# Effective field theories for gravity—Further reading

The QFT approach to GR was initiated by Weinberg, in two seminal papers [1, 2]. It was eventually completed by Deser [3], and by Boulware and Deser [4]. Feynman's gravity lectures [5] also take this approach. In modern QFT terms, it is spelled out in Weinberg's QFT texbook [6]. For a pedagogical review of the method, see my lecture notes [7].

General effective field theory ideas and methods are described in many excellent reviews—see for instance Polchinski's [8] and Rothstein's [9]. The first concrete application of these techniques to GR is probably that of Donoghue [10], who computed the leading quantum corrections to the Newtonian potential.

The cosmological constant problem is reviewed extensively in the classic review by Weinberg [11], who also proposed an anthropic solution [12].

For massive gravity, the original Fierz-Pauli theory was constructed in [13]. The vDVZ discontinuity was pointed out by van Dam and Veltman [14], and by Zakharov [15]. The Vainshtein effect was proposed in [16]. The general problem with the sixth mode in the non-linear theory was pointed out by Boulware and Deser in [17]. The modern approach based on the Stückelberg fields was initiated in [18]. It was used in [19] to understand the Boulware-Deser sixth mode problem in effective field theory terms. This problem was recently solved by de Rham and Gabadadze in [20], which also pointed out the relation between the improved theory of massive gravity and the galileon. This gave rise to a lot of activity on the subject, part of which is reviewed in detail by Hinterbichler [21]. The methods that worked for massive gravity have also been extended to 'bi-metric' and 'multi-metric' theories—see e.g. [22].

Models that are closely related to massive gravity, but which we did not discuss in class, are DGP and the galileon. The DGP model was introduced in [23]. Its self-accelerating cosmological solution was studied in [24, 25]. The 4D effective theory for the brane-bending mode was derived in [26], and further analyzed in [27], where many of its remarkable properties were pointed out. It was then generalized to the galileon effective field theory in [28]. The superluminality problem for these theories was pointed out—along with some associated $S$-matrix analiticity problems—in [29], and discussed further for the galileon in [28, 30, 31].

For a partial summary of and introduction to the subject of infrared modifications of gravity see also my ICTP lecture notes [32].

The EFT approach to gravitational wave emission was initiated by Goldberger and Rothstein in [33]. They later extended it to dissipative phenomena in [34], and, together with Porto, to spin effects in [35]. For a pedagogical review, see Goldberger's lecture notes [36].

# References


[1] S. Weinberg, "Photons and gravitons in $S$-matrix theory: derivation of charge conservation and equality of gravitational and inertial mass," Phys. Rev. **135**, B1049 (1964).

[2] S. Weinberg, "Photons and gravitons in perturbation theory: Derivation of Maxwell's and Einstein's equations," Phys. Rev. **138**, B988 (1965).

[3] S. Deser, "Selfinteraction and gauge invariance," Gen. Rel. Grav. **1**, 9 (1970) [gr-qc/0411023].

[4] D. G. Boulware and S. Deser, "Classical General Relativity Derived from Quantum Gravity," Annals Phys. **89**, 193 (1975).

[5] R. P. Feynman, F. B. Morinigo, W. G. Wagner and B. Hatfield, (ed.), "Feynman lectures on gravitation," Reading, USA: Addison-Wesley (1995) 232 p. (The advanced book program)

[6] S. Weinberg, "The Quantum theory of fields. Vol. 1: Foundations," *Cambridge, UK: Univ. Pr. (1995) 609 p.*

[7] A. Nicolis, lecture notes available for download at http://phys.columbia.edu/~nicolis/G8099.html

[8] J. Polchinski, "Effective field theory and the Fermi surface," In *Boulder 1992, Proceedings, Recent directions in particle theory* 235-274, and Calif. Univ. Santa Barbara - NSF-ITP-92-132 (92,rec.Nov.) 39 p. (220633) Texas Univ. Austin - UTTG-92-20 (92,rec.Nov.) 39 p [hep-th/9210046].

[9] I. Z. Rothstein, "TASI lectures on effective field theories," hep-ph/0308266.

[10] J. F. Donoghue, "General relativity as an effective field theory: The leading quantum corrections," Phys. Rev. D **50**, 3874 (1994) doi:10.1103/PhysRevD.50.3874 [gr-qc/9405057].

[11] S. Weinberg, "The Cosmological Constant Problem," Rev. Mod. Phys. **61**, 1 (1989).

[12] S. Weinberg, "Anthropic Bound on the Cosmological Constant," Phys. Rev. Lett. **59**, 2607 (1987).

[13] M. Fierz and W. Pauli, "On relativistic wave equations for particles of arbitrary spin in an electromagnetic field," Proc. Roy. Soc. Lond. A **173**, 211 (1939).

[14] H. van Dam and M. J. G. Veltman, "Massive and massless Yang-Mills and gravitational fields," Nucl. Phys. B **22**, 397 (1970).

[15] V. I. Zakharov, "Linearized gravitation theory and the graviton mass," JETP Lett. **12**, 312 (1970) [Pisma Zh. Eksp. Teor. Fiz. **12**, 447 (1970)].

[16] A. I. Vainshtein, "To the problem of nonvanishing gravitation mass," Phys. Lett. B **39**, 393 (1972).

[17] D. G. Boulware and S. Deser, "Can gravitation have a finite range?," Phys. Rev. D **6**, 3368 (1972).

[18] N. Arkani-Hamed, H. Georgi and M. D. Schwartz, "Effective field theory for massive gravitons and gravity in theory space," Annals Phys. **305**, 96 (2003) [hep-th/0210184].

[19] P. Creminelli, A. Nicolis, M. Papucci and E. Trincherini, "Ghosts in massive gravity," JHEP **0509**, 003 (2005) [hep-th/0505147].

[20] C. de Rham and G. Gabadadze, "Generalization of the Fierz-Pauli Action," Phys. Rev. D **82**, 044020 (2010) [arXiv:1007.0443 [hep-th]].

[21] K. Hinterbichler, "Theoretical Aspects of Massive Gravity," Rev. Mod. Phys. **84**, 671 (2012) [arXiv:1105.3735 [hep-th]].

[22] K. Hinterbichler and R. A. Rosen, "Interacting Spin-2 Fields," JHEP **1207**, 047 (2012) [arXiv:1203.5783 [hep-th]].

[23] G. R. Dvali, G. Gabadadze and M. Porrati, "4-D gravity on a brane in 5-D Minkowski space," Phys. Lett. B **485**, 208 (2000) [hep-th/0005016].

[24] C. Deffayet, "Cosmology on a brane in Minkowski bulk," Phys. Lett. B **502**, 199 (2001) [hep-th/0010186].

[25] C. Deffayet, G. R. Dvali and G. Gabadadze, "Accelerated universe from gravity leaking to extra dimensions," Phys. Rev. D **65**, 044023 (2002) [astro-ph/0105068].

[26] M. A. Luty, M. Porrati and R. Rattazzi, "Strong interactions and stability in the DGP model," JHEP **0309**, 029 (2003) [hep-th/0303116].

[27] A. Nicolis and R. Rattazzi, "Classical and quantum consistency of the DGP model," JHEP **0406**, 059 (2004) [hep-th/0404159].

[28] A. Nicolis, R. Rattazzi and E. Trincherini, "The Galileon as a local modification of gravity," Phys. Rev. D **79**, 064036 (2009) [arXiv:0811.2197 [hep-th]].

[29] A. Adams, N. Arkani-Hamed, S. Dubovsky, A. Nicolis and R. Rattazzi, "Causality, analyticity and an IR obstruction to UV completion," JHEP **0610**, 014 (2006) [hep-th/0602178].

[30] A. Nicolis, R. Rattazzi and E. Trincherini, "Energy's and amplitudes' positivity," JHEP **1005**, 095 (2010) [Erratum-ibid. **1111**, 128 (2011)] [arXiv:0912.4258 [hep-th]].

[31] P. Creminelli, A. Nicolis and E. Trincherini, "Galilean Genesis: An Alternative to inflation," JCAP **1011**, 021 (2010) [arXiv:1007.0027 [hep-th]].

[32] A. Nicolis, lecture notes available for download at http://indico.ictp.it/event/a11178/session/6/contribution/3/material/0/0.pdf

[33] W. D. Goldberger and I. Z. Rothstein, "An Effective field theory of gravity for extended objects," Phys. Rev. D **73**, 104029 (2006) doi:10.1103/PhysRevD.73.104029 [hep-th/0409156].

[34] W. D. Goldberger and I. Z. Rothstein, "Dissipative effects in the worldline approach to black hole dynamics," Phys. Rev. D **73**, 104030 (2006) doi:10.1103/PhysRevD.73.104030 [hep-th/0511133].

[35] R. A. Porto and I. Z. Rothstein, "The Hyperfine Einstein-Infeld-Hoffmann potential," Phys. Rev. Lett. **97**, 021101 (2006) doi:10.1103/PhysRevLett.97.021101 [gr-qc/0604099].

[36] W. D. Goldberger, "Les Houches lectures on effective field theories and gravitational radiation," hep-ph/0701129.