SME Gravity: Structure and Progress

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This proceedings contribution outlines the current structure of the gravity sector of the Standard-Model Extension and summaries recent progress in gravitational wave analysis.

1. Lorentz violation in gravity

The gravitational Standard-Model Extension (SME)\(^1\text{"} \text{-}^3\) provides a field theoretic test framework for Lorentz symmetry. Originally motivated by the search for new physics at the Planck Scale,\(^4\) the search for Lorentz violation using the SME continues to be an active and growing area of research several decades later, as illustrated by the scope of both these proceedings and the Data Tables for Lorentz and CPT Violation.\(^5\)

In terms of structure, the SME can be thought of as a series expansion about known physics as the level of the action. The additional terms are constructed from conventional fields coupled to coefficients for Lorentz violation, which can be thought of as providing directionalities to empty spacetime. The mass dimension of the additional operators labels the order in the expansion.\(^6\) The leading terms, which are of mass dimension \(d = 3, 4\), form a limit known as the minimal SME. In the gravity sector, a variety of complementary limits have been explored in the context of theory, phenomenology, and experiment. The goal of my contribution to the CPT’19 proceedings was to summarize the relations among, and the status of, these efforts,\(^7\) in part through the creation of Fig. 1, which remains a useful description of much of the gravity-sector structure, though additional work has been done in many of its areas. For additional discussion of Fig. 1, see Ref. 7. The evolution of the field since CPT’19 has led to an understanding of the content of Fig. 1 as being but one facet of an expanded array of areas to be explored via the framework of Ref. 8. Figure 2 highlights the addition of this prequel relative to the 2019 structure.
2. Reach, Separation, and Gravitational Waves

As can be seen from the data tables, experiments have achieved a high level of sensitivity to coefficients for Lorentz violation and have explored a large breadth of coefficient space. In performing such analysis, the question of which and how many coefficients to extract measurements for using a given data set naturally arises. Practical progress dictates that experimental
data be used to extract likelihood bounds on the coefficients for Lorentz violation in the context of a model involving a subset of the full (and in general infinite) coefficient space of the SME. This highlights the nature of the SME as a test framework rather than a model.

One popular approach is to consider each SME coefficient one-at-a-time, perhaps re-using a data set to attain likelihood bounds on multiple coefficients. This approach is sometimes referred to as a maximum reach approach because it characterizes the maximum reach that the experiment can attain for the coefficient. When these measurements are consistent with zero, they provide a good order-of-magnitude sense of how big the particular Lorentz-violating effect could be in nature in the absence of a model involving a fine-tuned cancelation of the effects of multiple coefficients in the observable under consideration.

When data permits, it is also common to obtain simultaneous measurements of all or multiple coefficients of the same observer tensor object, or even several tensor coefficients from a given sector at a given mass dimension. This is sometimes referred to as a coefficient separation procedure and it can more definitively exclude a larger set of models.

In my CPT’19 proceedings contribution, I highlighted two key expansions in experimental reach that had recently emerged at that time: the MICROSCOPE mission in the context of matter-gravity couplings and multimessenger astronomy in the form of gravitational wave (GW) event GW170817 and gamma ray burst GRB 170817A in the context of the minimal gravity sector. While little coefficient separation had been done at that time in the context of GW studies, the now extensive catalog of GW events has led to a blossoming of these studies.

By taking advantage of the arrival time at the different GW detectors situated around the Earth, simultaneous measurements of 4 of the 9 minimal gravity-sector coefficients have been achieved using data from the first GW catalog. A simultaneous extraction of all 9 minimal gravity sector coefficients using all suitable GW events released to date is in preparation.

The search for birefringence and dispersion of gravitational waves based on the dimension 5 and 6 coefficients has also now been the focus of numerous studies. Dimension 5 effects have been incorporated into into a version of the Laser Interferometer GW Observatory (LIGO) Algorithm Library suite LALSuite, and a sensitivity study has been performed using this implementation. Results from the body of recent gravitational wave events based on this implementation are in preparation. An implementation of
dimension 5 and 6 effects in the Bilby analysis code has also generated results\textsuperscript{19} based on recent GW events. Similar work has previously been done based on the duration of LIGO/Virgo chirps.\textsuperscript{18} Additional studies of GW Birefringence that are yet to incorporate direction dependence have also been done,\textsuperscript{34} and isotropic studies of dispersion are ongoing.\textsuperscript{35}

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