WORKING GROUP 1

“Modified Gravity”

“Cosmology and Astrophysics Network for Theoretical Advances and Training Actions (CANTATA)”

1st Grant Period Report

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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1. Overview

CANTATA aims at establishing a network of European experts to construct and develop an effective theory of gravity able to describe our Universe at all scales. The first working group (WG1), "Modified Gravity" (MG), is focused on the formulation and theoretical investigation of *Modified*, *Alternative* or *Extended Theories of Gravity* at infrared and ultraviolet scales. In particular, WG1 investigates modifications of general relativity to test their viability at Solar System scales, considering also the existing constraints on potential violations of the Equivalence Principle. On the other hand, it explores the high-energy regime to look not only for new phenomenology but also for a fundamental level interpretation of these theories. Consequently the results of this working group have to be combined with the deliverables of WG2 and WG3 to find viable theories of gravity and, therefore, WG1 connects the working groups of the action.

In the "kick-off" meeting Prof. Salvatore Capozziello (University of Naples "Federico II") and Dr María del Prado Martín Moruno (Complutense University of Madrid) were appointed leader and co-leader of WG1, respectively. During the 1st grant period both have lead the working group participants to achieve the scientific milestones presented in the memorandum of understanding through the suggestion of some specific tasks and the encouragement of networking activities. Furthermore, according to COST policies and the common objectives of CANTATA, WG1 is engaged in supporting, training and promoting early stage researchers, and empowering female scientists. To this aim two specific tasks have been proposed for the 1st grant period and the co-leader has joined the gender lab of the action to obtain relevant feedback for the working group.

2. Members profile

2.I Academic profile

Our members have interest and/or experience in one or more of the following topics:

- foundations of MG,
- Solar systems and other tests of MG,
- Mathematical cosmology in MG,
- Quantum effects and gravity.
- Quantum Cosmology

2.II Anthropological profile

From the beginning of the action WG1 has been leading the statistics of participation of researchers based at ITCs. The percentage of researchers based at ITCs has continued increasing during the grant period and, currently, we are leading the statistics regarding this COST policy.

On the other hand, during the first stage of the first grant period, we have noted a decrease of the percentage of female scientists in our WG at the same time that the percentage of participants from ITC countries increased. In particular, at 5 of July of 2016 there were a 17% of female scientists in WG1 against the 21% in the whole network. After interaction with members of the gender lab (being the co-leader part of this lab), the leader and co-leader of WG1 undertake the measure of contacting renowned female scientists based at CANTATA countries to inform them about the existence of the network and its potential beneficial impact. When the WG meeting took place, WG1 had improved their data to a 19.8% of female researchers against the 23.4% of the whole action. We took the opportunity to inform about this imbalance and ask for help to improve it to other members of the group. At the time this report is been written the statistics are even better in this respect (see table at the end of this section). It should be noted that, although the percentage of female scientists in WG1 is still slightly lower than the corresponding percentage in the whole action, WG1 is the second WG in female representation.

Finally, at a first stage of this grant period the WG1 also had slightly less participation of ECIs than other working groups. This potential imbalance, however, has been adjusted naturally due to the normal growth of the action. Nowadays WG1 is leader in ECIs participation.

111 members (data at 14 Feb. 17)	**#**	**%**	**% in CANTATA**
Students	34	**30.6**	33.3
ECIs	30	**27.0**	23.9
Researchers based at ITCs	46	**41.4**	30.8
Female researchers	23	**20.7**	22.4

3. Tasks

3.I Research tasks

The scientific tasks to be developed during the first grant period are:

T1. Provision of a robust classification of concurring theories at mathematical and physical level.

T2. To find discriminators to be compared with experiments at UV and IR scales. [In collaboration with WG2 and WG3.]

T3. To calculate post-Newtonian parameters towards Solar System and astrophysical scales tests. [In collaboration WG2]

T4. Comparison of MG with effective quantum field theory, classifying new phenomenology.

T5. To test MG with phenomenology coming from running experiments, and to consider the black hole information paradox in MG.

T6. Quantum cosmology

3.II Networking tasks

WG1 have also additional tasks to benefit the participants through networking:

- Training PhD students and post-docs. This activity will be promoted by frequent short visits of learning people.
- Promotion of ECIs by collaborating in filming and producing a movie, in which ECI disseminate the scientific basis of the network.

4. Scientific topics highlighted in the WG meeting

The WG meeting structure was chosen to strengthen scientific discussion between the participants. After a 5 minutes welcome to the session by the leader and a 10 minutes introduction to the WG presented by the co-leader, there were 3 25 minutes talks where some selected participants introduced some hot topics emphasizing open questions in the field. Later, there was a discussion of 1 hour and 15 minutes in which all the participants were able to ask the speakers, present their opinion on related topics, and/or present additional open question.

4.I A hybrid metric-Palatini gravitational CANTATA: Astrophysical and cosmological applications

[*Presented by Dr Francisco S. N. Lobo*]
Recently, the phenomenology of f(R) gravity has been scrutinized motivated by the possibility to account for the self-accelerated cosmic expansion without invoking dark energy sources. Besides, this kind of modified gravity is capable of addressing the dynamics of several self-gravitating systems alternatively to the presence of dark matter. It has been established that both metric and Palatini versions of these theories have interesting features but also manifest severe and different downsides. A hybrid combination of theories, containing elements from both these two formalisms, turns out to be also very successful accounting for the observed phenomenology and is able to avoid some drawbacks of the original approaches. We review the formulation of this hybrid metric-Palatini approach and its main achievements in passing the local tests and in applications to astrophysical and cosmological scenarios, where it provides a unified approach to the problems of dark energy and dark matter. In addition to this, we also attempt to build bridges with WG2 and WG3, by proposing several research projects.

4.II Dynamical constants as modified gravities

[*Presented by Prof. Mariusz Dabrowski*]
In my talk I will review various formulations of the three main dynamical constant theories: varying gravitational constant G theory, varying fine structure constant α theory, and most controversial varying speed of light c theory. These dynamical constants theories are obviously modified Einstein gravity theories and so I will then try to show how these theories are related to each other. In particular, to scalar field extended gravities, higher-order in curvature gravities or superstring and brane theories. I will also present some most important benefits of dynamical constant theories against general relativity and other alternative gravities. In order to be fair I will also rise some problems with dynamical constant theories. Finally, some challenges and open issues related to dynamical constants and modified gravities will be suggested in a provocative for a discussion manner.

4.III Torsional modified gravity and cosmology

[*Presented by Dr Emmanuel N. Saridakis*]
Almost all the efforts in modifying gravity have been performed in the usual curvature-based framework. On the other hand, it is well known that one can

equivalently describe gravity using torsion. We investigate the case where one modifies gravity based on its torsional-teleparallel formulation, and we study the corresponding cosmological applications. Moreover, we analyse the perturbations of the theory examining the growth history, we construct a cosmological bounce, and we use solar system and cosmological observations in order to impose constraints on the torsional modifications. Additionally, we analyse the charged black hole solutions of these theories. Finally, we study the case where torsion is non-minimally coupled to a scalar field or its derivatives, as well as other extensions of the theory, using higher-order torsion invariants, or various torsion-matter couplings.

4.IV Discussion

The discussion session was particularly prolific and many participants of different institutions took part of the discussion actively. In this report we include some topics of discussion, related with different tasks.

T1:

- How can we differentiate MG from dark energy models?
- Are different gravitational modifications with the same number of (extra) degrees of freedom equivalent?
- What is the proper formulation of varying c theories from the action principle (Lorentz symmetry violation)? In which MG framework can this work most natural?

T2:

- Can we discriminate hybrid metric-Palatini gravity from other MG theories?
- What new tests/telescopes can do to measure dynamical constants/MG effects more precisely?

T3:

- Can MG be a viable alternative to the dark matter problem? (e. g. explaining the bullet cluster)?

T5:

- What are the massive and massless modes of gravitational waves in hybrid metric-Palatini gravity?
- Can we measure the signal from other universes (e.g. through the wormhole) which may show different dynamics of constants than in our universe? How could we measure this (entanglement temperature influencing the cosmic microwave background)?

T5:

- Can MG give some insight into parallel universes evolution? Can this be explored in the LHC for the micro black hole and other particle states (e.g. separate universe problem)?

T6:

- There are self-consistent quantum cosmology scenarios related to MG? In particular, what is the role of the Wheeler–De Witt equation in MG?

5. Deliverables

CANTATA has encouraged scientific discussions leading to new research ideas. Apart of these important contributions, which are not measureable in a direct way, the interaction of members of WG1 and of theses members with those of other WGs has lead to more tangible deliverables that are detailed in this section. It should be noted that, in some cases, the classification of one deliverable as belonging only to one WG would be artificial; therefore, overlapping with the reports of other WGs should be expected in this regards.

5.I Publications

A CANTATA publication is a paper that it is co-authored by at least two authors based at two different CANTATA countries and acknowledges CANTATA for support. In this section, we include CANTATA publications that are oriented towards the accomplishment of the objectives of WG1, although overlapping with other WGs is in some cases completely necessary.

Reports in progress to be published in "General Relativity and Gravitation"

1. M. Bouhmadi-López, C. Kiefer and P. Martín-Moruno, "*Phantom singularities and their quantum fate: General Relativity and beyond*".
2. G. Olmo, D. Rubiera-García and H. Sanchís-Alepuz, "*Stellar structure in modified gravity*".

Articles

1. D. Brizuela, C. Kiefer and M. Krämer, "*Quantum-gravitational effects on gauge-invariant scalar and tensor perturbations during inflation: The slow-roll approximation*", Phys. Rev. D 94 (2016) no.12, 123527 doi:10.1103/PhysRevD.94.123527 [arXiv:1611.02932 [gr-qc]].
2. J. P. Mimoso and D. Pavón, "*Considerations on the thermal equilibrium between matter and the cosmic horizon*", Phys. Rev. D 94 (2016) no.10, 103507 doi:10.1103/PhysRevD.94.103507 [arXiv:1610.07788 [gr-qc]].
3. D. Bazeia, L. Losano, G. J. Olmo and D. Rubiera-Garcia, "*Geodesically complete BTZ-type solutions of 2+1 Born-Infeld gravity*", Class. Quant. Grav. 34 (2017) no.4, 045006 doi:10.1088/1361-6382/aa56f5 [arXiv: 1609.05827 [hep-th]].
4. C. Bambi, D. Rubiera-Garcia and Y. Wang, "*Black hole solutions in functional extensions of Born-Infeld gravity*", Phys. Rev. D 94 (2016) no.6, 064002 doi:10.1103/PhysRevD.94.064002 [arXiv:1608.04873 [gr-qc]].
5. S. Bahamonde, U. Camci, S. Capozziello and M. Jamil, "*Scalar-Tensor Teleparallel Wormholes by Noether Symmetries*", Phys. Rev. D 94 (2016) no.8, 084042 doi:10.1103/PhysRevD.94.084042 [arXiv:1608.03918 [gr-qc]].
6. J. Morais, M. Bouhmadi-López, K. Sravan Kumar, J. Marto and Y. Tavakoli, "*Interacting 3-form dark energy models: distinguishing interactions and avoiding the Little Sibling of the Big Rip*", Phys. Dark Univ. 15 (2017) 7 doi:10.1016/j.dark.2016.11.002 [arXiv:1608.01679 [gr-qc]].
7. J. Beltrán Jiménez, D. Rubiera-Garcia, D. Sáez-Gómez and V. Salzano, "*Cosmological future singularities in interacting dark energy models*", Phys.

Rev. D 94 (2016) no.12, 123520 doi:10.1103/PhysRevD.94.123520 [arXiv:1607.06389 [gr-qc]].
8. A. Addazi, S. Capozziello and S. Odintsov, "*Born–Infeld condensate as a possible origin of neutrino masses and dark energy*", Phys. Lett. B 760 (2016) 611 doi:10.1016/j.physletb.2016.07.047 [arXiv:1607.05706 [gr-qc]].
9. P. Avelino *et al.,* "*Unveiling the Dynamics of the Universe*", Symmetry 8 (2016) no.8, 70 doi:10.3390/sym8080070 [arXiv:1607.02979 [astro-ph.CO]].
10. A. K. Ahmed, M. Azreg-Aïnou, S. Bahamonde, S. Capozziello and M. Jamil, "*Astrophysical flows near f(T) gravity black holes*", Eur. Phys. J. C 76 (2016) no.5, 269 doi:10.1140/epjc/s10052-016-4118-5 [arXiv:1602.03523 [gr-qc]].

Preprints

1. P. Brax, A. C. Davis and R. Jha, "*Neutron Stars in Screened Modified Gravity: Chameleon vs Dilaton*", arXiv:1702.02983 [gr-qc].
2. C. Bejarano, G. J. Olmo and D. Rubiera-Garcia, "*What is a singular black hole beyond General Relativity?*", arXiv:1702.01292 [hep-th].
3. A. Izadi, S. S. Shacker, G. J. Olmo and R. Banerjee, "*Observational effects of varying speed of light in quadratic gravity cosmological models*", arXiv:1701.06923 [gr-qc].
4. J. M. Ezquiaga, J. García-Bellido and M. Zumalacárregui, "*Field redefinitions in theories beyond Einstein gravity using the language of differential forms*", arXiv:1701.05476 [hep-th].
5. V. Salzano, D. F. Mota, S. Capozziello and M. Donahue, "*Breaking the Vainshtein screening in clusters of galaxies*", arXiv:1701.03517 [astro-ph.CO].
6. S. Bahamonde and S. Capozziello, "*Noether Symmetry Approach in f(T,B) teleparallel cosmology*", arXiv:1612.01299 [gr-qc].
7. M. Mars, T. T. Paetz and J. M. M. Senovilla, "*Classification of Kerr-de Sitter-like spacetimes with conformally flat Scri*", arXiv:1610.09846 [gr-qc].
8. M. Bouhmadi-López, S. Capozziello and P. Martín-Moruno, "*Self-acceleration and matter content in bicosmology from Noether Symmetries*", arXiv: 1610.07346 [gr-qc].
9. E. Guendelman, E. Nissimov and S. Pacheva, "*Quintessential Inflation, Unified Dark Energy and Dark Matter, and Higgs Mechanism*", arXiv:1609.06915 [gr-qc].
10. Sepehri, A. F. Ali, K. Bamba, S. Capozziello, R. Pincak, A. Pradhan, F. Rahaman and E. N. Saridakis, "*Cosmological expansion and contraction from Pauli exclusion principle in M0-branes*", arXiv:1608.07683 [gr-qc].
11. A. Sepehri, R. Pincak, K. Bamba, S. Capozziello and E. N. Saridakis, "*Current density and conductivity through modified gravity in the graphene with defects*", arXiv:1607.01499 [gr-qc].
12. C. Bejarano, F. S. N. Lobo, G. J. Olmo and D. Rubiera-Garcia, "*Palatini wormholes and energy conditions from the prism of General Relativity*", arXiv:1607.01259 [gr-qc].

5.III Short term scientific missions (STSMs)

- Gabriel Farrugia (PhD student based at Malta). Visit to Greece to develop the project "*Open and closed universes in f(T) gravity*".
- Lavinia Heisenberg (ECI based at Switzerland). Visit to Portugal to develop the project "*Modified Gravity a la Born Infeld*".
- Manuel Krämer (ECI based at Poland). Visit to Portugal to develop the project "*Multiverse impact onto the cosmic microwave background and its relation to modified gravity*".

5.IV Outreach

- CANTATA video, http://cantata-cost.eu/multimedia/ by Prado Martin-Moruno, Diego Saez-Goméz, José Alberto Cembranos, Lavinia Heisenberg, Matteo Martinelli, Bridget Falck, Jackson Levi Said, Thomas Tram, Mariafelicia De Laurentis, Vincenzo Salzano. Promotional CANTATA video emphasizing the interconnection of different nodes and the influential role of ECIs within the action.
- "*Quantum black holes*" (in Spanish), Gonzalo J. Olmo, Valencia (Spain). Public Talk. https://www.youtube.com/watch?v=ne-FHGIwNRM
- "Black Holes, Wormholes, and Gravitational Waves" (in Spanish), Diego Rubiera-García, Gijón (Spain). Public talk.

6. Overview and comments for the next grant period

In summary, during the 1st grant period WG1 has growth rapidly by the addition of new participants from countries that were already included in the initial proposal and participants based at new countries that have joined CANTATA. During this growth, we have actively implemented measures according to COST strategy of promoting excellence and inclusiveness, encouraging the participation of researchers of different genders and affiliations at different stages of their careers. As a result, scientific interactions between researchers interested in formulating an effective theory of gravity able to describe our Universe at different scales have been established and strengthened.

The following concrete deliverables produced during the first grant period have to be emphasized: the beginning of collaborations oriented to produce reports that will be published in General Relativity and Gravitation; the publication of CANTATA papers in international journals, which are papers co-authored by researchers based at two (or more) CANTATA countries acknowledging CANTATA support; CANTATA preprints, which are available online but are not yet published in international journals; short term scientific missions funded by CANTATA to create new collaborations focused on particular hot topics; and, outreach activities acknowledging the network.

In order to improve our results for the next grant period we plan to implement concrete measures to continue encouraging the collaboration between the participants of the WG1 and of these researchers and those from other WGs within the action. Moreover, we plan to strengthen the outreach activity of WG1 to increment the impact of our results in the society.