Snowmass2021 Letter of Interest: Amplitudes Beyond GR

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Due primarily to the puzzles of dark energy and dark matter, exploring the large scale structure of gravity and its possible extensions remains an important research avenue. The traditional approach to constructing models of the dark sector involves writing a Lagrangian and deriving its consequence, with little concern for whether it possesses a UV completion or is equivalent to other known models. Our understanding of the structure of scattering amplitudes in quantum field theory has seen

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remarkable development over the last decade, and these advances now give us new tools to directly address many of the shortcomings of these traditional approaches.

For example, dispersion relations can give us constraints on the parameters of low energy effective field theories that derive from the necessity of a well-behaved UV completion [1]. These have already been fruitfully applied to massive gravity models [2] and other dark energy models with propagating massive high spin fields in order to narrow the range of parameters which may possess a UV completion [3–8]. Another recent class of constraints comes from demanding causality directly at the level of the S-matrix [9], and these have also started to be applied to massive models [10, 11]. Other techniques for classifying possible interactions directly from the S-matrix have allowed us to answer the question of whether the strong coupling scale for interacting massive high spin theories can be raised [12, 13], and whether there are Higgs mechanisms for gravity [14].

A natural advantage of amplitudes based methods is their independence of the Lagrangian and other unphysical choices such as field redefinitions and the adding and removing of non-dynamical auxiliary fields. Such methods can therefore quickly determine if new proposals are equivalent to other known models, as was recently done in [15] for the 4D Gauss Bonnet model proposed in [16].

A related set of questions apply to other *double copy* relations between gravitational and gauge theories, including the exact classical relations between metrics in Kerr-Schild form [17–21] (and general type D spacetimes [22]) and gauge field theories, and perturbative radiation scattering relations between such theories [23–30]. Extending these relationships beyond GR (for example to relationships between degrees of freedom representing the longitudinal modes of massive gauge fields and those of massive gravity), perhaps using the soft bootstrap approach [31, 32], might open up fascinating avenues for the study of cosmology in such theories.

Modern amplitude methods additionally provide the framework for a variety of state-of-the art binary inspiral calculations relevant to gravitational wave searches such as LIGO. Using techniques such as generalized unitarity, spinor-helicity methods, and effective field theory [33–36], the relevant amplitudes can be systematically constructed and then recast in terms of the observables relevant to such experimental efforts. Extending these methods to beyond-GR theories in order to provide points of comparison is a natural goal.

A successful program to explore and classify cosmological models from an amplitudes point of view has the potential to substantially improve our understanding of the space of possible dark energy and dark matter models, including their possible astrophysical signatures [37].

References

[1] A. Adams, N. Arkani-Hamed, S. Dubovsky, A. Nicolis, and R. Rattazzi, "Causality, analyticity and an IR obstruction to UV completion," JHEP **10** (2006) 014, arXiv:hep-th/0602178.

[2] C. de Rham, G. Gabadadze, and A. J. Tolley, "Resummation of Massive Gravity," Phys.

Rev. Lett. **106** (2011) 231101, arXiv:1011.1232 [hep-th].

[3] C. Cheung and G. N. Remmen, "Positive Signs in Massive Gravity," JHEP **04** (2016) 002, arXiv:1601.04068 [hep-th].

[4] J. Bonifacio, K. Hinterbichler, and R. A. Rosen, "Positivity constraints for pseudolinear massive spin-2 and vector Galileons," Phys. Rev. D **94** (2016) no. 10, 104001, arXiv:1607.06084 [hep-th].

[5] C. de Rham, S. Melville, A. J. Tolley, and S.-Y. Zhou, "UV complete me: Positivity Bounds for Particles with Spin," JHEP **03** (2018) 011, arXiv:1706.02712 [hep-th].

[6] C. de Rham, S. Melville, and A. J. Tolley, "Improved Positivity Bounds and Massive Gravity," JHEP **04** (2018) 083, arXiv:1710.09611 [hep-th].

[7] C. de Rham, S. Melville, A. J. Tolley, and S.-Y. Zhou, "Positivity Bounds for Massive Spin-1 and Spin-2 Fields," JHEP **03** (2019) 182, arXiv:1804.10624 [hep-th].

[8] L. Alberte, C. de Rham, A. Momeni, J. Rumbutis, and A. J. Tolley, "Positivity Constraints on Interacting Spin-2 Fields," JHEP **03** (2020) 097, arXiv:1910.11799 [hep-th].

[9] X. O. Camanho, J. D. Edelstein, J. Maldacena, and A. Zhiboedov, "Causality Constraints on Corrections to the Graviton Three-Point Coupling," JHEP **02** (2016) 020, arXiv:1407.5597 [hep-th].

[10] K. Hinterbichler, A. Joyce, and R. A. Rosen, "Massive Spin-2 Scattering and Asymptotic Superluminality," JHEP **03** (2018) 051, arXiv:1708.05716 [hep-th].

[11] J. Bonifacio, K. Hinterbichler, A. Joyce, and R. A. Rosen, "Massive and Massless Spin-2 Scattering and Asymptotic Superluminality," JHEP **06** (2018) 075, arXiv:1712.10020 [hep-th].

[12] J. Bonifacio and K. Hinterbichler, "Bounds on Amplitudes in Effective Theories with Massive Spinning Particles," Phys. Rev. D **98** (2018) no. 4, 045003, arXiv:1804.08686 [hep-th].

[13] J. Bonifacio and K. Hinterbichler, "Universal bound on the strong coupling scale of a gravitationally coupled massive spin-2 particle," Phys. Rev. D **98** (2018) no. 8, 085006, arXiv:1806.10607 [hep-th].

[14] J. Bonifacio, K. Hinterbichler, and R. A. Rosen, "Constraints on a gravitational Higgs mechanism," Phys. Rev. D **100** (2019) no. 8, 084017, arXiv:1903.09643 [hep-th].

[15] J. Bonifacio, K. Hinterbichler, and L. A. Johnson, "Amplitudes and 4D Gauss-Bonnet Theory," Phys. Rev. D **102** (2020) no. 2, 024029, arXiv:2004.10716 [hep-th].

[16] D. z. Glavan and C. Lin, "Einstein-Gauss-Bonnet Gravity in Four-Dimensional Spacetime," Phys. Rev. Lett. **124** (2020) no. 8, 081301, arXiv:1905.03601 [gr-qc].

[17] R. Monteiro, D. O'Connell, and C. D. White, "Black holes and the double copy," JHEP **12** (2014) 056, arXiv:1410.0239 [hep-th].

[18] A. Luna, R. Monteiro, D. O'Connell, and C. D. White, "The classical double copy for Taub–NUT spacetime," Phys. Lett. **B750** (2015) 272–277, arXiv:1507.01869 [hep-th].

[19] A. Luna, R. Monteiro, I. Nicholson, D. O'Connell, and C. D. White, "The double copy: Bremsstrahlung and accelerating black holes," JHEP **06** (2016) 023, arXiv:1603.05737 [hep-th].

[20] A. K. Ridgway and M. B. Wise, "Static Spherically Symmetric Kerr-Schild Metrics and Implications for the Classical Double Copy," Phys. Rev. **D94** (2016) no. 4, 044023, arXiv:1512.02243 [hep-th].

[21] M. Carrillo-Gonzalez, R. Penco, and M. Trodden, "The classical double copy in maximally symmetric spacetimes," JHEP **04** (2018) 028, arXiv:1711.01296 [hep-th].

[22] A. Luna, R. Monteiro, I. Nicholson, and D. O'Connell, "Type D Spacetimes and the Weyl Double Copy," Class. Quant. Grav. **36** (2019) 065003, arXiv:1810.08183 [hep-th].

[23] R. Saotome and R. Akhoury, "Relationship Between Gravity and Gauge Scattering in the High Energy Limit," JHEP **01** (2013) 123, arXiv:1210.8111 [hep-th].

[24] D. Neill and I. Z. Rothstein, "Classical Space-Times from the S Matrix," Nucl. Phys. **B877** (2013) 177–189, arXiv:1304.7263 [hep-th].

[25] A. Luna, R. Monteiro, I. Nicholson, A. Ochirov, D. O'Connell, N. Westerberg, and C. D. White, "Perturbative spacetimes from Yang-Mills theory," JHEP **04** (2017) 069, arXiv:1611.07508 [hep-th].

[26] W. D. Goldberger and A. K. Ridgway, "Radiation and the classical double copy for color charges," Phys. Rev. **D95** (2017) no. 12, 125010, arXiv:1611.03493 [hep-th].

[27] W. D. Goldberger, S. G. Prabhu, and J. O. Thompson, "Classical gluon and graviton radiation from the bi-adjoint scalar double copy," Phys. Rev. **D96** (2017) no. 6, 065009, arXiv:1705.09263 [hep-th].

[28] W. D. Goldberger and A. K. Ridgway, "Bound states and the classical double copy," Phys. Rev. **D97** (2018) no. 8, 085019, arXiv:1711.09493 [hep-th].

[29] W. D. Goldberger, J. Li, and S. G. Prabhu, "Spinning particles, axion radiation, and the classical double copy," Phys. Rev. **D97** (2018) no. 10, 105018, arXiv:1712.09250 [hep-th].

[30] M. Carrillo Gonzalez, R. Penco, and M. Trodden, "Radiation of scalar modes and the classical double copy," JHEP **11** (2018) 065, arXiv:1809.04611 [hep-th].

[31] H. Elvang, M. Hadjiantonis, C. R. Jones, and S. Paranjape, "Soft Bootstrap and Supersymmetry," JHEP **01** (2019) 195, arXiv:1806.06079 [hep-th].

[32] M. Carrillo Gonzalez, R. Penco, and M. Trodden, "Shift symmetries, soft limits, and the double copy beyond leading order," arXiv:1908.07531 [hep-th].

[33] C. Cheung, I. Z. Rothstein, and M. P. Solon, "From Scattering Amplitudes to Classical Potentials in the Post-Minkowskian Expansion," Phys. Rev. Lett. **121** (2018) no. 25, 251101, arXiv:1808.02489 [hep-th].

[34] D. A. Kosower, B. Maybee, and D. O'Connell, "Amplitudes, Observables, and Classical Scattering," JHEP **02** (2019) 137, arXiv:1811.10950 [hep-th].

[35] Z. Bern, C. Cheung, R. Roiban, C.-H. Shen, M. P. Solon, and M. Zeng, "Scattering Amplitudes and the Conservative Hamiltonian for Binary Systems at Third Post-Minkowskian Order," Phys. Rev. Lett. **122** (2019) no. 20, 201603, arXiv:1901.04424 [hep-th].

[36] Z. Bern, C. Cheung, R. Roiban, C.-H. Shen, M. P. Solon, and M. Zeng, "Black Hole Binary Dynamics from the Double Copy and Effective Theory," JHEP **10** (2019) 206, arXiv:1908.01493 [hep-th].

[37] D. J. Burger, R. Carballo-Rubio, N. Moynihan, J. Murugan, and A. Weltman, "Amplitudes for astrophysicists: known knowns," Gen. Rel. Grav. **50** (2018) no. 12, 156, arXiv:1704.05067 [astro-ph.HE].