Brussels, 30 October 2015

COST 049/15

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "Cosmology and Astrophysics Network for Theoretical Advances and Training Actions" (CANTATA) CA15117**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action Cosmology and Astrophysics Network for Theoretical Advances and Training Actions approved by the Committee of Senior Officials through written procedure on 30 October 2015.

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MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA15117
COSMOLOGY AND ASTROPHYSICS NETWORK FOR THEORETICAL ADVANCES AND TRAINING ACTIONS (CANTATA)

The COST Member Countries and/or the COST Cooperating State, accepting the present Memorandum of Understanding (MoU) wish to undertake joint activities of mutual interest and declare their common intention to participate in the COST Action (the Action), referred to above and described in the Technical Annex of this MoU.

The Action will be carried out in accordance with the set of COST Implementation Rules approved by the Committee of Senior Officials (CSO), or any new document amending or replacing them:

a. “Rules for Participation in and Implementation of COST Activities” (COST 132/14);
b. “COST Action Proposal Submission, Evaluation, Selection and Approval” (COST 133/14);
c. “COST Action Management, Monitoring and Final Assessment” (COST 134/14);
d. “COST International Cooperation and Specific Organisations Participation” (COST 135/14).

The main aim and objective of the Action is to construct an effective theory of gravity capable of encompassing both the phenomenology related to the lack of a quantum field theory of gravity, and phenomenology related to the various astrophysical and cosmological scales that cannot be explained within the framework of General Relativity without including dark matter and dark energy. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 32 million in 2015.

The MoU will enter into force once at least five (5) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14.

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OVERVIEW

Summary

Observations of unprecedented quality reveal a Universe that is at tension with the standard, and very successful description of matter and energy in Physics. Around 95% of the substratum of the Universe is of unknown nature, split into an accreting component (dark matter) and a repelling component (dubbed dark energy). There are auspicious prospects that the combination of state-of-the-art experiments, and theoretical advances will provide us with tools to elucidate this fundamental issue. This Action explores the viewpoint that cosmological observations reveal a degree of incongruous with theory not because of mysterious elements, but because of a need to review and extend Einstein Relativity to scales where it has not been properly tested. So this Action "***CANTATA***" gathers a team of European leading experts in gravitational physics and cosmology around the timely goal of investigating the extension of Einstein's theory of General Relativity. A program including complementary aspects of theoretical physics, cosmology and astrophysics is put forward which is set to consider, in a coordinated and multidisciplinary way, the build up self-consistent models at the various scales and, in principle, to find out some *"crucial feature"* capable of confirming or ruling out Extended Theories of Gravity with respect to General Relativity. This Action will enhance already existing collaborations and establish an European network with the goal of developing a synergy between expertise and competences, leverage female gender representation, and foster participation of young researchers.

Areas of Expertise Relevant for the Action	Keywords
● Physical Sciences: Fundamental interactions and fields (theory) ● Physical Sciences: Relativity ● Physical Sciences: Mathematical physics	● modified gravity ● relativistic effects ● observational discriminators

Specific Objectives

To achieve the main objective described in this MoU, the following specific objectives shall be accomplished:

Research Coordination

● Classify and define theoretical and phenomenological aspects of gravitational interaction that cannot be enclosed in the standard Einstein scheme but could be considered as "signatures" of alternative gravities.
● Produce numerical codes to simulate astrophysical and cosmological phenomena within the framework of gravity theories beyond General Relativity.
● Confront predictions of the background evolution of the Universe within the framework of extended theories of gravity with present days observational data from Supernovae Ia, Baryon Acoustic Oscillations and CMB shift parameter.
● Confront predictions of the matter linear perturbations at large scales within the framework of extended theories of gravity with present days observational data from galaxy surveys and cosmic microwave background.
● Build up self-consistent models at the various scales and, in principle, to find out some "crucial feature" capable of confirming or ruling out an Effective Theory of Gravity with respect to General Relativity.
● Study how Extended Theories of Gravity emerge from Quantum Field Theory, and how mechanisms produced by the latter may explain cosmological dynamics without assuming exotic ingredients
● Disseminate by setting up a website of excellence to reinforce an activity that is already qualified and could produce high impact results from the scientific and social viewpoints.

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Capacity Building

● Coordinate the leading researchers (experts in theoretical and observational cosmology, and theoretical physics) in order to develop a common standard among the various members and promote networking added value

● Develop synergies and interactions between (network) seniors members of the network and trainees (by seminars, working group meetings and theme workshops)

● Involve specific target groups by supporting, training and promoting Early Career Investigators and by empowering female scientists

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DESCRIPTION OF THE COST ACTION

1. S&T EXCELLENCE

1.1. Challenge

1.1.1. Description of the Challenge (Main Aim)

The COST Action "***CANTATA***" is a research program including complementary aspects of theoretical physics, cosmology and astrophysics. It will consider, in a coordinated and multidisciplinary way, the possibility to go beyond General Relativity (GR) on scales where Einstein's theory fails at ultraviolet (quantum gravity) and infrared (cosmology). The main goal is to construct an effective theory of gravity capable of encompassing both the phenomenology related to the lack of a quantum field theory of gravity, and the phenomenology related to the various astrophysical scales (e.g self-gravitating systems, galaxies, large scale structure) that cannot be explained within the framework of GR without including dark matter and dark energy. The paradigm resorts to gravitational field theories less restrictive than the one based on the Hilbert-Einstein action and search for their self-consistent theoretical foundation. Specifically, GR imposes an action linear in the Ricci scalar *R:* we will allow functions not linear in *R* or other curvature invariants*.* The aim is to show that such extended schemes naturally arise from fundamental theories of physics (UV scales) and could overcome the need of "dark" components (IR scales).

From a theoretical viewpoint, we intend to study how Extended Theories of Gravity (ETG) emerge from Quantum Field Theory (QFT), and how mechanisms produced by the latter may explain cosmological dynamics without assuming exotic ingredients. In particular, we want to compare the ΛCDM model, based on the need of dark matter and dark energy with extensions of GR. The starting points are existing scientific positive results, and an already well-established previous network structure. The final aim is to build up self-consistent models at the various scales and, in principle, to find out some *"crucial feature"* capable of confirming or ruling out ETG with respect to GR.

This COST Action will enhance already existing collaborations, and build a European network CANTATA with the goal of developing a synergy between expertise and competences. Capital points will be *i)* supporting, training and promoting early stage researchers, *ii)* interactions between (network) senior members of the network and trainees (by seminars, working group meetings and theme workshops), *iii)* empowering female scientists *iv)* setting up a website of excellence to reinforce an activity that, as documented, is already qualified and could produce high impact results from the scientific and social viewpoints. Last but not the least, the network seeks to involve from its inception researchers of other European (EU) sites.

1.1.2. Relevance and timeliness

This research program aims at revising and extending the theory of gravitational interaction in order to overcome the shortcomings of GR at quantum and cosmological scales. Experimental searches for direct evidence of dark candidates have not yielded up to now any conclusive results. Thus it seems reasonable to pursue schemes beyond Einstein's gravity to explain observations and phenomenology without introducing "ad hoc" ingredients. The approach focuses on allowing a gravitational action with a non-linear dependence on the Ricci scalar R. Yet, motivations based on effective theories displaying self-consistence, and comprehensiveness at microscopic and macroscopic scales are to be provided for this purely gravitational paradigm. The Action will search for signatures at UV scales: further polarizations of the gravitational field, particle mixing induced by gravity, microscopic black holes; and at IR scales: characteristic lengths (e.g. new gravitational radii) for astrophysical structures, dynamics of exotic self-gravitating objects, curvature induced late acceleration, etc. Therefore, this is a theoretical physics project involving both observational and phenomenological aspects of QFT, mathematical physics, cosmology and astrophysics.

Novel theoretical frameworks eagerly await for future surveys such as the Euclid space telescope, the Square Kilometre Array (SKA) radio telescope, the Dark Energy Survey (DES), and the Extended Baryon Oscillation Spectroscopic Survey (eBOSS), which will dramatically transform the precision and accuracy of measurements of the cosmic expansion, and the large-scale structure of the Universe, thus providing new testing opportunities. Some of the team members are part of ESA's Euclid mission for the dark universe. Presently, the scientific preparation of the Euclid mission is a main driver of the forefront research in cosmology, pushing to understand theoretical models concerning dark energy, modified gravity and the cosmological constant, in time for them to be confronted by the data of the mission, which makes this Action extremely timely.

1.2. Specific Objectives

1.2.1. Research Coordination Objectives

The Action is compelling from scientific and coordination viewpoints given the very fast evolution in the sector, the researchers involved, the increasing precision of observations (in which EU plays a forefront role through ESA, ESO and specific national programs), and the present lack of self-consistent effective theories of gravitational interaction encompassing phenomenology both at quantum and astrophysical scales. Furthermore, it is complementary with the standard searches for dark matter and dark energy from astrophysical surveys, and from ground-based experiments. The feasibility of the program is within the reach of CANTATA, thanks to the expertise, the existing collaborations among the various members, and the international context where the research places itself.

One of the main goals of the Action is the development of a synergy between a team of EU experts, by setting the appropriate conditions for their coordination, providing articulate and auspicious bounds between EU countries with disparate track records in Science and Technology. This COST Action team will definitely play a leading role worldwide in the field.

In addition to the scientific target, the development of this COST Action (CANTATA) will have a strong impact in view of the formation of young researchers, by driving them towards exciting and rapidly evolving research areas. This will foster their full potential, but will also provide them with the appropriate training environment for the search of novel answers to fundamental problems. To this goal, the financial budget will be devoted to the mobility of the researchers for workshops, dissemination meetings, and Short Term Scientific Missions (STMSs) to visit the various European Institutions involved.

1.2.2. Capacity-building Objectives

The Action combines several and different competences, which allow pursuing it in a multi-disciplinary and synergistic way. An essential phase of the capacity-building objectives will be devoted to the coordination of the leading researchers (experts in theoretical and observational cosmology, QFT and theoretical physics) in order to develop a common standard among the various members, and promote networking added value. Working Groups will be designed where one senior researcher and one junior researcher will cooperate in leading the program according to their expertise. The Action Chair (AC) will coordinate these groups with the overall supervision of the Transversality Agent (TA) and additional help of the Action Vice-Chair (AvC) if needed. A kick-off meeting will be organized in order to rigorously confirm tasks and timing already planned in the Memorandum of Understanding. Post-docs, PhD and Master Students will be assigned to the various Working Groups according to their research interests. The first step of the research will be

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to classify and define theoretical, and phenomenological aspects of the gravitational interaction that cannot be enclosed in the standard Einstein scheme, but could be considered as "signatures" of alternative gravities. The practical way to achieve this goal is to start an exchange (STSMs) of students and more experienced researchers from the first year, combined with attendance to workshops, dissemination meetings, and schools.

1.3. Progress beyond the state-of-the-art and Innovation Potential

1.3.1. Description of the state-of-the-art

Several theoretical and experimental reasons point in the direction that GR might not be the final theory of gravity, but some alternative theory should be considered. Renormalization approaches to GR in the 60s and 70s showed that counter-terms must be introduced: these terms alter the theory yielding fourth or higher order field equations instead of second order. From the physical point of view, this fact implies that extra degrees of freedom need to be introduced. The corrections introduced by renormalization are at least quadratic in the curvature invariants, and were employed in the R2-inflationary model for the early universe [Sta80]. By retaining corrections that are generic non-linear functions of R, one obtains the so-called f(R) theories of gravity [DeF10, Cap11]. When one tries to approach gravity from the high-energy side and obtain low-energy physics, GR is not recovered. For example, adopting string theory one gets a low energy limit that yields a scalar-tensor theory of gravity [Sch82]. Such theories have been long known and were developed initially following Dirac, Jordan, Fierz, and Thiery, and culminating in the Brans-Dicke theory [Bra61].

Modern interest in scalar-tensor gravity arises from string theories: Dilaton fields and their non-minimal couplings to the spacetime curvature are unavoidable features of string theories, shared with scalar-tensor gravity [Tse92]. It seems, therefore, that first loop corrections or attempts to fully quantize gravity enforce significant deviations from GR and extra degrees of freedom. The recent thermodynamics of spacetime approach to emergent gravity [Bar05] pictures GR as a thermodynamical state of equilibrium, among a wider spectrum of gravity theories. This only makes sense if extra degrees of freedom are allowed in addition to the standard spin two massless graviton of GR. Deviations from this equilibrium state will correspond to the excitation of these extra degrees of freedom and to deviations from GR.

From the experimental point of view, GR has been tested directly in the Solar System in its weak-field, slow motion approximation. Binary pulsars, most notably the famous Hulse-Taylor system PSR 1913 C 16 [Hul75], allow for indirect tests outside the Solar System, in the same regime. However, strong gravity tests are still missing and gravity is tested very poorly at the scale of galaxies and clusters, where Newtonian gravity is doubted. This has led to the introduction of MOND [Mil83] and TeVeS [Bek04] theories to replace galactic dark matter. From cosmology comes the indication that gravity may not be described exactly by GR: the 1998 discovery that the present expansion of the universe appears to be accelerated [Rie98] has left cosmologists scrambling for an explanation. In order to explain the cosmic acceleration within the context of GR, one needs to introduce the mysterious dark energy (its pressure P and energy density □ must satisfy P□ -□), which comprises approximately 70% of the energy content of the universe, and is not detected in the laboratory. Dark energy seems very much an ad hoc solution of the problem of the present acceleration of the universe and, understandably, alternatives have been looked for. Attempts to explain away dark energy using the back-reaction of inhomogeneities on the dynamics of the background universe have been, so far, unconvincing. In 2002, the idea was advanced [Cap02], soon followed by other authors [Car04,Noj03], that perhaps we are observing the first deviations from GR on the largest scales. f(R) theories of gravity were resurrected in an attempt to explain this phenomenon. Since these first attempts, the literature on f(R) and scalar-tensor gravity has flourished, and these modifications of gravity are now proposed as reliable alternatives to dark matter and dark energy.

1.3.2. Progress beyond the state-of-the-art

Recent high quality data coming from astrophysical and cosmological observations lead to the emerging picture of a universe that is spatially flat and presently undertaking an accelerated expansion. The observations supporting this come from a range of measurements encompassing estimates of galaxy cluster masses [All04], the correlation functions [You05] and the numerical cluster abundances in terms of redshift [Wan04], the Hubble diagram derived from type-Ia supernovae (SNeIa) observations [Rie04], the optical surveys of large scale structure [Col05], the measurements of cosmic microwave background radiation (CMBR) anisotropies [Spe03], the measurements of cosmic shear through gravitational weak lensing surveys [Sch07], etc.

The present accelerated expansion of the universe can be explained by admitting the existence of a cosmic fluid, with negative pressure, which does not suffer gravitational instability and therefore does not contribute to the formation of structures. In the simplest scenario this mysterious ingredient, known as dark energy, is represented by the cosmological constant Λ in Einstein equations, and accounts for about 70% of the global energy budget of the universe. The remaining 30% consists of a small fraction of baryons (4%) with the rest cold dark matter (CDM); these are gravitationally unstable and form the observed structures, i.e. galaxies and clusters of galaxies. From an astrophysical point of view, this simple model is in very good agreement with observations, and can be assumed as the first step towards a new standard cosmological model, the Concordance ΛCDM Model [Bah99]. Notwithstanding the satisfying agreement with observations, the ΛCDM model presents several lacks of congruence and shortcomings. If the cosmological constant represents the vacuum state, we have to explain the 120 orders of magnitude between the observed value and the value predicted by any quantum gravity theory [Wei89]. Furthermore, we have to solve the coincidence problem, for which the fractions of matter and dark energy are today of the same order of magnitude, even if they respond to completely different dynamics.

Several models have been proposed to address these issues. However, none are fully satisfactory, first of all because none of the dark components has been directly detected in experiments. Secondly, the □CDM model cannot fully explain several observational evidences at scales of galaxies and galaxy clusters. If, from one hand, the flat rotation curves, observed since the 70s in spiral galaxies, have reinforced the old hypothesis of the need of dark matter, the low concentration of the dark haloes of some systems, like low surface brightness (LSB) galaxies, is in disagreement with N-body cosmological simulations [deB03]. Analogously, the existence of elliptical and S0 galaxies, with a variable dark matter amount, could be due both to a different efficiency of the star formation processes and to a manifestation of the same concentration effect found in LSB galaxies, disagreeing with the □CDM model [Nap05]. The presence of a central cusp in the dark matter distribution of galaxy clusters, predicted by theoretical models and simulations, has not been determined with certainty [Car11]. However, it is not clear whether such discrepancies are due to observational problems, to the lack of understanding of the mechanisms ruling baryon physics, or to a substantial failure of the □CDM model.

There are two possibilities: either (i) we continue searching for the dark components until we do not actually find them, or (ii) we admit that the cosmic speedup and the “missing” mass are nothing else but signals that GR is unable to describe the universe at large scales. In this case, extensions of GR should be invoked [Cap08,Cap09], which in order to be fully satisfactory, should be accurately tested at all scales. Considering critically the approach, we have an almost equivalent description with respect to dark energy and dark matter universe and then the turning point could be to find out some "experimentum crucis" capable of discriminating between the two pictures.

From an astrophysical viewpoint, an adequate amount of observational data are available related to several mass tracers in galaxies and clusters of galaxies, and it is now conceivable to individuate experiments suited to verify or falsify the ETG approach. In fact, recent technological developments have increased the possibility to study properties of mass distribution (radial profile and shape) around a single galaxy or a cluster of galaxies, using long range tracers such as planetary nebulae [Nap12], globular clusters [Ric04], HI disks in spiral and polar ring galaxies [Arn97], and diffused X-ray emission [O'S04] or techniques like gravitational lensing [Koo03]. This accurate comparison of theory with data will be one of the main tasks of the present Action.

1.3.3. Innovation in tackling the challenge

The coordination and organization of research activities are to be directed to obtain solid scientific results in order to achieve clear evidence on the fact that effective theories of gravity (beyond GR), once they are compared with data and phenomenology, can be a viable approach towards quantum gravity, and self-consistent cosmological models. Positive results in this direction would lead to the revision and the extension of GR at the quantum, astrophysical and cosmological scales. In addition, since the project combines several competences, it can be pursued in a multi-disciplinary and synergistic way. On the other hand, as leader researchers in theoretical cosmology, QFT and theoretical physics constitute the team, the synergistic and complementary aspects of the Action can be achieved by coordinating the various research tasks.

1.4. Added value of networking

1.4.1. In relation to the Challenge

It is aimed at answering a very precise pair of questions: Is it possible to discriminate, among the concurring pictures of cosmic dynamics, the one that is a better fit to the largest set of data, with a minimum number of parameters? Is there any “experimentum crucis” in favour of either Modified Gravity or GR with dark components capable of definitely discriminating one of the two pictures? Tackling such a challenge would require looking beyond the usual individual work circles of the progenitors of the project. It became clear that this Action would give credibility to the possibility to achieve these goals.

Networking within the scientific realm in which the members operate means, essentially, talking to other researchers, establishing work links and sowing the seeds of a larger circle of influence. The creation of new long-term collaborations and the strengthening of existing ones will make the network do better science, and creating lasting impressions on the scientific community through these networking activities will serve the same purpose. Efforts in this direction will have a particularly crucial effect on the future careers of the trainees and/or early stage researchers, as they will be acquire skills with potential use in many other professional environments.

1.4.2. In relation to existing efforts at European and/or international level

So far there is no EU coordination of this kind of research, in particular at the theoretical level. One of the main aims of CANTATA is to organically coordinate these research topics. A peculiarity of the project is that it is not strictly related to some running or forthcoming experiment. In such a way, the Action is an independent challenge not biased by the expected final result.

2. IMPACT

2.1. Expected Impact

2.1.1. Short-term and long-term scientific, technological, and/or socioeconomic impacts

It is only fair to recognise that the subject of the CANTATA Network has no immediate, direct technological impact. However, understanding how the universe works ultimately is understanding who we are, and there can surely be no deeper question! It most significantly affects our society, both in its philosophical and cultural realms. This is very true, in particular, in what scientific culture is concerned. The sheer beauty inside the thought that we are made of the same stuff as the stars is truly inspirational, making people connected with the universe.

The deep question of ‘who we are’ has branched out throughout history into more complex questions, and has been at the cornerstone of the emergence of physics and mathematics, chemistry, even biology, and underlies all the scientific endeavour. Unveiling the Universe is an essential part of this goal, and very much it is the inspiration for much of the scientific progress activity across the whole world. It is a catalyst that attracts young people into physics and sciences in general, and this is certainly a major impact sought by CANTATA, since this will contribute for the renewal of EU Scientific fabric with highly trained new people. Having said this, it is appropriate to stress that many of the theoretical methods that are expected to be developed in this network, but more particularly the development of numerical codes and methods to achieve our goals, have the potential to be applied to scientific and technological uses outside the sheer boundaries of academia. This transfer of knowledge within EU, between Academic Teams and Industrial applications, certainly is one of the remarkable prospects that can be envisaged, and that will be inseminated by the mobility of young researchers in the course of their careers. Thus it is not just about pure knowledge, as EU science plays a continuous give and take game with the design, construction and development of the most sophisticated instrumentation.

And finally, it must not be forgotten that Science promotes the unhindered sharing of new thoughts and new knowledge, independent of race, religion and sexual orientation.

2.2. Measures to Maximise Impact

2.2.1. Plan for involving the most relevant stakeholders

Identifying the most relevant stakeholders of the project is a reflection exercise which may certainly help trace directions of action to promote the achievement of the goals of scientific excellence sketched, guarantee the impact of the project, and pave the way for future endeavours led by the same core of scientific leaders.

To begin with, the broad community of physicists that do not belong to this Action, but have with this Action an affinity of interest is perhaps the most direct stakeholder one may think of. Even though the vocation is to open the network (if awarded) to other researchers than the original subscribers, different circumstances will naturally make many researchers eventually remain out of the structure of the network. But the dissemination activities (ranging from high impact publications to meetings) will surely influence, inspire and feed the activity of those colleagues, thus empowering this research area as a whole. It is expected that geographic factors will play a key role, and it is expected that the network makes a positive difference in the already well-connected community of cosmologists, which celebrates annual meetings, and contributes a significant number of its best-reputed members to this network. Promotion of CANTATA will be sought by means of sponsored public talks, invited topical contributions and mini-workshops (and/or schools) presented as for example satellites of the Iberian Cosmology Meetings, the annually Spanish Relativity Meeting, the biennial Italian Relativity Meeting, the regular UK Cosmo meeting, which runs two to three times a year, the annual BritGrav meeting (which connects the GR community in the UK), or the recently forged annual (Spanish) Meetings on Fundamental Cosmology.

Looking beyond professional researchers, special attention must be paid to the pool of potential future researchers in the area; effort will have to be programmed and coordinated to promote the Action activity research at undergraduate levels so that new talents are attracted to our Training Schools. The main tool to achieve this goal will be outreach activities, guided and organized by one of the members of the management structure. Many members of the Action are teaching 3rd-and

4th year students in related subjects, and are thereby recruiting the strongest students into this field whenever possible. Complementarily, outreach activities are planned that aim at students who are about to decide what they want to study, before and after graduation. Finally, members' institutions will be beneficiaries of the Action activities. Not only through the inherent raise of production and quality of scientific publications and dissemination events, but also by providing hints towards the preparation of further successful applications, as local offices for international research affairs will be able to learn from the Action experience, and transfer this know-how to future applicants.

Last but not least, it is foreseen potential for an increase in the recruitment of females by the direct influence exerted by the role model set by the Main proposer, and also by the subtle yet hopefully moves it is intended to be done "behind the scenes". These include promoting the invitation of renowned females in the area, positioning female speakers at slots were the audience might be bigger, and complementing these with a gender dimension, in a periodic revision of practices. A statistical analysis of rates of participation in events, in specific key positions in those events, numbers of female PhD students accreted by the network, number of female authors in the publications of the network, and similar relevant indicators is also envisaged. And were this not enough, the Action intends to extend these good management and procedures to fostering equality of opportunities in other spheres like the promotion of the young and the socially or geographically handicapped broadly speaking.

2.2.2. Dissemination and/or Exploitation Plan

Field Theories, Astronomy, Gravitational Physics, the interwoven scientific cornerstones of this Action have the power to attract a great deal of interest from the media. This certainly happens when important breakthroughs occur, but otherwise they have a regular public appeal. It is therefore expected that the results of the present network will have the power to produce a most positive impact on the popular perception of science.

From a more technical viewpoint, the members are committed to excellence, and to producing sound scientific results that may be seen as relevant, and lasting contributions to science from a European team. Thus, the first dissemination goal is to achieve publications of high quality level.

As a parallel endeavour, the scientific achievements of the network will favour a success track for the young researchers involved. Highly trained people with in-depth analytical skills find it easier to get well-paid jobs in various industries, and usually good performers quickly get to responsibility positions and recognition where they are often far better paid that in academia.

Promoting network results and capabilities in conferences, meetings, workshops and schools is another key aspect. These actions can foster external knowledge of the achievements of the trainees, thus helping them get positions at top institutions. It is typically difficult for young researchers to give talks to relevant audiences, as established researchers are invited far more often or in some organization charts just keep the slots for themselves. This will not to be the case in this network, and on top of having an Equality Agent to overlook whether equality of opportunities in this respect is the Action practice, the Action will nominate the Working Groups Co-leaders (nominated among ECIs) the spokespeople for the project. Returning to a more general perspective on the dissemination plan, at all expertise levels attending and organizing this kind of events will enrich the Action knowledge, expand horizons and favour mobility of researchers.

Thirdly, the members of the Action will use the media services in their institutions to promote outreach/public dissemination of science. In this respect public lectures given by relevant researchers will be programmed in parallel to major Action meetings. It is also intended to take advantage of the communication power of social networks, and set up and maintain a Facebook

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page and Tweeter link related to the activities of the network, aiming at the widest audience possible. This is to be complemented at a more professional level with the participation on ResearchGate, Google Scholar and LinkedIn, which are tools that can offer further opportunities to promote the Action scientific achievements and career development potential.

2.3. Potential for Innovation versus Risk Level

2.3.1. Potential for scientific, technological and/or socioeconomic innovation breakthroughs

The Action lies in the interface of theoretical and phenomenological modeling, and in the corresponding analysis and interpretation of data that are currently being gathered or will be gathered soon. Its potential for innovation stems from its scientific results and from the methods that will be developed to achieve them, namely the development of appropriate, state-of-the-art numerical codes. There are thus now foreseeable hazardous risks. However it is possible to ascertain a Risk of Failure to be associated with the various components of the Network program. The latter range from low risk Work Packages up to high risk ones. Below we describe some of the main challenges of this Action and how this team can overcome them:

Low Risk: Cosmological structure formation can be broadly divided into large "linear" scales, where linear perturbation theory is valid, and the smaller nonlinear scales. On linear scales, it is in fact possible to parameterize modifications to gravity in terms of two functions of scale and redshift, which characterize the relation between matter and the metric potentials Φ and Ψ, respectively. Thus, on these very large scales, the main challenges lie in controlling the observational systematics of surveys. For redshift surveys targeting the large scale distribution of galaxies, these issues consist of the varying survey depth and seeing conditions; for imaging surveys targeting weak lensing, the main systematic issues are in controlling the point-spread function and understanding photometric redshift uncertainties. On the other hand, the bulk of cosmological information in large scale structure surveys is contained on smaller scales that are moderately to highly nonlinear, that is, perturbations from the homogeneous Universe are significant. Putting quantitative constraints on the nature of gravity through large scale structure data on these scales is very challenging. In addition to the intrinsic nonlinearity of the observables, any viable theory of gravity has to invoke some nonlinear mechanism in order to pass stringent Solar System constraints. Understanding these "screening" mechanisms, only a few of which are known to exist, in the context of cosmological structure formation adds another formidable challenge to the problem. This is a low risk challenge because the network has all the necessary skills and experience to overcome these issues: from the theoretical side, numerical and observational.

Medium Risk: One important issue with the observables used so far for placing observational constraints on gravity in cosmology is that they are not specific. That is, by adding some non-standard ingredients such as massive neutrinos or modifications to the initial conditions one can partially cancel the modified gravity effects on observables such as the cluster abundance or the matter power spectrum. Thus, it is important to make efforts to develop tests that directly target gravity. The most promising such test is the comparison between dynamical (velocity) probes and gravitational lensing. The difference in the two observables is a telltale sign of modifications of gravity that cannot be mimicked by other modifications to the cosmological model. The velocities of matter and tracers can be either measured through their redshifts via the Doppler shift or through the temperature of hot intergalactic gas emitting thermal X-rays, or through the kinetic Sunyaev-Zeldovich effect on the cosmic microwave background. A cosmological test based on this comparison is a generic and direct probe of gravity, and essentially extends the well-known and important Solar System tests of gravity by ten orders of magnitude in length scale. The Action will overcome the degeneracies between initial conditions / massive neutrinos with modified gravity via running high-resolution simulations and semi-analytical models.

High Risk: A major and generic difficulty in interpreting small-scale behaviors and astrophysical data in terms of gravitational theory is that uncertainties in baryonic physics can mimic or mask the non-linear gravitational terms. This is due to the uncertainties in modeling the small-scale physics of conventional baryonic matter. The network encompasses a wide range of skills and knowledge, and together will investigate in detail the baryonic effects on the cosmological observables and the impact on observations that aim to probe gravity beyond GR. One should point out that if such obstacles can be overcome, the success of using a comparison of large-scale and small-scale gravitational behaviors as a test of gravitational theory would be notable!

3. IMPLEMENTATION

3.1. Description of the Work Plan

3.1.1. Description of Working Groups

WG1: Modified gravity
An important goal of this Action is to perform a detailed theoretical and phenomenological analysis of the relation between the effective field yielding dark energy and non-canonical Lagrangians and non-linear gauge kinetic functions. Generalizations of the action functional can be approached in several ways. For instance, some prescriptions replace the linear scalar curvature term in the Einstein-Hilbert action by a function of the scalar curvature, $f(R)$, or by more general scalar invariants of the theory. An interesting novel possibility that will be analyzed in great detail includes a non-minimal coupling between the scalar curvature and the matter Lagrangian density. Another prescription considers one (or more) scalar fields coupled to the geometry, and playing a gravitational role. In this context, infrared modifications of GR will be extensively explored. All modified gravity models induce observational signatures at the post-Newtonian level, which are described by the parameterized post-Newtonian (PPN) metric coefficients arising from these extensions of GR. These ETGs will be tested against large-scale structure and lensing, astrophysical and laboratory measurements, as well as laboratory and space-based Equivalence Principle experiments. The tests from the solar system, large scale structure and lensing essentially restrict the range of allowed modified gravity models, and thus offer a window into understanding the perplexing nature of the cosmic acceleration and of gravity itself. These tests will be the milestones of WG1 for the project that have to be combined with results and deliverables of WG2 and WG3. Specifically, the WG2 and WG3 will be fundamental in the construction of viable ETGs.

WG2: Relativistic effects
Here, WG2 aim to discover relativistic effects capable of discriminating among different pictures of cosmic dynamics. The final goal is to find out some "*experimentum crucis*" pointing out if the modified gravity picture ("geometric picture") or new fundamental components ("particle picture") are consistent with cosmic dynamics at least at theoretical level. Some of these possible relativistic effects ranging from cosmology, particle physics and gravitational waves are described below
a) Inhomogeneous cosmologies. For a precision estimate of the dynamical influence of the inhomogeneities on the large-scale evolution of cosmological backgrounds, a covariant and gauge invariant averaging procedure can be developed, valid for both space-like [Gas09,Gas10] and null [Gas11] hypersurfaces. This can be applied to obtain a full computation, of the luminosity-redshift relation in a CDM [Ben12] and ΛCDM-dominated backgrounds, perturbed by inhomogeneity fluctuations of primordial (inflationary) origin. Preliminary results have shown that the contribution of "realistic" geometric fluctuations induces, in general, non-negligible backreaction effects on the averaged luminosity-redshift relation, but such effects seem to be too small to mimic a sizable fraction of dark energy. However, the dispersion due to stochastic fluctuations is much larger than the back-reaction itself, implying an irreducible scatter of the data that may limit to the percent level the precision attainable on cosmological parameters. This is a fundamental issue to retain or rule out any alternative theory of gravity with respect to dark components.

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b) Relic abundances. The new physics beyond the Standard Model of interactions, which predicts the existence of particles that are candidates for the dark matter constituent, is nowadays under deep scrutiny. Particle accelerators will provide information aimed to test theories of new physics beyond the Standard Model, while relativistic astroparticle physics offers a unique framework to determining the basic properties of the dark matter candidates. Thus, supersymmetric particles, such as WIMPs (weakly interacting massive particles) could be the leading candidate to explain the nature of dark matter, since their thermal production in the early universe may give rise to a relic density of the same order of magnitude of the present dark matter density. Particularly relevant in these scenarios could be ETGs, as these predict a thermal evolution of the universe different to the one based on GR. Thus, ETG predict a modification of the expansion rate of the universe with respect to the standard cosmology, so that the thermal relics decouple with larger relic abundances. As a consequence, the correct value of the relic abundance comes out from larger annihilation cross-section. An immediate application of these alternative cosmologies is to provide the correct value of the cross-section of thermal relics able to explain the recent data of PAMELA experiment [Cat10, Cap12]. A systematic investigation of this topic is one of the main objectives of the project.

c) Mixing fields, vacuum fluctuations and dark energy. It has recently been shown that a close connection between the mixing phenomenon and the dark energy problem exists, so that this mechanism could give an explanation to the cosmic acceleration in the realm of quantum physics [Capo09]. Actually, the experimental evidence for neutrino oscillations is one of the most important discoveries of today's particle physics, and, consequently, theoretical studies of particle mixing and oscillation phenomena have intensified. For example, it has been shown that the vacuum for mixing fields has the structure of a condensate of particle-antiparticle couples, for both fermions and bosons, so that observable quantities, like oscillation effects, present corrections which could explain the cosmological fluid giving rise to acceleration. Despite the fact that a full-fledged theory of quantum gravity is still lacking, semi-classical approaches to this issue led to the idea that quantum vacuum fluctuations, considered as a form of energy, must "gravitate" [Zel68]. The key question is: *do quantum vacuum fluctuations fulfill the equivalence principle of Relativistic Theories of Gravity?* In the laboratory, quantum fluctuations have also been proven to exist. These effects could be the source of *cosmic acceleration* through quantum vacuum fluctuations: which probe ETGs.

d) Further Gravitational modes. Further possible "*signatures*" could come from gravitational radiation. It has been pointed out that ETGs give rise to new polarizations for the gravitational waves with respect to the standard $+$ and $\times$ polarizations of GR [Cap08]. This seems a very significant feature for several relativistic theories of gravity that could be investigated by ground based and space interferometric experiments [Bel09, DeL11]. In conclusion, the main task of WG2 will be a systematic investigation of possible signatures capable of discriminating between the ETG picture and the particle dark side approach, and relies on a close synergy with WG1 and WG3. The identification of suitable relativistic effects is the main milestone for setting a given ETG at fundamental level.

WG3: Observational discriminators

ETGs offer a paradigm for nature fundamentally distinct from models of cosmic acceleration, even those that perfectly mimic the same expansion history, so it is fundamental to find an explicit distinction between models of dark energy and ETG. The reason is that ETGs can be mapped into some scalar-tensor theories. By considering solely the expansion rate of the Universe no discrimination is possible. But as these two alternatives will affect structure formation differently, information on the growth of structure, at different scales and redshifts, will break the degeneracy and discrimination will become possible. More specifically, using linear perturbation theory, these alternative models will affect differently the constraints imposed by the Einstein equations, and the second-order growth equation will be modified, consequently changing the growth factor. Thus, generic modifications of the dynamics of scalar perturbations, with respect to the ΛCDM background scenario, can be accounted for by two new degrees of freedom in the Einstein constraint equations, represented by the functions $Q(a,k)$ and $\eta(a,k)$, where *a* is the scale factor and *k* the perturbation scale.

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In the ETG context, $Q(a, k)$ arises from a mass-screening effect due to local modifications of gravity, and effectively modifies Newton's constant. In the context of dynamical dark energy models, the function Q incorporates additional clustering, or interaction with other fields, due to the perturbations. The function η, absent in ΛCDM, parameterizes the effective stresses due to the modification of gravity or specific dynamical dark energy models. Finally, the scale and time-dependence of both functions, Q and η, can be derived in the specific model considered and projected on a (Q, η) plane. We consider that ETG when there are additional contributions to the Poisson equation, which induces $Q \neq 1$, and where extra affective stresses arise, implying $\eta \neq 1$. Thus, ETG is used to denote models in which modifications are present in the gravitational sector and where dark energy clusters or interacts with other fields. Following this practical classification, in the context of first order perturbation theory, models with $Q = \eta = 1$ are denoted as standard dark energy models, for instance, a minimally-coupled scalar field with standard kinetic energy. On the other hand, models for $Q \neq 1$ and $\eta \neq 1$ are denoted "modified gravity", such as scalar-tensor theories and f(R) gravity, massive gravity and generalized galileons, Horndeski interactions, etc. Thus, in the context of the EUCLID mission, the definitions of the functions Q and η are extremely convenient, for instance, EUCLID can distinguish between standard dynamical dark energy and modified gravity by forecasting the errors on Q and η, and several combinations of these functions.
In summary, the precise reconstruction of functions Q and η is the main milestone of WG3.

TASKS:
WG1: Modified Gravity
This theoretical task will combine analytical techniques and numerical simulations. WG1 will look for cosmological models related to some ETG developing the following milestones:

M11: Calculating post-Newtonian parameters and testing possible GR extensions in connection with the experimental constraints derived at Solar System scales.
M12: Comparing ETG with effective QFTs, in order to look for a fundamental level interpretation of them (the existence of massive states of gravitational waves, the Casimir effect as a possible source of a cosmological constant, particle oscillations induced by gravitational field, CP violation, leptogenesis, CKM mechanism).
M13: Testing ETG with phenomenology coming from running experiments (e.g. LHC) in order to search for evidences of micro black holes or any gravitational states coming from high-energy scattering. In particular, the problem of the information paradox will be investigated in the process of black hole formation.
M14: The Early Universe may provide a deeper understanding of the role of quantum effects on a curved background. In this direction, WG1 will study the role of quantum corrections during inflation within the f(R) gravity models, which include as subcases two of the most successful inflationary models according to PLANCK: the Starobinsky and the Higgs models. Given their observational success, it is important to investigate their embedding into a more fundamental context. In particular, WG1 will study their stability under radiative corrections at one-loop level and beyond, as well as the corresponding observational signatures, using the powerful approach of the quantum effective action.

WG2: Relativistic effects
The main goal will be matching cosmological, astrophysical and quantum aspects in self-consistent effective models starting from previous results. Specifically, WG2 will search for cosmological models related to some effective theory of gravity developing the following milestones:

M21: Comparing the theoretical results derived from ETG with the rotation curves of both low and high surface brightness galaxies, and with the velocity dispersion profiles in elliptical galaxies. We will try to frame, in a self-consistent picture, some important scale relations, i.e., the Tully-Fisher and Faber-Jackson laws and Fundamental Plane of galaxies.

M22: Testing ETG at the galactic clusters scales, examining the mass profiles reconstructed from the gas component X-ray temperature and the hydrostatic equilibrium hypothesis.
M23: In addition, the presence of extra modes in the gravitational waves is usual within the framework of modified gravities, which may have consequences at the cosmological level, in particular in the B-modes of the polarization of the CMB. An analysis of this question that extends previous works provides an additional test of discriminating among theories.

WG3: Observational discriminators
WG3 make use of the most sophisticated and modern tools to constrain the models developed in WG1 and WG2. Results from the theoretical work in Tasks WG1 and WG2 will be consistently incorporated, and constraints will be derived using observational data. Specifically, WG3 will look for cosmological models related to some ETG developing the following milestones:

M31: Studying how growth of large scale structure influences the redshift evolution of galaxy clusters, so as to break degeneracies between pure and extended GR based setups.
M32: Studying the dynamical influence of the inhomogeneities on the large-scale evolution of cosmological backgrounds developing a covariant and gauge invariant averaging procedure, valid for both space-like and null hypersurfaces. Such a procedure will be used to obtain a full computation of the luminosity-redshift relation in ΛCDM backgrounds, perturbed by inhomogeneity fluctuations of primordial (inflationary) origin.
M33: Studying cosmological models coming from ETG, in order to get a picture of the universe as much as possible realistic at extremely high redshifts ($100 \ll z \ll 1000$), at high-intermediate redshifts ($1 \ll z \ll 100$) and at the present epoch ($0 < z < 2$).

Expected deliverables are at least one ISI indexed research paper per milestone and at least one invited talk (per milestone as well).

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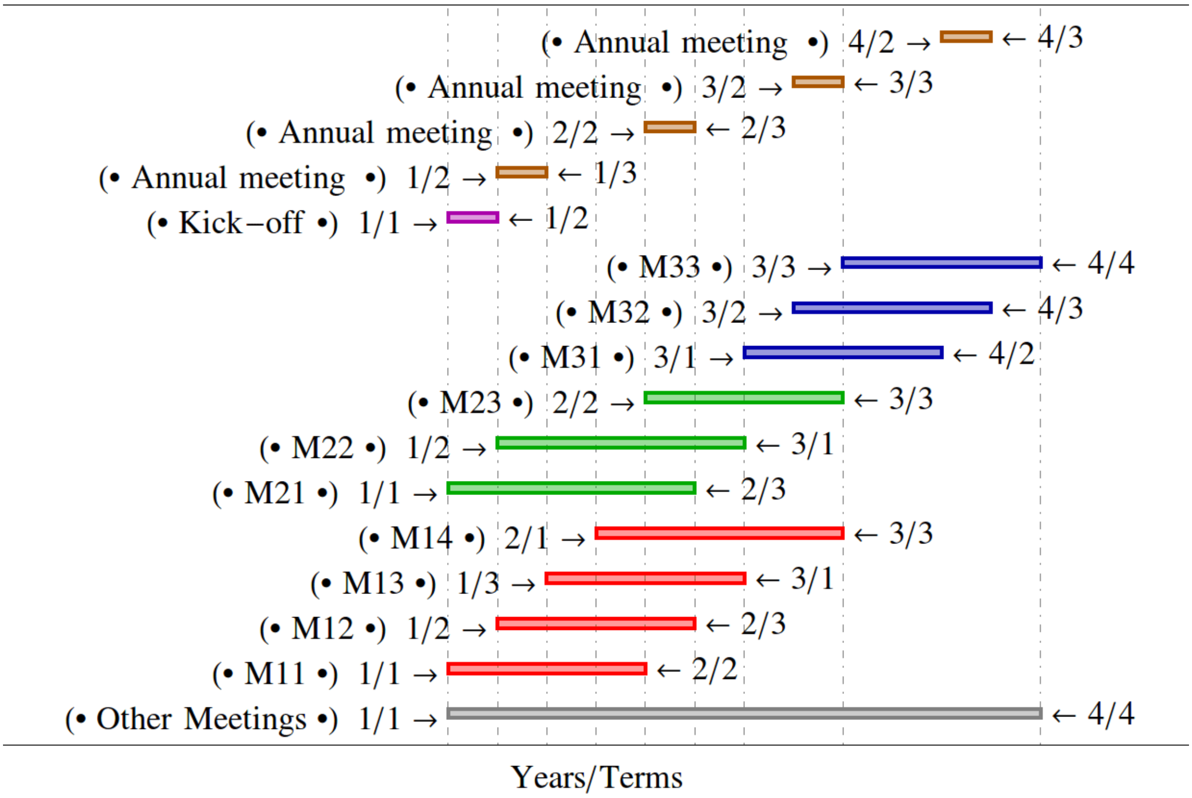
3.1.2. GANTT Diagram



3.1.3. Risk and Contingency Plans

Contingency planning for small scale trouble, which one can expect in scientific activity, in particular when an international wide team is involved, is a key move towards success. In order to draw such a plan a thorough analysis of the risks that the network may face will be necessary. Before making appointments to key management positions, at the time of sketching specific plans for the achievement of the scientific goals, and very importantly, when a key meeting is being prepared, critical functions within our structure will have to be addressed, mainly at the scientific and pure management levels, identify risks as for instance lack of expertise for some particular roles, difficulties to commit to a task, time periods when external activities demand attention, geographic mismatches, and several others. But it be necessary to prioritize risks as well, so as to plan adequately and not overact.

Probably the network will have to face reluctance to draw a contingency plan because of the typical lack of motivation to develop a “Plan B”, which will wash away previous efforts to implement “Plan A”, and because the low probability of big trouble makes the plan look as not urgent or needed at all. At every stage/level of the Action requiring a **tailored contingency plan,** the network will have to stick to some **guidelines**: keep the network under operation, setup a time schedule (in particular for deliverables, milestones and meetings), identify what could trigger putting the plan into action, keep it simple, analyse whether the solutions suggested by the plan will bring undesired consequences for any of the goals, have a clear picture of what is considered a success, ask every key member of the network to identify (report if necessary) their needs, keep a close eye of opportunities for functional improvement.

Once the plan has been drawn its **maintenance** will be most important as well. To that end, attention will be paid in communicating the plan to relevant network actors, revising/rethinking it (on a regular

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basis if time allows) and informing on modifications. Ideally electronic copies of it will be generated/maintained/modified.

Short-term **proactivity** in the design, implementation and maintenance of the plan will save time and resources on the long term and will surely pave the route for success in the fulfilment of the network's aims.

3.2. Management structures and procedures

MANAGEMENT STRUCTURE: The COST Action CANTATA will have the structure outlined below:
Action Chair (AC): highest responsible in the scientific, financial and administrative aspects of the action, main intermediary between CANTATA and the COST Office and/or other financial administrative stakeholders. Default media spokesperson.
Action Vice-Chair (AvC) : assistant to the AC in all aspects of the Action, also Website Manager (WM) and in charge of setting up and managing the Action's wikipage
Transversality Agent (TA): will be responsible for synergy between the WGs and will provide recommendations to them, will act as well as Outreach Coordinator.
Work Group Leaders (WGL): will care for the achievement of the scientific objectives according to the established work plan.
Work Group coLeaders (WGcL): assistants to the WGLs, supervisors of the implementation of the different tasks outlined within the work plan with respect to each WGs. Default spokespeople in scientific forums (to report on the progress of the Action). Appointee for these positions: some Early Career Investigators (ECIs).
Executive Committee (EC): formed by the above actors and responsible for tasks requiring urgency, and/or of sensitive nature.
Training Coordinator (TC): organizer of Training Schools and responsible for schemes for mobility actions (STSM) with a focus on training of ECIs and PhD students.
The **Management Committee (MC)**: in charge of the general strategy and the implementation of the work plan. Its members, respecting the rule of maximum of two members per participating country.

The network's management structure will have two more actors (immediately below) whose suggestions and analyses will be reported to the **MC** by the **EC.**
Community Manager (CM) will make the Action be present in relevant social networks (facebook, twitter, research gate, linkedin), close collaborator of the **WM** and **TA** (reporting to them).
Equality Agent (EA): will overlook the fulfilment of policies to ensure equality at the gender, (academic) age and geography spheres (to report to the **EC**, particularly to the **AC**)

The Action will thus mostly be collegiately managed, with shared high responsibilities, thus fostering implication and commitment, but if needed quick action will be easily manageable upon operation of the **EC**, an instrument to enhance flexibility and efficiency. Further vital management structure resides in the **MC**. Commands emanating from these committees will reach the WGLs and the WGcLs. The appropriate superior level(s) will supervise this chain of mandates.

REFERENCE DOCUMENTS: The Action coordination will be guided by documents defining the objectives (both scientific and technological), the work programme and the operational procedures of the **CANTATA** Action. These will be:

- The Memorandum of Understanding (**MoU**) along with this Technical Annex.
- The yearly Action Grant Agreements (**AGAs**), to be signed between the Grant Holder and the COST Association, and the annexed Work and Budget Plans (**WB&Ps**)
- Correspondence and minutes of meetings

PROGRESS MONITORING: WGLs (assisted by the WGcLs) will monitor and assess the progress of their task(s) by checking the status of the associated deliverables. WGLs will then report the relevant pieces of information to the EC. In turn, the EC will assess the progress of the project from an overall perspective. Conclusions on progresses will be communicated to the WGLs with the assistance of the WGcLs. Finally, written reviews of progress will be presented by the EC to be discussed at the annual meeting.
COMMUNICATIONS: E-mail and wiki pages will be used for daily communication between project participants as well as reporting and several other tasks. A variety of collaborative tools will be employed where appropriate, such as: collaborative document editors, planning systems and content management systems for sharing documents. Access to these tools will be granted appropriately with passwords and links.
MEETINGS: Kick-off (MC scale) meeting at the beginning of the Action to elect the **EC** and set the project effectively running**,** EC members teleconference every 3 months, live (science focused) annual meeting of the network participants open to external colleagues, live MC meeting in parallel to the (science) annual meeting, MC members teleconference in between 2 annual meetings (each mid-year teleconference will be preceded shortly in time by a preparation complementary teleconference with only the EC, the EA and the CM).
TRAINING SCHOOLS: Two schools, focused on training to develop key competences for the scientific goals of the project and to provide the trainees a state-of-the art overview of the field.
STSMs: Mobility actions will be encouraged at all academic levels (prioritizing juniors and ECIs) arranging visits to institutions other than one's host to make most of networking opportunities. The **TC** will be care for funds distribution and approval of the proposed schedules for the missions.
WORKSHOPS: To make the most of the training schools we will exploit the geographical concurrence presence of several seniors, associated external researchers and ECIs (in the framework of the schools) to hold one or two days workshops on very specific topics, ideally before the school itself takes place.
DISSEMINATION MEETINGS: Results of the Action will be disseminated in high profile meetings across the world, promoting the participation of ECIs as speakers.

3.3. Network as a whole

The initial core of proposers already covered the crucial range of expertise needed, it being constituted by a group of high profile researchers from Spain, Italy, Portugal, Norway, UK and Sweden. It has been also setup an unpaired web of secondary proposers who contribute their excellent expertise to the broad field of Extended Theories of Gravity. This capacity building effort has lead the network to extended our geographic spectrum to Poland, Russia and Greece as well, and, all in all, we compellingly serve the Horizon 2020 to engage Inclusiveness Target Countries (ITC) in excellence research activities so as to counterbalance inequalities in the reachability of knowledge itself and all sorts of resources involved in research activities.
Following COST policies, the Action targets the empowerment of three crucial collectivities. First of all, WGcL positions will be occupied by ECI researchers, to act as spokespeople in what regards science products of our activities, this will mean a significant boost to their visibility. Secondly, The Action will make a significant breakthrough in the representation of the female gender by bringing together a considerable number of women so that the network has more than 20% of female members, an extraordinarily high rate as compared to that of similar scientific associations (in related areas of Physics). Finally, the significance of the high participation of researchers from Inclusiveness Target Countries (ITC), in our case Poland and Portugal, in particular the latter contributes the largest number of researchers and acts as the centre of mass of the Action. Thus, summarizing this Action is a networking trans-European initiative aiming at impacting high profile research from many different yet complementary and vital aspects.

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