is difficult to capture the volume of work done in this area in this short summary, examples discussed in these proceedings include exploration of specific Lorentz-violating models that generate nonzero SME coefficients^{23,24} and the implications of geometric constraints on Lorentz violation.²⁵ The question of geometric constraints has also inspired consider-

ation of Finsler geometry as a geometric framework for Lorentz violation.²⁷

2. Maximal reach

Several recent and ongoing efforts have improved sensitivities to Lorentz violation in the minimal gravitational sector, or are expected to do so in the near future. A number of these are discussed elsewhere in these proceedings including improved sensitivities through matter–gravity couplings based on an analysis of data from the MICROSCOPE mission,¹⁰ results from the analysis of solar-system data,¹¹ and tests based on interferometric gyroscopes.^{12,28} Significant improvements in the laboratory were also achieved using gravimeters.²⁹ In this section, we summarize the recent effort providing the greatest reach, multimessenger astronomy.

On August 17, 2017, GWs and photons from the same astrophysical event were observed for the first time.³⁰ A gamma-ray burst arrived (1.74 ± 0.05) s after the GWs from the coalescence of a pair of neutron stars. This observation, along with modeling suggesting up to a few seconds of lag between the coalescence and gamma-rays emission, led to a best-ever comparison of the speed of GWs and light. Such tests provide a particularly sensitive probe of $d = 4$ SME gravity coefficients due to the long propagation distance involved and because GW tests based on birefringence^{15,17} and/or dispersion,^{15,17,31} while powerful for $d > 4$, are insensitive to $d = 4$ coefficients. Using a maximum-reach analysis, in which the nine minimal $\bar{s}_{jk}^{(4)}$ gravity-sector coefficients are taken as nonzero one at time, the reach for all nine coefficients was improved over prior limits, most of which came from the analysis of Čerenkov radiation by cosmic rays.¹⁴ The upper bound on the isotropic $\bar{s}_{00}^{(4)}$ coefficient was inaccessible to Čerenkov constraints, hence an improvement of ten orders of magnitude was achieved here, while improvements of up to a factor of 40 were achieved for the other coefficients. Future observations of multimessenger events offer several avenues of improvement. Events further away will improve the overall sensitivity, at least nine events distributed across the sky will enable the estimation of all nine $\bar{s}_{jk}^{(4)}$ coefficients together, and events at a variety of distances will disentangle speed differences from emission-time differences. The future is bright for seeking Lorentz violation with GWs.

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