Celebrating 40 years of Milgromian dynamics and charting the road ahead: opportunities and challenges in galaxies and cosmology

Abstracts

Chair: Françoise Combes

Introduction to MOND

Robert Sanders - Kapteyn Astronomical Institute

A brief scientific biography of Jacob Bekenstein

Here I review the career of Jacob Bekenstein, especially with respect to his contributions to Modified Newtonian Dynamics. As a student, Jacob already made fundamental achievements in theoretical physics, e.g., his proposal that black holes possess entropy proportional to the surface area of the event horizon, which led directly to the idea that information may be encoded on surfaces in higher dimensional space. Following Milgrom's initial papers proposing MOND, he joined with Milgrom to construct the aquadratic Lagrangian-based non-relativistic theory (AQUAL) which enjoyed fundamental conservation principles. In an appendix to this seminal paper, Bekenstein and Milgrom outlined a relativistic version of the theory (RAQUAL) that became a model for covariant theories of MOND as a modification of general relativity and led to a long search culminating in the first viable multi-field theory (TeVeS). This theory produced the correct magnitude of gravitational lensing but predicted (in its original version) sub-luminal propagation of gravitational radiation. Nonetheless, the theory evoked a burst of activity on Vector-Tensor theories (Einstein-Aether), leading to the current best theory (Skordis and Zlosnik) that is consistent with observations of the anisotropies in the cosmic microwave background while producing the observed luminal propagation of gravitational radiation. I reflect briefly on Jacob's personal qualities.

Stacy McGaugh - Case Western Reserve University

Predictions and Outcomes: Tests of ΛCDM and MOND

Predictive power is at the heart of the scientific method, with genuine a priori predictions made in advance of the relevant observations being the gold standard. From its inception, MOND made a number of predictions that were subsequently corroborated. These were surprising in terms of dark matter. I will discuss important examples, both old and new, as this process of making and testing novel predictions continues to this day. [Galaxies, 8 (2020) 35]

Disc galaxy rotation curves

Harry Desmond - University of Portsmouth

Three ways of looking at the radial acceleration relation

I will describe three recent works analysing the SPARC radial acceleration relation in novel ways. The first (arXiv:2301.04368, MNRAS 521: 2, p1817) applies symbolic regression to generate and score all possible functional forms for the RAR, including numerical optimisation of parameters. This suggests the data quality and quantity are not sufficient to infer for example the limiting logarithmic slopes with statistical confidence. The second (arXiv:2303.11314, MNRAS submitted) marginalises over the galaxy parameters upon which g_{bar} and g_{obs} depend (distance, inclination, luminosity, and mass-to-light ratios) to uncover the intrinsic RAR underlying that observed. This reveals an extremely small intrinsic scatter, 0.034+/-0.002 dex, and weak-to-moderate evidence for the external field effect. The third (arXiv:2305.19978) uses machine learning to assess the extent to which the RAR is fundamental, by which I mean that it possesses no residual correlations (so cannot be tightened by the inclusion of other variables), is the tightest projection of galaxies' dynamical parameter space, and is capable of explaining all other dynamical correlations. The answer seems to be yes, and furthermore that it is the uniquely fundamental correlation of late-type galaxy dynamics. This appears to provide strong evidence for MOND.

Kyu-Hyun Chae - Sejong University

Evidence for MOND-type modified gravity in galactic rotation curves and wide binary stars

Evidence for MOND-type modified gravity is presented based on recent analyses of galactic rotation curves and wide binary stars in an acceleration plane. It is shown that with plausible external fields of <0.1 a_0, modified gravity predicts correctly both the inner rising and outer quasi-flat parts of galactic rotation curves. It is also shown that with the Galactic external field of 1.9 a_0, the relative proper motions in wide binaries agree with the prediction of modified gravity but are in tension with the Newtonian prediction at 10σ significance. Distinguishing between two Lagrangian theories of modified gravity (AQUAL and QUMOND) and between modified gravity and modified inertia are discussed based on present and future data.

References:

[1] Chae, K.-H. 2022, ApJ, 941, 55;
[2] Chae, K.-H., et al. 2022, PRD, 106, 3025;
[3] Chae, K.-H. 2023, arXiv:2305.04613

Chair: Stacy McGaugh

Emergent gravity

Erik Verlinde – University of Amsterdam

MOND and the Emergence of Gravity

One of the striking features of MOND is the appearance of a universal acceleration scale, whose value appears closely connected to the Hubble expansion. In the last decade, a lot of progress has been made in the theoretical understanding of the emergence of the gravitational force from an underlying quantum description of space and time. Key ingredients in the theory of emergent gravity are the entropy and temperature associated with event horizons, as well as concepts from quantum information theory such as quantum entanglement and complexity. While initially these studies mostly concentrated on spacetimes with negative cosmological constant and on black hole spacetimes, recently important progress has been made towards applying these same insights to de Sitter space. In this talk, I will review these recent developments and argue that the MOND acceleration scale can be naturally explained within the context of an emergent theory of gravity.

Ruth Kastner - University of Maryland, College Park

Gravity from Transactions: Fulfilling the Entropic Gravity Program

We present new developments in entropic gravity in light of the Relativistic Transactional Interpretation (RTI). A transactional approach to spacetime events can give rise in a natural way to entropic gravity (in the way originally proposed by Erik Verlinde) while also overcoming extant objections to that research program. The theory also naturally gives rise to a Cosmological Constant and to Modified Newtonian Dynamics (MOND) and thus provides a physical explanation for the phenomena historically attributed to "dark energy" and "dark matter".

Elliptical galaxy dynamics

Tom Richtler - Universidad de Concepción

Isolated and central elliptical galaxies: the MONDian perspective

The comparison of brightness profiles of some isolated and central elliptical galaxies suggests (with the exception of the very central regions) universality expressed by the Modified Hubble Profile. In contrast, published mass profiles exhibit more individuality, which means that hypothetical dark matter halos do not leave imprints on brightness profiles. Central galaxies like NGC 1399 and M87 are well described as cored MONDian isothermal spheres, in strong disagreement with published mass profiles. Understanding this disagreement obviously bears importance for the role of MOND in galaxy clusters.

Pierfrancesco Di Cintio - National Council of Research - Institute of Complex Systems (CNR-ISC) & INAF-OAA

The halo mass - flattening relation of elliptical galaxies in the light of MOND

Deur (2014, 2020) and Winters et al. 2022 proposed an empirical power-law relation between the dark to total mass ratio and ellipticity in elliptical galaxies from their observed mass-to-light ratio data $M/L = (14.1 \pm 5.4)\varepsilon$. In other words, the larger is the content of dark matter in the galaxy, the more the stellar component would depart from spherical symmetry. This observational claim appears to be in stark contrast with the common intuition of the formation of galaxies inside dark halos with reasonable spherical symmetry. From the point of view of modified Newtonian dynamics (MOND), this translates into a velocity dispersion-flattening relation. By means of MOND and Newtonian N-body simulations, we investigate the origin of said relations during the process of cold dissipationless collapse. We find that in both paradigms, it should be ascribed to initial conditions characterized by a large amount of orbital radial anisotropy. However, independently of the specific gravity in use, the value of the power law exponent is rather different than that reported by Deur et al.

Chair: Benoit Famaey

Relativistic MOND

Constantinos Skordis - CEICO - FZU, Institute of Physics of the Czech Academy of Sciences

Extensions of General Relativity with a MOND and ΛCDM limit: Aether Scalar Tensor (AeST) theory and beyond

I will discuss extensions of General Relativity constructed so as to reduce to MOND in certain regimes in the weak quasistatic field limit and to ΛCDM in cosmological settings. I will focus on the Aether Scalar Tensor theory (AeST) and how it can fit the cosmic microwave background anisotropies and the large-scale structure power spectrum. If time permits, I will briefly present other possibilities.

Sergio Mendoza – Universidad Nacional Autónoma de México

Some relativistic metric MONDian extensions of gravity

I will describe how curvature-matter couplings constructed with Tully-Fisher and Faber-Jackson scalings in galaxies are able to explain astrophysical phenomenology and the accelerated expansion of the universe without introducing any dark matter/energy entities to the energy budget of the energy-momentum tensor.

The topics I discuss on this talk are mainly covered in the following publications:

(1) Barrientos, E.; Mendoza, S. MOND as the Weak Field Limit of an Extended Metric Theory of Gravity with a Matter-Curvature Coupling. Physical Review D, 2018, 98 (8), e084033. https://doi.org/10.1103/PhysRevD.98.084033.

(2) Barrientos, E.; Bernal, T.; Mendoza, S. Non-Vacuum Relativistic Extensions of MOND Using Metric Theories of Gravity with Curvature-Matter Couplings and Their Applications to the Accelerated Expansion of the Universe without Dark Components. International Journal of Geometric Methods in Modern Physics 2021, 18 (6), e2150086-433. https://doi.org/10.1142/S0219887821500869.

(3) Mendoza, S.; Hernandez, X.; Hidalgo, J. C.; Bernal, T. A Natural Approach to Extended Newtonian Gravity: Tests and Predictions across Astrophysical Scales. MNRAS, 2011, 411 (1), 226–234. https://doi.org/10.1111/j.1365-2966.2010.17685.x.

(4) Mendoza, S.; Bernal, T.; Hernandez, X.; Hidalgo, J. C.; Torres, L. A. Gravitational Lensing with $f(\chi) = \chi^{3/2}$ Gravity in Accordance with Astrophysical Observations. MNRAS, 2013, 433 (3), 1802–1812. https://doi.org/10.1093/mnras/stt752.

Weak gravitational lensing

Edwin Valentijn - Kapteyn Astronomical Institute, University Groningen

<u>Observational tests: constraining modified gravity and cold dark matter hypotheses</u>

I will review recent observations of the OmegaCAM KiDS and SAMI Fornax surveys and how these provide new insights into the merits of various modified gravity and cold dark matter hypotheses. The combined observations appear to point at a scale invariant common origin.

2021A&A...650A.113B Brouwer, Oman, Valentijn et.al
2022MNRAS.517.4714E Eftekhari et. al

Chair: Federico Lelli

Vertical gravity of the Galaxy

Hai-Xia Ma - Nagoya University

<u>Couplings between dark matter and baryonic matter on galactic scales: the radial vs. vertical</u>

In the equatorial plane of disk galaxies, the tight couplings between the excess gravity and the baryonic content, such as the Tully-Fisher relation and mass discrepancy-acceleration relation (MDAR), etc., have inspired modified theories of Newtonian gravity. In this work, we have confronted several different gravitational potential models of the Milky Way (MW) with kinematic data of Gaia DR2 astrometry, by invoking the complete form of Jeans equations that admit three integrals of motion. The results show that the calibrated fiducial model invoking a spherical dark matter (DM) halo and MOND are both consistent with the data at almost all spatial locations. The study emphasizes the effective equivalence between the quasi-linear MOND and DM, where the former has no free parameters while the latter necessitates precise tuning of baryonic parameters. Interestingly, this equivalence could potentially prompt a transcendental synthesis of the two paradigms, especially in the vertical direction. Thus, as the next phase, we are investigating the vertical dynamics of the MW using the best dataset of stars from Gaia DR3 and LAMOST DR8, hoping to give the final answer to the question of whether the MDAR fails in the vertical direction of disk galaxies; in other words, constraining observationally the shape of the (effective) DM halo.

Sofia Splawska - Case Western Reserve University

<u>How "MOND-like" is Quasilinear MOND? Investigating the Vertical Acceleration Field of the Milky Way</u>

The vertical acceleration field of disk galaxies can provide a sharp test to distinguish between MOdified Newtonian Dynamics (MOND) and Dark Matter. Previous work found that MOND is disfavored relative to Dark Matter due to an overprediction of the Milky Way's vertical acceleration compared to observations, but in this work the physically inconsistent pristine MOND was used as a proxy for all MOND-like theories. Here we explore whether the tension with Milky Way data exists with the Quasilinear MOND (QUMOND). We develop a QUMOND Poisson solver using Fourier methods and use it to compare the vertical acceleration fields in exponential disk galaxies with the pristine MOND prediction. Our results have the potential to provide evidence for MOND in the Milky Way or against it.

This work is not yet published but it is based on prior work by our group that has been published: Katherine Brown, Roshan Abraham, Leo Kell and Harsh Mathur, "The radial acceleration relation and a magnetostatic analogy in quasilinear MOND", New Journal of Physics 20, 063042 (2018).

Galaxy groups and clusters

Riccardo Scarpa - Instituto de Astrofísica de Canarias (IAC)

<u>On the orbital velocity of galaxy pairs</u>

Statistical de-projection of the radial inter-velocity for a large sample of isolated galaxy pairs, led to the unexpected discovery of a preferential orbital inter-velocity peak at around 150 km/s. Considering the masses and the physical separations of the involved galaxies, it is shown that this value is fully consistent with the MOND prediction for such systems. We discuss these findings and compare them to claims that a preferential inter-velocity is also consistent with recent ΛCDM numerical simulations. Future works will be focused on samples of galaxies at cosmological distances.

The results are based on work published in two papers:
Scarpa, Falomo, Treves 2022, MNRAS, 512, 544
Scarpa, Falomo, Treves 2022, MNRAS, 510, 2167

Yong Tian - Graduate Institute of Astronomy, National Central University

<u>Parallel Radial Acceleration Relation and Mass-Velocity Dispersion Relation on BCG-Cluster Scales</u>

We investigate dynamical and kinematic scaling relations in galaxy clusters, focusing on the central brightest cluster galaxies (BCGs) among different samples. We examine the radial acceleration relation utilizing weak lensing, strong lensing, and X-ray datasets for 20 high-mass clusters from the Cluster Lensing And Supernova survey with Hubble (CLASH). By incorporating the dynamics of 50 MaNGA BCGs, we identify a parallel Radial Acceleration Relation (RAR) at the BCG-cluster scale, $\log(g_{obs}) = 0.5\log(g_{bar} \times g_‡)$ with a larger acceleration scale $g_‡ = 2.0 \times 10^{-9}$ m/s². The implication of the RAR is a parallel baryonic Faber-Jackson relation. Consequently, we explore the kinematic scaling relation between baryonic mass (M_{bar}) and flat velocity dispersion (σ_{los}) on the BCG-cluster scale, using 29 HIFLUGCS clusters and 54 MaNGA BCGs. We discover the Mass-Velocity Dispersion Relation (MVDR) as $\log(M_{bar}/M_{Sun}) = (4.1 \pm 0.1)\log(\sigma_{los}/\text{km/s}) + (1.6 \pm 0.3)$. The MVDR displays a consistently larger acceleration scale $g_‡$. Notably, the slope of four for the MVDR deviates from the general prediction of a slope of three in the dark matter model.
Reference: Tian et al. (2020), ApJ, 896, 70; Tian et al. (2021), ApJ 910, 56; Tian et al. (2021), ApJL, 917, 24

Pengfei Li - Leibniz Institut für Astrophysik, Potsdam (AIP)

Challenge in galaxy clusters: can adding additional mass help MOND?

We probe the outer dynamical mass profiles of 10 galaxy clusters from the HIghest X-ray FLUx Galaxy Cluster Sample (HIFLUGCS) by numerically solving the spherical Jeans equation. This approach employs galaxy kinematics, which is more comparable to galactic rotation curves than the hydrostatic approach. Since galaxy distributions can be much more extended than X-ray emitting gas, this approach can probe accelerations as low as 10^{-11} ms^{-2}, comparable to the outskirts of individual late-type galaxies. We find that the dynamical masses at small radii are systematically higher than the predictions of the radial acceleration relation (RAR), confirming a well-known missing mass problem for MOND. However, at large radii, the total accelerations fall below what the RAR predicts. This suggests that there is no room to add additional mass in galaxy clusters in the MOND framework.
The talk is mainly based on my recent paper (https://arxiv.org/abs/2303.10175), which has been submitted to A&A. I will also mention some published papers showing similar results for discussion.

Chair: Robert Sanders

The Local Group

Guillaume Thomas - Instituto de Astrofísica de Canarias (IAC)

Probing the strong equivalence principle with Local Group globular clusters and their stellar streams

The strong equivalence principle is one of the pillars of the current gravitational paradigm, so testing its validity is a crucial point of modern Physics. In the MOND framework, this principle is challenged as the external gravitation field generated by a massive object such as a spiral galaxy can impact the internal dynamics of objects orbiting around them. This effect, known as the External Field Effect (EFE), has been shown to play a significant role on the morphology and dynamics of globular clusters, and can ultimately generate asymmetric stellar streams when the same stream is predicted to be symmetric in Newtonian gravity. In this presentation, I will first present the results of these works where we compared the prediction made in the MOND and Newtonian frameworks. In a second part, I will present how the mathematical formalism of an egg and future observational surveys, either photometric, like Euclid, or spectroscopic, like WEAVE or 4-MOST, would allow us to probe the validity of the strong equivalence principle or of the external field effect using Local Group globular clusters and their stellar streams.

Marcel S. Pawlowski - Leibniz Institut für Astrophysik, Potsdam (AIP)

The reports of the demise of the Planes of Satellite Galaxies Problem are greatly exaggerated

Satellite galaxies of several nearby hosts (Milky Way, Andromeda, Centaurus A), and potentially around many more distant ones, show a pronounced flattening and kinematic correlation. Satellite arrangements that are simultaneously as flattened and as kinematically correlated are rare in cosmological simulations and should each only be found in one out of many hundreds to thousand systems. This “planes of satellite galaxies problem” has been a major challenge to the established ΛCDM standard model of cosmology for almost two decades now. Recently, a number of publications have claimed that this tension is now resolved. These alleged successes are, among others, attributed to new cosmological simulations, novel proper motion data, the influence of a massive Large Magellanic Cloud on the orbital poles of satellite galaxies, or based on employing alternative metrics to measure plane coherence. I will review these claims and address their shortcomings, demonstrating that the plane of satellite galaxies problem is far from solved and thus in fact more serious than ever before.
In part based on Pawlowski et al. (2022, ApJ, 932, 70), and others to be submitted.

Kosuke Jamie Kanehisa - Leibniz-Institut für Astrophysik Potsdam (AIP)

Lopsidedness in Andromeda's satellite galaxy distribution: A renewed tension with ΛCDM simulations

Dwarf satellite galaxies around Andromeda (M31) and the Milky Way form thin, coherently rotating planes in tension with expectations from the cold-dark-matter (CDM) model of cosmology. For M31, this disagreement is compounded by a prominent asymmetry in its satellite distribution: over 80% of its dwarfs lie in the hemisphere facing the Milky Way. While lopsided dwarf galaxy systems appear to be ubiquitous in the local Universe, these more distant systems suffer from small observable satellite populations and possible contamination from background sources. Conversely, the local and richly-populated association of confirmed M31 satellites represents a highly lopsided system that any successful cosmology will need to replicate. Adopting a recently published set of homogeneous, RR Lyrae-based distances to the M31 satellites, we discovered that the existing asymmetry is strengthened. 34 out of 35 satellites are contained within a cone with an opening angle of 202° (or 213° facing the Milky Way), while the luminous dwarf M110 dominates the nearly hemispheric void on the other side. We further studied the rarity of similarly asymmetric dwarf galaxy distributions in several state-of-the-art cosmological simulations. Even when accounting for the look-elsewhere effect in selecting a preferred opening angle, less than 0.4% of M31 analogs host satellite systems that match or exceed the observed asymmetry. The degree of tension between the M31 satellites' observed asymmetry towards the Milky Way and CDM simulations now rivals that of M31's plane-of-satellites, cementing the Andromeda system as a striking outlier from cosmological expectations.

Theoretical aspects of MOND (A)

Mordehai Milgrom - Weizmann Institute

MOND as modified inertia

There are major, first-tier predictions that follow from only the basic tenets of MOND, such as asymptotic flatness of rotation curves, the mass-asymptotic speed relation, and the mass-velocity-dispersion relation for isolated, deep-MOND systems. However, the details of many other, lower-tier predictions can depend critically on the exact theory that embody the basic tenets. Specific modified gravity (MG) formulations of MOND, such as AQUAL/QUMOND (A/Q) have been extensively studied as regards their predictions. But it will be quite imprudent to equate MOND with these theories, only because they are the main workhorses at present. It is important to remember that other MOND theories, no less plausible and appealing, may differ, even substantially, from these theories as regards lower tier predictions, such as the exact strength of the external-field effect (EFE), effects in the solar system, the exact coefficient in the M-σ relation, etc.
Here, I discuss a different approach to MOND as being a modification of inertia (MI), not of the gravitational field, as in A/Q. After some general considerations regarding such theories, I describe a concrete example of a family of MI theories, and demonstrate that indeed they can make rather different lower-tier predictions than A/Q. For example, they can predict a stronger EFE than A/Q, suppressing, for example, MOND effects in wide binaries and vertical disc dynamics in the Galaxy. They also predict a negligible effect of the Galactic field on dynamics in the inner solar system, unlike A/Q, which predict a marginally detectable effect with present capabilities. Rotation curves have, almost exclusively, been tested (successfully) using the predictions of MI, but in this case the predictions of A/Q are, at present, hard to distinguish observationally from those of MI.

Asher Yahalom - Ariel University

MOND & Retarded Gravity

We will show that there are overlapping conditions for the need to apply retardation corrections in the weak approximation to General Relativity and the low acceleration conditions for MOND corrections to Newtonian gravity. We will also discuss the general relations between MOND and the weak approximation to General Relativity.

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2. Yahalom, A. The effect of Retardation on Galactic Rotation Curves. J. Phys.: Conf. Ser. 1239 (2019) 012006.
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4. Asher Yahalom "Lorentz Symmetry Group, Retardation, Intergalactic Mass Depletion and Mechanisms Leading to Galactic Rotation Curves" Symmetry 2020, 12(10), 1693; https://doi.org/10.3390/sym12101693
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8. A. Yahalom "The weak field approximation of general relativity, retardation, and the problem of precession of the perihelion for mercury" Proceedings of the International Conference: COSMOLOGY ON SMALL SCALES 2022 Dark Energy and the Local Hubble Expansion Problem, Prague, September 21-24, 2022. Edited by Michal Krizek and Yuri V. Dumin, Institute of Mathematics, Czech Academy of Sciences.
9. A. Yahalom "Lensing Effects in Galactic Retarded Gravity: Why ”Dark Matter” is the Same for Both Gravitational Lensing and Rotation Curves" IJMPD, received 23 May 2022, Accepted 31 August 2022, Online Ready. https://doi.org/10.1142/S0218271822420184
10. Yahalom, A. The Weak Field Approximation of General Relativity and the Problem of Precession of the Perihelion for Mercury. Symmetry 2023, 15, 39. https://doi.org/10.3390/sym15010039
11. Michal Wagman, Lawrence P. Horwitz, and Asher Yahalom "Applying Retardation Theory to Galaxies" accepted to the IARD 2022 proceedings.

Chair: Hongsheng Zhao

Theoretical aspects of MOND (B)

Robert Wilson - Queen Mary University of London

Quaternionic mass quantisation

MOND can be formulated as a modification of the concept of "mass", either as modified inertia or as modified gravity. Either way, mass becomes more complicated than a single real scalar quantity. Quantum mechanics suggests that the mass of an electron, proton, and neutron should be treated separately. If so, then Newton's law of gravitation must be a limiting case of a more general quaternionic equation, in which there are four fundamental gravitating particles. I propose such an equation, using the muon as the fourth particle, and show how it gives rise to MOND-like behaviour.
(Partly based on a paper in International Journal of Geometric Methods in Modern Physics, 19, 2250164.)

Igor Kanatchikov - National Quantum Information Center, Gdansk, Poland

<u>a_0 and Λ from pre-canonical quantum gravity</u>

Within the approach of pre-canonical quantization of gravity to be outlined, the quantum geometry of spacetime is a spin connection foam described in terms of the pre-canonical wave function and correlations on the spin connection bundle over spacetime, which obey the covariant analogue of the Schrödinger equation [1]. The minimal acceleration $a_0 = 8\pi G\hbar\kappa$ (in units with c=1) appears in the simplest solutions of this equation, which correspond to the wave functions reproducing the Minkowski spacetime in the classical limit [2]. Around a_0, the classical notion of the inertial frames loses sense and the dynamics of test particles at these accelerations is modified due to the influence of quantum fluctuations of spin connection around its (vanishing) value in the Minkowski spacetime (in Cartesian coordinates). The parameter κ of the dimension of the inverse spatial volume is introduced by the procedure of pre-canonical quantization of fields [3]. Its relation with the sub-nuclear scale of the mass gap in the non-Abelian gauge theories in 3+1 dimensions $\Delta m \sim (g^2\hbar\text{^}4\kappa)^{1/3}$ is found in [4]. The cosmological constant generated by the proper ordering of operators in the pre-canonical Schrödinger equation, $\Lambda \sim 4^2(8\pi G\hbar\kappa)^2$, leads to the approximate relation $a_0 \approx \Lambda^{1/2}/4$. The observed values are obtained if the scale of κ is around 100 MeV, in agreement with the estimation based on the mass gap. The current errors of the estimations of the values of a_0 and Λ, up to 6 and 12 orders of magnitude, respectively, are due to the uncertainties of the determination of κ from its relation with the Yang-Mills mass gap. These can be improved by further research in applications of pre-canonical quantization.

Based on:
[1] I. Kanatchikov, J. Phys. Conf. Ser. 442 (2013) 012041 (2013); arXiv:1302.2610.
[2] I. Kanatchikov, J. Phys. Conf. Ser. (2023) in press.
[3] I. Kanatchikov, J. Geom. Symmetry Phys. 37 (2015) 43; arXiv:1501.00480.
[4] I. Kanatchikov, Int. J. Geom. Meth. Math. Phys. 14 (2017) 1750123; arXiv:1706.01766.

High-redshift galaxies

Marco Castellano - INAF - Osservatorio Astronomico di Roma

<u>Evidence of an accelerated evolution of the first galaxies in early JWST observations</u>

JWST is transforming our understanding of the high-redshift universe and the epoch of cosmic dawn, with potential groundbreaking implications for cosmology. In this talk, I will present recent results from early JWST observations showing a possible accelerated evolution of the first galaxies and structures, in tension with the ΛCDM cosmological model. I will first focus on the results from the GLASS-JWST survey that led to the discovery of a number of UV-bright ($M_{UV}<-20$) candidates at z>10, which is significantly larger than predicted by theoretical models. I will then discuss the recent evidence of a high abundance of massive ($M>10^{10.5}$ M_{Sun}) galaxies at z~7-10, which is in tension at >2σ with the ΛCDM scenario and excludes a major fraction of the "dynamical dark energy" parameter space that is allowed by other existing probes. I will present these results in the broader context of the observational evidence of accelerated galaxy growth at early times, highlighting the need for detailed modelling of early galaxy evolution and reionization in MOND scenarios.

Relevant publications:
M. Castellano et al. ApJL 2022, https://ui.adsabs.harvard.edu/abs/2022ApJ...938L..15C/abstract
M. Castellano et al. ApJL subm, https://ui.adsabs.harvard.edu/abs/2022arXiv221206666C/abstract
N. Menci, M. Castellano et al. ApJL 2022, https://ui.adsabs.harvard.edu/abs/2022ApJ...938L...5M/abstract

Emiliano Merlin - INAF

Passive galaxies at the dawn of the Universe as a challenge for ΛCDM cosmology

The presence of massive and evolved galaxies at very high redshift is at odds with the predictions of the ΛCDM cosmological scenario, where galaxies are expected to form hierarchically over cosmic history. In the past decade, photometric and spectroscopic searches have confirmed the existence of a population of such "Red and Dead" sources up to z~4; JWST now allows us to observe even more remote epochs. I will review the state of the art about this topic, also presenting the latest findings from JWST in the context of previous results, and highlight the need for predictions of cosmological abundances of these sources in a MOND cosmological framework. I will also make the case for why it is crucial to properly perform a consistent comparison between the predictions from theoretical models and observations, forward modeling the output from simulations rather than naively taking raw numbers at face value, and introducing the code FORECAST, which our group has been developing recently.
Relevant publications: Merlin et al. 2018MNRAS.473.2098M, Merlin et al. 2019MNRAS.490.3309M, Merlin et al. 2022ApJ938L14M, Valentino et al. 2023arXiv230210936V

Federico Lelli - INAF - Arcetri Astrophysical Observatory

Testing MOND in high-z galaxies

I will discuss current efforts and future prospects to test MOND in the early Universe by measuring the rotation curves of high-z galaxies. At z=1-3, several rotation curves have been measured using ionized gas (Hα and [OII] emission lines from integral-field spectroscopy) and/or molecular gas (high-J CO transitions from ALMA interferometry). Both ionized and molecular gas probe only the inner regions of star-forming galaxies, where the typical accelerations are above the value of a_0 measured at z=0. Still, the existing rotation curves are able to rule out a strong increase of a_0 with cosmic time, such as a $(1+z)^b$ with b>4, but cannot probe the deep-MOND regime. At z=4-6, we are starting to measure rotation curves using ALMA observations of the [CII] line at 158 um, which is a multiphase gas tracer probing a combination of ionized, atomic, and molecular gas. The existing [CII] rotation curves are not very extended (a few kpc), but there is evidence that low-surface-brightness [CII] emission may extend out to larger radii (up to tens of kpc), so there is hope for tracing extended rotation curves with a significant investment of ALMA time. In addition, in the near future, JWST and ESO-ELT will provide rest-frame near-IR images of many high-z galaxies, probing their stellar mass distribution with high accuracy and resolution. Thus, we will be able to construct robust mass models to test MOND up to z=6. The next 10 years of MOND look very promising for studies of the early Universe.

Chair: Luc Blanchet

Tests on stellar scales

Harsh Mathur - Case Western Reserve University

MOND as an Alternative to the Planet Nine Hypothesis

A new class of Kuiper belt objects that lie beyond Neptune and are relatively unperturbed by the giant planets, show orbital anomalies that have been interpreted as evidence for an undiscovered ninth planet. We study the dynamics of these Kuiper belt objects under the influence of the Sun and the external field of the galaxy within quasilinear MOND. We find that the objects experience a strong quadrupolar field comparable to that caused by the hypothetical "Planet Nine". Using the well-established secular approximation of Solar System dynamics, we show that MOND predicts that the apsidal vectors of the Kuiper belt objects should be anti-aligned with the direction to the center of the Galaxy and that the orbits should cluster in phase space, in agreement with observations. Thus, MOND can explain the observed Kuiper belt anomalies without invoking a new planet.
Katherine Brown, Hamilton College, Clinton, NY USA
Harsh Mathur, Case Western Reserve University, Cleveland, OH USA

Xavier Hernández – IA- Universidad Nacional Autónoma de México (UNAM)

Internal kinematics of GAIA DR3 wide binaries

Using the recent Gaia DR3 catalogue, we construct a sample of Solar neighbourhood isolated wide binaries satisfying a series of strict signal-to-noise data cuts, exclusion of random association criteria, and detailed colour-magnitude diagram selections to minimize the presence of any kinematic contaminating effects having been discussed in the literature to date. Paying particular attention to minimising the presence of hidden tertiary systems, our final high-purity sample includes binary pairs within 200 pc of the sun and in all cases high-quality Gaia single-stellar fits for both components of each binary, both also restricted to the cleanest region of the main sequence. The results will be discussed during the presentation.

Tests on stellar scales

Charalambos Pittordis - Queen Mary University of London

Wide Binaries from GAIA EDR3: preference for GR over MOND?

Several recent studies have shown that velocity differences of very wide binary stars, measured to high precision with GAIA, can potentially provide an interesting test for modified gravity theories which attempt to emulate dark matter. These systems should be entirely Newtonian according to standard dark matter theories, while the predictions for MOND-like theories are distinctly different, if the various observational issues can be overcome. Here we provide an updated version of our 2019 study using the recent GAIA EDR3 data release: we select a large sample of 73,159 candidate wide binary stars with distance <300 parsec and magnitudes G<17 from GAIA EDR3, and estimate component masses using a main-sequence mass-luminosity relation. We then examine the frequency distribution of pairwise relative projected velocity (relative to circular-orbit value) as a function of projected separation, compared to simulations; as before, these distributions show a clear peak at a value close to Newtonian expectations, along with a long 'tail' which extends to much larger velocity ratios that may well be caused by hierarchical triple systems with an unresolved or unseen third star. We then fit these observed distributions with a simulated mixture of binary, triple, and flyby populations, for GR or MOND orbits, and find that standard gravity is somewhat preferred over one specific implementation of MOND; though we have not yet explored the full parameter space of triple population models and MOND versions. Improved data from future GAIA releases, and follow-up of a subset of systems to better characterise the triple population, should allow wide binaries to become a decisive test of GR vs. MOND in the future.
The Open Journal of Astrophysics, Vol 6, page 4
https://doi.org/10.21105/astro.2205.02846

Indranil Banik - University of Saint Andrews

Strong constraints on MOND from Gaia DR3 wide binaries

I will present a detailed test of MOND using wide binary stars (WBs) with separations of 2-30 kAU. Locally, the WB orbital velocity in MOND should exceed the Newtonian prediction by about 20% at asymptotically large separations given the Galactic external field effect (EFE; MNRAS, 480, 2660). I investigate this with a detailed statistical analysis of Gaia DR3 data on 10290 WBs within 300 pc of the Sun. Orbits are integrated in a rigorously calculated gravitational field that directly includes the EFE. I also allow line of sight contamination and undetected close binary companions to the stars in each WB. I interpolate between the Newtonian and Milgromian predictions using the parameter α_{grav}, with 0 indicating Newtonian gravity and 1 indicating MOND. Directly comparing the best Newtonian and Milgromian models reveals that Newtonian dynamics is preferred at 18σ confidence. Using a complementary Markov Chain Monte Carlo analysis, I find that α_{grav} = –0.036+0.064–0.055, which is fully consistent with Newtonian gravity but excludes MOND at 16σ confidence. This is in line with the similar result of Pittordis and Sutherland (Arxiv:2205.02846, accepted) using a somewhat different sample selection and less thoroughly explored population model. I show that although the best-fitting model does not fully reproduce the observations, an overwhelmingly strong preference for Newtonian gravity remains in a considerable range of variations to my analysis. Adapting the MOND interpolating function to explain this result would cause tension with rotation curve constraints. I discuss the broader implications of these results in light of other works, concluding that MOND must be substantially modified on small scales to account for local WBs.

Hongsheng Zhao - University of St Andrews

What kind of MOND could pass the Wide Binary Test?

I will discuss how current data constrains the nature of MOND and Dark Matter, focusing especially on how the wide binary and CMB set a common scale on curvature, where MOND transits to Einsteinian gravity.

Chair: Indranil Banik

Dwarf galaxies

Jonathan Freundlich - Observatoire astronomique de Strasbourg

Coma cluster ultra-diffuse galaxies as a testing ground for MOND

One of the consequences of Modified Newtonian Dynamics (MOND) as a classical modification of gravity is that the strong equivalence principle – which requires the dynamics of a small, free-falling, self-gravitating system not to depend on the external gravitational field in which it is embedded – should be broken. We test the corresponding MOND external field effect (EFE) on ultra-diffuse galaxies (UDGs) of the Coma cluster, which both have singularly low internal gravitational accelerations and reside within a strong external field. We find that the velocity dispersion profiles of these systems are in full agreement with isolated MOND predictions, but not with the MOND predictions including the EFE. We discuss several options to explain this within the context of MOND and speculate that these results could mean that the EFE is screened in cluster UDGs.
Reference: https://ui.adsabs.harvard.edu/abs/2022A%26A...658A..26F

Srikanth Nagesh - Observatoire Astronomique de Strasbourg

Galaxy clusters in MOND: the case of ultra-diffuse galaxies in the Coma cluster

Ultra-diffuse galaxies (UDG), low-surface brightness objects with large effective radii, inside galaxy clusters have very low internal gravity, which renders them ideal candidates for testing the Modified Newtonian Dynamics (MOND) paradigm as a possible alternative to dark matter. Freundlich et. al. (2022) studied the velocity dispersions of several UDGs in the Coma cluster and compared them with the predictions of MOND. While the agreement would have been excellent if these galaxies were isolated, there seems to be an apparent disagreement because of the so-called ‘external field effect’ (EFE) related to the gravitational influence of the cluster. The authors have proposed several scenarios that could possibly explain this discrepancy. Building on this work, I will be presenting results of numerical simulations of UDGs orbiting around the Coma cluster, in MOND. We look at some of their dynamical properties, compare them with observations, and subsequently try to explain whether the UDGs are within the realm of reconciliation or beyond.

Dwarf galaxies

Elena Asencio – University of Bonn

The distribution and morphologies of Fornax Cluster dwarf galaxies suggest they lack dark matter

Due to their low surface brightness, dwarf galaxies are particularly susceptible to tidal forces. The expected degree of disturbance depends on the assumed gravity law and whether they have a dominant dark halo. This makes dwarf galaxies useful for testing different gravity models. In this project, we use the Fornax Deep Survey (FDS) dwarf galaxy catalogue to compare the properties of dwarf galaxies in the Fornax Cluster with those predicted by the Lambda cold dark matter (ΛCDM) standard model of cosmology and Milgromian dynamics (MOND). We construct a test particle simulation of the Fornax system. We then use the MCMC method to fit this to the FDS distribution of tidal susceptibility η (half-mass radius divided by theoretical tidal radius), the fraction of dwarfs that visually appear disturbed as a function of η, and the distribution of projected separation from the cluster centre. This allows us to constrain the η value at which dwarfs should get destroyed by tides. Accounting for an r′-band surface brightness limit of 27.8 magnitudes per square arcsec, the required stability threshold is η_{destr} = 0.25+0.07−0.03 in ΛCDM and 1.88+0.85−0.53 in MOND. The ΛCDM value is in tension with previous N-body dwarf galaxy simulations, which indicate that $\eta_{destr} \approx 1$. Our MOND N-body simulations indicate that η_{destr} = 1.70±0.30, which agrees well with our MCMC analysis of the FDS. We therefore conclude that the observed deformations of dwarf galaxies in the Fornax Cluster and the lack of low surface brightness dwarfs towards its centre are incompatible with ΛCDM expectations but well consistent with MOND.
Monthly Notices of the Royal Astronomical Society, Volume 515, Issue 2, September 2022, Pages 2981–3013, https://doi.org/10.1093/mnras/stac1765

Michal Bílek - Paris Observatory

Can the observation of globular clusters in low-mass galaxies exclude MOND modified gravity?

Globular clusters (GCs) have the potential to bring light to the missing mass problem. It has been argued earlier that dark matter halos of dwarf galaxies must have central cores, to prevent their GCs quickly settling into their galaxy nuclei: the time necessary for dynamical friction to remove the GC's energy and angular momentum would come out less than the age of the clusters if the halos were cuspy. The sunk GCs would form nuclear star clusters. It was found analytically that the problem of fast GC sinking is even more severe for MOND, a leading alternative to dark matter that otherwise well reproduces galaxy dynamics. The problem was anticipated for low-mass low-surface-brightness galaxies. We inspected the issue using high-resolution simulations. We initially investigated GCs of gas-free ultra-diffuse galaxies. We found that first GCs indeed approach the center of their host galaxy quickly, but then, once the GC moves within the central half effective radius of the galaxy, the sinking almost stops, opposing the analytic predictions. This comes from simplifying assumptions made when deriving analytically the dynamical friction effect. The phenomenon called core stalling occurs, that had previously been described in Newtonian gravity and is the reason why GCs can survive for a long time in cored dark matter halos. Next, we explored the consistency of MOND with the existence of GCs in isolated dwarf galaxies. These disky galaxies hold a large fraction of their baryons in the form of gas. We found that a GC will indeed spiral quickly into the center, but only if it moves inside the disk, co-rotates, is relatively massive ($\sim 10^5\ M_{Sun}$), and supernova explosions do not affect the distribution of interstellar gas noticeably. If any of these conditions is broken, then the GC has no problem to survive for a Hubble time. In MOND, supernova explosions cause strong fluctuations in the gravitational potential of the galaxy, giving random velocity kicks to the GCs, preventing them falling into the galaxy center.
Based on Bilek+2021, Astronomy & Astrophysics, Volume 653, id.A170, 17 pp. and work in progress.

Chair: Moti Milgrom

MOND-like theories

Luc Blanchet - Institut d'Astrophysique de Paris

Dipolar Dark Matter

Dipolar dark matter is a hybrid model to account for the MOND formula at galactic scales and the standard cosmological model ΛCDM at cosmological scales. This model is based on the dielectric analogy of MOND and interprets the phenomenology of MOND as resulting from an effect of "gravitational polarization" of a medium made of dipole moments, aligned in the gravitational field of ordinary masses, and representing a new form of dark matter.

Tobias Mistele - Case Western Reserve University

Hybrid MOND dark matter models confronted with weak lensing data

Hybrid MOND dark matter models aim to explain both the successes of ΛCDM on cosmological scales and those of MOND on galactic scales. Recent examples of such models are superfluid dark matter (SFDM) and Aether Scalar Tensor theory (AeST). Around galaxies, both models postulate a MOND-like force as well as a special type of condensate. Sufficiently close to galaxies, where rotation curves are measured, the condensate is unimportant. Thus, these models reproduce MOND there and can explain the observed regularities in rotation curves. Further away from galaxies, however, the condensate becomes important, leading to deviations from MOND. Unfortunately, these deviations often set in at galactocentric radii that are too large to be probed by rotation curves. In contrast, weak gravitational lensing observations extend to much larger galactocentric radii. Indeed, a recent lensing analysis found MOND-like behavior up to ~1 Mpc. I discuss how these observations constrain AeST and rule out SFDM.

Françoise Combes - Paris Observatory

Is there an alternative to MOND?

Some models of dark matter, in particular cold dark matter, face problems at galaxy scales, especially the cusp/core challenge in their centre. Solutions have been proposed in terms of fluctuations of the potential due to baryonic irregularities. Another scenario is based on axions, with a large de Broglie length, as large as the core. This latter model produces quantum fluctuations in the potential that lead to strong constraints on the axion mass. Simulations will be described to quantify these constraints. Based on El Zant et al 2020, MNRAS 492, 877 and Hashim et al 2023, MNRAS 521, 772

Large-scale structure

Tessa Baker - Queen Mary University of London (QMUL)

Twin Tests of Cosmological Gravity

I will introduce the landscape of relativistic modified gravity theories motivated in cosmology. We will discuss their experimental tests with both electromagnetic and gravitational wave observations, and review some of the major developments over the past few years. We will also meet some of the software tools being developed to analyse departures from GR with both large-scale structure and gravitational waves, and the different modelling challenges faced in each regime.

Alfie Russell - University of St Andrews

Can cosmological simulations of vHDM ease the large-scale tensions in cosmology?

The “Standard Model of Cosmology” (ΛCDM) is increasingly in tension with new observations. High redshift galaxies observed by JWST and galaxy clusters such as El Gordo are too massive too early, voids such as the local KBC void are too wide and too deep, whilst the Hubble Tension casts doubt onto our understanding of Dark Energy. The vHDM model aims to solve these tensions by combining MONDian gravity with a Hot Dark Matter (HDM) component. The HDM will free stream out of galactic scales allowing MOND to dominate, whilst on larger scales MOND will enhance structure formation. To probe the large-scale structure formation in this model, I am carrying out Gpc-scale N-body simulations using the Phantom of Ramses code. Initial results confirm the production of larger clusters and deeper voids, with comparisons to the observed Cluster Mass Function allowing constraints to be placed on compatible Dark Matter particle masses. The simulations will also test whether bulk flows out of an analogous KBC void would ease the Hubble Tension in this model.

Poster contributions

Francis Duey - University of Oregon

The Baryonic Tully-Fisher Relation from WISE Photometry of SPARC Galaxies

We present the new WISE baryonic Tully-Fisher relation (bTFR) for the SPARC (Spitzer Photometry and Accurate Rotation Curves) sample with improved photometry, new M/L models, and extended gas masses. The SPARC sample with redshift independent Cepheid or TRGB distances are added with the Ponomareva et al. (2018) sample to form a new, distance independent bTFR of 62 galaxies. The new bTFR has a slope of 4.00±0.09, in agreement with predictions from MOND, and in sharp tension with values predicted by ΛCDM models. In addition, the new WISE distance bTFR provides an opportunity to deduce a value of H_0 using every galaxy with an accurate rotation curve by varying the expected total baryon mass until a minimal fit is obtained. Such an experiment results in a value of H_0 of 74.8 ± 1.8 (stat) ± 1.5 (sys) km//Mpc.

Mike Gerrard - Imperial College of London

A Modified Inertia Interpretation of MOND

A Modified Inertia Interpretation of MOND
M.B. Gerrard and T.J Sumner, Imperial College

A five-dimensional framework applied to orbital dynamics supports a modified inertia interpretation of MOND and, in particular, can be used to derive transition functions between the Newtonian and MOND regimes for galaxy rotation curves, both with and without the External Field Effect. These are tested against data published by Chae et al. The same five-dimensional framework when applied to an expanding universe can derive the MOND acceleration (a_0) without reference to orbital dynamics, as a function of the gravitational constant, baryonic mass density of the Universe, and the speed of light (without any free parameters). The value of a_0 arising from this analysis is in good agreement with that deduced from galaxy rotation curves by Milgrom et al. The five-dimensional framework can also support gravitational lensing beyond GR expectations. The additional (fifth) dimension considered in this analysis does not represent a degree of freedom of motion. The universe so modelled has two modes of expansion: that of three-dimensional space and that of the fifth dimension itself, where the latter expansion is a path of least action. These complementary modes of expansion, in turn, lead to Hubble’s constant (H_0) being comprised of two terms: the first provides a theoretical basis for the MOND approximation, identified by Milgrom, namely $cH_0 \sim a_0$; and the second (much smaller) term provides a possible explanation for tension between values for H_0 derived from the CMB and those derived from either supernovae or gravitational lensing data. The same five-dimensional framework also provides a good fit to the observed relationship between distance modulus and redshift for Type 1a supernovae, without an accelerating expansion of the universe, and so without the inference of Dark Energy.
A paper based on this analysis has been submitted to the Foundation of Physics journal and is currently under peer review. Some of the concepts were presented at the Marcel Grossmann conference in Rome (2018) and published in the proceedings.

Carlo Nipoti - Università di Bologna

Testing QUMOND theory with Galactic globular clusters in a weak external field

Author: Antonio Sollima (in memoriam, poster presented by the co-authors C. Nipoti, F. Calura, R. Pascale and H. Baumgardt)

We developed self-consistent dynamical models of stellar systems in the framework of quasi-linear modified Newtonian dynamics (QUMOND), constructed from the anisotropic distribution function of Gunn & Griffin (1979). We have used these models, and their Newtonian analogues, to fit the projected density and the velocity dispersion profiles of a sample of 18 Galactic globular clusters, using the most updated datasets of radial velocities and Gaia proper motions. We have thus obtained, for each cluster, estimates of the dynamical mass-to-light ratio (M/L) for each theory of gravity. The selected clusters have accurate proper motions and a well-sampled mass function down to the very-low mass regime, which allows us to constrain the degree of anisotropy and to provide, from comparison with stellar evolution isochrones, a dynamics-independent estimate of the minimum mass-to-light ratio $(M/L)_{min}$. Comparing the best-fitting dynamical M/L with $(M/L)_{min}$, we find that for none of the analyzed clusters are the two significantly incompatible, although for one of them (NGC 5024), the dynamical M/L predicted by QUMOND lies a 2.8σ below $(M/L)_{min}$. Our results suggest that the kinematics of globular clusters in a relatively weak external field can be a powerful tool to prove alternative theories of gravitation.
This contribution presents the last work led by our friend and colleague Antonio Sollima, who unfortunately passed away two months ago. It is based on a paper (Sollima, Nipoti, Calura, Pascale, Baumgardt , in prep.), which we are going to submit to MNRAS.

William Beordo - University of Turin - Istituto Nazionale di Astrofisica (INAF)

Milky Way rotation curves with Gaia DR3: direct comparison between DM, MOND, and General Relativistic paradigms.

Rotation curves constitute the distinctive signature of disc galaxies and their stellar kinematics trace the gravitational potential due to different matter components. We therefore select 719,143 young disc stars within $|z| < 1$ kpc and up to $R = 19$ kpc from the Gaia DR3, providing a much larger sample of high-quality astrometric and spectrophotometric data of unprecedented homogeneity. This sample comprises 241,918 OBA stars, 475,520 RGB giants, and 1705 Cepheids that we use to compare three different dynamical models: a classical one with a dark matter halo, the MOND analogue, and a general relativistic one derived from a dust disc-scale metric. The three models are found to explain, with similar quality, the new observed rotational velocities of the different stellar populations of our Galaxy, providing parameter estimates consistent with previous works. Moreover, predictions on the total baryonic mass are in agreement between the models, at least within the radial range covered by our samples. Finally, the geometrical effect is expected to drive the velocity profile from 10 kpc outwards, while being responsible for 30 - 37 % of this profile already at the Sun's distance, similarly to the halo contribution in the classical model and the pure Mondian boost in the low acceleration regime. With the best ever Gaia data at our disposal, the three scenarios are shown to be statistically equivalent.
[This contribution is based on a paper of Beordo W., Crosta M., Lattanzi M., Re Fiorentin P., Spagna A., which will soon be submitted].

Michal Bílek - Paris Observatory

Imprint of the galactic acceleration scale on globular cluster systems

Mass discrepancies are observed in galaxies at galactocentric radii that are larger than the MOND radius, the radius where the gravitational acceleration generated by the baryons of the galaxy is lower than the constant $a_0 = 1.2\times10^{-10}$ m/s^2. The constant a_0 is sometimes called the galactic acceleration scale. Most galaxies are orbited by globular clusters. We found previously for massive early-type galaxies that the radial number-density profiles of their globular cluster systems are described by broken power laws and the breaks occur at the MOND radii. We newly analyzed a catalog of globular cluster candidates in the Fornax galaxy cluster from the recent Fornax Deep Survey and an archival HST catalog. This allowed us to confirm that 1) the coincidence between MOND radii and the break radii of globular cluster systems is valid for early-type galaxies of all masses; and 2) the same finding applies to the red and blue sub-populations of globular clusters separately. The breaks are consistent for globular cluster candidates selected photometrically and spectroscopically. We investigated preliminarily several potential explanations of the match of the break and MOND radii, nevertheless none of them works perfectly.
Based on Bilek et al. 2019, Astronomy & Astrophysics, Volume 629, id.L5, 5 pp. and work in progress.

Michal Bílek - Paris Observatory

What is the origin of the different kinematic morphologies of early-type galaxies?

Early-type galaxies (i.e. elliptical and lenticular) are divided into slow and fast rotators according to the appearance of their maps of line-of-sight velocity. Fast rotators show clear ordered rotation, while slow rotators are supported mostly by velocity dispersion. I will present our work on investigation of the origin of this diversity. Inspired by cosmological simulations, we assumed that galaxies first form as fast rotators and then mergers transform some of them to slow rotators. We investigated the correlations of a measure of rotational support with various properties of galaxies that are sensitive to mergers. These include stellar ages, the presence of tidal features, and kinematically distinct cores. Each of these parameters is sensitive to a different type of merger and has a different lifetime. The found correlations, or their lack, together with observations of the high-redshift Universe, are explained the easiest if the rotation support of early-type galaxies was decreased by multiple minor wet mergers more than 10 Gyr ago. The results indicate that the formation of early-type galaxies in the ΛCDM-based simulations is too extended, and that late-time mergers play relatively little role in the evolution of these galaxies.
Based on Bilek et al. 2023, arXiv:2210.02478 (A&A, accepted)

Michal Bílek - Paris Observatory

Origin of the prominent tidal features in the galaxy NGC 474

NGC 474 is a nearby lenticular galaxy famous for its dramatic system of tidal shells and streams. Such structures form in galaxy collisions. One of the shells and the galaxy itself were recently studied spectroscopically by two teams. We contributed to the investigations of this prominent object by applying the analytical shell identification method for estimating the time since the collision from the observed sizes of shells. We moreover run N-body simulations in Newtonian and MOND gravities that reproduce much of the morphology of the observed galaxy. This allowed us to build a detailed scenario of what has been happening in the galaxy over the last ~1 Gyr and how the tidal features formed. This includes the time since the merger, the geometry of the collision, and the explanation of the young stellar populations in the galaxy. The scenario accounts for all observational constraints. This work demonstrates how useful MOND is for deciphering the formation of galaxies. More elaborate simulations of the galaxy can hopefully distinguish between MOND and the dark matter hypothesis.
Based on Bilek+2022, Astronomy & Astrophysics, Volume 660, id.A28, 20 pp.

Sara Tosi - University of Oregon

The Baryonic Size-Mass Relationship for SPARC Galaxies

We explore the mass-size relation for the SPARC galaxy dataset, a kinematically selected sample of rotating galaxies with excellent Spitzer photometry. A dichotomy in the baryon mass-isophotal radius plane is found, with late-type galaxies outlining a distinct sequence from bulge-dominated early-type galaxies. Although both sequences contain strictly rotating disks, the presence of a bulge has an inverse effect on the size of the disk as the stellar mass of the bulge becomes an increasing component of the total baryonic mass. We compare the mass-size relation of early-type galaxies at redshift 0 with the GLASS-JWST sample at a redshift of 6 and deduce a factor of ten increase in galaxy effective radius since that epoch.
Publication: American Astronomical Society Meeting #241, id. 410.04. Bulletin of the American Astronomical Society, Vol. 55, No. 2 e-id 2023n2i410p04

Federico Re - Università di Milano Bicocca

Evolution of the equivalent Newtonian systems in MOND and QuMOND simulations

For a given stellar system in modified Newtonian dynamics (MOND), one can always define the so-called Equivalent Newtonian Systems (ENS), a system with the same baryon distribution of the parent MONDian model embedded in a dark matter (DM) halo such that their total potential and force field are the same as the original system in MOND. The phantom DM density however is not always positively defined at all radii, in particular for highly flattened mass distributions. On the other hand, an ENS with positive phantom DM halo can correspond to a MOND system that violates the Positive Mass Theorem. In this work, we study the DM density evolution of the ENSs in MOND dissipationless collapses. We find that some end states of some simulations, perfectly compatible with the scaling laws of elliptical galaxies, are however reached via processes that in Newtonian gravity would have involved negative dark mass, at least at some radii.

Kurt Koltko

MOND and Gauge CPT: Similarities, Differences, and Connection

The weak field Gauge CPT force law is presented and compared with the MOND low acceleration formula. The origin of the same 1/r dependence is presented as a property of the Gauge CPT Lagrangian. The origin of the different square root of neutrino luminosity source term of gauge CPT as a property of the same Lagrangian is also presented. The connection between MOND and Gauge CPT is discussed by determining the gauge CPT force strength constant from the characteristic MOND acceleration, or vice versa. Gauge CPT has no problems with the Bullet Cluster, is derived from an experimentally verified symmetry, and has cheap verifiable experimental predictions.

This poster is based on my peer-reviewed publications in the “Foundations of Physics, Letters” paper “A Gauge Theory of CPT Transformations to first order,” pp. 299-304, volume 15, 2002; “Proceedings of the International Conference: Cosmology on Small Scales, Excessive Extrapolations and Selected Controversies in Cosmology, Prague, September 2020,” paper “The baryonic Tully-Fisher law and the Gauge Theory of CPT Transformations,” pp. 84-92; “Proceedings of the International Conference: Cosmology on Small Scales, Dark Energy and the Local Hubble Expansion Problem, Prague, September 2022,” paper “Gauge CPT experimental predictions,” pp. 114-120; an invited review paper “Gauge CPT: a Review and Use in Constructing New Affine Connections,” currently under review for “The International Journal of Geometric Methods in Modern Physics”; and an invited contribution “A Brief Tour of Gauge CPT,” currently under review for the Proceedings of the DICE2022 Conference, Castigniocello, Italy, September 2022.

Valentina Cesare – INAF - Osservatorio Astrofisico di Catania

Dynamics of Disk and Elliptical Galaxies in Refracted Gravity

We test Refracted Gravity (RG) by investigating the dynamics of disk galaxies in the Disk Mass Survey (DMS) and three elliptical E0 galaxies in the SLUGGS survey without the aid of dark matter. RG reproduces the rotation curves, the vertical velocity dispersions, and the observed Radial Acceleration Relation (RAR) of DMS galaxies and the velocity dispersions of stars and blue and red globular clusters of the E0 galaxies. Our results show that RG can compete with other theories of gravity to describe the gravitational dynamics on galactic scales.
Publications:
[1] Cesare V., Diaferio A., Matsakos T., and Angus G., 2020, A&A, 637, A70, https://doi.org/10.1051/0004-6361/201935950
[2] Cesare V., 2021, Phys. Sci. Forum, 2(1), 34, https://doi.org/10.3390/ECU2021-09292
[3] Cesare V., Diaferio A., and Matsakos T., 2022, A&A 657, A133, https://doi.org/10.1051/0004-6361/202140651
[4] Cesare V., 2023, Universe, 9(1), 56, https://doi.org/10.3390/universe9010056

Xavier Hernández – IA - Universidad Nacional Autónoma de México (UNAM)

Will observed wide binaries in UFDs and dynamical friction falsify the CDM hypothesis?

Since their discovery, ultra-faint galaxies, at the smallest edge of the galactic spectrum, have revealed through their stellar kinematics the need for the highest relative amounts and the highest local densities of dark matter found in any astronomical class of systems, under standard gravitational assumptions. The assumed dark matter halos perfectly account for the observed stellar kinematics but also imply a further effect through dynamical friction. Any binary star found within such a dark matter halo will inevitably evolve towards a tighter configuration as its internal angular momentum is slowly dissipated into the dark matter halo. Timescales for this process are generally much larger than the Hubble time, but on reaching the $\rho_{DM} \approx 1\ M_{Sun}\ pc^{-3}$ and low velocity dispersion values of UFDs, wide binaries with internal separations wider than a few tens of pc will show important tightening over the extended lifetimes of these very old stellar populations. Here I show that recent detections of wide binaries in Reticulum II with internal separations ≈1 pc are already close to falsifying the dark matter hypothesis for this galaxy, while the future detection of such populations in other smaller UFDs would be incompatible with the presence of the dark matter halos necessary to explain their observed stellar velocity dispersions.

Mark Huisjes - Utrecht University

<u>Accelerations from Molecular Clouds in the Milky Way: Testing MOND on the ~30 parsec scale?</u>

Miville-Deschênes et al. (2017, hereafter MD17) have published a large molecular cloud catalogue for the Milky Way from which baryonic and observed accelerations can easily be computed. The physical parameters of these clouds are determined using the kinematic distance method matching line of sight velocities to a rotation curve. MD17 uses a rather old rotation curve that stays perfectly flat in the outer galaxy instead of slowly declining, so it can be improved upon. This poster presents the MD17 dataset with updated kinematic distances for almost half the sample using the rotation curve by McGaugh (2019). Despite these systems being embedded in an external field of 2 a_0 due to the Milky Way, a rather RAR-like behaviour is apparent in the data. Much work still needs to be done to better understand the nature of the tidal forces, magnetic support, and the external fields on these systems.

List of participants

1. James Arathoon (Symdex Limited)
2. Elena Asencio (University of Bonn)
3. Tessa Baker (Queen Mary University of London)
4. Indranil Banik (University of St Andrews)
5. William Beordo (University of Turin)
6. Michal Bílek (Paris Observatory)
7. Luc Blanchet (Institut d'Astrophysique de Paris (CNRS))
8. Marco Castellano (Osservatorio Astronomico di Roma (INAF))
9. Valentina Cesare (Osservatorio Astrofisico di Catania (INAF))
10. Kyu-Hyun Chae (Sejong University)
11. Françoise Combes (Paris Observatory)
12. Oscar Cray (University of St Andrews)
13. Harry Desmond (University of Portsmouth)
14. Pierfrancesco Di Cintio (Arcetri Observatory (INAF))
15. Francis Duey (University of Oregon)
16. Amel Durakovic (Central European Institute for Cosmology and Fundamental Physics)
17. William Ehrlich (Tesla)
18. Benoit Famaey (Observatoire astronomique de Strasbourg (CNRS))
19. Jonathan Freundlich (Obsevatoire Astronomique de Strasbourg)
20. Mike Gerrard (Imperial College London)
21. Konstantin Haubner (University of Erlangen)
22. Phillip Helbig
23. Xavier Hernández (Universidad Nacional Autónoma de México)
24. T.F Hodgkinson (University of Salford)
25. Mark Huisjes (Utrecht University)
26. Vasileios Kalaitzidis (University of St Andrews)
27. Igor Kanatchikov (National Quantum Information Centre (KCIK))
28. Kosuke Jamie Kanehisa (Leibniz-Institut für Astrophysik Potsdam)
29. Ruth Kastner (University of Maryland)
30. Kurt Koltko
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49. Federico Re (Università di Milano-Bicocca)
50. Tom Richtler (Universidad de Concepción)
51. Peter Rix
52. Alfie Russell (University of St Andrews)
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60. Yong Tian (National Central University)
61. Sara Tosi (University of Oregon)
62. Edwin Valentijn (Kapteyn Astronomical Institute)
63. Erik Verlinde (University of Amsterdam)
64. Robert Wilson (Queen Mary University of London)
65. Michael Wright
66. Asher Yahalom (Ariel University)
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68. Hongsheng Zhao (University of St Andrews)