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A unifying theory of dark energy and dark matter: Negative masses and matter creation within a modified ΛCDM framework[★, ★★]

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Abstract

Dark energy and dark matter constitute 95% of the observable Universe. Yet the physical nature of these two phenomena remains a mystery. Einstein suggested a long-forgotten solution: gravitationally repulsive negative masses, which drive cosmic expansion and cannot coalesce into light-emitting structures. However, contemporary cosmological results are derived upon the reasonable assumption that the Universe only contains positive masses. By reconsidering this assumption, I have constructed a toy model which suggests that both dark phenomena can be unified into a single negative mass fluid. The model is a modified ΛCDM cosmology, and indicates that continuously-created negative masses can resemble the cosmological constant and can flatten the rotation curves of galaxies. The model leads to a cyclic universe with a time-variable Hubble parameter, potentially providing compatibility with the current tension that is emerging in cosmological measurements. In the first three-dimensional N-body simulations of negative mass matter in the scientific literature, this exotic material naturally forms haloes around galaxies that extend to several galactic radii. These haloes are not cuspy. The proposed cosmological model is therefore able to predict the observed distribution of dark matter in galaxies from first principles. The model makes several testable predictions and seems to have the potential to be consistent with observational evidence from distant supernovae, the cosmic microwave background, and galaxy clusters. These findings may imply that negative masses are a real and physical aspect of our Universe, or alternatively may imply the existence of a superseding theory that in some limit can be modelled by effective negative masses. Both cases lead to the surprising conclusion that the compelling puzzle of the dark Universe may have been due to a simple sign error.

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* The codes used for the N-body simulations can be downloaded at: https://github.com/jamiefarnes/negative-mass-simulator
** Movies associated to Figs. 3 and 6 are available at https://www.aanda.org

1. Introduction

One of the most fascinating aspects of scientific history is that regarding Einstein's efforts with the cosmological constant. It is well known that Einstein added a cosmological constant to his equations in order to provide a static Universe. Due to this bias, he failed to predict the expansion of the Universe that was soon observed by Hubble (Hubble 1929). Famously, upon learning of the Universe's expansion, Einstein set the cosmological constant equal to zero and reportedly called its introduction his "biggest blunder".

Most contemporary physicists are familiar with the fact that prior to Hubble's discovery, Einstein associated the cosmological constant term with a constant of integration. However, Einstein did not always believe this to be the case, and important details are currently absent from the historical narrative. In 1918, before famously discarding the cosmological constant, Einstein made the first physical interpretation of the new Λ term that he had discovered:

> *"a modification of the theory is required such that "empty space" takes the role of gravitating negative masses which are distributed all over the interstellar space"* (Einstein 1918).

Despite this insight, within a year Einstein reformulated his interpretation:

> *"the new formulation has this great advantage, that the quantity Λ appears in the fundamental equations as a constant of integration, and no longer as a universal constant peculiar to the fundamental law"*[1] (Einstein 1919).

What led Einstein to believe that negative masses could provide a solution to the cosmological constant is therefore of interest. To understand the physics of negative masses further, we need to "polarise" the Universe so that mass consists of both positive and negative counterparts. Polarisation appears to be a fundamental property of the Universe. Indeed, all well-understood physical forces can be described through division into two opposing polarised states. For example, electric charges (+ and −), magnetic charges (N and S), and even quantum information (0 and 1) all appear to be fundamentally polarised phenomena. It could therefore be perceived as odd that gravitational charges – conventionally called masses – appear to only consist of positive monopoles.

While electromagnetism and quantum theory appear quite comprehensively understood, there are numerous indications that our understanding of the nature of mass remains incomplete on all spatial scales. In the standard model of particle physics (e.g. ATLAS Collaboration 2012), the mass of fundamental particles such as the nine charged fermions (six quarks and three leptons) and the Higgs boson are all free parameters that cannot be calculated from first principles. In cosmology, the observed matter in the Universe only accounts for 5% of the observed gravity, while the remaining 26% and 69% are accounted for via dark matter and dark energy respectively (e.g. Planck Collaboration XIII 2016). The physical nature of both these dark phenomena is completely unknown, and the quest to identify the Universe's missing mass has even given rise to modifications to Newton's and Einstein's theories of gravity (e.g. Ferreira & Starkman 2009). Nevertheless, our understanding of general relativity has been robustly verified by every experimental test (e.g. Abbott et al. 2016).

understanding of cosmology. In this case, particles could have the property of positive, zero, or negative mass. In Newtonian physics, this can allow for a variety of different types of negative mass as the inertial and gravitational masses can differ in sign. However, throughout this paper I specifically only consider a negative mass that is consistent with general relativity, so that the weak equivalence principle always holds and negative mass matter always has identical inertial and gravitational mass.

While positive mass is familiar to all of us, the concept of negative mass is rather exotic[2]. However, such negative masses have a number of basic properties, as shown in Fig. 1. While a positive mass gravitationally attracts all surrounding masses, a negative mass will gravitationally repel all surrounding masses. If a force is exerted on a positive mass, the mass will move in the direction of the applied force. However, if a force is exerted on a negative mass, the mass will move towards the applied force. Nevertheless, a negative mass at the surface of the Earth would fall downwards in a similar manner to a positive mass.

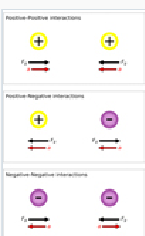

Fig. 1.

Schematic cartoon of gravitational interactions between positive (in yellow) and negative (in purple) mass particles. Black vectors indicate the direction of the gravitational force, $F_g = -GM_1M_2/r^2$, that is experienced by a given particle. Red vectors indicate the direction of the acceleration, $a = F_g/M$, that is experienced by a given particle when the weak equivalence principle holds. There are three possible cases: (i) *top row*: the familiar positive–positive mass interaction, in which both particles accelerate towards one another via gravitational attraction, (ii) *middle row*: the positive–negative mass interaction, in which both particles accelerate in the same direction – pointing from the negative mass towards the positive mass. This case is sometimes referred to as runaway motion, and (iii) *bottom row*: the negative–negative mass interaction, in which both particles accelerate away from one another via gravitational repulsion.

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One of the more bizarre properties of negative mass is that which occurs in positive–negative mass particle pairs. If both masses have equal magnitude, then the particles undergo a process of runaway motion. The net mass of the particle pair is equal to zero. Consequently, the pair can eventually accelerate to a speed equal to the speed of light, *c*. Due to the vanishing mass, such motion is strongly subject to Brownian motion from interactions with other particles. In the alternative cases where both masses have unequal magnitudes, then either the positive or the negative mass may outpace the other – resulting in either a collision or the end of the interaction.

Although counterintuitive and “preposterous” (Bonnor 1989), all of these behaviours violate no known physical laws. Negative masses are consistent with both conservation of momentum and conservation of energy (Forward 1990), and have been shown to be fully consistent with general relativity in the seminal work of Bondi (1957). Crucially, negative masses are a natural cold dark matter candidate, as negative mass material could not gravitationally coalesce in order to form astrophysical structures that can initiate fusion and emit light. As negative masses are attracted towards positive masses, they seem capable of applying pressure onto positive masses that could possibly modify a galaxy’s rotation curve. Furthermore, negative masses also make a natural dark energy candidate, as a diffuse background of mutually-repelling negative masses could drive the expansion of the Universe. The repulsive negative masses would behave as a dark fluid. The