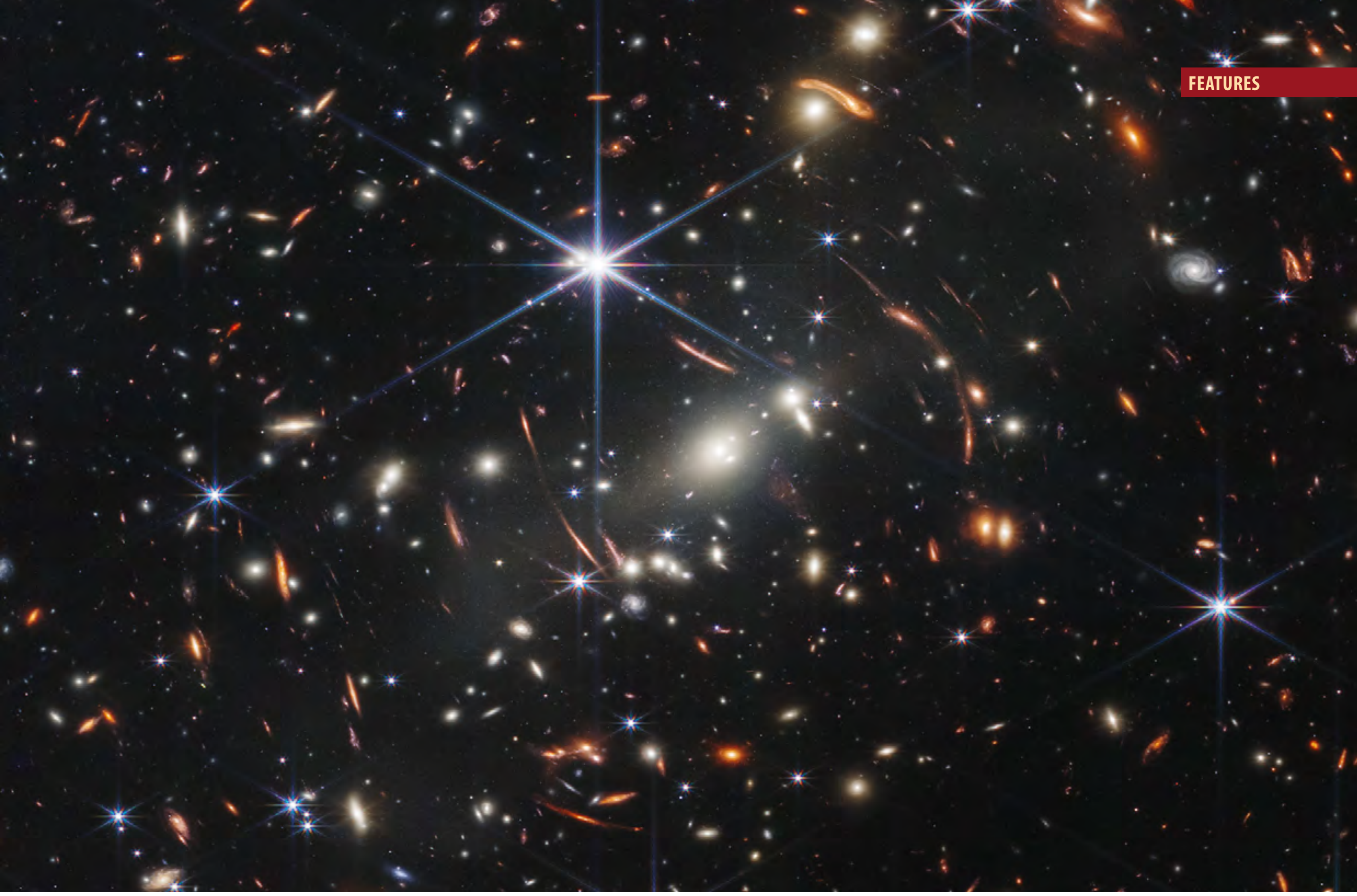

PHYSICS
BRIDGING THE INFINITIES

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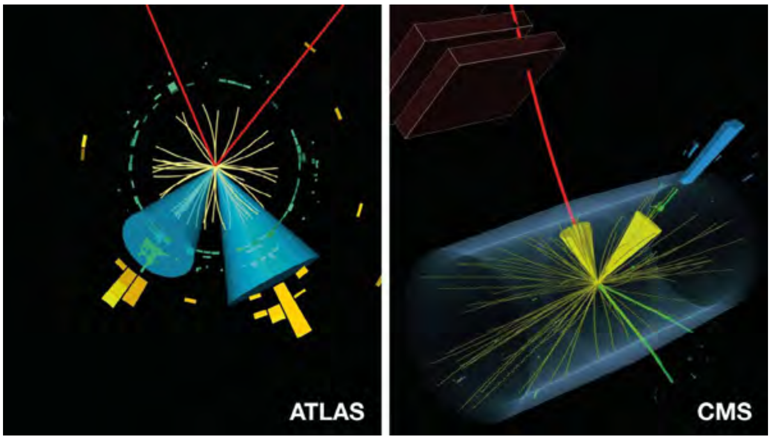
At the horizon 2050, our physics textbooks will have to be rewritten. The contributions in the first chapter of the EPS Grand Challenges explain why. Will all or many of the open questions be answered at the horizon 2050? There is justified hope, supported by a plethora of theoretical developments and experimental facilities on Earth and in space. Will new questions arise? You bet.

The contributions in the first chapter of the EPS Grand Challenges reflect the main research directions that are undertaken to find an answer to the many open questions.

The Higgs boson - When the Higgs boson was found in 2012 at CERN's Large Hadron Collider (LHC) in Geneva, history was made. The Higgs particle, and its associated field, are the reasons why atoms, stars, galaxies, and people are tangible entities. In addition, a tiny asymmetry between matter and antimatter that developed soon after the Big Bang, made it possible that we can exist at all. Without the Higgs boson and this asymmetry, only radiation would permeate the Universe. Fig. 1 shows collision

▲ Thousands of galaxies flood this near-infrared image of galaxy cluster SMACS 0723. High-resolution imaging from NASA's James Webb Space Telescope combined with a natural effect known as gravitational lensing made this finely detailed image possible. @NASA, ESA, CSA, STScI



▲ **FIG. 1:** Decays of a Higgs boson into a Z boson and a charm-anticharm quark pair, seen by the ATLAS and CMS Collaborations. In the ATLAS event, the Z boson decays into two muons depicted by the red tracks, whereas the charm-anticharm quark pair is not directly visible, since free quarks cannot exist. They hadronise, thus producing collimated sprays of particles around the original flight directions of the charm or anticharm quarks. In the CMS event, the Z boson decays to an electron and a positron, depicted by the green tracks. In both ATLAS and CMS the two charm-anticharm quark jets are depicted by blue or yellow cones. © CERN, for the ATLAS and CMS Collaborations

▲ **FIG. 2:** The heart of the XENON1T project, the Time Projection Chamber TPC after assembly in a clean room. @XENON1T team.

events with a Higgs boson decaying into a Z boson and two particle jets from charm-anticharm quarks, recorded by the ATLAS and CMS experiments at CERN. These events represent just a few of the possibilities how the Higgs boson can decay.

Detailed studies of the Higgs boson at current or future colliders, as well as precision measurements of the properties of matter and antimatter at a multitude of different experiments will reveal how the standard model of particle physics has to be amended.

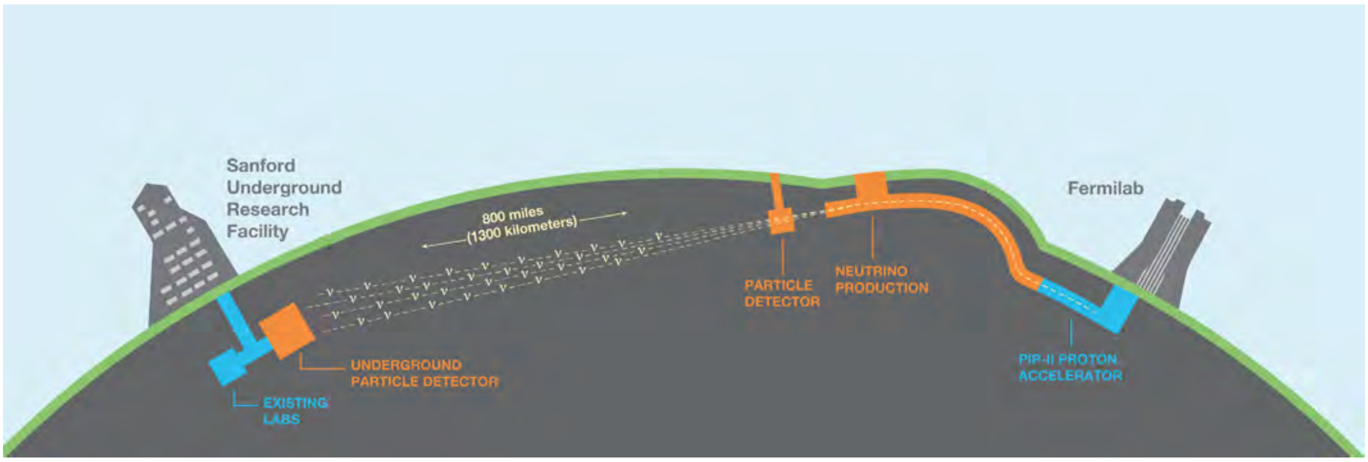
Read more: Particle physics: physics beyond the standard model, Freya Blekman.

Dark matter and dark energy - That it needs to be extended is evident. It does not contain dark matter, whose existence was already manifest decades ago. Another phenomenon, only discovered in 1998 through the study of the brightness of supernovae as a function of their distance, is dark energy, which makes our Universe expand in an accelerated fashion. Known or "visible" matter, the so-called baryonic matter, only accounts for 5% of the Universe, and is well described by the standard model of particle physics. The rest are dark matter (27%), and dark energy (68%). We have hardly any clues, but many ideas of what they could be (Fig. 2).

Read more: What is the Universe made of? Searching for dark energy and dark matter, Emmanuel N. Saridakis and Jochen Schieck.

Neutrinos - Although postulated already in 1930, neutrinos are another category of particles that are still mysterious. It was only ascertained in the 1990's that they have mass, in contrast to the assumption in the standard model of particle physics, and that they come in different

▼ **FIG. 3:** Cutaway illustration showing the path of neutrinos in the Deep Underground Neutrino Experiment. A proton beam is produced in Fermilab's accelerator complex. The beam hits a target, producing a neutrino beam that travels through a particle detector at Fermilab, then through 1,300 km of earth, and finally reaches the far detectors at the Sanford Underground Research Facility. @FNAL.



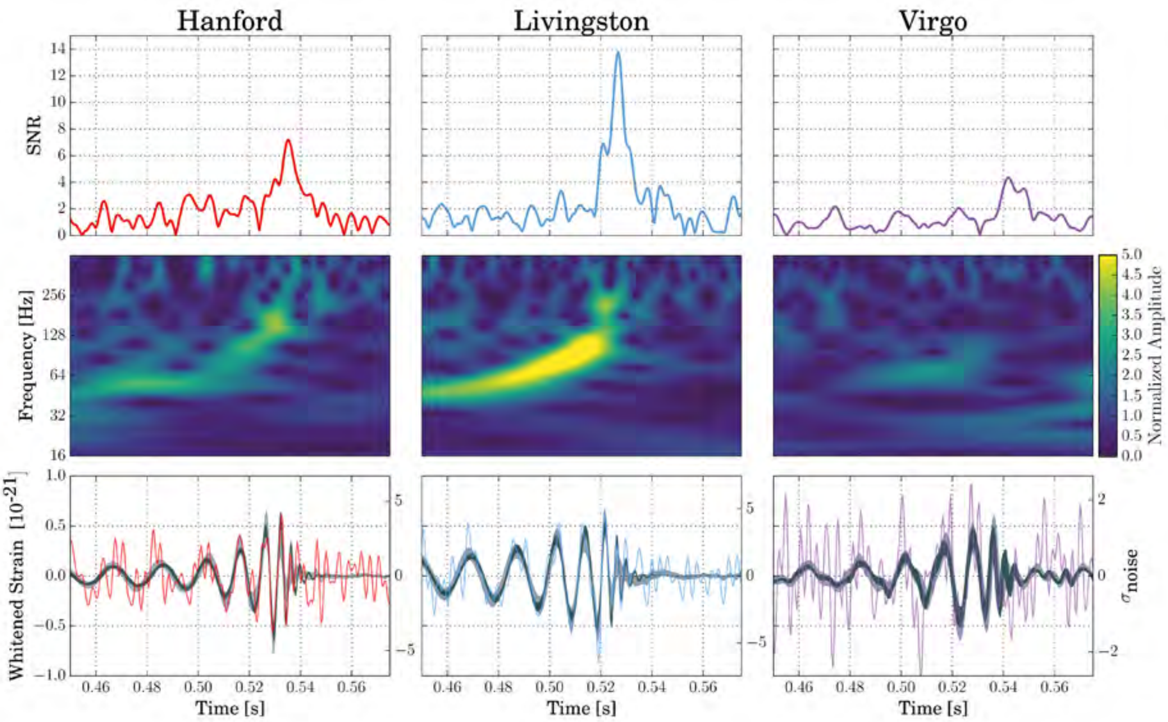
Read more in Chapter 1 of the EPS Grand Challenges.

flavours that can transform into each other. There might even be more varieties – sterile neutrinos, which do not interact through the forces described by the standard model, but only through gravity (Fig. 3).

Gravitational waves - Gravity is so present in our everyday life and the movements of objects in the cosmos, it is the least understood force, and is not part of the standard model of particle physics. We do not even have a quantum-mechanical formulation of the theory of gravity yet, which would allow us to describe this force down to the smallest scales of the Universe. Our current understanding is based on Einstein's theory of general relativity, which however breaks down at the Big Bang and the centre of black holes. Everywhere else, it has so far been proven to be perfectly descriptive and accurate. The spectacular direct discovery of gravitational waves in 2015 – ripples in space-time predicted to arise from violent events in the cosmos, such as mergers of black holes or neutron stars – confirmed it once more. The first observation of a gravitational-wave event on 14 August 2017 in the VIRGO interferometer in Italy, hosted by the European Gravitational Observatory, together with the corresponding signals measured in the two LIGO detectors in the United States, at Hanford (Washington) and Livingston (Louisiana), respectively, is depicted in Fig. 2.
Read more: Quantum gravity – an unfinished revolution, Claus Kiefer

Multi-messengers astronomy - The discovery of gravitational waves has further opened up a new field called multi-messenger astronomy. We are no longer limited to observing the sky with our eyes or with telescopes detecting light or other electromagnetic waves, but we now also have gravitational waves, and neutrinos, at our disposal as messengers from cosmic sources. We can study all kinds of signals in a coordinated fashion, in experimental facilities around the globe and even in space.
Read more: A gravitational universe : black holes and gravitational waves, Nelson Christensen.

Nuclear physics - There are many bridges between the smallest and the largest scales. Nuclear physics, with its quest to understand the origins of known matter, from the primordial soup made of quarks and gluons, the protons and neutrons, the atomic nuclei, to the formation of the heavy chemical elements in explosions of stars, connects these infinities. It also has a large potential for technological spin-offs, such as nuclear fusion to ensure the supply • • •

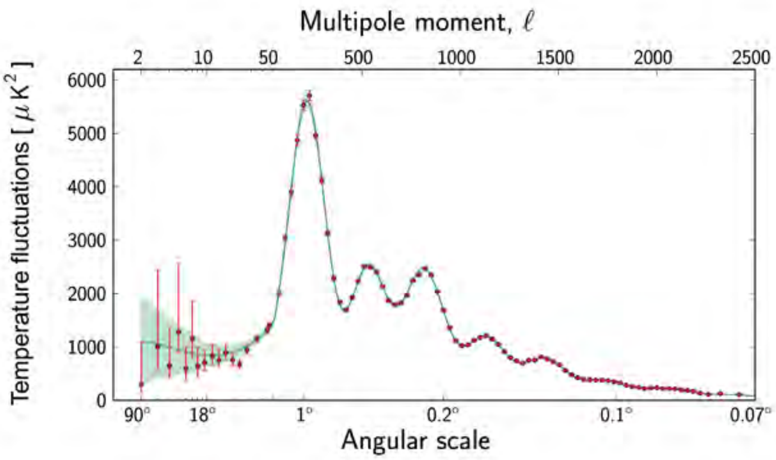


▸ **FIG. 4:** First gravitational-wave event (GW170814) detected by VIRGO, and seen in LIGO. © LIGO and VIRGO Collaborations

of electric power, and medical applications such as cancer therapy, as well as efficient and affordable isotope production for diagnostic purposes. For the latter, imaging techniques using artificial intelligence and other means are drivers for improving diagnostic accuracy, rapidity, and the comfort of patients. Astrophysics and high-energy particle physics are also connecting the scales, and have given rise to the new field of astro-particle physics. *Read more: Nuclear physics: the origin of visible matter in the Universe, Angela Bracco*

Cosmology - with its quest to understand the largest scales and nothing less than the fate of our Universe, cosmology needs information about its smallest components. Amongst others, measurements by space observatories such as Planck operated by the European Space Agency have helped establish the now widely accepted standard model of cosmology, as can be seen from Fig. 5. For the time being, we are at a turning point in the knowledge about the future of our Universe. Soon we should know more about its evolution, and in particular, whether it will be confirmed to expand continuously forever, or to rip apart, or even contract again.

▾ **FIG. 5 :** The power spectrum as measured by Planck. The green curve represents the best fit of the standard model of cosmology, currently the most widely accepted scenario for the origin and evolution of the Universe to the Planck data. © Planck Collaboration and ESA



Other research areas - The stars, the sun and the planets, including our own, still have secrets themselves. Their formation and evolution are vibrant research areas, tackled through computations and observations, and exploiting a multi-disciplinary approach. The study of exoplanets has also become a central subject in astrophysics. More down-to-earth, geophysics addresses topics that can affect us all, such as volcanic eruptions, earthquakes, or even changes in the Earth's magnetic field. The understanding of these phenomena can help predict their occurrence, for the benefit of mankind.
Read more: Stars, the Sun, and planetary systems as physics laboratories, Patrick Eggenberger and Physics of the Earth's interior, Emanuel Dormy

Acknowledgement

The authors would like to thank Freya Blekman, Angela Bracco, Nelson Christensen, Emmanuel Dormy, Patrick Eggenberger, Claus Kiefer, Emmanuel Saridakis and Jochen Schieck for their valuable contributions to the EPS Grand Challenges project.