Dark Matter = Modified Gravity?

Scrutinising the spacetime-matter distinction through the modified gravity/ dark matter lens

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When applying the laws of gravity to the luminous matter that we observe around us in the universe, one obtains an evolution of that matter which is not empirically adequate---at the scale of galaxies and galaxy clusters as well as at the cosmological scale. We face a dilemma between two options that seem to be obviously distinct: either the matter sector needs to be complemented with non-luminous (i.e. dark) matter (DM), or the gravity sector needs to be modified (MG) (or perhaps a bit of both).

Although this dichotomy indeed seems to hold up when merely applying Newtonian Gravity, as is often sufficient at the level of galaxies, this distinction becomes much less clear when moving to relativistic and quantum theories. Features that are historically taken to be paradigmatic hallmarks of matter suddenly feature in theories labeled as modified gravity theories, and vice versa. Instances of self-identified modified gravity theories feature novel degrees of freedom, which are dynamical, often contain mass terms in the Lagrangian, sometimes even have an associated stress-energy-momentum tensor, and/or exhibit violations of versions of the equivalence principle. Instances of self-identified dark matter theories contain fractional powers of the dark matter field in the Lagrangian, rendering a standard field theoretic treatment in terms of Feynman diagrams implausible. Sometimes the coupling of the DM to the Standard Model fermions obtains only indirectly, via the Higgs boson, which is associated with mass (even if not gravitational mass). Moreover, one can obtain certain DM theories from MG theories via a simple conformal transformation, and vice versa. And taking back a step: were we ever clear on why the metric tensor should be considered more geometrical than, say, the electromagnetic vector potential? Einstein doubted it.

In this paper we investigate what criterion, if any, distinguishes DM theories from MG theories. In doing so, we not only draw upon literature on the broader distinction between matter on the one hand and spacetime/gravity/geometry on the other, we also move in the other direction by pointing out the implications of the ambiguities inherent in the DM/ MG dichotomy for this broader distinction. More specifically, we compare Khoury and Berezhiani's Superfluid Dark Matter with Hossenfelder's Lagrangian formulation of Verlinde's emergent gravity. We extract from the literatures on spacetime functionalism and on the substantivalism-relationalism debate---in particular responses to the hole argument---a family of candidates for being necessary and/or sufficient criteria for an object being (dark) matter, as well as a similar family of criteria that determine whether an object is a (modified) spacetime. Both of the above theories score maximally with respect to both families of criteria: both theories are as much of a dark matter theory as possible, as well as being as much of a modified spacetime/gravity theory as possible.

This case study is a first sign that the distinction between modified gravity and dark matter theories is much less clear than usually assumed, in a variety of respects---and by extension the spacetime-matter distinction. Or, at the very least, if one insists in holding on to a strict criterion, several candidate theories have been incorrectly labeled as DM or MG theories. This blurring severely undermines the current animosity between dark matter advocates and modified gravity advocates, as well as the substantivalism-relationalism debate (where both camps agree that spacetime and matter are clearly conceptually distinct).