ABSTRACT

Understanding the basic components of the Universe, its structure, and evolution is one of the noblest and most ambitious undertakings of humanity. The fundamental laws of nature are the basis of all technology. Finding and understanding them requires exploring both the elementary components of matter at the smallest scales and the observable Universe at the largest scales. Only through understanding the laws that dictated the first instances of the Universe we will be able to find the ultimate reason for its actual appearance and future fate. Challenges in physics are intimately associated with technological challenges for the design and building of telescopes, space missions or accelerators, reactor and underground experiments, as well as developments in mathematics. Their resolution requires a worldwide, transdisciplinary effort and the orchestrated involvement of researchers, engineers, and technicians. The challenges described here are fully aligned with the priorities identified in international and European strategies.

KEYWORDS

Origin of mass | Symmetries and matter | QCD | Origin and fate of the Universe | Formation and evolution of galaxies | Cycle of matter in the Universe | Nature of gravity | Instruments and experimental techniques | Geometry and analysis | Matter and radiation under extreme conditions

INTRODUCTION

Understanding the basic components of the Universe, its structure and evolution is a complex of questions at the heart of humanity and has been one of its noblest and most ambitious undertakings. It can be traced back to the first natural philosophers of the antique world, but it gathered enormous impact and speed with the emergence of the scientific method in modern times. This quest has a double impact on society. On the one hand, there are the profound mental, emotional, philosophical, and potentially even political - if one thinks of the global environmental movement - changes that are prompted by our increasing understanding of our place in the Universe. On the other hand, fundamental mathematical and physical science is the basis of all of modern technology.

By its very nature, it is often impossible to predict where breakthrough discoveries will be made in fundamental science. So called “blue sky” research is one of its inherent, necessary features, combined with rigorous progress on precision and accuracy. Contrary to applied sciences, the way forward is rarely clear, with the exception of the need for permanent improvement of the experimental facilities, equipment, theoretical/numerical knowledge and skills. Time scales between fundamental discoveries and their direct technical application can be long. From past experience they can range up to ~100 years.

Understanding the Universe from the smallest to the largest scales, including its origin, evolution and fate, is a monumental challenge that requires a worldwide effort and the orchestrated involvement of theoretical and experimental researchers, together with engineers and technicians, across different fields: particle physics, cosmology, astrophysics, nuclear, molecular and materials science, as well as mathematics and microelectronics. A combination of abstract methods in theoretical physics and mathematics, technological developments and experimental scrutiny is equally needed.

Finding the fundamental laws of Nature requires us to explore both the elementary components of matter at the smallest scales and to observe the Universe, from our Solar System to galaxies across the visible Universe. Extreme objects and phenomena in the Universe can also provide key insights into environments that cannot be reproduced on Earth. Only through understanding the laws that dictated the first instances of the Universe we will be able to find the ultimate reason for its actual appearance and future fate.

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The Standard Model of particle physics is the theory that represents our best understanding of the fundamental components of matter and their interactions. It is the legacy of the twentieth century and describes (almost) all the experimental data, predicting the existence of new phenomena with highest precision. The discovery of the Higgs boson at the CERN Large Hadron Collider in 2012, fifty years after its prediction, was a seminal breakthrough and a major milestone in particle physics. However, the Standard Model cannot be considered a complete description of Nature as it does not explain some observed phenomena (such as the dominance of matter over antimatter in the Universe, the nature of dark matter or the non-zero neutrino masses) and does not include gravity. We are still confronted with many unresolved puzzles.

For example, we do not understand yet why there are three families of quarks and leptons and their mass hierarchy. Although the existence of the Higgs boson provides an answer to the question of how elementary particles acquire mass, our current understanding of the underlying principles behind this mechanism is very limited, and we cannot explain the values of the observed masses. While classical gravity is beautifully described by General Relativity, it clashes with Quantum Theory at the smallest scales, and attempts to reconcile those two fundamental, extremely successful physical theories have so far failed. The recent discovery of gravitational waves, 100 years after their prediction, opens a new window onto the physics of gravity and compact objects. The Standard Model is in principle a very predictive theory, but achieving a precise prediction of many observables, including proton and heavy ion collisions or basic properties of matter in extreme conditions, requires a deep understanding of the complex phenomena encompassed by the theory of the strong interactions.

The Standard Model of Cosmology, the so-called LambdaCDM model, can fit the observational data extremely well. Cosmological observations point to a spatially flat Universe containing 5% of baryonic matter, 26.8% of non-baryonic dark matter, and 68.3% of dark energy, which is responsible for the accelerated expansion of the Universe. However, embarrassingly, the natures of dark matter and dark energy are completely unknown. In current cosmological models inflation is the mechanism responsible for seeding the cosmic web of matter and galaxies, but so far we lack any observational evidence for it, such as the detection of a predicted stochastic background of gravitational waves. It is also extremely hard to explain the observed absence of antimatter in a Universe without a fine-tuned asymmetry in the initial conditions.

Understanding how the first luminous structures and galaxies arose from the dark ages about 300 million years after the Big Bang and subsequently evolved towards the diversity of galaxies in the actual Universe, requires to shed light on the mechanisms that regulate the connection between the dark matter halos originated from primordial fluctuations and the growth and evolution of cosmic filaments, galaxies, and galaxy (super)clusters. It is also crucial to understand the processes that form and transform nuclei, atoms, molecules and dust into stars and planets across the history of the Universe. A deep exploration of the properties of matter and radiation in the vicinity of compact objects (such as black holes or neutron stars) is essential to understand the most energetic and catastrophic events and the behavior of matter under the most extreme conditions in the Universe.

The open questions in our basic understanding of the Universe, from the smallest to the largest scales, are not independent, but deeply connected, reflecting the maturity of the achieved global understanding and the strong links between the involved fields.

Challenges in physics are intimately associated with technological challenges in the development of the appropriate tools for the design and building of telescopes, space missions or accelerators, reactor and underground experiments. These tools comprise a wide range of aspects that go beyond radiation and particle sensors and include, among others, readout electronics and data acquisition systems, intelligent data filtering in real time, mechanical structures, control of the environment, etc. Of equal importance is the development and management of large facilities.

Developments in the area of instrumentation enable tool-driven revolutions that can open the door to future discoveries. New mathematical developments in the fields of geometry and analysis as well as the application of cutting edge mathematics are also essential to face the above challenges in physics.

The efforts towards achieving a better fundamental understanding of the Universe have been divided in this document into the following ten challenges:

1. Origin of mass of elementary particles
2. Finding the underlying symmetries behind the fundamental components of matter
3. Solving Quantum Chromodynamics
4. Origin and fate of the Universe

5. Formation and evolution of large structures and galaxies
6. Understanding the cycle of matter in the Universe.
7. Understanding Gravity
8. New instrumentation and techniques for understanding the Universe, its structure and evolution.
9. New developments in geometry and mathematical analysis driven by the equations of physics.
10. Understanding matter and radiation under extreme conditions.

The CSIC institutes participating in these activities are:

- Centro de Astrobiología (CAB, CSIC-INTA)
- Centro Nacional de Microelectrónica (IMB-CNM, CSIC)
- Instituto de Astrofísica de Andalucía (IAA, CSIC)
- Instituto de Ciencias del Espacio (ICE, CSIC)
- Instituto de Nanociencia y Materiales de Aragón (INMA, CSIC-UZ)
- Instituto de Ciencia de Materiales de Barcelona (ICMAB, CSIC)
- Instituto de Ciencia de Materiales de Madrid (ICMM, CSIC)
- Instituto de Ciencias de Matemáticas (ICMAT, CSIC-UAM-UC3M-UCM)
- Instituto de Estructura de la Materia (IEM, CSIC)
- Instituto de Física de Cantabria (IFCA, CSIC-UC)
- Instituto de Física Corpuscular (IFIC, CSIC-UV)
- Instituto de Física Fundamental (IFF, CSIC)
- Instituto de Física Teórica (IFT, UAM-CSIC)

The resolution of the challenges described in this chapter can only be achieved within a worldwide collaborative effort and are also identified as main goals in the corresponding international and European strategies. The CSIC institutes involved have groups with an internationally recognized expertise. Only in this way CSIC (and Spain) can play an important (and sometimes leading) role in future ground-breaking discoveries yielding a fundamental improvement in knowledge and technology, including future applications.

By their very nature, all the challenges laid out here lean on large, international research collaborations and major international facilities, as well as technological progress. For example, CSIC researchers can be world-leading in their fields, even though 90% of their collaborators work outside CSIC and even outside of Spain. It is therefore difficult to identify focused challenges that can be approached at the sub-global, sub-national, and even institutional level. Given the complexity and longtime scales of the tasks there are, however, several overarching, general requirements that show up in all challenges:

- The necessity to have teams of critical mass and sufficient time coherence.
- Outstanding researchers with a high international profile are joining CSIC in temporary positions with some of the new excellence programs at the national and regional levels. A career path for these researchers should be a priority.
- The participation in large, international research facilities should be supported decisively. For example, the creation of a CSIC group at CERN would strengthen the CSIC position and visibility there or a point of contact at CSIC to liaise with the ESA's Science Program would also be very helpful for the different groups developing instrumentation for ESA missions.
- The long time scales of technology developments call for an urgent need of a separate technological career at CSIC, both for engineers and scientists.
- Postdoctoral scientists tend to be fundamental to progress because they can focus on science and are not burdened by administrative tasks and tend to move a lot, thus bringing fresh ideas. A CSIC specific program for both postdoctoral researchers and PhD students would be highly beneficial, which could also include a permanent assignment of necessary positions to the research groups.
- The strengthening of international relations by facilitating and funding long exchange visits in both directions.
- Making CSIC a more welcoming institution for researchers from other countries by minimizing obstacles that arise from problems in information flow, bureaucracy, or language.
- A coordinated action towards strengthening the ties of the CSIC groups involved in these challenges would be important to take advantage of the diverse and complementary expertise available at CSIC in different disciplines. The creation of transversal research groups including researchers and engineers of various centers, also external ones, could be the way to achieve this. The support of CSIC to existing national networks (such as the "Redes Temáticas") and coordinating bodies such as CPAN (Centro Nacional de Física de Partículas, Astropartículas y Nuclear) will also be instrumental.