DARK MATTER
AND
MODIFIED GRAVITY

Schedule & Abstracts
Interdisciplinary perspectives on the underdetermination between dark matter & modified gravity

“Dark Matter Modified Gravity” is a 3-day conference taking place from 6 to 8 February 2019 at RWTH Aachen University, Germany. It aims to bring together physicists as well as philosophers, historians and sociologists of physics/science working at the interface of dark matter and modified gravity. This conference is organized by the project “LHC and Gravity” within the interdisciplinary, DFG-funded research unit “Epistemology of the LHC”.

Astrophysical and cosmological observations as well as explanatory gaps in the Standard Model of particle physics imply the existence of Dark Matter and/or a modification of our theory of space and time. A decision between the Dark Matter (DM) and Modified Gravity (MG) approaches is hampered by problems of underdetermination at different levels and of different kinds. The plethora of Dark Matter and Modified Gravity approaches, and the corresponding underdetermination, even in the light of the vast amount of relevant collider based and astrophysical observations, clearly illustrates the complexity of this scientific problem. On the other hand, the overlap of the collider and astrophysical domains may allow for reducing the underdetermination, thus leading to a simplification of the model landscape. One focus of this conference is Dark Matter searches at the Large Hadron Collider and the connection between LHC results and theories of gravity. We will address the question of different kinds of underdetermination, both in choosing between the two research programs of Dark Matter and Modified Gravity, and also in choosing between different models within each program. In particular, we aim to provide an assessment of the explanatory power and the explanatory gaps of the Dark Matter and Modified Gravity hypotheses, and the extent to which these might reduce the issues of underdetermination.

Research topics include, but are not limited to:

- Is a strict conceptual distinction between DM and MG justified? How does this relate to the distinction between matter and spacetime?
- What are the explanatory successes and failures of the DM research programme, and of the MG research programme? Which models of explanation are being employed by the respective programmes, and how do those relate?
- Sociology of the DM-MG debate
- How do data, constraints and explanations at the LHC, in astrophysics and cosmology relate?
• Could the LHC, in principle, confirm dark matter by itself?
• Virtues and vices of simplified (dark matter) models. Do simplified models explain?
• Hybrid models, fifth forces & exotic theories that are neither MG nor DM
• Connections between dark energy and DM/MG
• Novel predictions, fine-tuning and falsifiability

Michael Krämer (RWTH Aachen University)
Dennis Lehmkuhl (University of Bonn)
Niels Martens (RWTH Aachen University)
Miguel Ángel Carretero Sahuquillo (University of Wuppertal)
Erhard Scholz (University of Wuppertal)

February 4, 2019
If you are reading the digital version of this document, click [here](#) to access the Google Calendar version of the schedule.

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The first day of the conference focuses on old questions within the general philosophy of science, in the new context of the dark matter vs modified gravity debate. We consider issues of methodology and epistemology: underdetermination, prediction, confirmation, falsification, and explanation. The aim of this day is twofold: using established insights from the general philosophy of science to further the debate, but also updating those insights in light of this pressing and unique dilemma in modern physics.

08:15–08:50  Registration, Coffee & Tea
08:50–09:00  Opening  
Chair: Stacy McGaugh

09:00–10:00  Conceptual differences between Dark Matter, Dark Energy and Modified Gravity
Julien Lesgourgues

10:00–11:00  Galaxy rotation curves: prediction vs. modeling
Robert Sanders

11:00–11:30  Coffee & Tea

11:30–12:30  Progress in Cosmology: An Epistemological Perspective
David Merritt

12:30–14:00  Lunch  
Chair: Gregor Schiemann

14:00–14:45  Underdetermination, disagreement, and the missing mass problem
Abhishek Kashyap

14:45–15:30  Jump Ship, Shift Gears, or Just Keep on Chugging: Assessing the Responses to Tensions between Theory and Evidence in Contemporary Cosmology
Nora Mills Boyd & Siska de Baerdemaeker

15:30–16:15  Can Small-Scale Problems of Cosmology Tell Us About the Nature of Dark Matter?
Marcel Pawlowski

16:15–16:45  Coffee & Tea  
Chair: Martin King

16:45–17:45  Do dark matter computer simulations explain?
Michela Massimi

17:45–18:30  Methodology Round Table
Discussion of the following issues surrounding the general theme ‘Scientific methodology in the context of the DM/MG debate’:
• underdetermination
• prediction
• confirmation
• explanation
• falsifiability

18:30–19:30  Reception
One of the few things that advocates of both camps agree on is that there are indeed two distinct camps. The second day of the conference is dedicated to discussing whether such a strict conceptual dichotomy is indeed fruitful or even tenable. One interesting way in which we will be approaching this question is by comparing two novel theories—superfluid dark matter and entropic/ emergent gravity—which, despite being formally and conceptually quite similar, are standardly labeled as if they fall on opposite sides of the putative dark matter vs modified gravity dichotomy. This discussion will be had alongside a discussion of the tenability of the broader spacetime–matter distinction, in the expectation that those discussions will be mutually beneficial.

09:00–09:30  Coffee & Tea  
Chair: Michela Massimi

09:30–10:30  Superfluid Dark Matter  
Lasha Berezhiani

10:30–11:00  Coffee & Tea  
Chair: Nora Boyd

11:00–12:00  Emergent Gravity and Superfluid Dark Matter: Beyond the Dichotomy of Dark Matter vs. Modified Gravity  
Tobias Mistele

12:00–13:00  Dark Matter = Modified Gravity? Scrutinising the spacetime–matter distinction through the modified gravity/ dark matter lens  
Niels Martens & Dennis Lehmkuhl

13:00–14:30  Lunch  
Chair: Niels Linnemann

14:30–15:15  Alternatives to General Relativity and the Nature of Gravitation  
Marc Holman

15:15–16:15  How to Decide between Dark Matter and Alternative Theories of Gravity  
Erik Curiel

16:15–16:45  Coffee & Tea  
Chair: Joshua Rosaler

16:45–18:00  Dichotomy Round Table  
Discussion of the following issues surrounding the general theme ‘Distinguishing dark matter & modified gravity’:  
• DM/MG dichotomy  
• Spacetime/matter dichotomy  
• Sociology of the DM/MG debate

18:00–20:00  Conference Dinner
Fri 8 Feb – Looking back & moving forward

The final day of the conference considers which lessons can be learnt from the past, in order to guide the future of the dark matter vs modified gravity debate.

08:30–09:00  *Coffee & Tea*  
**Chair:** Kian Salimkhani

09:00–10:00  **How Dark Matter Came to Matter**  
Jaco de Swart & Jeroen van Dongen

10:00–11:00  **Scale invariance at low accelerations (MOND) and the acceleration discrepancies in the Universe**  
Mordehai Milgrom

11:00–11:30  *Coffee & Tea*  
**Chair:** Jaco de Swart

11:30–12:30  **Incommensurate Realities: Predictive Successes of Dark Matter and Modified Gravity**  
Stacy McGaugh

12:30–14:00  *Lunch*  
**Chair:** David Merritt

14:00–15:00  **The Gravity Landscape, 2019**  
Tessa Baker

15:00–15:45  **MOND as a clue to quantum gravity**  
Indranil Banik

15:45–16:15  *Coffee & Tea*  
**Chair:** Radin Dardashti

16:15–17:15  **Dark matter beyond the usual assumptions**  
Felix Kahlhoefer

17:15–18:00  Open Round Table
My talk will be based on what we have learnt from cosmological observations, including the very crucial observation of the CMB anisotropy map. I will explain why on this basis, most cosmologists believe, on the one hand, that the distinction between a Modified Gravity and a Dark Energy model is subtle, and that it is not clear whether one of these two directions is more promising for explaining the acceleration of the universe; while on the other hand, the problems usually requiring a Dark Matter explanation are essentially impossible to solve with a Modified Gravity model.

Galaxy rotation curves: prediction vs. modeling

Robert Sanders
University of Groningen (The Netherlands)

The dark matter approach to rotation curves is very much like the pre-Copernican approach to planetary motion: any improvement in the precision of observations could be accommodated by adding more unseen crystal spheres. The system worked perfectly but finally became rather cumbersome. Moreover, totally new observations could not be accommodated, for example, the observed phases of Venus which are readily explained in the context of the Copernican system. The Platonic system was inherently reactive, not predictive, and the same is true with respect to dark matter. The initial predictions that have been made by cosmic dark matter simulations – cusps in the dark halo mass distribution, for example – are not validated by observations of rotation curves, so there follow decades of work adding new effects to accommodate the models to the facts. The role of modified Newtonian dynamics in addressing galaxy rotation curves is fundamentally different: it is inherently a predictive and not a fitting algorithm and it has been quite successful on the scale of galaxies. I give a number of examples of this basic predictability and discuss the larger implications.
Much effort by philosophers of science in the 20th century was directed toward answering two questions: (1) Are there normative criteria that distinguish science from non-science? (2) If two theories claim to explain the same data, how does one choose between them? According to one influential school of epistemology, the answer to both questions lies in methodology: successful theories tend to predict novel facts in advance of their discovery; unsuccessful theories tend to give post-hoc explanations of chance discoveries, or of facts anticipated by a rival theory. I summarize the basis for these ideas and suggest some applications to current cosmological theories, with a particular emphasis on Milgromian dynamics.

Astrophysical data shows dynamical discrepancy which requires modifications to either the Standard Model (DM), or General Relativity (MG), or both. We infer this as an underdetermination that goes deeper than just the failure to know a priori which modification is required. This account of underdetermination that we propose is significant not because it undermines epistemic attitude towards scientific theories, but because it gives a normative justification for a specific type of sustained disagreement in science. We refer to the developments in the current DM-MG debate to support our arguments.

When is it reasonable to abandon a research program? When would it be premature? We take up these questions in context of a contemporary debate at the border between astrophysics and cosmology, the so-called “small-scale challenges” to the cold dark matter paradigm—discrepancies between outputs of cosmological simulations and observational surveys such as the Missing Satellites Problem, the Cusp/Core Problem, and the Too-Big-to-Fail Problem. We argue that these challenges do not currently support a wholesale abandonment or even modification of cold dark matter. Indeed, the nature of the challenges suggests prioritizing the incorporation of known physics into cosmological simulations.
Can Small-Scale Problems of Cosmology Tell Us About the Nature of Dark Matter?

Marcel Pawlowski
Leibniz-Institut für Astrophysik, Potsdam (Germany)

The standard cold dark matter (CDM) model of cosmology is plagued by a number of small-scale problems. These are mismatches between observations on the scales of (dwarf) galaxies and the results of cosmological simulations. Some researchers see these as falsifications of the underlying theory of CDM, while others attempt to solve the issue by either modifying the simulations, or the properties of dark matter. I will discuss which problems can be addressed in which way, and what fundamental questions this current controversial debate poses for the philosophy of science.

Do dark matter computer simulations explain?

Michela Massimi
University of Edinburgh (UK)

In this talk, I review the role that dark matter computer simulations are playing to explain growth of structure at large scale and to retrieve the Baryonic Tully-Fisher (BTF) relation at the scale of individual galaxies. While an industry has flourished around DM simulations, critics have argued that at best simulations accommodate the BTF evidence, but do not really explain it. In this talk, I take a closer look at the issue of how explanatory DM simulations can be.

Superfluid Dark Matter

Lasha Berezhiani
Max Planck Institute for Physics (Munich, Germany)

After a brief review of some of the empirical correlations between dark and baryonic sectors within galaxies, I will discuss a theory of dark matter superfluidity as a potential explanation of this observations. I will argue that, depending on the mass and self-interaction cross section of dark matter particles, the superfluid may in principle be formed in the central regions of galactic halos. After this, I will discuss the criteria that need to be met by superfluid properties in order to account for the above-mentioned empirical correlations.
Emergent Gravity and Superfluid Dark Matter: Beyond the Dichotomy of Dark Matter vs. Modified Gravity

Tobias Mistele
Frankfurt Institute for Advanced Studies (Germany)

The putative effects of dark matter are most easily explained by a collisionless fluid on cosmological scales, by Modified Newtonian Dynamics on galactic scales, and are absent on solar system scales. In this talk, I will argue that a simple explanation for this different behavior on different scales is in terms of different phases of a single underlying substance. To this end, I will discuss some theories where such an explanation is (at least partially) implemented. In particular, I will discuss aspects of Verlinde’s emergent gravity, a covariant version of Verlinde’s emergent gravity, and superfluid dark matter. I will argue that these theories do not belong to either side of the dark matter vs. modified gravity dichotomy. Moreover, I will present specific predictions, e.g. regarding gravitational lensing.

Dark Matter = Modified Gravity? Scrutinising the spacetime–matter distinction through the modified gravity/dark matter lens

Niels Martens\textsuperscript{1} & Dennis Lehmkuhl\textsuperscript{2}

\textsuperscript{1}RWTH Aachen University; \textsuperscript{2}University of Bonn (Germany)

We investigate what criterion, if any, is supposed to conceptually distinguish dark matter (DM) theories from modified gravity (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 uncovered ambiguities inherent in the DM/MG dichotomy for this broader distinction. We extract from the literature a family of criteria for an object being (dark) matter, as well as a similar family of criteria that determine whether an object is a (modified) spacetime. These criteria are used to evaluate the new field postulated by Khoury and Berezhiani’s theory of ‘Superfluid Dark Matter’ (which resembles Hossenfelder’s Lagrangian formulation of Verlinde’s emergent gravity in crucial ways). It scores (almost) maximally with respect to both families of criteria: the field is (almost) as much of a dark matter field as possible, as well as being (almost) as much of a modification of spacetime/gravity as possible. We discuss how this result should be interpreted. This case study is a first sign that the distinction between modified gravity and dark matter theories—and by extension the spacetime–matter dichotomy—is much less clear than usually assumed, even before reaching the regime where quantum gravity reigns. 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).
Alternatives to General Relativity and the Nature of Gravitation

Marc Holman
Rotman Institute of Philosophy, Western University (Canada)

I review the line of argument that, modulo a few isolated exceptions, the only gravity theories that have a hope of being viable are so-called metric theories, i.e., theories that conform to what is usually referred to as the Einstein Equivalence Principle (EEP). Accepting this line of argument will be seen to provide independent evidence to call into question the prima facie physical difference between “dark stress-energy” fields and “additional gravity” fields and, hence, the usual dichotomy between models based on concordance cosmology and models based upon alternatives to general relativity.

How to Decide between Dark Matter and Alternative Theories of Gravity

Erik Curiel
Black Hole Initiative, Harvard University (USA); Munich Center for Mathematical Philosophy (Germany)

Multiple discrepancies between astrophysical observations of different systems and our theoretical models of them point to the need to modify those models. There are two commonly accepted ways to attempt to explain the discrepancies, and so modify the models. The first is to hypothesize the existence of a form of matter that has not yet been detected by any known observational means, viz., dark matter; this modifies the matter content of the inaccurate models. The second is to propose theories of gravity alternative to general relativity; this modifies the structural and dynamical components of the model. Based on a strengthened version of Lovelock’s classic theorem, showing the uniqueness of the Einstein tensor under physically natural conditions, I argue that there are principled ways to decide whether a proposed particular modification to a theoretical model counts as one or the other. Then, based on an analysis of the evidential structure of our astrophysical observations, I argue that there can be—and in fact there are—principled grounds for deciding whether the evidence favors one or the other type of modification in general.
How Dark Matter Came to Matter
Jaco de Swart & Jeroen van Dongen
University of Amsterdam (The Netherlands)

In 1974, two landmark papers were published by independent research groups in the U.S. and Estonia, that concluded on the existence of missing mass: a yet-unseen type of matter distributed throughout the universe whose presence could explain several problematic astronomical observations. This conclusion is what we now understand as the dark matter problem. In this talk we discuss how the dark matter anomaly was established, and reflect on the historical conditions that made its establishment possible. In particular, we argue that the dark matter problems history is not as straightforward as is often believed.

Scale invariance at low accelerations (MOND) and the acceleration discrepancies in the Universe
Mordehai Milgrom
Weizmann Institute of Science (Israel)

Galactic systems, and the Universe at large, exhibit much larger accelerations than are predicted by Newtonian dynamics and general relativity, if only the matter we actually observe is responsible for gravity. The mainstream comes to the rescue of these revered paradigms by invoking large quantities of ‘dark matter’ – which purportedly supplies the needed extra accelerations – and also of ‘dark energy’, to account for the unexplained accelerated expansion of the Universe. The MOND paradigm offers a different solution: a breakdown of standard dynamics (gravity and/or inertia) in the limit of low accelerations – below some acceleration \( a_0 \). In this limit, dynamics become space-time scale invariant, and is controlled by a gravitational constant \( A_0 \equiv G a_0 \), which replaces Newton’s \( G \). With the new dynamics, the various detailed manifestations of the anomalies in galaxies are predicted with no need for dark matter. An intriguing aspect of MOND is that the MOND constant turns out to carry cosmological connotations: \( a_0 \sim c^2/R_U \), \( R_U \) being ‘the radius of the Universe’. There are MOND theories in which this ‘coincidence’ is natural. I draw on enlightening historical and conceptual analogies to limelight aspects of MOND.
Incommensurate Realities: Predictive Successes of Dark Matter and Modified Gravity

Stacy McGaugh
Case Western Reserve University (USA)

Predictive power is at the root of the scientific method. At present, we are faced with abundant evidence for mass discrepancies that might be explained by the presence of dark matter or the modification of dynamical laws. These programs both enjoy some degree of predictive success that are not obviously explicable by the other. I will highlight what I consider to be the greatest successes and biggest challenges for each.

The Gravity Landscape, 2019

Tessa Baker
Queen Mary University of London (UK)

I will give an overview of current efforts to test the nature of gravity with upcoming experiments. The past decade has seen an evolution from focussed tests of specific gravity models to more agnostic, model-independent campaigns. I’ll explain the theoretical underpinnings of this evolution, and the targets that have emerged as priorities for future galaxy surveys. I’ll also discuss in detail the profound impact that direct gravitational wave detections have had on the landscape of gravity theories, and indicate some novel probes of gravity that are likely to develop over the coming years.

MOND as a clue to quantum gravity

Indranil Banik
University of Bonn (Germany)

As an early career researcher in modified gravity, I will explain what I think are the main motivating factors behind this small yet growing community. Of particular relevance are recently developed hybrid models which attempt to retain the successes of both the dark matter and modified gravity approaches. In the real world, both may exist. This necessitates carefully designed tests. Tests for the presence of dark matter may turn out positive, and yet gravity may still be non-Newtonian (or ‘modified’). I have recently published on a novel test of Newtonian gravity at low accelerations, which I will discuss if possible.
Dark matter beyond the usual assumptions

Felix Kahlhoefer
RWTH Aachen University (Germany)

Dark matter is commonly assumed to be a cold and collisionless fluid with conserved comoving number density. In this talk I will review and challenge these assumptions, focusing on scenarios with dark matter self-interactions and scenarios with non-trivial dark matter density and temperature evolution. I will discuss which observations may help us to discriminate between different forms of dark matter and whether available data may actually disfavour the standard picture.