WORKING GROUP 3

“Observational Discriminators”

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

1st Grant Period Report

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1. Members profile

On February 28th 2017, about one month before the official end of the first grant period, the WG3 is made up of 51 people, resulting in the most homogeneous and balanced of the three WGs.
Participants come from 9 countries, 4 of which are "Inclusiveness Target Countries" (ITC), namely, Poland, Portugal, Serbia and Turkey; plus France, Germany, Netherlands, Spain and United Kingdom.
We have, by large, the highest percentage of women, about 31%; and of Ph.D. students, about 40%. Comparing such numbers with the percentage for the same categories in the whole CANTATA, WG3 is largely above the average.
We also show good statistics about "Early Career Investigators" (ECIs), with a 23%; and the ITC countries contribute with about 23% to the total WG3 human resource.

One element which emerged during the first official CANTATA meeting, held in Lisbon on November 14th-15th, is that the presence of women in/from ITC countries is strongly under-represented. The same problem was also shared by other WGs. We have thus envisaged, as one the primary tasks for future planning, to try to improve the presence of women from ITC countries in our working group.

Moreover, the WG3 is clearly the "youngest" group in the Action. This element, together with the presence of many more-senior experts in the field of numerical codes related to cosmology in the same group, has quite naturally led to the final decision that the first school (i.e. an Action activity devoted to the training of young students and researchers) should have been characterized by a strong "numerical" side, in order to fulfil the requirements of the participants and the goals of the same Action.

51 members (@ 15 Mar. 2017)	#	%	% in CANTATA
Students	20	**39,2**	33,3
ECIs	12	**23,5**	23,9
Researchers based at ITC	12	**23,5**	30,8
Female researchers	16	**31,4**	22,4

2. 1st WG meeting

2.1 - Scientific Talks

During the first meeting held in Lisbon on November 14th-15th, in order to present to the whole Action audience what are the expertises involved in WG3, and what are the possible routes to follow in the future, the leader of the group, in collaboration with the Action Chair and the co-leader, has selected three researchers to give a talk at the above meeting.

Dr. Matteo Martinelli, an ECI currently affiliated to the Leiden Institute (NL), previously member of the *Planck* collaboration, and now actively involved in the

EUCLID ESA mission. In his talk titled *"Current and future data for dark energy and modified gravity"*, he has briefly reviewed some of the latest available cosmological data, focusing in particular on the (statistical) tension between different observations which might hint for deviations from the standard consensus model, the ΛCDM paradigm. He has also discussed upcoming surveys which will allow to improve current observations, and experiments possibly providing new ways of investigating the evolution of the Universe.

Dr. Noemi Frusciante, an ECI currently affiliated to the Instituto de Astrofisica e ciências do espaco, Science Faculty of the University of Lisbon (PT, ITC). In her talk, *"Stability requirements when exploring Large Scale Structure Observables"*, she has provided a glimpse on the possible implications of a correct development of modified gravity models and its implementation in numerical codes. Given the wide sample of dark energy and modified gravity models (DE/MG) that address late time accelerated scenario and the hight precision data, it becomes crucial to test DE/MG theories against data on large scales. Irrespectively of the MG model adopted, one has to ensure that the evolution of the modes associated to the extra degrees of freedom (DoF) does not lead to pathological instabilities, such as ghost, gradient and tachyonic instabilities. In particular, when studying cosmological perturbations the additional DoF is couple to one or more DoFs representing the matter fields dynamics, then these couplings imply that a consistent and complete study of the stability of the whole system can not be done without considering the interaction with the matter sector. In fact, the stability conditions might be altered by the presence of the additional matter fields, thus changing the viability space of the theory. Identifying the correct viability requirements is important when testing MG theories with cosmological data by using statistical tools, as they can reduce the viability space one needs to explore. She has presented a thorough stability analysis of modified gravity theories when the coupling to matter field is considered. With the aim to obtain general results, she has emplyed the Effective Field Theory for DE/MC formalism to parametrize in a model independent way deviations from General Relativity.

Dr. Ismael Tereno, senior researcher at the the Instituto de Astrofisica e ciências do espaco, Science Faculty of the University of Lisbon (PT, ITC). In his talk, titled *"Observational discriminants: the case of weak lensing"*, he has sketched the weak lensing pipeline for cosmological model testing, focusing on the importance of self-consistency and accuracy of theoretical predictions in a time of high-precision data.

2.2 - Discussion

Following the presentation of such talks, we have had a discussion with all the participants, also from other groups.

First of all, we have made clear what are the possibilities of the WG3. It is obvious it has a clear self-identity: we have many people joining it, each one bringing his/her own expertise and research interests. Now that we have a more clear idea of who participates to the group, we can start to identify tasks and sub-groups in order to improve cooperation and take advantage of the network in an active way, not only relying on the "my-own-backyard" work from each one. In light of such

organization, one of the main goal of the WG3 activity will be to try to offer to other WGs a sort of list of agnostic tests of Modified Gravity (MG) teories. This would be quite desirable, because such tests would be completely model-indepedent, i.e. not depending on any possible theoretical input coming from, for example, WG1. This is a quite high-level task: to come up with new powerful ideas of observables that could open a new branch to test gravity and give indications to WG1/WG2 about the road to follow for the final Action objective, i.e., a consistent generalized theory.

On the other hand, it is also clear that the WG3 is, by its nature, very strongly tied to both WG1 and WG2. In this sense, it can be a perfect expression of the COST keywords, i.e. network and collaborative effort: it can perfectly be a cross-group, joining people and scientific results from different "geographic location and different scientific interests". In some case, theoretical models are able to give direct clues about "where and how" to act; WG3 will have to analyze proposals from WG1 and WG2 and test them. This will provide useful feedback on the optimal observables to focus on. In order to do this in an efficient way, we will have to build a prioritized list of models of extended gravity to compare with observational discriminators. Such approach is clearly a model-dependent analysis of observables, but has its own purposes, as to confute or confirm a particular model.

As non-scientific issue, we have also tried to involve participants in a discussion related to a more basic issue: to find out the best way to communicate, at least, internally to WG3. We have thus created a GoogleDoc document, which we have shared with all the WG3 participants, so that they can answer our questions and leave suggestions and/or opinions, and make us able to organize the network in the best way possible. In particular, we have asked them to specify what are their present competencies; what they would like to work on; if there is any topic they would be trained; and if they have any idea about possible immediate cooperation.

3. Deliverables

The work conducted by WG3 participants within CANTATA in this first grant period has come out in a series of tangible and easily quantifiable deliverables, mainly works which ended up in already published (or accepted for publication) papers, and/or collaborations made available to the scientific community through the most common on-line archive, arXiv, but still at an early stage of referring process.

Below, an updated (at February 28th) list of such papers. We have considered only works from, at least, 2 CANTATA countries. And we will list, as WG3 deliverables, only works with a majority of co-authors from WG3 and/or whose topic matches objectives of WG3.

3.1 - Papers Published

1. Title: *"Breaking the Vainshtein screening in clusters of galaxies"*
Main WG: WG3
Authors: Vincenzo Salzano (PL, WG3), David F. Mota (NO, WG2), Salvatore Capozziello (IT, WG1), Megan Donahue
Journal: To be published on Physical Review D

doi: http://10.1103/PhysRevD.95.044038
Notes: Collaboration among all WGs and three countries (Poland, Norway, Italy)

2. Title: *"No need for dark matter in galaxy clusters within Galileon Theory"*
Main WG: WG3
Authors: Vincenzo Salzano (PL, WG3), David F. Mota (NO, WG2), Salvatore Capozziello (IT, WG1)
Journal: JCAP 1610 (2016) no. 10, 033 (2016-10-20)
doi: 10.1088/1475-7516/2016/10/033
Notes: Collaboration among all WGs and three countries (Poland, Norway, Italy)

3.2 - Papers Under Review

1. Title: *"SNe Ia and BAO observational constraints on hybrid metric-Palatini gravity"*
Main WG: WG3
Authors: Iker Leanizbarrutia (ES, WG3, Ph.D. student), Francisco S.N. Lobo (PT, WG1), Diego Saez-Gomez (ES, WG1, ECI)
link: arxiv.org/1701.08980
Notes: Collaboration among WG3 and WG1 and two countries (Spain, Portugal), one of which is ITC, and involving 1 Ph.D. Student and 1 ECI.

2. Title: *"Observational effects of varying speed of light in quadratic gravity cosmological models"*
Main WG: WG3
Authors: Azam Izadi (IRAN, WG1, ECI), Shadi Sajedi Sacker (DE, WG3), Gonzalo J. Olmo (ES, WG1), Robi Banerjee
link: arxiv.org/1701.06923
Notes: Collaboration among WG3 and WG1, two CANTATA countries (Germany, Spain) and one xxx (Iran) (what is Iran?)

3. Title: *"Field redefinitions in theories Beyond Einstein gravity using the language of differential forms"*
Authors: Jose Maria Ezquiaga (ES, WG3), Juan Garcia-Bellido (ES, WG3), Miguel Zumalacarregui (SE, WG2, ECI)
Link: arxiv.org/1701.05476
Notes: Collaboration between two WG3 and WG2, and two CANTATA countries (Spain, Sweden)

4. Title: *"On the stability conditions for theories of modified gravity coupled to matter fields"*
Main WG: WG3
Authors: Antonio De Felice, Noemi Frusciante (PT, WG3, ECI), Georgios Papadomanolakis (NL, WG3, Ph.D. student)
link: arxiv.org/1609.03599
Notes: Collaboration between two countries (Netherlands, Portugal), one of which is ITC, and involving two young members (1 ECI and 1 Ph.D. Student) who have also been granted for STSM.

3.3 - GRG reviews/reports

Due to the direct involvement of our Action Chair, there is the possibility to propose invited reviews/reports to the scientific journal General Relativity and Gravitation (GRG), that can help to promote the network.
This kind of contributions will undergo the usual referring process, and they will be tagged electronically, so, even though they will appear separately on printed issues, they will all be collected to appear together electronically, in a sort of "A Cantata Cost Action volume".

People from WG3 have been actively involved and are being involved in the organization of such GRG reviews and reports: not only we have members who will support actively such projects giving their direct scientific contribution, but they have been also the main proposers for some of them. As it is easily possible to verify, such projects are intended to be, in perfect agreement with COST spirit, as collaborations among all the working groups, and to involve as much large number of CANTATA countries as possible.

1. Title: *"Effective field theory approach to the misteries of modified gravity dark energy"*
Participants: Christian Marinoni (FR, WG3), Alessandra Silvestri (NL, WG3), Miguel Zumalacarregui (SE, WG2, ECI), Federico Piazza (FR), Noemi Frusciante (PT, WG3, ECI)

Abstract: The discovery of the acceleration of the Universe (dark energy) has triggered a consistent body of theoretical work aimed at modelling its phenomenology and understanding its fundamental physical nature. In recent years, a powerful formalism that accomplishes both these goals has been developed. It can capture the behavior of a wide class of modified gravity theories and classify them according to the imprints they leave on the smooth background expansion history of the universe and on the linear growth rate of its density inhomogeneities. The effective field theory (EFT) of dark energy is based on a Lagrangian description of cosmological perturbations that depends on a number of functions of the time, some of which are non-minimal couplings representing genuine deviations from standard gravity. Such a formalism is thus particularly convenient to fit and interpret the wealth of new data that will be provided by future galaxy surveys. Despite its recent appearance, the EFT formalism has already allowed a systematic investigation of what lies beyond the standard gravity landscape and provided a conspicuous amount of theoretical predictions and observational results. In this review, we report on these achievements.

Comments: The project involves people from two WGs (WG3 and WG2), 4 countries (France, Netherlands, Portugal and Sweden) and the participation of 2 ECI.

2. Title: *"Screening mechanisms – break them or not, to discriminate among modified gravity theories?"*
Participants: Jose Beltran-Jimenez (ES, WG3, ECI), Philippe Brax (FR, WG1), Salvatore Capozziello (IT, WG1), Bridget Falck (NO, WG1, ECI), Lavinia Heisenberg (SW, WG1, ECI), Max Groncke (NO, WG2, Ph.D.), David Mota (NO, WG2), Nelson Nunes (PT, WG3), Vincenzo Salzano (PL, WG3, ECI).

Abstract: Screening mechanisms are the main property which any MG theory, based on the introduction of new fields, mediators of the so-called fifth force, needs

in order to be able to behave like dark energy at cosmological scales, and being opportunely hidden at Solar System scales. That is needed because, at the present stage, we have not detected any deviation from General Relativity, or any new field at those former scales. Moreover, whatever is the MG theory, and the mechanism behind the different behaviour of gravity at very large cosmological scales, it has always to recover the well-known General Relativity behaviour at the well-tested "local" scales. Here, we will review the state-of-the-art of the screening mechanisms theory, but we will also try to come up with some new ideas. For example, what if there is a partial break in such screening mechanisms, which, while making the theory consistent with Solar System constraints, might be able not only to describe dark energy on cosmological scales, but also dark matter on astrophysical (galactic) ones? First of all, we will try to put order in the wide zoo of theoretical models which are now on the market. Then, we will try to state what are the requirements and the limits we can put on such screening mechanisms as derived from numerical codes simulations. Finally, we will analyse how they fit to observational data.

Comments: this project is highly inter-disciplinary. It will involve a total of 9 people, from all the CANTATA WGs. We will have contributions from 7 countries, 2 of which are ITC: France, Italy, Norway, Poland, Portugal, Spain, Switzerland. We have tried to have a balance between expertises from more senior members and from younger people, involving 4 ECI and 1 Ph.D. Student in the project. While the title is provisional, the main idea is clear: we won't only give a short but exhaustive state-of-the-art about the topic, but each participant will have to describe what is his/her contribution to the field, and enlighten possible developments, consistently with CANTATA objectives.

4. STSM

During the first grant period, we have had 2 STSM related to WG3 tasks and objectives, involving two young members, 1 ECI and 1 Ph.D. Student.

1. STSM: Noemi Frusciante (ECI)
STSM affiliation: Instituto de Astrofisica e ciências do espaco, Science Faculty of the University of Lisbon (PT, ITC)
Visiting Institute: Instituut Lorentz, Leiden University (NL)
Date: from 2017-02-11 to 2017-02-18
Title: *"H_0 discrepancy: a signature for modified gravity?"*
Abstract: Determining the correct value of the Hubble constant (H_0) is extremely important as it gives the length scale of the Universe. Its measurement can be obtained from intrinsic properties of some astrophysical objects, or by using the CMB or correlations between large samples of galaxies. All of them give information about the geometry of the Universe and hence on H_0. In particular the *Planck* data favour a present value for H_0 given by 66.93 ± 0.62km s−1 Mpc−1, which has been obtained assuming the six-parameters ΛCDM model. Such result shows a discrepancy with respect to others measurements as it prefers a lower value. CMB estimation of H_0 has the limit of being an indirect model dependent measurement as a ΛCDM cosmology as been assumed, which might be a possible source of the discrepancy. Given the wide sample of dark energy and modified gravity models (DE/MG) that address late time accelerated scenario and the high

precision data, it becomes crucial to test DE/MG theories against data on large scales. In the quest of a model independent parameterization for gravity theories, the effective field theory formalism (EFT) has been applied to the phenomenon of cosmic acceleration. The STSM (and collaborators) have implemented this framework into CAMB/CosmoMC creating EFTCAMB/EFTCosmoMC. These patches allow to test gravity theories with cosmological data. The visit at the Instituut Lorentz, Leiden University (Leiden, Netherlands) will be focused on investigating the discrepancy of the H_0 parameter in the context of DE/MG. This work will be done in collaboration with Dr. Matteo Martinelli (ECI), Simone Peirone (Ph.D. Student), Dr. Alessandra Silvestri (WG3 leader) and Georgios Papadomanolakis (Ph.D. student). The STSM and collaborators will employ EFTCAMB to evolve the dynamics of perturbations as the code does not rely on quasi-static approximation and will investigate the above discussed discrepancy for several gravity models which span from pure EFT parameterizations to full-mapping models. They will also employ CosmicFish which is a library for cosmological forecasts and it does not rely on the Limber approximation. They will use available real data sets in their analysis as well as forecasts from future surveys (*EUCLID*/SKA). This project is relevant for the CANTATA purposes in the context of testing MG models with cosmological data. Indeed, the final goal of the present proposal will be to find a possible source of signature for MG. This analysis will allow to understand if a departure from General Relativity has to be considered only at level of the background or a more involved modification is necessary.

2. STSM: Georgios Papadomanolakis (Ph.D. student)
STSM affiliation: Instituut Lorentz, Leiden University (NL)
Visiting Institute: Instituto de Astrofisica e ciências do espaco, Science Faculty of the University of Lisbon (PT, ITC)
Date: from 2017-03-18 to 2017-03-25
Title: *"H_0 discrepancy: a signature for modified gravity?"*
Abstract: As the search for alternatives to the ΛCDM model intensifies, the sheer amount of models of modified gravity (MG) demand the development of efficient testing methods For MG models which add a scalar degree of freedom (DoF) a very prominent candidate to achieve this is the Effective Field Theory of Dark Energy and Modified Gravity (EFT). Inspired by the EFT of Inflation it represents the most general action describing cosmological linear perturbations in all gravity theories containing one additional scalar DoF. This provides a unifying framework allowing for agnostic studies yet also model dependent ones as most of the known models have been mapped into this formalism. Additionally, it proves to be very effective in a numerical sense as cosmological tools, such as EFTCAMB, have been developed based on this formalism. A fundamental question, raised when one constructs gravity theories with additional DoFs, is the one regarding stability. A naive construction can yield catastrophic issues such as the appearance of ghostlike DoFs. As the EFToDE/MG is build at the level of the action it is ideal for such an analysis providing very general and model independent constraints. The STSM visit to Lisbon will be centered around two projects related to the EFT formalism and the issue of stability, to be developed with Dr. Noemi Frusciante. The first one centers around the study of the EFToDE/MG in a de Sitter background. This will initially include the search for the stability conditions related to this case with a main focus lying on the mass of the additional DoF. Subsequently, deviations from

the de Sitter background will be studied in this framework, by adopting an expansion approach of the action in terms of parameters measuring the deviation from de Sitter. The second project revolves around the ambition to push the EFT to non-linear regimes. This proposition is of particular interest considering that a major aspect of most MG theories are the screening mechanisms, usually a highly non-linear effect. Hence, the possibility to include such effects in the EFT formalism and study them from a model independent point of view is of high interest. The identification of the relevant operators allowed by the symmetries and their ramifications will be the first step. Both these projects, as they are based on and aim to extend the EFToDE/MG, are particularly relevant to the CANTATA goal to develop and improve methods to test alternative theories of gravity.

3. STSM: Maria Ortiz Banos (Ph.D. student)
STSM affiliation: University of the Basque Country (ES)
Visiting Institute: Institute of Physics, University of Szczecin (PL, ITC)
Date: from 2017-03-20 to 2017-03-30
Title*: "f(R) gravity modifications from the action to the data"*
Abstract: The framework of knowledge where our project lies is the theoretical description of the accelerated universe in the context of the modified gravity theories, specifically, the so-called f(R) models. In such scenarios, present acceleration is not driven by a real energy-matter fluid (generally dubbed as dark energy), but instead is the effect of the breakthrough of General Relativity on large cosmological scales. One of the main obstacles to the full exploitation of such theories relies in the intrinsic complexity reached by most of the equations related to cosmological observations when a generalization of the standard Hilbert-Eistein lagrangian is applied, from simple cosmological background to more insightful perturbation equations. It is also true that most of such theories are introduced from the very beginning in the action as function of geometrical and quite abstract quantities, like, for example, the Ricci scalar (from which they derive their name). In such a way, it is hard to recover how they are related to more easily observable quantities, as the cosmological redshift. In this project we want to perform an observer-friendly approach to the problem: we will always start from the action, but we will propose f(R) expressions not in terms of R, but directly in terms of the redshift. In order to do that we will explore certain features which f(R) should have in a more general theoretical context, trying to provide a bridge between these alternative models and more standard dark energy scenarios. This will help us to propose models not randomly but with some reasonable basis.
Our specific goals are the following:
a) to write f(R) gravity in terms of the redshift, which is a fundamental variable in cosmology. In order to get this kind of expression we will try to avoid randomness by restricting the limits of these theories;
b) we will analyze different standard DE models and check if there is any common trend in them, when the connection between the Ricci scalar and the redshift is made explicit;
c) if a common pattern is found out, we will "perturb" it by introducing new parameters which should give us a direct test of how much information we can derive from observations about a possible difference from the LCDM model;
d) the main equation we will work with is the solution of the generalized Einstein's equations, that is, the modified Friedmann equation which results when

considering the action associated to an f(R) theory. We will solve this equation numerically in order to get an expression for the Hubble parameter which will depend on the parameters of the model we provide;
e) to test the selected models against cosmological observations. We will use the most updated set of cosmological data including: Type Ia SN; expansion rate data; CMB; BAO. We will employ MonteCarlo Markov Chain methods to find the best fit parameters for our models.
Our final aim is to detect if there is any noticeable deviation with respect to the standard model of cosmology, the LCDM model. This topic fully agrees with CANTATA scientific goals, aimed to explore reliability of modified gravity theories, and in particular with tasks of the Working Group 3 "Observational discriminatore", as we will compare LCDM model and theories that generalize Einstein's General Relativity with cosmological data. During this short term scientific mission, in quality of Ph.D. Student of the University of the Basque Country under the supervision of Prof. Ruth Lazkoz Saez, I will collaborate with Dr. Vincenzo Salzano (ECI) postdoctoral researcher based at the Institute of Physics and working for the Cosmology Group lead by Prof. Mariusz Dabrowski.

5. Outreach/Dissemination

CANTATA video, http://cantata-cost.eu/multimedia/ by Prado Martin-Moruno (ES, co-leader WG1, ECI), Diego Saez-Goméz (ES, WG1, ECI), José Alberto Ruiz Cembranos (ES, WG3), Lavinia Heisenberg (SW, WG1, ECI), Matteo Martinelli (NL, WG3, ECI), Bridget Falck (NO, WG1, ECI), Jackson Levi Said (MT, WG1, ECI), Thomas Tram (DK, WG2, ECI), Mariafelicia De Laurentis (DE, co-leader WG2), Vincenzo Salzano (PL, co-leader WG3, ECI). Promotional CANTATA video emphasizing the interconnection of different nodes and the influential role of ECIs within the action.

6. Overview and comments for the next grant period

Following up on discussion in Lisbon, and in accordance to the memorandum of understanding of CANTATA, few specific topics have been identified for WG3 to tackle in the near future.

- Including Palatini theories of gravity in the effective field theory formalism for dark energy (in synergy with WG1)
- Unified Dark Matter/Dark Energy (DM/DE) scenarios: a census of models and observational signatures.
- New possible observational signatures for modified gravity: e.g. strong field tests of modified gravity

We are also going on with activities which should improve the participation of the members to the action. we have re-circulated among WG3 participants the GoogleDoc we created during the Lisbon meeting, in order to have more feedback and collect new possible ideas to develop within CANTATA. Here is the link to the above document:

https://docs.google.com/document/d/1gLJ7ckf7FtKsNOVzutqbTC1DPulK4mmBT-BMapYdCX4/edit