Chapter 4

Origin and fate of the Universe

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"How did the Universe begin?" is one of humanity's oldest questions. The approach to this question gets inputs from many fields, varying from the largest to the smallest scales, from cosmology to particle physics. The last century provided the opportunity to apply the scientific method to this question with results that have established a first comprehensive understanding of the origin, content, and fate of the Universe. The tremendous leap forward in technology experienced in this new century will allow us to challenge this model to extreme levels, establishing it robustly or leading to new and deeper open questions. This chapter is about the understanding of the content of the Universe, its history, and its ultimate fate.

4.1 Introduction and general description

This challenge will address one of the most fundamental and important topic in sciences: “How did the Universe begin and how it evolved to its current form?”. The approach to these questions have taken, and it will, most of the effort from many fields ranging from the largest to the smallest scales, cosmology to particle physics. The last century provided the opportunity to apply the scientific method to these questions with results that have established a first comprehensive understanding of the origin, content, and fate of the universe. The tremendous leap forward in technology of this new century will allow us to challenge this model to extreme levels, establishing it robustly or leading to new and deeper open questions.

Cosmology, astrophysics and astroparticle physics, on the one side, and particle physics, on the other, are deeply interrelated and try to understand the global properties of the Universe from its origin to the present. In order to address this challenge many topics varying from cosmic inflation as the mechanism responsible for seeding the cosmic web to the understanding of the origin of the baryons in the universe, from the nature of dark matter (DM) as the main source of gravitational force to the one of dark energy (DE) encoding the accelerated cosmic expansion at late times.

In order to understand these questions, we specifically address the following issues from a theoretical and experimental point of view using the present and review the future experiments available. The use of gravitational waves as a new and revolutionary tool to approach to the precise determination of cosmological distances with both standard and dark sirens will be discussed in here.

• **Cosmic inflation.** Current cosmological observations of the Cosmic Microwave Backgrouns (CMB) and the Large Scale Structure (LSS) point to cosmic inflation as the mechanism responsible for seeding the cosmic web. Ongoing and future experiments measuring the microwave sky and mapping the large-scale structure of the universe could yield the final proof of the validity of cosmic inflation and, even more, could also provide details on the specific properties of the inflationary potential.

• **Baryogenesis.** Visible matter in the Universe is made of fundamental pieces: the elementary particles, divided into fermions and bosons. Among fermions, we have quarks, which are the constituents of protons and neutrons; and charged leptons (electron, muon, and tau particles) or neutral leptons (neutrinos). For each elementary particle, there is an antiparticle that has the exactly the very same properties but opposite charge. Then, why we do detect any significant amount of antimatter in the universe?

Unravelling the origin of the matter-antimatter asymmetry in the universe (Baryogenesis), which cannot be an initial condition in an inflationary stage of the early universe, is also one of the major unsolved challenges in physics.

• **Dark Matter.** Understanding the nature of DM is one of the fundamental questions of physics in astro-, particle- and cosmology physics. This is endorse by committees such as Astronet, the European Strategy Particle Physics 2020 (that includes CERN, DESY, and all the largest labs and institutions, including representations from other countries) and the DOE/NSF in their DM initiatives [40, 41, 42]. Although gravitational effects provide us with overwhelming evidence of its existence, its nature still is unknown and the realm of possibilities for DM is still enormous from particles or waves to compact objects such as primordial black holes. The range of masses of potential DM candidate could cover 90 orders of magnitude in mass. The ideal case would be to be able to cover as much as possible, no stone left unturned in all fields involved.

• **Dark Energy.** The discovery in 1998 that the expansion of the Universe is accelerating has turned into one huge mystery. By now, we have a better established cosmological model and overwhelming evidence of such expansion, but yet little fundamental understanding of its reasons. The simplest explanation in terms of a cosmological constant is extremely fine-tuned and possibly not fully successful. Alternative models have been proposed, including new fundamental particle physics and/or fields or modifications to Einstein's general gravity at ultra-large scales. Ongoing and future galaxy surveys will be devoted to establish the nature of Dark Energy, distinguishing among these possibilities.

• **Gravitational Waves.** The recent detection of Gravitational Waves (GWs) by LIGO-Virgo has opened a new observational window to the Universe. GWs from astrophysical sources carry a wealth of precious information about their production (via a wave-form analysis) and propagation (via the luminosity distance) which, in turn, depend on the underlying gravitational theory. Thus, gravitational-wave astronomy is an opportunity to test general relativity as well as theories beyond Einstein gravity The primordial background of GWs (PGWs) from inflation, as well as from reheating after inflation, is a fundamental prediction of any model, and both are potentially detectable by future gravitational wave experiments. The collapse to primordial black holes during the radiation era could also leave a signature on scales that will be probed by LISA and Einstein Telescope. Moreover, astrophysical phenomena like supernovae and kilonovae emit light, GW and neutrinos and their simultaneous detection has opened-up *multi-messenger astronomy* as a revolutionary approach that can shed light to many, if not all, our challenges.

4.2 Impact on Basic Science and possible applications

Understanding the origin and content of the Universe will have a crucial impact both on basic science and at a philosophical level. Getting advances, total or partial, in each of the key challenge addressed will have a clear impact on the fundamental physics that described the laws of the universe. It will help the advance in other areas, thus it will enlighten the path to get the necessary theoretical developments needed to complete the Standard Model of particle physics to explain certain observations, for instances, or the Standard Cosmological model.

Basic science leads to discoveries of enormous economic and practical importance although very often there is time-lag between the fundamental discoveries and their exploitation, but very generally it turns out to be highly profitable, examples such as WWW, the application in medicine, GPS or quantum computing or wireless. These challenge will impact directly in the following:

- Important advances in handling and analysis of large amounts of data in the context of international experiments and Space Science (CERN, ESA, NASA or JAXA).
- Advancing in quantum computing, including the hardware, software and analysis techniques in this area.
- it will trigger the development of applied science and technology because of the detectors and sensor we have to develop for the experiments: development of new materials, new communication technologies, use of quantum sensors for imaging, newer and faster electronics.

The scientific innovation and the technological background needed to fulfils these challenge will allow to generate Technological based companies, as the ones already created and are a success, such as Alibava Systems. These companies strengthened the linkage between universities and industry, and also have a significant impact on regional economic and social development. These challenge provides an excellent training for the Phd students, engineers , technicians, and so on in problem-solving that it is very useful to go on to work in applied research or development in industry. Furthermore, this creates very valuable networks of links between researchers in different industries and in academia, which would not exist if all training took place in industry. This transfer of technology provides jobs for graduates and others within the local community, and this generated back into the scientific groups as a whole, and more rapid development of technological advances into useful products for the marketplace. Finally, the scientific community and the general public stand to benefit from improved communication of basic scientific research. Having a science-literate, or even sympathetic, public has major implications for both the health of our society and for the climate for public funding of research.

4.3 Key challenges

The origin and fate of the Universe evolved through four different regimes: inflation, radiation, dark matter and dark energy dominated era. Despite remarkable success of the standard cosmological model (ΛCDM) in the last 25 years, determination of a number of cosmological parameters has gone from 100% to 1% precision; or the completeness of the standard model of particle physics and interactions (SM) with the discovery of the Higgs boson, still is not understood the physics of each on the above mentioned eras. The knowledge we have so far comes from decades of theories and innovative experiments. The use of telescopes on the ground and in space has taught us what the universe looked like when it was young and how it has been evolving. The use of particle accelerators has taught us the basic physics of the very high-energy environment of the early universe.

We define the following key challenges to research deeper into all these open issues and try to give and answer to them, although it is worth recalling that there is a strong interaction among them, since they all-together provide a genuine and unitary view on the origin and fate of the universe. Addressing these key challenges is a paramount task that involves a very large fraction of the astronomical, cosmological and particle physics communities, in particular, within the CSIC framework. This objective requires of detailed plans and make use of the significant human, material and computational resources.

4.3.1 Understanding inflation

Cosmic inflation is the most studied and convincing mechanism of generation of primordial perturbations, which acted as seeds of the cosmic web. In particular, this is supported by the high degree of homogeneity and isotropy of the universe at scales above a few hundreds of mega-parsecs, the spatially flat geometry of the universe, and the nearly scale-invariant power spectrum of the primordial fluctuations, which correspond to scalar and adiabatic perturbations of the metric, following an almost Gaussian distribution, as established by the Planck collaboration [43].

However, it is commonly accepted that the detection of PGWs generated during inflation will probably confirm this mechanism. The direct detection of PWGs is a tremendous challenge. A stochastic background given by the superposition of gravitational waves of different amplitudes and phases coming from all directions in the universe has not been observed yet but future missions such as LISA have the capability of detection.

Nevertheless, it is believed that the most promising way to probe the PGWs produced by standard inflation, is through the imprint left on the B-mode polarization of the CMB. The amplitude on these anisotropies is directly related to the energy scale of inflation. This amplitude is commonly defined as the ratio with respect to the scalar perturbations (r), being current constraints $r \lesssim 0.06$ at 95%, when combining information from Planck, WMAP, BICEP2 Keck Array and Baryonic Acoustic Oscillations (BAOs). Future CMB experiments such as LiteBIRD [44], Simons Observatory, CM-Stage IV or the European Low Frequency Survey aim to detect primordial gravitational waves associated with $r > 0.001$, which corresponds to inflation energy scales $\gtrsim 5.3 \times 10^{15}$ GeV.

It is worth recalling that, for inflationary models beyond the standard single-field slow-roll, precise information about them could be obtained from the direct detection of the stochastic PWGs . In particular, specific features of the inflation potential may enhance the amplitude of the primordial power spectrum of curvature fluctuations on intermediate scales. Such scenario would leave very specific signatures in both the binary black hole coalescence events seen by LIGO and future 3G detectors like the Einstein Telescope, and a stochastic GWs background on the nanoHertz to mHz range of frequencies, detectable with Pulsar Timing Arrays on ground and LISA in space.

Besides the PGWs science, further constraints on inflation can be obtained from the CMB and LSS data. First, the CMB can be used to test the statistical isotropy of the universe, one of the fundamental consequences of standard inflation. Current observations from Planck have provided strong evidences for it, although some *anomalies* have been found at very large scales. Cosmic variance-dominated polarization maps as the one expected from LiteBIRD could help to shed light on the nature of the large-scale *anoma-*

lies. In addition, galaxy surveys covering large volumes (e.g, Euclid, LSST or JPAS) are also fundamental to study the homogeneity and isotropy of the universe. Second, observations of both, the CMB and the LSS, are also very powerful to probe the probability density distribution of primordial fluctuations and their Gaussian nature, as predicted by the simplest cosmic inflationary models. The CMB has already placed strong constraints on primordial non-Gaussianity, but the most important improvement in the sensitivity to detect any primordial non-Gaussianity will come from different LSS tracers.

4.3.2 Baryogenesis

In 1967 Sakharov formulated the required conditions to generate a baryon asymmetry in the early universe: (a) baryon number should not be conserved, (b) Charge symmetry and Charge-Parity symmetry must be broken, and (c) there should be a deviation from thermal equilibrium in the universe's expansion. Charge-conjugation parity-reversal (CP) symmetry implies that the physical laws should not change in an antimatter mirror world and it is a key ingredient to explain why there is an excess of matter over antimatter in the universe. Even if the SM has all the three ingredients required to produce a baryon asymmetry in an initially baryon-symmetric universe, it is not large enough to match the observations. Baryogenesis may therefore require new sources of CP violation and far from equilibrium conditions that may be attained in extensions of the SM. A very appealing possibility is to link this asymmetry to the neutrino sector (leptogenesis). Searches for leptonic CP violation and also for lepton number violation processes are crucial to test the theoretical leptogenesis framework. Very recent results from the T2K Collaboration exclude leptonic CP conservation (suggesting therefore that leptonic CP violation has occurred) at a 95% confidence level, providing the first hint to the origin of the matter–antimatter asymmetry in our universe [45]. Regardless the soundness of this result, a much higher statistical significance in the measurement of leptonic CP violation is needed before making strong claims. Future neutrino experiments are being designed to find a definite and conclusive answer to the question. These highly multidisciplinary experiments will also test other properties of neutrinos, such as their mass ordering, will serve as neutrino telescopes for supernova neutrino searches and they will also look for neutrinos and antineutrinos from DM decays or annihilations in the galactic halo, in the Sun or in the Earth's interior. The T2HK experiment in Japan and the Deep Underground Neutrino Experiment (DUNE) based at the Sanford Underground Research Facility (SURF) in South Dakota (US), could provide a definitive answer in the quest for leptonic CP violation in the following 15 years.

4.3.3 Dark Matter

Understanding the nature of DM is one of the most important goals in modern science. Revealing the nature of dark matter —its cosmological origin, its constituents (if any), its interactions among and other properties— connects such disparate scientific areas as the formation of stars and galaxies, the earliest moments of our Universe, and particle physics. But also involves synergies across multiple levels: between experimentalists and theorist and between the areas above and other disciplines, such as nuclear, atomic, and condensed matter physics. So far, evidence for DM comes from astrophysical observations. BAOs derived from LSS tracers and the CMB, among other cosmological probes, requires about 85% of the mass to be in the form of DM. Also, these observations confirm that the DM is mostly *cold*, i.e., they behave as non-relativistic particles. Many new DM candidates have emerged lately together with the "traditional" ones such as Weakly Interactive Massive Particles (WIMPs) or axions, because none of those could be found experimentally so far. These new candidates are highly motivated either from theoretical considerations or driven by experimental data, but are qualitatively different in their experimental implications. Theoretical developments have highlighted the importance of searching for DM particles in a range from the lightest mass consistent with galactic structure, could be possible as light as 10^{-22} eV to candidates as massive as primordial black holes of tens of solar masses. There exists also the alternative interpretation that DM does not exist, but instead hints at a necessary modification of the theory of gravity.

In order to achieve this range, a diverse and innovative set of experimental proposals, including potential game changers, has been suggested; These potential new candidates could be discovered due to its special interactions with the medium and new materials and technologies need to be developed to exploit this. This brings a strong synergy with the technological challenge.

Solving the mystery of the nature of DM will allow to understand its role in the structure formation of the universe as well as the role of DM in starting the higher-density “seeds” that led to the formation of galaxies. And since many galaxies have large halos made of dark matter, a question is: How does this affect their interactions with one another?

The DM is, certainly, a very important topic for several other challenges addressed in this White Paper. Nevertheless, the ’Origin an fate of the Universe’ provides a unique umbrella to address the understanding of DM from an ambitious perspective. This is due to the synergic essence of this challenge, that, on the one side, contemplates the astronomical, cosmological and particle physics point of views of the role played by the DM on the origin and evolution of the universe, and on its specific properties related to its interaction, constituents, and nature. On its own, this is, by itself, and important step-forward, since these are communities that only recently are approaching together to solve this question. In addition, the challenge also covers the instrumental developments, the observational strategies, the data analysis techniques, and the theoretical interpretations needed to approach this key task. For all these reasons, the solution to this key challenge requires of a strong collaboration among different national and international groups, going beyond the typical collaborative networks. Obviously, here we concentrate our efforts on boosting the collaboration within the CSIC groups.

4.3.4 Dark Energy

The beginning of the last century saw the establishment of General Relativiy (GR) and soon after the recognition that the Universe was expanding, supported by direct observations by E. Hubble in 1929 and later by the detection of a cosmic microwave background temperature, consistent with an early dense and hot phase of the Universe. GR predicts that the cosmic expansion, in a homogeneous universe filled with matter or radiation, will slow down over time. However towards the end of the century different observations, as well as the simplest models of Inflation, started to point towards the existence of an unknown matter component (cold dark matter) and to the Universe being spatially flat and filled with less than critical mass, implying the need for an energy component with very particular physical properties.

The pivotal change came in the late 1990's when two independent studies of distant supernovae showed that their distance-redshift relation provided direct evidence that the expansion of the universe has accelerated over the last five billion years. Since then, cosmic acceleration has become one of the most profound puzzles in contemporary physics, with explanations that go from energy components which are not solutions and rise key questions, to abounding General Relativity as the correct theory on large scales.

Mathematically, the simplest solution to the cosmic acceleration is a cosmological constant, that is, the presence of a fluid whose density is constant in time and with negative pressure. In that context, the last two decades have seen the establishment a concordance cosmological model, flat Lamda-CDM, that describes several observations together with the accelerated expansion of the Universe. The model relies on two "dark components": DM, unseen directly but essential for the formation of structure, and Dark Energy (DE), the mysterious mechanism set to explain the acceleration.

But the nature of the accelerated cosmic expansion (or "dark energy" as is commonly refereed to) remains a mystery. From a physical point of view this could be viewed as the gravitational contribution of quantum fluctuations, but the required density is small, too small, compared to predictions by particle physics. Other alternatives include fields with time-evolving equations of state (the relation between pressure and density), or non-trivial modifications of GR affecting only large scales (e.g. gravity leaking into extra-dimensions or changing the gravitational action). Any of these theoretical alternatives is in rather desperate need of observational input.

Therefore, the profound implications of cosmic acceleration have motivated the development of wide and deep massive galaxy surveys that map a good fraction of the observable Universe collecting information for hundreds of millions of galaxies, with the aim of measuring the history of the expansion and the growth of structure with percent level precision. The four most well established methods for making such measurements are: the study of the correlated shapes of galaxies (Weak lensing) and their correlated positions (BAO) on large-scales, the abundance of the rare objects (Clusters) and the distance to exploding stars as provided by their standardised luminosity function (SNIa).

These observations use different astrophysical objects, all tracing the large-scale structure, and hence dealing with completely different observational and theoretical systematics while undergoing different reduction pipelines and calibrations. And they are all complementary to the high redshift window to a completely different Universe provided by the CMB. For the moment, some mild tensions have surfaced, e.g. on the dark matter density, the amplitude of fluctuations and the value of the local expansion rate H_0 [4-8], which makes this quest even more exciting and important. Next generation surveys will dominate the field of DE and challenge the cosmological model as never before, hopefully settling our understanding of dark energy.

4.3.5 A transverse key challenge: observation of gravitational waves

The recent detection of Gravitational Waves by LIGO-Virgo [46] has opened a new observational window on the Universe. Binary systems of compact objects such as black holes and neutron stars emit tiny ripples in spacetime when they inspiral and merge into a new object. The ground-based interferometric system LIGO-Virgo is measuring several such events with astounding precision and a new generation of experiments, both ground-based and space-borne, will be taking life in the next two decades, among which KAGRA [47] has just begun operations, LISA [48] is unfolding an ambitious science program, and projects such as Einstein Telescope [49] and DECIGO [50, 51] are on the table.

Some astrophysical phenomena like supernovae and kilonovae emit not only light but also neutrinos and gravitational waves, which can be used to understand both the source and the propagation to us of those “messengers". In this context, *multi-messenger astronomy* is a revolutionary approach, with completely different systematics, to the precise determination of cosmological distances with both standard and dark sirens. Future interferometers will allow us to determine the contribution of primordial black holes to DM, and also open the possibility of detecting the stochastic background of gravitational waves (see section 4.3.1) from the early universe, let it be from inflation, from cosmic phase transitions or from alternative scenarios.

GW astronomy constitutes a challenge on its own due to the science involved, and, indeed, it is largely covered on other chapters of this White Paper, but here it is just considered as an additional source of information that opens a new window for unravelling the key challenges previously described.

4.4 CSIC leadership and multi-/inter-disciplinarity

4.4.1 Research Groups

There are very active groups in several CSIC institutes working in this challenge: ICE, IEM, IFCA, IFIC, IFT, IAA, IEEC, CAB, ICMAB, CNM-IMB, as well as in Universities: UAM, UIB, Barcelona, UCM, Granada, UPV-Bilbao, Santiago, Valencia, Zaragoza, and OPIs: IFAE, CIEMAT, IAC, DIPC. Many of them work together in international collaborations and specialised thematic networks like CPAN, SPADES, RENATA, REDONGRA, LHC-NETWORK, etc. Canfranc Underground Laboratory (LSC), the only underground facility in Spain and one of the few in the world dedicated to astroparticle physics and research in underground physics, is also a recognised ICTS.

4.4.2 Leadership of CSIC in the international community

The impact of CSIC at the international level will also be gauged through its participation, both in terms of individual CSIC researchers and, especially, at the corporate level, in big infrastructures (e.g., CTA, SKA, ET, LHC, future accelerators) as well as in ongoing, or planned, frontier experiments. In many cases, this participation is supported by a strong instrumental and management commitment.

• On the side of CMB observations, CSIC Institutes have a key participation in international collaborations and initiatives, as LiteBIRD, QUIJOTE, E-CMB (ELFS) and the NASA Mission Study PICO. It was also the case for the ESA Planck data, that although already finished as a formal collaboration, is still under exploitation.

• On the LSS side, the CSIC Institutes have a strong involvement in some of the most advanced and promising experiments and collaborations: DES, PAU, Euclid, DESI, LSST, JPAS and WFIRST. In a longer time scale, the SKA collaboration is particularly important for the scientific objectives included in this Challenge, with the Spanish participation in SKA coordinated from a CSIC Institute.

• Similarly, CSIC also plays a capital role in collider experiments for detection of DM (e.g, LHC-ATLAS/CMS/LHCb, Belle2 in KEK or theory) where they are main authors of data analysis, lead or co-lead working groups within the collaborations and theory divisions and also have management positions. Worth noting the important roles in the detector side, leading sub-detector working groups that contribute to improve the sensibility of the experiments. CSIC, through all its groups, has an important role at CERN, CSIC researches lead or co-lead working groups that join all LHC experiments. They have also got important at the management position in policy committees of the Lab.

• Institutes have been participating in on-going (e.g., Magic, Antares, T2K) or planned (e.g., DUNE, CTA, Km3Net) collaborations of astroparticle physics. CSIC leads groups of the missions and telescopes for the DM indirect detection search (CTA, DES, DESI, Euclid, MAGIC, Fermi, Fermi-LAT, notice that many are already use for other purposes in this challenge), at present, CSIC researchers are leading, or co-leading, most ongoing DM-related works within Fermi-LAT and CTA as well.). They are also at the front of the DM working groups in the neutrino collaborations (Antares, DUNE, T2K, KM3NET) leading analyses to search for an excess of high energy neutrinos coming from the sun. Lately, a direct search effort has started participating in collaborations such in DAMIC-M and IAXO, where in the latter Spain has has the leading role.

• The study and detection of primordial gravitational waves is another of the scientific objectives that counts with an important participation from CSIC researchers and Institutes. Besides the involvement on CMB polarization experiments for indirect detection of primordial gravitational waves, the CSIC institutes also participate in collaborations dedicated to detect the stochastic gravitational-wave background of from astrophysical objects (e.g., LISA and ET).

4.5 Strategic plan and resources

Our first strategy is to actively collaborate with keyplayer international institutions such as agencies (ESA, NASA, JAXA,DOE), Laboratories (Fermilab, SLAC, CERN, DESY, Modane, Gran Sasso, LSC) and telescopes (e.g. ESO, ENO, NOAO).

Secondly, we need to create an inter-disciplinary synergy among groups, in particular CSIC ones, in fundamental physics, particle and astroparticle physics, astrophysics and cosmology, involving professionals in the theoretical, experimental, computational, and data-analysis sectors, as well as top experts in engineering and materials science.

Thirdly, continue the active involvement in ongoing and future state-of-the art instruments and experiments at all levels (see Table 4.1), but in particular their science exploitation.

Fourthly, the strategic plan also aims at multi-messenger searches: for instance, measurements from microwave, optical, radio, gamma ray, neutrino and gravitational wave detectors and telescopes together with collider, underground laboratory or ground telescopes will be optimally combined to improve the impact of our research outcome.

Lastly, focus on the scientific mentoring and training of young scientists and engineers, which will have the unique opportunity of joining the scientific environment of large infrastructures, where world-class researchers are deeply involved, providing a unique atmosphere to develop and improve computing, presentation and collaboration skills, always crucial tools, regardless of their future career profile.

4.5.1 Specific plans and contributions

The specific plans of the CSIC research groups described in the previous sections, in relation to the key scientific challenges already mentioned are aligned with the on-going and planned (at short-, medium-, and large-time scales) missions, experiments and international collaborations, in which they have different commitments, which go from instrumental developments to leadership roles in data analysis and theoretical interpretation. These commitments are recognised by the international community on the grounds of the expertise achieved in past experiments, where the CSIC groups have shown their capabilities. A summary of the most important projects is given in Table 4.1 with the current CSIC involvement; in the future more institutes could join different projects. We will review the strategy to address the key challenges presently and for the next 5, 20 and beyond years.

On the CMB side, the major expertise is founded on the leadership role in the ESA Planck mission, where the CSIC had instrumental, data analysis and management duties besides the scientific contributions. Future plans run on two different and complementary roads: measurements from the ground and the exploration from space. The major scientific objective is to probe inflation via the detection of primordial gravitational waves.

The QUIJOTE experiment, in which the CSIC is being contributing very significantly, is one of the fundamental seeds for future plans to map the CMB polarization from the ground. In particular, the European CMB community (E-CMB) has recognized the capital need to explore the lowest range of the microwave spectrum (from 10 to 120 GHz). This initiative, called European Low Frequency Survey (ELFS), aims to provide a survey of the CMB anisotropies with instrumental characterises allowing to probe cosmic inflation. The are several reasons for pursuing this kind of experiment. First, Europe in general, and Spain in particular (through CSIC), has a strong leadership of detector technologies particularly suitable for this frequency ranges, namely, radiometers and Kinetic Inductance Devices (KIDs). This will provide polarization sensitivities of around a few microkelvins and a large frequency range to exploit the spectral diversity of Galactic foregrounds, which would allow to measure the imprint of primordial gravitational waves) with an amplitude of $r \sim 10^{-3}$, compatible with the level predicted by the Higgs or the Starobinsky inflationary models. Second, this frequency range is complementary to higher frequencies already planned to be observed by US-led programmes (e.g, CMB-Stage) IV. Third, the lowest frequencies of the ELFS programme (from 10 to 40 GHz) are also a very interesting complement to future space missions such as LiteBIRD, offering a high-sensitivity mapping of radio foregrounds.In addition, CSIC CMB technological developments also account for exploring novel interferometric approaches to map the relic fluctuations, in which the microwave detection is afterwards correlated on the optical/infrared range.

Finally, the CSIC is also participating in the JAXA LiteBIRD satellite (with collaborations from NASA, Canada and Europe): up to date, the only approved space mission (to be launched in 2027) to map the CMB polarization. This is an outstanding experiment, and represents a unique opportunity for the CMB science, in which the European community is exporting the know-how achieved thanks to the Planck mission. LiteBIRD allows further studies of cosmic inflation, not only through the detection of the primordial B-mode, but also, by probing statistical isotropy and Gaussianity of the E-mode, offering a new opportunity to explore the so-called CMB large-scale anomalies. The most important duty of the spanish community so far is related to the instrumental calibration, led by CSIC.

The origin of the observed matter-antimatter asymmetry could be related to the process of baryogenesis in the early universe, via out of equilibrium phenomena occurring immediately after inflation, with new sources of CP violation, or via leptogenesis, with a subsequent conversion into baryons thanks to high-energy sphaleron transition. These new sources of CP violation are searched for in high energy colliders, e.g, LHC-b and Belle2, also ATLAS and CMS could complement these studies.

For testing whether or not baryogenesis took place via leptogenesis processes in the early universe, leptonic CP violation searches are crucial, as mentioned above. The future DUNE detector will use several thousand tonnes of liquid argon to detect neutrino from an man-made accelerator neutrino beam at Fermilab in Batavia, Illinois (US), about 1300 km away from the SURF facility. This experiment is therefore complementary to the Japanese one, T2HK, as they use different detector technologies and different baselines.

CSIC has been contributing heavily to the construction and exploitation of two detector demonstrators at CERN, ProtoDUNE-SP and ProtoDUNE-DP, which have demonstrated the feasibility of the large-scale DUNE detector. With important responsibilities in the design and construction of the first two far detector modules at SURF, particularly in the areas of photon detection and cryogenic instrumentation. CSIC researchers are very active in a number of physics working groups, including long-baseline neutrino oscillations, supernova neutrino detection, baryon number violation searches, ProtoDUNE data analysis, and phenomenology including therefore a strong contingent of theoretical physicists. Experiments at LHC, such LHCb and ATLAS/CMS, search for new sources of CP violation, recent results show that there is a ligh deviation but compatible with SM, more data will be need it to clear this out.

The nature of Dark Matter and its interactions can be probed by several experiments. These different types of searches are complementary. Each come with very different sensitivities in relation to the details of the SM–DM interaction, the detection techniques used, and the assumptions in terms of astrophysics that help to infer the true nature of DM. CSIC already participates actively in this effort in several ways. Together with others it is participating in experimental and theoretical programs to search for DM or Dark Sectors in the next years that comprise constructions, operation, maintenance and participation in missions, telescopes, experiments and large collaborations. The particle and astroparticles physics program for the next 10 years is being discussed now[41], but this is a very active area, thus the groups will have to be ready to adapt depending on the results found during the research process.

The search in accelerators attempts to create DM particles from collisions of standard-model particles. They must be produced together with SM particles in order to be detected. The search for the particles mediating between Standard-Model ones open a full spectrum of new particles, for instances the ones associated to the Dark Sectors such as dark photons, or for long-lived particles(LLP)[1] are becoming a hot topic. These particles are important not only for their contribution to DM but also to study baryogenesis processes. Alternatively it could be that dark sector communicates with the Standard Model, via portals, such as the Higgs, vector, axion, neutrinos.

The colliders and the detectors are the main tools for this. LHC enters a period of hibernation until spring 2021, then data will be taken for 3 years until next stop to prepare for HL-LHC. This program will offer huge opportunities to do significant advances relative to today's landscape knowledge, thanks to renewed the detectors and to maximise the LHC potential. The developments in theoretical models that provides different signatures are crucial for this[2].

CSIC groups search for DM candidates associated to top or Higgs and the more traditional SUSY searches. For the future, these analyses will be improved with better analysis tools, Machine Learning techniques or others. Improved tracker, calorimeter subdetector or trigger systems together with created new subdetectors, such timing detectors will be

[1] https://arxiv.org/abs/1903.04497

[2] https://lpcc.web.cern.ch/content/lhc-dm-wg-dark-matter-searches-lhc

an asset to reach a full DM program. LLPs searches have already appeared as benchmark channels in the detector Upgrade Technical Design Reports and of the Yellow Reports.

DM can be search via their scattering with a detector medium. Measuring this process would provide information on the candidates and their interaction probability with ordinary matter that complements the information from other sources. There are many initiatives to try to cover a wide range of candidates exploiting different characteristics of the possible interaction with ordinary matter and are technological challenges.

CSIC participates in the DAMIC experiment based on the CCDs originally developed for DES. It has been proven that the technology works for mass sensitivity below 1 GeV. Recently they got the best sensitivity to light DM particles interacting with electrons. Soon a new experiment made of 1kg mass of CCDs with single electron resolution, called DAMIC-M, will be ready to take data in 2024. It will search for low-mass in range from 1 eV to few GeV with unprecedented sensitivity to DM-electron scattering and hidden-photon. The CCDs program continues with a future project called OSCURA that it is in the R&D phase funding for the DOE.

CSIC also participates in the search for axions with the haloscope technique in a mass range of 10-100 μeV using an array of small microwave cavities connected by rectangular rises, in an arrangement commonly used in radio-frequency filters. There is a prototype in CAST but they are working in the upgrade exploiting the knowledge of KIDs devices from the CMB, capable of energy-resolving single photons. A future goal will be to installed an instrument in the magnet of the future axion helioscope IAXO.

Neutrino experiments, used as well for Baryogenesis studies, can be used to search for DM. Antares has successfully shown the feasibility of the undersea water Cherenkov technique with a rich harvest of scientific results. KM3NeT is being deployed and will mean a tremendous step forward in neutrino astronomy. The search for DM is one of main goals of the experiment. Neutrino telescopes, and KM3NeT in particular, offer the possibility of looking at several kinds of sources, not all of them available to other indirect searches. CSIC researcher lead the DM analyses in these experiments, have important responsibilities in the detectors

DM can be searched for in the anomalous components in cosmic rays due to the annihilation of DM pairs in the galactic halo, on the top of the standard astrophysical production, as well as in γ-rays and, more generally, in multi-wavelength photons. The decay products is pursued by means of ground-based telescopes, balloon-borne detectors and space-based experiments. CSIC researchers are member of Fermi-LAT, they used the data to search for gamma rays coming from WIMP annihilation's over the gamma-ray background from different sources. Analysis in WIMPs and ALPs were explored using LAT data, this provides an alternative and complementary information to those axions searches performed by experiments at the lab

CSIC is involved in understanding the Cherenkov Telescope Array(CTA's), ground-based gamma-ray instrument in the energy range extending from some tens of GeV to about 300 TeV, capabilities to search for DM. Current efforts focus on providing realistic predictions in the search of DM in galactic (both dark and visible) satellites and in galaxy clusters. In the future, the combination of Fermi-LAT and CTA data should allow to robustly test the full WIMP miracle[52], by testing the thermal relic cross section for WIMP masses between few GeV up to dozens of TeV.

On smaller scales, strong gravitational lensing can map directly the distribution of dark matter in galaxies and galaxy clusters. The latter have provided some of the most direct proofs of DM, especially in colliding clusters, for which the bulk of the baryonic mass physically separates from the DM, offering a pristine view of the DM. Observations of the strong gravitational lensing effect, combined with X-ray observations of the Bullet cluster have been used to set upper limits on the self-interacting cross section. These limits will be improved in the near future with more detailed observations of this, and other clusters. On even smaller scales, microlensing is being used as well to set limits on the abundance of yet another candidate to dark matter, primordial black holes, that could also be responsible for some of the gravitational waves observed by LIGO/Virgo.

In turn, the Square Kilometre Array (SKA) will be a multi-purpose radio-interferometer with a collecting area of 1 km^2, distributed over a distance of at least 3000 km, co-located in Africa and Australia. Qualified as landmark project in the European Strategy Forum on Research Infrastructures (ESFRI) and high-priority in the ASTRONET roadmaps, SKA is a unique science instrument, with up to 10 times more sensitivity, and hundred times faster survey capabilities than current radio- interferometers, that will provide leading edge science in the 21st century involving multiple science disciplines. The physics cases of this future multidisciplinary powerful telescope include Cosmology and Large Scale Structure, Epoch of Reionization (EoR). Concerning cosmology, SKA will be able to probe DM properties (interactions, velocities and nature) through the detection of the redshifted 21 cm line in neutral hydrogen, during the so-called Dark Ages, before the period of reionization. SKA will also be able to test the Dark Energy properties and the difference between some modified gravity and Dark energy scenarios through HI galaxy number counts, by detecting the 21cm emission line of neutral hydrogen (HI) from around a billion galaxies over 3/4 of the sky, out to a redshift of $z \sim 2$.

The study of DE and cosmic acceleration revolves around the deployment of very large mappings of the LSS of the Universe, with instruments from both space and ground. Spain, and CSIC in particular, has a long standing tradition in being part in such experiments (SDSS, BOSS, DES). The largest 3D survey of the next decade is DESI, a 14000 deg^2 spectroscopic redshift survey that will use a multifiber spectrograph to collect the 3D position of 20M galaxies out to redshift 3.5. It will measure the growth of structure using the anisotropic galaxy clustering pattern. CSIC technological contributions include Guiding Focusing and Alignment cameras and software.

By 2023, the Large Synoptic Survey Telescope (LSST) will start imaging 18000 deg^2 of the Southern sky multiple times with an unprecedented sampling rate and to an accumulated depth of 27 mag$_{\rm AB}$. It science objectives are several and include the study of dark energy using weak gravitational lensing. Clearly its database will be an invaluable source for astronomical and cosmological research. CSIC groups are planning to contribute to the LSST through a technical effort in partnership with other Spanish institutions, and negotiations are ongoing.

In turn, Euclid is the biggest European astronomical consortium, selected in 2011 to be one of the next M-class ESA missions. After its launch, scheduled for 2022, it will dominate the field of dark-energy studies by measuring weak lensing and baryon acoustic oscillations over 15000 deg^2. In particular, it will measure the shapes of 1.5 billion galaxies down to magnitude 24.5 and the precise redshifts of over 50 million Hα galaxies in the redshift range 0.9 to 2.1. Spain has made a strong contribution to Euclid since its design phase and CSIC is the largest Spanish contributor. Spanish institutions play a very important role in several aspects, also at the management level (the chair of the Euclid Consortium Board). Technological and technical contributions include the NISP Filter Wheel Assembly, a Spanish Science Data Center (PIC), lead of OU-SIM (image simulations), lead of the ESO Large Programme for follow-up spectroscopy, the NISP Instrument Control Unit and coordination of various science working groups. The experience gained has led to the development of smaller but very complementary experiments and instruments fully designed, constructed and operated at the national level, such as PAU and JPAS. These galaxy surveys measure positions using low-resolution spectra from multi narrow band photometry, combining the pros and cons of the larger surveys.

The study of gravitational waves can be used as an instrument to understand the origin and the fate of the universe. We might be able to link at least some aspects of the key challenges (Dark Matter and Dark Energy) through the study of Gravitational Waves. We can clearly argue that GW-events provide (dark) standard sirens which can be use to study the distance-redshift relation and the expansion of the Universe, putting stringent constraints on Dark Energy Models. In the near future we might the able to study the spatial distribution of GW sources. On the other hand, GW from binary coalescence can shed light on the issue of primordial black holes as a significant constituent of Dark Matter. The angle highlighted here is one that cuts through both challenges with a single physical effect which can bind several currently independent communities within CSIC.

CSIC contribution to LISA is to LISA-pathfinder, both in the construction and the scientific exploitation level and also contributed to the creation of the Cosmology and Fundamental physics Working Group. The groups have developed the codes for waveform analysis of GW bursts from BH encounters, as well as searching for specific signatures from massive PBH since recombination; also in studies to the capability of LISA to discriminate among models and theories beyond Einstein gravity through the study of the gravitational-wave luminosity distance of standard sirens.

4.5.2 Resources for the Key Challenges

The challenges addressed in this chapter are so complex that in general require long-term planning and large (international) collaborations designing, developing and exploiting cutting-edge instruments and facilities. Appropriate funds are required to ensure the progress in the different key challenges but all the needs should be met with funding plans based on long term foresight. We have identified five different aspects that require

Table 4.1: Instruments and collaborations with current direct CSIC involvement at the infrastructure level and their contribution in terms of our key challenges. Red tick-marks indicate their main scientific goal, and black ones their transversality into other challenges.

a (Instrumentation) - b (Data & Software) - c (Simulations) - d (Theory) - e (Management)

INSTRUMENT	KC1	KC2	KC3	KC4	TKC	INSTITUTES
CURRENT						
DESI	✓		✓	✓		ICE^{a,c,d}, IFT^{c,d}
PAU				✓		ICE^{a,b,c,d,e}, IFT^{c,d,e}
JPAS	✓		✓	✓		IFCA^{b}
QUIJOTE	✓				✓	IFCA^{a,b,c,e}
DAMIC/DAMIC-M			✓			IFCA^{a,b,c}
LHC		✓	✓			(IFCA,IFIC)^{a,b,c,d,e}, IFT^{d,e,c}
Fermi-LAT			✓			IFT^{b,e}
Belle2		✓	✓			IFIC^{a}
ANTARES						IFIC^{a,b,c,e}
KM3NET			✓	✓		IFIC^{a,b,c,d,e}
T2K		✓	✓			IFIC^{b}
FUTURE						
EUCLID	✓		✓	✓		ICE^{a,b,c,d,e}, IFCA^{b}, IFT^{c,d,e}
LSST	✓		✓	✓		ICE, IFT (*negotiating participation*)
SKA	✓			✓	✓	IFCA^{b}, IFIC^{d}, IAA^{a,b,c,e}, CAB^{b,c,d,e}, ICE^{d}
JWT			✓			IFCA^{b}
ET	✓		✓	✓	✓	ICE^{a,d,e}, IEM^{c,d}, IFT^{b,c,d,e}
ELGAR			✓	✓	✓	ICE^{a,d,e}
LiteBIRD	✓				✓	IFCA^{a,b,c,e}
ELFS	✓				✓	IFCA^{a,b,c,e}, CAB^{a}
LISA	✓		✓	✓	✓	ICE^{a,b,c,d,e}, IFT^{c,d}, IEM^{d}, IFIC^{d}
DAMIC-M/OSCURA			✓			IFCA^{a,b,c}
HL-LHC		✓	✓			(IFCA,IFIC)^{a,b,c,d,e}, IFT^{e,d}
RADES			✓			IFCA^{a,b},CAB^{a}
CTA			✓			IFT^{b,c,e,d}
future accelerators		✓	✓			IFT^{b,c,e,d}
DUNE		✓	✓			IFIC^{a,b,c,e,d}, IFT^{d}

KC1 (Inflation) - KC2 (Baryogenesis) - KC3 (Dark Matter) - KC4 (Dark Energy) - TKC (Grav. Waves)

particular planning and support in order to guarantee a leading role of CSIC:

• **Human Resources.** Several of the current and next decade experiments are already advanced and large infrastructure contributions are not expected. However, the data exploitation and hence scientific return to CSIC is strongly dependent on the number of human resources allocated to them. In this regard, all the profiles of the scientific career should be maintained at a constant and sufficient rate: PhD students, postdocs, and technicians. All these profiles are capital to achieve the goals of this challenge and the participation on the related experiments. Eventually, there should be a sufficient pool of permanent positions to maintain the best researchers, and to attract experimented scientists from our network collaborations.

• **Computing Facilities.** Many of our contributions to the different experiments rely on our ability to take part of the corresponding data processing centers. Some of the CSIC groups related to this *challenge* already account for large computing infrastructures (e.g., IFCA, IFIC, IFISC). However, many of the commitments in future experiments (e.g., LiteBIRD, LHC (and associated experiements), Euclid, LSST) will greatly benefit from a dedicated High Performance Computing (HPC) facility to support the CSIC participation in the projects. An easy and equal access to this infrastructure, and/or enlarge existing ones in a coordinated way, will be essential to be able to comply with the commitments.

Instrumentation and Engineering : Our technological commitments require to maintain an adequate budget to design, develop and deliver the different instrumental devices that are done or planned by the CSIC groups. Particularly important is the infrastructure programme, that helps to maintain and grow the laboratories of the groups. This applies to LiteBIRD, ELFS, LHC/HL-LHC, Direct DM searches experiments, CTA, SKA, etc. Also, it is crucial to have a permanent group of engineers and technicians at the institutes to keep the technical knowledge and know-how through the different experiments, to have a leading position in them and propose new actions. All these profiles are capital to achieve the goals of this challenge and the participation on the related experiments. One recurrent issue that needs a long-term solution deserves special mention here and is the lack of a clear stabilization path for engineers and technicians within the CSIC administration.

Continuing Support : The support to large existing infrastructures such as LHC, CTA, KEK, Neutrino platform, etc, and also to small initiatives, such as the ones proposed in direct searches, are crucial to move forward in this challenge. Get even stronger groups with visibility within the collaborations at international level with capability to take decisions. But as important than positioning CSIC internationally is to be able to adapt quickly to unexpected results that could change the current scenario.

For the understanding of DM, and many others issues, the support to the Spanish infrastructures Canfranc Subterranean Laboratory (LSC) is crucial and also enhance collaborations with other Spanish groups outside CSIC that are worldwide recognised in the field (Univ. de Zaragoza, IFAE, IGFAE, Univ. de Illes Balears among others).

Future commitments : As pointed earlier, the sheer size of many of the project that will shape the future of our challenges in the next 20-50 years need careful planning ahead and positioning. In this sense, some key projects still require institutional commitments and MoUs, in order to give access to the CSIC groups to them and, more importantly, to access to leading roles. This is the case for:

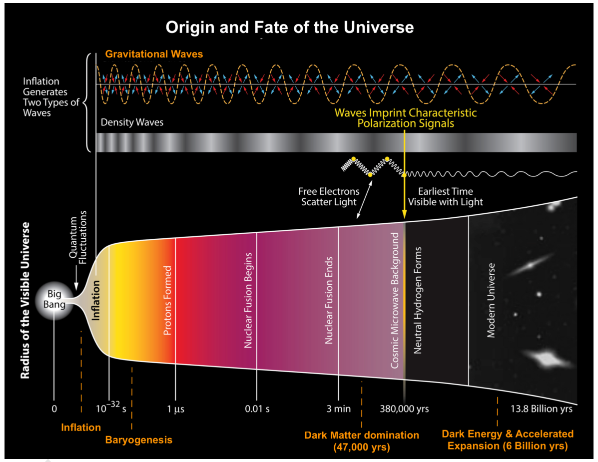
- The support of the Einstein Telescope is a fundamental priority in the field, endorsed by the Letter of Intent (MoU) signed by CSIC to support the ET proposal to the ESFRI roadmap
- Spanish participation and support in LSST is also fundamental. An initial proposal to US funding agencies from some CSIC groups has been pre-approved, subject to further negotiation during 2020.
- Spain is a member of SKA since 2018 and CSIC plays a major role aspiring to become a SKA Regional Centre. Further increasing the involvement and interplay between the SKA Science and the Particle, Astroparticle, Planetary, Astrobiology and the Cosmology communities is a unique chance to link all these areas within a single experiment.
- Some projects that either require or would be tremendously benefited from institutional support, both at the CSIC and the Ministerial levels, among them are: LiteBIRD, ELFS, LISA, PAU, JPAS.
- Institutional support for the upgrades of the experiments at HL-LHC, also to Neutrino Platform at CERN, Fermilab, KEK or other underground labs is needed to continue with a strong program. A stronger presence in this labs as CSIC and not as each individual institution will increase the position of these groups to take decisions for the future.

Annex: One slide summary for experts

Topic 9: Understanding the basic components of the Universe, its structure and evolution.

4 - Origin and Fate of the Universe

How did it begin ? How did it evolve? What will be its future?



WHAT?

- Inflation: needs confirmation from Cosmic Microwave, Large-Scale Structure and GW background
- Baryogenesis: Explore conditions at electroweak scale and beyond, leptogenesis
- Dark Matter: Nature, origin, and interactions ?
- Dark Energy: cosmological constant, new field or break down of General Relativity on cosmological scales ?
- Gravitational Waves: standard sirens, primordial black holes as dark matter, background from early Universe

HOW? Synergies of

- Theory + observation + instrumentation: astrophysics, cosmology, particle physics, mathematics, engineering.
- Key facilities: Ground and space telescopes, neutrino and dark matter detectors , particle colliders

IMPACT

- Base of our scientific and philosophical understanding of the world.
- Massive technological and methodological progress from quantum computing to big data & electronics

WHO?

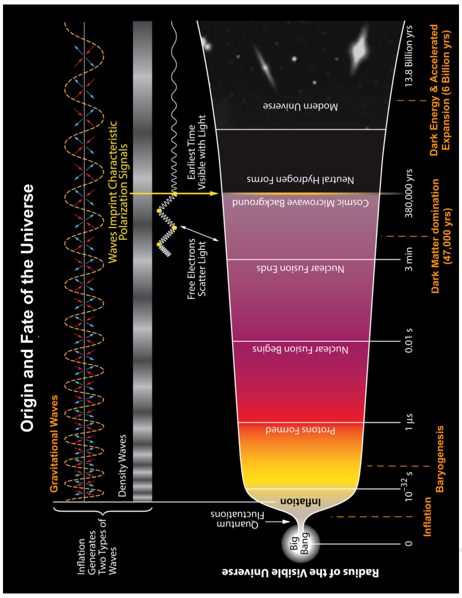
- ICE, IEM, IFCA, IFIC, IFT, CAB, IAA, ICMAB, CNM-IMB
- Collaboration with international agencies/infrastructures (e.g. **CERN, Fermilab, SLAC, DESY, KEK, LSC, Euclid, SKA, LISA**) and national partners (universities and laboratories)

Annex: One slide summary for the general public

Topic 9: Understanding the basic components of the Universe, its structure and evolution.

4 - Origin and Fate of the Universe

How did it begin ? How did it evolve? What will be its future?



WHAT?

- Inflation: seed of initial structures
- Baryogenesis: generation of elements
- Dark Matter: main driver of structure formation
- Dark Energy: accelerating the expansion today
- Gravitational Waves: new observational window!

HOW? Synergies of

- Theory + observation + instrumentation: astrophysics, cosmology, particle physics, mathematics, engineering.
- Key facilities: Ground and space telescopes, neutrino and dark matter detectors , particle colliders

IMPACT

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