AstroParticle Observatories and GEoscience Innovation Actions

APOGEIA

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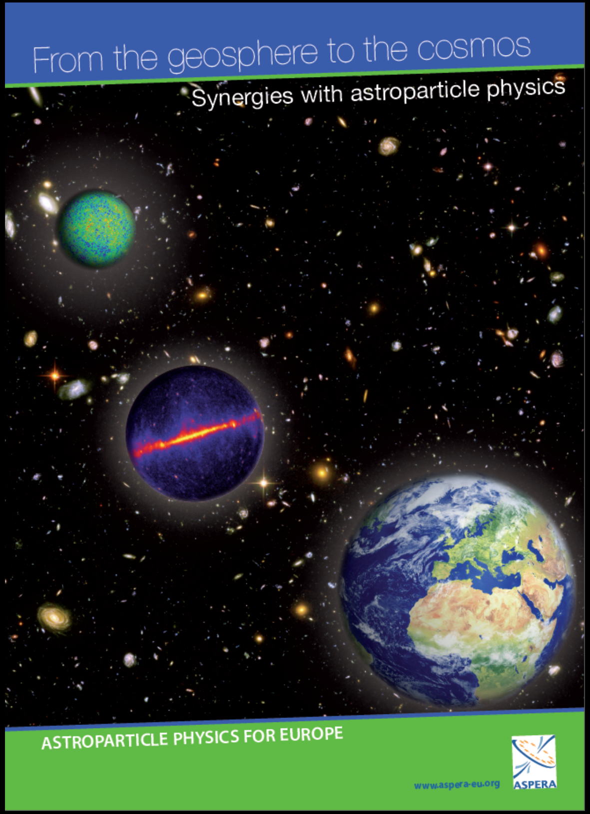
29 April 2022

The origins of the APOGEIA proposal

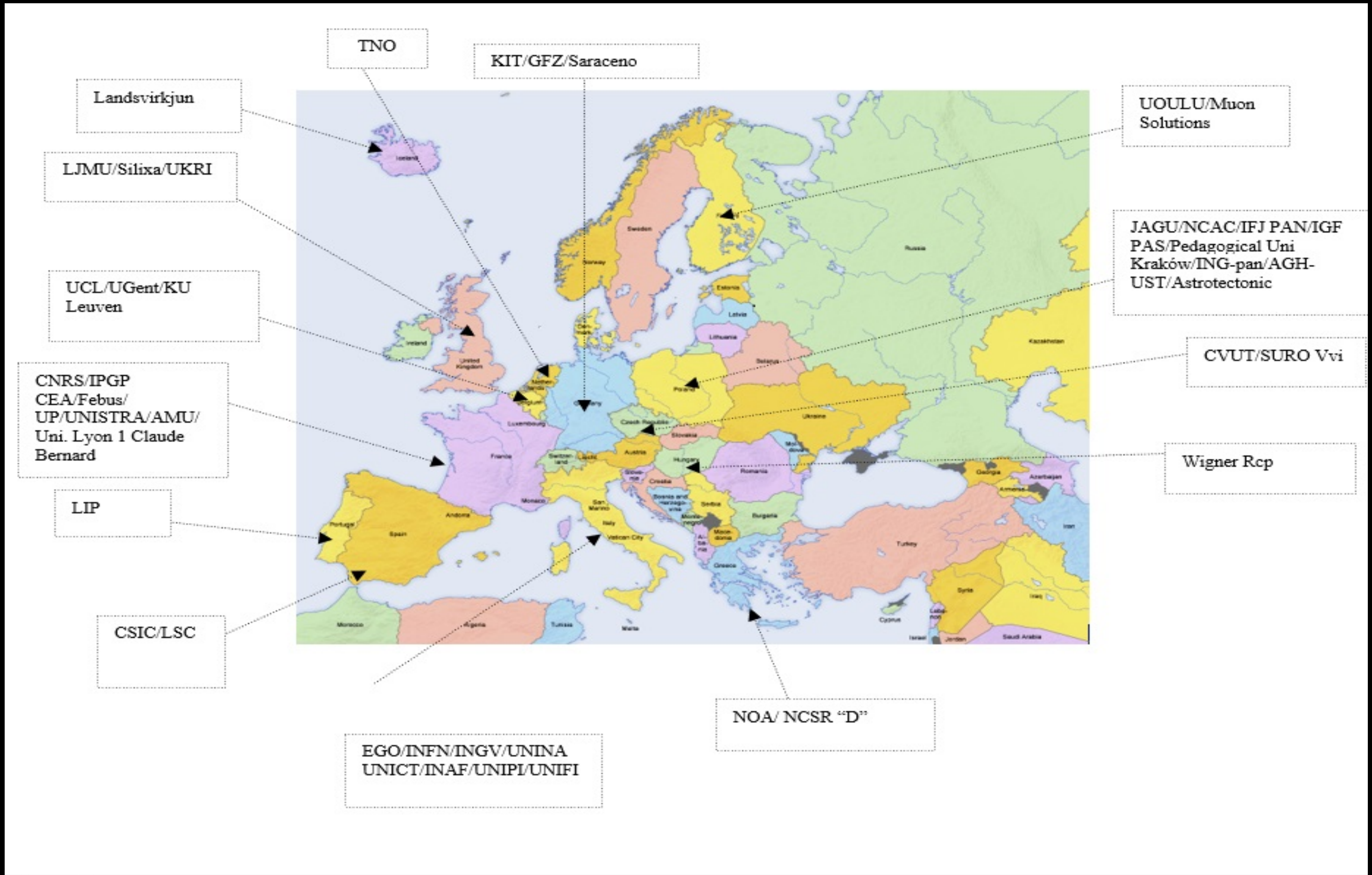
- On February, 11-12 2019 GEO.8, APPEC and the Academia Europaea organized the Workshop on Observatory Synergies for Astroparticle Physics and Geoscience at the Institut de Physique du Globe de Paris (IPGP) (https://indico.in2p3.fr/event/18287/). The aim was to discuss the scientific and technical overlapping topics of the astro and geo communities and to promote a common strategy for the future. It is also important to note that ASPERA/APPEC had organised three workshops in the period 2011-2012 and a brochure (From the Geosphere to the Cosmos) had been prepared in order to address and develop synergies between astroparticle physicists and geoscientists.
- Among the findings: Earth and Astroparticle sciences share a mutual scientific culture based on common objects of study, methods and approaches. First, the Geosphere, a direct object of study of Geoscientists, is both the target and the detecting medium for Astroparticle observatories. Second, Astroparticle Physicists and Geoscientists both deal with complex natural large scale systems, deploy large sensor networks, sometimes in extreme environments (sea, desert, underground, space), use long series of precise observations acquired over long time scales. They also use large infrastructures, which allow for fast and massive data manipulation and worldwide networking, including distribution of alert. Both develop techniques of monitoring, new technologies new deep and machine learning tools.

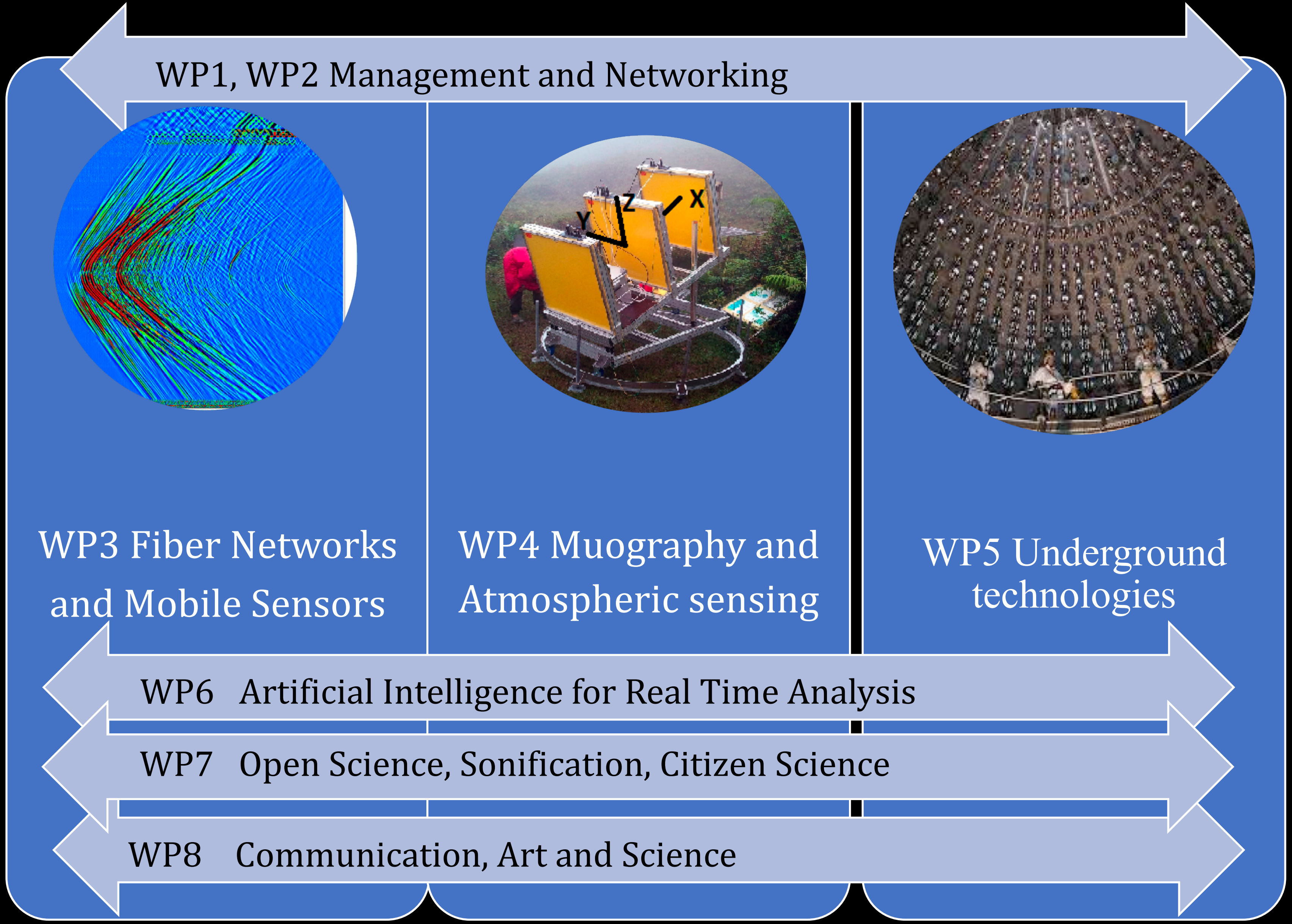


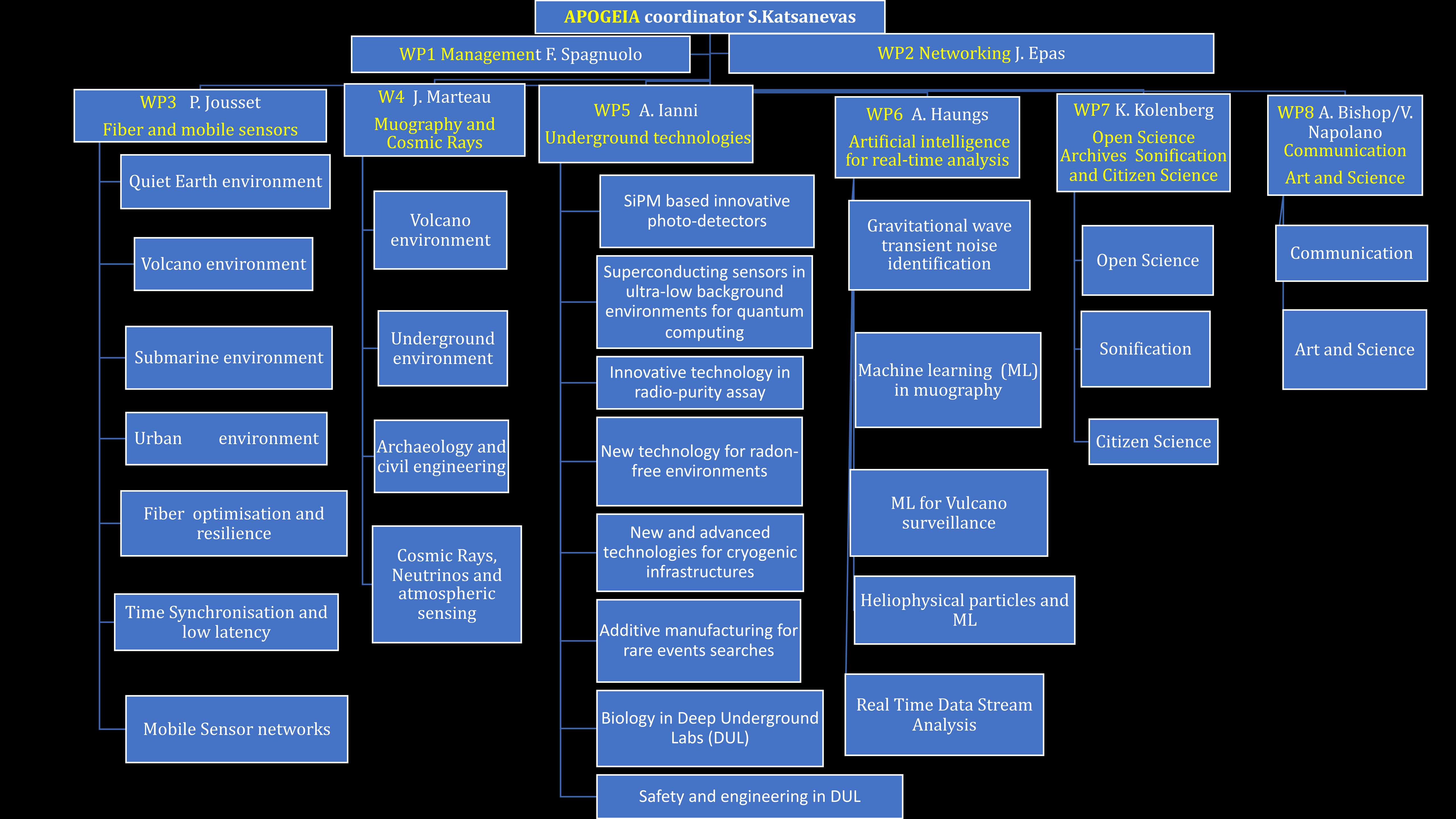
- In order to realize ambitious collective projects, the APPEC, GEO.8, Academia Europeae representatives recommended the development of a roadmap for the upcoming years.
- Then the pandemic came in March 2020, and given the lockdown, it was possible to prepare the first APOGEIA proposal to EU in one month and a half as an Integrated Activity. The proposal raised a lot of enthusiasm, in the community, but was rejected by the EU. It created a precedent, a community and an obligation to continue.

Université Catholique Louvain (UCL)	Belgium
Universiteit Gent (UGent)	Belgium
Katholieke Universiteit Leuven (KU Leuven)	Belgium
Ceske Vysoke Uceni Technicke V Praze (CVUT)	Czechia
Statni Ustav Radiacni Ochrany (SURO v.v.i.)	Czechia
University of Oulu (UOULU)	Finland
Muon Solutions Oy	Finland
Commissariat a l’energie atomique et aux énergies alternative (CEA)	France
Institut de Physique du Globe de Paris (IPGP)	France
Centre National de la Recherche Scientifique (CNRS)	France
Université Paris Cité (UP) (Affiliated)	France
Université de Strasbourg (UNISTRA) (Affiliated)	France
Université D’Aix Marseille (AMU) (Affiliated)	France
Université Lyon 1 Claude Bernard (Lyon) (Affiliated)	France
Febus Optics	France
Karlsruher Institut für Technologie (KIT)	Germany
Helmholtz Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ)	Germany
Studio Tomás Saraceno GmbH (Studio Saraceno)	Germany
National Observatory of Athens (NOA)	Greece
National Center for Scientific Research – Demokritos (NCSR “D”)	Greece
Wigner Fizikai Kutatokozpont (Wigner RCP)	Hungary
Landsvirkjun	Iceland
European Gravitational Observatory (EGO) (Coordinator)	Italy
Istituto Nazionale di Geofisica e Vulcanologia (INGV)	Italy
Università degli Studi di Napoli Federico II (UNINA)	Italy
Istituto Nazionale di Astrofisica (INAF)	Italy
Istituto Nazionale di Fisica Nucleare (INFN)	Italy
Università degli Studi di Catania (UNICT)	Italy
Università di Pisa (UNIPI)	Italy
Università di Firenze (UNIFI)	Italy
Nederlandse Organisatie Voor Toegepast Natuutwetenschappelik Onderzoek (TNO)	Netherlands
Uniwersytet Jagielloński (JAGU)	Poland
Centrum Astronom. Im. Mikołaja Kopernika Polskiej Akademii Nauk (NCAC)	Poland
The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Science (IFJ PAN)	Poland
Astrotectonic (Affiliated)	Poland
Instytut Geofizyki Polskiej Akademii Nauk (IGF PAS)	Poland
Pedagogical University of Krakow	Poland
Instytut Nauk Geologicznych Polskiej Akademii Nauk (ING-PAN)	Poland
Akademia Gornico-Hutnicza Im. Stanislava StaszicaW Krakowie (Agh / Agh-ust)	Poland
Laboratorio de Instrumentacao e Fisica Experimental de Particulas (LIP)	Portugal
Consejo Superior de Investigaciones Científicas (CSIC)	Spain
Consorcio para el equipamiento y Explotación del Laboratorio Subterráneo de Canfranc (LSC)	Spain
Silixa LTD	UK
Liverpool John Moores University (LJMU)	UK
United Kingdom Research and Innovation (UKRI)	UK

NEW APOGEIA as INFRATECH 45 partners of which 7 companies from 14 European countries

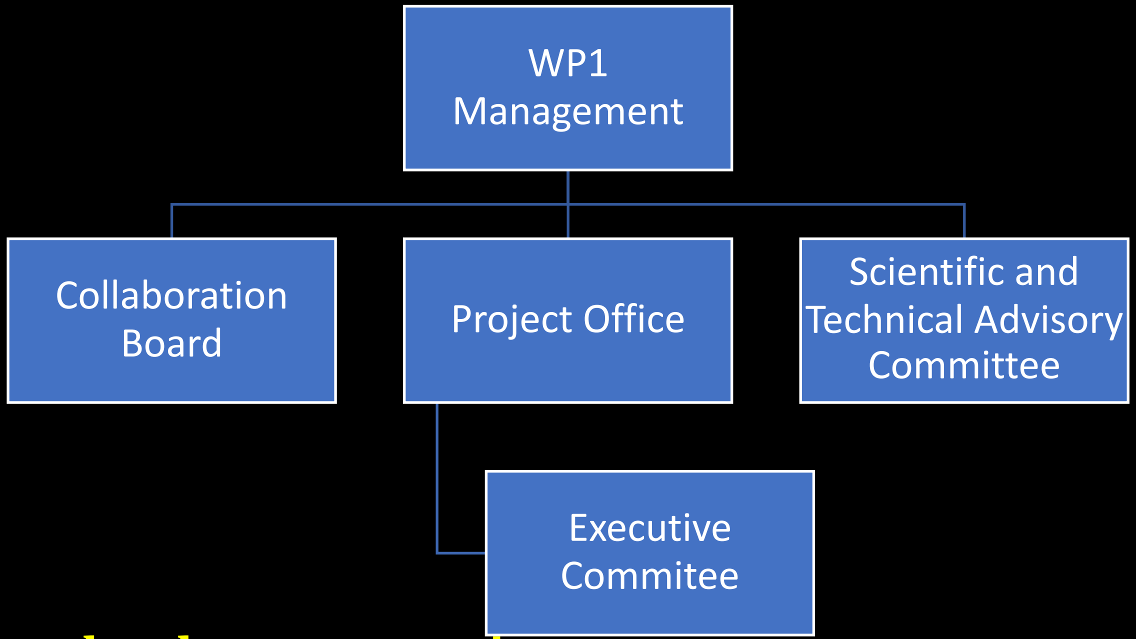



WP1, WP2 Management and Networking
Y
Z
X
WP3 Fiber Networks and Mobile Sensors
WP4 Muography and Atmospheric sensing
WP5 Underground technologies
WP6 Artificial Intelligence for Real Time Analysis
WP7 Open Science, Sonification, Citizen Science
WP8 Communication, Art and Science


APOGEIA coordinator S.Katsanevas
WP1 Management F. Spagnuolo
WP2 Networking J. Epas
WP3 P. Jousset
Fiber and mobile sensors
Quiet Earth environment
Volcano environment
Submarine environment
Urban environment
Fiber optimisation and resilience
Time Synchronisation and low latency
Mobile Sensor networks
W4 J. Marteau
Muography and Cosmic Rays
Volcano environment
Underground environment
Archaeology and civil engineering
Cosmic Rays, Neutrinos and atmospheric sensing
WP5 A. Ianni
Underground technologies
SiPM based innovative photo-detectors
Superconducting sensors in ultra-low background environments for quantum computing
Innovative technology in radio-purity assay
New technology for radon-free environments
New and advanced technologies for cryogenic infrastructures
Additive manufacturing for rare events searches
Biology in Deep Underground Labs (DUL)
Safety and engineering in DUL
WP6 A. Haungs
Artificial intelligence for real-time analysis
Gravitational wave transient noise identification
Machine learning (ML) in muography
ML for Vulcano surveillance
Heliophysical particles and ML
Real Time Data Stream Analysis
WP7 K. Kolenberg
Open Science Archives Sonification and Citizen Science
Open Science
Sonification
Citizen Science
WP8 A. Bishop/V. Napolano
Communication
Art and Science
Communication
Art and Science

WP1 Management

- **Oversight**
  - **Collaboration Board (Partners)**
  - **STAC (10 Independent experts)**
- **Executive**
  - **Project Office (APOGEIA Coordinator+ Project officer + Project Scientist)**
  - **Executive Office (WP leaders+ PO)**



WP2 Networking , 5 Workshops on best practices and technology concerning

1. Large sensor networks for locating multiple sources of signal noise. On the scientific part, we aim, at one hand, at better understanding the Earth System and on the other hand, characterizing sea, seismic and atmospheric sources will be crucial for the next generation of Astroparticle Physics Infrastructures. Also, R&D towards better sensitivity, with better timing techniques, including a proper integration of clock network service
2. European Underground Laboratories, promoting the dialogue within the European underground laboratories, international infrastructures and industry with the scope to develop a roadmap towards a full alignment of standards, opportunities for economies of scale, radioactivity free environments for science and society, CO_2 capture and storage techniques , hyper-sensitive quantum sensors.
3. Muon Tomography and atmospheric monitoring networks to maximize scientific return for Geoscience and Astrophysics communities.
4. Machine and Deep learning techniques to all the above technology fronts.
5. Multimodal characterization of sites (fiber, mobile sensors, underground technologies, machine learning)

WP3 Fibers and Mobile sensors I

1. **"Quiet Earth environment".** Test the capability of various fibre optic instrumentation (interrogators) in quiet environments in order to reach the ultimate performance of fibre optic technologies. Use underground laboratories such as LSBB (France) and BFO (Germany).
2. **"Volcano environment".** Take advantage of the new interrogators, of existing infrastructure and deploying new fibres for Energy and Hazard societal objectives. Iceland and Italy are chosen targets. (Krafla KMT, Stromboli, Etna)
3. **"Deep ocean and submarine environment"** Design, assembly and integration of a hydrophone array based on fibre laser optics in Southern Greece, KM3Net
4. **"Urban environment"** A recently acquired DAS dataset in the city of Barcelona will be used to identify the best strategies to efficiently process noisy DAS data, serving as a benchmark for future implementations. Three experiments will be dedicated to record long periods of noise along different portions of the optic fiber telecommunication network in the Lyon metropole area. We will use the DAS data obtained underneath urban areas such as the metropolitan area of Athens, to achieve spatially continuous site characterization and consequently improve seismic hazard assessment in urban environments. DAS datasets already (2019) acquired in urban environments on Mount Etna eastern flank will be analysed in order to search for potential faults associated with Etna tectonic activity.
5. **"Infrastructure and space environments"** Test and calibrate antenna with engineered cable at EGO/Virgo. Deploy an EFDAS antenna consisting of two 3 km long EFDAS fiber cables disposed in an L form along the interferometric arms and a perpendicular borehole below the central building at the corner of the L at Virgo. Measure of the seismic, acoustic and Newtonian noise of the detector, in view of the next 10-15 years of Virgo and the third generation GW interferometer (Einstein Telescope). EFDAS portability and space TRL for Moon future mission. Fiber network coordination, data availability, engagement and inclusion issues.

WP3 Fibers and Mobile sensors II

6. **Network Synchronisation and time/frequency distribution.** Explore the capacity of ultra-stable optical frequency dissemination and ultra-high-performance time transfer with sub picosecond resolution. Study how high-performance synchronization and syntonisation methods could contribute to strengthen the detection capacities of large baseline interferometers, for astrophysics observation and geophysics experiments. Dissemination of time and frequency reference to astroparticle sites, e.g. EGO, Gran Sasso and KM3Net (2 sites in Sicilia and South of France), where a network extension would be needed. Underground laboratories as Gran Sasso, Black Forest Observatory, and Canfranc will be considered for a paper study and implementation roadmap. Studies of demonstration of a new array of sensor, connecting together by fiber optical clocks, microwave clocks, and absolute gravimeters, in a noisy urban environment.

7. **Mobile sensors networks.** Preparation and testing of a swarm of sensors with control software. The single mobile platform will contain several sensors, including seismic and infrasound acoustic sensors, magnetic field sensors, temperature, humidity, and CO_2 concentration probes. A local GPS repeater will be necessary to ensure time tagging in indoor environments like experimental buildings (EGO) or underground caverns (deep inside a mine Sos Enattos mine or ex-railway tunnel Canfranc Underground Astroparticle Laboratory) where seismic noise will be studied. The mobile platform will be useful for several tasks: monitoring seismic and environmental noises in gravitational wave detector sites, optimization and reconfiguration of sensor networks, monitoring structures, monitoring conditions at hardly accessible locations. Aslo , mobile High Sensitivity Gravity Gradiometers, e.g. portable Eötvös-type gravity gradiometers with 1-0.01E sensitivity.

WP4 Muography and Atmospheric sensing I

1. **Volcano Muography** of active European volcanoes. These range from quiescent volcanoes such as Vesuvius, Snaëffelsjökull and La Soufriere, to open-conduit volcanoes such as Etna, and Stromboli. It also includes a muography of Sakurajima volcano in Japan.

2. **Underground Muon tomography.** Build a network of complementary underground facilities, allowing different muon tomography actors and attain a large spectrum of educational/research/industrial goals in the field of subsurface monitoring. Lousal mining museum (LMM, Portugal, -20m); Laboratoire Souterrain à Bas Bruit (LSBB, France, -518m). ; Laboratorio Subterraneo de Canfranc (LSC, Spain, -780m).; Callio lab. (CL, Finland, –1.430m). Operation of muon hodoscopes (with technology benchmarking: TPC, RPC, scintillators, emulsions) for underground density mapping, performance assessing, methods benchmarking and geophysical prospection. Operation of a network of 20 autonomous detectors for monitoring the critical zone hydrodynamics towards sustainable groundwater management. Development of joint analysis methods using CR detection and DAS measurements in complement to gravimetry and ERT. Long-term study of the hydrogeological dynamics, the groundwater dynamics, the underground infrastructure stability, the Newtonian noise characterization for the future ET experiment.

3. **Archaeology & civil engineering.** Applicability of various technologies in the most relevant (underground, surface-based) scenarios. Case examples Napoli sites, Surface-based archeological targets: Manfredonic castle at Mussomeli (Sicily). Mining industry relies on the full understanding of the large scale environment and infrastructure of the site. This includes monitoring, characterization (evaluation of the rock stability), prospecting (actual mineralization or boundary discovery). Civil engineering and construction industry. The building stability monitoring system, called MONRAD, allows long term, low cost high precision geometric referencing, even in very complicated historically relevant structures. Case examples are historical buildings, additional applications in dams, bridges.

WP4 Muography and Atmospheric sensing II

4. **Cosmic Rays, Neutrinos & Atmospheric sensing.** Cosmic-Ray Detectors at adv.Virgo, as part of a future monitoring system at Einstein Telescope. Effect of electron precipitation on the atmosphere: Investigate the feasibility of using precipitating electron populations as a proxy for changes in related atmospheric measurements. Use of broad-band seismometers to monitor geomagnetic phenomena. Although this sensitivity has been regarded as a problem by seismologists, it can be turned into an opportunity to better monitor space weather, as in many areas, the number of available seismic stations is larger than for magnetometers.Development of mathematical analysis tools for cosmic ray/earthquakes (CR/EQ) correlation and CR monitoring - Early Warning System of EQs.

5. **Earth tomography with atmospheric neutrinos and seismic data.** Neutrinos providing tomographic information on the innermost Earth layers (mantle and core). The advent of a new generation of large-scale neutrino Cherenkov telescopes such as KM3NeT and IceCube, that will accumulate unprecedented samples of atmospheric neutrinos, has finally brought this idea into a concrete possibility that may be investigated with real data. Neutrino tomography can be combined with seismological data to provide new insights on the matter density and composition of the mantle and core, whose 3D profile is difficult to infer from seismic information only.

WP5 Underground Technologies

1. **S**iPM based innovative photo-detectors (see talk by A. Razetto)
2. Superconducting sensors in ultra-low background environments for quantum computing (see talk by JP. Mosquera)
3. Innovative technology in radio-purity assay (see talk of P. Scovell)
4. New technology for radon-free environments (see talk by C. Vescovi)
5. New and advanced technologies for cryogenic infrastructures (see talk by P. Gorla)
6. Additive manufacturing for rare events searches (see talk by S. Piro)
7. Biology in DULs (see talk by CP. Garay)
8. Safety and engineering in DULs (see talk by P.Rosu)

WP6 Artificial Intelligence for Real Time Analysis

Use advanced techniques and concepts for real-time analyses, using optimized infrastructures and software, such as deep-learning techniques, and existing data streaming systems (like e.g., apache kafka), up to tests on ad hoc hardware for triggering systems (e.g. at an FPGA). We will develop AI pipelines with 2 main different input data: image based and time series based.

1. **Gravitational Wave transient noise identification** Find correlation between GW transient noise signal and events identified by seismic or cosmic ray sensors in real time.
2. **Machine-Learning enhancement of muography.** Exploit ML in classification problems (muons vs fakes), regression problems (momentum inference), imaging, and forecasting. The momentum of the muons will be determined via a multivariate regression. At a higher analysis level, density inference, e.g. for 3D muography as well as forecasting of eruptions or other dynamic geophysical phenomena will be performed by ML via the combination of muography data with other geophysical inputs such as gravimetry and seismo-tomography.
3. **Machine learning for vulcano surveillance with fiber optics**. ML algorithms will be implemented for the data analysis of DAS systems to reduce the size of informative datasets, to denoise the raw data, to automatically identify and classify patterns associated with discrete natural and anthropogenic events. The outcomes will complement volcano event detection and classification with implications for volcanic hazard assessment.
4. **Heliophysical particles and machine learning** This task will explore measurements of heliophysical particles from multiple spacecraft, considering their temporal changes, and develop machine learning infrastructure to monitor and nowcast their evolution in the near-Earth space environment.
5. **Real Time Data Stream Analysis.** Analysis of the correlation between cosmic rays and seismic disturbances by use of deep learning methods to analyze archival and real-time data to search for anomalies in cosmic-ray data eventually correlated with seismic activity.

WP7 Open Science Archive, Sonification and Citizen Science

1. **Creation of Astroparticle and Geoscience Open Science Centre.** We will create the AGOSC virtual site profiting also from our experience in the EU funded ESCAPE and H2020 projects in which many of the partners participate. Data from underground laboratories will be also added. In more detail the objectives of this task will aim at: an agreement on sharing data between communities from the mentioned data source; agreement on a standardisation of data and metadata formats to allow interoperability of data; common data platform and common analysis tools for educational examples. Deliverables: **Web Site, Data Platform, Tools to accompany the users**
2. **Sonification.** This task will integrate into the analysis of the information the auditory model of auditory salience, neurological mathematical models designed to dampen noise, and audio visualization. This will subsequently be applied to the identification of gravitational waves and other astroparticle and seismic measurements. At EGO we have been working on the design of perception experiments for which we are gathering results right now (e.g., a multisensorial telescope including sound and haptic next to vision). IFJ/PAN is studying a possible matching sonification and the concept of cosmic ray detection with smartphones being practiced within CREDO. We will create a **sound search database**, that will allow scientists and the general public to retrieve data in ranges of auditory parameters to then import it into other software of their preference for further analysis.
3. **Citizen Science.** The members of the APOGEIA consortium have a rich experience on citizen science, having produced four programs already: (1) on Gravitational waves (Virgo), (2) on underwater neutrinos (KM3NET), (3) on pulsating stars and (4) on cosmic rays embedded in the global citizen science portal Zooniverse (REINFORCE) using both visual and acoustic data and analysis. In this context we develop, in a collaboration with the world-renowned blind astronomer Dr. Wanda Merced-Diaz, a program of sonification of astronomical and environmental data permitting visually impaired citizens to participate to the adventure of science, but also in return augment the discovery potential of gravitational wave research by the inclusion of new sensorial (acoustic) data. In the context of APOGEIA, we will extend the citizen science ways of participation to underground laboratory science and the sites that will be monitored through the new networks that will be supported by APOGEIA (fibers, cosmic rays, underground laboratories).

WP8 Communication , Art and Science

- Shape the emerging new cultural horizon with multiple initiatives and actions, which will be mutually reinforcing:by (a) Informing and engaging the general public, students and educators about the background and recent discoveries in the exciting scientific interface between Geoscience, Astroparticle Physics, Multimessenger Astronomy; b) introducing innovative tools to inform and engage the general public, students and educators on the impact on society of science at the interface between these two fields and their possible scientific convergence; c) promoting the value of innovative dialogues between the knowledge of Geoscience and Astroparticle Physics and Multimessenger Astronomy with Traditional Environmental Knowledge (TEK) and interdisciplinary research in distributed, participatory and nonhuman sensing, towards data sharing and collaboration between indigenous researchers, scholars in the applied humanities and fundamental sciences; d) inspiring young people to follow careers in astrophysics and geosciences; e) promoting the profound innovative value of the convergence of different skills and disciplines, as well as the worldwide collaboration through people, resources and cultures from different countries.

- In addition, a special program of participatory Art and Science activities and actions will be carried out, which brings the research of APOGEIA into dialogue with IK/ TEK and participatory practices of planetary and citizen sensing. The world-famous artist Tomás Saraceno — who has exhibited a constant attention to both fundamental science and to the risks and human impact on the Geosphere and environment — will lead this special program for attracting the attention and engaging the public at large on the new cultural horizon of APOGEIA. Various digital tools, interdisciplinary artistic methods, apps, online and in person exhibitions and other creative tools will be used. Other artists have already expressed their willingness to contribute. Some of these focus on how the insertion of research infrastructures in a specific environmental context generates new cognitive and aesthetic perspectives, unexpected connections, as well as new information about the context that hosts them. (Donald Fortescue, Tim Otto Roth Carol Müller)

In summary:

Fiber and mobile sensors	Muon and particle detectors	Underground technologies (cryogenic, cold atom, quantum) and environments (low vibrational and radioactive noise)

- Multiprobe prospective of sites (Volcanoes, Underground,sea, Research Infrastructures, urban)
- Distributed multiple intelligent sensors in hostile environments
- Low latency networks of sensors for astroparticle signals and climate alerts
- TRL range from very high, to lower and a promising industrial future
- Extreme synchronisation and advanced sensor R&D (Cryogenic, Quantum , Cold Atom)
- Atmosphere/Geosphere correlations through seismicity/CR particles
- Machine and deep learning synergies
- Climate change , natural catastrophes, cosmological studies and planetary missions
- Multisensorial possibilities (sonification), citizen's science, Art and Science

RQ: Even if the proposal is rejected, isn't it it a common effort worth pursuing ?