Brussels, 19 May 2025

COST 010/25

DECISION

Subject: Memorandum of Understanding for the implementation of the COST Action "Testing Fundamental Physics with Seismology" (FuSe) CA24101

The COST Member Countries will find attached the Memorandum of Understanding for the COST Action Testing Fundamental Physics with Seismology approved by the Committee of Senior Officials through written procedure on 19 May 2025.

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA24101
TESTING FUNDAMENTAL PHYSICS WITH SEISMOLOGY (FuSe)

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 bridge fundamental physics and Earth scientists, focusing on seismic data's potential to uncover new physics. Through interdisciplinary collaboration, advanced methodologies, and SME engagement, it advances understanding of Earth's structure, astrophysical phenomena, and improves natural catastrophe alert systems. 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

The FuSe Action tackles challenges in fundamental physics by exploring seismic phenomena and earthquake precursors, providing new opportunities for testing. It aims to bridge the gap between fundamental physicists and Earth scientists, leveraging advanced technologies such as Big Data, machine learning, and AI, and working with small technological enterprises to translate theoretical insights into practical applications.

At the heart of FuSe is the belief that **seismic phenomena** could reveal **new aspects of fundamental interactions** and lead to the discovery of new physics. By analysing seismic data and studying the underlying physical principles, FuSe aims to explore imprints of unknown physics that may be embedded in these natural processes. On the other hand, the study of fundamental physics can also improve our knowledge of the Earth. This effort draws on interdisciplinary expertise, with a focus on how seismic events could deepen our understanding of the fundamental forces that govern the universe.

FuSe's innovative approach combines diverse scientific fields to pursue both theoretical and practical advancements. This synergy has the potential to transform our knowledge of both fundamental physics and seismic activity, contributing to a broader understanding of Earth's interior and the cosmos.

Areas of Expertise Relevant for the Action	Keywords
● Physical Sciences: Fundamental interactions and fields (theory) ● Earth and related Environmental sciences: Physics of earth's interior, seismology ● Earth and related Environmental sciences: Databases, data mining, data curation, computational modelling	● Fundamental physics ● Seismology ● Geophysics ● Material science ● Big Data

Specific Objectives

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

Research Coordination

● To promote collaboration between researchers in distant communities like fundamental physicists, geophysicists, and material scientists through joint workshops, training, and cross-disciplinary initiatives leading to new scientific insights; and build a common language and methodology to tackle challenges at the intersection of physics and seismology.

● To establish a shared understanding of theoretical and experimental challenges by creating online resources, hosting meetings, and producing collaborative reviews.

● Combining seismic, earthquake precursors, and experimental data developing comprehensive research strategies may lead to identifying new physics signatures. Developing and promoting the toolkits will help interfacing all these data with the fundamental physics models.

● To disseminate findings to the public and stakeholders to raise awareness and support for the field, including outreach to companies and startups in relevant sectors. With SMEs as secondary proposers of FuSe, the Action can reach a wider technological audience.

Capacity Building

● To enhance collaboration across disciplines through meetings and joint initiatives, building a cohesive research agenda.
● To facilitate mobility and joint projects between different research communities, prioritizing cross-disciplinary ideas, e.g. in STSM proposals and interdisciplinary talks and seminars during meetings.
● To provide opportunities and visibility for young researchers, underrepresented groups, and researchers from ITCs.
● To implement a code of conduct, include career development and diversity discussions at events, and raise awareness. To ensure gender balance in conferences and public events.

TECHNICAL ANNEX

1. S&T EXCELLENCE

1.1. SOUNDNESS OF THE CHALLENGE

1.1.1. DESCRIPTION OF THE STATE OF THE ART

Fundamental physics aims to describe nature's laws across all scales, from the standard model (SM) of particle physics to the cosmos governed by the laws of general relativity (GR). Integrating gravity’s geometric structure with quantum principles, still remains an open challenge [1]. There exist different partial fundamental and phenomenological models of quantum gravity, which introduce corrections to GR and quantum mechanics that can potentially be tested [2]. In addition to these theoretical difficulties, phenomena like dark energy, driving the universe's accelerated expansion [3], and dark matter, which influences galaxy formation and large-scale structure [4], remain unexplained [5].
Adding to this enigmatic picture, emerging from the observation of gravitational effects, on the particle physics side, massive neutrinos pose another of modern physics' great mysteries. Unlike dark matter, which interacts only gravitationally, neutrinos also interact through the weak nuclear force, making their detection equally challenging. Despite being exceptionally elusive, it is now well established that neutrinos have mass, though incredibly small [6]. This mass plays a critical role in both particle physics and cosmology, influencing everything from the behaviour of the early universe to the large-scale structure of galaxies [7]. Their presence adds yet another layer of complexity to the fundamental questions about the universe's composition. While we know neutrinos have mass, understanding its exact value and the broader implications of this discovery remains an open question, highlighting the intricate role these subtle particles play in shaping the cosmos [8].
The Earth [9-11], Moon [12], and other astrophysical objects serve as natural laboratories for fundamental physics due to our rich knowledge of their internal structures [13-17]. For instance, hypothetical dark matter particles, when captured by these bodies, could annihilate and release heat, affecting their thermal behaviour. Measuring this heat allows to constrain dark matter properties. Additionally, extensions to GR predict different cooling rates for astrophysical objects, providing further means to test such theories against observational data [18-20]. The Moon's lack of internal heat and white dwarfs’ predictable cooling offer valuable opportunities for detecting exotic particles and testing alternative theories of gravity [21-24]. Those natural conditions provide powerful insights into particles’ interactions and extensions to GR, complementing lab-based experiments.
Meanwhile, seismology, especially asteroseismology, has established itself as a key method for probing fundamental physics. Asteroseismology studies the deep interior of stars by analysing brightness fluctuations from time-series observations [25,26]. These fluctuations reveal various resonant oscillations in stars—e.g., pressure modes and gravity modes—which provide insights into stellar structure and evolution. Acoustic modes (or pressure) are generally excited in the convective envelopes of low mass stars (solar-like and evolved red giant stars) [27] whereas gravity modes are in the radiative envelopes of massive stars. These modes allow us to understand fundamental processes of nuclear physics, chemical evolution, convection, rotation, and magnetism within stars. In addition to providing insights into the internal structure of stars, stellar (and planetary) oscillations allow us to explore dark matter, dark energy, and modifications to GR. The frequency spectrum of stellar oscillations allows us to set constraints on the mass and/or radius of a neutron star, and eventually obtain the nuclear equation of state, through the observation of oscillations [28-31]. For instance, the oscillation frequencies of stars and neutron stars may carry signatures of scalar fields (“fifth force”), potentially linked to dark energy or agents of cosmological inflation, and may also reveal the presence of exotic particles [32-35]. Therefore, asteroseismic modelling, especially of solar-like stars, has been instrumental in setting new exclusion limits on dark matter and placing constraints on deviations from Einstein's theory of gravity. Furthermore, seismic data has been used to test cosmic-time variations in the gravitational constant and other fundamental constants [36]. By comparing observed stellar oscillation frequencies with theoretical models, researchers can limit the changes in these constants over time. In the case of the Sun, its highly detailed eigenspectrum offers a precise view of its interior, serving as a powerful probe for studying fifth forces and potential deviations from standard physics [37,38]. Seismology offers insight into stars and acts as a natural laboratory for exploring physics beyond the SM.
On the other hand, structural seismology aims to infer the properties of Earth's interior by analysing seismic wave observations. Standard spherical models of the planet include variations in

wave speed and density (PREM [39]; IASP91 [40]; ak135 [41]), as well as parameters that describe anelastic properties, which account for observed wave attenuation and dispersion. Most seismic data, however, are primarily sensitive to wave speeds, as these depend on the ratio of elastic moduli to density. Only at long wavelengths (low frequencies) do seismic waves exhibit direct sensitivity to density, as self-gravitation becomes significant. Additional constraints on the density come from Earth's mass and moment of inertia measurements. Spherical models continue to be extrapolated and used in modelling both terrestrial and gaseous planets, such as Jupiter and Saturn [42,43]. However, rocks in extreme environments, like exoplanets or Jovian planets, exhibit properties distinct from those on Earth, including metallic-like electrical and thermal conductivity [44]. These unique characteristics can generate magnetic fields with greater amplitudes and longer lifespans, enhancing heat flow to the surface of terrestrial planets. This, in turn, increases the likelihood of planet-quakes and volcanic activity.

Since the early 1980s, research has increasingly focused on lateral variations in seismic properties, which arise from Earth's internal dynamics, specifically mantle convection driven by temperature and compositional differences over millions of years. These lateral variations in seismic wave speeds are inferred through seismic tomography, a widely used technique to study Earth's interior (e.g. [45-53]).

All these studies involve solving inverse problems, where data, assumed to follow known physical laws, are used to infer unknown parameters like seismic wave speeds or density. These inverse problems are often underdetermined, meaning there may be many possible models that fit the data. Optimization techniques are typically used to find the best-fitting model, but additional constraints are required to narrow down the solutions. Bayesian inference formalises this process, but applying it on large scales for geophysical modelling remains a challenge [54-56].

Aside from structural seismology, particle physics provides remarkable insights into the Earth's depths without relying on gravity-based methods [57,58]. Neutrinos, due to their elusive nature, have both challenged and advanced our understanding of the universe. Their weak interaction with matter makes them incredibly difficult to detect, yet they serve as extraordinary probes for exploring the Earth's most inaccessible regions. Since the mid-twentieth century, geoneutrinos—electron antineutrinos produced by β decay within the Earth—have become invaluable tools for studying our planet's interior [59]. The lack of precise constraints on radiogenic heat contributions and the absence of direct geochemical data from deep layers make neutrino geoscience both complex and essential. With advancements in multi-site detection through the past (Borexino) [60], ongoing (KamLAND [61] and SNO+ [62]), and upcoming (JUNO [63]) experiments. The next decade promises transformative discoveries, offering deeper insights into Earth's composition and energetics.

Current geophysical and astrophysical models are based on Newtonian physics, but some effective gravity theories introduce modifications to the standard equations [64-67]. A key question is whether such new physics, in appropriate weak-field limits, can be integrated into geophysical modelling, and what impact this would have on our understanding of Earth's internal structure [68,69]. The integration of seismic data into the realm of fundamental physics has proven invaluable for advancing our understanding of gravitational models and astrophysical phenomena [70]. Seismic data have already contributed to constraining models of gravity with greater precision than those offered by cosmological observations alone [71]. Moreover, these gravitational effects extend to the microscopic properties of materials, affecting thermodynamic parameters such as specific heat or elasticity and bulk modulus [72,73], which are foundational to structural seismology. The bulk modulus, for instance, reflects how incompressible a material is, providing insights into the internal pressures and stability of planetary layers. Understanding these properties is essential for accurately modelling seismic wave propagation and interpreting seismic data in the context of planetary interiors. Moreover, the elasticity of materials within astrophysical objects influences their response to external forces, such as tidal interactions or rotational stresses. This can lead to observable phenomena like planet-wide quakes or deformation, which are critical for understanding the dynamic behaviour of celestial bodies. All of this underscores how seismology is integral to testing fundamental physics through various experiments, bridging Earth sciences with fundamental theories.

The experimental reproduction of the extreme pressures and temperatures found in the Earth's deep interior, including those present in the upper/lower mantle and core has been improved by the development of diamond anvil cells (DACs) which have been instrumental. When combined with laser heating, DACs can achieve temperatures exceeding several thousand kelvins, accurately simulating the thermal conditions at such depths. Advanced techniques like Brillouin scattering [74] or ultrasonic interferometry [75] are employed to precisely measure the acoustic velocities in minerals under these conditions, providing essential data on how seismic waves propagate through the Earth. Additionally, synchrotron-based X-ray diffraction or imaging is critical for structural characterization of minerals, allowing researchers to identify and monitor the phase transitions and polymorphs that occur in minerals as pressure and temperature change. This structural data, paired with acoustic velocity measurements, is vital for understanding the composition, elasticity, and dynamic behaviour of Earth's interior under varying pressure and temperature. To effectively integrate gravitational and geophysical research, precise identification and separation of environmental effects from material signals, alongside detailed material modelling, are essential. Challenges include distinguishing between static and dynamic deformation moduli [76,77], a key issue for example in the sensitivity and instrumentation [78] of the Einstein Telescope, the new European ground-based gravitational wave detector. Additionally, the sensitivity of torsion balances to atmospheric pressure changes, complicating geophysical observations [79]. Dipole-based instruments may reveal vectorial fifth-force effects, potentially explaining observed deviations in the original equivalence principle experiments, yet corresponding modified gravity theories remain untested [80,81]. Historically, instruments like the Eötvös balance were crucial in verifying fundamental principles such as the equivalence principle, which continues to be central in testing theories of gravity [82,83]. An Eötvös balance with enhanced sensitivity could potentially detect candidate earthquake precursors [84]. On the other hand, quantum sensing is emerging as a game-changer, particularly in seismology and earthquake detection. Quantum sensors, leveraging quantum mechanics principles such as superposition and entanglement, offer unprecedented sensitivity and accuracy compared to classical methods. This could revolutionise seismographic technology, improving detection of small ground vibrations and enabling early earthquake warnings [87].

Seismic events, while valuable for testing fundamental interactions and revealing the structure of astrophysical bodies, have devastating effects on human life. Earthquakes rank among the most destructive natural disasters, posing immense social and economic challenges worldwide. A major unresolved issue is the inability to accurately predict the timing, the location and the magnitude of seismic events. Although the seismic activity in Europe is typically characterised by frequent low-to-moderate magnitude earthquakes [88], with only occasional large-magnitude events (such as the historical Mw>8.0 earthquakes in Crete 1303 and Lisbon 1755, [89]), the seismic hazard is high in many regions. Over time, seismic events have resulted in substantial destruction, as also seen in the recent 2023 Kahramanmaraş Mw=7.8 earthquake in Turkey, as well as in the 2009 L'Aquila Mw=6.3 and 2016 Amatrice Mw=6.0 earthquakes in Italy. Throughout the 20th century, earthquakes in Europe resulted in more than 200,000 deaths and over €250 billion in economic losses (EFEHR, 2023). Understanding earthquake precursors is crucial, and it may benefit from fundamental physics. Radon anomalies observed prior to earthquakes suggest that radon may serve as a potential precursor to seismic activity, though further testing and analysis of environmental factors are needed for reliable forecasting. Additionally, changes in the ionosphere, detected through electromagnetic signals, have been noted days to minutes before earthquakes, hinting at a possible connection between ionospheric disturbances and seismic events. The detection of gravity perturbations caused by mass redistribution during earthquakes, as demonstrated by [90], provides another promising method for early warning, allowing for rapid magnitude estimation. Moreover, the study of cosmic rays has revealed potential correlations with seismic activity, suggesting a possible cosmic component in earthquake prediction [91]. The working hypothesis is that perturbations to the geomagnetic field [92] occurring before, during and after an earthquake will alter the steady cosmic ray flux that includes charged particles, thus resulting in a potentially detectable signature. To improve forecasting, a multi-channel approach integrating ground and space-based observations is essential. This includes monitoring electronic perturbations, which involve variations in electric and magnetic fields and plasma parameters, and examining seismo-induced radon exhalation linked to electromagnetic disturbances. Studying thermal anomalies due to geochemical fluid movements and frictional effects along seismic faults also offers valuable insights. Additionally, electromagnetic field measurements from both ground-based and space-based sources, magnetometer analyses, and particle precipitation observations can further enhance our understanding of seismic precursors. Integrating these diverse data sources could lead to a more comprehensive and accurate forecasting system. Small companies working on earthquake detectors, particularly those integrating mobile platforms with Distributed Acoustic Sensing and machine learning techniques [93,94], aim to improve the probability of accurate forecasts. By deploying mobile, underwater, and aerial sensors to monitor time-varying seismic signals, these companies are pushing the boundaries of current seismological methods [95]. The use of cosmic ray monitoring as part of a multi-messenger approach, combined with neural networks [96], has shown promise in refining prediction models and increasing confidence in earthquake forecasts as well as in possibly testing deviations from GR, ultimately benefiting both scientific research and the public. In addition, developing theoretical models and simulations that accurately capture the key aspects of the Earth's geomagnetic dynamics is essential for understanding the behaviour of the aforementioned phenomena. Insights from fundamental physics are crucial for studying these precursors in relation to earthquakes, and there is significant potential to enhance our predictive capabilities by integrating these insights into our forecasting methods.

1.1.2. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

In recent years, the connection between fundamental physics and seismology has been identified, pointing to the importance of a better understanding of the interrelations between the subtle effects of fundamental physics with the planetary (including Earth and Moon) and stellar interiors. However, exploring these intersections presents significant challenges due to differences in the **scientific language and methods** used across various fields. Each scientific community—whether in physics or seismology—possesses specialised expertise, distinct research questions, and unique terminologies. This diversity can pose a challenge in achieving an unified understanding. Nevertheless, the integration of these perspectives offers an opportunity for novel and important insights.

The main aim of the proposal is to **identify and investigate the key questions** that are critical to both fundamental physics and geophysics; it is essential to convene a diverse team of scientists with complementary expertise. This collaborative effort should focus on exploring the intersections of multiple disciplines, including particle physics, gravity, microphysics, planetary science, seismology, and applications to technology. By bringing together experts in both experimental and theoretical research, along with innovative contributors from small and medium-sized enterprises (SMEs), the Action will create a **dynamic environment** that fosters novel insights and breakthroughs. Leveraging Big Data and advanced models, researchers can analyse seismic data in an unprecedented detail, uncovering subtle signals that may hint at the new physics beyond the SM. It is clear that complementary approaches expand our understanding of various phenomena as evidenced by the multiple previous COST Actions, so too can the collaboration between seismologists and fundamental physicists enhance our knowledge of both disciplines. The goal is to exploit their complementarity, where **insights from seismology inform fundamental physics and vice versa**, paving the way for groundbreaking discoveries at the intersection of these disciplines. The main aims of the COST Action FuSe are:

- **Building a common language and methodology.** The Action will bridge the gap between fundamental physics and seismology by fostering cross-disciplinary collaborations. By building a common language and methodology, the Action aims to equip the next generation of scientists with the skills needed to tackle complex challenges at the intersection of these fields. This approach will leverage cutting-edge technologies and methodologies to explore new paradigms beyond traditional models. FuSe will act as a catalyst for innovation, facilitating the exchange of knowledge and best practices across Europe, ultimately leading to breakthroughs in understanding both fundamental physics and seismic phenomena.
- **Interfacing seismologists, astro-seismologists with theoretical physicists.** The Action will foster the creation of dynamic research groups that unite experts from diverse backgrounds in fundamental physics and geophysics. By promoting interdisciplinary networking, the Action aims to build a robust community of researchers who can collaboratively address the complex challenges at the interface of these fields. The network will provide a platform for exchanging ideas and methodologies, encouraging the formation of new research partnerships and the development of innovative approaches. This collaboration will enhance our understanding of fundamental physics and seismic processes and also drive the creation of novel solutions to long-standing scientific questions.
- **Seismic data to probe Fundamental Physics.** Incorporating seismic data into fundamental physics has significantly advanced our comprehension of gravitational models and astrophysical phenomena. Notably, the Preliminary Reference Earth Model (PREM), though widely used in astrophysical and particle physics studies, is based on an outdated and incomplete understanding of the Earth's interior. By leveraging more recent seismic data alongside a more realistic model of the Earth's structure, we can achieve more reliable theoretical bounds on gravity models and enhance our description of exoplanets. Moreover, seismic data provide an unique opportunity to examine gravitational effects on a micro scale, as gravity introduces subtle corrections to the statistical description of various materials. This allows for a deeper investigation into how seismic phenomena can inform our understanding of gravitational forces. In addition to its role in gravitational studies, the Earth's density profile is set to play an important role in particle physics over the coming years. It will be extensively used in the analysis of observations from neutrino telescopes (IceCube and KM3NeT), which are essential for illuminating the neutrino oscillation mechanism and searching for new physics beyond the SM. A more realistic modelling of the Earth's interior will lead to a more robust understanding of the neutrino sector, enabling scientists to refine their knowledge of neutrino behaviour and interactions. By integrating seismic data with these advanced neutrino observations, we can unlock new insights into the fundamental forces that govern our universe. By continuing to integrate seismic data into the study of fundamental physics, we can uncover new paradigms that expand our comprehension of the universe. The collaboration between seismology and fundamental physics promises to drive innovative breakthroughs, offering fresh perspectives on longstanding scientific questions and paving the way for new discoveries in both fields.
- **Fundamental Physics to probe the Earth's interior structure and other astrophysical objects**. The influence of fundamental physics on the structure of astrophysical objects is profound and multifaceted. Gravity dictates the overall shape and structure of celestial bodies and it also affects their internal composition and dynamics. Various gravitational models offer differing predictions regarding the density

profiles and layer structures of planets, illustrating the importance of precise gravitational theories in astrophysical studies. Moreover, gravitational effects on the microscopic properties of materials in Earth's layers significantly influence their thermodynamic parameters, such as elasticity and bulk modulus. Understanding how gravitational forces affect material stiffness and compressibility is essential for revealing the internal pressures and stability of planetary layers, as well as their response to external forces, which in turn affects the dynamic behaviour of celestial bodies. While gravity is a significant player in shaping celestial structures, particle physics also offers valuable insights, particularly regarding the Earth's profile. Neutrino propagation and neutrino flavour oscillations within the Earth are sensitive to its matter density profile and composition. This sensitivity allows scientists to infer the terrestrial density profile through a technique known as neutrino tomography. By analysing how neutrinos interact with different layers of the Earth, researchers can gain a more detailed understanding of its internal structure. By integrating fundamental physics with seismological observations, the Action can develop more comprehensive models of astrophysical objects which will offer more insights into the composition and evolution of celestial bodies, enhancing our understanding of both the macroscopic and microscopic processes that govern their behaviour. This interdisciplinary approach paves the way for more accurate predictions and analyses, ultimately contributing to our broader knowledge of the universe and Earth.

- **Cross-disciplinary data integration for advanced scientific research.** The Action will rely on observational, experimental and model data from multiple sources and distinct scientific areas. This includes seismic data from the Earth and Moon, and other astrophysical objects, data from earthquake precursors, particle physics, geospatial and geomagnetic data. A dedicated effort will be directed to establish a common ground enabling researchers to become familiar, understand, and meaningfully apply in their own line of work data originated in another scientific community. Data consolidation will be undertaken to optimise data for internal use in the Action, and produce AI-ready data streams, contributing to add value to already existing datasets, and foster data re-usage in novel applications and distinct scientific areas. The data will be compliant to the FAIR principles, and aligned with the European Open Science and Open Data strategies in terms of FAIR data models and detailed metadata attribution, in order to improve the fit for re-use. Open science best practices will be followed in the Action in order to foster the sharing of scientific research outputs (e.g., results, publications, software, etc.) .
- **Strengthening collaboration with SMEs.** Collaboration with SMEs is quite beneficial for advancing sensor networks and AI algorithms used in natural catastrophe alert systems. SMEs contribute innovative technologies, such as specialised detectors and mobile platforms, that enhance real-time data processing and sensor deployment. Their role is pivotal in refining detection capabilities, mitigating noise interference, and integrating cutting-edge AI techniques into seismological and geophysical applications. By fostering partnerships with SMEs, the Action can accelerate the development of distributed, dynamic perception systems for diverse environmental monitoring and disaster management scenarios.

Addressing these points will help us identify relevant research questions and highlight potential collaborations between fundamental physicists, geophysicists, seismologists, technology experts, and big data analysts. By bridging these disciplines, the Action aims to uncover new insights at the intersection of physics and seismic processes, leading to innovative solutions and discoveries.

1.2. PROGRESS BEYOND THE STATE OF THE ART

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

FuSe aims to bridge fundamental physics and geophysics by integrating experimental research with big data emerging tools. This coordination will leverage recent advances to explore gravity's fundamental nature and its quantum interactions, contributing to the cutting edge of scientific and technological innovation. Addressing these questions is crucial for progress in this area:

- Can we obtain a better understanding of fundamental physics models, taking into account more realistic descriptions of the astrophysical bodies and the structure of materials they are made of?
- Can we improve the understanding of the Earth and other astrophysical bodies' structure and composition from fundamental physics?
- Can Earth science give us insights about fundamental physics, hinting at new physics?
- Can we improve earthquake forecasting?

To advance in these directions, FuSe requires collaboration between fundamental physics and geophysics researchers, material science experimentalists, and big data experts with the focus on:

- **Incorporating a more realistic description of the Earth to study fundamental physics**. We can gain a deeper understanding of fundamental physics by incorporating more realistic descriptions of astrophysical bodies like Earth. The specific actions include: refining the Earth's shape and rotational sensitivity by estimating the equatorial and polar moments of inertia, and incorporating ellipticity corrections into the 1D PREM global reference model (or others); addressing the limitations of 1D model (defined by spherical shells with uniform properties) by accounting for 3D lateral heterogeneities in seismic and density structure across different parts of the Earth's mantle, crust, and core; utilising the equation of state to model core density and bulk moduli, including gravity effects on Earth minerals; considering thermodynamic processes such as temperature and heat exchange between Earth's layers; integrating the latest seismic data with future observations from neutrino telescopes while performing a thorough analysis of uncertainties; utilising geoneutrino measurements from multiple experiments to extract valuable insights into the Earth's radioactivity and heat budget.

- **Evaluating new models with existing experimental data of materials at the extreme conditions found within planets**, experimental tools—such as those developed using both static and dynamic high-pressure techniques—are utilised in the literature to replicate these environments in the laboratory or in large facilities.
- **Predicting which elemental combinations and pressures could be employed to replicate the desired environments,** since experimental trial-and-error high pressure synthesis is quite expensive, time-consuming, and the results are difficult to analyse. Chemical intuition or data-mining techniques are somehow limited for these purposes, because these have mainly been developed based upon data gathered at Earth-like conditions. Fortunately, the advances in High Performance Computing, together with advances in crystal structure prediction techniques, combined with Density Functional Theory, has led to interaction between experiment and theory in the high pressure research field.
- **Preparing the simulations of neutrino telescopes** IceCube and KM3NeT **for the prompt analysis of their data** after its release.
- **Creating and expanding a meta-repository** that will serve as a centralised hub for standardising and integrating important datasets, facilitating access and collaboration in several research domains. The goal is to provide **an unified framework** for combining diverse information from different fields, **fostering collaboration and innovation, and making it easier for researchers to access and utilise high-quality data.** The Action will coordinate the inputs to the repository**.** Initially, the meta-repository will aggregate metadata and data from other existing repositories and participating institutions. It will house experimental data, computational results, and publicly available datasets related to the targeted fields. Over time, the repository will grow as new contributions and tools emerge from collaborative efforts of the Action. This will include data and software developed through the Action. The repository is intended to benefit Young Researchers and Innovators (YRIs) and researchers from Inclusiveness Target Countries (ITCs), who may not have access to comprehensive resources. It will provide these researchers with easier access to valuable datasets and tools. FuSe will share best practices, promote the creation of benchmark datasets, and help standardise future research and development efforts across the various interdisciplinary fields.

1.2.2. Objectives

1.2.2.1. Research Coordination Objectives

FuSe will coordinate three key communities—fundamental physics, planetary and stellar science, and data science—while actively involving SMEs. The specific objectives of the Action are as follows:

- **Foster Collaboration**: Promote collaboration between researchers in distant communities like fundamental physicists, geophysicists, and material scientists through joint workshops, training, and cross-disciplinary initiatives leading to new scientific insights; build a common language and methodology to tackle challenges at the intersection of physics and seismology.
- **Develop Common Frameworks**: Establish a shared understanding of theoretical and experimental challenges by creating online resources, hosting meetings, and producing collaborative reviews. This will enhance training and knowledge of YRIs across these interdisciplinary fields as well as incorporate and increase visibility of ITCs.
- **Integrate Experimental Data**: By combining seismic, earthquake precursors, and experimental data and results to develop comprehensive research strategies may lead to identifying new physics signatures. Developing and promoting the toolkits will help interfacing all these data with the fundamental physics models.
- **Enhance Public Engagement**: Disseminate findings to the public and stakeholders to raise awareness and support for the field, including outreach to companies and startups in relevant sectors. With SMEs in FuSe, the Action can reach a wider technological audience.

1.2.2.2. Capacity-building Objectives

FuSe's capacity-building objectives focus on creating a robust research network in fundamental physics, planetary and stellar science, data science, and experimental methods, with active SME involvement:

- **Foster Expertise Exchange**: Enhance collaboration across disciplines through meetings and joint initiatives, building a cohesive research agenda.
- **Promote Multidisciplinary Collaboration**: Facilitate mobility and joint projects between different research communities, prioritising cross-disciplinary proposals.
- **Support Emerging Talent**: Provide opportunities and visibility for young researchers, underrepresented groups, and researchers from ITCs .
- **Advance Diversity, Equity and Inclusion Principles**: Implement a code of conduct, include career development and diversity discussions at events, and raise awareness. the Action will ensure gender balance in conferences and public events.

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

FuSe will establish a critical bridge between fundamental physics, geophysics, materials science, and data science, fostering collaborative research at the intersection of these disciplines. At present, there is no dedicated network that unites these efforts, hindering researchers from forming a comprehensive understanding of the connections between fundamental physics and seismology. While past COST Actions like G2NET (2018-2023), QGMM (2019-2023), TIDES (2011-2015), and GWVerse (2017-2021), independently advanced geophysics and fundamental physics, the link between the two fields remains unexplored. FuSe aims to strengthen ongoing European and international initiatives by integrating diverse research domains and optimising the potential of existing networks.

Existing initiatives in fundamental physics include international organisations, like the International Society for Quantum Gravity (ISQG) and national societies such as the Polish Society on Relativity or the Spanish Society on Gravitation and Relativity, which tackle quantum gravity and relativity from theoretical perspectives. In the astrophysical domain, the European Consortium for Astroparticle Theory (EuCAPT) brings together the European community of theoretical astroparticle physicists and cosmologists, while the Center for Interstellar Catalysis (InterCat) focuses on astrochemistry and quantum simulations, providing key insights into molecular formation and material design. At the intersection of gravitational waves and geophysics, the European Laboratory for Gravitation and Atom-interferometric Research (ELGAR) aims to deepen our understanding of Earth's internal structure and gravitational interactions, while one of the goals of Einstein Telescope is the mitigation of environmental noise to enhance its sensitivity to gravitational wave detection. Initiatives addressing matter under extreme conditions include the European High Pressure Research Group and the International Association for the Advancement of High Pressure Science and Technology.

FuSe will build on existing initiatives by establishing a collaborative platform that connects fundamental physics, planetary and stellar science, data science, and experimental methods, with contributions from SMEs. By bridging these areas, FuSe will promote the integration of experimental data with theoretical models, advance geoneutrino research, and foster an unified approach to understanding gravity and quantum systems. This effort will contribute to reinforcing Europe's leadership in global scientific research and innovation.

2.2. ADDED VALUE OF NETWORKING IN IMPACT

2.2.1. SECURING THE CRITICAL MASS, EXPERTISE AND GEOGRAPHICAL BALANCE WITHIN THE COST MEMBERS AND BEYOND

The FuSe COST Action is a pioneering initiative designed to bridge the gap between fundamental physics and seismology by fostering interdisciplinary collaboration across Europe and beyond. With members rooted in Physical Sciences, in Earth and Environmental Sciences, and additional expertise in fields like Computer Science, Electrical and Material Engineering, FuSe brings together a diverse and dynamic network of researchers. This initiative aims to build a common language and methodology, equipping the next generation of scientists with the tools needed to tackle complex challenges at the intersection of these fields.

By promoting cross-disciplinary networking, FuSe will create a robust research community where experts in fundamental physics and planetary science can collaboratively address key scientific questions. The integration of seismic data with advanced gravitational models will offer unprecedented insights into both astrophysical phenomena and the Earth's structure. Moreover, the network will leverage big data from multiple sources, enhancing the utility of existing datasets and fostering new applications in AI-driven data analysis.

FuSe also emphasises the importance of new technologies in enhancing real-time data processing for natural catastrophe alert systems. By advancing sensor networks and refining detection algorithms, the Action aims to make significant contributions to both scientific research and societal safety. Through these efforts, FuSe is set to drive innovative breakthroughs and unlock new paradigms at the intersection of fundamental physics and seismology, paving the way for groundbreaking discoveries.

The FuSe COST Action network comprises COST Full Member Countries, Near Neighbour Country, and International Partner Countries, as well as European RTD and 2 International Organisations. The Action also includes SMEs, further broadening the scope of collaboration. Throughout the Action's duration, efforts will be made to maintain and potentially enhance the diversity within the network.

2.2.2. INVOLVEMENT OF STAKEHOLDERS

The primary stakeholders of the Action are scientists working in fundamental physics, seismology, and data science, across both experimental and theoretical domains. They will benefit from the creation of the FuSe network, with their home institutions—European and international universities and research centres—serving as hosts for Action activities. A significant portion of events will be held in ITC countries, both to acknowledge and support their local research communities. FuSe will foster the professional growth of YRIs through STSMs and interdisciplinary training schools, which will extend their collaboration network, sharpen their skills and broaden their career horizons. Scientific activities will offer YRIs a platform to showcase their work and gain recognition within the scientific community.

FuSe will bridge gaps by coordinating with ISGQ and EuCAPT (other stakeholders) to amplify the impact of quantum gravity, astroparticle theory and cosmology workshops, ensuring a broader integration of findings across various disciplines. Additionally, FuSe will collaborate with InterCat and ELGAR to advance interdisciplinary research on astrochemistry, seismology and gravitational physics.

FuSe will build on existing research efforts by integrating various stakeholders to create an unified platform for advancing seismic and fundamental physics research. The Action will enhance ongoing efforts by fostering collaboration between experiments crucial for understanding cosmic phenomena and Earth's internal processes. FuSe will also engage with SMEs and start-ups in the earthquake forecasting sector, facilitating the application of cutting-edge research in practical technologies. This will support the development of competitive skills among YRIs through STSMs in both academia and SMEs, ensuring long-term career prospects in academia and/or industry.

Public outreach will be a key component, with dedicated events and online platforms aimed at educating and engaging the general public on fundamental research and its societal implications.

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 FuSe Action aims to **bridge the gap between distinct scientific communities**, fostering collaboration and **establishing a common language** across the diverse fields which currently operate largely in isolation, with entirely different terminologies, methodologies and research aims. All this hinders the ability to work together effectively. FuSe will play an important role in overcoming these barriers by creating a platform where experts from these disciplines can converge, share knowledge, and collaborate on joint projects, considerably impacting scientific developments. The networking activities will generate substantial short-term scientific impacts during the lifetime of the Action, by fostering dynamic exchange among experts in gravity, particle physics, seismology, machine learning, artificial intelligence, geophysics, data science, experiments, and instrumentation. This will be particularly vital in **developing new paradigms that merge seismic and earthquake precursors data with insights from fundamental physics, having a significant impact in both fields** and leading to a deeper understanding and enabling **knowledge creation** and **scientific developments** across disciplines. By enriching each discipline through **integration of knowledge**, experiences, and techniques from other areas, the Action will foster both theoretical and experimental progress contributing to the **advancement of** these **research fields**. A central pillar of the Action is the groundbreaking potential of seismology **to advance our understanding** of fundamental physics, including the comprehension of the universe's most elusive mysteries. Seismic data, traditionally used to study the Earth's interior, offers an unique and untapped resource for probing the fundamental forces that govern our universe. By analysing seismic waves and their interactions with different layers of the Earth, researchers can **gain insights into gravitational effects and other fundamental forces** that are not easily accessible through other means. This approach has already shown promise in refining models of gravity and **could potentially reveal new physics** beyond the current theoretical frameworks. By building a robust network between physicists and seismologists with complementary skills and enhancing the study of fundamental physics through seismological methods FuSe will contribute to **strengthening these interdisciplinary connections**. FuSe is dedicated to harnessing this potential by integrating seismic data into the study of fundamental physics in innovative ways. For example, the density profile of the Earth, derived from seismic measurements, plays a critical role in understanding neutrino behaviour and can be used to refine models of neutrino oscillations. This **enhances our knowledge of particle physics** and contributes to **development of more accurate models of astrophysical objects**. This interdisciplinary approach positions FuSe at the forefront of scientific innovation, with the **potential to make significant contributions to both fields, enabling collaborations and leading to transformative discoveries and to strengthening EU research**. Another key impact would be the **enhancement of communication and collaboration among researchers across fields facilitating knowledge exchange** by encouraging sharing of ideas and methodologies. Annual conferences, workshops, regular online seminars and collaborative research projects will promote cross-disciplinary interaction and help **establish** a **comprehensive glossary of terms** used across various fields, **enabling more effective collaboration and innovation, building a new multidisciplinary community** of researchers equipped to tackle the challenges at the intersection of seismology and fundamental physics. This will involve **training the next generation** of scientists, with a particular focus on YRI, to ensure that they are well-versed in the methodologies and technologies that are essential for this interdisciplinary work, making them adept in both theoretical and experimental approaches and boosting their career opportunities. Through these efforts, FuSe will **lay the groundwork for future collaborations** and research projects that extend beyond the lifetime of the Action, ultimately leading to potentially groundbreaking discoveries and innovations.

In **the long-term**, FuSe aims to **establish** itself as a leading **network for interdisciplinary research**, driving forward **technological advancements** that have direct implications for both science and society. By creating a cohesive and collaborative research environment, FuSe will contribute to the development of high-precision measurement techniques and other innovations from which **in the longer term** the **scientific community**, **industry** and **public interest** will benefit. While the primary focus is on fostering collaboration between experts and institutions, FuSe will also promote the refinement of algorithms that process real-time seismic data. This effort has the potential to improve the accuracy and timeliness of disaster alerts, particularly in urban areas, enhancing public safety by providing earlier warnings. After the Action's end FuSe plans to **establish and keep up a Multidisciplinary Research Community** building up on the network developed thanks to the Action**.** This community of researchers will continue to explore the intersection of fundamental physics and seismology, driving collaborative efforts toward groundbreaking discoveries. The fulfilment of the Action's activities has also the **potential to shape future experiments**, guide the design and clarify the requirements for future experiments in seismology and fundamental physics as well as potential to lead to improved observational techniques and data analysis methods (pioneer high-precision and quantum-enhanced measurement methods with potential applications in technology and industry, contributing to technological advancements).

Socioeconomic Impacts will be generated through various initiatives:

- **Promoting Open Access:** FuSe will make all research outputs freely available, enhancing transparency and facilitating the wide dissemination of knowledge. This open access approach will ensure that valuable insights and discoveries are accessible to a global audience.
- **Boosting Collaboration and Mobility:** FuSe will encourage partnerships and researcher mobility across different geographical regions and disciplines. This will create a robust network that supports ongoing scientific progress and knowledge sharing.
- **Supporting Young Researcher** by giving opportunities to present their work, FuSe will enhance their visibility and provide valuable career development opportunities. This will be achieved through targeted networking activities, mentoring, and training programs.
- **Promoting diversity and inclusiveness**, by advocating for diversity, equity, and inclusiveness through outreach programs, ensuring gender balance across events, LQBTQ+ visibility and empowering young researchers and innovators (YRIs) from diverse backgrounds.
- **Engaging with the general public** and enhancing awareness about the significance of fundamental research in physics and seismology through outreach, online presence, and public events. These efforts will highlight the impact of this research on science and inform policymakers about its societal and economic benefits, fostering a science-literate society that supports evidence-based policy

Potential Innovations and Breakthroughs may be achieved by :

- **Advancing Fundamental Research**: Push the boundaries of our understanding of fundamental physics, leading to new theories and models that can explain currently unresolved phenomena.

- **Fostering Cross-Disciplinary Innovation**: The Action will nurture a culture of interdisciplinary collaboration, enabling researchers to address complex problems from multiple angles. This approach will drive innovation and lead to possible advancements.
- **Supporting the development of advanced alert systems**: Innovate in the development of detectors and data analysis tools, potentially leading to breakthroughs in earthquake prediction and other applications.
- **Improving Societal Resilience**: Enhance the ability to predict and mitigate the impacts of seismic events, contributing to improved safety and preparedness for natural disasters.

By integrating cutting-edge research with interdisciplinary collaboration, the FuSe Action will drive significant scientific, technological, and socioeconomic progress, fostering a collaborative environment that supports innovation and societal benefit.

3.2. MEASURES TO MAXIMISE IMPACT

3.2.1. KNOWLEDGE CREATION, TRANSFER OF KNOWLEDGE AND CAREER DEVELOPMENT

The Action will focus on fostering knowledge creation, efficient transfer of knowledge, and career development through a series of structured and collaborative activities enabled by COST. The Action's working groups, through regular meetings and collaboration, will leverage expertise from various domains, including gravity, particle physics, seismology, machine learning, artificial intelligence, geophysics, data science, and experimental instrumentation, to achieve its scientific objectives. The FuSe Action will employ a multi-faceted approach to ensure **effective knowledge creation and transfer between experts of different fields**, via:

- **Online Regular Seminars** and **Annual Conferences**, and training schools. Regular online seminars (tentatively monthly) and annual conferences will be organised to share methods, techniques and results across different fields. These events will facilitate the creation of a joint vocabulary, enhancing communication among researchers from diverse backgrounds and enable collaborations.
- **Lecture notes and recordings** from the **Training Schools**, containing thoroughly and pedagogically explained common concepts from each field will play a crucial role in transferring knowledge between research domains. The lecture notes and recordings will be publicly available on the Action's webpage. Additionally, FuSe will publish the current research updates at the intersection of fundamental physics and seismology. This will help researchers stay updated with the latest methods, techniques, and findings across related fields. Involvement of young researchers and students in the Training Schools will contribute to the long-term impact of the Action by ensuring that the new generation of researchers will gain knowledge across the various interdisciplinary fields involved in the Action.
- **Short-Term Scientific Missions** (STSMs) will be a key tool for knowledge transfer, promoting direct human contact and training through collaborative research. These missions will prioritise establishing new collaborations between YRIs and experts, as well as experienced researchers and researchers from ITCs or underrepresented groups. **Internships** (via STSMs) at the SMEs, which are part of the Action, will enable transfer of knowledge to the technological sector. SMEs representatives will also be invited to be present at the Annual Conferences and online seminars ensuring two-way transfer of knowledge.
- An **online training portal** will be established on the Action's website, containing recordings of training school lectures, conference talks, and seminars. The portal will also include relevant materials such as codes, examples, presentations, and links to Action publications and related works, providing long-lasting support to FuSe members and the international community.

The FuSe Action is dedicated to fostering the **career development** of young researchers through several initiatives. FuSe will organise interdisciplinary **training schools** to expose students and early career researchers to knowledge, methods and techniques from fields not directly related to their own research topics contributing to **broadening their expertise**, expanding their skills, enabling them to excel in their fields. This will make YRI involved in the Action more **competitive** in the job market. YRI will be given opportunities to present their own work, **increasing** their **visibility.**
The multidisciplinarity of the Action and the links to SMEs will also **enhance the career prospects** of young researchers via **industry engagement.** The FuSe Action places a strong emphasis on engaging with industry, particularly SMEs that are pioneering innovative technologies in the fields of seismic monitoring and disaster preparedness. To accelerate the transfer of knowledge to the technological sector, FuSe will expand the network by other companies and start-ups working in related technological fields. Additionally, the FuSe initiative will engage with SMEs focused on applying machine learning and data science to seismic monitoring and other disaster-related challenges. By harnessing the power of

AI and big data, these companies aim to improve the accuracy of predictive models and enhance the effectiveness of real-time disaster response efforts. This industry engagement is expected to foster innovation and lead to more robust solutions for protecting communities. Company representatives will be invited to participate in annual conferences and online seminars, facilitating the exchange of ideas and initiating potential collaborations. Via STSMs at the SMEs, students and YRI will be able to **gain work experience**, making them competitive in the job market beyond academia.

By integrating these strategies, the FuSe Action aims to create a vibrant, collaborative environment that fosters innovation, facilitates knowledge transfer, and supports the career development of researchers in the field of fundamental physics and seismology.

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

The research outputs will be available in **open access platforms** (in the form of pre-prints on arXiv) and **published in** high-impact scientific **journals** with acknowledgement of the COST support. The research outputs will be disseminated on **conferences and workshops** either organised by the FuSe Action or attended by Action's members. FuSe Action will encourage all members to attend interdisciplinary international conferences and workshops to broaden the visibility of the results enabled by the Action. To promote gender balance and early career scientists as well as researchers from ITC's the preference will be given to researchers with these characteristics.

Dissemination of knowledge will be maximised throughout the network and all Action's news will be published in the **dedicated website** and **social media profiles**. All publications and events (seminars, conferences, training schools, public talks) will be listed on the webpage and publicised through social media to reach a wider and more diversified audience and to keep them informed about the Action's activities. The **recordings of conference talks, seminars and lectures** from the training schools will be linked to the webpage and shared via social media. Lecture notes from the training schools will also be freely available at the Action's website and on arXiv.

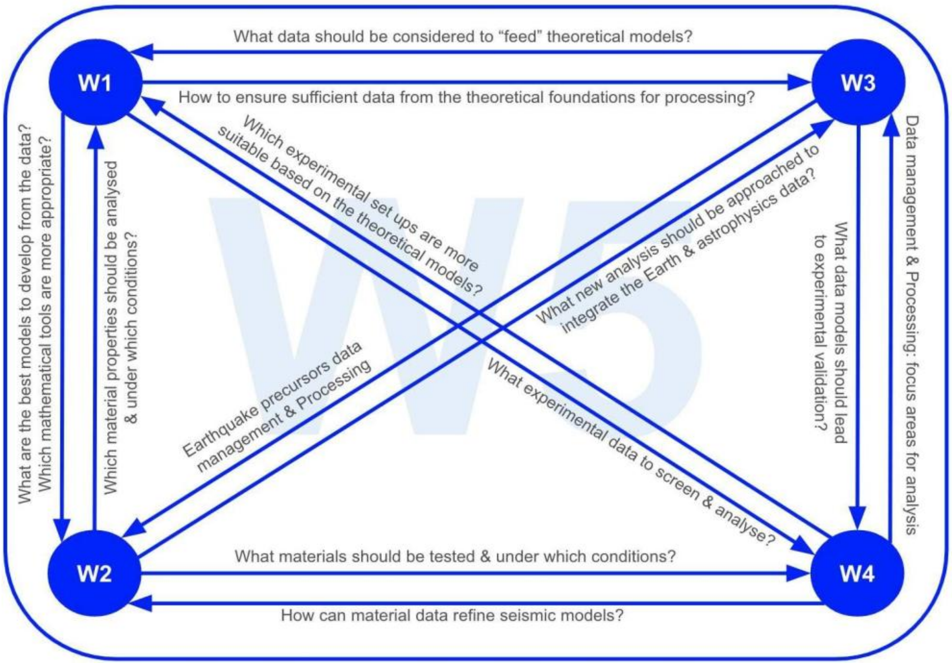
The social aspects, contributing to the **dialogue between the scientific community and the general public**, allowing **easy access to the scientific advancements** are an important part of the FuSe Action. FuSe will aim to increase awareness of the importance of integrating seismology and fundamental physics, promoting scientific research in Europe. The research findings will be disseminated to the general public via public lectures (outreach talks will be associated with the Annual Conferences), social media engagement and educational events. The members of FuSe Action will be available in their countries for contact with the media, both classical (radio, newspapers) and by novel ways of communication. The FuSe experts will use the social media presence (X, Instagram, YouTube, Facebook) to communicate to the general audience by publishing the recordings and important talks from the FuSe Action events. The Action experts will be present on local science-fairs and science-themed events. Action will also encourage the visits of FuSe experts at the local schools to inspire the young generations. To promote **gender balance and LGBTQ+ community** in science, female and LGBTQ+ members of the Action will be encouraged to present at the outreach events as well as articles, videos for the public will be collected on the Action's website and then shared through social media.

4. IMPLEMENTATION

4.1. COHERENCE AND EFFECTIVENESS OF THE WORK PLAN

4.1.1. DESCRIPTION OF WORKING GROUPS, TASKS AND ACTIVITIES

Apart from the standard COST Action structure, FuSe will introduce a Diversity and Inclusion Coordinator. The Action's structures are divided into five WGs. WG1 and WG2 focus on theoretical development, WG3 on data, and WG4 on experimental tests. WG5 promotes interdisciplinary collaboration, fostering partnerships among fundamental physicists, seismologists, and other experts, while coordinating scientific meetings. A key goal is to bridge differences in focus and terminology across disciplines.
Each WG will hold workshops, online meetings, produce publications, and participate in outreach. Annual Conferences, regular online seminars (tentatively monthly), and STSMs will strengthen communication and collaboration. The Diversity and Inclusion Coordinator, alongside WG Vice-leaders, will promote diversity, coordinate networking, and manage outreach activities through social media and educational events.



<u>WG1: Fundamental physics</u> uniting researchers focused on fundamental physics, with the goal of refining structural and thermodynamic equations, improving particle interaction models, and generating theoretical predictions based on the proposed framework. WG1 will collaborate closely with WG2 to enhance the assumptions of the "toy models" and with WG4 to effectively plan experiments and analyse existing experimental data. The key tasks of WG1 include:

- **Advancing Theoretical Frameworks for Fundamental Physics Predictions** by establishing a robust theoretical foundation for models, such as the thermodynamics of solids and liquids and the geometry of astrophysical objects.
- **Incorporating Realistic Assumptions** by developing realistic astrophysical models which requires the insights and data provided by WG2 and WG3.
- **Analysing the results from neutrino telescopes to reconstruct the Earth density profile** and compare them with existing seismological models.
- **Providing mathematical tools** in helping in development of problems arising in WG2.

<u>WG2: Planetary and stellar physics</u> bringing together researchers focused on theoretical approaches to geophysics and astrophysics, aiming to model the Earth and other celestial bodies. They will work closely with WG1 to refine the thermodynamic description of matter and develop the structural equations necessary for accurately modelling astrophysical bodies. WG2 will collaborate with WG3 and WG4, which will supply crucial data, including the ones from materials under varying pressure regimes, seismic data, and non-seismic data revealing structural changes in the Earth's composition. The key tasks of WG2 include:

- **Investigating the behaviour of various materials under perturbations** to understand potential structural phase transitions, as well as examining phase transitions in compounds that constitute the Earth's deep mantle and the cores of rocky planets. This will include studying the properties of rocks and liquids under conditions that are likely to exist on Jupiter, Saturn, exoplanets, and stellar objects.
- **To generate and implement new ideas about inverse problems**, relying on the interactions with WG3 (Big Data, AI and Machine Learning)
- **To study earthquake precursors** and provide relevant data for data management by WG3.
- **To study and develop earthquake precursors**, relevant data (geophysical, astrophysical, environmental) managed by WG3 are explored, based on physical properties and IA. As well as exploring the relationship between earthquakes at various depths within the Earth's layers and the physical properties of materials in these zones to gain deeper insights into how stress accumulates and is released within the Earth's interior.
- **To exploit deeper seismic and geodetic data to infer properties of the planetary and stellar interiors**, aided by the newly implemented tools, including IA. A better resolution of the density structure of the celestial bodies interiors require a joint inversion of seismic and geodetic data.
- **To study interactions between fluid layers and seismicity through tidal stress and surficial mass**

loading. Tidal stress and mass (un)loading are responsible for quakes on Earth. They need to be investigated on celestial bodies.

WG3: Data integration and engineering bringing together researchers specialising in data, AI, and machine learning. They will collaborate closely with all other groups, with coordination support from WG5, to integrate and process critical data—whether observational, experimental, or theoretical. Their efforts will ensure that the data is ready and accessible for use by participants in the Action for their research. WG3 will address all aspects related to the data relevant to the Action, including:

- **Data sources** from observations, experiments, and simulations, **with management handled by each WG and centralised** via a Quality Management System that oversees data lifecycles, workflows, control, security, and management.
- **A Research Data Curator**, following the “Data Repositories: Technology, Organisation and Certification” guidelines and Dataverse Curation Guide, will be used.
- Best practices will focus on **auditability, data access rules, licensing policies** (e.g., Open Data Commons or Creative Commons), **dataset timeliness, lifecycle, and quality metrics**.
- The work **aligns with European Open Science and Open Data strategies**, fostering sharing, verifiability, reproducibility of scientific outputs and FAIR-compliant data across disciplines and society.
- **Open science policies will be centralised to publish, find, and reuse data, tools, and services for research, innovation, and education**. For instance, Earth science data can be reused in Materials Science to study mineral properties under geologically relevant conditions.

WG4: Experiments, observations and instrumentation will comprise of scientists working in experimental domains. This group will collaborate closely with WG3 on data management, with WG2 on parallel earthquake observations using seismometers, and with WG1 to test various theories. The core responsibilities of WG4 include:

- **To establish and maintain close contacts with the relevant experimental collaborations**, such as IceCube, KM3NeT, Borexino, KamLAND, SNO+, JUNO, Jinping, LiquidO, Einstein Telescope, High Energy Density (HED) instrument at XFEL and High Pressure beamlines at synchrotron large facilities.
- **To conceive and develop innovative ideas for future experiments** aimed at addressing the unresolved questions in fundamental physics and seismology, with a focus on pushing the boundaries of our current understanding. This includes identifying gaps in existing research and proposing novel approaches that can unlock new insights into the complex interactions between seismic phenomena and fundamental physical forces.
- **To connect experts and utilise cutting-edge techniques** in state-of-the-art facilities like synchrotron and free electron laser beamlines, we can better simulate the harsh environments within planetary interiors. Through organised workshops, training schools, and dissemination activities, we will actively engage with both established and emerging research communities, promoting a broader understanding of the experimental possibilities.
- **To support cosmic ray data collection initiatives**, WG4 will facilitate the design and deployment of medium-sized cosmic ray detectors in seismic regions, leveraging the expertise of participating scientists. These detectors, strategically placed in seismic areas, will collect observational data continuously over several years. Through collaboration and knowledge exchange, WG4 will ensure the effective implementation of these projects, aligning with the broader objectives of FuSe.
- **New models developed by WG3 should lead to experimental validation**, paving the way for new experiments that utilise cutting-edge techniques and foster collaboration among theoretical and experimental communities from different fields.
- Development of robot based and fibre optics based novel geophysics data collections technologies
- **To follow-up Eötvös balance experiment,** especially the one related to measurement of several different material pairs with a sensitive Pekár-type balance as it is required to test the material sensitivity of the weak equivalence principle. Also the installation of an Eötvös balance network for seismological observations provides data different from seismometers.

WG5: Integration of WGs 1-4 will consist of scientists operating at the intersection of fundamental physics, geophysics, and astrophysics, both in theoretical and experimental domains. Its primary role will be to foster collaboration between all WGs and drive the development of fundamental physics and Earth models across various scales. The key responsibilities of WG5 are as follows:

- **To explore and address the questions that arise at the intersection of fundamental physics and earth science** by comparing the diverse approaches these fields have taken and developing interdisciplinary methods to tackle these challenges.
- **To analyse existing experimental results from seismic and table-top experiments**, aiming to establish the strongest constraints on models informed by fundamental physics (gravity, neutrino physics, dark matter, dark energy) and seismology, while identifying key features relevant to both fields.

- **To coordinate efforts across all WGs** in creating an online **vademecum** that comprehensively explains the essential concepts.
- **To coordinate the collaboration between all WGs and action activities.**
- **To investigate potential signatures of new physics** that may be uncovered through Big Data analysis, focusing on the detection of possible anomalies.
- **To explore the potential for developing new, specialised experimental setups** aimed at detecting possible signatures of new physics.

4.1.2. DESCRIPTION OF DELIVERABLES AND TIMEFRAME

The table below lists the Action's deliverables. The months in the first column indicate the deadline for completing each deliverable within the Action's duration (for recurring events, each month listed marks the timing of one occurrence). D - deliverable.

	Month	Deliverable	WG
D1	12	Set up of Action web page and social media	5
D2	12,24,36,48	Publication of the recordings/slides of seminars from the CA Conference	1-5
D3	12,24,36,48	Recording of a public outreach event attached to each CA Conference	5
D4	12,24,36,48	Publication of at least 8 pre-prints per year aimed at high impact, international journals	1-5
D5	12,24,36,48	Reports on STSMs successfully completed	5
D6	12,24,36,48	Coordination of inputs to an harmonised database of the existing data	2,4
D7	24,48	Publication of the recordings and lecture notes of the Training School	1-5
D8	24	Publication of an online vademecum that comprehensively explains the essential concepts and its maintenance	1-5
D9	24	Diversity and gender balance survey	1-5
D10	24,48	Coordination of inputs to a comprehensive meta-repository of standardised data and software.	3
D11	36,48	Systematic collection on theoretical models	1,2,4
D12	12,24,36,48	Data processing and management reports on the meta-repository implementation will be available internally and to the public upon approved request.	3

4.1.3. RISK ANALYSIS AND CONTINGENCY PLANS

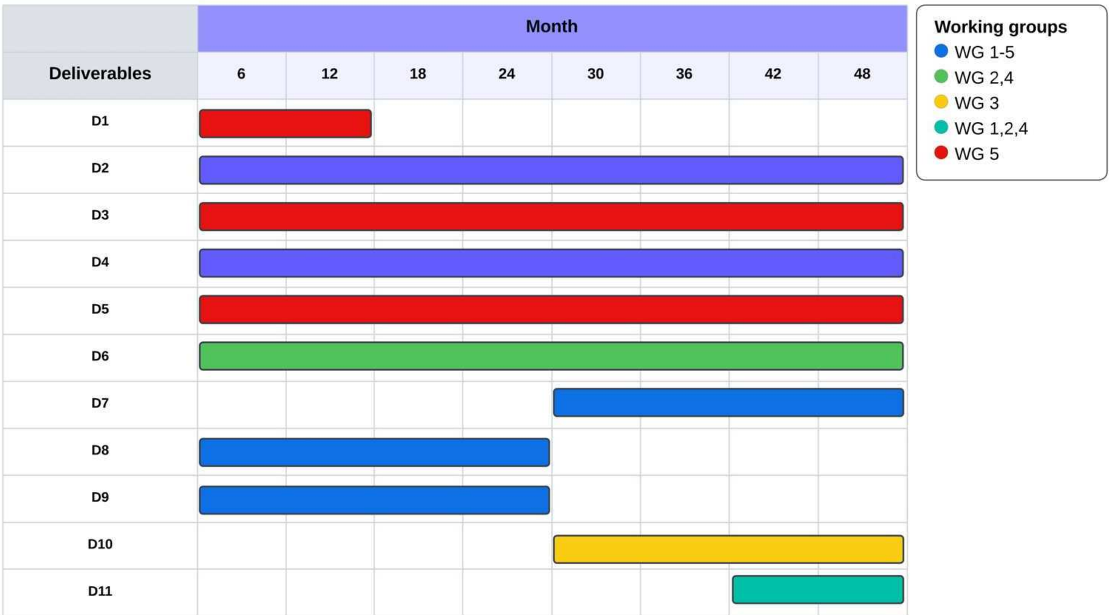
Risk	Risk level	Mitigation plan of the risk
A lack of coordination and interaction among the communities	Medium	Fostering collaboration through online meetings, joint efforts like vademecum writing, and Training School lectures, WG5 drives progress across key fields.
Travel restrictions	Medium	Online and/or hybrid meetings and training.
Delayed progress in obtaining experimental outcomes	Low	This initiative isn't a research project, so no experiments are planned, but discussions may inspire future studies. Mitigation: Pilot studies will provide preliminary data for potential follow-up projects.

Problems in implementing computational methodologies	Medium	Requirement of other methodological frameworks to be implemented.
Incomplete data and/or lack of data permission	Medium	Use of other sources of data.
Not sufficient experts to deliver the training lectures for non specialists	Low	We will train internal staff, collaborate with academic and industry partners for workshops, and invite external experts with more generalised insights.

4.1.4. GANTT Diagram

The GANTT diagram shows the duration of each activity throughout the Action timeline.

FuSe GANTT Diagram



5. REFERENCES

1. Loll et al., arXiv:2206.06762, 2022.
2. Addazi et al., arXiv:2111.05659, 2021.
3. Riess et al., AJ 116, 1009, 1998.
4. Rubin et al., AJ 159, 379ff, 1970.
5. CANTATA Collaboration, Springer International Publishing, 2021.
6. Fukuda et al. (Super-Kamiokande Collaboration), PRL 81, 1562, 1998.
7. Ballardini, et al JCAP 10 (2020) 044.
8. Volkas, arXiv:2409.09992, 2024
9. Hunter et al., Science 339, 928, 2013.
10. Luo et al, AJ 751, 16, 2012.
11. Parnell et al., PRD, 101, 122002, 2020.
12. Garcia et al., Space Sci. Rev., 215, 1, 2019.
13. Bramante et al., PRD, 101, 043001, 2020.
14. Fedderke et al., PRD, 104, 075023, 2021.
15. Arza et al., PRD, 105, 095007, 2022.
16. Leane et al., PRL, 126, 161101, 2021.
17. Raffelt et al., University of Chicago Press, 1996.
18. Benito et al., PRD, 103, 064032, 2021.
19. Wojnar, PRD, 104, 104058, 2021.
20. Kalita et al., PRD, 107, 044072, 2023.

21. Garani et al., Phys Lett. B, 804, 135403, 2020.
22. Chan et al., PRD, 102, 023024, 2020.
23. Panotopoulos et al., PRD, 101, 023017, 2020.
24. Isern et al., FSPAS, 9, 815517, 2022.
25. Aerts et al., Asteroseismology, Springer Science & Business Media, 2010.
26. Aerts RMP, 93, 015001, 2021.
27. De Ridder et al., Nature, 459, 398, 2009.
28. Andersson et al., PRL, 77, 4134, 1996.
29. Andersson et al., MNRAS, 299, 1059, 1998.
30. Kokkotas et al., MNRAS, 320, 307-315, 2001.
31. Benhar et al., PRD, 70, 124015, 2004
32. Casanellas et al., Astrophys. J. Lett., 765, L21, 2013.
33. Rato et al., MNRAS, 507, 3434-3443, 2021
34. Sotani et al. PRD, 70, 084026, 2004
35. Pratten et al., Nat.Commun., 11, 2553, 2020.
36. Bellinger et al., Astrophys.J.Lett., 887, L1, 2019
37. Saltas, et al., PRL, 123, 091103, 2019.
38. Saltas, et al., A&A, 667, A115, 2022.
39. Dziewonski, et al., Phys.Earth.Planet.Inter., 25, 297, 1981.
40. Kennett, et al., Geophys.J.Int., 105, 429, 1991.
41. Kennett, et al., Geophys.J.Int., 122, 108, 1995.
42. Seager, et al. AJ, 669, 1279, 2007.
43. Weppner, et al., MNRAS, 452, 1375, 2015.
44. Umemoto, et al., Science, 311, 983, 2006.
45. van der Hilst, et al., Nature, 386, 578, 1997.
46. Zhao, Earth.Planet.Sci.Lett., 192, 251, 2001.
47. Piromallo et al., J.Geophys.Res., 108, 2065, 2003.
48. Ritsema et al., Geophys.J.Int., 184, 1223, 2011.
49. Schivardi et al., Geophys.J.Int., 185, 469, 2011.
50. Zhu et al. Nat., Geosci., 5, 493, 2012..
51. Auer et al., J.Geophys.Res. Solid Earth, 119, 3006, 2014.
52. Li et al., Geophys.Res.Lett., 47, e2019GL086856, 2020.
53. Bezada M. J., et al., J.Geophys.Res.: Solid Earth, 128, e2023JB027299, 2023.
54. Stuart Acta Numer., 19, 451, 2010.
55. Bui-Thanh et al., SIAM J. Sci. Comput., 35, A2494, 2013.
56. Cui et al., Geophys.J.Int., 239, 478, 2024.
57. Akhmedov et al., JHEP, 06, 053, 2005.
58. Donini et al., Nat. Phys., 15, 37, 2019.
59. Bellini et al., Riv.Nuovo.Cim., 45, 1, 2021.
60. Agostini et al., PRD, 101, 012009, 2020.
61. Abe et al., Geophys.Res.Lett., 49, e2022GL099566, 2022.
62. Andringa et al., Adv.High Energy Phys., 2016, 1, 2016.
63. Abusleme et al., Prog. Part. Nucl. Phys., 123, 2022.
64. Olmo et al., Phys. Rept., 876, 1-75, 2020.
65. Pachol et al., EPJC, 83(12), 1097, 2023.
66. Wojnar, PRD, 107, 044025, 2023.
67. Riasat et al., EPJ Plus, 138, 1, 2023..
68. Kozak et al., PRD, 104, 084097, 2021.
69. Kozak et al., Universe, 8, 3, 2021.
70. Kozak et al., PRD, 108, 044055, 2023.
71. Aguiar et al., JCAP, 01, 011, 2024.
72. Pachol et al., Class.Quant.Grav., 40, 195021, 2023.
73. Wojnar et al., Phys.Lett.B, 850, 138494, 2024.
74. Murakami et al., Nature, 485, 90, 2012
75. Gréaux et al., Nature, 565, 218, 2019.
76. Davarpanah et al., Geomech. Geophys. Geo-Energy Geo-Resources, 6, 29, 2020.
77. Ván et al., Eur. Phys. J. Spec. Top., 228, 1693, 2019.
78. Amann et al., Rev. Sci. Instrum., 91, 094504, 2020.
79. Tóth et al., Int. Conf. Precision Phys. Fundamental Phys. Constants—FFK2019, 9, 14, 2019.
80. Fischbach et al., Proceedings of International Conference on Precision Physics and Fundamental Physical Constants — PoS(FFK2019), 2019.
81. Fischbach et al., PLA, 399, 127300, 2021.

82. Eötvös et al., Ann. Phys., 373, 11, 1922.
83. Will, Liv.Rev.Relat., 17, 1, 2014.
84. Völgyesi et al.,arXiv:2202.09607, 2022.
85. Stray et al., Nature, 602, 590, 2022.
86. Antoni-Micollier et al., Geophys.Res.Lett., 49, e2022GL097814, 2022
87. Lanzagorta et al., Radar Sensor Technol. XX, 9829, 423, 2016.
88. Storchak et al., Seismol. Res. Lett., 84, 810, 2013.
89. Stucchi et al., J. Seismol., 17, 523, 2013.
90. Vallée et al., Science, 358, 1164, 2017.
91. Homola et al., J. Atmos. Solar-Terr. Phys., 247, 106068, 2023.
92. Schaeffer et al, Geoph.J.Inter., 211, 1, (2017), 1–29.
93. Daley et al., Leading Edge, 32, 699, 2013.
94. Bonsignorio, In: 50 years of artificial intelligence, 112, Springer, 2007.
95. Bonsignorio, 1st Conf. Mach. Learn. GW, Geophys., Robotics, 2019.
96. Castillo et al., Rev. Mex. Fis., 4, 021123-1, 2023