Proposal for an INFN Research Project (Iniziativa Specifica)

Section I:

Title: MOdeling Nuclear STructure and REactions

Acronym: MONSTRE

National Coordinator (Responsabile Nazionale):

name: Danilo Gambacurta
INFN Unit:LNS
e-mail:danilo.gambacurta@lns.infn.it

Local Coordinators (Responsabili Locali):
(add as many items as necessary)

- name: Paolo Finelli
  INFN section: Bologna
  e-mail: paolo.finelli@bo.infn.i

- name: Isaac Vidana
  INFN section: Catania
  e-mail: isaac.vidana@ct.infn.it

- name: Maria Colonna
  INFN section: LNS
  e-mail: colonna@lns.infn.it

- name: Javier Roca Maza
  INFN section: Milano
  e-mail: xavier.roca.maza@mi.infn.it

- name: Lorenzo Fortunato
  INFN section: Padova
  e-mail: lorenzo.fortunato@pd.infn.it

- name: Alessandro Roggero
  INFN section: TIFPA-Trento
  e-mail: a.roggero@unitn.it

Keywords related to the topic of the proposal (*up to five)*:
Nuclear Structure and Reactions – Many-body methods – Density functionals – *Ab initio* approaches – Quantum Computing

Abstract of the proposal:

Our project aims to establish a comprehensive and integrated framework for the study of atomic nuclei, nuclear reactions, and strongly interacting matter. The synergistic efforts of the various units, based on their complementary expertise in advanced many-body and computational methods, will be devoted to the study of complex nuclear phenomena occurring at different scales of energy and size. Modern *ab initio* techniques will be refined and applied making use of microscopic interactions, derived from nuclear effective field theories. Density functionals will be developed using *ab initio* and/or phenomenogical constraints and applied to the calculation of bulk, spectroscopic, and decay properties of finite nuclei throughout the whole nuclear chart, Collective modes will be studied making use of many body techniques including beyond mean-field correlations. The consistent merging of structure and reaction theories will offer the opportunity to directly compare theoretical calculations with empirical data for nuclear systems under extreme conditions, also deriving microscopic optical potentials. These investigations will also be performed by developing mathematical methods, quantum computing-based algorithms and machine learning techniques specifically tailored for the study of the nuclear many-body problem. Special attention will be devoted to the current experimental projects related to the production of rare isotopes, dark-matter detection, and the physics of electroweak interactions, including neutrino physics and double-beta decay. Combined astrophysical and terrestrial constraints, together with predictions based on state-of-the-art models, will be employed to achieve an improved, multi-faceted understanding of the nuclear equation of state.

Composition of the participant Research Units:

- INFN Unit Bologna
    - Staff members
        - Paolo Finelli (Professore Associato, Università di Bologna) (100%)

- INFN Unit Catania
    - Staff members
        - Edoardo Lanza (Primo Ricercatore – INFN-Catania) (70%)
        - Massimo Papa (Primo Ricercatore - INFN-Catania) (60%)
        - Michelangelo Sambataro (Dirigente di Ricerca – INFN-Catania (100%)
        - Isaac Vidana (Primo Ricercatore – INFN-Catania) (50%)
    - Other participants (Post-docs, Ph.D students,...)
        - Rui Wang (Post-doc) (100%)

- INFN Unit LNS
    - Staff members
        - Stefano Burrello (Ricercatore – INFN-LNS) (100%)
        - Maria Colonna (Dirigente di Ricerca - INFN-LNS) (80%)
        - Danilo Gambacurta (Primo Ricercatore – INFN-LNS) (90%)

    - Other participants (Post-docs, Ph.D students,...)
        - Jessica Bellone (Assegno di Ricerca - INFN-LNS) (50%)
        - Angela Bonaccorso (Associato Senior, INFN-Pisa) (100%)
        - Angela Gargano (Primo Ricercatore, INFN-Napoli) (70%)

- INFN Unit Milano
    - Staff members
        - Carlo Barbieri (Professore Associato, Università di Milano) (70%)
        - Gianluca Colò (Professore Ordinario, Università di Milano) (70%)

        - Javier Roca Maza (Professore Associato, Università di Milano) (70%)
        - Enrico Vigezzi (Dirigente di Ricerca, INFN Milano) (70%)

    - Other participants (Post-docs, Ph.D students,...)
        - Pietro Klausner (Ph.D student) (100%)
        - Francesco Marino (Ph.D student) (100%)
        - Imane Moumene (Post-doc, EUROLABS) (100%)

- INFN Unit Padova
    - Staff members
        - Lorenzo Fortunato (Professore Associato, Università di Padova) (100%)
        - Silvia Monica Lenzi (Professore Ordinario, Università di Padova (20%)
        - Paolo Lotti (Ricercatore, INFN-Padova) (50%)

- INFN Unit TIFPA-Trento
    - Staff members
        - Maurizio Dapor (Senior Researcher, ECT*) (25%)
        - Alessandro Lovato (Ricercatore, INFN-TIFPA/ANL) (100%)
        - Francesco Pederiva (Professore Ordinario, Università di Trento) (100%)
        - Alessandro Roggero (Ricercatore RTD-B, Università di Trento) (70%)
        - Simone Taioli (Senior Researcher, ECT*) (25%)

    - Other participants (Post-docs, Ph.D students,...)
        - Valentina Amitrano (Dottorando, Università of Trento) (100%)
        - Luca Vespucci (Dottorando, Università of Trento) (50%)
        - Iyadh Chaker (Dottorando, Università of Trento) (50%)

Section II:

Status of the relevant research field; scientific context, objectives, methodology and envisaged achievements of the proposed program: (max 2 pages)

MONSTRE is a research project established in 2020, gathering several Italian groups working on the theory of nuclear structure and reactions. The main goal of this collaboration is to implement an integrated framework for the physics of atomic nuclei, nuclear reactions, and strongly interacting matter. The past activity was successful and produced a substantial number of publications, as detailed at https://www0.mi.infn.it/monstre/. During a recent collaboration meeting (https://agenda.infn.it/event/35823/), it has been decided to extend our activity for the next three years. The project will attack some of the most significant challenges of our field, capitalizing on the expertise and competences of the different units, and taking also advantage of the collaborations that have been strengthened within the last three-year project. Part of the activities are closely connected to experimental studies, both at INFN National Laboratories and at international facilities. The project is structured in four Work-Packages (WPs), which have been somewhat modified with respect to the original project, to better reflect the main trends of our activity, as specified in more detail below and in the next section.

WP1) *Ab initio* many body methods for nuclei and nuclear matter: increasing the accuracy and predictive power

In the last decade, *ab initio* approaches have shown remarkable advances in the description of nuclear matter as well as of nuclear structure, reaching medium-, and in specific cases, even heavy-mass nuclei. The main goal of this WP is to refine approaches such as Self-consistent Green's functions (SCGF), Quantum Monte Carlo (QMC) and Shell Model (SM), employing effective interactions derived within the chiral EFT including 3-nucleon (3N) terms. New computational schemes will be devised, including Configuration Interaction Monte Carlo (CIMC), the automatic computation of Feynman diagrams and the use of quantum computing and neural-network quantum states (see WP4), to extend the domain of applicability of these approaches, in particular concerning nuclear and hyperonic matter, exotic and deformed nuclei. We also plan to perform consistent calculations of nuclear reactions, deriving accurate optical nucleon- and nucleus-nucleus potentials within the SCGF approach at low energy and improving the applications of multiple scattering at higher energies.

WP2) Advanced theoretical studies of nuclear phenomena: addressing the experimental challenges

The MONSTRE project is characterized by a strong connection with the experimental activities carried out worldwide, focusing on evidences which are not yet fully understood, and concerning both nuclear structure and reactions. Theoretical studies, based on the methods discussed in WP1 as well as in the framework of Density Functional Theory (DFT) will be performed. Efforts are underway to connect Energy Density Functional (EDF) models with *ab initio* approaches. Atomic parity-violating experiment are providing data that challenge current EDF models. New phenomenological functionals incorporating this kind of information will be developed. Attempts to include short-range-correlations (SRCs) within the EDF approach will be made, to describe recent evidences from nucleon knock-out experiments of high-energy electrons.

Exotic nuclei pose several challenges for theory, such as the evolution of the shell structure, where the 3N force plays a crucial role, or the appearance of low-lying structures in the energy spectrum, like the Pygmy Dipole Resonance (PDR), whose properties are still to be fully clarified. Phenomenological nucleus-nucleus optical potentials (OPs) for exotic nuclei will be derived and used to extract spectroscopic information via breakup and transfer reactions. Attention will be devoted to direct reactions populating weakly bound systems and/or unbound low-energy resonances.

Collective modes represent a very important source of information on the Equation of State (EoS), and an increasing number of experiments focus on deformed nuclei. A quantitative understanding of the properties of collective modes requires advanced models, possibly overcoming the mean-field approximation by including many-body correlations and/or restoring broken symmetries. We plan to perform extensive calculations for different multipolarities, re-examining the relationship between giant resonance properties and bulk nuclear matter parameters.

Single and double-beta decay represent also an important challenge. The comparison among different models (Quasi-particle Random Phase Approximation (QRPA), Second RPA, particle-vibration coupling (PVC), SM) can shed light on open issues, such as the quenching problem and the large uncertainties on the nuclear matrix elements of the neutrino-less double-beta decay. Single and double-charge reactions might also provide useful information in this regard.

The quantitative microscopic understanding of clustering represents a major open problem in nuclear structure. The role of molecular orbitals and antisymmetrization thereof is a key aspect to be studied before embarking in systematic studies, and reactions involving cluster nuclei will be studied by merging symmetry methods with molecular models. Alpha-like correlations induced by the proton-neutron pairing force are crucial importance in medium-heavy N=Z nuclei. We have developed an approach to describe these nuclei in a formalism of quartets which will be applied to understand anomalies observed in elastic alpha-scattering and alpha-decay.

WP3) Nuclear matter under extreme conditions: from nuclear dynamics to compact objects

The goal of this WP is the study of the properties of nuclear matter, focusing on the investigation of the EoS far from stability, which is crucial for the physics of compact stars. Heavy ion collisions (HICS) at Fermi/intermediate energies represent a powerful tool to this purpose. DWBA, Coupled-Channel (CC) calculations, semi-classical and transport models will be used to study the collision mechanism. An important international effort is currently underway, to compare different transport codes, to minimize the model-dependence and improve the robustness of the extracted EoS constraints, making use of advanced statistical analyses to combine astrophysical and terrestrial information. The study of exotic nuclei will help understanding how the in-medium nucleon-nucleon interaction depends on isospin asymmetry and how this impacts the EoS. The formation of clustering structures at sub-saturation densities is crucial for the modelization of the EoS as well as for nuclear structure and reaction properties. These clustering phenomena will be studied within extended EDF approaches incorporating SRCs and the Constrained Molecular Dynamics Model (CoMD).

WP4: Emerging computational technologies: quantum information and machine learning techniques

Quantum Computing (QC) and Quantum Information are rapidly growing fields. The application of QC to nuclear physics poses great challenges related to the complex features of the nuclear interaction, but their payoff is remarkable. On the one hand, simulations on quantum devices could represent efficient means to access physical observables, including inclusive and semi-exclusive scattering cross sections, and to deal with non-equilibrium phenomena, that are difficult to treat within *ab initio* approaches on classical computers; on the other hand, key concepts developed in quantum information like entanglement can serve as fertile ground to complement our understanding of low-energy effective theories of quantum chromodynamics and many-body correlations acting in nuclear systems. Artificial neural networks are able to represent compactly quantum many-body states in systems characterized by non-perturbative interactions. Recent progress includes the development of variational Monte Carlo methods based on neural network quantum states that solve the nuclear Schrödinger equation in a systematically improvable manner with a cost scaling polynomially with the number of nucleons. In addition, they are well-suited for next-generation computers, as they are designed to leverage the power of GPUs.

Proposed activities and role of the various Research Units (max 3 pages)

WP1: *Ab initio* many body methods for nuclei and nuclear matter: increasing the accuracy and predictive power

[Units: Milano, Trento] The research on QMC methods and their applications will develop following these main directions: a) Use of the CIMC method in momentum space to extend current studies to the EoS of symmetric nuclear matter with non-local versions of chiral forces, which can also be used to gauge *ab initio* grounded density functionals (see WP2); b) Application of the variational method based on artificial neural network quantum states to determine matrix elements for scattering of neutrinos and dark matter of medium mass nuclei, also in view of the setup of new experiments. c) Use of artificial neural network quantum states to study light and medium/mass hypernuclei, to understand some parts of the hyperon-nucleon (YN) interaction that still present some ambiguity (in particular charge symmetry breaking and the isospin dependence); d) Extension of the Gorkov-SCGF with chiral forces to full third-order correlations and to optimized (non harmonic oscillator) bases allowing to reach heavy nuclei (A=100-200) and an order of magnitude better correlation energy in open shell isotopes; e) Extending the SCGF approaches with full Diagrammatic Monte Carlo resummations to improve *ab initio* OPs also at energies up to 100 MeV/nucleon (relevant to transfer measurements).

[Unit: LNS] The SM effective Hamiltonian derived within the many-body perturbation theory has been recently extended to include genuine chiral 3N forces and induced 3N contributions originating from the 2-nucleon force for pf-shell nuclei [LNS3], deriving transition effective operators consistently (but without including renormalization due to the subnucleonic degrees of freedom). We plan to: a) study the effects of the different components of the chiral 3N force at N2LO on the nuclear structure and in particular on the spin-orbit splitting; b) extend the calculations with 3N forces to heavier nuclei; c) include higher-order contributions with 3N vertices; d) calculate consistently all the effective operators by including two-body meson-exchange corrections.

[Units: Bologna, Milano] Our current approach to derive a microscopic OPs for nucleon-nucleus reactions at bombarding energies of a few hundred MeV, based on the spectator expansion and the impulse approximation, has provided interesting results and will be improved including second-order effects and in-medium correlations (and dynamical correlations calculated by SCGF). The impulse approximation will also be combined with SCGF theory to improve the current self-energy implementation of the OPs. Moreover, we aim to extend our formalism to other reaction processes like inelastic scattering transitions (DWBA or CC) and nucleus-nucleus collisions.

WP2: Advanced theoretical studies of nuclear phenomena: addressing the experimental challenges

[Units: Milano, LNS] We will continue our efforts to construct EDFs fully based on *ab initio* input, after our first encouraging results based on the Local Density Approximation [Mi2]. EDF gradient and spin-gradient terms will be constrained by *ab initio* calculations of nuclear matter perturbed by a weak, periodic potential. We will also consider using reverse engineering (A. Liardi et al., PRC 105, 034309, 2022) techniques in this context and build new EDFs based on general theoretical guidelines and constrained by current experimental data. Precise measurements of the weak charge and radius via parity violating electron scattering by nuclei will be used [P.-G. Reinhard et al. Phys. Rev. Lett. 129, 232501 (2022); ibid. 127, 232501 (2021)] to constrain and improve EDFs. Cluster degrees of freedom will be explicitly incorporated within the relativistic EDF framework, in a full covariant and self-consistent scheme, based on the many-body Dirac equations. The two-nucleon systems will be considered as a first step, to embed at once a quasi-deuteron modelization of SRCs.

[Units: Milano, Catania, LNS, Trento] a) We plan to develop an angular momentum projection on top of Skyrme-QRPA calculations, in order to extract reliable information on the nuclear response of intrinsically deformed nuclei. b) The impact of beyond mean-field correlations on collective excitations (giant resonances and PDR [CT5]) and the associated bulk nuclear matter parameters [Mi1], will be studied within the

QRPA+PVC (see the recent study on the Giant Monopole Resonance, Z.Z. Li et al., arXiv:2211.01264) and the Second RPA (see [LNS4] for a study on the Gamow-Teller strength). The two approaches are also very promising in the context of the single- and double-beta decay, for which we plan to evaluate both hadronic and leptonic matrix elements in an *ab initio* framework (T. Morresi et al., Adv. Theory Simul. 11/2018). c) Double charge-exchange (DCE) and competing multi-nucleon transfer reactions will be studied in the framework of DWBA and CC approaches. The structure kernel is provided by EDF or SM calculations and the corresponding predictions will be compared. DCE Nuclear Matrix Elements (NME), important also for their analogies with neutrino-less double beta decay NMEs, can be singled out from cross section calculations [LNS1] and constrained by experimental data. d) Systematic Hartree-Fock calculations of single-Lambda hypernuclei will be performed by using the Gogny force for both nucleon-nucleon and YN interactions, whose parameters will be obtained by fitting experimental Lambda binding energies of hypernuclei.
[Unit: Catania] N=Z nuclei are characterized by the appearance of alpha-like correlations ("quartets") induced by the proton-neutron pairing force [CT1]. Such correlations produce "anomalies" in experiments involving Z=N nuclei, such as elastic alpha-scattering and alpha-decay. We are developing an approach to describe these nuclei in a formalism of quartets [CT2] with special concern to their spectroscopy and the mentioned experiments.
[Unit: Padova] We will merge symmetry methods (discrete and continuous groups) with molecular models of the nucleus, to reach a high qualitative level of description for low-lying and highly excited nuclear states. An accurate description is mandatory to use this information in nuclear reaction codes describing the dynamics of reactions involving cluster nuclei. Computer programs for calculating normal modes of clustered nuclei and for nuclear reaction networks (that might be applied to nuclear astrophysics or to the yield of nuclear reactors) are being written.
[Units: Padova, LNS] We will study low-lying spectroscopy in medium mass isobars, in the regions of heavy zinc isotopes and neighbouring nuclei. More in general, refined interactions for SM calculations will be derived for related studies of neutron-rich nuclei.

[Units: Milano, Padova, LNS] Transfer reactions in weakly bound nuclei and the population of low-lying resonances in the continuum will be studied taking into account the effects of the coupling with collective core excitation. Moreover, the phenomenological nucleus-nucleus optical potentials discussed in WP3 will be employed to describe nuclear breakup reactions involving exotic projectiles, in order to extract their spectroscopic information.

WP3: Nuclear matter under extreme conditions: from nuclear dynamics to compact objects

[Units: LNS, Catania] We plan to investigate dissipative HICs, with the aim of inferring the EoS of asymmetric nuclear matter. The reaction dynamics will be described within upgraded time-dependent approaches (transport theories), employing EDFs, as in structure studies, and incorporating many-body correlations and clustering effects. We will take advantage of recent developments on EDFs including (quasi-)clusters as explicit degrees of freedom, which reproduce the features of clustered nuclear matter at sub-saturation densities and also account for the existence of SRCs in the neighbourhood of saturation density [LNS2]. The extension of this approach to finite temperature will lead to new applications of broad scope, concerning both astrophysics and the general features of HIC dynamics. We also intend to pursue ongoing efforts to verify the consistency among different transport approaches currently available, to minimise the model-dependence, and to undertake a comprehensive analysis of new experiments, from light-cluster to meson production, exploring different density regimes [CT3; M.Colonna et al., PRC 104,024603 (2021)].

[Units: LNS, Milano] Advanced statistical (e.g, Bayesian) analyses to combined astrophysical and terrestrial (nuclear structure and reactions) constraints, making use of the available model predictions, will allow to achieve an improved, multi-verified understanding of the EoS.

[Unit: LNS] Radioactive exotic beams are produced only in limited ranges of energies, thus no reliable phenomenological nucleus-nucleus OPs exist [LNS5]. Usually, double folding potentials using theoretical densities and either phenomenological nucleon-nucleon interactions or microscopic G-matrices, are employed. We have developed an alternative single folding method which uses theoretical densities for the projectile and our phenomenological nucleon-target potentials. We propose a systematic construction of such potentials for exotic projectiles and their application to the theory of nuclear breakup to extract spectroscopic information.

[Units: Catania] An extensive comparison of CoMD calculations with experimental data concerning the dipolar signal in reactions with different degrees of centrality will be performed. This comparison aims to extend previous studies, where an evaluation of parameters of the iso-vectorial interaction was obtained. In future studies, larger values of the effective densities (with respect to the saturation value) can be explored.

WP4: Emerging computational technologies: quantum information and machine learning techniques

[Unit: Trento] Scalable quantum algorithms for applications in *ab initio* nuclear physics as well as their deployment on current quantum technologies will be designed, leveraging the existing agreement between INFN, CERN and IBM. The specific needs of simulations in nuclear physics, (e.g. explicit spin-isospin dependent interactions and three-nucleon forces), pose a unique challenge in the design of efficient algorithms to prepare low energy states and to study both near and far from equilibrium dynamics. New techniques will be studied for the preparation of the initial states for nuclear reactions. We plan to explore in detail different possible encodings of pion-less effective theory and compare their effectiveness for light-nuclei where independent benchmark calculations could be performed by available classical means. We will also study the flavor evolution of neutrinos in dense astrophysical environments, initiating more direct explorations of fully out of equilibrium phenomena like thermalization. We also plan to exploit advances in classical simulation strategies based on QMC methods to extract information about entanglement properties of light nuclei and infinite nuclear matter to characterize many-nucleon correlations, determining how they depend on the resolution scale of the theory.

[Unit: Trento] We aim to expand the range of applicability of variational MC methods based on neural network quantum states (VMC-NQS). These methods allow for accurate parameterization of nuclear wave functions, in contrast to conventional diffusion MC methods, which only provide MC samples of the wave functions. Our primary focus will be on systematic calculations of binding energies and radii for selected stable and exotic nuclei containing up to A=40 nucleons, using pion-less effective field theory Hamiltonians and carefully analyzing the convergence of the theory. In addition, we will utilize currents derived consistently within pion-less effective field theory to compute electroweak transitions in these nuclei and compare the results with available experimental data.

[Unit: Milano] The use of neural network quantum states to represent the wave function and propagators will be extended to large nuclei, using chiral EFT Hamiltonians in momentum or coordinate space. We aim at exploiting lattice representations of the network that can hold up to about A=100 nucleons, and will first focus on ground states, possibly deformed.

[Unit: Catania] We intend to employ feed-forward artificial neural network networks to determine the astrophysical S-factor extrapolated to low energies for reactions of astrophysical interest such as 14N(p,gamma)15O which plays a crucial role for the energy production of massive main sequence stars and the detailed understanding of the neutrino spectrum from the sun.

Section III:

List of the most significant publications of the last five years of each Research Unit related to the proposal (up to 5 publications for each Unit)**:**

- INFN Unit Bologna

    1. [Bo1] *“Elastic Proton Scattering off nonzero spin nuclei*”, M. Vorabbi. M. Gennari, P. Finelli, C. Giusti, P. Navratil, R. Machleidt, Phys. Rev. C 105, 014621 (2022)
    2. [Bo2] “*Ab-initio computation of charge densities for Sn and Xe isotopes*”, P. Arthuis, C. Barbieri, M. Vorabbi, P. Finelli, Phys. Rev. Lett. 125, 182501 (2020)
    3. [Bo3] “*Elastic Anti-Proton Scattering form Chiral Forces*”, M. Vorabbi, M. Gennari, P. Finelli, C. Giusti P. Navratil, Phys. Rev. Lett. 124, 162501 (2020)
    4. [Bo4] “*Impact of Three-Body Forces on Elastic Nucleon-Nucleus Scattering Observables*”, M. Vorabbi, M. Gennari, P. Finelli, C. Giusti P. Navratil, R. Machleidt, Phys. Rev. C 103, 02460 (2021)
    5. [Bo5] “*Incorporating the weak mixing angle dependence to reconcile the neutron skin measurement on Pb208 by PREX-II*”, M.A. Corona, M. Cadeddu, N. Cargioli, P. Finelli, M. Vorabbi,   Phys. Rev. C 105, 055503 (2021)

- INFN Unit Catania

    1. [CT1] “*α-Like quartetting in the excited states of proton-neutron pairing Hamiltonians*”, M. Sambataro and N. Sandulescu, Phys. Lett. B 820, 136476 (2021)
    2. [CT2] “*Band-like structures and quartets in deformed N = Z nuclei*“, M. Sambataro and N. Sandulescu, Phys. Lett. B 827, 136987 (2022)
    3. [CT3] “*Transport model comparison studies of intermediate-energy heavy-ion collisions*”, H. Wolter, M. Colonna et al., Progress in Particle and Nuclear Physics 125,103962 (2022)
    4. [CT4] “*Machine learning light hypernuclei*”, I. Vidana, Nucl. Phys. A 1032, 122625 (2023)
    5. [CT5] "*Theoretical studies of Pygmy Resonances*", E.G. Lanza, L. Pellegri, A. Vitturi, M.V. Andrés, Progress in Particle and Nuclear Physics 129, 104006 (2023)

- INFN Unit LNS

    1. [LNS1] “*Two-step description of heavy ion double charge exchange reactions*”, J.I. Bellone, S. Burrello, M. Colonna, J.A. Lay, H. Lenske, Phys.Lett.B 807, 135528 (2020)
    2. [LNS2] “*Embedding short-range correlations in relativistic density functionals through quasi-deuterons*”, S. Burrello, S. Typel, Eur. Phys. J. A58, 120 (2022).
    3. [LNS3] “*Shell-model study of calcium isotopes toward their drip line*”, L. Coraggio et al., Phys. Rev. C 102, 054326 (2020)
    4. [LNS4] "*Gamow-Teller Strength in 48Ca and 78Ni with the Charge-Exchange Subtracted Second Random-Phase Approximation*", D. Gambacurta, M. Grasso, J. Engel, Phys. Rev. Lett. 125, 212501 (2020)
    5. [LNS5] “*Quenching of single-particle strength from direct reactions with stable and rare-isotope beams*”, T. Aumann, C. Barbieri, D. Bazin, C. A.

Bertulani, A. Bonaccorso et al., Prog. Part. Nucl. Phys. 118, 103847 (2021)

- INFN Unit Milano
    1. [Mi1] “*Nuclear equation of state from ground and collective excited state properties of nuclei*”, X. Roca-Maza, N. Paar, Prog. Part. Nucl. Phys. 101, 96 (2018)
    2. [Mi2] “*Nuclear energy density functionals grounded in ab initio calculations*”, F. Marino, C. Barbieri, A. Carbone, G. Colò, A. Lovato, F. Pederiva, X. Roca-Maza, and E. Vigezzi, Phys. Rev. C 104, 024315 (2021)
    3. [Mi3] “*Quantum entanglement in nuclear Cooper-pair tunneling with gamma rays*”, G. Potel, F. Barranco, E. Vigezzi, R.A. Broglia, Phys. Rev. C 103, 021601 (2021)
    4. [MI4] “*Nuclear Density Functional Theory*”, G. Colò, Adv. Phys. X, 5. 1740061 (2020)
    5. [Mi5] “*Ab Initio Computation of Charge Densities for Sn and Xe Isotopes*”, P. Arthuis, C. Barbieri, M. Vorabbi, P. Finelli, Phys. Rev. Lett. 125, 182501 (2020)

- INFN Unit Padova
    1. [Pd1] "*The 29F nucleus as a lighthouse on the coast of the island of inversion*", L. Fortunato, J. Casal, W. Horiuchi, Jagjit Singh, and A. Vitturi, Commun. Phys. 3, 132 (2020)
    2. [Pd2] ``*Quantum phase transitions in algebraic and collective models of nuclear structure*'', L. Fortunato, Prog. Part. Nucl. Phys. 121, 103891 (2021)
    3. [Pd3] “*Pairing enhancement in a two-neutron transfer process through the continuum*", G. Singh, L. Fortunato and A. Vitturi, Phys. Lett. B 834, 137413 (2022)
    4. [Pd4] “*First Evidence of Axial Shape Asymmetry and Configuration Coexistence in ^{74}Zn: Suggestion for a Northern Extension of the N=40 Island of Inversion*”, M. Rocchini, P.E. Garrett, M. Zielinska, S.M. Lenzi, et al. Phys.Rev.Lett. 130, 122502 (2023)
    5. [Pd5] “*Mirror energy differences above the $0f_{7/2}$ shell: First γ-ray spectroscopy of the T_z=-2 nucleus ^{56}Z*”, A. Fernandez, A.Jungclaus, P.Doornenbal, M.A.Bentley, S.M.Lenzi, et al., Phys.Lett. B 823, 136784 (2021)

- INFN Unit TIFPA-Trento
    1. [Tn1] “*Variational Monte Carlo Calculations of Nuclei with an Artificial Neural-Network Correlator Ansatz*”, C. Adams, G. Carleo, A. Lovato, N. Rocco, Phys. Rev. Lett. 127, 022502 (2021)
    2. [Tn2] “*Ab Initio Study of (nu_l, l^-) and (bar nu_l, l^+) Inclusive Scattering in 12C: Confronting the MiniBooNE and T2K CCQE Data*”, A. Lovato, J. Carlson, S. Gandolfi, N. Rocco, R. Schiavilla, Phys. Rev. X 10, 031068 (2020)
    3. [Tn3] “*Dynamic linear response quantum algorithm*”, A. Roggero, J. Carlson, Phys Rev C 100, 034610 (2019)
    4. [Tn4] “*Standard model physics and the digital quantum revolution: thoughts about the interface*”, N. Klco, A. Roggero, M.J. Savage, Rep. Progr. Phys. 85, 064301 (2022)
    5. [Tn5] “*Optimal control for the quantum simulation of nuclear dynamics*”, E.T. Holland, K.A. Wendt, K. Kravvaris, X. Wu, W.E. Ormand, J.L. DuBois, S. Quaglioni, F. Pederiva, Phys Rev A 101, 062307 (2020)

List of the main national or international collaborations related to the proposal:

Theory collaborations

Belgium

- *University of Brussels, Bruxelles, Belgio:* (P. Descouvemont, J. Dohet-Eraly)

Canada

- *TRIUMF, Vancouver:* (P. Navratil)
- *University of Toronto: (N. Wiebe)*

China

- *Lanzhou University:* (Y. Niu)
- *North China Electric Power University:* (L.G. Cao)
- *Peking University:* (Furong Xu)
- *South China Normal University-Guangzhou:* (Yuanzhuo Ma)

Croatia

- *Zagreb University:* (N. Paar)

France

- *CEA Saclay:* (T. Duguet, V. Somà, A. Porro)
- *CEA France:* (A. Pastore)
- *CNRS/IN2P3, IJCLab*: (M. Grasso, D. Lacroix, P. Napolitani,E. Khan)
- *IPHC Strasbourg:* (F. Nowacki, K. Sieja)
- *LPC Caen:* (F. Gulminelli)

Germany

- *Dept. fur Physik, Universitat Munchen:* (H.H. Wolter)
- *Erlangen University:* (P.G. Reinhard)
- *GSI-Darmstadt:* (R. Mancino)
- *Honda Research Institute Europe GmbH:* (S. Schmitt)
- *Institut für Kernphysik, Technische Universität, Darmstadt:* (S. Typel)
- *University of Giessen:* (H. Lenske)
- *University of Mainz M. Gorchtein:* (Johannes Gutenberg)
- *University of Johannes Gutenberg:* (W. Jiang, J. Sobczyk,)

India

- *Deenbandhu Chhoturam University of Science and Technology, Murthal, Sonepat, Haryana:* (R. Kumar)

Italy

- *ECT* Trento: (*D. Binosi)
- *UNICampania and INFN-NA:* (L. Coraggio, G. De Gregorio,N. Itaco)

- *Università di Pavia: (C. Giusti)*
- *Università di Trento:* (P. Hauke)

Japan

- *Aizu University:* (H. Sagawa)
- *Kyoto University:* (K. Hagino)
- *Kyushu University-Fukukoa:* (T. Fukui)
- *Osaka, RNCP:* (W. Horiuchi)
- *RIKEN:* (T. Oishi)
- *Tokyo University:* (H.Z. Liang,,T. Otsuka, T. Naito,)

Romania

- *ELI-NP, Bucharest:* (C.J. Yang)
- *Nat. Inst. Phys. and Nuc. Eng., Bucharest:* (V.Baran,T. Popa, N. Sandulescu)

Spain

- *Univ. Aut. Madrid:* (A. Poves)
- *Univ. Barcelona:* (M. Centelles, X. Vinas, A Rios-Huguet, J. Menendez)
- *Univ. Huelva*: (F. Perez-Bernal)
- *Univ. Sevilla:* (C.E. Alonso, M. V. Andrés, J.M.Arias, F. Barranco, J. Gomez-Camacho, J. A. Lay, A. Moro, J, Casal)

Sweden

- *Lund University:* (A.Idini)

Switzerland

- *CERN:* (M. Grossi**)**
- *IBM, Zurich:* (A. Miessen, F. Tacchino, I.Tavernelli)
- *Univ. of Geneve:* (O. Kiss)

United Kingdom

- *University of York:* (M. Bentley)
- *University of Surrey:* (E. Yüksel, M. Vorabbi)

United States

- *Argonne National Laboratory:* (R.B. Wiringa)
- *California Berkeley University,:* (E. Rrapaj)
- *Fermilab*: (G.N. Perdue, A.C. Li, D.M. Kurkcuoglu, N. Rocco)
- *Florida State University, Tallahassee:* (J. Piekarewicz, A. Volya)
- *IBM, USA:* (M. Motta, J. Cohn)
- *Institute for Nuclear Theory, Seattle:* (M.J. Savage, V. Cirigliano, F. Turro, R. Baskhar)
- *Lawrence Berkeley Laboratory:* (G. Potel)

- *Lawrence Livermore National Laboratory:* (J.L. Dubois, K. Kravvaris, S. Quaglioni, K.A. Wendt, X. Wu)
- *Los Alamos National Laboratory:* (J. Carlson, S. Gandolfi, J.D. Martin, D. Neill, R. Gupta)
- *Michigan State University:* (M. Hjorth-Jensen,D. Lee, J. Watkins)
- *North Carolina University:* (Jonathan Engel)
- *Oak Ridge National Laboratory:* (A.Baroni)
- *Texas AM:* (C.A. Bertulani)
- *University of New Mexico:* (H. Duan)
- *Washington University, St. Louis:* (R. Charity, L. Sobotka)
- *Washington University , Seattle:* (S.C. Hsu)

Other Collabarations

- *Transport Model Evaluation Project (TMEP) collaboration*

Experimental collaborations

- *Asfin collaboration, LNS Italia*
- *Chimera Collaboration, LNS Italia*
- *CHIRONE - NUCLEX collaboration INFN-Catania and LNS-Catania*
- *GAMMA Experiment, INFN, Italy*
- *INDRA-FAZIA international collaboration*
- *LAND-Chimera collaboration, GSI Darmstadt, Germania*
- *MAGNEX and NUMEN collaboration, LNS Italia*
- *SπRIT international collaboration*
- *Australian National University-Canberra, Australia:* (A. E. Stuchbery, T. G. Gray)
- *CSIC, Madrid, Spain:* (A. Jungclaus)
- *i-Themba, Capetown, South Africa:* (R. Neveling, L. Pellegri)
- *Oak RIdge NL, USA:* (J.M. Allmond)
- *Research Center for Nuclear Physics ,Osaka, Japan:* (A. Tamii)
- *RIKEN, Japan:* (T. Suda)
- *Technische Universität Darmstadt, Germany:*(T. Aumann, A. Obertelli, P. von Neumann-Cosel)
- *Thomas Jefferson National Accele*rator Facility, Newport News, USA: (J.M. Grames)