COST
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Brussels, 23 June 2017

COST 025/17

DECISION

Subject: **Memorandum of Understanding for the implementation of the COST Action "The multi-messenger physics and astrophysics of neutron stars" (PHAROS) CA16214**

The COST Member Countries and/or the COST Cooperating State will find attached the Memorandum of Understanding for the COST Action The multi-messenger physics and astrophysics of neutron stars approved by the Committee of Senior Officials through written procedure on 23 June 2017.

COST
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

MEMORANDUM OF UNDERSTANDING

For the implementation of a COST Action designated as

COST Action CA16214
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS (PHAROS)

The COST Member Countries and/or the COST Cooperating State, accepting 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 (the 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 new document amending or replacing them:

a. "Rules for Participation in and Implementation of COST Activities" (COST 132/14);
b. "COST Action Proposal Submission, Evaluation, Selection and Approval" (COST 133/14);
c. "COST Action Management, Monitoring and Final Assessment" (COST 134/14);
d. "COST International Cooperation and Specific Organisations Participation" (COST 135/14).

The main aim and objective of the Action is to tackle key challenges in the physics involved in neutron stars by facing them via an innovative multi-disciplinary approach, spanning astrophysics, gravitational and nuclear physics. This will be achieved through the specific objectives detailed in the Technical Annex.

The economic dimension of the activities carried out under the Action has been estimated, on the basis of information available during the planning of the Action, at EUR 80 million in 2016.

The MoU will enter into force once at least five (5) COST Member Countries and/or COST Cooperating State have accepted it, and the corresponding Management Committee Members have been appointed, as described in the CSO Decision COST 134/14.

The COST Action will start from the date of the first Management Committee meeting and shall be implemented for a period of four (4) years, unless an extension is approved by the CSO following the procedure described in the CSO Decision COST 134/14.

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TECHNICAL ANNEX

OVERVIEW

Summary

The recent discovery of gravitational waves will allow in the following years an unprecedented view of previously invisible parts of the Universe. This will unravel the physics of the most compact stars, the neutron stars, which are unique objects whose emission encompasses all the available multi-messenger tracers: electromagnetic waves, cosmic rays, neutrinos, and gravitational waves. These relativistic stars are also unique laboratories where not only the most extreme gravity and electromagnetism can be probed, but also the strong and weak interaction can be studied in regimes that have no hope of being explored on Earth.

The study of these objects transcends the traditional astrophysical approach and requires a multidisciplinary effort that spans from particle and nuclear physics to astrophysics, from experiment to theory, from gravitational waves to the electromagnetic spectrum. PHAROS has the ambitious goal of attacking key challenges in the physics involved in neutron stars by facing them via an innovative, problem based approach, focussing on current, and new, data and experiments, and that hinges on interdisciplinary Working Groups. Each group will have all the diversified expertise that is needed to tackle different aspects of the data and physics of neutron stars, and will deliver to the different communities several tools and deliverables prepared in a shared language. Furthermore, a key priority of this Action is promoting via training, mobility, gender and outreach activities, enthusiastic students and young researchers that will grow and spread the Action's innovative multi-disciplinary approach, with a special attention of promoting Inclusiveness Target Countries.

Areas of Expertise Relevant for the Action	Keywords
● Physical Sciences: Nuclear astrophysics (theory) ● Physical Sciences: Astrophysics, astronomy, space sciences ● Physical Sciences: Gravitational astronomy ● Physical Sciences: Relativistic astrophysics ● Physical Sciences: High energy and particles astronomy, X-rays, cosmic rays, gamma rays, neutrinos	● compact objects ● gravitational physics ● nuclear and subnuclear physics ● relativity ● astrophysics

Specific Objectives

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

Research Coordination

● The Action will aim at answering how can the neutron star Equation of State (EoS) be investigated with different astrophysical and gravitational observations. Answering this question requires the communities to interact with nuclear physicists to set standard parameters for different EoS species to be implemented in astrophysical and gravitational simulations.

● The Action will aim at answering how can transport phenomena in neutron stars be modelled after or during their formation, also accounting for superfluidity and superconductivity, consistently with the EoS.

● The Action will aim at answering which different gravitational signals are expected from different neutron star systems, and how can they be characterized with real observables, and distinguished from other gravitational wave emitters.

● The Action will aim at answering how does the magnetic field evolve in isolated and accreting systems, how do turbulence and instabilities affect field formation and evolution and how does this affect the neutron star populations that we observe today.

● The Action will aim at answering how can the physics of neutron stars be tested by studying their interaction with the local environment, how can jets be launched in different neutron star systems or progenitors, as well as how can plasma physics in high-field regimes be modelled.

Capacity Building

● Promote the interaction, and deliver common tools, between close communities interested in the same astrophysical objects from very different but complementary research approaches.

● Train a young generation of students to a multi-disciplinary approach in their research activity, and help them grow and develop a shared language among close communities.

● Encourage young women and early career researchers to take leadership roles in PHAROS, and provide young science students with young and senior women as role models. This has an extreme importance especially given the extremely low gender balance currently present in European scientific environments.

1. S&T EXCELLENCE

1.1. CHALLENGE

1.1.1. DESCRIPTION OF THE CHALLENGE (MAIN AIM)

In this new era of gravitational waves as new and exciting astrophysical messengers, neutron stars will play a crucial role. To interpret and exploit future gravitational wave detections, it is necessary to consolidate the common ground that exists between different communities working on neutron star physics and astrophysics. Neutron stars emission encompasses all the available multi-messenger tracers: electromagnetic waves, cosmic rays, neutrinos, and gravitational waves. They are the only laboratories the most extreme phases of matter can be studies: not only probing extremes of gravity and electromagnetism, but also the strong and weak interaction can be studied in regimes that have no hope to be explored on Earth. The study of these objects transcends the traditional astrophysical approach and requires a multidisciplinary effort that spans from particle and nuclear physics to astrophysics, from experiment to theory, from gravitational waves to the electromagnetic spectrum. PHAROS has the ambitious goal of tackling key challenges in the physics involved in neutron stars by facing them via an innovative, problem based approach, that hinges on focused, interdisciplinary working groups. Each group will have all the diversified expertise needed to tackle different open aspects of the physics of neutron stars, and will provide to the different communities several tools and deliverables prepared in a shared language, and of easy access for scientists coming from different physics, ranging, for example, from nuclear physics to radio astronomy. Furthermore, key priority of this Action is promoting via training, mobility, equal opportunity and outreach activities, enthusiastic students and young researchers from all over Europe, that will grow and spread the Action's innovative multi-disciplinary approach. Collaboration is an indispensable feature of high-quality and innovative research, and the deeper we dive into specific exciting and complex fields, the more the need of brainpower and resources from complementary kinds of expertise is of crucial importance. This will build on the multi-disciplinary network that PHAROS will create.

1.1.2. RELEVANCE AND TIMELINESS

PHAROS will create a timely and unique structure for interaction between the different communities working on neutron stars: the nuclear physics community, the astrophysics community and the gravitational physics community. PHAROS will thus foster a multi-disciplinary and detailed understanding of the complex physics of neutron stars, and in more general terms of dense matter, strong gravity and strong magnetic fields. This network-building and young researcher training effort is timely within Europe's investments plans.
The pathfinders for the Square Kilometer Array (SKA), namely MeerKAT and ASKAP, and the FAST single dish, are starting now to be functional and releasing the first radio results to the community in view of the SKA era. Significant time is dedicated to the study of neutron stars, and in some years the number of objects known will more than double thanks to these new facilities.
The Cherenkov Telescope Array (CTA) will also start to be partly functional during this Action, giving us an unprecedented view of the very high energy emission from pulsar magnetospheres and their shocked environments, which will dominate the Galactic gamma-ray sky.

The eROSITA X-ray mission is also expected to fly and provide the first results during this Action, and its soft X-ray energy band is ideal to study thermal emission from neutron stars, especially in preparation for the ESA Athena X-ray observatory expected to be launched in a decade or so.
The Large Hadron Collider (LHC) at CERN is now fully operational and it is performing its long sought heavy-ion program. The regimes of gravity and magnetic fields that can be reached on Earth remain many orders of magnitudes weaker than what a neutron star laboratory might offer, but PHAROS's activities complement ideally the most extreme side of what LHC is investigating. The detection of gravitational waves by the LIGO/Virgo collaboration in 2015 opened a new astronomical window to the Universe, and neutron stars play a key role in this respect, having the potential of being extremely prolific gravitational emitters in terms of expected detection rates, and probably the only ones with an expected electromagnetic counterpart.
Neutron stars are also used themselves as gravitational wave detectors under the European Pulsar Timing Array and the International Pulsar Timing Array projects, that are very close to reach the sensitivity for their first direct gravitational wave detection in the next few years.
Other relevant experiments supported by Europe, on somewhat larger timelines, such as The Einstein Telescope, space missions funded or co-funded by ESA (Athena, LISA, and the James Webb Space Telescope; JWST), The European Extremely Large Telescope (EELT), the CERN Future Circular Collider (FCC), or the Facility of Antiproton and Ion Research (FAIR) will benefit from the interdisciplinary sub-ground that PHAROS will create.

1.2. SPECIFIC OBJECTIVES

1.2.1. RESEARCH COORDINATION OBJECTIVES

PHAROS will coordinate different communities working on neutron stars, with problem based objectives studied from different perspectives, and providing all communities with deliverables in a common understandable language, crucial to advance each other research activity. See section 3.1.1. for specific objectives for the individual working groups (WGs), which, in accordance with the SMART framework, will be used to measure progress towards the overall goals of the proposal.

1. How can the neutron star Equation of State (EoS) be investigated with different astrophysical and gravitational observations? Answering this question requires the communities to interact with nuclear physicists to set standard parameters for different EoS species to be implemented in astrophysical and gravitational simulations. (**WG1**; with WG2+WG3+WG4)
2. How can transport phenomena in neutron stars be modelled after or during their formation, also accounting for superfluidity and superconductivity, consistently with the EoS? How can theoretical predictions be consistently tested and constrained with astrophysical observations, including gravitational waves? (**WG2**; with WG1+WG3+WG4+WG5)
3. Which different gravitational signals are expected from different neutron star systems or during their formation? How can they be characterized with real observables, and distinguished from other gravitational wave emitters? How do the gravitational wave predictions depend on the EoS and the magnetic field configuration/evolution/instability? What physics can a Pulsar Timing Array constrain? (**WG3**; with WG1+WG4+WG5)
4. How does the magnetic field evolve in isolated and accreting systems? How do turbulence and instabilities affect field formation and evolution and how does this affect the neutron star populations that we observe today? How can these phenomena be investigated with multi-messenger astrophysical observations? (**WG4**; with WG1+WG2+WG3+WG5)
5. How can the physics of neutron stars be tested by studying their interaction with the local environment? How can jets be formed and launched in different neutron star

systems (i.e. pulsar wind nebulae or accreting neutron star binaries) or progenitors (i.e. supernovae, gamma-ray bursts)? How can plasma physics in high-field regimes as in pulsar magnetospheres, or particle acceleration processes and shocks be modelled? Which common physics is involved in jets, particle acceleration and plasma/B-field interaction in neutron star related systems compared to black holes, white dwarfs or even young stellar objects? (**WG5**; WG2+WG3+WG4)

PHAROS will also provide a General Web-portal comprising existing (or create new ones when needed) databases which are now sparse over the internet, often lacking general explanation on specific parameters, and that are difficult to reach and use for scientists from different communities.

1.2.2. CAPACITY-BUILDING OBJECTIVES

PHAROS aims to:

- Promote the interaction, and deliver common tools, between close communities interested in the same astrophysical objects from very different but complementary research approaches.
- Train a young generation of students to a multi-disciplinary approach in their research activity, and help them grow and develop a shared language among close communities: too often the cause of slower than needed research progress.
- Encourage young women and early career researchers to take leadership roles in PHAROS (in boards, as speakers in workshops, as lecturers), and provide young science students with young and senior women as role models. This has an extreme importance especially given the extremely low gender balance currently present in European scientific environments.
- Encourage young researchers to think out of the box of their own research field, acquiring skills that will be valuable also in case some of them leave the academia.
- Encourage brilliant researchers of any gender that recently re-integrated in scientific research after a long career break (for parental, health or any other personal reason) by giving them visible roles in the Action.
- Place activities in Inclusiveness Target Countries to promote their intra-European partnership collaboration, as well as promoting their connection with International Partners

1.3. PROGRESS BEYOND THE STATE-OF-THE-ART AND INNOVATION POTENTIAL

1.3.1. DESCRIPTION OF THE STATE-OF-THE-ART

Neutron stars are the remnants of the supernova explosion of massive stars, the existence of which was first theoretically predicted around the thirties (Landau 1932; Baade & Zwicky 1934) and then observed for the first time more than 30 years later (Hewish et al. 1968). They were predicted all along as very dense and degenerate stars holding about 1.4 solar masses in a sphere of only 12km in radius, possessing intense magnetic fields ranging from 10^8–10^{15} Gauss. Thousands of neutron stars are known today, in different environments: isolated or in binary systems with a large variety of companions. The extreme gravitational, rotational and magnetic energy can accelerate particles up to the TeV energy range, and make neutron stars one of the key sources of gravitational waves.
The different extremes of physics present in neutron stars place them at the intersection of traditionally distinct research communities. Neutron stars are used, for example, by the nuclear physics community as a laboratory to probe matter at extreme densities, by the astrophysics community to study the most extreme magnetic fields in the universe and by the gravitational physics community as both a source and, in Pulsar Timing Arrays, a detector, of gravitational waves.

In particular, the interior densities of such compact stars can exceed nuclear saturation density and lead to Fermi energies that are high compared to the thermal energy. This is an entirely different regime of physics from that probed with terrestrial experiments, such as accelerators and heavy ion colliders, which probe low density, high temperature aspects of the strong and weak interaction. Theoretical ab-initio models cannot extend to this regime, and several approaches have been developed to model both the force acting between baryons, and the overall many-body problem. Recent experiments have provided a wealth of data, but the high density region remains uncertain, with the strongest constraints here coming mainly from astrophysical observations of neutron stars, and in particular measurements of masses, and hopefully radii in the near future (Oertel et al. 2016). The astrophysical effort has always been very much connected with the available instrumentation. In the past decades, thanks to the availability of new generation X-ray instruments (among others ROSAT and ESA's XMM-Newton), there were high-impact discoveries in the neutron star research: i.e. close-by (few hundreds light-years) thermally emitting magnetic neutron stars (the so-called XDINSs), extremely magnetic neutron stars, known as magnetars, from which crust-quakes during luminous Giant Flares were observed, accreting millisecond pulsars, jets and wind-blown nebulae probing their powerful particle winds, etc. (Kaspi & Kramer 2016). Observations of X-ray bursts in systems accreting at the Eddington luminosity have even allowed to develop techniques to measure neutron star radii. Radio timing of pulsars has allowed to not only test General Relativity with unprecedented accuracy (Stairs, 2003), but also lead to the discovery of the most massive neutron stars, with masses approximately twice that of the Sun, which strongly constrain the equation of state of dense matter (Demorest et al. 2010). In this contest, note that two Nobel Prizes were awarded on discoveries in neutron star physics so far (Ryle and Hewish 1974; Hulse and Taylor 1993).

The long sought-after detection of gravitational waves has opened a new window on the universe (Abbott et al. 2016), and it is only a matter of time before neutron star signals are detected. Double neutron stars binaries are expected to be one of the dominant signals for Advanced LIGO, and astronomers can also expect signals from supernovae, unstable modes of oscillation in binaries and isolated neutron star and many more scenarios, some expected and probably many more unexpected. Gravitational wave signals are, however, weak, and detailed models are necessary not only to extract the signal from the noise, but also to interpret it and begin to unravel the physics of dense matter. This has lead to a rapid development of astrophysical models and numerical simulations of neutron stars in recent years. Current efforts are centered on dynamical relativistic models of neutron star binary mergers, on modeling supernova explosions, modelling the thermal and magnetic evolution of the star, neutron star astroseismology and on the dynamics of superfluid and superconducting components in the interior of the star (see e.g. Faber & Radio 2012, Foglizzo et al. 2015, Lasky 2015, Mereghetti et al. 2015).
In order to bring together the most advanced developments from all these fields a multi-disciplinary approach it is now indispensable. In Europe there is unique expertise on all the different topics, and PHAROS will provide a common platform to coordinate the different efforts in a common shared language. A COST Action, with a problem-based focus, is the natural choice to rapidly advance in the field in preparation for the first gravitational wave detections of neutron stars, and to train the new generation of young researchers in this broad, flexible, and wide-open research approach.

1.3.2.PROGRESS BEYOND THE STATE-OF-THE-ART

It is clear that the research on neutron stars is well developed, well-funded and a highly active field on a European level. A careful reader will, however, have noticed how progress, be it theoretical, experimental or observational, has been significant in the past decade, but has proceeded on parallel tracks, focusing on the main challenges for each sub-field.
As we begin to open our windows to the gravitational wave sky, it is imperative to build on the successes in these fields and build truly quantitative models of compact stars that can make use of gravitational and electromagnetic signatures to constrain fundamental physics at high density.

All the fundamental forces of nature play a role in neutron star modelling, which also depends on constraints derived from both terrestrial experiments in accelerators, heavy ion colliders, and astronomical observations, both electromagnetic and gravitational.

A COST Action is thus the ideal tool to make progress in this field, by bringing together experts in each aspect of the problem from all over Europe, and allowing them to work together, and involve also Near Neighbour Countries and International Partners.

PHAROS will develop frameworks and standards to make available, for the first time, the tools to facilitate the creation of a new generation of neutron star models. In particular, this Action will set the scene for the creation of dynamical, relativistic simulations that can make use of the most advanced models for the equation of state, transport coefficients, and magnetic field of the star from the interior to the magnetosphere. The tools and expertise to tackle each of these issues individually exist, but bringing them together with shared goals will increase drastically the pace of theoretical innovation.
Crucially, the next five years will also see a dramatic increase in the quantity and quality of observational data relating to compact stars: as probably the first gravitational wave detection of neutron star binaries, observations with the fully operational SKA and CTA pathfinders and eROSITA, and automated multi-wavelength (including gravitational waves) observations of astrophysical transient events will become routine. These data enable researchers from different fields to probe neutron stars as cosmic laboratories, i.e. test our models of fundamental physics. PHAROS will implement a crucial step in this process, and allow for the observational and theoretical community to work in close contact to develop shared frameworks and sets of standards. These will relate observables to physical quantities, and enable the direct comparison of theoretical models and data.
This COST Action will organize a series of schools to train young scientist in the use of these new tools, multi-messenger data analysis, and encourage cross-disciplinary developments and collaborations. This will not only encourage European mobility, especially with the ITC Countries, but also ensure that students have a broad knowledge of techniques, which can then be transferred to industry as they move on with their careers, thus fostering new cutting-edge developments throughout Europe.

1.3.3. INNOVATION IN TACKLING THE CHALLENGE

The approach of PHAROS, enabling the development of neutron star physics and gravitational wave astronomy, is highly innovative, as for the first time a problem-based approach, fully data/experiments-oriented, is proposed.
Separate groups in the main three areas involved in PHAROS, astrophysics, gravitation and high-energy nuclear physics in Europe are highly productive, relatively well funded and have a strong potential for innovation. The bottleneck in tackling the full compact star problem occurs when communication and input is necessary from other groups of different communities, that often have different standards and approaches.
This COST Action plan to intervene on this part of the process, the slowest, and develop the tools to speed it up, thus allowing each group to express its full potential and develop a new generation of advanced compact star models that can be compared to electromagnetic and gravitational wave data. This Action will be the first to focus on producing standards and frameworks to allow for the different communities to use the state of the art inputs from different branches of physics in their compact star research, and to allow for a coherent and rapid comparison with experiment and observations.
In recent years the communities have come together and started developing a common language. PHAROS will thus move beyond this and for the first time allow the communities to work together.
To facilitate the effectiveness of the Action, 5 problem-based Working Groups that tackle specific problems are presented, and, crucially, that already contain within them all the expertise from the relevant different communities. This will ensure rapid and agile communication, and will be effective in removing the bottlenecks.

1.4. ADDED VALUE OF NETWORKING

1.4.1. IN RELATION TO THE CHALLENGE

Neutron stars have been studied for many years and from many different perspectives. In particular from a nuclear physics point of view to determine the properties of dense matter, from the astrophysical perspective, both theoretical and observational, and finally as source of gravitational waves. These communities follow distinct research paths, distinct approaches, and their research is often based on somewhat different scientific languages. Nevertheless, advances in computational methods and infrastructure and new observational facilities such as Advanced LIGO, SKA, CTA, and eROSITA now call for a joint approach on the subject. In particular many issues concerning the neutron star EoS, transport coefficients, magnetic field evolution or crustal composition are of interest to all the different communities: in some cases as a research output, in other as a simulation input, in many more as possible applications of new observations. The time when fully functional new generation multi-band facilities will be available is fast approaching, and gravitational waves from neutron star systems will be probably detected during the life of this COST Action. It is now the golden moment to create this network between different communities, tackle concrete common-problems in a shared language, and provide deliverables to all different researchers working on neutron stars in a simple and easy format.

1.4.2. IN RELATION TO EXISTING EFFORTS AT EUROPEAN AND/OR INTERNATIONAL LEVEL

This Action represents an innovative effort at the European level, but connects with and makes use of large scale investments in science research and infrastructure.

Europe has a large stake in international observational facilities crucial for this Action, such as LIGO/Virgo, SKA, CTA, eROSITA and nuclear physics experiments such as the LHC in Geneva, Facility of Antiproton and Ion Research (FAIR) in Darmstadt, and Grand Accélérateur National d'Ions Lourds (GANIL) in Caen. Both the observational and theoretical research for the Action are also well funded by national grants and European level grants from H2020, i.e. the LEAP project or the European Pulsar Timing Array.

The only other comparable COST Action that exists at the moment (but finalizes in 2017) is “Exploring fundamental physics with compact stars” (NewCompstar; MP1304). PHAROS complements this effort ideally, as NewCompstar focuses on communicating research on compact stars between different communities, but stops short of the kind of focused problem and more data-oriented approach that PHAROS aims at.

The nuclear physics part of this Action also intersects with part of the currently funded “Theory of hot matter and relativistic heavy-ion collisions” THOR (CA15213). The focus of this Action is specific to heavy ion collisions, but is relevant for the kind of experimental constraints needed for WG1 and WG2. Similarly there is overlap regarding astrophysical nucleo-synthesis in neutron stars with the Action CA16117, “Chemical Elements as Tracers of the Evolution of the Cosmos” (ChETEC).

PHAROS will ensure interaction with scientists currently involved in THOR and ChETEC, or previously involved in NewCompstar, i.e. inviting representatives from this Action as speakers at conferences and workshops.

Finally the Action CA16104, “Gravitational waves, black holes and fundamental physics” (GWniverse), while focusing on black holes and not neutron stars, is relevant for the gravitational wave detection part of PHAROS (WG3), so that attention will be payed to building a constructive dialogue with all gravitational wave observers involved.

2. IMPACT

2.1. EXPECTED IMPACT

2.1.1. SHORT-TERM AND LONG-TERM SCIENTIFIC, TECHNOLOGICAL, AND/OR SOCIOECONOMIC IMPACTS

Short-term impact:
- PHAROS will allow a faster progress on neutron star research, by having the different communities work in close contact on well defined problems, and establishing standard deliverables that can be efficiently used by the nuclear, gravitational and astrophysical communities working on neutron stars.
- User friendly web-based tools will be delivered to all communities, as well as white papers written in a shared language presenting open and closed problems, to help concretely the planning of future experiments and theoretical work in the different fields.
- Workshops, Training Schools, and Short-term research visits will create a lively and strong interaction and training network within Europe, and with Inclusiveness Target Countries that will support recently flourishing or new experiments (LIGO/Virgo, SKA, CTA, eROSITA, etc.).
- Outreach Activities for the public and for schools, and the special Social Network projects planned within this Action, will ensure a fast spread of the PHAROS activities also outside the scientific community, in the Inclusiveness Target Countries, all International Partners and beyond.

Long-term impact:
-Training young students and researchers in a multi-disciplinary research environment will strengthen connection in the European scientific communities and create a wide-thinking new class of researchers.
- The particular attention of PHAROS activities to create role models and leadership for minorities in science will have large socio-economic impact in Europe, and in Inclusiveness Target Countries.
- The inter-disciplinary skills acquired by young researchers will be valuable also in case some of them leave to work outside of academia.
- The large number of women (57.5% of all supporters) already involved in this COST Action (atypical in Physical Sciences in general) will ensure a fast improvement in the generally scarse gender balance among the different communities.
- PHAROS will foster intra-community connections that will provide a strong base ground to refine and exploit planned future facilities in all fields, such as ESA's Athena mission, The Einstein Telescope, LISA and future collider facilities (as the CERN FCC, or FAIR)
-The kind of multi-disciplinary knowledge and techniques acquired by new researchers and students will be transferred to industry and foster innovation, especially in Inclusiveness Target Countries.
-Training young researchers to communicate science to the general public will contribute to scientific awareness of the society and attracting students to the fields of science and technology

2.2. MEASURES TO MAXIMISE IMPACT

2.2.1. PLAN FOR INVOLVING THE MOST RELEVANT STAKEHOLDERS

The Network of proposers already involves about 106 active researchers from different research fields (more than 57.5% are women), spanning 23 countries, of which 45% are COST Inclusiveness Target Countries. This already secures active Action participants who will be fully involved in the proposed activities of PHAROS. Furthermore, the Management Committee will identify and incorporate other countries currently missing. Guest scientists, instrument PIs or representatives, and experts in related topics, will be invited to take part in workshops and schools, to maximize the impact of the Action also outside the targeted communities.

2.2.2. DISSEMINATION AND/OR EXPLOITATION PLAN

Dissemination of the Action will involve at a *Scientific level*: 1) Organizing workshops, outreach events, international conferences, within Europe and especially within Inclusiveness Target Countries; 2) Scientific and outreach publications from the Action participants will acknowledge the support from PHAROS; 3) A mailing list will be created including active researchers in different fields to inform a wider community on the Action activities; 4) A public General Web-Site with all the scientific deliverables of the Action will be created. At a *Social level*: 1) Facebook/Twitter/Wiki/Blog accounts will be periodically updated to enlarge the reach of PHAROS, especially at the youngest generations; 2) Local activities for schools and training for teachers will be organized, and preference for speakers will be given to young researches/women/minorities in the Action, to reinforce role models in the very young generation of potential scientists; 3) A general e-Newsletter will be distributed every 6-months comprising all PHAROS news and small outreach articles (with on-line translations in all different PHAROS languages) for the reach of students or non-experts; 4) An interactive discussion web-portal will be constructed to answer/discuss questions or curiosities posed by the Public; 5) Outreach activities and open discussion will be organized in local SMEs and industries, to foster interaction and exchange.

2.3. POTENTIAL FOR INNOVATION VERSUS RISK LEVEL

2.3.1. POTENTIAL FOR SCIENTIFIC, TECHNOLOGICAL AND/OR SOCIOECONOMIC INNOVATION BREAKTHROUGHS

Technological advances in the past century flourished thanks to the large investments, especially in Europe, in the understanding of the physics of matter under different regimes electromagnetism, and to some extends also of gravity. In the past few years most of the international companies working in connection with technology or health diagnosis and treatments, opened entire research departments on matter and magnetism interactions, in view of the next generation of discoveries. The potential for innovation of this Action is high, as by facilitating communication and removing the obstacles for the exchange of state of the art solutions between different sub-fields, paving the way for scientific results that are currently un-thought of.

The lack of well defined standards and a common framework, in fact, currently prevent scientists working on neutron stars from attempting to implement cutting-edge solutions from other sub-fields, mainly because to do so would require a large investment of time, a steep learning curve and uncertain returns. To illustrate this with an example, a scientist working on numerical relativity simulations of neutron star mergers may not attempt to implement the most realistic equations of state for nuclear matter, despite being aware of their existence, as they are not available in a form that can be readily used for numerics. Without this kind of multi-disciplinary models it will, however, be impossible to truly start doing gravitational wave astronomy and effectively use neutron stars as a laboratory to understand fundamental physics at high densities.

By providing standards and a clear framework for comparing observables PHAROS will facilitate and expedite the process of including a broad range of state of the art physics in compact star models. By removing the hurdles associated with this process and significantly decreasing the investment of time and resources associated with it, and also significantly reducing the risks involved in carrying out this kind of multi-disciplinary research.

This Action is thus encouraging the use of cutting edge solutions in neutron star modeling and observing, and fostering the potential for new and revolutionary discoveries.

The problem-based approach and the composition of the Working Groups, that include all the inter-disciplinary expertise, ensure that there is a low level of risk, as delays in one part of the implementation will not affect the rest of the program. In addition, each group will produce self-

standing deliverables, that ensure that even partial success of the Action will deliver an increased potential for scientific breakthroughs in astronomy and fundamental physics.
Furthermore a new generation of scientists will benefit from intra-European mobility and hands-on training in cutting edge techniques in diverse fields of not only physics, but also signal and data processing. Knowledge of a problem-based approach to tasks will also allow them easily fit in to teams in geographically and scientifically diverse institutions and companies. As these young scientists continue their careers, there is no doubt they will be well equipped to foster innovation not only in science, but also in industry throughout Europe.

3. IMPLEMENTATION

3.1. DESCRIPTION OF THE WORK PLAN

PHAROS's will be implemented via specific problem-based and data-oriented Working Groups (WGs). Members of each WGs are chosen such to have complementary research interests and skills from the different communities, and early career researchers and women will be preferred when assigning leading roles within each WG. General common activities and coordination plans are listed below, which are somehow common to all WGs, while specific objectives, tasks, deliverables and milestones are listed in Section 3.1.1, and all timescales arranged in the GANTT Diagram.

An important aim of PHAROS is collecting in a General Web-site useful links, with the due commentary and information, that are now scattered on the web such as: the Glitch catalog, the ATNF pulsar catalogue, the McGill magnetar catalogue, the Cooling NS catalog, the RRATalog, the EPN pulse profile database, the DURHAM HEP database, the CompOSE EoS database, etc. This General Web-site will provide comments on the reported parameters of several on-line data-bases, to make this information useful for a wide range of scientific communities having often different jargons, and will collect also other web-based deliverables produced by the different WGs.

PHAROS General Milestones:

1st Month (P1): First MC meeting, election of Steering Committee

3rd Month (P2): Steering Committee on-line meeting (6monthly repetition)

4th Month (P3): First Short Term Scientific Missions Deadline (4monthly repetition)

6th Month (P4): Kick-off PHAROS Scientific Conference

10th Month (P5): First Training School: General

12th Month (P6): Second MC meeting, WG deliverables general planning

15th Month (P7): Outreach Activity for Public/Secondary Schools/Science Writers

18th Month (P8): Training School (Hands-on): Multi-messenger data Analysis/Coding

24th Month (P9): Mid-term PHAROS Report: initial Web-release

25th Month (P10): PHAROS General Scientific Conference

28th Month (P11): Outreach Activity for Public/ Secondary Schools/Science Writers

30th Month (P12): Open discussion/Minutes: how to promote minorities in science

34th Month (P13): Training School (Multi-disciplinary): Observational tests on data/Simulations

38th Month (P14): Third MC meeting, White papers planning/On-line Releases

42th Month (P15): Final PHAROS Scientific Conference.

46th Month (P16): Final PHAROS report and White Papers announcement

3.1.1. DESCRIPTION OF WORKING GROUPS

WG1. Equation of State of dense matter

This WG will focus on providing unified equations of state that can be used for the whole star and satisfy the most modern experimental constraints. The main objective and deliverable for this Working Group is thus an online equation of state catalogue, that builds on existing online repositories in an innovative manner, upgrading them in such a way as to provide data in a form that can easily be used in numerical simulations and for direct comparison with astrophysical observables. By having members of the three communities work together this group will ensure the creation of a standard, that will allow astrophysicists to use advanced equations of state directly and easily, and for nuclear physicists to simply make their results available.

Objectives:

- Collaboration between communities to determine standards.
- Provide benchmarks to test the correct implementation/functioning.
- Provide unified and consistent EOSs.
- Collaboration with WG2 to determine consistent transport parameters.

Tasks

- Set up specific task forces to tackle individual aspects of the objectives.
- Manage and edit an online repository of EoS, together with WG2 (transport).
- Report WG activities to the MC.

Activities

- Two specialized and two intra-meeting during the Action.
- STSMs relating to the objectives of the WG.
- Regular monthly remote web-meetings.
- Lectures on WG related subjects at the Action Training Schools.

Deliverables

- D1.1: Web-based repository of several EoS in easy readable formats standardized over different communities.
- D1.2: White paper describing the theoretical and observational state of the art and the methods and procedures used in the website. Update of General website.

Milestones

- M1.1 Meeting 1: Set the specifications for standard format EoS and set the web-page.
- M1.2 Meeting 2: Interaction Meeting with WG2 and WG4.
- M1.3 Meeting 3: Final setting for the launch of the website, and white paper planning.
- M1.4 Meeting 4: Interaction Meeting with WG2 and WG3.

WG2. Superfluidity/Superconductivity in dense matter and transport coefficients

To quantitatively model astrophysical phenomena, from supernova explosions to gravitational wave emission, it is necessary not only to understand the static properties of the equation of state, but also to determine the transport coefficients of dense matter (for which one must consider not only the strong, but also weak and electromagnetic interactions in strong gravity). Crucially, in mature neutron stars temperatures are also low enough and densities high enough, that neutrons are expected to be superfluid and protons superconducting (Baym et al. 1969). This has profound consequences on the dynamics, as now the superfluid can 'flow' relative to the 'normal' component of the star and quantum vortices develop on a microscopic scale. Furthermore many micro-physical reactions are quenched, altering the viscosity and conductivity of the interior.

This WG will set standards for calculating transport parameters, such as viscosities, thermal conductivities and neutrino emissivities, consistently with the equation of state (also considering superfluidity) and define which quantities must be priorities for neutron star simulations.

Additionally it will set standards to compare astrophysical observables to theoretical predictions. In particular data from radio pulsar glitches will be considered, which are currently the main observational probe of neutron star superfluidity, and provide a unified framework/data-base to present observational results.

Objectives:

- Determine micro-physical inputs for glitch and gravitational wave modeling.
- Provide consistent transport coefficients and superfluid gaps for EoSs from WG1.
- Provide fitting formulae for numerical use.
- Determine standards for glitch observables, in preparation for SKA data.

Tasks

- Set up specific task forces to tackle individual aspects of the objectives.
- Manage and edit an online repository of tables and formulae, together with WG1.
- Compare existing glitch catalogues.
- Report WG activities to the MC.

Activities

- Two specialized and two intra-meeting during the Action.
- STSMs relating to the objectives of the WG.
- Regular monthly remote meetings.
- Lectures on WG related subjects at the Training Schools.

Deliverables

- D2.1: Web-based repository of transport coefficients with tables and fitting formulae for numeric.
- D2.2: White paper describing the theoretical and observational state of the art and the methods and procedures used in the website. Update of General website.

Milestones

- M2.1 Meeting 1: Set the specifications for tables and transport formulae.
- M2.2 Meeting 2: Interaction Meeting with WG1 and WG4.
- M2.3 Meeting 3: Preliminary web-catalog, and set clear prospects for tests with future data.
- M2.4 Meeting 4: Interaction Meeting with WG1 and WG3.

WG3. Gravitational wave signals from neutron stars

Neutron star systems are one of the main sources of gravitational waves, from chirps in binary inspirals, to bursts in supernova explosions, from continuous signals from modes of oscillation to a stochastic background due to young neutron stars. Models are crucial to build templates to extract these weak signals from the detector noise, and when gravitational wave data will start to be routinely collected, this will give us an unprecedented view of the high-density interior of these compact stars. This WG will focus on setting standards for observables that theoretical models must deliver to the gravitational wave detection community, and on assessing the input that is needed from nuclear physics and electromagnetic astronomy. Prospects for possible systematics in gravitational wave detection by a Pulsar Timing Array due to micro and macro-physical assumptions in the neutron star nuclear physics will be discussed.

Objectives:

- Determine micro-physical and observational inputs required for models.
- Determine standards to allow gravitational wave observers to use models effectively.
- Closer collaboration between theorists and observers to develop models.

Tasks

- Set up specific task forces to tackle individual aspects of the objectives.
- Report WG activities to the MC.

Activities

- Two specialized and two intra-meetings during the Action.
- STSMs relating to the objectives of the WG.
- Regular monthly remote meetings.
- Lectures on WG related subjects at the Training Schools,

Deliverables

- D3.1: White paper describing the theoretical and observational state of the art, and describing standards to be used by the community. Update of General website.

Milestones

- M3.1 Meeting 1: Set standards and needs for the gravitational physics community.
- M3.2 Meeting 2: Interaction Meeting with WG4+WG5 to discuss astrophysical inputs.
- M3.3 Meeting 3: Set up of the General Web-base collection.
- M3.4 Meeting 4: Intra-meeting with WG1+WG2 to discuss micro-physics inputs.

WG4. Magnetic field formation, evolution, (in)stability and neutron star population study

This Working Group is set to compare different analytical or MHD approaches (and their validity limits, simplifications and assumptions) used to model massive star magnetic field evolution, neutron star magnetic formation and evolution, magnetic evolution in binaries after accretion episodes, as well as magnetic instabilities/reconnection in different systems and environment (i.e. massive stars, supernovae, young and old neutron stars). The treatment of magnetic fields and turbulence is important in different communities modelling supernovae, gamma-ray bursts, neutron star oscillations, binary mergers, etc., but too often these communities do not communicate efficiently with each other, nor with scientists working on micro-physical inputs needed in these simulations. This Working Group will also analyse the inputs needed to neutron star Population Synthesis codes from astrophysical observers and nuclear physicist, as well as test neutron star Population Synthesis codes in comparison with proto-neutron star numerical simulations and supernovae and gamma-ray burst rates.

Objectives:

- Compare different magnetic evolution/formation/oscillations codes.
- Determine systematic differences, verify assumptions and validity in different communities.
- Closer collaboration between observers and theorists to set up observational tests.

Tasks

- Set up specific task forces composed by expert in different communities.
- Report WG activities to the MC.

Activities

- Two specialized and two intra-meetings during the Action.
- STSMs relating to the objectives of the WG.
- Regular remote monthly meetings.
- Lectures on WG related subjects at the Training Schools.

Deliverables

- D4.1: White paper describing the different available magnetic formation and evolution codes with a clear discussion of the differences and limits of each code, as well as of the advances envisaged in the future. This will include a clear table with all B-field generation mechanisms with relative timescales, strength, properties, validities.
- D4.2 Update of General website.

Milestones

- M4.1 Meeting 1: Code comparison for B-formation, evolution from different communities.
- M4.2 Meeting 2: Interaction Meeting with WG1+WG2 to discuss microphysical inputs.
- M4.3 Meeting 3: Interaction Meeting with WG3+WG5 to discuss B-field acceleration mechanisms and consequences for gravitational wave emission.
- M4.4 Meeting 4: Comparison of different numerical simulation codes.

WG5. Neutron star magnetospheres, acceleration mechanisms, environment and jets

Neutron star magnetospheres are very efficient particle accelerators, and these energetic particles are observed to interact with the surrounding interstellar medium creating shocks observed e.g. as Pulsar Wind Nebulae. On the other hand, also in accreting binary systems physically similar shocks are observed between the pulsars and the accreted material, and in both cases jets can be launched with different scales. Similarly during neutron stars formation large particle accelerations are produce, often via jets (i.e. gamma-ray bursts). This Working Group will create a platform for interaction between observers, plasma physicists, and astrotheorists and numerical simulation experts, to discuss pulsar magnetospheres, particle acceleration and jets formation studies in different communities, especially in preparation with the CTA first light.

Objectives:

- Compare analytical, radiative and numerical models for pulsar magnetospheres and wind nebulae.
- Determine systematic differences, and verify assumptions and validity.

Tasks

- Set up specific task forces composed by expert in different communities.
- Report WG activities to the MC.

Activities

- Two specialized and one intra-meetings during the Action.
- STSMs relating to the objectives of the WG.
- Regular remote monthly meetings .
- Lectures on WG related subjects at the Training Schools.

Deliverables

- D5.1 White paper describing different sites and regimes of particle acceleration in pulsar magnetospheres, environments and accreting systems, and the basic ingredients and those missing in current analytical or numerical approaches in different astrophysical scenarios. Update of General website.

Milestones

- M5.1 Meeting 1: Particle acceleration in neutron stars and their environments in different astrophysical scenarios and numerical code comparison.
- M5.2 Meeting 2: Interaction Meeting with WG3+WG4 to set B-field roles and gravitational wave models.
- M5.3 Meeting 3: Set observables with future instrumentations, and white paper planning.

3.1.2. GANTT DIAGRAM

Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
MC	P1		P2	P3		P4		P3	P2	P5		P6	P3		P7	P2
WG1						M1.1										
WG2						M2.1										
WG3						M3.1										
WG4						M4.1										
WG5						M5.1										

Month	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
MC	P3	P8		P3		P2		P9	P10	P3		P11		P12	P2	P3
WG1		M1.2														M1.3

Month	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
WG2		M2.2														M2.3
WG3							M3.2									M3.3
WG4		M4.2					M4.3									
WG5							M5.2									

Month	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
MC		P13		P3	P2	P14		P3		P15				P16		
WG1	D1.1							M1.4								D1.2
WG2	D2.1							M2.4								D2.2
WG3								M3.4								D3.1
WG4								M4.4	D4.1							D4.2
WG5										M5.3						D5.1

3.1.3. RISK AND CONTINGENCY PLANS

The construction of self-standing, inter-disciplinary and problem-based WGs significantly reduces the level of risk involved in this Action.
Each Working Group has all the expertise that is needed in the main research areas, and has well defined goals. The interaction among the WGs will also be important and several meetings are devoted to WG interaction. Furthermore individual deliverables are tuned to individual problems and will thus individually allow for scientific results and breakthroughs. The overall success of the Action is thus guaranteed, even if individual tasks are delayed.
The only risk derives from specification from the community changing during the life of the Action, as research techniques evolve and new data arrives. However the agile method of managing the Working Groups, which includes regular meetings and a small manageable group of experts from each sub-field in each group, will allow to rapidly resolve such issues should they arise, and redefine the nature of the deliverables much more swiftly than if the issue were addressed by a larger, less coordinated, community.

3.2. MANAGEMENT STRUCTURES AND PROCEDURES

The management of PHAROS, in accordance with the COST rules, will be based on the election of an *Action Chair (AC)* and *Vice-Chair (AVC),* and of a *Management Committee (MC)* that will oversee all the activities of the Action. To facilitate the flexibility of the decision making tree, a *Steering Committee (SC)* will be elected in the first Action meeting, that will encompass the *Action Chair* and *Vice-Chair*, the *Working Group Leaders*, and other key roles in the Action planning, that will all be elected during the first MC meeting. In particular:

Working Group Leaders (WGLs) are expected to be responsible of all the scientific activities within their Working Group. Five Working Groups are expected in PHAROS. Each WGL will also elect two Task Leaders that together with the WGLs need to complement the three different general expertise (astrophysics, gravitational and nuclear physics) in the same working group. Task Leaders and WGLs are responsible for the advance of their own Objectives and Deliverables within the WG, and are expected to report minutes on their scientific activity every 6 months to the Steering Committee as a whole to have a broader feedback and interaction where needed.

Equal Opportunity Agent (EOA) is responsible to oversee all the activities of the Action, intervening if needed to establish a balanced program in terms of equal opportunity for minorities of any kind. The EOA is also responsible to ensure a ~50% gender balance within each WG. The EOA will organize child-friendly activities during PhD schools, meetings and conferences.

Website Agent (WA) is responsible for all what concerns the Action website, for uploading contents after a general MC agreement, and for keeping all the Action activities updated in the web-portal.

Outreach Coordinator (OC) is in charge of coordinating the outreach activities of the Action by preparing Outreach videos, organizing outreach seminars during the Action annual conferences, possibly preparing material such as constructible satellites, or small pulsars that can be assembled by kids of elementary schools.

Social Network Agent (SNA) is responsible for posting short weekly updates on the Action activities/opening-calls/outreach activities/WG advances, etc on a dedicated Blog/Twitter/Facebook account to ensure the largest spread of the Action results, especially among European students and young researchers. She/He will also be responsible for the 6-months e-Newsletter and a virtual-discussion portals to enlarge the reach of PHAROS.

The *Steering Committee (SC)* will then count a total of 11 MC members, and it is meant to facilitate the *Management Committee* in the final decision making of the Action.

3.3. NETWORK AS A WHOLE

The challenge of modelling neutron star physics in the era of gravitational wave astronomy is timely and fundamental. Experts in astrophysics, gravitational and nuclear physics, throughout Europe and the world, are working on the different aspects of this problem as a matter of priority, as testified by the interest that the Action has already generated at the proposal stage, also in many International Partner Countries and Near Neighbour Countries. As described previously, however, an interdisciplinary effort is necessary for this field to yield results and decipher the signatures of fundamental physics at high densities.
The three different communities described above, have been focused on the problem for several years now. The community as a whole is thus mature to start working together and remove communication bottlenecks, by developing shared protocols and frameworks to share data and results. This kind of effort can naturally only be accomplished by a wide network of scientists, that have expertise in all aspects of the problem, and can contribute at all levels, from more experienced researchers to early career ones. A broad geographical and balanced gender distribution of participants will thus not only ensure that each Working Group has key expertise in all elements of the problem, thus reducing communication lags, but also promote mobility and ensure that young researchers can learn-by-doing from more senior scientist, and contribute to the network well beyond the life of this Action. To ensure the effectiveness of this element, training activities and meetings will be spread throughout Europe, focusing in particular on Inclusiveness Target Countries. Furthermore a key priority of the Action will be gender and outreach activities, in order to build a truly diverse and inclusive community and allow for the largest possible pool of outstanding researchers to participate in the network.