THE EPISTEMOLOGY OF DARK MATTER AND MODIFIED GRAVITY

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Book of Abstracts

1. Rethinking Evidence for Dark Matter: Robust Sources, Gravitational Theory and Physical Principles

Adán Sus – University of Valladolid

It is difficult to question that the historical development of the dark matter problem challenges traditional philosophical accounts of hypothesis confirmation, refutation, and ad-hocness. To put simply, it is both too simplistic and unconvincing to describe the situation as a series of continuous refutations of the dark matter hypothesis, aimed at resolving the discrepancy between gravitational theory-based predictions (whether Newtonian or relativistic) and astronomical or cosmological observations, followed by ad hoc modifications of the initial hypothesis.

However, more illuminating accounts of the evidential framework in gravitational research are possible. One such approach, inspired by the perspective developed in Closing the Loop by George E. Smith, would suggest that rather than testing gravitational theory itself, physicists investigating dark matter are primarily using it as a tool to identify robust sources of the gravitational field. As I interpret it, this approach intensifies the challenge of characterising what constitutes evidence for dark matter. In this talk, I aim to address this issue.

In the first part of the talk, I will examine how Smith's perspective applies to the dark matter problem, in line with previous applications of this methodology to the dark energy problem (Smeenk and Weatherall, 2024). This analysis requires us primarily to clarify the notion of a "robust source" in the context of dark matter research. One might argue that the difficulty here lies in the fact that robustness judgments themselves presuppose gravitational theory, raising doubts about whether the loop can truly be closed in this case.

I will argue that this discussion suggests a need to shift perspective in order to break the deadlock in the philosophical debate on dark matter. Specifically, we should engage in an analysis of the fundamental principles presupposed in dark matter research which allow to identify some observations as dark matter robust sources of the gravitational interaction—principles that alternative theories of modified gravity may not incorporate. To implement this strategy, the second part of my talk will examine the principles underlying claims that certain gravitational lensing phenomena constitute evidence for the dark matter hypothesis. In particular, I will explore which versions of key principles—such as the equivalence principle—are implicitly assumed in these evidential claims. My hope is that analysing some of these principles will allow us to develop a framework for distinguishing between the different possible responses to the dark matter problem and, consequently, to make explicit which fundamental assumptions different theories of Modified Gravity must abandon.

I will conclude by addressing the broader philosophical question of how to interpret these principles and their role in spacetime theories, considering how this discussion connects to broader debates about the function of principles in the formulation of physical theories.

2. Interacting Dark Matter-Dark Energy Cosmologies

Olga Mena – IFIC, CSIC-University of Valencia

Cosmological observations have provided us clear evidences for the existence of both a dark energy and a dark matter components, but their nature and putative interactions, beyond the pure gravitational one, remain unknown. Since observations allow it, one could extend the minimal cosmological model by introducing a new non-gravitational interaction in the dark sector, i.e. between dark energy and dark matter. That is, while the strength of interactions between ordinary matter and the dark energy sector is severely constrained by observations, interactions among the dark sectors are still allowed. Interacting dark matter-dark energy cosmologies are therefore very appealing scenarios where to alleviate current cosmological problems, such as the cosmic coincidence (i.e. the so-called why now? problem, that is, why precisely today the energy densities of dark matter and dark energy are so similar) and cosmological tensions, such as the one between cosmic microwave background estimates and SH0ES (Supernovae and H0 for the Equation of State of dark energy) measurements of the Hubble constant, with a very high significance. Therefore, over the last several years, the intriguing possibility of an interaction between the dark matter and dark energy fluids has been thoroughly investigated using different available cosmological observations. As previously anticipated, the basic underlying idea in these theories relies on the possible non-gravitational interaction between dark matter and dark energy . Such an interaction can be characterized by a continuous flow of energy and/or momentum between these dark sectors. This energy flow modifies the expansion history of the universe both at the background and perturbation levels. In this talk, we shall review the current status of interacting cosmologies, focusing on the fact that interacting dark matter-dark energy cosmologies are known to modify significantly the growth rate of structures in our universe. Analysing the most recent cosmological observations, we will present the current status of interacting dark matter-dark energy cosmologies.

3. From Particles to Pluralism the Changing Ontology and Epistemology of Dark Matter

Simon Allzén – University of Stockholm

The current state of belief about the nature of dark matter in the scientific community is that it is a non-baryonic particle (in the quantum field theoretical sense) which interacts little or nothing electromagnetically. Although this belief appears ubiquitous, this has not always been the case. This paper takes a historical and data driven approach to account for when and why the particle turn of dark matter came to fruition. It also hints at the decline of the particle hegemony as the growth of a new and fragmented ontological landscape is emerging.

4. Dark Matter Realism Reconsidered

Siska De Baerdemaeker – University of Stockholm

Several authors have recently argued against realism about dark matter due to it being empirically unconfirmed or too conceptually thin. In response, Vaynberg (2024) has convincingly argued in favor of dark matter realism based on Bullet Cluster observations. However, anti-realist concerns about conceptual thinness or future empirical detection may linger. I argue that these can be diffused by distinguishing between two different dark matter concepts, which I call astrophysical dark matter and fundamental dark matter. I submit that anti-realist concerns about future dark matter detection conflate empirical confirmation for fundamental dark matter with empirical confirmation for astrophysical dark matter. I further argue that the resulting realist commitment to astrophysical dark matter is more substantive than dark matter anti-realists recognize: it organizes a structured space of possibilities for fundamental dark matter, and it guides further research.

5. A Bayesian Approach to the Copernican Principle

George Papadopoulos – University of Athens

The topic of my presentation is the different definitions of the Copernican Principle and possible ways to test it. The Copernican Principle postulates that we do not occupy a privileged position in the universe and it is strongly linked with the Cosmological Principle, one of the foundational assumptions of our current most accepted model ΛCDM. I begin by examining the relation between the Copernican and the Cosmological principle and I argue that there is a gap between the two principles that we might not be able to bridge entirely. I then discuss different tests of the Copernican principle that can be found in the literature and argue that these tests fail to test the Copernican principle in its entirety. I then try to justify the principle by attempting a Bayesian Analysis on the intuitive idea that it is highly unlikely that we occupy a central position in a spherically symmetric but inhomogeneous universe to conclude that such an analysis is not feasible. Finally, I will attempt a categorization of the different definitions of the Copernican Principle and I will argue that a definition of the form "We are typical observers of the universe" fits its intended use adequately.

6. In which way can we be realists about dark matter?

Nikos Alexiou – University of Athens

The notion of dark matter plays a crucial role in the current standard model of cosmology, namely ΛCDM. Dark matter is considered to make up approximately the 25% of the total mass-energy of the universe and its total exceeds that of ordinary (baryonic) matter by a factor of five. Although there are a lot of theoretical candidates for dark matter, until now none of them has been detected. Nevertheless, various observations indirectly support the existence of DM, such as the Cosmic Microwave Background spectrum and the Bullet Cluster. In this paper, I will investigate the ontological and epistemic status of dark matter and examine whether, and in what ways, we can be realists about its existence. I will analyze dark matter from the perspective of three popular approaches in the philosophy of science. First, I will consider it through the lens of Bas van Fraassen's constructive empiricism, which holds that unobservable entities are merely scientific tools for making predictions and need not be considered literally real. Second, in the light of Ian Hacking's "entity realism", namely the view that theoretical entities can be considered real as long as they can be experimentally manipulated. Finally, within the framework of scientific realism as enriched and analyzed by Stathis Psillos, through which I will examine the metaphysical, epistemic and semantic status of dark matter.

These philosophical perspectives have been applied to unobservable elementary particles However, I shall argue that dark matter should be approached in a slightly different way. On the one hand elementary particles of dark matter, whatever they might be, and thus face the same philosophical challenges as unobservable entities. On the other hand, the present epistemic status of dark matter remains obscure in the framework of modern physics and its ontology is even more problematic.

I will also examine how well the "no miracles argument" can be applied to the case of dark matter. I focus on predictions about the existence of CMB's spectrum anisotropies, due to DM, made in the early 80's, as well as on large-scale, cosmic structure simulations, using DM as a crucial element. Additionally, I will show that Ian Hacking's "entity realism" is inapplicable to this case, as we cannot yet manipulate dark matter experimentally.

I will conclude that in the case of dark matter we have to accept a more moderate thesis, midway between constructive empiricism and scientific realism. We can be metaphysical realists about the existence of DM even though we do not observe it in a fundamental level. We can also be semantic realists about it, meaning that the notion dark matter can be understood literally, as denoting a purportedly real element of our Universe. However, we should not underestimate the fact that the epistemic status of DM remains obscure, and therefore we cannot be epistemic realists about it. Given this uncertainty, I will argue that van Fraassen's constructive empiricism provides a more adequate context for interpreting the status of dark matter within the framework of modern physics.

7. Limiting Reduction and Modified Gravity

Lorenzo Lorenzetti – Università della Svizzera italiana

Modified Newtonian Dynamics (MOND) is a framework of theories that adjust Newton's laws of gravity to explain effects such as galactic rotation anomalies, offering an alternative to dark matter. This essay examines the justification of MOND by assessing its inter-theoretical relationship to established theories across relevant scales, in particular its connection to Newtonian gravitation. We argue that MOND fails a key condition for a theory's justification -- what we call `reduction-wise justification' -- since it does not adequately reduce to Newtonian gravity in a non-arbitrary way. More precisely, despite satisfying the standard formal criteria for successful limiting reduction, MOND does not properly reduce to Newtonian gravitation because of (i) the absence of a fundamental theoretical framework to justify the interpolating function introduced in MOND and (ii) the lack of a unified mathematical structure working across all scales, independent of Newtonian theory. Hence, the case study of MOND provides crucial results for the general debate on inter-theoretic reduction in science: MOND’s failure as a case of reduction highlights important limitations in standard accounts of limiting reduction. We respond by proposing a more refined framework for limiting reduction that introduces two additional criteria to better distinguish successful from pathological reductions. More broadly, this case illustrates how analysing reduction-wise justification can serve as a powerful tool for evaluating the validity of novel theories that are not yet empirically established.

8. Extensions of General Relativity and cosmological dark matter

Konstantinos Skordis – CEICO, Institute of Physics, CzAS

Assuming that gravity on cosmological scales is described by General Relativity (GR) and its non-relativistic approximation, Newtonian gravity, observations indicate that 80% of matter is in the form dark matter. Observations gathered over the last 30 years or so, indicate that dark matter must be approximately cold, and the underlying cosmological model, ΛCDM, provides a superb fit to the data on scales of around 1 Mpc or larger. However, the dark matter particle responsible is so far undetected, and moreover, galactic dynamics display an element of regularity, suggesting a fundamental description that is not easily provided by a dark matter particle.

In this talk, I will briefly touch on the observational evidence for dark matter and focus on two specific systems which display simple empirical laws: spiral galaxies and large-scale cosmology. I will argue that there can be gravitational theories encompassing both and that this implies Lorentz violation in the gravitational sector and present example theories of how this can happen. I will then focus on two specific models, the Aether-Scalar-Tensor and the extended Khronon model, which are particularly tied to the problem at hand, by showing how they can address cosmological observations without having a dark matter particle. I will briefly present the status of these models and discuss future directions.

9. Circularity in Dark Matter Detection Experiments

Rami Jreige – École Normale Supérieure, Paris

Dark matter detection experiments face persistent challenges in interpretation and cross-comparison of results. This paper presents an in-depth investigation into the multifaceted use of models within dark matter detection, proposing a comprehensive taxonomy that distinguishes among background theory, theoretical models, phenomenological models, experimental models, and data models. It will be argued that, while the background theory establishes abstract causal relations and mathematical constraints, it does not directly yield testable results. Rather, it provides a necessary backdrop against which more specific models are developed, and these subsequent models must be constructed with autonomous, independently sourced constraints in order to avoid circular reasoning in the interpretation of experimental data.

The paper categorizes the models into five distinct types. Background theory offers the general structural and relational conditions, but without an explicit object domain. The theoretical model, by contrast, incorporates a domain of objects that introduces additional constraints and specifies interaction properties. This is followed by the phenomenological model, which translates abstract relations into a causal narrative by incorporating the specific details of the particles that are under investigation. The experimental model then adapts these phenomenological constraints to the specifics of detector design and experimental setup in order to communicate between the experimental data and theoretical framework. Finally, data models are developed from the experimental outcomes with the experimental model in mind, serving to either compare observed results with the predictions, or can be used as constraints on the experimental model that will be contrasted against the phenomenological one.

A central argument of the paper is that experimental models must be methodologically independent from their theoretical and phenomenological counterparts. In dark matter detection, this independence is crucial because the detectors are tasked not only with discovering whether dark matter exists, but also with finding out the particle's mass. The dual role of the detector complicates interpretation; since similar interaction signals can be produced by particles with different masses and velocities, the experimental model is burdened with disentangling these overlapping parameter spaces. Moreover, because different experiments employ distinct target materials and methods, direct model-independent comparisons across experimental results remain elusive.

In response to these challenges, the paper also examines several alternative approaches that have been proposed in the literature. Competing models offer divergent causal explanations for the astrophysical phenomena that originally motivated the dark matter hypothesis and can take into account the inconsistent and difficult to interpret results that the detectors have captured. Additionally, model-independent methodologies have been advanced to mitigate the reliance on uncertain phenomenological inputs, though these too face limitations due to residual experimental uncertainties.

The paper will conclude that the persistent lack of conclusive dark matter detection, despite substantial indirect evidence from cosmology, underscores the necessity of critically re-examining the hierarchical and autonomous nature of model construction in experimental practice. By clearly delineating the roles and dependencies of various model types, the paper provides new insights into why inconsistencies persist in the field.

10. Evidence in Cosmology: How Galaxies Became Complicated

Anastasiia Lazutkina – University of Wuppertal

It is a widely accepted view in the philosophy of science that what counts as evidence for a theory depends on the theory itself. However, the question of how a theory selects its evidential base remains largely underexplored. This paper addresses this gap by analyzing a case study in cosmology: the evolving role of galaxies as evidence for cosmological models, particularly those involving dark matter, from the 1970s until now. While galaxies were central to testing and constructing cosmological models, they have, over time, lost their status as decisive evidence. This shift raises questions: Why and how did this happen? What criteria determine whether galaxies count as evidence for particular phenomena and our theories of them?

I trace the historical role of galaxies, showing how phenomena like galactic tidal tails and galaxy morphology provided critical data for evaluating cosmological scenarios of structure formation in the 1970s–1980s. Since the 1980s, advances in the precision, depth, and scope of galaxy observations have been remarkable, but the current standard cosmological model, Lambda Cold Dark Matter (ΛCDM), struggles to account for them (so-called small scales problems). Despite these challenges, the cosmological community largely does not interpret galactic discrepancies as evidence against ΛCDM (De Baerdemaeker & Boyd 2020). Instead, galaxies are considered "too complicated" to provide clean tests of the model. This attitude marks a shift: galaxies, once crucial, are now often dismissed as unreliable sources of evidence. I ask: How did galaxies become "too complicated"? What changed in the epistemic practices of cosmology to account for this shift?

To address these questions, I engage with Harper's (2011) claim that "converging measurements of parameters across diverse phenomena" solidified ΛCDM's status in the early 2000s. I argue that this convergence was selective, as galactic-scale challenges known since the 1990s (e.g. Moore 1994) were excluded from the body of evidence. This suggests that the very notion of evidential convergence is contingent on the theory's criteria for selecting evidence. To analyze these criteria, I employ Curiel's (2024, forthcoming) framework grounded on the idea of epistemic control – an understanding of how a theory connects with empirical data, including its regime of applicability and conditions under which its formalism can be considered physically meaningful. I argue that the loss of epistemic control at galactic scales—due to the complex, multiscale nature of baryonic physics—has rendered galaxies "epistemically untrustworthy" within the ΛCDM framework.

My main argument is that the selection of evidence by a theory is governed by the level of epistemic control over the phenomena in question. When the users of theory lack control over the regime of applicability, e.g. in the case of ΛCDM and galaxies, the phenomena are dismissed as too complex to provide reliable evidence. Curiel's framework not only explains the historical trajectory of galaxies in cosmology but also provides general criteria for understanding how theories determine their evidential bases.

11. Whence the Desire to Close the Universe?

Antonis Antoniou – University of Athens

The spatial geometry of the universe is today widely believed to be flat based on combined data obtained during the 2000s. Prior to this, the geometry and the overall shape of the universe were essentially unknown. However, within the relevant literature one finds claims indicating a strong preference for a (nearly) closed universe, based on philosophical and other ``non-experimental'' reasons. The main aim of this article is to identify these reasons and assess the extent to which philosophical reasoning influenced the establishment of the dark matter hypothesis and the development of models for a closed universe. Building on groundwork laid by \cite{deSwart2020}, this study expands the discussion by (a) arguing that opinions on the geometry of the universe during the 1970s and 1980s were more divided than often assumed, (b) uncovering a lesser-known Machian argument for flat geometry proposed by Dennis Sciama, and (c) presenting a fine-tuning argument stemming from the `coincidence problem' articulated by Robert Dicke. The study provides a nuanced perspective on how philosophical considerations contributed to shaping early views on cosmology and dark matter and highlights the significant role philosophical reasoning can play in guiding scientific inquiry in physics.