European Cooperation in the field of Scientific and Technical Research - COST -

Brussels, 24 May 2013

COST 034/13

MEMORANDUM OF UNDERSTANDING

Subject :	Memorandum of Understanding for the implementation of a European Concerted Research Action designated as COST Action MP1304: Exploring fundamental physics with compact stars (NewCompStar)

Delegations will find attached the Memorandum of Understanding for COST Action MP1304 as approved by the COST Committee of Senior Officials (CSO) at its 187th meeting on 15-16 May 2013.

MEMORANDUM OF UNDERSTANDING
For the implementation of a European Concerted Research Action designated as

COST Action MP1304
EXPLORING FUNDAMENTAL PHYSICS WITH COMPACT STARS (NewCompStar)

The Parties to this Memorandum of Understanding, declaring their common intention to participate in the concerted Action referred to above and described in the technical Annex to the Memorandum, have reached the following understanding:

1. The Action will be carried out in accordance with the provisions of document COST 4154/11 "Rules and Procedures for Implementing COST Actions", or in any new document amending or replacing it, the contents of which the Parties are fully aware of.

2. The main objective of the Action is to provide an innovative connection between the micro- and macrophysics of compact stars, thus exploring the behaviour of matter and spacetime under the most extreme physical conditions, not accessible to laboratory experiments.

3. 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 88 million in 2013 prices.

4. The Memorandum of Understanding will take effect on being accepted by at least five Parties.

5. The Memorandum of Understanding will remain in force for a period of 4 years, calculated from the date of the first meeting of the Management Committee, unless the duration of the Action is modified according to the provisions of Chapter IV of the document referred to in Point 1 above.

A. ABSTRACT AND KEYWORDS

Compact stars, such as neutron stars, strange stars or hybrid stars, are unique laboratories that allow us to probe the building blocks of matter and their interactions at regimes that terrestrial laboratories cannot explore. These exceptional objects have already led to breakthrough discoveries in nuclear and subnuclear physics, quantum chromodynamics (QCD), general relativity and high-energy astrophysics. The upcoming generation of observatories and gravitational-wave detectors will continue to nurture innovative and fundamental discoveries complementary to those achieved through the nuclear and subnuclear experimental facilities. This Action will bring together the leading experts in astrophysics, nuclear physics and gravitational physics to address this fascinating but challenging research area through an interdisciplinary approach. In addition to an innovative and well-defined research agenda, the network will provide a dedicated training program for a new generation of scientists with wide-ranging expertise and multiple skills oriented also towards knowledge transfer and innovation.
Keywords: nuclear and subnuclear physics, astrophysics, gravitational physics, compact stars

B. BACKGROUND

B.1 General background

The last five years have witnessed a radical transformation in the way in which progress can be made in fundamental-physics research. After decades in which the physics of the microscopic (*i.e.* nuclear and subnuclear physics) and that of the macroscopic (*i.e.* astrophysics and cosmology) have marched forward along two different, sometimes parallel, but distinct routes, it is now evident that major breakthroughs are to be expected only when these two routes actually overlap. This is the spirit behind the recent birth and flourishing of *astronuclear physics*, a world-wide effort in which physicists and astrophysicists (both experimentalists/observers and theoreticians) share expertise, insight and data, in an attempt to address some of the most pressing questions in physics and astronomy: What is the equation state of nuclear matter? What are the properties of spacetime near a compact object?

It is in the context of this worldwide effort that this Action places itself. The physics and astrophysics of compact stars, such as neutron stars, strange stars and hybrid stars, is a theme ripe for exploration within a large-scale collaborative project. This will be particularly true in the coming years thanks to the developments of experimental facilities worldwide that will inevitably lead to new observations and breakthrough discoveries. This Action represents the new challenge that the European community of astronuclear physics is ready to take and for which it has already worked actively over the last years through a ESF funded Research Networking Programme (CompStar). A generation of students has been trained in a cross-disciplinary fashion and is now entering the job market as young researchers in academic institutions and as skilled scientists in the industrial and technological sector. CompStar has become a unique reference for astronuclear physics in Europe and also a model that other international communities, such as those in the USA and Japan, are inspired by. The training of young researchers provided by CompStar, however, acted only as a first attempt to break the barriers between the three disciplines on which the physics of compact stars is based. It is now time for a change of route and for a novel and more focussed effort dedicated to research more than to training, in order to coordinate and boost the research in astrophysics, nuclear/subnuclear physics and gravitational physics. This effort will allow us to make real progress in the understanding of the properties of dense hadronic matter as found in compact stars, and, ultimately, it will nurture the generation of young researchers that have been created with CompStar.

B.2 Current state of knowledge

Compact stars are ideal "laboratories" to study matter under extreme conditions of temperature, density, magnetic field and spacetime curvature. Indeed they represent the only environment in the universe where all these extreme conditions can be found, since only their enormous gravitational fields can compress matter well above nuclear saturation density. Recent years have seen many important developments as far as observations of compact stars are concerned. The launch of a new generation of satellites (e.g., Chandra, XMM Newton, Swift, Integral, Agile, Fermi) has allowed us to collect unprecedented data on the high-energy emission (X-ray and gamma-ray) of compact stars. This data, together with ground-based astronomical observations at different wavelengths (mainly radio and optical) has significantly advanced our understanding of compact stars, yielding more accurate measurements of their physical properties, as well as adding new classes of objects to the ones already known. Among the many examples worth mentioning: 1) the few upper limits for neutron-star surface temperatures of a few years ago have been replaced by detailed thermal spectra for more than 30 X-ray compact sources; 2) accurate mass measurements and tests of general relativity have been possible in newly-discovered binary systems consisting of two compact stars, one of which contains two pulsars; 3) the study of anomalous X-ray pulsars and of soft gamma-ray repeaters has brought more and more evidence for the existence of *magnetars*, young neutron stars with extremely high magnetic fields which power their emission; 4) the accurate measurements via radio observations of neutron stars with masses around two solar masses has set important constraints on the nuclear equation of state, ruling out some theoretical models; 5) observations of the compact object in the Cassiopeia-A remnant has provided evidence for superconductivity and superfluidity in neutron star interiors.

In addition, new projects, such as the gravitational-wave detectors Advanced LIGO and Advanced Virgo are being installed, while even more ambitious projects, such as the proposed ESA-M3 X-ray mission LOFT (Large Observatory for X-ray Timing), are planned in the near future. In the radio domain, LOFAR (the LOw Frequency ARray) is already taking exciting new data, while FAST (Five hundred meter Aperture Spherical Telescope) and SKA (the Square Kilometer Array) are under development and will provide us with an unprecedented wealth of information about pulsars. On the nuclear-physics side, data obtained at Alternating Gradient Synchrotron (AGS, Brookhaven, USA) and Super Proton Synchrotron (SPS, CERN, Switzerland) will be completed and improved by new experiments that will take place in several sites in Europe, e.g., the Helmholtz Centre for Heavy Ion Research, GSI (Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany) or Nuclotron (Dubna, Russia) and new exotic beam facilities such as Facility for Antiproton and Ion Research (FAIR) at GSI (Darmstadt, Germany) and "Système de Production d'Ions Radioactifs en Ligne" - generation 2 (SPIRAL2) at Grand Accélérateur National d'Ions Lourds (GANIL, National Large Heavy Ion Accelerator, Caen, France).

It is only now that observations are starting to yield results that can discriminate between different theoretical scenarios and that nuclear and subnuclear facilities are performing experiments that could advance our understanding of the dense matter equation of state. However, a proper exploitation of this large pool of observational and experimental data can be achieved only through a collaborative effort in which scientific communities that traditionally work independently are brought together to analyse the different phenomena that take place in compact objects. The synergy that will result, will lead to a comprehensive and consistent theoretical picture to interpret and explain the observed phenomenology and understand the properties of matter and spacetime in its most extreme realization. A COST Action represents therefore the best opportunity for interconnecting and educating a class of researchers able to work across the borders of three disciplines that have been so far fragmented. Because the Action will represent much more than the sum of the single parts, the scientific research and production that will follow will benefit enormously and major progress will be achieved in the understanding of some of the most fascinating objects in the universe.

B.3 Reasons for the Action

The wide range of observational and experimental data that is about to be collected serves to illustrate two important aspects of the work in this area. Firstly, it shows it is a very active and productive field, reasonably well-funded on a national level and which will foster new generations of scientists working on the astrophysics of compact stars, *or* on the nuclear/subnuclear physics aspects, *or* on the gravitational ones. At the same time, however, it shows the need for a European-wide support for this type of research, thus calling for an initiative in which all the national initiatives are collected within a wider networking activity. Indeed, while funding for research in each of the relevant disciplines has been, and is, available in most countries, thus making possible the training of young scientists and the development of research lines in each of these specific fields, very little has been done so far to break the barriers between the three disciplines. What is needed now to significantly advance our knowledge of compact stars does not require significant additional research funding at national levels, but rather a cross-disciplinary effort to create a synergy between the different areas of knowledge, so that the existing but fragmented lines of research can be coordinated and interact. CompStar was focused on the *training* of students and young postdocs in the three fields and has formed a lively new pool of researchers with a broad interdisciplinary education. The COST Action aims at a different, novel goal while exploiting what has been built with CompStar. While maintaining continuity with the crucial training of new generations, this Action aims instead at networking the existing fragmented communities to boost *cross-disciplinary research* and at promoting new approaches, using the previously-formed young scientists to catalyse discussion and collaboration among the three disciplines. This objective is a necessary one to interpret and understand the wealth of observational data expected in the near future, and which must be analysed as complementary parts of a complex puzzle. The instruments offered by a COST Action are ideally suited for this goal. In addition, the COST framework will offer the possibility of networking with new countries, thus going beyond a purely European scenario. Indeed, countries such as Armenia, Australia, Brazil, Mexico, Russia, and South Africa have research groups and observational facilities that justify their involvement and have expressed enthusiastic support to this initiative.

Although the physics of compact stars lies mostly within the realm of fundamental research, it can have an indirect impact on industry. The investigations of nuclear matter, in fact, can influence many real-world applications, such as the construction of improved nuclear magnetic resonance tools in medicine and the development of more accurate nuclear cures for cancer. A deeper knowledge of the properties of hadronic matter in extreme environments can also help studies towards more secure and cleaner sources of energy. Similarly, astronuclear physics can have a direct impact also on society through the training of highly-skilled scientists whose ability as problem solvers could be of use in the non-academic world. The interaction between theorists and observers, which is a distinguishing feature of this Action, will help create young scientists with multiple expertise, ranging from complex mathematical tools and advanced supercomputing techniques over to the ability to interrogate large and complex data sets. All of these skills can be employed profitably in a diverse range of high-end jobs in Europe and worldwide.

B.4 Complementarity with other research programmes

To the best of our knowledge, there is no similar COST Action or other significant European-funded initiative running currently. However, it should be noted the existence of two other COST Actions with which collaboration is possible in principle. Firstly, the Action "Black holes in a violent universe" (MP0905) deals with the physics of black holes and not with the structure of dense matter. It therefore has a very different scientific focus, but shares from the astronomical side many of the facilities that will be important for us. Hence, a collaborative effort, mostly on the observational side, with the scientists in MP0905 will benefit both Actions and will be sought actively.

Secondly, the Action "The String Theory Universe" (MP1210) has some resonance with this Action, at least as far as the QCD aspects of string theory are concerned. MP1210 is a highly theoretical one and does not have the strong experimental/observational counterparts of the present Action. However, there are some complementary aspects, which can be beneficial to both parties. In particular, the predictions from string theory about some extreme scenarios of dense matter can find optimal testbeds in the phenomenology of compact stars. At the same time, the new scenarios explored in the String-Action can be used for novel interpretations of the experimental and observed data of relevance in this Action. Also in this case, a collaboration will be promoted.

C. OBJECTIVES AND BENEFITS

C.1 Aim

The main objective of the Action is to provide an innovative connection between the micro- and macrophysics of compact stars, thus exploring the behaviour of matter and spacetime under the most extreme physical conditions, not accessible to laboratory experiments

C.2 Objectives

The main objectives of this Action are:

- **Coordination.** The Action aims at coordinating the research efforts of the currently disjoint astrophysical, nuclear and gravitational-physics communities and at promoting collaborations across different disciplines.
- **European leadership.** The Action aims at securing Europe as the global leader in astronuclear physics, serving as a role model for the research efforts in other parts of the world.
- **Training.** The Action aims at training a new generation of young scientists with broad skill sets, vital for successful research, but also for careers in the wider world, e.g. industry and technology.
- **Gender Issues.** The Action aims at providing an environment where female scientists, currently under-represented in the field, receive the necessary encouragement and support.
- **Dissemination of results.** The Action aims at disseminating the scientific results achieved on the largest scale possible, including the traditional scientific communities, but also the wider public and, whenever appropriate, policy makers.

C.3 How networking within the Action will yield the objectives?

The objectives of the Action described above will be achieved as follows:

Coordination:

- Three interdisciplinary *Working Groups* (WGs) will be set up and meet regularly (see Section D.1).
- Three *Synergy Agents* (SAs) will be appointed, whose role is to ensure close dialogue among the three WGs. They will be senior scientists, with both the scientific vision and the personal prestige to make sure an efficient networking takes place (see Section D.1).

European leadership:

- Senior members of the Action will participate in major international conferences as spokespersons of the activities of the Action.
- During the second part of the Action, a "white paper" will be prepared to document the prospects and potential of future astronuclear physics initiatives. The paper will serve as a reference for the planning of future research in the field.

Training:

- A series of interdisciplinary schools and workshops will be organized (see Section E.1)
- Early Stage Researchers (ESRs), that is, students and junior postdoctoral researchers, will spend time at an institution whose core expertise lies outside that of their home institution.
- Exchange visits of young and senior scientists across participating groups will be arranged.

Gender Issues:

- A *Gender Coordinator* (GC) will be appointed and will be member the Steering Committee (SC). Her/his role will be to represent gender issues within the Action and to promote the suppression of gender barriers where present (see Section E.4).
- The Action will actively promote women to leading and coordinating positions.
- An online *FemmeNet*, inspired by a similar initiative of the Max-Planck society, will be established within the Action. Overseen by the GC, it will provide mentoring and counselling on family and career issues.

Dissemination of results:

The Action will setup a Website with several areas presenting results both for the scientific community and for the public at large.

The Action will build *Compose*, an online database containing the equations of state, reaction rates and transport properties produced by researchers within and outside the Action. It will be highly flexible, allowing for the easy upload and download of information about several equations of state and their properties. This novel tool will be publicly available and will be part of the long-term legacy of the Action.

C.4 Potential impact of the Action

- Creation of a new generation of scientists with genuinely multidisciplinary skills oriented towards knowledge transfer and innovation to be used in both basic research and industry.
- Building of an interdisciplinary European astronuclear community that will act as a role model for the extra-European international communities.
- Attraction of the general public to the fascinating world of compact stars and of their rich physical and astrophysical phenomenology.

- Exploration of the building blocks of nuclear/subnuclear matter that could ultimately lead to future cleaner and safer sources of energy and novel applications in medical diagnostics and cures.

C.5 Target groups/end users

- The international scientific community, which will benefit from the advances in research facilitated by this Action.
- The European industrial and technological sector, which will benefit from the young and brilliant researchers trained within the Action and equipped with unusually broad skill-sets. Many of these will later search employment out of academia, thus providing the European industry and technology with a much-needed high-education expertise.
- All scientists needing information about equations of state for their research in astronuclear physics. Through their access to the *Compose* online database, they will have a single point of access to a variety of information which is now largely dispersed and difficult to obtain.
- The nuclear-fission sector, since the hydrodynamic flows studied in this Action have close parallels with phenomena in nuclear fission reactors.
- The nuclear-fusion sector, since the magnetohydrodynamical (MHD) flows studied in this Action have close parallels with phenomena in magnetically confined fusion.
- The researchers interested in development of new materials, since the heavy-ion collisions studied in this Action can produce heavy isotopes with novel properties that can find immediate industrial and technological use.

D. SCIENTIFIC PROGRAMME

D.1 Scientific focus

Although astronuclear physics has a rich and intricate astrophysical phenomenology, it revolves around a few questions that are still fundamentally open:

1. What are the transport properties of hot/cold dense matter?
2. What is the role of the equation of state in core-collapse supernovae?
3. What is the role of the equation of state in binary neutron star mergers?
4. Are binary neutron star mergers behind short gamma-ray bursts (GRBs)?
5. How does the equation of state influence pulsar/magnetar dynamics?

6. How can observations of neutron stars (isolated or in binaries) constrain the equation of state?
7. How do matter properties change under extremely strong electromagnetic fields?
8. How can neutron stars be used to test general relativity and other theories of gravity?

All of these questions involve astrophysics, nuclear/subnuclear physics and gravitational physics, with a direct impact on our understanding of matter, of astronomy and of strong-field gravity. This Action will address these questions by carrying out research in three main interdisciplinary WGs that reflect the present expertise of the different communities. The work in these WGs will be interconnected through the activities of the three SAs, who will promote the breakdown of traditional barriers and transfuse knowledge across areas.

The three WGs of the Action will be:

WG1: observations and modelling of compact stars

The recent past has seen substantial advances in our understanding of the astrophysics of compact stars, thanks to the availability of new telescopes and space observatories. The input of these instruments has been crucial for our understanding of compact stars. In addition, planned instruments, (e.g., FAST being the world's largest single dish radiotelescope, LOFT with its novel pulse profile modelling and SKA with its very high sensitivity) will provide us with an unprecedented wealth of information on compact stars. The theoretical work so far has tended to neglect the effects of the magnetic field and was usually restricted to one-dimensional simulations. Only in the last decade, multidimensional studies have been carried out to explore in detail the effect of magnetic fields in scenarios such as core-collapse supernovae, the long-term cooling of strongly magnetized neutron stars, the bursting activity of magnetars, the merger of neutron-star binaries, or the crustal cooling after an active period in low-mass X-ray binaries. This Action will use the existing experience of its members to include magnetic fields and rotation, together with state-of-the-art microphysics inputs, in multidimensional simulations of the different astrophysical scenarios involving compact stars. By close interaction with the theoretical and observational teams, this Action will develop an all-encompassing approach to the diverse manifestations of neutron stars, taking input both from the microphysics results of WG2 and from the theoretical modelling of the spacetime of WG3. Our ultimate goal is to link the various, partly contradictory results, in an approach that uses radio, X-ray and gamma-ray observations, and to contrast them with the theoretical predictions (e.g., neutron star hydrodynamical and MHD simulations, pulsar glitch models, emission processes, atmospheric and magnetospheric models) and their implications (through neutron star population synthesis). The results of this effort will be both timely and important, amplifying enormously the scientific impact of the new generation of satellites exploring high-energy astrophysics.

WG2: physics of the strong interaction, theory and experiment

Compact stars, and the observed astrophysical processes related to them, give stringent constraints on the properties of dense and hot hadronic matter, such as equation of state, superfluidity, transport coefficients and elasticity parameters. Probing strongly interacting matter under extreme conditions requires bringing together experts in low-energy QCD and in many-body theories. Indeed, one of the main theoretical issues is that the theory describing the interaction and dynamics of quarks and gluons, i.e., QCD, is non-perturbative in the regimes of interest for compact stars. Additionally, many-body effects such as pairing or collective behaviour make the phase diagram of hadronic matter very rich and at the same time, subtle to describe.

Several important issues will be explored in detail by this Action using the information coming from the observations and modelling of compact stars, thus in close interaction with WG1 and WG3. The first one is the structure of the phase diagram of strongly-interacting matter, with a possible deconfinement of quarks in compact stars and core-collapse supernovae or a transition to hyperonic matter. A second one concerns the properties of purely nucleonic matter. The nature of the bare nuclear interaction, in fact, is still largely debated and the recent developments of effective field-theory approaches or renormalisation-group methods illustrate its liveliness. The short-range nature of the bare nuclear interaction determines, to a large extent, the in-medium correlations, as well as the importance of many-body interactions. Additional long-range correlations, such as pairing among Cooper pairs or collective behaviour, have also important consequences on the microscopic properties of dense matter, and thence on observable processes such as cooling, pulsar glitches and oscillations of compact stars. A third issue concerns the statistical description of nuclei at finite temperature and in dilute matter, which is important for the modelling of the equation of state, but also for the reaction-rates of electron-capture, photo-dissociation, and neutrino scattering in core-collapse supernovae. This Action will calculate these reaction-rates and the transport properties as applications of the best nuclear reaction models and build the background microphysical knowledge needed by WG1 and WG3.

Although at much smaller densities, nuclear experiments also represent a different way to probe the nuclear interaction and the in-medium correlations in the best-controlled systems, providing constraints on the properties of finite nuclei in their ground and excited states, and in the out-of-equilibrium plasma produced in heavy-ion collisions. The relation between nuclear experiments and the physics of compact stars is not straightforward, but the novel synergy between nuclear experiments and astronomical observations of compact stars will impact on all of the theoretical modelling relevant to this Action.

WG3: gravitational physics theory and observations

The strong gravitational fields of neutron stars make them potentially detectable sources of gravitational waves, both as members of binary systems, and as individual emitters when they are produced in a core-collapse supernova, when they collapse to a black hole, or undergo any sort of non-spherical oscillation. Indeed, the inspiral and coalescence of neutron star binary systems (either as double neutron star systems or when considering the presence of a black hole) are the prime candidates for the first ever detection of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO)/Virgo (gravitational wave) detector network. Their discovery would provide an important test of strong-field general relativity, but such detections require accurate signal templates. Most significantly for this Action, the late stages of the coalescence, and the merger itself, will be sensitive to the equation of state of the colliding stars. The construction of sensitive templates, by means of large-scale numerical computations, will be a central task of WG3, and provides an intimate connection between this and WG2. The final merger itself is likely to produce a short GRB. Detailed numerical modelling of this process connects therefore with the activities of WG1, and, through possibly populating the Galaxy with heavy elements, has important repercussions for the nuclear/subnuclear physics explored in WG2. Equally important, individual neutron stars can emit gravitational waves through a variety of mechanisms. These include non-axisymmetries of rotating stars induced by elastic/magnetic strains, and excitation of normal modes of oscillation. Both of these are sensitive to detailed properties of the equation of state and are closely related to the calculations of WG2, while the effect of gravitational wave emission on neutron star spin frequency provides a natural link with the activities of WG1.
As outlined above, in addition to WGs and their work described above, the research will be catalysed by three SAs. These will be senior scientists with interdisciplinary expertise, who will ensure that a high level of communication is setup among the various WGs and will provide input on possible new synergies.

D.2 Scientific work plan methods and means

Below are detailed the main topics which will be addressed in each WG and which reflect the eight fundamental questions introduced in Section D.1.

WG1: modelling and observations of compact stars

1. Understand core-collapse supernovae and their connection with GRBs. The WG will use the existing codes in the Action and extend them to include realistic microphysical inputs to simulate the collapse of stellar cores, the formation of proto-neutron stars and its connection with long GRBs, and also the merger of binary neutron stars and its connection with short GRBs.
2. Understand cooling properties of middle-age neutron stars and magnetars. By using cooling codes, the WG will follow the self-consistent evolution of the temperature and the rotational properties when coupled to the magnetic field evolution, comparing the predictions with the observations.
3. Understand magnetar bursts, flares and quasi-periodic oscillations. The WG will model the release of built-up strain (in terms of seismic waves, Alfven waves and heat) through numerical multidimensional simulations, in order to provide a complete picture of magnetar flares and of the subsequent quasi-periodic oscillations.
4. Understand pulsar emission and timing. The WG will investigate the magnetospheric processes leading to the radio-emission and relate these to the spectral and timing properties identified by pulsar observations. Models for pulsar glitches will also be constrained by or developed from new observations.
5. Understand the emission from X-ray binaries containing a neutron star. The WG will simulate the burst and subsequent cooling of the star after an active period and confront it with observational data to infer properties of the crust. It will deduce mass-radius measurements through different spectral and timing techniques and will study the physics of the plasma-magnetospheric interaction.

The main methods and means used within this WG will be:

- Hydrodynamical and magnetohydrodynamical (MHD) simulations in multidimensions.
- Spectral data-analysis from observations in the radio, infrared, optical, X-ray and gamma bands.
- Timing data-analysis from observations in the radio, X-ray and gamma bands.
- Simplified modelling of compact stars for first rough explanations of the observed phenomenology.
- Modelling of radiative transfer for photons and neutrinos.
- Perturbative analysis of oscillating stars with different levels of magnetization.

WG2: physics of the strong interaction, theory and experiment

1. Validate available equation of state across different experiments and observations. The WG will define a protocol where the equation of state, and the underlying interactions, are consistently checked and compared with nuclear experiments and observations of compact stars.
2. Investigate the predictions for the phase diagram of hot and dense matter, clarifying the role of phase transitions and exotic degrees of freedom predicted by nuclear physics and low-energy QCD.
3. Investigate superfluidity and superconductivity in dense matter. The WG will employ the numerous observations to understand the occurrence of superfluidity and superconductivity in various regions of compact stars and predict signatures revealing their presence in compact stars.
4. Calculate the transport properties and the reaction rates for validated equations of state. The WG will supply the simulations modelling core-collapse supernovae and binary neutron-star mergers with the transport properties and reaction rates of hot and dense nuclear matter.

The main methods and means used within this WG will be:

- Density functional theory.
- Mean-field theory and its extensions to collective behaviour and to pairing properties.
- Ab-initio approaches including Green-function, Brueckner, Fermi Hyper-Netted Chain, and MonteCarlo methods.
- Renormalization group techniques and effective field theory.
- Band-theory approaches.
- Statistical modelling for dilute nuclear matter.
- Thermodynamical approaches to phase transitions.

WG3: gravitational physics theory and observations

1. Produce accurate models for the inspiral and merger of binary neutron stars. The WG will use large-scale multidimensional simulations in numerical-relativity to extract the radiating gravitational fields far from source, in form suitable for generation of templates for data analysis by observers.
2. Correlate the gravitational-wave signal to the neutron star equation of state. The WG will carry out a thorough exploration of how different candidate equations of state affect

the emitted gravitational waves. Once observations will be available, these will be used to constrain the equation of state.

3. Establish properties of electromagnetic counterparts to binary neutron star merger/GRBs. The WG will carry out the subsequent evolution of the ejecta produced in the merger to establish a link between the progenitor masses/equation of state and the electromagnetic emission. It will also investigate how the neutron-rich ejecta contribute to the chemical enrichment of the universe.

4. Quantify efficiency of gravitational-wave emission mechanisms from individual stars. In parallel with the above tasks, the WG will build detailed models of individual stars to examine the extent to which non-axisymmetries and oscillations produce gravitational waves.

The main methods and means used within this WG will be:

- Numerical-relativity hydrodynamical and MHD simulations in multidimensions.
- Perturbative analysis of oscillating stars.
- Post-Newtonian approximations to dynamics of binary systems.
- Simplified modelling of isolated stars for first rough explanations of observed phenomenology.
- Modelling of radiative transfer for photons and neutrinos.
- Match-filtering and time-frequency data-analysis techniques for gravitational wave signals.

To illustrate the high level of synergy among the different WGs, the table below reports how the different WGs address the fundamental questions listed in D.1.

	Quest. 1	Quest. 2	Quest. 3	Quest. 4	Quest. 5	Quest. 6	Quest. 7	Quest. 8
WG1	X	X		X	X	X	X	X
WG2	X	X	X		X	X	X	
WG3		X	X	X		X		X

This table will serve as a reference for the tasks and initiatives of the SAs. The filling factor in the table is already very high, indicating synergies well identified between the different WGs and hence among the different scientific communities. The goal of this Action is to strengthen these synergies and increase this filling factor even further.

E. ORGANISATION

E.1 Coordination and organisation

The management of this Action has a well-defined structure to ensure that all the goals are met and it will conform to the COST document "Rules and procedures for implementing COST Actions".

(a) Management

Management Committee (MC). The Action will be governed by the MC**,** which will be chaired by the Action Chair (AC), assisted by a vice-Chair (AVC).

Work Group Leaders (WGL). The WGLs will preside over the coordination of the different WGs, ensuring that the scientific goals are met and that the recommendations of the SAs are implemented and pursued. They will meet face-to-face twice a year during the "hands-on" workshops and at least every two months via teleconferencing together with the SAs (see Section E.2).

Synergy Agents (SA). The SAs will be responsible for the synergy between two or more WGs and will provide recommendations to the WGLs. They will meet face-to-face twice a year during the "hands-on" workshops and at least every two months via teleconferencing together with the WGLs (see Section E.2).

Topic Leaders (TL). Each WGL will nominate a TL to supervise one of the several activities in its WG. As a result, there will be a TL for WG1a, one TL for WG1b, and so on (see Section D.2). TLs will be selected among junior scientists who wish to acquire management skills. They will meet face-to-face twice a year during the "hands-on" workshops and at least once a month via teleconferencing (see Section E.2).

Website Manager (WM). The WM will preside over the building and maintenance of the Website (see Section E.1). The WM will have monthly teleconferencing meetings with the Gender Coordinator and the Outreach Coordinator for improvements and updates of the Website.

Gender Coordinator (GC). The GC will function as gender-balance coordinator, alerting the MC of potential conflicts and promoting the role of women at all levels. The GC will be responsible for *FemmeNet*, the gender forum on the Website that provides mentoring and counselling on family and career issues (see E.4). The GC will collaborate with the WM for the gender area on the Website.

Outreach Coordinator (OC). The OC will be responsible for the organization of the outreach and dissemination activities of the Action. The OC will manage a yearly budget allocated to outreach initiatives and will collaborate with the WM on the outreach and dissemination area on the Website.

Steering Committee (SC). A SC will be appointed by the MC to ensure a more efficient management. It will be composed of: the AC and the AVC, the WGLs, the SAs, the GC, the OC and the WM, for a total of 11 members. The SC will be responsible for the preparation of all the documents required for the MC meetings and will propose most of the initiatives of the Action. The members of the SC will be elected during the kick-off meeting and their activities will have to be approved by the MC. The members of the SC will meet face-to-face twice a year during the "hands-on" workshops and every two months via teleconferencing (see Section E.2).

(b) Scientific Coordination and Networking

Scientific coordination and networking will be achieved through the following activities:

1. **Workshops and Training Schools.** An annual Workshop will be organized during the four years of the Action and the first three Workshops will be held in conjunction with a Training School. Each Training School will have a special but not exclusive focus on one of the three WGs of the Action. Each Workshop will provide a complete view of the research on compact stars, covering therefore topics in astrophysics, nuclear/subnuclear physics and gravitational physics. The Workshops will also be used by WGLs and SAs to report, advise and plan future research, while by the MC for administrative and steering purposes. Near the end of the Action there will be an interdisciplinary world-scale conference that will reflect the leading role of Europe in the field and will serve as a platform for discussing the future of the activities.
2. **Hands-on (scientific strategic) workshops.** WGLs and/or SAs will meet in short, concentrated, smaller-scale meetings with the TLs to ensure active collaboration within WGs and among WGs. Together with meetings at the time of the general Workshop, WGLs, TLs and SAs will also meet at least once more a year (preferably 6 months after the main Workshop). These additional meetings can take place at different times and places depending on the agendas of the different WGs. WGLs and SAs will also have monthly meetings via teleconferencing facilities.
3. **Seminar sharing.** Whenever possible, seminars scheduled on the Website will be shared via videoconferencing to all the institutions able to receive them either passively (e.g., via direct streaming) or actively (e.g., via the H.323 protocol).
4. **Dissemination of the Action.** A Website will be built following the COST Office requirements. Dissemination will include information about research activities, workshops, training schools, training courses, seminars, job opportunities, and gender forum.

(c) Milestones

The Action will run for four years. The main milestones will be:

Year	MILESTONES	DELIVERABLES
1	Kick-off meeting; all members of SC are appointed. 1st School and Workshop; MC meeting; Workplan established	Website fully operational WG reports, Annual Report 1st School and Workshop
2	2nd School and Workshop; MC meeting; Workplan established. Hand-on SC and WG/SA meetings. Compose released.	WG reports, Annual Report Gender/Outreach activities 2nd School and Workshop
3	3rd School and Workshop; MC meeting; Workplan established. Hand-on SC and WG/SA meetings. Compose updated.	WG reports, Annual Report Gender/Outreach activities 3rd School and Workshop
4	4th Workshop. MC meeting; white paper started. Hand-on SC and WG/SA meetings. Compose updated. Final conference; planning of future activities. White paper	WG reports, Final Report Gender/Outreach activities 4th Workshop Final conference; white paper

E.2 Working Groups

The Action's scientific plan is structured in three Working Groups: WG1 (astrophysics), WG2 (nuclear/subnuclear physics), WG3 (gravitational physics). Within each WG a senior WGL will be appointed by the MC, who will then select junior TLs for each of the topics of the WG (see D.2 for a description of the WG topics). One of the TLs will act as vice-WGL, replacing the WGL at meetings that cannot be attended. WGLs will coordinate the WG networking, report to the SC and the MC, and provide the scientific input for the annual reports. Depending on the scientific progress, as well as on the progress of the research within the Action, the WGs might be adapted at a later stage. The SAs will coordinate with the WGLs the networking research activities described in Section D to facilitate the synergy between different WGs. After two years, the MC may nominate new WGLs and SAs.

E.3 Liaison and interaction with other research programmes

As mentioned in Section B.4, there are two COST Actions that have a very different focus to the one here, but with which this Action may have some points of interaction. For example, for "Black holes in a violent universe" (MP0905), there may be common interests in observations of galactic X-ray binary systems, irrespective of whether they contain a black hole or a neutron star. For "The String Theory Universe" (MP1210), there could be a common interest in exploring new phases of the QCD phase diagram. This Action will interact with these other Actions by fostering the organization of common workshops, invitations of speakers to the Action workshops and schools. Moreover, the Action will serve as a catalyst for existing collaborations between groups in the Action and other high-ranking scientific institutions or research programmes e.g. European Research Council (ERC) projects related to the field, or Horizon 2020 programmes, both within and outside Europe. The Action will attract these partners to its schools and workshops, encouraging common initiatives.

E.4 Gender balance and involvement of early-stage researchers

This COST Action will respect an appropriate gender balance and considerable involvement of early stage researchers (ESR) in all its activities and the Management Committee (MC) will place this as a standard item on all its MC agendas.

The MC will appoint a Gender Coordinator (GC), who will be an active member of the SC (see Section E.1).

More specifically, through the activities of the GC, the MC will:

- Promote active participation of women scientists within the network. Particular attention will be paid to ensure the presence of women in scientific committees and as speakers in Workshops and Training Schools. Senior female scientists, as well as outstanding young researchers will act as role models for subsequent generations.
- Identify and adopt best practices across Europe for addressing the gender imbalance, e.g., by publicizing the impact of dedicated Ph.D. scholarships to outstanding young female researchers.
- Mentor and support young women at the beginning of their scientific careers through a dedicated forum on the Action Website.
- Monitor the growth of the scientific female community by collecting data on the number of female participants in Training Schools and Workshops and of female lecturers and speakers.

The Action will also be committed to provide high-level and cross-disciplinary education to ESRs. The Action will provide additional means in educating students with a wide area of expertise and interdisciplinary competences. The Action will coach the ESRs by the following means:

- "Learning on the job": Collaboration between experienced researchers and ESRs at all levels, including devolving management tasks and outreach activities to ESRs.
- Acquisition of managing skills by selecting TLs among ESRs and through the supervision of WGLs. These management skills will prove useful for future careers, both academic and not.
- Acquisition of proposal-writing skills by requiring students to submit proposals for exchange visits which will be funded only when the proposal will appear convincing to the SC.
- Participation of ESRs in the WG meetings, workshops and conferences.
- Training Schools and Workshops will expose ESRs to the current research and open problems. ESRs will be encouraged to present their results and to participate in the organization activities.
- Internships at institutions with core expertise that are outside those of ESR's home institution. These will be encouraged to be a standard aspect of the doctoral thesis preparation.
- Promotion of the mobility of ESRs through short-term scientific visits. These provide an excellent opportunity for broadening their scientific horizons, for acquiring new skills and for promoting interdisciplinary activities among the different communities in the Action.

F. TIMETABLE

The Action will be executed over four years, as shown in the planned timetable below. Due to the nature of the open and flexible framework of this Action, a readjustment of the scientific and organizational activities could be easily arranged, should this become necessary. The required changes will be identified by the MC and implemented by the SC. The first six months will be dedicated to initiate the entire Action.

Activity/Year	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4
WG1	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
WG2	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
WG3	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Other activities																

kick-off meeting	x															
MC appoints SC	x															
Establish WGs	x															
Establish Workplan	x															
Setup of Website		x														
Release of *Compose*					x											
MC, SC meetings			x			x		x		x		x		x		x
WG/SA meetings			x			x		x		x		x		x		x
Training School			x			x				x				x		
Workshop			x			x				x				x		
Final Conference																x
Gender activities	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Outreach activities		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

G. ECONOMIC DIMENSION

The following COST countries have actively participated in the preparation of the Action or otherwise indicated their interest: AT, BE, CH, CZ, DE, DK, EL, ES, FR, HR, HU, IL, IT, NL, NO, PL, PT, RO, SE, SK, TR, UK. On the basis of national estimates, the economic dimension of the activities to be carried out under the Action has been estimated at 88 Million € for the total duration of the Action. This estimate is valid under the assumption that all the countries mentioned above but no other countries will participate in the Action. Any departure from this will change the total cost accordingly.

H. DISSEMINATION PLAN

H.1 Who?

The outreach and dissemination activities will be under the responsibility of the OC, who will be a member of the SC and who will interact closely with the WM and the GC. The dissemination plan will be directed towards two main target groups, internal and external to the Action, and the relevant material will be adapted to these different targets.

The internal group will consist of scientists who have joined the Action:

- Staff scientists and young researchers, with special attention to female scientists and students.
- Graduate students (MSc and PhD).

The external group will consist of people or institutions outside the Action:

- Other researchers and students interested in the physics of compact stars.
- Universities and research institutions worldwide.
- National and European funding agencies.
- Opinion formers and governmental research-policy decision-makers at national and EU levels.
- Media: scientific and non-scientific press, digital media and TV.
- High-school students, physics and astronomy fairs, and planetariums.
- Members of foundations and cultural societies.
- General public.

H.2 What?

The dissemination plan will be based on four main initiatives:

1. The setup of a web-based mailing list containing all members of the Action and which will be used for rapid exchange of information and effective coordination.

2. The setup of a dedicated Website, managed and updated by the WM, containing different levels of access:

- A password-protected area with information of pertinence to the MC members, e.g. minutes of the meetings, budgetary tables, communications from funding agencies, etc.
- An open-access area containing information about activities and events within the Action, seminars at different institutions, job opportunities, and student fellowships.
- An open-access area containing a dynamically updated database of the members of the Action with their contact information, a database of publications produced by the members of the Action, information about activities and events worldwide related to the physics of compact stars, the management and group structure of the Action.
- An open-access area containing all of the scientific results obtained within the Action, but also work from colleagues worldwide.
- An open-access area directed to the general public and designed to communicate in a non-technical style the aim and purpose of the Action, the most relevant results obtained, and more generally to inform the general public about the physics and

astrophysics of compact stars and their relevance for understanding the fundamental properties of matter.

- *FemmeNet*, an open-access web-based gender forum, to allow female scientists and students to exchange experience and advice. Overseen by the GC, the forum will also provide counselling on family development and career opportunities for female scientists.

3. The organization of events for internal and external target groups:

- Training Schools, Workshops and Conferences organized by the Action and targeted to the students and/or the researchers of the Action, but also to the general scientific community with interests overlapping with those of the Action.
- Outreach activities for school students, non-technical talks in high schools, cultural societies and planetariums, participation of Action scientists to physics and astronomy fairs or special events, popular articles and press releases.

4. The dissemination of numerical codes developed within the Action and needed for the research on the physics of compact stars. Two main password-protected repositories will be setup and containing:

- Multidimensional codes; these will be provided by the different groups in the Action and made available to students and young researchers, both within the Action and outside of it.
- The *Compose* database, developed within the Action and containing suitably formatted tables for the different available equations of state of hot and cold dense matter. The material in *Compose* will be available to all scientists within the Action and more in general to anyone working in astronuclear physics.

H.3 How?

This Action will monitor the dissemination activities through the following routes:

- The Website will be the main tool for the dissemination strategy, directed to the three levels (MC members, scientists, and general public) by including conferences, workshops, training schools, publications, proceedings, job opportunities, open calls, access to scientific and annual reports, minutes and information on MC and WG meetings.
- A mailing list will be setup including all members of the Action and allowing for rapid information exchange and coordination.

- The Workshops and Training Schools organized by the Action will be key dissemination points to other research groups. Slides relative to all scientific presentations made during the Workshops and lectures given at the Training Schools will be posted on the Website and made publicly available.
- Seminars scheduled on the Website will be shared via videoconferencing facilities to all the institutions able to receive them either passively (e.g., via direct streaming) or actively (e.g., via the H.323 protocol).
- All the publications related to the activities of the Action will quote the Action in the acknowledgements statement using a standardized sentence.
- Talks delivered by scientists for the general public about the fascinating world of compact stars will be made publicly available on the Action Website.
- Staring from the kick-off meeting, this Action will begin monitoring the following indicators of the effectiveness of our dissemination plan:
  - Number of scientists subscribing to the Action mailing list and to the scientists database.
  - Number of scientists of countries not in the Action requesting subscription to the mailing list.
  - Number of announcements relative to job offers, student fellowships, conferences, and seminars made on the Action’s Website.
  - Number of collaborative publications among members of the Action.
  - Number of public-outreach initiatives, such as talks in schools, planetariums, foundations and cultural societies.