Brussels, 27 May 2022

COST 050/22

DECISION

Subject: Memorandum of Understanding for the implementation of the COST Action "Addressing observational tensions in cosmology with systematics and fundamental physics" (CosmoVerse) CA21136

The COST Member Countries will find attached the Memorandum of Understanding for the COST Action Addressing observational tensions in cosmology with systematics and fundamental physics approved by the Committee of Senior Officials through written procedure on 27 May 2022.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA21136
ADDRESSING OBSERVATIONAL TENSIONS IN COSMOLOGY WITH SYSTEMATICS AND FUNDAMENTAL PHYSICS (CosmoVerse)

The COST Members through 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, 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 document amending or replacing them.

The main aim and objective of the Action is to connect observational cosmology to fundamental physics using novel approaches to data analysis. The Action will do this by creating a community whereby the different branches of cosmology can cooperate more directly, and which is inclusive of all stakeholders. This will be achieved through the specific objectives detailed in the Technical Annex.

The present MoU enters into force on the date of the approval of the COST Action by the CSO.

OVERVIEW

Summary
Our understanding of the Universe is at a turning point with the predictions of the standard model of cosmology (or concordance model) and the observations from different surveys are showing tensions in several key areas. The disagreement is expressed in the value of cosmic expansion as well as in the growth of large-scale structure in the Universe. New cosmological surveys, many of which are European, may expose tension in additional areas of the concordance model. The question of cosmological tensions can be confronted in a number of ways. Firstly, survey data needs to be further analyzed for potential systematic uncertainties or biases. It would also be interesting to explore predictions from possible combined survey data, which is something survey collaborations cannot normally explore. Secondly, there have been numerous advances in approaches to data analysis and statistical approaches, some of which provide less dependence on cosmological models to make cosmological parameter estimates. Lastly, there are a plethora of new proposals from fundamental physics which range from novel neutrino physics to dark energy proposals (and others) which may contribute to a solution to the cosmological tensions problem. These represent the three research themes through which cosmological tensions will either be alleviated or resolved.

The main aim of **CosmoVerse** is to establish a **synergy between these research areas and foster a sustainable network** based on **interdisciplinary research** in order to confront the growing challenges of tensions in cosmological survey data. CosmoVerse will take a **harmonized approach** involving all key communities.

Areas of Expertise Relevant for the Action	**Keywords**
● Physical Sciences: Cosmology ● Physical Sciences: Dark matter, dark energy ● Physical Sciences: Astrophysics, astronomy, space sciences	● Cosmological surveys ● Observation systematics ● Gravitation ● Fundamental physics ● Dark Energy, Dark Matter

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

Research Coordination
● Organising, developing, and disseminating research efforts and tools to address the challenge of cosmological tensions in the next decade. CosmoVerse will encourage and support the development of computational tools that make it easier to interpret observational data using fundamental physics beyond LCDM.
● Creating a long-lasting network synergy between previously disjoint communities to maximize European leadership in current and future precision cosmological surveys. CosmoVerse will establish a network between collaborations so that data analysts can design better simulations and make the current state of observational cosmology clearer for researchers working in fundamental physics.
● Training early career investigators in forefront cosmology with no boundaries between the Action research themes in order to prepare them for cross-disciplinary problem-solving fields (and other transferable skills) through training schools and a large devotion of funds to short-term scientific missions.

● Peer-reviewed publications of at least 8 papers per year. Additionally, the Action will promote virtual collaborations and encourage collaborative works of this kind.
● Performing Europe-wide public dissemination through a strong online presence, outreach events, and highlighting individuals in the network, as well as providing constructive teaching tools for educators.

Capacity Building
● Develop a common language for fundamental physicists and observational cosmologists to discuss probes of cosmology. This is a crucial step in breaking barriers between communities.
● Promote software and coding tools publicly available for investigating the cosmic discordances that are more versatile to probing models beyond the standard flat LCDM cosmology.
● Build bridges between communities that have historically only worked on part of this problem. CosmoVerse, through its networking tools, will bring together researchers that do not regularly interact with each other, which will promote more cross-disciplinary research.
● Train Early Career Investigators, with a focus on addressing gender imbalances in the community, in order to boost the career prospects through workshops, training schools, and mentoring programmes.
● Train Early Career Investigators with leadership and interdisciplinary (transferable) skills.
● Produce a White Paper for an interdisciplinary research strategy to better direct the development of new physically motivated models and the development of data analysis tools directed at current and future observational cosmology.
● Boost integration of inclusiveness target countries researchers and promote the participation of ECIs (especially underrepresented groups) in all activities.
● Encourage the interaction of inclusiveness target countries by locating networking activities in those counties as a priority.

EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

TECHNICAL ANNEX

1. S&T EXCELLENCE

1.1. SOUNDNESS OF THE CHALLENGE

1.1.1. DESCRIPTION OF THE STATE OF THE ART

The standard Lambda Cold Dark Matter (LCDM) cosmological model provides an effective model for a wide range of astrophysical and astronomical data. High quality cosmological observations from recent missions point to a Universe that is nearly homogeneous and isotropic, and close to being spatially flat [1-4], while being in general agreement with measurements of the nuclei abundances produced shortly after the big bang [5], and is currently undergoing a period of accelerated expansion [6,7]. This LCDM model is able to describe to a good extent the expansion and structure formation history of the Universe, whereas cosmological observations have an enormous potential to inform and to rule out some possible alternative scenarios, leading to an exciting and fruitful interplay between fundamental theory and observations.

Over the last few years, the parameters governing LCDM have been constrained with unprecedented accuracy using observational estimates from galaxy clusters, the Hubble diagram using standard candles, large-scale structure (LSS) measurements, weak lensing surveys and precision measurements of the Cosmic Microwave Background (CMB) [1-7]. The 2018 legacy release from the Planck satellite's analysis of the CMB anisotropies [1], as well as the latest 2020 ACT-DR4 [8] and 2021 SPT-3G measurements [9], that combined with WMAP give independent results [10], have provided a fantastic confirmation of the standard LCDM cosmological model. However, despite its incredible success, LCDM relies on a number of key assumptions on the matter-energy sector whose nature still remains largely unknown. These are Dark Energy (DE), Dark Matter (DM) and the driving sources for an early-time inflationary period. Moreover, a conclusive direct observation of DM either from accelerators or from underground laboratories is still missing [11]. The DM paradigm also shows inconsistencies at galactic scales as the cusp-core problem, the disagreement between the number of observed satellite galaxies and the predictions of galactic N-body simulations based on LCDM [12]. In addition, a number of fundamental open questions persist, such as the fine-tuning of the cosmological constant, the physical processes of inflationary reheating and baryogenesis, the validity of General Relativity (GR) and the possibility of extra dimensions [13,14]. Observational cosmology is now at a key point of its development. While the LCDM model seems to be well-established, its confrontation with observational data requires many parameters to be fine-tuned, and different observational biases (i.e., unknown systematics, foregrounds, etc.) need to be taken into account. Despite living in the age of "precision cosmology", we are still facing many problems with data interpretation in the framework of the LCDM model as demonstrated, for instance, by the current growing tensions between the parameters measured by late-time observations and those estimated by model dependent predictions from early-time observations assuming LCDM [15,16]. While some of these discrepancies may have a systematic origin, their magnitude, persistence across probes, and distribution between the different experiments (all the late-time probes are consistent between themselves and the same happens for the early-time probes) strongly hint at cracks in the standard cosmological scenario and the need for new physics.

The most statistically significant and long-lasting tension is between the estimation of the Hubble constant H0 from the CMB assuming LCDM, and the direct local distance ladder measurements, calibrating Supernovae with Cepheids [17]. In particular, the Planck collaboration finds a constraint that is model dependent and in disagreement at 4.2σ with the 2020 SH0ES collaboration value [1,17]. However, the tension involves many other H0 measurements and there is no direct late-time probe that provides a value for H0 lower than an indirect early-time probe, that is assuming LCDM [18]. This tension is robust and if we average the direct measurements all together in different combinations, or remove a few of them, it still ranges in between 3σ and 6σ with Planck [19]. A solution involving systematic errors in the experiments should explain multiple and independent measurements simultaneously, but it is unlikely to completely cancel out the disagreement. At the same time, models that can alleviate the H0 tension are extremely difficult to find. The H0 tension is a crucial topic in virtually all areas of cosmology, and its importance is highlighted from the thousands of works written in the last few years looking for a solution, the numerous conferences devoted to the Hubble tension, telescope time awarded to address the problem, and the LIGO collaboration placing the Hubble constant solutions as a chief goal. Finding a solution to the H0 tension is very much a work in progress. The resolution of this puzzle will surely require coordinated efforts from the side of the cosmological probes, which are expected to improve observation methods and extricate systematic errors, data analysis, which is expected to refine the codes and techniques used to fit the data, and fundamental physics, which is expected to suggest new first principle scenarios.

In addition to the well-known H0 disagreement, another important tension at about 3σ, quantified using the S8 parameter, which parametrizes the growth of LSS in the Universe, exists between the CMB data and weak lensing measurements [16]. This discordance regarding the S8 value, that is the combination of the matter density parameter Ωm and the clustering parameter σ8, and quantifies the growth of LSS in the Universe, could be due to systematic errors, but it could also be due to new physics beyond the standard LCDM model. Moreover, as with the H0 tension, it can be re-expressed as a disagreement between measurements in the early Universe, which are in agreement between themselves, and those in the late Universe, that agree with each other. In particular, the discordance is between the high S8 value estimated by Planck, and the low values obtained by KiDS-1000 [20] or DES-y3 [2], all of them assuming LCDM. An important feature is that the parameters H0 and S8 are strongly correlated for the CMB probes, and the solutions studied to reduce the Hubble puzzle are actually exacerbating the S8 problem. Complementary to the S8 tension, we find the σ8 tension between the CMB and the galaxy clusters using the Sunyaev-Zel'dovich (SZ) effect, that are measuring the number of clusters of a certain mass M over a range of redshifts, and the fσ8 tension, between the CMB and the galaxy redshift space distortions (RSD) [14]. Also, we soon expect percent-level measurements of the expansion and growth history, together with new CMB experiments, that will either reveal a systematic error cause, or will make the tension stronger from a statistical perspective, helping to constrain models beyond LCDM.

Furthermore, there are additional open questions at the level of 2-3σ present in the Planck 2018 release that arouse curiosity. There is a preference for a closed Universe at about 3.4σ [1,21], confirmed by the re-analysis of the Planck data with the alternative likelihood at more than 99% CL, and the indication for a Modified Gravity (MG) scenario at more than 2σ [1]. Both of them are reshaping the anomalous excess of lensing measured in the CMB power spectra assuming LCDM. This is not a direct measurement of the lensing and could simply be due to a statistical fluctuation or unforeseen systematics in the Planck data. However, despite several years of looking for a systematic source that can explain this feature of the Planck data, the anomaly persists and is robust even with the addition of complementary data, such as baryon acoustic oscillation (BAO). This excess of lensing is strongly degenerate with the curvature of the Universe Ωk, and with MG scenarios. It is of crucial importance to understand the nature of this feature because it can bias the parameters that are lensing related (as the neutrino mass scale). The

possibility of a local inhomogeneity biasing our determination of the curvature can be detected by next-generation experiments measuring CMB spectral distortions such as the kinematic SZ (kSZ) effect and Compton-y distortions. If instead it is found that a departure from flatness occurs at a superhorizon scale, this will have consequences on the inflationary scenarios, with a fine-tuning at the level of about one percent.

Additionally, the Planck high-precision CMB temperature maps confirmed two anomalous features previously hinted at by the WMAP satellite [10]. One is an asymmetry in the average temperatures on opposite hemispheres of the sky, with higher average temperatures in the southern ecliptic hemisphere and lower average temperatures in the northern ecliptic hemisphere. This runs counter to the prediction made by the standard model that the Universe should be broadly similar in all directions. There is also a cold spot that extends over a patch of sky that is much larger than expected. Recent polarization data has not been able to confirm or discard those anomalies.

Another important parameter is the age of the Universe, connecting quantities that are measured in both the early and late Universe, such as H0 and Ωm. This parameter can be predicted by CMB data assuming LCDM, but can also be measured using very old stellar objects, and it seems much older than expected. The level of the tension is not statistically significant, for the poor level of precision reached by the different age determinations, which is dependent on the stellar models being assumed. However, stellar models are expected to significantly improve, possibly revealing a tension in the age of the Universe, strongly correlated to H0. To have an older Universe we need a lower value for H0, worsening the Hubble problem, or pointing to a positive cosmic curvature. In addition, there is the "lithium problem", i.e., the excess abundance of Lithium in the early Universe. The Big Bang Nucleosynthesis theory, combined with the Planck baryon density estimate assuming LCDM, makes tight predictions for the abundances of the lightest elements [1]. While the Deuterium and 4He measurements agree well with expectations, the 7Li observations are a factor 3-4 below. Finally, we have the EDGES anomaly that detected a signal for the 21-cm line of neutral Hydrogen twice the largest predicted value of LCDM.

The resolution of the cosmological tensions is a cutting-edge field which has grown over the last few years. For example, **“**tensions in cosmology**”** is also one of the main topics of the 2021 Cosmology Intertwined (CI) SNOWMASS call, which will be used by a project prioritization panel in the US to decide on funding in the next few years [22]. These tensions may stem from specific, not well understood, biases in diverse data sets, but they may also lead to new physical explanations, among them theories beyond LCDM. On the other hand, these scenarios may yield even more problems both computationally, since they need even more parameters, in terms of data interpretation, since many derived physical parameters are usually obtained under the assumption of a model. We argue that challenges posed by fitting different, often complex, models to ever more complex data requires an efficient and close collaboration between theorists, observers, and data scientists, which is not always the case. Thus, one of the main goals of this Action is to **facilitate a discussion between these 3 groups on how to efficiently and correctly, in the statistical and physical sense, address the problem of fitting models to the data**.

From the point of view of the observations, we need multiple precise and robust measurements of the same observable, while on the data analysis side we need blind analyses of observational data. From the point of view of fundamental physics, we need testable predictions for proposed physical models beyond LCDM, that can be studied with observational data and improved data analysis techniques. It is therefore of primary importance to open dialogues and synergies among experts in these 3 major areas, with the aim of progressing our understanding of fundamental questions in modern cosmology. If we want to produce a comprehensive new model that can explain more fully the available data, we need to connect these pieces of the puzzle through a network of experts in all these different fields.

1.1.2. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

The coming decade promises to see extraordinary advances in observational cosmology that will test the robustness of our current understanding of the Universe to an unprecedented level. It is expected that further confirmation of the H0 tension will be obtained together with more information about the exact nature of the S8 problem, which are crucial indicators of the evolution of the Universe. Obtaining tighter constraints on these parameters may also shed light on other relevant questions such as how flat the Universe really is and whether age of the Universe calculations continue to be in agreement with each other at the right precision level, as well as tests of the cosmological principle.

A multifaceted approach must be taken to confront these tensions in the fundamental indicators in cosmology, which will be centred on:

1. **Bridging observational cosmology with fundamental physics.** The reporting of cosmological surveys depends on LCDM in many circumstances where cosmological parameters are presented. Connecting an improved understanding of cosmology with more complex settings such as non-linear scale physics and possible sources of systematic uncertainties may shed light on the source of recent cosmological tensions. The tension between reported values of H0 and other parameters may be resolved by a better working model of the underlying physics.
2. **Decouple data analysis tools from standard assumptions.** Tools for analysing cosmological data depends on standard flat LCDM at many levels, such as for example for interpreting BAO data, making it difficult to probe other physics in the context of cosmological tensions. By establishing more robust criteria and testing strategies within these frameworks will make the possibility of testing core assumptions and new physics ingredients in the LCDM model more streamlined. The Action will bring researchers together to optimize the adaptability of these tools to allow for new approaches to fundamental physics to be developed, as well as the testing of base assumptions in cosmology.
3. **Defining observationally driven benchmark criteria for new physics.** Challenges to the standard flat LCDM model have come from various directions such as possible departures from flatness at superhorizon scales as well as other possible additional contributors to LCDM. In the context of the numerous surveys currently available, further harmonization and clarity is needed in establishing criteria on which physical theories should be pursued. Through the networking tools available, CosmoVerse will define and promote these criteria in clearer terms.
4. **Cross-disciplinary exchanges.** CosmoVerse will accelerate efforts to confront tensions in cosmological surveys by enhancing the skill set of the next generation of cosmologists through training them in new technologies which rely less on the standard flat LCDM model and open more possibilities for testing new physics. The network will be a catalyst in this ongoing effort, and impact dissemination of this knowledge across Europe.

1.2. PROGRESS BEYOND THE STATE OF THE ART

1.2.1. APPROACH TO THE CHALLENGE AND PROGRESS BEYOND THE STATE OF THE ART

The LCDM model appears to be an approximation to a more realistic scenario not yet fully understood. However, since LCDM provides a good fit of the data, deviations from it are not expected to be phenomenologically too drastic, even if maybe conceptually really different. In particular, the discrepancies listed above between early and late cosmological time observations may involve the addition of new ingredients in the minimal LCDM model, and for this reason, it is timely to investigate them. In other words, current discrepancies may offer crucial insights in our understanding of the Universe. For example, the standard distance ladder result has many steps in common with the discovery of the accelerating Universe (which gave cosmology the motivation for DE). So, whatever the definitive resolution of these tensions turns out to be, and whether it involves galaxies and their

evolution, DE or something else, it is going to have far-reaching consequences for cosmology. Addressing the following key questions is thus a priority for the international community:

- What is the origin of the tension in the observed and inferred values of H0, fσ8, S8, etc.?
- Is part of this tension due to unforeseen systematic errors in the measurements, and can be explained without changing the standard flat LCDM cosmology?
- Are these tensions statistical flukes or is there underlying new physics that can solve them?
- Can new approaches to data analysis yield more information in the currently available data sets?

Other major challenges which are the basis of the previous points can be summarized in:

- What is the nature of DE and DM?
- Did the Universe have an inflationary period? How did it happen?
- Does gravity behave like GR even at horizon size scales?
- Is the Universe flat, open or closed?
- What is the age of the Universe?

To advance in our understanding of the above open questions, LCDM must be transformed from an effective to a fundamental model. Over the next years the international community must:

- Improve the understanding of systematic uncertainties.
- Maximize the amount of information that can be extracted from survey data by considering new analysis frameworks and exploring alternative connections between the different phenomena.
- Improve the understanding of physics on non-linear scales.
- De-standardize some of the LCDM assumptions, or carefully label them in the survey analysis pipelines, to pave the road for beyond LCDM model tests to be carried out by different groups.

To a large extent, this program could be effectively implemented in the next few years by means of coordinated efforts from the side of fundamental physics, data analysis, and observation surveys. CosmoVerse will create a genuine cross-disciplinary network of researchers working in precision tests, fundamental physics and forefront techniques in data science with cosmological observations and systematics, which are currently largely disjoint. The Action will create the conditions to work towards a systematic approach to study current and future cosmological tests, considering a combination of possible systematic errors in the experiments or possible new concordance models.

Observational cosmology is currently experiencing a "golden age" with numerous surveys in an active stage of development, and an even larger number at an advanced planning phase. The next few years will provide a compelling and complementary view of the cosmos through a combination of enhanced statistics, refined analyses afforded by upgraded experiments, and next-generation space-missions and facilities on Earth. In particular, we will see improvements on the local distance ladder observations, and on the measurements using strongly lensed quasars and Supernovae (SNe) via gravitational time delays. A vast amount of data will also open a window to establishing new classes of standardizable candles to measure distances at higher redshifts. We will have new data coming from JWST and the next generation of large ground based extremely large telescopes. New experiments will be built and will release their data, such as CMB-S4 [23], the Euclid space-based survey mission [24], which will map out the formation of cosmic structures over a large fraction of the sky, the LSST (Rubin Observatory Legacy Survey of Space and Time) [25], the Roman Space Telescope (formerly known as WFIRST), and SKA, which will be the largest radio telescope ever built and may expose more of the Universe history of structure formation in its early phases. Current and future data sets, both spectroscopic (e-BOSS, DESI), photometric (DES, HSC, LSST) and of mixed capabilities (Euclid, Roman) will provide statistical power as never seen before. New methods and observations will be considered, such as CMB spectral distortions or voids, which will be detected in upcoming surveys, or gravitational wave (GW)

coalescence events, thanks to the LIGO-Virgo-KAGRA network [26], or the LISA Mission, which will be a space-based GW observatory with a higher sensitivity to primordial GWs [27]. Future deep multiband imaging of the sky will also facilitate the constraints on the expansion rate at high redshifts by means of cross-correlating GW observations of binary black hole mergers with catalogues of galaxy photometric redshifts from large cosmological surveys. An important role will be played by gravitational waves standard sirens, i.e., observations of electromagnetic counterparts of binary neutron star mergers observed in the GW domain. The current constraint from kilonova GW170817 is weak and in agreement with all the other measurements [28], but it does not require a distance ladder and at the same time it is largely independent of the LCDM assumptions, even if it depends on our models for peculiar velocity.

These surveys will change cosmology in a research field in which huge amounts of information will be available, making the testing of cosmological models an increasing sophisticated task. Over the next decade, the volume and production rate of data available for cosmological studies will increase by orders of magnitude. With these advances, however, there are also some open issues:

- How to store and transfer such huge data sets?
- How to assure quality control of derived parameters and software being developed?
- How to assure efficient exchange of expertise and information between different projects?

While some projects (like Euclid, LSST, SKA) provide networking opportunities within their organisational structures, there is an **urgent need for a network that facilitates cooperation**, shares expertise, and harnesses the synergies of different data sets. This is an area that CosmoVerse aims to have a significant impact on, among others. For instance, cosmological simulations provide a relatively easy way for different assumptions to produce different cosmological scenarios. However, observational data sets are very challenging as they depend on understanding complex non-linear effects in baryonic matter. This requires the close collaboration of different areas of computational physicists, theorists, observers, and specialists on modelling galaxy evolution. The Action will bring these groups together to address challenges of this nature.

Future observations of various distance indicators will largely improve constraints on the expansion history and independent absolute distance calibrations. In this context, observations from JWST will play an important role. Moreover, the next decade will see the development of future CMB experiments such as the Simon Observatory [29] and CMB-S4, and once combined with large galaxy surveys such as Euclid and LSST, they will reach unprecedented precision in H0. There will be RSD measurements coming from DESI and 4MOST, the maps measured by the Euclid satellite, and the peculiar motions of galaxies using SNe obtained from LSST. Moreover, BAO surveys and weak gravitational lensing measurements using 21 cm intensity mapping are expected by SKA, and additional 21 cm neutral hydrogen experiments by CHIME and HIRAX, that will measure the cosmic expansion history. The SPHEREx satellite or the ground-based COMAP instrument will give BAO data using line-intensity mapping from star-forming galaxies. Euclid and SKA are also expected to help with the constraints on the spatial curvature and MG models, breaking the parameter correlations.

A large portion of these projects have **total or deep European involvement**. CosmoVerse will thus provide a common space of discussion for a more concerted effort to probe the results of these surveys, **facilitating an interdisciplinary approach**, stimulating the flow of novel ideas on fundamental physics, motivating more powerful experiments, contributing to the development of better statistical tools and improved data analysis techniques. The link between the important novel fundamental physics that is currently being developed and the current and future observational projects will be the efficiency and innovativeness of data science strategies. There is currently a large effort in testing LCDM with ever more precise tests. On the other end of the spectrum, there exists a growing effort to perform similarly

precise tests on new fundamental physics models. **This Action can strengthen that momentum and coordinate the inclusion of other promising models and data analysis techniques**.

It is **thus only through the intertwined network of 3 working groups (WG)** that this Action can concretely achieve its objectives using the skills of experts in observations and systematics, data analysis, and theoretical models beyond LCDM, to probe novel fundamental physics with precision data science approaches.

1.2.2. OBJECTIVES

1.2.2.1 Research Coordination Objectives

CosmoVerse will coordinate between 3 different strong communities working on challenging LCDM using multiple cosmological surveys. The common goal is to improve our knowledge of the Universe and fundamental physics, using high precision survey data and advanced data analysis techniques. The 3 themes of the Action will strengthen European collaboration and leadership by:

- **Organising, developing, and disseminating** research efforts and tools to address the challenge of cosmological tensions in the next decade. CosmoVerse will encourage and support the development of computational tools that make it easier to interpret observational data using fundamental physics beyond LCDM. This will be achieved by facilitating coordination between European research centres and leading experiments in the coming years. One way to do this is through annual conferences that merge contributions from the observational cosmologists, data analysts and fundamental physics communities in a holistic and interdisciplinary way. A dialogue can also be opened between these communities by hosting workshops that tackle cross-disciplinary topics such as incorporating more aspects of observational cosmology in data analysis pipelines, and how fundamental physics can more fluidly produce predictions that are easily used by observational surveys and simulation designers.
- **Creating a long-lasting network synergy** between previously disjoint communities to maximize European leadership in current and future precision cosmological surveys. As more mission surveys come online, it will be crucial to establish a solid network between these collaborations so that data analysts can design better simulations and make the current state of observational cosmology clearer for researchers working in areas of fundamental physics.
- **Training early career investigators (ECIs)** in forefront cosmology with no boundaries between the Action research themes in order to prepare them for cross-disciplinary problem-solving fields (and other transferable skills) through training schools and a large devotion of funds to short term scientific missions (STSMs). In more concrete terms, this means supporting STSMs that bring together different communities which will create long-lasting and native links between observation, data analysis and fundamental physics communities and strengthen cosmology across Europe.
- **Peer-reviewed publications** of at least 8 papers per year which will be a combination of works that result from STSMs and outputs from work performed at workshops over the course of the 4-year period of the Action. Additionally, the Action will promote virtual collaborations and encourage collaborative works of this kind.
- **Performing Europe-wide public dissemination** through a strong online presence, outreach events and highlighting individuals in the network, as well as providing constructive teaching tools for educators. These Actions and tools will connect the broader public and students across Europe with ongoing research related to observational advances in cosmology as well as efforts in confronting cosmological tensions in recent surveys.

1.2.2.2 Capacity-building Objectives

The overarching theme of CosmoVerse is to consolidate effects to investigate the current cosmological discordances by establishing an interdisciplinary framework across observation cosmology, data

science and fundamental physics communities with a strengthened and long-lasting base in Europe. This will be achieved through capacity-building through the following measures

- **Develop a common language** for fundamental physicists and observational cosmologists to discuss probes of cosmology. This is a crucial step in breaking barriers between communities.
- **Promote software and coding tools publicly available** for investigating the cosmic discordances that are more versatile to probing models beyond the standard flat LCDM cosmology.
- **Build bridges** between communities that have historically only worked on part of this problem. CosmoVerse, through its networking tools, will bring together researchers that do not regularly interact with each other, which will promote more cross-disciplinary research.
- **Train ECIs** with leadership and interdisciplinary (transferable) skills.
- **Produce a White Paper** for an interdisciplinary research strategy to better direct the development of new physically motivated models and the development of data analysis tools directed at current and future observational cosmology.
- **Boost integration** of ITC researchers and promote the participation of ECIs (especially underrepresented groups) in all activities.
- **Encourage the interaction of ITCs** by locating networking activities in those counties as a priority.

By bringing researchers closer together academically through the Action activities, the network will support progress in the **state-of-the-art that is better organised and better coordinated. This will empower researchers to implement novel approaches to fundamental physics through data science approaches.**

2. NETWORKING EXCELLENCE

2.1. ADDED VALUE OF NETWORKING IN S&T EXCELLENCE

2.1.1. ADDED VALUE IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

CosmoVerse is the first network based on **connecting core efforts in observational cosmology consortia, data analysis approaches in cosmology and fundamental physics incorporating several European countries** with the aim of addressing the challenge of tensions in cosmology. Some aspects of this initiative have been funded at the national level but, for this reason, there is a lack of coordination between the many research groups operating at the European level. It is thus crucial that these efforts are linked together, not only to advance the field, but also to identify knowledge gaps and harmonize the portability of scientific knowledge among contributors within CosmoVerse. This network will leverage the knowledge generated by national research projects over the last years to strategically plan and direct efforts towards the integration needs of current and future observation projects with robust approaches to cosmological data analysis and fundamental approaches to address these tensions. Through CosmoVerse, complementary research **initiatives across the European community will be more coherently focused to meet the needs of cosmology over the next decade**.

In the near future, a number of key (totally or partially) European cosmology missions will be built and start their data release cycles, such as Euclid, which has over 1500 members from 100 Euclid consortium institutions, LISA with 32 participating countries and around 1160 members, SKA is made up of 15 participating countries and is expected to cost around €1.8 billion, and BINGO which has 10 member countries, among others. However, these projects suffer from a **critical European-wide bottleneck** as most of the unused funding for hardware is mainly directed to astrophysical analyses or cosmology very much within the standard flat LCDM model. This leaves limited possibilities for building

a cohesive European framework for tackling cosmological tensions through new approaches. Given the mammoth hardware challenges that such missions face, one gets the impression that these considerations can be managed by national funding agencies or tackled by future projects. However, the network between observational missions and the data analysis and fundamental physics communities will take time not only to mature but also to focus efforts at the confluence of their respective problem domains. **CosmoVerse will bring together disparate efforts across Europe** (especially Inclusiveness Target Countries (ITC) where there is little or no funding for networking) into a more ambitious pan-European network to foster a more borderless culture of developing ideas from observational cosmology to fundamental physics and their implementation in data analysis simulations.

The Action will thus provide a platform and support on which to discuss the different approaches to address recent and future tensions in cosmology. The CosmoVerse community will achieve this by funding frequent meetings with an annual global meeting and many WG meetings (cf. Sec. 4). These meetings will also include specific activities ECI-targeted activities such as networking events and incorporating ECI presenters into the most popular timetable sessions. They will also be encouraged to attend CosmoVerse schools which will help **train the next generation of cosmologists with specific tools to connect fundamental physics with observational data through data analysis simulations** that are more likely to probe physics beyond LCDM cosmology in a more native way. To this end, the Action will fund scientific visits (both within and outside Europe) with a focus on ECIs which will **promote cross-disciplinary** projects. Through these actions the already fruitful collaborations of the network proposers will be further strengthened and more competitive on the international stage.

2.2. ADDED VALUE OF NETWORKING IN IMPACT

2.2.1. SECURING THE CRITICAL MASS AND EXPERTISE

One of the main drivers for CosmoVerse is the urgent need to provide a network framework on which current and future surveys can interact, which includes cross-disciplinary discussions and collaborations with experts that promote advances in data analysis and fundamental physics. As already mentioned, this Action will build on the progress made in the respective initiative of the 2021 CI SNOWMASS call. To this end, CosmoVerse will not only keep to the spirit of CI SNOWMASS but will also bring together significant expertise from across Europe. This includes leaders of all the major surveys already discussed such as Euclid, LISA, KiDS, SKA and others. The network is also composed of, or has direct contact with, expert stakeholders working on frontier advances in data analysis approaches and new physics directed at meeting the observational challenges that the theme of tensions in cosmology raises. Through CI SNOWMASS, the survey leaders, and these links, the network will consist of a unique and global network of expertise centred in Europe with international links. CosmoVerse is composed of outstanding critical mass and possesses the appropriate expertise to achieve the objectives proposed by the Action.

The Action structure will enhance survey consortia by actively supporting joint projects to better understand how systematic sources and joint survey analyses can affect parameter estimates. CosmoVerse will also expand CI SNOWMASS by strengthening the portability of observationally motivated fundamental physics along with new approaches to data analysis beyond flat LCDM. The Action will actively encourage mobility between observational survey teams and across the thematic lines of the WGs which will increase the critical mass of the Action across Europe and internationally thus advancing the state-of-the-art concurrently. These mobility activities will be directed at ECIs with a focus on training activities between disciplines. Special attention will be given to ITCs, especially those with ICT-priority areas which will be easily integrated within the Action WGs.

The objectives described in Sec. 1.2.2 will all contribute to increasing the critical mass and expertise of the Action. On this point, the Action already has consolidated and recognised expertise in observational surveys and their systematics, new approaches to data analysis, and fundamental physics beyond flat LCDM cosmology. This will be crucial to providing the support and training for the ECIs who will train the next generation of cosmologists which will only increase with each new member of the Action.

2.2.2. INVOLVEMENT OF STAKEHOLDERS

Below, we identify the stakeholders together with the plan to involve them in the Action:

Survey collaborations: The landscape of survey collaborations is disjointed, CosmoVerse will bring together these core stakeholders by inviting survey leaders to occupy or actively participate in the network, as well as organising specific events to open a dialogue between the different respective consortia. A significant part of the networking activities will also be assigned to the ECI by these collaborations. CosmoVerse is already composed of senior consortium members of Planck, KiDS, Euclid, and has links to many others. This will increase as the Action activities develop. These researchers will be heavily involved in Action activities such as giving talks at CosmoVerse conferences and workshops, or being part of the lecture series in training schools, and scientific visits. Experienced researchers will also be involved in the Action products (e.g., White Paper).

CI SNOWMASS consortium: Some key stakeholders are part of the CI SNOWMASS initiative, many of whom will be part of the CosmoVerse network, also centred on the theme of tensions in cosmology. The broader CI SNOWMASS collaboration involves over 200 active researchers, many of whom are located in Europe. These stakeholders will form an integral part of the Action. This will ensure an adequate level of representation as well as adding an important layer of support for the European side of the CI SNOWMASS collaboration. CosmoVerse will provide support to ECIs in this network to visit expert researchers in cross-disciplinary fields and provide training on current and new approaches in the field of tensions in cosmology. This will not only train the next generation of cosmologists but will also provide a long-term legacy beyond the term of the Action. CosmoVerse will offer network experts an opportunity to disseminate research results in numerous conferences and workshops.

International networks and organisations: CosmoVerse intends to actively engage with international networks based in Europe (e.g., SKA) and not (e.g., CMB-S4). This will mainly imply invited talks at conferences and workshops but may also involve a contribution to Action outcomes such as the White Paper. This will allow Action members to meet and open a dialogue with important expert stakeholders in consortia not already integrated in the CosmoVerse network.

General public: Public outreach as well as material and events for the education sector, and online resources for all audiences will be an important component of all CosmoVerse activities. In the context of the enormous effort being invested in cosmological surveys and further research, the general public needs to understand how this translates into creating knowledge beyond the current state-of-the-art and how this relates to our understanding of the Universe. CosmoVerse expert members will firstly organise activities to communicate Action developments and outcomes locally through public dialogues (such as science café and school outreach events). Each CosmoVerse event (conference, workshop, training school) will somehow involve interactions with the general public and a key stakeholder through public talks, school visits, and round tables. This will be complemented by a website and social media presence (e.g., Twitter, Instagram, YouTube) which will be used to communicate recordings and general public information material more broadly.

2.2.3. MUTUAL BENEFITS OF THE INVOLVEMENT OF SECONDARY PROPOSERS FROM NEAR NEIGHBOUR OR INTERNATIONAL PARTNER COUNTRIES OR INTERNATIONAL ORGANISATIONS

CosmoVerse seeks to strengthen the collaboration between European research in cosmology and that across the CI SNOWMASS consortium as well as with other cosmological survey organisations. We expect CosmoVerse to have a global impact and an international network of experts who will contribute to the activities and goals of the Action. These are: **Prof. Adam Riess** (Nobel Prize in Physics, 2011) from Johns Hopkins University. **Prof. Daniel M. Scolnic** from Duke University. **Prof. Laura Mersini-Houghton** from the University of North Carolina at Chapel Hill. **Prof. Antonella Palmese** from the University of California Berkeley. **Prof. John Blakeslee** from the NSF's National Optical-Infrared Astronomy Research Laboratory. **Prof. Celia Escamilla-Rivera** from the Institute of Nuclear Sciences (Mexico). The nexus of this base of international stakeholders will benefit the Action in achieving its network goals and research aims.

3. IMPACT

3.1. IMPACT TO SCIENCE, SOCIETY AND COMPETITIVENESS, AND POTENTIAL FOR INNOVATION/BREAKTHROUGHS

3.1.1. SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS (INCLUDING POTENTIAL INNOVATIONS AND/OR BREAKTHROUGHS)

The Action will create a synergy between the different themes of cosmology through which there will be accelerated progress in observational systematics and joint analyses, the application of new approaches in data analysis and fundamental physics in relation to cosmology. This is expected to have significant impacts on our understanding of the Universe, which will provide important insights into its evolution from the very early Universe. The Action constitutes an essential step in building the scientific tools and the network to fully exploit the results of recent and future observational cosmology surveys, promoting and supporting cohesion and collaboration between the various disciplines working on tensions in cosmology. The topic of tensions in cosmology connects to several branches in the field, by promoting healthier cross-disciplinary research the Action will lead to major scientific advances and knowledge creation.

CosmoVerse will **strengthen research and collaboration structures across Europe** in a number of direct and indirect ways, namely: (1) Harmonize the process by which new physics is developed and then constrained through survey data and reassessed (through the Action White Paper and workshops/annual conference special sessions); (2) Maximize the dissemination of knowledge throughout the network (increasing the participation of ECIs in training schools and STSMs, and promoting new approaches across the community); (3) All research outputs (publications, White Paper, etc.) of CosmoVerse will be available on open access scientific portals that will make the scope of the Action truly global; (4) CosmoVerse will interact with other networks with similar focal areas to bring the impacts of the networks closer to reality; (5) The Action will create a climate of cross-disciplinary approaches that involves the 3 Action research areas.

After the 4-year term of the Action, the research portfolio and network organisation will have established an ideal framework for future projects such as consolidating grants. In addition, by encouraging the link and mobility between geographical areas and disciplinary themes, CosmoVerse will contribute to future

progress by consolidating collaborations across these borders. The Action will also promote the visibility of ECIs and underrepresented groups by focusing networking activities (such as conferences and workshops) on them. This will be complemented by mentoring and training derived from the STSM projects.

The general public is also a key stakeholder in CosmoVerse, besides the strong public interest in topics surrounding the Universe, the Action seeks to encourage further interest and greater education on the state-of-the-art. This will be achieved through the inclusion of public events and talks as part of some Action events (annual conference and all workshops) which will be delivered by one or more experts who are already part of the network. The Action will also sustain an active online presence through the website social media to support the public audience.

3.2. MEASURES TO MAXIMISE IMPACT

3.2.1. KNOWLEDGE CREATION, TRANSFER OF KNOWLEDGE AND CAREER DEVELOPMENT

CosmoVerse will achieve its scientific objectives through 3 interdisciplinary WGs that will coordinate and meet regularly to work on specific themes that will fuel the global networking Action activities. It will do this by exploiting the available networking tools of COST in order to bring together target groups of experts and ECIs from the different communities relevant for this Action.

One of the key pillars of the Action will be the knowledge transfer between members of the groups involved and from the Action to the global community, which will mainly take place via:

- **STSM:** One effective way to ensure knowledge transfer is direct human contact and training through common research. For this CosmoVerse will launch STSMs among the members of the different WGs, giving priority to establish new collaborations between ECIs and experts in the field as well as between experienced researchers and ITCs or underrepresented groups. Besides boosting the research output of the Action participants, these tools will help to increase the global capabilities of the community and strengthen efforts to achieve the Action objectives.
- **White Paper:** A comprehensive review with contributions from the different WGs will initiate an internal debate within the Action in order to bring together disparate topics in a state-of-the-art representation. This work will highlight efforts towards developing new cosmological probes beyond LCDM theories, particularly in the context of the next generation of observations. In addition, the paper aims to set a road map for the future of the topic, laying the foundations for new collaborations and innovative research projects within and beyond the Action.

Another pivotal element that CosmoVerse will use to transfer and communicate knowledge through the network will consist of different types of meetings, namely:

- **International conferences:** An annual international conference will be organized. This event will aim to bring experts in the different topics of interest for the Action and help the rest of the community, especially ECIs and ITC researchers, to interact with them and other experts. These events should act as a catalyst for new collaborations that could be implemented via STSMs. In addition, these conferences will also be useful to highlight relevant results from STSMs and the work of underrepresented groups, ITC researchers, and ECIs.
- **Workshops:** CosmoVerse will also feature regular workshops for more focused research areas and WG interfaces which will accelerate many of the Action's objectives.

Finally, CosmoVerse will train and promote ECIs by complementing their career development with several Action activities, which will be:

- **Training schools:** CosmoVerse aims to organise two large training schools that will equip the next generation of researchers with the skills to use new approaches in fundamental physics along with new cosmological tests and data analysis approaches. These will be interdisciplinary in nature and will host leading researchers as instructors who will be crucial in achieving the highest standards. Schools will equip students with the technical know-how to excel in the field as well as the general skills in organisation, management, communication, presentation, and networking to succeed inside or outside academia.
- **Online training portal:** To extend the impact of the schools and to provide long-lasting support to CosmoVerse members and the international community at large, the Action website will include a training portal that will contain recordings of training school lectures and conference talks and seminars organized by the Action, news and links of relevant online talks, materials such as codes, examples, presentations, and links to the Action publications and related works.

3.2.2. PLAN FOR DISSEMINATION AND/OR EXPLOITATION AND DIALOGUE WITH THE GENERAL PUBLIC OR POLICY

CosmoVerse will spread its activity and results through different channels following a dissemination strategy coordinated by our Science Communication Manager aimed at maximizing its visibility. For this purpose, we will use the following tools:

- **Website:** Besides a training portal and listings of publications and events related to the Action, CosmoVerse's website will contain a news section and a blog area to advertise upcoming events (webinars, meetings, etc.) and publicise/discuss relevant results and works by Action members. STSM grantees and ECIs will be invited to write posts on their missions, work and interests, and experts will contribute summaries of their works in accessible language. This will increase the online visibility of CosmoVerse and its members, while also allowing us to keep a quantitative track of the reach and impact of these activities. Training and tips on the use of outreach services/tools, such as https://theconversation.com and https://growkudos.com, will be provided.
- **Social networks:** CosmoVerse public profiles on Facebook, Instagram, Twitter, etc. will be used to reach a wider and more diversified audience to keep them informed about the Action's activities. We will use the statistical tools of these outlets to assess the impact of these activities.
- **International conferences and workshops:** CosmoVerse will encourage its members to attend interdisciplinary international conferences and workshops to publicise important results as part of its knowledge creation strategy [Sec. 3.2.1]. It will also finance participation in these events through the ITC conference fund tool. Our meetings will produce regular proceedings.

In addition to the above online dissemination activities, CosmoVerse will also endeavour other types of live activities to engage with the general public in different scenarios:

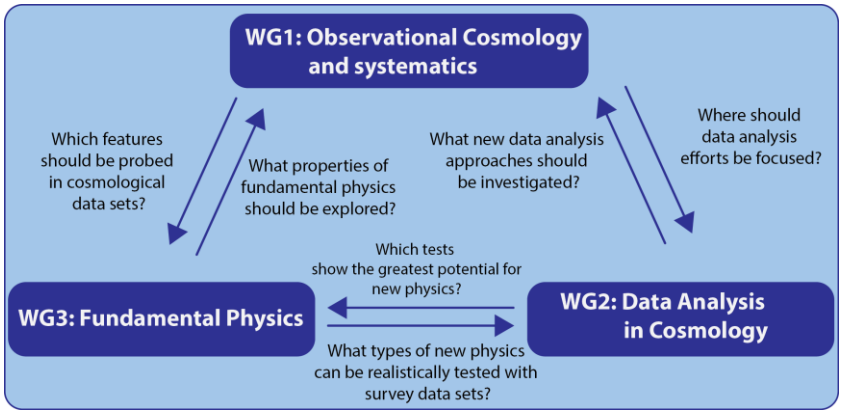
- **Public engagement events:** Event organisers will be recommended to hold an associated public engagement event where experts will interact with the general public via dissemination talks, round tables, etc. that will be recorded, posted on the web, and shared on social media.
- **School visits, interviews, and educational resources:** We will promote among Action members the need to interact with school/high school teachers and pupils to inspire the next generation of educators and scientists. To this end, we will encourage dissemination talks in schools, participation in online "Ask a Scientist" events, and the development of educational resources with up-to-date information on the cosmos and the Action's activities.

4. IMPLEMENTATION

4.1. COHERENCE AND EFFECTIVENESS OF THE WORKPLAN

4.1.1. DESCRIPTION OF WORKING GROUPS, TASKS AND ACTIVITIES

CosmoVerse will be composed of 3 WGs that are critical to address the growing significance of cosmological tensions in recent survey analyses. Each of the WGs are related together in an integral way, as described below. Through these distinct approaches CosmoVerse aims to explore possible solutions to the cosmological tensions problem.



The WG core topics and focus areas will be established and prioritized in a kick-off workshop attended by all Action members. While the WGs are separate from each other they share important interrelated features from which new cross-disciplinary research questions can be investigated as part of CosmoVerse.

CosmoVerse is structured into 3 WGs, described below, that correspond to the Action objectives.

WG1: Observational Cosmology and systematics

Unveiling the nature of the existing cosmological tensions and other possible anomalies discovered in the future will require a multi-path approach involving a wide range of cosmological probes, various multiwavelength observations and diverse strategies for data analysis. Cross-correlations between various complementary data sets and cross-validations of different methodologies will be essential to understand and quantify systematic effects, and eventually to create a solid empirical basis for the future endeavour to deepen our understanding of the theoretical foundations of the standard cosmological model. The **main objective of WG1** is to support this goal by facilitating communication and expertise transfer between different groups of researchers via workshops, training, data challenge initiatives and critical reviews of the field. This decade will see data from “all sky” surveys, and the ultimate analysis of these large data sets will include combinations and cross-correlations of different probes of LSS. Each probe is sensitive to certain aspects of the cosmological model. Their combination, therefore, will not only break degeneracies that exist in the model parameters, but also will act as a powerful tool for understanding and controlling systematic effects. With large overlap between different surveys, we can probe the same structures using different data and therefore attribute any differences to systematic effects. Consequently, another **objective of WG1** will be to favour a cross disciplinary and survey effort, that is mandatory to produce the most robust data analysis by the end of this decade. For example, both Euclid and LSST will observe the shape of the same galaxies over most of the sky. Due to their differing nature, their images will suffer from very different observational systematic effects. Their synergy will therefore be crucial for disentangling systematics from real physical effects. Large samples of type Ia SNe to be observed by surveys like LSST will enable improvement of the SNe standardization and a better understanding of systematic errors, which is crucial to reaffirm the Hubble constant tension and obtain reliable constraints on the DE equation of state. A large number of new lensing systems to be discovered by the upcoming wide-field surveys complemented by dedicated follow-up observations will greatly improve the accuracy and precision of this measurement, which is currently limited by systematic uncertainties of the lens models [30]. Addressing the problem of the Hubble constant tension will also require more in-depth robustness tests of the primary distance indicators, such as Cepheids and tip of red-giant branch, and the secondary distance indicators alternative to type Ia SNe such the surface brightness fluctuation technique. Finally, tensions emerge when comparing late Universe results with CMB observations. The path forward beyond the standard model is paved with a coordinated effort

between different surveys and probes. Additional **objectives of WG1** will be to provide a platform for communication between a wide array of experts and experiments, and also train new scientists.

WG2: Data Analysis in Cosmology

Presently, cosmological models are largely tested by using well-established methods, such as Bayesian approaches, that are usually combined with Monte Carlo Markov Chain (MCMC) methods as a standard tool to provide parameter constraints. MCMC analyses also offer a consistent and impactful way to combine different data sets together. However, an interesting development of data science has been the emergence of machine learning (ML) and artificial intelligence techniques, and there are 3 main reasons to use them in cosmology. 1) Automation: the huge size of future data sets means manual intervention is only possible in highly exceptional circumstances. Many data analysis tasks need to be automated. 2) Acceleration: ML can provide shortcuts to costly physical simulations. ML indeed offers the possibility of adapting cosmological models that acquire features by using observational data as a training set. 3) High performance: trained on physical models and data, “emergent” algorithms can sometimes exceed performance of “designed” algorithms. For example, in astrophysics ML has been used to identify and classify galactic and stellar objects, and to produce full high-resolution cosmological simulations that are an essential part of teasing out many aspects of structure formation. Currently most of the information embedded into cosmological surveys is not used since it is located on small scales where no accurate theoretical prediction is reliable enough. In principle, ML algorithms that determine correlations between features can be used to constrain cosmological parameters from non-Gaussian density fields. Moreover, ML offers numerous approaches to differentiate preferences in data between new cosmological models versus flat LCDM. While this area significantly developed over the past decade, some researchers still tend to apply certain methods with a poor understanding of their limitations. Conversely, statisticians who approach astronomical data often make wrong assumptions about their properties. The need for an interdisciplinary network of data scientists, statisticians, programmers, and astronomers/observational cosmologists is stronger than ever today, and this is **the main objective of WG2.** The increased use of ML techniques requires on the one hand a very good understanding of the observational data, and on the other hand an adequate understanding of the theory behind popular ML tools, so that the results are understood correctly. A second **objective of WG2** will be to address these two parts by including them as topics in training schools, inviting experts to discuss them in schools and/or virtual seminars and annual conferences, so that the next generation of researchers is adequately introduced to these novel methods. A third **objective of WG2** will be to create a database containing the links to models used in cosmology, easily accessible for new researchers in the field. It will also encourage the publication of the files related to their models when applicable (i.e., training data, python files, chains, etc). This will improve the transparency and the reproducibility within the field and will aid the combination of data or the use of new ML techniques. This represents the **synergy between WG1, WG2 and WG3** and will be a visible output from the Action.

WG3: Fundamental Physics

Given the observational tensions among different data sets, and the unknown quantities on which the model is based, alternative scenarios should be considered. The **main objective of WG3** will be to work on the following key scientific topics: 1) Challenging the basic cosmological hypothesis, such as homogeneity, isotropy and flatness of the Universe at the moment implicitly assumed in the standard model. For example, the acceleration of the Universe would not exist if there were a breaking of homogeneity, and the interest for anisotropic and inhomogeneous cosmologies is motivated by anomalies in the CMB distribution. Moreover, a small curvature seems to be in agreement with the current data challenging the flatness condition. 2) Challenging Einstein’s theory of gravity with DE and MG. The expansion rate of the Universe has accelerated twice, once at very primordial times and high energies (inflation phase) and then through a second much later period that is still ongoing (DE phase).

The necessity of invoking accelerating expansion twice might even cast doubts on the very basic geometrical description inherited from classical GR. Only by improving our knowledge of the growth of structure in the Universe can we hope to progress towards breaking the degeneracy between DE and MG. 3) Constraining neutrino physics. While there is evidence for a finite total neutrino mass from oscillation experiments, the neutrino mass is assumed to be fixed to the lowest value allowed when analysing cosmological data. A complete analysis should include massive neutrinos, as it has been shown that they can help with cosmological tensions. Moreover, while the number of active neutrinos is known, there is the possibility of additional sterile neutrinos at recombination that can change the number of relativistic degrees of freedom. 4) DM in LCDM is composed of cold and collisionless particles. However, there is the possibility that these interact with the other components (baryons, neutrinos and DE), decay, and that are relativistic at recombination, increasing the effective neutrino numbers (as for example with thermal axions). All these possibilities can solve the cosmological tensions. 5) DE is a cosmological constant in the standard model. However, this component can have a free equation of state, be dynamical, or be interacting. Additionally, an Early DE component, present before the recombination, but rapidly dissolving after, has been proposed to solve the cosmological tensions. 6) A unified description for DM and DE. The appearance of two unknown components in the standard cosmological model, DM and DE, has prompted discussion of whether they are two facets of a single underlying dark component. This concept goes under the name of quintessence, or unified DM. A priori this is attractive, replacing two unknown components with one, and in principle it might explain the coincidence problem.

4.1.2. DESCRIPTION OF DELIVERABLES AND TIMEFRAME

Building on the established objectives of Sec. 1.2.2, CosmoVerse will bring about the following **deliverables (D)**, **organisational milestones (O)**, and **scientific milestones (S)** in a timely manner to ensure an effective implementation of the vision of the Action.

Deliverable		**Organisational milestones**		**Scientific Milestones**	
D1	Publication of at least 8 papers per year in major high-impact international journals (month 48) [O1]	O1	Annual Management Committee (MC) Meetings (Months 1, 9, 16, 28, 40)	S1	Probe survey data for systematic sources for cosmic tensions (WG1)
D2	Complete a White Paper summarizing and going beyond the state-of-the-art (month 24) [O5, O6, O9]	O2	Formation of WGs and Action structure (Month 1)	S2	Expand robust combinations of different survey data sets (WG1)
D3	Training school videos and tools on web portal (months 24, 48) [O3, O6, O7, O8]	O3	Action website and social media accounts (month 3)	S3	Create a database of novel data analysis approaches with training material (WG2)
D4	Hold recorded public dissemination events and make available online (months 12, 24, 36, 48) [O4]	O4	Periodic WG Meetings (at least 2 per WG) (month 48)	S4	Development of novel tools to probe cosmologies beyond flat LCDM (WG2)
D5	Publicly available online portal of the results of S1	O5	Produce an online portal on the Action website	S5	Build better motivated cosmological models using

	and S2 with comparative and updated results of cosmology beyond LCDM (months 24, 48)		where training videos and tools will be collected for ECIs (month 24)		input from different research areas (WG3)
		O6	Two large Training schools (months 20 and 44)	S6	Develop more fundamental explanations for cosmic inflation, DM and DE (WG3)
		O7	Annual international conference (months 9, 21, 33, 45)		
		O8	STSMs successfully completed (2 calls per year) (month 48)		

4.1.3. RISK ANALYSIS AND CONTINGENCY PLANS

The table below describes the core risks for CosmoVerse together with their associated risk level (low – medium – high) and our risk mitigation measures.

Risk	**Risk Level**	**Mitigation measures**
Reluctance to develop tools for new approaches in fundamental physics	Medium	CosmoVerse seeks to expose current and new tools to new physics by making them more accessible. There is the possibility that ECIs may be reluctant to work on this. However, we expect the uptake of the tasks related with these activities to be high given the expanding support in the community for such projects.
Limited interest of stakeholder to take part in networking activities	Low	Networking activities are being designed to correlate strongly with the current direction of the proposer's networks which will ensue critical mass is available to successfully complete the objectives of the Action.
Travel restrictions	Medium	While travel restrictions are unlikely to be reimposed, the Action is being designed to have a strong online presence for hybrid activities in cases such a scenario materializes.
Not all code can be made freely available	Low	Most cosmology tools in LCDM are already either online or available in some form. Within this culture, the risk of not being able to make the products of CosmoVerse activities public is expected to be reasonably very low.

4.1.4. GANTT DIAGRAM

Activities	**1st Year**				**2nd Year**				**3rd Year**				**4th Year**			
Organisational Activities	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
MC meetings	O1															
Setup of WGs	O2															
Action website and social media accounts setup and updates	O3															

WG meetings			O4													
Training videos and tools portal								O5								
Training Schools							O6									
International conferences																
STSM Visits			O8													
Deliverables																
High-impact Publications	D1															
White Paper	D2															
Training School Videos								D3								
Public Engagement Events	D4															
Community tools on website								D5								
WG Activities																
WG1																
Probe survey data for systematic sources for cosmic tensions		S1														
Expand robust combinations of different survey data sets					S2											
WG2																
Create a database of new data analysis approaches with training material		S3														
Development of new tools to probe cosmologies beyond flat LCDM		S4														
WG3																
Build theoretically motivated cosmological models using input from different research areas						S5										
Understand the physical nature of Cosmic inflation, DM and DE		S6														

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