# Round table: Dark matter vs. alternative gravitation
# Dark matter or another kind of gravity?

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**Resumen** / En esta nota ofrezco una breve discusión sobre la necesidad de postular la materia oscura para nuestra comprensión del Universo.

**Abstract** / I offer a brief discussion on the dispensability of dark matter for our understanding of the Universe.

*Keywords* / gravitation — dark matter

## 1. Introduction: the dark matter problem

The so-called Standard Model of Cosmology includes: 1) gravitation described by general relativity (GR), 2) the assumption of the large-scale homogeneity and isotropy of space-time, 3) around 5 % of ordinary matter (baryons and leptons), 4) $\sim$ 25 % of dark matter (DM), 5) $\sim$ 70 % of a field with negative energy density (dark energy), and 6) initial conditions that ensure expansion and the formation of structure in the cosmic fluid. Not surprisingly, this model is somehow uncomfortable: $\sim$ 95 % of whatever exists remains unknown and, even worst, mysterious. This tension is usually alleviated by the slightest possible modification to 1): a term with a "cosmological constant" is introduced in order to allow for a gravitational repulsive behavior that results in the accelerated expansion inferred from astronomical observations of supernovae of Type 1a. The resulting model is dubbed the $\lambda$CDM model. The observed anomalous dynamics on size-scales from galaxies to clusters of galaxies is explained in this model by the existence of an hypothetical "cold dark matter" (CDM) component. This matter can exert gravitational interactions but is immune to electromagnetic and nuclear forces. The only particle in the standard model of particle physics with these characteristics is the neutrino (and its anti-particle) but cosmological constraints require a non-relativistic equation of state for the DM. Hence, if DM exists it must be something radically different from what we know. The primary candidate are weakly interactive massive particles (WIMPs), in particular supersymmetric partners of neutrinos. Alas, supersymmetry has never been proved to be a symmetry of nature and supersymmetric particles remain completely speculative so far. Moreover, all experiments designed for detecting DM particles have failed. Indirect searches based on the detection of annihilation radiation from putative DM particles have also been unsuccessful. After many years of systematic searches and despite huge efforts, the only evidence for DM is gravitational: the very reason of its postulation as an ingredient of the Universe.

## 2. Ontological economy

The scholastic thinker William of Ockham is famously charged with the sentence *Entia non sunt multiplicanda sine necessitate* —although this well-known formulation of the principle of ontological parsimony is not to be found in any of Ockham's extant writings. He actually formulated it as: "For nothing ought to be posited without a reason given". Of course, many theoretical entities have been posited in theoretical science before their actual discovery. The neutrino, the positron, and planet Neptune are just a few examples. Other entities, once postulated and considered very real, are now vanished shadows. In this category we find once popular concepts such as the aether and the phlogiston, among many others.

What makes the postulation of an entity a justified scientific step in the search for a valid explanation? The basic answer is related to the explanatory power of the new concept. If a new idea or concept can explain the known data and lead to new predictions that are successfully tested, then the new concept remains. Otherwise, it is supplemented with new hypothesis in order to face the new evidence, until this process becomes to costly and the whole hypothesis is abandoned. Let us consider, for instance, the aether. It was postulated to reconcile some predictions of electromagnetic field theory with the classical mechanics of waves. When experiment was unable to detect the aether, subsidiary hypotheses were added: the Earth, in its motion, drags the aether, and then we cannot detect relative motion with respect to the latter. This, in turn, introduces new tensions (if the aether is frictionless as required by the stability of the Solar System, how is it possible to drag it?). The accumulation of lack of positive evidence and the absence of new predictions make the whole system of hypotheses to collapse when an alternative theory, with plenty new propositions about reality, is proposed. When relativity theory was formulated, the aether conjecture fell apart.

What is the ontological status of DM in our current cosmological theories? Well, I maintain that it is not too different from that of the aether in electromagnetic theory at the beginning of 20th Century. My reasons are: 1) we are trying to explain observations that are at variance with our most accepted theory of gravitation by postulating entities that obey gravity but require unknown physics with respect to the other forces, i.e. we are explaining the unknown by something that it is even more unknown. Conversely, when we postulated the neutrino or the positron, we were just using well-known conservation laws. 2) Of course, new physical laws can be legitimately postulated in scientific research, but then overwhelming experimental results should support the existence of these new laws. So far, and after decades of search, we have not the slightest evidence for the existence of WIMPs or any other DM candidate. 3) If supersymmetric partners are not found in particle accelerators, it is always possible to claim that they exist but "at higher energies". This makes this hypothesis degenerative from an epistemological point of view.

Under such conditions, it seems legitimate to ask: is it possible to explain the phenomena attributed to DM only with gravity? Not surprisingly the answer is yes.

## 3. Modifying gravity

There are different types of theories of modified gravity. Milgrom (1983) proposed a non-covariant modification of Newtonian gravity that reproduces pretty well the observed rotation curves of galaxies. Bekenstein (2004) and Moffat (2006) proposed covariant gravitational theories that in the adequate limits reduce to Einstein's and Milgrom's theories. In particular, the scalar-tensor-vector gravity theory (STVG), also referred as MOdified Gravity (MOG), is an alternative theory for the gravitational interaction formulated by John Moffat, where the gravitational coupling, $G$, is a scalar field whose numerical value can exceed Newton's constant $G_{\rm N}$. This assumption serves to describe correctly the rotation velocity curves of H I in galaxies (Brownstein & Moffat, 2006), the dynamics of clusters of galaxies (Moffat & Rahvar, 2014), the Bullet Cluster phenomenology (Brownstein & Moffat, 2007), and cosmological data (Moffat & Toth, 2007), without requiring the existence of DM. Moffat proposed also a gravitational repulsive Yukawa vector field $\phi^{\mu}$ through whose effects STVG coincides with GR in the Solar System.

In STVG theory, gravity is not only an interaction mediated by a tensor field, but has also scalar and vector aspects. The action of the full gravitational field is:

$$S = S_{\rm GR} + S_{\phi} + S_{\rm S} + S_{\rm M}, \tag{1}$$

where

$$S_{\rm GR} = \frac{1}{16\pi}\int {\rm d}^4x\,\frac{\sqrt{-g}R}{G}, \tag{2}$$

$$S_{\phi} = -\omega\int {\rm d}^4x\,\sqrt{-g}\left(\frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\mu^2\phi^{\mu}\phi_{\mu}\right), \tag{3}$$

$$S_{\rm S} = \int {\rm d}^4x\,\sqrt{-g}\left[\frac{1}{G^3}\left(\frac{1}{2}g^{\mu\nu}\nabla_{\mu}G\,\nabla_{\nu}G + V(G)\right) + \frac{1}{G\mu^2}\left(\frac{1}{2}g^{\mu\nu}\nabla_{\mu}\mu\,\nabla_{\nu}\mu + V(\mu)\right)\right]. \tag{4}$$

Here, $g_{\mu\nu}$ denotes the spacetime metric, $R$ is the Ricci scalar, $\nabla_{\mu}$ the covariant derivative, $\phi^{\mu}$ denotes a Proca-type massive vector field, $\mu$ is the mass, $B_{\mu\nu} = \partial_{\mu}\phi_{\nu} - \partial_{\nu}\phi_{\mu}$, and $\omega$ is the empirical constant $1/\sqrt{12}$. $V(G)$ and $V(\mu)$ denote possible potentials for the scalar fields $G(x)$ and $\mu(x)$, respectively. I adopted the metric signature $\eta_{\mu\nu} = {\rm diag}(1,-1,-1,-1)$, and units such that $c = 1$. The term $S_{\rm M}$ refers to possible matter sources.

Varying the action with respect to $g^{\mu\nu}$ and doing some simplifications, the field equations result $G_{\mu\nu} = 8\pi G\left(T^{\rm M}_{\mu\nu} + T^{\phi}_{\mu\nu}\right)$, where $G_{\mu\nu}$ denotes the Einstein tensor, and $T^{\rm M}_{\mu\nu}, T^{\phi}_{\mu\nu}$ are the matter and vector field energy-momentum tensors, respectively. The enhanced gravitational coupling is $G = G_{\rm N}(1+\alpha)$, where $G_{\rm N}$ denotes Newton's gravitational constant, and $\alpha$ is a free parameter. STVG coincides with GR for $\alpha = 0$.

Variation of the simplified action with respect to $\phi_{\mu}$ yields:

$$\nabla_{\nu}B^{\mu\nu} = -\frac{\sqrt{\alpha G_{\rm N}}}{\omega}J^{\mu}, \tag{5}$$

where $J^{\mu}$ denotes the four-current matter density, and $\sqrt{\alpha G_{\rm N}}$ is determined to adjust the phenomenology. This vector field is completely absent in GR.

## 4. Tests

How can we test the validity of theories such as STVG? The answer: through their strong field effects. In this regime the field behaves differently from GR. Hence, studies of black holes, radiative effects in their surroundings, neutron stars, and other astrophysical objects where gravity is strong, are paramount to establish the validity of these theories well beyond the regime for which they were devised and originally applied.

## 5. Summing up

Dark matter is not a name for a type of known matter. It is just a hypothesis. And as any hypothesis in science, it must be put to the test. Only if it survives such tests and its explanatory power is stronger than alternative hypotheses, it will survive in our conceptual framework for understanding the Universe. Otherwise, it will perish, as many other illustrious conjectures of the past have perished before.

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